

UC Riverside

UC Riverside Electronic Theses and Dissertations

Title

Search For Heavy, Neutral Gauge Bosons Decaying To Boosted Top Quark Pairs At The LHC

Permalink

<https://escholarship.org/uc/item/6gp975z3>

Author

Babb, John

Publication Date

2012

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Search For Heavy, Neutral Gauge Bosons Decaying To Boosted Top Quark Pairs At The
LHC

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

John Michael Babb

September 2012

Dissertation Committee:

Dr. Stephen Wimpenny, Chairperson

Dr. Robert Clare

Dr. John Ellison

Copyright by
John Michael Babb
2012

The Dissertation of John Michael Babb is approved:

Committee Chairperson

University of California, Riverside

Acknowledgements

Innumerable thanks to Steve Wimpenny, the best adviser a ne'r-do-well graduate student could ask for. Thanks for all the jokes and talks and advice and motivation. Thanks to Bob Clare and John Ellison for enduring my defense talk and not giving it the scorn it probably deserved.

Thanks to Ryan and Nick and Jordan for countless taco nights and "working meetings" at R1 at CERN. Thanks to Ryan and Jared for some of the finest bike trips and hikes that the Rhone Valley and surrounding mountains have to offer.

Thanks to Matt and Jared and Arun for thirsty thursdays and for keeping things fun in the Physics Building and for making work not feel like work and to Mark for long chats about life over golf.

Thanks to Shih Chuan for being the finest roommate at CERN that one could ask for and for letting me pick his brain every night over cheese and wine.

Thanks to Mark for letting me live in and abuse his condo for a number of years and for all the nights of poker played during that time.

To Elizabeth, for all your love and encouragment and sarcasm. Thank you for all of the joy you have brought me and for always pushing me to do my best in everything.

Thanks to my parents for all the love and encouragement. Thanks for never judging me when I want to do stupid things...like get a PhD in physics.

To Mom and Dad. Thanks for all the sandwiches...

ABSTRACT OF THE DISSERTATION

Search For Heavy, Neutral Gague Bosons Decaying To Boosted Top Quark Pairs At The LHC

by

John Michael Babb

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, September 2012
Dr. Stephen Wimpenny, Chairperson

One of the important early searches at the Large Hadron Collider at CERN is for high mass Z -like objects. Such objects are predicted in a number of extensions to the Standard Model and the analyses may become sensitive to their decays at fairly modest integrated luminosities. This thesis describes a search for a neutral, heavy gague boson decaying into boosted top quark pairs using the first 5.0 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ data from the 2011 physics run of the LHC. By exploiting the semi-muonic decays of the top pairs: $t\bar{t}X \rightarrow \mu\nu q\bar{q}b\bar{b}$, and using boosted decision trees to perform the final event selection we set upper limits on the cross section of a heavy, Z -like gague boson of $\sim 5 \text{ pb}$ at the lowest masses (500 GeV) to less than 1 pb for masses above 1 TeV.

Contents

List of Tables	xi
List of Figures	xiv
1 The Standard Model	1
1.1 Quarks and Leptons	2
1.2 Particle Interactions	6
1.3 The Top Quark	12
2 Z' Theory and Phenomonology	17
2.1 The model-independent Z'	17
2.2 Z' constraints from electroweak precision data	22
2.3 Direct searches from the Tevatron	24
3 The Large Hadron Collider	27
3.1 Injection System	31
3.1.1 LHC Filling Scheme	37

3.2	Magnets	39
3.3	RF Systems	43
3.4	Interaction Points	45
4	The CMS Detector	48
4.1	Silicon Tracking System	51
4.2	Electromagnetic Calorimeter	54
4.3	Hadronic Calorimeter	59
4.4	Superconducting Solenoid	62
4.5	Muon System	63
4.6	Trigger	67
5	Event Simulation	70
6	Lepton Isolation and Event Preselection	72
6.1	Isolated Muon Identification for $\sqrt{s} = 10$ TeV	72
6.1.1	Complications due to Energy Loss	75
6.1.2	Alternative muon identification methods for Z' events	76
6.1.3	2D Cut Optimization	86
6.1.4	Fake Muon Background Determination	89
6.1.5	Use with particle flow reconstruction	92
6.1.6	Application to electrons	93
6.1.7	Optimization for 7 TeV data	95

6.1.8	Jet p_T thresholds	95
6.1.9	Cut optimization	97
6.1.10	Results	97
6.1.11	Lepton Selection Efficiencies	101
6.2	Event Preselection	103
6.2.1	Trigger	106
6.2.2	Primary Vertex	107
6.2.3	Muons	107
6.2.4	Electrons	109
6.2.5	Jets	109
6.2.6	Missing Transverse Energy	110
6.2.7	b -jets	113
6.3	Monte Carlo Datasets	116
7	Validation of the Data Modeling	118
8	Top Quark Reconstruction	127
8.1	Leptonic W Reconstruction	128
8.2	Jet Selection	130
8.3	Reconstruction Validation	132
9	Boosted Decision Trees	137
9.1	BDT Definition	138

9.1.1	Growing	138
9.1.2	Boosting	140
9.1.3	Pruning	141
9.2	Implementation	142
9.3	Optimization of the BDT Classifier Cut	150
10	Final Event Selection	154
11	Systematic Error Analysis	159
11.1	Rate-changing uncertainties	160
11.2	Shape-changing uncertainties	161
12	Limits on a Narrow Width Z'	169
12.0.1	Statistical Implementation	169
12.0.2	Results	173
13	Conclusion	176
	Bibliography	177

List of Tables

1.1	Properties of leptons and quarks.	3
3.1	LHC beam characteristics at nominal running	30
3.2	LHC proton beam parameters from LINAC2	34
3.3	PS beam characteristics at extraction	35
3.4	SPS beam characteristics at extraction	37
3.5	LHC beam configurations	45
3.6	LHC IP configurations	45
4.1	Parameters of the CMS superconducting solenoid	63
5.1	Datasets used to model signal and background	71
6.1	Signal and background acceptances for various ΔR_{min} cuts	84
6.2	Signal and background acceptances for various $p_T^{rel}(\mu, jet)$ cuts	84
6.3	Signal acceptances for various p_T^{rel} and ΔR_{min} cuts for the 2 TeV Z' sample .	89

6.4	Background rates for various p_T^{rel} and ΔR_{min} cuts for the 2 TeV internal background	90
6.5	Fake muon rates per jet $E_T > 30$ GeV for Standard Model $t\bar{t}$ production and Z' events with mass between 1 TeV and 4 TeV.	91
6.6	Fake muon rates per jet $E_T > 30$ GeV in low and high $\hat{s}$ inclusive muon events.	91
6.7	Signal muon acceptance for RelIso compared with the 2D Cut for both CMSSW 226 and 361	99
6.8	Fake muon rates per jet with $p_T \geq 30 GeV$	100
6.9	2D Cut efficiencies in simulation (MC) and data.	103
6.10	Signal and background datasets used CMSSW_2_2_6	116
6.11	Signal and background datasets used in CMSSW_3_6_1	117
6.12	Signal and background datasets used in the event preselection optimization.	117
7.1	Summary of theoretical cross-sections.	118
7.2	Final scale factors for simulation processes.	126
8.1	Parameters and resolutions used in the χ^2 calculations.	131
9.1	Full list of BDT training variables ordered by initial training ranking.	144
9.2	Reduced list of BDT training variables ordered by final training ranking.	150
9.3	Limit results for various BDT classifier cuts.	151
10.1	Event yields and uncertainties for each MC channel	158

11.1	Summary of sytematic uncertainties.	165
11.2	Jet energy resolution scale factors and errors.	168
11.3	Q^2 and factorization/renormalization nominal values and variations.	168
12.1	95% CLs upper limits on the Z' cross-section for selected mass points com- pared to expectations from a model for a Topcolor Leptophobic Z'	173

List of Figures

1.1	A table of Standard Model particles	2
1.2	Quark decays in the Standard Model	7
1.3	One photon exchange between an electron and a positron.	9
1.4	Rutherford scattering between an Alpha particle and a nucleus.	10
1.5	A Feynmann diagram of nuclear beta-decay	10
1.6	Main Top quark pair production mechanisms.	12
1.7	A semi-leptonic top quark pair decay.	13
1.8	Top pair branching fractions.	13
1.9	An detector view of a semi-leptonic top pair decay.	15
1.10	Standard model single top quark production mechanisms.	16
1.11	Examples of Standard Model backgrounds.	16
2.1	A four-fermion contact interaction.	23
2.2	Results from the D0 collaboration in the $Z' \rightarrow e^+e^-$ channel.	25
2.3	Results from the CDF collaboration in the $Z' \rightarrow \mu^+\mu^-$ channel.	26

3.1	The LHC ring as seen from overhead	28
3.2	The LHC ring and experiments as seen from underground	28
3.3	The LHC ring and experiments as seen from underground	31
3.4	The CERN accelerator complex	32
3.5	The CERN Linac2 linear accelerator.	34
3.6	PSB-PS transfer schemes: PS single-batch filling for SPS physics (top), PS two-batch filling for LHC (bottom).	38
3.7	Proton bunches in the PS, SPS and one LHC ring.	39
3.8	Magnetic field curve for NbTi.	40
3.9	Cross-section of an LHC dipole magnet.	41
3.10	Magnetic field of an LHC dipole magnet.	42
3.11	RF four-cavity cryomodule	43
3.12	An assembled RF module	44
3.13	Beam optics at IP1 and IP5	46
3.14	An extended view of the right side of the insertion region at IP1	47
3.15	An extended view of the left side of the insertion region at IP3	47
4.1	A 3-D view of the CMS detector	50
4.2	Particle identification in CMS	51
4.3	Simulation of a Higgs boson decaying to 4 muons in the CMS detector	52
4.4	View of the CMS silicon tracker	52
4.5	Layout of the silicon tracker in CMS	53

4.6	One PbWO_4 ECAL crystal	55
4.7	Layout of the CMS electromagnetic calorimeter	56
4.8	ECAL energy resolution as a function of electron energy	57
4.9	HCAL transverse energy resolution as a function of jet transverse energy for three regions of the HCAL	58
4.10	Layout and lateral segmentation of the CMS Hadronic Calorimeter	59
4.11	Picture of completed hadronic calorimeter cells	62
4.12	A computer model of the CMS solenoid	64
4.13	A side view of the CMS muon system and the iron return yoke	64
4.14	A view of one of the disks in the Endcap Muon System	65
4.15	Momentum resolution in CMS in the barrel region (left) and endcap region (right)	67
4.16	The CMS Level-1 trigger architecture	68
6.1	Muon selection efficiency as a function of RelIso threshold.	73
6.2	Rejection efficiency as a function of uncorrected jet E_T threshold for veto cone jets in $W \rightarrow \mu\nu$ decays from $t\bar{t}$ events.	77
6.3	Separation of the muon and the nearest jet in decays in $W \rightarrow \mu\nu$ events. a) no suppression and b) with 15 GeV threshold suppression of veto cone jets . .	77
6.4	Comparison of the μ spectra from W and b-decays in the 2 TeV Z' events in terms of: a,b) $\Delta R_{min}(\mu, jet)$, c,d) $p_T^{rel}(\mu, jet)$, e,f) $\Delta R_{min}(\mu, jet)$ vs $p_T^{rel}(\mu, jet)$	80

6.5	Comparison of the μ spectra from W and b-decays in the 2 TeV Z' events in terms of: a,b) $m(\mu \text{ jet})$ and c,d) p_T^{rel}/p	81
6.6	$\Delta R_{min}(\mu, jet)$ spectra in 2 TeV Z' events for a) $b \rightarrow \mu X$ b) $c \rightarrow \mu X$ c) π/K in-flight decays and d) combined background	83
6.7	$p_T^{rel}(\mu, jet)$ spectra in 2 TeV Z' events for a) $b \rightarrow \mu X$, b) $c \rightarrow \mu X$, c) π/K in-flight decays and d) combined background	85
6.8	$p_T^{rel}(\mu, jet)$ vs $\Delta R_{min}(\mu, jet)$ for muons from W -decay (black points) and background (blue points)	86
6.9	Signal acceptance as a function of p_T^{rel} and ΔR_{min} for a) 1 TeV, b) 2 TeV, c) 3 TeV, d) 4 TeV	88
6.10	Background rate as a function of p_T^{rel} and ΔR_{min} for a) 1 TeV, b) 2 TeV, c) 3 TeV, d) 4 TeV, e) InclusiveMuon15, f) InclusiveMuon5pt350	89
6.11	2D Cut selection efficiency (blue points) and RelIso selection efficiency (red points) for $\sqrt{s} = 10$ TeV.	90
6.12	ΔR_{min} Vs p_T^{rel} for a.) PAT layer1 muons and b.) particle flow muons	92
6.13	ΔR_{min} vs p_T^{rel} for a.) particle flow muons and b.) particle flow electrons	94
6.14	ΔR_{min} vs p_T^{rel} for a.) calorimeter electrons and b.) particle flow electrons	94
6.15	ΔR_{min} vs p_T^{rel} for jet comparison p_T thresholds of a.) 30 GeV and b.) 20 GeV for calorimeter muons and jets.	96
6.16	ΔR_{min} vs p_T^{rel} in a.) CMSSW 361 b.) CMSSW 226	98

6.17	Signal acceptance rate as a function of ΔR_{min} and p_T^{rel} for a.) $t\bar{t}$ b.) $Z'(1$ TeV) c.) $Z'(2 \text{ TeV})$ d.) $Z'(3 \text{ TeV})$	99
6.18	Background acceptance rate as a function of ΔR_{min} and p_T^{rel} for a.) $t\bar{t}$ in- ternal background b.) $Z'(2 \text{ TeV})$ internal background c.) InclusiveMu 15 d.) InclusiveMu 5pt50 e.) InclusiveMu 5pt150 f.) InclusiveMu 5pt250	100
6.19	Comparison of 2D Cut and RelIso signal efficiencies in a.) CMSSW 361 b.) CMSSW 226	101
6.20	Muon selection efficiency in Z^0 MC as a function of a) $p_T^{rel}(\mu, jet)$, b) $\Delta R_{min}(\mu, jet)$, c) η_μ , d) p_T^μ	104
6.21	Muon selection efficiency in data as a function of a) $p_T^{rel}(\mu, jet)$, b) $\Delta R_{min}(\mu, jet)$, c) η_μ , d) p_T^μ	105
6.22	Leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.	111
6.23	Second leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events. . .	112
6.24	Third leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events. . . .	113
6.25	Missing Transverse Energy for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.	114
7.1	Control plots for ≥ 2 b-tag events using only theory cross section.	120
7.2	Control plots for ≥ 2 b-tag events after scaling $t\bar{t}$	121
7.3	Control plots for 1 b-tag events after scaling $t\bar{t}$	122
7.4	Control plots for 1 b-tag events after scaling $t\bar{t}$ and W/Z + jets.	123
7.5	Control plots for preselection prior to scaling.	124

7.6	Control plots for preselection after scaling.	125
8.1	A detector view of a semi-leptonic top pair decay.	127
8.2	Reconstructed mass for leptonic W decays in simulated $t\bar{t}$ events.	130
8.3	a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in SM top quark events.	133
8.4	a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for reconstruction using MC truth (red) and the best permutation (blue) in SM top quark events.	134
8.5	a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in Z' ($m = 1$ TeV) events.	135
8.6	a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in Z' ($m = 1.5$ TeV) events.	136
9.1	A decision tree example	138
9.2	Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.	145
9.3	Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.	146

9.4	Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.	147
9.5	Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.	148
9.6	Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.	149
9.7	Final BDT classifier distribution.	151
9.8	a.) The BDT classifier response of all signal and background events for the test sample. b.) Background rejection Vs. signal efficiency for the test sample, c.) The efficiencies as a function of classifier cut.	152
9.9	Expected CLs limits for event selections passing BDT classifier cuts at a.) -0.1, b.) -0.05, c.) 0.0, d.) 0.05, e.) 0.1, f.) 0.15.	153
10.1	Control plots for the final event selection.	155
10.2	Control plots for the final event selection.	156
10.3	Control plots for the final event selection.	157
10.4	a.) $m_{t\bar{t}}$ spectrum for the final event selection. b.) Log plot of $m_{t\bar{t}}$. Three Z' samples with masses from 1000-1500 GeV are included for reference and are scaled to a cross-section of 50 pb each.	158
11.1	Ratios of systematic V+jets samples with respect to the nominal samples: a.) Matching Down, b.) Matching Up, c.) Scale Down, d.) Scale Up.	166

11.2	Effects on $M_{t\bar{t}}$ in simulated $t\bar{t}$ events due to systematic shifts in a.) BDT classifier cut, b.) b-tagging, c.) jet energy resolution, d.) jet energy scale, e.) monte carlo generator matching, f.) Q^2 —scale.	167
12.1	a.) 95% CLs upper limits on the Z' cross-section. b.) 95% Bayesian limits on the Z' cross-section.	173
12.2	Log plots of a.) 95% CLs upper limits on the Z' cross-section. b.) 95% Bayesian limits on the Z' cross-section.	174
12.3	Comparison of all the CMS $Z' \rightarrow t\bar{t}$ analyses.	175

Chapter 1

The Standard Model

In the last few decades the Standard Model of Particle Physics (SM) [19, 45, 44]¹ has seen remarkable success as a low energy, effective theory of particles and their interactions. The model is based on the $SU(3) \times SU(2) \times U(1)$ gauge group where the $SU(3)$ group describes the interactions of quarks and gluons via the strong nuclear force and the $SU(2) \times U(1)$ group describes the electroweak forces mediated by the weak gauge bosons $W^\pm$, Z^0 and the photon γ .

In a sense the SM can be thought of as the interactions between forces and particles. This is illustrated by the discoveries of the electron by Thompson and the theory of the Electromagnetic field by Maxwell and the further realization that they were different aspects of the same fundamental force. Particle physics during the next 100 years can be summed up by the discovery of two new forces, the strong and weak nuclear forces and complimentary particles

¹Most of this chapter is taken from [19].

that they act on. Fig. 1.1 shows the fundamental constituents of the SM: quarks and leptons, the force carrying particles, and the as yet undiscovered Higgs Boson.

THE STANDARD MODEL						
		Fermions			Bosons	
Quarks		<i>u</i> up	<i>c</i> charm	<i>t</i> top	<i>γ</i> photon	Force carriers
		<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	<i>Z</i> Z boson	
Leptons		<i>ν_e</i> electron neutrino	<i>ν_μ</i> muon neutrino	<i>ν_τ</i> tau neutrino	<i>W</i> W boson	
		<i>e</i> electron	<i>μ</i> muon	<i>τ</i> tau	<i>g</i> gluon	
					<i>Higgs*</i> boson	

*Yet to be confirmed

Source: AAAA

Figure 1.1: A table of Standard Model particles

1.1 Quarks and Leptons

There are two types of matter particles in the SM: quarks and leptons. Both are spin $\frac{1}{2}$ (in units of $\hbar$) and are structureless at currently probed scales. They both interact via the electromagnetic and weak forces, but only the quarks also interact via the strong force. These interactions are described by the Electroweak ($SU(2) \times U(1)$) and Quantum Chromodynamic

Table 1.1: Properties of leptons and quarks.

Lepton	Q/e	Mass (MeV/c)	Lepton Flavor
ν_e	0	$< 2.2 \times 10^{-6}$	$L_e = 1$
e	-1	0.511	$L_e = 1$
ν_μ	0	< 0.17	$L_\mu = 1$
μ	-1	105.66	$L_\mu = 1$
ν_τ	0	< 18.2	$L_\tau = 1$
τ	-1	1777.0	$L_\tau = 1$
Quark	Q/e	Mass (GeV/c)	Quark Flavor
u	+2/3	$1.7 - 3.3 \times 10^{-3}$	N/A
d	-1/3	$4.1 - 5.8 \times 10^{-3}$	N/A
c	+2/3	1.27	$C = 1$
s	-1/3	0.101	$S = -1$
t	+2/3	170.9	$T = 1$
b	-1/3	4.19	$B = -1$

($SU(3)$) parts of the model, respectively. A summary of leptons and quarks and their properties are given in Table 1.1

Decades after the discovery of the electron the first member of a second generation of leptons was discovered. The particle, now called the muon was originally thought to be the particle postulated by Yukawa as the field quantum of the strong nuclear field. However, it was found to interact only weakly and electromagnetically with identical interaction strengths as that of the electron. The third charged lepton, the tau was found much later in 1975 and also replicated the electron interactions.

Further study showed that the 3 generations of leptons are indeed separate particles and not the excited states of some composite system. They all have the same spin ($\frac{1}{2}$) and they do not decay via electromagnetic transitions (of the form $\mu^- \rightarrow e^- + \gamma$) as would be expected if this were the case. The lack of electromagnetic decays (lower bound: 1.2×10^{-11} at the

90% confidence level for $\mu^- \rightarrow e^- + \gamma$) implies there is some other factor involved in lepton decays. This is described by imposing a new constraint called lepton number (L) which must be conserved in all leptonic interactions. If we assign to each lepton the lepton number characteristic of that generation of lepton (i.e. $L_e = 1$ for the electron and electron neutrino and $L_\mu = 1$ for the muon and muon neutrino and $L_{e,\mu} = -1$ for their anti-particles) then we can think about decays and interactions in terms of lepton number conservation. This effect can be seen in β – decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (1.1)$$

where the initial neutron has lepton number $L_e = 0$ and the final state has an electron ($L_e = 1$) and an anti-neutrino of electron flavor with $L_e = -1$.

This description only works if neutrinos also come in 3 flavors (ν_e, ν_μ, ν_τ). An early experiment by Danby *et al* [35] showed that neutrinos from the decay:

$$\pi^- \rightarrow \mu^- + \bar{\nu} \quad (1.2)$$

always produced muons when interacting with matter, providing evidence of flavors of neutrinos. Later experiments involving solar neutrino oscillations [52] established that neutrinos can change from one flavor to another. Neutrinos were once thought to be massless, but because the quantum mechanical states cannot mix if the neutrinos are massless the presence of mixing indicates a non-vanishing neutrino mass.

Quarks also come in three different generations. Each generation is an isospin ($I = \frac{1}{2}$)

doublet with one 'up-type' and one 'down-type' quark per generation. The up and down type quarks have $Q = \frac{2}{3}e$ and $Q = -\frac{1}{3}e$ electric charge, respectively. They also exhibit the characteristic of flavor conservation. Flavor is more complicated than in the case of leptons, however, as there are different colors for each quark and also different flavor conservation rules depending on the type of interaction.

Quarks are not only able to interact weakly and electromagnetically but also strongly. This was seen in the production:

$$\pi^- + p \rightarrow K^0 + \Lambda^0 \quad (1.3)$$

and the subsequent decays:

$$K^0 \rightarrow \pi^+\pi^- \text{ and } \Lambda^0 \rightarrow p\pi^- \quad (1.4)$$

where the initial production is via the strong interaction in associated pairs but the decays of the Λ^0 and the K^0 are independent of each other and done via weak interactions giving them a long lifetime. Independent proposals by Gell-Mann and Nishijima in the mid-1950's attempted to assign a scheme of quantum numbers to hadronic interactions to describe these sorts of decays. A new quantum number called 'strangeness' was assigned to certain particles and was additively conserved in strong interactions and violated in weak interactions. The need for this is seen at the quark level in 1.3 where the quark content of each hadron is:

$$(\bar{u}d) + (uud) \rightarrow (\bar{s}d) + (uds) \quad (1.5)$$

where we have on either side a total strangeness of $S = 0$. The weak decays of the Λ^0 and the K^0 in 1.4 do not conserve strangeness as there are no strange quarks in the final states.

Given the existence of the Strange quark it would be reasonable to expect a fourth quark - the weak isospin partner of the s quark - to complete the second generation. The existence of the Charm quark carrying a new quantum number C was postulated by Glashow, Iliopoulos and Maiani in 1970 with a mass that would be in the 3-4 GeV region. This calculation was then updated at the one-loop level using renormalizable electroweak theory by Gaillard and Lee and predicted a mass of $m_c \approx 1.5$ GeV which was confirmed upon discovery of the J/ψ which was found to be a $c\bar{c}$ composite of around 3.1 GeV.

A third generation of quarks were to be found later, the Bottom (b) and Top (t) quarks with charges $-\frac{1}{3}$ and $\frac{2}{3}$ and flavor $B = -1$ and $T = 1$ respectively.

Quarks decay preferentially within each generation: $c \rightarrow s + e^- + \bar{\nu}_e$ but can also decay via inter-generational decays such as $c \rightarrow d + e^- + \bar{\nu}_e$ which are considerably more suppressed. Fig. 1.2 shows the possible decays of each quark with relative decay strengths.

1.2 Particle Interactions

It was very hard for Maxwell to describe the 'action at a distance' aspect of his equations. They were remarkably successful despite having no conducting medium through which to act except for the 'ether' postulated by many at the time which was eventually given up on

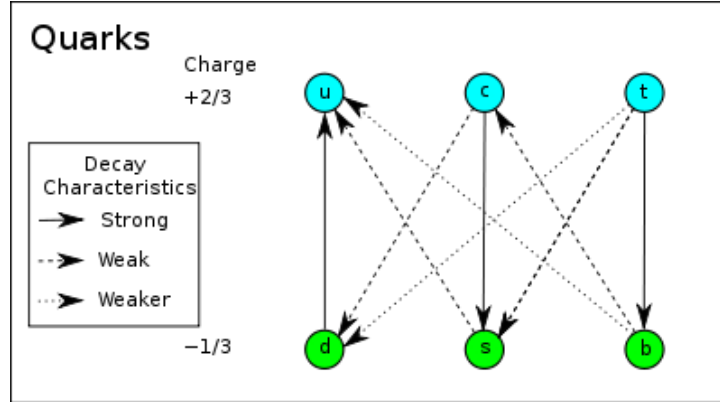


Figure 1.2: Quark decays in the Standard Model

by Maxwell, deciding instead to let his field equations stand on their own. Eventually quantum effects on particles became obvious. With electromagnetic waves showing particle-like aspects as in the Compton effect and particles such as electrons showing wave-like properties such as interference and diffraction it was clear that there was more going on than just Maxwell's theory.

Yukawa's paper in 1935 [70] set the foundations in quantum field theory for particle interactions to be attributed to exchange of virtual quanta which mediate force. Yukawa began by considering what kind of potential would describe a strong interaction between a neutron and a proton. He postulated a potential of the form:

$$U(\mathbf{r}) = \frac{-g_s^2}{4\pi} \frac{e^{-r/a}}{r} \quad (1.6)$$

which would die off sufficiently fast with distance. The ' g_s ' is a charge analogous to the electric charge and ' a ' is a range parameter specific to the force. The potential satisfies the

equation:

$$\left(\nabla^2 - \frac{1}{a^2}\right) U(\mathbf{r}) = g_s^2 \delta(\mathbf{r}) \quad (1.7)$$

then treating $U(\mathbf{r})$ quantum mechanically and adding time-dependance and assuming a plane-wave solution in the form of:

$$U \propto \exp(i\mathbf{p} \cdot \mathbf{r}/\hbar - iEt/\hbar) \quad (1.8)$$

from which we get the energy of the quantum:

$$E = \left[c^2 \mathbf{p}^2 + \frac{c^2 \hbar^2}{a^2} \right]^{1/2} \quad (1.9)$$

which implies the mass of Yukawa's quantum to be: $m_U = \frac{\hbar}{ac}$ and putting in the known range of the n-p interaction (~ 2 fm) gave the mass to be ~ 100 MeV, Yukawa's prediction for the mass of the nuclear force quantum. Wick in 1938 interpreted the relationship $a = \hbar/m_U c$ in terms of the uncertainty principle $\Delta E \Delta t \geq \hbar/2$ relating the distance scale a on which an energy fluctuation ΔE can borrow the energy needed to produce a field quanta. The quanta associated with Yukawa's theory was the pion and was discovered in 1947 with a mass of ≈ 140 MeV. Even though Yukawa's interpretation eventually was not the complete description of what happens in nuclear interactions it help set the framework for what would become quantum field theories of force and particle interactions.

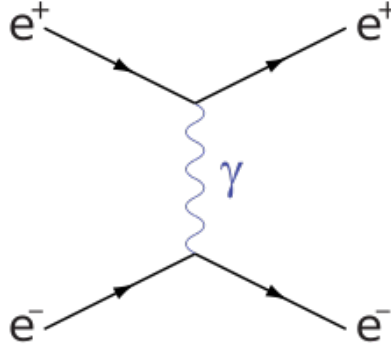


Figure 1.3: One photon exchange between an electron and a positron.

Electromagnetic interactions such as the photon exchange between two leptons seen in Fig. 1.3 may be regarded as a special case of the Yukawa force. The Yukawa force has a scattering cross section of:

$$f(\mathbf{q}) = -\frac{g_s^2}{\mathbf{q}^2 + m_U^2} \quad (1.10)$$

where $\mathbf{q}$ is the momentum transfer of the exchanged quanta. If g_s^2 is replaced by the electromagnetic charge (e) and $m_U \rightarrow m_\gamma = 0$ the scattering potential returns to the Coulomb potential: $U(r) = -\frac{e^2}{4\pi r}$ and the scattering amplitude becomes: $f = e^2/q^2$. These results can be used to understand Rutherford scattering 1.4 if the Alpha particle is scattered elastically off of an infinitely heavy nucleus and the momentum transfer is defined to be the difference in initial and final Alpha particle momentum so that $q^2 = -(\mathbf{k} - \mathbf{k}')^2$ then $q^2 = -2\mathbf{k}^2(1 - \cos \theta) = -4\mathbf{k}^2 \sin^2 \theta/2$ returning the observed $\sin^2 \theta/2$ behavior and implying that Rutherford scattering does indeed take place because of the exchange of a massless photon.

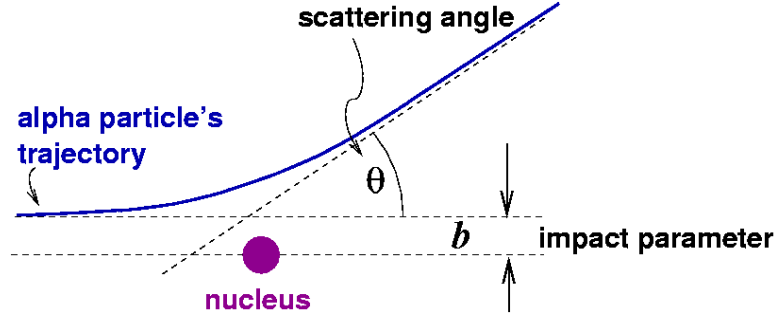


Figure 1.4: Rutherford scattering between an Alpha particle and a nucleus.

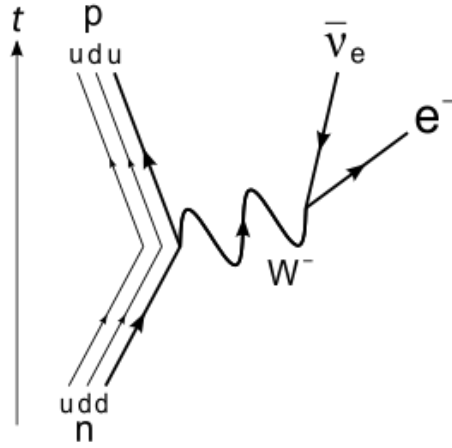


Figure 1.5: A Feynmann diagram of nuclear beta-decay

Yukawa tried to extend his force to in interpretation of the weak force, which mediates interactions like nuclear β -decay , but this was found not to be successful because the masses of the mediating quanta make the range of the weak force much smaller than nuclear dimensions. β -decay, shown in Fig. 1.5, is now known to be mediated at the quark level by the $W^\pm$ -boson as a 'charged current' process. There is also the 'neutral current' process mediated by the Z^0 -boson. Like the photon the $W^\pm$ and the Z^0 are all four-vectors but unlike the photon the W and Z are quite massive with $m_W = 80.4 \text{ GeV}$ and $m_Z = 91.2 \text{ GeV}$. The

massive nature of the gauge boson forces it to only be effective on very small distance scales. Scales normally smaller than that of hadronic matter, causing the weak force to appear so 'weak'. This relative weakness can be seen from another viewpoint. If the amplitudes of electromagnetic and weak interactions are proportional to $g^2/(q^2 + M^2)$ where g is the coupling constant for each interaction, q is the momentum transfer and M is the mass of the gauge boson. If the coupling constants for both interactions are the same order of magnitude then for $q^2 \ll M_W^2$ then the electromagnetic interaction will be much stronger than the weak interaction. But for large q^2 the two processes contribute roughly equally.

The strong interaction is very different from the weak or the electromagnetic force, despite all of them being gauge theories, because of the property of quark confinement. Confinement causes the potential between quarks to increase as the distance between the quarks increases, a remarkably different behavior from the other forces. Eventually as the quarks reach a large enough separation the energy increases to a point where the pair splits and creates a new $q\bar{q}$ -pair. Confinement also keeps quarks from being observed as isolated particles. Quarks bind themselves into hadrons within an interaction volume of 1 fm^3 so that no free quarks are observed. The quantum of the strong force is the gluon, it is similar to the photon in that it has spin-1 and is massless. The gluon also carries the color charge of the strong force. Quarks and gluons all carry a color charge which comes in three different varieties (red, blue and green) giving three different types of each quark - u_r, u_b, u_g for example. Color is not seen by itself because when quarks hadronize they form color-neutral ('white')

states. A simple model for the $q\bar{q}$ potential due to the strong force is of the form:

$$V = -\frac{a}{r} + br \quad (1.11)$$

where the first term dominates at small r and arises from single-gluon exchange and the second term models the confinement at large r .

1.3 The Top Quark

The Top quark was first observed [13, 16] in 1995 by the CDF and d0 collaborations at the Tevatron at Fermilab. It was found to be a $Q = 2/3, S = 1/2$ up-type quark with a mass of ~ 175 GeV, making it by far the most massive elementary particle found at the time. The Top quark was produced in pairs with a cross section of $\sigma \sim 7$ pb at a center of mass energy of 1.98 TeV. At the LHC the larger center of mass energy will mean a larger cross-section of $\sigma \sim 1700$ pb at $\sqrt{s} = 14$ TeV.

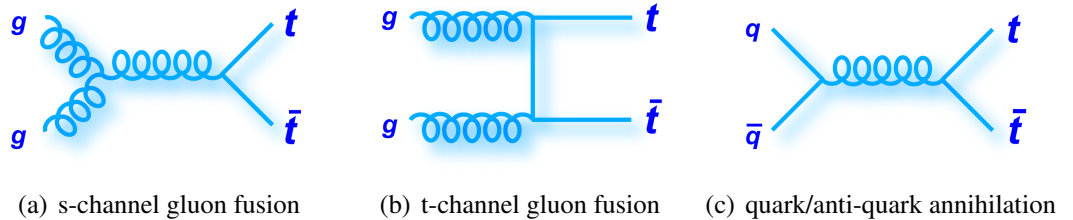


Figure 1.6: Main Top quark pair production mechanisms.

The production mechanisms for $t\bar{t}$ -pairs are shown in Fig. 1.6. The predominant production mechanism for top quarks in p - p collisions at the LHC is from gluon fusion ($\sim 90\%$) with some additional contribution from ($\sim 10\%$) q - $\bar{q}$ annihilation. This is in contrast to Top production at the Tevatron which was $\sim 85\%$ q - $\bar{q}$ annihilation and $\sim 15\%$ gluon fusion.

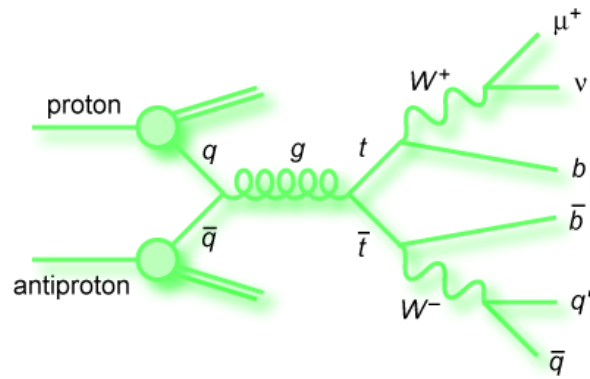


Figure 1.7: A semi-leptonic top quark pair decay.

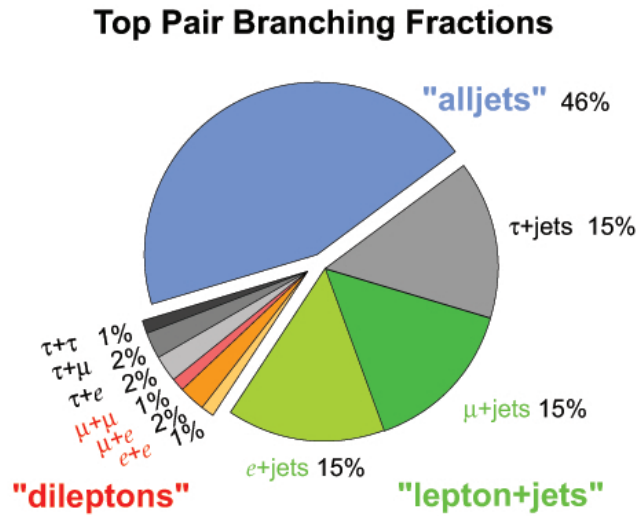


Figure 1.8: Top pair branching fractions.

Top quarks decay nearly 100% of the time to a b -quark and a W -boson. Although it is also possible for them to decay to an s -quark or a d -quark with a W -boson it is extremely rare and happens $< 1\%$ of the time. This means in a Top quark event the signature is determined by the decay of the W -boson. The W will decay either leptonically as $W \rightarrow l\bar{\nu}_l$ (where $l = e, \mu, \tau$) as in Fig. 1.7 or it will decay into $q\bar{q}$ pairs ($u\bar{d}, c\bar{s}$ for W^+ or $\bar{u}d, \bar{c}s$ for W^-). Each event has two Top quarks going to a final state with two b -quarks and two W -bosons. Fig. 1.8 shows the branching fractions for each decay channel possible for $t\bar{t}$ -pairs. The W is most likely to decay into a $q\bar{q}$ pair because even though the quark combinations are restricted to $\bar{u}d$ and $\bar{c}s$ -pairs the fact that quarks come in 3 colors means there are 3 times as many quark decay channels as there would be without the color charge. This means that for each W -boson there are 9 possible decays: 3 for the leptons, 3 for the $\bar{u}d$ color states and 3 for the $\bar{c}s$ color states. So for $t\bar{t}$ decays the final state decay products are a representation of the combined probabilities of each W decay. For instance both W s decaying via $W \rightarrow \mu\bar{\nu}_\mu$ will happen $\frac{1}{9} \cdot \frac{1}{9} = \frac{1}{81} \approx 1\%$ of the time.

This analysis will focus on the 'semi-muonic' decay channel in which one W will decay to a muon and a muon neutrino and the other W decaying hadronically. This is shown graphically in Fig. 1.9.

Top quarks are also produced singly in the standard model via the electroweak interaction. Fig. 1.10 shows the mechanisms by which single top quarks are produced. While these events are more rare than the $t\bar{t}$ pair production they still have a substantial cross-section of ~ 320 pb at $\sqrt{s} = 14$ TeV where the production will be dominated by the t -channel. This

process provides a background to the $t\bar{t}$ events that will be studied in this analysis.

There are a number of other Standard Model backgrounds that we must contend with while searching for Top-pairs. The most important are the QCD multi-jet events and W and Z -boson decays that are produced in association with quark and gluon jets as seen in Fig. 1.11. The cross-sections for these processes are very large and they must be filtered out and rejected with high efficiency. The remaining events that pass selection be modeled as best as possible to determine contamination from these processes.

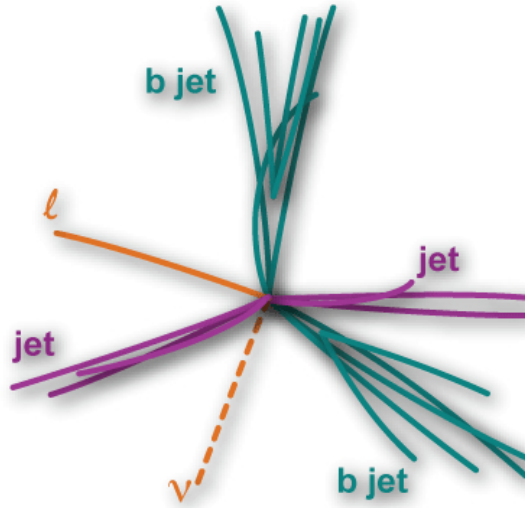


Figure 1.9: An detector view of a semi-leptonic top pair decay.

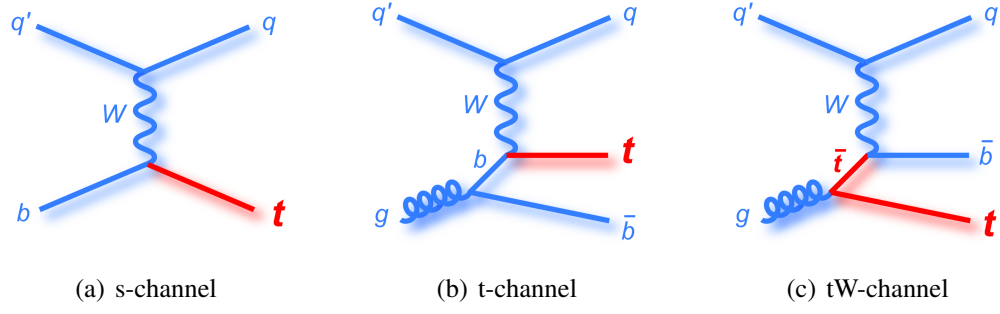


Figure 1.10: Standard model single top quark production mechanisms.

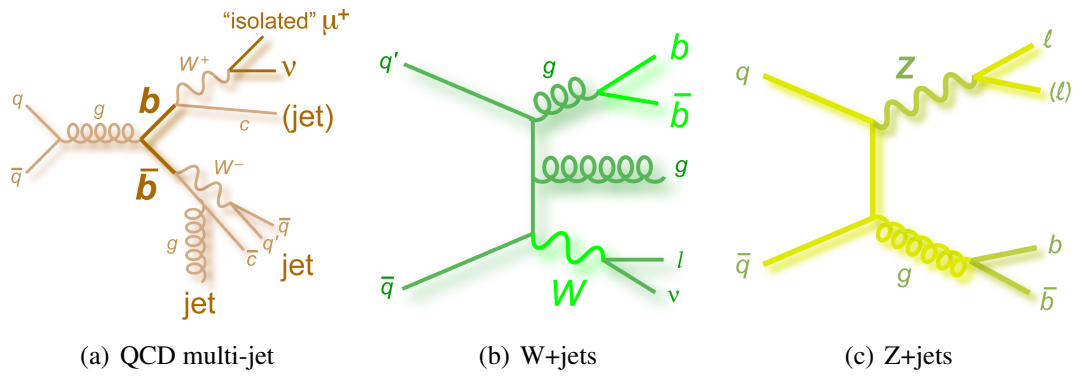


Figure 1.11: Examples of Standard Model backgrounds.

Chapter 2

Z' Theory and Phenomonology

2.1 The model-independent Z'

While the Standard Model has been an incredible success up to this point it is still regarded by many as a low-energy, effective theory that requires new physics at higher energies. One of the simplest extensions to the Standard Model is to add an extra $U(1)$ group to the usual $SU(3) \times SU(2) \times U(1)$ Standard Model gauge group. This extra $U(1)$ is normally associated with an extra heavy, neutral gauge boson, the Z' . This shows up in many theoretical frameworks beyond the Standard Model: Grand unification schemes ($SO(10)$ and E_6) [23, 29], models with dynamic electroweak symmetry breaking (Technicolor, Topcolor) [49, 55], Little Higgs models [36], and models with extra dimensions [22, 63] all have an extra, heavy Z -like gauge boson. Each of these models has a distinct set of Z' charges under the extra $U(1)$ group and a set of couplings to fermions which is dependant on the underlying theory.

This leads to the possibility of models where the Z' couples preferentially to third generation fermions or where the Z' decays preferentially to quarks (Leptophobic Z'). It is also possible to create a generic, model-independant Z' ([54] and references within) where the extra $U(1)$ may or may not be embedded in some higher framework.

Assuming a gauge group larger than $SU(5)$, such as $SO(10)$ we have:

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U'(1) \quad (2.1)$$

where the couplings to fermions are generation-independant and the only additional particle is an exotic (non-SM), heavy right-handed neutrino. The neutral current Lagrangian for this extended group is:

$$-\mathcal{L}_{NC} = \bar{f}\gamma^\beta \left\{ gT_3^f W_{3\beta} + g'_{11} Y^f B'_\beta + g'_{12} Y^f Z'_{2\beta} + g'_{21} Q'^f B'_\beta + g'_{22} Q'^f Z'_{2\beta} \right\} f \quad (2.2)$$

where T_3^f is the standard model isospin, Y^f is the hypercharge, Q'^f is the new charge under the new $U'(1)$ and B'/Z'_2 are the particles associated with the $U(1)_Y$ and $U'(1)$ symmetries.

If g'_{12} and g'_{21} are non-zero then there is mixing between the Z and Z' fields described by:

$$\begin{pmatrix} B'_\beta \\ Z'_{2\beta} \end{pmatrix} = \begin{pmatrix} \cos \theta_k & -\sin \theta_k \\ \sin \theta_k & \cos \theta_k \end{pmatrix} \begin{pmatrix} B_\beta \\ Z_\beta \end{pmatrix} \quad (2.3)$$

where θ_k is the kinetic mixing angle between the Z and Z' fields. The neural current Lagrangian then becomes:

$$- \mathcal{L}_{NC} = \bar{f} \gamma^\beta \left\{ g T_3^f W_{3\beta} + g_{11} Y^f B_\beta + g_{12} Y^f Z'_\beta + g_{22} Q'^f Z'_\beta \right\} f \quad (2.4)$$

where the couplings g_{ij} are related to g'_{ij} by the mixing in Eq. 2.3.

The mass matrix of the Z and Z' is then:

$$\mathcal{L}_M = \frac{1}{2} \begin{pmatrix} Z & Z' \end{pmatrix} M_{Z,Z'}^2 \begin{pmatrix} Z \\ Z' \end{pmatrix} \quad (2.5)$$

If there is mass mixing between the Z and Z' then the mass eigenstates Z_1 and Z_2 are related to the fields by a rotation through the mixing angle θ_M :

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_M & \sin \theta_M \\ -\sin \theta_M & \cos \theta_M \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix} \quad (2.6)$$

and the masses, M_1 and M_2 , of these eigenstates are given by:

$$M_{1,2}^2 = \frac{1}{2} \left[M_Z^2 + M_{Z'}^2 \pm \sqrt{(M_Z^2 - M_{Z'}^2)^2 + 4(\delta M^2)^2} \right] \quad (2.7)$$

This implies that $M_1 = M_Z$ and $M_2 = M_{Z'}$ if $\theta_M = 0$. θ_M is related to the mass matrix entries by:

$$\tan 2\theta_M = \frac{2\delta M^2}{M_Z^2 - M_{Z'}^2} \quad (2.8)$$

where $\delta M^2 = \sin \theta_M \cos \theta_M (M_1^2 - M_2^2)$.

The couplings of the Z' field to the Standard Model fermions can be obtained by writing the neutral current Lagrangian in terms of fermion currents:

$$-\mathcal{L}_{NC} = e A_\beta J_\gamma^\beta + g_1 Z_\beta J_Z^\beta + g_2 Z'_\beta J_{Z'}^\beta \quad (2.9)$$

where the currents J_i^β are:

$$J_\gamma^\beta = \sum_f \bar{f} \gamma^\beta v_f(0) f, \quad J_Z^\beta = \sum_f \bar{f} \gamma^\beta [v_f - \gamma_5 a_f] f, \quad J_{Z'}^\beta = \sum_f \bar{f} \gamma^\beta [v'_f - \gamma_5 a'_f] f$$

Setting the SM couplings to fermions to γ and Z gives

$$g_0 \equiv e = \sqrt{4\pi\alpha}, \quad v_f(0) = Q^f, \quad a_f(0) = 0$$

for the photon couplings and

$$g_1 = \frac{e}{2 \sin \theta_W \cos \theta_W} = \left(\sqrt{2} G_\mu M_Z^2 \right)^{1/2}, \quad v_f = T_3^f - 2Q^f \sin^2 \theta_W, \quad a_f = T_3^f$$

for the SM Z -boson. Therefore for the electron we find that $T_3^e = -\frac{1}{2}$ and $Q^e = -1$ as one would expect in the Standard Model. We can then write the Z' couplings, v'_f and a'_f , in terms of Q'^f and Y^f as:

$$v'_f = Q'^{fL} + Q'^{fR} + \frac{g_{12}}{g_{21}} (Y^{fL} + Y^{fR}) = Q'^{fL} + Q'^{fR} + \frac{g_{12}}{g_{21}} \sqrt{\frac{3}{5}} (-T_3^f + 2Q^f)$$

and

$$a'_f = Q'^{fL} - Q'^{fR} + \frac{g_{12}}{g_{21}} (Y^{fL} - Y^{fR}) = Q'^{fL} - Q'^{fR} + \frac{g_{12}}{g_{21}} \sqrt{\frac{3}{5}} (-T_3^f)$$

and defining couplings to left- and right-handed fermions as:

$$L'_f = \frac{1}{2} (v'_f + a'_f) \quad \text{and} \quad R'_f = \frac{1}{2} (v'_f - a'_f) \quad (2.10)$$

and ignoring the possibility of $Q'^{\nu_L} = -Q'^{\nu_R}$ (treating right-handed neutrinos as exotic fermions) and requiring $\left[Q'^f, T_3^f \right] = 0$ we then must have $Q'^{u_L} = Q'^{d_L} \equiv Q'^{q_L}$ and $Q'^{e_L} = Q'^{\nu_L} \equiv Q'^{l_L}$ in order to preserve $SU(2)_L$ gauge invariance. This leaves us with 5 independant couplings:

$$L'_u = L'_d \equiv L'_q, \quad L'_e = L'_\nu \equiv L'_l \quad \text{and} \quad R'_u, R'_d, R'_e. \quad (2.11)$$

The width of the Z' mass eigenstate (Z_2) into fermion pairs ($f\bar{f}$) is:

$$\Gamma(Z' \rightarrow f\bar{f}) = N_f \mu M_2 \frac{g_2^2}{12\pi} \left\{ [v_f^2 + a_f^2] \left(1 + 2 \frac{m_f^2}{M_2^2} \right) - 6 a_f^2 \frac{m_f^2}{M_2^2} \right\} \quad (2.12)$$

where N_f is the color coefficient and μ is a phase-space factor coming from massive final state fermions. While this is just a generalization of what kind of parameters one would expect out of a new heavy gauge boson it is useful to describe a Z -like gauge boson with generation-independant couplings. The real couplings, charges, width and mass will be determined by the particle found and identified as the Z' at the LHC or elsewhere.

