The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/162999

Please be advised that this information was generated on 2019-02-06 and may be subject to change.
Measurement of the Inelastic Proton-Proton Cross Section at \(\sqrt{s} = 13\) TeV with the ATLAS Detector at the LHC

M. Aaboud et al.*
(ATLAS Collaboration)
(Received 9 June 2016; published 26 October 2016)

This Letter presents a measurement of the inelastic proton-proton cross section using 60 \(\mu b^{-1}\) of \(pp\) collisions at a center-of-mass energy \(\sqrt{s}\) of 13 TeV with the ATLAS detector at the LHC. Inelastic interactions are selected using rings of plastic scintillators in the forward region (2.07 < \(|\eta|\) < 3.86) of the detector. A cross section of 68.1 \(\pm\) 1.4 \(mb\) is measured in the fiducial region \(\xi=M_X^2/s > 10^{-6}\), where \(M_X\) is the larger invariant mass of the two hadronic systems separated by the largest rapidity gap in the event. In this \(\xi\) range the scintillators are highly efficient. For diffractive events this corresponds to cases where at least one proton dissociates to a system with \(M_X > 13\) GeV. The measured cross section is compared with a range of theoretical predictions. When extrapolated to the full phase space, a cross section of 78.1 \(\pm\) 2.9 \(mb\) is measured, consistent with the inelastic cross section increasing with center-of-mass energy.

DOI: 10.1103/PhysRevLett.117.182002

The rise of the total proton-proton (\(pp\)) cross section with center-of-mass energy \(\sqrt{s}\), predicted by Heisenberg [1] and observed at the CERN Intersecting Storage Rings [2], probes the nonperturbative regime of quantum chromodynamics (QCD). Arguments based on unitarity, analyticity, and factorization imply an upper bound on the chromodynamics (QCD). Arguments based on unitarity, analyticity, and factorization imply an upper bound on the chromodynamics (QCD).

Many experiments have measured \(\sigma_{\text{inel}}\) and found an increase with \(\sqrt{s}\) [6]. The TOTEM and ATLAS collaborations determined \(\sigma_{\text{inel}}\) at \(\sqrt{s} = 7\) and 8 TeV using the optical theorem and a measurement of the elastic cross section with Roman pot detectors [7–11]. Using a variety of alternative techniques, the ATLAS, CMS, ALICE, and LHCb experiments have made measurements of \(\sigma_{\text{inel}}\) at \(\sqrt{s} = 7\) TeV [12–15] and \(\sqrt{s} = 2.76\) TeV (ALICE) [14].

The Pierre Auger Collaboration measured the inelastic \(p\)-air cross section at \(\sqrt{s} = 57\) TeV and extracted \(\sigma_{\text{inel}}\) using the Glauber model [16].

This Letter presents a measurement of the inelastic cross section \(\sigma_{\text{inel}}\) using \(pp\) collisions at \(\sqrt{s} = 13\) TeV with the ATLAS detector at the Large Hadron Collider (LHC). It is performed using two sets of scintillation counters in a data set corresponding to an integrated luminosity of 60.1 \(\pm\) 1.1 \(\mu b^{-1}\) collected in June 2015. In inelastic interactions, one or both protons dissociate as a result of colored (nondiffractive) or colorless (diffractive) exchange. The counters are insensitive to elastic \(pp\) scattering and diffractive dissociation processes in which neither proton dissociates into a system, \(X\), of mass \(M_X > 13\) GeV, or equivalently, \(\xi = M_X^2/s > 10^{-6}\). The cross-section measurement is reported in this fiducial region, \(\xi > 10^{-6}\), and after extrapolation to the total inelastic cross section using models of inelastic interactions.

The ATLAS detector is a cylindrical particle detector composed of several subdetector layers [17]. The inner tracking detector (ID) is immersed in a 2 T magnetic field provided by a superconducting solenoid. Around the tracker is a system of electromagnetic and hadronic calorimeters, which use liquid argon and lead, copper, or tungsten absorber for the electromagnetic and forward (\(|\eta| > 1.7\)) [18] hadronic components of the detector, and scintillator-tile active material and steel absorber for the central (\(|\eta| < 1.7\)) hadronic component.

