

# Study of high- $p_T$ charged particle suppression in PbPb compared to pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The CMS Collaboration\*  
CERN, Geneva, Switzerland

Received: 12 February 2012 / Revised: 26 February 2012

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**Abstract** The transverse momentum spectra of charged particles have been measured in pp and PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV by the CMS experiment at the LHC. In the transverse momentum range  $p_T = 5\text{--}10$  GeV/ $c$ , the charged particle yield in the most central PbPb collisions is suppressed by up to a factor of 7 compared to the pp yield scaled by the number of incoherent nucleon–nucleon collisions. At higher  $p_T$ , this suppression is significantly reduced, approaching roughly a factor of 2 for particles with  $p_T$  in the range  $p_T = 40\text{--}100$  GeV/ $c$ .

## 1 Introduction

The charged particle spectrum at large transverse momentum ( $p_T$ ), dominated by hadrons originating from parton fragmentation, is an important observable for studying the properties of the hot, dense medium produced in high-energy heavy-ion collisions. The study of the modifications of the  $p_T$  spectrum in PbPb compared to pp collisions at the same collision energy can shed light on the detailed mechanism by which hard partons lose energy traversing the medium [1, 2], complementing recent studies of jet quenching and fragmentation properties using fully reconstructed jets [3, 4].

Using data collected by the Compact Muon Solenoid (CMS) experiment at the LHC, this paper presents measurements of charged particle yields as a function of  $p_T$  and event centrality in PbPb collisions at a center-of-mass energy per nucleon pair  $\sqrt{s_{NN}} = 2.76$  TeV. The PbPb charged particle spectra are compared to the corresponding  $p_T$ -differential cross sections measured in pp collisions at the same center-of-mass energy, a measurement that follows closely the analysis described in Ref. [5]. Charged tracks are measured in the pseudorapidity range  $|\eta| < 1$ , where

$\eta = -\ln[\tan(\theta/2)]$ , with  $\theta$  the polar angle of the track with respect to the counterclockwise beam direction.

The measurements are motivated by lower-energy results [6–9] from the Relativistic Heavy Ion Collider (RHIC), where high- $p_T$  particle production was found to be strongly suppressed relative to expectations from an independent superposition of nucleon–nucleon collisions. This observation is typically expressed in terms of the nuclear modification factor,

$$R_{AA}(p_T) = \frac{d^2 N_{ch}^{AA}/d p_T d\eta}{\langle T_{AA} \rangle d^2 \sigma_{ch}^{pp}/d p_T d\eta}, \quad (1)$$

where  $N_{ch}^{AA}$  and  $\sigma_{ch}^{pp}$  represent the charged particle yield per event in nucleus–nucleus (AA) collisions and the charged particle cross section in pp collisions, respectively. In order to compare the yield of high- $p_T$  charged particles produced in PbPb and pp collisions, a scaling factor, the nuclear overlap function  $T_{AA}$ , is needed to provide a proper normalization at a given PbPb centrality. This factor is computed as the ratio between the number of binary nucleon–nucleon collisions  $N_{coll}$ , calculated from the Glauber model of the nuclear collision geometry [10], and the inelastic nucleon–nucleon (NN) cross section  $\sigma_{inel}^{NN} = 64 \pm 5$  mb at  $\sqrt{s} = 2.76$  TeV [11]. It can be interpreted as the NN-equivalent integrated luminosity per collision at any given PbPb centrality. The mean of the nuclear overlap function  $\langle T_{AA} \rangle$ , averaged over a given centrality bin, is used to determine the nuclear modification factor at that PbPb centrality.

In addition, the centrality dependence of the PbPb spectrum can also be examined through the  $T_{AA}$ -scaled ratio of spectra in central and peripheral bins,

$$R_{CP}(p_T) = \frac{(d^2 N_{ch}^{AA}/d p_T d\eta)/\langle T_{AA} \rangle [\text{central}]}{(d^2 N_{ch}^{AA}/d p_T d\eta)/\langle T_{AA} \rangle [\text{peripheral}]}. \quad (2)$$

In the absence of initial- and/or final-state effects on the PbPb  $p_T$  spectrum, the factors  $R_{AA}$  and  $R_{CP}$  at high  $p_T$  are

\* e-mail: [cms-publication-committee@cern.ch](mailto:cms-publication-committee@cern.ch)

unity by construction. However, as observed first at RHIC in 200 GeV AuAu collisions [6–9] and later by ALICE in 2.76 TeV PbPb collisions [12], the yield of  $p_T \sim 5\text{--}10$  GeV/ $c$  charged particles is suppressed in the most central heavy-ion collisions by up to a factor of five compared to that in pp collisions. The CMS measurement presented in this paper confirms these results with improved experimental uncertainties and extends the measured transverse momentum range to 100 GeV/ $c$ .

## 2 Data sample and analysis procedures

This measurement is based on  $\sqrt{s_{NN}} = 2.76$  TeV PbPb data samples corresponding to integrated luminosities of  $7 \mu\text{b}^{-1}$  and  $150 \mu\text{b}^{-1}$ , collected by the CMS experiment in 2010 and 2011, respectively. The pp reference measurement uses a data sample collected in  $\sqrt{s} = 2.76$  TeV collisions in the 2011 LHC run, corresponding to an integrated luminosity of  $230 \text{nb}^{-1}$ .

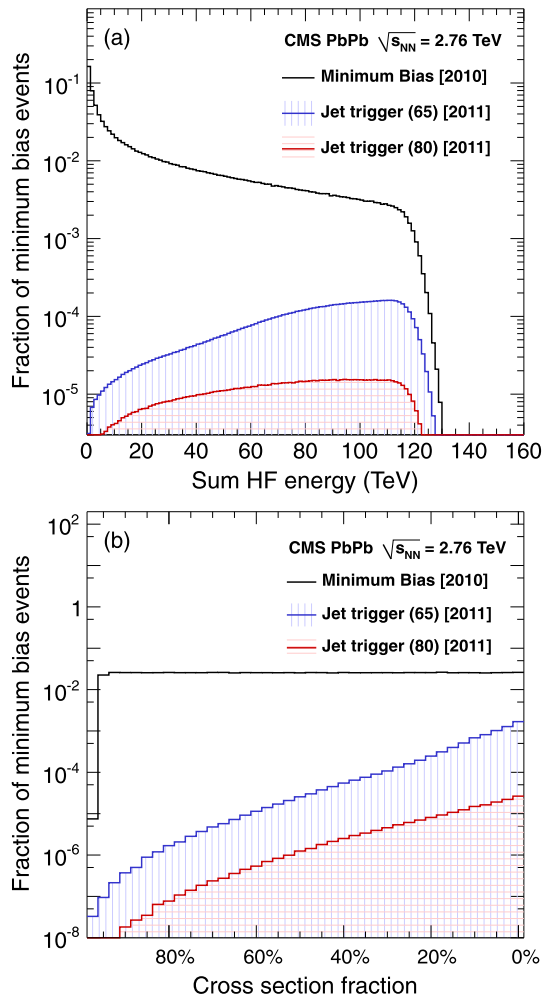
A detailed description of the CMS detector can be found in Ref. [13]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing an axial magnetic field of 3.8 T. Immersed in the magnetic field are the pixel tracker, the silicon strip tracker, the lead-tungstate crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas ionization detectors embedded in the steel return yoke. The tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules and measures charged particle trajectories within the nominal pseudorapidity range  $|\eta| < 2.4$ . The pixel tracker consists of three 53.3 cm long barrel layers and two endcap disks on each side of the barrel section. The innermost barrel layer has a radius of 4.4 cm, while for the second and third layers the radii are 7.3 cm and 10.2 cm, respectively. The tracker is designed to provide a track impact parameter resolution of about 100  $\mu\text{m}$  and a transverse momentum resolution of about 0.7 (2.0) % for 1 (100) GeV/ $c$  charged particles at normal incidence ( $\eta = 0$ ) [14]. The beam scintillator counters (BSCs) are located at a distance of 10.86 m from the nominal interaction point (IP), one on each side, and cover the  $|\eta|$  range from 3.23 to 4.65. Each BSC is a set of 16 scintillator tiles. The BSC elements provide hit and coincidence rates with a time resolution of 3 ns and an average minimum ionising particle detection efficiency of 95.7 %. The two steel/quartz-fibre hadron forward calorimeters (HF), which extend the calorimetric coverage beyond the barrel and endcap detectors to the  $|\eta|$  region between 2.9 and 5.2, are used for further offline selection of collision events. For online event selection, CMS uses a two-level trigger system: a hardware level (L1) and a software-based higher level (HLT).

