Measurement of the inelastic proton–proton cross-section at s=7 TeV with the ATLAS detector

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Measurement of the inelastic proton–proton cross-section at √s = 7 TeV with the ATLAS detector

The ATLAS Collaboration¹,*

The dependence of the rate of proton–proton interactions on the centre-of-mass collision energy, √s, is of fundamental importance for both hadron collider physics and particle astrophysics. The dependence cannot yet be calculated from first principles; therefore, experimental measurements are needed. Here we present the first measurement of the inelastic proton–proton interaction cross-section at a centre-of-mass energy, √s, of 7 TeV using the ATLAS detector at the Large Hadron Collider. Events are selected by requiring hits on scintillation counters mounted in the forward region of the detector. An inelastic cross-section of 60.3 ± 2.1 mb is measured for ξ > 5×10⁻⁶, where ξ is calculated from the invariant mass, Mₜ, of hadrons selected using the largest rapidity gap in the event. For diffractive events, this corresponds to requiring at least one of the dissociation masses to be larger than 15.7 GeV.
Since the earliest days of particle physics, measurements of the total pp and p̄p cross-sections and their theoretical understanding have been topics of much interest. The cross-sections cannot yet be calculated by quantum chromodynamics, and many approaches have been used to describe the existing measurements. General arguments based on unitarity and analyticity imply a bound (the Froissart bound\(^{3,4}\)) on the high-energy behaviour of total hadronic cross-sections. This bound is independent of the details of the strong interaction dynamics and states that the total cross-section cannot rise faster than \(\ln(s)\), where \(s\) is the centre-of-mass energy. Recently, it has been extended to the inelastic cross-section\(^{1}\). Existing experimental data\(^2\) show a rise in the hadronic cross-sections with \(s\), but it is unclear whether the asymptotic behaviour has already been reached. In this letter, a direct measurement of the inelastic pp cross-section at the highest energy collider to date is presented. Measurements of the inelastic p–p̄ cross-section in the multi-TeV regime are available from cosmic-ray shower detection experiments\(^3,5\), and have been used to infer the pp cross-section albeit with significant uncertainties. The measurement presented here is of direct relevance for the modelling of high energy cosmic ray showers.

The most common models that describe the data up to \(\sqrt{s} = 1.8\) TeV predict a rise of the total cross-section with a simple power law \((\propto s^{3.8})\), where \(\alpha(0)\) denotes the Pomeron-trajectory intercept\(^{3,10}\) or with a power law depending on \(\ln(s)\) (refs 12–16). Others employ quantum chromodynamics for aspects of the calculation\(^8\). However, although the phenomenological description of the existing data is largely adequate, there are significant uncertainties on the extrapolation to higher energies, partly due to a long-standing 2.7σ discrepancy between the two highest energy collider measurements of the total pp cross-section by CDF\(^{11}\) and E811 (ref. 22). The inelastic pp cross-section at \(\sqrt{s} = 7\) TeV is measured with data taken by the ATLAS experiment\(^{23}\) at the Large Hadron Collider (LHC)\(^{24}\). The data considered were collected during a single 8-hour fill beginning 31 March 2010, corresponding to an integrated luminosity of 20.3±0.7 mb\(^{-1}\) and a peak instantaneous luminosity of 1.2×10\(^{32}\) cm\(^{-2}\) s\(^{-1}\). The mean number of interactions per crossing in this fill is ~0.01. The analysis uses highly efficient scintillation counters, the minimum bias trigger scintillator (MBTS) detectors, to detect inelastic collisions. They are insensitive to diffractive dissociation processes in which the dissociation systems have small invariant masses, \(M_y\). Their acceptance corresponds approximately to \(\xi = M_y^2/s > 5 \times 10^{-6}\), equivalent to \(M_y > 15.7\) GeV for \(\sqrt{s} = 7\) TeV. The cross-section measurement presented here is restricted to this kinematic range. However, to compare the data with previous measurements, an extrapolation of the cross-section is performed to the full \(\xi\) range, \(\xi > m_y^2/s\) where \(m_y\) is the proton mass.