At \(z = \pm 3.6\) m, thin plastic scintillation counters, the minimum-bias trigger scintillators (MBTS), are installed on the front face of each endcap calorimeter. These detectors cover the region 2.07 < \(|\eta|\) < 3.86. They are similar to those described in Ref. [17] but were rebuilt during 2014, when the coverage was slightly extended from 2.08 < \(|\eta|\) < 3.75 after the \(\sqrt{s} = 7\) TeV run. The MBTS are divided into inner (4 counters in 149 < \(r\) < 445 mm) and outer (8 counters in 444.5 < \(r\) < 895 mm) octagonal rings.

The ATLAS experiment uses a multistage trigger to select events at about 1 kHz for offline analysis. Three trigger configurations were used to collect data for this analysis. The primary triggers use the MBTS detector and constant-fraction discriminators to select events when two proton bunches collide in the detector. To facilitate background studies, data were also collected with the same selection when no proton bunch (“empty”) or a single proton bunch from only one of the two beams (“single
"beam") was passing through the center of ATLAS. All of these triggers require at least one MBTS hit above threshold. Two additional triggers were used to collect data to determine the MBTS trigger efficiency, requiring either hits in a forward $(5.6 < |\eta| < 5.9)$ Cherenkov detector (LUCID) or a far forward $(|\eta| > 8.4)$ tungsten-scintillator calorimeter detector (LHCf [19]) located at $z = \pm 17$ m and $\pm 140$ m, respectively. The LHCf detector is an independent detector, but for the runs considered in this analysis, its trigger signals were incorporated into the ATLAS readout.

Monte Carlo (MC) simulation samples were produced to correct the fiducial measurement and to compare to the data. The detector response is modeled using a simulation based on GEANT4 [20–22]. The data and MC simulated events are passed through the same reconstruction and analysis software.

The primary MC samples are based on the PYTHIA8 generator [23,24] either with the A2 [25] set of tuned underlying-event parameters and the MSTW 2008 LO PDF set [26] or with the Monash [27] set of tuned parameters and the NNPDF 2.3 LO PDF set [28]. The samples are divided into four components: single-dissociation (SD, $pp \rightarrow pX$), double-dissociation (DD, $pp \rightarrow Xp$), central-dissociation (CD, $pp \rightarrow pXp$), and all involving colorless exchange, and nondiffractive dissociation (ND) wherein color flow is present between the two colliding protons. For all dissociation event types, the Monash tune is used.

PYTHIA8 uses a pomeron-based diffraction model [29] to describe colorless exchange with a default pomeron flux model by Schuler and Sjöstrand (SS) [30,31]. Alternative MC samples are generated with the pomeron flux model of Donnachie and Landshoff (DL) [32] and with the minimum-bias Rockefeller (MBR) model [33]. In the DL model, the pomeron Regge trajectory is given by $\alpha(t) = 1 + \epsilon + \alpha' t$, where $\epsilon$ and $\alpha'$ are free parameters. In most samples used for this analysis, the value of $\alpha'$ is 0.25, the PYTHIA8 default. The $\epsilon$ parameter is varied from 0.06 to 0.10 (the PYTHIA8 default is 0.085). An additional sample produced with $\alpha' = 0.35$ is found to be statistically consistent with the $\alpha' = 0.25$ default samples in each aspect of this analysis. The ranges of $\epsilon$ and $\alpha'$ considered are motivated by previous total, inelastic, elastic, and diffractive cross-section measurements, including measurements of low-mass diffraction by the ATLAS and CMS collaborations [34,35]. For the DL and SS models the CD component is neglected. The MBR model is tuned to data as described in Ref. [33] and includes a small CD component.

The EPOS LHC and QGSJET-II event generators are also used to simulate $pp$ collisions. EPOS LHC [36] uses a “cut pomeron” model for diffraction and differs significantly from PYTHIA8 in its modeling of hadronization and the underlying event. QGSJET-II [37,38] uses Reggeon field theory to describe pomeron-pomeron interactions. Both EPOS LHC and QGSJET-II have been developed primarily to model cosmic-ray showering in the atmosphere.