2.2 Z' constraints from electroweak precision data

At collision energies far below the resonance mass, the effects of the Z' can be seen indirectly from precision electroweak measurements. Z' effects are subtle and appear, for example, as an increase in cross-section ($\Delta\sigma_f$) of two fermion final states or as the presence of a forward-backward asymmetry A_{FB} between initial and final state fermions due to the presence of a Z' . This type of analysis was studied extensively at electron-positron colliders such as LEP or SLAC. [54]. The most straightforward method of study is looking for an increase in the dilepton final state cross section due to the presence of contact interactions of the form seen in Fig. 2.1.

The presence of a contact interaction implies the presence of new physics at a high mass

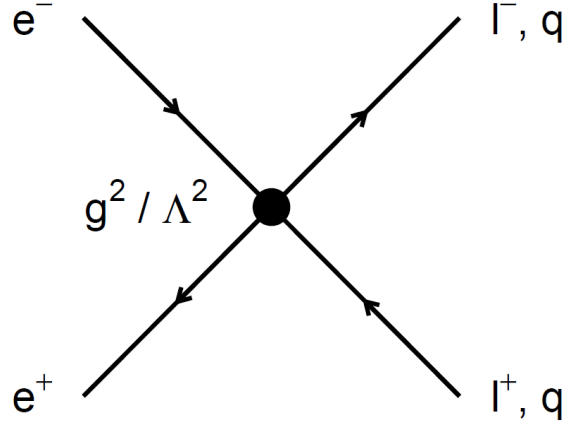


Figure 2.1: A four-fermion contact interaction.

scale which will appear as a deviation from standard model predictions at lower energies.

[60] These can be included in the theory as an effective lagrangian of the form:

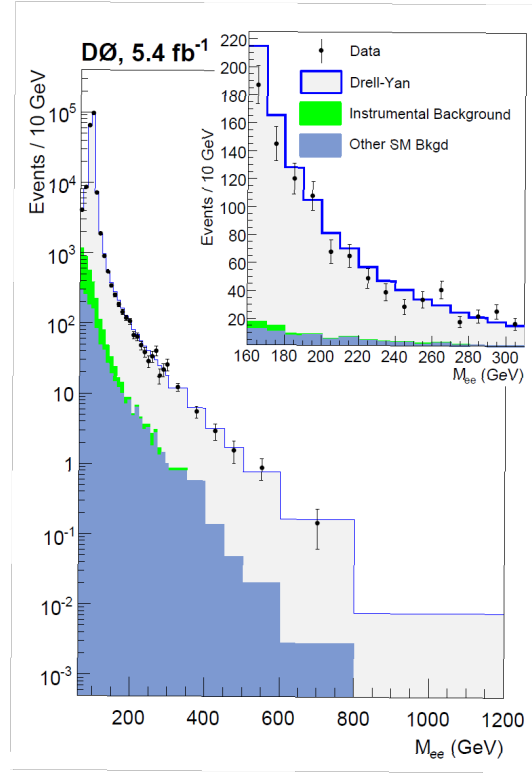
$$\mathcal{L}_{CI} = g \sum_{ij} \frac{\eta_{ij}}{\Lambda_{ij}^2} (\bar{f}_i \gamma_\mu f_i) (\bar{f}_j \gamma^\mu f_j) \quad (2.13)$$

where g is the coupling, Λ is the energy scale of the new physics and $|\eta| = \pm 1$ depending on the chirality of the final state fermions. Effects of this nature are very small and expected to be of the order $s/\alpha\Lambda$ (where α is the SM coupling) so high luminosities are needed to search for these effects. So far no evidence has been found for an extra gauge boson in precision measurements at LEP and SLAC. Studies of Standard Model parameters such as the Z invisible width [37] and the differential cross-section of the final state leptons ($\Delta d\sigma_l/d\cos\theta$) [47] have shown no statistically significant deviations from Standard Model predictions and have put lower limits on the mass scale of the contact interactions from 1.5-10.2 TeV, depending on the type of interaction and final state fermions. [15, 24]

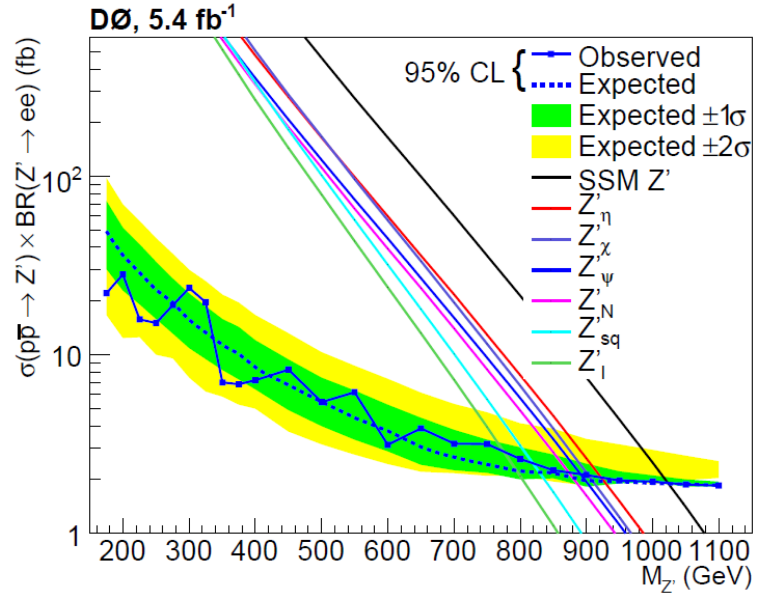
2.3 Direct searches from the Tevatron

The second method of searching for a heavy gauge boson is direct-production searches at high energy hadron colliders like the Tevatron [28, 56] or the LHC. These are normally much simpler to perform as one can just choose the decay channel and search for resonance peaks in the invariant mass spectrum of the chosen final state. The most straightforward of these are the dilepton channels such as $Z' \rightarrow e^+e^-$ and $Z' \rightarrow \mu^+\mu^-$. Because of the relatively small backgrounds and the simplicity of the reconstruction, this channel is usually the analysis of choice for the Z' hunter. These channels, however, are not capable of searching for some specific model-dependant gauge bosons such as a leptophobic Z' or a Z' that couples preferentially to third-generation fermions.

The CDF and D0 collaborations have analyzed data from the Tevatron. Their efforts have been mainly focused on the dilepton channels [64, 14] but there has also been efforts made to examine the dijet spectrum as well [21]. These searches involve scanning the dilepton or dijet invariant mass distribution for narrow resonances or "bumps". The main backgrounds are Drell-Yan production for the electron and muons and QCD multijet events for the jet studies. These are irreducible backgrounds and they must be understood well and their shapes modeled correctly in order to set limits. The results of the muon and electron analyses are shown in Figs. 2.3 and 2.2 respectively. The invariant mass spectra shows no significant excesses and the corresponding lower limits on the cross-sections various Z' models are included and stated to be in the range between 0.7 and 1.1 TeV, depending on the model. This implies

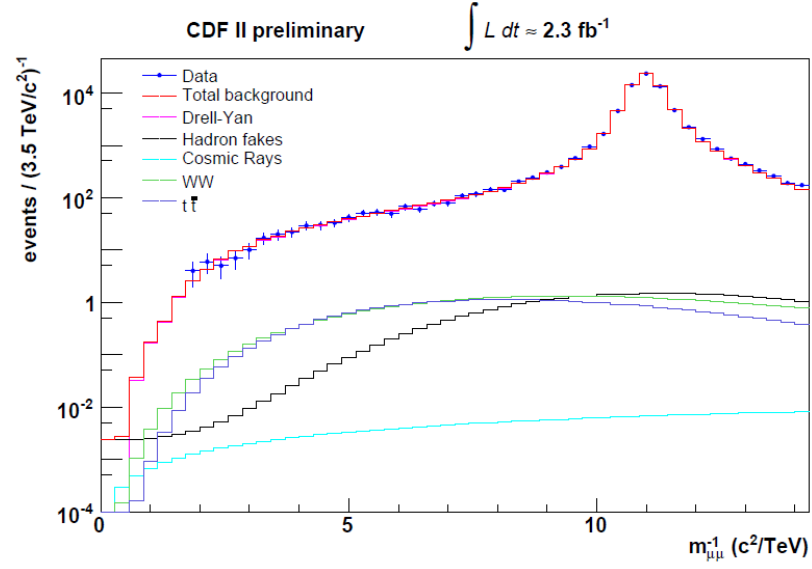


(a) Dielectron invariant mass

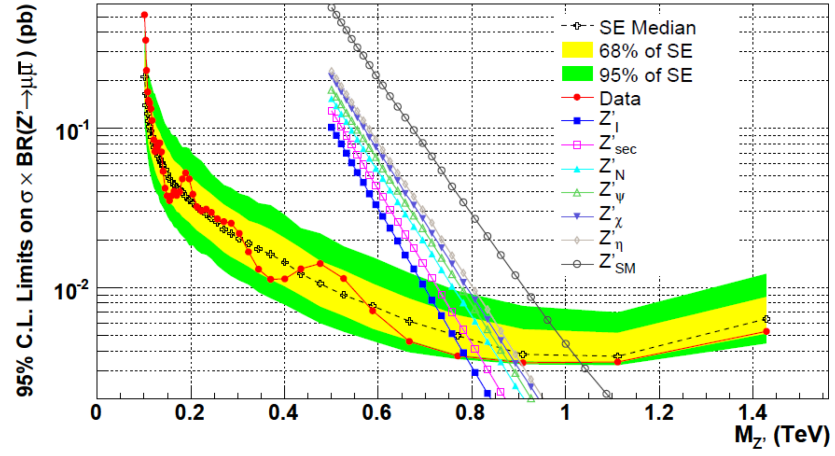


(b) Cross-section limits for various Z' models

Figure 2.2: Results from the DØ collaboration in the $Z' \rightarrow e^+e^-$ channel.



(a) Dimuon invariant mass



(b) Cross-section limits for various Z' models

Figure 2.3: Results from the CDF collaboration in the $Z' \rightarrow \mu^+ \mu^-$ channel.

that early LHC analyses will be able to begin searching in the region around 750 GeV and up.

Chapter 3

The Large Hadron Collider

The Large Hadron Collider (LHC) is CERN's flagship accelerator. In March 2010 it became the highest energy particle collider in the world when it ran at a center of mass energy of $\sqrt{s} = 7$ TeV. The accelerator was designed to be installed in the already existing 26.7 km Large Electron-Positron (LEP) collider tunnel located under the French-Swiss countryside as seen in Fig. 3.1. It is comprised of 1232 superconducting dipole magnets used to bend the beam, 386 superconducting quadrupole used for beam focusing and thousands of other specialty magnets (superconducting and room temperature). The LHC has four main experiments associated with it: Two large all-purpose detectors, ATLAS and CMS which are located on opposite sides of the LHC ring at Points 1 and 5, respectively, and the 2 smaller experiments which are to be used for dedicated physics studies are ALICE at Point 2 will be used for heavy ion experiments and LHCb at Point 8 will search for CP violation and rare b -quark decays. The locations of all four experiments is shown in Fig. 3.2.

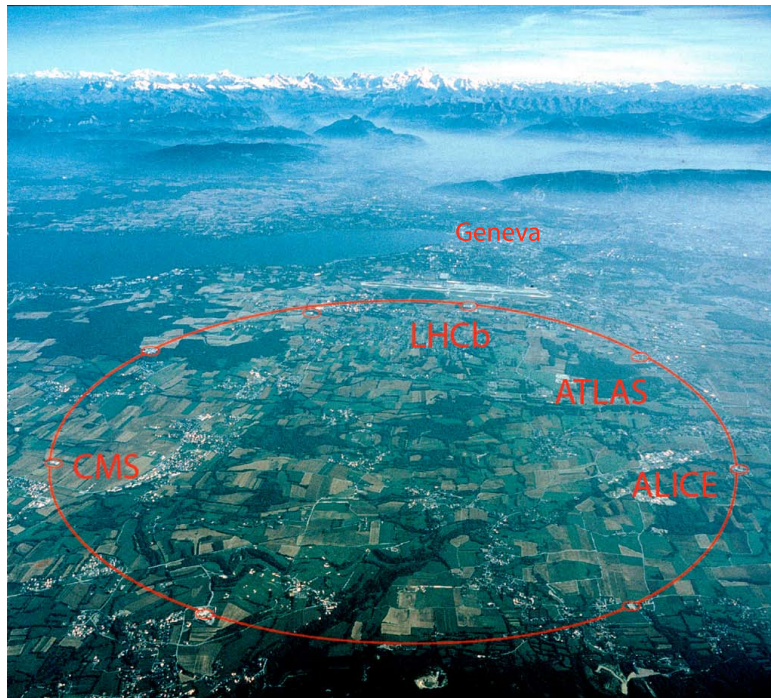


Figure 3.1: The LHC ring as seen from overhead

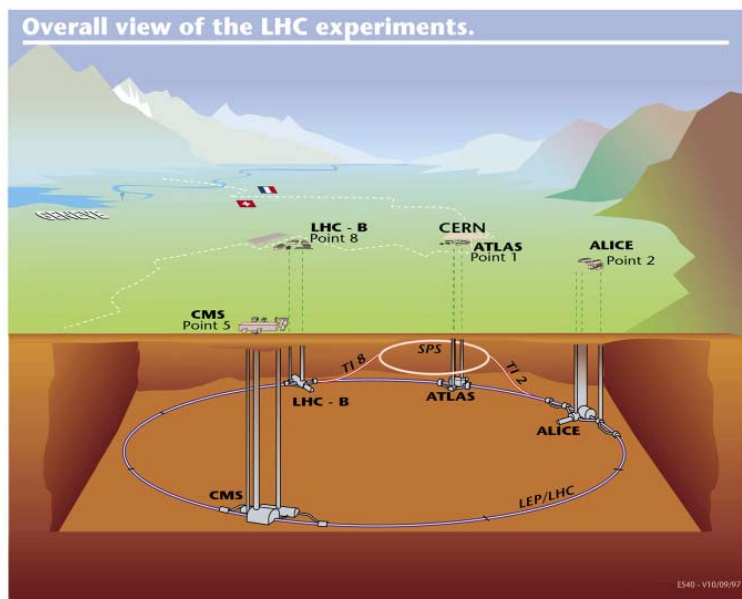


Figure 3.2: The LHC ring and experiments as seen from underground

When it runs at full design energy, the LHC will collide protons at a center of mass energy of $\sqrt{s} = 14$ TeV and will deliver a peak luminosity of $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to ATLAS and CMS. The luminosity of an accelerator is given by:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta} F \quad (3.1)$$

where N_b is the number of particles per bunch, n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ_r is the relativistic form factor, ε_n is the normalized transverse beam emittance, β is the beta function at the collision point and F is the geometric luminosity reduction factor due to parameters such as beam crossing angle, bunch length and transverse beam size. This determines the number of events of a specific type per second that will be created by collisions according to:

$$N_{event} = L \sigma_{event} \quad (3.2)$$

where σ_{event} is the cross-section of the event in question. The LHC was designed to maximize both the center of mass energy and the luminosity.

The luminosity does not remain constant during a machine fill because of factors such as collisions at the interaction points and other effects such as interactions with residual beam gas. The luminosity will peak upon beam injection and slowly decline with time. The luminosity of the beams at the LHC have an estimated lifetime of $\tau_L = 14.9$ hours for nominal machine settings. The lifetime of the beam and the total time of the physics running of the LHC

determine the integrated luminosity of the LHC according to:

$$L_{int} = L_0 \tau_L [1 - e^{-T_{run}/\tau_L}] \quad (3.3)$$

where L_0 is the nominal luminosity. Assuming running 200 days per year gives an average integrated luminosity of $80 - 120 \text{ fb}^{-1}$ depending on the average turnaround time of the machine [42].

At full design luminosity each beam will have $n_b = 2808$ proton bunches with a bunch spacing of 25 ns. Each bunch will have a maximum number of 1.15×10^{11} protons where the limit comes from the mechanical aperture of the LHC arcs. A list of the operating parameters of the LHC beam are given in Tab. 3.1. The LHC has 8 dedicated points on

Table 3.1: LHC beam characteristics at nominal running

Beam Parameter		Nominal Value
Energy	[GeV]	7000
Luminosity	[$\text{cm}^{-2}\text{s}^{-1}$]	10^{34}
Number of Bunches		2808
Bunch Spacing	[ns]	24.95
Intensity per Bunch	[p/b]	1.15×10^{11}
Beam Current	[A]	0.58
Transverse Norm. RMS Emittance	[μm]	3.75
Longitudinal Emittance	[eVs]	2.5
Bunch Length	[ns]	1.0
Energy Spread		0.45×10^{-3}

the ring for beam interactions and maintenance as shown in Fig. 3.3. Points 1 and 5 are the high luminosity interaction points for the ATLAS and CMS experiments. Point 2 is the ALICE cavern which is used for heavy-ion studies and point 8 the LHCb cavern. Points 2

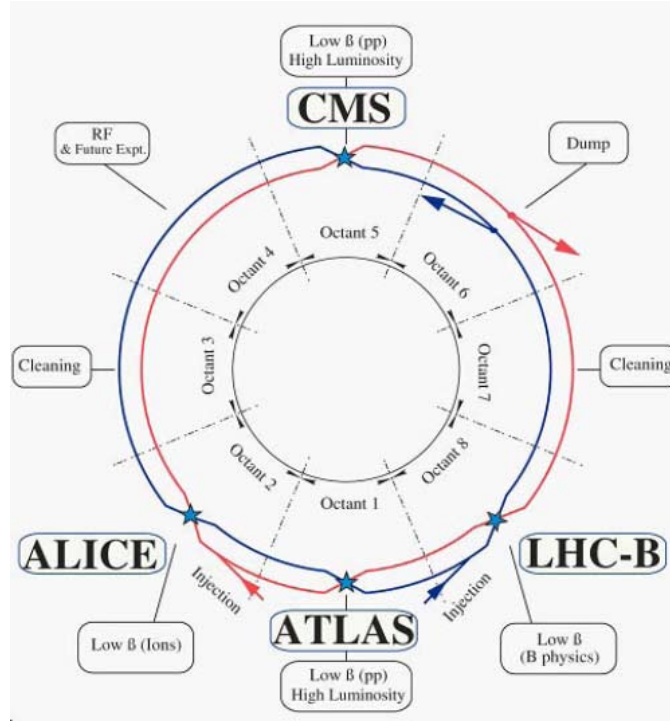


Figure 3.3: The LHC ring and experiments as seen from underground

and 8, in addition to being experimental regions, are also injections points for the LHC beam. Point 6 contains the beam dump for both beams and Point 4 houses the RF equipment that accelerates the protons in the LHC. Points 3 and 6 are used for beam cleaning.

3.1 Injection System

In order to inject protons into the LHC ring it is necessary to first accelerate protons up to the LHC injection energy of 450 GeV per beam using the 4 stage process [39], [66] which can be seen in Fig. 3.4. Beginning with the CERN Linear Accelerator (Linac2) [9] accelerating protons from 2 to 50 MeV the protons then get passed on to the Proton Synchrotron

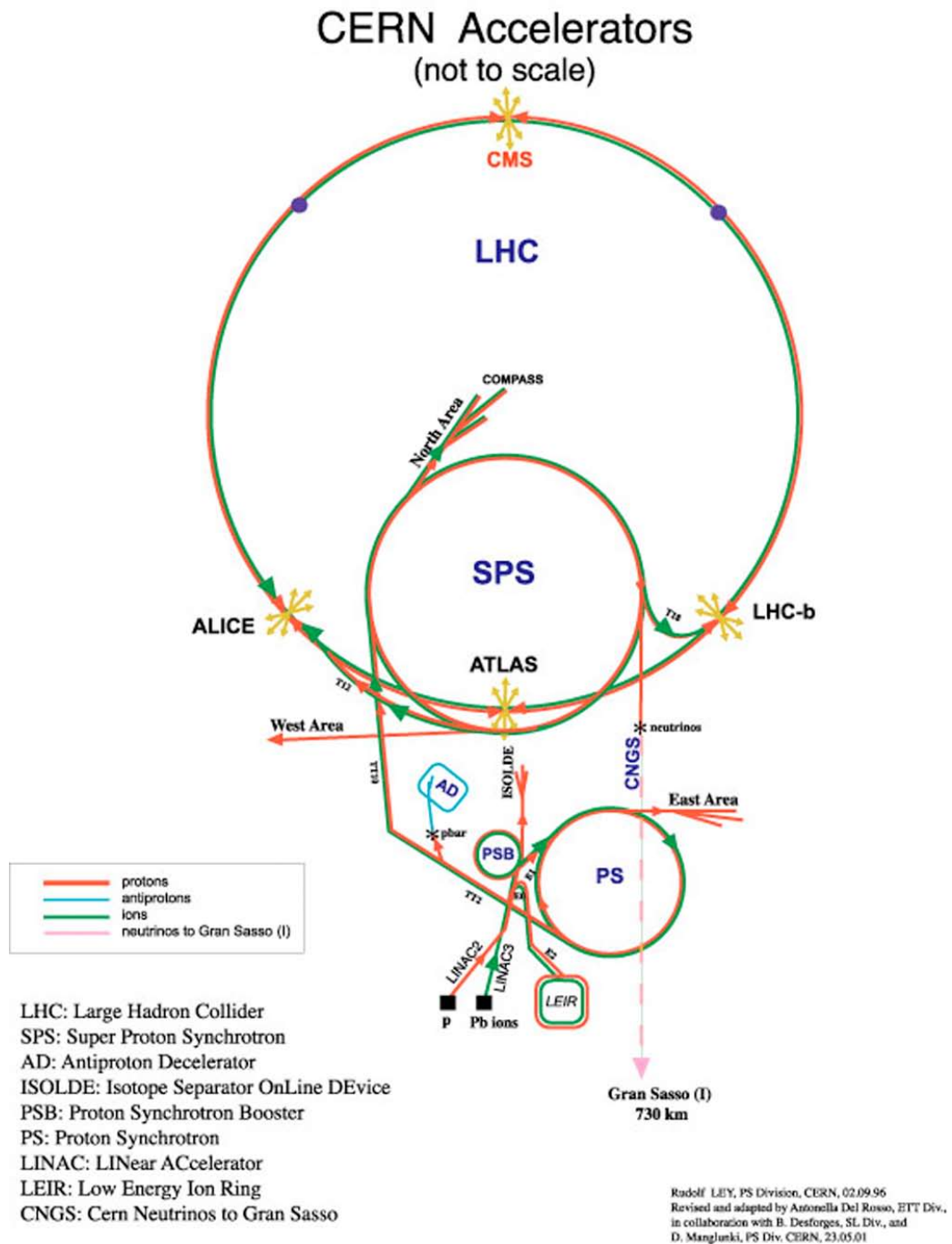


Figure 3.4: The CERN accelerator complex

Booster (PSB) [61] which accelerates them to 1.4 GeV. This is followed by the Proton Synchrotron (PS) [10] which increases the energy to 28 GeV and then finally the Super Proton Synchrotron (SPS) [33] which accelerates the protons to 450 GeV before they are injected into the LHC main ring.

The Linac2 linear accelerator was originally installed in 1978 and has recently been upgraded to meet the demands of the LHC. It is used to accelerate and deliver pulsed, 50 MeV proton beams at 180 mA every 1.2 s to the PSB. Linac2's proton source is a 300 mA, 100 kV hydrogen duoplasmatron which takes in 6 mL/min of hydrogen gas into a cathode chamber along with electrons. Interactions with the electrons charge the hydrogen and create a plasma that is left to expand, forming the proton source. The proton beam is then sent to the 4-vein RF Quadrupole magnets that focus the beam and bunch the protons together and bring the beam to an energy of 750 keV before injection into Linac2. Linac2 (shown in Fig. 3.5) accelerates the protons via radio frequency (RF) electric fields operating within successive resonance cavities to an energy of 50 MeV. These rapidly oscillating RF fields produce a potential which interacts with the protons to accelerate and group the protons together in bunches to be sent to the PSB with the properties found in Tab. 3.2 [10].

The beam is then transferred from the Linac2 to the PSB via an 80 m long, high-current beam line comprised of 20 quadrupole magnets, 2 bending magnets, 8 steering magnets and a debuncher cavity. The PSB is responsible for both increasing the energy of the beam from 50 MeV to 1.4 GeV and to start the creation of the bunch pattern required by the LHC. The PSB is a synchrotron that is split into 4 layers stacked on top of each other which consecutively

Table 3.2: LHC proton beam parameters from LINAC2

Parameter	LHC Specification	Achieved	Units
Current during pulse	180	182	mA
Pulse length	30	>100	μs
Transverse norm. rms emittance	1.2	1.2	μm
Momentum spread ($\pm 2\sigma$)	$\pm 0.15\%$	$\pm 0.15\%$	



Figure 3.5: The CERN Linac2 linear accelerator.

sends bunches in two batches to the PS. The challenge for the beam leaving the PSB are the constraints from LHC conditions such as high intensity and low emittance. Problems for the PSB mainly arise via space charge effects that limit the beam brightness. These requirements have driven necessary upgrades to the PSB such as higher beam energies (1.4 GeV) and new $h = 1$ (0.6 - 1.7 MHz) harmonics for the bunch production. These allow the PSB to avoid problems such as emittance blow-up and deliver a high quality beam to the PS.

The cern Proton Synchrotron project [10], [67] was started in 1959 and has been the

heart of the CERN PS complex ever since. The versatility of the PS allows it to accelerate multiple types of particles (e^+ , e^- , p^+ , p^- , Pb^{53+}) and new and more stringent demands by the recipients of the PS's particles over the years have spurred many upgrades. The PS now operates at energies ranging from 0.6 to 26 GeV and intensities of between 10^8 and 2.5×10^{15} particles per pulse. The current PS RF acceleration system consists of 20, 40 and 80 MHz systems to take the initial $h = 7$ PS harmonic (used to meet LHC requirements) to the $h = 84$ harmonic and the 5 ns bunch length which gets injected into the SPS. The nominal PS beam parameters are shown in Tab. 3.3.

The Super Proton Synchrotron (SPS) takes the beam from the PS and accelerates to an

Table 3.3: PS beam characteristics at extraction

Beam Parameter		Nominal Value	
Proton kinetic energy	[GeV]	25	
Number of PS batches to fill SPS		3 or 4	Limited by SPS peak intensity
PS repetition time	[s]	3.6	PS 2-batch filling from PSB
Number of bunches in PS		72	$h = 84$, 12 empty buckets from extraction kicker
Bunch spacing	[ns]	24.97	
Number of protons per bunch		1.15×10^{11}	100% transfer assumed
Transverse normalized rms emittance	$[\mu\text{m}]$	3.0	
Bunch area (longitudinal emittance)	[eV/s]	0.35	
Bunch length (total)	[ns]	4	Limited by SPS 200 MHz buckets
Relative momentum spread $\Delta p/p$		0.004	Limited by transfer line acceptance

energy of 450 GeV which is the LHC injection energy. Originally commissioned in 1976, the

CERN SPS was once the center of the accelerator physics program at CERN. It consists of over 1300 room temperature magnets, 774 dipoles for bending the beam and a large number of additional magnets for focusing the beam. The magnets for the SPS are layed out in 12 sectors. First a series of dipoles bends the beam through a 30 degree angle followed by a long, straight section where quadrupole and radial field magnets focus and correct the beam. Every six sections there is a set of correcting magnets that consist of:

- 36 quadrupoles
- 72 sextupoles
- 36 octupoles

which are used mainly to compensate for saturation effects in the main magnet.

Two main upgrades have taken place to convert the SPS to LHC specifications. The transfer line upgraded to new beam monitoring systems on the injection (from PS) and extraction (to LHC) lines. The West extraction line (to Point2 at the LHC) magnets are the same as before but a new East extraction line (to Point8) has been installed and consists of new kicker, bumper, septa and quadrupole magnets as well and the beam monitoring electronics. The RF system has also been upgraded. The old SPS had six RF systems. Three 100 MHz and two 200 MHz standing wave cavities and a LHC prototype 352 MHz superconducting cavity. These have been replaced with a system of four 200 MHz travelling wave cavities, used for capture and acceleration, two 800 MHz travelling wave cavities, which provide controlled emittance increase or extra Landau damping, four new 400 MHz superconducting cavities

used, if necessary, for bunch compression at extraction, and three 200 MHz standing wave cavities, used for longitudinal feedback [33]. The final SPS beam parameters at extraction for nominal LHC running are given in Tab. 3.4.

Table 3.4: SPS beam characteristics at extraction

Beam Parameter		Nominal Value
Momentum	[GeV]	450
Machine Radius	[m]	1100
Revolution Frequency	[kHz]	43.3
Number of Bunches		243
Protons per Bunch		1.05×10^{11}
Bunch Spacing	[ns]	25
Bunch Frequency	[MHz]	40
Bunch Length	[ns]	1.74
Transverse Normalized Emittance	[μm]	3.5
Longitudinal Emittance	[eVs]	0.5-1.0
Main RF Frequency	[MHz]	200

3.1.1 LHC Filling Scheme

The LHC injector chain from Linac2 to the SPS have all been optimised for LHC running. In order to transfer the beam to the LHC ring while maintaining the high beam intensity and low emittance blow-up needed to fit inside the aperture of the LHC and to provide the desired luminosity an elaborate LHC filling scheme has been developed.

The initial beam, having been transferred to the PSB is accelerated and bunched using the PSB harmonic $h = 1$ or $h = 2$. The PSB rings are 1/4 of PS radius each and are ejected sequentially to fill the PS either in one batch using ($h = 2$) or two batches ($h = 1$) at 1.2 s intervals as in Fig. 3.6. For the LHC the two-batch filling is used in order to keep

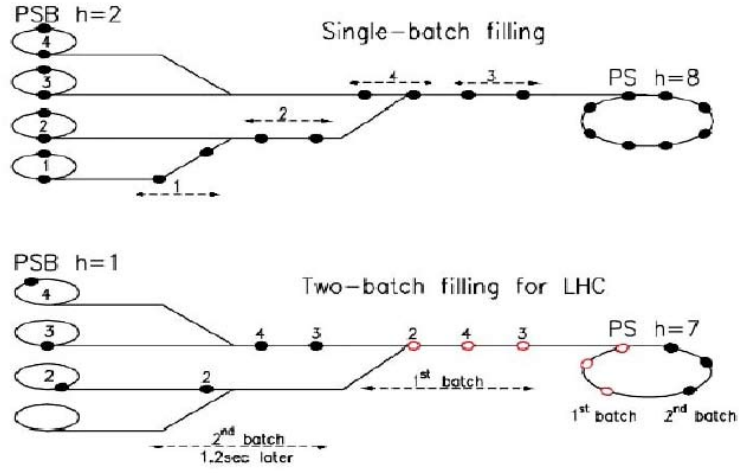


Figure 3.6: PSB-PS transfer schemes: PS single-batch filling for SPS physics (top), PS two-batch filling for LHC (bottom).

the pulse intensity down and avoid space charge effects on injection into the PS. To cope with the longitudinal impedance of the PS, a multiple-splitting scheme was developed [41] which also provides greater flexibility on bunching structures to allow for difficulties such as ejection kicker rise times. The multiple splitting process begins with the PS capturing six bunches (batches of 3+3 or 4+2 bunches) on PS harmonic $h = 7$. The bunches are split into three and re-bunched on $h = 21$ and accelerated to 25 GeV in the PS. Then the 20 and 40 MHz RF systems split and re-bunch to 72 bunches on harmonic $h = 84$ followed by a shortening of the bunches to ~ 4 ns by the 80 MHz systems to fit in the 200 MHz SPS buckets. The 12 empty buckets correspond to a gap of around 320 ns which allows for the rise time of the ejection kicker magnets to send the beam to the SPS.

An overview of the total PS to LHC filling scheme is shown in Fig. 3.7. Three or four sets of 72 bunches each are injected every 3.6 s into the SPS and fill 3/11 of the SPS. The

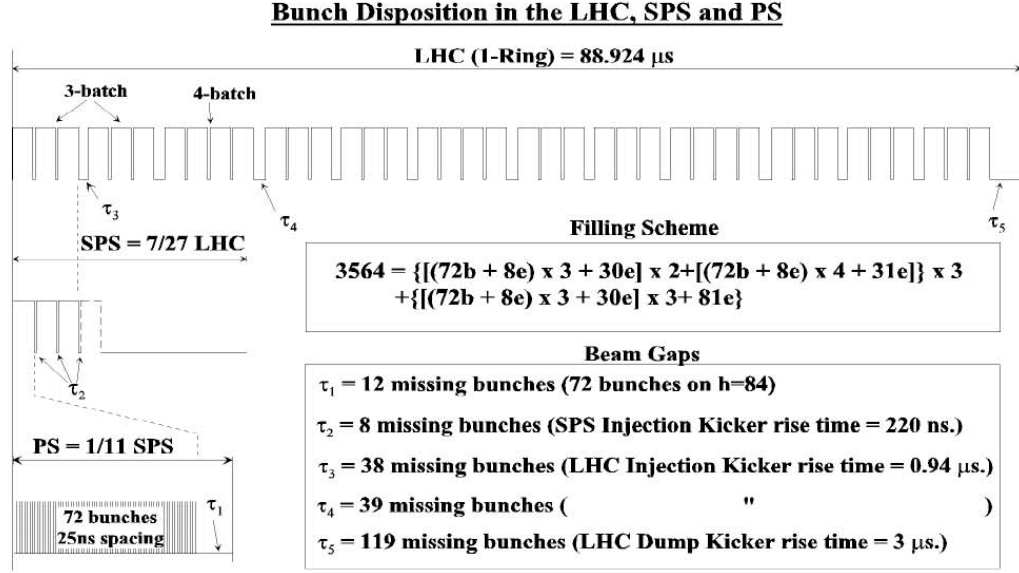


Figure 3.7: Proton bunches in the PS, SPS and one LHC ring.

bunches are accelerated to 450 GeV where a 1 second flat-top period is required in order to use the 400 MHz system to compress the bunches and re-phase the SPS with the LHC. Each LHC beam is filled with 12 supercycles of the SPS for a total LHC beam filling time of ~ 3 min.

3.2 Magnets

In order to reach the beam energies needed for the LHC the magnets used for bending the trajectory of the beam must make use of superconducting technology. The beam momentum is determined by the magnetic field according to:

$$B = \frac{p}{qR} \quad (3.4)$$

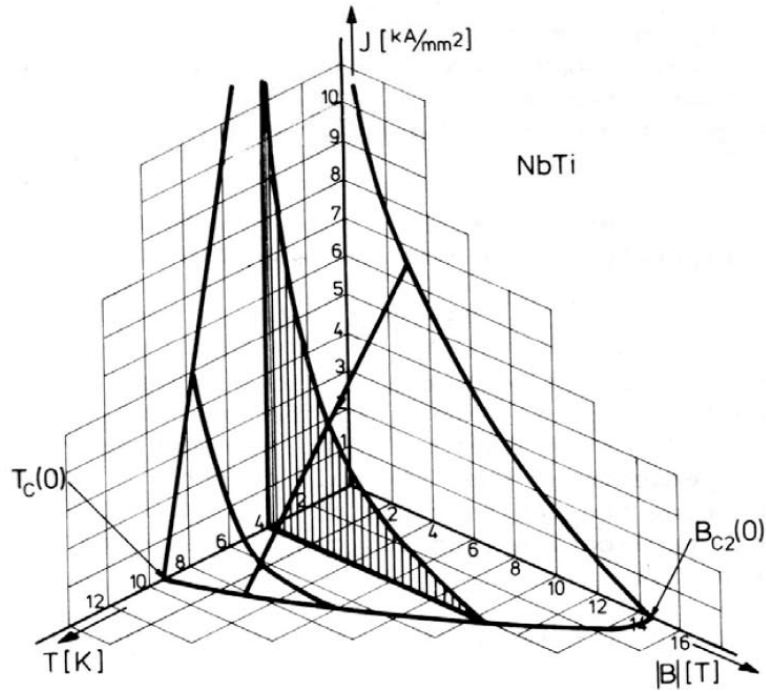


Figure 3.8: Magnetic field curve for NbTi.

where p is the particle momentum, q is the electric charge of the particle and R is the accelerator radius. A 7 TeV beam momentum then requires a bending field of 8.33 T. Existing technology based on superconducting NbTi cables are used to create the 8.33 T magnetic field required at the LHC. Whereas previous accelerators (Tevatron, HERA, DESY) used the same cable technology, the LHC magnets are able to produce a higher field than previously achieved due to the use of supercritical helium cooling at temperatures below 2 K (compared to around 4 K with previous accelerators). This increases the bending field by nearly a factor of 2 (see Fig. 3.8).

The bending of the beam is done in the arcs of the LHC using 110 m cells consisting of 6 dipole magnets, 2 focusing quadrupole, 1 defocusing quadrupole, 3 correcting sextupole

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999

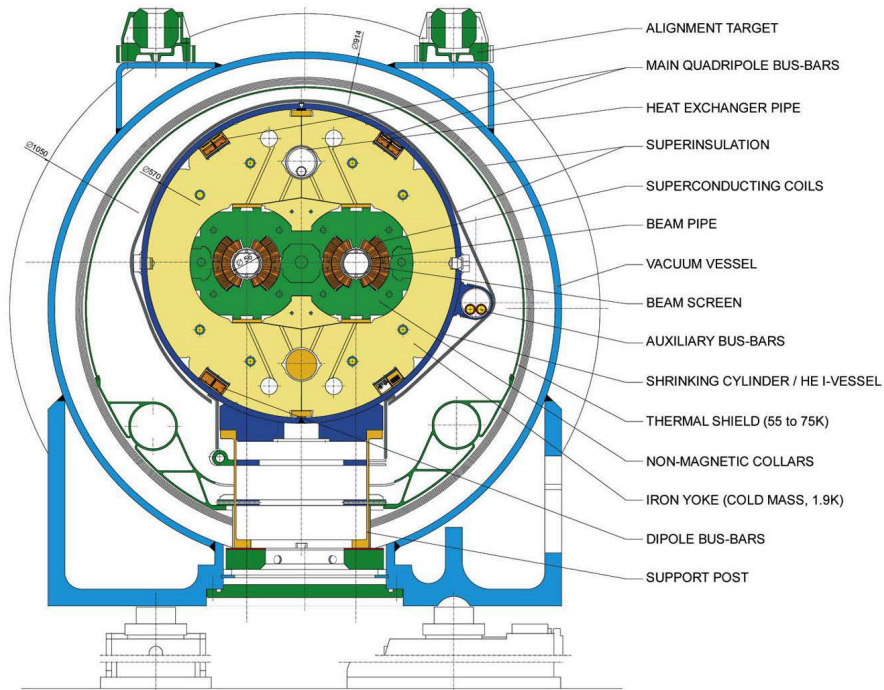


Figure 3.9: Cross-section of an LHC dipole magnet.

magnets and small sextupole and decapole correcting magnets located at the ends of the dipoles.

There are 1232 dipole magnets which are the main component of the LHC. A cross-section of one of the magnets is shown in Fig. 3.9. The superconducting coil is wound around the copper beam pipe and surrounded by non-magnetic collars. The ferromagnetic iron yoke takes up the bulk of the magnetic cold mass that operates at 1.9 K and surrounds the non-magnetic collars. The cold mass is curved in the horizontal plane at an angle of 5.1 mrad to match the trajectory of the particles. It must be aligned precisely in order to maintain a constant field through the length of the magnet (see Fig. 3.10). This means very strict tolerances for cable winding and stacking and their orientation with respect to the iron

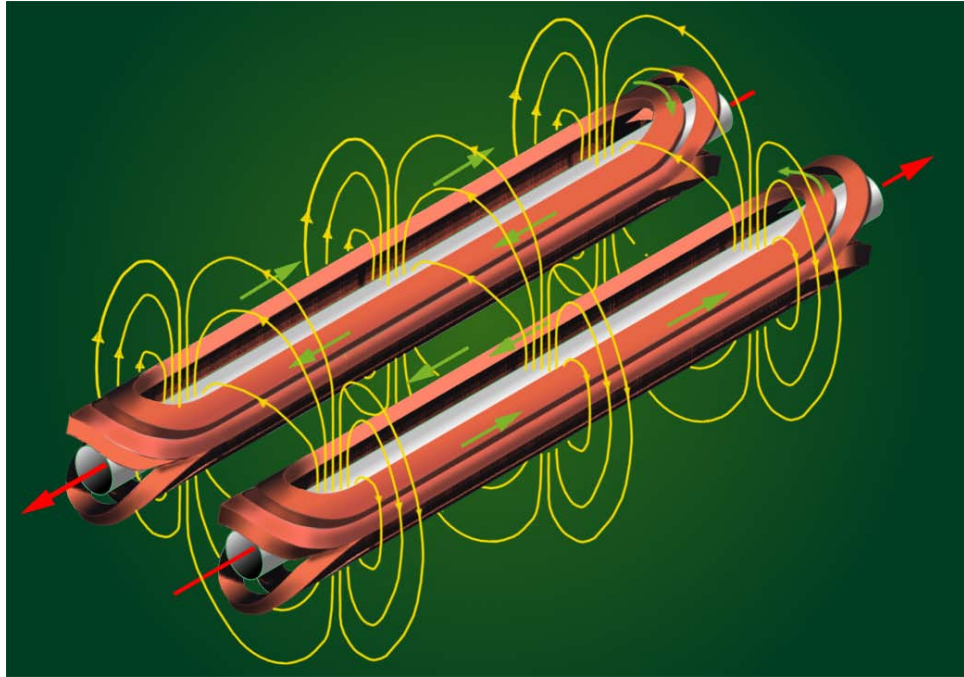


Figure 3.10: Magnetic field of an LHC dipole magnet.

yoke must be taken into consideration. In addition, the size constraints of the LEP tunnel necessitated the use of twin-bore magnets [25] (magnets which house both beam lines in the same cold mass) which have the added restriction of magnetically and mechanically coupling the superconducting coils requiring careful alignment between every component to produce the desired field.

The quadrupole magnets are similar mechanically to the dipoles, making use of the same twin-bore technology. The quadrupoles have 4 magnetic poles, 2 north and 2 south and are used to focus and defocus the beam. A quadrupole magnet will focus the beam in one direction, the horizontal direction, for example, and defocus the beam in the other direction. This requires a series of alternating focusing and defocusing quadrupoles in order to focus the beam in both directions.

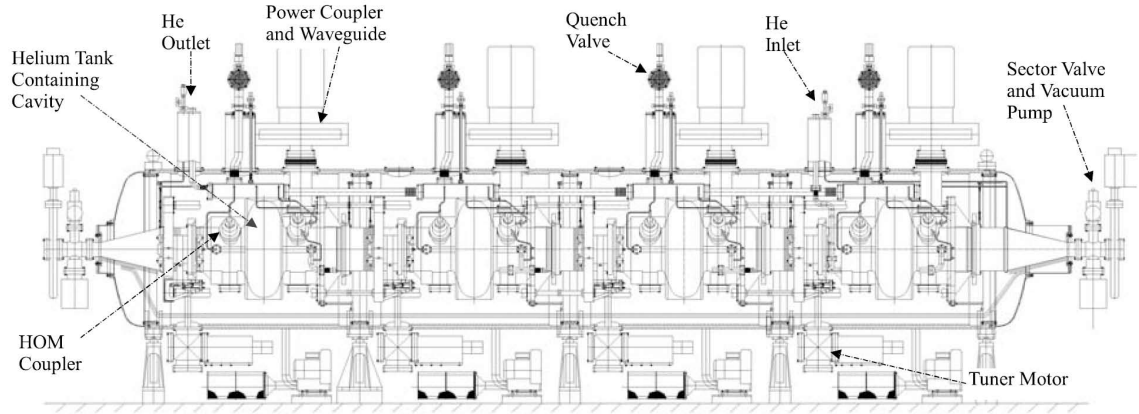


Figure 3.11: RF four-cavity cryomodule

In addition to the dipole and quadrupole magnets, over 6200 correcting magnets (sextupole, octupole and decapole) are used to correct for field imperfections in the dipoles and to stabilize trajectories and momenta of outlying particles.

3.3 RF Systems

The Radio-Frequency acceleration system [40, 42, 26] located at Point 4 on the LHC ring is responsible for accelerating the LHC beam from 450 GeV to 7 TeV. The system consists of 8 superconducting niobium-sputtered cavities per beam which operate at a temperature of 4.5 K. Four of the cavities are housed in a single cryostat and each cavity is powered by its own 300 kW RF power source. Each cavity generates a 2 MV accelerating voltage at full power for a total voltage of 16 MV per beam. The acceleration from 750 GeV to 7 TeV takes ~ 20 min at an average increase in energy of 0.5 MeV per turn. A diagram of one of the cryostats



Figure 3.12: An assembled RF module

is shown in Fig. 3.11 and an assembled RF module is shown in 3.12.

The RF system is also responsible for capturing and storing the beam and shaping the bunches. The 400 MHz system provides 35,640 buckets with a separation of 2.5 ns between adjacent buckets. At most, every tenth bucket can be filled creating a minimal distance between bunched of 25 ns or ~ 7.5 m. In practice, there are larger gaps to allow for magnets rise times and dumping the beam. The LHC RF system is very flexible, however, and provides a number of different bunch patterns that can be used during running. Table 3.5 shows some of the configurations that will be used for early LHC operation.

In the 43×43 and 156×156 some of the bunches are displaced from their nominal placement to balance ALICE and LHCb. The other multi-bunch schemes have larger gaps to account for injection kicker rise-times which are $\leq 3\mu\text{s}$.

Table 3.5: LHC beam configurations

Scheme	Bunch Spacing (ns)	Number of Bunches	Comments
43×43	2025	43	No crossing angle necessary
156×156	525	156	No crossing angle necessary
25ns	25	2808	Nominal proton filling
50ns	50	1404	
75ns	75	936	
Ion Nominal	100	592	Nominal ion filling
Ion Early	1350	62	No crossing angle necessary

3.4 Interaction Points

Table 3.6: LHC IP configurations

Crossing Point	Crossing Plane	Crossing Angle
ALICE	Vertical	$240\mu\text{rad}$
ATLAS	Vertical	$280\mu\text{rad}$
CMS	Horizontal	$280\mu\text{rad}$
LHCb	Horizontal	$300\mu\text{rad}$

The interactions points of the LHC take the beams from separate tubes and bring them into the same beampipe in order to produce collisions. Once they are in the same beampipe and outside the collision region the beams are kept as far apart as possible to avoid unwanted collisions. Just before the IP the beams are crossed (see Fig. 3.13) in the vertical or horizontal plane to allow collisions (see Tab. 3.6). Although this reduces unwanted beam-beam interactions it has the effect of reducing luminosity because of the finite bunch length and the fact that the collisions that are not completely head-on.

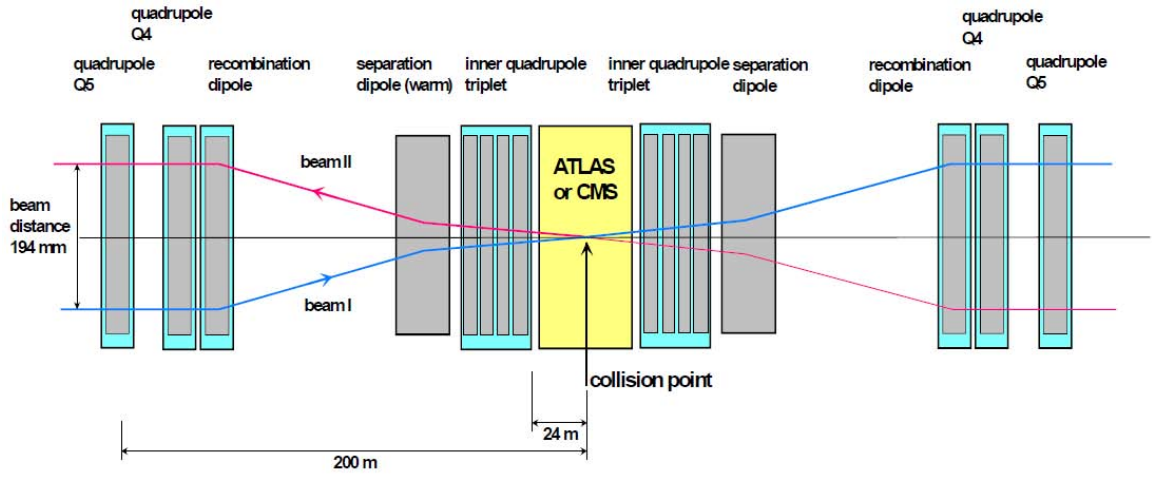


Figure 3.13: Beam optics at IP1 and IP5

The optics of the beam insertion zones for the ATLAS and CMS IPs are shown in more detail in Fig. 3.14. The IPs consist of (from left to right) [42]:

- A small- β triplet of superconducting quadrupole magnets that shrinks the beam envelope for collisions to $16\mu\text{m}$ using a beam gradient of 205 T/m. The current for the two outer quadrupoles is 6450 A while the inner quadrupoles need a much larger current of 10630 A to reach the same field.
- The D1 room-temperature dipole magnets with a nominal field of 1.38 T are outside of the quadrupole triplet and are used for separating and combining the two beams.
- The D2 dipole is the closest of the twin-bore superconducting dipoles next to the IPs operating at a temperature of 4.5 K and a field of 3.8 T.