A sample of minimum bias events from PbPb collisions was collected, based on a trigger requiring a coincidence between signals in the opposite sides of either the HF or the BSCs. To ensure a pure sample of inelastic hadronic collision events, additional offline selections were performed. These include a beam-halo veto, based on the BSC timing, an offline requirement of at least 3 towers on each HF with an energy deposit of more than 3 GeV per tower, a reconstructed vertex, based on at least two pixel tracks with  $p_T > 75$  MeV/ $c$ , and a rejection of beam-scraping events, based on the compatibility of pixel cluster shapes with the reconstructed primary vertex. Further details can be found in Ref. [4].

The collision event centrality is determined from the event-by-event total energy deposition in both HF calorimeters. The distribution of this observable in minimum bias events from the 2010 data sample, shown in Fig. 1(a), is used to divide the event sample into 40 centrality bins, each corresponding to 2.5 % of the total inelastic cross section. Figure 1(b) shows the distribution of events according to centrality bin, which is flat by construction for the minimum bias selection, except in the most peripheral events where the trigger and offline event selection are no longer fully efficient. Figure 1 also shows the distributions of the total HF energy and of the cross-section fraction for the events selected by single-jet triggers with calibrated transverse energy thresholds of  $E_T = 65$  GeV (Jet65) and 80 GeV (Jet80) from the 2011 data samples. The reconstruction of calorimeter-based jets in heavy-ion collisions in the online trigger as well as in the offline analysis is performed with an iterative cone algorithm modified to subtract the soft underlying event on an event-by-event basis [15]. The overall selection efficiency is estimated to be  $(97 \pm 3)$  % based on Monte Carlo (MC) simulations [4]. For the pp analysis, there is an uncertainty from the estimated number of additional collision interactions in a given beam crossing (i.e. “event pile-up”) in addition to the uncertainties from the event selection efficiency. For the PbPb analysis, the uncertainty due to the event pile-up fraction is negligible ( $< 0.1$  %).

For this analysis, the events are analyzed in six centrality bins: 0–5 % (most central), 5–10 %, 10–30 %, 30–50 %, 50–70 %, and 70–90 % (most peripheral). Details of the centrality determination are described in Ref. [4].

The event centrality, specified as a fraction of the total inelastic cross section, can be related to properties of the PbPb collisions such as the number of nucleons undergoing at least one inelastic collision ( $N_{\text{part}}$ ) and the total number of binary nucleon–nucleon collisions ( $N_{\text{coll}}$ ). The calculation of these properties is based on a Glauber model of the incoming nuclei [10] and studies of bin-to-bin smearing, caused by finite resolution effects and evaluated using fully simulated and reconstructed MC events [4]. The



**Fig. 1** (a) Probability distribution of the total HF energy for minimum bias events (black line), Jet65-triggered (blue-shaded region), and Jet80-triggered (red-shaded region) events. (b) Distribution of bins of fractional cross section for minimum bias (black line), Jet65-triggered (blue-shaded region), and Jet80-triggered (red-shaded region) events. By convention, 0 % denotes the most central events and 100 % the most peripheral

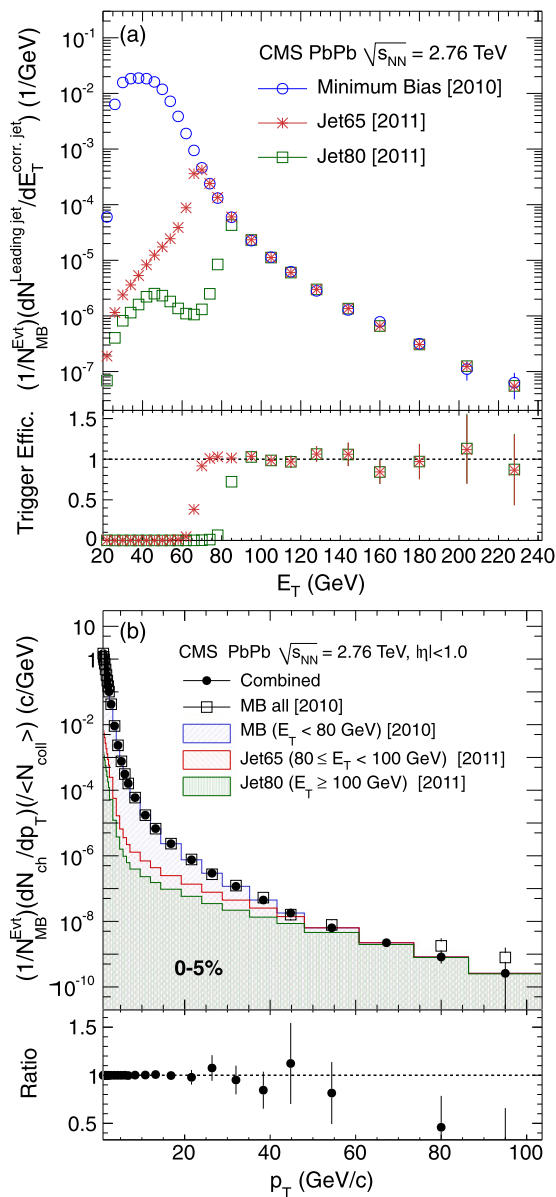
**Table 1** The average number of participating nucleons ( $N_{part}$ ), number of binary nucleon–nucleon collisions ( $N_{coll}$ ), and nuclear overlap function ( $T_{AA}$ ) for the centrality bins used in this analysis. The r.m.s.

Centrality bin	$\langle N_{part} \rangle$	r.m.s.	$\langle N_{coll} \rangle$	r.m.s.	$\langle T_{AA} \rangle$ (mb <sup>-1</sup> )	r.m.s.
0–5 %	381 ± 2	19.2	1660 ± 130	166	25.9 ± 1.06	2.60
5–10 %	329 ± 3	22.5	1310 ± 110	168	20.5 ± 0.94	2.62
10–30 %	224 ± 4	45.9	745 ± 67	240	11.6 ± 0.67	3.75
30–50 %	108 ± 4	27.1	251 ± 28	101	3.92 ± 0.37	1.58
50–70 %	42.0 ± 3.5	14.4	62.8 ± 9.4	33.4	0.98 ± 0.14	0.52
70–90 %	11.4 ± 1.5	5.73	10.8 ± 2.0	7.29	0.17 ± 0.03	0.11
50–90 %	26.7 ± 2.5	18.84	36.9 ± 5.7	35.5	0.58 ± 0.09	0.56

mean and r.m.s. of the  $N_{part}$ ,  $N_{coll}$ , and  $T_{AA}$  distributions, along with their corresponding systematic uncertainties, are listed in Table 1 for the six centrality bins used in this analysis. The uncertainties on the centrality variables are derived from propagating the uncertainties on the event selection efficiency and on the parameters of the Glauber model.

