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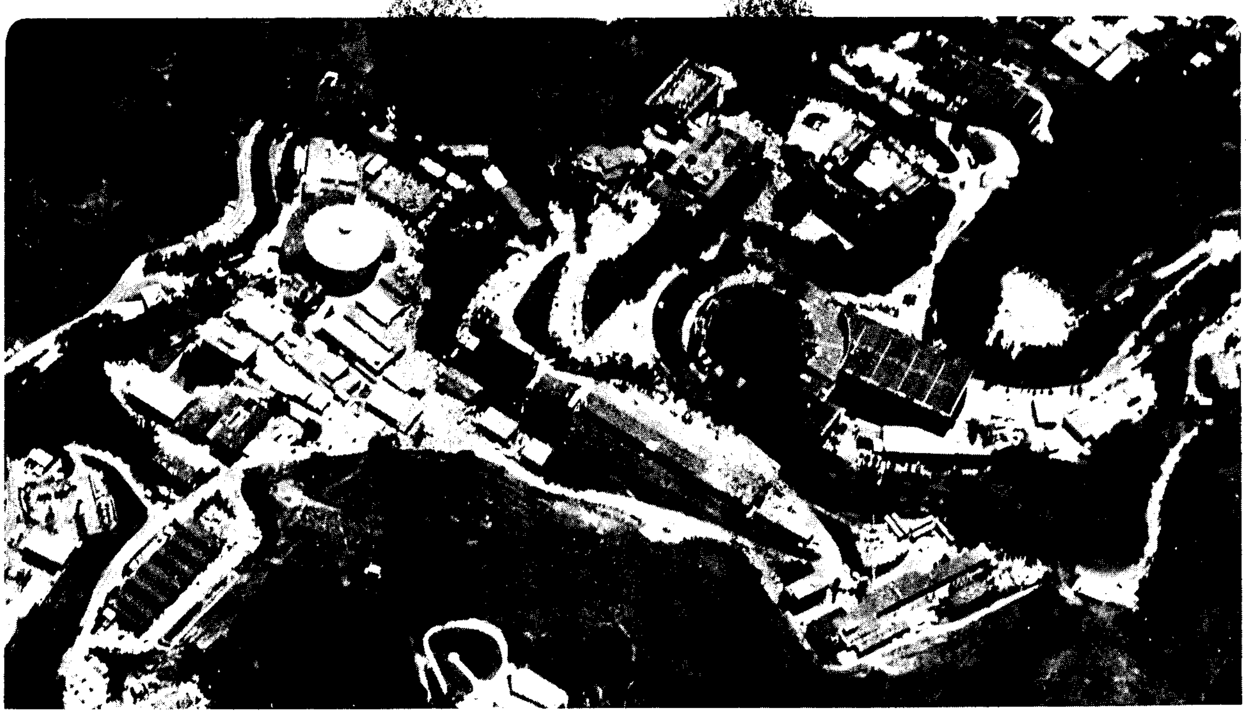

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LIMITS FOR SUPERSYMMETRY FROM A COMPREHENSIVE STUDY OF CERN MISSING-ENERGY EVENTS

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Invited talk presented at the XXth Rencontre de Moriond, "New Trends in Electroweak Interactions," Les Arcs, Savoie, France, March 17–23, 1985.

ABSTRACT

We have performed a comprehensive analysis of supersymmetric processes which can lead to missing-energy events such as those observed by the UA1 collaboration. Several critical aspects of the theoretical analysis are discussed here including fragmentation, backgrounds, and evolution of gluinos. When the experimentalists publish their final data, excellent limits will be set for $M_{\tilde{g}}$ and $M_{\tilde{q}}$, and it is possible that certain mass regions will not be excluded as explanations of the data. This work was in collaboration with H. Haber and G. Kane.

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Any product should have a warning label for the user (reader). Here the warnings should include the limitations of perturbative QCD; K-factors, fragmentation, initial-state radiation, etc. are at best partially understood. Second, a theorist analyzing the data can only model the cuts, triggers, and jet selection criteria. Third, the current data of interest here are very limited statistically and have had only a preliminary analysis by the experimentalists and include backgrounds.

