



# Measurement of the inelastic cross section in proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV

CMS Collaboration <sup>\*</sup>

CERN, Switzerland



## ARTICLE INFO

### Article history:

Received 13 September 2015  
 Received in revised form 11 June 2016  
 Accepted 12 June 2016  
 Available online 16 June 2016  
 Editor: M. Doser

### Keywords:

CMS  
 Forward physics  
 Proton–lead  
 Cross section

## ABSTRACT

The inelastic hadronic cross section in proton–lead collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV is measured with the CMS detector at the LHC. The data sample, corresponding to an integrated luminosity of  $\mathcal{L} = 12.6 \pm 0.4 \text{ nb}^{-1}$ , has been collected with an unbiased trigger for inclusive particle production. The cross section is obtained from the measured number of proton–lead collisions with hadronic activity produced in the pseudorapidity ranges  $3 < \eta < 5$  and/or  $-5 < \eta < -3$ , corrected for photon-induced contributions, experimental acceptance, and other instrumental effects. The inelastic cross section is measured to be  $\sigma_{\text{inel}}(\text{pPb}) = 2061 \pm 3(\text{stat}) \pm 34(\text{syst}) \pm 72(\text{lumi}) \text{ mb}$ . Various Monte Carlo generators, commonly used in heavy ion and cosmic ray physics, are found to reproduce the data within uncertainties. The value of  $\sigma_{\text{inel}}(\text{pPb})$  is compatible with that expected from the proton–proton cross section at 5.02 TeV scaled up within a simple Glauber approach to account for multiple scatterings in the lead nucleus, indicating that further net nuclear corrections are small.

© 2016 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

The measurement of the inelastic cross section in proton–lead collisions,  $\sigma_{\text{inel}}(\text{pPb})$ , at a centre-of-mass energy per nucleon pair of 5.02 TeV performed by the CMS experiment at the CERN LHC is presented. The inelastic cross section (also called “particle-production” [1] or “absorption” [2] cross section in previous studies) is defined to include all hadronic events, including contributions from diffractive processes, except those from the quasi-elastic excitation of the lead nucleus—estimated to amount to about 100 mb for the pPb system [3]. Inelastic electromagnetic (photon–proton) collisions are also excluded from the measurement.

While being one of the most inclusive observables in hadronic collisions, the inelastic cross section is one of the least theoretically accessible quantities, as it cannot be determined from first-principles calculations of the theory of the strong interaction, quantum chromodynamics. In proton–proton (pp) and nucleus–nucleus collisions at the LHC, particles produced in hadronic interactions come mostly from the hadronisation of quarks and gluons, either produced in semi-hard scatterings (“minijets”) [4] or emitted at very forward rapidities from “spectator” partons, as well as from soft diffractive processes in “peripheral” interactions. From

the measured inelastic proton–proton (or nucleon–nucleon) cross section at a given collision energy, one can theoretically derive the corresponding proton–nucleus and nucleus–nucleus cross sections by means of Glauber [5,6] or Gribov–Regge [7] multiple-scattering approaches that take into account the known transverse matter profile of nuclei. Key quantities for the experimental comparison between nucleus–nucleus and pp collisions—such as the nuclear overlap function, the number of nucleon–nucleon collisions and of participant nucleons [8,9]—are also commonly computed through such approaches. Validating the Glauber and Gribov–Regge predictions with proton–nucleus collisions at LHC energies has important implications beyond collider physics. Such approaches constitute crucial ingredients in the Monte Carlo modelling of cosmic ray air showers at the highest energies [10], for which the inelastic cross sections measured in the laboratory must be extrapolated over a wide energy range. In fact, the inelastic proton–air (mostly proton–nitrogen and proton–oxygen) cross section introduces one of the largest uncertainties for air shower simulations [11,12].

The Glauber multiple-collision model, based on the eikonal limit (i.e. straight-line trajectories of the colliding nucleons), is the simplest and most economical approach often used to derive inclusive proton–nucleus quantities from the pp cross sections and, vice versa, to obtain pp cross sections from the cosmic ray measurements [13]. However, some of the approximations applied in the model—foremost the absence of short-range nucleon correlations [14] and of inelastic screening [15]—impact the computed

<sup>\*</sup> E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

cross section values. This is observed for fixed-target proton–carbon data [16–20] and estimated for collider [21,22] as well as ultra-high cosmic ray [13] energies, where corrections to the proton–air cross section of the order of 10% have been obtained. Short-range correlations increase the number of nucleon–nucleon collisions at small impact parameters yielding a larger nucleus–nucleus cross section. On the other hand, screening affects the number of nucleons that are diffractively excited in the multiple collisions but revert back to their ground state before the scattering process is completed, thereby reducing the nuclear cross section. Different implementations of such effects exist in the current hadronic interaction models [15,23–29]. A measurement of  $\sigma_{\text{inel}}$  in pPb collisions at the LHC can test if the precision of the standard Glauber calculation is sufficient, and at which energies corrections to the Glauber approach may become relevant.

## 2. Experimental setup and Monte Carlo simulations

The measurement presented here is based on pPb data taken with the CMS experiment at the LHC at the beginning of 2013. A detailed description of the apparatus can be found in [30]. The main detector used in this analysis is the hadron forward (HF) calorimeter that covers the pseudorapidity interval  $3 < |\eta| < 5$ . The calorimeter is composed of quartz fibres in a steel matrix with a  $0.175 \times 0.175$  segmentation in the azimuthal angle  $\phi$  (in radians) and pseudorapidity  $\eta$ . The quartz fibres pick up the Cherenkov light produced by the charged component of showers. This light is then measured by photodetector tubes. The hadronic and electromagnetic signals of each segment, as derived from fibres of two different lengths and depths, are combined to form a *tower* signal.

The data used in this analysis comprise an integrated luminosity of  $\mathcal{L} = 12.6 \pm 0.4 \text{ nb}^{-1}$ . This dataset combines the integrated luminosities of the two possible directions of the proton and lead beams:  $5.0 \pm 0.2 \text{ nb}^{-1}$  and  $7.6 \pm 0.3 \text{ nb}^{-1}$ , for the proton beam going respectively in the clockwise (negative  $\eta$ ) and anticlockwise (positive  $\eta$ ) direction. The events are collected using an unbiased trigger, only requiring the presence of both beams in the interaction point, as determined by the “Beam Pickup Timing for the eXperiments” (BPTX) devices. Detector noise is studied with events that are randomly read out in the absence of both beams in the detector. The luminosity determination technique was calibrated by means of a van der Meer scan [31] for both beam directions independently, with an uncertainty of 3.5% [32].

A Monte Carlo event simulation based on a GEANT4 detector description [33] is used to model the experimental response and derive the reconstruction efficiencies. Different event generators are used to simulate hadronic proton–nucleus collisions. Three models are based on the Gribov–Regge formalism: DPMJET 3.06 [34], EPOS-LHC [25], and QGSJETII-04 [26]; and a fourth one is based on a minijet+Glauber approach: HIJING 1.383 [35]. In addition, particle production from photon–proton ( $\gamma p$ ) interactions in “ultraperipheral” collisions, at impact parameters larger than the sum of proton and lead radii, needs to be taken into account [36]. Given the large Pb ion charge, and the associated large “equivalent photon flux” of its electromagnetic field [36], inelastic photon–proton collisions result in a non-negligible particle production contribution. Pure photon–photon interactions, mostly producing exclusive electron–positron pairs, and photon–nucleus interactions (where the photon emitted from the proton collides with the Pb ion) have orders-of-magnitude smaller visible cross sections and are neglected. Photon–proton processes are generated with the STARLIGHT programme [37] combined either with DPMJET 3.05 or PYTHIA 6.4.26 [38].

