

Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton–proton collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*
CERN, Geneva, Switzerland

Received: 3 April 2012 / Revised: 22 October 2012 / Published online: 16 November 2012
© CERN for the benefit of the CMS collaboration 2012. This article is published with open access at Springerlink.com

Abstract A study of dijet production in proton–proton collisions was performed at $\sqrt{s} = 7$ TeV for jets with $p_T > 35$ GeV and $|y| < 4.7$ using data collected with the CMS detector at the LHC in 2010. Events with at least one pair of jets are denoted as “inclusive”. Events with exactly one pair of jets are called “exclusive”. The ratio of the cross section of all pairwise combinations of jets to the exclusive dijet cross section as a function of the rapidity difference between jets $|\Delta y|$ is measured for the first time up to $|\Delta y| = 9.2$. The ratio of the cross section for the pair consisting of the most forward and the most backward jet from the inclusive sample to the exclusive dijet cross section is also presented. The predictions of the Monte Carlo event generators PYTHIA6 and PYTHIA8 agree with the measurements. In both ratios the HERWIG++ generator exhibits a more pronounced rise versus $|\Delta y|$ than observed in the data. The BFKL-motivated generators CASCADE and HEJ+ARIADNE predict for these ratios a significantly stronger rise than observed.

The measurement of inclusive jet production in pp collisions provides an important testing ground for the Standard Model. Inclusive jet production is well described at LHC energies, over a wide range in jet transverse momentum and rapidity [1, 2], by calculations at next-to-leading-order (NLO) in perturbative quantum chromodynamics (QCD) using the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) approach [3–7] and collinear factorization. The rapidity y is defined as $y = (1/2) \log[(E + p_z)/(E - p_z)]$, where E is the jet energy and p_z is the component of the jet momentum along the beam axis. As shown in [8], the production of dijets with invariant mass above 165 GeV and $|y|$ less than 2.5 is also well described by NLO predictions. When

jets are well separated in rapidity, the description of the data becomes worse [2].

When the collision energy \sqrt{s} is considerably larger than the hard scattering scale given by the jet transverse momentum, p_T , the average number of produced jets grows rapidly, along with the phase space available in rapidity. This kinematic regime is expected to be described by the Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution [9–11] and k_T factorization [12–14]. An effective theory has been developed which describes strong interactions in this kinematic domain [15].

The ratio of the dijet production cross section in “inclusive” events to that in “exclusive” events, $R^{\text{incl}} = \sigma^{\text{incl}}/\sigma^{\text{excl}}$, as a function of the rapidity separation $|\Delta y|$ between two jets, is a sensitive probe of effects beyond collinear factorization [16]. Only jets with transverse momenta above a minimal value of p_T^{min} are considered. Events with at least one pair of jets are denoted as “inclusive”. Events with exactly one pair of jets are called “exclusive”. In the inclusive case, the rapidity separation is evaluated for each pairwise combination of jets above threshold [16]. Mueller–Navelet jet pairs [17] are a subset of the inclusive dijet class. In this case only the jet at highest rapidity (i.e. most forward) and that at lowest rapidity (most backward) are considered. At low $|\Delta y|$, the inclusive dijet ratio, R^{incl} , is always larger than the corresponding Mueller–Navelet dijet ratio, $R^{\text{MN}} = \sigma^{\text{MN}}/\sigma^{\text{excl}}$, because all the jets in the rapidity interval between the Mueller–Navelet jets contribute to the inclusive cross section.

From the theoretical point of view, an advantage of the ratios R^{incl} and R^{MN} with respect to the individual dijet production cross sections is that the influence of the uncertainty of the parton distribution functions is greatly reduced; in addition, the ratios are particularly sensitive to the parton radiation pattern [16]. At large enough energies, the parton subprocesses involve a large number of partons with compa-

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

rable transverse energies. Such subprocesses, governed by BFKL evolution, lead to an increase of the ratios with increasing $|\Delta y|$ [16–18]. Experimentally, an additional advantage of the R^{incl} and R^{MN} ratios defined above is the cancellation of most of the systematic uncertainties affecting both numerator and denominator.

Earlier measurements of Mueller–Navelet jets with $|\Delta y|$ up to 5 were made at the Tevatron by the D0 experiment [19, 20]. D0 did not find indications of BFKL effects in the azimuthal decorrelation data [19]; however, a stronger than expected \sqrt{s} dependence of the dijet production cross section was observed [20] when comparing the data at $\sqrt{s} = 630$ and 1800 GeV for dijets with large rapidity separation. The ATLAS Collaboration recently studied various dijet production cross section ratios at $\sqrt{s} = 7$ TeV for $|\Delta y| < 6$ [21]; the results are roughly in agreement with the DGLAP predictions. At the HERA ep collider, deviations from DGLAP were observed in studies of forward jets by the ZEUS [22, 23] and H1 [24, 25] Collaborations. However, no compelling evidence for BFKL effects was found.