The fiducial region of the measurement is determined using MC simulation. In each generated event, the largest rapidity gap between any two final-state hadrons is used to define the boundary between two collections of hadrons. These collections define the dissociation systems in an event-generator-independent manner. The invariant mass of each collection is calculated, and the larger of the two masses, denoted $M_X$, is used to define $\xi = M_X^2 / s$. The variable $\xi$ is constrained to be $> 6 \times 10^{-6}$ by the elastic limit of $m_p^2 / s$ where $m_p$ is the proton mass. This measurement is restricted to $\xi > 10^{-6}$, the region in which the event selection efficiency exceeds 50%.

Two samples of data events passing the MBTS trigger requirements are selected: an inclusive sample and a single-sided sample. The inclusive selection requires at least two MBTS counters with a charge above 0.15 pC ($n_{MBTS} \geq 2$). This threshold is chosen to be well above the electronic noise level of the counters. Requiring two hits rather than one substantially reduces background due to collision-induced radiation and activation. To constrain the diffractive component of the cross section and reduce the uncertainty in extrapolation to $\sigma_{inel}$, an additional single-sided selection is defined, requiring hits in at least two counters on one side of the detector and no hits on the other. In the data, 4,159,074 events pass the inclusive selection and 442,192 events pass the single-sided selection.

The fiducial cross section is determined by

$$\sigma_{inel}^{fid}(\xi > 10^{-6}) = \frac{N - N_{BG}}{\epsilon_{trig} \times \mathcal{L} \times \epsilon_{sel}} \times \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{sel}},$$

where $N$ is the number of observed events passing the inclusive selection, $N_{BG}$ is the number of background events, $\epsilon_{trig}$ and $\epsilon_{sel}$ are factors accounting for the trigger and event selection efficiencies, and $1 - f_{\xi < 10^{-6}}$ accounts for the migration of events with $\xi < 10^{-6}$ into the fiducial region, and $\mathcal{L}$ is the integrated luminosity of the sample.

Sources of background include interactions between the beam and residual gas in the beam pipe; interactions between the beam and collimators upstream of the detector, which can send charged particles through the detector parallel to the beam; collision-induced radiation; and activation backgrounds. Backgrounds from cosmic rays and instrumental noise are negligible. The mean number of $pp$ collisions in the same LHC bunch crossing was $2.3 \times 10^{-3}$ for the recorded data set. Thus, the contribution from multiple collisions is also negligible. The beam-related background components are extracted from single-beam events and dominate the total background. They are normalized by scaling the number of selected single-beam events by a factor of $37 / 4 \times 2$, accounting for the 37 colliding pairs of bunches and 4 bunches producing the single-beam data in this run. The factor of 2 accounts for the presence of two colliding bunches. The number of protons per bunch producing these single-beam events
agrees with that in the colliding bunches to within 10%. The radiation and activation-induced backgrounds are implicitly part of this background estimate. Double-counting of these components is removed using estimates from empty events. The total background contributions to the inclusive and single-sided data samples are determined to be 1.2% and 5.8%, respectively. The classification of single-sided events as double-sided due to noise or other backgrounds is estimated to be below 0.1%. A systematic uncertainty of 50% is assigned to the background based on studies of the background composition and the relative contributions of the background components. This uncertainty is treated as fully correlated between the single-sided and inclusive selections.

The trigger efficiency for events passing the inclusive selection, \( \varepsilon_{\text{trig}} \), is measured with respect to events selected with the LUCID detector after subtracting the background. A trigger efficiency of 99.7% (97.4%) is measured for the inclusive (single-sided) event sample. In both cases the statistical uncertainty is below 0.1%. The efficiency is also measured with events selected by the LHCf detector and agrees within ±0.3% with the LUCID determination. This difference is taken as a systematic uncertainty.