The data are from the UA1 collaboration.[1] Integrated luminosities of approximately 100 and 300 nb^{-1} were collected in 1983 and 1984 at $\sqrt{s} = 540$ and 630 GeV respectively. Among the phenomena observed were a number of events which can be loosely described a having large missing transverse energy, a hadronic jet with $E_T^{jet} \gtrsim 25$ GeV and sometimes other jets with $E_T^{jet} \geqslant 12$ GeV. If all secondary jets have less than 12 GeV, then the event has been labeled as a "Monojet", while events with one secondary jet greater than 12 GeV are called "Dijets". Clearly this distinction (though necessary) is a subtle one.

These data can have important consequences[2] for supersymmetric extensions of the Standard Model of the fundamental interactions. Since Jean-Marie Frère has given at this conference a very good introduction to the motivations for and nature of supersymmetry, I will not review those topics. The work reported here was done by H. Haber, G. Kane, and myself, and can be summarized by:

1) The matrix elements of *all* supersymmetric processes which contribute to missing-energy events were calculated; these include the decay of the final-state squarks and gluinos.
2) Since some processes require knowledge of the gluino structure function, we wrote a computer program to perform the QCD evolution of this function.
3) An efficient Monte Carlo program was written for each process to calculate rates and distributions for monojets, dijets, and multijets. Several checks were built-in to assure accuracy.
4) UA1 cuts, triggers, and jet selection criteria were modeled as accurately as possible in this program.
5) Fragmentation and gluon bremsstrahlung were incorporated inherently in the program.
6) Initial-state p_T distribution was included when appropriate.
7) Experimental resolution is incorporated in new versions of our program but not in the results reported here.
8) Most values of $M_{\tilde{g}}$ and $M_{\tilde{q}}$ were studied for all processes.
9) All relevant data will be analyzed.
10) Many backgrounds giving missing-energy events have been calculated (rates and distributions).
11) Our results are given independent of supergravity models and cosmology.

The minimal extension of the Standard Model (SU(3)×SU(2)×U(1)) is used. Supersymmetry breaking is parameterized by arbitrary soft-supersymmetry-breaking terms. Predictions can then be made as a function of the masses of squarks and gluinos. Squark masses are taken as degenerate and the photino is assumed to be the lightest supersymmetric particle ($m_{\tilde{\gamma}} = 0$ here).

We calculate the production of $\tilde{q}\bar{\tilde{q}}$, $\tilde{q}\bar{\tilde{q}}$ via W production, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{\gamma}$, $\tilde{g}\tilde{g}$, and $\tilde{g}\tilde{\gamma}$. Each of these typically involves the calculation of several diagrams.

An essential ingredient of our analysis is the inclusion of processes in which one of the *initial* partons is a gluino.[3] This is important because for $M_{\tilde{g}} < 25$ GeV the gluino structure is quite large. The large magnitude occurs because $\tilde{g}(x,Q^2) = 6q(x,Q^2)$ where q refers to a heavy quark of the same mass as the gluino. The dominant process with an initial-state gluino is $\tilde{g} + q \rightarrow \tilde{q}$ where one needs a heavy squark (>60 GeV) to pass the cuts.

The matrix elements we calculate also involve the decays of the squarks and gluinos. The nature of these decays depends on the *relative* masses of the two particles. We additionally sometimes consider decays with smaller branching ratios when the resulting processes is more likely to pass the experimental cuts. In total, we have therefore, calculated 16 independent processes each requiring a separate program because of differing kinematics.

There are a number of subtleties in handling cuts and triggers. I will mention one example here. The missing transverse energy, E_T^{miss}, is required to obey $E_T^{miss} > 4\sigma$ where $\sigma = 0.7\sqrt{E_T}$ to eliminate events which result from non-uniform calorimetry and other mismeasurements. E_T is the scalar sum of all transverse energy whether or not it is in a jet. This quantity is not calculated by theorists. We have therefore used the equivalent distribution for minimum-bias events scaled up to energies appropriate for events with jets and then added the energies of outgoing partons. A comparison of our distribution to the preliminary data is shown in Fig. 1. Our distribution is certainly plausible. A more detailed discussion of this and other cuts and triggers will appear in a long paper in preparation.[4]

We impose cuts of either $E_T^{miss} > 32$ GeV or $E_T^{miss} > 40$ GeV to minimize mismeasurement effects and backgrounds and to reduce dependence on the details of cuts and triggers. We also check the region $E_T^{miss} < 32$ GeV for certain processes where needed.