The component of the CMS detector [26] most relevant for this analysis is the calorimeter system extending to pseudorapidities $|\eta| = 5.2$, where $\eta = -\log[\tan(\theta/2)]$, and θ is the polar angle relative to the anticlockwise proton beam direction. The crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadronic calorimeter (HCAL) extend to pseudorapidities $|\eta| = 3.0$. The HCAL cells map to an array of ECAL crystals to form calorimeter towers projecting radially outwards from the nominal interaction point. The pseudorapidity region $3.0 < |\eta| < 5.2$ is covered by the hadronic forward (HF) calorimeter, which consists of steel absorber wedges with embedded radiation-hard quartz fibers, oriented parallel to the beam direction. The calorimeter towers in the barrel region have segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, becoming progressively larger in the endcap and forward regions ($\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ at $\eta \sim 4.5$).

The CMS trigger system consists of a hardware Level-1 trigger and a software high-level trigger. Jets formed online by the trigger system use ECAL, HCAL and HF inputs for energy clustering and are not corrected for the jet energy response. The minimum-bias trigger was defined as the coincidence of a signal from one of the two beam scintillation counters covering the range $3.23 < |\eta| < 4.65$ and a signal from one of the beam pick-up timing devices.

The data were collected in 2010, when LHC collided protons at $\sqrt{s} = 7$ TeV. Various triggers were used to cover the largest possible range in rapidity separation between jets. Dijets with moderate $|\Delta y|$ were selected by a single-jet trigger with a threshold on the raw (uncorrected) jet transverse momentum of 15 GeV. This trigger was significantly prescaled as the instantaneous luminosity increased, and the effective integrated luminosity recorded with it is $\simeq 33 \text{ nb}^{-1}$.

Dijet events with large rapidity separation are rare. Therefore, a dedicated trigger for forward–backward dijets was developed. This forward–backward–dijet trigger selects events with two jets in opposite hemispheres and $|\eta| > 3.0$, and jet raw transverse momentum $p_{\text{T}} > 15$ GeV. It was operated with moderate prescaling, and the effective integrated luminosity recorded with it is $\simeq 5 \text{ pb}^{-1}$. This allowed to collect a number of dijet events at high $|\Delta y|$ values more than 100 times larger than with the single-jet trigger.

The trigger efficiency was measured by means of a control sample selected with the minimum-bias trigger. The single-jet trigger was found to be 100 % efficient for dijets with corrected $p_{\text{T}} > 35$ GeV. The single-jet trigger was also used for the determination of the efficiency of the forward–backward–dijet trigger. The latter was 100 % efficient for dijets with $p_{\text{T}} > 35$ GeV.

Jets were reconstructed offline from the energy depositions in the calorimeter towers, clustered with the anti- k_{T} algorithm [27, 28] with a distance parameter $R = 0.5$. In the reconstruction process, the contribution from each tower was assigned a momentum, the absolute value and the direction of which were given by the energy measured in the tower, and the coordinates of the tower, respectively. The raw jet energy was obtained from the sum of the tower energies, and the raw jet momentum from the vectorial sum of the tower momenta. The raw jet energies were then corrected to establish a uniform relative response of the calorimeter in η and a calibrated absolute response in transverse momentum p_{T} [29]. The jet energy resolution for calorimeter jets with $p_{\text{T}} \sim 35$ GeV is about 22 % for $|\eta| < 0.5$ and about 10 % for $4 < |\eta| < 4.5$ [30]. The uncertainty of the jet energy calibration for jets with $p_{\text{T}} \sim 35$ GeV depends on η and is $\simeq 7\text{--}8$ % [29].

In the offline analysis, at least one well-reconstructed primary vertex is required to be present within ± 24 cm of the nominal interaction point along the beamline [31]. In order to reduce the sensitivity to overlapping pp collisions (the so-called “pile-up” events), events with only one primary vertex reconstructed within the luminous region were used for the measurement.

Loose jet quality cuts [32] were used to suppress the effect of calorimeter noise. Events with at least two jets with $p_{\text{T}} > 35$ GeV and $|y| < 4.7$ were selected; only jets satisfying these criteria were used for the analysis. All pairwise combinations of jets from the selected events entered the inclusive distribution. For studies of Mueller–Navelet jets, only the pair consisting of the most forward and the most backward jet was considered. The exclusive dijet sample is a subset of the inclusive and Mueller–Navelet samples, and consists of events where exactly one pair of jets is found. The measured observables, R^{incl} and R^{MN} , are defined as the ratios of the yield of inclusive or Mueller–Navelet dijets to the yield of exclusive dijets in a specific $|\Delta y|$ bin, respectively.

