MIT Libraries | DSpace@MIT

MIT Open Access Articles

# *Observation of a diffractive contribution to dijet production in proton-proton collisions at √s=7 TeV*

The MIT Faculty has made this article openly available. ***Please share*** how this access benefits you. Your story matters.

**Citation:** Chatrchyan, S. et al. "Observation of a Diffractive Contribution to Dijet Production in Proton-proton Collisions at Sqrt[s]=7 TeV." Physical Review D 87.1 (2013).

**As Published:** http://dx.doi.org/10.1103/PhysRevD.87.012006

**Publisher:** American Physical Society

**Persistent URL:** http://hdl.handle.net/1721.1/77043

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of use:** Creative Commons Attribution 3.0

Massachusetts Institute of Technology

PHYSICAL REVIEW D **87,** 012006 (2013)

# Observation of a diffractive contribution to dijet production in proton-proton collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 9 September 2012; published 8 January 2013)

The cross section for dijet production in proton-proton collisions at $\sqrt{s} = 7$ TeV is presented as a function of $\tilde{\xi}$, a variable that approximates the fractional momentum loss of the scattered proton in single-diffractive events. The analysis is based on an integrated luminosity of 2.7 $\mathrm{nb}^{-1}$ collected with the CMS detector at the LHC at low instantaneous luminosities, and uses events with jet transverse momentum of at least 20 GeV. The dijet cross section results are compared to the predictions of diffractive and non-diffractive models. The low-$\tilde{\xi}$ data show a significant contribution from diffractive dijet production, observed for the first time at the LHC. The associated rapidity gap survival probability is estimated.

DOI: 10.1103/PhysRevD.87.012006 PACS numbers: 13.87.Ce, 12.38.Qk, 12.40.Nn

## I. INTRODUCTION

A significant fraction of the total inelastic proton-proton cross section at high energies is attributed to diffractive processes, characterized by the presence of a large rapidity region $\Delta y$ with no hadrons, usually called "rapidity gap" [rapidity is defined as $y = (1/2)\ln[(E + p_Z)/(E - p_Z)]$, where $E$ and $p_Z$ are the energy and longitudinal momentum of the final-state particle, respectively]. Diffractive scattering is described in the framework of Regge theory as mediated by a strongly interacting color-singlet exchange with the vacuum quantum numbers, the so-called "pomeron trajectory" [1]. Diffractive events with a hard parton-parton scattering are especially interesting because they can be studied in terms of perturbative quantum chromodynamics (pQCD). In diffractive events the proton emitting the pomeron either remains intact, losing only a few percent of its momentum, or is found in a low mass excited state. In addition, since the vacuum quantum numbers are exchanged, no particles are produced in a large rapidity range adjacent to the scattered proton (or its dissociation products).

Diffraction with a hard scale has been studied in proton-antiproton ($\mathrm{p\bar{p}}$) and electron-proton (ep) collisions at CERN [2], Fermilab [3–6], and DESY [7–10]. Such hard diffractive processes can be described in terms of the convolution of diffractive parton distribution functions (dPDFs) and hard scattering cross sections, which are calculable in pQCD. In this approach, the pomeron is treated as a color-singlet combination of partons with the vacuum quantum numbers. The dPDFs have been determined by the HERA experiments [7,9] by means of QCD fits to inclusive diffractive deep inelastic scattering data, and have been successfully used to describe different hard diffractive processes in ep collisions. This success is based on the factorization theorem for diffractive electron-proton interactions, and on the validity of the QCD evolution equations for the dPDFs [11–13]. However, in hard diffractive hadron-hadron collisions factorization does not hold because of soft scatterings between the spectator partons, leading to the suppression of the observed diffractive cross section. The suppression is quantified by the so-called "rapidity gap survival probability" [14], which is a nonperturbative quantity with large theoretical uncertainties [15–18]. It was measured to be about 10% in diffractive dijet production in $\mathrm{p\bar{p}}$ collisions at the Tevatron [5].

This paper presents a study of dijet production in proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. The data were collected with the Compact Muon Solenoid (CMS) detector at the LHC in 2010 and correspond to an integrated luminosity of 2.7 $\mathrm{nb}^{-1}$. The cross section for production of dijets is presented as a function of $\tilde{\xi}$, a variable that approximates the fractional momentum loss of the proton, for events in which both jets have transverse momenta $p_{\mathrm{T}}^{\mathrm{j1,j2}} > 20$ GeV and jet axes in the pseudorapidity range $|\eta^{\mathrm{j1,j2}}| < 4.4$. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle relative to the anticlockwise proton beam direction, and is equal to the rapidity in the limit of a massless particle. The measurements are compared to the predictions of nondiffractive (ND) and diffractive models, and the rapidity gap survival probability is estimated.