Gluinos (and squarks) cannot emerge as free particles; they must first hadronize. From study of quarks we know[5] that E(D meson) < E(c quark) and E(B meson) < E(b quark). Similarly if we define G as the resulting hadron containing the gluino, then $E(G) < E(\tilde{g})$. This implies that the photino (the source of missing-energy) from G decay has less energy than we would have calculated from the decay of the bare gluino. This means that fewer events pass the E_T^{miss} cut.

Let us define $z \equiv p_{out}/p_{in}$. There are three sources of photino energy loss. There is gluon bremsstrahlung from the gluino (large compared to that from quarks because the coupling is $\frac{9}{4}$ larger). We use the parameterization[6] $D_b = A(1-z_1)^{A-1}$ with $A = \frac{36}{25}\ell n[\ell n\,\hat{s}/\Lambda^2 / \ell n\,4m^2/\Lambda^2]$. The fragmentation of heavy particles into hadrons has been parameterized[7] by $D_h = \dfrac{c(1-z_2)^2}{[(1-z_2)^2 + (\frac{0.6}{m})^2 z_2]^2}$. And finally, though we neglect it, the photino spectrum from the decay of G is slightly softer[8] than that from a free gluino.

We convolute the D_b and D_h and place the result directly into our Monte Carlo program. We find that fragmentation effects are very important for gluinos as heavy as 20 GeV (a factor of 2 when using the $E_T^{miss} > 32$ GeV cut).