## 3. Event selection and analysis

In this analysis three types of cross sections are measured: (i)  $\sigma_{\text{obs}}$  after removal of noise and correction for pileup, (ii)  $\sigma_{\text{vis}}$  after further removal of electromagnetic contributions and translation into a hadron-level quantity, and (iii)  $\sigma_{\text{inel}}$  including the final extrapolation to the total inelastic hadronic cross section. Two different approaches are used to determine the number of inelastic events: (1) a **single-arm** event selection that requires a localised calorimetric energy signal above a given threshold in the HF detector either at positive or negative pseudorapidities, and (2) a **double-arm** event selection that requires a localised signal above threshold in both HF detectors. The advantage of using these two event selections is that they have very different sensitivities to diffractive and photon–proton events as well as to detector noise. Denoting by  $E_{\text{HF}+}$  ( $E_{\text{HF}-}$ ) the highest energy measured in an HF tower at positive (negative) pseudorapidity, an event is tagged as a candidate for an inelastic collision if it has a value of

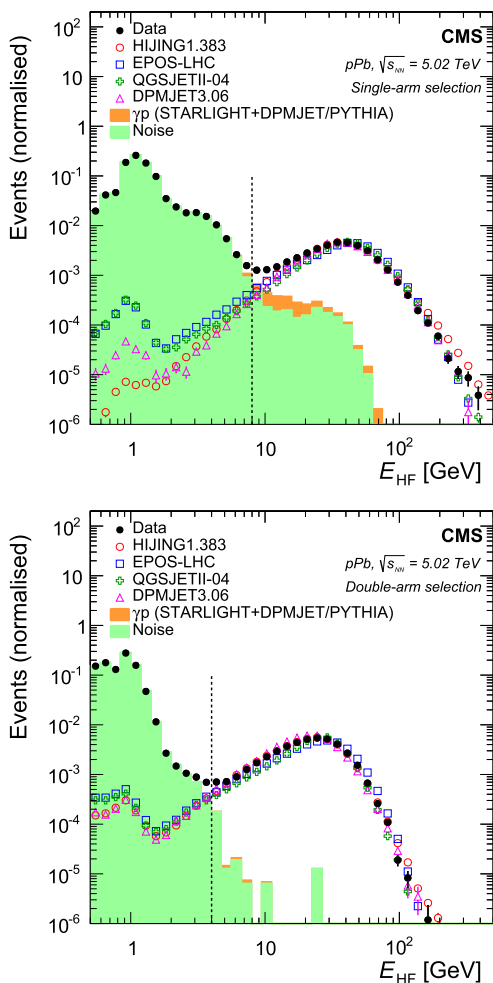
$$E_{\text{HF}} = \begin{cases} \max(E_{\text{HF}+}, E_{\text{HF}-}) & \text{for single-arm selection} \\ \min(E_{\text{HF}+}, E_{\text{HF}-}) & \text{for double-arm selection} \end{cases} \quad (1)$$

above a given threshold.

The observed distribution of  $E_{\text{HF}}$  is well reproduced by the combined hadronic inelastic, photon–proton, and detector noise contributions as shown in the top (bottom) panel of Fig. 1 for the single-arm (double-arm) selection. The size of the various contributions to the HF energy deposition is determined from data and simulations. The signal is identified as that coming from hadronic collisions whereas the backgrounds arise from electromagnetic photon–proton interactions and detector noise. The expected number of photon–proton collisions is  $N_{\gamma p} = f_{\gamma p} \sigma_{\gamma p} \mathcal{L}$ , where  $f_{\gamma p}$  is the fraction of simulated photon–proton events passing the selection and  $\sigma_{\gamma p}$  is the predicted STARLIGHT cross section. The number of misidentified events produced by electronic noise in the detector is  $N_{\text{noise}} = N f_{\text{noise}}$ , where  $f_{\text{noise}}$  is the fraction of events read out randomly in the absence of beams that pass the selection criteria, and  $N$  is the number of events recorded with the unbiased trigger. The estimate of  $N_{\text{noise}}$  includes  $N_{\text{obs+noise}} = N_{\text{obs}} f_{\text{noise}}$  events that contain also an observed inelastic collision, where  $N_{\text{obs}}$  is the number of observed inelastic events. The double-counted events are explicitly subtracted from  $N_{\text{noise}}$ . The uncertainty on  $N_{\text{noise}}$  is derived from variations in different data-taking periods. The background induced by beam-gas collisions is found to be negligible deduced from the fraction of events selected with the trigger indicating the presence of a single beam in the interaction point.

Of the number of inelastic hadronic collisions,  $N_{\text{inel}}$ , the ones that are observed by the detector and pass the event selection are defined as  $N_{\text{had}}$ . The purity of the event selection is  $N_{\text{had}} / (N_{\text{had}} + N_{\gamma p} + N_{\text{noise}})$ , and the acceptance is given by the ratio  $\epsilon_{\text{acc}} = N_{\text{had}} / N_{\text{inel}}$ . Both the purity and the acceptance depend on the energy threshold used for the selection. Higher purity is achieved for the double-arm selection, since photon–proton interactions lead to a typical final state where most of the secondary products are asymmetrically emitted towards the direction of the proton beam. Noise events are also suppressed by the coincidence requirement. The acceptance is in general smaller for the double-arm selection due to the smaller chance of selecting diffractive events characterised by large rapidity gaps devoid of activity in one or both HF sides.

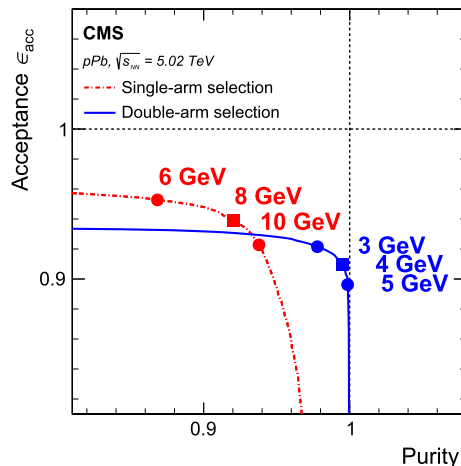
The dependence of  $\epsilon_{\text{acc}}$  on the HF tower energy threshold is shown in Fig. 2. For the single-arm selection the working point is chosen to be  $E_{\text{HF}} > 8 \text{ GeV}$ . This value is the result of a compromise between acceptance (about 93–94%) and contamination, while the



**Fig. 1.** Distribution of the energy deposited in the HF calorimeter ( $E_{\text{HF}}$ ) for the single-arm (top) and double-arm (bottom) event selections. The data sample, shown exemplarily for one period with stable run conditions, comprises  $1.31 \text{ nb}^{-1}$  recorded with an unbiased trigger. The contribution from noise is obtained from a random trigger normalised to the same number of triggers as that in the collision data. The average number of photon–proton processes simulated with STARLIGHT+DPMJET and STARLIGHT+PYTHIA is treated as background and stacked on top. Four hadronic interaction models (EPOS, DPMJET, HIJING, and QGSJETII) are overlaid and normalised to the number of data events with  $E_{\text{HF}} > 10 \text{ GeV}$ , where the contribution from the background is small. The vertical line represents the threshold energy of 8 GeV (4 GeV) for the single-arm (double-arm) selection used in this analysis.

probability to have a tower above the threshold does not depend much on the beam direction. The double-arm selection uses  $E_{\text{HF}} > 4 \text{ GeV}$  yielding 99% purity and 91% acceptance. The value  $\epsilon_{\text{acc}}$  for a specific  $E_{\text{HF}}$  threshold is determined by averaging over the results of the EPOS and QGSJETII models. The results of HIJING and DPMJET, which do not include nuclear effects for diffraction, are not considered for this purpose. Indeed, we have verified that both latter models are unable to describe the very-forward energy spectra measured with the CASTOR detector ( $-6.6 < \eta < -5.2$ ) in events with large rapidity gaps, which are particularly sensitive to diffractive interactions.

