Title
Measurement of the W charge asymmetry in the $W \rightarrow \mu \nu$ decay mode in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

Permalink
https://escholarship.org/uc/item/00v305t6

Journal
Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, 701(1)

ISSN
0370-2693

Authors
Aad, G
Abbott, B
Abdallah, J
et al.

Publication Date
2011-06-27

DOI
10.1016/j.physletb.2011.05.024

License
CC BY 4.0

Peer reviewed
Measurement of the $W$ charge asymmetry in the $W \rightarrow \mu\nu$ decay mode in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

The measurement of the charge asymmetry of leptons originating from the decay of singly produced $W$ bosons at $pp$, $p\bar{p}$ and $ep$ colliders provides important information about the proton structure as described by parton distribution functions (PDFs). The $W$ boson charge asymmetry is mainly sensitive to valence quark distributions [1] via the dominant production process $ud(\bar{u}d) \rightarrow W^+(-)$ and provides complementary information to that obtained from measurements of inclusive deep inelastic scattering cross-sections at the HERA electron–proton collider [2–5]. The HERA data do not strongly constrain the ratio between $u$ and $d$ quarks in the kinematic regime of low $x$, where $x$ is the proton momentum fraction carried by the parton [6]. A precise measurement of the $W$ asymmetry at the Large Hadron Collider (LHC) [7] on the other hand, can contribute significantly to the understanding of PDFs and quantum chromodynamics (QCD) in the parton momentum fraction range $10^{-3} \lesssim x \lesssim 10^{-1}$ [8].

In $pp$ collisions the overall production rate of $W^+$ bosons is significantly larger than the corresponding $W^-$ rate, since the proton contains two $u$ and one $d$ valence quarks. The first measurements of the inclusive $W^{\pm}$ cross-sections at the LHC by the ATLAS [9] and the CMS [10] Collaborations confirmed the difference predicted by the Standard Model. The asymmetry in $pp$ collisions is symmetric with respect to the $W$ rapidity, whereas in $p\bar{p}$ collisions it is antisymmetric; the small sensitivity to sea-quark contributions is strongly suppressed in $p\bar{p}$ compared to $pp$ collisions [11]. Measurements in $p\bar{p}$ collisions have been performed at the Tevatron by both the CDF [12,13] and DØ [14,15] Collaborations, also using an iterative procedure extracting the $W$ asymmetry as a function of $y_W$ [16]. The data have been included in global fits of parton distributions [17,18].

This Letter presents a differential measurement of the muon charge asymmetry from the decay of $W$ bosons produced in proton–proton collisions at a centre-of-mass energy of $7$ TeV with the ATLAS experiment at the LHC. The asymmetry is measured in the $W \rightarrow \mu\nu$ decay mode as a function of the muon pseudorapidity using a data sample corresponding to a total integrated luminosity of 31 pb$^{-1}$. The results are compared to predictions based on next-to-leading order calculations with various parton distribution functions. This measurement provides information on the $u$ and $d$ quark momentum fractions in the proton.

A. H. Weerts

Available online 27 May 2011
Received in revised form 9 May 2011
Received 15 March 2011
Editor: H. Weerts

© 2011 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

DOI: 10.1016/j.physletb.2011.05.024
muons with two independent detector systems. These two inde-
pendent measurements allow systematic uncertainties to be con-
trolled. The results presented are based on data collected in 2010
with an integrated luminosity of 31 pb$^{-1}$. These results signifi-
cantly improve on the previous measurement by the ATLAS Collab-
oration [9], which is based on a data set approximately 100 times
smaller.

2. The ATLAS detector

The ATLAS detector [19,20] consists of an inner tracking system
(inner detector, or ID) surrounded by a superconducting solenoid
providing a 2 T magnetic field, electromagnetic and hadronic
calorimeters and a muon spectrometer (MS). The ID consists of
pixel and silicon microstrip (SCT) detectors, surrounded by a tran-
sition radiation tracker (TRT). The electromagnetic calorimeter is
a lead liquid-argon (LAr) detector in the barrel and the endcap,
and in the forward region copper LAr technology is used. Hadron
calorimetry is based on two different detector technologies, with
scintillator tiles or LAr as the active media, and with either steel,
copper, or tungsten as the absorber material. There is a poorly
instrumented transition region between the barrel and endcap
calorimeter, 1.37 < |η| < 1.52, where electrons cannot be precisely
measured. In view of a later combination, this motivates the binn-
ing in that region for the present muon analysis. The MS is based
on three large superconducting toroids, and a system of three sta-
tions of chambers for trigger and precise tracking measurements.
There is a transition between the barrel and endcap muon detec-
tors around |η| = 1.05.