The ratio of the number of events passing the single-sided event selection to the number passing the inclusive selection \( R_{SS} \) is used to adjust, for each model, the fractional contribution of the single- and double-diffractive dissociative cross section \( (\sigma_{SD} + \sigma_{DD}) \) to the inelastic cross section, \( f_{D} = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel} \). The measured value is \( R_{SS} = 10.4\% \) with a total uncertainty of ±0.4%. The dominant systematic uncertainty arises from the background subtraction in the single-sided sample. For each MC model, \( f_{D} \) is varied until it matches the observed \( R_{SS} \) value in data. The data uncertainty is used to set the error in the constrained \( f_{D} \) for each model. An additional uncertainty in the ratio of single- to double-diffractive events is determined by taking the diffractive events to be entirely SD or to be evenly divided between SD and DD.

Using this method, the fitted \( f_{D} \) in the PYTHIA8 samples is between 25% and 31%, depending on the model (the default value is 28%). For the QGSJET-II (EPOS LHC) model the fitted \( f_{D} \) is 35% (37%), differing significantly from the default value of 21% (28%). The observed \( R_{SS} \) and the MC predictions of its dependence on \( f_{D} \) are shown in Fig. 1. The fitted \( f_{D} \) is used when determining the acceptance corrections \( \varepsilon_{\text{sel}} \) and \( f_{x<10^{-6}} \) for each model.

In Fig. 2 the \( n_{MBTS} \) distributions in data are compared to the ones from MC simulated samples utilizing the fitted \( f_{D} \) values for both the inclusive and single-sided selections. The estimated background is subtracted from the measured distribution, and the trigger efficiency measured in data is applied to the simulation. The data distributions and MC simulation are peaked at high multiplicity values. In the single-sided case, \( n_{MBTS} = 12 \) corresponds to hits in all counters on one side of the detector. The data agree best with the DL models, particularly in the low-\( n_{MBTS} \) range. The MBR-based distribution provides a slightly worse description of the data. The PYTHIA8 sample using the SS model does not describe data well in the low-multiplicity region. EPOS LHC and QGSJET-II also do not describe the data well, particularly in the single-sided hit multiplicity distribution. Therefore, the PYTHIA8 DL model with \( \varepsilon = 0.085 \) is chosen as the nominal MC model for the \( \varepsilon_{\text{sel}} \) and \( f_{x<10^{-6}} \) corrections, and only the DL and MBR models are considered for systematic uncertainties related to the MC corrections.

The event selection efficiency, \( \varepsilon_{\text{sel}} \), depends upon the MBTS counter sensitivity. This sensitivity is tested using isolated charged particles, reconstructed as ID tracks in the region \( 2.07 < |y| < 2.5 \) where the coverages of the MBTS and ID overlap. Over the full coverage of the MBTS counters, the calorimeter is used to measure the counter efficiency with respect to particles that deposit sufficient energy in the calorimeter to seed a topological energy cluster [39]. Differences between the efficiencies in data and MC simulation are accounted for by adjusting the MBTS charge threshold in MC simulation until the simulated efficiencies match those observed in the data. The residual uncertainty in the counter efficiency after these corrections is ±0.5% for the outer and ±1.0% for the inner counters. Additionally, an uncertainty arising from the knowledge of the material in front of the MBTS detector is estimated using MC samples with an increased amount of material in front of the MBTS. Based on the MC samples, the uncertainty in the efficiency measurement due to modeling of hadronization and the underlying event is estimated to be negligible.

After adjusting the counter charge threshold, \( \varepsilon_{\text{sel}} \) is determined from the nominal PYTHIA8 DL MC simulations, using the fitted \( f_{D} \) corresponding to this model, to be 99.34% with a statistical uncertainty of ±0.03%. The uncertainty in the MBTS counter efficiencies results in
only a ±0.1% uncertainty in the overall event selection efficiency, because many counters are hit in typical events. In addition, an uncertainty of ±0.2% in $\epsilon_{\text{sel}}$ arises from the knowledge of the material in front of the MBTS.

The fraction of events passing the inclusive selection with $\xi < 10^{-6}$ represents an additional background component in the fiducial cross-section measurement. It is determined using the same PYTHIA8 DL MC to be $f_{\xi<10^{-6}} = (1.37 ± 0.05)$%, where the uncertainty is statistical.