In order to extend the statistical reach of the  $p_T$  spectra in the highly prescaled minimum bias sample, data recorded in 2011 by unprescaled single-jet triggers, Jet65 and Jet80, are included in the analysis. The jet  $E_T$  thresholds in the trigger are applied after subtracting the contribution from the underlying event and correcting for the calorimeter response. Transverse energy distributions of the most energetic reconstructed jet with  $|\eta| < 2$ , referred to as the leading jet, are shown in the upper panel of Fig. 2(a) for the three samples (minimum bias, Jet65, and Jet80) as a function of corrected  $E_T$ , and normalized per minimum bias event. The distribution for the Jet80 trigger has a peak in the low- $E_T$  region as a consequence of stricter ECAL and HCAL noise elimination, as well as a tighter pseudorapidity requirement in the offline leading-jet selection than in the trigger. This feature is less prominent in the lower threshold Jet65 jet trigger because the rate of noise triggers relative to the rate of true jet triggers is smaller at lower jet  $E_T$ . The lower panel in Fig. 2(a) shows the trigger efficiency given by the ratio of each jet-triggered distribution to that from the immediately looser selection. The Jet65 (Jet80) trigger becomes fully efficient above  $E_T = 80$  (100) GeV. Following the procedure introduced in the analogous measurement of the charged particle spectra in 0.9 and 7 TeV pp collisions [5], the spectra for  $|\eta| < 1.0$  are calculated separately in three ranges of leading-jet  $E_T$ , below 80 GeV, between 80 and 100 GeV, and above 100 GeV, each corresponding to a fully efficient trigger path, and then combined to obtain the final result. Figure 2(b) shows the contributions from the three ranges to the combined spectrum. The lower panel of the figure compares the combined spectrum to the minimum bias spectrum alone, which is in good agreement within statistical uncertainties. As in the previous analysis [5], a  $p_T$ -dependent

values give the spread over the centrality bins, which are expressed as fractions of the total inelastic PbPb cross section



**Fig. 2** (a) *Upper panel:* Corrected transverse energy  $E_T$  of leading jets with  $|\eta| < 2$  for a minimum bias trigger and two jet triggers normalized to the number of selected minimum bias events  $N_{MB}^{EVT}$ . *Lower panel:* efficiency curves for the jet triggers with corrected energy thresholds of 65 and 80 GeV. (b) *Upper panel:* The three trigger contributions to the charged particle transverse momentum spectrum and their sum (filled circles) for the 0–5% most central events. *Open squares* show the minimum bias spectrum for all values of leading-jet  $E_T$ . *Lower panel:* the ratio of the combined spectrum to the minimum bias spectrum

normalization uncertainty of 0–4% is assigned to this procedure of matching the spectra from the different triggered samples.

The reconstruction of charged particles in PbPb collisions, based on hits in the silicon pixel and strip detectors, is performed similarly to what is done in pp collisions [5, 16]. However, some criteria have been fine-tuned to cope with the challenges presented by the much higher hit density in

central PbPb collisions. First, prior to track reconstruction, the three-dimensional primary vertex position is fitted from a collection of pixel-only tracks reconstructed with three hits in the pixel detector and extrapolating back to a region around the beam spot. Next, to reduce the random combinatorial background, track candidates are built from triplet seeds alone, consisting of hits in three layers of the pixel barrel and endcap detectors. The seeds from a restricted region within 2 mm of the primary vertex are constructed with a minimum  $p_T$  of 0.9 GeV/c. Further selections are made on the normalized goodness-of-fit (i.e.  $\chi^2$ ) of the track fit and on the compatibility of the fitted triplet seeds with the primary vertex, before propagating the seed trajectories through the strip tracker to build fully reconstructed tracks.

To improve the track reconstruction efficiency, two more iterations of the tracking are performed after removing hits unambiguously belonging to the tracks found in the first iteration. This procedure is based on the standard pp iterative tracking [16]. More efficient pp-based pixel-pair and triplet-track seedings are used in the second and third iterations, respectively. The tracks found in the later iterations are merged with the first-iteration tracks after removing any duplicate tracks, based on the fraction of shared hits. Lastly, the calorimeter (ECAL and HCAL) information is used to improve tracking efficiency at high  $p_T$  ( $\gtrsim 30$  GeV/c) by requiring looser quality criteria for tracks that are determined to be calorimeter compatible. This is possible because genuine charged hadron tracks with high  $p_T$  are expected to leave large energy deposits in the calorimeter. Tracks are matched to the closest calorimeter cell in  $(\eta, \phi)$ , where  $\phi$  is the azimuthal angle of the track. A track is determined to be compatible with the matched calorimeter cell if the sum of the transverse energy measured by the ECAL and HCAL cells is above a minimum fraction (30%) of the track transverse momentum. Finally, tight quality criteria are imposed for tracks that are incompatible with their matched calorimeter cell energy. These include requirements of at least 13 hits on the track (counting stereo strip layers separately), a relative momentum resolution of less than 5%, a normalized  $\chi^2$  of less than 0.15 times the number of hits, and transverse and longitudinal impact parameters of less than three times the sum in quadrature of the uncertainties on the impact parameter and the corresponding vertex position.

Each track is weighted by a factor that accounts for the geometrical acceptance of the detector, the efficiency of the reconstruction algorithm, the fraction of the tracks for which a single charged particle is reconstructed as more than one track, the fraction of tracks corresponding to non-primary charged particles, and the fraction of misidentified tracks that do not correspond to any charged particle. These correction factors are applied differentially as functions of pseudorapidity, transverse momentum, transverse energy of the leading jet, and event centrality. The various correction

terms are estimated based on simulated minimum bias PbPb events from the HYDJET [17] generator. To improve the statistical precision of the correction factors at high  $p_T$ , HYDJET MC samples are also mixed at the level of simulated hits with dijet events generated with different settings of the hard-scattering scale ( $\hat{p}_T = 30, 50, 80, 110, \text{ and } 170 \text{ GeV}/c$ ) from PYQUEN [17], a generator for the simulation of rescattering as well as radiative and collisional energy loss of hard partons in heavy-ion collisions.

Before applying the tight quality selections on the reconstructed tracks, the charged particle reconstruction efficiency is studied by inserting simulated pion tracks or PYQUEN dijet events into two different background samples: (i) simulated minimum bias HYDJET events by mixing GEANT4 [18] detector hits, and (ii) PbPb data events by combining the raw digitized detector signals. The efficiencies estimated by these two methods agree within 3.0–5.7 % in the range  $1 < p_T < 100 \text{ GeV}/c$ . Due to limitations in the data-mixing technique, the two cannot be compared on an equal footing after applying all of the quality cuts, in particular those involving the consistency of a track with the primary vertex. However, it is possible to ensure that the distributions on which the selections are made (i.e. the  $\chi^2$  of the track fit, the distance of closest approach between track and vertex, the number of hits in the silicon pixel and strip detectors) are consistent between the data and the MC simulations, both as a function of  $p_T$  and event centrality. To this end, an additional series of checks is performed by varying the requirements imposed during the track selection and in the determination of the corresponding MC-based corrections. The resulting variations in the corrected results are within the quoted systematic uncertainties.

The fraction of misidentified tracks estimated from simulated events for each leading-jet  $E_T$  sample as a function of track  $p_T$  is checked against an estimate from data that uses the sidebands of the impact parameter distributions. Studies of simulated events reveal that, at low  $p_T$  and in peripheral events (e.g. 50–90 %), the sidebands are dominated by secondaries and products of weak decays because of their displaced vertex positions. However, in central events (e.g. 0–5 %) and at high  $p_T$  they are mostly misidentified tracks. Based on varying the functional form of the sideband extrapolation under the peak from correctly reconstructed primary tracks, a 2.5–4.0 % systematic uncertainty is quoted for the fraction of misidentified tracks remaining after all selection cuts. An additional check is performed for tracks with  $p_T$  above  $10 \text{ GeV}/c$  to correlate the reconstructed track momentum with the energy deposited in the ECAL and HCAL. The fraction of high- $p_T$  tracks with an atypically small amount of energy deposited in the calorimeters is consistent with the quoted uncertainty on the misidentification rate.