3. Data and simulated event samples

The data used in this analysis were collected from the end
of September to the end of October 2010. Basic requirements on
beam, detector, stable trigger conditions and data-quality were
used in the event selection, resulting in a total integrated luminos-
ity of 31 pb$^{-1}$. Events in this analysis are selected using a single-
muon trigger with a requirement on the momentum transverse to
the beam ($p_T$) of at least 13 GeV. The trigger includes three lev-
els of event selection: a first level hardware-based selection using
hit patterns in the MS and two higher levels of software-based re-
quirements.

Simulated event samples are used for the background estima-
tion, the acceptance calculation and for comparison of data with
theoretical expectations. The processes considered are the $W \to
µν$ signal, and backgrounds from $W \to τν$, $Z \to µµ$, $Z \to ττ$, $t\overline{t}$
and jet production via QCD processes (referred to as “QCD back-
ground” in the text). The simulated signal and background samples
(except $t\overline{t}$) were generated with PYTHIA 6.421 [21] using MRST
2007 LO [22] PDFs. The $t\overline{t}$ sample was generated with POWHEG-
HQV v1.01 patch 4 [23]; the PDF set was CTEQ 6.6M [24] for the
NLO matrix element calculations, while CTEQ 6.1 was used for the
parton shoring and underlying event via the POWHEG inter-
face to PYTHIA. The radiation of photons from charged leptons
was treated using PHOTOS v2.15.4 [25] and TAUOLA v1.0.2 [26]
was used for tau decays. The underlying and pile-up events were
simulated according to the ATLAS MC09 tune [27]. The gener-
sated samples were passed through the GEANT4 [28] simulation
of the ATLAS detector [29], reconstructed and analysed with the
same analysis chain as the data. The cross-section predictions for
$W$ and $Z$ were calculated to next-to-next-to-leading-order (NNLO)
using FEWZ [30] with the MSTW 2008 [31] PDFs. The $t\overline{t}$ cross-
section was obtained at next-to-leading-order (plus next-to-
next-to-leading-log, NNLL) using POWHEG [32]. The Monte Carlo
(MC) were generated with, on average, two soft inelastic collisions over-

4. Event selection

The criteria for the event selection and muon identification fol-
low closely those used for the $W$ boson inclusive cross-section
measurement [9], with an improved muon quality selection [33].
Events from $pp$ collisions are selected by requiring a collision ver-
tex with at least three tracks each with transverse momentum
greater than 150 MeV. A beam-spot constraint has been applied in
the collision vertex reconstruction stage significantly improving the
resolution on the collision vertex position in the transverse plane.
To reduce the contribution of cosmic-ray and beam-halo events,
induced by proton losses from the beam, the analysis requires the
collision vertex position along the beam axis to be within 20 cm
of the nominal interaction point. The collision vertex is defined as
the vertex closest in $z$ to the selected muon.

Events with a high transverse momentum muon are selected by
imposing stringent requirements to ensure good discrimination
of $W \to µν$ events from background. The muon parameters are
first reconstructed separately in the MS and ID. Subsequently, the
tracks from the ID and MS are matched. Their parameters are then
combined, weighted by their respective errors, to form a combined
muon. The $W$ candidate events are required to have at least one
combined muon track with $p_T > 20$ GeV and $p_T$ measured by
the MS alone greater than $p_T^{MS} > 10$ GeV, within the range |$η_μ$| < 2.4.
The difference between the ID and MS $p_T$, corrected for the mean
energy loss in the material traversed between the ID and MS, is
required to be less than 0.5 times the ID $p_T$.

$p_T^{MS}$ (energy loss corrected) – $p_T^{ID} < 0.5p_T^{ID}$.

This requirement increases the robustness against track recon-
struction mismatches, including decays-in-flight of hadrons. In ad-
dition, a minimum number of hits in the ID is required to ensure
high quality tracks [33]. In order to further reduce non-collision
backgrounds, the difference between the z position of the muon
track extrapolated to the beam line and the $z$ coordinate of the
collision vertex is required to be less than 1 cm. A track-based isola-
tion for the muon is defined as $\sum p_T^T / p_T < 0.2$, where $\sum p_T^T$
is the scalar sum of transverse momenta of all other tracks mea-
sured in the ID belonging to the same collision vertex. In ad-
dition, a minimum number of hits in the ID is required.