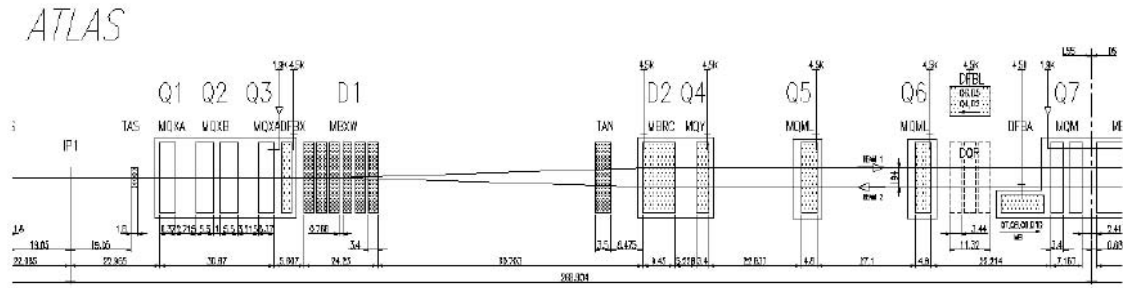


Figure 3.14: An extended view of the right side of the insertion region at IP1

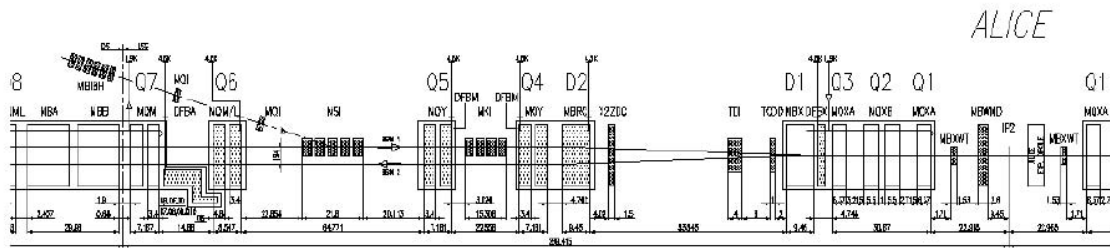


Figure 3.15: An extended view of the left side of the insertion region at IP3

- Finally a series of four matching quadrupole magnets. The first is a wide-aperture magnet operating at a temperature of 4.5 K and nominal field gradient of 160 T/m and the outer three are normal-aperture quadrupoles operating at 1.9 K and 200 T/m

The interaction regions for ALICE and LHCb are similar in construction except for the extra magnets and instrumentation required to allow the beam injection from the SPS. IP 3 and IP 8 have a series of injection septa and kicker magnets (see Fig. 3.15) interspersed within the outer quadrupoles to collect the beam from the SPS.

Chapter 4

The CMS Detector

The Compact Muon Solenoid (CMS) experiment [32] is one of two multi-purpose detectors located at the LHC. When operating at design conditions, the LHC will deliver a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This corresponds to a total proton-proton cross-section of 100 mb and an interaction rate of 10^9 inelastic events/s. These numbers dictate the design parameters of the CMS detector. The detector and its electronics must have high granularity and a fast response time to be able to untangle the ~ 1000 charged particles per bunch crossing and it must also be radiation-hard to deal with the high-flux environment. The CMS trigger system must reduce this extremely large rate down to the rate of ~ 100 events/s which can be stored by the data acquisition (DAQ) system.

The detector has a traditional, layered design (see Fig. 4.1) of subdetectors consisting of:

- Three layers of pixel detectors closest to the interaction point to give good track and secondary vertex resolution.

- Ten layers of silicon tracker strips outside the pixels with high granularity to deal with the high-multiplicity environment.
- Electromagnetic and hadronic calorimeters which sit outside the tracking system to give measurements of charged particle and jet energies.
- The superconducting solenoid magnet sits between the calorimeters and the muon system and provides a 4 Tesla bending field for the experiment.
- The muon system is located on the outside of the detector and consists of four layers of drift-tube chambers (barrel) and cathode strip chambers (endcap) alternating with resistive plate chambers and the solenoid's iron return yoke. This gives a secondary muon momentum measurement and muon identification.

The subdetectors work together to identify and reconstruct various types of particles according to the signatures they leave while passing through the detector. Fig. 4.2 shows a schematic of particle tracks as they pass through a slice of the detector. Charged particles such as electrons, pions, kaons or protons leave tracks in the silicon tracker via ionization, are bent in the magnetic field and eventually deposit their energy in the calorimeter. Neutral particles such as neutrons and photons leave no tracks in the tracker and are instead absorbed by the hadronic and electromagnetic calorimeters. Muons pass through the entire detector and are seen as tracks in the tracker and muon systems and as minimum ionizing particles in the calorimeters. Missing transverse energy (E_T^{miss}) from neutrinos are measured as an imbalance in the transverse energy in the calorimeters as neutrinos do not interact with the

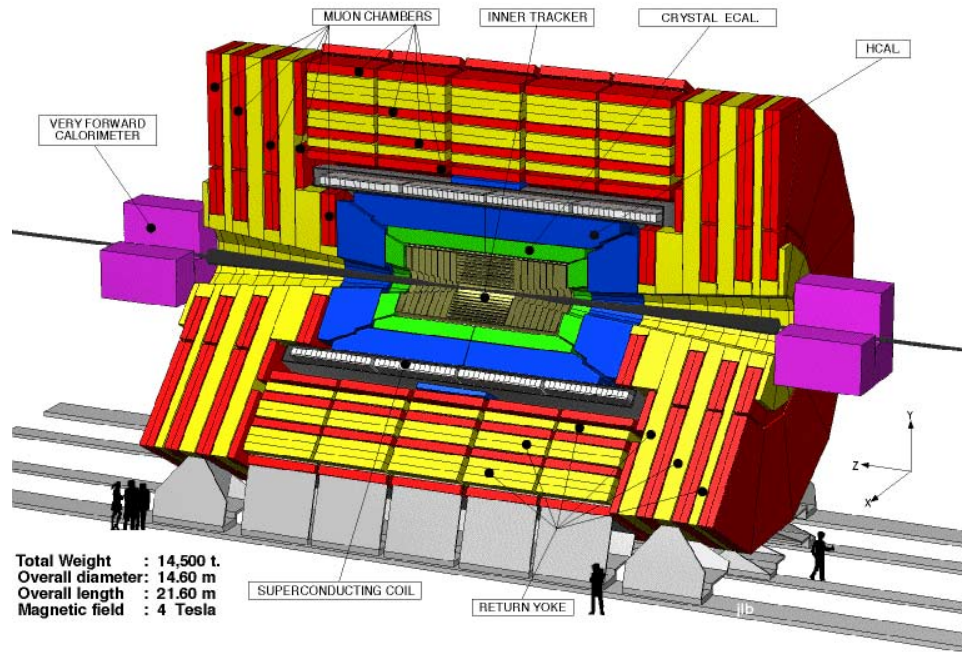


Figure 4.1: A 3-D view of the CMS detector

detector. The subdetectors will work together in this manner to measure physical quantities and reconstruct particles and entire events.

The LHC physics program was also taken into account when CMS was designed. The LHC will reach much larger center-of-mass energies and luminosities than previous hadron colliders and will start to probe physics at the TeV scale for the first time. The main goal of the LHC is to understand the nature of electroweak symmetry breaking and to search for the Higgs Boson (Fig. 4.3) which is believed to be responsible for it. In addition there is a large amount of interest in probing physics beyond the Standard Model (BSM) and CMS will actively look for the signatures of the particles predicted by Supersymmetry and other BSM models.

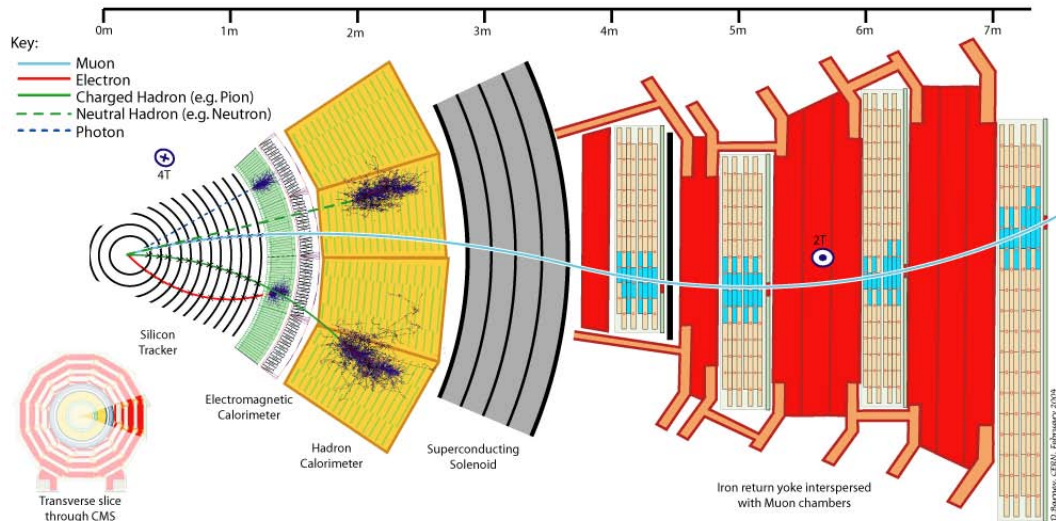


Figure 4.2: Particle identification in CMS

In order to carry out these and other studies it is necessary for CMS to be able to identify and reconstruct particles effectively. Also, particle energy and momentum resolutions must be kept as high as possible and the detectors must have excellent spatial coverage.

4.1 Silicon Tracking System

The CMS silicon tracking system consists of 1440 pixel modules which are placed nearest to the primary vertex and 15,148 silicon strips (4.4) which are placed around the pixel detector. The large number of detector modules is needed to low module occupancy, excellent coverage and momentum resolution in the region of $|\eta| < 2.5$.

The tracker layout is shown in Fig. 4.5. The pixel layers (shown in green) in the barrel region surround the main interaction point at radii of 4.4, 7.3 and 10.2 cm. They

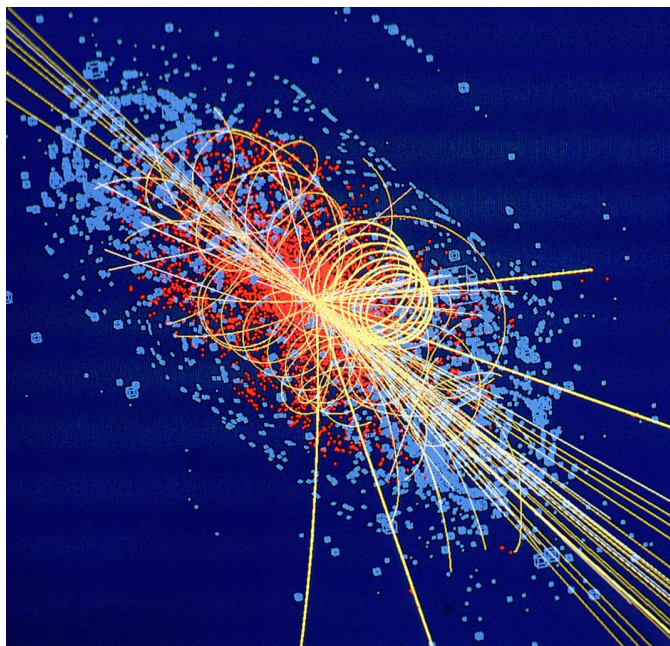


Figure 4.3: Simulation of a Higgs boson decaying to 4 muons in the CMS detector

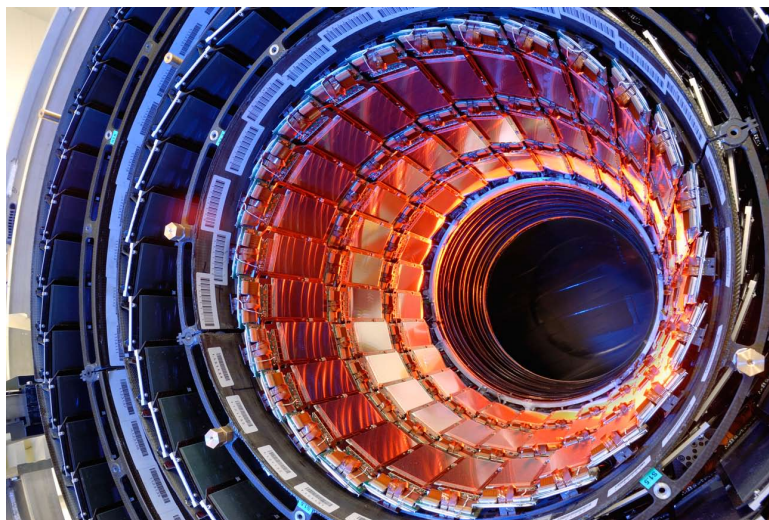


Figure 4.4: View of the CMS silicon tracker

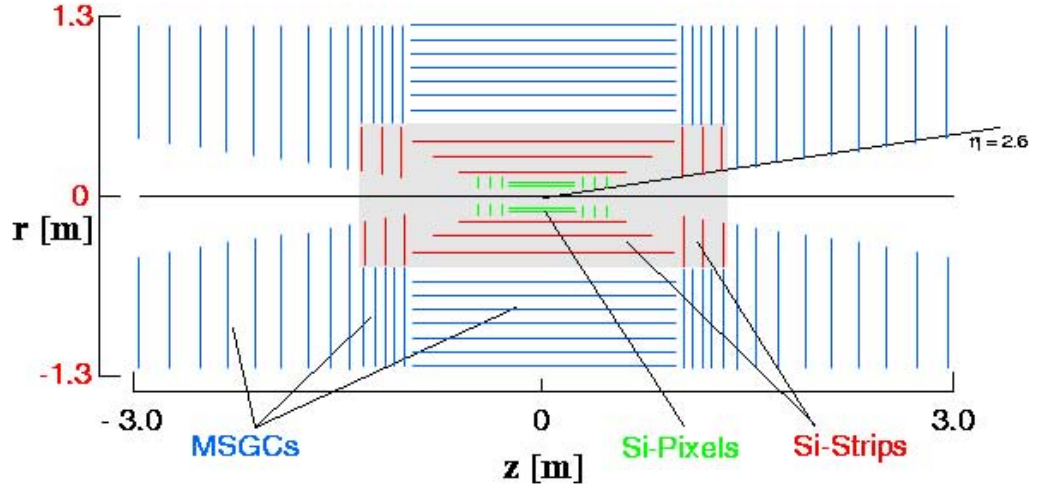


Figure 4.5: Layout of the silicon tracker in CMS

are accompanied by three disks of pixels on either side of the IP. The pixels provide three precision measurements for each charged particle trajectory passing through the detector. In total the pixel detector covers an area of 1m^2 and contains a total of 66 million pixels.

The silicon tracker consists of 10 layers of silicon strip detectors arranged in concentric barrels which extend to a radius of 116 m from the IP. The inner part of the silicon detector (shown in red) consists of three barrel layers and three disks on each end of the endcaps. The inner silicon strip tracker provides 4 trajectory measurements in the $r - \phi$ directions using $320\text{ }\mu\text{m}$ thick silicon strips which are oriented parallel to the beam line in the barrel and in the radial direction in the endcaps which give a maximum single point resolution of $23\text{ }\mu\text{m}$. The outer silicon strip tracker (pictured in blue) also consists of two parts. The barrel detector has six layers of $500\text{ }\mu\text{m}$ thick strips which give another six $r - \phi$ measurements with a point resolution of $35\text{ }\mu\text{m}$. The rest of the outer tracker has nine disks of silicon strips

in each endcap which have up to seven rings of strips in each disk providing a further nine ϕ measurements. Many layers also contain secondary strips placed back to back to provide stereo measurements of particle trajectories which give secondary direction information (z in the barrel and r on the disks) which are used to make up to 4 2-D hits per trajectory. The total active area of the CMS silicon strip detector is 198 m^2 and it uses 9.8 million silicon strips to reconstruct charged particles passing through it.

The performance of the CMS inner tracker is very good. For single muons of momentum of $\sim 100 \text{ GeV}$ the transverse momentum resolution is around $1 - 2\%$ in the barrel and slightly less for $|\eta| > 1.6$. Multiple scattering of muons at $p \sim 100 \text{ GeV}$ contributes around $20 - 30\%$ to the muon resolution, while at lower energies it is the dominant contribution. The transverse and longitudinal impact parameter measurement is also degraded by multiple scattering but the main source of error is the spatial resolution on the first pixel layer. For high energy muons the impact parameter resolution is around $10 \text{ }\mu\text{m}$. The total muon efficiency for the inner tracker is $> 99\%$ with small losses due to gaps in the pixel system and the reduced coverage by the forward pixel disks.

4.2 Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) consists of 75848 lead tungstate (PbWO_4) crystals (61200 in the barrel region and 7324 in each endcap) like the one shown in Fig. 4.6. Lead tungstate was chosen because the high density (8.28 g/cm^3), short radiation length (0.89 cm)

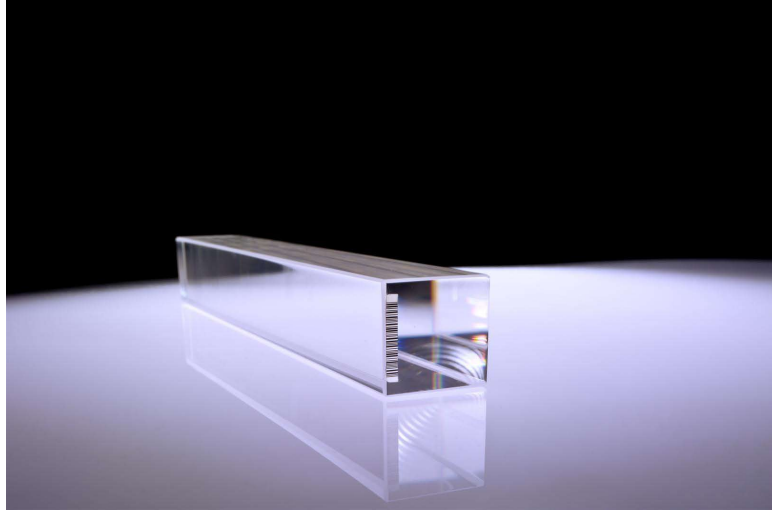


Figure 4.6: One PbWO_4 ECAL crystal

and small Molière radius (2.2 cm) allow for a very compact design with high granularity. PbWO_4 crystals are radiation-hard and have a very fast scintillation decay time of around 25ns for 80% of the light.

The ECAL is a hermetic homogenous calorimeter that covers a pseudorapidity range of $|\eta| < 3.0$. The overall layout is shown in Fig. 4.7. The barrel detector (EB) covers out to $|\eta| < 1.479$. The crystal cross-section in the barrel is 0.0174×0.0174 in $\eta - \phi$ which corresponds to a 360-fold granularity in ϕ and (2×85) -fold in η . The crystals are tapered to maintain constant $\eta - \phi$ granularity. This leads to a crystal size of $22 \times 22 \text{ mm}^2$ on the front face of the crystal and $26 \times 26 \text{ mm}^2$ on the back face. The crystals are mounted in a quasi-projective geometry which is angled 3 degrees in both the η and ϕ projections with respect to the vector pointing to the primary vertex in order to avoid particle trajectories that are aligned with the cracks in the ECAL. The EB crystals are 230 mm long, corresponding to $25.8 X_0$, and built up into modules of 400-500 crystals. Four of these modules are then

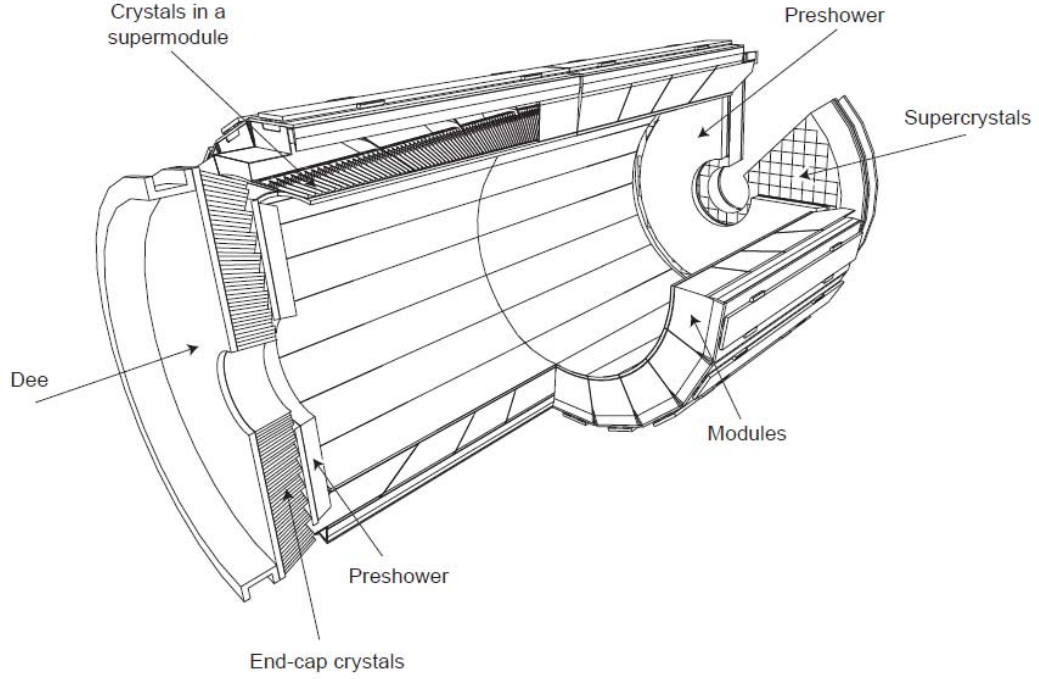


Figure 4.7: Layout of the CMS electromagnetic calorimeter

combined to form a supermodule of 1700 crystals. All of the services (cooling, cables, etc.) are routed to the back end of the supermodules and 18 supermodules (20 degrees each in ϕ) are combined to form half of the EB.

The ECAL endcaps (EE) cover the pseudorapidity range of $1.479 < |\eta| < 3.0$. The crystals in the EE are similar to the barrel with dimensions of $28.62 \times 28.62 \text{ mm}^2$ in the front and $30.0 \times 30.0 \text{ mm}^2$ in the back and a length of 220 mm ($24.7 X_0$). The crystals are grouped into 5×5 groups called supercrystals (SCs) and then 18 SCs and 18 partial SCs are grouped together form an endcap Dee which forms one-half of an endcap.

The crystals are read out using avalanche photodiodes (APDs) in the barrel and vacuum phototriodes (VPTs) in the endcap. Both are required to be radiation resistant, fast and able

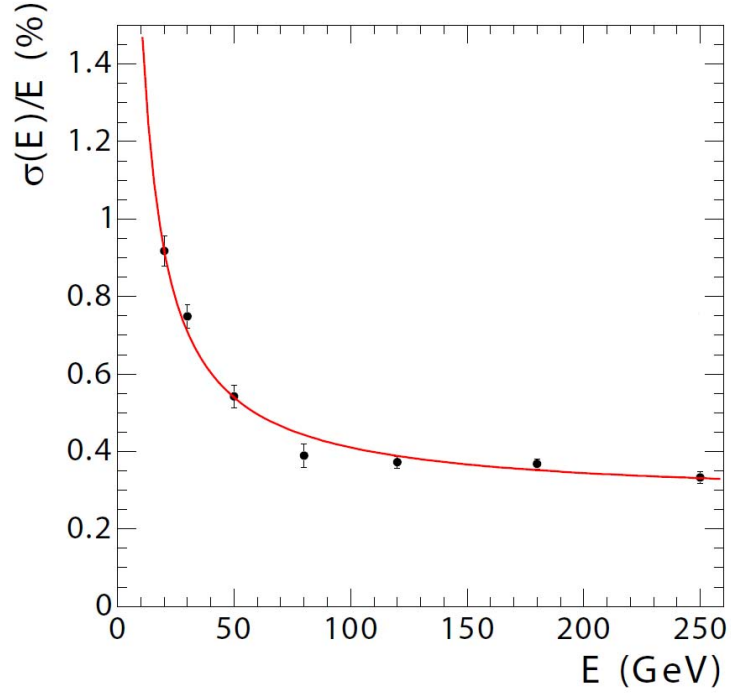


Figure 4.8: ECAL energy resolution as a function of electron energy

to work in the CMS 4 T magnetic field. The photodetectors must be able to read out the relatively small light emitted by the PbWO_4 crystals and at the same time be able to ignore particles traveling through them.

The ECAL energy resolution is shown in Fig. 4.8 as a function of electron energy. Below 500 GeV the energy resolution of the ECAL can be parametrized as follows:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2 \quad (4.1)$$

S is the stochastic term due to fluctuations in the lateral shower containment, photostatistics, and discrepancies between what is measured and what is actually deposited in the preshower.

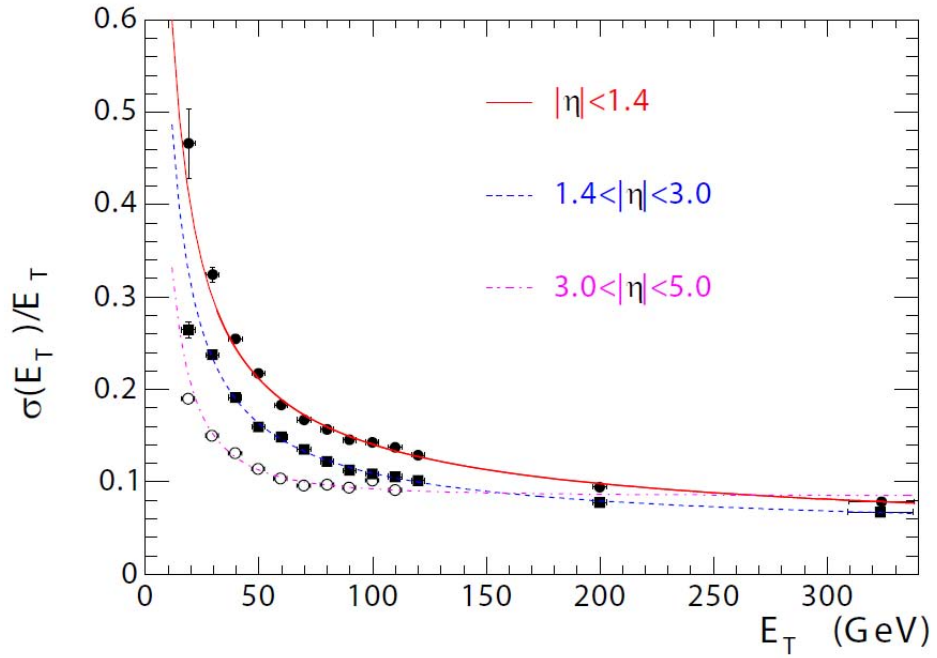


Figure 4.9: HCAL transverse energy resolution as a function of jet transverse energy for three regions of the HCAL

N is a noise term due to electronics, digitization and pile-up noise. The constant term (C) is due to non-uniformity of light collection, leakage out of the back of the calorimeter and intercalibration errors. A typical energy resolution found during beam tests was around:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (30\%)^2$$

Where E is the electron energy in GeV.

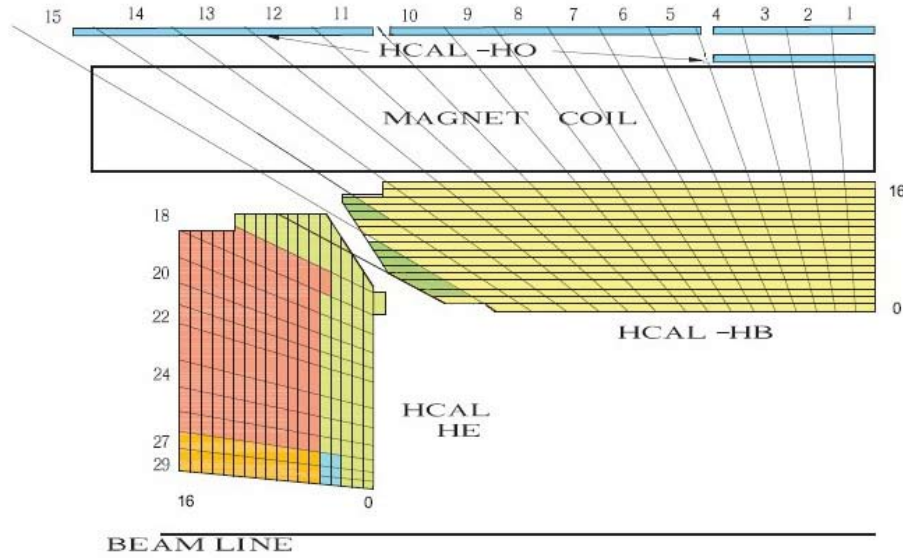


Figure 4.10: Layout and lateral segmentation of the CMS Hadronic Calorimeter

4.3 Hadronic Calorimeter

The hadronic calorimeter (HCAL) sits between the ECAL and the superconducting solenoid and extends from $R = 1.77$ m to 2.59 m in the barrel region. It is divided into four regions as seen in Fig. 4.10. The barrel calorimeter (HB) covers the central area of the detector in a pseudorapidity range of $|\eta| < 1.3$, the endcap calorimeter (HE) covers the endcaps from $1.3 < |\eta| < 3.0$, the forward calorimeter (HF) covers the far forward regions in the endcaps from $3.0 < |\eta| < 5.0$. Outside the solenoid, to ensure that there is enough sampling depth and stopping power in the barrel region, an outer calorimeter (HO) or *tail catcher* is used ($|\eta| < 1.3$) to ensure that there is no leakage out of the back of the calorimeter and into the muon system. Figure 4.9 shows the transverse jet energy resolution for the three eta regions covered by the calorimeter. The best resolution is obtained at higher energies ($\sim 10\%$ at

200 GeV) and is better in the forward regions (shown in purple) than in the barrel (red) and endcap (blue).

The HB consists of 36 identical azimuthal (ϕ) wedges constructed out of flat steel/brass absorber plates which are aligned parallel to the beam axis. Each wedge is divided into four azimuthal regions and the plastic scintillator between the plates is divided into 16 η sections which give the HB a granularity of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. The absorber consists of a 40 mm thick steel front plate, followed by eight 50.5 mm thick brass plates, six 56.5 mm thick brass plates, and a 75 mm thick steel back plate. The total absorber thickness at 90 degrees is 5.82 interaction lengths (λ_I) and increases with η to a maximum value of $10.3 \lambda_I$ at $\eta = 1.305$. The scintillator is sandwiched between the absorbers and is made from 3.7 mm thick Kuraray SCSN81 plastic scintillator. The light from the scintillators is collected using 0.94 mm diameter green wavelenth-shifting (WLS) fibers and then sent through clear fibers to an Optical Decoding Unit (ODU) which sends the light to the Hybrid Photodiodes (HPDs). Fig. 4.11 shows a set of completed HB cells.

The HE is designed to minimize dead zones in the absorber material using staggered brass plates 79 mm thick and spaced 9 mm apart to accomodate the plastic scintillators. The total length of the HE is around $10 \lambda_I$ counting the ECAL crystals in front of it. The staggered geometry of the HE results in a granularity of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$ for $\eta < 1.6$ and $(\Delta\eta, \Delta\phi) = (0.17, 0.17)$ for $\eta \geq 1.6$. As in the HB the scintillator is plastic and read out using WLS fibers and HPDs.

The outer HCAL (HO) is a tail-catcher designed to stop hadronic showers for $|\eta| < 1.3$

that are able to pass through the ECAL and HB and also identify late-developing showers. The HO consists of plastic scintillator and WLS fibers same as the HB and HE. The HO is placed outside the solenoid thus using the solenoid to gain $1.4/\sin\theta$ interaction lengths of stopping power, bringing the total barrel thickness to a minimum of $11.8 \lambda_I$. The HO layout follows that of the muon system because of the constraints of the iron return yoke. The scintillator trays must be divided into 12 ϕ regions and 5 wheels sections and placed on the outside of the first iron layer (the tail-catcher iron) at a radial distance of 4.07 m. The central wheel also has another layer of scintillator on the inside of the tail-catcher iron at a radial distance of 3.82 m to compensate for the minimal absorber depth at $\eta = 0$. The segmentation of the HO is designed to match the $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$ granularity of the HB.

The forward calorimeter (HF) is designed to handle the high particle fluxes and energy depositions in the region $3.0 < |\eta| < 5.0$. Because of the high radiation the calorimeter uses quartz fibers as the active medium. Alternating long and short fibers are embedded into a 5 mm steel absorber with the difference in length being necessary to discern between electrons and photons that shower in the front of the HF and the hadrons which shower throughout the HF. The fibers are bundled together to form cells of size $(\Delta\eta, \Delta\phi) = (0.175, 0.175)$ and built up into 20 degree azimuthal wedges. The light travels through fibers that are embedded into a steel shielding that protects the read-out photomultiplier tubes from radiation.



Figure 4.11: Picture of completed hadronic calorimeter cells

4.4 Superconducting Solenoid

The CMS superconducting solenoid (Fig. 4.12) sits outside of the HCAL and before the muon system. The magnet is 12.5 m long and has an inner bore diameter of 6 m and produces a homogenous 4 T magnetic field with a stored energy of 2.6 GJ at full current. The cold mass of the solenoid weighs 220 t and consists of 4 layers of NbTi Rutherford cables that are co-extruded with pure aluminium and reinforced with aluminium alloy for strength. The reinforcement is necessary as the high ratio of stored energy to cold mass (11 kJ/kg) causes a large mechanical deformation (0.15%) upon energising.

The iron return yoke of the magnet system is comprised of 5 barrel wheels and 6 endcap disks (3 per endcap). The weight of each varies from 400 t at the lightest to 1920 t for the central wheel. The iron yoke layers alternate in the outer part of the detector (shown in yellow in 4.13) with the muon system drift tube chambers in the barrel and the cathode strip

Table 4.1: Parameters of the CMS superconducting solenoid

General Parameters	
Magnetic length	12.5 m
Cold bore diameter	6.3 m
Central magnetic induction	4 T
Total Ampere-turns	41.7 MA-turns
Nominal current	19.14 kA
Inductance	14.2 H
Stored energy	2.6 GJ
Cold Mass	
Radial thickness of cold mass	312 mm
Radiation thickness of cold mass	$3.9 X_0$
Weight of cold mass	220 t
Maximum induction on conductor	4.6 T
Temperature margine wrt operating temperature	1.8 K
Stored energy/unit cold mass	11.6 kJ/kg
Iron Yoke	
Outer diameter of the iron flats	14 m
Length of barrel	13 m
Thickness of iron layers in barrel	300, 630 and 630 mm
Mass of iron in barrel	6000 t
Thickness of iron disks in endcaps	250, 600 and 600 mm
Mass of iron per endcap	2000 t
Total mass of iron in return yoke	10000 t

chambers in the endcaps to provide the bending field for muons in the muon system.

A summary of parameters of interest for the magnetic system can be found in Tab. 4.1.

4.5 Muon System

The muon system surrounds the inner detectors and the magnet and consists of three types of gaseous detection chambers. In the barrel region drift tube chambers (DT) are used to measure position and momentum while the cathode strip chambers (CSC) perform the same

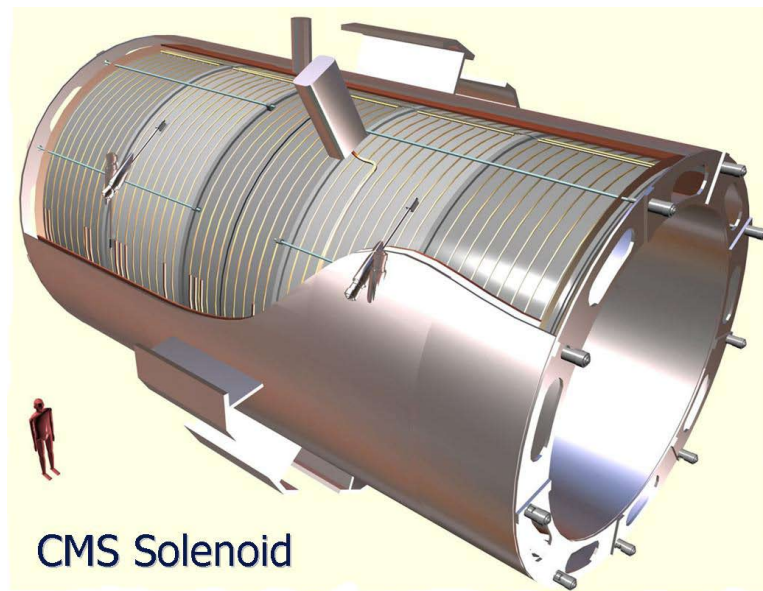


Figure 4.12: A computer model of the CMS solenoid

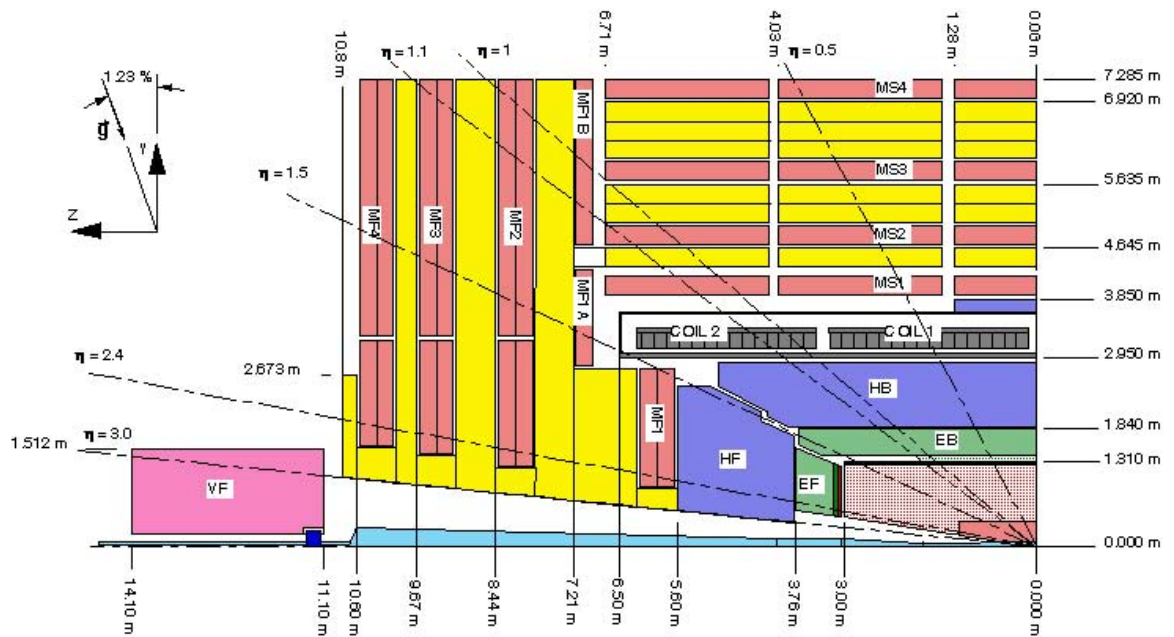


Figure 4.13: A side view of the CMS muon system and the iron return yoke

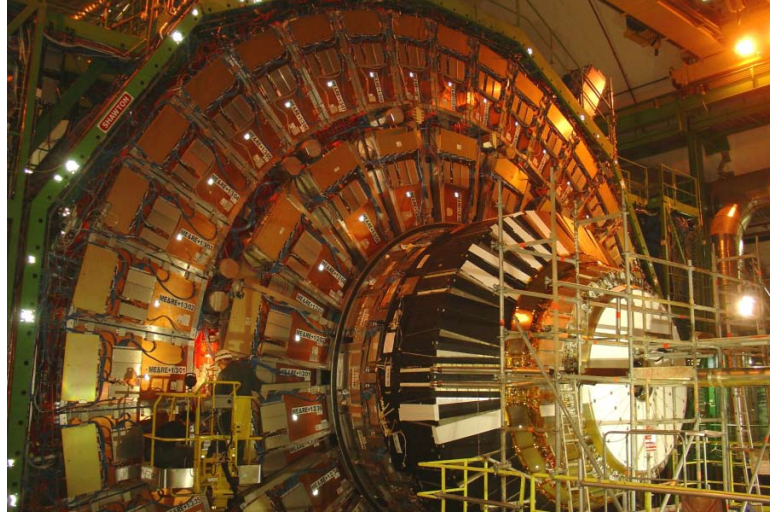


Figure 4.14: A view of one of the disks in the Endcap Muon System

function in the endcaps. Resistive plate chambers (RPC) are placed throughout the muon system and are used mainly for timing purposes. Fig. 4.13 shows the DT and CSC modules in red interspersed between the iron return yoke shown in yellow. The RPCs are not shown but are attached to the opposite side of the iron from the DTs and the CSCs.

The DTs form 4 concentric barrels of chambers around the beampipe and 5 rings in the z -direction. These barrels form 4 stations of 60 chambers each in the first 3 stations and 70 chambers in the outermost station. The standard DT is composed of 3 superlayers that contain 4 layers of rectangular cells staggered by half a cell each. The cells are 2.4 m long, corresponding to a maximum drift time of 380 ns when filled with an 85% Ar + 15% CO₂ gas mixture. The outer 2 superlayers have their wires oriented parallel to the beampipe to measure the magnetic bending in the $r - \phi$ direction while the inner superlayer is oriented perpendicular to the beampipe to measure the z direction. The DTs have a global $r - \phi$ resolution of 100 μm which is achieved by the 8 ϕ measurements in each chamber.

The endcap muon system consists of 468 CSC chambers in the LHC start-up configuration. Some additional chambers will be added to the outermost disks at a later date. The CSCs are arranged in concentric rings around the beampipe with 3 rings forming each disk (2 on the fourth disk) with 4 disks in each endcap. Fig. 4.14 shows one of the inner endcap disks with the hadronic endcap calorimeter covering the inner ring of chambers. Each chamber is trapezoidal and covers either 10 or 20 degrees in ϕ . The CSCs are constructed out of 6 layers of anode wires oriented azimuthally to measure the track's r coordinate and 7 layers of cathode strips that are oriented radially and are tapered to be constant in ϕ to measure the track ϕ coordinate. The chambers use a gas combination of 40% Ar + 50% CO₂ + 10% CF₄ which gives a gas gain of $\sim 7 \times 10^4$ at the nominal operating voltage of 3.6 kV. The $r - \phi$ spatial resolution of the CSCs is 75 μm for chambers in the first two rings of the innermost endcap disks and 150 μm for all of the other chambers.

The resistive plate chambers (RPC) are gaseous chambers made of two gas cells with readout strips between them. While the spatial resolution of the RPCs is not that great the timing resolution is smaller than the 25 ns bunch crossing time of the LHC allowing a dedicated muon trigger to be based off of RPC signals. The layout of the RPC system mimics that of the CSCs and DTs and are located throughout the detector.

The muon system momentum resolution must be small ($\sim 1\%$ at 100 GeV) and the charge must be able to be identified unambiguously up to momenta of ~ 1 TeV in order to provide the dimuon invariant mass measurements desired for physics measurements. The transverse momentum resolution is shown in Fig. 4.15 for the muon system alone (black), the inner

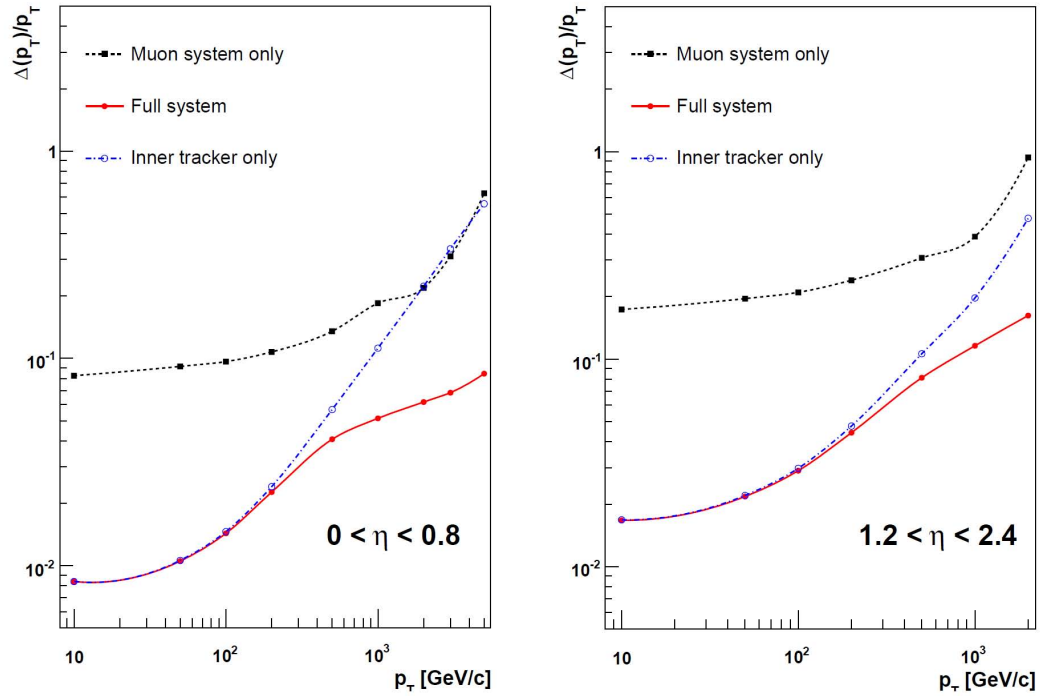


Figure 4.15: Momentum resolution in CMS in the barrel region (left) and endcap region (right)

tracker alone (blue) and the full system (red). The inner tracker dominates the p_T resolution up to momenta of ~ 1 TeV. While the tracker momentum measurements are far superior than the momentum measurement from the muons system alone, it relies on information from the muon system to identify which tracks correspond to muons.

4.6 Trigger

At nominal running the LHC will provide about 20 proton-proton interactions per bunch crossing at a rate of 25 ns between crossings. The large numbers of particles per crossing

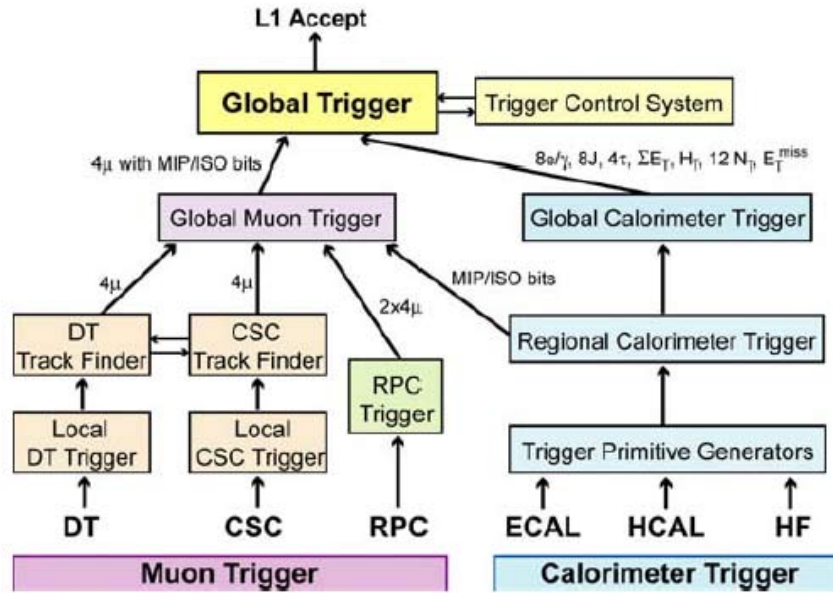


Figure 4.16: The CMS Level-1 trigger architecture

requires an effective filter to decrease the event rate to a level that can be processed and recorded. The CMS trigger system is designed to achieve this level of data reduction. The trigger architecture is divided into two parts: Level 1 and the High Level Trigger which decrease the trigger rate from 20×40 MHz down to ~ 30 kHz.

The Level 1 trigger uses dedicated electronics such as field programmable gate arrays, application-specific integrated circuits and look-up tables to deliver coarsely segmented data from the calorimeters and the muon system; while the High Level Trigger is a software system that uses a processor farm and a large fraction of the offline reconstruction software to make further decisions on the validity of an event.

Fig. 4.16 shows the Level 1 trigger architecture. The local or regional triggers are derived from pattern matches in the muon chambers or energy depositions in the calorimeters. This

information is spatially matched by region using pattern recognition software to provide preliminary muon, electron and jet candidates within each event. The global muon and calorimeter triggers then take all of the candidates from the local trigger systems and further process them to pick the highest level object to send to the global muon or calorimeter trigger, which decides whether or not to send the event to the High Level Trigger.

The High Level Trigger uses the information passed from the Level 1 and processes the information through standard reconstruction and isolation logic to determine the content of the event. The events are tagged according to criteria defined by trigger tables such as muons and electrons of a certain p_T or missing transverse energy for analysis.

Chapter 5

Event Simulation

The simulations in these studies are performed using the **PYTHIA** [68], **MadGraph** [57] and **powheg** [20] event generators. The muon-enriched QCD multi-jet samples and the diboson (WW , WZ , ZZ) samples are generated in **PYTHIA** while the $W, Z, t\bar{t}$ + jets are generated by performing the matrix-element calculations using **MadGraph** and matched to parton showers calculated by **PYTHIA**. In addition, the single top are calculated at next to leading order (NLO) using **powheg** and also run through **PYTHIA**. The signal is modelled using the same combination of **MadGraph** and **PYTHIA** as the $t\bar{t}$ and W, Z samples where the masses of the Z' resonances are generated between 500 GeV and 2 TeV with a 1% width and the same couplings to Standard Model fermions as the Z^0 -Boson.

The datasets used for the boosted decision tree training and the Z' cross-section limit setting are given in Table 5.1.