The paper is organized as follows: in Sec. II a brief description of the CMS detector is provided. The definitions of the kinematic variables are introduced in Sec. III. The event selection is explained in Sec. IV. Section V describes the main features of the Monte Carlo (MC) generators used in this analysis. The cross section determination for dijets as a function of $\tilde{\xi}$ and the systematic uncertainties of the measurements are discussed in Sec. VI.

*Full author list given at the end of the article.

*Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.*

 © 2013 CERN, for the CMS Collaboration

The results are presented in Sec. VII, and the summary is given in Sec. VIII.

## II. EXPERIMENTAL SETUP

A detailed description of the CMS detector can be found elsewhere [19]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadronic calorimeter (HCAL). The tracker measures charged particles within the pseudorapidity range $|n| < 2.4$. ECAL and HCAL provide coverage in pseudorapidity up to $|n| < 3$ in the barrel region and two endcap regions. The HCAL, when combined with the ECAL, measures jets with an energy resolution $\Delta E/E \approx 100\%/\sqrt{E\ (\mathrm{GeV})} \oplus 5\%$. The calorimeter cells are grouped in projective towers, of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ at central rapidities and $0.175 \times 0.175$ at forward rapidities, where $\phi$ is the azimuthal angle in radians. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The forward part of the hadron calorimeter, HF, consists of steel absorbers and embedded radiation-hard quartz fibers, which provide a fast collection of Cherenkov light. The pseudorapidity coverage of the HF is $2.9 < |\eta| < 5.2$. In the current analysis only the range $3.0 < |\eta| < 4.9$ was used, thus restricting the data to a region of well-understood reconstruction efficiency. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 $\mu$s. The High Level Trigger processor farm further decreases the event rate from around 100 kHz to around 300 Hz, before data storage.

## III. KINEMATICS AND CROSS SECTIONS

Diffractive dijet production (Fig. 1) is characterized by the presence of a high-momentum proton (or a system $Y$ with the same quantum numbers as the proton) with fractional momentum loss smaller than a few percent and a system $X$, which contains high-$p_{\mathrm{T}}$ jets and is separated from the proton by a large rapidity gap, with $\Delta y \geq 3$ or 4 units. The kinematics of this reaction is described by the masses of the systems $X$ and $Y$, $M_X$ and $M_Y$, and the squared four-momentum transfer $t$ at the proton vertex. For the events selected in this analysis both $M_X$ and $M_Y$ are much smaller than $\sqrt{s}$.

The cross section for single-diffractive (SD) dijet production (i.e. when the forward-going system $Y$ is a proton) is usually expressed in terms of the variable $\xi = M_X^2/s$, which approximates the fractional momentum loss of the scattered proton. Under the assumption of QCD factorization, the cross section can be written as

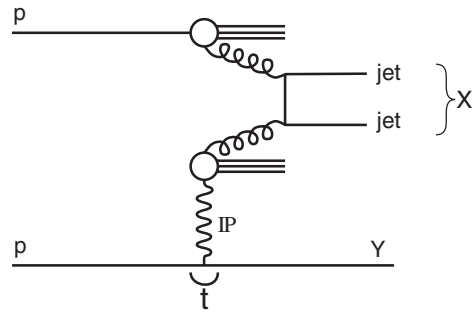


FIG. 1. Schematic diagram of diffractive dijet production. The diagram shows the example of the $gg \to$ jet process; the $qq$ and $gq$ initial states also contribute.