Detector effects were accounted for by applying bin-by-bin corrections derived from Monte Carlo (MC) simulations. Simulated events produced with the generators PYTHIA6 (version 6.422) tune Z2 [33–35] and HERWIG++ [36] (version 2.4.2 with default settings) were passed through the full CMS detector simulation based on the GEANT4 package [37], and were input to the same event-reconstruction program as used for the data. To quantify detector effects, the distributions obtained from detector-level quantities were compared to the distributions obtained at the level of stable particles (lifetime τ such that $c\tau > 10$ mm). The ratios of the stable-particle level and detector-level quantities in a given bin were used to correct the data.

Because of the finite p_T and y resolutions, the detector-level distributions deviate from the corresponding ones at stable-particle level. Events can migrate to and from the exclusive or the inclusive samples because of fluctuations of the measured transverse jet momentum around the p_T^{\min} threshold. The amount of these migrations was estimated not to exceed 20 %. Similarly, the $|\Delta y|$ value measured at detector level may fall into a different $|\Delta y|$ bin compared to the stable-particle level; this effect, for the present data, is typically around 5–10 % and reaches 15–25 % at most. The influence of these migrations on the measured ratios R^{incl} and R^{MN} is minimal as the effects for numerator and denominator are similar. The uncorrected R^{incl} and R^{MN} ratios are reasonably well reproduced by the PYTHIA6 events and less well by HERWIG++ events, both of which have been passed through the detector simulation. The p_T and η distributions of the jets at the detector level for both MC generators agree with the data within the jet energy scale uncertainty (see also [2]). The correction factors were therefore obtained with PYTHIA6, while their model dependence was estimated from the difference between the PYTHIA6 and HERWIG++ corrections.

The following sources of systematic effects were considered:

- (1) Uncertainty of the jet energy calibration. The uncertainty of the measurement was estimated by shifting the jet energy scale (JES) by the p_T - and η -dependent uncertainties derived in [29]. The resulting variation of the measurements does not exceed 4.2 % for R^{incl} and 3.8 % for R^{MN} .
- (2) Uncertainty of the corrections for detector effects.
 - (a) Uncertainty due to model dependence of the correction factors. As discussed above, correction factors were determined by using HERWIG++ and PYTHIA6, and corrected measurements were obtained for each case. The difference in the results was taken as a measure of the model dependence of the correction factors; it does not exceed 3.4 % for R^{incl} and 3.3 % for R^{MN} .

Table 1 Sources of systematic effects and associated uncertainties. The ranges correspond to the variation of the uncertainty with $|\Delta y|$. For different uncertainty sources, the minimum and maximum values may correspond to different $|\Delta y|$ bins. For asymmetric uncertainties the upper and lower limits are shown

Source	R^{incl} uncertainty (%)	R^{MN} uncertainty (%)
Jet energy scale	+ (2.2–4.2) – (1.0–3.0)	+ (0.2–3.8) – (0.2–2.3)
Uncertainty of detector corrections	\pm (1.5–3.5)	\pm (0.1–3.4)
Pile-up	< 1.3	< 1.3
Total	+ (2.8–5.6) – (2.7–4.5)	+ (0.2–4.8) – (0.2–3.7)

- (b) Uncertainty related to the quality of the MC description of the jet p_T and y resolutions. These resolutions were modified by ± 10 % in the simulation as recommended in [30]. A conservative estimate of the uncertainty associated to this effect does not exceed ± 1.0 %.
- (3) An additional systematic effect may originate from the extra energy and jets due to pile-up collisions. As noted earlier, the measurement was restricted to events with only one reconstructed primary vertex to reduce the impact of pile-up. However, a contribution from interactions undetected because of vertex reconstruction inefficiency may still be present. By comparing data taken at different instantaneous luminosities, an upper limit of 1.3 % was estimated for this effect. The value was obtained for pairs of jets in the forward region, where the impact of pile-up on jet reconstruction is more significant [29]; the effect is thus expected to be smaller for jets at central rapidities.

The total systematic uncertainty was calculated as the quadratic sum of the individual uncertainties. The total uncertainty is $|\Delta y|$ dependent but always smaller than 5.6 % for R^{incl} and 4.8 % for R^{MN} (Table 1).

