# EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)





# Production of leading charged particles and leading charged-particle jets at small transverse momenta in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration\*

# Abstract

The per-event yield of the highest transverse momentum charged particle and charged-particle jet, integrated above a given  $p_T^{min}$  threshold starting at  $p_T^{min} = 0.8$  and 1 GeV, respectively, is studied in pp collisions at  $\sqrt{s} = 8$  TeV. The particles and the jets are measured in the pseudorapidity ranges  $|\eta| < 2.4$  and 1.9, respectively. The data are sensitive to the momentum scale at which parton densities saturate in the proton, to multiple partonic interactions, and other key aspects of the transition between the soft and hard QCD regimes in hadronic collisions.

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<sup>\*</sup>See Appendix A for the list of collaboration members

# 1 Introduction

The production of jets with large transverse momenta  $p_T \gg \Lambda_{QCD} \approx 0.2 \text{ GeV}$  in high-energy proton-proton (pp) collisions originates from the scattering of partons, a process described by perturbative quantum chromodynamics (pQCD), through the convolution of the parton-parton cross section with the density of partons inside the protons. Jet production in pp collisions at the LHC, at transverse momenta  $p_T > 20 \text{ GeV}$  and in the pseudorapidity range  $|\eta| < 3$ , is well described by next-to-leading-order pQCD calculations [1–3]. However, most of the final-state hadrons produced in pp collisions arise from the hadronisation of quarks and gluons scattered through "semi-hard" interactions with exchanged momenta of  $\mathcal{O}(1-3 \text{ GeV})$ . At such low values of  $p_T$ , the theoretical partonic cross section,  $d\sigma/dp_T^2 \propto \alpha_S^2(p_T)/p_T^4$ , where  $\alpha_S$  is the strong coupling, becomes very large, and the integrated cross section  $\sigma(p_T^{min}) = \int_{p_T^{min}} dp_T^2 d\sigma/dp_T^2$  exceeds the total inelastic pp cross section,  $\sigma_{\text{inel}}$ . At  $\sqrt{s} = 8 \text{ TeV}$ , where  $\sigma_{\text{inel}} \approx 70 \text{ mb}$  [4], this occurs at  $p_T^{min}$  values of  $\mathcal{O}(3 \text{ GeV})$ , much larger than the QCD scale,  $\Lambda_{QCD}$ , at which the strong coupling diverges [5, 6].

Model calculations of hadronic collisions often regulate such an infrared divergence through an effective parameter connected to the confinement scale of hadrons [7], such that the leading particle or leading jet production cross sections do not exceed the value of  $\sigma_{inel}$ . Contrary to the inclusive particle or jet production cross sections, the *leading* particle or *leading* jet production cross sections must indeed approach the total inelastic cross section because only one particle or one jet, the one with highest  $p_T$  in this case, is considered per event. In addition, at small  $p_T$ , the parton densities are probed in a region where parton recombination, i.e. saturation (see e.g. Ref. [8]), may occur.

Reference [9] proposes that the jet cross section integrated over  $p_T > p_T^{\min}$  can be used as a probe of the transition from the perturbative  $(p_T^{\min} \gg \Lambda_{QCD})$  to the non-perturbative region  $(p_T^{\min} \rightarrow \Lambda_{QCD})$ . According to Ref. [9], this transition should also be visible for cross sections defined in restricted ranges of pseudorapidity.

The results presented in this paper are based on measurements of single charged particles and jets reconstructed from charged particles alone. The advantage of jets is that they include more particles originating from the outgoing partons, while single charged hadrons carry only a fraction of the parent parton momentum. On the other hand, jets are sensitive to the underlying event (UE) activity, consisting of particles originating from multiple partonic interactions (MPI) and initial and final state radiation, while single leading tracks are not. The measurements based on leading particles and leading jets are therefore complementary. Throughout the text, the term "track-jets" refers to detector-level jets, reconstructed from charged-particle tracks observed in the detector, while "charged-particle jets" or just "jets" denote corrected, stable-particle level jets, consisting of stable charged particles from the final state.

In this paper, the yields,  $r(p_T^{\min})$ , for pp collisions with a leading charged particle or a leading jet are measured as a function of a minimum transverse momentum,  $p_T^{\min}$ :

$$r(p_{\rm T}^{\rm min}) = \frac{1}{N_{\rm evt}} \int_{p_{\rm T}^{\rm min}} \mathrm{d}p_{\rm T}^{\rm lead} \left(\frac{\mathrm{d}N}{\mathrm{d}p_{\rm T}^{\rm lead}}\right),\tag{1}$$

where  $N_{\rm evt}$  is the number of selected events with a leading charged particle with  $p_{\rm T} > 0.4 \,{\rm GeV}$ and  $|\eta| < 2.4$ , and N is the number of events with a leading charged particle or a leading jet with transverse momentum  $p_{\rm T}^{\rm lead}$  within  $|\eta| < 2.4$  or 1.9, respectively.