Because the efficiency and migration corrections are correlated, they are combined in a single correction factor, $C_{\text{MC}} = (1 - f_{\xi<10^{-6}})/\epsilon_{\text{sel}}$, for which systematic uncertainties are assessed. The systematic uncertainties include the counter efficiency variations, the impact of the material uncertainty, the uncertainty in the fitted value of $f_D$, and the variation in $C_{\text{MC}}$ found by comparing the PYTHIA8 DL and MBR models. Of these sources of uncertainty, the last is most important at ±0.5%. The value of $C_{\text{MC}}$ is $(99.3 ± 0.5)$%. The uncertainty also implicitly contains an uncertainty due to the CD contribution, since this is included in only some of the models.

The uncertainty in the integrated luminosity is ±1.9%. It is derived, following a methodology similar to that detailed in Refs. [40,41], from a calibration of the luminosity scale using X-Y beam-separation scans performed in August 2015. This calibration uncertainty is slightly smaller than what has been reported in Ref. [42] because the low-luminosity data set used in this Letter is not affected by the uncertainties related to high-luminosity runs.

The components of the fiducial cross-section calculation [Eq. (1)] are shown in Table I with their systematic uncertainties. The statistical uncertainties are negligible. The measured fiducial cross section is determined to be

$$\sigma_{\text{inel}}^{\text{fid}} = 68.1 ± 0.6(\text{exp}) ± 1.3(\text{lum}) \text{ mb},$$

where the first uncertainty refers to all experimental uncertainties apart from the luminosity and the second refers to the luminosity only.

The PYTHIA8 DL model predicts values of 71.0 mb, 69.1 mb, and 68.1 mb for $\epsilon = 0.06$, 0.085, and 0.10, respectively, all of which are compatible with the measurement. The PYTHIA8 MBR model predicts 70.1 mb, also in agreement with the measurement. The Epos LHC (71.2 mb) and QGSJET-II (72.7 mb) predictions exceed the data by 2–3σ. The PYTHIA8 SS model predicts 74.4 mb, and thus exceeds the measured value by $\sim 4\sigma$.

The extrapolation to $\sigma_{\text{inel}}^{\text{fid}}$ uses constraints from previous ATLAS measurements to minimize the model dependence of the component that falls outside the fiducial region. $\sigma_{\text{inel}}^{\text{fid}}$ can be written as

$$\sigma_{\text{inel}} = \sigma_{\text{inel}}^{\text{fid}} + \sigma^{7 \text{TeV}}(\xi < 5 \times 10^{-6}) \\
\times \frac{\sigma_{\text{MC}}^{7 \text{TeV}}(\xi < 5 \times 10^{-6})}{\sigma^{7 \text{TeV}}(\xi < 5 \times 10^{-6})},$$

Table I. Inputs to the calculation of the measured cross section and their systematic uncertainties.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events passing the inclusive selection (N)</td>
<td>4 159 074</td>
<td>...</td>
</tr>
<tr>
<td>Number of background events ($N_{\text{BG}}$)</td>
<td>51 187</td>
<td>±50%</td>
</tr>
<tr>
<td>Integrated luminosity [$\text{pb}^{-1}$] ($L$)</td>
<td>60.1</td>
<td>±1.9%</td>
</tr>
<tr>
<td>Trigger efficiency ($\epsilon_{\text{trig}}$)</td>
<td>99.7%</td>
<td>±0.3%</td>
</tr>
<tr>
<td>MC correction factor ($C_{\text{MC}}$)</td>
<td>99.3%</td>
<td>±0.5%</td>
</tr>
</tbody>
</table>

The term $\sigma^{7 \text{TeV}}(\xi < 5 \times 10^{-6}) = \sigma_{\text{inel}} - \sigma^{7 \text{TeV}}(\xi > 5 \times 10^{-6}) = 9.9 ± 2.4 \text{ mb}$ is the difference between $\sigma_{\text{inel}}$...
FIG. 3. The inelastic proton-proton cross section versus $\sqrt{s}$. Measurements from other hadron collider experiments [6,7,9,14,15] and the Pierre Auger experiment [16] are also shown. Some LHC data points have been slightly shifted in the horizontal position for display purposes. The data are compared to the PYTHIA8, EPOS LHC and QGSJet-II MC generator predictions. The uncertainty in the ATLAS ALFA measurement is smaller than the marker size.

measured at 7 TeV using the ALFA detector [8], $\sigma_{\text{inel}}^7\text{TeV}$, and $\sigma_{\text{inel}}$ measured at 7 TeV for $\xi > 5 \times 10^{-6}$ using the MBTS [12] (The 7 TeV result is corrected upward by 1.9% following an improved luminosity calibration [40]). The uncertainties of the two measurements are uncorrelated.