The measured ratios, corrected for detector effects, were compared to the predictions of several MC generators at the stable-particle level. A DGLAP leading-order parton shower approach is used in PYTHIA6 (version 6.422) tune Z2 [35], PYTHIA8 (version 8.145) [38] tune 4C [39] and HERWIG++ (version 2.5.1) tune UE-7000-EE-3 [36, 40]. For the simulation of the non-perturbative fragmentation, PYTHIA uses the Lund string model, and HERWIG++ the cluster fragmentation approach. The tunes mentioned above include multiple parton interactions (MPI) as a part of the underlying event (UE) modeling. The dijet observables might be affected by MPI through jets that do not originate from the same hard interaction. The effect was estimated by switching off the MPI options in PYTHIA6 and HERWIG++; no significant change in the predictions was observed.

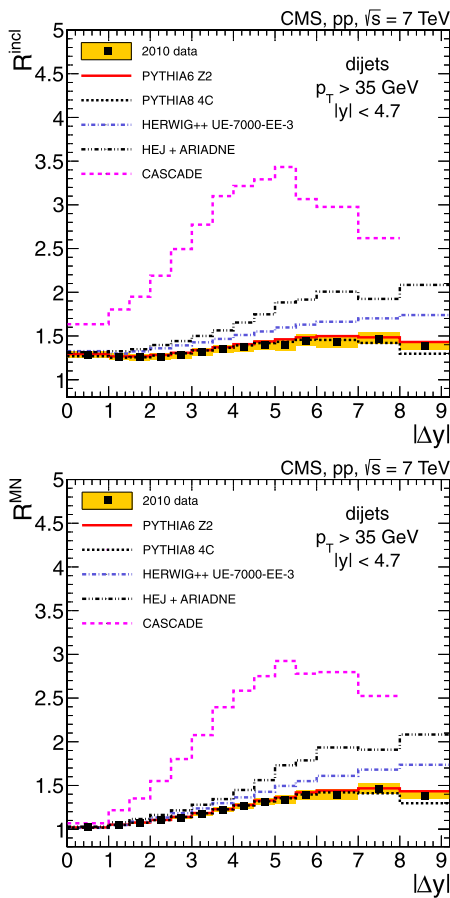


Fig. 1 Ratios of the inclusive to exclusive dijet cross sections as a function of the rapidity separation $|\Delta y|$ between the two jets, R^{incl} (top panel) and R^{MN} (bottom panel), compared to the predictions of the DGLAP-based MC generators PYTHIA6, PYTHIA8 and HERWIG++, as well as of CASCADE and HEJ+ARIADNE, which incorporate elements of the BFKL approach. The shaded band indicates the size of the total systematic uncertainty of the data. Statistical uncertainties are smaller than the symbol sizes. Because of limitations in the CASCADE generator, it was not possible to obtain a reliable prediction for $|\Delta y| > 8$

The Monte Carlo generators CASCADE (version 2.2.03) [41] and HEJ (version 1.3.2) [42] are motivated by the leading-logarithmic BFKL approach and incorporate parts of a next-to-leading logarithmic approximation. The HEJ generator produces parton-level jets; the corresponding showers were produced with the ARIADNE program [43]. The HEJ+ARIADNE package [44] version 0.99b, consisting of HEJ 1.3.2 and ARIADNE 4.12, was used.

The ratio R^{incl} of inclusive to exclusive dijet production as a function of $|\Delta y|$ is presented in Fig. 1 (top panel). On average the inclusive cross section is 1.2–1.5 times larger than the exclusive cross section. The ratio R^{incl} grows with increasing $|\Delta y|$, as expected because of the larger phase space for hard parton radiation. At the highest $|\Delta y|$, R^{incl} is expected to decrease because energy-momentum conservation suppresses the emission of extra jets. The $|\Delta y|$ value

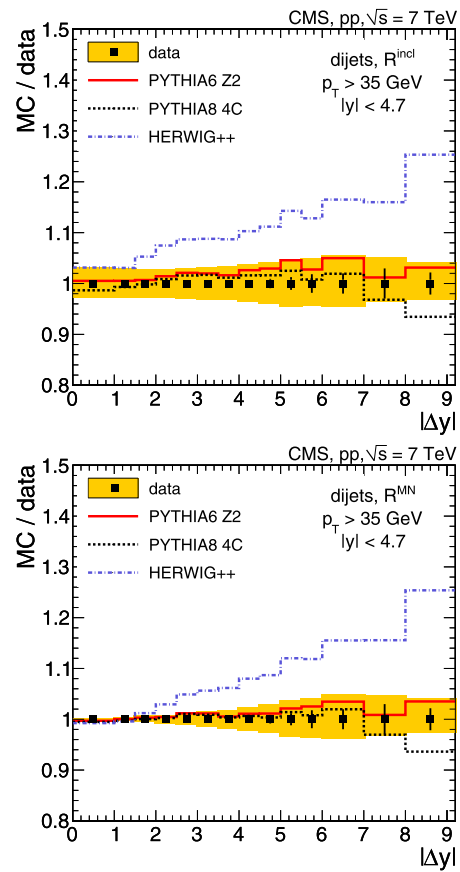


Fig. 2 Predictions for R^{incl} (top) and R^{MN} (bottom) from DGLAP-based MC generators presented as ratio to data corrected for detector effects. Both BFKL-motivated generators CASCADE and HEJ+ARIADNE (not shown) lead to a MC/data ratio well above unity. The shaded band indicates the size of the total systematic uncertainty of the data while statistical uncertainties are shown as bars

where R^{incl} starts to decrease varies from one MC generator to another, as can be seen in Fig. 1.