**Results**

**Acceptance determination.** Monte Carlo (MC) simulations are used to determine the acceptance of the event selection and to assess systematic uncertainties. The detector response to the generated events is simulated using the ATLAS simulation\(^{25}\) based on Geant4 (ref. 26), and both the simulated and data events are reconstructed and analysed with the same software. The Pythia6 (ref. 27), Pythia8 (ref. 28) and Phojet\(^{29,30}\) generators are used to predict properties of inelastic collisions. These generators distinguish between different processes that contribute to inelastic pp interactions: single dissociative (SD) processes, pp→p̄pX, in which one proton dissociates; double dissociative (DD) processes, pp→XY, in which both protons dissociate with no net colour flow between the systems X and Y; and non-diffractive (ND) processes in which colour flow is present between the two initial-state protons. The model by Schuler and Sjöstrand\(^31\), used by Pythia6 and Pythia8, predicts cross-sections of 48.5, 13.7 and 9.3 mb for the ND, SD and DD processes, respectively. Whereas the cross-sections used by Pythia6 and Pythia8 are identical, they differ in the modelling of the hadronic final state. Phojet predicts the corresponding cross-sections as 61.6 mb (ND), 10.7 mb (SD) and 3.9 mb (DD). Because of differences in implementation of the interface between large \(\xi\) diffractive (SD and DD) processes and ND processes in Pythia and Phojet, the fractional contribution of these processes is a model-dependent quantity. Phojet also includes a 1.1 mb contribution from central diffraction (CD), pp→ppX, a process not implemented in Pythia, wherein neither proton dissociates, but the Pomeron–trajectory exchange results in energy loss for the protons and the production of a central system of particles. The MC generators define the inelastic cross-section as the sum of these contributions, and thus Schuler and Sjöstrand (Phojet) predicts an inelastic cross-section of 71.5 mb (77.3 mb). Other recent predictions for this cross-section at \(\sqrt{s} = 7\) TeV are 69 mb (ref. 15), 65–67 mb (ref. 17) and personal communication with the author), 68 mb (refs 18,19) and 60–75 mb (ref. 20).

Although the cross-section measured here is quoted for a restricted \(\xi\)-range, \(\xi\) is not directly measured. However, the \(\eta\) coverage of the MBTS implies a lower bound on the range of \(\xi\) values for events that the detectors can observe. To study the acceptance as a function of \(\xi\), MC generators are used. The variable \(\eta\) is defined at the particle level by dividing the final state particles from the MC generators into two systems, X and Y. The mean \(\eta\) of the two particles separated by the largest pseudorapidity gap in the event is used to assign all particles with greater pseudorapidity to one system and all particles with smaller pseudorapidity to the other\(^2\). The mass, \(M_{xy}\), of each system is calculated, and the higher mass system is defined as X while the lower mass system is defined as Y. In the case of SD, Y is the non-dissociated proton. The variable \(\eta\) is then given by \(\eta = M_{xy}/s\) and it is bounded by the elastic limit, satisfying \(\eta > m_y^2/s\). As expected from kinematic considerations, a strong correlation is observed, independently of the MC model used to determine \(\xi\) between \(\xi\) and the pseudorapidity of the hadron from X that is farthest from the initial-state proton pseudorapidity. Therefore, the upper limit of the MBTS detector acceptance of \(|\eta| < 3.84\) (see Methods) can be translated into a limit on the \(\xi\) of observed events. Thus the measurement is restricted in its \(\xi\)-range; there is no requirement on \(M_y\). Several models are used for the dependence of the diffractive cross-sections on \(\xi\). The Schuler and Sjöstrand model has a relatively flat dependence on \(\xi\), whereas the Phojet model predicts a slight decrease with decreasing \(\xi\). Pythia8 has several extra predictions for the \(\xi\)-dependence of the diffractive cross-sections that are considered. In the low \(\xi\) regime, Bruni and Ingelman\(^32\) predict a flat \(\xi\)-dependence whereas Donnachie and Landshoff (DL)\(^33\) and Berger et al.\(^35\) predict