The tendency for finite bin widths and finite transverse-momentum resolution to deform a steeply falling  $p_T$  spec-

**Table 2** Summary of the various contributions to the systematic uncertainties affecting the PbPb and pp  $p_T$  spectra, and the nuclear modification factors  $R_{AA}$  and  $R_{CP}$

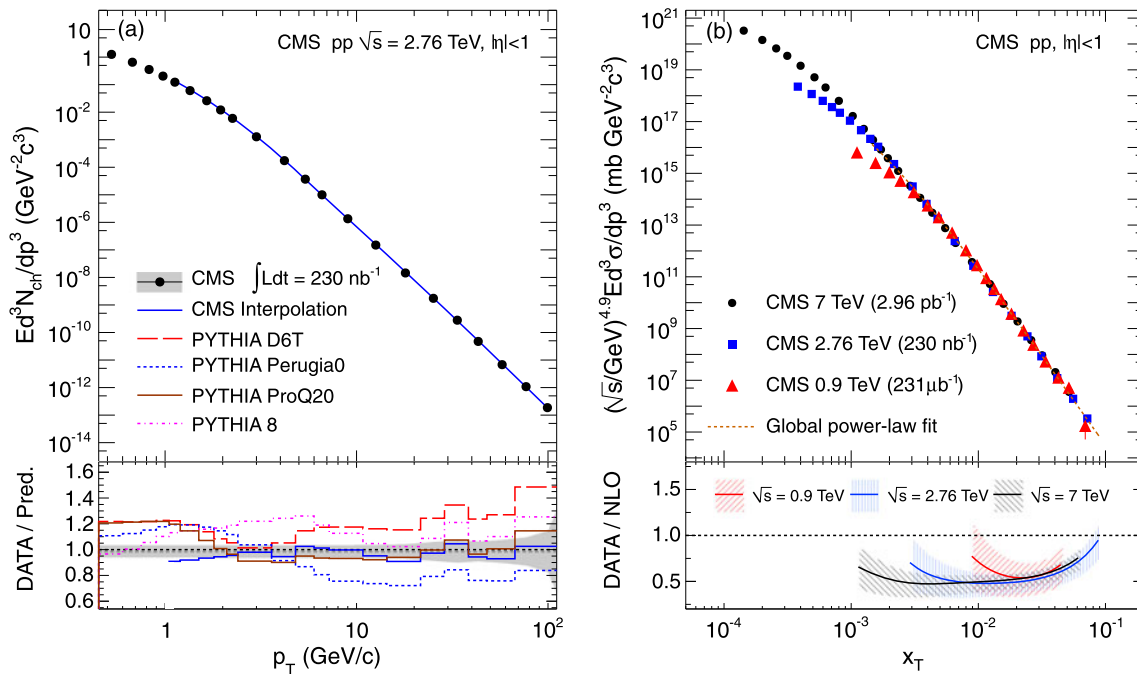
Source	Uncertainty [%]	
	PbPb	pp
Track reconstruction efficiency	3.0–5.7	2.2–3.6
Non-primary and misidentified tracks	2.5–4.0	1.0–3.2
Momentum resolution and binning	3.0	0.3–2.7
Normalization of jet-triggered spectra	0.0–4.0	0.0–6.0
Event selection	3.0	3.5
Pile-up estimation	<0.1	1.2
Total for $p_T$ spectra	5.8–9.1	4.4–9.0
Luminosity	–	6.0
$T_{AA}$ determination	4.1–18.0	–
Total for $R_{CP}$	6.7–20.0	–
Total for $R_{AA}$	9.9–23.0	–

trum is corrected for in the analysis of the pp spectrum [5]. The higher occupancy in PbPb events than in pp events has negligible effect on the momentum resolution. The resulting 3.0 % systematic uncertainty is dominated by the uncertain shape of the momentum spectrum at high  $p_T$ . For the  $R_{AA}$  and  $R_{CP}$  measurements, a 2.0 % systematic uncertainty is quoted after subtracting the correlated uncertainty between the PbPb and pp  $p_T$  spectra, or between the central and peripheral PbPb  $p_T$  spectra. A summary of all the contributions to the systematic uncertainty affecting the PbPb and pp  $p_T$  spectra, and the resulting  $R_{AA}$  and  $R_{CP}$  values, is given in Table 2.

### 3 Results

The charged particle invariant differential yield ( $E d^3 N_{ch}/d p^3$ ) averaged over the pseudorapidity  $|\eta| < 1.0$  in pp collisions is shown in Fig. 3(a). The invariant and  $p_T$ -differential pp cross section is obtained by normalizing the corresponding yield by the integrated luminosities described in Refs. [19, 20]. Also shown in Fig. 3(a) are various generator-level predictions from the PYTHIA MC [21] for different tunes [22–25], and the ratios of the data to the various MC predictions. The pp measurement is also compared to the empirical global power-law scaling prediction [26] with an exponent  $n = 4.9$  determined from the previous CMS measurements [5] by plotting  $(\sqrt{s})^{n=4.9} E d^3 \sigma/d p^3$  versus the scaling variable  $x_T = 2p_T/\sqrt{s}$ , as shown in Fig. 3(b).

The pp measurement at  $\sqrt{s} = 2.76 \text{ TeV}$  is consistent with the global power-law fit established in Ref. [5]. The next-to-leading-order (NLO) prediction [26] for  $\sqrt{s} = 2.75 \text{ TeV}$



**Fig. 3** (a) *Upper panel*: Invariant charged particle differential yield for  $|\eta| < 1.0$  in pp collisions at  $\sqrt{s} = 2.76$  TeV compared with the predictions of four tunes [22–25] of the PYTHIA MC generator and with the CMS interpolated spectrum using data at 0.9 and 7 TeV [5]. *Lower panel*: the ratio of the measured spectrum to the predictions of the four PYTHIA tunes and to the interpolated spectrum. The grey band corresponds to the statistical and systematic uncertainties of the measurement added in quadrature. (b) *Upper panel*: Inclusive charged particle

invariant differential cross sections, scaled by  $(\sqrt{s})^{4.9}$ , for  $|\eta| < 1.0$  as a function of the scaling parameter  $x_T$  for CMS data at 0.9 and 7 TeV [5] and this analysis at 2.76 TeV. The result is the average of the positive and negative charged particles. *Lower panel*: ratios of the differential cross sections measured at 0.9, 2.76, and 7 TeV to those predicted by NLO calculations [26]. The bands show the variations in the predictions when changing the factorization scales from 0.5 to 2.0  $p_T$

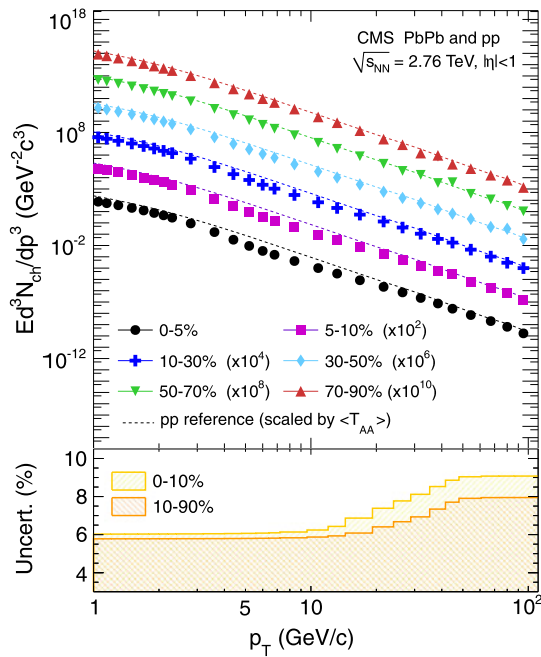
overestimates the measured cross section by almost a factor of two, as shown in Fig. 3(b).

The PbPb spectrum is shown for six centrality bins and compared to the measured pp reference spectrum, scaled by the nuclear overlap function, in Fig. 4. For easier viewing, several sets of points have been scaled by the arbitrary factors given in the figure. By comparing the PbPb measurements to the dashed lines representing the scaled pp reference spectrum, it is clear that the charged particle spectrum is strongly suppressed in central PbPb events compared to pp, with the most pronounced suppression at around 5–10 GeV/c.