The predictions from PYTHIA6 and PYTHIA8 agree with the measurement. HERWIG++ overestimates the ratio R^{incl} at medium and large rapidity intervals. A detailed comparison between the data and the predictions of the DGLAP-based MC generators is presented as a ratio in Fig. 2 (top panel). It was checked explicitly that the results obtained from PYTHIA6 and HERWIG++ at parton level are close to the corresponding ones at stable-particle level. The different behaviour of PYTHIA6 and HERWIG++ is also observed at parton level.

The ratio R^{MN} and the corresponding MC to data ratio are presented in the bottom panels of Figs. 1–2. At large $|\Delta y|$, R^{MN} approaches R^{incl} as extra jet radiation contributing to R^{incl} tends to concentrate at moderate rapidities. The quality of the predictions of the DGLAP-based MC generators for R^{MN} is similar to those for R^{incl} . The MC generators CASCADE and HEJ+ARIADNE considerably overestimate the measurements of both R^{incl} and R^{MN} .

The ATLAS Collaboration measured several observables for dijets as functions of the rapidity separation between jets [21]. One is the fraction of events without jets with p_T above p_T^{veto} in the rapidity interval between the most forward and the most backward jets, which is equal to $1/R^{\text{MN}}$. A difference between data and the parton-level HEJ prediction at large $|\Delta y|$ for $70 < \langle p_T \rangle < 90$ GeV, $p_T^{\text{veto}} = \langle p_T \rangle$ and $|\Delta y| < 6$ was reported (Fig. 8 from [21]), which is in qualitative agreement with the result presented here.

To conclude, the first measurement of the ratios R^{incl} and R^{MN} in a wide range of rapidity separation, up to $|\Delta y| = 9.2$, in proton–proton collisions at $\sqrt{s} = 7$ TeV was presented. A moderate rise of the ratio of the inclusive to exclusive dijet production cross sections as a function of $|\Delta y|$ is observed. The predictions of the PYTHIA6 and PYTHIA8 generators agree with the measurements. The predictions of the HERWIG++ generator are larger than the measurement especially at large $|\Delta y|$. The BFKL-motivated generators CASCADE and HEJ+ARIADNE predict for these ratios a significantly stronger rise than observed. The moderate rise of the measured dijet ratios indicates that the BFKL effects are not dominant for jets with $p_T > 35$ GeV at the present collision energy of 7 TeV.

Acknowledgements We 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, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