# 2 Phenomenological models

The measured distributions are compared to the predictions of different hadronic interaction models whose tunable parameters (mostly connected to non-perturbative and semi-hard QCD phenomena) are obtained from comparisons to LHC data such as those on UE activity, inclusive multiparticle production and diffraction.

The PYTHIA 6 [10] and 8 [11] event generators tame the low- $p_T$  behaviour of the leadingorder pQCD 2 $\rightarrow$ 2 cross sections with a phenomenological factor [5, 6]  $[\alpha_s^2(p_{T,0}^2 + p_T^2)/\alpha_s^2(p_T^2)]$  $[p_T^4/(p_{T,0}^2 + p_T^2)^2]$ , where  $p_{T,0}$  is a (tunable) infrared regulator that runs with centre-of-mass energy. The tunes 4C [12], CUET [13], and MONASH [14] are used, featuring different choices of the  $p_{T,0}$  cutoff, proton transverse profile, and/or parton distribution functions.

The HERWIG++ [15] Monte Carlo (MC) includes a hard (pQCD 2 $\rightarrow$ 2 interactions) [16] and a soft (non-perturbative) component for multiple interactions [17]. The soft part is parametrised phenomenologically as  $d\sigma/dp_T^2 = Ae^{-\beta p_T^2}$ . The transition scale between the hard and the soft regions is set by the parameter  $p_{T,0}$ , obtained from fits to MPI and UE data, as well as to the effective cross section for double-parton scatterings. The parameters *A* and  $\beta$  are fixed by the requirements that the transverse momentum distribution be continuous at the matching scale  $p_{T,0}$ , and that the model reproduces the measured total cross section. HERWIG++ with tune CUETHS1 [?] is used to compared the measurement at reconstruction level. HERWIG++ is not used in the comparison of the final results, as it does not contain any diffractive component.

The other two models, QGSJET-II [18] and EPOS [19, 20], are based on Regge-Gribov effective field theory [21], which allows for a consistent treatment of soft and hard scattering processes in terms of the same degrees of freedom (reggeons and pomerons), based on unitarity cuts of the corresponding elastic scattering diagrams. Perturbative parton-parton processes are obtained via "cut (hard) pomeron" diagrams, and multi-scattering phenomena (saturation, MPI) are implemented through various procedures [22]. The two models differ in their approximations for the collision configurations (with exact energy sharing imposed in the case of EPOS), and the treatment of diffractive and perturbative contributions (the effective soft-hard transition occurs at  $p_{T,0} \sim 1.6 \text{ GeV}$  for QGSJET-II and at  $p_{T,0} \sim 2 \text{ GeV}$  for EPOS). Finally, in contrast to other MCs, EPOS includes also collective expansion effects in the final state that boost the final  $p_T$  distribution of the produced hadrons. It is worth to highlight that, for all MC models, the (centre-of-mass energy dependent)  $p_{T,0}$  cutoff plays a very similar role to the "saturation scale" ( $Q_{sat}$ ), which controls the onset of gluon fusion effects in the parton densities [23].

# 3 Experimental analysis

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator sampling hadron calorimeter are located within the volume of the solenoid.

The inner silicon tracker measures charged-particle trajectories ("tracks" in the following) within the pseudorapidity range  $|\eta| < 2.5$ . It provides an impact parameter resolution of about 100  $\mu$ m and a  $p_T$  resolution of about 0.7% for 1 GeV tracks at  $\eta = 0$  [24]. A more detailed description of the CMS detector, together with definitions of the coordinate system and kinematic variables can be found in Ref. [25].

The data analysed in this study were collected during a dedicated proton-proton run with an integrated luminosity of  $45 \,\mu b^{-1}$  at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV. This run has a low

instantaneous luminosity and a low probability ( $\sim 2\%$ ) of multiple pp interactions occurring in the same bunch crossing (pileup). Pileup events are rejected by requiring exactly one vertex, following the method described in Ref. [26].

Minimum bias events were selected online with the TOTEM T2 telescopes [27] that are placed symmetrically at about 14 m on both sides from the interaction point (IP). Single tracks are reconstructed in these telescopes with almost 100% efficiency for  $p_T > 20 \text{ MeV}/c$ , but because of multiple scattering and the effect of the magnetic field, tracks can be identified as coming from the IP with an efficiency that increases as a function of  $p_T$  and is greater than 80% for  $p_T > 40 \text{ MeV}/c$  [28]. The minimum bias trigger, defined by the requirement of the presence of at least one track candidate in either of the T2 detectors [29], has an efficiency close to 100% [26] for events where a charged particle is produced within the T2 acceptance. According to the PYTHIA 8 and QGSJETII-04 [18] generators, about 91–96% of the total inelastic cross section at  $\sqrt{s} = 8$  TeV is seen by T2 [4], with the uncertainty coming mainly from low mass diffractive events. The present analysis follows the procedure described in Ref. [26], where more details are given on the trigger, data selection, and correction procedures.