The nuclear modification factor  $R_{AA}$  is constructed according to Eq. (1) by dividing the PbPb  $p_T$  spectrum for each centrality range by the scaled pp reference spectrum (i.e. the filled points by the dashed lines in Fig. 4). It is presented as a function of  $p_T$  in Fig. 5 for each of the six centrality bins. The yellow boxes around the points show the systematic uncertainties, including those from the pp reference spectrum, listed in Table 2. An additional systematic uncertainty from the  $T_{AA}$  normalization, common to all points and also listed in Table 2, is displayed as the shaded band around unity in each plot. The statistical uncertainties do not increase monotonically as a function of  $p_T$ , as seen

most prominently in the peripheral bins, as a consequence of combining the highly prescaled minimum bias sample with the two unrescaled jet triggers, as discussed in Sect. 2. In the most peripheral events (70–90 %), a moderate suppression of about a factor of 2 ( $R_{AA} \approx 0.6$ ) is observed at low  $p_T$ , with  $R_{AA}$  rising slightly with increasing transverse momentum. The suppression becomes more pronounced in the more central collisions, as expected from the increasingly dense final-state system and longer average path-lengths traversed by hard-scattered partons before fragmenting into final hadrons. In the 0–5 % centrality bin,  $R_{AA}$  reaches a minimum value of about 0.13 at  $p_T = 6$ –7 GeV/c. At higher  $p_T$ , the value of  $R_{AA}$  rises and levels off above 40 GeV/c at approximately 0.5. A rising  $R_{AA}$  may simply reflect the flattening of the unquenched nucleon–nucleon spectrum at high  $p_T$  if one assumes a constant fractional energy loss, although the magnitude of the rise varies among the different theoretical models.

The  $T_{AA}$ -scaled ratio of spectra in central and peripheral bins,  $R_{CP}$ , is constructed according to Eq. (2). The peripheral interval used for the normalization is chosen as the combined 50–90 % centrality bin to improve the statistical precision at high  $p_T$ . This approach removes the 4.4–9.0 % systematic uncertainty from the pp reference. Also part of the



**Fig. 4** *Upper panel:* Invariant charged particle differential yield in PbPb collisions at 2.76 TeV in bins of collision centrality (*symbols*), compared to that of pp at 2.76 TeV, normalized by the corresponding pp invariant cross sections scaled by the nuclear overlap function (*dashed lines*). The spectra for different centrality bins have been scaled by the arbitrary factors shown in the figure, for easier viewing. The statistical uncertainty is smaller than the marker size for most of the points. *Lower panel:* The average relative systematic uncertainties of the PbPb differential yields for the 0–10 % and 10–90 % centrality intervals, as a function of  $p_T$

$T_{AA}$  uncertainties is correlated between centrality bins and cancels out in the  $R_{CP}$  ratio. The resulting values of  $R_{CP}$  for the four most central bins are shown in Fig. 6. The statistical uncertainty of  $R_{CP}$  does not increase monotonically with  $p_T$  for the same reasons as mentioned for  $R_{AA}$ . As in the measurement of  $R_{AA}$ , the  $R_{CP}$  results show that the  $p_T$  spectra in central PbPb collisions are significantly suppressed compared to peripheral collisions.

The evolution of the nuclear modification factor with center-of-mass energy, from the SPS [27, 28] to RHIC [29, 30] and then to the LHC [12], is presented in Fig. 7. Note that RHIC results are shown for both neutral pions and charged hadrons, the latter being less suppressed below  $p_T \approx 8$  GeV/c [29, 30] possibly due to parton recombination processes that enhance proton production and thus the overall yield of charged hadrons [31]. Below  $p_T \approx 10$  GeV/c, charged hadron production at the LHC is found to be about 50 % more suppressed than at RHIC, and has a similar suppression value as for neutral pions measured by PHENIX [29].

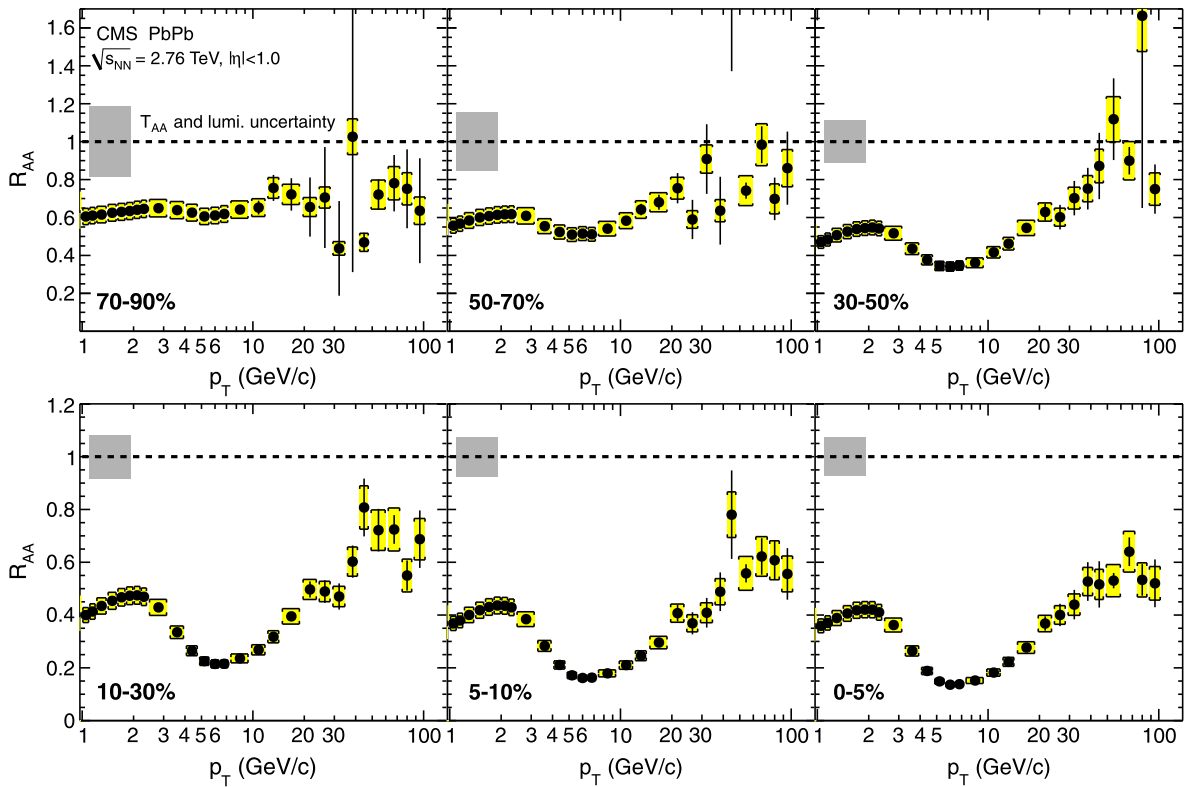
The CMS measurement of  $R_{AA}$  presented in this paper for the 0–5 % centrality interval is compared to the ALICE result [12] in Fig. 7. Note that the pp spectrum measured

by CMS at  $\sqrt{s} = 2.76$  TeV is roughly 5–15 % higher than the ALICE spectrum obtained by interpolating their 0.9 and 7 TeV spectra [12]. The two  $R_{AA}$  results are in agreement within their respective statistical and systematic uncertainties.

The high- $p_T$  measurement of  $R_{AA}$  from this analysis, up to  $p_T = 100$  GeV/c, is also compared to a number of theoretical predictions, for the LHC design energy of  $\sqrt{s_{NN}} = 5.5$  TeV (PQM [32] with medium transport-coefficient  $\langle \hat{q} \rangle = 30\text{--}80$  GeV<sup>2</sup>/fm and GLV [33, 34] for various values of the medium gluon pseudorapidity density  $dN_g/dy$ ) and for the actual collision energy of  $\sqrt{s_{NN}} = 2.76$  TeV (ASW [35, 36] and YaJEM [37] including a model for elastic energy loss parameterized with the  $P_{esc}$  variable). While most models predict the generally rising behavior of  $R_{AA}$  that is observed in the data at high  $p_T$ , the magnitude of the predicted slope varies greatly between models, depending on the assumptions for the jet-quenching mechanism. The new CMS measurement presented here should help in constraining the quenching parameters used in these models and improve the understanding of parton energy loss in a hot and dense medium.