\[
\frac{d\sigma_{\text{SD}}}{d\xi} = \frac{1}{\xi^{1+\epsilon}}
\]

where \(\epsilon = \alpha(t) - 1\). Values of \(\epsilon\) between 0.06 and 0.10, and of \(\alpha'\) between 0.10 and 0.40 GeV\(^{-2}\) are considered for the DL model. \(\alpha'\) is the slope of the Pomeron trajectory that is assumed to be linear such that \(\alpha(t) = \alpha(0) + \alpha' t\). The DL model with \(\epsilon = 0.085\) and \(\alpha' = 0.25\) GeV\(^{-2}\) with Pythia8 fragmentation is the default model in this analysis, and the other models are used to assess uncertainties in the modelling of diffractive events.

**Cross-section calculation elements.** Experimentally the cross-section is calculated using

\[
\sigma_{\text{inel}}(\xi > 5 \times 10^{-6}) = \frac{(N - N_{\text{bg}})}{e_{\text{fin}} \times 1 \text{fb} \times \int \text{d}t} \frac{1 - f_{\xi < 5 \times 10^{-6}}}{e_{\text{fin}}}
\]

where \(N\) is the number of selected events, \(N_{\text{bg}}\) is the number of background events, \(f_{\xi < 5 \times 10^{-6}}\) is the fraction of events that pass the event
selection but have $\xi < 5 \times 10^{-6}$, $\int L dt$ is the integrated luminosity, and $\varepsilon_{\text{ref}}$ and $\varepsilon_{\text{unq}}$ are the trigger and offline event selection efficiencies in the selected $\xi$-range. For $\xi = 5 \times 10^{-6}$, $\varepsilon_{\text{ref}}$ is 50%, rising to nearly 100% for $\xi > 10^{-5}$. The dependence of the efficiency on $\xi$ is similar for the SD and DD processes and for different MC generators. The measurement is quoted for $\xi > 5 \times 10^{-6}$ that gives the smallest correction factor, $(1 - f_{\xi < 5 \times 10^{-6}})/\varepsilon_{\text{ref}}$, and thus yields the smallest systematic uncertainty on the measurement due to the underlying $\xi$-distribution.

In this measurement, $N_{\text{inc}}$ and $\varepsilon_{\text{unq}}$ are determined directly from the data. The MBTS individual counter efficiencies in the MC simulation are tuned to match the observed efficiencies in data. Then $\varepsilon_{\text{ref}}$ and $f_{\xi < 5 \times 10^{-6}}$ are taken from the tuned MC simulation. To reduce the uncertainties in the factors taken from MC simulation, the relative diffractive dissociation cross-section, $f_\text{D} = (\sigma_\text{D} + \sigma_\text{ref} + \sigma_\text{CM})/\sigma_\text{ref}$ for each generator is constrained. Each of these steps is described in detail below.

The MBTS functions as a trigger by determining the number of scintillation counters with a signal passing a leading-edge discriminator; in this analysis, at least one trigger signal must be present. In the offline reconstruction, the MBTS signals are fit to obtain the total charge and timing of the signal. The offline event selection requires at least two counters with a charge larger than 0.15 pC. This threshold is set to be well above the noise level, which is well described by a Gaussian centred at zero width 0.02 pC. This inclusive sample contains 1,220,743 data events. To constrain the diffractive components, a subset of events that have at least two hits on one side of the MBTS detector and no hits on the opposing side (in $z$) are selected. In the data, 122,490 of these single-sided events are observed.