The uncertainties on the  $\epsilon_{\text{acc}}$  and  $N_{\text{yp}}$  values are estimated from the maximum absolute differences obtained from the results of different event generators, averaged over a wide  $E_{\text{HF}}$  interval between 2 and 10 GeV. The uncertainties on  $\epsilon_{\text{acc}}$  are 0.005 (0.014) and of  $N_{\text{yp}}/\mathcal{L}$  are 11 mb (0.05 mb) for the single-arm (double-arm) event selections.



**Fig. 2.** Acceptance versus purity of the two event selections, as derived from the EPOS and QGSJETII generators. The symbols indicate different values of the  $E_{\text{HF}}$  thresholds. The chosen thresholds are marked with squares.

In this analysis no vertex reconstruction is performed and the impact of contributions from additional pileup (PU) collisions recorded in any given event is consistently evaluated with the HF detector. The number of simultaneous collisions is Poisson-distributed with an expectation value corresponding to the interaction probability  $\lambda$ . If one collision is selected with probability  $\epsilon_{\text{acc}}$ , then  $i$  simultaneous collisions are selected with probability  $P_i \approx 1 - (1 - \epsilon_{\text{acc}})^i$ . The approximation assumed in the equation, which does not account for energy deposits of multiple events in the HF towers, was verified to be valid by means of a toy Monte Carlo simulation. The number of collisions is then corrected with the factor  $f_{\text{PU}} = \epsilon_{\text{acc}} \lambda / \sum_{i=1}^{\infty} P_i \text{Poisson}(i; \lambda)$ . The interaction probability  $\lambda$ , which amounts to 2–8% depending on the data-taking period, is calculated recursively from the ratio of the number of inelastic events to the number of unbiased triggers. The pileup correction increases the measured cross section by 2% for both event selections, and introduces an uncertainty on the final pPb cross section that is smaller than 0.1%.

To facilitate the direct comparison of the results to model predictions, detector level quantities, such as  $E_{\text{HF}}$ , are translated to hadron-level quantities. For this purpose,  $p_{\text{HF}}$  is defined equivalently to Eq. (1) but replacing  $E_{\text{HF}}$  by the largest absolute value among the momenta,  $|\vec{p}|$ , of all generated final-state particles (with lifetimes above  $1 \text{ cm}/c$ ), within the pseudorapidity intervals of the HF calorimeters ( $3 < |\eta| < 5$ ), excluding muons and neutrinos. A correction factor  $c_{\text{vis}}$ , obtained from simulations, is used to translate the measured cross section into a hadron-level quantity, defined by the ratio of the number of visible events, which fulfil a given requirement on  $p_{\text{HF}}$ , to the number of observed events, which pass the selection on  $E_{\text{HF}}$ . Thus,  $c_{\text{vis}}$  is larger than unity for requiring  $p_{\text{HF}} > 0$ , but will approach zero for very high thresholds. The threshold can be chosen freely, and for the present analysis the requirement on the minimal value of  $p_{\text{HF}}$  is chosen such that the fractions of events passing this selection and passing that on  $E_{\text{HF}}$  are equal. The factor  $c_{\text{vis}}$  then becomes equal to unity and has no numerical effect on the central value of the derived cross section. This procedure leads to the choice of selecting events that fulfil the requirement  $p_{\text{HF}} > 21.3 \text{ GeV}/c$  (11.3 GeV/c) for the single-arm (double-arm) analysis. For the chosen thresholds, the mean of the  $c_{\text{vis}}$  values of all four hadronic interaction models is unity and the slight dependence on models is taken into account as a systematic uncertainty on  $c_{\text{vis}}$  equal to the standard deviation of the four values.

**Table 1**

Central values and uncertainties for the two event selections for noise cross section contribution ( $N_{\text{noise}}/\mathcal{L}$ ) and the fraction of noise events ( $f_{\text{noise}}$ ) as derived from data. Additionally, the quantities acceptance ( $\epsilon_{\text{acc}}$ ), electromagnetic cross section contribution ( $N_{\gamma p}/\mathcal{L}$ ), and hadron-level correction factor ( $c_{\text{vis}}$ ) as derived from simulations are listed.

Selection	$N_{\text{noise}}/\mathcal{L}$ [mb]	$f_{\text{noise}}$	$\epsilon_{\text{acc}}$	$N_{\gamma p}/\mathcal{L}$ [mb]	$c_{\text{vis}}$
Single-arm	$102 \pm 25$	$(2.0 \pm 0.5) \times 10^{-3}$	$0.939 \pm 0.005$	$63 \pm 11$	$1.000 \pm 0.004$
Double-arm	$9 \pm 3$	$(1.8 \pm 0.8) \times 10^{-4}$	$0.910 \pm 0.014$	$0.33 \pm 0.05$	$1.000 \pm 0.002$

The values of the acceptance, backgrounds, and correction factors are summarised in Table 1.

The number of observed inelastic events,  $N_{\text{obs}}$ , is derived from the number of events passing the event selection,  $N_{\text{sel}}$ , and is corrected for noise ( $N_{\text{noise}}$ ), double counting ( $N_{\text{obs}+\text{noise}}$ ), and pileup ( $f_{\text{PU}}$ ). Dividing this number by the integrated luminosity yields the observed cross section:

$$\sigma_{\text{obs}} = \frac{N_{\text{obs}}}{\mathcal{L}} = (N_{\text{sel}} - N_{\text{noise}} + N_{\text{obs}+\text{noise}}) \frac{f_{\text{PU}}}{\mathcal{L}}. \quad (2)$$

Using the relation  $N_{\text{obs}+\text{noise}} = N_{\text{obs}} f_{\text{noise}}$  one obtains

$$\sigma_{\text{obs}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}}}{1/f_{\text{PU}} - f_{\text{noise}}}. \quad (3)$$

The visible cross section for hadronic collisions is derived by subtracting the photon–proton contamination and applying the correction factor  $c_{\text{vis}}$ . Its numerical value is, by definition, equal to the part of the observed cross section related to hadronic collisions:

$$\sigma_{\text{vis}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}} - N_{\gamma p}}{1/f_{\text{PU}} - f_{\text{noise}}} c_{\text{vis}}. \quad (4)$$

The inelastic cross section is obtained by correcting for the limited detector acceptance ( $\epsilon_{\text{acc}}$ ):

$$\sigma_{\text{inel}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}} - N_{\gamma p}}{1/f_{\text{PU}} - f_{\text{noise}}} \frac{1}{\epsilon_{\text{acc}}}. \quad (5)$$

The ratio of the visible hadronic cross section obtained with the single-arm selection to the one obtained with the double-arm selection is sensitive to the fraction of diffractive pPb events. The measured value of this ratio allows one to constrain the diffractive cross section,  $\sigma_{\text{diff}}$ , in the models. In order to be compatible within 2 standard deviations of the data, the EPOS diffractive cross section cannot be scaled up or down by more than  $\pm 13\%$  from its default value, while for QGSJETII those limits are  $\pm 20\%$ . This propagates into an  $\epsilon_{\text{acc}}(\sigma_{\text{diff}})$  uncertainty on  $\sigma_{\text{inel}}$ , conservatively assumed to be symmetric, of 0.8% (1.1%). For this and the following uncertainties, the first number is related to the single-arm selection and the bracketed one to the double-arm selection. The model-dependence of the acceptance corrections results in an uncertainty for  $\epsilon_{\text{acc}}(\text{models})$  of 0.5% (1.6%) for the two selections, respectively.