1. CMS Collaboration, Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 7$ TeV. Phys. Rev. Lett. **107**, 132001 (2011). doi:10.1103/PhysRevLett.107.132001, arXiv:1106.0208
2. CMS Collaboration, Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s} = 7$ TeV. J. High Energy Phys. **1206**, 036 (2012). doi:10.1007/JHEP06(2012)036, arXiv:1202.0704
3. V.N. Gribov, L.N. Lipatov, Deep inelastic ep scattering in perturbation theory. Sov. J. Nucl. Phys. **15**, 438 (1972)
4. V.N. Gribov, L.N. Lipatov, $e^+ e^-$ pair annihilation and deep inelastic ep scattering in perturbation theory. Sov. J. Nucl. Phys. **15**, 675 (1972)
5. L.N. Lipatov, The parton model and perturbation theory. Sov. J. Nucl. Phys. **20**, 94 (1975)
6. G. Altarelli, G. Parisi, Asymptotic freedom in parton language. Nucl. Phys. B **126**, 298 (1977). doi:10.1016/0550-3213(77)90384-4
7. Y.L. Dokshitzer, Calculation of the structure functions for deep inelastic scattering and $e^+ e^-$ annihilation by perturbation theory in quantum chromodynamics. Sov. Phys. JETP **46**, 641 (1977)
8. CMS Collaboration, Measurement of the differential dijet production cross section in proton–proton collisions at $\sqrt{s} = 7$ TeV. Phys. Lett. B **700**, 187 (2011). doi:10.1016/j.physletb.2011.05.027, arXiv:1104.1693
9. E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Multi-reggeon processes in the Yang–Mills theory. Sov. Phys. JETP **44**, 443 (1976)
10. E.A. Kuraev, L.N. Lipatov, V.S. Fadin, The Pomeron singularity in nonabelian gauge theories. Sov. Phys. JETP **45**, 199 (1977)
11. I.I. Balitsky, L.N. Lipatov, The Pomeron singularity in quantum chromodynamics. Sov. J. Nucl. Phys. **28**, 822 (1978)
12. E.M. Levin et al., Heavy quark production in semihard nucleon interactions. Sov. J. Nucl. Phys. **53**, 657 (1991)
13. S. Catani, M. Ciafaloni, F. Hautmann, High-energy factorization and small-x heavy flavour production. Nucl. Phys. B **366**, 135 (1991). doi:10.1016/0550-3213(91)90055-3
14. J.C. Collins, R.K. Ellis, Heavy quark production in very high-energy hadron collisions. Nucl. Phys. B **360**, 3 (1991). doi:10.1016/0550-3213(91)90288-9
15. L. Lipatov, Small x physics in perturbative QCD. Phys. Rep. **286**, 131–198 (1997). doi:10.1016/S0370-1573(96)00045-2, arXiv:hep-ph/9610276
16. V.T. Kim, G.B. Pivovarov, BFKL QCD pomeron in high-energy hadron collisions: inclusive dijet production. Phys. Rev. D **53**, 6 (1996). doi:10.1103/PhysRevD.53.R6, arXiv:hep-ph/9506381
17. A.H. Mueller, H. Navelet, An inclusive minijet cross-section and the bare pomeron in QCD. Nucl. Phys. B **282**, 727 (1987). doi:10.1016/0550-3213(87)90705-X
18. B. Andersson et al., Small x phenomenology: summary and status. Eur. Phys. J. C **25**, 77 (2002). doi:10.1007/s10052-002-0998-7, arXiv:hep-ph/0204115
19. D0 Collaboration, The azimuthal decorrelation of jets widely separated in rapidity. Phys. Rev. Lett. **77**, 595 (1996). doi:10.1103/PhysRevLett.77.595, arXiv:hep-ex/9603010
20. D0 Collaboration, Probing BFKL dynamics in the dijet cross section at large rapidity intervals in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV and 630-GeV. Phys. Rev. Lett. **84**, 5722 (2000). doi:10.1103/PhysRevLett.84.5722, arXiv:hep-ex/9912032
21. ATLAS Collaboration, Measurement of dijet production with a veto on additional central jet activity in pp collisions with $\sqrt{s} = 7$ TeV using the ATLAS detector. J. High Energy Phys. **09**, 053 (2011). doi:10.1007/JHEP09(2011)053, arXiv:1107.1641v2.
22. ZEUS Collaboration, Forward jet production in deep inelastic scattering at HERA. Eur. Phys. J. C **6**, 239 (1999). doi:10.1007/s100529801018, arXiv:hep-ex/9805016v1
23. ZEUS Collaboration, Forward-jet production in deep inelastic ep scattering at HERA. Eur. Phys. J. C **52**, 515 (2007). doi:10.1140/epjc/s10052-007-0418-0, arXiv:0707.3093