Signal
/Zprime_M500GeV_W5GeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
/Zprime_M750GeV_W7500MeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
/Zprime_M1000GeV_W10GeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
/Zprime_M1250GeV_W1250MeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
/Zprime_M1500GeV_W15GeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
/Zprime_M2000GeV_W20GeV-madgraph/Summer11-PU_S4_START42_V11-v2/AODSIM
Background
/TTJets_TuneZ2_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v2/AODSIM
/QCD_Pt-20_MuEnrichedPt-15_TuneZ2_7TeV-pythia6/Summer11-PU_S4_START42_V11-v2/AODSIM
/DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/T_TuneZ2_s-channel_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/Tbar_TuneZ2_s-channel_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/T_TuneZ2_t-channel_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/Tbar_TuneZ2_t-channel_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/WWTo2L2Nu_TuneZ2_7TeV_pythia6_tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/WZTo3LNu_TuneZ2_7TeV_pythia6_tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/ZZTo2L2Nu_TuneZ2_7TeV_pythia6_tauola/Summer11-PU_S4_START42_V11-v1/AODSIM

Table 5.1: Datasets used to model signal and background

Chapter 6

Lepton Isolation and Event Preselection

6.1 Isolated Muon Identification for $\sqrt{s} = 10$ TeV

Isolated muons in CMS are identified using a combined energy and track isolation variable,

RelIso:

$$RelIso = \frac{\sum_{\Delta R < 0.3} E_T^{em}}{E_T^\mu} + \frac{\sum_{\Delta R < 0.3} E_T^{had}}{E_T^\mu} + \frac{\sum_{\Delta R < 0.3} p_T^{trk}}{p_T^\mu} \quad (6.1)$$

The first two sums run over the ECAL and HCAL cells crossed by the muon track and the third sum is a track p_T sum for tracks around the muon in the tracker, where all of these summations are in a cone of $\Delta R < 0.3$ around the muon. In addition, to remove the effects of the muon itself, the two calorimeter E_T sums are corrected for the energy deposited in the cells crossed by the track. A similar correction is made to the track p_T sum by subtracting the summed track p_T in a smaller veto cone of $\Delta R < 0.15$, which is drawn around the muon track direction [53]. In the standard model $t\bar{t}$ and electroweak analysis a cut of $RelIso <$

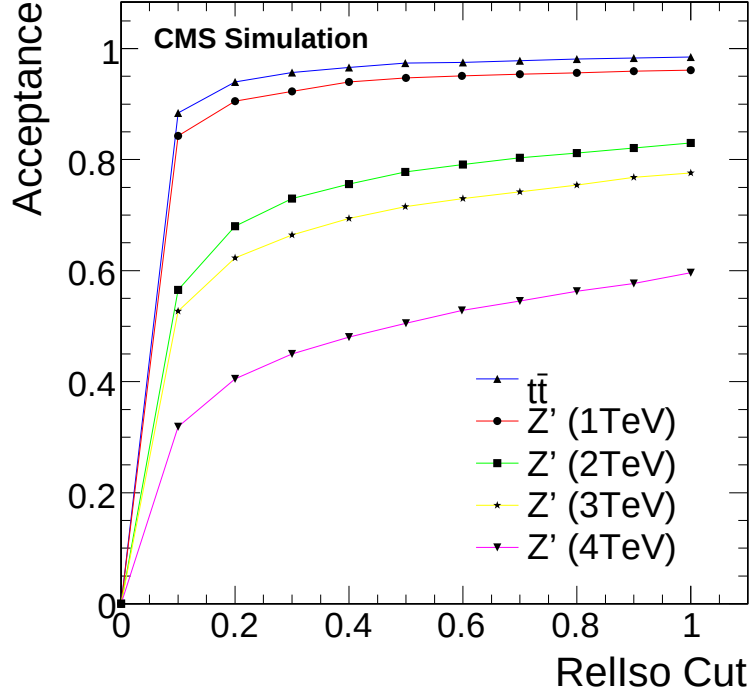


Figure 6.1: Muon selection efficiency as a function of RelIso threshold.

0.10 [8] is used to identify isolated muon candidates.

Figure 6.1 shows the muon selection efficiency for $t\bar{t}$, QCD and Z' events for masses between 1 and 4 TeV as a function of the RelIso cut threshold. Here, the muon tracks have been pre-selected to have $p_T \geq 30$ GeV and $|\eta| < 2.1$ with at least 11 hits in the tracker, an impact parameter < 200 microns and a global track normalized chisquare of $\chi^2 < 10$. A RelIso threshold of 0.10 gives high efficiency and low QCD background acceptance for both standard model $t\bar{t}$ events and Z' events with mass 1 TeV. However, as the mass of the Z' is increased, the acceptance drops off quite quickly, falling to $\sim 63\%$ at 2 TeV and $\sim 35.5\%$ at 4 TeV. Such a mass-dependence is far from ideal for a search analysis and the acceptance at large mass is quite poor. This is a direct consequence of the merging of the t -decay products

due to the boost given to the $t\bar{t}$ system.

The loss in acceptance is the result of cutting on energy (momentum) flow around the muon in events where there is substantial nearby jet activity. In nearly all cases the jet is from the $b(\bar{t})$ from the same parent t -quark. In the analyses presented here, we have studied alternative algorithms which rely on the muon-jet topology and which do not explicitly use energy-momentum flow. These are topological, are more robust for changing beam conditions, and do not depend on the details of the event energy-momentum flow. One of the principal backgrounds to a $Z' \rightarrow t\bar{t}$ comes from the muons produced in or close to a QCD jet. Typically these are from:

1. Semileptonic decays of b -quarks, either directly or via chain-decays where the b -quarks are produced in the jet fragmentation chain:

$$b \rightarrow \mu X, b \rightarrow cX \rightarrow \mu X$$

2. Semileptonic decays of c -quarks from the same source:

$$c \rightarrow \mu X$$

3. In-flight decays of high momentum charge π and K -mesons produced within the jet fragmentation.

The efficiency of the RelIso algorithm comes from the presence of the associated hadronic debris in 1) and 2) and the presence of additional particles in 3). To be viable, any alternative method must also maintain good rejection of all three types of QCD background muons.

6.1.1 Complications due to Energy Loss

Before entering into the methods we need first to consider more carefully the muon signature in the detector. For momenta below ~ 250 GeV, muons behave like minimum ionizing particles, and they lose energy via dE/dx as they pass through material. A typical muon will deposit around 6-7 GeV along its path as it travels through the ECAL and HCAL via dE/dx . As it is passing through a magnetic field, it also has a finite probability to radiate one or more photons via QED bremsstrahlung. These are typically emitted at low angle with respect to the muon track and at large values of p_T^μ will merge with the dE/dx trace in the ECAL. The net effect is a deposition of around 8-12 GeV along the track direction in the ECAL+HCAL. As this is frequently above the 10 GeV which is used as the minimum threshold in jet-finding, it results in the production of a pseudo-jet centered on the muon track. After application of the standard energy corrections, these are corrected to create a jet of $\sim 20 - 25$ GeV. In the case of the standard RelIso selection, the dE/dx deposition is handled by the use of the veto cone around the track direction which attempts to remove this energy from the ΔR sums. These effects have to be handled carefully in any alternative algorithm as they appear as legitimate jets in the event jet list. In the following discussion we will refer to these “jets” as “veto-cone jets” and we will attempt to find a simple and efficient method for their removal.

If we are concerned with removal of the veto-cone jets, then a simple search for jets centered on the muon track with uncorrected energy below some threshold will suffice. Alternatively, if the issue is that of verification of the consistency between the observed and expected dE/dx deposition, then summing the energy in the crossed cells of the ECAL and

HCAL is probably more correct. For our purposes, we will use the former method.

To study the rejection of the veto cone jets we need a sample of isolated muon tracks at large p_T . This can be done with either $W \rightarrow \mu\nu$ or $Z^0 \rightarrow \mu^+\mu^-$ montecarlo events. However, as we are eventually going to apply the results to studies of top decays, we prefer to use a sample of $t\bar{t}$ events in which we select the semimuonic decays (i.e. $t\bar{t} \rightarrow \mu\nu q\bar{q}b\bar{b}$). To ensure that we are picking up the muons from the W -decay and not from one of the b -quarks, we apply a $\text{RelIso} < 0.1$ cut. For the surviving muon candidates we search for jets reconstructed within the $\Delta R < 0.15$ veto cone and study the rejection efficiency as a function of uncorrected E_T threshold. The results are shown in Fig. 6.2.

To demonstrate the effect of this cut, Fig. 6.3 shows the minimum opening angle between the muon and the nearest jet ($\Delta R_{\min}(\mu, \text{jet})$) for the muons in the sample. Fig. 6.3 a) is the result with no rejection and Fig. 6.3 b) corresponds to a threshold of 15 GeV. While the uncorrected distribution is clearly incorrect, the corrected distribution shows good agreement with the expectation for a $W \rightarrow \mu\nu$ decay. For the subsequent studies presented in this report we use a 15 GeV cut to remove these jets from our analysis. This corresponds to a veto-cone jet rejection efficiency of $\sim 98\%$.

6.1.2 Alternative muon identification methods for Z' events

In this section we consider a variety of algorithms which attempt to differentiate between the characteristics of muons coming from W and QCD-decays. We consider the specific case of

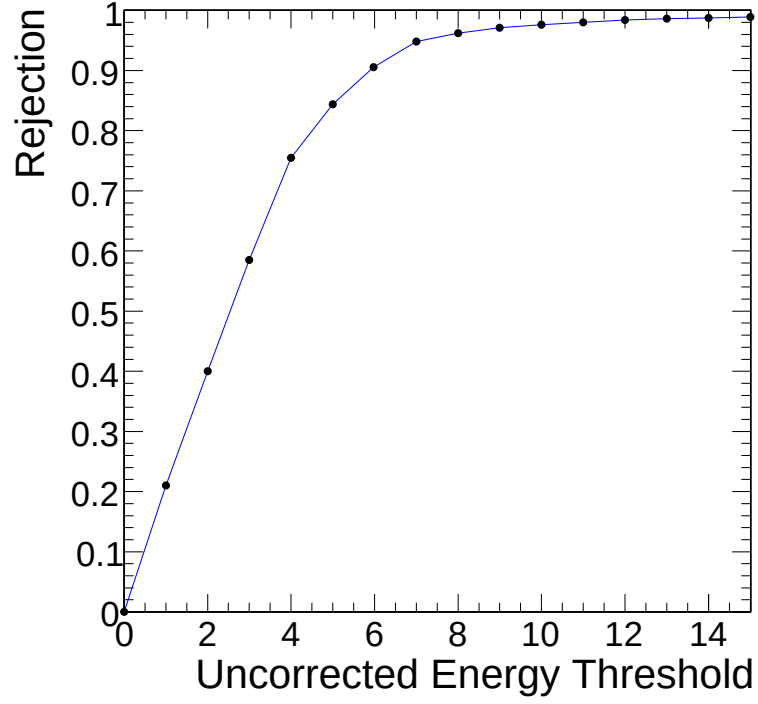


Figure 6.2: Rejection efficiency as a function of uncorrected jet E_T threshold for veto cone jets in $W \rightarrow \mu\nu$ decays from $t\bar{t}$ events.

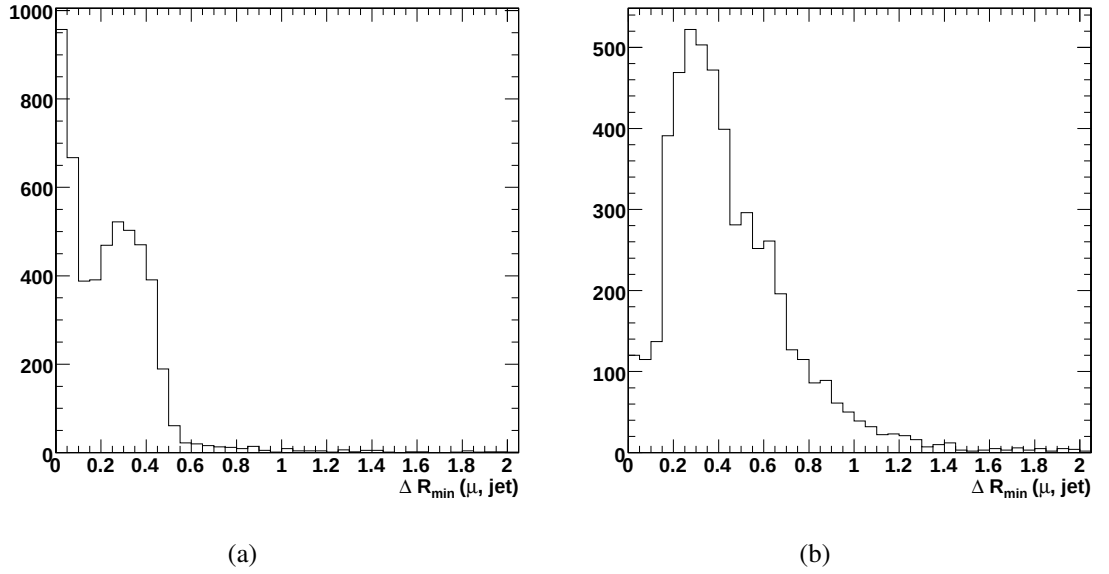


Figure 6.3: Separation of the muon and the nearest jet in decays in $W \rightarrow \mu\nu$ events. a) no suppression and b) with 15 GeV threshold suppression of veto cone jets

$Z' \rightarrow t\bar{t}$ decays with Z' mass above 1 TeV for which t -decay product merging is present.

The algorithms studied use spatial and kinematic variables built from the combination of the muon track and the nearest neighbor jet. Five different methods are considered:

1. $\Delta R_{min}(\mu, jet)$ - in the case of QCD background the muon is clearly correlated to direction of the accompanying hadronic debris(jet), whereas a muon originating from a nearby W -decay is almost independent of the direction of the neighboring jet activity. Thus a muon from a W -decay which is overlapping with a jet will tend to be at significantly larger values of ΔR_{min} than a muon from a QCD background.
2. $p_T^{rel}(\mu, jet)$ - this is a variable commonly used in soft lepton b -tagging algorithms. A muon from a $b \rightarrow \mu X$ decay is typically produced at relatively small p_T with respect to the axis of accompanying hadronic jet (p_T^{rel}). Muons from $W \rightarrow \mu\nu$ decay are typically larger in p_T and are not strongly correlated to the jet direction. Thus signal muons should occur at significantly larger values of p_T^{rel} than those from the QCD background.
3. $\Delta R_{min}(\mu, jet)$ vs $p_T^{rel}(\mu, jet)$ - as the two variables are not 100% correlated, using their combination may be more sensitive than either separately.
4. $m(\mu jet)$ - the requirement of a 50 GeV threshold on the invariant mass of the muon and its neighboring jet was suggested by the authors of reference * as a possible way

to separate muons from W - and b -decays. This method relies of the combination of the directional information and the differences in the muon kinematics.

5. p_T^{rel}/p - in a manner similar to $m(\mu, jet)$, this attempts to combine the muon-jet topology information and the difference in the muon momentum spectra to separate the two types of muons.

As a benchmark we take the 2 TeV mass point for which a significant amount of decay product overlap has already occurred. The use of the RelIso method of isolated muon selection results in a 30% acceptance loss relative to a mass of 1 TeV. We start by selecting a sample of muons with $p_T > 30$ GeV and $\eta < 2.1$ which satisfy all of the track quality cuts described in section 1. This is followed by the analysis of the muon parentage and jet-parton matching which allows us to separate the different contributions to the muon track sample. Figs 6.4 and 6.5 show a comparison of the muons from W and b -decay in terms of each of the above variables. The first three show significant separation between the two types of μ , whereas while the last two show no clear separation. We therefore drop the last two variables and proceed to study the first three in more detail.

$$\underline{\Delta R_{min}(\mu, jet)}$$

Fig. 6.6 shows the $\Delta R_{min}(\mu, jet)$ spectra for each of the three categories of background separately and combined. Fig. 6.6 a.) is the muons from $b \rightarrow \mu X$, b.) $c \rightarrow \mu X$, c.) π/K in-flight decays and d.) is the sum of the three contributions. As expected the spectra from both the

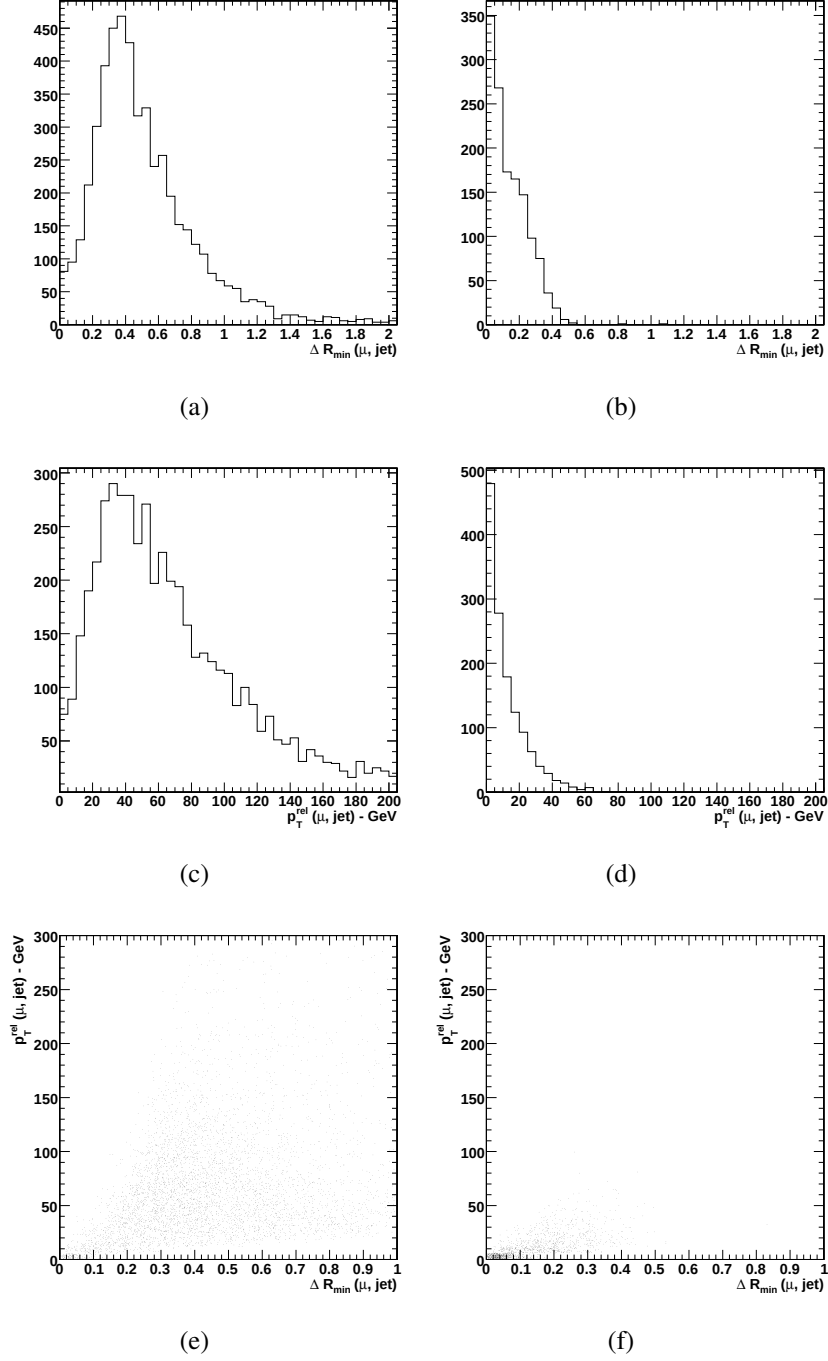
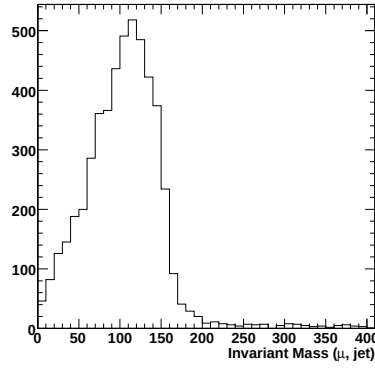
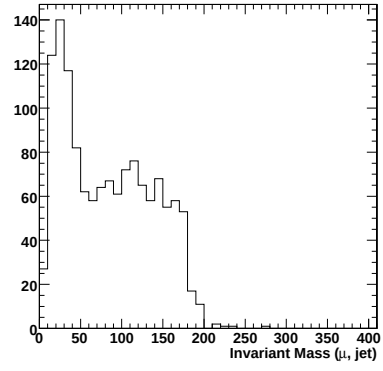


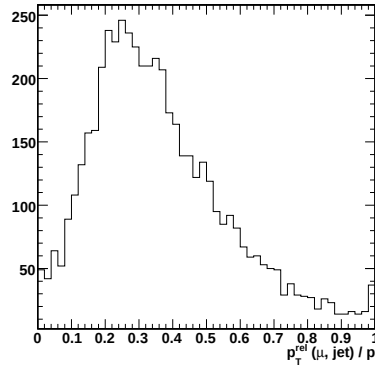
Figure 6.4: Comparison of the μ spectra from W and b-decays in the 2 TeV Z' events in terms of: a,b) $\Delta R_{min}(\mu, jet)$, c,d) $p_T^{rel}(\mu, jet)$, e,f) $\Delta R_{min}(\mu, jet)$ vs $p_T^{rel}(\mu, jet)$



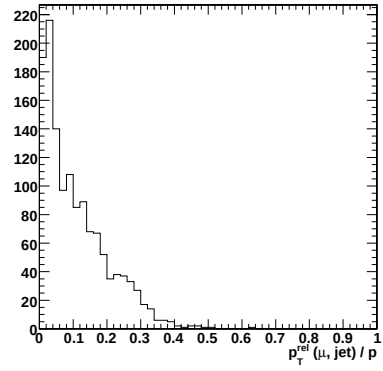
(a)



(b)



(c)



(d)

Figure 6.5: Comparison of the μ spectra from W and b-decays in the 2 TeV Z' events in terms of: a,b) $m(\mu \text{ jet})$ and c,d) p_T^{rel}/p

charm and in-flight decays are somewhat softer than those of the b -decays. We can, therefore, use either the b -decay (or the combined) spectrum to proceed to calculate the acceptance for signal muons and the residual background from non- W muons. The acceptance is defined as:

$$Acceptance = \frac{\text{number of muons from } W \rightarrow \mu\nu \text{ decays selected}}{\text{number of muons from } W \rightarrow \mu\nu \text{ decays passing the muon pre-selection}}$$

And similarly the background rate is defined:

$$Background = \frac{\text{number of non-}W \text{ muons selected}}{\text{number of jets } E_T > 30 \text{ GeV in fiducial region}}$$

The results are shown in Table 6.1.2. We conclude that we can obtain comparable or better signal acceptance to that obtained using the RelIso method while maintaining a high level of background rejection.

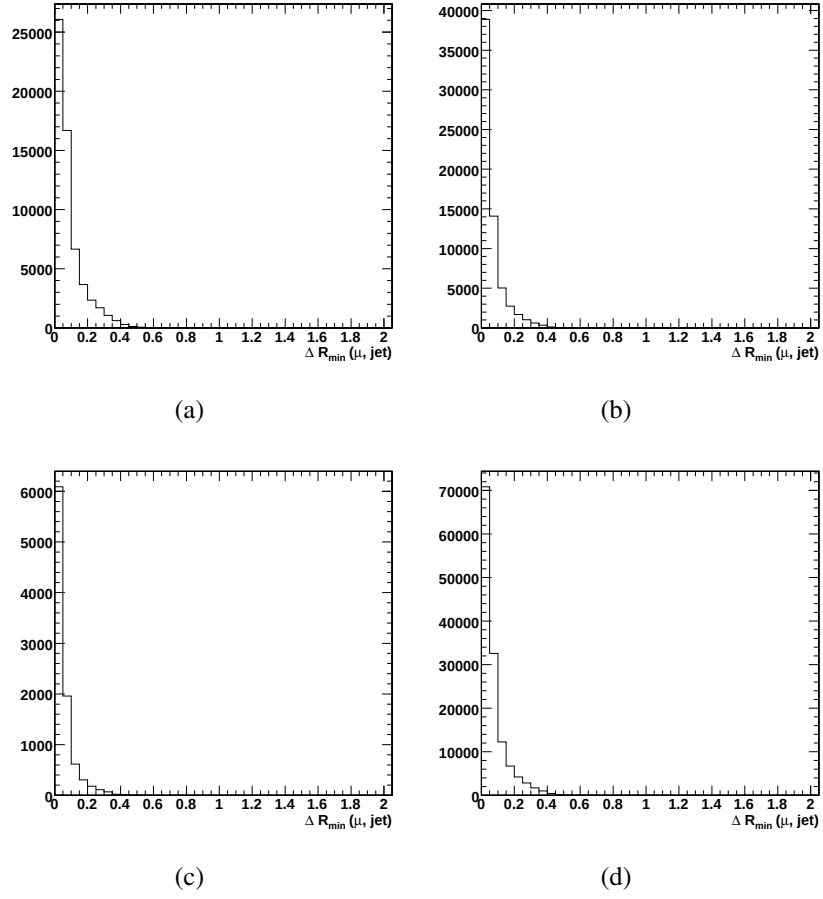


Figure 6.6: $\Delta R_{min}(\mu, jet)$ spectra in 2 TeV Z' events for a) $b \rightarrow \mu X$ b) $c \rightarrow \mu X$ c) π/K in-flight decays and d) combined background

ΔR_{min} threshold	Signal Acceptance (%)	Background Rate
0.1	97.1	0.0100
0.2	90.8	0.0051
0.3	78.1	0.0019
0.4	59.9	0.0004
0.5	44.4	0.0001

Table 6.1: Signal and background acceptances for various ΔR_{min} cuts

$p_T^{rel}(\mu, jet)$

We reach a similar conclusion from the study of the $p_T^{rel}(\mu, jet)$ spectra which are show in Fig. 6.7 a.)-d.) and Table 6.1.2. Comparison of Table 6.1.2 and Table 6.1.2 suggests that $p_T^{rel}(\mu, jet)$ may give slightly better signal:background than $\Delta R_{min}(\mu, jet)$.

$p_T^{rel}(\mu, jet)$ cut (GeV)	Signal Acceptance (%)	Background Rate
5	99.0	0.0120
10	97.3	0.0076
15	94.6	0.0048
20	90.9	0.0032
30	81.6	0.0014
40	70.5	0.0006
50	60.0	0.0002

Table 6.2: Signal and background acceptances for various $p_T^{rel}(\mu, jet)$ cuts

$p_T^{rel}(\mu, jet)$ vs $\Delta R_{min}(\mu, jet)$

As both $\Delta R_{min}(\mu, jet)$ and $p_T^{rel}(\mu, jet)$ give quite good signal:background discrimination, it is clear that a 2-D cut on the correlation of the two variables should give comparable or better results. To test this we choose a semi-arbitrary operating point of 0.35 in ΔR_{min} and 50 GeV in p_T^{rel} . For this we obtain a background rate of 0.0016 muons/jet and a signal acceptance

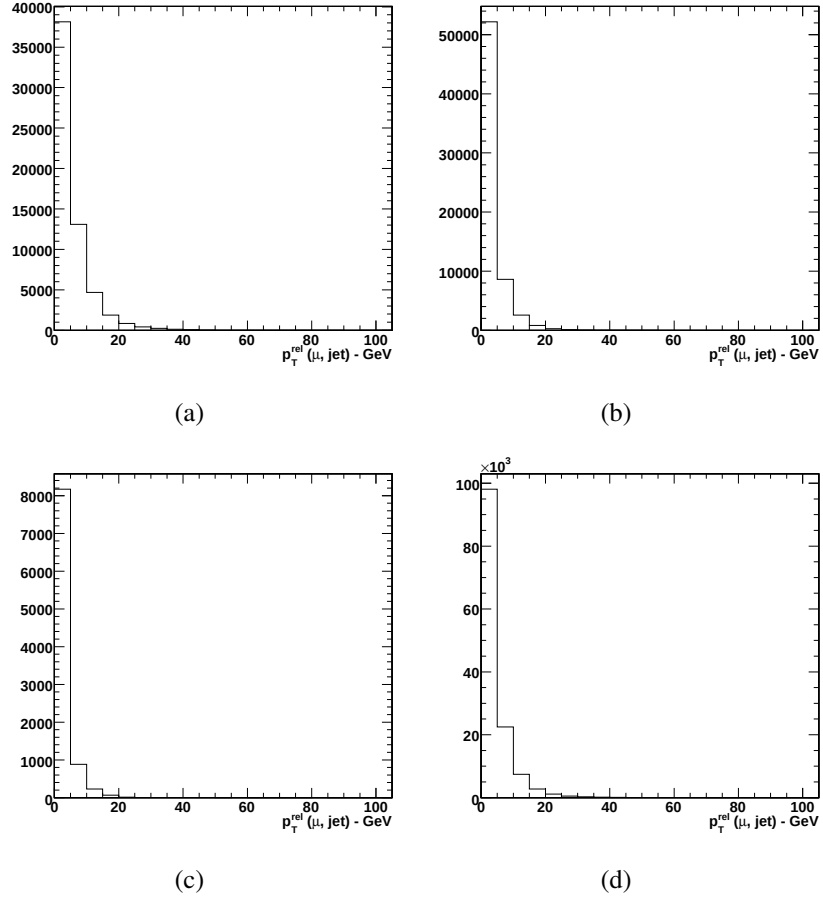


Figure 6.7: $p_T^{\text{rel}}(\mu, \text{jet})$ spectra in 2 TeV Z' events for a) $b \rightarrow \mu X$, b) $c \rightarrow \mu X$, c) π/K in-flight decays and d) combined background

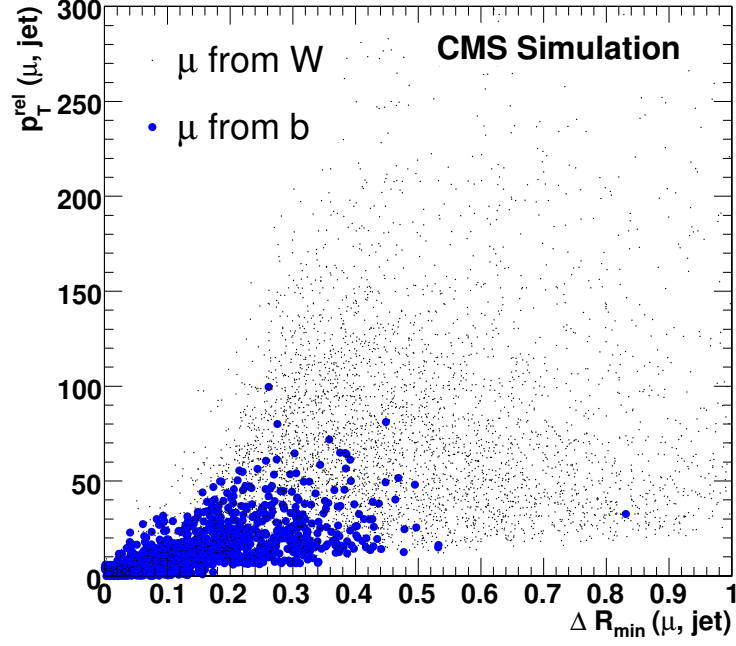


Figure 6.8: $p_T^{rel}(\mu, jet)$ vs $\Delta R_{min}(\mu, jet)$ for muons from W -decay (black points) and background (blue points)

of 82.2%. For completeness, we show $\Delta R_{min}(\mu, jet)$ vs $p_T^{rel}(\mu, jet)$ for the signal (black) and combined background (blue) in Figure 6.8. This algorithm has the best performance of those studied. In the following section we attempt to find which cut thresholds give the optimum signal acceptance and background rejection.

6.1.3 2D Cut Optimization

Fig. 6.9 shows the acceptance for muons from $W \rightarrow \mu\nu$ for Z' masses of 1, 2, 3 and 4 TeV respectively as a function of p_T^{rel} and ΔR_{min} . We show results for p_T^{rel} thresholds of up to 50 GeV and ΔR_{min} thresholds of up to 0.5. The acceptance varies quite slowly over this range,

with a slow drop-off in acceptance as the thresholds are raised.

To study the QCD background we consider two types, which we label internal and QCD. The internal background consists of the muons coming from b -, c - and π/K in-flight decay within the Z' decay events themselves. The QCD background is due to muons from the same sources, but originating from QCD multijet processes. We have studied two different regions of the QCD phase-space and compare the results. The largest part of the multijet cross section is at low- $\hat{s}$ where the jets and the associated muons tend to be low p_T . At the other extreme are the very high $\hat{s}$ QCD events in which the jets are of several hundred GeV in p_T and both the jets and the muons have similar kinematics to those of the Z' events.

Fig. 6.10 shows the corresponding background rates for the four internal background samples (a.-d.), the low- $\hat{s}$ background (e.) and the high- $\hat{s}$ background (f.). Comparison with Fig. 6.9 shows that the internal backgrounds are somewhat harder than the the QCD inclusive backgrounds. However, in all cases, the background falls quite rapidly as the p_T^{rel} and/or ΔR_{min} thresholds are raised.

To optimize the selection criteria, we have performed a localized grid search in the high threshold region where the signal acceptance is high and the background rates are low. Results for the 2 TeV Z' mass are shown in Tables 6.1.3 and 6.1.3. For a low mass analysis (Z' mass below ~ 2 TeV) the best performance is obtained for thresholds of $\Delta R_{min} > 0.4$ and $p_T^{rel} > 35$ GeV. Because of the stiffer nature of the internal backgrounds at larger masses, a slightly higher threshold of $\Delta R_{min} > 0.4$ and $p_T^{rel} > 40$ GeV is preferred.

Fig. 6.11 shows the comparison between the acceptances for the optimized 2D Cut

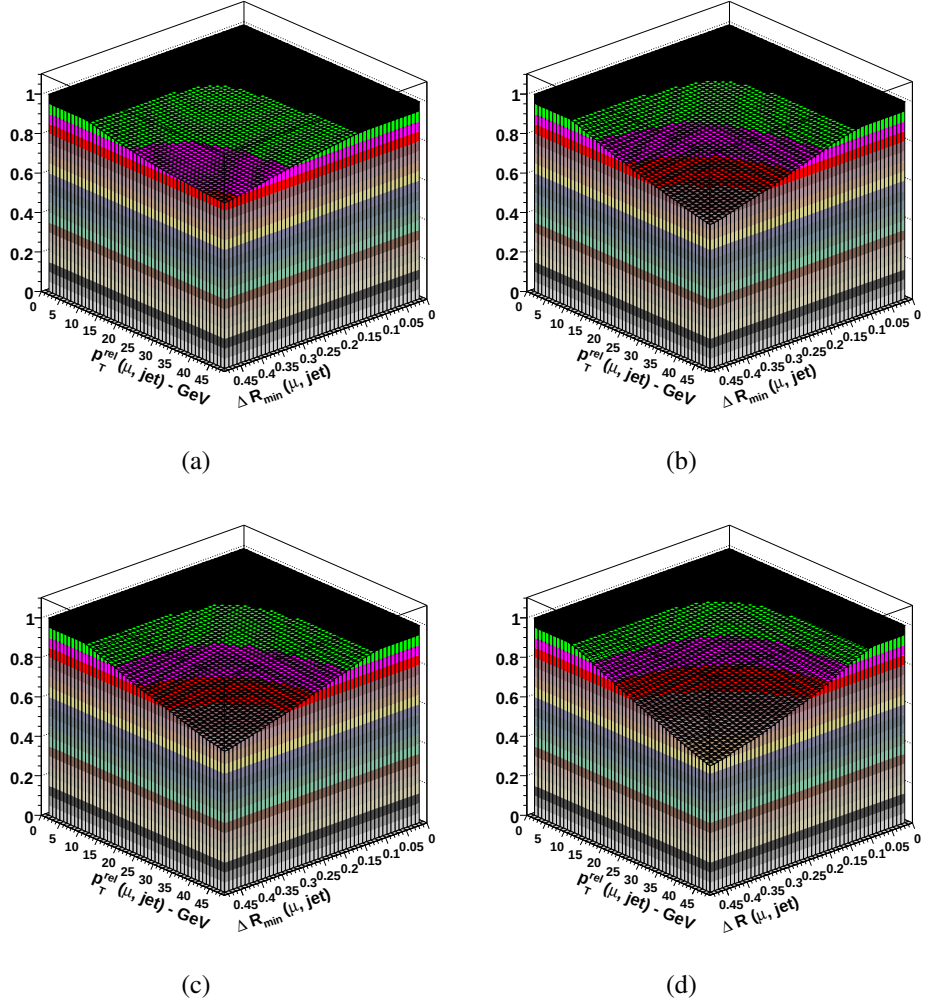


Figure 6.9: Signal acceptance as a function of p_T^{rel} and ΔR_{min} for a) 1 TeV, b) 2 TeV, c) 3 TeV, d) 4 TeV

thresholds and the RelIso method for standard model $t\bar{t}$ events and the four Z' samples. The 2D Cut algorithm performs better for all masses and is much less sensitive to an increase in the mass of the $t\bar{t}$ system.

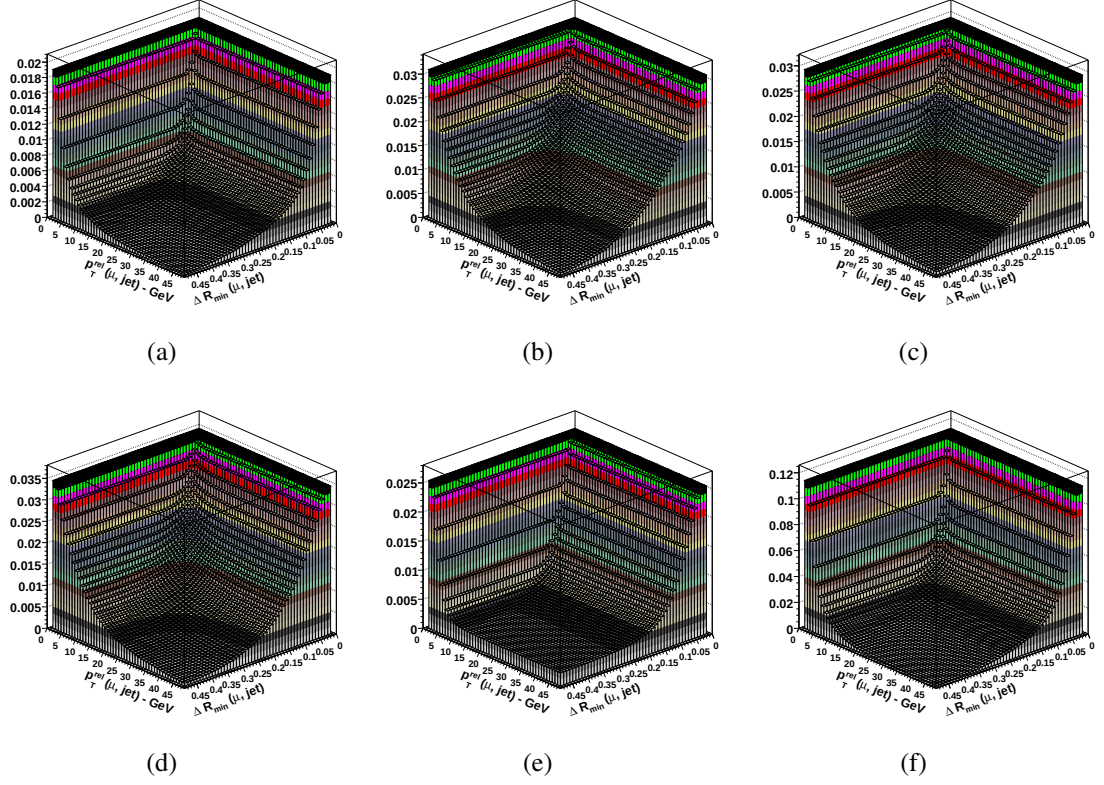


Figure 6.10: Background rate as a function of p_T^{rel} and ΔR_{min} for a) 1 TeV, b) 2 TeV, c) 3 TeV, d) 4 TeV, e) InclusiveMuon15, f) InclusiveMuon5pt350

Signal		ΔR_{min}				
		0.30	0.35	0.40	0.45	0.50
p_T^{rel} (GeV)	30	90.2	88.9	87.9	86.9	86.0
	35	88.8	87.1	85.6	84.3	83.2
	40	87.7	85.6	83.7	81.9	80.4
	45	86.4	83.7	81.5	79.2	77.4
	50	85.4	82.2	79.6	76.8	74.9

Table 6.3: Signal acceptances for various p_T^{rel} and ΔR_{min} cuts for the 2 TeV Z' sample

6.1.4 Fake Muon Background Determination

In Table 6.5 we show the combined rate for internal background normalized to the rate of jet production with $E_T > 30$ GeV within the analysis fiducial region. Results are shown for

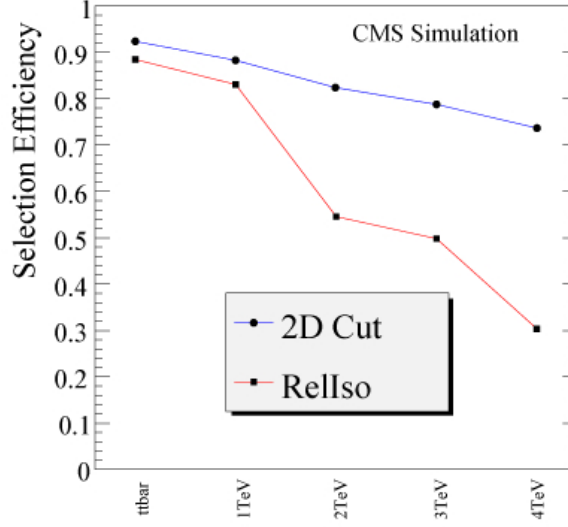


Figure 6.11: 2D Cut selection efficiency (blue points) and RelIso selection efficiency (red points) for $\sqrt{s} = 10$ TeV.

Background		ΔR_{min}				
		0.30	0.35	0.40	0.45	0.50
p_T^{rel} (GeV)	30	0.00278	0.00205	0.00172	0.00150	0.00145
	35	0.00238	0.00160	0.00125	0.00102	0.00096
	40	0.00221	0.00135	0.00099	0.00076	0.00067
	45	0.00207	0.00118	0.00077	0.00052	0.00043
	50	0.00196	0.00105	0.00063	0.00038	0.00030

Table 6.4: Background rates for various p_T^{rel} and ΔR_{min} cuts for the 2 TeV internal background

standard $t\bar{t}$ and Z' decays with masses between 1 and 4 TeV. With the exception of the 1 TeV point the results are essentially independant of mass. We have further investigated the 1 TeV dataset and find that this is due to a statistical fluctuation in this MC dataset. The results are essentially constant across the datasets.

To model these rates from data we will use the rates determined from inclusive muon data. After application of a p_T threshold of 30 GeV, the dominant non-QCD background

contributions come from $W \rightarrow \mu\nu$ and $Z^0 \rightarrow \mu^+\mu^-$ events. These can be removed by the application of cuts on the W transverse and Z^0 invariant mass distributions, respectively. In Table 6.6 we show the background rates from two such analyses. The low $\hat{s}$ result [InclusiveMu15] is representative of the background from soft QCD events and the high $\hat{s}$ result [InclusiveMu5pt350] models the background from hard QCD events in which the jet kinematics is similar to that of the signal events. Comparison shows good consistency between both the QCD rates and the internal backgrounds. We conclude that the fake muon background rates determined in this manner can be used to calculate both classes of background and we estimate a conservative rate uncertainty of $\sim 30\%$ based on the variation between the results. For later analyses at larger luminosities the same method can be used to map the background rates as a function of muon p_T and η . For initial analyses this is not necessary.

Dataset	Internal Muon Background
$t\bar{t}$	0.00133
$Z'(1 \text{ TeV})$	0.00028
$Z'(2 \text{ TeV})$	0.00125
$Z'(3 \text{ TeV})$	0.00128
$Z'(4 \text{ TeV})$	0.00139

Table 6.5: Fake muon rates per jet $E_T > 30 \text{ GeV}$ for Standard Model $t\bar{t}$ production and Z' events with mass between 1 TeV and 4 TeV.

Dataset	Muon Background from QCD
Low- $\hat{s}$	0.00091
High- $\hat{s}$	0.00111

Table 6.6: Fake muon rates per jet $E_T > 30 \text{ GeV}$ in low and high $\hat{s}$ inclusive muon events.

6.1.5 Use with particle flow reconstruction

2D Cut isolation can be used for both the standard PAT [17] layer1 muon and calorimeter jet collections as well as for the particle flow [46] muon and jet collections. There is a caveat when using the particle flow reconstruction, as the variable *combinedIsolationCut* must be set to a large number (i.e. 99999999.) in order to treat every muon as isolated within the particle flow reconstruction. If this variable is not set (for both muons and electrons) then muons and electrons not passing a *combinedIsolationCut* cut will be treated as non-isolated and will be treated as part of the parent jet and are removed from the PFmuon collection. Without this cut in place we are free to use our isolation method in the same way as for the standard construction.

Fig. 6.12 shows ΔR_{min} vs p_T^{rel} for muon channel for the two cases.

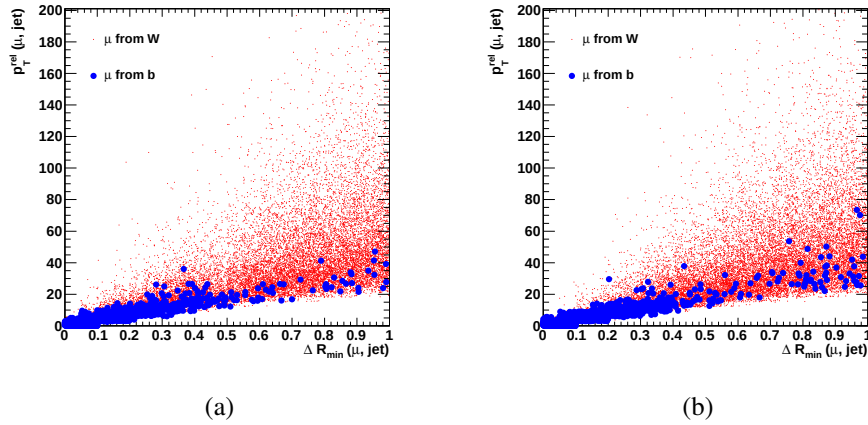


Figure 6.12: ΔR_{min} Vs p_T^{rel} for a.) PAT layer1 muons and b.) particle flow muons

6.1.6 Application to electrons

We have shown that this method works well for muons so it is quite natural to want to extend the algorithm to electrons as the event topology should be essentially the same. Fig. 6.13 shows that this is actually the case and that we should be able to define a set of cut thresholds which can be used for both the muon and electron channels. However some problems arise in the reconstruction chain for calorimeter electrons and jets, however, which make it problematic to use the 2D Cut with the layer 1 electron and Calo jet collections. When attempting to use the 2D Cut on calorimeter electrons it was found that in the majority of events studied a calorimeter jet was reconstructed on top of an isolated electron from a W decay. Unless we are able to throw out the majority of these "fake jets" (without getting rid of b -jets at the same time) then it is not possible to perform a proper cut optimization for these collections.

We have attempted many methods to remove these fake jets at the PAT layer1 level but with minimal success. The most successful method of removing these we have found is to require that jets within $\Delta R < 0.1$ of the electron have an electromagnetic fraction less than 0.99. This removes around 30 – 50% of the fake jets without removing many b -jets thus keeping the background event topology intact. There remains around 20 – 30% of the electrons in the calorimeter collection that have fake jets overlapping them, reducing the acceptance for μ from W to around 60% for $t\bar{t}$ and $Z' \rightarrow t\bar{t}$ events. Fig. 6.14 shows the difference between the calorimeter electrons and the particle flow electrons. There is an heavy population near $\Delta R_{min} = p_T^{rel} = 0$ for calorimeter electrons due to the overlapping jets giving the appearance of very small values of ΔR_{min} and thus p_T^{rel} . This implies that we will only be able to use the

2D Cut for particle flow electrons at this time.

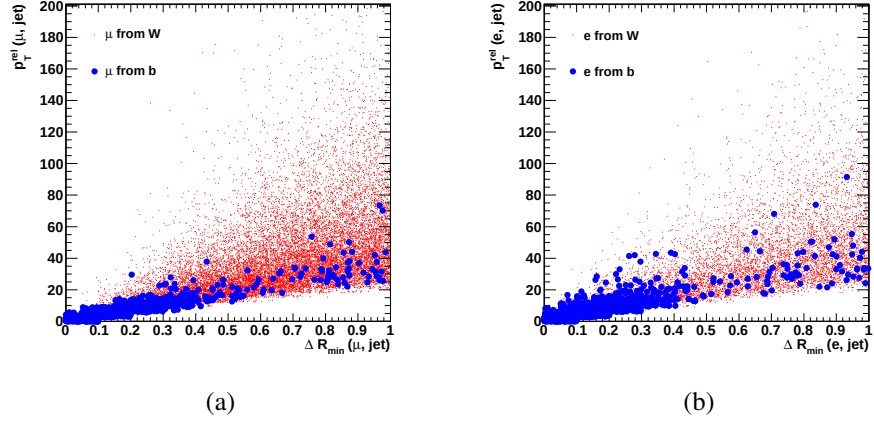


Figure 6.13: ΔR_{min} vs p_T^{rel} for a.) particle flow muons and b.) particle flow electrons

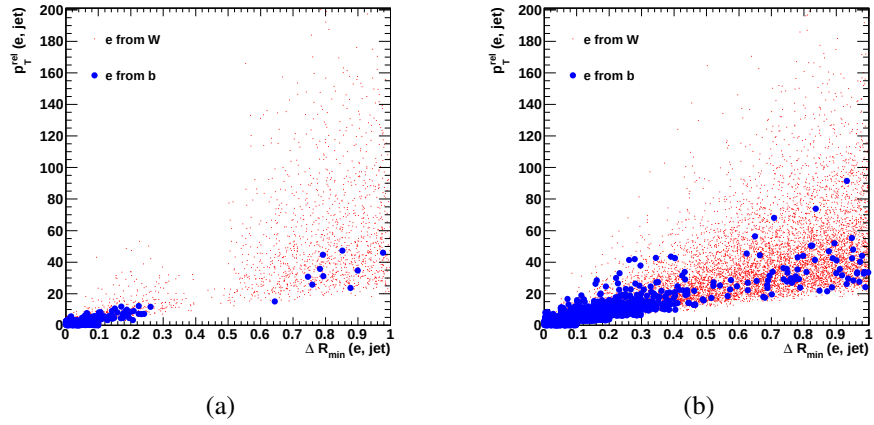


Figure 6.14: ΔR_{min} vs p_T^{rel} for a.) calorimeter electrons and b.) particle flow electrons

6.1.7 Optimization for 7 TeV data

6.1.8 Jet p_T thresholds

The 2D Cut method relies upon comparing the muon to the proper jet for the purposes of calculating ΔR_{min} and p_T^{rel} correctly. For the case of $W \rightarrow \mu\nu$ this simply means the closest jet. But for $b \rightarrow \mu + X$ it is important to select and use the parent b -jet when performing the calculation of ΔR_{min} and p_T^{rel} , otherwise the muon will appear isolated from the perspective of the 2D Cut.

