MIT Libraries | DSpace@MIT

MIT Open Access Articles

Measurement of the inelastic proton–proton cross section at √s = 7 TeV

The MIT Faculty has made this article openly available. ***Please share*** how this access benefits you. Your story matters.

Citation: Chatrchyan, S., et al. "Measurement of the Inelastic Proton–Proton Cross Section at S=7 TeV." Physics Letters B, vol. 722, no. 1–3, May 2013, pp. 5–27. © 2013 CERN. Published by Elsevier B.V.

As Published: http://dx.doi.org/10.1016/J.PHYSLETB.2013.03.024

Publisher: Elsevier BV

Persistent URL: http://hdl.handle.net/1721.1/116432

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of use: Attribution 3.0 Unported (CC BY 3.0)

Massachusetts Institute of Technology

Physics Letters B 722 (2013) 5–27

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 25 October 2012
Received in revised form 3 March 2013
Accepted 15 March 2013
Available online 21 March 2013
Editor: M. Doser

Keywords:
CMS
Physics
Inelastic cross section
Tracking efficiency
Forward energy
Total cross section
LHC

ABSTRACT

A measurement is presented of the inelastic proton–proton cross section at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. Using the CMS detector at the LHC, the inelastic cross section is measured through two independent methods based on information from (i) forward calorimetry (for pseudorapidity $3 < |\eta| < 5$), in collisions where at least one proton loses more than 5×10^{-6} of its longitudinal momentum, and (ii) the central tracker ($|\eta| < 2.4$), in collisions containing an interaction vertex with more than one, two, or three tracks with transverse momenta $p_T > 200$ MeV/c. The measurements cover a large fraction of the inelastic cross section for particle production over about nine units of pseudorapidity and down to small transverse momenta. The results are compared with those of other experiments, and with models used to describe high-energy hadronic interactions.

© 2013 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

1. Introduction

Total hadronic cross sections, as well as their major subdivisions into elastic, inelastic diffractive and inelastic non-diffractive contributions, comprise fundamental quantities that have been studied in high-energy particle, nuclear, and cosmic-ray physics over the past 60 years, in experiments covering many orders of magnitude in centre-of-mass energy [1–5].

The bulk of the total cross section in proton–proton (pp) hadronic interactions cannot be calculated through perturbative quantum chromodynamics, but phenomenological approaches based on fundamental principles of quantum mechanics, such as unitarity and analyticity, can be used to accommodate the experimental results (e.g. Ref. [6], and references therein). Although phenomenological models of cross sections at low centre-of-mass energies ($\sqrt{s} \leqslant 100$ GeV) provide a rather precise description of the data, there are large uncertainties in extrapolating to the energy range of the Large Hadron Collider (LHC). The measured inelastic pp cross section (σ_{inel}) serves as an input to these phenomenological models, and provides basic information needed for tuning hadronic Monte Carlo (MC) generators. The values of σ_{inel} are also used to estimate the number of pp interactions as a function of luminosity at colliders, and are relevant to studies of high-energy cosmic rays [7] and to the characterization of global properties of heavy-ion collisions, especially in the context of the Glauber model [8].

This Letter presents a measurement of the inelastic pp cross section at $\sqrt{s} = 7$ TeV, using data collected with the Compact Muon Solenoid (CMS) detector at the LHC. The analysis is based mostly on the central silicon tracker and the forward hadron calorimeters (HF) of the CMS apparatus. The combination of these two detectors provides sensitivity to a large part of the inelastic cross section, including central diffractive production, where particles can be produced at small values of pseudorapidity.

The measurement using the HF calorimeters covers a region of phase space corresponding to values of fractional momentum loss of the scattered proton of $\xi = (M_X c^2)^2/s > 5 \times 10^{-6}$, equivalent to $M_X > 16$ GeV/c^2, where M_X is defined as the larger mass of the two dissociated proton systems in the final state. This coverage is the same as that used in recent publications by the ATLAS [3] and the ALICE [5] Collaborations.

2. Experimental apparatus

A detailed description of the CMS apparatus can be found in Ref. [9], and the features most relevant to the present analysis are sketched below. The CMS detector comprises a 6 m diameter, 13 m long, 3.8 T solenoid magnet, with a combined silicon pixel and strip tracker covering the region $|\eta| < 2.5$, a lead-tungstate electromagnetic calorimeter and a brass/scintillator hadronic calorimeter covering the region $|\eta| < 3.0$; these detectors are contained within the volume of the magnetic field. The pseudorapidity is defined

☆ © CERN for the benefit of the CMS Collaboration.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

0370-2693 © 2013 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
http://dx.doi.org/10.1016/j.physletb.2013.03.024

as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle of any particle with respect to the anticlockwise circulating beam. Several layers of muon chambers (drift-tube, resistive-plate and cathode-strip chambers) form the outer part of the detector. The charged-particle resolution of the central tracker for a transverse momentum of $p_T = 1$ GeV/c is between 0.7% at $|\eta| = 0$ and 2% at $|\eta| = 2.5$ [9].

On each side of the detector, at $3.0 < |\eta| < 5.2$, reside the hadron forward calorimeters (HF), each composed of 18 iron wedges, with embedded quartz fibres running along the beam direction. Each wedge is subdivided into 13 η-segments, called towers.

The beam-sensitive "pick-up" detectors, consisting of two pairs of button electrodes located at ±175 m from the centre of the detector, provide almost 100% detection efficiency and accurate timing of proton bunches at CMS. The luminosity is calculated from dedicated Van der Meer scans, using information from the beam profile and beam current measurements, with a precision of 4% that is dominated by the uncertainty of the beam current determination [10,11].

3. Estimating the inelastic cross section using the HF calorimeters

In this method, the inelastic pp cross section is measured by counting the number of events that deposit at least 5 GeV of energy in either of the two HF calorimeters. The threshold $E_{HF} > 5$ GeV is set to minimize the effect of detector noise on the efficiency of selecting pp collisions.

3.1. Event selection and analysis

The analysis is performed using data collected in low-luminosity runs with an average of 0.007 to 0.11 collisions per bunch crossing. The events are collected using three triggers: (i) a coincidence trigger that requires the presence of two colliding bunches, used to select an unbiased sample of pp events, (ii) a single-bunch trigger, requiring the presence of just one unpaired bunch, used to estimate beam-induced backgrounds, and (iii) a random "empty" trigger, requiring absence of both beams, which is used to estimate detector noise. All these triggers are formed from information provided by the beam pick-up detectors.

The analysis is based on counting the number of pp collisions with $E_{HF} > 5$ GeV in either of the two HF calorimeters. The cross section is evaluated in terms of the variable ξ, which is defined through MC studies as follows. For each MC event, generator-level information is used to order final-state particles in rapidity and to find the largest gap between two consecutive particles. This "central" gap is used to separate all particles into two groups, by assigning each particle, according to its rapidity position relative to that gap, to system A or system B. Finally, the masses of system A and B are calculated, and the larger of the two is called M_X, while the smaller one M_Y, thereby defining $\xi = (M_X c^2)^2/s$. In single-diffractive events, ξ corresponds to the fraction of momentum lost by the proton in the collision. The ξ distribution is bound by the elastic limit of $\log_{10}((m_{\text{proton}}c^2)^2/s) \approx -7.75$.

The distributions in ξ values for $E_{HF} > 4$ and > 5 GeV are shown in Fig. 1 for three Monte Carlo models: PYTHIA 6 (version 6.422) [12], PYTHIA 8 (version 8.135, 8.145) [13], and PHOJET (version 1.12-35) [14,15]. These selected models differ in the treatment of non-perturbative processes and use a different set of assumptions for soft pp interactions. They capture qualitative features of diffraction well, and they also cover reasonable variations of simulated distributions of ξ. As the plots illustrate, to maintain large detection efficiency, and to mitigate model-dependence, it appears adequate to restrict the range of ξ to values greater than 5×10^{-6}.