Corrections for the contribution of background events triggered by T2 but without a charged primary particle in the T2 acceptance are estimated with simulated events from PYTHIA 8 and EPOS. These models were found to enclose the measured pseudorapidity distributions of charged particles in the forward region [26]. The average corrections for the two models vary from 4% and 1% at  $p_T^{min} \approx 1$  GeV to 7% and 5% at  $p_T^{min} \approx 45$  GeV, for the track and trackjet analysis, respectively. The deviation of PYTHIA 8 and EPOS from the average correction is taken as an estimate of the systematic uncertainty related to the T2 trigger efficiency; it is less than 0.7% for the leading track measurement and varies between 0.1 and 1.0% for the leading track-jet measurement [26].

Events are selected offline by requiring the presence of a leading track in the region  $|\eta| < 2.4$  with  $p_T > 0.4$  GeV. These events are used to normalise the integrated distributions in both the leading track and the track-jet measurements. Track-jets are reconstructed offline from tracks with  $p_T > 0.1$  GeV and  $|\eta| < 2.4$ , clustered by using the anti- $k_T$  algorithm [30–32] with a distance parameter of 0.5. The track-jet momentum is determined from the sum of all track momenta in the track-jet. The pseudorapidity restriction  $|\eta^{jet}| < 1.9$  assures that the track-jet is contained within the tracker acceptance.

Detailed MC simulations of the CMS and T2 detectors are based on GEANT4 [33]. Simulated events are processed and reconstructed in the same manner as collision data. For the correction of detector effects, as well as for comparison with models, both the PYTHIA 6 [10] (version 6.426) event generator with tune Z2\* [34] and the PYTHIA 8 (version 8.153) generator with tune 4C are used. The final correction is obtained by averaging those from the two generators.

The data are corrected to the stable-particle level, which is defined to include primary charged particles with lifetimes of  $c\tau > 1$  cm, either directly produced in the pp collisions or from decays of particles with shorter lifetimes. According to this definition,  $K_S^0$  and  $\Lambda$  hadrons are considered stable. Generated events are selected at the stable-particle level if at least one charged particle with  $p_T > 40$  MeV is present within the range  $5.3 < |\eta| < 6.5$ , and at least one charged particle with  $p_T > 0.4$  GeV is found within  $|\eta| < 2.4$ . In each event, the highest- $p_T$  charged particle within  $|\eta| < 2.4$  and  $p_T > 0.8$  GeV is selected as the leading particle. Charged particles are clustered into jets by using the anti- $k_T$  algorithm with a distance parameter of 0.5 with no restriction on  $p_T$  or  $\eta$ . The leading charged-particle jet is then defined as the charged-particle jet with the highest  $p_T$  above 1 GeV and  $|\eta^{\text{jet}}| < 1.9$ .

The average systematic uncertainty in the track reconstruction efficiency is taken to be 3.9% [35]. Its effect is studied by randomly rejecting 3.9% of the tracks and then repeating the analysis. In the jet analysis, for tracks with low  $p_T$ , the rejection probability is taken as 15% for  $p_T < 1$  GeV. However, since the measurement is integrated over  $p_T$ , it is nearly insensitive to even such large values of the rejection probability. The resulting uncertainty varies between 0.4% and 3.7% for the leading charged particle analysis and between 2% and 12% for the leading jet analysis. The larger uncertainties correspond to higher  $p_T^{min}$ .

The  $p_T$  distribution of leading track-jets is unfolded to the stable-particle level by applying the iterative procedure [36] implemented in ROOUNFOLD [37] in order to correct for the jet reconstruction efficiency and for migrations in jet  $p_T$ . Thanks to the good  $p_T$  resolution of the reconstructed tracks a simple correction for the track-finding efficiency is found to be sufficient for obtaining the  $p_T$  distribution of leading charged particles. The PYTHIA 6 and PYTHIA 8 MC models are used to generate the response matrices and efficiency corrections, and the average correction from the two generators is used to obtain the  $p_T$  distributions at stable-particle level. The corrections vary between 5% and 10% at  $p_T \approx 1$  GeV, to 10% and 40% at  $p_T \approx 45$  GeV, for the charged particle and the jet measurements, respectively. The deviation from the average is taken as an estimate of the systematic uncertainty related to the correction procedure. This uncertainty varies from 0.6 to 3% for the leading charged particle analysis, and from 2 to 10% for the leading jet analysis, depending on  $p_T^{min}$ .