Formerly we had chosen a jet p_T threshold of 30 GeV to perform our comparative calculations. This threshold was used to suppress problems that arose in older versions of the jet reconstruction when radiation from the muon was overcorrected by jet algorithms and made into fake jets. This can be suppressed by requiring that the muon satisfy the following criteria [8]:

1. The total energy from the electromagnetic calorimeter present within the muon veto cone be less than 4 GeV.
2. The total energy from the hadronic calorimeter in the same cone be less than 6 GeV.

This effectively removes the problem of the “veto cone jets” that were present in our earlier studies and we are now able to lower the jet p_T comparator thresholds used to make our calculations. Fig. 6.15 shows the problems that arise when too high a jet p_T threshold is used to perform the calculations. If the jet threshold is set too high the correct parent b -jet will not be selected and the muon will be compared to a jet other than the parent b -jet which causes

it to appear to have too high a value of ΔR_{min} and p_T^{rel} . This effect can be seen in Fig. 6.15 where plot a.) has a larger number of muons with high ΔR_{min} and p_T^{rel} from not picking the correct jet. This problem is substantially decreased by lowering the jet p_T threshold down to 20 GeV as in plot b.) of Fig. 6.15.

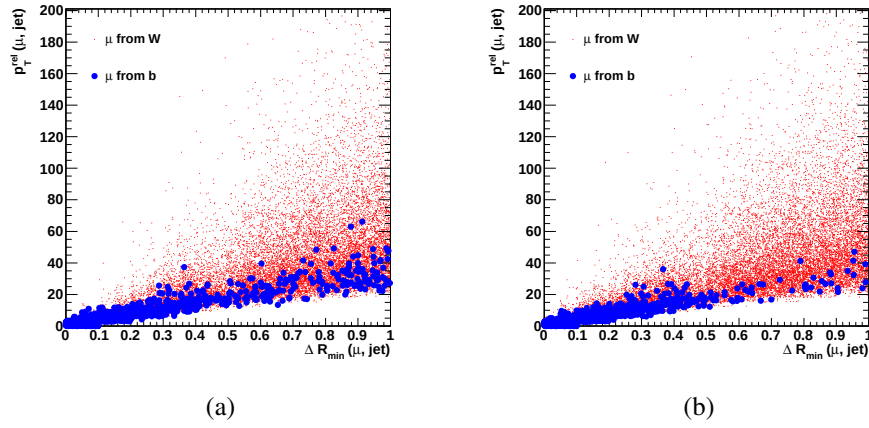


Figure 6.15: ΔR_{min} vs p_T^{rel} for jet comparison p_T thresholds of a.) 30 GeV and b.) 20 GeV for calorimeter muons and jets.

We have studied jet p_T thresholds from 10-30 GeV and have found that the best jet thresholds are:

- 20 GeV for calorimeter jets
- 10 GeV for particle flow jets

6.1.9 Cut optimization

After lowering the jet p_T comparison thresholds we can do a better job in the removal of the background better than in the previous study. This will require that a new set of cuts for ΔR_{min} and p_T^{rel} be implemented. Fig. 6.16 shows the comparison of our results for 10 TeV and the new results for 7 TeV. The new background muon spectrum is softer in p_T^{rel} which will allow us to lower the p_T^{rel} cut. This allows us to improve the QCD rejection by increasing the threshold in ΔR_{min} while retaining essentially a constant signal acceptance. This removes more of the tail of the background distribution than was previously possible.

The 3-dimensional plots in Fig. 6.17 show that for all mass points the signal acceptance remains high for reasonable threshold values. This allows the optimization of the background rejection to determine the new cut values. Fig. 6.18 shows the corresponding distributions for the background. The shapes are quite similar and are almost independent of the mass of the Z' . The only exception is for $b \rightarrow \mu$ in high mass Z' events where the large boost to the system gives rise to higher p_T muons and thus muons with higher p_T^{rel} . After a 2D-grid study of the signal and background efficiencies we conclude that cut thresholds of $\Delta R_{min} > 0.5$ and $p_T^{rel} > 25$ GeV are the best choice. This applies to both the calorimeter and particle flow object collections and to both the electron and muon channels.

6.1.10 Results

Fig. 6.19 and Table 6.7 show the efficiency for each of the signal samples for both the RelIso energy-flow isolation algorithm [8] and for the 2D Cut method. For comparison, Table 6.7

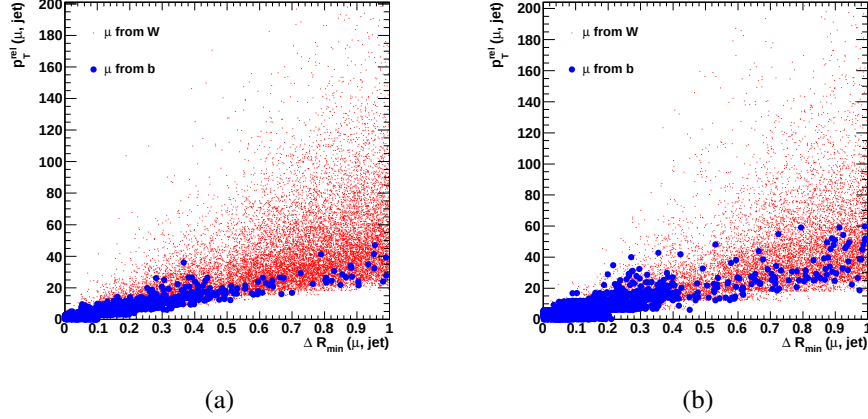


Figure 6.16: ΔR_{min} vs p_T^{rel} in a.) CMSSW 361 b.) CMSSW 226

also lists the results from a study at 10 TeV using CMSSW 226. The RelIso cut is 0.1 in both plots. The 2D Cut values are for cuts of $\Delta R_{min} < 0.4$ and $p_T^{rel} < 35$ GeV for the CMSSW 226 study and $\Delta R_{min} < 0.5$ and $p_T^{rel} < 25$ GeV for the updated study. As a by-product of our new optimization, we find that, while the low mass signal acceptance is essentially the same as before, we no longer see any mass dependence. These results are also consistent between object collections and for both particle flow muon and electrons.

Table 6.8 shows the corresponding background rates, expressed on a per-jet basis with $p_T > 30$ GeV. The rates are consistent between the internal background (μ from b, c in the Z' and $t\bar{t}$ decays) and the QCD background (μ from b, c in multijet events). While the background rates are slightly higher than for the 2D Cut than for the RelIso method, they are still within manageable levels and will not contribute significantly to feed-in from QCD events. The results in Table 6.8 are quoted for Calo muon and jet collections and are similar for the PF collections. The background rates are similar for both particle flow muons and electrons

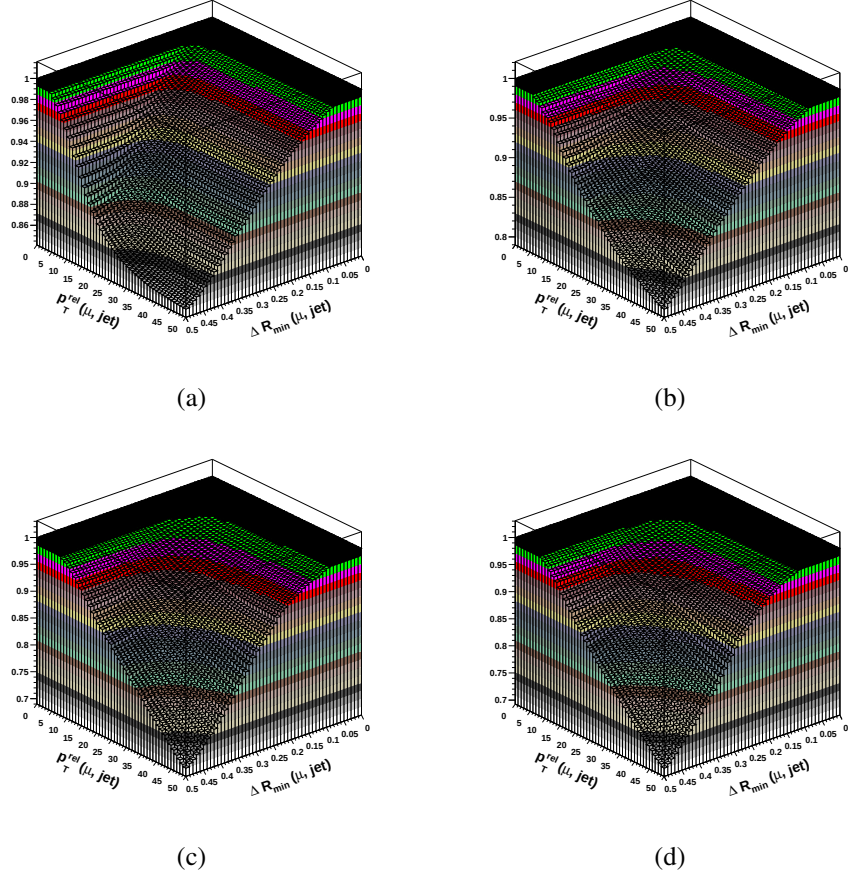


Figure 6.17: Signal acceptance rate as a function of ΔR_{min} and p_T^{rel} for a.) $t\bar{t}$ b.) $Z'(1 \text{ TeV})$ c.) $Z'(2 \text{ TeV})$ d.) $Z'(3 \text{ TeV})$

and the 2D Cut will work just as well for all object collections.

Dataset	RelIso(226)	2D Cut(226)	RelIso(361)	2D Cut(361)
$t\bar{t}$	0.88 ± 0.01	0.92 ± 0.01	0.86 ± 0.01	0.88 ± 0.01
$Z'(1 \text{ TeV})$	0.84 ± 0.01	0.89 ± 0.01	0.82 ± 0.01	0.88 ± 0.01
$Z'(2 \text{ TeV})$	0.56 ± 0.01	0.88 ± 0.01	0.59 ± 0.01	0.86 ± 0.01
$Z'(3 \text{ TeV})$	0.53 ± 0.01	0.85 ± 0.01	0.56 ± 0.01	0.86 ± 0.02

Table 6.7: Signal muon acceptance for RelIso compared with the 2D Cut for both CMSSW 226 and 361

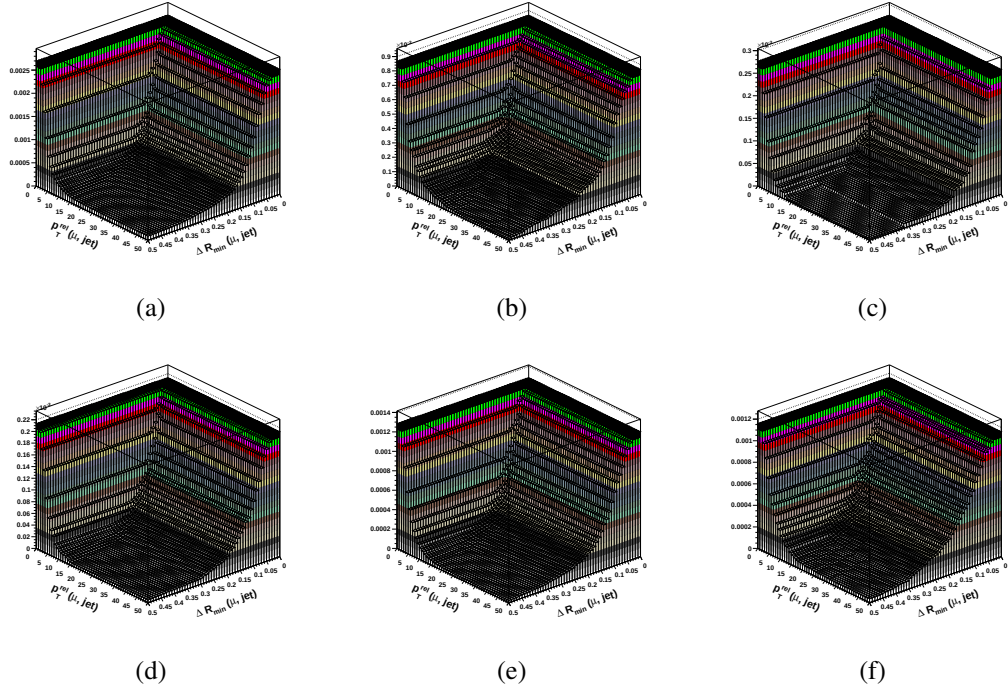


Figure 6.18: Background acceptance rate as a function of ΔR_{min} and p_T^{rel} for a.) $t\bar{t}$ internal background b.) $Z'(2 \text{ TeV})$ internal background c.) InclusiveMu 15 d.) InclusiveMu 5pt50 e.) InclusiveMu 5pt150 f.) InclusiveMu 5pt250

Dataset	Rate/jet
$t\bar{t}$	$9.5 \pm 0.9 \times 10^{-05}$
$Z'(1 \text{ TeV})$	$5.2 \pm 1.3 \times 10^{-05}$
$Z'(2 \text{ TeV})$	$2.8 \pm 0.9 \times 10^{-05}$
$Z'(3 \text{ TeV})$	$4.2 \pm 1.1 \times 10^{-05}$
InclusiveMu 15	$3.4 \pm 3.4 \times 10^{-06}$
InclusiveMu 5pt30	$1.5 \pm 1.5 \times 10^{-06}$
InclusiveMu 5pt50	$4.6 \pm 1.9 \times 10^{-06}$
InclusiveMu 5pt150	$2.4 \pm 0.6 \times 10^{-05}$
InclusiveMu 5pt250	$4.9 \pm 1.3 \times 10^{-05}$
InclusiveMu 5pt350	$2.7 \pm 0.9 \times 10^{-05}$

Table 6.8: Fake muon rates per jet with $p_T \geq 30 \text{ GeV}$

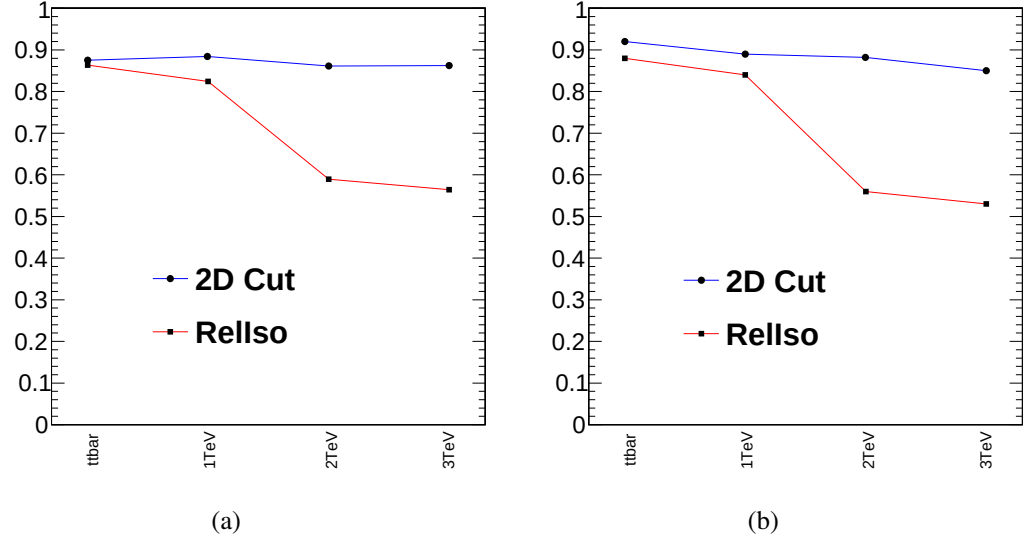


Figure 6.19: Comparison of 2D Cut and Rellso signal efficiencies in a.) CMSSW 361 b.) CMSSW 226

6.1.11 Lepton Selection Efficiencies

In order to determine the muon selection efficiency in data we perform a tag and probe analysis using a control sample of $Z^0 \rightarrow \mu^+ \mu^-$ to determine the ratio of acceptance between monte carlo and data. We begin by selection muons according to the standard top selection [3] where each muon is required to pass:

- Must be both a Global Muon and a Tracker Muon
- $p_T \geq 35$ GeV
- $|\eta| < 2.1$
- Normalized $\chi^2 < 10$
- Number of valid muon pattern hits > 0

- Number of valid silicon tracker hits > 10
- 2D impact parameter (d_0) < 0.02 cm
- Absolute distance in the z-direction from the Primary Vertex < 1 cm
- Pixel layers with measurement ≥ 1
- Number of matches in the muon station > 1

the only difference is that we have ignored the standard muon isolation requirements in order to determine the efficiency of our 2D Cut isolation. In order to select the control sample of Z-bosons we first select one muon passing the quality cuts defined above and passing the 2D Cut ($\Delta R_{min} \geq 0.5$ or $p_T^{rel} \geq 25$ GeV) which will serve as the Tag Muon. We then check if there is a second muon in the event which passes the initial quality cuts which is defined as the probe muon. The ability of the probe muon to pass the isolation requirements will determine the efficiency of the 2D Cut in data. Using Z^0 monte carlo and the control sample of $Z^0 \rightarrow \mu^+ \mu^-$ from the data we will be able to determine the relative acceptance between the simulation and the data and will use this information to determine the ratio of the efficiency we measure in $t\bar{t}$ monte carlo to what we would expect to see for muons originating from top quark production in data. The efficiency of probe muons as a function of relevant muon kinematic and topological variables are shown for monte carlo and data in Figs. 6.20 and 6.21, respectively. The acceptance is well-behaved except for outlying values of small p_T and large ΔR where the statistics are minimal or the acceptance is expected to be small. We can then estimate the acceptance for muons coming from top quarks in data by:

$$\epsilon_t^{data} = \epsilon_t^{MC} \frac{\epsilon_{Z^0}^{data}}{\epsilon_{Z^0}^{MC}} \quad (6.2)$$

The results are presented in Table 6.9 and are consistent with the MC studies within errors and we anticipate a selection efficiency of muons from semileptonic top quark decays to be 0.95 ± 0.06 .

Sample	Efficiency
Z^0 (MC)	0.95 ± 0.02
Z^0 (Data)	1.00 ± 0.06
$t\bar{t}$ (MC)	0.90 ± 0.01
$t\bar{t}$ (Data)	0.95 ± 0.06

Table 6.9: 2D Cut efficiencies in simulation (MC) and data.

6.2 Event Preselection

It is important at this time to use an event preselection that will allow us to efficiently remove a large amount of the softer background events from W +jets and QCD multi-jet events while retaining a high signal acceptance from either Standard Model $t\bar{t}$ or $Z' \rightarrow t\bar{t}$ events. This will allow us to focus the training of the boosted decision tree algorithms on the more complex backgrounds. Because we are following the preselection with a more sophisticated multivariate event selection we are free to keep our preselection criteria somewhat loose with respect to the normal top quark analyses. The reconstruction for these events is performed using the full Particle Flow [46] reconstruction sequence in the CMS software framework (CMSSW)

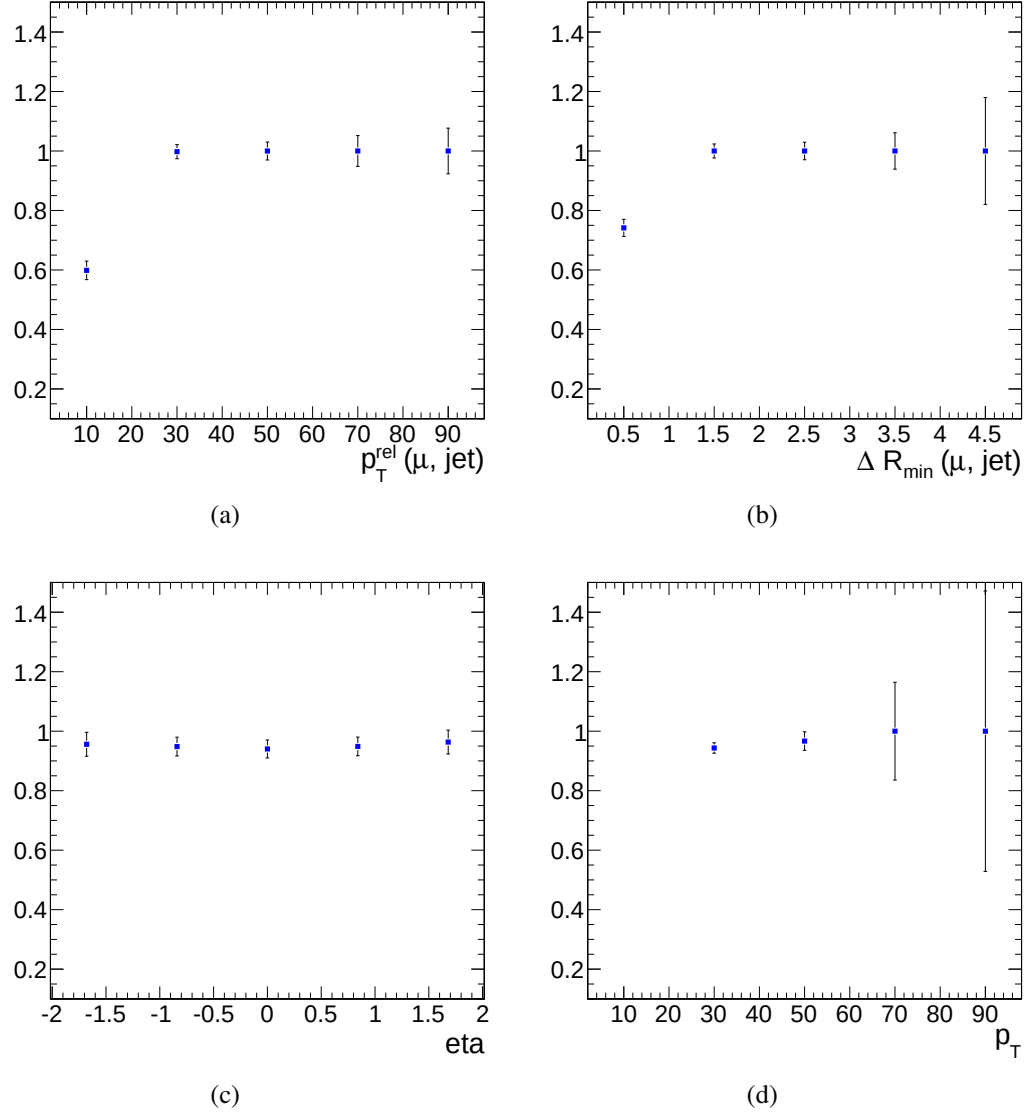


Figure 6.20: Muon selection efficiency in Z^0 MC as a function of a) $p_T^{\text{rel}}(\mu, \text{jet})$, b) $\Delta R_{\text{min}}(\mu, \text{jet})$, c) η_μ , d) p_T^μ .

and while the object selection will, for the most part, follow the standard CMS top quark criteria [3], we will modify many of the cuts to suit the needs of this analysis. The complete object cuts and reasoning for each are treated individually for each type of object in the fol-

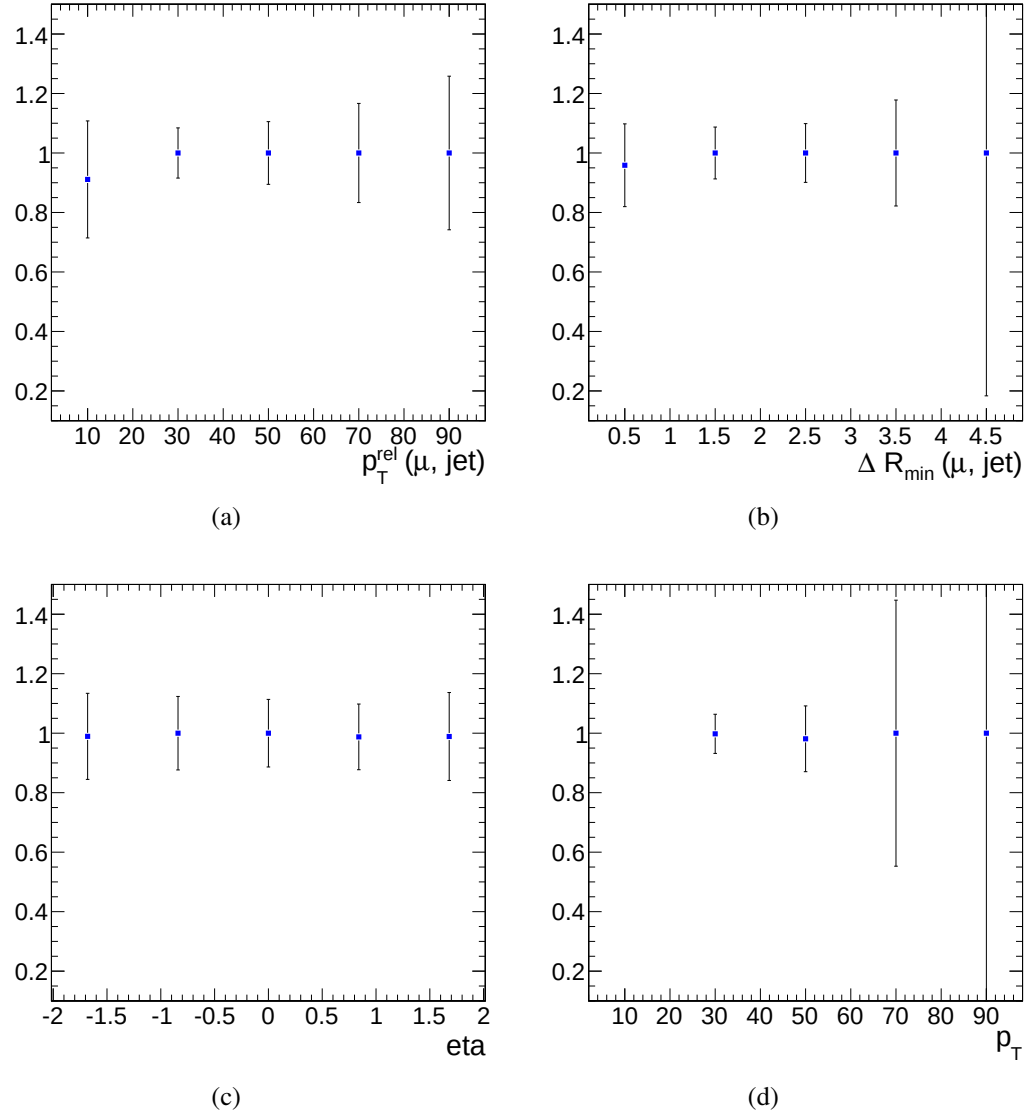


Figure 6.21: Muon selection efficiency in data as a function of a) $p_T^{rel}(\mu, jet)$, b) $\Delta R_{min}(\mu, jet)$, c) η_μ , d) p_T^μ .

lowing sections.

6.2.1 Trigger

For events in the 2011 data run we filter the data by requiring the muon in the event to fire the High Level Trigger (HLT) with a trigger object p_T dependant on the instantaneous luminosity of the LHC run being processed. For 2011 data we will use a combination of the following isolated muon triggers.

- HLT_IsoMu12
- HLT_IsoMu15
- HLT_IsoMu17
- HLT_IsoMu20
- HLT_IsoMu24
- HLT_IsoMu30

Where these triggers use tracker based isolation that is looser than the the particle flow isolation that will be used in the final muon selection. There are a number of versions of each of these triggers as well depending on what run range and trigger table are implemented in the on-line reconstruction. Trigger tables in monte carlo will be much more restrictive and will only have a few of these and the skims will be performed using HLT_IsoMu30 for the Summer11 MC series. This will not be a problem as we will be using a sufficiently high muon p_T cut in our preselection and will not experience any significant efficiency change, after preselection, from using a lower threshold trigger.

6.2.2 Primary Vertex

We require the existence of at least 1 good quality, Primary Vertex in the event with the following parameters:

- Must be a valid vertex (i.e. not fake)
- Number of tracks associated with the vertex > 4
- z-position in the detector: $|z| < 24.0$ cm
- Transverse distance from the vertex to the beam line: $\rho < 2.0$

6.2.3 Muons

When selecting muons we wish to select isolated muons coming from leptonic top quark decays and reject non-isolated muons coming from b and c quarks and in-flight π and K decays.

We will also want to throw away events with more than one isolated muon to suppress Drell-Yan production and $Z^0 \rightarrow \mu^+ \mu^-$ decays. Our muon selection follows the recommendations of the Top PAG very closely. Originally we were going to make use of the muon isolation studied in Section 6.1. The problem with this is that the HLT object p_T thresholds have become too high in the later trigger tables for the single muon triggers and the the muon-jet cross triggers. This requires us to move to the isolated muon triggers to find more reasonable thresholds. We will have to use particle-flow, energy-cone isolation together with this trigger because the isolation definition at the trigger level is based on energy flow in the tracker and

the 2D isolation is based on the topology of Z' events. The selection criteria for muons are as follows:

- Must be found as a muon in both the silicon tracker and the muon detector
- $p_t > 35 \text{ GeV}$
- $|\eta| < 2.1$
- Particle Flow based isolation: $\text{pFIso} < 0.2$
- Normalized $\chi^2 < 10$
- Number of valid muon hits in the hit pattern > 1
- Number of hits in the silicon tracker > 10
- Absolute impact parameter with respect to the beamspot $< 0.02 \text{ cm}$
- Distance from the muon z-coordinate at the muon vertex to the PV z-component $< 1 \text{ cm}$
- Number of pixel layers with measurement ≥ 1
- Number of matches to track segments in muons chambers > 1

We require each event to have one and only one of these muons. Events with more than one selected muon are assumed to be Drell Yan or Z^0 and are thrown out.

6.2.4 Electrons

In order to reject possible dilepton events (where both top quarks decay leptonically) where one isolated muon and one isolated electron are present we need to veto events with one or more high- p_T , isolated electrons. The criteria are fairly simple:

- An electron as defined by the particle flow algorithm
- $p_T > 15 \text{ GeV}$
- $\Delta R_{min}(e, \text{jet}) \geq 0.5$ or $p_T^{rel}(e, \text{jet}) \geq 25 \text{ GeV}$ (as defined in Section 6.1).

6.2.5 Jets

While the jet quality cuts are set by the Particle Flow and Jet/MET working groups we are free to determine a set of jet p_T thresholds to suit this analysis. The standard quality cuts for quark jets reconstructed by the particle flow jet algorithms are:

- Number of daughter particles in the jet > 1
- Charged electromagnetic energy fraction < 0.99
- Neutral hadronic energy fraction < 0.99
- Neutral electromagnetic energy fraction < 0.99
- Charged hadronic energy fraction > 0.0

- Charged particle multiplicity > 0

In addition, we also require jets to be in the region of $|\eta| < 2.4$.

We can then determine the desired jet p_T thresholds to use. Most top analyses will require at least 3 or 4 calorimeter jets of $p_T > 30$ GeV to cut back the W +jets background to a manageable level. The particle flow jets we are using have better energy resolution and are thus reconstructed with a softer E_T spectrum than their calorimeter counterparts which means we can lower our selection thresholds if necessary. Figs. 6.22, 6.23, and 6.24 show the first, second and third leading jet thresholds for QCD, W +jet, $t\bar{t}$, and Z' events. Using $t\bar{t}$ as a benchmark we will select jets keeping as much $t\bar{t}$ as possible when placing p_T requirements on the first 3 jets. It can be seen that cuts on the first 3 jets of:

- $p_T^{jet1} > 30$ GeV
- $p_T^{jet2} > 30$ GeV
- $p_T^{jet3} > 30$ GeV

will cut out a large amount of the W +jets and QCD background without removing much signal. And since we are following the preselection with a multivariate event selection we are free to relax the fourth jet p_T requirement.

6.2.6 Missing Transverse Energy

While the majority of the 2010 top quark analyses have no cut on missing transverse energy (MET) we impose a small cut to remove the remainder of the QCD multijet and Z^0 events left

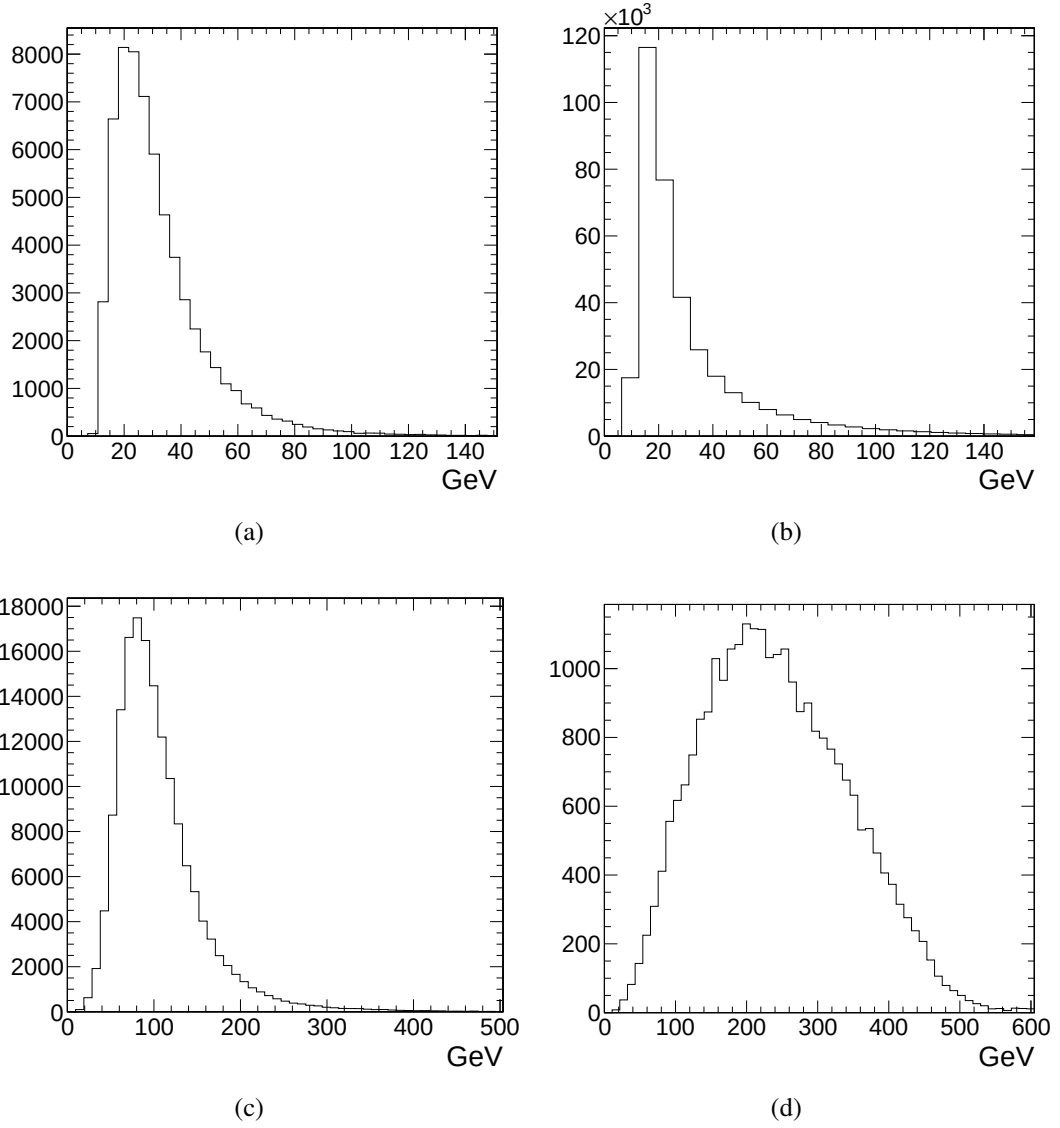


Figure 6.22: Leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.

over after the muon and jet requirements. Fig. 6.25 shows the MET distribution for various signal and background. As the MET from Z' events should be harder than MET from Standard Model $t\bar{t}$ we are free to use the lower end of the $t\bar{t}$ MET spectrum as a reference point to make our cut. The plots in Fig. 6.25 contain events where one isolated muon has been selected and no thresholds have been placed on the MET. A cut at 20 GeV removes most of

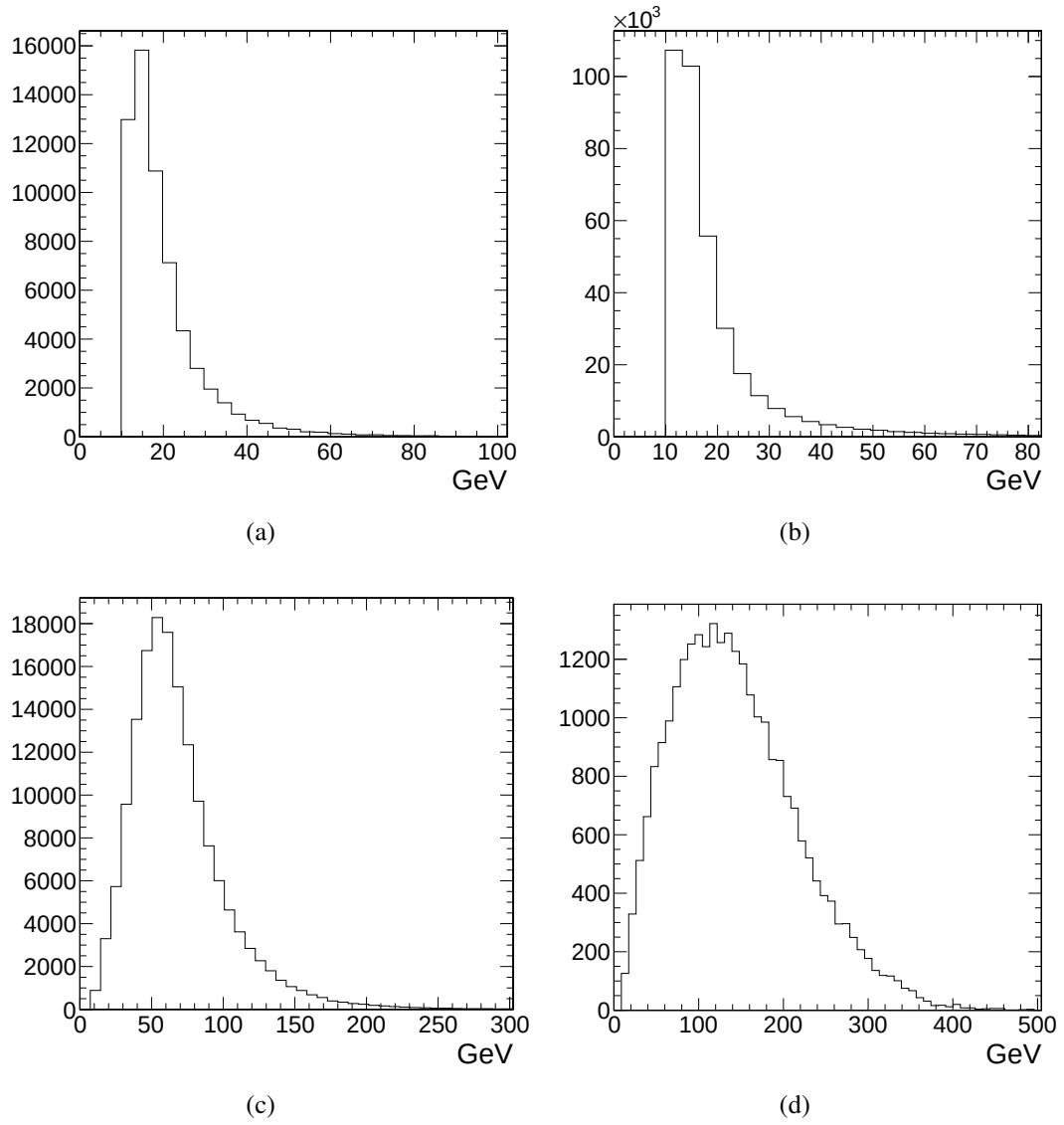


Figure 6.23: Second leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.

the remaining QCD without rejecting a significant amount of the signal.

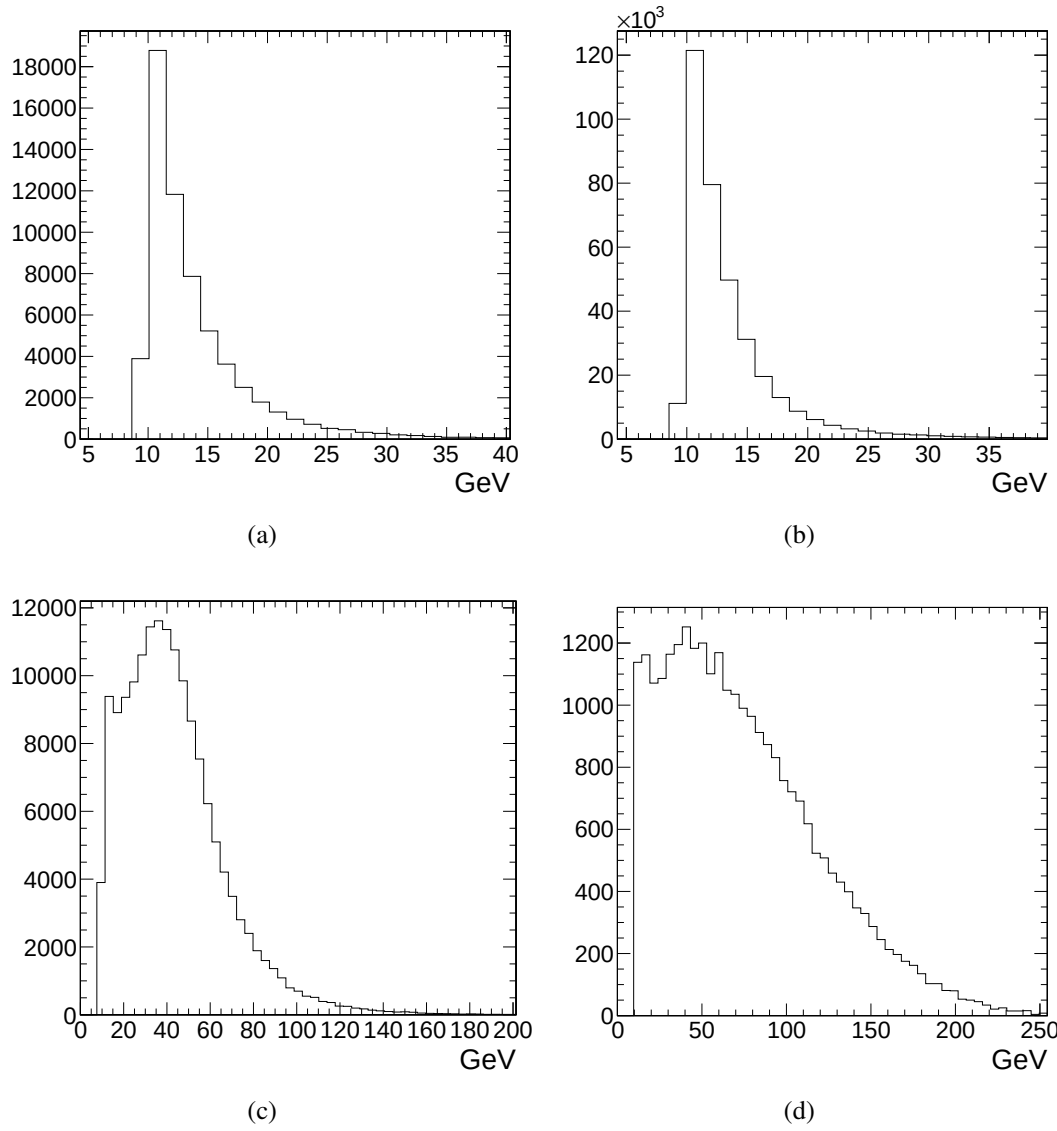


Figure 6.24: Third leading jet p_t for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.

6.2.7 b -jets

Finally we require at least 1 tagged b -jet in the event. We use the Combined Secondary Vertex (CSV) b -tagging algorithm [69] to identify jets as b -jets. The CSV tagger is a multivariate tagger that combines reconstructed secondary vertices as well as topological and kinematic

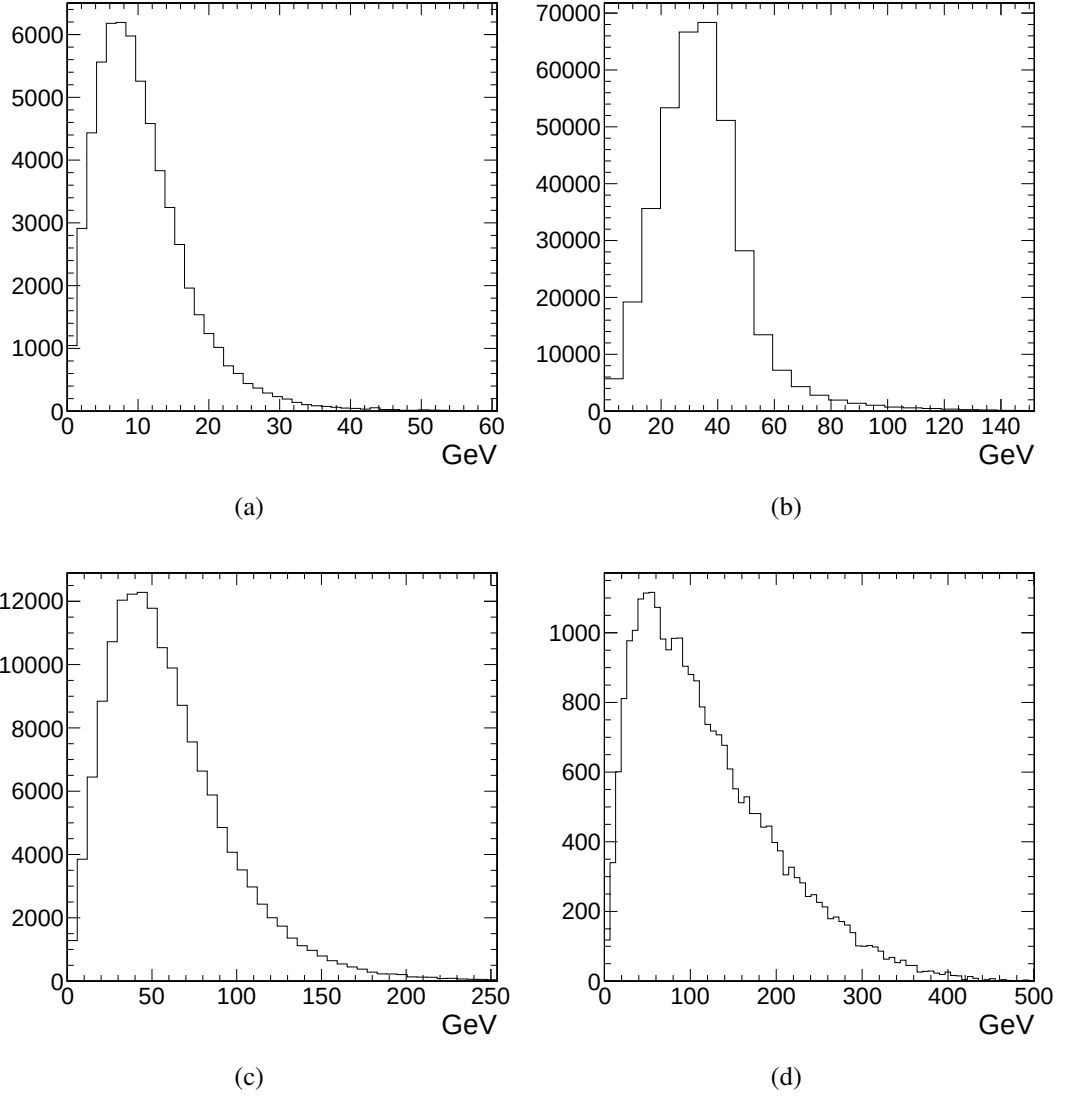


Figure 6.25: Missing Transverse Energy for a) QCD multi-jet, b) W +jets, c) $t\bar{t}$, d) Z' events.

information to produce a final classifier value. The algorithm initially selects secondary vertex candidates based on the following criteria:

- Transverse distance from primary to secondary vertex $0.1\text{cm} < L_T < 2.5\text{cm}$.
- The transverse distance from primary to secondary vertex divided by its error greater than 3: $\frac{L_T}{\sigma_{L_T}} > 3.0$.

- Invariant mass of charged particles in secondary vertex < 6.5 GeV
- Two oppositely charged particles must not have an invariant mass within 50 MeV of the K_S^0 .

Then based on whether or not there is a reconstructed vertex in the event or not the event is classified as *RecoVertex*, *PseudoVertex* or *NoVertex*. Here *PseudoVertex* refers to an event that does not contain a proper secondary vertex as described above but contains at least 2 tracks not associated with the primary vertex that can be reconstructed into a vertex.

After the event is classified based on vertex criteria a multivariate discriminant is created based on a event-type specific combination of the following kinematic and topological variables:

- Invariant mass of charged particles in the secondary vertex.
- Charged particle multiplicity in the secondary vertex.
- $\frac{L_T}{\sigma_{L_T}}$
- The energy of the charged particles in the secondary vertex divided by the energy of all the charged particles in the jet.
- The rapidities of the charged particle tracks associated with the secondary vertex with respect to the jet axis.
- The track impact parameter significance of the first track that exceeds the value of track impact parameter significance associated with charm jets.