24. H1 Collaboration, Transverse energy and forward jet production in the low x regime at HERA. *Phys. Lett. B* **356**, 118 (1995). doi:[10.1016/0370-2693\(95\)00804-T](https://doi.org/10.1016/0370-2693(95)00804-T)
25. H1 Collaboration, Measurement of the azimuthal correlation between the most forward jet and the scattered positron in deep-inelastic scattering at HERA. *Eur. Phys. J. C* **52**, 1910 (2012). doi:[10.1140/epjc/s10052-012-1910-8](https://doi.org/10.1140/epjc/s10052-012-1910-8), arXiv:[1111.4227](https://arxiv.org/abs/1111.4227)
26. CMS Collaboration, The CMS experiment at the CERN LHC. *J. Instrum.* **03**, S08004 (2008). doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004)
27. M. Cacciari, G.P. Salam, G. Soyez, The anti-kt jet clustering algorithm. *J. High Energy Phys.* **04**, 063 (2008). doi:[10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063), arXiv:[0802.1189](https://arxiv.org/abs/0802.1189)
28. M. Cacciari, G.P. Salam, Dispelling the N^3 myth for the kT jet-finder. *Phys. Lett. B* **641**, 57 (2006). doi:[10.1016/j.physletb.2006.08.037](https://doi.org/10.1016/j.physletb.2006.08.037), arXiv:[hep-ph/0512210](https://arxiv.org/abs/hep-ph/0512210)
29. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. *J. Instrum.* **6**, P11002 (2011). doi:[10.1088/1748-0221/6/11/P11002](https://doi.org/10.1088/1748-0221/6/11/P11002), arXiv:[1107.4277](https://arxiv.org/abs/1107.4277)
30. CMS Collaboration, Jet performance in pp collisions at $\sqrt{s} = 7$ TeV, CMS physics analysis summary CMS-PAS-JME-10-003 (2010)
31. CMS Collaboration, Tracking and primary vertex results in first 7 TeV collisions, CMS physics analysis summary CMS-PAS-TRK-10-005 (2010)
32. CMS Collaboration, Calorimeter jet quality criteria for the first CMS collision data, CMS physics analysis summary CMS-PAS-JME-09-008 (2010)
33. T. Sjöstrand, S. Mrenna, P. Skands, Pythia 6.4 physics and manual. *J. High Energy Phys.* **05**, 026 (2006). doi:[10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026)
34. R. Field, Early LHC underlying event data—findings and surprises (2010). arXiv:[1010.3558](https://arxiv.org/abs/1010.3558)
35. CMS Collaboration, Measurement of the underlying event activity at the LHC with $\sqrt{s} = 7$ TeV and comparison with $\sqrt{s} = 0.9$ TeV. *J. High Energy Phys.* **09**, 109 (2011). doi:[10.1007/JHEP09\(2011\)109](https://doi.org/10.1007/JHEP09(2011)109), arXiv:[1107.0330](https://arxiv.org/abs/1107.0330)
36. M. Bähr et al., HERWIG++ physics and manual. *Eur. Phys. J. C* **58**, 639 (2008). doi:[10.1140/epjc/s10052-008-0798-9](https://doi.org/10.1140/epjc/s10052-008-0798-9)
37. S. Agostinelli et al., Geant4—a simulation toolkit. *Nucl. Instrum. Methods A* **506**, 250 (2003). doi:[10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
38. T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1. *Comput. Phys. Commun.* **178**, 852 (2008). doi:[10.1016/j.cpc.2008.01.036](https://doi.org/10.1016/j.cpc.2008.01.036)
39. R. Corke, T. Sjöstrand, Interleaved parton showers and tuning prospects. *J. High Energy Phys.* **3**, 32 (2011). doi:[10.1007/JHEP03\(2011\)032](https://doi.org/10.1007/JHEP03(2011)032), arXiv:[1011.1759](https://arxiv.org/abs/1011.1759)
40. S. Gieseke et al., HERWIG++ 2.5 release note, arXiv:[1102.1672v1](https://arxiv.org/abs/1102.1672v1)
41. H. Jung et al., The CCFM Monte Carlo generator CASCADE version 2.2.03. *Eur. Phys. J. C* **70**, 1237 (2010). doi:[10.1140/epjc/s10052-010-1507-z](https://doi.org/10.1140/epjc/s10052-010-1507-z), arXiv:[1008.0152](https://arxiv.org/abs/1008.0152)
42. J.R. Andersen, J.M. Smillie, Multiple jets at the LHC with high energy jets. *J. High Energy Phys.* **06**, 010 (2011). doi:[10.1007/JHEP06\(2011\)010](https://doi.org/10.1007/JHEP06(2011)010), arXiv:[1101.5394](https://arxiv.org/abs/1101.5394)
43. L. Lönnblad, Ariadne version 4: a program for simulation of QCD cascades implementing the colour dipole model. *Comput. Phys. Commun.* **71**, 15 (1992). doi:[10.1016/0010-4655\(92\)90068-A](https://doi.org/10.1016/0010-4655(92)90068-A)
44. J. Andersen, L. Lönnblad, J. Smillie, A parton shower for high energy jets. *J. High Energy Phys.* **7**, 110 (2011). doi:[10.1007/JHEP07\(2011\)110](https://doi.org/10.1007/JHEP07(2011)110), arXiv:[1104.1316](https://arxiv.org/abs/1104.1316)

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. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rabbaran, 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. Vanelderden, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

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

S. Bagemez, G. Bruno, L. Ceard, J. De Favereau De Jeneret, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², 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. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, 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. Anjos³, C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, S.S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev¹, P. Iaydjiev¹, 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. Plestina⁵, D. Polic, I. Puljak¹

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. Assran⁶, A. Ellithi Kamel⁷, S. Khalil⁸, M.A. Mahmoud⁹, A. Radi^{8,10}

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, 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. Bluj¹¹, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

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

J.-L. Agram¹², J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹², F. Drouhin¹², C. Ferro, J.-C. Fontaine¹², D. Gelé, U. Goerlach, P. Juillot, M. Karim¹², 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. Chierici¹, 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. Zhukov¹³

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[†], J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teysier, 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. Bergholz¹⁴, A. Bethani, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁴, 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. Schmidt¹⁴, 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. Guthoff¹, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹³, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, 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. Manolakos, 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. Foudas¹, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