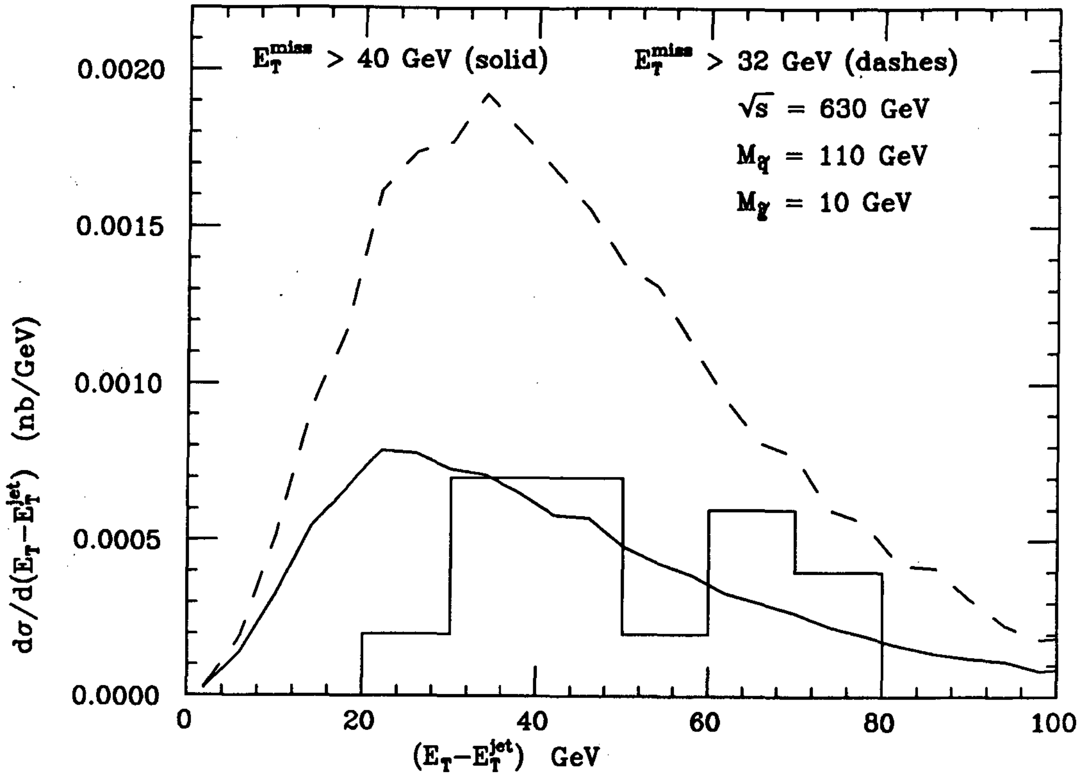

Fig. 1 - The distribution of the total scalar E_T minus E_T^{jet} (leading) in $p\bar{p}$ scattering from missing-energy events passing the UA1 cuts and $E_T^{miss} > 32$ GeV (dashed) and $E_T^{miss} > 40$ GeV (solid). The curves show the sums of contributions from all supersymmetric processes when $M_{\tilde{q}} = 110$ GeV and $M_{\tilde{g}} = 10$ GeV. The data (Ref. 1) shown as a histogram are for $E_T^{miss} > 40$ GeV only, are preliminary, and have not had background events removed.

I believe it is best to study the missing-energy events by *combining* the data for monojets, dijets, and multijets. These events all have large total E_T and most have secondary jets of 6–15 GeV. Since nonperturbative QCD corrections, spectator activity, fragmentation effects, experimental resolution, etc. can add or subtract from a given secondary jet, the defined boundary at 12 GeV becomes very fuzzy. Clearly it is preferable to use all the data, increase the statistical significance and decrease sensitivity to theoretical and experimental limitations. However, the dijet-monojet ratio does contain important information which with careful study may yield further results concerning supersymmetry. Based on the observed jets accompanying W bosons, we expect that single squark production will have accompanying 12 GeV jets from gluon emission in roughly 35% of the events.

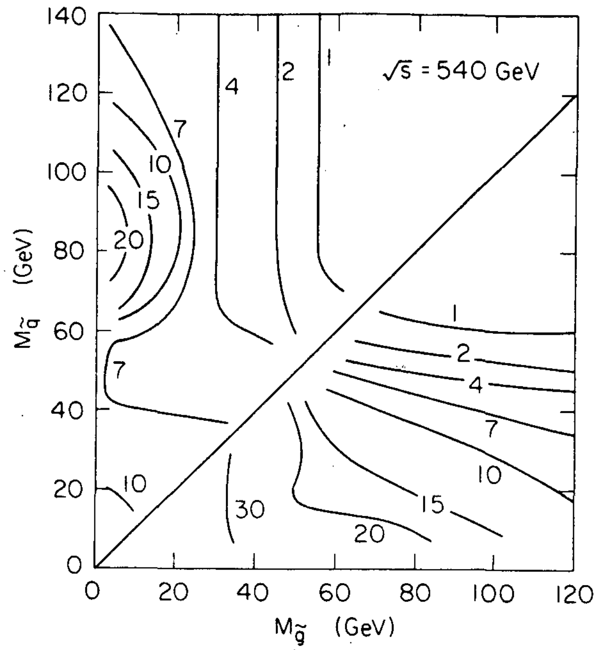

Fig. 2 - The number of monojet events at $\sqrt{s}$ = 540 GeV per 100 nb^{-1} passing the UA1 cuts plus the $E_T^{miss} > 32$ GeV cut are shown as a contour plot as a function of $M_{\tilde{g}}$ and $M_{\tilde{q}}$. This number is the total from all supersymmetric sources. Fragmentation effects are not included.

We have not quite finished updating our rate calculations for the 1984 data at $\sqrt{s}$ = 630 GeV by summing all missing-energy events (not just monojets), by installing the 1984 cuts and triggers and by including fragmentation effects and resolution effects. These have only been done so far for selected mass values. Fig. 2 shows our old figure for monojet rate per 100 nb^{-1} as a simultaneous function of gluino and squark mass. as an example, for a light gluino and a heavier squark, the rate shown may come from:

$\tilde{g}\tilde{g}$		3.3 events / 100 nb^{-1}
$\tilde{g}\tilde{q}$	$(\tilde{q} \to q + \tilde{\gamma})$	0.4 "
$\tilde{g}\tilde{q}$	$(\hat{q} \to q + \tilde{g})$	0.6 "
$\tilde{q}$	$(\tilde{q} \to q + \tilde{\gamma})$	1.3 "
$\tilde{q}$	$(\tilde{q} \to q + \tilde{g})$	4.4 "
others		negligible
Total		9.9 events /100 nb^{-1}

When we complete the updated version of Fig. 2 and when the 1984 data are published, we will be able to set strict limits for supersymmetry from this figure.[4] We may also be able to identify regions where the signal might have supersymmetric origins.