These variables are then combined into a likelihood-based multivariate classifier which is cut on to determine if the jet will be tagged as a b -jet or not. For this analysis we use the CSV medium operating point which mistags 1% of u, d, s, g jets as b -jets. The cut for the CSVM tagger will be > 0.679 .

6.3 Monte Carlo Datasets

The specific datasets used for the optimization of the 2D muon isolation are given in Tables 6.10 and 6.11. The datasets used for the optimization of the event selection are given in Table 6.12.

Signal
Zprime_ttbar_semileptonic_m1000_w10_RECO/CMSSW_2_1_8-Madgraph-FullSim-IDEAL_V9-10TeV/RECO
Zprime_ttbar_semileptonic_m2000_w20_RECO/CMSSW_2_1_8-Madgraph-FullSim-IDEAL_V9-10TeV/RECO
Zprime_ttbar_semileptonic_m3000_w300_RECO/CMSSW_2_1_8-Madgraph-FullSim-IDEAL_V9-10TeV/RECO
Zprime_ttbar_semileptonic_m4000_w40_RECO/CMSSW_2_1_8-Madgraph-FullSim-IDEAL_V9-10TeV/RECO
Background
InclusiveMuPt15/Summer08_IDEAL_V9_v1/GEN-SIM-RECO
InclusiveMu5Pt350/Summer08_IDEAL_V9_v1/GEN-SIM-RECO

Table 6.10: Signal and background datasets used CMSSW_2_2_6

Signal
TtbarJets-madgraph/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
Zprime_M1TeV_W10GeV-madgraph/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
Zprime_M2TeV_W20GeV-madgraph/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
Zprime_M3TeV_W30GeV-madgraph/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
Background - Muon Channel
InclusiveMu15/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
InclusiveMu5_Pt30/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
InclusiveMu5_Pt50/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
InclusiveMu5_Pt150/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
InclusiveMu5_Pt250/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
InclusiveMu5_Pt350/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
Background - Electron Channel
QCD_BCtoE_Pt20to30/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
QCD_BCtoE_Pt30to80/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
QCD_BCtoE_Pt80to170/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
QCD_EMEnriched_Pt20to30/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
QCD_EMEnriched_Pt30to80/Spring10-START3X_V26_S09-v1/GEN-SIM-RECO
QCD_EMEnriched_Pt80to170/Spring10-START3X_V26_S09-v3/GEN-SIM-RECO

Table 6.11: Signal and background datasets used in CMSSW_3_6_1

Signal
/Zprime_M500GeV_W50GeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/Zprime_M750GeV_W7500MeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/Zprime_M1000GeV_W10GeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/Zprime_M1250GeV_W1250MeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/Zprime_M1500GeV_W15GeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/Zprime_M2000GeV_W20GeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
Background
/TTJets_TuneZ2_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v2/AODSIM
/TToBLNu_TuneZ2_s-channel_7TeV-madgraph/Fall10-START38_V12-v1/GEN-SIM-RECO
/TToBLNu_TuneZ2_t-channel_7TeV-madgraph/Fall10-START38_V12-v2/GEN-SIM-RECO
/TToBLNu_TuneZ2_tW-channel_7TeV-madgraph/Fall10-START38_V12-v2/GEN-SIM-RECO
/ZZtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/GEN-SIM-RECO
/WZtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/GEN-SIM-RECO
/WWtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/GEN-SIM-RECO
/DYJetsToLL_TuneD6T_M-50_7TeV-madgraph-tauola/Fall10-START38_V12-v2/GEN-SIM-RECO
/WJetsToLNu_TuneD6T_7TeV-madgraph-tauola/GEN-SIM-RECO
/QCD_Pt-20_MuEnrichedPt-15_TuneZ2_7TeV-pythia6/Fall10-START38_V12-v1/GEN-SIM-RECO

Table 6.12: Signal and background datasets used in the event preselection optimization.

Chapter 7

Validation of the Data Modeling

In order to determine if there is any presence of signal events we must first fit the simulation to the data by adding a scale factor to the most predominant background processes. These scale factors will be determined by first scaling the events passing the preselection to the next-to-leading-order (NLO) and next-to-next-to-leading-order (NNLO) cross sections as given by theory [6] (see Table 7.1). We begin the scaling by $t\bar{t}$ to the data using a ≥ 2 b -jet event

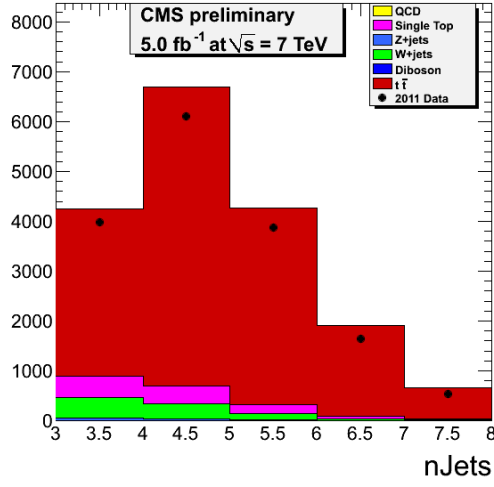
Table 7.1: Summary of theoretical cross-sections.

Process	Cross Section (pb)	Uncertainty (pb)
$t\bar{t}$	165	± 10
$W + \text{jets}$	31314	± 407
$Z/\gamma^* + \text{jets}$	3048	± 34
Single Top s-Channel	4.63	± 0.07
Single Top t-Channel	64.57	$+2.09 - 0.71$
Single Top tW-Channel	15.74	± 0.40
WW	43	± 1.5
WZ	18.2	± 0.7
ZZ	5.9	± 0.15
QCD multijet	296600000	Not Available

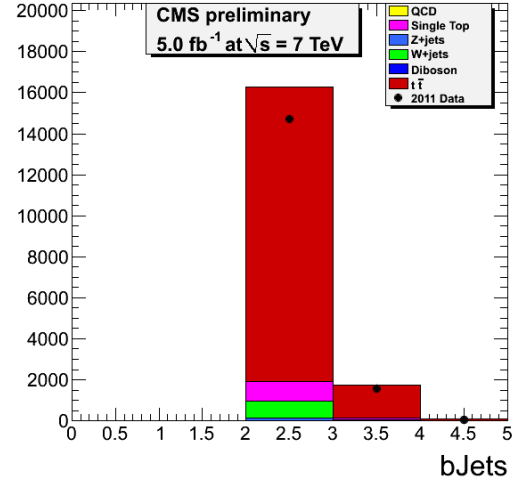
selection. The ROOT [1] package MINUIT [51] is used to perform a negative log likelihood fit of the parameter of interest (in this case the scale factor for the $t\bar{t}$ rate) to the data. Fig. 7.1 shows a number of distributions for the ≥ 2 b -jet event selection prior to any sort of cross-section scaling. The p_T^μ histogram is monitored because we will use this histogram to fit the simulation rate to the data. The jet multiplicity histograms (both total jets and b -jets) are used to check that the number of jets in the event (which directly affects the reconstruction of $m_{t\bar{t}}$) and the overall event rates are both in good agreement with data. We also monitor $m_{t\bar{t}}$ because this plot will be used to set limits on the Z' cross-section and good agreement is necessary for accurate limits. The NLL fit is performed by fitting the $t\bar{t}$ simulation to data in the region of the muon p_T spectrum above 100 GeV where the $t\bar{t}$ contribution is dominant. A scale factor of 0.896 is found by the minimizer and applied to the distributions in Fig. 7.2. The simulation now is in much better agreement with the data and we are free to then scale the W/Z + jets in the 1 b -jet selection.

The procedure for the fitting of the simulation to data for the W/Z + jets in the 1 b -jet selection are similar. The W and Z contributions are combined and are fit to the data in the region of $p_T^\mu < 100$ GeV and the scale factor on the W/Z + jets cross-section is found to be 1.258. The results of this scaling are shown in Figs. 7.3 and 7.4 where the plots are shown before and after the W/Z + jets scaling respectively.

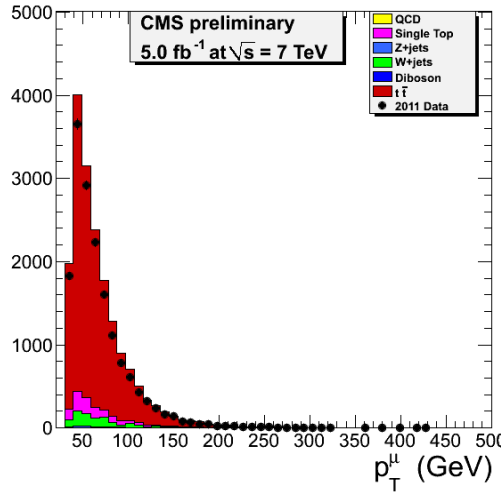
Finally we show the agreement between data and simulation for the full preselection before and after the scaling process in Figs. 7.5 and 7.6 respectively and the final scale factors used for $t\bar{t}$ and W/Z + jets are shown in Table 7.2.



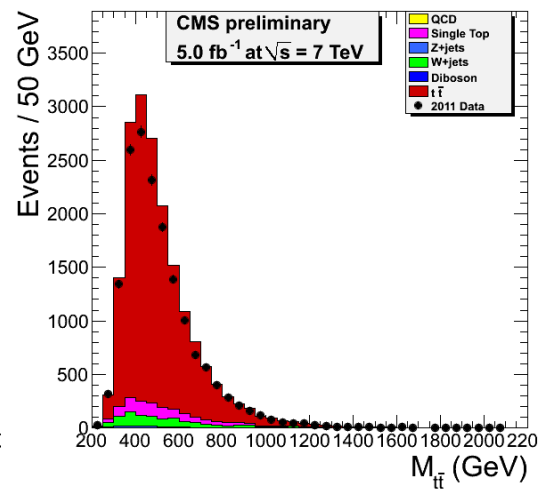
(a)



(b)

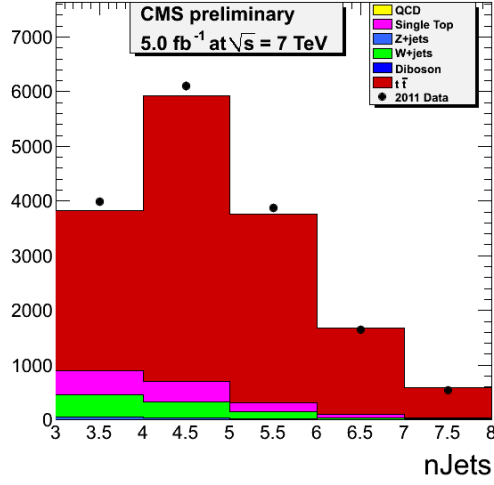


(c)

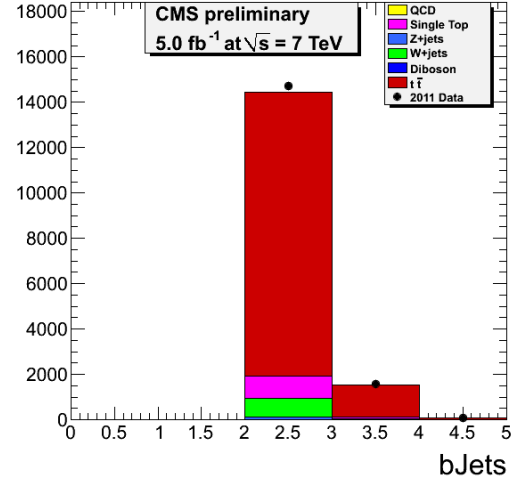


(d)

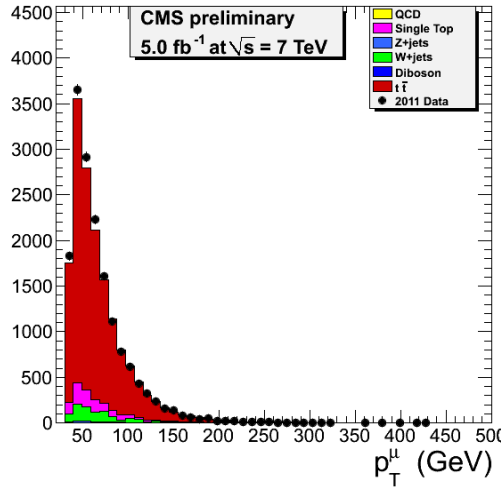
Figure 7.1: Control plots for ≥ 2 b-tag events using only theory cross section.



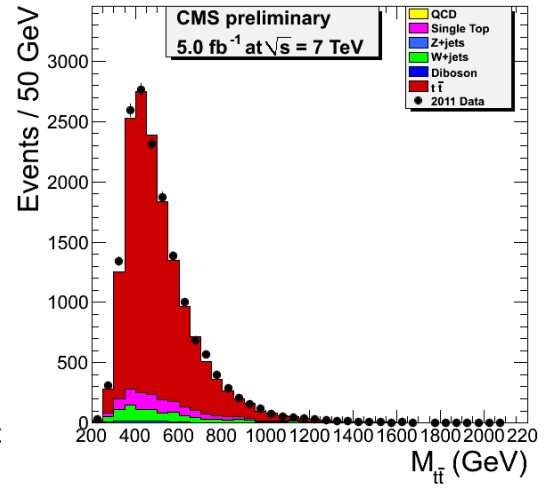
(a)



(b)



(c)



(d)

Figure 7.2: Control plots for ≥ 2 b-tag events after scaling $t\bar{t}$.

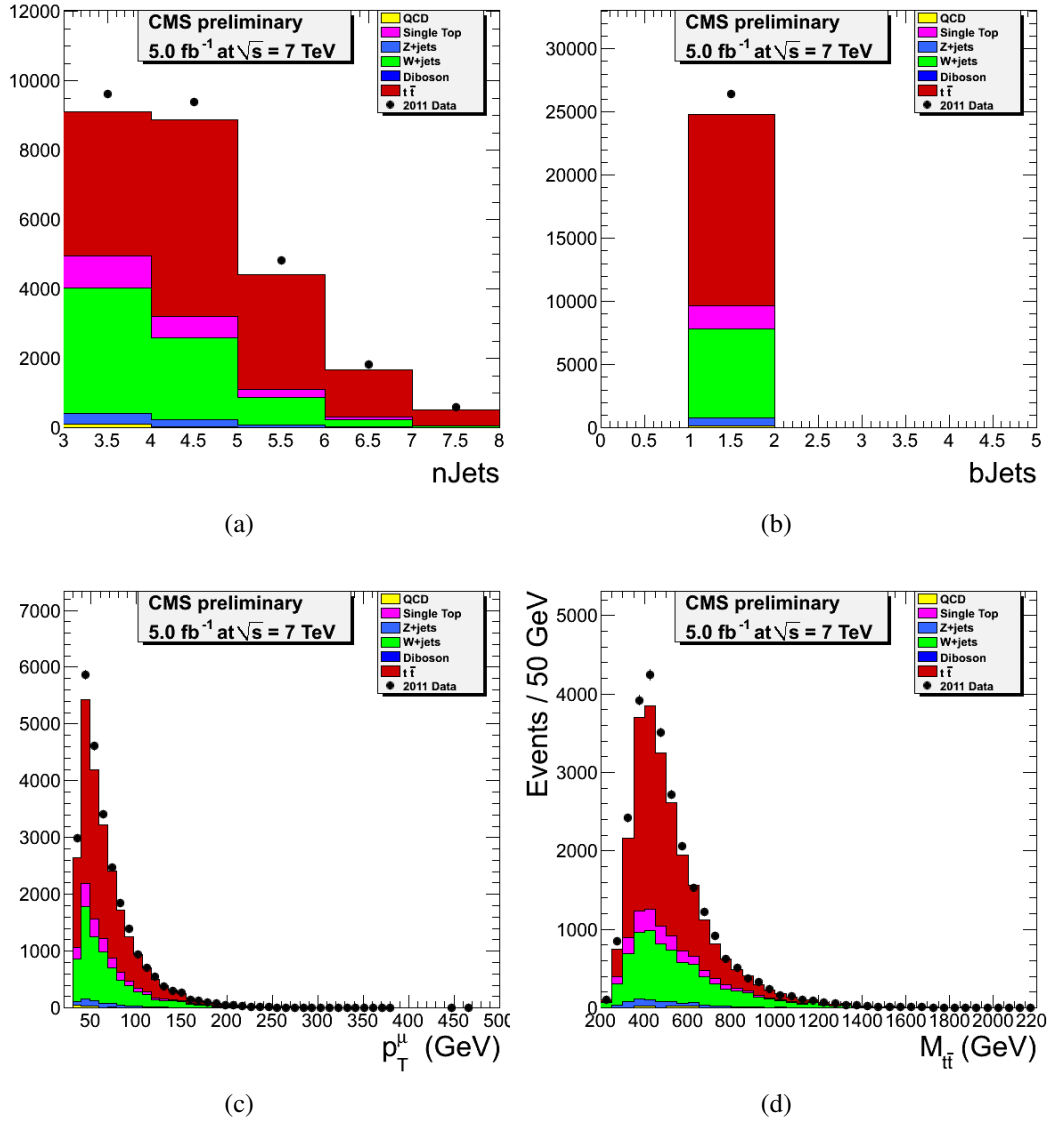


Figure 7.3: Control plots for 1 b-tag events after scaling $t\bar{t}$.

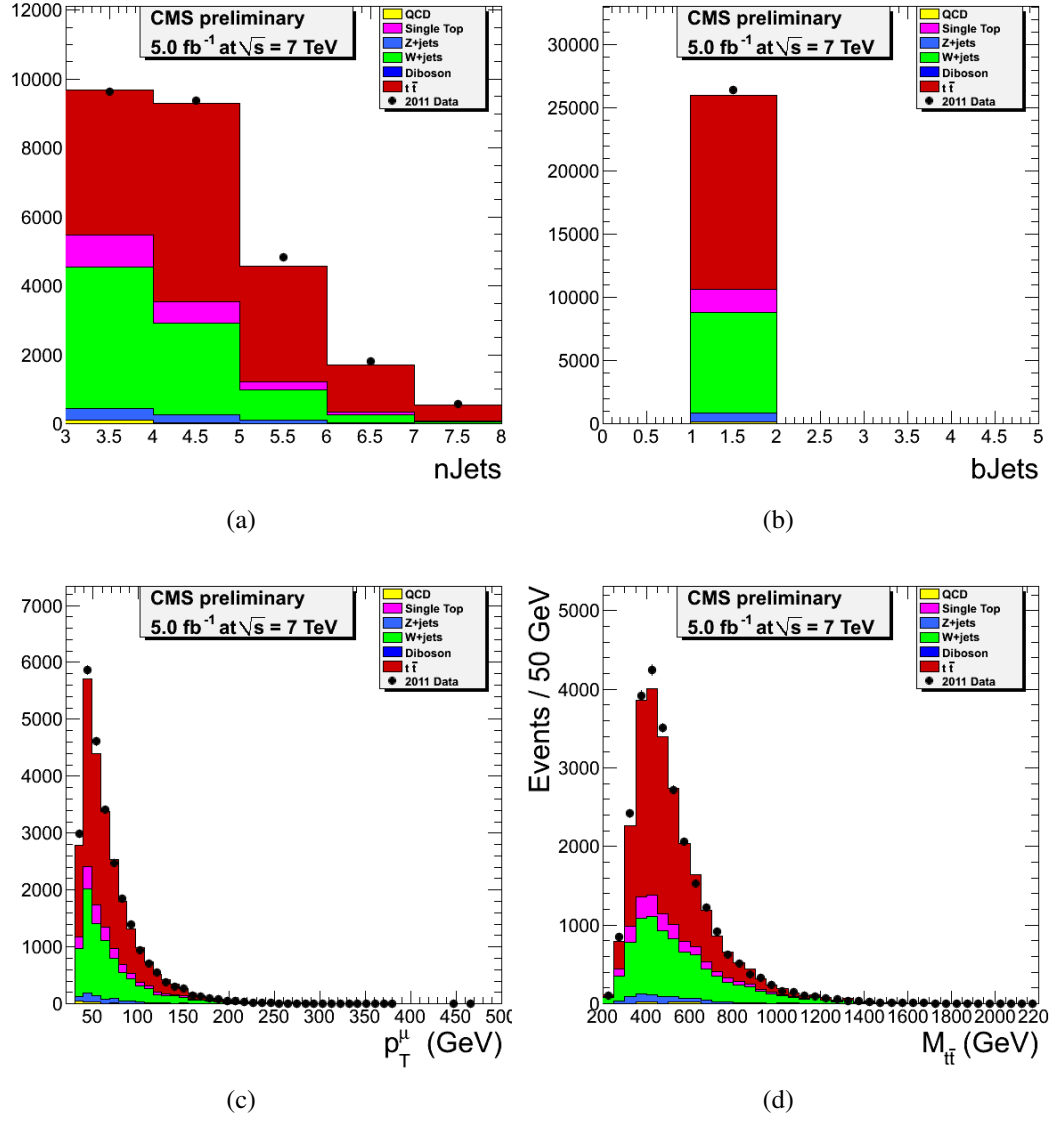
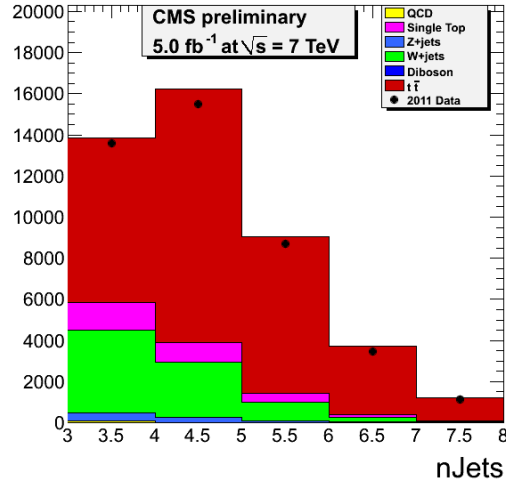
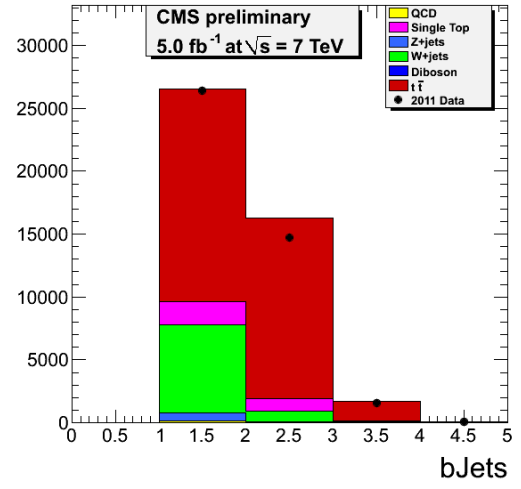


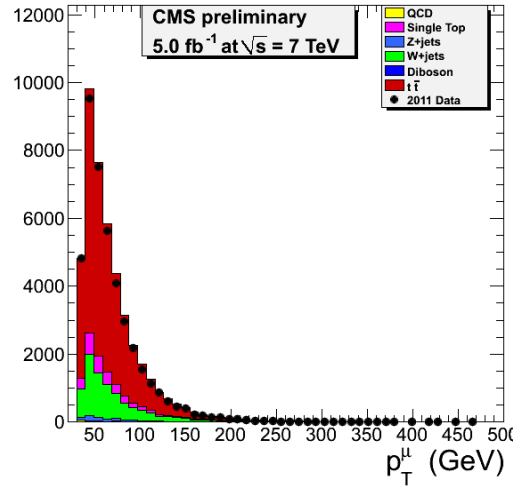
Figure 7.4: Control plots for 1 b-tag events after scaling $t\bar{t}$ and $W/Z + \text{jets}$.



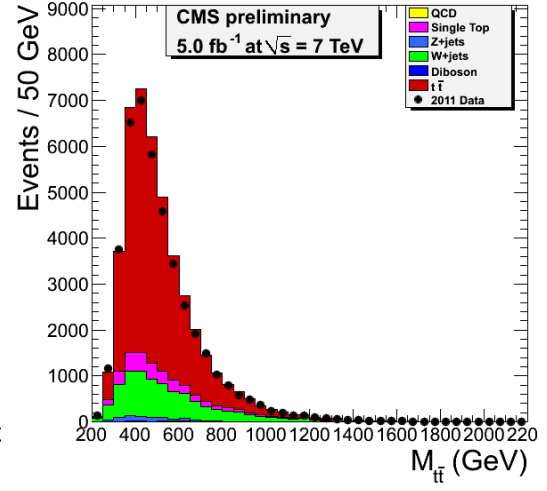
(a)



(b)

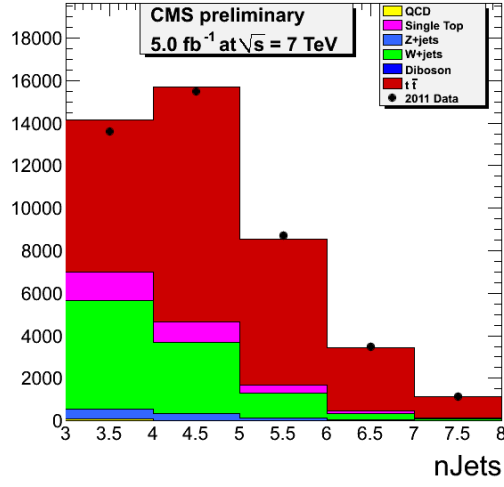


(c)

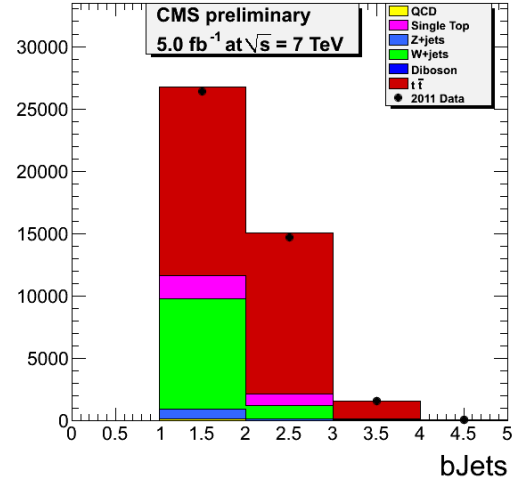


(d)

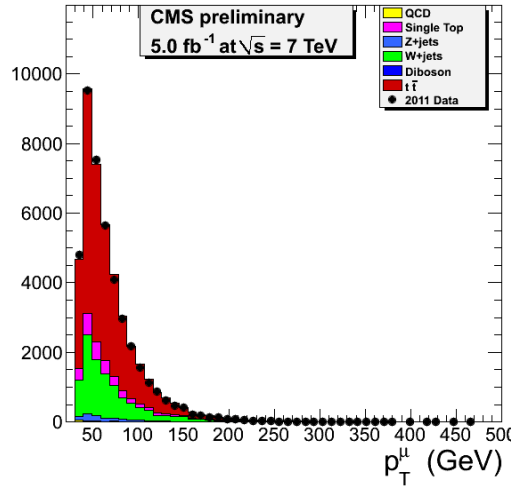
Figure 7.5: Control plots for preselection prior to scaling.



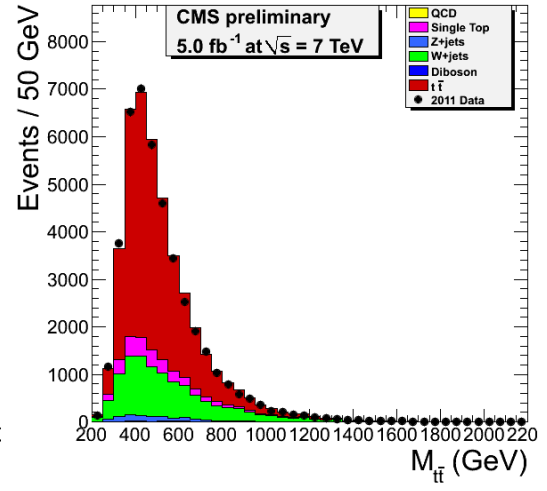
(a)



(b)



(c)



(d)

Figure 7.6: Control plots for preselection after scaling.

Table 7.2: Final scale factors for simulation processes.

Process	Scale Factor
$t\bar{t}$	0.896
$W/Z + \text{jets}$	1.258

Chapter 8

Top Quark Reconstruction

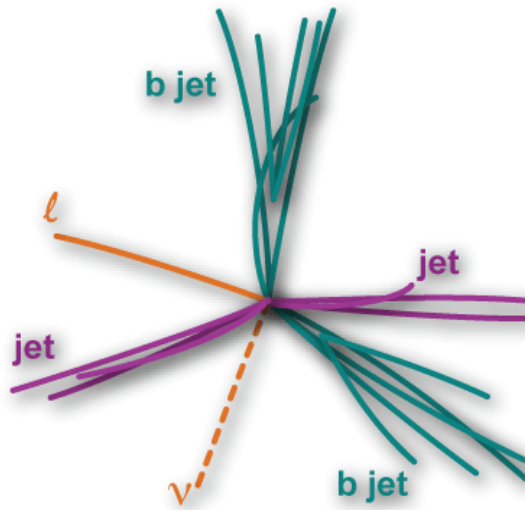


Figure 8.1: A detector view of a semi-leptonic top pair decay.

Before we move onto the final event selection it is important to demonstrate that we can accurately reconstruct the both hadronic and leptonic W -bosons and also the two top quarks in the event. This allows the use the mass and kinematic information from the reconstructed

particles as variables in the boosted decision tree training. Fig. 8.1 shows a schematic of a typical semileptonic $t\bar{t}$ event. The signature consists of:

- 1 Muon (μ)
- 2 b -quark jets (one from each top quark decay)
- 2 light-flavor jets (from the hadronic W decay)
- Missing Transverse Energy (E_T^{miss}) (from the undetected neutrino (ν) from the leptonic W decay).

While the majority of the $t\bar{t}$ events we analyze will look like this, it is important to also be able to reconstruct events with 3 jets in which one jet is lost from the acceptance of two of the jets have merged. The latter is especially important for large Z' masses where the $t\bar{t}$ receives a significant boost.

8.1 Leptonic W Reconstruction

We initially reconstruct the $W \rightarrow \mu\nu$ system from the selected muon and the missing transverse energy of the event. The invariant mass of the $\mu - \nu$ system (using $\hbar = c = 1$) is given by:

$$M_W^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \mathbf{p}_i\right)^2 = (E_\nu + E_\mu)^2 - (\mathbf{p}_\nu + \mathbf{p}_\mu)^2 \quad (8.1)$$

This requires the determination of the z -component of the neutrino momentum (p_z^ν). Equation 8.1 gives p_z^ν in terms of three quantities A, C and C which are functions of the W mass,

muon kinematics and missing transverse energy.

$$p_z^\nu = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (8.2)$$

where:

$$A = 4[(p_z^\mu)^2 - (E^\mu)^2], \quad (8.3)$$

$$B = 4p_z^\mu[(M_W)^2 - (E^\mu)^2 - (p_T^\nu)^2 + (p_z^\mu)^2 + (p_x^\mu + p_x^\nu)^2 + (p_y^\mu + p_y^\nu)^2], \quad (8.4)$$

and

$$C = [(M_W)^2 - (E^\mu)^2 - (p_T^\nu)^2 + (p_z^\mu)^2 + (p_x^\mu + p_x^\nu)^2 + (p_y^\mu + p_y^\nu)^2]^2 - 4(E^\mu)^2(p_T^\nu)^2 \quad (8.5)$$

If there are two real-valued solutions for p_z^ν , the solution which better reconstructs the leptonic top quark mass is used. If the solution has an imaginary part, that is if $B^2 - 4AC < 0$, then we use only the real part of p_z^ν to reconstruct the leptonic top quark. Constraining the $\mu - \nu$ system using the W mass means that the distribution of the Leptonic W mass is a delta function at M_W with a tail on the high side due to events with imaginary solutions for p_z^ν . This is shown in Fig. 8.2 for a set of simulated semileptonic $t\bar{t}$ decays.

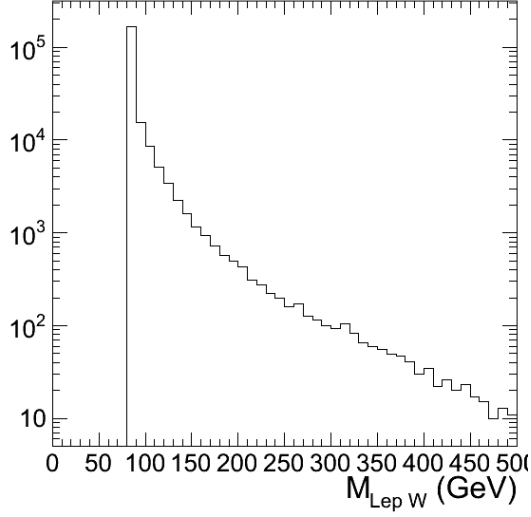


Figure 8.2: Reconstructed mass for leptonic W decays in simulated $t\bar{t}$ events.

8.2 Jet Selection

In the case of events containing ≥ 4 jets, we permute over all the jets, assigning 2 jets to the hadronic W, 1 to the leptonic top and 1 to the hadronic top to reconstruct the entire $t\bar{t}$ system. If there is one or more identified b-jet in the event we explicitly require it to be used as a b-jet in the mass reconstruction. We then select the permutation with the lowest χ^2 calculated according to eq. 8.6. The same procedure is used for 3 jet events except that we assign only 1 jet to the hadronic top, assuming that the decay products from the hadronic W have merged together because of a high boost.

$$\chi^2 = \frac{(m_t - m_{hadtop})^2}{\sigma_{hadtop}^2} + \frac{(m_t - m_{leptop})^2}{\sigma_{leptop}^2} + \frac{(m_W - m_{hadW})^2}{\sigma_{hadW}^2} + \frac{(p_T^{t\bar{t}} - 0)^2}{\sigma_{p_T^{t\bar{t}}}^2} + \frac{(H_T^{ratio} - 1)^2}{\sigma_{H_T^{ratio}}^2} \quad (8.6)$$

Here m_t is the nominal top quark mass, m_W is the known W mass, m_{hadtop} is the reconstructed hadronic top mass, m_{lepton} is the reconstructed leptonic top mass, and m_{hadW} is the reconstructed hadronic W mass. Two extra parameters are used in the sorting algorithm, the sum p_T of the two top quarks ($p_T^{t\bar{t}}$) and the total p_T of the jets used in the reconstruction divided by the total p_T of all the jets in the event (H_T^{ratio}). These help to discriminate against problems from events with large amounts of pile-up, and improves the mass resolution at high invariant mass. The resolutions (σ_{hadtop} , etc.) are calculated by using simulated events in which the parton level information has been matched to reconstructed jets. For the mass terms, a gaussian fit is applied to the peak of each mass distribution and the means and widths are taken from the fits. The nominal value of $p_T^{t\bar{t}}$ is 0 because the $t\bar{t}$ system is assumed to be at rest and the nominal H_T value is 1 because all of the highest p_T jets in the event are assumed to come from the $t\bar{t}$ system. The resolutions for the two final terms are just taken to be the total width of the distributions from the parton-reconstructed jet matching. The values used for each parameter are listed in Table 8.1. The uncertainties on the masses are generally dominated by the uncertainty on the jet energy scale and jet energy corrections.

Table 8.1: Parameters and resolutions used in the χ^2 calculations.

	Reference Value	σ
Hadronic W	81.34 GeV	9.18 GeV
Hadronic Top	169.17 GeV	16.56 GeV
Leptonic Top	169.58 GeV	16.32 GeV
$p_T(t\bar{t})$	0.0	38.9
Jet p_T ratio	1.0	0.153

8.3 Reconstruction Validation

In order to validate the reconstruction we compare permutation with the best value of the χ^2 to all the possible permutations. Fig. 8.3 shows strong peaking at the input mass for $m_{t\bar{t}}$ and a significant improvement in the resolution for all of the other parameters used in the χ^2 definition. Fig. 8.4 shows that the selected permutation also matches up very well compared to the reconstruction that uses parton truth information to match jets to their parent top quarks.

Lastly, we show results of using this method on simulated samples of $M_{Z'} = 1, 1.5$ TeV (Figs. 8.5 and 8.6 respectively). It is clear that the χ^2 algorithm also works quite well for narrow Z' decays.

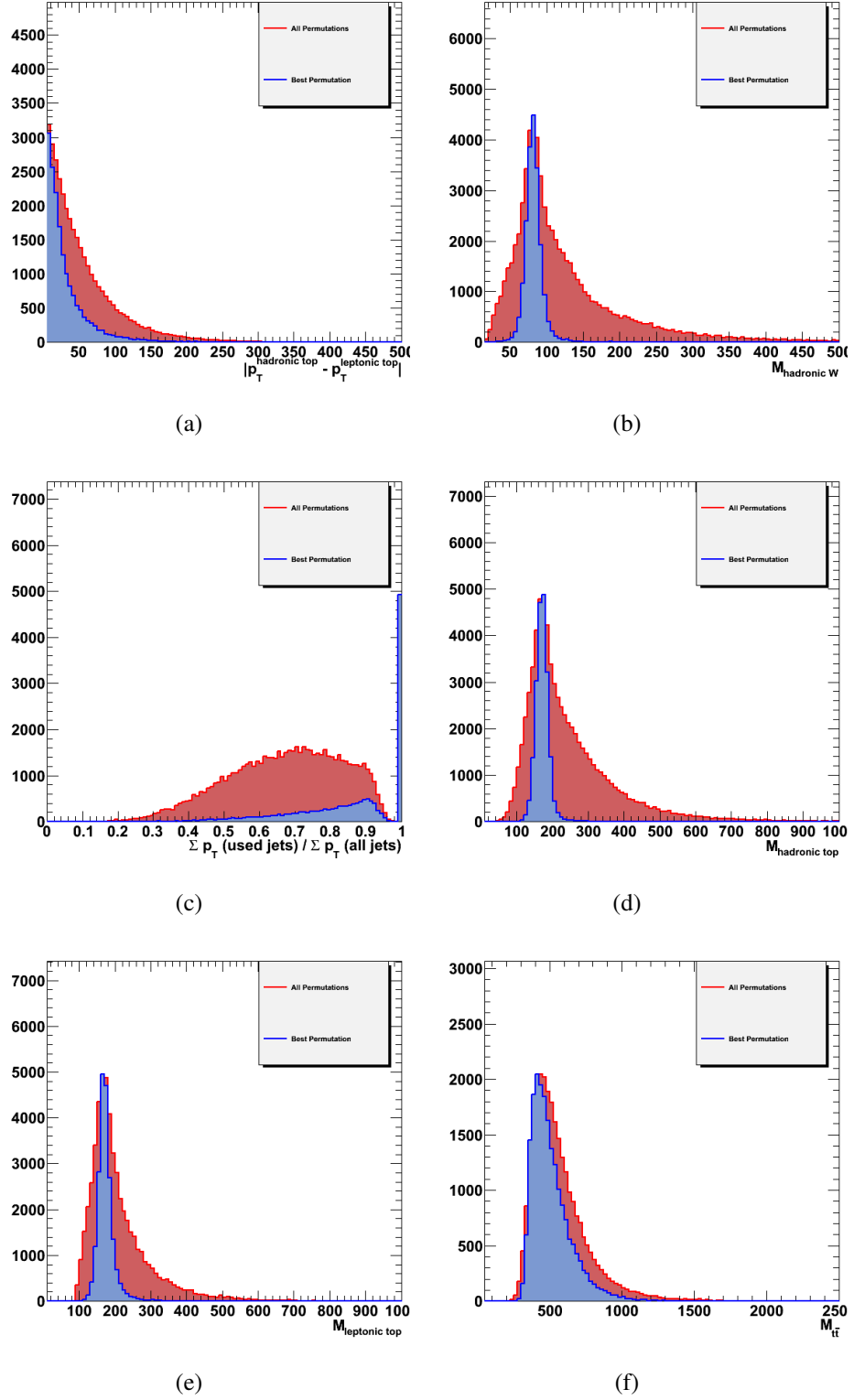
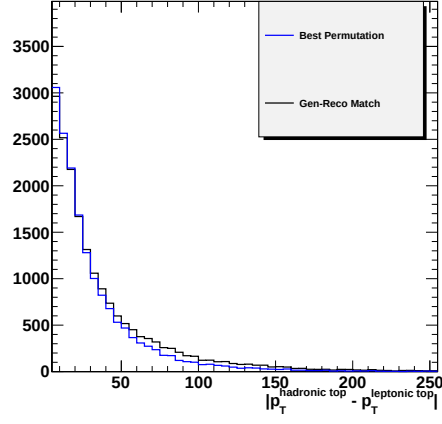
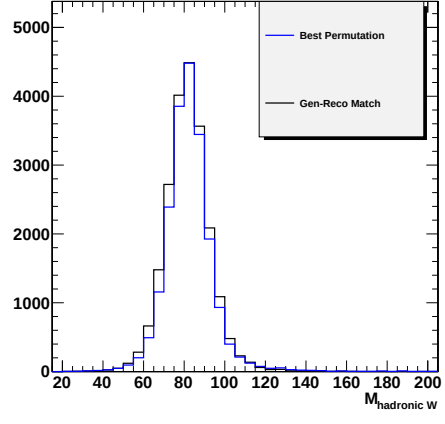


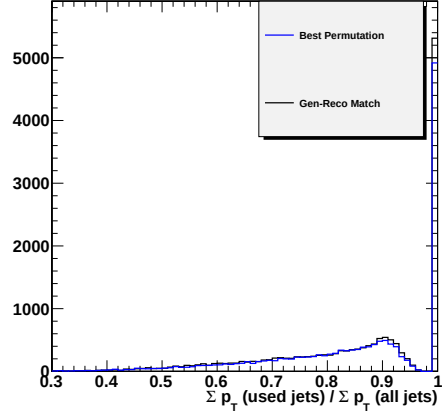
Figure 8.3: a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in SM top quark events.



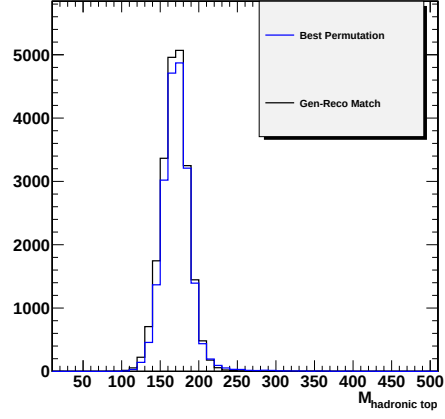
(a)



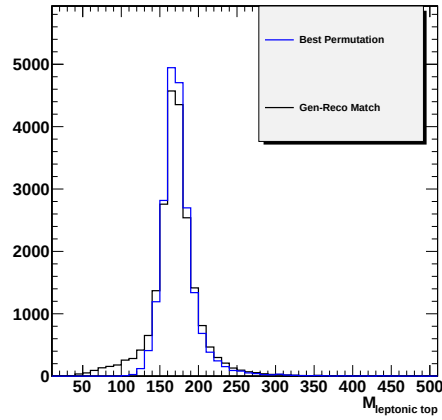
(b)



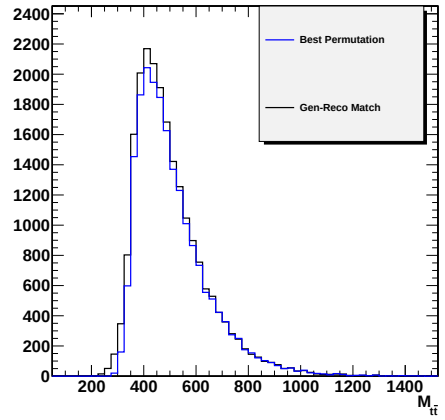
(c)



(d)



(e)



(f)

Figure 8.4: a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for reconstruction using MC truth (red) and the best permutation (blue) in SM top quark events.

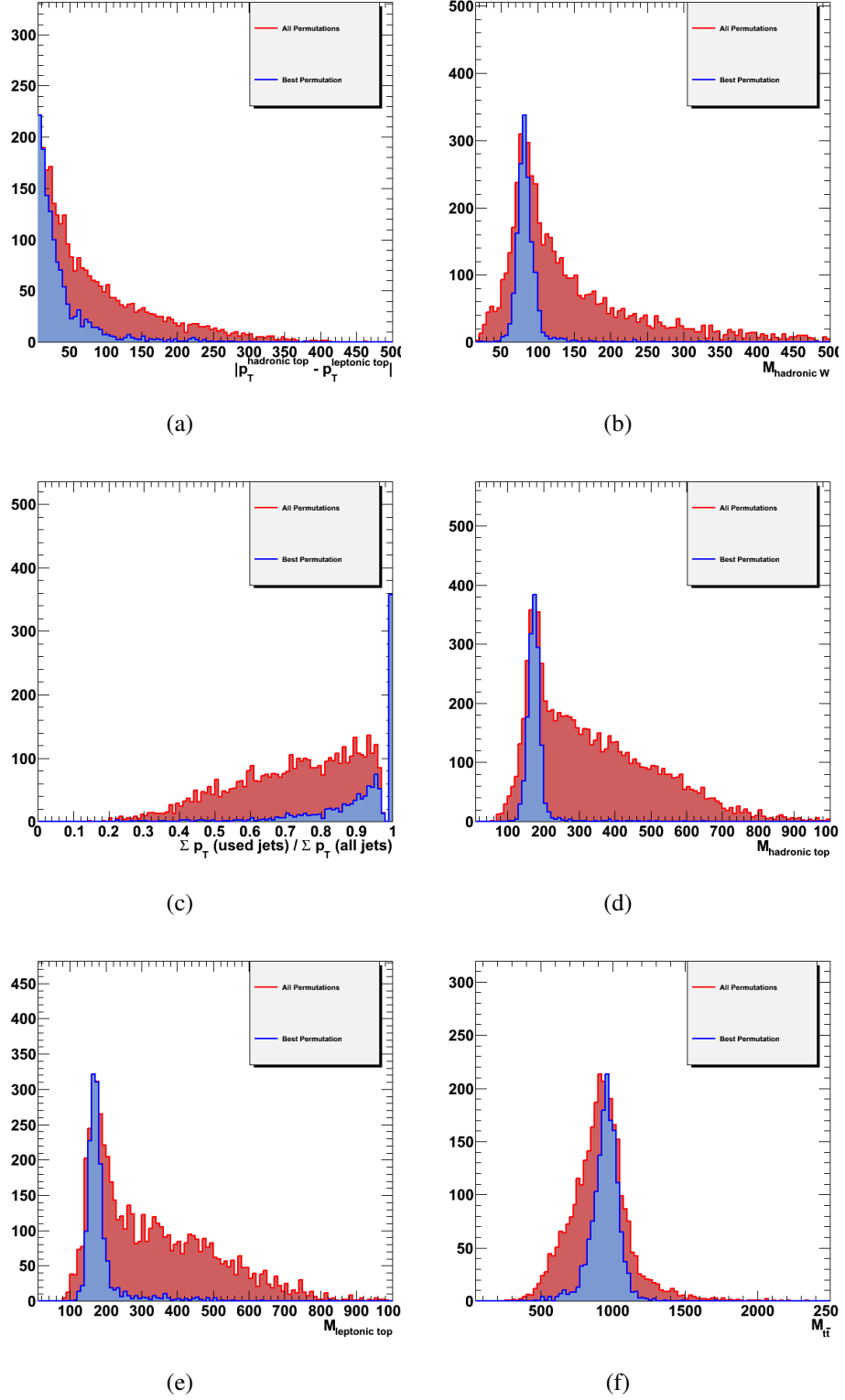


Figure 8.5: a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in Z' ($m = 1$ TeV) events.

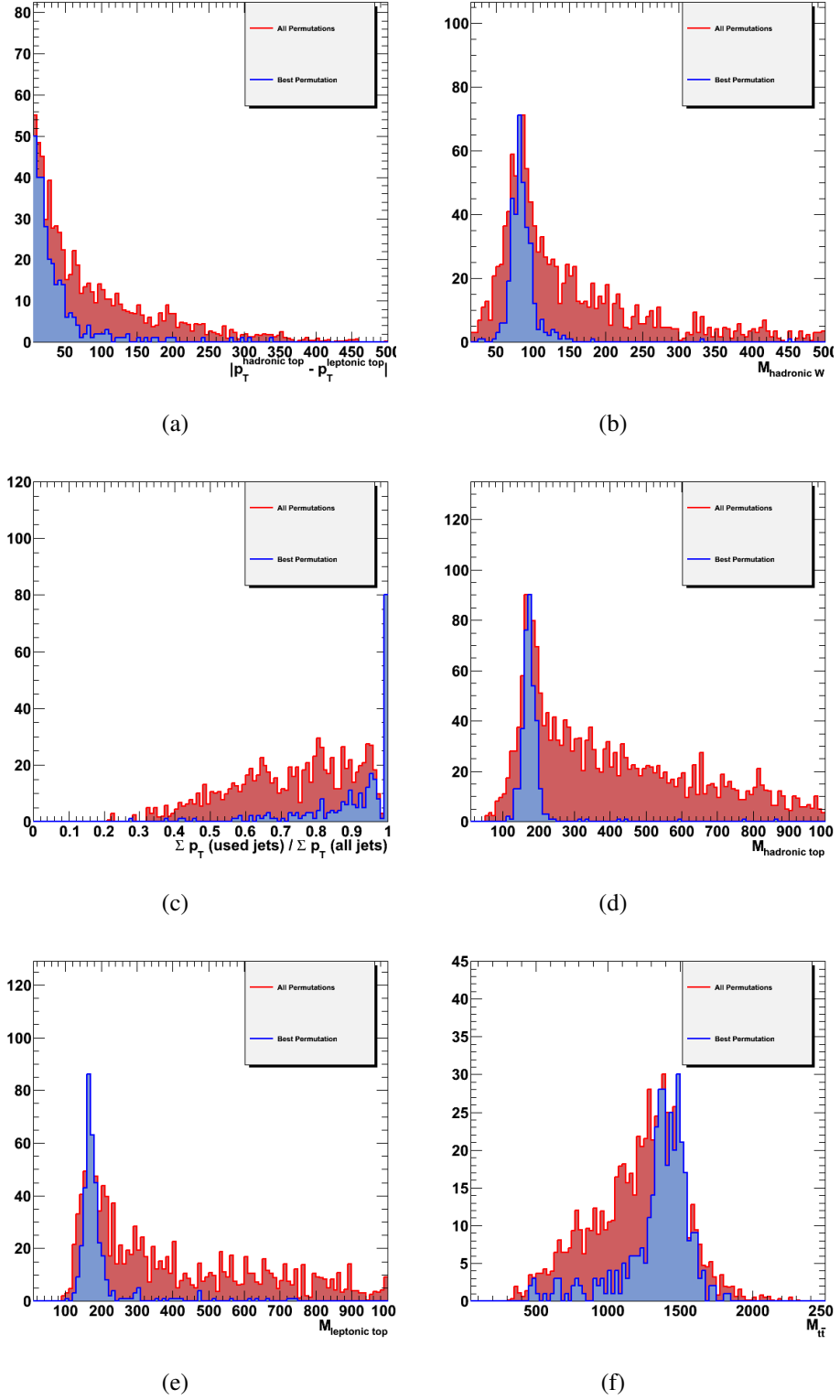


Figure 8.6: a.) Sum p_T of the $t\bar{t}$ system, b.) Hadronic W mass, c.) H_T ratio, d.) Leptonic top mass, e.) Leptonic top mass, f.) $t\bar{t}$ invariant mass for all jet permutations (red) and the best permutation (blue) in Z' ($m = 1.5$ TeV) events.