Table 1
Values of efficiency (ϵ_ξ) and contamination (b_ξ) for events with $\xi > 5 \times 10^{-6}$ using the selection criterion of $E_{HF} > 5$ GeV, obtained for three Monte Carlo models of hadronic production.

Generator	ϵ_ξ (%)	b_ξ (%)
PYTHIA 6	97.5 ± 0.6	2.0
PYTHIA 8	99.3 ± 0.2	2.0
PHOJET	99.1 ± 0.2	1.2

The measured values of σ_{inel} are corrected using two quantities obtained through MC simulation: the selection efficiency ϵ_ξ, which represents the fraction of pp interactions with $\xi > 5 \times 10^{-6}$ that are selected by requiring $E_{HF} > 5$ GeV, and the contamination b_ξ, which is the fraction of events that have $E_{HF} > 5$ GeV, but originate from $\xi < 5 \times 10^{-6}$. Table 1 gives the values of ϵ_ξ and b_ξ estimated in the three Monte Carlo models. These efficiencies carry a small (< 1%) uncertainty due to the HF energy scale uncertainty, estimated as the difference between the efficiencies obtained with different HF energy thresholds (corresponding to 20% energy scale variations). As the table shows, the criterion $E_{HF} > 5$ GeV selects a large fraction of events with $\xi > 5 \times 10^{-6}$, with only a small contamination from events with $\xi < 5 \times 10^{-6}$ that characterize contributions originating from low-mass single-proton or double-proton fragmentation.

3.2. Measurement of the inelastic cross section

The analysis is performed using ≈9.2 million events, corresponding to an integrated luminosity of 2.78 μb^{-1}, collected under the two-bunch coincidence condition, of which 2.1% have $E_{HF} > 5$ GeV. The fractions of $E_{HF} > 5$ GeV events selected by the single-bunch and empty triggers are, respectively, 0.30% and 0.32%, suggesting that most of the single-bunch events are from detector noise rather than beam-gas collisions. This is confirmed by the observation that, in the single-bunch triggered sample, the number of events with at least one track is very small. For this reason, beam-gas contributions are considered negligible.

The number of detected inelastic collisions (N_{inel}) contained in the total number of coincidence trigger events (N_{coinc}) is obtained as follows:

$$N_{\text{inel}} = N_{\text{coinc}}\big[(\mathcal{F}_{\text{coinc}} - \mathcal{F}_{\text{empty}}) + \mathcal{F}_{\text{empty}}(\mathcal{F}_{\text{coinc}} - \mathcal{F}_{\text{empty}})\big], \quad (1)$$

where $\mathcal{F}_{\text{empty}}$ and $\mathcal{F}_{\text{coinc}}$ correspond to the fractions of empty and coincidence triggers with $E_{HF} > 5$ GeV. The term $N_{\text{coinc}}\mathcal{F}_{\text{empty}} \times (\mathcal{F}_{\text{coinc}} - \mathcal{F}_{\text{empty}})$ represents the number of true collisions in $N_{\text{coinc}}\mathcal{F}_{\text{empty}}$ events.

The value of N_{inel} has to be corrected for event pileup, i.e. the possibility that more than one collision with $E_{HF} > 5$ GeV occurs in the same trigger, but all such collisions are counted as just a single event. The number of collisions per trigger is assumed to follow Poisson statistics, for which the probability of i simultaneous collisions ($i = 1, 2, 3, \ldots$) is given by

$$P(n, \lambda) = \frac{\lambda^n e^{-\lambda}}{n!}, \quad (2)$$

where λ is the mean number of interactions with $E_{HF} > 5$ GeV, which depends on the instantaneous luminosity (L). The fraction f_{pu} of overlapping collisions, each with $E_{HF} > 5$ GeV, is computed as

$$f_{\text{pu}} = \frac{\sum_{n=2}^{\infty} P(n, \lambda)}{\sum_{n=1}^{\infty} P(n, \lambda)} = \frac{1 - (1+\lambda)e^{-\lambda}}{1 - e^{-\lambda}} \sim \frac{\lambda}{2} - \frac{\lambda^2}{12} + \mathcal{O}(\lambda^3), \quad (3)$$

where λ is evaluated from the fraction of detected interactions $r_{\text{int}} = N_{\text{inel}}/N_{\text{coinc}}$:

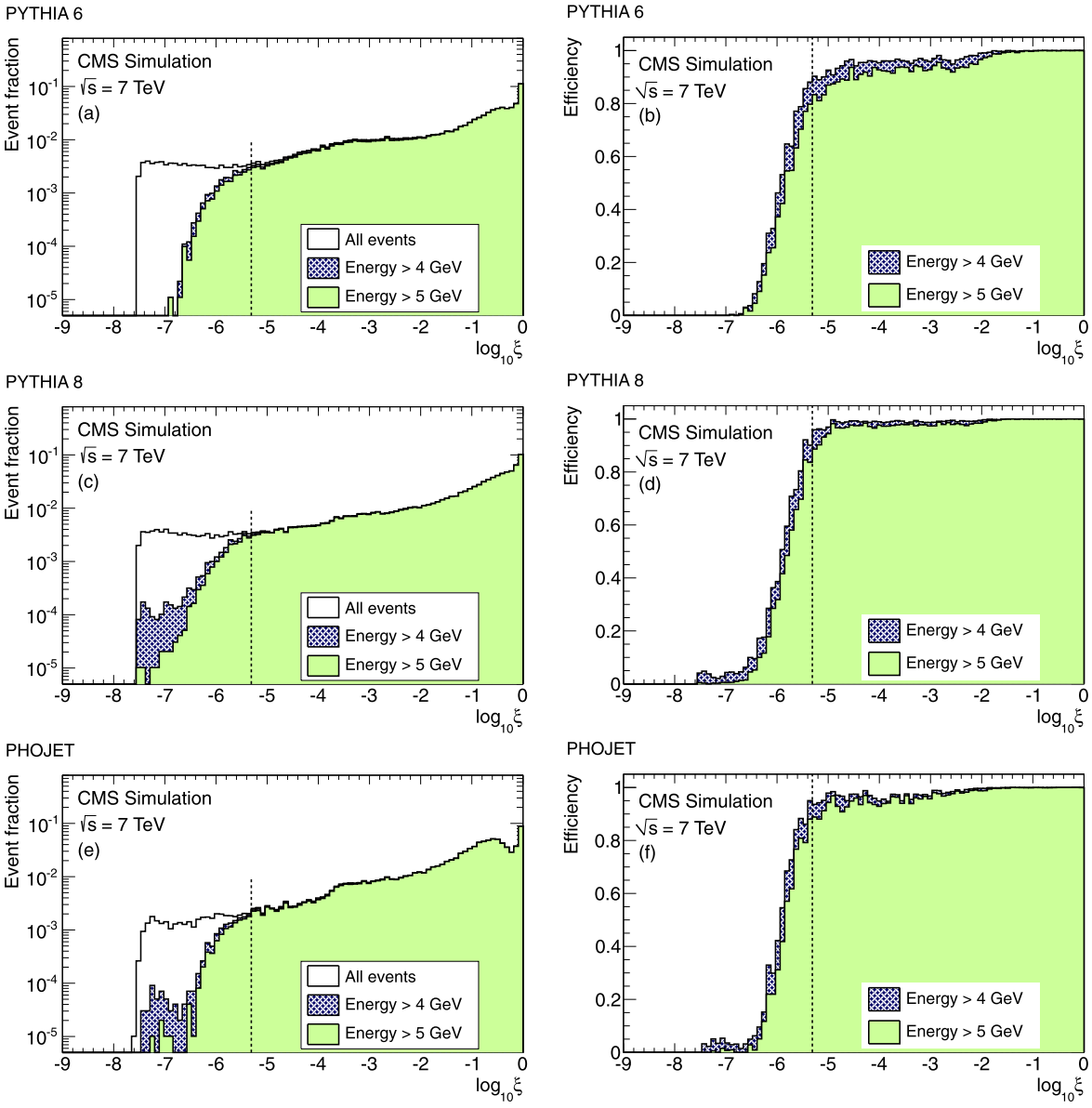

Fig. 1. The normalized ξ distributions for $E_{\mathrm{HF}} > 4$ and $E_{\mathrm{HF}} > 5$ GeV from MC simulation of inelastic pp collisions using (a) PYTHIA 6, (c) PYTHIA 8, and (e) PHOJET, are shown for the full range of ξ. The corresponding efficiencies are shown in (b), (d), and (f), respectively. The cut value of ξ used in this analysis of 5×10^{-6} is shown on the plots as a dashed vertical line.

