

Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

Results are presented of a search for the production of new particles decaying to pairs of partons (quarks, antiquarks, or gluons), in the dijet mass spectrum in proton-proton collisions at $\sqrt{s} = 8$ TeV. The data sample corresponds to an integrated luminosity of 4.0 fb^{-1} , collected with the CMS detector at the LHC in 2012. No significant evidence for narrow resonance production is observed. Upper limits are set at the 95% confidence level on the production cross section of hypothetical new particles decaying to quark-quark, quark-gluon, or gluon-gluon final states. These limits are then translated into lower limits on the masses of new resonances in specific scenarios of physics beyond the standard model. The limits reach up to 4.8 TeV, depending on the model, and extend previous exclusions from similar searches performed at lower collision energies. For the first time mass limits are set for the Randall-Sundrum graviton model in the dijet channel.

Submitted to Physical Review Letters

We report on a search for narrow dijet resonances in pp collisions at $\sqrt{s} = 8$ TeV. This search holds for all new particles for which the natural resonance width is small compared to the CMS dijet mass resolution [1]. The data sample corresponds to an integrated luminosity of 4.0 fb^{-1} collected with the Compact Muon Solenoid (CMS) [2] at the CERN Large Hadron Collider (LHC) in the spring of 2012.

Many extensions of the standard model (SM) predict the existence of new massive objects that couple to quarks or antiquarks (q or \bar{q}) and gluons (g), resulting in resonances in the dijet mass spectrum. The most stringent bounds on these resonances come from previous CMS [3–5] and ATLAS [6–9] searches. The results presented in this Letter extend the search sensitivity to higher values of the resonance masses.

We consider the following specific models of narrow dijet resonances produced via the s -channel: string resonances [10, 11]; E_6 diquarks [12]; excited quarks assuming the dimensionless constants accounting for possible deviations from the standard model couplings to be $f = f' = f_s = 1$ [13, 14]; axigluons [15, 16]; color-octet colorons [17]; the S8 resonance predicted in technicolor models [18]; new gauge bosons (W' and Z') [19]; Randall–Sundrum (RS) gravitons assuming $k/\bar{M}_{\text{Pl}} = 0.1$, where k is related to the curvature of the 5th dimension and \bar{M}_{Pl} is the effective 4-D Planck scale [20]. More details on these models and the parameters we assume can be found in Ref. [1, 4].

A detailed description of the CMS experiment can be found elsewhere [2]. The CMS coordinate system has the origin at the centre of the detector. The z axis points along the direction of the counter-clockwise beam; y is the vertical direction and x is chosen to make a right-handed coordinate system; ϕ is the azimuthal angle, θ is the polar angle, and the pseudorapidity is defined as $\eta \equiv -\ln[\tan(\theta/2)]$. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial field of 3.8 T. Within the field volume are located the silicon pixel and strip tracker ($|\eta| < 2.5$), as well as the barrel and endcap calorimeters ($|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter. An iron/quartz fiber calorimeter is located in the forward region ($3 < |\eta| < 5$), outside the field volume. For triggering purposes and to facilitate jet reconstruction, the calorimeter cells are grouped into towers projecting radially outward from the centre of the detector.

Offline particle candidates are reconstructed by using the particle flow (PF) algorithm [21], which categorizes the candidates as muons, electrons (with associated bremsstrahlung photons), photons (unconverted and converted), and charged/neutral hadrons. These PF candidates are then clustered into jets using the anti- k_T algorithm [22] with a distance parameter $R = 0.5$, implemented in the FASTJET package [23]. The jet four-momentum, computed as the vectorial sum of the four-momenta of the constituent PF candidates, is adjusted with corrections derived from Monte Carlo (MC) simulations, test beam results, and pp collision data [24]. The corrections also account for the presence of multiple pp collisions in the same or adjacent bunch crossings (pileup interactions) [25].

Events are selected by requiring at least one reconstructed primary vertex in each event within the range $|z| < 24$ cm. We select jets with $p_T > 30$ GeV and $|\eta| < 2.5$ that meet identification criteria based on the number of constituent particles and their energy fractions [26]. The other jets in the event are ignored. Events with fewer than two selected jets are discarded.

To improve the dijet invariant mass resolution, we account for final state radiation (FSR) by forming a wide jet [4, 27] around each leading jet. The wide jets are formed by clustering additional jets to the closest leading jet within a distance $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1.1$. The four-momentum of each wide jet is computed as the sum of the four-momenta of the constituent jets.