Fig. 2 indicates only the magnitude of event rates and not the shape of distributions. The shapes will further limit $M_{\tilde{g}}$ and $M_{\tilde{q}}$. However the data for distributions also contain backgrounds which ideally should be subtracted out. But even short of that, certain mass regions can be ruled out if supersymmetry predicts events with characteristics which are not observed.

Shapes of distributions are quite independent of $\sqrt{s}$, so we have combined the 1983 ($\sqrt{s}$ = 540 GeV) and the preliminary 1984 ($\sqrt{s}$ = 630 GeV) data. The 1984 data have not yet had backgrounds or some mismeasured events subtracted out. They are only shown to indicate that supersymmetry is a plausible source for the observed events (assuming that the rate is greater than that for backgrounds). The solid and dashed curves in Figs. 3–4 show our results for the two different E_T^{miss} cuts. I believe it may be impossible to learn the source of missing-energy events unless the events between E_T^{miss} = 32 and 40 GeV are also studied. Note that these curves do include fragmentation but not resolution effects.

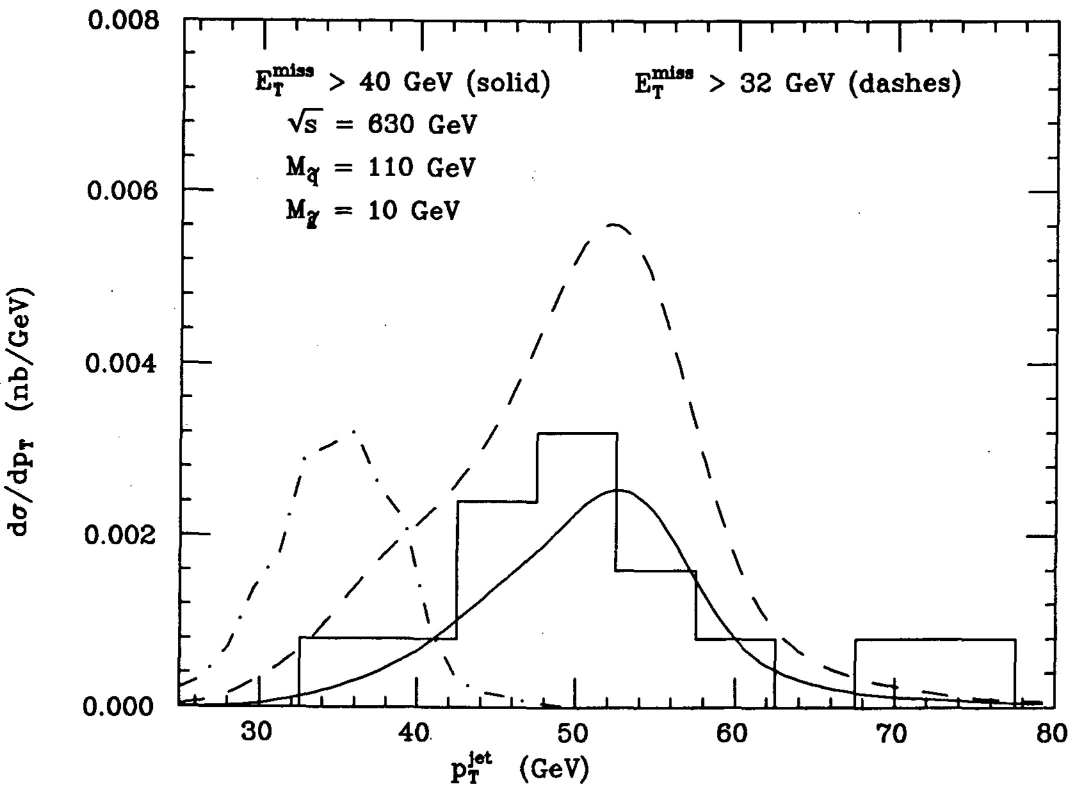

Fig. 3 - The E_T^{jet} (leading jet) distribution in $p\bar{p}$ scattering from missing-energy events passing the UA1 cuts and E_T^{miss} > 32 GeV (dashed) and E_T^{miss} > 40 GeV (solid). The curves show the sums of contributions from all supersymmetric processes when $M_{\tilde{q}}$ = 110 GeV and $M_{\tilde{g}}$ = 10 GeV. The data are for E_T^{miss} > 40 GeV only and see the remarks in Fig. Cap. 1. The dot-dashed curve shows the background from $W \rightarrow \tau\nu$ with E_T^{miss} > 32 GeV.

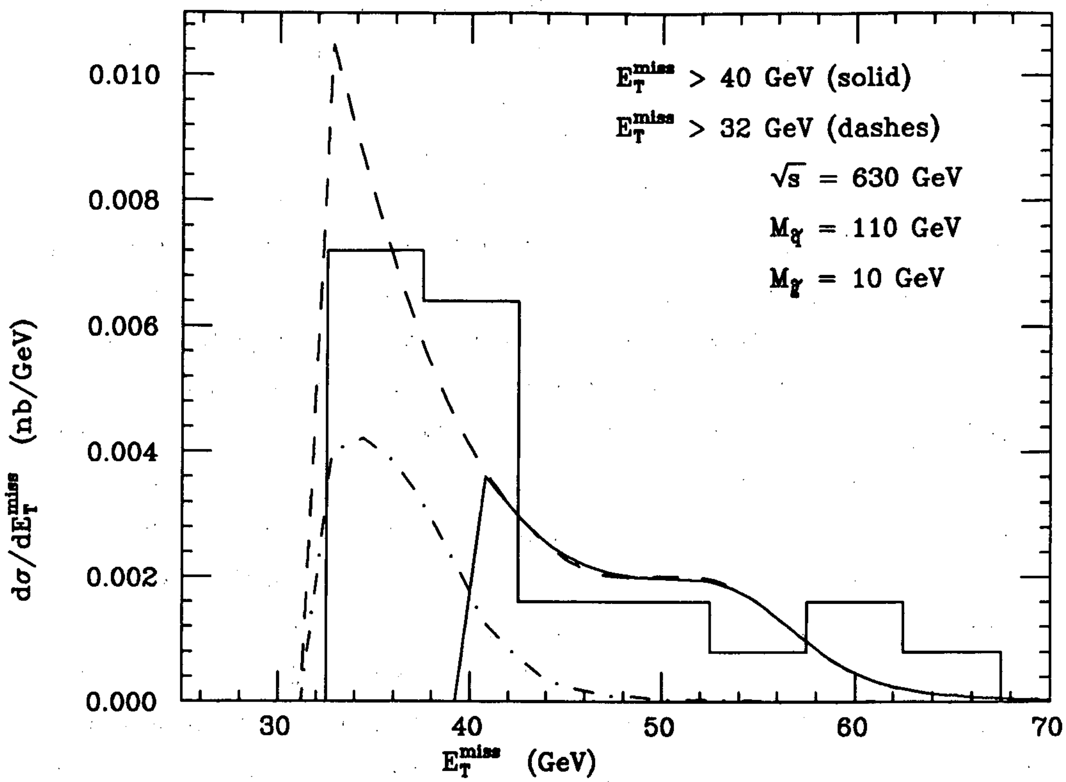

Fig. 4 - The missing-energy E_T^{miss} distribution in $p\bar{p}$ scattering from missing-energy events passing the UA1 cuts and $E_T^{miss} > 32$ GeV (dashed) and $E_T^{miss} > 40$ GeV (solid). The curves show the sums of contributions from all supersymmetric processes when $M_{\tilde{q}}$ = 110 GeV and $M_{\tilde{g}}$ = 10 GeV. The data are for $E_T^{miss} > 32$ GeV; otherwise see the remarks in Fig. Cap. 1. The dot-dashed curve shows the background from $W \to \tau\nu$ with $E_T^{miss} > 32$ GeV.