### 4 Summary

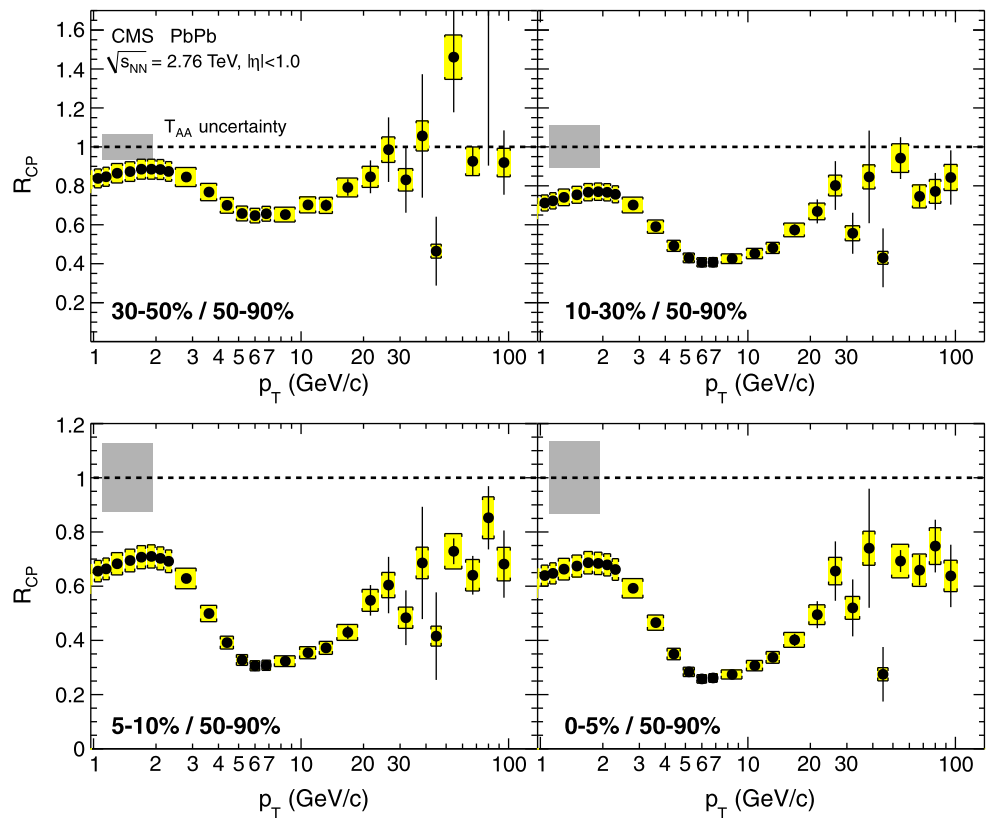
Measurements of the charged particle transverse momentum spectra have been presented for  $\sqrt{s_{NN}} = 2.76$  TeV pp and PbPb collisions. The results for the PbPb collisions have been compared to the measured pp  $p_T$  spectrum scaled by the corresponding number of incoherent nucleon–nucleon collisions. The high- $p_T$  yields in central PbPb collisions are significantly suppressed when compared to peripheral PbPb and pp collisions. In the range  $p_T = 5\text{--}10$  GeV/c, the suppression is stronger than that seen at RHIC. Beyond 10 GeV/c, both  $R_{AA}$  and  $R_{CP}$  show a rising trend, as already suggested by data from the ALICE experiment, limited to  $p_T = 20$  GeV/c. The CMS measurement, with improved statistical precision, clearly shows that this rise continues at higher  $p_T$ , approaching a suppression factor  $R_{AA} \approx 0.5\text{--}0.6$  in the range 40–100 GeV/c. The overall  $p_T$  dependence of the suppression can be described by a number of phenomenological predictions. The detailed evolution of the  $R_{AA}$  rise from 6 to 100 GeV/c depends on the details of the models. Together with measurements of high- $p_T$  charged hadron azimuthal anisotropies, inclusive jet spectra, fragmentation functions, and dijet transverse energy balance, this measurement of the nuclear modification factors as a function of  $p_T$  and collision centrality should help elucidate the mechanism of jet quenching and the properties of the medium produced in heavy-ion collisions at collider energies.



**Fig. 5** Nuclear modification factor  $R_{AA}$  (filled circles) as a function of  $p_T$  for six PbPb centralities. The error bars represent the statistical uncertainties and the yellow boxes represent the  $p_T$ -dependent systematic

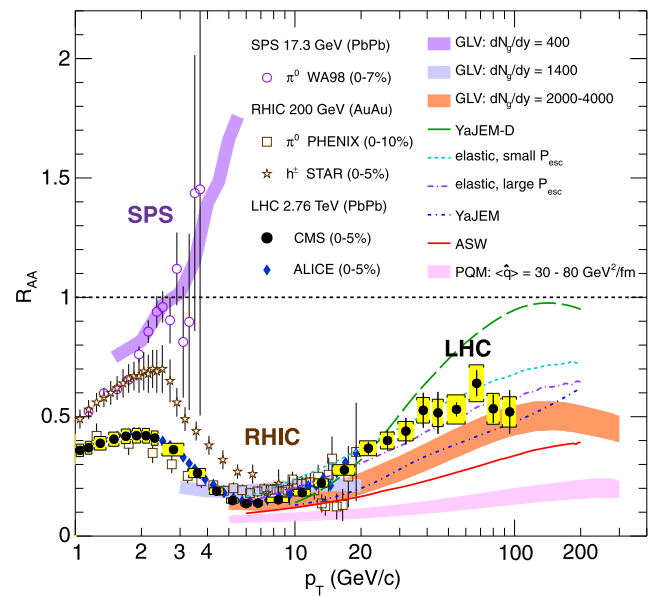
uncertainties. An additional systematic uncertainty from the normalization of  $T_{AA}$  and the pp integrated luminosity, common to all points, is shown as the shaded band around unity in each plot

**Fig. 6**  $T_{AA}$ -scaled ratio of  $p_T$  spectra in central and peripheral bins,  $R_{CP}$ , as a function of  $p_T$  for four PbPb centralities. The error bars represent the statistical uncertainties and the yellow boxes the  $p_T$ -dependent systematic uncertainties. An additional systematic uncertainty from the normalization of  $T_{AA}$ , common to all points, is shown as the shaded band around unity in each plot





**Fig. 7** Measurements of the nuclear modification factor  $R_{AA}$  in central heavy-ion collisions at three different center-of-mass energies, as a function of  $p_T$ , for neutral pions ( $\pi^0$ ), charged hadrons ( $h^\pm$ ), and charged particles [12, 27–30], compared to several theoretical predictions [32–37] (see text). The error bars on the points are the statistical uncertainties, and the yellow boxes around the CMS points are the systematic uncertainties. Additional absolute  $T_{AA}$  uncertainties of order  $\pm 5\%$  are not plotted. The bands for several of the theoretical calculations represent their uncertainties



**Acknowledgements** We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes. This work was supported by the Austrian Federal Ministry of Science and Research; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Recurrent financing contract SF0690030s09 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules/CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives/CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Office for Research and Technology, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Korea; the Lithuanian Academy of Sciences; the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Science and Innovation, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Science and Technological Development of Serbia; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the National Science Council, Taipei; the Scientific and Technical Re-

search Council of Turkey, and Turkish Atomic Energy Authority; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. 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 Council of Science and Industrial Research, India; and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

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## The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

**Institut für Hochenergiephysik der OeAW, Wien, Austria**

W. Adam, T. Bergauer, M. Dragicovic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer<sup>1</sup>, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka<sup>†</sup>, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

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

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

**Universiteit Antwerpen, Antwerpen, Belgium**

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

**Vrije Universiteit Brussel, Brussel, Belgium**

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

**Université Libre de Bruxelles, Bruxelles, Belgium**

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, A. Léonard, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