To suppress background events coming from quantum chromodynamics (QCD) processes, we require that the pseudorapidity separation of the two wide jets satisfies $|\Delta\eta_{jj}| < 1.3$, and that both wide jets are reconstructed in the region $|\eta| < 2.5$. The dijet mass is given by $m_{jj} = \sqrt{(E_{j1} + E_{j2})^2 - |\vec{p}_{j1} + \vec{p}_{j2}|^2}$, where E_{ji} and \vec{p}_{ji} ($i = 1, 2$) are the energy and the momentum of a wide jet. We select events with $m_{jj} > 890$ GeV.

Events are filtered using a two-tier trigger system. Events satisfying loose jet requirements at the first level (L1) are passed to the high level trigger (HLT), where jets are clustered from PF candidates built online. Online jets with transverse momenta $p_T > 40$ GeV and $|\eta| < 3.0$ are used to compute H_T , the scalar sum of the jet p_T , and m_{jj} , the invariant mass of the two wide jets. Events with $H_T > 650$ GeV or $m_{jj} > 750$ GeV are accepted. For the offline analysis selection presented above the combined L1 and HLT triggers are found to be more than 99.9% efficient.

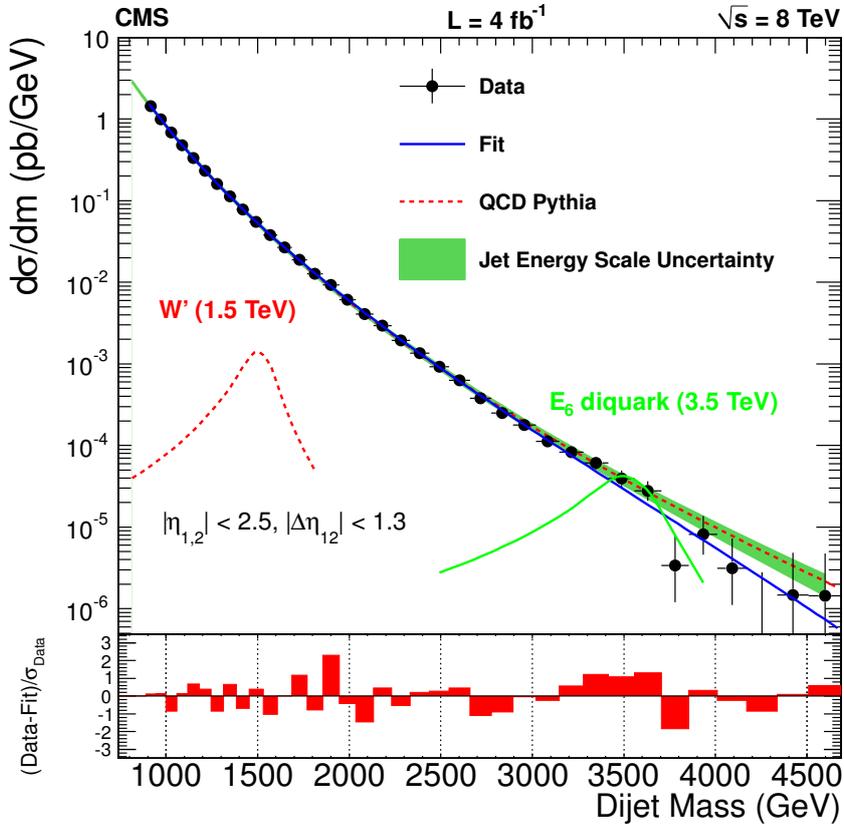


Figure 1: The dijet mass spectrum from wide jets (points) compared with a smooth fitted curve (solid line) and with the predicted QCD background [28] (dashed line). The background curve has been normalized to the data (see text) and a linear smoothing between the bins has been applied. The vertical bars on the data points represent the statistical uncertainty, the horizontal bars indicate the bin widths. The shaded band shows the contribution from the systematic uncertainty in the jet energy scale. Also shown is the shape of the distribution expected for a W' boson with a mass of 1.5 TeV, and an E_6 diquark with a mass of 3.5 TeV. The bottom part of the plot displays the bin-by-bin residuals (data minus the integral over a bin of the smooth function fitted to the data) divided by the statistical uncertainty in the data.