Chapter 9

Boosted Decision Trees

The boosted decision tree (BDT) is a multivariate classifier [27] that has become a popular alternative to conventional cut-based or neural network analyses [62]. Decision trees have the benefit of being quick to program and train, they have a small number of parameters to tune, and are easy to understand. The visualization as a series of simple yes or no decisions based on a chain of optimal cuts on successive observation variables is conceptually simple. However, decision trees have the drawback of being unstable with regard to fluctuations in the training samples. Small changes in the variable distributions can cause the tree to choose the wrong variable to split on and can adversely affect the further growth of the tree. To deal with this problem a number of boosting algorithms have been developed. These stabilize the classifier training by creating ensembles (forests) of trees that are more stable with respect to statistical fluctuations. However, even after boosting, decision trees are not without their drawbacks as one must take care not to create too specific a criteria for event classification

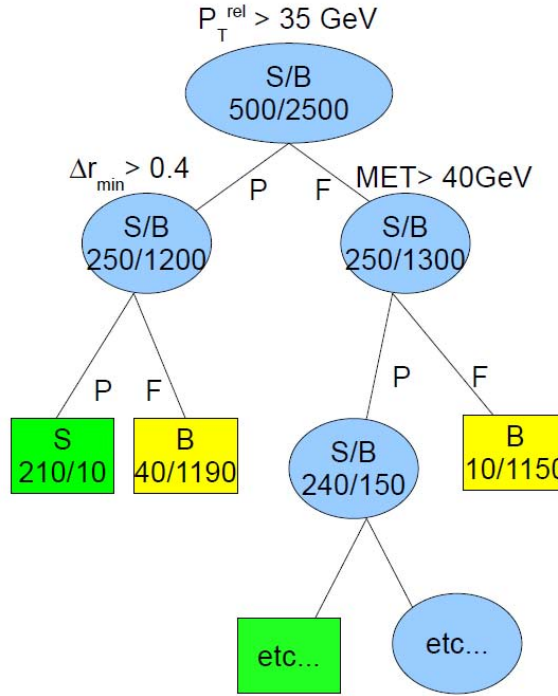


Figure 9.1: A decision tree example

and over-train trees on individual events. Many methods, such as tree pruning, can be invoked in order to avoid this problem and stabilize the classifier to be used. In the following sections, we discuss the BDT implementation for the analysis presented here.

9.1 BDT Definition

9.1.1 Growing

A BTD (see Fig. 9.1) is created (grown) by starting at a root node using samples of simulated signal and background events. The definition of signal and background must be provided to the BDT prior to training. The training algorithm will then determine the variable with the

highest separation power between signal and background and find the optimal cut on that variable and the first split will be made. Two daughter branches are then made for events that pass and those that fail the initial cut, hereby creating two daughter nodes. At each of these new variable are chosen and further splits takes place. The purity of each sample at each node is defined as

$$P = \frac{\sum_s W_s}{\sum_s W_s + \sum_b W_b} \quad (9.1)$$

which is the ratio of the sum of weighted signal events to the weighted sum of all events on the node. For each node a separation criterium is defined to determine the best variable to split on. In this analysis the gini index is used which calculates for each branch:

$$Gini = \left(\sum_{i=1}^n W_s \right) P(1 - P) \quad (9.2)$$

where the summation is over the number of events on that node. The factor $P(1 - P)$ is 0 for pure signal or pure background and 0.5 for an equal number of signal and background. The *Gini* index is then used to find the next splitting variable by finding the one that maximizes the quantity:

$$Gini_{parent\ node} - Gini_{right\ daughter} - Gini_{left\ daughter} \quad (9.3)$$

This process is iterated until the number of events per node reaches a chosen lower limit (minimum leaf size) or the desired purity is reached. The resulting terminal nodes (leafs) are classified as signal or background depending on the majority type.

9.1.2 Boosting

To increase stability and avoid over-training a single tree can be boosted into a forest of many trees by the Adaptive Boosting (ADABOOST) method [43, 65]. ADABOOST works by taking a set of N events $x_i = \{x_1, \dots, x_N\}$ where each x_i is described by a set of identification variables and by a *a priori* classification $y_i = \{y_1, \dots, y_N\}$ where $y \in \{-1, +1\}$ is $+1$ for signal events and -1 for background events. The boosting process is then performed as follows:

- Construct a distribution of weights for each event $D_t(i)$ (where t is the tree index) on $\{1, \dots, N\}$ where the initial weight of each event is $D_1(i) = \frac{1}{N}$.
- Find a weak classifier (a single decision tree in this case) $h_t(i)$ that gives $h_t(i) \in \{-1, +1\}$, $+1$ if the tree chooses signal and -1 if the tree chooses background for a given x_i .
- Let $I(y_i \neq h_t(i)) = 1$ if $y_i \neq h_t(i)$ and -1 if $y_i = h_t(i)$ (One can also use $I(y_i = h_t(i)) = 0$ if $y_i = h_t(i)$ if it is desired to keep the weight of properly classified events the same instead of decreasing the weight).
- The error on a single tree is then:

$$\epsilon_t = \frac{\sum_{i=1}^N D_t(i) I(y_i \neq h_t(i))}{\sum_{i=1}^N D_t(i)} \quad (9.4)$$

- Let $\alpha_t = \frac{1}{2} \ln\left(\frac{1-\epsilon_t}{\epsilon_t}\right) > 0$ and update each weight by:

$$D_{t+1}(i) = \frac{D_t(i)}{Z_t} e^{-\alpha_t I(y_i \neq h_t(i))} \quad (9.5)$$

where $Z_t = 2\sqrt{\epsilon_t(1-\epsilon_t)}$ is a normalization factor.

The final classifier is then:

$$H_{final}(X) = \text{sign} \left(\sum_t \alpha_t h_t(X) \right) \quad (9.6)$$

if the output is to be binary and $H_{final}(X) = \sum_t \alpha_t h_t(X)$ if a distribution is desired. The final weight of each event is:

$$D_{final}(i) = \frac{1}{N} \frac{e^{-y_i \sum_t \alpha_t h_t(x_i)}}{\prod_t Z_t} \quad (9.7)$$

and $\prod_t Z_t = \prod_t 2\sqrt{\epsilon_t(1-\epsilon_t)}$ is the training error on the final classifier. The final classifier can then be thought of as a series of weighted binary decisions where each tree has a weighted yes or no vote on the event.

9.1.3 Pruning

To further limit the possibilities of over-training, the fully-grown tree can be pruned to remove statistically insignificant nodes that do not improve the overall signal and background

separation [38]. To do this the forest of trees is grown completely and then each individual tree is pruned by removing some of the branches from the tree. This is done after the boosting process to preserve the original error fraction used by ADABOOST. For this analysis the Expected Error method is used.

The method starts from the bottom nodes and works its way up. It compares the statistical error estimate of a parent node to the combined statistical error of all of the subsequent nodes below it and the lower nodes are recursively removed if the combined error of the daughters is higher than that of the parent node. The error is defined by the binomial error $\sqrt{P(1-P)/n}$ where n is the number of events at the node and P is the node purity. In this way superfluous nodes are removed and the tree is cut down to a more reasonable size.

9.2 Implementation

The final event selection depends on the number of b jets tagged in the event. We reject all events with 0 b jets as they are dominated by W/Z background and keep all events with ≥ 2 b jets as these are nearly all $t\bar{t}$. For the 1 b jet sample, which is about half signal and half background, a forest of boosted decision trees is trained and a threshold cut on the classifier is used to remove as much of the background as possible while keeping high signal acceptance.

The BDTs used in this analysis are configured using the ROOT package TMVA [50]. For the training, standard model $t\bar{t}$ is used to model the signal and the sum of W/Z +jets, QCD multijet, diboson and single top (production of single top quarks in the s , t and tW

channels) events is used to model the background. The events are weighted prior to training according to their predicted cross sections in order to focus the training on the predominant backgrounds (W +jets and single top).

Internal parameters for the BDT training are set as follows in TMVA:

- Number of trees = 100
- Minimum events per leaf = 20
- Node purity limit = 0.5
- Prune strength is calculated automatically by TMVA

These are chosen to give a reasonable balance between the computing time required for training and processing the events and the necessity to train enough trees so that we obtain a smooth classifier distribution while not over or under training the forest. We have checked to ensure the classifier distribution is insensitive to reasonable changes to the values of each of these parameters.

The forest is trained on all 1 b-tag simulated events that pass the preselection. The sample is then divided into test and train samples within TMVA. An initial training is performed using a set of 42 variables (see Table 9.1). The top 20 variables (see Table 9.2) are taken from the initial training and a second forest of trees are trained. This is done to remove variables that are used infrequently and to help guard against possible overtraining. The distributions for the variables used in the final training are shown in Figs. 9.2-9.5. These are for events passing preselection with 1 b-tag. The simulation and data are in good agreement in all cases.

This means that there will be no problems from poorly modeled variables entering into the BDT training process. Fig 9.7 shows that this is indeed the case as there is good overall agreement in the classifier distributions for data and simulation. Fig. 9.7 also shows the classifier values for simulated Z' samples with masses of 750, 1000 and 1250 GeV. These are included for comparison and not used in the training process.

The results of the training are shown in Fig. 9.8. The rejection vs efficiency curve shows that high background rejection can be achieved in the region of 40-60% signal efficiency and classifier distributions for the predicted $t\bar{t}$ signal and backgrounds are in very good agreement with data. While it is possible to use $S/(S+B)$ as in Fig. 9.8 c.) to select a classifier cut it is better to select a cut based on the optimal upper limits on the Z' cross section.

Table 9.1: Full list of BDT training variables ordered by initial training ranking.

Rank	Variable Name	Frequency of Use	Rank	Variable Name	Frequency of Use
1	$N^{jets} (p_T > 20 \text{ GeV})$	8.848e-02	26	$\Delta R(jet1, jet3)$	1.328e-02
2	Leptonic Top Mass	6.325e-02	27	$ \eta^\mu $	1.298e-02
3	$\Delta R(jet1, jet2)$	6.061e-02	28	p_T^{jet1}	1.249e-02
4	p_T^{jet3}	6.055e-02	29	$ \eta^{Hadronic W} $	1.234e-02
5	Hadronic W Mass	4.964e-02	30	$ \eta^{jet2} $	1.191e-02
6	$\Delta R_{max}(\mu, \text{nearest jet})$	4.777e-02	31	Centrality	1.034e-02
7	$\Delta R_{min}(jet1, \text{nearest jet})$	4.319e-02	32	$p_T^{Leptonic W}$	1.014e-02
8	Aplanarity	3.711e-02	33	$\Delta\phi(\mu, E_T^{miss})$	9.281e-03
9	Hadronic Top Mass	3.191e-02	34	Sphericity	9.198e-03
10	$\Delta p_T(t, \bar{t})$	3.081e-02	35	Leptonic Top Energy	9.001e-03
11	Hadronic W Energy	2.717e-02	36	$\Delta R_{min}(jet2, \text{nearest jet})$	8.775e-03
12	$p_T(\mu)$	2.607e-02	37	$H(jets + \mu + E_T^{miss})$	8.268e-03
13	$\Delta R_{min}(\mu, \text{nearest jet})$	2.517e-02	38	$ \eta(jet2, jet3) $	8.157e-03
14	$ \eta^{jet3} $	2.325e-02	39	$M(jet1, jet2)$	8.027e-03
15	$\Delta M(t, \bar{t})$	2.322e-02	40	$p_T^{Hadronic Top}$	7.977e-03
16	$\Delta R_{min}(jet3, \text{nearest jet})$	2.230e-02	41	Leptonic W Energy	7.402e-03
17	Leptonic W Mass	2.026e-02	42	$M(jet1, jet3)$	7.009e-03
18	E_T^{miss}	2.014e-02	43	p_T^{jet2}	6.485e-03
19	$p_T^{relative}(\mu, \text{nearest jet})$	1.943e-02	44	$ \eta^{Leptonic W} $	5.325e-03
20	$M(\mu, jet1)$	1.911e-02	45	$ \eta^{Leptonic Top} $	4.784e-03
21	$H_T(jets + \mu + E_T^{miss})$	1.597e-02	46	$p_T^{Leptonic Top}$	3.025e-03
22	$ \eta(jet1, jet3) $	1.556e-02	47	$ \eta^{jet1} $	3.694e-04
23	$M_T(\mu, E_T^{miss}, \text{nearest jet})$	1.422e-02	48	$\Delta E(t, \bar{t})$	3.625e-04
24	Hadronic Top Energy	1.389e-02	49	$ \eta^{Hadronic Top} $	1.644e-04
25	$M(jet2, jet3)$	1.381e-02	50	$ \eta(jet1, jet2) $	3.976e-05

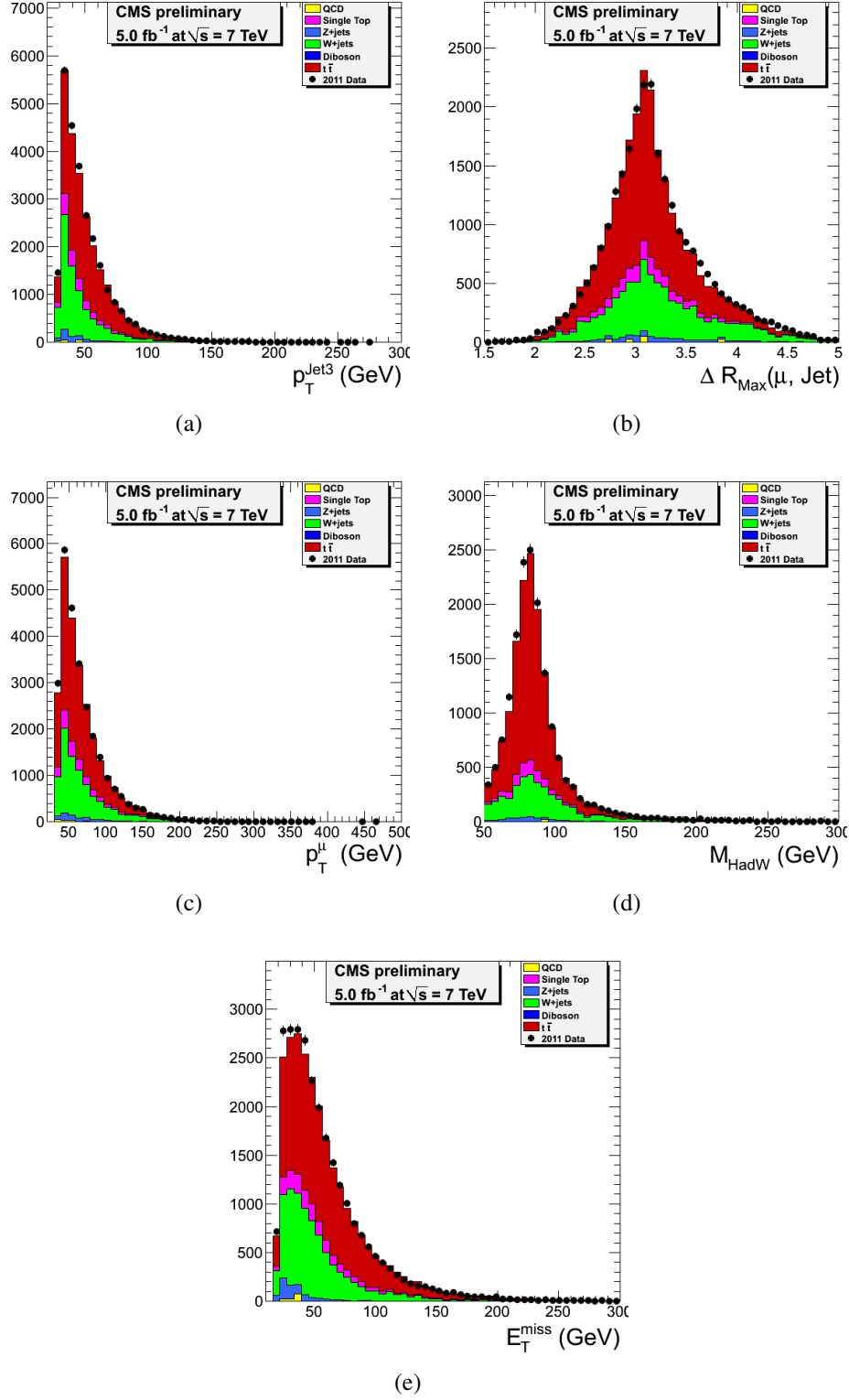


Figure 9.2: Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.

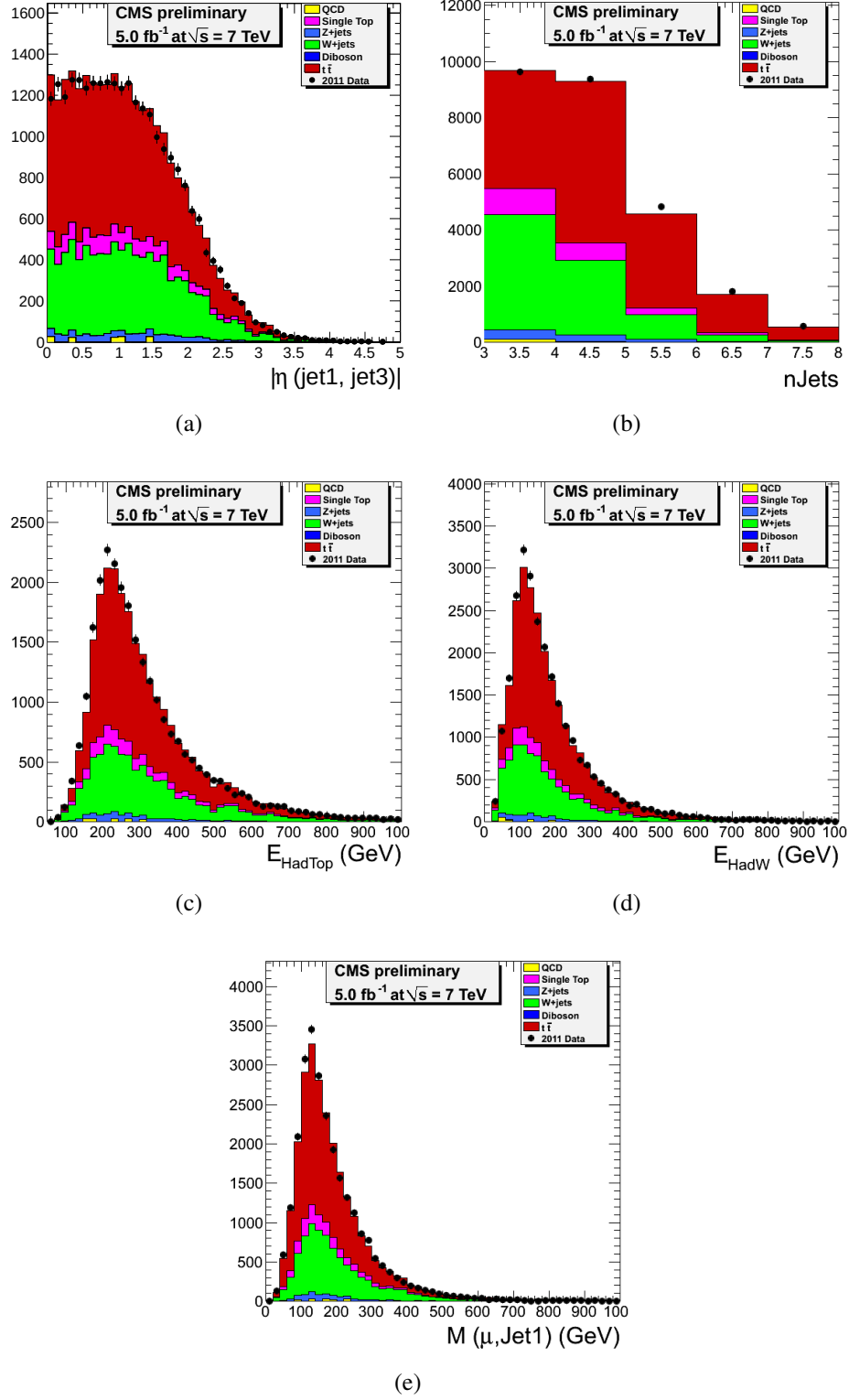


Figure 9.3: Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.

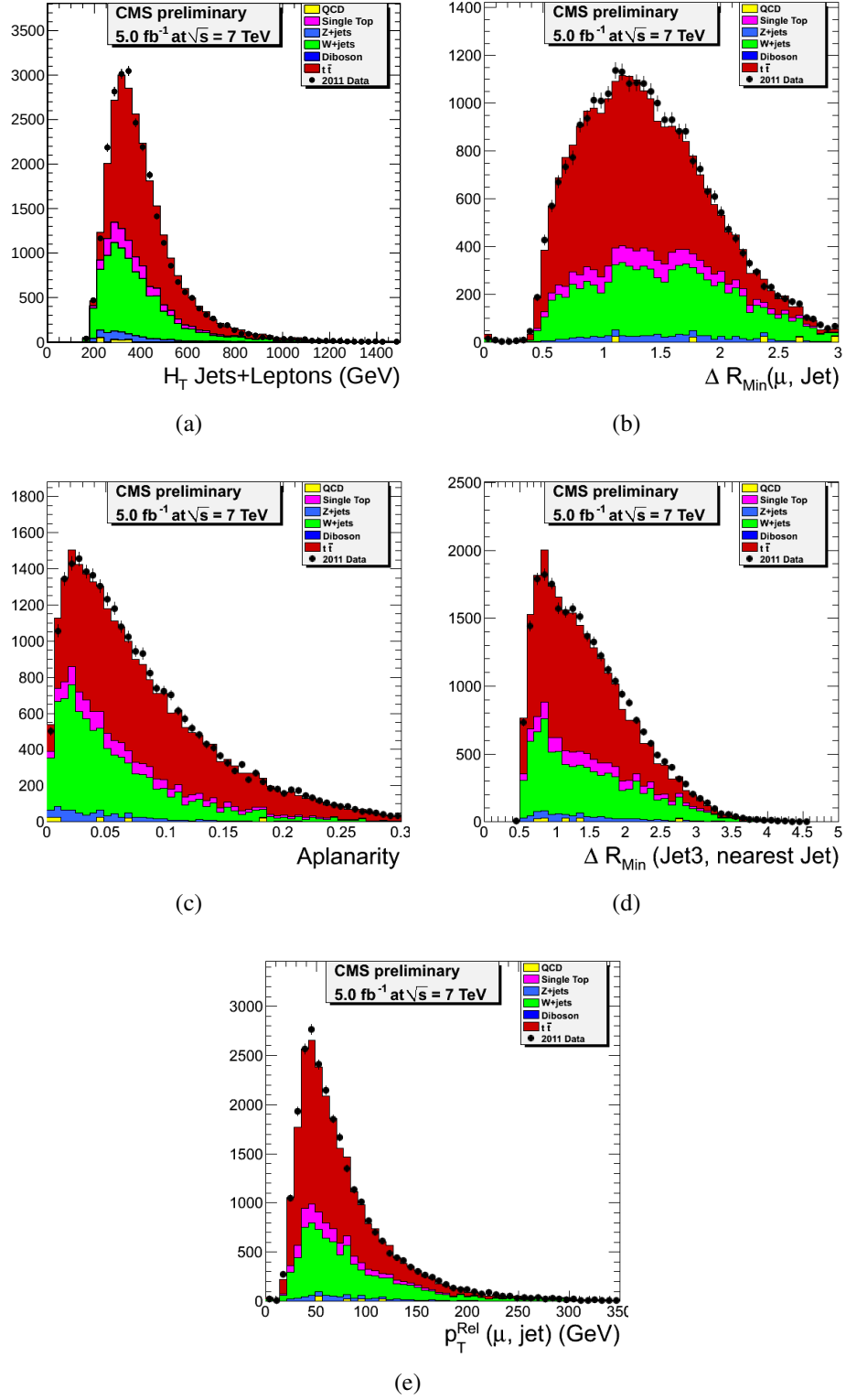


Figure 9.4: Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.

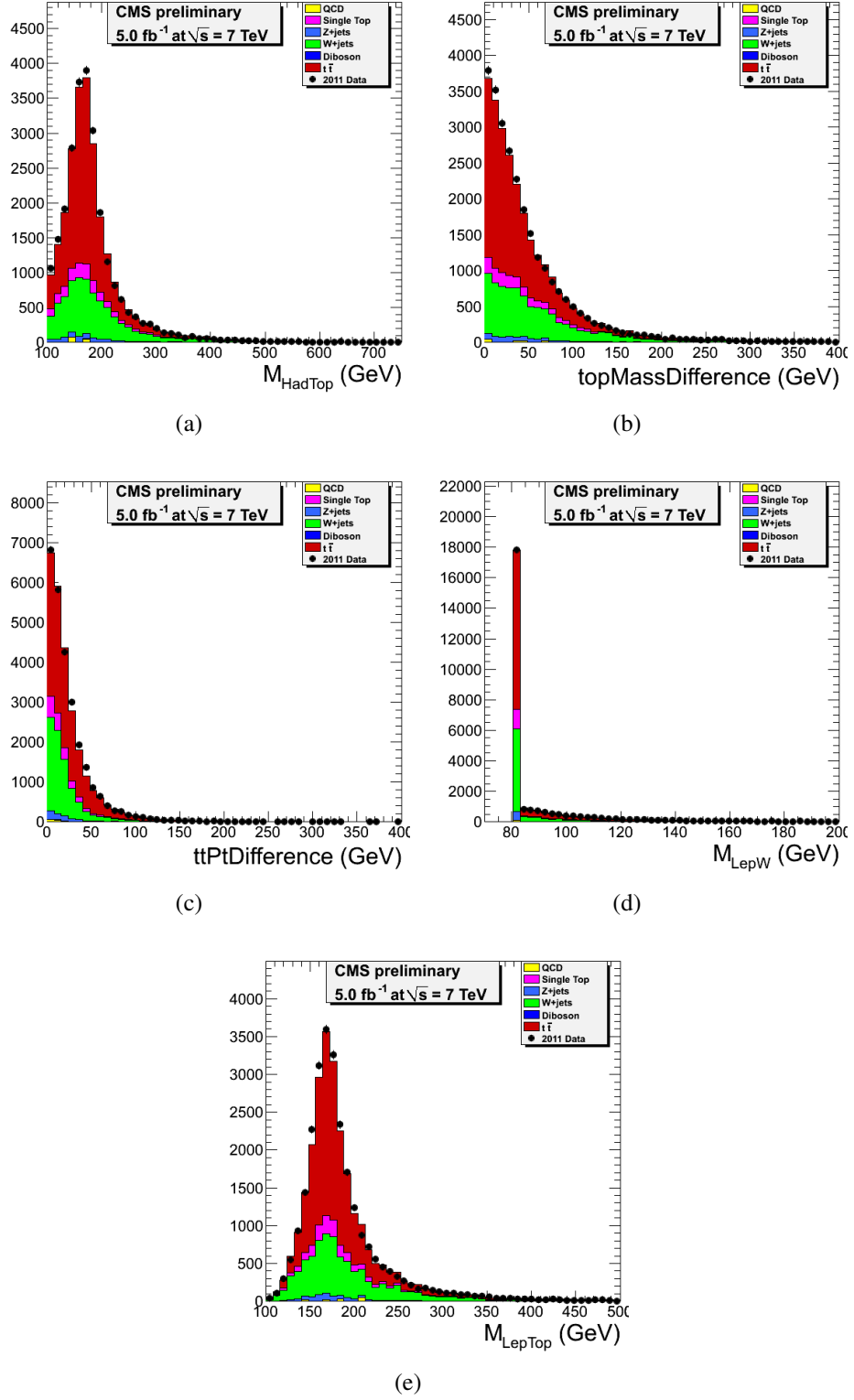


Figure 9.5: Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.

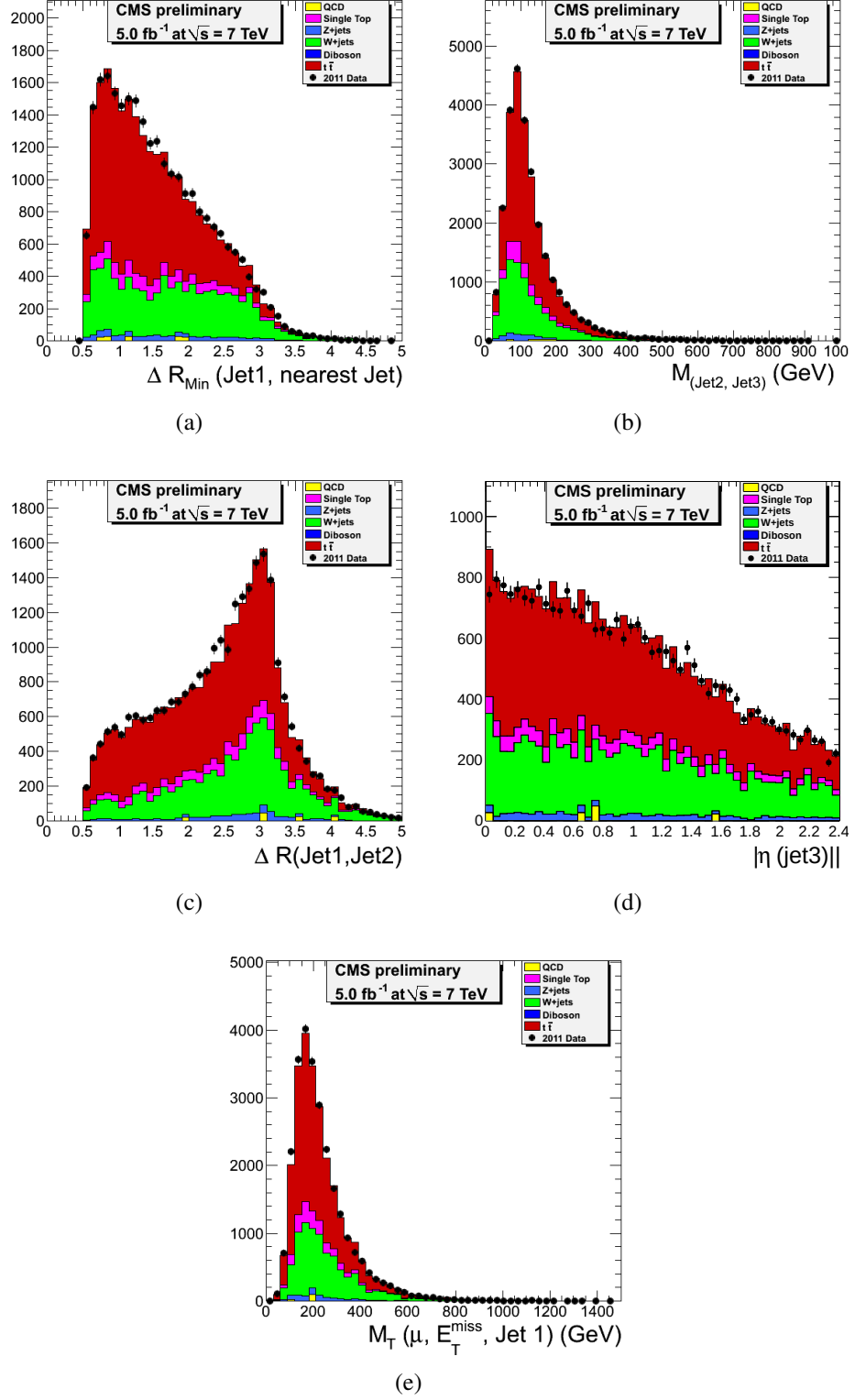


Figure 9.6: Distributions for the 1 b-tag sample only of all the variables used in the final BDT training.

Table 9.2: Reduced list of BDT training variables ordered by final training ranking.

Rank	Variable Name	Frequency of Use
1	p_T^{jet3}	1.273e-01
2	$\Delta R_{max}(\mu, \text{nearest jet})$	1.231e-01
3	$p_T(\mu)$	1.056e-01
4	Hadronic W Mass	6.612e-02
5	E_T^{miss}	5.367e-02
6	$ \eta(jet1, jet3) $	4.818e-02
7	$N^{jets}(p_T > 20 \text{ GeV})$	4.677e-02
8	Hadronic Top Energy	4.185e-02
9	Hadronic W Energy	4.075e-02
10	$M(\mu, jet1)$	3.752e-02
11	$H_T(jets + \mu + E_T^{miss})$	3.548e-02
12	$\Delta R_{min}(\mu, \text{nearest jet})$	3.331e-02
13	Aplanarity	3.115e-02
14	$\Delta R_{min}(jet3, \text{nearest jet})$	2.509e-02
15	$p_T^{\text{relative}}(\mu, \text{nearest jet})$	2.421e-02
16	Hadronic Top Mass	2.203e-02
17	$\Delta M(t, \bar{t})$	2.119e-02
18	$\Delta p_T(t, \bar{t})$	2.018e-02
19	Leptonic W Mass	1.943e-02
20	Leptonic Top Mass	1.916e-02
21	$\Delta R_{min}(jet1, \text{nearest jet})$	1.897e-02
22	$M(jet2, jet3)$	1.316e-02
23	$\Delta R(jet1, jet2)$	1.273e-02
24	$ \eta^{jet3} $	1.252e-02
25	$M_T(\mu, E_T^{miss}, \text{nearest jet})$	5.690e-04

9.3 Optimization of the BDT Classifier Cut

To optimize the choice of the BDT cut the expected upper limits on the Z' cross-section are used to determine which classifier value gives the best expected upper limits on the Z' cross section. To do this the events passing the classifier cut on the 1 b-tag sample are combined with those from the 2 b-tag sample and a CLs upper limit calculation is performed. This is done using the values for the expected limits for Z' masses between 500 and 2000 GeV. The results are shown in Fig. 12.1 and Table 9.3. It can be determined from Table 9.3 that

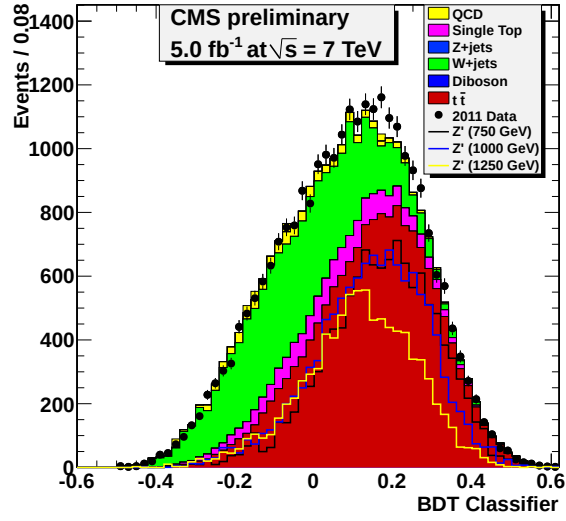
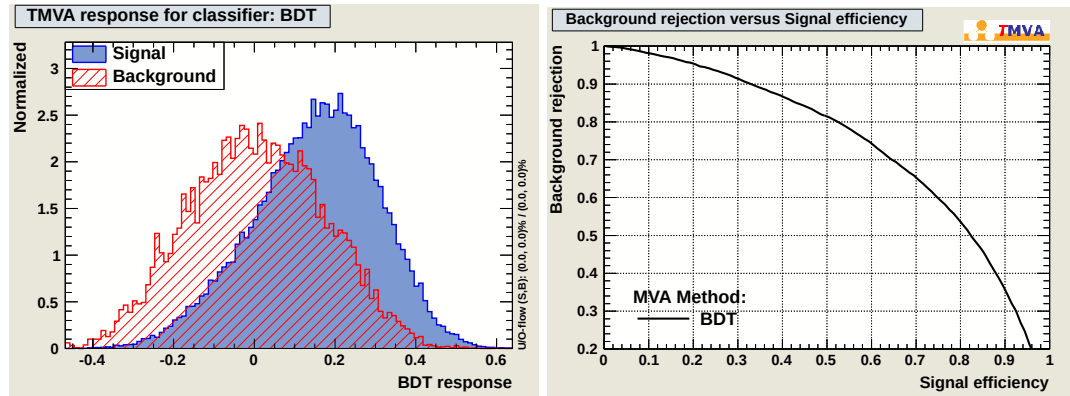


Figure 9.7: Final BDT classifier distribution.

the best limits correspond to a classifier cut of 0.05. The limit plots (Fig. 12.1) show that the agreement between the expected and observed upper limits agree about the same for all choices of classifier cut. We therefore choose a classifier cut of 0.05 for the final event selection and use this selection to set upper limits on the Z' cross-section.

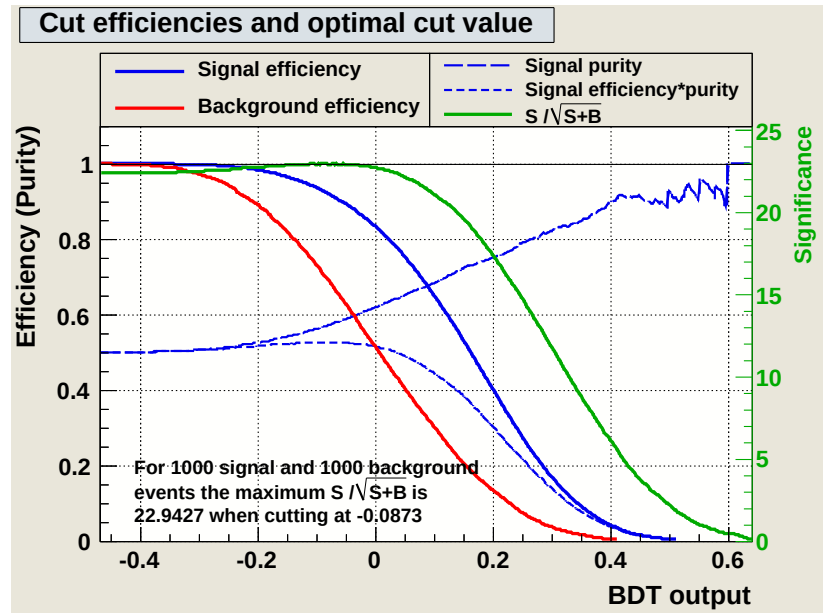
Table 9.3: Limit results for various BDT classifier cuts.

BDT Cut	500 GeV	700 GeV	1000 GeV	1300 GeV	1500 GeV	2000 GeV
-0.1	4.64	1.32	0.655	0.303	0.254	0.185
-0.05	4.82	1.23	0.578	0.295	0.230	0.180
0.0	4.64	1.26	0.583	0.265	0.237	0.191
0.05	4.47	1.24	0.570	0.275	0.227	0.210
0.1	4.75	1.20	0.537	0.257	0.251	0.225
0.15	4.90	1.29	0.557	0.269	0.256	0.244



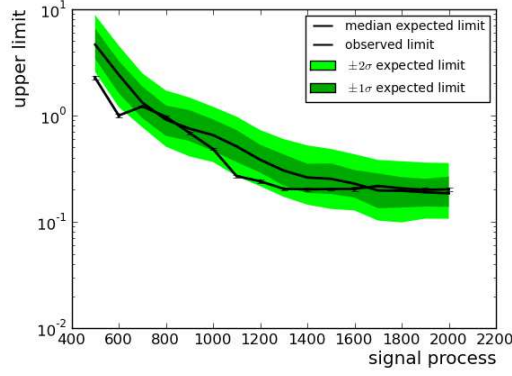
(a)

(b)

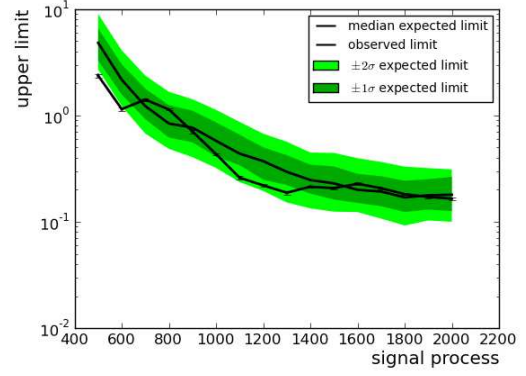


(c)

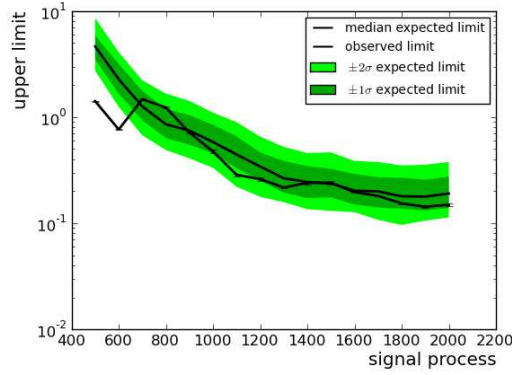
Figure 9.8: a.) The BDT classifier response of all signal and background events for the test sample. b.) Background rejection Vs. signal efficiency for the test sample, c.) The efficiencies as a function of classifier cut.



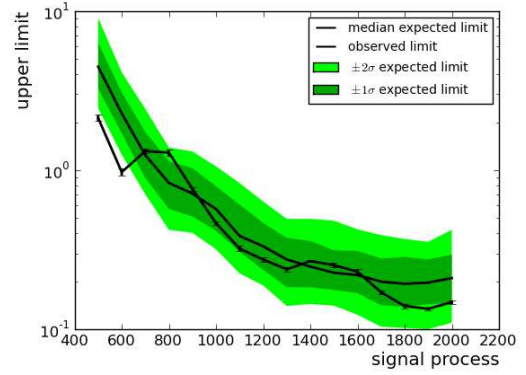
(a)



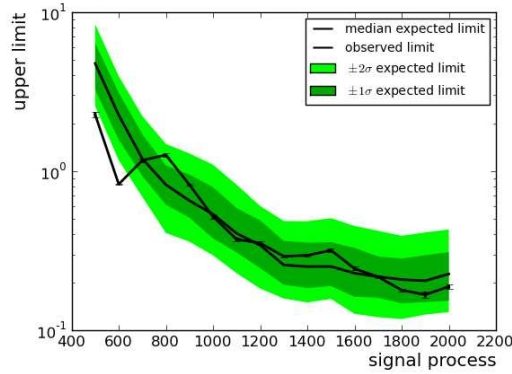
(b)



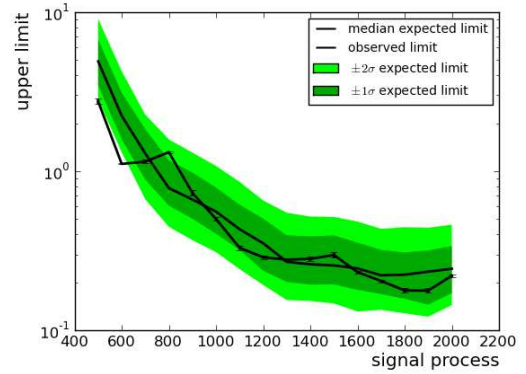
(c)



(d)



(e)



(f)

Figure 9.9: Expected CLs limits for event selections passing BDT classifier cuts at a.) -0.1, b.) -0.05, c.) 0.0, d.) 0.05, e.) 0.1, f.) 0.15.

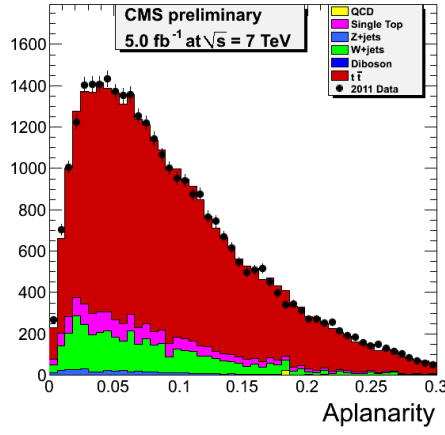
Chapter 10

Final Event Selection

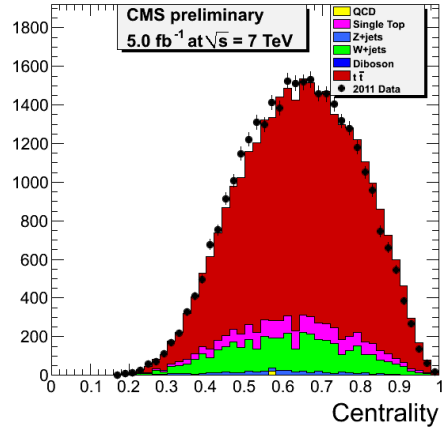
The final event selection is as follows:

- Reject 0 b-tag events
- Keep 1 b-tag events that pass the BDT classifier at a cut of > 0.05
- Keep all 2 b-tag events

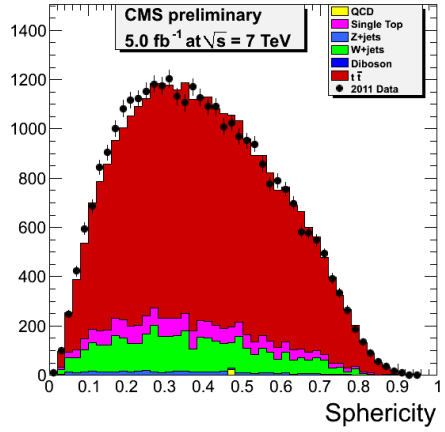
Figs. 10.1-10.3 compares the data and simulation for a number of control distributions. The agreement is very good across all distributions and it is clear that the variables are modelled properly. Fig. 10.4 shows the corresponding $t\bar{t}$ pair mass distribution. The agreement here is also quite good and no excesses are seen which may indicate the presence of a Z' signal. The event yields for the data and simulated backgrounds after the final selection are listed in Table 10.1. The errors quoted are statistical and we observe very good agreement between



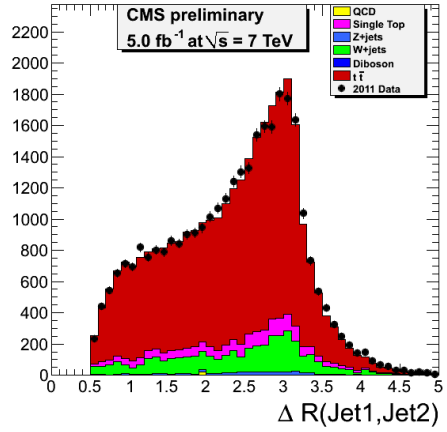
(a)



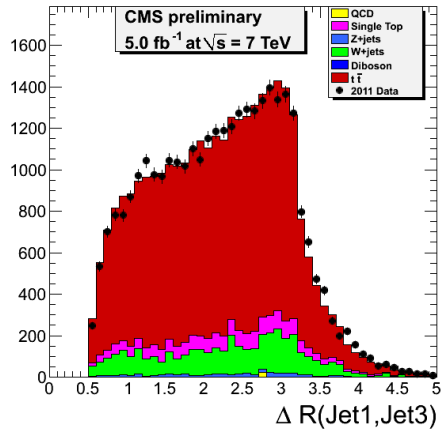
(b)



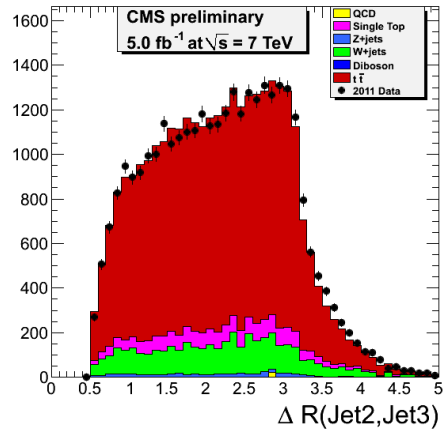
(c)



(d)



(e)



(f)

Figure 10.1: Control plots for the final event selection.