**Ghent University, Ghent, Belgium**

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

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

S. Basesmez, G. Bruno, L. Ceard, J. De Favereau De Jeneret, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>2</sup>, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

**Université de Mons, Mons, Belgium**

N. Bely, T. Caeberts, E. Daubie

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

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

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

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

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

T.S. Anjos<sup>3</sup>, C.A. Bernardes<sup>3</sup>, F.A. Dias<sup>4</sup>, T.R. Fernandez Perez Tomei, E.M. Gregores<sup>3</sup>, C. Lagana, F. Marinho, P.G. Mercadante<sup>3</sup>, S.F. Novaes, S.S. Padula

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

V. Genchev<sup>1</sup>, P. Iaydjiev<sup>1</sup>, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

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

**Institute of High Energy Physics, Beijing, China**

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

**State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China**

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

**Universidad de Los Andes, Bogota, Colombia**

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

**Technical University of Split, Split, Croatia**

N. Godinovic, D. Lelas, R. Plestina<sup>5</sup>, D. Polic, I. Puljak<sup>1</sup>

**University of Split, Split, Croatia**

Z. Antunovic, M. Dzelalija, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

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

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Finger, M. Finger Jr.

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

Y. Assran<sup>6</sup>, A. Ellithi Kamel<sup>7</sup>, S. Khalil<sup>8</sup>, M.A. Mahmoud<sup>9</sup>, A. Radi<sup>8,10</sup>

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

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

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

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

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

**Lappeenranta University of Technology, Lappeenranta, Finland**

K. Banzuzi, A. Korpela, T. Tuuva

**Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France**

D. Sillou

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

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj<sup>11</sup>, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, C. Veelken, A. Zabi

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

J.-L. Agram<sup>12</sup>, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte<sup>12</sup>, F. Drouhin<sup>12</sup>, C. Ferro, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim<sup>12</sup>, A.-C. Le Bihan, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France**

F. Fassi, D. Mercier

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

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici<sup>1</sup>, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**

D. Lomidze

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov<sup>13</sup>

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

M. Ata, J. Caudron, E. Dietz-Laursonn, M. Erdmann, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske<sup>†</sup>, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

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

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz<sup>14</sup>, A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung<sup>1</sup>, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann<sup>14</sup>, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, M. Rosin, J. Salfeld-Nebgen, R. Schmidt<sup>14</sup>, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

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

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, J. Berger, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, M. Guthoff<sup>1</sup>, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov<sup>13</sup>, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, E.B. Ziebarth

**Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece**

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

**University of Athens, Athens, Greece**

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

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas<sup>1</sup>, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

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

A. Aranyi, G. Benceze, L. Boldizsar, C. Hajdu<sup>1</sup>, P. Hidas, D. Horvath<sup>15</sup>, A. Kapusi, K. Krajczar<sup>16</sup>, F. Sikler<sup>1</sup>, G. Vesztegombi<sup>16</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

**University of Debrecen, Debrecen, Hungary**

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

**Panjab University, Chandigarh, India**

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

**University of Delhi, Delhi, India**

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

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, S. Jain, R. Khurana, S. Sarkar

**Bhabha Atomic Research Centre, Mumbai, India**

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty<sup>1</sup>, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research-EHEP, Mumbai, India**

T. Aziz, S. Ganguly, M. Guchait<sup>17</sup>, A. Gurtu<sup>18</sup>, M. Maity<sup>19</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, A. Saha, K. Sudhakar, N. Wickramage

**Tata Institute of Fundamental Research-HECR, Mumbai, India**

S. Banerjee, S. Dugad, N.K. Mondal

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

H. Arfaei, H. Bakhshiansohi<sup>20</sup>, S.M. Etesami<sup>21</sup>, A. Fahim<sup>20</sup>, M. Hashemi, H. Hesari, A. Jafari<sup>20</sup>, M. Khakzad, A. Mohammadi<sup>22</sup>, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>23</sup>, M. Zeinali<sup>21</sup>

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c,1</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, L. Lusito<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, N. Manna<sup>a,b</sup>, B. Marangelli<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, N. Pacifico<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, F. Romano<sup>a,c</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, G. Singh<sup>a,b</sup>, S. Tuppiti<sup>a,b</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</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,1</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, M. Meneghelli<sup>a,b</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, F. Odorici<sup>a</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. Siroli<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

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

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, 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. Frosali<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,1</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, S. Colafranceschi<sup>24</sup>, F. Fabbri, D. Piccolo

**INFN Sezione di Genova, Genova, Italy**

P. Fabbricatore, R. Musenich

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

A. Benaglia<sup>a,b,1</sup>, F. De Guio<sup>a,b</sup>, L. Di Matteo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a,1</sup>, A. Ghezzi<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, A. Martelli<sup>a,b</sup>, A. Massironi<sup>a,b,1</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>, S. Sala<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli "Federico II"<sup>b</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup>, C.A. Carrillo Montoya<sup>a,1</sup>, N. Cavallo<sup>a,25</sup>, A. De Cosa<sup>a,b</sup>, O. Dogangun<sup>a,b</sup>, F. Fabozzi<sup>a,25</sup>, A.O.M. Iorio<sup>a,1</sup>, L. Lista<sup>a</sup>, M. Merola<sup>a,b</sup>, P. Paolucci<sup>a</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Università di Trento (Trento)<sup>c</sup>, Padova, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a,1</sup>, P. Bellan<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, K. Kanishchev<sup>a</sup>, S. Lacaprara<sup>a,26</sup>, I. Lazzizzera<sup>a,c</sup>, M. Margoni<sup>a,b</sup>, M. Mazzucato<sup>a</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Michelotto<sup>a</sup>, M. Nespolo<sup>a,1</sup>, L. Perrozzi<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,1</sup>, S. Vanini<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

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

P. Baesso<sup>a,b</sup>, U. Berzano<sup>a</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Torre<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>, C. Viviani<sup>a,b</sup>

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

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, B. Caponeri<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, A. Lucaroni<sup>a,b,1</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Nappi<sup>a,b</sup>, F. Romeo<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, S. Taroni<sup>a,b,1</sup>, M. Valdata<sup>a,b</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**

P. Azzurri<sup>a,c</sup>, G. Bagliesi<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>, R.T. D'Agnolo<sup>a,c</sup>, R. Dell'Orso<sup>a</sup>, F. Fiori<sup>a,b</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, A. Kraan<sup>a</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,27</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, F. Palmonari<sup>a</sup>, A. Rizzi<sup>a</sup>, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b,1</sup>, A. Venturi<sup>a,1</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma<sup>a</sup>, Università di Roma "La Sapienza"<sup>b</sup>, Roma, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b,1</sup>, M. Diemoz<sup>a</sup>, C. Fanelli<sup>a</sup>, D. Franci<sup>a,b</sup>, M. Grassi<sup>a,1</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, F. Micheli<sup>a</sup>, S. Nourbakhsh<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a,b</sup>, R. Paramatti<sup>a</sup>, S. Rahatlou<sup>a,b</sup>, M. Sigamani<sup>a</sup>, L. Soffi<sup>a</sup>

**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Università del Piemonte Orientale (Novara)<sup>c</sup>, Torino, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, C. Biino<sup>a</sup>, C. Botta<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, R. Castello<sup>a,b</sup>, M. Costa<sup>a,b</sup>, N. Demaria<sup>a</sup>, A. Graziano<sup>a,b</sup>, C. Mariotti<sup>a,1</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, V. Sola<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, A. Vilela Pereira<sup>a</sup>

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, M. Marone<sup>a,b</sup>, D. Montanino<sup>a,b,1</sup>, A. Penzo<sup>a</sup>