We show in Fig. 1 the dijet mass distribution in bins approximately equal in width to the dijet mass resolution [3]. The data are compared with the expected leading-order (LO) QCD back-

ground generated by using PYTHIA v6.424 [28], including a GEANT4-based [29] simulation of the CMS detector. This approach follows closely that described in [30], but uses the CTEQ6L PDF (Z2 tune) instead of the CTEQ5L PDF (Z1 tune). The QCD prediction uses a renormalization and factorization scale $\mu = p_T$ of the hard-scattered partons and CTEQ6L1 parton distribution functions [31], and has been normalized to the data. The normalization factor of 1.34 was found to be consistent with the next-to-leading order K-factor [32, 33]. The shape of the PYTHIA prediction agrees with the data within the statistical precision.

For comparison we also display in Fig. 1 the shape expected for a W' boson with a mass of 1.5 TeV and an E_6 diquark with a mass of 3.5 TeV. The signal samples are generated by using PYTHIA with the D6T tuning [28] and the same GEANT4-based CMS simulation used for the QCD background sample. The predicted mass distributions have a Gaussian core from the jet energy resolution and a tail towards lower mass values, primarily due to FSR. The contribution of this low-mass tail to the line-shape depends on the parton content of the resonance (qq, $q\bar{q}$, qg and gg). Resonances decaying to gluons, which are more susceptible than quarks to the FSR, have a larger tail. For high-mass resonances, there is also another significant contribution depending on both parton distributions and the natural width of the Breit–Wigner resonance shape: when the resonance is produced by interaction of non-valence partons in the proton, the low-mass component of the Breit–Wigner resonance shape is amplified by a larger parton probability at low fractional momentum, producing a large tail at low mass values. The shapes shown for a hypothetical W' boson and an E_6 diquark in Fig. 1 result from Crystal ball [34] fits to the generated event distributions.

The background from QCD multijet production is described by the analytical function

$$\frac{d\sigma}{dx} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3 \ln(x)}},$$

with the variable $x = m_{jj}/\sqrt{s}$ and four free parameters P_0 , P_1 , P_2 , and P_3 . This functional form has been used in previous searches [3, 6, 7, 35] to describe both data and QCD predictions. The data fit, shown in Fig. 1, has a chi-squared (χ^2) of 25.7 for 32 degrees of freedom. The bottom part of the figure shows the difference between the data and the fit value, normalized to the statistical uncertainty in the data. No deviations that are statistically significant are observed between the distribution of the data points and the smooth fit.

The smooth fit to the data has been chosen as the most reliable estimate of the background. We use the dijet mass spectrum from wide jets, the background parametrization, and the dijet resonance shapes to set specific limits on new particles produced from and decaying to a same parton pair qq (or $q\bar{q}$), qg, and gg. A separate limit is determined for each process (denoted simply qq, qg, gg) because of the dependence of the signal line-shape on the final state.

The systematic uncertainty in the determination of the dijet mass is dominated by the uncertainty in the jet energy scale [24] and the uncertainty in the jet energy resolution. The jet energy scale uncertainty translates into a 1.3% relative uncertainty in the dijet mass, roughly independent from the mass value; it is propagated to the search by shifting the reconstructed dijet mass of the signal by 1.3% compared to the nominal resolution value. The jet energy resolution uncertainty translates into an uncertainty of 10% in the resolution of the dijet mass [24]; this uncertainty is propagated to the search by smearing and unsmearing the reconstructed dijet mass of the signal according to a Gaussian distribution with σ fixed at 10% of the mass value.

The precision of the overall signal normalization is limited by the knowledge of the integrated luminosity (4.4%) [36]. The statistical uncertainty in the background parametrization introduces a systematic uncertainty in the signal strength. We verified that the use of different

parametrizations for the description of the background has a negligible effect compared to the statistical uncertainty in the data, over the whole dijet spectrum. Similarly, MC studies show that the dependence of the signal mass shapes on the number of pileup interactions is negligible. The systematic uncertainties included in this analysis reduce the lower limit on resonance masses by less than ~ 15 GeV, depending on the model.

To set upper limits on the signal cross section we use a Bayesian formalism [37] with a uniform prior for the positive signal cross section; a null probability is assigned to negative values of the cross section; log-normal priors are used to model systematic uncertainties, which are treated as nuisance parameters. We calculate the posterior probability density as a function of resonance cross section independently at each value of the resonance mass. The data are fitted to the background function plus a signal lineshape, the signal cross section being a free parameter. The resulting fit function with the signal cross section set to zero is used as the background hypothesis. The uncertainty in the background shape is incorporated by marginalizing over the background fit parameters (not including the signal cross section) after diagonalizing the covariance matrix to account for the correlations in the parameters. This method of using the data first to constrain the background fit and second to extract the limit induces a bias in the coverage of the limits. The actual coverage was estimated for the qq resonances to be $92.1 \pm 0.4\%$, $95.2 \pm 0.4\%$ and $95.8 \pm 0.3\%$ at respective signal masses of 1500, 2500 and 3000 GeV.