### Backgrounds

Backgrounds arise from beam-related interactions, such as collisions of the beam with gas particles in the beam-pipe or with material upstream from the detector, and slowly-decaying, collision-induced radiation termed ‘afterglow’

Additionally, instrumental noise and cosmic rays provide backgrounds that were studied and found to be negligible for this analysis. The beam-related backgrounds are determined using the number of selected events collected in this fill with the non-colliding bunches, that is, when only one proton bunch was passing through ATLAS’

They are normalized by the ratio of the number of protons in the colliding to the non-colliding bunches. The single-sided selection contains 422 $\pm$ 28 background events and the inclusive sample contains $N_{\text{inc}} = 1,574 \pm 54$ background events, corresponding to 0.3% and 0.1% of the total samples, respectively. In addition, there is an in-time afterglow component owing to the scattering of secondary low-energy particles produced in the same collision event that can give extra hits, causing low-activity events to migrate into the selected event sample. This contribution is evaluated to be at most 0.4% for the inclusive, and 3.6% for the single-sided samples, by examining the asymmetry of the absolute timing measurement of the MBTS counters. We conservatively assume a 100% uncertainty on both background sources that covers any residual impact of the afterglow on the background subtraction, any uncertainty in the beam current measurements and the uncertainty due to in-time afterglow. The resulting overall uncertainty on the number of background events $N_{\text{bg}}$ is given by the quadratic sum of the two components and is 0.4%.

### Detector efficiency and modelling

The trigger efficiency of the MBTS detector, with respect to the offline requirement, $\varepsilon_{\text{ref}}$ is measured to be $99.96^{+0.03}_{-0.02}$% (statistical errors) using events triggered randomly on colliding beams. The systematic uncertainty on $\varepsilon_{\text{unq}}$ is determined using a second, independent trigger as reference. The difference between the two efficiency determinations leads to a 0.1% uncertainty on the cross-section measurement.

The data and MC simulation agreement in the MBTS counter response is checked using other detector subsystems with overlapping $\eta$ ranges: charged particles reconstructed by the tracking detector ($2.09 < |\eta| < 2.5$), and calorimeter showers in the inner wheel of the electromagnetic calorimeter ($2.5 < |\eta| < 3.2$) and in the forward calorimeter ($3.1 < |\eta| < 3.84$). The efficiency with respect to a track (calorimeter energy deposit) to have a signal above the 0.15 pC threshold in the outer (inner) counters is on average 98.5% (97.5%) for the data and a constant 99.4% (98.7%) in the MC simulation. The individual counter efficiencies deviate by up to 2.0% (2.5%) from the average in the data. The MC simulation is corrected to match the data efficiency, and the maximum variations in the counter responses are considered as a systematic uncertainty. This results in a 0.1% uncertainty on the cross-section measurement.

The offline selection efficiency, $\varepsilon_{\text{ref}}$, depends on the amount of material traversed by particles before hitting the MBTS detector. The rate of photons (primarily from $\pi^0$ decays) converting to electrons that are subsequently detected by the MBTS increases with extra material, resulting in an increase of $\varepsilon_{\text{unq}}$. Second order effects arise from charged particles scattering out of the MBTS acceptance region (decreasing $\varepsilon_{\text{unq}}$), or charged particles scattering into the acceptance region (increasing $f_{\xi < 5 \times 10^{-6}}$). Within the tracking volume ($|\eta| < 2.5$), the material distribution has been studied using conversion electrons and $K^0_S \rightarrow \pi^+\pi^-$ decays, and is known to be within ± 5% in the central region of the detector and to ± 30% for $2.2 < |\eta| < 2.5$ (ref. 38). In the region $|\eta| > 2.5$, the material is dominated by the cooling and electrical services to the silicon pixel detector, and an uncertainty of ±40% is assumed. This is validated in-situ using the fraction of events wherein we observe significant energy in the forward calorimeters but no signal (above noise) in the MBTS detector. The resulting systematic uncertainty on the cross-section is 0.2%.

Misalignments of the MBTS detector with respect to the nominal centre of the detector could change the event selection efficiency for a particular value of $\xi$. Misalignments of up to 10 mm were considered and found to have a negligible impact. A misalignment of 10 mm is conservative compared with the survey precision and any known misalignments within the ATLAS experiment.

