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 high-energy behavior of total hadronic cross sections that prevents them from rising more rapidly than \( \ln^2(s) \) [3–5].

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 (\( |\eta| > 1.7 \)) 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
beams”) 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) 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, $pp \rightarrow XX$), central-dissociation (CD, $pp \rightarrow pXp$), all involving colorless exchange, and nondissociative 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 $\alpha(t) = 1 + \varepsilon + \alpha' t$, where $\varepsilon$ and $\alpha'$ are free parameters. In most samples used for this analysis, the value of $\alpha'$ is 0.25, the PYTHIA8 default. The $\varepsilon$ 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 $\varepsilon$ 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

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

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, $1 - f_{\xi < 10^{-6}}$ accounts for the migration of events with $\xi < 10^{-6}$ into the fiducial region, and $L$ 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, $\epsilon_{\text{trig}}$, 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 $\pm 0.3\%$ 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, $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{\text{inel}}$ [12]. The measured value is $R_{SS} = 10.4\%$ with a total uncertainty of $\pm 0.4\%$. 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 $\epsilon_{\text{sel}}$ and $f_{z<10^{-6}}$ for each model.

In Fig. 2 the $n_{\text{MBTS}}$ 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, $n_{\text{MBTS}}=12$ corresponds to hits in all counters on one side of the detector. The data agree best with the DL models, particularly in the low-$n_{\text{MBTS}}$ 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 $\epsilon_{\text{sel}}$ and $f_{z<10^{-6}}$ corrections, and only the DL and MBR models are considered for systematic uncertainties related to the MC corrections.

The event selection efficiency, $\epsilon_{\text{sel}}$, depends upon the MBTS counter sensitivity. This sensitivity is tested using isolated charged particles, reconstructed as ID tracks in the region $2.07 < |\eta| < 2.5$ 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 $\pm 0.5\%$ for the outer and $\pm 1.0\%$ 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, $\epsilon_{\text{sel}}$ 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 $\pm 0.03\%$. 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, $C_{MC} = (1 - f_{\xi<10^{-6}})/\epsilon_{\text{sel}}$, 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 $C_{MC}$ 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 $C_{MC}$ 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

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

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 $\varepsilon = 0.06$, 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 2–3$\sigma$. The PYTHIA8 SS model predicts 74.4 mb, and thus exceeds the measured value by ~4$\sigma$.

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

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

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 
\textsc{Pythia8}, 
\textsc{Epos Lhc} and 
\textsc{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 
\textsc{Pythia8 DL} and 
\textsc{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 ± 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 78.6 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; BMWFW 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; MURA, ERDF, and ERAB, Croatia; CSC and Tekes, Finland; FZJ, Germany; 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; SRC and Wallenberg Foundation, Sweden; SERI, SNSF 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, FQRNT, 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
6LBNL, Batavia, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, The University of Texas at Austin, Austin, 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
20Department of Physics, Bogazici University, Istanbul, Turkey
20aDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20bBahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
20cCentro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
20dINFN Sezione di Bologna, Italy
21Physikalisches Institut, University of Bonn, Bonn, Germany
21aDepartment of Physics, Boston University, Boston, Massachusetts, USA
21bDepartment of Physics, Brandeis University, Waltham, Massachusetts, USA
21cUniversidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
21dElectrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
21eFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
21fInstituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
21gPhysics Department, Brookhaven National Laboratory, Upton, New York, USA
21hTransilvania University of Brasov, Brasov, Romania, Romania
21iNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
21jNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
21kUniversity Politehnica Bucharest, Bucharest, Romania
21lWest University in Timisoara, Timisoara, Romania
21mDepartamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
21nCavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
21oDepartment of Physics, Carleton University, Ottawa, ON, Canada
21pCERN, Geneva, Switzerland
21qEnrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
21rDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
21sDepartamento de Física, Universidad Técnica Federico Santa Maria, Valparaiso, Chile
21tInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
21uDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
21vDepartment of Physics, Nanjing University, Jiangsu, China

S. Zimmermann,50 Z. Zinonos,56 M. Zinser,84 M. Ziolkowski,141 L. Živković,14 G. Zobernig,172 A. Zoccoli,22a,22b
M. zur Nedden,17 and L. Zwalinski32