We show in Fig. 2 the observed generic upper limits at the 95% confidence level (CL) on $\sigma \times \mathcal{B} \times A$, i.e. the product of the cross section (σ), the branching fraction (\mathcal{B}) of the resonance into the relevant final state, and the acceptance (A) for the kinematic requirements $|\Delta\eta_{jj}| < 1.3$ and $|\eta| < 2.5$, for narrow resonances which decay into qq, qg, and gg final states. For example the acceptance for an isotropic decays is $A \approx 0.6$, roughly independent of resonance mass. For the RS graviton, which couples either to a pair of gluons or to a quark-antiquark pair, the model-dependent limits on cross section are derived using a weighted average of the qq and gg dijet mass shapes, where the weights correspond to the relative branching fractions for these two final states, calculated at LO [20]. The expected limits on cross sections shown in Fig. 2 are estimated with pseudo-experiments generated using background shapes which are determined by signal-plus-background fits to the data.

The observed and expected upper limits can be compared with the predictions of $\sigma \times \mathcal{B} \times A$ at the generator level, without any detector simulation, in order to determine mass limits on new particles. The calculations shown are obtained in the narrow-width approximation using CTEQ6L1 parton distributions [31]. New particles are excluded at the 95% CL in mass regions for which the theoretical curve lies above our upper limit for the appropriate final state.

We list in Table 1 the observed cross section limits for qq, qg, and gg resonances, as a function of the resonance mass. We determine the expected lower limit on the mass of new resonances by comparing the expected cross section limits to the model predictions. The observed and expected mass exclusions are reported in Table 2 for various models.

In summary, a search for narrow resonances decaying into a pair of jets has been performed using a data sample corresponding to an integrated luminosity of 4.0 fb^{-1} collected in pp collisions at $\sqrt{s} = 8 \text{ TeV}$. In the analyzed data sample there is no significant evidence for new particle production. Upper limits are set on the product $\sigma \times \mathcal{B} \times A$ that can be applied to any model of narrow dijet resonance production. Specific lower limits are presented on the mass of string resonances, excited quarks, axigluons, colorons, S8 resonances, E_6 diquarks, W' and Z' bosons starting at 1.0 TeV and extending up to 4.8 TeV for some models. In most cases, these limits extend the previous exclusions obtained using the dijet mass spectrum. The first mass limit on Randall–Sundrum gravitons decaying to dijets is shown.

Table 1: Observed upper limits at the 95% CL on $\sigma \times \mathcal{B} \times A$ for resonances decaying to qq , qg , and gg final states as a function of the resonance mass. Systematic uncertainties are taken into account in the limit calculation.

Mass [GeV]	Upper limit on $\sigma \times \mathcal{B} \times A$ (pb)		
	qq	qg	gg
1000	0.62	0.75	1.6
1200	0.37	0.40	0.69
1400	0.18	0.19	0.27
1600	0.12	0.15	0.21
1800	0.16	0.18	0.23
2000	0.050	0.058	0.089
2200	0.036	0.041	0.055
2400	0.031	0.034	0.043
2600	0.019	0.021	0.029
2800	0.010	0.012	0.016
3000	0.012	0.015	0.020
3200	0.017	0.020	0.026
3400	0.016	0.018	0.024
3600	0.0090	0.011	0.015
3800	0.0039	0.0047	0.0063
4000	0.0026	0.0034	0.0045
4200	0.0021	0.0026	0.0036
4400	0.0020	0.0026	0.0036
4600	0.0017	0.0023	0.0035
4800	0.0016	0.0021	0.0031

Table 2: Observed and expected exclusions at the 95% CL on the mass of various resonances. Systematic uncertainties are included.

Model	Final state	Observed excluded mass range [TeV]	Expected excluded mass range [TeV]
String Resonance	qg	[1.0, 4.78]	[1.0, 4.75]
Excited Quark	qg	[1.0, 3.19]	[1.0, 3.47]
E_6 Diquark	qq	[1.0, 4.28]	[1.0, 4.16]
Axigluon/Coloron	$q\bar{q}$	[1.0, 3.27]	[1.0, 3.60]
S8 Resonance	gg	[1.0, 2.79]	[1.0, 2.54]
W' Boson	$q\bar{q}$	[1.0, 1.73]	[1.0, 1.97]
Z' Boson	$q\bar{q}$	[1.0, 1.62]	[1.0, 1.58]
RS Graviton	$q\bar{q} + gg$	[1.0, 1.45]	[1.0, 1.29]