The PYTHIA8 DL and PYTHIA8 MBR MC samples are used to assess the systematic uncertainty in the MC-derived ratio of cross sections in Eq. (2), which is determined to be $1.015 \pm 0.081$. (The value of the ratio arises from an approximately 20% increased cross section from increasing $\sqrt{s}$ which is largely compensated by a 15% decrease due to the change in the $\xi$ distribution.) These models also agree with the measurement of $\sigma_{\text{inel}}^7\text{TeV}(\xi < 5 \times 10^{-6})$ to within 2σ.

The measured value for $\sigma_{\text{inel}}$ is

$$\sigma_{\text{inel}} = 78.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.6(\text{extrap}) \text{ mb}.$$  

This and other inelastic cross-section measurements are compared to several Monte Carlo models in Fig. 3. Additional predictions range between 76.6 and 81.6 mb [43–47]. Compared to the measurement with the ALFA detector at $\sqrt{s} = 7$ TeV the cross section is higher by (9 ± 4)%.

In summary, a measurement of the inelastic cross section in 60 $\mu$b$^{-1}$ of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC is presented. The measurement is performed in a fiducial region $\xi > 10^{-6}$, and the result is extrapolated to the inelastic cross section using measurements at $\sqrt{s} = 7$ TeV. The measured cross section agrees well with a variety of theoretical predictions and is consistent with the inelastic cross section increasing with center-of-mass energy, as observed at lower energies.

We thank CERN for the very successful operation of the LHC, 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; BMWFFW and FWF, Austria; ANAS, Azerbaijan; SSTC, 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 and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT; Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/ NRF, South Africa; MINECO, Spain; SFC and Wallenberg Foundation, Sweden; SERI, SNF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FRQNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [48].

Swiss National Science Foundation

[18] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, $\phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.


(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, AB, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, The University of Texas at Austin, Austin, Texas, USA
12Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
14Institute of Physics, University of Belgrade, Belgrade, Serbia
15Department for Physics and Technology, University of Bergen, Bergen, Norway
16Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
17Department of Physics, Humboldt University, Berlin, Germany
18Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20aDepartment of Physics, Bogazici University, Istanbul, Turkey
20bDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20cIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
20dBahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
21Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22aINFN Sezione di Bologna, Italy
22bDipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23Physikalisches Institut, University of Bonn, Bonn, Germany
24Department of Physics, Boston University, Boston, Massachusetts, USA
25Department of Physics, Brandeis University, Waltham, Massachusetts, USA
26aUniversidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
26bElectrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
26cFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
26dInstituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27Physics Department, Brookhaven National Laboratory, Upton, New York, USA
28aTransilvania University of Brasov, Brasov, Romania, Romania
28bNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
28cNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
28dUniversity Politehnica Bucharest, Bucharest, Romania
28eWest University in Timisoara, Timisoara, Romania
29Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
30Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31Department of Physics, Carleton University, Ottawa, ON, Canada
32CERN, Geneva, Switzerland
33Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
34aDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
34bDepartamento de Física, Universidad Técnica Federico Santa Maria, Valparaiso, Chile
35Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
35bDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
35cDepartment of Physics, Nanjing University, Jiangsu, China

182002-15

PRL 117, 182002 (2016) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2016
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

deceased.

Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at TRIUMF, Vancouver BC, Canada.

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.

Also at Department of Physics, California State University, Fresno, CA, USA.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Departamento de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Louisiana Tech University, Ruston, LA, USA.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Department of Physics, National Tsing Hua University, Taiwan.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York, NY, USA.

Also at Hellenic Open University, Patras, Greece.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at School of Physics, Shandong University, Shandong, China.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Eötvös Lorand University, Budapest, Hungary.

Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, USA.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford, CA, USA.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Flensburg University of Applied Sciences, Flensburg, Germany.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.