Since less than half of the diffractive events, mostly with a high-mass diffractive system, pass the hadron-level selection, the uncertainty on  $c_{\text{vis}}$  is smaller than that on  $\epsilon_{\text{acc}}$ . The 1 standard deviation differences found among the four hadronic interaction models on the hadron-level correction,  $c_{\text{vis}}$ , propagate into uncertainties on  $\sigma_{\text{vis}}$  of 0.4% (0.2%) for the single-arm (double-arm) selection. The subtraction of photon–proton events (with the  $N_{\gamma p}$  uncertainty shown in Table 1), results in an uncertainty of 0.6% (<0.1%) on  $\sigma_{\text{inel}}$  and  $\sigma_{\text{vis}}$ . The uncertainty on  $N_{\text{noise}}$  propagates into a 1.3% (0.2%) uncertainty in the final cross sections. The effect on the event selection of the radiation damage in the HF fibres is assessed by rescaling the signals of the simulated HF

**Table 2**

List of the systematic uncertainties, propagated into the final pPb cross sections, for the two event selections.

Source of uncertainty	Single-arm	Double-arm
Noise subtraction ( $N_{\text{noise}}$ )	1.3%	0.2%
Pileup correction ( $f_{\text{PU}}$ )	<0.1%	<0.1%
Acceptance ( $\epsilon_{\text{acc}}(\text{models})$ )	0.5%	1.6%
Acceptance ( $\epsilon_{\text{acc}}(\sigma_{\text{diff}})$ )	0.8%	1.1%
Hadron-level correction ( $c_{\text{vis}}$ )	0.4%	0.2%
Photon–proton subtraction ( $N_{\gamma p}$ )	0.6%	<0.1%
Detector simulation	1.7%	0.8%
HF energy thresholds	0.6%	0.4%
Integrated luminosity ( $\mathcal{L}$ )	3.5%	3.5%

response to match data in segments of pseudorapidity. The rescaling factors are calculated using the average response produced by EPOS, HIJING, and QGSJETII. These scaling factors are found to be consistent with the observed radiation damage of HF and range from 1 to 0.67, depending on pseudorapidity. The amount of radiation damage is estimated from a comparison of  $dE/d\eta$  distributions measured in proton–proton collisions at  $\sqrt{s} = 2.76$  TeV recorded in 2013 and in 2010. The systematic uncertainty induced on the cross section by this approach is estimated by repeating the measurement without the radiation damage correction, which introduces an effect of 1.7% (0.8%) on the cross section. As a further check of the HF tower energy resolution, the cross sections are computed by increasing the selection thresholds to  $E_{\text{HF}} > 10$  GeV (5 GeV). To account for both effects, a systematic uncertainty on the cross section of 0.6% (0.4%) is added. The cross sections measured for the two beam directions are found to be consistent. Consequently, no dedicated systematic uncertainty is assigned to this effect.

All the different sources of uncertainty of the measurement are listed in Table 2 for the single-arm and double-arm event selections. The three derived cross sections have different systematic uncertainties since not all contributions are relevant to each of them. For  $\sigma_{\text{inel}}$ , all uncertainties but the one due to the hadron-level correction contribute. The total uncorrelated systematic uncertainty is therefore 2.5% (2.2%) for the single-arm (double-arm) selection. For  $\sigma_{\text{vis}}$ , the dominant uncertainty is due to the hadron-level correction instead of the correction for  $\epsilon_{\text{acc}}$ . The value of the uncertainty is therefore reduced to 2.3% (0.9%). The uncertainties for detector simulation and photon–proton correction do not contribute to  $\sigma_{\text{obs}}$  and, hence, its uncertainty becomes 1.4% (0.5%). For all cross sections, a (dominant) integrated luminosity uncertainty of 3.5% is added. The main contributions to the latter arise from the model used to describe the beam profile, the length scale of the beam displacement, and the bunch-to-bunch variations [32].

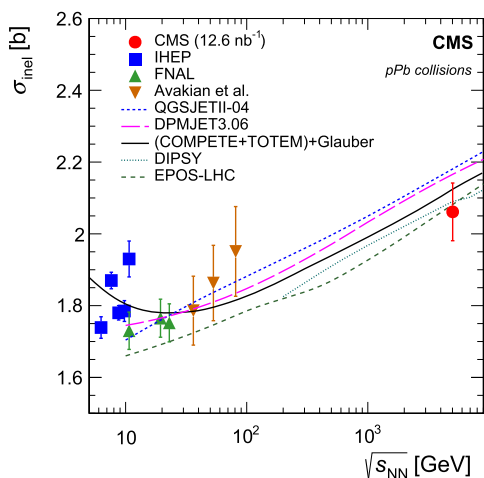
#### 4. Results and summary

The measured cross sections for the single-arm and double-arm event selections are listed in Table 3, compared to the predictions of the hadronic interaction models DPMJET, EPOS, and QGSJETII. Due to the different acceptance, the extrapolations from the hadron-

**Table 3**

Summary of cross sections obtained from the two different event selections. The acceptance definition for  $\sigma_{\text{vis}}$  is based on the production of stable particles within  $3 < |\eta| < 5$  with momentum  $p_{\text{HF}} > 21.3$  GeV/c (11.3 GeV/c) for the single-arm (double-arm) event selections.

	Selection	$\sigma_{\text{obs}}$ (mb)	$\sigma_{\text{vis}}$ (mb)	$\sigma_{\text{inel}}$ (mb)
Data	Single-arm	$2003 \pm 76$	$1937 \pm 82$	$2063 \pm 89$
	Double-arm	$1873 \pm 66$	$1872 \pm 68$	$2059 \pm 85$
EPOS-LHC	Single-arm	–	1947	2082
	Double-arm	–	1883	–
QGSJETII-04	Single-arm	–	2059	2181
	Double-arm	–	1998	–
DPMJET 3.06	Single-arm	–	2116	2166
	Double-arm	–	2055	–



**Fig. 3.** Inelastic hadronic cross sections for pPb collisions as a function of the centre-of-mass energy. The measurement described here (circle, with error bars obtained from the quadratic sum of all uncertainties) is compared to lower energy data (squares and triangles) [2,39,40] and to different model predictions (curves).

level to the inelastic cross section are of different magnitude, but the models reproduce well the approximately 65 mb difference between the two selections. The values of the inelastic cross sections obtained from the single-arm and double-arm methods agree well within the uncertainties.