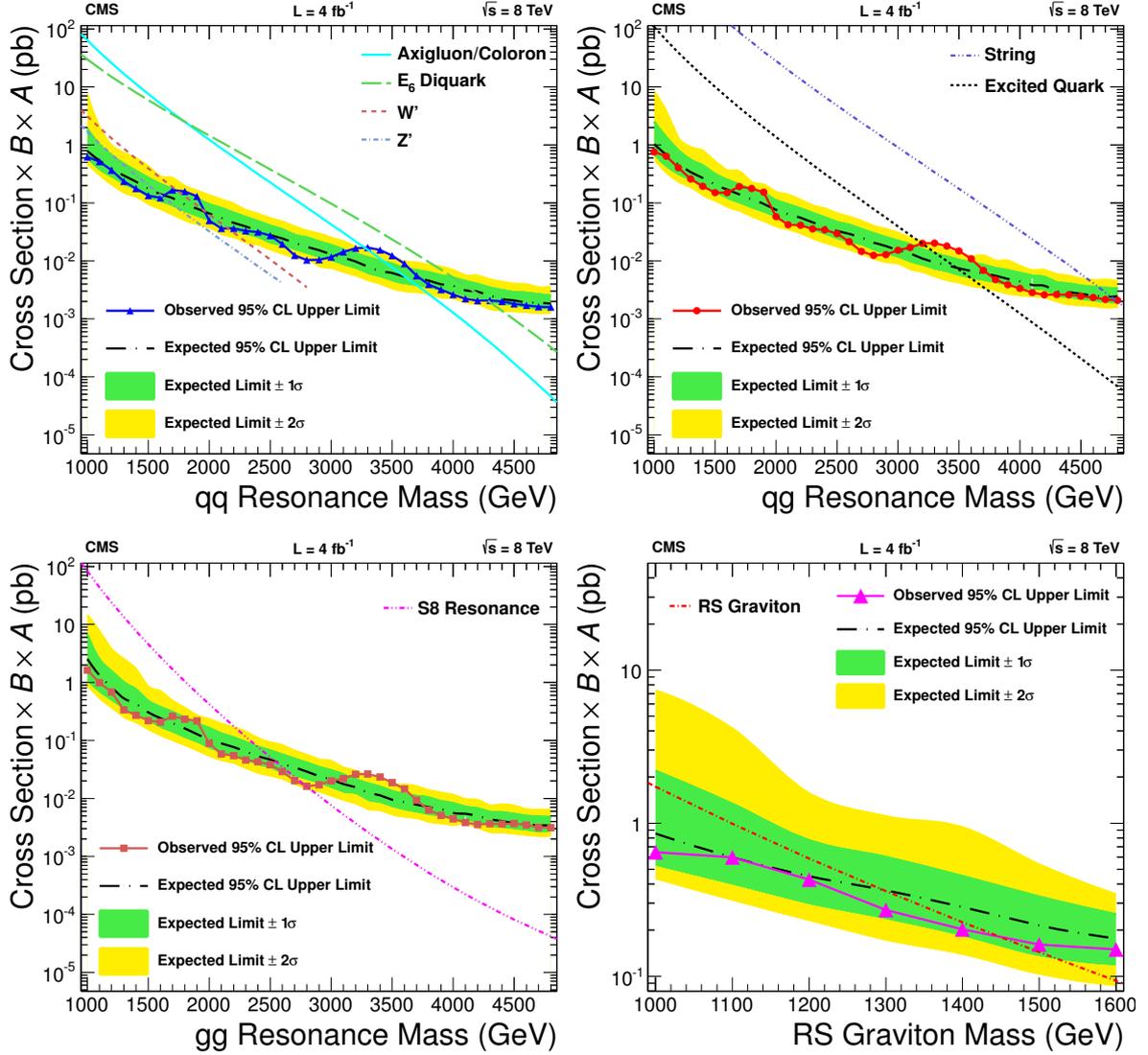


Figure 2: Observed upper limits at 95% CL on $\sigma \times \mathcal{B} \times A$ for resonances decaying to qq , qg , and gg final state (points and solid lines) compared with the expected limits (dot-dashed dark lines) and their variation at the 1σ and 2σ levels (shaded bands). Predicted cross sections for various resonance assumptions are shown. The signal shape for the RS model is obtained by weighting the shapes for qq and gg final states according to LO calculations of the relative branching fractions.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and

CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEP-Center, IPST and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