The systematic uncertainties are summarised in Table 1.

Table 1: The systematic uncertainties for the leading charged particle ( $0.8 < p_T^{min} < 50 \text{ GeV}$ ) and leading jet ( $1 < p_T^{min} < 50 \text{ GeV}$ ) measurements.

Source	Uncertainty (%)	
	Leading charged particle	Leading jet
T2 trigger efficiency	0.7	0.1–1.0
Tracking efficiency	0.4–3.7	2–12
Correction procedure	0.6–3.0	2.0–10
Total	0.7–4.6	2.5–16

The per-event yields, defined in Eq. (1), are obtained experimentally as

$$r(p_{\rm T}^{\rm min}) = \frac{1}{N_{\rm evt}} \sum_{p_{\rm T}^{\rm lead} > p_{\rm T}^{\rm min}} \Delta p_{\rm T}^{\rm lead} \left(\frac{\Delta N}{\Delta p_{\rm T}^{\rm lead}}\right), \tag{2}$$

where  $N_{\text{evt}}$  is the number of events with a leading charged particle within  $|\eta| < 2.4$  and with  $p_{\text{T}} > 0.4 \text{ GeV}$ ,  $\Delta p_{\text{T}}^{\text{lead}}$  is the bin width, and  $\Delta N$  is the number of events with a leading charged particle or leading jet in the bin.

# 4 Results

Figure 1 shows the integrated distributions for the leading charged particle and leading jet events for  $p_T^{min} > 0.8$  and 1 GeV, respectively. The distributions fall steeply at large transverse momenta, and by construction approach unity at small  $p_T^{min}$ . The turnover from a relatively flat to a steeply-falling distribution takes place between 1 and 10 GeV. However, the turnover point is different for the leading charged particles and the leading jet measurements. This reflects the fact that when particles are clustered into jets, more energy from additional particles is collected within the jet cone. In fact, when the jet cone size is reduced, the leading jet distribution approaches the leading charged particle distribution.



Figure 1: The integrated yield,  $r(p_T^{min})$ , of events with a leading charged particle within  $|\eta| < 2.4$  (top) and with a leading jet within  $|\eta| < 1.9$  (bottom), as a function of  $p_T^{min}$ . The data are compared to predictions from several PYTHIA 6 tunes (left) and various other event generators (right). The lower panels show the ratios of the MC and the data yields (MC/Data). The error bars indicate the statistical uncertainty and the red shaded area (only visible in the ratio plots) represents the systematic uncertainty. The predictions are scaled to the measured value of  $r(p_T^{lead} > 9.0 \text{ GeV})$  (top) and  $r(p_T^{lead} > 14.3 \text{ GeV})$  (bottom). The prediction from PYTHIA 6 with MPI off and no parton saturation is not shown in the MC/data ratio plot (left) because of the large disagreement with the data.

For the comparison of the data to predictions of QCD MC generators the latter are rescaled to describe the high- $p_T^{\text{lead}}$  region. This rescaling is applied because the normalisation to the total visible cross section, which depends on the low- $p_T$  regularisation, affects the values of r also at high- $p_T^{\text{lead}}$ , where in fact theoretical predictions are more robust and agree better with the data. The exact choice of the normalisation point is arbitrary— $r(p_T^{\text{lead}} > 9.0 \text{ GeV})$  for the leading charged particle, and  $r(p_T^{\text{lead}} > 14.3 \text{ GeV})$  for the leading jet—and the conclusions from this study are drawn from the shape of the distributions alone. The predictions at small  $p_T^{\text{lead}}$  thus give information on the modelling of the transition region from large to small  $p_T^{\text{lead}}$ .

In Fig. 1 (left plots) the yields  $r(p_T^{min})$  as a function of  $p_T^{min}$  are compared to the predictions of the event generator PYTHIA 6 with tunes Z2\* and CUET, as well as with the default version of PYTHIA 6, both with and without MPI. Also shown is the impact of turning off the regularisation of the cross section, labeled "PYTHIA 6 (default, MPI off, no sat)". At low  $p_T^{min}$ , the distribution predicted by this latter model differs by more than one order of magnitude from predictions with the regularised cross section.

In Fig. 1 (right plots) the leading charged particle and leading jet data are compared with PYTHIA 8 with tunes 4C, CUET, and MONASH, HERWIG++ (version 2.7.0) with tune UE-EE-5C, EPOS (version 1.99) with LHC tune, and QGSJETII-04.

The leading charged particle and leading jet cross sections are best described by EPOS, which deviates only by up to 10% from the data at very low  $p_T^{min}$  and reproduces the data well for  $p_T^{min} > 4$  GeV. The event generator HERWIG++ (UE-EE-5C tune) describes the leading jet cross sections fairly well, but does not reproduce the transition from large to small  $p_T$  in the leading charged particle cross section. The event generators PYTHIA 6 (Z2\* and CUET tunes) and PYTHIA 8 (4C, CUET, and MONASH tunes) predict a somewhat different shape for the measured distributions at small  $p_T$ .