There are a number of possible sources of backgrounds. 1) Detector limitations. 2) The process[9] $p\bar{p} \to W^{\pm}+X$ with $W^{\pm} \to \tau\nu$ and $\tau \to \nu +$ jet. Since $W^{\pm} \to e\nu$ is measured one can calculate this background accurately (though experimental resolution and efficiency may affect the result). We wrote a Monte Carlo program for this process. 3) The process[10] $p\bar{p} \to Z^0 +$ gluon or quark with $Z^0 \to \nu\bar{\nu}$. For $p_T(Z^0) \ll m(Z^0)$, the QCD corrections are difficult to calculate accurately. To get a rough idea of rates and distributions, we have written a Monte Carlo program for the leading-order process. 4) The process[10] $p\bar{p} \to W^{\pm} +$ gluon or quark with $W^{\pm} \to e\nu$ and the electron missed.

The dot-dashed curves in Figs. 3–4 show the $W \to \tau\nu$ results for $E_T^{miss} > 32$ GeV. The data in Fig. 3 are only for $E_T^{miss} > 40$ GeV. The $Z^0 \to \nu\bar{\nu}$ results which will be shown elsewhere are harder than the $W \to \tau\nu$ results and are somewhat similar in shape to the supersymmetry curves.

The rate for $Z^0 + g$ can be estimated three ways: 1) Determine the K-factor as the ratio of the experimental to theoretical $W \to e\nu$ rates. This ratio is larger than the theoretical K-factor found by log summation techniques. 2) The rate for $Z^0 \to \nu\bar{\nu}$ is expected to be 6 times that for $Z^0 \to e^+e^-$ which is measured.

From Altarelli et al[11] we can find the fraction of Z^0 with $\overline{p}_T(Z^0) > p_0 = E_T^{miss}$. 3) the 1983 UA1 data for W bosons with an accompanying jet with $E_T^{jet} > 25$ GeV are roughly 2% of the total. These three techniques yield:

1.2 1.3 1. events/100 nb^{-1} for $E_T^{miss} > 32$ GeV

0.5 0.7 - events/100 nb^{-1} for $E_T^{miss} > 40$ GeV.

These are clearly consistent. Detailed calculations for this and background (4) are being reported by Ellis, Stirling, and Kleiss.[10] At this time it is possible that these backgrounds are smaller than the signal.

In order to minimize backgrounds and mismeasurements, the experimentalists have sometimes applied a cut $\theta < 150°$ on the angle between the large jet and either a secondary jet or the residual p_T For $\tilde{q}\tilde{q}$ production the resulting angular distribution peaks between 80° and 150°. However, for $\tilde{g}\tilde{g}$ production with light gluinos the peak is 150°–180°. If one assumes that the total p_T in the center-of-mass of the initial-state partons is the same as that seen in $p\overline{p} \to W$, the peak moves to 130°–170°. Therefore I would like to emphasize that a $\theta < 150°$ cut *may* throw out the baby with the bath water.

In conclusion: Fragmentation is very important for gluinos as heavy as 20 GeV. I believe it is best to combine monojet, dijet, and multijet data. Study of the region $E_T^{miss} > 32$ GeV is at least as important as that above 40 GeV. We will need all possible data fully analyzed by the experimentalists. A full theoretical-experimental calculation of backgrounds is essential. If no events above backgrounds are observed, then excellent limits on $M_{\tilde{g}}$ and $M_{\tilde{q}}$ will be obtained with our comprehensive analysis. Two regions which we will investigate thoroughly are $M_{\tilde{q}} \approx 100$ GeV with $M_{\tilde{g}} \approx 10$ GeV, and $M_{\tilde{q}} = 40$–70 GeV with $M_{\tilde{g}}$ somewhat larger. Ultimately our ability to decide whether there is evidence for supersymmetry may rest on our ability to eliminate "Explainatons." Explainatons are particles with the characteristic that their properties change with time to explain whatever data are available today.