- [1] R. M. Harris and K. Kousouris, “Searches for Dijet Resonances at Hadron Colliders”, *Int. J. Mod. Phys. A* **26** (2011) 5005, doi:10.1142/S0217751X11054905, arXiv:1110.5302.
- [2] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [3] CMS Collaboration, “Search for Dijet Resonances in 7 TeV pp Collisions at CMS”, *Phys. Rev. Lett.* **105** (2010) 211801, doi:10.1103/PhysRevLett.105.211801, arXiv:1010.0203.
- [4] CMS Collaboration, “Search for narrow resonances and quantum black holes in inclusive and b -tagged dijet mass spectra from pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **1301** (2013) 013, doi:10.1007/JHEP01(2013)013, arXiv:1210.2387.
- [5] CMS Collaboration, “Search for heavy resonances in the W/Z -tagged dijet mass spectrum in pp collisions at 7 TeV”, (2012). arXiv:1212.1910. Submitted to *Phys. Lett. B*.
- [6] ATLAS Collaboration, “Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC”, *Phys. Rev. Lett.* **105** (2010) 161801, doi:10.1103/PhysRevLett.105.161801, arXiv:1008.2461.
- [7] ATLAS Collaboration, “Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at $\sqrt{s} = 7$ TeV Measured with the ATLAS Detector”, *New J. Phys.* **13** (2011) 053044, doi:10.1088/1367-2630/13/5/053044, arXiv:1103.3864.
- [8] ATLAS Collaboration, “Search for New Physics in the Dijet Mass Distribution using 1 fb^{-1} of pp Collision Data at $\sqrt{s} = 7$ TeV collected by the ATLAS Detector”, *Phys. Lett. B* **708** (2012) 37, doi:10.1016/j.physletb.2012.01.035, arXiv:1108.6311.
- [9] ATLAS Collaboration, “ATLAS search for new phenomena in dijet mass and angular distributions using pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **1301** (2013) 029, doi:10.1007/JHEP01(2013)029, arXiv:1210.1718.
- [10] L. A. Anchordoqui et al., “Dijet signals for low mass strings at the LHC”, *Phys. Rev. Lett.* **101** (2008) 241803, doi:10.1103/PhysRevLett.101.241803, arXiv:0808.0497.
- [11] S. Cullen, M. Perelstein, and M. E. Peskin, “TeV strings and collider probes of large extra dimensions”, *Phys. Rev. D* **62** (2000) 055012, doi:10.1103/PhysRevD.62.055012, arXiv:hep-ph/0001166.

- [12] J. L. Hewett and T. G. Rizzo, "Low-energy phenomenology of superstring inspired E_6 models", *Phys. Rept.* **183** (1989) 193, doi:10.1016/0370-1573(89)90071-9.
- [13] U. Baur, I. Hinchliffe, and D. Zeppenfeld, "Excited Quark Production at Hadron Colliders", *Int. J. Mod. Phys. A* **2** (1987) 1285, doi:10.1142/S0217751X87000661.
- [14] U. Baur, M. Spira, and P. M. Zerwas, "Excited-quark and -lepton production at hadron colliders", *Phys. Rev. D* **42** (1990) 815, doi:10.1103/PhysRevD.42.815.
- [15] P. H. Frampton and S. L. Glashow, "Chiral color: An alternative to the standard model", *Phys. Lett. B* **190** (1987) 157, doi:10.1016/0370-2693(87)90859-8.
- [16] R. S. Chivukula et al., "Production of massive color-octet vector bosons at next-to-leading order", *Phys. Rev. D* **85** (2012) 054005, doi:10.1103/PhysRevD.85.054005, arXiv:1111.7261.
- [17] E. H. Simmons, "Coloron phenomenology", *Phys. Rev. D* **55** (1997) 1678, doi:10.1103/PhysRevD.55.1678, arXiv:hep-ph/9608269.
- [18] T. Han, I. Lewis, and Z. Liu, "Colored resonant signals at the LHC: largest rate and simplest topology", *JHEP* **12** (2010) 085, doi:10.1007/JHEP12(2010)085, arXiv:1010.4309.
- [19] E. Eichten et al., "Supercollider physics", *Rev. Mod. Phys.* **56** (1984) 579, doi:10.1103/RevModPhys.56.579.
- [20] L. Randall and R. Sundrum, "An Alternative to compactification", *Phys. Rev. Lett.* **83** (1999) 4690, doi:10.1103/PhysRevLett.83.4690, arXiv:hep-th/9906064.
- [21] CMS Collaboration, "Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss} ", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, (2009).
- [22] M. Cacciari, G. P. Salam, and G. Soyez, "The anti- k_t jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [23] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57, doi:10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.
- [24] CMS Collaboration, "Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS", *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [25] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [26] CMS Collaboration, "Jet Performance in pp Collisions at $\sqrt{s}=7$ TeV", CMS Physics Analysis Summary CMS-PAS-JME-10-003, (2010).
- [27] CMS Collaboration, "Search for resonances in the dijet mass spectrum from 7 TeV pp Collisions at CMS", *Phys. Lett. B* **704** (2011) 123, doi:10.1016/j.physletb.2011.09.015, arXiv:1107.4771.
- [28] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