The comparison of the MC predictions for MPI switched on and off indicates that the effect of MPI is small for leading charged particles, since the particle multiplicity plays only a minor role. However, when clustering particles into jets, the additional particles from MPI play a role, and a large difference is seen when such interactions are switched off in the simulation as in Fig. 1 (bottom left); this brings PYTHIA 6 closer to the data at low  $p_T^{min}$ .

The predictions with MPI and saturation turned off (dashed curves in Fig. 1, left plots) exhibit a significant deviation from the data at small  $p_{\rm T}$ .

In general, PYTHIA and HERWIG++ describe the trend of the measured distributions but fail to reproduce the details in the O(1-5 GeV) region, which calls for an improvement in their modelling of the transition from the non-perturbative to perturbative regime.

# 5 Summary

The integrated yields of events with a leading charged particle or a leading charged-particle jet with  $p_{\rm T}$  above a given  $p_{\rm T}^{\rm min}$  threshold, starting at  $p_{\rm T}^{\rm min} = 0.8$  and 1 GeV, respectively, have been measured in pp collisions at  $\sqrt{s} = 8$  TeV in a data sample corresponding to an integrated luminosity of 45  $\mu$ b<sup>-1</sup>. The particles and jets are measured in the pseudorapidity ranges  $|\eta| < 2.4$  and 1.9, respectively.

The yields are found to be relatively flat in the  $p_T^{min}$  region around 1 GeV—where the fixedorder perturbative parton-parton cross section diverges in the absence of any mechanism that saturates or unitarises the pQCD scattering—followed by a steep decrease for  $p_T^{min} > 10$  GeV.

### References

The flattening behaviour observed at very low  $p_T^{min}$  is best described by EPOS, which deviates by at most 10% from the data. The comparison of the data with different phenomenological predictions of hadronic interaction models may help to improve the description of the transition between the perturbative and non-perturbative QCD regimes, which is dominated by the effects of parton density saturation and multiple partonic interactions.

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# A The CMS Collaboration

# Yerevan Physics Institute, Yerevan, Armenia

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

# Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

# Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, S. Bansal, 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 Spilbeeck

# Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

# Université Libre de Bruxelles, Bruxelles, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè<sup>2</sup>, A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

# Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi<sup>3</sup>, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov<sup>5</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

# Université de Mons, Mons, Belgium

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

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

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, J. Molina, C. Mora Herrera, M.E. Pol, P. Rebello Teles

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

W. Carvalho, J. Chinellato<sup>6</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

# Universidade Estadual Paulista<sup>*a*</sup>, Universidade Federal do ABC<sup>*b*</sup>, São Paulo, Brazil

C.A. Bernardes<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>, S.F. Novaes<sup>*a*</sup>, Sandra S. Padula<sup>*a*</sup>

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

A. Aleksandrov, V. Genchev<sup>2</sup>, R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

## University of Sofia, Sofia, Bulgaria

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

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

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>7</sup>, F. Romeo, J. Tao, Z. Wang

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China** C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang<sup>8</sup>, L. Zhang, W. Zou

# Universidad de Los Andes, Bogota, Colombia

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

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

N. Godinovic, D. Lelas, D. Polic, I. Puljak

# **University of Split, Faculty of Science, Split, Croatia** *Z*. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia** V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

# University of Cyprus, Nicosia, Cyprus

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

### **Charles University, Prague, Czech Republic** M. Bodlak, M. Finger, M. Finger Jr.<sup>9</sup>

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt Y. Assran<sup>10</sup>, S. Elgammal<sup>11</sup>, A. Ellithi Kamel<sup>12</sup>, M.A. Mahmoud<sup>13</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia** M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

**Department of Physics, University of Helsinki, Helsinki, Finland** P. Eerola, M. Voutilainen

# Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, 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, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland** J. Talvitie, T. Tuuva

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

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, J. Malcles, J. Rander, A. Rosowsky, M. Titov

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

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

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

J.-L. Agram<sup>14</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet<sup>7</sup>, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo<sup>2</sup>, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, 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

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

Z. Tsamalaidze<sup>9</sup>

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, 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, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer

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

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

# Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borras, 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, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel<sup>15</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>15</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol,

D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>15</sup>, B. Lutz, R. Mankel, I. Marfin<sup>15</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, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

# University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

# Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann<sup>2</sup>, T. Hauth, U. Husemann, I. Katkov<sup>5</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

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

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

# University of Athens, Athens, Greece

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

# University of Ioánnina, Ioánnina, Greece

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

# Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>16</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>17</sup>, A.J. Zsigmond