### Fractional diffractive event contribution

The fractional contribution of diffractive events, $f_\text{D}$, is constrained by the ratio of single-sided to inclusive events, $R_\text{inc}$. The MC generators predict that less than 1% of the ND process pass the single-sided event selection, whereas 27–41% of the SD and DD processes pass the single-sided selection. For all models, the inclusive sample is dominated by ND events; therefore, the ratio of single-sided to inclusive events is sensitive to the relative fraction of diffractive events.

The measured $R_\text{inc}$ in the data is $R_\text{inc} = [10.02^{+0.03}_{-0.02}\text{ (stat.)}]^{+0.01}_{-0.01}\text{ (syst.)}$%, where the systematic error includes the uncertainties on the backgrounds, the MBTS response and the material.

Figure 1 compares the observed value of $R_\text{inc}$ to the predictions of several models as a function of $f_\text{D}$. The intersection of the $R_\text{inc}$ value measured in data with the prediction is used as the central value of $f_\text{D}$ for each model. The systematic uncertainty on $f_\text{D}$ is determined by the maximum and minimum values consistent with the 1σ uncertainty on the data when varying the double- to single-dissociation event ratio between 0 and 1. The resulting value using the default DL model is $f_\text{D} = 26.9^{+2.5}_{-1.5}$%.

### Uncertainty on acceptance

The acceptance calculation relies on the MC generators to provide an adequate description of the particle multiplicity in the acceptance region. The validity of the MC description is assessed by examining the hit multiplicity in the MBTS detector in the inclusive and single-sided event samples as shown in Figure 2. Whereas none of the generators gives a perfect...
The final result for the measured inelastic cross-section is calculated using the default DL model of $\varepsilon = 0.085$ and $\alpha' = 0.25$, which yields $f_0 = 26.9\%$, $\epsilon_{\text{inc}} = 98.77\%$, and $f_{\text{rel}} = 0.968\%$. Together with $\epsilon_{\text{inc}} = 99.98\%$, $N = 1,220,743$, $N_{\text{MC}} = 1,574$, and $|\Delta|_{\text{MC}} = 20.25 \text{ mb}^{-1}$ this results in $\sigma_{\text{inel}}(\xi > 5 \times 10^{-6}) = 60.3 \pm 0.05(\text{stat.}) \pm 0.5(\text{syst.}) \pm 2.1(\text{lumi.}) \text{ mb}$.

The systematic uncertainty includes all contributions discussed above and listed in Table 1. The dominant uncertainty arises from the luminosity calibration and is quoted separately.

**Discussion**

The measurement is compared with the predictions in Figure 3 and Table 2. The predictions by the Schuler–Sjöstrand model (66.4 mb) and the Phojet model (74.2 mb) are both higher than the data. The prediction of 51.8–56.2 mb by Ryskin et al. and personal communication, is slightly lower than the data.

To compare with previous measurements and analytic models, the fractional contribution to the inelastic cross-section of events passing the $\xi > 5 \times 10^{-6}$ cut is determined from the models and used to extrapolate the measurement to the full inelastic cross-section. This fraction is 87.3% for the default model of DL with $\varepsilon = 0.085$ and $\alpha' = 0.25$. The other models considered give fractions ranging from 96% (Phojet) to 86% (DL with $\varepsilon = 0.10$). Recent calculations also yield values between 79 and 84% (ref. 17). Thus...
The pseudorapidity is defined in terms of the polar angle \( \eta \), which is measured relative to the LHC beam pipe. The coordinate system and sub-detectors relevant to this measurement are described in detail elsewhere.

### Methods

The ATLAS detector. All measurements in this letter are made with the ATLAS detector, which is described in detail elsewhere. Here the detector coordinate system and sub-detectors relevant to this measurement are described.

ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis aligned along the LHC beam pipe. The x-axis points from the interaction point to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates \((\rho, \phi)\) 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

\[
\eta = -\ln \tan \frac{\theta}{2}.
\]

87.3% is taken as the default value for this fraction and an uncertainty of 10% is taken because of the extrapolation uncertainty on the \( \xi \)-dependence. The resulting inelastic cross-section value is \( \sigma_{\text{inel}} = 69.1 \pm 2.4 \text{(exp.)} \pm 6.9 \text{(extr.)} \text{mb} \), where the experimental uncertainty includes the statistical and experimental systematic errors, and the extrapolation uncertainty results from the uncertainty on the \( \xi \)-dependence of the cross-section.

This result is shown in Figure 3 and compared with several theoretical predictions and a variety of data at lower \( \sqrt{s} \). The measurement within the kinematic range \( \xi > 5 \times 10^{-6} \) is significantly lower than the predictions of Schuler and Sjöstrand and Phojet. The extrapolated value agrees within the large extrapolation uncertainty with the predictions from Pythia, which uses a power law dependence on \( \frac{1}{s} \). It also agrees with Block and Halzen\(^{15}\) (which has a logarithmic \( \frac{1}{s} \) dependence), and with other recent theoretical predictions that vary between 60 and 72 mb (refs 17–20). It should be stressed that this extrapolation relies on the prediction of the \( \xi \)-dependence of the cross-section.

The measurement and a variety of theoretical predictions are also summarized in Table 2.

In conclusion, a first measurement of the inelastic cross-section has been presented for \( p\bar{p} \) collisions at \( \sqrt{s} = 7 \text{ TeV} \) with a precision of 3.5%. The measurement is limited to the kinematic range corresponding to the detector acceptance: \( \xi > 5 \times 10^{-6} \). Phenomenological predictions for both a power law dependence and a logarithmic rise of the cross-section with energy are consistent with the measurement.

### References


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Author contributions
All authors have contributed to the publication, being variously involved in designing and building the detector, writing offline software, and operating and calibrating the detector and analysing the processed data.

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1University at Albany, Albany, New York, USA.
2Department of Physics, University of Alberta, Edmonton, Alberta, Canada.
3Department of Physics, Ankara University, Ankara, Turkey; 4Department of Physics, Dumlupinar University, Kutahya, Turkey; 5Department of Physics, Gazi University, Ankara, Turkey; 6Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey; 7Turkish Atomic Energy Authority, Ankara, Turkey.
8LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France.
9High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA.
10Department of Physics, University of Arizona, Tucson, Arizona, USA.
11Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA.
12Physics Department, University of Athens, Athens, Greece.
13Physics Department, National Technical University of Athens, Zografou, Greece.
14Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
15Institut de Fisica d'Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain.
16Institute of Physics, University of Belgrade, Belgrade, Serbia.
17Department for Physics and Technology, University of Bergen, Bergen, Norway.
18Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA.
19Department of Physics, Humboldt University, Berlin, Germany.
20Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland.
21School of Physics and Astronomy, University of Birmingham, Birmingham, UK.
22Department of Physics, Bogazici University, Istanbul, Turkey; 23Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey; 24Department of Physics, Istanbul Technical University, Istanbul, Turkey.
25Department of Physics, University of Timisoara, Timisoara, Romania.
26Physikalisches Institut, University of Bonn, Bonn, Germany.
27Department of Physics, Boston University, Boston, Massachusetts, USA.
28Department of Physics, Brandeis University, Waltham, Massachusetts, USA.
29Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil; 30Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil.
31Physics Department, Brookhaven National Laboratory, Upton, New York, USA.
32National Institute of Physics and Nuclear Engineering, Bucharest, Romania; 33University Politehnica Bucharest, Bucharest, Romania; 34West University in Timisoara, Timisoara, Romania.
35Department of Física, Universidad de Buenos Aires, Buenos Aires, Argentina.
36Cavendish Laboratory, University of Cambridge, Cambridge, UK.
37Department of Physics, Carleton University, Ottawa, Ontario, Canada.
38CERN, Geneva, Switzerland.
39Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA.
40Department de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; 41Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile.
42Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; 43Department of Modern Physics, University of Science and Technology of China, Anhui, China; 44Department of Physics, Nanjing University, Jiangsu, China; 45High Energy Physics Group, Shandong University, Shandong, China.
46Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France.
47Nevis Laboratory, Columbia University, Irvington, New York, USA.
48Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark.
49INFN Gruppo Collegato di Cosenza, Arcavacata di Rende, Italy; 50Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy.
51Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
52The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland.
53Physics Department, Southern Methodist University, Dallas, Texas, USA.
54Physics Department, University of Texas at Dallas, Richardson, Texas, USA.
55DESY, Hamburg and Zeuthen, Germany.
56Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany.
57Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany.
58Department of Physics, Duke University, Durham, North Carolina, USA.
59SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK.
60Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria.
61INFN Laboratori Nazionali di Frascati, Frascati, Italy.
62Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany.
63Section de Physique, Université de Genève, Geneva, Switzerland.
64INFN Sezione di Genova, Genova, Italy; 65Dipartimento di Fisica, Università di Genova, Genova, Italy.
66Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia.
67II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany.
68SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, UK.
69II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
70Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France.
71Department of Physics, Hampton University, Hampton, Virginia, USA.
72Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA.
73Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; 74Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; 75ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany.
ARTICLE