The final  $\sigma_{\text{inel}}$  value is obtained by taking the weighted average of the measured values in the two event selections. The statistical uncertainties and the uncertainty on the luminosity are correlated between the selections. The degree of correlation among the remaining systematic uncertainties is much smaller and they are taken as uncorrelated. This yields a final result for the inelastic hadronic cross section of

$$\sigma_{\text{inel}}(\text{pPb}) = 2061 \pm 3(\text{stat}) \pm 34(\text{syst}) \pm 72(\text{lumi}) \text{ mb.}$$

This result is shown in Fig. 3 compared to other measurements at different centre-of-mass energies and to various theoretical predictions. A pPb cross section was also measured by the ALICE Collaboration, amounting to 2090–2120 mb with an uncertainty of 70 mb [41]. A direct comparison of this observed cross section to the one measured in the present analysis is not possible due to the unknown to us ALICE detector acceptance and possible contamination from noise and photon–proton interactions.

The inelastic cross section measured by the CMS experiment is compared to the Glauber-model prediction (solid curve in Fig. 3) obtained using a pp inelastic cross section at  $\sqrt{s} = 5.02$  TeV of  $70.0 \pm 1.5$  mb, derived from the COMPETE parametrisation [42] including the measurement of the TOTEM Collaboration at  $\sqrt{s} =$

7 TeV [43] (where the assigned uncertainty is that measured by the latter). The Glauber calculation yields  $2130 \pm 40$  mb and is compatible with the measurement presented here indicating that effects neglected by the calculation (such as nucleon correlations and screening) are either small or approximately cancel out. The experimental result is also consistent with the prediction of the DIPSY model [44,45] based on a dipole-model approach including parton saturation and multiple-scattering. Among the Gribov–Regge models, the EPOS prediction is compatible with the measurement within uncertainties, whereas DPMJET and QGSJETII predict a value more than 1 standard deviation above the data, with a larger discrepancy appearing for the  $\sigma_{\text{vis}}$  cross sections (Table 3). The EPOS and QGSJETII models are commonly used for cosmic ray air shower simulations. Thus, at the corresponding cosmic ray proton energies of  $E_{\text{cr}} = s/(2m_{\text{p}}) = 10^{16.1}$  eV, where  $m_{\text{p}}$  is the mass of the proton, there are no indications for data-model deviations above  $\approx 5\%$  in the proton–lead collisions studied here. Note, however, that our measurement deals with an ion much heavier than those involved in proton–air interactions. Corrections to the Glauber model are possibly larger in the latter case [3,13]. In summary, the measurement of the cross sections in pPb collisions presented here is the first such fully corrected measurement at multi-TeV energies and, thus, provides important constraints on hadronic interaction models commonly used in high-energy heavy ion and cosmic ray physics.

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union,

Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation, contract C-1845.