182002-15
82 Fysiska institutionen, Lunds universitet, Lund, Sweden
83 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
84 Institut für Physik, Universität Mainz, Mainz, Germany
85 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
86 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
87 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
88 Department of Physics, McGill University, Montreal, QC, Canada
89 School of Physics, University of Melbourne, Victoria, Australia
90 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
91 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
92a INFN Sezione di Milano, Italy
92b Dipartimento di Fisica, Università di Milano, Milano, Italy
93 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
94 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
95 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
96 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
100 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102 Nagasaki Institute of Applied Science, Nagasaki, Japan
103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
104a INFN Sezione di Napoli, Italy
104b Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
108 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York, New York, USA
111 Ohio State University, Columbus, Ohio, USA
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
114 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
115 Palacký University, RCP TM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
117 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 INFN Sezione di Pavia, Italy
121a Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
123 National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
124 INFN Sezione di Pisa, Italy
124a Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
126 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
126a Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
126b Department of Physics, University of Coimbra, Coimbra, Portugal
126c Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
126d Departamento de Física, Universidade do Minho, Braga, Portugal
126e Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126f Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
130 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
INFIN Sezione di Roma, Italy
Dipartimento di Fisica, Sapienza Universita\' di Roma, Roma, Italy
INFIN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Universita\' di Roma Tor Vergata, Roma, Italy
INFIN Sezione di Roma Tre, Italy
Dipartimento di Matematica e Fisica, Universita\' Roma Tre, Roma, Italy

Faculte des Sciences Ain Chock, Re\'seau Universitaire de Physique des Hautes Energies—Universite Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Faculte des Sciences Semlalia, Universite Cadi Ayyad, LPTPUMarrakech, Morocco
Faculte des Sciences, Universite Mohamed Premier and LPTPM, Oujda, Morocco
Faculte des sciences, Universite Mohammed V, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
Department of Physics, University of Washington, Seattle, Washington, USA
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universitat Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby, BC, Canada
SLAC National Accelerator Laboratory, Stanford, California, USA
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Cape Town, Cape Town, South Africa
Department of Physics, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, ON, Canada
TRIUMF, Vancouver, BC, Canada
Department of Physics and Astronomy, York University, Toronto, ON, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFIN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Universita\' di Udine, Udine, Italy
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana, Illinois, USA

Instituto de Fisica Corpuscular (IFIC) and Departamento de Fisica Atomica, Molecular y Nuclear and Departamento de Ingenieria Electronica y Instituto de Microelectronica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultat für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, 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

174 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

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

176 Yerevan Physics Institute, Yerevan, Armenia

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

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
c Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
da Also at Novosibirsk State University, Novosibirsk, Russia.
e Also at TRIUMF, Vancouver BC, Canada.
f Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
g Also at Department of Physics, California State University, Fresno, CA, USA.
h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
i Also at Departamento de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
j Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
k Also at Tomsk State University, Tomsk, Russia.
l Also at Universita di Napoli Parthenope, Napoli, Italy.
m Also at Institute of Particle Physics (IPP), Canada.

178 a Also at Department of Physics, King’s College London, London, United Kingdom.
179 b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
180 c Also at Novosibirsk State University, Novosibirsk, Russia.
181 d Also at TRIUMF, Vancouver BC, Canada.
182 e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
183 f Also at Department of Physics, California State University, Fresno, CA, USA.
184 g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
185 h Also at Departamento de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
186 i Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
187 j Also at Tomsk State University, Tomsk, Russia.
188 k Also at Universita di Napoli Parthenope, Napoli, Italy.
189 l Also at Institute of Particle Physics (IPP), Canada.
190 m Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
191 n Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
192 o Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
193 p Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
194 q Also at Louisiana Tech University, Ruston, LA, USA.
195 r Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
196 s Also at Graduate School of Science, Osaka University, Osaka, Japan.
197 t Also at Department of Physics, National Tsing Hua University, Taiwan.
198 u Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
199 v Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
200 w Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
201 x Also at CERN, Geneva, Switzerland.
202 y Also at Georgian Technical University (GTU), Tbilisi, Georgia.
203 z Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
204 aa Also at Manhattan College, New York, NY, USA.
205 ab Also at Hellenic Open University, Patras, Greece.
206 ac Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
207 ad Also at School of Physics, Shandong University, Shandong, China.
208 ae Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
209 af Also at Section de Physique, Université de Genève, Geneva, Switzerland.
209 bg Also at Eotvos Lorand University, Budapest, Hungary.
210 bh Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, USA.
211 bi Also at International School for Advanced Studies (SISSA), Trieste, Italy.
212 bj Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
213 bk Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
214 bm Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
215 bn Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
216 bo Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
217 bp Also at National Research Nuclear University MEPhI, Moscow, Russia.
218 bq Also at Department of Physics, Stanford University, Stanford, CA, USA.
219 br Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
220 bs Also at Flensburg University of Applied Sciences, Flensburg, Germany.
221 bt Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
222 bu Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.