- [29] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [30] R. Field, "Early LHC underlying event data – findings and surprises", (2010).
arXiv:1010.3558.
- [31] J. Pumplin et al., "New generation of parton distributions with uncertainties from global QCD analysis", *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012,
arXiv:hep-ph/0201195.
- [32] S. D. Ellis, Z. Kunszt, and D. E. Soper, "Two jet production in hadron collisions at order α_s^3 in QCD", *Phys. Rev. Lett.* **69** (1992) 1496, doi:10.1103/PhysRevLett.69.1496.
- [33] W. T. Giele, E. W. N. Glover, and D. A. Kosower, "Higher order corrections to jet cross-sections in hadron colliders", *Nucl. Phys. B* **403** (1993) 633,
doi:10.1016/0550-3213(93)90365-V, arXiv:hep-ph/9302225.
- [34] T. Skwarnicki, "A study of the radiative CASCADE transitions between the Upsilon-Prime and Upsilon resonances". PhD thesis, Cracow Institute of Nuclear Physics, 1986. DESY-F31-86-02.
- [35] CDF Collaboration, "Search for new particles decaying into dijets in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. D* **79** (2009) 112002,
doi:10.1103/PhysRevD.79.112002, arXiv:0812.4036.
- [36] CMS Collaboration, "CMS Luminosity Based on Pixel Cluster Counting - Summer 2012 Update", CMS Physics Analysis Summary CMS-PAS-LUM-12-001, (2012).
- [37] Particle Data Group, J. Beringer, et al., "Review of Particle Physics", *Phys. Rev. D* **86** (2012) 010001, doi:10.1103/PhysRevD.86.010001. See Section 36: Statistics.

A 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, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], D. Rabady², B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, H. Van Haeevermaet, 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, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco³, J. Hollar, V. Lemaître, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, M. Selvaggi, J.M. Vizán Garcia

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, 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, J. Chinellato⁴, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder, E.J. Tonelli Manganote⁴, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

T.S. Anjos^b, C.A. Bernardes^b, F.A. Dias^{a,5}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, C. Lagana^a, F. Marinho^a, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev², P. Iaydjiev², S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, 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, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

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

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

Universidad de Los Andes, Bogota, Colombia

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

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, 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. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, A.M. Kuotb Awad¹⁰, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

A. Korpela, T. Tuuva

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

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaer,

P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici², D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze¹⁵

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

C. Autermann, S. Beranek, B. Calpas, 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. Zhukov¹⁶

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

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

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

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann², A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille¹⁸, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderren

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff², C. Hackstein, F. Hartmann², T. Hauth², M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov¹⁶, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

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

G. Anagnostou, G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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

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

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, 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. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India

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

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, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, R.M. Chatterjee, S. Ganguly, M. Guchait²¹, A. Gurtu²², M. Maity²³, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

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

H. Arfaei²⁴, H. Bakhshiansohi, S.M. Etesami²⁵, A. Fahim²⁴, M. Hashemi²⁶, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁷, M. Zeinali

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,2}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De

Filippis^{a,c,2}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, P. Verwilligen^a, G. Zito^a

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

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,2}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{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,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁸, F. Fabbri, D. Piccolo

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

P. Fabbricatore^a, R. Musenich^a, S. Tosi^{a,b}

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

A. Benaglia^a, F. De Guio^{a,b}, L. Di Matteo^{a,b,2}, S. Fiorendi^{a,b}, S. Gennai^{a,2}, A. Ghezzi^{a,b}, M.T. Lucchini², S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Università della Basilicata (Potenza) ^c, Università G. Marconi (Roma) ^d, Napoli, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Cosa^{a,b,2}, O. Dogangun^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}

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

P. Azzi^a, N. Bacchetta^{a,2}, D. Bisello^{a,b}, A. Branca^{a,b,2}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, M. Galanti^{a,b}, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, S. Ventura^a, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