$$r_{\mathrm{int}} = \sum_{n=1}^{\infty} P(n,\lambda) = 1 - P(0,\lambda) = 1 - \mathrm{e}^{-\lambda},$$

$$\lambda = -\ln(1 - r_{\mathrm{int}}). \tag{4}$$

The denominator in Eq. (3) assumes independent probabilities for detecting each of the simultaneous collisions, which is a good approximation for $E_{\mathrm{HF}} > 5$ GeV.

Table 2 lists the values of λ and f_{pu}, as calculated using the exact formula in Eq. (3), and their statistical uncertainties for different data runs. The accuracy on the correction factor f_{pu} is limited mostly by the number of events in each run.

The relationship used to evaluate the cross section for $\xi > 5 \times 10^{-6}$, taking account of corrections for pileup, efficiency, and contamination corresponds to:

$$\sigma_{\mathrm{inel}}\left(\xi > 5 \times 10^{-6}\right) = \frac{N_{\mathrm{inel}}(1 - b_{\xi})(1 + f_{\mathrm{pu}})}{\epsilon_{\xi} \int L\,\mathrm{d}t}, \tag{5}$$

Table 2
Mean number of collisions with $E_{\mathrm{HF}} > 5$ GeV per coincidence trigger (λ) and fraction of overlapping collisions (f_{pu}) for the runs used in this analysis.

Run No.	λ	f_{pu}
132 601	$(0.64 \pm 0.01)\%$	0.0032 ± 0.0001
132 599	$(0.78 \pm 0.01)\%$	0.0039 ± 0.0001
133 877	$(1.74 \pm 0.02)\%$	0.0087 ± 0.0001
133 874	$(3.34 \pm 0.05)\%$	0.0166 ± 0.0002
137 027	$(4.59 \pm 0.17)\%$	0.0228 ± 0.0009
135 575	$(8.41 \pm 0.04)\%$	0.0415 ± 0.0002
135 175	$(9.98 \pm 0.05)\%$	0.0491 ± 0.0003

where $\int L\,\mathrm{d}t$ is the integrated luminosity of the data sample.

3.3. Results and systematic uncertainties

The value of σ_{inel} for $\xi > 5 \times 10^{-6}$ is calculated by averaging the results obtained from Eq. (5) for the different pileup conditions of

Table 3
List of systematic sources and their effects on the value of the inelastic cross section measured using HF calorimeters. The integrated luminosity contributes an additional uncertainty of 4% to this measurement.

Systematic source	Uncertainty on σ_{inel}	Change in σ_{inel}
Run-to-run variation	± 0.8 mb	$\pm 1.3\%$
Selection efficiency	± 0.6 mb	$\pm 1.0\%$
Contamination from $\xi < 5 \times 10^{-6}$	± 0.3 mb	$\pm 0.5\%$
HF tower exclusion	± 0.3 mb	$\pm 0.4\%$
HF energy threshold	± 0.1 mb	$\pm 0.2\%$
Total (in quadrature)	± 1.1 mb	$\pm 1.8\%$

Table 2. The largest systematic uncertainty, besides the 4% uncertainty of the absolute luminosity value, is due to fluctuations in the luminosity determination of the different low-pileup runs. The model dependence of the efficiency ϵ_ξ contributes $\pm 1\%$, while the correction for the contamination from events below the ξ threshold is uncertain by $\pm 0.5\%$ as given by the standard deviation of the $(1 - b_\xi)$ factors obtained from the three MC simulations studied. The exclusion of noisy HF towers in the calculation of HF energy changes the results by $\pm 0.4\%$, a value that is taken as a systematic uncertainty. Finally, lowering the value of the calorimeter threshold E_{HF} from 5 to 4 GeV introduces a change of 0.2% in the final result.

Table 3 lists the individual systematic uncertainties, and their total impact, calculated by adding the separate contributions in quadrature. The inelastic pp cross section for events with $\xi > 5 \times 10^{-6}$ is found to be:

$$\sigma_{\text{inel}}\left(\xi > 5 \times 10^{-6}\right) = \big[60.2 \pm 0.2\,(\text{stat.}) \pm 1.1\,(\text{syst.}) \pm 2.4\,(\text{lum.})\big]\ \text{mb}. \quad (6)$$

This result is in agreement with equivalent measurements from the ATLAS Collaboration $\sigma_{\text{inel}}^{\text{ATLAS}}(\xi > 5 \times 10^{-6}) = [60.3 \pm 0.05\,(\text{stat.}) \pm 0.5\,(\text{syst.}) \pm 2.1\,(\text{lum.})]$ mb [3], and from the ALICE Collaboration $\sigma_{\text{inel}}^{\text{ALICE}}(\xi > 5 \times 10^{-6}) = [62.1^{1.0}_{-0.9}\,(\text{syst.}) \pm 2.2\,(\text{lum.})]$ mb [5]. The uncertainties on luminosity of the three measurements are highly correlated.

4. Estimating the inelastic cross section by counting event vertices

A vertex-counting method is also used to measure the inelastic pp cross section. The method relies on the accuracy of the CMS tracking system and not upon any specific Monte Carlo simulation. This method assumes that the number (n) of inelastic pp interactions in a given bunch crossing follows the Poisson probability distribution of Eq. (2), where λ is calculated from the product of the instantaneous luminosity for a bunch crossing and the total inelastic pp cross section: $\lambda = L \cdot \sigma_{\text{inel}}$. The probability of having n inelastic pp interactions, each producing a vertex with > 1, > 2, or > 3 charged particles with $p_{\text{T}} > 200$ MeV/c within $|\eta| = 2.4$, for n between 0 and 8, is measured at different luminosities to evaluate σ_{inel} from a fit of Eq. (2) to the data.

4.1. Event selection and method of analysis

Inclusive samples of $\approx 3 \times 10^6$ two-electron candidate events, and $\approx 1.5 \times 10^6$ single-muon candidate events, are selected for this analysis. The specific trigger requirements are not important, as long as their efficiencies do not depend on the number of pileup interactions. The "triggering interaction", i.e. the process associated with the production of either the two electrons or the single muon, is not included in the vertex count, but is used just to sample unbiased pileup interactions, given by the additional vertices in the same bunch crossing.

The analysis is performed using data collected with the single-muon sample, while the data collected with the two-electron trigger are used to perform a systematic check on the effect of the choice of the trigger on the result. For each of the two data samples, the distributions in the fraction of events with 0 to 8 pileup interactions are measured as a function of luminosity. A bin-by-bin correction is applied to these measurements to obtain true distributions which are then fitted to Eq. (2), to extract a common value of σ_{inel}. This correction is mainly due to vertex reconstruction efficiency and p_{T} migration. The distribution of the bin-by-bin correction factors is centered around 1 with all values contained in the interval 0.7–1.3.