**Kangwon National University, Chunchon, Korea**

S.G. Heo, S.K. Nam

**Kyungpook National University, Daegu, Korea**

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

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

J.Y. Kim, Z.J. Kim, S. Song

**Konkuk University, Seoul, Korea**

H.Y. Jo

**Korea University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

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

**Vilnius University, Vilnius, Lithuania**

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

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

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

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

H.A. Salazar Ibarguen

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

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

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

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

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

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

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

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

**Soltan Institute for Nuclear Studies, Warsaw, Poland**

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

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela<sup>1</sup>, P.Q. Ribeiro, J. Seixas, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

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

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

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

**Institute for Nuclear Research, Moscow, Russia**

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

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

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov<sup>1</sup>, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

**Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva<sup>†</sup>, V. Savrin, A. Snigirev, I. Vardanyan

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

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

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin<sup>1</sup>, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic<sup>28</sup>, M. Djordjevic, M. Ekmedzic, D. Krpic<sup>28</sup>, J. Milosevic

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

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

**Universidad Autónoma de Madrid, Madrid, Spain**

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

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizán Garcia



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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini<sup>29</sup>, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez<sup>30</sup>, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet<sup>5</sup>, W. Bialas, G. Bianchi, P. Bloch, A. Bocci, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, G. Mavromanolakis, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi<sup>31</sup>, T. Rommelskirchen, C. Rovelli<sup>32</sup>, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>33</sup>, D. Spiga, M. Spiropulu<sup>4</sup>, M. Stoye, A. Tsirou, G.I. Veres<sup>16</sup>, P. Vichoudis, H.K. Wöhri, S.D. Worm<sup>34</sup>, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

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

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, P. Lecomte, W. Luster, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nageli<sup>36</sup>, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, A. Starodumov<sup>37</sup>, B. Stieger, M. Takahashi, L. Tauscher<sup>†</sup>, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli, J. Weng

**Universität Zürich, Zurich, Switzerland**

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

**National Central University, Chung-Li, Taiwan**

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

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

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

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>38</sup>, S. Cerci<sup>39</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk<sup>40</sup>, A. Polatoz, K. Sogut<sup>41</sup>, D. Sunar Cerci<sup>39</sup>, B. Tali<sup>39</sup>, H. Topakli<sup>38</sup>, D. Uzun, L.N. Vergili, M. Vergili

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

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

**Bogazici University, Istanbul, Turkey**

M. Deliomeroğlu, E. Gülmez, B. Isildak, M. Kaya<sup>42</sup>, O. Kaya<sup>42</sup>, S. Ozkorucuklu<sup>43</sup>, N. Sonmez<sup>44</sup>

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

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

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

L. Basso<sup>45</sup>, A. Belyaev<sup>45</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

**Imperial College, London, United Kingdom**

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko<sup>37</sup>, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi<sup>46</sup>, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

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

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K. Hatakeyama, H. Liu, T. Scarborough

**The University of Alabama, Tuscaloosa, USA**

C. Henderson

**Boston University, Boston, USA**

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

**Brown University, Providence, USA**

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

**University of California, Davis, Davis, USA**

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

**University of California, Los Angeles, Los Angeles, USA**

V. Andreev, K. Arisaka, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein<sup>†</sup>, J. Tucker, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**

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

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

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

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalsky<sup>1</sup>, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, C. West

**California Institute of Technology, Pasadena, USA**

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

**Carnegie Mellon University, Pittsburgh, USA**

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

**University of Colorado at Boulder, Boulder, USA**

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edlmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

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**Fairfield University, Fairfield, USA**

A. Biselli, G. Cirino, D. Winn

**Fermi National Accelerator Laboratory, Batavia, USA**

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**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic<sup>49</sup>, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

**Florida International University, Miami, USA**

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

**Florida State University, Tallahassee, USA**

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

**Florida Institute of Technology, Melbourne, USA**

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

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

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde<sup>50</sup>, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, D. Strom, N. Varelas

**The University of Iowa, Iowa City, USA**

U. Akgun, E.A. Albayrak, B. Bilki<sup>51</sup>, W. Clarida, F. Duru, S. Griffiths, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya<sup>52</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

**Johns Hopkins University, Baltimore, USA**

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

**The University of Kansas, Lawrence, USA**

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

**Kansas State University, Manhattan, USA**

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

**Lawrence Livermore National Laboratory, Livermore, USA**

J. Gronberg, D. Lange, D. Wright

**University of Maryland, College Park, USA**

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

**Massachusetts Institute of Technology, Cambridge, USA**

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

**University of Minnesota, Minneapolis, USA**

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

**University of Mississippi, University, USA**

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

**University of Nebraska-Lincoln, Lincoln, USA**

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

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

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

**Northeastern University, Boston, USA**

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

**Northwestern University, Evanston, USA**

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

**University of Notre Dame, Notre Dame, USA**

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

**The Ohio State University, Columbus, USA**

B. Bylsma, L.S. Durkin, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, C. Vuosalo, G. Williams

**Princeton University, Princeton, USA**

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

**University of Puerto Rico, Mayaguez, USA**

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

**Purdue University, West Lafayette, USA**

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

**Purdue University Calumet, Hammond, USA**

S. Guragain, N. Parashar

**Rice University, Houston, USA**

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

**University of Rochester, Rochester, USA**

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

**The Rockefeller University, New York, USA**

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

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

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

**University of Tennessee, Knoxville, USA**

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

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

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>53</sup>, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

**Texas Tech University, Lubbock, USA**

N. Akchurin, C. Bardak, J. Damgov, P.R. Duderu, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans

**Vanderbilt University, Nashville, USA**

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, A. Gurrola, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

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

**University of Wisconsin, Madison, USA**

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

†: Deceased

- 1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 3: Also at Universidade Federal do ABC, Santo Andre, Brazil
- 4: Also at California Institute of Technology, Pasadena, USA
- 5: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 6: Also at Suez Canal University, Suez, Egypt
- 7: Also at Cairo University, Cairo, Egypt
- 8: Also at British University, Cairo, Egypt
- 9: Also at Fayoum University, El-Fayoum, Egypt
- 10: Now at Ain Shams University, Cairo, Egypt
- 11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 12: Also at Université de Haute-Alsace, Mulhouse, France
- 13: Also at Moscow State University, Moscow, Russia
- 14: Also at Brandenburg University of Technology, Cottbus, Germany
- 15: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 16: Also at Eötvös Loránd University, Budapest, Hungary
- 17: Also at Tata Institute of Fundamental Research-HECR, Mumbai, India
- 18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 19: Also at University of Visva-Bharati, Santiniketan, India
- 20: Also at Sharif University of Technology, Tehran, Iran
- 21: Also at Isfahan University of Technology, Isfahan, Iran
- 22: Also at Shiraz University, Shiraz, Iran
- 23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
- 24: Also at Facoltà Ingegneria Università di Roma, Roma, Italy

- 25: Also at Università della Basilicata, Potenza, Italy
- 26: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 27: Also at Università degli studi di Siena, Siena, Italy
- 28: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 29: Also at University of California, Los Angeles, Los Angeles, USA
- 30: Also at University of Florida, Gainesville, USA
- 31: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 32: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 33: Also at University of Athens, Athens, Greece
- 34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 35: Also at The University of Kansas, Lawrence, USA
- 36: Also at Paul Scherrer Institut, Villigen, Switzerland
- 37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 38: Also at Gaziosmanpasa University, Tokat, Turkey
- 39: Also at Adiyaman University, Adiyaman, Turkey
- 40: Also at The University of Iowa, Iowa City, USA
- 41: Also at Mersin University, Mersin, Turkey
- 42: Also at Kafkas University, Kars, Turkey
- 43: Also at Suleyman Demirel University, Isparta, Turkey
- 44: Also at Ege University, Izmir, Turkey
- 45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 47: Also at Utah Valley University, Orem, USA
- 48: Also at Institute for Nuclear Research, Moscow, Russia
- 49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 50: Also at Los Alamos National Laboratory, Los Alamos, USA
- 51: Also at Argonne National Laboratory, Argonne, USA
- 52: Also at Erzincan University, Erzincan, Turkey
- 53: Also at Kyungpook National University, Daegu, Korea