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

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹⁵, A. Kapusi, K. Krajczar¹⁶, F. Sikler¹, V. Veszpremi, G. Vesztergombi¹⁶

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

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, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait¹⁷, A. Gurtu¹⁸, M. Maity¹⁹, 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. Bakhshiansohi²⁰, S.M. Etesami²¹, A. Fahim²⁰, M. Hashemi, H. Hesari, A. Jafari²⁰, M. Khakzad, A. Mohammadi²², M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²³, M. Zeinali²¹

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

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

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,1}, P. Giacomelli^a, C. Grandi^a, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁴, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^{a,b,1}, F. De Guio^{a,b}, L. Di Matteo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a,1}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,1}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli^a, Università di Napoli "Federico II"^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,1}, N. Cavallo^{a,25}, A. De Cosa^{a,b}, O. Dogangun^{a,b}, F. Fabozzi^{a,25}, A.O.M. Iorio^{a,1}, L. Lista^a, M. Merola^{a,b}, P. Paolucci^a

INFN Sezione di Padova^a, Università di Padova^b, Università di Trento (Trento)^c, Padova, Italy

P. Azzi^a, N. Bacchetta^{a,1}, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^{a,26}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, L. Perrozzi^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b,1}, A. Triossi^a, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

U. Berzano^a, M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{a,b}

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy

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

INFN Sezione di Roma^a, Università di Roma "La Sapienza"^b, Roma, Italy

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

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

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

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b}, D. Montanino^{a,b,1}, A. Penzo^a

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. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarquen

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. Szeleper, 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. Pela¹, 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, V. Karjavin, V. Konoplyanikov, 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, G. Pivovarov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov¹, 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, M. Dubinin⁴, L. Dudko, A. Ershov, L. Khein, O. Kodolova, I. Lokhtin, A. Markina, S. Obratsov, M. Perfilov, A. Proskuryakov, L. Sarycheva[†], V. Savrin, A. Snigirev

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. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, 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. Adzic²⁸, M. Djordjevic, M. Ekmedzic, D. Krpic²⁸, 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. Piedra Gomez²⁹, J.M. Vizán García

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. Felcini³⁰, 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, 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. Bernet⁵, 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. Rolandi³¹, T. Rommelskirchen, C. Rovelli³², M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³³, D. Spiga, M. Spiropulu⁴, M. Stoye, A. Tsiros, G.I. Veres¹⁶, P. Vichoudis, H.K. Wöhri, S.D. Worm³⁴, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁵

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. Nageli³⁶, 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. Starodumov³⁷, B. Stieger, M. Takahashi, L. Tauscher^f, 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, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁸, S. Cerci³⁹, 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. Ozturk⁴⁰, A. Polatoz, K. Sogut⁴¹, D. Sunar Cerci³⁹, B. Tali³⁹, H. Topakli³⁸, 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. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya⁴², O. Kaya⁴², S. Ozkorucuklu⁴³, N. Sonmez⁴⁴

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. Newbold³⁴, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴⁵, K.W. Bell, A. Belyaev⁴⁵, 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. Nikitenko³⁷, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴⁶, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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[†], 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. Jeng⁴⁷, 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

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, I. Sfiligoi, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁴⁸, F. Würthwein, A. Yagil, J. Yoo

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. Kovalskyi¹, 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. Edelmaier, 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

Cornell University, Ithaca, USA

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

Fairfield University, Fairfield, USA

A. Biselli, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁹, C. Newman-Holmes, V. O'Dell, J. Pivarski, R. Pordes, O. Prokofyev, T. Schwarz, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

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. Milenovic⁵⁰, 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. Vodopiyanov

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. Kunde⁵¹, 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. Bilki⁵², W. Clarida, F. Duru, S. Griffiths, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya⁵³, 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, 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. Boutemour, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, 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, D. Puigh, 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, D. Bortoletto, M. De Mattia, A. Everett, L. Gutay, Z. Hu, M. Jones, O. Kobasi, 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. Goulios, 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. Kamon⁵⁴, 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. Duerdo, 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, L. Borrello, 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 Florida, Gainesville, USA
- 30: Also at University of California, Los Angeles, Los Angeles, USA
- 31: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 32: Also at INFN Sezione di Roma; Università di Roma "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 University of Sydney, Sydney, Australia
- 48: Also at Utah Valley University, Orem, USA
- 49: Also at Institute for Nuclear Research, Moscow, Russia
- 50: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 51: Also at Los Alamos National Laboratory, Los Alamos, USA
- 52: Also at Argonne National Laboratory, Argonne, USA
- 53: Also at Erzincan University, Erzincan, Turkey
- 54: Also at Kyungpook National University, Daegu, Korea