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REFERENCES

1. G. Arnison, et al., Phys. Lett. **139B**, 115 (1984); M. Mohammedi, talk at the 1st Annual Aspen Winter Physics Conference, Aspen, Colorado, Jan. 6–12, 1985; J. Rohlf, talk at the Workshop on "Experimental and Theoretical Investigations of Family Problems," Santa Barbara, Jan. 7–9, 1985.
2. P. Fayet, Phys. Rep **105C**, 21 (1984); R.M. Barnett, H.E. Haber, and G.L. Kane, Phys. Rev. Lett. **54**, 1983 (1985); P.R. Harrison and C.H. Llewellyn Smith, Nucl. Phys. **B213**, 223 (1983) (E: **B223**, 542 (1983)); I. Antoniadis, L. Baulieu, and F. Delduc, Z. Phys. **C23**, 119 (1984); S. Dawson, E. Eichten, and C. Quigg, Phys. Rev. **D31**, 1581 (1985); M.J. Herrero, L.E. Ibanez, C. Lopez, and F.J. Yndurain, Phys. Lett. **132B**, 199 (1983); **145B**, 430 (1984); H.E. Haber and G.L. Kane, Phys. Lett. **142B**, 212 (1984); G. Altarelli and R. Ruckl, Phys. Lett. **144B**, 126 (1984); N.D. Tracas and S.D.P. Vlassopulos, Phys. Lett. **149B**, 253 (1984); J. Ellis and H. Kowalski, Phys. Lett. **142B**, 441 (1984); Nucl. Phys. **B246**, 189 (1984); preprint CERN-TH.4126/85; E. Reya and D.P. Roy, Phys. Rev. Lett. **51**, 867 (1983); (E: **51**, 1307 (1983)); ibid., Phys. Lett. **141B**, 442 (1984); Dortmund preprint, DO-TH 84/19 (1984); M. Gluck, E. Reya, and D.P. Roy, preprint DO-TH 85/1 (1985); V. Barger, K. Hagiwara, and J. Woodside, Phys. Rev. Lett. **53**, 641 (1984); V. Barger, K. Hagiwara, and W.-Y.Keung, Phys. Lett. **145B**, 147 (1984); V. Barger, K. Hagiwara, W.-Y.Keung, and J. Woodside, Phys. Rev. **D31**, 528 (1985) and preprint MAD/PH/230 (1985).; A.R. Allan, E.W.N. Glover, and A.D. Martin, Phys. Lett. **146B**, 247 (1984); A.R. Allan, E.W.N. Glover, and S.L. Grayson, Durham preprint DTP/84/28 (1984); A. De Rûjula and R. Petronzio, preprint CERN-TH-4070/84; F.M. Renard and P. Sorba, preprint LAPP-TH-127 (1985); K. Enqvist, D.V. Nanopoulos, and A.B. Lahanas, preprint CERN-TH-4095/85.
3. M.J. Herrero, Ref. 2 and B.A. Campbell, J. Ellis, and S. Rudaz, Nucl. Phys. **B198**, 1 (1982); I. Antoniadis, C. Kounnas, and R. Lacaze, Nucl. Phys. **B211**, 216 (1983); C. Kounnas and D.A. Ross, Nucl. Phys. **B214**, 317 (1983); S.K. Jones and C.H. Llewellyn Smith, Nucl. Phys. **B217**, 145 (1983); M.J. Herrero, C. Lopez, and F.J Yndurain, Nucl. Phys. **B244**, 207 (1984).
4. R.M. Barnett, H.E. Haber, and G.L. Kane, paper in publication.
5. J.M. Izen, preprint DESY 84-104 (1984).
6. A. De Rûjula, Ref. 2.
7. C. Peterson et al., Phys. Rev. **D27**, 105 (1983).
8. E. Franco, Phys. Lett. **124B**, 271 (1983); G. Altarelli et al., Nucl. Phys. **B208**, 365 (1982).
9. M. Mohammedi, Ref. 1.
10. S.D. Ellis, R. Kleiss, and W.J. Stirling, preprint CERN-TH-4096/85.
11. G. Altarelli et al., preprint FERMILAB-PUB-84/107-T (1984); and Nucl. Phys. **B246**, 12 (1984).