The bin-by-bin corrections, evaluated from full Monte Carlo simulation (PYTHIA 6) and reconstruction of events in the CMS detector, do not depend on any specific production model, but only on an accurate simulation of the CMS tracking system. The distributions of charged particles in transverse momentum and in track multiplicity in MC events are reweighted to provide agreement with the data, as these two quantities influence the vertex reconstruction efficiency. The track multiplicity distribution has a broad maximum between 4 and 8 and extends up to 70 tracks. Cross sections are measured for inclusive pp interactions with > 1, > 2, and > 3 charged particles, with $p_{\text{T}} > 200$ MeV/c and $|\eta| < 2.4$, where "charged particles" refer to those with decay lengths $c\tau > 1$ cm.

4.2. Vertex definition and reconstruction

To be counted, a pileup interaction has to have a sufficient number of tracks to provide a vertex of good quality [16]. The vertex quality depends upon the number and characteristics of the individual tracks attributed to each vertex. A vertex is also required to have the longitudinal z position within 20 cm of the nominal interaction point.

There are two main reasons that lead to incorrect vertex reconstruction: (i) overlap with another vertex, i.e. the reconstruction program merges two vertices, and (ii) an insufficient number of tracks, or tracks too poorly measured to pass vertex-quality requirements. The vertexing algorithm is very efficient in distinguishing vertices that are further apart than 0.06 cm along the beam direction, and this analysis requires a minimum distance of 0.1 cm. Minimum distances of 0.06 cm and of 0.2 cm are used to check for any systematic effects from this requirement. The fraction of vertices lost from merging depends on luminosity and is almost negligible in the lowest luminosity bin while it becomes around 2% in the highest bin, an effect that is well reproduced by MC simulation, and is therefore corrected. The second source of inefficiency in vertex reconstruction depends on the number of tracks per vertex. Vertices with a large number of tracks are always well reconstructed, while vertices with less than 10 tracks suffer some degradation in reconstruction efficiency: this efficiency is 80% for four-track vertices, 65% for three-track vertices and 40% for two-track vertices.

There are also two main sources of secondary vertices that are not related specifically to σ_{inel}: additional vertices generated through decays of long-lived particles, and false secondary vertices generated by splitting a single vertex into two distinct vertices. Misidentified secondary vertices can often be rejected, as they have a much lower track multiplicity, and they are not necessarily positioned along the beam line: for this last reason, the transverse position of the vertex is required to be within ± 0.06 cm from the nominal beam line.

The correction of number of candidate vertices to the true number of pileup interactions is considered as a function of luminosity.

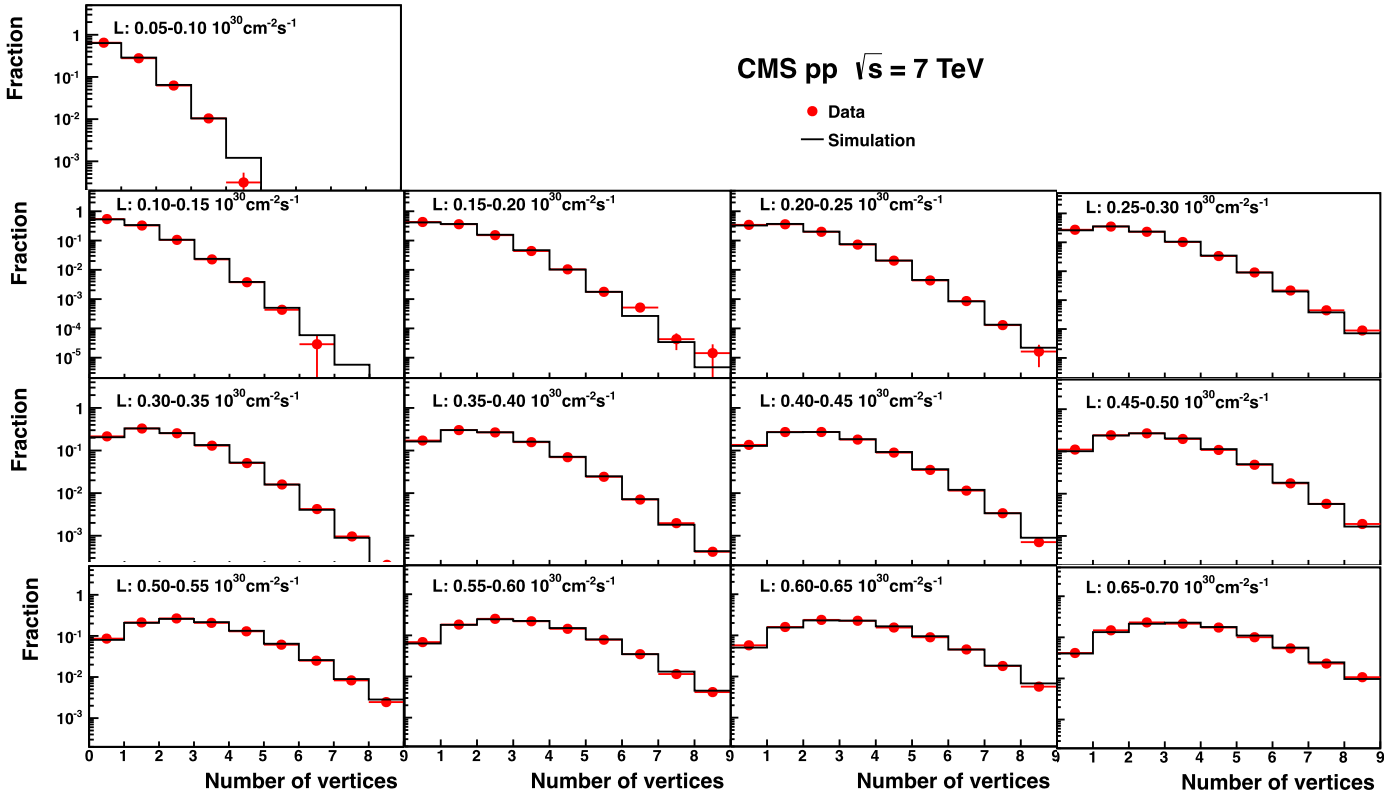

Fig. 2. Fraction of reconstructed events with more than one track, corrected for efficiency, measured as a function of the number of vertices, in data (dots) and in Monte Carlo (histogram), for instantaneous bunch-crossing luminosities between 0.05×10^{30} and 0.7×10^{30} cm^{-2} s^{-1}.

In particular, a 2-vertex event recorded at low luminosity is most likely to correspond to a true 2-vertex event, while a 2-vertex event recorded at high luminosity is most likely a 3 or 4-vertex event, in which 1 or 2 vertices are merged. We divide the data into 13 equal intervals of instantaneous bunch-crossing luminosity, from 0.05×10^{30} to 0.7×10^{30} cm^{-2} s^{-1}. To obtain the true pileup distribution in each luminosity interval, we proceed as follows:

(i) Using Eq. (2), the expected distribution of pileup interactions is calculated for the specific luminosity interval, assuming some trial value $\sigma_{\text{inel}}^{\text{trial}}$ for the inelastic cross section.
(ii) The Monte Carlo simulation is reweighted to generate a pileup distribution matching the one calculated in step (i). Steps (i) and (ii) are repeated several times for different $\sigma_{\text{inel}}^{\text{trial}}$, until good agreement is reached between data and the reconstructed pileup distributions for MC events.
(iii) The generated pileup distributions for inclusive interactions with >1, >2, and >3 tracks, each with $p_{\text{T}} > 200$ MeV/c and $|\eta| < 2.4$, is obtained from the reweighted Monte Carlo.
(iv) The bin-by-bin corrections are computed using the ratio of reconstructed to generated Monte Carlo pileup distributions for >1, >2, and >3 tracks, yielding thereby the correction factors for each of these three inclusive sets of events.

The corrected fractional distributions of events, for interactions with more than 1 track in data or in the MC, are compared in Fig. 2 as a function of the number of vertices (n) for the thirteen bins in instantaneous luminosity.