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159 Faculty of Science, Hiroshima University, Hiroshima, Japan.
160 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan.
161 Department of Physics, Indiana University, Bloomington, Indiana, USA.
162 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria.
163 University of Iowa, Iowa City, Iowa, USA.
164 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA.
165 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia.
166 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan.
167 Graduate School of Science, Kobe University, Kobe, Japan.
168 Faculty of Science, Kyoto University, Kyoto, Japan.
169 Kyoto University of Education, Kyoto, Japan.
170 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina.
171 Physics Department, Lancaster University, Lancaster, UK.
172 INFN Sezione di Lecce, Lecce, Italy; Dipartimento di Fisica, Università del Salento, Lecce, Italy.
173 Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK.
174 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia.
175 Department of Physics, Queen Mary University of London, London, UK.
176 Department of Physics, Royal Holloway University of London, Surrey, UK.
177 Department of Physics and Astronomy, University College London, London, UK.
178 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
179 Fysiska institutionen, Lunds universitet, Lund, Sweden.
180 Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain.
181 Institut für Physik, Universität Mainz, Mainz, Germany.
182 School of Physics and Astronomy, University of Manchester, Manchester, UK.
183 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
184 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA.
185 Department of Physics, McGill University, Montreal, Québec, Canada.
186 School of Physics, University of Melbourne, Victoria, Australia.
187 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA.
188 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.
189 INFN Sezione di Milano, Milano, Italy; Dipartimento di Fisica, Università di Milano, Milano, Italy.
190 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus.
191 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus.
192 Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
193 Group of Particle Physics, University of Montreal, Montreal, Québec, Canada.
194 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia.
195 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia.
196 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
197 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
198 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany.
199 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany.
200 Nagasaki Institute of Applied Science, Nagasaki, Japan.
201 Graduate School of Science, Nagoya University, Nagoya, Japan.
202 INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy.
203 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA.
204 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
205 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands.
206 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA.
207 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia.
208 Department of Physics, New York University, New York, New York, USA.
209 Ohio State University, Columbus, Ohio, USA.
210 Faculty of Science, Okayama University, Okayama, Japan.
211 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA.
212 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA.
213 Palacký University, RCPTM, Olomouc, Czech Republic.
214 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA.
215 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.
216 Graduate School of Science, Osaka University, Osaka, Japan.
217 Department of Physics, University of Oslo, Oslo, Norway.
218 Department of Physics, Oxford University, Oxford, UK.
219 INFN Sezione di Pavia, Pavia, Italy; Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy.
220 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA.
221 Petersburg Nuclear Physics Institute, Gatchina, Russia.
222 INFN Sezione di Pisa, Pisa, Italy; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
223 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.