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary** N. Beni, S. Czellar, J. Karancsi<sup>18</sup>, J. Molnar, J. Palinkas, Z. Szillasi

# University of Debrecen, Debrecen, Hungary

A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

# National Institute of Science Education and Research, Bhubaneswar, India S.K. Swain

# Panjab University, Chandigarh, India

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

# University of Delhi, Delhi, India

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

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

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

### Bhabha Atomic Research Centre, Mumbai, India

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

# Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik<sup>19</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>20</sup>, G. Kole, S. Kumar, M. Maity<sup>19</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>21</sup>

**Indian Institute of Science Education and Research (IISER), Pune, India** S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>22</sup>, A. Fahim<sup>23</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>24</sup>, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

# 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>, C. Calabria<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>, 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*,2</sup>, G. Selvaggi<sup>*a*,*b*</sup>, A. Sharma<sup>*a*</sup>, L. Silvestris<sup>*a*,2</sup>, R. Venditti<sup>*a*,*b*</sup>, P. Verwilligen<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*,*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>

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

S. Albergo<sup>*a,b*</sup>, G. Cappello<sup>*a*</sup>, M. Chiorboli<sup>*a,b*</sup>, S. Costa<sup>*a,b*</sup>, F. Giordano<sup>*a,2*</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>, E. Gallo<sup>*a*</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>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

R. Ferretti<sup>*a*,*b*</sup>, F. Ferro<sup>*a*</sup>, M. Lo Vetere<sup>*a*,*b*</sup>, E. Robutti<sup>*a*</sup>, S. Tosi<sup>*a*,*b*</sup>

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

M.E. Dinardo<sup>*a,b*</sup>, S. Fiorendi<sup>*a,b*</sup>, S. Gennai<sup>*a,2*</sup>, R. Gerosa<sup>*a,b,2*</sup>, A. Ghezzi<sup>*a,b*</sup>, P. Govoni<sup>*a,b*</sup>, M.T. Lucchini<sup>*a,b,2*</sup>, S. Malvezzi<sup>*a*</sup>, R.A. Manzoni<sup>*a,b*</sup>, A. Martelli<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>

# INFN Sezione di Napoli<sup>*a*</sup>, Università di Napoli 'Federico II'<sup>*b*</sup>, Napoli, Italy, Università della Basilicata<sup>*c*</sup>, Potenza, Italy, Università G. Marconi<sup>*d*</sup>, Roma, Italy

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

# INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy

P. Azzi<sup>*a*</sup>, N. Bacchetta<sup>*a*</sup>, M. Bellato<sup>*a*</sup>, M. Dall'Osso<sup>*a*,*b*</sup>, T. Dorigo<sup>*a*</sup>, S. Fantinel<sup>*a*</sup>, F. Gonella<sup>*a*</sup>, A. Gozzelino<sup>*a*</sup>, M. Gulmini<sup>*a*,25</sup>, S. Lacaprara<sup>*a*</sup>, M. Margoni<sup>*a*,*b*</sup>, A.T. Meneguzzo<sup>*a*,*b*</sup>, F. Montecassiano<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>, M. Sgaravatto<sup>*a*</sup>, F. Simonetto<sup>*a*,*b*</sup>, E. Torassa<sup>*a*</sup>, M. Tosi<sup>*a*,*b*</sup>, S. Vanini<sup>*a*,*b*</sup>, S. Ventura<sup>*a*</sup>, P. Zotto<sup>*a*,*b*</sup>, A. Zucchetta<sup>*a*,*b*</sup>

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

M. Gabusi<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>, P. Vitulo<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>, 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. Santocchia<sup>*a*,*b*</sup>, A. Spiezia<sup>*a*,*b*,2</sup>

INFN Sezione di Pisa<sup>*a*</sup>, Università di Pisa<sup>*b*</sup>, Scuola Normale Superiore di Pisa<sup>*c*</sup>, Pisa, Italy K. Androsov<sup>*a*,26</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*,26</sup>, R. Dell'Orso<sup>*a*</sup>, S. Donato<sup>*a*,*c*,2</sup>, G. Fedi, F. Fiori<sup>*a*,*c*</sup>, L. Foà<sup>*a*,*c*</sup>, A. Giassi<sup>*a*</sup>, M.T. Grippo<sup>*a*,26</sup>, F. Ligabue<sup>*a*,*c*</sup>, T. Lomtadze<sup>*a*</sup>, L. Martini<sup>*a*,*b*</sup>, A. Messineo<sup>*a*,*b*</sup>, C.S. Moon<sup>*a*,27</sup>, F. Palla<sup>*a*,2</sup>, A. Rizzi<sup>*a*,*b*</sup>, A. Savoy-Navarro<sup>*a*,28</sup>, A.T. Serban<sup>*a*</sup>, P. Spagnolo<sup>*a*</sup>, P. Squillacioti<sup>*a*,26</sup>, R. Tenchini<sup>*a*</sup>, G. Tonelli<sup>*a*,*b*</sup>, A. Venturi<sup>*a*</sup>, P.G. Verdini<sup>*a*</sup>, C. Vernieri<sup>*a*,*c*</sup>