4.3. Results and systematic uncertainties

Fig. 3 displays the data points from Fig. 2 as a function of the instantaneous luminosity, for events with $n = 0$ to 8 pileup vertices. For each n, the values of the Poisson distribution given by Eq. (2) are fitted as a function of $\lambda = L \cdot \sigma_{\text{inel}}$ to the data, providing nine estimates of the inelastic cross section. Their weighted average provides the final result shown in Fig. 4(a). The error bars and the values of goodness of fit per degree of freedom (χ^2/NDOF) for each result are obtained from the individual Poisson fits of Fig. 3. Fig. 4(b) shows the normalized χ^2 values for each of the fits to Eq. (2). The equivalent plots for vertices with more than two and more than three tracks are very similar, as the overlap among the datasets is above 95%.

The main source of systematic uncertainty is the 4% uncertainty on CMS luminosity, which leads to an uncertainty $\Delta\sigma_{\text{lum}} = \pm 2.4$ mb. The largest contribution arising from the method of analysis, $\Delta\sigma_{\text{vtx}} = \pm 1.4$ mb, is the uncertainty on the vertex-reconstruction efficiency, which is evaluated using a Monte Carlo simulation and a method based on data. This second technique utilizes measured quantities such as the distribution of the longitudinal z position of the vertex and the distribution of the minimum distance between two vertices to evaluate the vertex-reconstruction efficiency. Other uncertainties linked to vertex selection are estimated by: (i) reducing the range used for accepting longitudinal positions of vertices from $|z| < 20$ to $|z| < 10$ cm relative to the centre of the CMS detector, (ii) modifying the vertex-quality requirements, (iii) changing the minimum distance between two vertices from $\Delta z < 0.1$ cm to 0.06 cm and 0.2 cm, and (iv) changing the maximum allowed transverse coordinate of the vertex from ± 0.06 cm to ± 0.05 cm and ± 0.08 cm.

Several other possible sources of uncertainty have also been checked by: (i) performing the analysis on sets of data collected with different trigger requirements (two-electron or single-muon trigger) to measure the effect of the trigger on the selection of pileup events, (ii) changing the luminosity interval used in the fit by $\pm 0.05 \times 10^{30}$ cm^{-2} s^{-1}, and (iii) repeating the analysis without

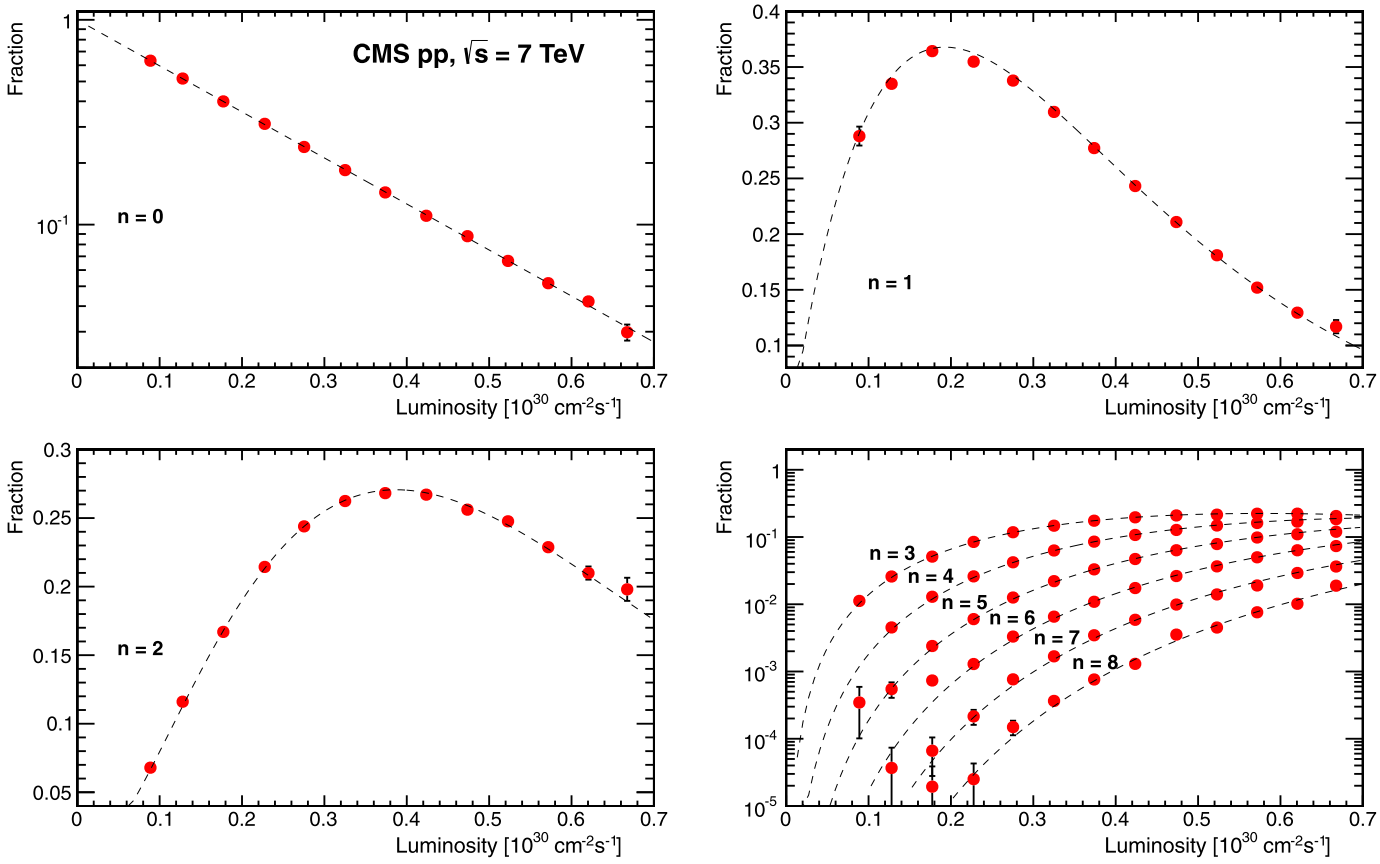

Fig. 3. Fraction of pp events with n pileup vertices, for $n = 0$ to 8, containing more than one charged particle, as a function of instantaneous bunch-crossing luminosity. The dashed lines are the fits described in the text. The data points are plotted at the mean of the differential distribution in each bin.

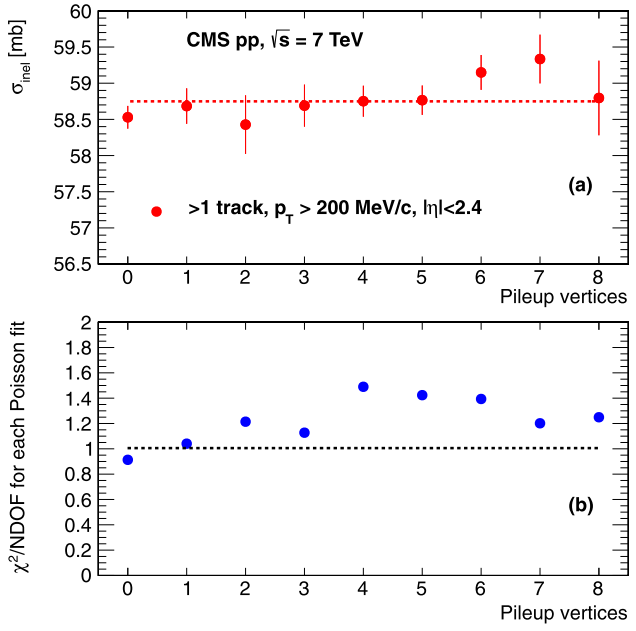

Fig. 4. (a) Values of the inelastic pp cross section σ_{inel} and (b) their associated goodness of fit χ^2/NDOF, obtained for each of the fits in Fig. 3, as a function of the number of pileup vertices, in interactions with > 1 track with $p_{\text{T}} > 200$ MeV/c and $|\eta| < 2.4$. The line in (a) is the result of a fit to the 9 individual values of σ_{inel}, while the dashed line in (b) indicates $\chi^2/\text{NDOF} = 1$.

reweighting the track-multiplicity distributions in the MC, to evaluate the effect of an incorrect track-multiplicity shape, which should not influence the bin-by-bin correction to first order. The uncertainty attributed to each systematic source is defined by the largest change in σ_{inel}. The full list of the systematic sources is shown in Table 4. Adding all the uncertainties in quadrature yields a total systematic uncertainty on the method of $\Delta\sigma_{\text{syst}} = \pm 2.0$ mb.