The reconstruction of the missing transverse energy ($E_T^{miss}$)
and the transverse mass ($m_T$) follows the prescription in [9].
The $E_T^{miss}$ is determined from the energy deposits of calibrated
calorimeter cells in three-dimensional clusters and is corrected for
the momentum of all muons reconstructed in the event. Jet-quality
requirements are applied to remove a small fraction of events
where sporadic calorimeter noise and non-collision backgrounds
may affect the $E_T^{miss}$ reconstruction [34]. The transverse mass is
defined as

\[
m_T = \sqrt{2p_T^µp_T^ν(1 - \cos(φ^µ - φ^ν))},
\]

where the highest $p_T$ muon is used and the $(x, y)$ components of
the neutrino momentum are inferred from the corresponding
$E_T^{miss}$ components. Events are required to have $E_T^{miss} > 25$ GeV
and $m_T > 40$ GeV, yielding 129157W candidates.

$ΔR$ is defined as $ΔR = \sqrt{Δx^2 + Δy^2}$. 
5. \(W^\pm\) signal yield and background estimation

Many components in the \(W\) cross-section measurement, such as the luminosity or detector efficiencies, are in principle the same for positive and negative muons and therefore mostly cancel in the asymmetry calculation. The main experimental biases on the asymmetry measurement come from possible differences in the reconstruction of positive and negative muons. Each effect (trigger and reconstruction efficiency and momentum scale) is examined to check that the two charges behave in the same way within the systematic uncertainties. These studies are performed in absolute pseudorapidity in order to reduce the uncertainty associated with the limited size of the data samples used.

As in past \(W\) analyses, trigger [33] and muon reconstruction [9, 33] efficiencies as a function of muon \(\eta_\mu\) have been measured in data using a sample of unbiased muons from \(Z \rightarrow \mu\mu\) decays, which provides a source of muons with small background. The trigger efficiency is determined relative to a reconstructed muon satisfying the selection criteria of the analysis. The average trigger efficiencies after the full \(W\) selection are \((81 \pm 2\%)\) in the central detector region or low-\(\eta\) region, \(\langle \eta_\mu \rangle < 1.05\), and \((94 \pm 1\%)\) in the forward detector region or high-\(\eta\) region, \(1.05 < \langle \eta_\mu \rangle < 2.4\), where the differences are due to the geometrical acceptance of the muon trigger chambers. In the same muon sample, the muon reconstruction efficiency relative to an ID track is measured to be \((93 \pm 1\%)\) overall. The efficiency for reconstructing an ID track is \((99 \pm 1\%)\) [9]. The quoted uncertainties on these efficiencies are statistical.

Corrections have been applied to the simulated samples to account for differences in the trigger and reconstruction efficiencies between data and simulation. These are based on the ratio of the efficiency in data and in simulation, and are computed as a function of the muon \(\eta_\mu\) and charge. The corrections for each charge agree within the statistical uncertainties, so the charge-averaged result is applied. For the trigger, the corrections are 0.98 and 1.03 in the central and forward MS regions, respectively. For the reconstruction efficiency, the correction factors are about 0.99 per \(\eta_\mu\) bin except for the central-forward MS transition region (\(\langle \eta_\mu \rangle\) about 1.05) where the correction factor is 0.94.

The muon momentum resolution is affected by the amount of material traversed by the muon, the spatial resolution of the individual track points and the degree of internal alignment of the ID and MS [35]. This resolution has been measured as a function of \(\eta_\mu\) for the main detector regions (in \(\eta_\mu\) ranges delimited by 1.05, 1.7, 2.0 and 2.4) from the width of the di-muon invariant mass distribution in \(Z \rightarrow \mu\mu\) decays and from the comparison of the momentum measurements in the ID and MS in \(Z \rightarrow \mu\mu\) and \(W \rightarrow \mu\nu\) decays. The measured resolution is worse than expected from simulation by 1–5%, with the maximum discrepancy reached in the high-\(\eta_\mu\) region of the detector [36]. The discrepancy is due to residual mis-alignments in the ID and MS, imperfections in the description of the inert material in simulation and an imperfect mapping of the magnetic field in the MS transition region where the field is highly non-uniform. Smearing corrections are therefore applied to the simulation in order to improve the agreement with data.