$$\frac{d\sigma}{d\xi dt} = \sum \int dx_1 dx_2 d\hat{t} f(\xi, t) f_{\mathbb{P}}(x_1, \mu) f_p(x_2, \mu) \frac{d\hat{\sigma}(\hat{s}, \hat{t})}{d\hat{t}}, \tag{1}$$

where the sum is over all parton flavors. The variables $x_{1,2}$ are the parton momentum fractions in the pomeron and proton, the scale at which the PDFs are evaluated is indicated with $\mu$, and $\hat{\sigma}(\hat{s}, \hat{t})$ is the hard-scattering subprocess cross section, which is a function of the partonic center-of-mass energy squared $\hat{s}$ and momentum transfer squared $\hat{t}$. The function $f_p(x_2, \mu)$ is the inclusive PDF of the proton that breaks up, while the dPDF of the surviving proton is written as $f_{\mathrm{diff}}(\xi, t, x_1, \mu) = f(\xi, t) f_{\mathbb{P}}(x_1, \mu)$, where $f(\xi, t)$ is the so-called pomeron flux and $f_{\mathbb{P}}(x_1, \mu)$ is the pomeron structure function. The cross section dependence on $\xi$ and $t$ is driven by the pomeron flux, usually parametrized according to Regge theory as

$$f(\xi, t) = \frac{e^{Bt}}{\xi^{2\alpha_{\mathbb{P}}(t)-1}}, \tag{2}$$

where $\alpha_{\mathbb{P}}(t)$ is the pomeron trajectory and $B$ is the slope parameter. This ansatz is consistent with the HERA ep data [7–9], but is known not to hold between the ep and the Tevatron ($p\bar{p}$) data [3–6], where an extra suppression (gap survival probability) factor is needed.

In this analysis $\xi$ is approximated by the variables $\tilde{\xi}^+$ (system $X$ going in the $-z$ direction) and $\tilde{\xi}^-$ (system $X$ going in the $+z$ direction) defined at the level of stable particles as

$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}}, \tag{3}$$

where $E^i$ and $p_z^i$ are the energy and longitudinal momentum of the $i$th final-state particle with $-\infty < \eta < 4.9$ for $\tilde{\xi}^+$ and $-4.9 < \eta < +\infty$ for $\tilde{\xi}^-$. In the region of low $\tilde{\xi}^{\pm}$, this variable is a good approximation of $\xi$ for single-diffractive events. This is illustrated for single-diffractive dijet events simulated by PYTHIA8 [20] in Fig. 2, where the correlations between the values of $\xi$ and $\tilde{\xi}^+$, determined at

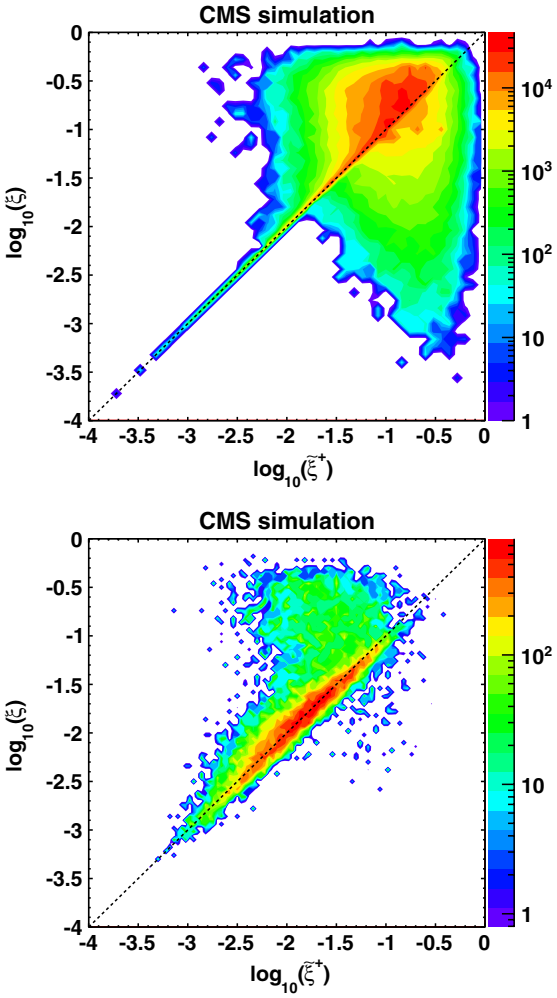


FIG. 2 (color online). The generated $\xi$ versus generated (top panel) and reconstructed (bottom panel) $\tilde{\xi}^{+}$ correlations for single-diffractive dijet events simulated by PYTHIA8; events in the bottom panel are those passing the selection described in Sec. IV.

generated and reconstructed (see Sec. IV) levels, are shown. The mass of the forward-going system $Y$, which includes all particles with $\eta > 4.9$ (or $\eta < -4.9$), was also estimated with the PYTHIA8 generator; the mass is limited by the pseudorapidity range and is typically smaller than 30–40 GeV, with average ~5 GeV.