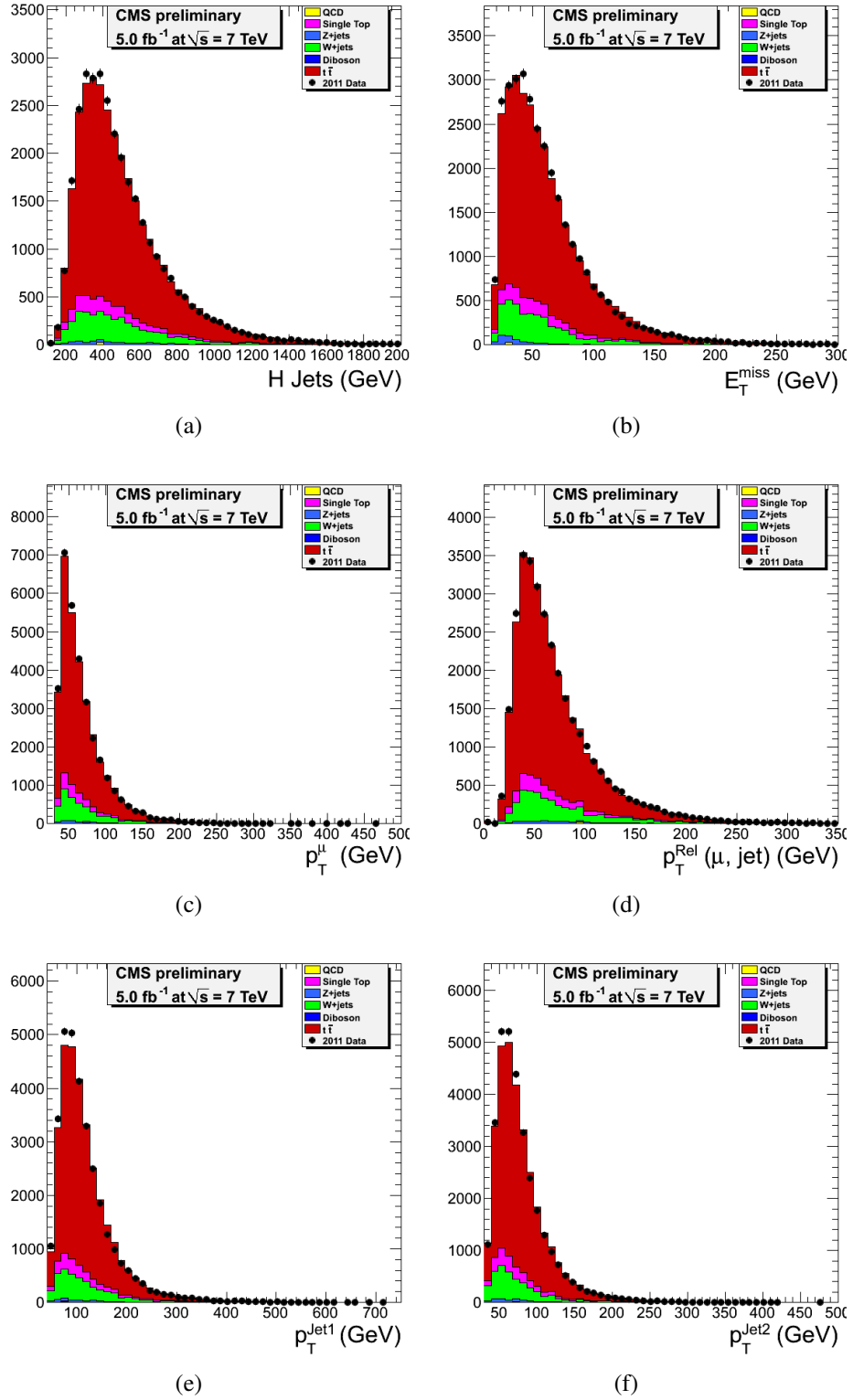
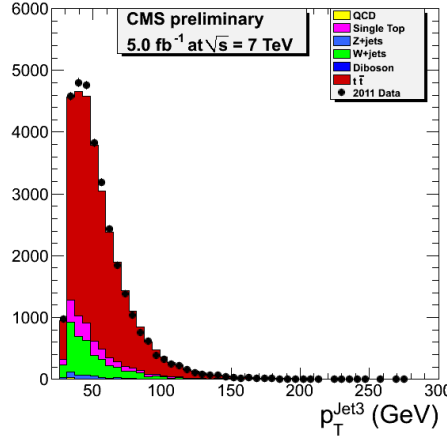
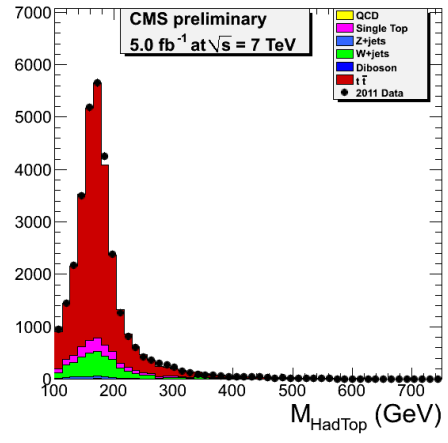


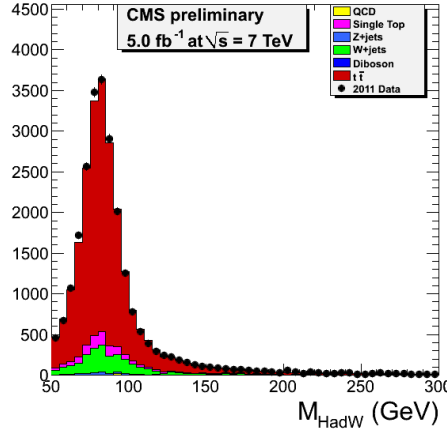
Figure 10.2: Control plots for the final event selection.



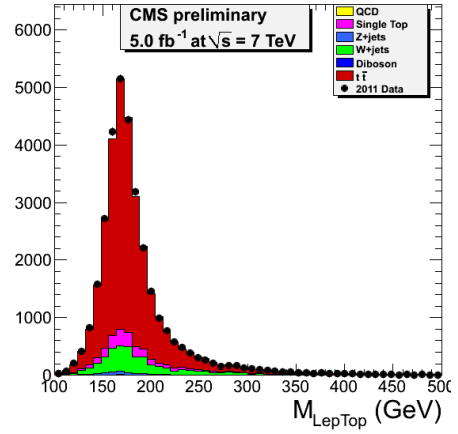
(a)



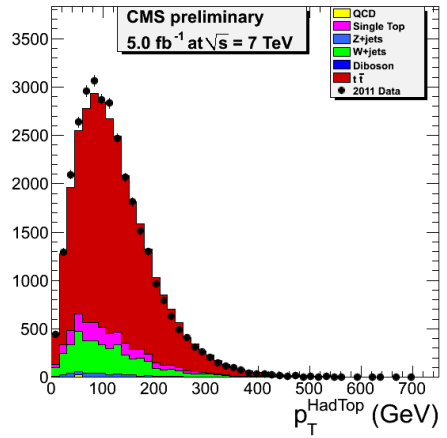
(b)



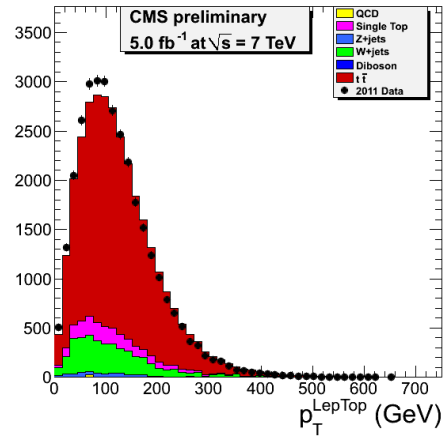
(c)



(d)



(e)



(f)

Figure 10.3: Control plots for the final event selection.

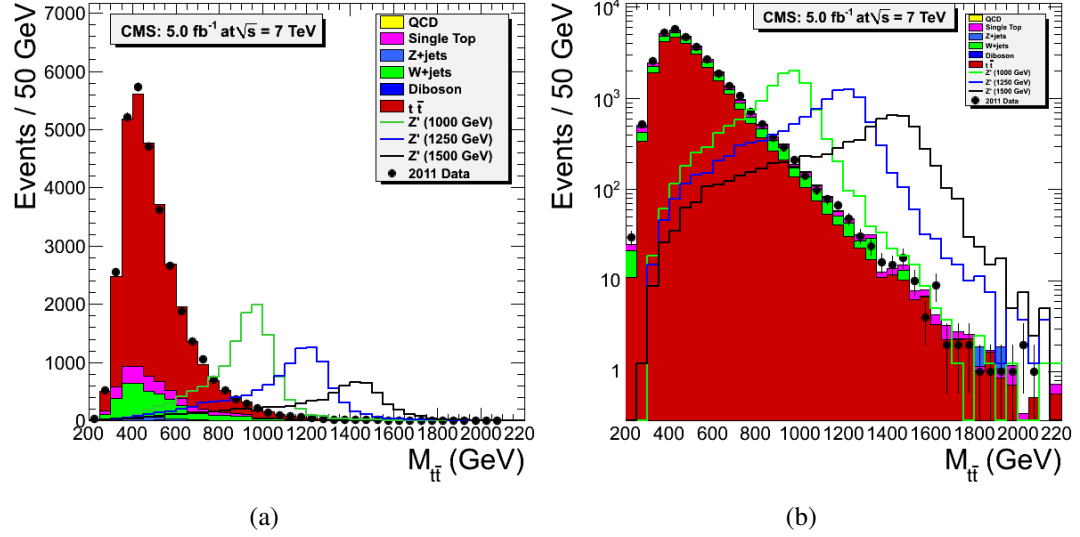


Figure 10.4: a.) $m_{t\bar{t}}$ spectrum for the final event selection. b.) Log plot of $m_{t\bar{t}}$. Three Z' samples with masses from 1000-1500 GeV are included for reference and are scaled to a cross-section of 50 pb each.

the predicted and observed yields. As a cross check we measure the SM $t\bar{t}$ cross section to be 147.84 pb which is well within NLO theoretical values of $157.5^{+23.2}_{-24.4}$.

Table 10.1: Event yields and uncertainties for each MC channel

Process	Events
$t\bar{t}$	26170 ± 162
$W/Z + \text{jets}$	4189 ± 65
Single Top	1986 ± 45
VV	4 ± 2
QCD Multijet	22 ± 5
Total Background	32371 ± 180
Observed Events	32056

Chapter 11

Systematic Error Analysis

The treatment of the systematic errors in this analysis is performed according to the prescription recommended by the CMS Top Quark Physics Analysis Group (TOP PAG) [4]. The errors are divided into rate and shape changing categories. The rate category affect the event rates and the shape errors affect both the shape and rate of the $t\bar{t}$ mass distribution. These are summarized in Table 11.1.

All uncertainties for the W and Z backgrounds are combined into a common (V +jets) systematic. This is done because the differences between the masses of the W and Z are small compared to the masses we are interested in, and it also allows us to deal better with the limited statistical precision of the simulated event samples. This introduces a negligible uncertainty into this analysis.

11.1 Rate-changing uncertainties

The muon efficiency uncertainty is the combination of the identification, isolation and trigger uncertainties. This was determined using tag-and-probe studies of di-muon pairs from Z -boson events. Fits were done to the resonance peak and then the uncertainty was determined by varying the fit function by reweighting the kinematics of the probe muon to match the signal simulation muons and recalculating the data/simulation scale factor. The difference between this and the original scale factor is taken as the systematic uncertainty. [30]. The lepton identification is modeled very well and this leads to only a 1% uncertainty [7].

Changing beam conditions (luminosity, number of vertices per event) over the duration of the 2011 data run leads to a difference in the number of vertices (and the number of pile-up jets) per event between the simulation and the data. In order to better model this a reweighting of the simulation has been done using in and out of time N_{vertex} distributions derived from the data. A comparison is made between the simulated N_{vertex} distribution to that of the data is used to create a weight for each event. The uncertainty in the correction is evaluated by varying the weights up and down by 8% from the nominal value.

Because we are working with a restricted part of phase-space, for the uncertainties on the cross sections we make conservative assumptions that are larger than the theoretical uncertainties on the inclusive cross-sections of each process. There is also a large uncertainty in the calculation of the QCD multijet background because of the difficulty in calculating all of the sub-processes. For this we assign a 100% uncertainty. This has little effect because the

residual contamination for this source is very small. This is also true for the VV contribution to which we assign a 30% uncertainty. The $t\bar{t}$ yield is fitted to the data and so a much smaller (but still rather conservative) 10% error is assigned. The V +jets and the single top yields are fitted to the data for the subset of each contained in the 1 b-tag channel. Because of the small contributions the uncertainties are much higher at 50% and 30% respectively. The higher V +jets uncertainty comes from the lack of knowledge about the cross sections of the $W+b\bar{b}$, $W+c\bar{c}$ and $W+c$ processes which are the dominant W background contributions.

11.2 Shape-changing uncertainties

The jet energy resolution is narrower in the simulation than in data, so the jet energy of the simulated jets must be smeared to compensate. This is done by smearing the jet energy based on the eta of the reconstructed jet and the difference in p_T between the generated and reconstructed jet. The jet energy resolution uncertainties are parametrized as a function of p_T and η and are provided by the CMS JetMET group [5]. The factors used for smearing the simulated jets and for determining the associated systematic error are shown in Table 11.2.

The jet energy scale uncertainty reflects the error in the jet energy correction factors applied to the data and the simulation. These are also provided by the JetMET group and are calculated for each jet based on the p_T and $|\eta|$ of the reconstructed jet. The uncertainty is derived from the sum of the contributions listed below:

- **Absolute:** The overall jet energy scale uncertainty.
- **High p_T extrapolation:** Uncertainty for high- p_T jets due to differences in fragmentation and underlying event in the simulation.
- **Single pion High p_T extrapolation** based on single particle response to particle flow jets.
- **Flavor** Different uncertainties for gluon, light flavor, charm and b-jets.
- **Jet energy correction time dependence** Due to an observed response instability in the encap region.
- **Relative jet energy resolution** Eta-dependant uncertainty of jet p_T resolution.
- **Relative final state radiation** Eta-dependant uncertainty due to a correction for FSR.
- **Relative statistical** Due to the statistical uncertainty in the determination of jet energy eta dependence.
- **Pile-up** Uncertainties due to pile-up corrections from data-simulations differences, out of time pile-up, differences in Zero-Bias and nominal QCD simulation, and observed jet rate variation in single-jet triggers in 2011 data.

The simulated jet p_T is then scaled up (or down) by the amount of uncertainty calculated from the sources above to determine the net systematic uncertainty.

There are two uncertainties due to the choice of parameters used in the generation of the

$t\bar{t}$ and V +jets events. The first is due to the choice of the Q^2 variable that is used to set the strong coupling constant α_s where α_s is related to Q^2 according to:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)(\log(Q^2/\Lambda^2))} \quad (11.1)$$

where Λ is the QCD scale. The second is the issue of overlapping simulations due to the use of both parton showering and matrix element calculations in event generation. The parton showering calculations are used to simulate softer, collinear jets and the matrix element calculations of fixed order. There is a small overlap in phase space between the two simulation methods and cuts must be implemented to avoid double counting of jets. Both of these parameters affect the jet multiplicities in events (and thus the overall topologies and kinematics) and their effects need to be determined in the final selection. To determine these uncertainties the Q^2 and monte carlo generator matching systematics are included via specially generated **MADGRAPH** samples with a generated variation of the parameters. The Q^2 and jet p_T nominal thresholds and variations used in matching matrix element to parton showering jets are shown in Table 11.3. These generated samples are also meant to cover initial and final state radiation variations. The main issue with using these samples is the limited statistics that have been generated for the W/Z +jets samples. This can be dealt with by reweighting the bins of the nominal samples to reshape the nominal $m_{t\bar{t}}$ distribution to match that of the systematic samples. This is done by taking the ratio of the systematic histogram to the nominal and fitting the distribution with a linear fit as a function of $m_{t\bar{t}}$ and then the nominal

histogram is reweighted according to the fit. The fits used are shown in Fig. 11.1.

The b -tag rate is different in the simulation and the data and a scale factor is used to correct for this and obtain the proper simulated b -tag multiplicity. The b jets tagged in the simulation are reclassified as either b , c or light flavor quarks based on the p_T and $|\eta|$ of the jet and the efficiencies for b , c and light flavor quarks. The scale factors for b , c and light flavor are linear functions of the Combined Secondary Vertex discriminant and the efficiencies (and their uncertainties) are cubic or quartic functions of the discriminant value. All of the uncertainties are propagated into the error analysis. The values used are taken from the studies of the b -tag working group in CMS [2]. The values are p_T and flavor dependant and are summarized below:

- b -jets ($p_T < 670$ GeV): 4%
- c -jets ($p_T < 670$ GeV): 8%
- lf -jets ($p_T < 670$ GeV): 10%
- b -jets ($p_T > 670$ GeV): 8%
- c -jets ($p_T > 670$ GeV): 16%
- lf -jets ($p_T > 670$ GeV): 20%

In addition to the standard systematic errors already discussed we also include a systematic associated with the choice of the BDT classifier cut. For this we take a variation of ± 0.05 around the nominal value of the classifier and evaluate the uncertainty accordingly.

The effects of these errors are implemented in the final limit setting either in the form of a gaussian nuisance parameter (in the case of rate-changing systematics) or in the form of "up" and "down" histograms that are compared to the nominal histograms in the limit calculation. The effects of the shape changing uncertainties can be seen in Fig. 11.2 where the nominal histograms (in red) are compared to the $+1\sigma$ ("up" histograms in blue) and -1σ ("down" histograms in green). The effects are small in all cases.

Table 11.1: Summary of systematic uncertainties.

Process	Uncertainty
Rate Changing	
Luminosity	2.2%
Muon Efficiency	1.0%
$t\bar{t}$ Rate	10%
V +jets Rate	50%
Single Top Rate	30%
VV Rate	30%
QCD Rate	100%
Shape Changing	
BDT Cut	± 0.05 on classifier cut
Jet Energy Scale	p_T, η dependant
Jet Energy Resolution	p_T, η dependant
Pile-Up Effects	8%
Q^2 Scale	$\pm$ generated differences
MC Matching	$\pm$ generated differences
b-tagging (b jets $p_T < 240$ GeV)	10%
b-tagging (b jets $p_T > 240$ GeV)	20%
b-tagging (c jets)	Twice the b jet rate

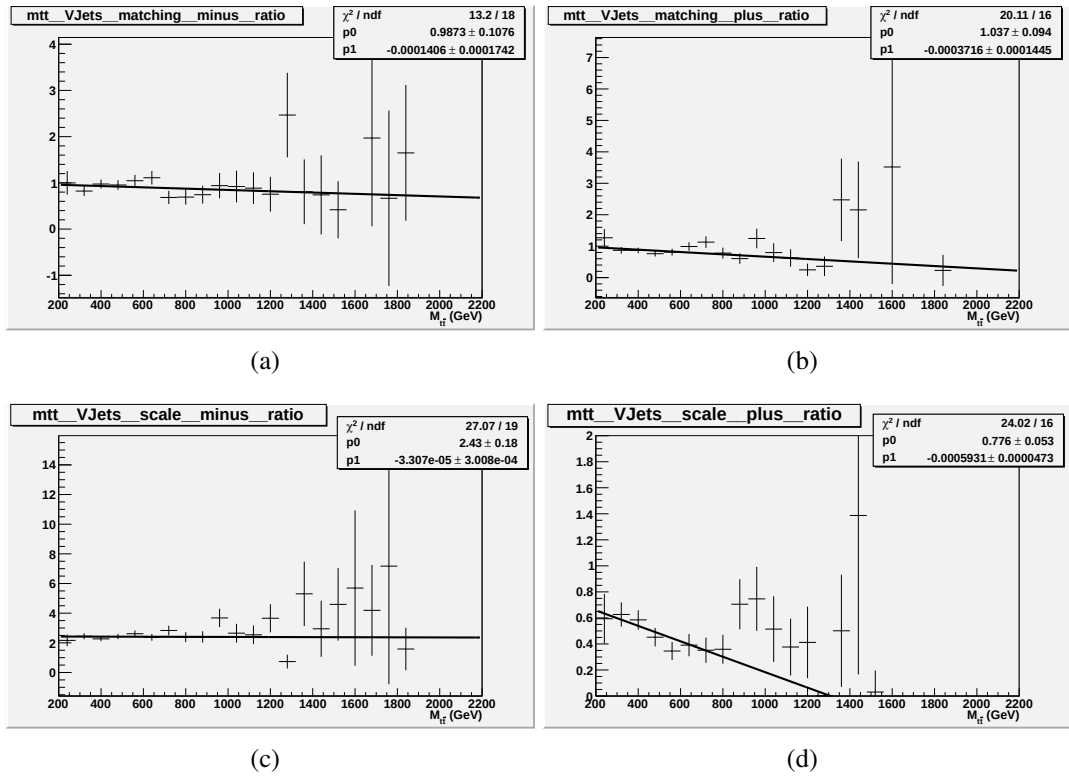


Figure 11.1: Ratios of systematic V +jets samples with respect to the nominal samples: a.) Matching Down, b.) Matching Up, c.) Scale Down, d.) Scale Up.

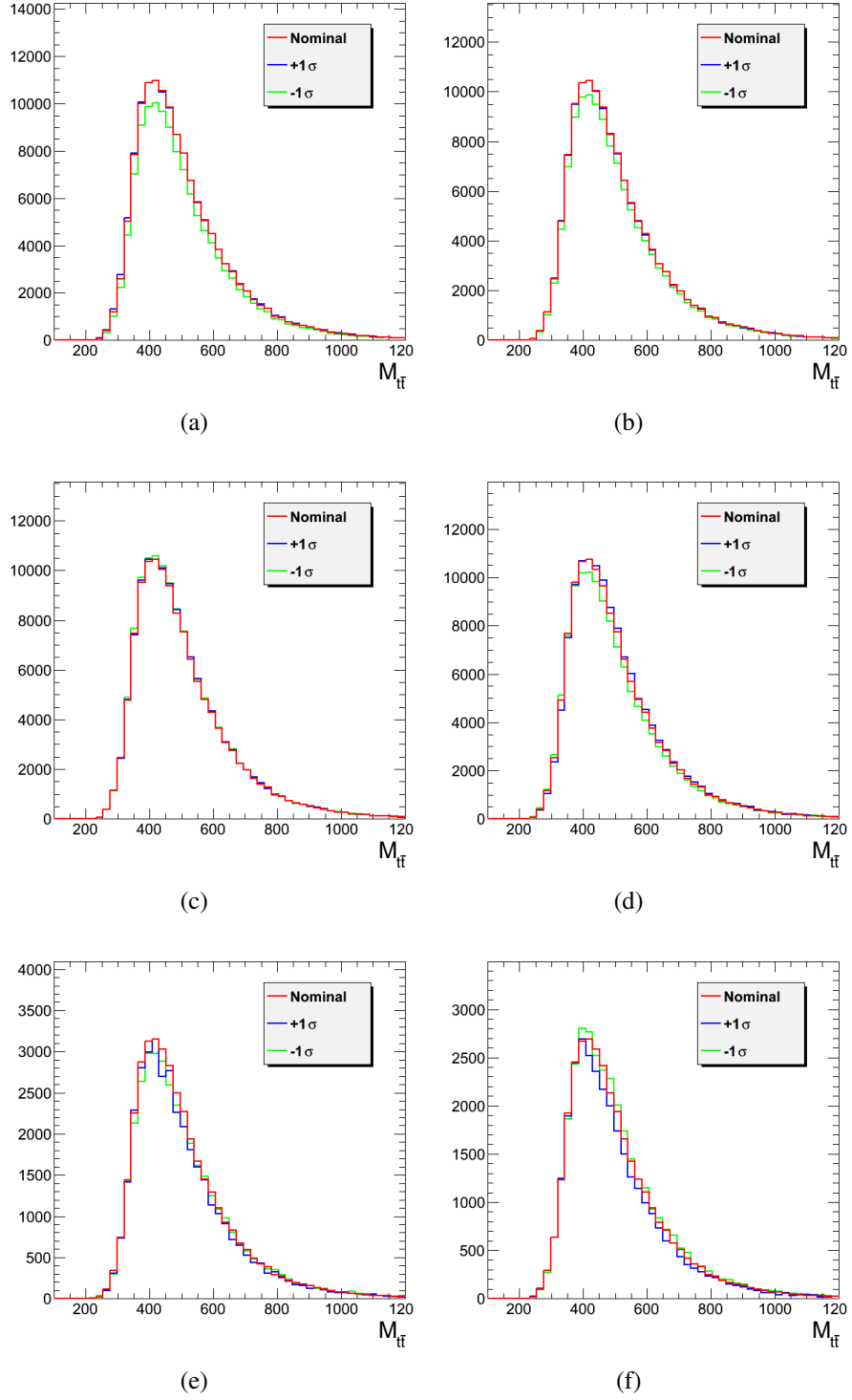


Figure 11.2: Effects on $M_{t\bar{t}}$ in simulated $t\bar{t}$ events due to systematic shifts in a.) BDT classifier cut, b.) b-tagging, c.) jet energy resolution, d.) jet energy scale, e.) monte carlo generator matching, f.) Q^2 -scale.

Table 11.2: Jet energy resolution scale factors and errors.

Eta Range	Scale Factor	σ_{JER}
0.0 – 0.5	1.052	+0.062/-0.061
0.5 – 1.1	1.057	+0.056/-0.055
1.1 – 1.7	1.096	+0.063/-0.062
1.7 – 2.3	1.134	+0.087/-0.085
2.3 – 5.0	1.288	+0.155/-0.153

Table 11.3: Q^2 and factorization/renormalization nominal values and variations.

Parameter	Nominal	Scale Up	Scale Down
$t\bar{t}$			
Q^2	$Q^2 = M_t^2 + \Sigma(p_T^{jet})^2$	$4Q^2$	$0.25Q^2$
Matching	20 GeV	10 GeV	40 GeV
$V + \text{jets}$			
Q^2	$Q^2 = M_t^2 + \Sigma(p_T^{jet})^2$	$4Q^2$	$0.25Q^2$
Matching	10 GeV	5 GeV	20 GeV

Chapter 12

Limits on a Narrow Width Z'

12.0.1 Statistical Implementation

The `Theta` software package [59] is used to set the upper limits on the Z' production cross-section. In `Theta` the signal and backgrounds are modelled using a binned probability density function (Pdf) which is built up from the sum of the Pdfs of the individual processes.

This can be expressed as:

$$Pdf^{S+B}(m_{t\bar{t}}, \sigma^r, \sigma^s) = N^{signal}(\sigma^r, \sigma^s) \cdot Pdf^S(m_{t\bar{t}}, \sigma^s) \quad (12.1)$$

$$+ \sum_i N_i^{background}(\sigma^r, \sigma^s) \cdot Pdf_i^B(m_{t\bar{t}}, \sigma^s) \quad (12.2)$$

where σ^r and σ^s are the rate and shape changing uncertainties respectively. The expected event yield for the signal (N^{signal}) is given by:

$$N^{signal} = \mu \cdot N_{nominal}^{signal} \cdot \prod_j s_j(\sigma_{signal}^r) \cdot \prod_k s_k(\sigma_{signal}^s) \quad (12.3)$$

where μ is the signal strength modifier which is the parameter of interest when the limits are calculated. The background ($N^{background}$) is modelled similarly as the sum of the Pdfs of the individual processes:

$$N_i^{background} = N_{i,nominal}^{background} \cdot \prod_j s_j(\sigma_i^r) \cdot \prod_k s_k(\sigma_i^s) \quad (12.4)$$

While the rate changing uncertainties only modify the expected event yields, the shape changing uncertainties modify the Pdf. This is implemented by adding the terms $\Delta Pdf_i(m_{t\bar{t}}, \sigma_{i,j}^s)$:

$$Pdf_i(m_{t\bar{t}}, \sigma^s) = Pdf_i^{nominal}(m_{t\bar{t}}) + \sum_j (\Delta Pdf_i(m_{t\bar{t}}, \sigma_{i,j}^s)) \quad (12.5)$$

Here the subscript i is for the process affected by the uncertainty and the subscript j runs over all of the contributing uncertainties. For the limit calculations we will use both the CLs and Bayesian methods. Both the CLs and Bayesian limit calculations model the systematic uncertainties as bayesian priors $\rho(\theta|\tilde{\theta})$. The treatment of the errors is as follows:

- **Unconstrained nuisance parameters** are modeled with flat priors

- **General nuisance parameters** that can take on positive and negative values are modeled with by Gaussian distributions.
- **Positive-only systematic errors** on observables are modeled as log-normal distributions.

In order to implement the shift in the Pdf from shape-changing systematic uncertainties `Theta` uses a template morphing algorithm to interpolate between nominal histograms and histograms that vary the uncertainty by $\pm 1\sigma$. This is done for each bin in the histogram as a function of the uncertainty and the value of the bin:

$$f(\sigma_s) = h_{nom} - 0.5(h_{up} + h_{down} - 2h_{nom})\sigma_s^3 \quad (12.6)$$

$$+ (h_{up} + h_{down} - 2h_{nom})\sigma_s^2 + 0.5(h_{up} - h_{down})\sigma_s \quad (12.7)$$

for $\sigma_s > 0$ and

$$f(\sigma_s) = h_{nom} + 0.5(h_{up} + h_{down} - 2h_{nom})\sigma_s^3 \quad (12.8)$$

$$+ (h_{up} + h_{down} - 2h_{nom})\sigma_s^2 + 0.5(h_{up} - h_{down})\sigma_s \quad (12.9)$$

for $\sigma_s < 0$ where $|\sigma_s| < 1$ for both cases. The interpolation function is linear for $|\sigma_s| > 1$.

For the limit setting using the CLs method, we use a modified CLs technique (modified in the sense that the systematics are treated as bayesian priors) that uses a test statistic similar to the LHC Higgs Boson Combination paper [31]. The main difference from the standard

CLs calculation is that the signal strength parameter in the numerator of the likelihood ratio is set to zero ($\mu = 0$) which eliminates the one-sidedness of the CLs limits. The test statistic then becomes:

$$q_\mu = \frac{L(data|0, \hat{\theta}_\mu)}{L(data|\hat{\mu}, \hat{\theta})}, \text{ where } 0 \leq \hat{\mu} \leq \mu \quad (12.10)$$

The numerator is maximized for a signal strength of 0 while the denominator is maximized globally for all values of $\hat{\mu}$ and $\hat{\theta}$. The CLs value is then computed as:

$$CLs = 0.05 = \frac{p_\mu}{p_0} = \frac{P\left(q_\mu \geq q_\mu^{obs} | \mu \cdot S(\hat{\theta}_\mu) + B(\hat{\theta}_\mu)\right)}{P\left(q_\mu \geq q_\mu^{obs} | B(\hat{\theta}_\mu)\right)} \quad (12.11)$$

where p_μ is the probability of observing a test statistic value at least as large as observed given the signal-plus-background hypothesis and p_b is similarly defined for the background only hypothesis ($\mu = 0$).

As a cross-check of the results we also use `Theta` to calculate Bayesian limits using a Markov Chain Monte Carlo [58] algorithm to perform a numerical integration. The treatment of systematics and the Pdf are the same as before and MCMC is used to find μ numerically from the integral:

$$0.95 = \int_0^\mu p(\mu|data) d\mu \quad (12.12)$$

where $p(\mu|data)$ is the bayesian posterior found from:

$$p(\mu|data) = \frac{1}{C} \int p(data|\mu \cdot S(\theta) + B(\theta)) \rho_\theta(\theta) \pi_\mu(\mu) d\theta \quad (12.13)$$

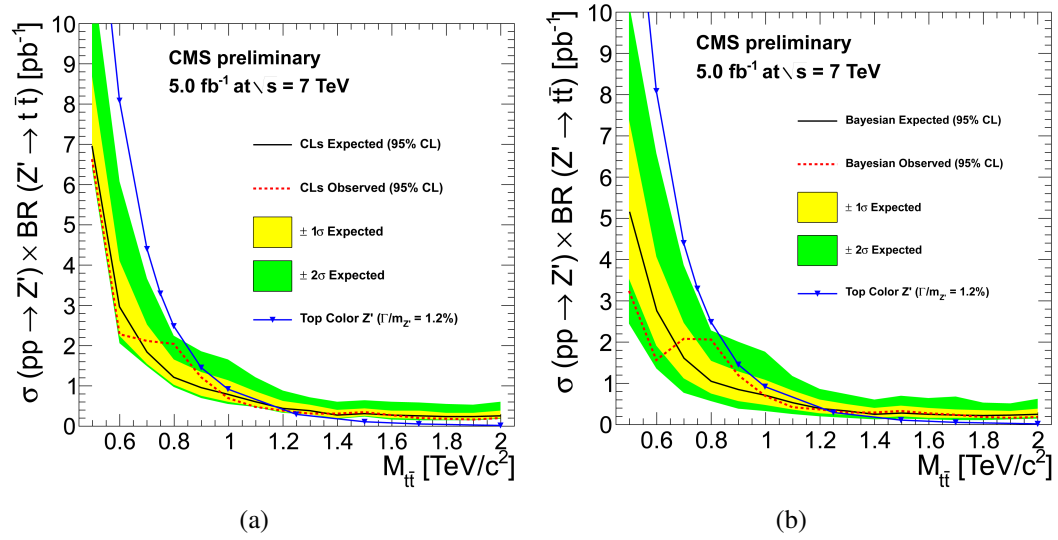


Figure 12.1: a.) 95% CLs upper limits on the Z' cross-section. b.) 95% Bayesian limits on the Z' cross-section.

where $\rho_\theta(\theta)$ are the priors for the systematic errors and $\pi_\mu(\mu)$ is the prior for the signal strength which is taken to be a flat prior for positive values of μ and 0 otherwise.

12.0.2 Results

Table 12.1: 95% CLs upper limits on the Z' cross-section for selected mass points compared to expectations from a model for a Topcolor Leptophobic Z'

Z' Mass (GeV)	Expected (pb)	Observed (pb)	Leptophobic Z' (pb)
500	6.95	6.63	14.61
600	2.95	2.28	8.07
700	1.83	2.10	4.39
800	1.21	2.03	2.47
900	0.943	1.20	1.44
1000	0.782	0.686	0.905
1500	0.316	0.336	0.0987
2000	0.254	0.189	0.0141

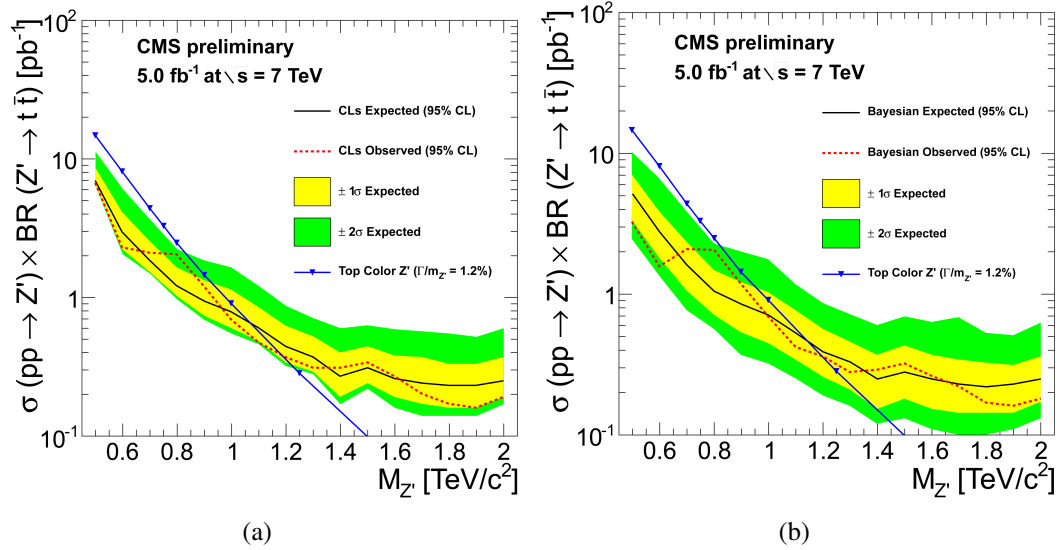


Figure 12.2: Log plots of a.) 95% CLs upper limits on the Z' cross-section. b.) 95% Bayesian limits on the Z' cross-section.

The results from the two limit calculations are shown in Figs. 12.1 and 12.2 on linear and logarithmic scales, respectively. The CLs and Bayesian results agree quite well in both shape and the scale of the limits on the Z' cross-section and the observed limits never differ from the expected by more than 1σ except for the area around 800 GeV where there is around a 1.5σ excess in the data.

The results are comparable to other analyses performed by the CMS collaboration. Fig. 12.3 shows limits from this analysis compared to limits from the other $Z' \rightarrow t\bar{t}$ analyses [11, 12, 34, 18] and our limits are comparable in scale to the other studies performed using the 2011 dataset.

Finally the calculated limits are compared to the predicted cross-section of a Leptophobic Topcolor Z' [48] in Table 12.1. By comparing the limits and the model predictions, we

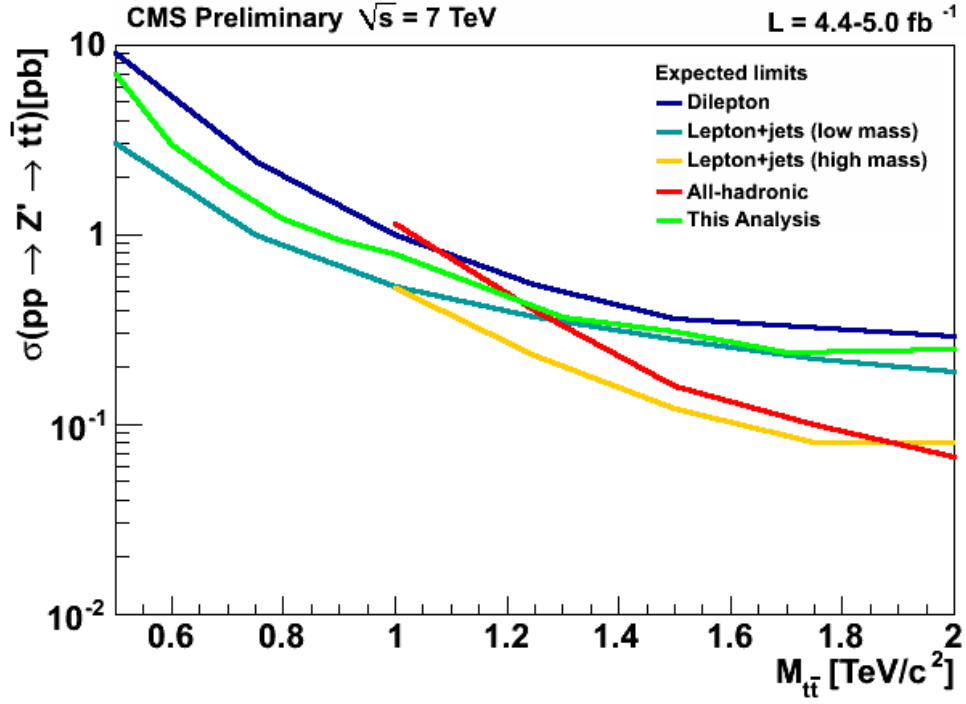


Figure 12.3: Comparison of all the CMS $Z' \rightarrow t\bar{t}$ analyses.

can exclude the production of a Leptophobic Z' at 95% CL for masses below 1050 GeV (Expected) and 1100 GeV (observed). These are significantly higher limits than those from previous experiments at the Fermilab Tevatron [64, 14, 21].

Chapter 13

Conclusion

We have analyzed $5.0fb^{-1}$ of 2011 LHC collisions at $\sqrt{s} = 7$ TeV and have studied the $m_{t\bar{t}}$ spectrum up to masses of 2 TeV. We find the data to be in good agreement with Standard Model predictions. We use this agreement to set upper limits on the predicted cross-sections for a new Z' gauge boson in the case where the decay width of the Z' is 1% of its mass. Both Bayesian and modified CLs limits are used and the results are in good agreement. The calculations give limits which vary from ~ 5 pb at the lowest masses (500 GeV) to less than 1 pb for masses above 1 TeV. If we compare the results to the expectation for a Leptophobic Z' , as was proposed from observations of the Tevatron data, the data from the LHC excludes such a particle up to masses of 1.1 TeV.

Bibliography

- [1] ROOT User's Guide.
- [2] Btag POG Twiki Page.
- [3] Top Quark Lepton + Jets Twiki Page.
- [4] Top Reference Systematic Twiki Page.
- [5] JetMET TTwiki Page.
- [6] Standard Model Cross Sections for CMS at 7 TeV.
- [7] Top Quark Lepton ID and Isolation Twiki Page.
- [8] V+Jets Cross PAG twiki page.
- [9] The linac2 web page, cern. <http://linac2.home.cern.ch/>.
- [10] The ps complex as proton pre-injector for the lhc - design and implementation report. *CERN 2000-03*, CERN, 2000.
- [11] A search for resonances in semileptonic top pair production. 2012.
- [12] Search for z' bosons decaying to top-antitop pairs in dilepton+jets final state in pp collisions at $\sqrt{s} = 7$ tev. 2012.
- [13] S. Abachi et al. Search for high mass top quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ tev. *Phys. Rev. Lett.*, 74(13):2422–2426, Mar 1995.
- [14] Victor Mukhamedovich Abazov et al. Search for a heavy neutral gauge boson in the dielectron channel with 5.4 fb⁻¹ of ppbar collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Lett.*, B695:88–94, 2011.
- [15] G. Abbiendi et al. Tests of the standard model and constraints on new physics from measurements of fermion pair production at 183-GeV at LEP. *Eur. Phys. J.*, C6:1–18, 1999.
- [16] F. Abe et al. Observation of top quark production in $p\bar{p}$ collisions with the collider detector at fermilab. *Phys. Rev. Lett.*, 74(14):2626–2631, Apr 1995.

- [17] W. Adam et al. Pat: the cms physics analysis toolkit. *CMS Conference Report*, CR-2009/083, 2009.
- [18] Mark Adams et al. Search for high-mass resonances decaying to tt in the lepton+jets channel. *CMS Analysis Note*, CMS AN-2012/120, 2012.
- [19] I J R Aitchison and A J G Hey. *Gauge Theories in Particle Physics*. Adam Hilger Limited, 1982.
- [20] Simone Alioli, Paolo Nason, Carlo Oleari, and Emanuele Re. A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *JHEP*, 1006:043, 2010.
- [21] T. Alltonen et al. *Phys. Rev. D*, 79, 2009.
- [22] Thomas Appelquist, Hsin-Chia Cheng, and Bogdan A. Dobrescu. Bounds on universal extra dimensions. *Phys. Rev. D*, 64(3):035002, Jun 2001.
- [23] A. Aydemir, H. Arslan, and A. Topaksu. The estimation of the z' gauge boson mass in e_6 models. *Physics of Particles and Nuclei Letters*, 6:304–308, 2009. 10.1134/S1547477109040049.
- [24] R. Barate et al. Study of fermion pair production in e^+e^- collisions at 130-GeV to 183-GeV. *Eur. Phys. J.*, C12:183–207, 2000.
- [25] J. P. Blewett. 200 gev intersecting storage accelerators. *Proceedings of the 8th International Conference on High-Energy Accelerators*, CERN, 1971.
- [26] Daniel Boussard and Trevor Paul R Linnecar. The lhc superconducting rf system. Technical Report LHC-Project-Report-316. CERN-LHC-Project-Report-316, CERN, Geneva, Dec 1999.
- [27] L. Breiman, J.H. Friedman, R.A. Olshen, and C.J. Stone. *Classification and Regression Trees*. Wadsworth International, Canada, 1984.
- [28] Marcela S. Carena, Alejandro Daleo, Bogdan A. Dobrescu, and Timothy M. P. Tait. Z' gauge bosons at the Tevatron. *Phys. Rev.*, D70:093009, 2004.
- [29] G.-C. Cho. Looking for Z' Bosons in Supersymmetric E_6 Models through Electroweak Precision Data. *Modern Physics Letters A*, 15:311–331, 2000.
- [30] CMS Collaboration. Performance of cms muon reconstruction in cosmic-ray events. *Journal of Instrumentation*, 5(03):T03022, 2010.
- [31] CMS Collaboration. Search for standard model higgs boson in pp collisions at $\sqrt{s} = 7$ tev. *CMS Physics Analysis Summary*, CMS PAS HIG-11-011, 2011.
- [32] The CMS Collaboration and S Chatrchyan et al. The cms experiment at the cern lhc. *Journal of Instrumentation*, 3(08):S08004, 2008.

- [33] P. Collier. The sps as injector for the lhc. *CERN-SL-97-07-DI*, CERN, 1997.
- [34] John Conway et al. Search for bsm ttbar production in the boosted all-hadronic final state. *CMS Analysis Note*, CMS AN-2011/194, 2011.
- [35] G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Phys. Rev. Lett.*, 9(1):36–44, Jul 1962.
- [36] Alex G. Dias, C. A. de S. Pires, and P. S. Rodrigues da Silva. Bounds on the Simplest Little Higgs Model Mass Spectrum Through Z Leptonic Decay. *Phys. Rev.*, D77:055001, 2008.
- [37] Jens Erler and Paul Langacker. Indications for an extra neutral gauge boson in electroweak precision data. *Phys. Rev. Lett.*, 84:212–215, 2000.
- [38] Floriana Esposito, Donato Malerba, and Giovanni Semeraro. A comparative analysis of methods for pruning decision trees. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 19:476–491, 1997.
- [39] B. Goddard et al. Aperature and delivery precision of the lhc injection system. *EPAC '04, Lucerne, Switzerland*, 2004.
- [40] E. Ciapala et al. Commissioning of the 400 mhz lhc rf system. *Proceedings of EPAC08, Genoa, Italy*, pages 847–849, 2008.
- [41] F. Blas et al. Conversion of the ps complex as lhc proton pre-injector. (CERN-PS-97-048-DI):3 p, Jun 1997.
- [42] Lyndon Evans and Philip Bryant (editors). Lhc machine. *Journal of Instrumentation*, 3(08):S08001, 2008.
- [43] Yoav Freund and Robert E. Schapire. Experiments with a new boosting algorithm, 1996.
- [44] Mary K. Gaillard, Paul D. Grannis, and Frank J. Sciulli. The standard model of particle physics. *Rev. Mod. Phys.*, 71(2):S96, Mar 1999.
- [45] J.D. Griffiths. *Introduction to Elementary Particle Physics*. Wiley VCH, 08 2008.
- [46] The Particle Flow Physics Object Group. Particle flow reconstruction of jets, taus, and met. *CMS Note*, 2009/039, 2009.
- [47] A. V. Gulov and V. V. Skalozub. Model-independent search for the Abelian Z' boson and the LEP data. 2001.
- [48] Robert M. Harris and Supriya Jain. Cross Sections for Leptophobic Topcolor Z' decaying to top-antitop. 2011.

- [49] Christopher T. Hill. Topcolor assisted technicolor. *Physics Letters B*, 345(4):483 – 489, 1995.
- [50] A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, H. Voss, M. Backes, T. Carli, O. Cohen, A. Christov, D. Dannheim, K. Danielowski, S. Henrot-Versille, M. Jachowski, K. Kraszewski, A. Krasznahorkay Jr, M. Kruk, Y. Mahalalel, R. Ospanov, X. Prudent, A. Robert, D. Schouten, F. Tegenfeldt, A. Voigt, K. Voss, M. Wolter, and A. Zemla. Tmva - toolkit for multivariate data analysis. *POSACAT*, 040, 2007.
- [51] F. James and M. Roos. Minuit: A System for Function Minimization and Analysis of the Parameter Errors and Correlations. *Comput. Phys. Commun.*, 10:343–367, 1975.
- [52] Teruyuki Kitabayashi and Masaki Yasu. Large solar neutrino mixing and radiative neutrino mechanism. *Physics Letters B*, 524(3-4):308 – 318, 2002.
- [53] S. Krutelyov. Status of Muon Isolation. *Particle Flow Integration Meeting*, 2009.
- [54] A. Leike. The phenomenology of extra neutral gauge bosons. *Phys.Rept.317*, pages 143–250, 1999.
- [55] Guo-Li Liu. Probing topcolor-assisted technicolor from lepton flavor violating processes in photon-photon collision at ILC. 2010.
- [56] Kevin R. Lynch, Elizabeth H. Simmons, Meenakshi Narain, and Stephen Mrenna. Finding Z' bosons coupled preferentially to the third family at LEP and the Tevatron. *Phys. Rev.*, D63:035006, 2001.
- [57] Fabio Maltoni and Tim Stelzer. Madevent: Automatic event generation with madgraph. *JHEP*, 02:027, 2003.
- [58] Nicholas Metropolis, Arianna W. Rosenbluth, Marshall N. Rosenbluth, Augusta H. Teller, and Edward Teller. Equation of state calculations by fast computing machines. *The Journal of Chemical Physics*, 21(6):1087–1092, 1953.
- [59] T Muller, J Ott, and J Wagner-Kuhr. **theta** - a framework for template-based modeling and inference. *CMS Internal Note*, CMS IN-2010, 2010.
- [60] A. A. Pankov. Model-independent analysis of four-fermion contact interaction at e+ e- collider. 2004.
- [61] K. H. Reich. The cern proton synchrotron booster. *Nuclear Science, IEEE Transactions on*, 16(3):959–961, June 1969.
- [62] Byron P. Roe, Hai-Jun Yang, Ji Zhu, Yong Liu, Ion Stancu, and Gordon McGregor. Boosted decision trees as an alternative to artificial neural networks for particle identification. *NUCL.INSTRUM.METH.A*, 543:577, 2005.

- [63] V. A. Rubakov. Large and infinite extra dimensions. *PHYS-USP* 44 (9), page 871893, 2001.
- [64] A. Safonov. Searches for New Neutral Gauge Bosons and Leptoquarks at the Tevatron. 2010.
- [65] Robert E. Schapire. Msri workshop on nonlinear estimation and classification, 2002. the boosting approach to machine learning an overview. 2007.
- [66] K. Shindl. The injector chain for the lhc. *Chamonix IX, CERN*, 1997.
- [67] D. J. Simon. The cern ps: A versatile particle factory. *EPAC96, CERN*, 1996.
- [68] Torbjrn Sjstrand, Patrik Edn, Christer Friberg, Leif Lnnblad, Gabriela Miu, Stephen Mrenna, and Emanuel Norrbin. High-energy-physics event generation with 6.1. *Computer Physics Communications*, 135(2):238 – 259, 2001.
- [69] Christian Weiser. A combined secondary vertex based b-tagging algorithm in cms. Technical Report CMS-NOTE-2006-014, CERN, Geneva, Jan 2006.
- [70] H. Yukawa. On the interaction of elementary particles. *Proc. Phys. Math. Soc. Jap.*, 17:48, 1935.