If the accuracy of the muon momentum measurement is different for positive and negative muons, this difference can produce a bias in the acceptance of \(\mu^+\) with respect to \(\mu^-\). Differences in the muon \(p_T\) measurement between data and simulation have been evaluated comparing the curvature of muons from \(W\) candidates in data and in templates derived from simulation. A binned likelihood fit for a momentum-scale correction that yields the best agreement between data and simulation is performed as a function of \(\eta_\mu\) separately for positive and negative charges. The measured biases in the \(p_T\) scale between the two charges are < 1%, but they increase to about 3% in the transition and high-\(\eta_\mu\) regions due to residual mis-alignments in the ID and MS. These corrections are applied to the muon momenta in the simulated samples.

Fig. 1 shows the pseudorapidity distribution of the selected positive and negative muons. Data distributions are compared to the PYTHIA MC simulation, normalised to the total number of events in data. The shape of the simulation agrees well with the shape of the data after the corrections for the reconstruction and trigger efficiencies, and the muon-momentum scale and resolution.

The main backgrounds to \(W \rightarrow \mu\nu\) arise from heavy flavour decays in multijet events and from the electro-weak background from \(W \rightarrow \tau\nu\) where the tau decays to a muon, \(Z \rightarrow \mu\mu\) where one muon is not reconstructed and produces fake \(E_T^{miss}\), and \(Z \rightarrow \tau\tau\) where one tau decays to a muon, as well as semileptonic \(t\bar{t}\) decays in the muon channel. Backgrounds from the production of di-bosons (\(WW, WZ\) and \(ZZ\)) and single top quarks are found to be negligible. The \(W \rightarrow \tau\nu\) contribution is treated as a background. While this contribution presents the same asymmetry as the \(W \rightarrow \mu\nu\) signal, it is difficult to include in PDF fits, which assume that the asymmetry is a function of \(\eta_\mu\) for \(W \rightarrow lv\). No explicit veto on events with a second muon is applied.

The background estimates of the electro-weak and \(t\bar{t}\) backgrounds and the QCD background closely follow the methods used in the \(W\) inclusive cross-section measurement [9]. They are determined separately for positive and negative muons as a function of \(\eta_\mu\). The electro-weak and \(t\bar{t}\) backgrounds are estimated using MC simulation. The QCD background comes primarily from \(b\) and \(c\) quark decays, with a smaller contribution from pion and kaon decays in flight. This background is estimated using a data-driven method similar to the one described in [9]. The sample of events fulfilling the full \(W\) selection criteria with the exception of the muon isolation requirement is compared before and after the isolation requirement. The isolation efficiency for non-QCD events is measured in data with the \(Z \rightarrow \mu\mu\) sample. The efficiency for QCD events is estimated in a control sample of low-\(p_T\) muons extrapolated to the high-\(p_T\) and high-\(E_T^{miss}\) signal region using the simulated jet sample. Since the samples before and after isolation can be defined in terms of a QCD and non-QCD component, the expected number of QCD events can thus be determined.

The expected background amounts to 7% of the selected events; 6% is the electro-weak and \(t\bar{t}\) contribution (3% \(Z \rightarrow \mu\mu\), 2\% \(W \rightarrow \tau\nu\), and 1\% for the sum of \(t\bar{t}\) and \(Z \rightarrow \tau\tau\)) and the remainder is the QCD background. The cosmic ray background contamination is estimated to be smaller by a factor of \(10^5\) compared to the signal and thus negligible. The \(W^\pm\) candidate events and expected background contributions are summarised in Table 1.

Fig. 2 shows the transverse momentum distribution for positive and negative muons after the full event selection. They are compared with the distributions predicted by the corrected PYTHIA MC simulation normalised to the total number of events in data. The correction factors, \(C_{\text{Wplus}}\), corresponding to the ratio of reconstructed over generated events in the simulated \(W\) sample, satisfying all kinematic requirements of the event selection, \(p_T > 20\text{ GeV}, p_T^\tau > 25\text{ GeV}, m_{\tau\nu} > 40\text{ GeV},\) are also listed in Table 1. No correction is made to the full acceptance. The discrepancies between data and MC are taken into account by the systematic uncertainty assigned to the measurement of muon momenta explained in Section 6. The \(C_{\text{Wplus}}\) factors include trigger and muon reconstruction scale factors to correct for observed deviations between data and MC efficiencies. Due to a reduced geometric acceptance in the trigger, the \(C_{\text{Wplus}}\) factors for the lowest \(\eta_\mu\) bins are significantly smaller than those for the higher \(\eta_\mu\) regions.
into the signal and various background components. POWHEG is used for the