## IV. EVENT SELECTION

The data were collected with the CMS detector in 2010 at low luminosities. The average number of extra pp interactions for any given event (the so-called pileup interactions) in the data is 0.09. The low number of pileup interactions simplified the extraction of the diffractive signal, since the particles produced in such interactions may fill the rapidity gap and hence reduce the visible diffractive cross section. However, the requirement of low pileup limits the available data sample since only a small amount of low-luminosity runs was collected.

At the trigger level events were selected by requiring at least one jet with uncorrected transverse-momentum greater than 6 GeV. The efficiency of the trigger, estimated using a minimum-bias data sample, was found to be greater than 95% for the dijet events considered in this analysis.

Offline, the jets were reconstructed with the anti-$k_T$ inclusive jet finding algorithm [21] with a distance parameter of 0.5. The jet clustering algorithm was used to reconstruct jets from particle-flow (PF) objects [22], which are particle candidates obtained by combining the information of the tracking system and of the calorimeters in an optimal way. The reconstructed jet momenta were fully corrected to the level of stable particles (with lifetime $\tau$ such that $c\tau > 10$ mm, hereafter referred to as "particle level"), by means of a procedure partially based on MC simulation and partially on data [23].

The quantities $\tilde{\xi}^{+}$ and $\tilde{\xi}^{-}$ were reconstructed using Eq. (3) from the energies and longitudinal momenta of all PF objects measured in the $|\eta| < 4.9$ range. For charged PF objects ($|\eta| < 2.4$, the region covered by the tracker) a minimum transverse momentum of 0.2 GeV was required. In the forward region, $3.0 < |\eta| < 4.9$, particularly relevant for this analysis, PF candidates were selected with energy greater than 4 GeV. A constant scale factor $C = 1.45 \pm 0.04$, determined from the MC simulation by comparing the generated and reconstructed values of $\tilde{\xi}^{\pm}$, is applied to the measured $\tilde{\xi}^{\pm}$. The error on the correction factor $C$ is estimated by changing the MC models used to evaluate it. The value of $C$ reflects the fact that not all final-state particles are detected because of the limited acceptance and imperfect response of the detector. It also takes into account the inefficiency of PF object reconstruction. In practice, $C$ acts as a scale calibration for $\tilde{\xi}^{\pm}$; it depends only slightly on the value of $\tilde{\xi}^{\pm}$ and on the MC generator used. This dependence, of the order of a few percent, is included in the systematic uncertainty. The resolution of $\tilde{\xi}^{\pm}$, in the region of the present measurement, is ~25%, and practically independent of $\tilde{\xi}^{\pm}$.

Events were selected offline by applying the following requirements:

(i) the jets should pass the standard CMS quality criteria [23];

(ii) events should have at least two jets, each with transverse momentum, corrected to particle level, greater than 20 GeV. This requirement ensures high trigger efficiency;

(iii) the axes of the two leading jets (jets were ordered in $p_{\mathrm{T}}$ with the first, leading jet having the highest $p_{\mathrm{T}}$) should be in the pseudorapidity region $|\eta^{\mathrm{j1,j2}}| < 4.4$ so that the reconstructed jets are fully contained in the detector;

(iv) a primary vertex should be within a longitudinal distance $|z| < 24$ cm of the center of CMS;

(v) beam-scraping events, in which long horizontal sections of the pixel tracker are hit by charged particles

traveling parallel to the beam, were rejected with a special algorithm [24];

(vi) to enhance the diffractive contribution, the requirements $\eta_{\max} < 3$ ($\eta_{\min} > -3$) were also applied. Here $\eta_{\max}$ ($\eta_{\min}$) is the pseudorapidity of the most forward (backward) PF object. The $\eta_{\max}$ ($\eta_{\min}$) selection together with the pseudorapidity coverage of the detector, $|\eta| < 4.9$, is equivalent to imposing a pseudorapidity gap of at least 1.9 units, with no PF objects with energy greater than 4 GeV in the HF calorimeter.

The number of selected events before the $\eta_{\max}$ ($\eta_{\min}$) requirement is 277 953. The number of events passing also the $\eta_{\max} < 3$ ($\eta_{\min} > -3$) selection is 804 (774); of these, 222 (220) have $\tilde{\xi}^{+} < 0.01$ ($\tilde{\xi}^{-} < 0.01$). The differential cross section for dijet production was calculated separately as a function of $\tilde{\xi}^{+}$ and $\tilde{\xi}^{-}$. The final results were averaged, and the average is presented as a function of $\tilde{\xi}$.