The measured values of σ_{inel} for inclusive interactions with >1, >2, and >3 charged particles with $|\eta| < 2.4$ and $p_{\text{T}} > 200$ MeV/c, as well as their individual uncertainties, are listed in Table 5. The statistical error is below 0.1 mb and is ignored.

5. Results and comparison with Monte Carlo models

The two techniques presented to measure the inelastic pp cross section complement each other. The calorimeter-based method is very sensitive to events that produce forward energy deposition, and, in particular, small M_X values that comprise particle systems highly boosted along the beam line. However, the method is less sensitive to central diffractive dissociation events, with particle production concentrated at small pseudorapidities. Conversely, the vertex-counting method is geared toward measurement of centrally-produced events, and is not optimal for events with particles produced mostly at large η. The concurrent use of these two methods provides therefore almost complete coverage of all types of pp inelastic events, with particle production in the range of $|\eta| \lesssim 5$.

Fig. 5 compares the CMS results with the measurements presented by the TOTEM [2], the ATLAS [3] and the ALICE [5] Collaborations, as well as with predictions of two groups of Monte Carlo models. The first group comprises several versions of PYTHIA: PYTHIA 6 (tunes D6T, Z1_LEP [17], AMBT1, DW-Pro, and Pro-PT0

Table 4
List of systematic sources and their effects on the value of the inelastic cross section measured using the vertex-counting method. The % changes are shown for the results of the $\sigma_{\text{inel}}(>1\text{ track})$ measurement. The integrated luminosity contributes an additional uncertainty of 4% to this measurement.

Systematic source	Uncertainty on σ_{inel}	Change in $\sigma_{\text{inel}}(>1\text{ track})$
Vertex reconstruction efficiency	±1.4 mb	±2.4%
Longitudinal position of vertex	±0.1 mb	±0.2%
Vertex quality	±0.7 mb	±1.3%
Minimum distance between vertices	±0.1 mb	±0.2%
Transverse position of vertex	±0.3 mb	±0.6%
Different sets of data	±0.9 mb	±1.6%
Range of luminosity used in fit	±0.2 mb	±0.4%
Reweighting MC track distribution	±0.2 mb	±0.4%
Total (in quadrature)	±2.0 mb	±3.3%

Table 5
σ_{inel} values for interactions with >1, >2 and >3 charged particles, with their uncertainties from systematic sources of the method and from luminosity. The statistical error is below 0.1 mb and is ignored.

Measurement	Result
$\sigma_{\text{inel}}(>1\text{ track})$	$[58.7 \pm 2.0(\text{syst.}) \pm 2.4(\text{lum.})]$ mb
$\sigma_{\text{inel}}(>2\text{ tracks})$	$[57.2 \pm 2.0(\text{syst.}) \pm 2.4(\text{lum.})]$ mb
$\sigma_{\text{inel}}(>3\text{ tracks})$	$[55.4 \pm 2.0(\text{syst.}) \pm 2.4(\text{lum.})]$ mb

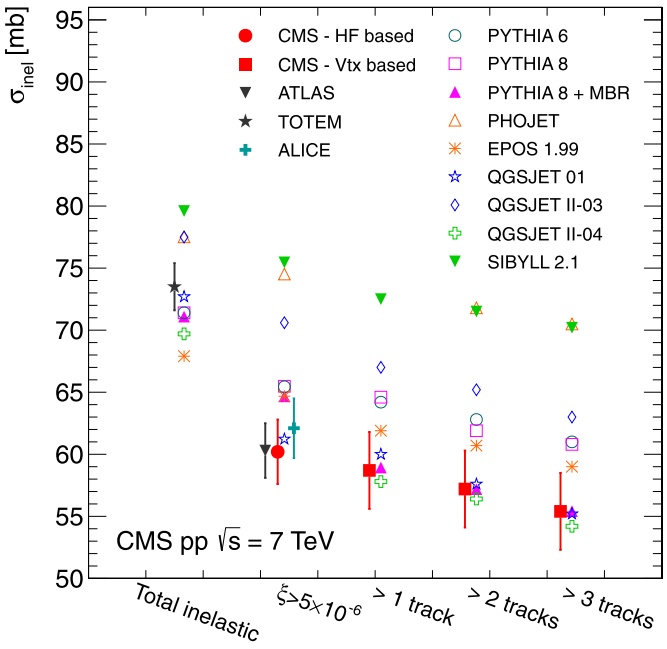

Fig. 5. The two types of CMS measurements of the inelastic pp cross section (red filled circle and squares) compared to predictions from several Monte Carlo models for different criteria, as labeled below the abscissa axis. The MC predictions have an uncertainty of 1 mb (not shown). The label PYTHIA 6 (tunes D6T, Z1_LEP, AMBT1, DW-Pro, and Pro-PT0) and PYTHIA 8 (versions 8.127–8.139, Tunes 2C 8.140 Cor10a, Tune 2M 8.140 Cor10a, and Tune 4C 8.145 Cor10a) indicates several versions that give equivalent results. Other LHC experimental results are also included for comparison.

provide very similar results), PYTHIA 8 (versions 8.135 Tune 1, 8.145 Tunes 2C, Tune 2M, and Tune 4C are equivalent) and the recent PYTHIA 8 MBR tune [18] (version 8.165). The second group includes MC generators based on the same Regge–Gribov phenomenology, but with different implementations of model ingredients [19]: PHOJET, as well as three MC programs commonly used in cosmic-rays physics, such as QGSJET 01 [20], QGSJET II (versions 03 and 04) [21], SIBYLL (version 2.1) [22] and EPOS (version 1.99) [23].

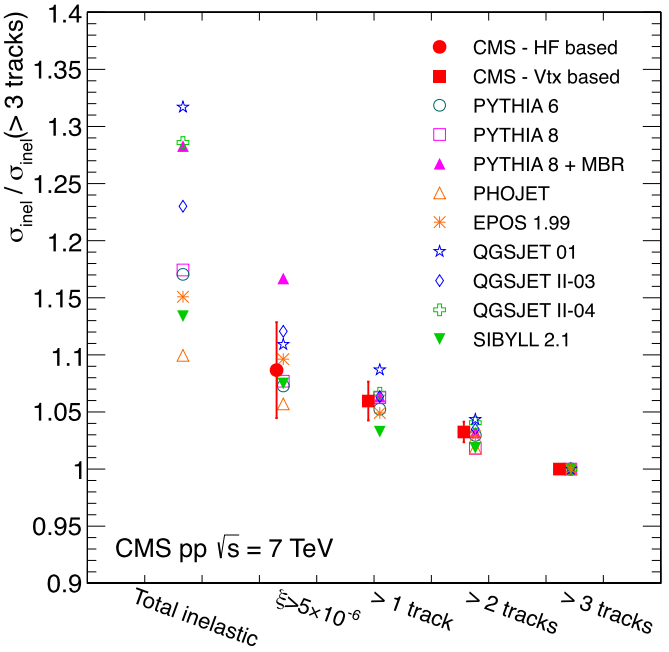

Fig. 6. Comparison of the measured inelastic pp cross sections with predictions of several Monte Carlo models, for different criteria, normalized to the value obtained for >3 tracks.

Table 6
Measured inelastic pp cross sections normalized to $\sigma_{\text{inel}}(>3\text{ tracks})$, and their uncertainties.