6. Systematic uncertainties

All systematic uncertainties on the asymmetry measurement are determined in each $|\eta_\mu|$ bin accounting for correlations between the charges and are summarised in Table 2. The dominant sources of systematic uncertainty on the asymmetry come from the trigger and reconstruction efficiencies. The determination of these efficiencies is affected by the statistical uncertainty due to the small available sample of $Z \rightarrow \mu\mu$ events. Systematic uncertainties on the efficiencies are determined from studies of the impact of the selection criteria and backgrounds, and no significant charge biases are found. There is a loss of trigger efficiency in the low pseudorapidity region due to reduced geometric acceptance, resulting in a larger statistical error. As a result,
the trigger systematic uncertainty on the asymmetry is largest in the low pseudorapidity bins (6–7% for central $|\eta_{\mu}|$ and 2–3% for forward $|\eta_{\mu}|$). Similarly, the uncertainties associated with the reconstruction efficiency are larger in the lowest pseudorapidity bin (about 7%), and in the MS central-forward transition region (about 3%), due to geometrical acceptance effects associated with reduced chamber coverage. In the remaining regions, the uncertainty is about 1–2%.

The muon momentum scale and resolution corrections contribute to the uncertainty primarily due to limited statistics for the fitting procedures used to measure the differences between the data and simulation. An additional source of uncertainty arises from potential biases in the template shapes. The size of this effect is determined by using different templates created by shifting the resolution parameters in opposite directions to account for possible charge biases. Uncertainties associated with the modelling of the background contributions to the templates, particularly the QCD background, are also included. The resulting uncertainty on the asymmetry is in the 1–2% range, with little dependence on $\eta_{\mu}$.

The redundant ID and MS momentum measurements result in a rate of charge mis-identification smaller than $10^{-4}$ in the $p_T$ range considered, resulting in a negligible impact on the asymmetry.

The momentum-scale-correction procedure is further tested by exploiting the redundant muon-momentum measurements offered by the ATLAS detector. The full asymmetry measurement is performed with the ID and MS components of the combined muon separately, including the scale corrections. Fig. 3 compares the two independently corrected charge-asymmetry distributions, showing good agreement within the systematic uncertainty associated with the momentum-scale correction.

The systematic uncertainties on the QCD background arise primarily from the uncertainty on the isolation efficiency for muons in QCD events due to possible mis-modellings of the extrapolation of the isolation efficiency to the large $p_T$ and $E_T^{miss}$ region in the QCD simulation (40%). This has been derived from differences in the efficiency predictions between data and simulation in the low muon $p_T$ control region and in sideband regions where the muon $p_T$ or $E_T^{miss}$ cuts are reversed. The electro-weak and $t\bar{t}$ background and signal contributions are subtracted from data in these comparisons. Additional uncertainties due to the non-QCD isolation efficiency and the statistical uncertainty are included in the total uncertainty on the QCD background estimate. The corresponding systematic uncertainty on the asymmetry is 1–2%, with little dependence on $\eta_{\mu}$.

For the electro-weak and $t\bar{t}$ backgrounds, the uncertainties in the cross-sections include the PDF uncertainties (3%), and the uncertainties estimated from varying the renormalization and factorization scales: 5% for $W$ and $Z$, and 6% for $t\bar{t}$ [37,38,9]. These uncertainties are taken as overall uncertainties, no $\eta$ dependence is accounted for. An additional uncertainty from the luminosity of 11% is included, since the backgrounds are scaled to the luminosity measured in data. The combination of all these contributions results in an uncertainty on the asymmetry of less than 1%.

The impact of using an NLO MC using the CTEQ 6.6 PDF rather than PYTHIA with MRST LO PDF in the $c_W^{\mu\tau}$ factor calculation has been evaluated and an additional systematic uncertainty of about 3% is included to account for the small variations observed, as listed in Table 2 as the uncertainty due to theoretical modelling. PYTHIA uses a leading-log calculation for $W$ production and is expected to give a reasonably accurate prediction for the low $W$ transverse momentum $p_T^W$ region whereas MC@NLO [39] uses higher-order matrix elements and is therefore expected to be more reliable in the high $p_T^W$ region. Therefore the differences in the scale factors associated with these two MC calculations gives a reasonable estimate of the associated systematic error.