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

L. Barone<sup>*a,b*</sup>, F. Cavallari<sup>*a*</sup>, G. D'imperio<sup>*a,b*</sup>, D. Del Re<sup>*a,b*</sup>, M. Diemoz<sup>*a*</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*,2</sup>, G. Organtini<sup>*a,b*</sup>, R. Paramatti<sup>*a*</sup>, S. Rahatlou<sup>*a,b*</sup>, C. Rovelli<sup>*a*</sup>, F. Santanastasio<sup>*a,b*</sup>, L. Soffi<sup>*a,b*</sup>, P. Traczyk<sup>*a,b*,2</sup>

# INFN Sezione di Torino <sup>*a*</sup>, Università di Torino <sup>*b*</sup>, Torino, Italy, Università del Piemonte Orientale <sup>*c*</sup>, Novara, 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>, R. Bellan<sup>*a,b*</sup>, C. Biino<sup>*a*</sup>, N. Cartiglia<sup>*a*</sup>, S. Casasso<sup>*a,b,2*</sup>, M. Costa<sup>*a,b*</sup>, R. Covarelli, D. Dattola<sup>*a*</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>, M. Musich<sup>*a*</sup>, M.M. Obertino<sup>*a,c*</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>, 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>

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

# Kangwon National University, Chunchon, Korea

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

**Kyungpook National University, Daegu, Korea** D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

# Chonbuk National University, Jeonju, Korea

T.J. Kim, M.S. Ryu

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

J.Y. Kim, D.H. Moon, S. Song

### Korea University, Seoul, Korea

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

**Seoul National University, Seoul, Korea** H.D. Yoo

**University of Seoul, Seoul, Korea** M. Choi, J.H. Kim, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania A. Juodagalvis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia J.R. Komaragiri, M.A.B. Md Ali<sup>29</sup>, W.A.T. Wan Abdullah

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico** E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico** I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico A. Morelos Pineda

**University of Auckland, Auckland, New Zealand** D. Krofcheck

University of Canterbury, Christchurch, New Zealand P.H. Butler, S. Reucroft

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

# National Centre for Nuclear Research, Swierk, Poland

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

# Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>30</sup>, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim<sup>31</sup>, E. Kuznetsova, 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, A. Pashenkov, D. Tlisov, A. Toropin

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

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

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

V. Andreev, M. Azarkin<sup>32</sup>, I. Dremin<sup>32</sup>, M. Kirakosyan, A. Leonidov<sup>32</sup>, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

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

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, 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>33</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, C. Battilana, 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

### Universidad Autónoma de Madrid, Madrid, Spain

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

# Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, 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

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

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. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>34</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco,

M. Dobson, M. Dordevic, B. Dorney, N. Dupont, A. Elliott-Peisert, J. Eugster, 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, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>35</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>36</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres<sup>17</sup>, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

# Paul Scherrer Institut, Villigen, Switzerland

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

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

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, C. Nägeli<sup>37</sup>, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov<sup>38</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

# Universität Zürich, Zurich, Switzerland

C. Amsler<sup>39</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, Y. Yang

# National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

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

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

# **Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand** B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

## Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci<sup>40</sup>, S. Cerci<sup>41</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>42</sup>, A. Kayis Topaksu, G. Onengut<sup>43</sup>, K. Ozdemir<sup>44</sup>, S. Ozturk<sup>40</sup>, A. Polatoz, D. Sunar Cerci<sup>41</sup>, B. Tali<sup>41</sup>, H. Topakli<sup>40</sup>, M. Vergili, C. Zorbilmez

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

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan<sup>45</sup>, B. Isildak<sup>46</sup>, G. Karapinar<sup>47</sup>, K. Ocalan<sup>48</sup>, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey** E.A. Albayrak<sup>49</sup>, E. Gülmez, M. Kaya<sup>50</sup>, O. Kaya<sup>51</sup>, T. Yetkin<sup>52</sup>

**Istanbul Technical University, Istanbul, Turkey** K. Cankocak, F.I. Vardarlı

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine L. Levchuk, P. Sorokin

# University of Bristol, Bristol, United Kingdom

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>53</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

# Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev<sup>54</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, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

# Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>53</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko<sup>38</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

# Brunel University, Uxbridge, 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

# Baylor University, Waco, USA

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu

### The University of Alabama, Tuscaloosa, USA

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

# Boston University, Boston, USA

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

# Brown University, Providence, USA

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

# University of California, Davis, Davis, 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, Los Angeles, USA

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

### University of California, Riverside, Riverside, USA

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

#### University of California, San Diego, La Jolla, 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, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