Ratio	Result
$\sigma_{\text{inel}}(>2\text{ tracks})/\sigma_{\text{inel}}(>3\text{ tracks})$	1.032 ± 0.009
$\sigma_{\text{inel}}(>1\text{ track})/\sigma_{\text{inel}}(>3\text{ tracks})$	1.060 ± 0.017
$\sigma_{\text{inel}}(\xi > 5 \times 10^{-6})/\sigma_{\text{inel}}(>3\text{ tracks})$	1.087 ± 0.042

The PHOJET and SIBYLL models overestimate the observed cross sections by more than 20%, while the EPOS, QGSJET II-03, PYTHIA 6, and PYTHIA 8 tunes provide predictions that are about 10% larger than the measured inelastic cross sections. QGSJET 01 and QGSJET II-04 agree within one standard deviation with the data points. The PYTHIA 8-MBR tune reproduces rather well the vertex-based measurements, while it overestimates the calorimeter-based result.

A comparison of the trends in the data with the MC models is shown in Fig. 6, where the cross sections are now normalized to the σ_{inel} value measured for events with >3 tracks. In these ratios both the systematic and statistical uncertainties are reduced as the correlations between the four measurements are very large. The values and uncertainties of the cross sections ratios are shown in Table 6. The dependence of σ_{inel} on the nature of the final states

relative to the results for >3 tracks, is well reproduced by most MC simulations.

The TOTEM Collaboration [2] has recently measured a total pp inelastic cross section of $\sigma_{\text{inel}} = 73.5^{+2.4}_{-1.9}$ mb. Although several Monte Carlo models such as EPOS, QGSJET 01, QGSJET II-4, PYTHIA 6, and PYTHIA 8 reproduce this value (Fig. 5), only QGSJET 01 and QGSJET II-04, and PYTHIA 8-MBR (but less so) are able to simultaneously reproduce the less inclusive CMS measurements. This observation suggests that most of the Monte Carlo models overestimate the contribution from high-mass diffraction to the total inelastic cross section, and underestimate the component at low mass.

6. Summary

The inelastic cross section in pp collisions at $\sqrt{s} = 7$ TeV has been measured using two methods that incorporate information either from central or from forward detectors of CMS. The results for the different choices of final states considered are:

$$\sigma_{\text{inel}}\left(\xi > 5 \times 10^{-6}\right) = \left[60.2 \pm 0.2\,(\text{stat.}) \pm 1.1\,(\text{syst.}) \pm 2.4\,(\text{lum.})\right] \text{mb},$$

$$\sigma_{\text{inel}}(> 1 \text{ track}) = \left[58.7 \pm 2.0\,(\text{syst.}) \pm 2.4\,(\text{lum.})\right] \text{mb},$$

$$\sigma_{\text{inel}}(> 2 \text{ tracks}) = \left[57.2 \pm 2.0\,(\text{syst.}) \pm 2.4\,(\text{lum.})\right] \text{mb},$$

$$\sigma_{\text{inel}}(> 3 \text{ tracks}) = \left[55.4 \pm 2.0\,(\text{syst.}) \pm 2.4\,(\text{lum.})\right] \text{mb},$$

where each track must have $p_{\text{T}} > 200$ MeV/c and $|\eta| < 2.4$. The comparison of these results with the cross section expected from Monte Carlo models used in collider and cosmic-rays studies shows that PHOJET and SIBYLL largely overestimate σ_{inel}. The EPOS, QGSJET II-03, PYTHIA 6, and PYTHIA 8 (except the MBR tune) programs predict values about 10% above the data, while QGSJET 01, QGSJET II-04 agree well with the measurements. PYTHIA 8 + MBR agrees well with the track-based measurements, but overestimates the prediction for σ_{inel} for $\xi > 5 \times 10^{-6}$. All models agree broadly with the relative dependence of the cross section on the criteria used to define the final states.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staffs at CERN and other CMS institutes, and acknowledge support from BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEP, IPST and NECTEC (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

[1] J. Beringer, et al., Particle Data Group, Phys. Rev. D 86 (2012) 010001, http://dx.doi.org/10.1103/PhysRevD.86.010001.
[2] G. Antchev, et al., TOTEM Collaboration, Europhys. Lett. 96 (2011) 21002, http://dx.doi.org/10.1209/0295-5075/96/21002, arXiv:1110.1395.
[3] ATLAS Collaboration, Nature Commun. 2 (2011) 463, http://dx.doi.org/10.1038/ncomms1472, arXiv:1104.0326.
[4] P. Abreu, et al., Pierre Auger, The Pierre Auger observatory II: Studies of cosmic ray composition and hadronic interaction models, arXiv:1107.4804, 2011.
[5] ALICE Collaboration, Measurement of inelastic, single- and double-diffraction cross sections in proton–proton collisions at the LHC with ALICE, arXiv:1208.4968, 2012.
[6] S. Donnachie, H.G. Dosch, O. Nachtmann, P. Landshoff, in: Nuclear Physics and Cosmology, in: Cambridge Mongraphs on Particle Physics, vol. 19, Cambridge University Press, 2005.
[7] R. Ulrich, R. Engel, M. Unger, Phys. Rev. D 83 (2011) 054026, http://dx.doi.org/10.1103/PhysRevD.83.054026, arXiv:1010.4310.
[8] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205, http://dx.doi.org/10.1146/annurev.nucl.57.090506.123020, arXiv:nucl-ex/0701025.
[9] CMS Collaboration, JINST 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[10] S. van der Meer, Calibration of the effective beam height in the ISR, CERN Note ISR-PO-68-31, https://cdsweb.cern.ch/record/296752, 1968.
[11] CMS Collaboration, Measurement of CMS luminosity, CMS Physics Analysis Summary CMS-PAS-EWK-10-004, http://cdsweb.cern.ch/record/1279145, 2010.
[12] T. Sjöstrand, S. Mrenna, P.Z. Skands, JHEP 0605 (2006) 026, http://dx.doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
[13] T. Sjöstrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. 178 (2008) 852, http://dx.doi.org/10.1016/j.cpc.2008.01.036, arXiv:0710.3820.
[14] F.W. Bopp, R. Engel, J. Ranft, Rapidity gaps and the PHOJET Monte Carlo, arXiv:hep-ph/9803437, 1998.
[15] R. Engel, Z. Phys. C 66 (1995) 203, http://dx.doi.org/10.1007/BF01496594.
[16] CMS Collaboration, Tracking and primary vertex results in first 7 TeV collisions, CMS Physics Analysis Summary CMS-PAS-TRK-10-005, http://cdsweb.cern.ch/record/1279383/, 2010.
[17] R. Field, Early LHC underlying event data – findings and surprises, arXiv:1010.3558, 2010.
[18] R. Ciesielski, K. Goulianos, MBR Monte Carlo simulation in PYTHIA8, arXiv:1205.1446, 2012.
[19] D. d'Enterria, R. Engel, T. Pierog, S. Ostapchenko, K. Werner, Astropart. Phys. 35 (2011) 98, http://dx.doi.org/10.1016/j.astropartphys.2011.05.002, arXiv:1101.5596.
[20] S. Ostapchenko, Nucl. Phys. Proc. Suppl. 151 (2006) 143, http://dx.doi.org/10.1016/j.nuclphysbps.2005.07.026, arXiv:hep-ph/0412332.
[21] S. Ostapchenko, Phys. Rev. D 83 (2011) 014018, http://dx.doi.org/10.1103/PhysRevD.83.014018, arXiv:1010.1869.
[22] R.S. Fletcher, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. D 50 (1994) 5710, http://dx.doi.org/10.1103/PhysRevD.50.5710.
[23] K. Werner, F.-M. Liu, T. Pierog, Phys. Rev. C 74 (2006) 044902, http://dx.doi.org/10.1103/PhysRevC.74.044902, arXiv:hep-ph/0506232.