## References

- [1] R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, Proton–proton cross-section at  $\sqrt{s}$  similar to 30 TeV, Phys. Rev. D 58 (1998) 014019, <http://dx.doi.org/10.1103/PhysRevD.58.014019>, arXiv:hep-ph/9802384.
- [2] A.S. Carroll, I.-H. Chiang, T.F. Kycia, K.K. Li, M.D. Marx, D.C. Rahm, W.F. Baker, D.P. Earty, A.M. Giacomelli, A.M. Jonckheere, P.F.M. Koehler, P.O. Mazur, R. Rubinstein, O. Fackler, Absorption cross-sections of  $\pi^\pm$ ,  $K^\pm$ , p and  $\bar{p}$  on nuclei between 60 GeV/c and 280 GeV/c, Phys. Lett. B 80 (1979) 319, [http://dx.doi.org/10.1016/0370-2693\(79\)90226-0](http://dx.doi.org/10.1016/0370-2693(79)90226-0).
- [3] M. Alvioli, C. Ciofi degli Atti, B.Z. Kopeliovich, I.K. Potashnikova, I. Schmidt, Diffraction on nuclei: effects of nucleon correlations, Phys. Rev. C 81 (2010) 025204, <http://dx.doi.org/10.1103/PhysRevC.81.025204>, arXiv:0911.1382.
- [4] I. Sarcevic, S.D. Ellis, P. Carruthers, QCD minijet cross-sections, Phys. Rev. D 40 (1989) 1446, <http://dx.doi.org/10.1103/PhysRevD.40.1446>.
- [5] R.J. Glauber, Cross-sections in deuterium at high-energies, Phys. Rev. 100 (1955) 242, <http://dx.doi.org/10.1103/PhysRev.100.242>.
- [6] R.J. Glauber, G. Matthiae, High-energy scattering of protons by nuclei, Nucl. Phys. B 21 (1970) 135, [http://dx.doi.org/10.1016/0550-3213\(70\)90511-0](http://dx.doi.org/10.1016/0550-3213(70)90511-0).
- [7] V.N. Gribov, A reggeon diagram technique, Sov. Phys. JETP 26 (1968) 414.
- [8] D. d'Enterria, Hard scattering cross-sections at LHC in the Glauber approach: from pp to pA and AA collisions, arXiv:nucl-ex/0302016, 2003, originally published in CERN Yellow Report on “Hard probes in heavy ion collisions at the LHC”, 2003.
- [9] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high energy nuclear collisions, Annu. Rev. Nucl. Part. Sci. 57 (2007) 205, <http://dx.doi.org/10.1146/annurev.nucl.57.090506.123020>, arXiv:nucl-ex/0701025.
- [10] D. d'Enterria, R. Engel, T. Pierog, S. Ostapchenko, K. Werner, Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics, Astropart. Phys. 35 (2011) 98, <http://dx.doi.org/10.1016/j.astropartphys.2011.05.002>, arXiv:1105.5596.
- [11] R. Ulrich, R. Engel, M. Unger, Hadronic multiparticle production at ultra-high energies and extensive air showers, Phys. Rev. D 83 (2011) 054026, <http://dx.doi.org/10.1103/PhysRevD.83.054026>, arXiv:1010.4310.
- [12] R.D. Parsons, C. Bleve, S.S. Ostapchenko, J. Knapp, Systematic uncertainties in air shower measurements from high-energy hadronic interaction models, Astropart. Phys. 34 (2011) 832, <http://dx.doi.org/10.1016/j.astropartphys.2011.02.007>, arXiv:1102.4603.
- [13] P. Abreu, et al., Pierre Auger, Measurement of the proton–air cross-section at  $\sqrt{s} = 57$  TeV with the Pierre Auger observatory, Phys. Rev. Lett. 109 (2012) 062002, <http://dx.doi.org/10.1103/PhysRevLett.109.062002>, arXiv:1208.1520.
- [14] L.L. Frankfurt, M.I. Strikman, D.B. Day, M. Sargsian, Evidence for short range correlations from high  $Q^2$  ( $e, e'$ ) reactions, Phys. Rev. C 48 (1993) 2451, <http://dx.doi.org/10.1103/PhysRevC.48.2451>.
- [15] M.L. Good, W.D. Walker, Diffraction dissociation of beam particles, Phys. Rev. 120 (1960) 1857, <http://dx.doi.org/10.1103/PhysRev.120.1857>.
- [16] U. Derssch, et al., SELEX, Total cross section measurements with  $\pi^-$ ,  $\Sigma^-$  and protons on nuclei and nucleons around 600 GeV/c, Nucl. Phys. B 579 (2000) 277, [http://dx.doi.org/10.1016/S0550-3213\(00\)00204-2](http://dx.doi.org/10.1016/S0550-3213(00)00204-2), arXiv:hep-ex/9910052.
- [17] G. Bellettini, G. Cocconi, A.N. Diddens, E. Lillethun, G. Matthiae, J.P. Scanlon, A.M. Wetherell, Proton–nuclei cross sections at 20 GeV, Nucl. Phys. 79 (1966) 609, [http://dx.doi.org/10.1016/0029-5582\(66\)90267-7](http://dx.doi.org/10.1016/0029-5582(66)90267-7).
- [18] R.P.V. Murthy, C.A. Ayre, H.R. Gustafson, L.W. Jones, M.J. Longo, Neutron total cross-sections on nuclei at Fermilab energies, Nucl. Phys. B 92 (1975) 269, [http://dx.doi.org/10.1016/0550-3213\(75\)90182-0](http://dx.doi.org/10.1016/0550-3213(75)90182-0).
- [19] J. Engler, K. Horn, F. Monnig, P. Schludecker, W. Schmidt-Parzefall, H. Schopper, P. Sievers, H. Ullrich, R. Hartung, K. Runge, Y. Galaktionov, Neutron–nucleus total cross-sections between 8 GeV/c and 21 GeV/c, Phys. Lett. B 32 (1970) 716, [http://dx.doi.org/10.1016/0370-2693\(70\)90453-3](http://dx.doi.org/10.1016/0370-2693(70)90453-3).
- [20] A. Babaev, et al., The neutron total cross section measurements on protons and nuclei in the energy range of 28–54 GeV, Phys. Lett. B 51 (1974) 501, [http://dx.doi.org/10.1016/0370-2693\(74\)90321-9](http://dx.doi.org/10.1016/0370-2693(74)90321-9).
- [21] C. Ciofi degli Atti, B.Z. Kopeliovich, C.B. Mezzetti, I.K. Potashnikova, I. Schmidt, Number of collisions in the Glauber model and beyond, Phys. Rev. C 84 (2011) 025205, <http://dx.doi.org/10.1103/PhysRevC.84.025205>, arXiv:1105.1080.
- [22] M. Alvioli, C. Ciofi degli Atti, L.P. Kaptari, C.B. Mezzetti, H. Morita, Nucleon momentum distributions, their spin–isospin dependence and short-range correlations, Phys. Rev. C 87 (2013) 034603, <http://dx.doi.org/10.1103/PhysRevC.87.034603>, arXiv:1211.0134.
- [23] N.N. Kalmykov, S.S. Ostapchenko, The nucleus–nucleus interaction, nuclear fragmentation, and fluctuations of extensive air showers, Phys. At. Nucl. 56 (1993) 346.
- [24] V. Guzey, M. Strikman, Proton–nucleus scattering and cross section fluctuations at RHIC and LHC, Phys. Lett. B 633 (2006) 245, <http://dx.doi.org/10.1016/j.physletb.2008.04.010>, arXiv:hep-ph/0505088.
- [25] K. Werner, F.-M. Liu, T. Pierog, Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron–gold collisions at RHIC, Phys. Rev. C 74 (2006) 044902, <http://dx.doi.org/10.1103/PhysRevC.74.044902>, arXiv:hep-ph/0506232.
- [26] S. Ostapchenko, Total and diffractive cross sections in enhanced Pomeron scheme, Phys. Rev. D 81 (2010) 114028, <http://dx.doi.org/10.1103/PhysRevD.81.114028>, arXiv:1003.0196.
- [27] S. Ostapchenko, Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model, Phys. Rev. D 83 (2011) 014018, <http://dx.doi.org/10.1103/PhysRevD.83.014018>, arXiv:1010.1869.
- [28] L. Frankfurt, G.A. Miller, M. Strikman, Evidence for color fluctuations in hadrons from coherent nuclear diffraction, Phys. Rev. Lett. 71 (1993) 2859, <http://dx.doi.org/10.1103/PhysRevLett.71.2859>, arXiv:hep-ph/9309285.
- [29] D.R. Harrington, Triple pomeron matrix model for dispersive corrections to nucleon nucleus total cross-section, Phys. Rev. C 67 (2003) 064904, <http://dx.doi.org/10.1103/PhysRevC.67.064904>, arXiv:nucl-th/0206032.
- [30] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [31] S. van der Meer, Calibration of the effective beam height in the ISR, Technical Report CERN-ISR-PO-68-31. ISR-PO-68-31, CERN, 1968, <https://cdsweb.cern.ch/record/296752>.
- [32] CMS Collaboration, Luminosity calibration for the 2013 proton–lead and proton–proton data taking, CMS Physics Analysis Summary CMS-PAS-LUM-13-002, CERN, 2014, <http://cds.cern.ch/record/1643269>.
- [33] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [34] F.W. Bopp, J. Ranft, R. Engel, S. Roesler, Antiparticle to particle production ratios in hadron–hadron and d–Au collisions in the DPMJET-III Monte Carlo, Phys. Rev. C 77 (2008) 014904, <http://dx.doi.org/10.1103/PhysRevC.77.014904>, arXiv:hep-ph/0505035.
- [35] X.-N. Wang, M. Gyulassy, HIJING: a Monte Carlo model for multiple jet production in pp, pA and AA collisions, Phys. Rev. D 44 (1991) 3501, <http://dx.doi.org/10.1103/PhysRevD.44.3501>.
- [36] A.J. Baltz, et al., The physics of ultraperipheral collisions at the LHC, Phys. Rep. 458 (2008) 1, <http://dx.doi.org/10.1016/j.physrep.2007.12.001>, arXiv:0706.3356.
- [37] O. Djuvsland, J. Nystrand, Single and double photonuclear excitations in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV at the CERN large hadron collider, Phys. Rev. C 83 (2011) 041901, <http://dx.doi.org/10.1103/PhysRevC.83.041901>, arXiv:1011.4908.
- [38] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [39] S.P. Denisov, S.V. Donskov, Y.P. Gorin, R.N. Krasnokutsky, A.I. Petrukhin, Y.D. Prokoshkin, D.A. Stoyanova, Absorption cross-sections for pions, kaons, protons and anti-protons on complex nuclei in the 6 to 60 GeV/c momentum range, Nucl. Phys. B 61 (1973) 62, [http://dx.doi.org/10.1016/0550-3213\(73\)90351-9](http://dx.doi.org/10.1016/0550-3213(73)90351-9).
- [40] V.V. Avakian, S.P. Gevorgian, V.M. Zhamkochian, G.V. Karagezian, M.I. Keropian, E.A. Mamidzhanian, R.M. Martirosov, Determining inelastic interaction cross-sections for nucleons and pions incident on carbon and lead nuclei at 0.5 TeV–5 TeV, Bull. Acad. Sci. USSR, Phys. Ser. 50 (1986) 4.
- [41] ALICE Collaboration, Measurement of visible cross sections in proton–lead collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in van der Meer scans with the ALICE detector, J. Instrum. 9 (2014) P11003, <http://dx.doi.org/10.1088/1748-0221/9/11/P11003>, arXiv:1405.1849.
- [42] J.R. Cudell, V.V. Ezhela, P. Gauron, K. Kang, Y.V. Kuyanov, S.B. Lugovsky, E. Martynov, B. Nicolescu, E.A. Razuvaev, N.P. Tkachenko, COMPETE, Benchmarks for the forward observables at RHIC, the Tevatron Run II and the LHC, Phys. Rev. Lett. 89 (2002) 201801, <http://dx.doi.org/10.1103/PhysRevLett.89.201801>, arXiv:hep-ph/0206172.
- [43] G. Antchev, et al., TOTEM, Luminosity-independent measurements of total, elastic and inelastic cross-sections at  $\sqrt{s} = 7$  TeV, Europhys. Lett. 101 (2013) 21004, <http://dx.doi.org/10.1209/0295-5075/101/21004>.
- [44] E. Avsar, G. Gustafson, L. Lonnblad, Energy conservation and saturation in small-x evolution, J. High Energy Phys. 07 (2005) 062, <http://dx.doi.org/10.1088/1126-6708/2005/07/062>, arXiv:hep-ph/0503181.
- [45] C. Flensburg, G. Gustafson, L. Lonnblad, Inclusive and exclusive observables from dipoles in high energy collisions, J. High Energy Phys. 08 (2011) 103, [http://dx.doi.org/10.1007/JHEP08\(2011\)103](http://dx.doi.org/10.1007/JHEP08(2011)103), arXiv:1103.4321.