### 7. Results and conclusions

The measured differential muon charge asymmetry in eleven bins of muon absolute pseudorapidity is shown in Table 3 and Fig. 4. The statistical and systematic uncertainties per $|\eta_{\mu}|$ bin are included and contribute comparably to the total uncertainty. Table 3 and Fig. 4 also show expectations for the muon asymmetry from $W$ predictions at NLO with different PDF sets: CTEQ 6.6 [18], HERA 1.0 [5] and MSTW 2008 [17]; all predictions are presented with 90% confidence-level error bands. All MC predictions are calculated using MC@NLO, with all kinematic selection criteria applied to the truth particles. The PDF uncertainty bands are obtained by summing in quadrature the deviations of each of the PDF error sets [40] from the respective nominal predictions, according to the specifications of the corresponding PDF Collaboration to get 90% C.L. bands. These uncertainties for all predictions include experimental uncertainties as well as model and parameterization uncertainties. The HERA 1.0 [5] set also includes the uncertainty in $\alpha_s$, which, however, is not the dominant source of uncertainty.

While the predictions with different PDF sets differ within their respective uncertainty bands [41,42], they follow the same global trend, rising with $\eta_{\mu}$. The measured asymmetry agrees with this expectation. As demonstrated graphically in Fig. 4, the data are roughly compatible with all the predictions with different PDF sets, though some are slightly preferred to others. A $\chi^2$-comparison using the measurement uncertainty and the central value of the PDF predictions yields values per number of degrees of freedom of 9.16/11 for the CTEQ 6.6 PDF sets, 35.81/11 for the HERA 1.0 PDF sets and 27.31/11 for the MSTW 2008 PDF sets.

In summary, this Letter reports a measurement of the $W$ charge asymmetry in $pp$ collisions at $\sqrt{s} = 7$ TeV performed in the $W \to \mu\nu$ decay mode using 31 pb$^{-1}$ of data recorded with the ATLAS detector at the LHC. Until the start of the LHC, it has not been kinematically possible to precisely measure the valence quark distributions in particular to constrain the ratio of $u/d$ quarks below $x \leq 0.05$ as assessed by [17]. Whereas none of the predictions with different PDF sets are inconsistent with these data, the predictions are not fully consistent with each other since they are all phenomenological extrapolations in $x$. The input of the data presented here is therefore expected to contribute to the determination of
the next generation of PDF sets, helping reduce PDF uncertainties, particularly the shapes of the valence quark distributions in the low-$x$ region.

Acknowledgements

We wish to thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; STC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSA, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MINSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NRC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL- T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Aubière Cedex, France
34 Nevis Laboratory, Columbia University, Irvington, NY, United States
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Casenova; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas, TX, United States
40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
41 DESY, Hamburg und Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham, NC, United States
45 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria
47 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
48 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
50 Faculty of Science, Hiroshima University, Hiroshima, Japan
51 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
52 Department of Physics, Indiana University, Bloomington, IN, United States
53 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
54 Department of Physics, Iowa, Iowa City, IA, United States
55 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
56 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
57 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
58 Graduate School of Science, Kobe University, Kobe, Japan
59 Faculty of Science, Kyoto University, Kyoto, Japan
60 Kyoto University of Education, Kyoto, Japan
61 Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
62 Physics Department, Lancaster University, Lancaster, United Kingdom
63 (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
64 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
65 Department of Physics, Józef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
66 Department of Physics, Queen Mary University of London, London, United Kingdom
67 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
68 Department of Physics and Astronomy, University College London, London, United Kingdom
69 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Idelot and CNRS/IN2P3, Paris, France
70 Fysikav institutionen, Lunds universitet, Lund, Sweden
71 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
72 Institut für Physik, Universität Mainz, Mainz, Germany
73 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
74 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
75 Department of Physics, University of Massachusetts, Amherst, MA, United States
76 Department of Physics, McGill University, Montreal QC, Canada
77 School of Physics, University of Melbourne, Victoria, Australia
78 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
79 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
80 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
81 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
82 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
83 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
84 Group of Particle Physics, University of Montreal, Montreal QC, Canada
85 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
86 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
87 Moscow Engineering and Physics Institute (MPEI), Moscow, Russia
88 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
89 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
90 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
91 Nagasaki Institute of Applied Science, Nagasaki, Japan
92 Graduate School of Science, Nagoya University, Nagoya, Japan
93 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
94 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
95 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
96 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
97 Department of Physics, Northern Illinois University, Dekalb, IL, United States