CMS Collaboration

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka [†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, J. Gartner, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

T.S. Anjos [3], C.A. Bernardes [3], F.A. Dias [4], T.R. Fernandez Perez Tomei, E.M. Gregores [3], C. Lagana, F. Marinho, P.G. Mercadante [3], S.F. Novaes, Sandra S. Padula

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

V. Genchev [5], P. Iaydjiev [5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [6], D. Polic, I. Puljak [5]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran [7], S. Elgammal [8], A. Ellithi Kamel [9], M.A. Mahmoud [10], A. Radi [11,12]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram [14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [14], F. Drouhin [14], C. Ferro, J.-C. Fontaine [14], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

F. Fassi, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici [5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

V. Roinishvili

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [16], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [16], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt [16], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [5], C. Hackstein, F. Hartmann, T. Hauth [5], M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov [15], J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [17], F. Sikler, V. Veszpremi, G. Vesztergombi [18], A.J. Zsigmond

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty [5], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait [19], M. Maity [20], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi [21], S.M. Etesami [22], A. Fahim [21], M. Hashemi, H. Hesari, A. Jafari [21], M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [23], M. Zeinali [22]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b,5], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c,5], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], L. Lusito [a,b], G. Maggi [a,c], M. Maggi [a], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a,b], A. Pompili [a,b], G. Pugliese [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], R. Venditti [a], G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], A.C. Benvenuti [a], D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b,5], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], M. Meneghelli [a,b,5], A. Montanari [a], F.L. Navarria [a,b], F. Odorici [a], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], R. Travaglini [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], G. Cappello [a,b], M. Chiorboli [a,b], S. Costa [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], S. Frosali [a,b], E. Gallo [a], S. Gonzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi [24], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore [a], R. Musenich [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia [a,b], F. De Guio [a,b], L. Di Matteo [a,b,5], S. Fiorendi [a,b], S. Gennai [a,5], A. Ghezzi [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [a,b], A. Massironi [a,b,5], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], S. Sala [a], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], C.A. Carrillo Montoya [a], N. Cavallo [a,25], A. De Cosa [a,b,5], O. Dogangun [a,b], F. Fabozzi [a,25], A.O.M. Iorio [a], L. Lista [a], S. Meola [a,26], M. Merola [a,b], P. Paolucci [a,5]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli "Federico II", Napoli, Italy*

P. Azzi [a], N. Bacchetta [a,5], D. Bisello [a,b], A. Branca [a,b,5], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], I. Lazzizzera [a,c], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b,5], S. Vanini [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento (Trento), Padova, Italy*

M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Torre [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], L. Fanò [a,b], P. Lariccia [a,b], A. Lucaroni [a,b,5], G. Mantovani [a,b], M. Menichelli [a], A. Nappi [a,b,†], F. Romeo [a,b], A. Saha [a], A. Santocchia [a,b], A. Spiezia [a,b], S. Taroni [a,b]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

P. Azzurri [a,c], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c], R. Dell'Orso [a], F. Fiori [a,b,5], L. Foà [a,c], A. Giassi [a], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,27], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a,28], P. Spagnolo [a], P. Squillacioti [a,5], R. Tenchini [a], G. Tonelli [a,b,5], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], D. Del Re [a,b], M. Diemoz [a], C. Fanelli [a,b], M. Grassi [a,b,5], E. Longo [a,b], P. Meridiani [a,5], F. Micheli [a,b], S. Nourbakhsh [a,b], G. Organtini [a,b], R. Paramatti [a], S. Rahatlou [a,b], M. Sigamani [a], L. Soffi [a,b]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], N. Demaria [a], C. Mariotti [a,5], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a,5], M.M. Obertino [a,c], N. Pastrone [a], M. Pelliccioni [a], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], A. Vilela Pereira [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale (Novara), Torino, Italy*

S. Belforte [a], V. Candelise [a,b], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], M. Marone [a,b,5], D. Montanino [a,b,5], A. Penzo [a], A. Schizzi [a,b]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

Korea University, Seoul, Republic of Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [4], L. Dudko, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, A. Proskuryakov, L. Sarycheva [†], V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [5], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic [29], M. Djordjevic, M. Ekmedzic, D. Krpic [29], J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [30], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet [6], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi [31], C. Rovelli [32], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [33], D. Spiga, A. Tsirou, G.I. Veres [18], J.R. Vlimant, H.K. Wöhri, S.D. Worm [34], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille [35]

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [36], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [37], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci [38], S. Cerci [39], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar [40], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [41], A. Polatoz, K. Sogut [42], D. Sunar Cerci [39], B. Tali [39], H. Topakli [38], L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [43], M. Kaya [44], O. Kaya [44], S. Ozkorucuklu [45], N. Sonmez [46]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [34], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [47], K.W. Bell, A. Belyaev [47], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith,

C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [37], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi [48], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp †, A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein †, P. Traczyk, V. Valuev, M. Weber

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng [49], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech [50], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko [51], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [52], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

University of Illinois at Chicago (UIC), Chicago, USA

U. Akgun, E.A. Albayrak, B. Bilki [53], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya [54], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar [55], W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

State University of New York at Buffalo, Buffalo, USA

G. Alverson *, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, NY, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

Rutgers, The State University of New Jersey, Piscataway, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [56], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.
E-mail address: George.Alverson@cern.ch (G. Alverson).
† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[3] Also at Universidade Federal do ABC, Santo Andre, Brazil.
[4] Also at California Institute of Technology, Pasadena, USA.
[5] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[6] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[7] Also at Suez Canal University, Suez, Egypt.
[8] Also at Zewail City of Science and Technology, Zewail, Egypt.
[9] Also at Cairo University, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.
[11] Also at British University in Egypt, Cairo, Egypt.
[12] Now at Ain Shams University, Cairo, Egypt.
[13] Also at National Centre for Nuclear Research, Swierk, Poland.
[14] Also at Université de Haute-Alsace, Mulhouse, France.
[15] Also at Moscow State University, Moscow, Russia.
[16] Also at Brandenburg University of Technology, Cottbus, Germany.
[17] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[18] Also at Eötvös Loránd University, Budapest, Hungary.
[19] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
[20] Also at University of Visva-Bharati, Santiniketan, India.
[21] Also at Sharif University of Technology, Tehran, Iran.
[22] Also at Isfahan University of Technology, Isfahan, Iran.
[23] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[24] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[25] Also at Università della Basilicata, Potenza, Italy.
[26] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[27] Also at Università degli Studi di Siena, Siena, Italy.
[28] Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
[29] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[30] Also at University of California, Los Angeles, Los Angeles, USA.
[31] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[32] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
[33] Also at University of Athens, Athens, Greece.
[34] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[35] Also at The University of Kansas, Lawrence, USA.
[36] Also at Paul Scherrer Institut, Villigen, Switzerland.
[37] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[38] Also at Gaziosmanpasa University, Tokat, Turkey.
[39] Also at Adiyaman University, Adiyaman, Turkey.
[40] Also at Izmir Institute of Technology, Izmir, Turkey.
[41] Also at The University of Iowa, Iowa City, USA.
[42] Also at Mersin University, Mersin, Turkey.
[43] Also at Ozyegin University, Istanbul, Turkey.
[44] Also at Kafkas University, Kars, Turkey.
[45] Also at Suleyman Demirel University, Isparta, Turkey.

[46] Also at Ege University, Izmir, Turkey.
[47] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[48] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[49] Also at University of Sydney, Sydney, Australia.
[50] Also at Utah Valley University, Orem, USA.
[51] Also at Institute for Nuclear Research, Moscow, Russia.
[52] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[53] Also at Argonne National Laboratory, Argonne, USA.
[54] Also at Erzincan University, Erzincan, Turkey.
[55] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[56] Also at Kyungpook National University, Daegu, Republic of Korea.