**CMS Collaboration**

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

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, V. Knünz, A. König, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý<sup>2</sup>, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeek

*Universiteit Antwerpen, Antwerpen, Belgium*

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

*Vrije Universiteit Brussel, Brussel, Belgium*

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>3</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. McCartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

S. Basegmez, C. Beluffi<sup>4</sup>, O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silva, C. Delaere, D. Favart, L. Forthomme, A. Giammanco<sup>5</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>6</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Bely, G.H. Hammad

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>7</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>7</sup>, A. Vilela Pereira

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

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>b</sup>, A. De Souza Santos<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>,  
E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, C.S. Moon<sup>a,8</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad,  
J.C. Ruiz Vargas

<sup>a</sup> Universidade Estadual Paulista, São Paulo, Brazil

<sup>b</sup> Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, V. Genchev<sup>†</sup>, R. Hadjiiska, P. Iaydjiev, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov,  
M. Vutova

*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

*University of Sofia, Sofia, Bulgaria*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>9</sup>, F. Romeo,  
S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

*Institute of High Energy Physics, Beijing, China*

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

*Universidad de Los Andes, Bogota, Colombia*

N. Godinovic, D. Lelas, D. Polic, I. Puljak, P.M. Ribeiro Cipriano

*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

*Institute Rudjer Boskovic, Zagreb, Croatia*

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

*University of Cyprus, Nicosia, Cyprus*

M. Bodlak, M. Finger<sup>10</sup>, M. Finger Jr.<sup>10</sup>

*Charles University, Prague, Czech Republic*

A.A. Abdelalim<sup>11</sup>, A. Mahrous<sup>12</sup>, A. Radi<sup>13,14</sup>

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

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

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

*Helsinki Institute of Physics, Helsinki, Finland*



J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

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

J.-L. Agram<sup>15</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>15</sup>, X. Coubez, J.-C. Fontaine<sup>15</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin<sup>2</sup>, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

T. Toriashvili<sup>16</sup>

*Georgian Technical University, Tbilisi, Georgia*

I. Bagaturia<sup>17</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov<sup>6</sup>

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann<sup>2</sup>, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gzhko,

P. Gunnellini, J. Hauk, M. Hempel<sup>18</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>18</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>18</sup>, R. Mankel, I. Marfin<sup>18</sup>, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo<sup>2</sup>, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderren, A. Vanhoefer

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann<sup>2</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>2</sup>, I. Katkov<sup>6</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

*University of Athens, Athens, Greece*

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath<sup>19</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>20</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karacsi<sup>21</sup>, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>22</sup>, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

*University of Debrecen, Debrecen, Hungary*

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

*National Institute of Science Education and Research, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, N. Nishu, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik<sup>23</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>24</sup>, G. Kole, S. Kumar, B. Mahakud, M. Maity<sup>23</sup>, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar<sup>23</sup>, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage<sup>25</sup>

Tata Institute of Fundamental Research, Mumbai, India

S. Chauhan, S. Dube, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>26</sup>, A. Fahim<sup>27</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>28</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>2</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

<sup>c</sup> CSFNSM, Catania, Italy

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Gonzi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>, L. Viliani<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, M.R. Monge<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> *INFN Sezione di Genova, Genova, Italy*

<sup>b</sup> *Università di Genova, Genova, Italy*

L. Brianza, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, R. Gerosa<sup>a,b</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, B. Marzocchi<sup>a,b,2</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

<sup>a</sup> *INFN Sezione di Milano-Bicocca, Milano, Italy*

<sup>b</sup> *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,2</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen

<sup>a</sup> *INFN Sezione di Napoli, Napoli, Italy*

<sup>b</sup> *Università di Napoli 'Federico II', Napoli, Italy*

<sup>c</sup> *Università della Basilicata, Potenza, Italy*

<sup>d</sup> *Università G. Marconi, Roma, Italy*

P. Azzi<sup>a,2</sup>, N. Bacchetta<sup>a</sup>, M. Bellato<sup>a</sup>, L. Benato<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Branca<sup>a,b</sup>, M. Dall'Osso<sup>a,b,2</sup>, T. Dorigo<sup>a</sup>, F. Fanzago<sup>a</sup>, F. Gonella<sup>a</sup>, A. Gozzelino<sup>a</sup>, K. Kanishchev<sup>a,c</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, G. Maron<sup>a,29</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Michelotto<sup>a</sup>, F. Montecassiano<sup>a</sup>, M. Passaseo<sup>a</sup>, J. Pazzini<sup>a,b</sup>, M. Pegoraro<sup>a</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b,2</sup>

<sup>a</sup> *INFN Sezione di Padova, Padova, Italy*

<sup>b</sup> *Università di Padova, Padova, Italy*

<sup>c</sup> *Università di Trento, Trento, Italy*

A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

<sup>a</sup> *INFN Sezione di Pavia, Pavia, Italy*

<sup>b</sup> *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b,2</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>, A. Spiezia<sup>a,b</sup>

<sup>a</sup> *INFN Sezione di Perugia, Perugia, Italy*

<sup>b</sup> *Università di Perugia, Perugia, Italy*

K. Androsov<sup>a,30</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,30</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a,c,2</sup>, G. Fedi, L. Foà<sup>a,c,†</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,30</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,31</sup>, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, P. Squillacioti<sup>a,30</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

<sup>a</sup> *INFN Sezione di Pisa, Pisa, Italy*

<sup>b</sup> *Università di Pisa, Pisa, Italy*

<sup>c</sup> *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, G. D'imperio<sup>a,b,2</sup>, D. Del Re<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, C. Jorda<sup>a</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, P. Meridiani<sup>a</sup>, F. Micheli<sup>a,b</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, P. Traczyk<sup>a,b,2</sup>

<sup>a</sup> *INFN Sezione di Roma, Roma, Italy*

<sup>b</sup> *Università di Roma, Roma, Italy*

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c,2</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b,2</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>

M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, U. Tamponi<sup>a</sup>, P.P. Trapani<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b,2</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, C. La Licata<sup>a,b</sup>, M. Marone<sup>a,b</sup>, A. Schizzi<sup>a,b</sup>, T. Umer<sup>a,b</sup>, A. Zanetti<sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

S. Song

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

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali<sup>32</sup>, F. Mohamad Idris<sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz<sup>34</sup>, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