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, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}, S. Taroni^{a,b}

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

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c,2}, R. Dell'Orso^a, F. Fiori^{a,b,2}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,29}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,30}, P. Spagnolo^a, P. Squillacioti^{a,2}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli^{a,b}, M. Grassi^{a,b,2}, E. Longo^{a,b}, P. Meridiani^{a,2}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, 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, N. Cartiglia^a, S. Casasso^{a,b}, M. Costa^{a,b}, N. Demaria^a, C. Mariotti^{a,2}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,2}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a

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

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^{a,2}, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,2}, D. Montanino^{a,b}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

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

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

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

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, Y. Roh

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

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

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, J. Martínez-Ortega, A. Sanchez-Hernandez, 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 Ibarguen

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

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

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szeleper, G. Wrochna, 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, W. Wolszczak

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas², J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

P. Bunin, M. Gavrilenko, I. Golutvin, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, A. Volodko, A. Zarubin

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

A. Belyaev, E. Boos, M. Dubinin⁵, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin², V. Kachanov, D. Konstantinov, 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. Adzic³¹, M. Djordjevic, M. Ekmedzic, D. Krpic³¹, 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, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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. Felcini³², M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, J.F. Benitez, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. d'Enterria, A. Dabrowski, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³³, C. Rovelli³⁴, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, A. Tsiros, G.I. Veres²⁰, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁶, 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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁷, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁸, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

C. Amsler³⁹, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tuppusti, M. Verzetti

National Central University, Chung-Li, Taiwan

M. Cardaci, Y.H. Chang, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, E. Simili, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴⁰, S. Cerci⁴¹, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar⁴², A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴³, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴¹, B. Tali⁴¹, H. Topakli⁴⁰, 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, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁶, S. Ozkorucuklu⁴⁷, N. Sonmez⁴⁸

Istanbul Technical University, Istanbul, Turkey

H. Bahtiyar⁴⁹, E. Barlas, K. Cankocak, Y.O. Günaydin⁵⁰, F.I. Vardarli, M. Yücel

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

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. Newbold³⁶, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁵¹, K.W. Bell, A. Belyaev⁵¹, 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, M. Kenzie, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³⁸, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁵², D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

K. Hatakeyama, H. Liu, T. Scarborough

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, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, USA

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

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, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, 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, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵³, 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, C. George, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutelyov, S. Lowette, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

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. 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, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos⁵⁴, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵⁵, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁶, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

V. Gaultney, S. Hewamanage, 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, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁷, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁸, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, H. Ogul, Y. Onel, F. Ozok⁴⁹, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

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, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, 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

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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, 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, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA

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

Purdue University Calumet, Hammond, USA

S. Guragain, N. Parashar

Rice University, Houston, USA

A. Adair, B. Akgun, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, 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, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, 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, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

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. Kamon⁵⁹, 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, J. Damgov, C. Dragoiu, P.R. Duderu, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

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

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

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

- 5: Also at California Institute of Technology, Pasadena, USA
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at British University in Egypt, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at National Centre for Nuclear Research, Swierk, Poland
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at The University of Kansas, Lawrence, USA
- 19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 20: Also at Eötvös Loránd University, Budapest, Hungary
- 21: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 22: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 23: Also at University of Visva-Bharati, Santiniketan, India
- 24: Also at Sharif University of Technology, Tehran, Iran
- 25: Also at Isfahan University of Technology, Isfahan, Iran
- 26: Also at Shiraz University, Shiraz, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 29: Also at Università degli Studi di Siena, Siena, Italy
- 30: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 31: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 32: Also at University of California, Los Angeles, USA
- 33: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 34: Also at INFN Sezione di Roma, Roma, Italy
- 35: Also at University of Athens, Athens, Greece
- 36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 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 Izmir Institute of Technology, Izmir, Turkey
- 43: Also at The University of Iowa, Iowa City, USA
- 44: Also at Mersin University, Mersin, Turkey
- 45: Also at Ozyegin University, Istanbul, Turkey
- 46: Also at Kafkas University, Kars, Turkey
- 47: Also at Suleyman Demirel University, Isparta, Turkey
- 48: Also at Ege University, Izmir, Turkey
- 49: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 50: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
- 51: Also at School of Physics and Astronomy, University of Southampton, Southampton,

United Kingdom

52: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy

53: Also at Utah Valley University, Orem, USA

54: Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom

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

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

57: Also at Argonne National Laboratory, Argonne, USA

58: Also at Erzincan University, Erzincan, Turkey

59: Also at Kyungpook National University, Daegu, Korea