## University of California, Santa Barbara, Santa Barbara, USA

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

### California Institute of Technology, Pasadena, USA

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

## Carnegie Mellon University, Pittsburgh, USA

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

# University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

# Cornell University, Ithaca, USA

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

### Fairfield University, Fairfield, USA

D. Winn

## Fermi National Accelerator Laboratory, Batavia, 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, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, 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, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

### University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenovic<sup>55</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

**Florida International University, Miami, USA** S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

#### Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, 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

# The University of Iowa, Iowa City, USA

B. Bilki<sup>56</sup>, W. Clarida, K. Dilsiz, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>57</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>49</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

### Johns Hopkins University, Baltimore, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, M. Xiao

#### The University of Kansas, Lawrence, 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, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

#### Kansas State University, Manhattan, USA

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

# Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

# University of Maryland, College Park, USA

A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, Y. Lu, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

# Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, R. Barbieri, K. Bierwagen, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

# University of Minnesota, Minneapolis, USA

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

# University of Nebraska-Lincoln, Lincoln, USA

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

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

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

# Northeastern University, Boston, USA

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

### Northwestern University, Evanston, USA

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

# University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, Y. Musienko<sup>30</sup>, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

## The Ohio State University, Columbus, USA

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

# Princeton University, Princeton, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland<sup>2</sup>, C. Tully, J.S. Werner, A. Zuranski

#### University of Puerto Rico, Mayaguez, USA

E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

# Purdue University, West Lafayette, USA

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

# Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

### **Rice University, Houston, USA**

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

## University of Rochester, Rochester, 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, S. Korjenevski, G. Petrillo, M. Verzetti, D. Vishnevskiy

### The Rockefeller University, New York, USA

R. Ciesielski, L. Demortier, K. Goulianos, C. Mesropian

# Rutgers, The State University of New Jersey, Piscataway, 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, S. Kaplan, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

### University of Tennessee, Knoxville, USA

K. Rose, S. Spanier, A. York

# Texas A&M University, College Station, USA

O. Bouhali<sup>58</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>59</sup>, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

#### Texas Tech University, Lubbock, USA

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

# Vanderbilt University, Nashville, USA

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

# University of Virginia, Charlottesville, 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

## Wayne State University, Detroit, USA

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

### University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods

- †: Deceased
- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

6: Also at Universidade Estadual de Campinas, Campinas, Brazil

7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

8: Also at Université Libre de Bruxelles, Bruxelles, Belgium

9: Also at Joint Institute for Nuclear Research, Dubna, Russia

10: Also at Suez University, Suez, Egypt

11: Also at British University in Egypt, Cairo, Egypt

12: Also at Cairo University, Cairo, Egypt

13: Also at Fayoum University, El-Fayoum, Egypt

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Brandenburg University of Technology, Cottbus, Germany

- 16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 17: Also at Eötvös Loránd University, Budapest, Hungary

18: Also at University of Debrecen, Debrecen, Hungary

19: Also at University of Visva-Bharati, Santiniketan, India

20: Now at King Abdulaziz University, Jeddah, Saudi Arabia

21: Also at University of Ruhuna, Matara, Sri Lanka

22: Also at Isfahan University of Technology, Isfahan, Iran

23: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

25: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy

26: Also at Università degli Studi di Siena, Siena, Italy

27: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France

28: Also at Purdue University, West Lafayette, USA

29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

30: Also at Institute for Nuclear Research, Moscow, Russia

31: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

32: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

33: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

34: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy

35: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

36: Also at University of Athens, Athens, Greece

37: Also at Paul Scherrer Institut, Villigen, Switzerland

38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

39: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

40: Also at Gaziosmanpasa University, Tokat, Turkey

41: Also at Adiyaman University, Adiyaman, Turkey

42: Also at Mersin University, Mersin, Turkey

43: Also at Cag University, Mersin, Turkey

44: Also at Piri Reis University, Istanbul, Turkey

45: Also at Anadolu University, Eskisehir, Turkey

46: Also at Ozyegin University, Istanbul, Turkey

47: Also at Izmir Institute of Technology, Izmir, Turkey

48: Also at Necmettin Erbakan University, Konya, Turkey

49: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

50: Also at Marmara University, Istanbul, Turkey

51: Also at Kafkas University, Kars, Turkey

52: Also at Yildiz Technical University, Istanbul, Turkey

53: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

54: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

55: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

56: Also at Argonne National Laboratory, Argonne, USA

57: Also at Erzincan University, Erzincan, Turkey

58: Also at Texas A&M University at Qatar, Doha, Qatar

59: Also at Kyungpook National University, Daegu, Korea