**A. Morelos Pineda**

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

**D. Krofcheck**

*University of Auckland, Auckland, New Zealand*

**P.H. Butler, S. Reucroft**

*University of Canterbury, Christchurch, New Zealand*

**A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib**

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

**H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski**

*National Centre for Nuclear Research, Swierk, Poland*

**G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak**

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

**P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela, P. Vischia**

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

**S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>35</sup>, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin**

*Joint Institute for Nuclear Research, Dubna, Russia*

**V. Golovtsov, Y. Ivanov, V. Kim<sup>36</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev**

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

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

*Institute for Nuclear Research, Moscow, Russia*

**V. Epshteyn, V. Gavrilo, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin**

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

**A. Bylinkin**

*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*

**V. Andreev, M. Azarkin<sup>37</sup>, I. Dremin<sup>37</sup>, M. Kirakosyan, A. Leonidov<sup>37</sup>, G. Mesyats, S.V. Rusakov, A. Vinogradov**

*P.N. Lebedev Physical Institute, Moscow, Russia*

**A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev**

*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, 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<sup>38</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

*Universidad Autónoma de Madrid, Madrid, Spain*

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, 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, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>39</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, T. du Pree, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli<sup>40</sup>, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi<sup>41</sup>, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>42</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres<sup>20</sup>, N. Wardle, H.K. Wöhri, A. Zagodzinska<sup>43</sup>, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov<sup>44</sup>, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*

T.K. Aarrestad, C. Amsler<sup>45</sup>, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, K.H. Chen, T.H. Doan, C. Ferro, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

*National Central University, Chung-Li, Taiwan*

R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tzeng

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Adiguzel, S. Cerci<sup>46</sup>, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>47</sup>, A. Kayis Topaksu, G. Onengut<sup>48</sup>, K. Ozdemir<sup>49</sup>, S. Ozturk<sup>50</sup>, B. Tali<sup>46</sup>, H. Topakli<sup>50</sup>, M. Vergili, C. Zorbilmez

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak<sup>51</sup>, G. Karapinar<sup>52</sup>, U.E. Surat, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E.A. Albayrak<sup>53</sup>, E. Gülmez, M. Kaya<sup>54</sup>, O. Kaya<sup>55</sup>, T. Yetkin<sup>56</sup>

*Bogazici University, Istanbul, Turkey*

K. Cankocak, S. Sen<sup>57</sup>, F.I. Vardarli

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold<sup>58</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>59</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, L. Thomas, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>58</sup>, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko<sup>44</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>60</sup>, T. Virdee, S.C. Zenz

*Imperial College, London, United Kingdom*



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

*Brunel University, Uxbridge, United Kingdom*

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

*Baylor University, Waco, USA*

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

*The University of Alabama, Tuscaloosa, USA*

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

*Boston University, Boston, USA*

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

*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, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

*University of California, Davis, Davis, USA*

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

*University of California, Los Angeles, USA*

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Iova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>61</sup>, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

*University of California, Santa Barbara, Santa Barbara, USA*

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H.A. Weber, A. Whitbeck, F. Yang, H. Yin

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>62</sup>, G. Mitselmakher, L. Muniz, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

*Florida International University, Miami, USA*

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

*Florida State University, Tallahassee, USA*

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

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

B. Bilki<sup>63</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>64</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>53</sup>, A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

*Johns Hopkins University, Baltimore, USA*

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

*The University of Kansas, Lawrence, USA*

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, I. Svintradze, S. Toda

*Kansas State University, Manhattan, USA*

D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

*University of Maryland, College Park, USA*

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. McGinn, C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

*State University of New York at Buffalo, Buffalo, USA*

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

*Northeastern University, Boston, USA*

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco, S. Won

*Northwestern University, Evanston, USA*

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>35</sup>, T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

*Princeton University, Princeton, USA*

S. Malik

*University of Puerto Rico, Mayaguez, USA*

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, USA*

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

*Rice University, Houston, USA*

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

*University of Rochester, Rochester, USA*

L. Demortier

*The Rockefeller University, New York, 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, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>65</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>66</sup>, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer<sup>2</sup>

*Texas A&M University, College Station, USA*

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderov, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

*Texas Tech University, Lubbock, USA*

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

*University of Virginia, Charlottesville, USA*

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

*Wayne State University, Detroit, USA*

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless,

# A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin, Madison, USA

† Deceased.

- 1 Also at Vienna University of Technology, Vienna, Austria.
- 2 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- 3 Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
- 4 Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
- 5 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
- 6 Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- 7 Also at Universidade Estadual de Campinas, Campinas, Brazil.
- 8 Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France.
- 9 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
- 10 Also at Joint Institute for Nuclear Research, Dubna, Russia.
- 11 Also at Zewail City of Science and Technology, Zewail, Egypt.
- 12 Also at Helwan University, Cairo, Egypt.
- 13 Also at British University in Egypt, Cairo, Egypt.
- 14 Now at Ain Shams University, Cairo, Egypt.
- 15 Also at Université de Haute Alsace, Mulhouse, France.
- 16 Also at Tbilisi State University, Tbilisi, Georgia.
- 17 Also at Ilia State University, Tbilisi, Georgia.
- 18 Also at Brandenburg University of Technology, Cottbus, Germany.
- 19 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- 20 Also at Eötvös Loránd University, Budapest, Hungary.
- 21 Also at University of Debrecen, Debrecen, Hungary.
- 22 Also at Wigner Research Centre for Physics, Budapest, Hungary.
- 23 Also at University of Visva-Bharati, Santiniketan, India.
- 24 Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- 25 Also at University of Ruhuna, Matara, Sri Lanka.
- 26 Also at Isfahan University of Technology, Isfahan, Iran.
- 27 Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- 28 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- 29 Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- 30 Also at Università degli Studi di Siena, Siena, Italy.
- 31 Also at Purdue University, West Lafayette, USA.
- 32 Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- 33 Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- 34 Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- 35 Also at Institute for Nuclear Research, Moscow, Russia.
- 36 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- 37 Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- 38 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- 39 Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- 40 Also at National Technical University of Athens, Athens, Greece.
- 41 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- 42 Also at University of Athens, Athens, Greece.
- 43 Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- 44 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- 45 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- 46 Also at Adiyaman University, Adiyaman, Turkey.
- 47 Also at Mersin University, Mersin, Turkey.
- 48 Also at Cag University, Mersin, Turkey.
- 49 Also at Piri Reis University, Istanbul, Turkey.
- 50 Also at Gaziosmanpasa University, Tokat, Turkey.
- 51 Also at Ozyegin University, Istanbul, Turkey.
- 52 Also at Izmir Institute of Technology, Izmir, Turkey.
- 53 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- 54 Also at Marmara University, Istanbul, Turkey.
- 55 Also at Kafkas University, Kars, Turkey.
- 56 Also at Yildiz Technical University, Istanbul, Turkey.
- 57 Also at Hacettepe University, Ankara, Turkey.
- 58 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- 59 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 60 Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- 61 Also at Utah Valley University, Orem, USA.
- 62 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

<sup>63</sup> Also at Argonne National Laboratory, Argonne, USA.

<sup>64</sup> Also at Erzincan University, Erzincan, Turkey.

<sup>65</sup> Also at Texas A&M University at Qatar, Doha, Qatar.

<sup>66</sup> Also at Kyungpook National University, Daegu, Korea.