The $\eta_{\max}$, $\eta_{\min}$ requirements reject most pileup interactions. The remaining pileup background was estimated with minimum-bias MC samples (PYTHIA6 Z1 and PYTHIA8; see next section) and was found to be less than 2%.

## V. MONTE CARLO SIMULATION

The simulation of ND dijet events was performed with the PYTHIA6 (version 6.422) [25] and PYTHIA8 (version 8.135) [20] generators; the events were generated in PYTHIA6 with tunes Z2 [26] and D6T [27], and in PYTHIA8 with tune 1 [20]. The more recent PYTHIA8 tune 4C [28] yields similar results as the tune 1 used here. Minimum-bias events were generated with PYTHIA6 tune Z1 [26] and with PYTHIA8 tune 1.

Diffractive dijet events were simulated with the POMPYT [29], POMWIG [30], and PYTHIA8 generators. The PYTHIA8 generator can simulate inclusive, nondiffractive as well as diffractive dijet events; separate samples were produced for the two processes. The modeling of diffractive events in these generators is based on the Ingelman and Schlein approach [31], which considers the diffractive reaction as a two-step process: one proton emits a pomeron with fractional momentum $\xi$ and then the pomeron interacts with the other proton. All three diffractive generators were used with dPDFs from the same fit to diffractive deep inelastic scattering data (H1 fit B [7]). The parametrization of the pomeron flux in POMPYT and POMWIG is also based on the QCD fits to the HERA data [7], while it is different in PYTHIA8 [32]. This leads to different predictions for the diffractive cross sections calculated by PYTHIA8 and POMPYT or POMWIG (notably in their normalization). The effect of the rapidity gap survival probability is not simulated in any of the three diffractive generators.

The main difference between POMPYT and POMWIG is that POMPYT uses the PYTHIA framework while POMWIG is based on HERWIG [33]. Both programs generate single-diffractive dissociation. In PYTHIA8 double-diffractive dissociation (DD), in which both protons dissociate, is also included. The contribution from central diffractive dissociation, in which both protons stay intact, was estimated with POMWIG. It amounts to ~1% of the diffractive contribution in the $\tilde{\xi}$ region used in the analysis and was neglected. Only pomeron exchange was assumed; the Reggeon exchange contribution in the region $\tilde{\xi} < 0.01$ was estimated with POMPYT and was found to be less than 2%, and less than 1% in the lowest $\tilde{\xi}$ bin used in the analysis.

The diffractive component of the dijet cross section was also computed at next-to-leading (NLO) accuracy with the POWHEG [34] framework using the CTEQ6M PDF for the proton that breaks up and H1 fit B for the dPDF. The parton shower and hadronization were carried out with PYTHIA8 (tune 1).

The generators used are listed in Table I along with some of their features. All generated events were processed through the simulation of the CMS detector, based on GEANT4 [35] and reconstructed in the same manner as the data. All samples were generated without pileup. The measurements were corrected for detector acceptance and resolution with a suitable combination of nondiffractive (PYTHIA6 Z2) and diffractive (POMPYT) models (see Sec. VA).

Figure 3 shows the comparison between the uncorrected data and detector-level MC simulations for the reconstructed $p_{\mathrm{T}}$ distributions of the leading and second-leading jets with axes in the range $|\eta^{\mathrm{j1,j2}}| < 4.4$. The simulated distributions are normalized to the number of events in the corresponding distributions for the data. The data and MC simulations are in agreement, for both PYTHIA6 Z2 and PYTHIA8 tune 1.

Figure 4 presents the comparison between data and MC simulations for the reconstructed (detector-level) pseudorapidity distributions of the leading and second-leading jets.

TABLE I. Monte Carlo generators used in this work with details on their model ingredients.

| Model | PDF | dPDF | Parameter tune | Process |
|---|---|---|---|---|
| PYTHIA6 | CTEQ6L1 | none | Z2, D6T | Nondiffractive jets |
| PYTHIA8 | CTEQ5L | H1 fit B | Tune 1 | Diffractive plus nondiffractive jets |
| POMPYT | CTEQ6L1 | H1 fit B | PYTHIA6 D6T | Diffractive jets only |
| POMWIG | CTEQ6L1 | H1 fit B | HERWIG | Diffractive jets only |
| POWHEG | CTEQ6M | H1 fit B | PYTHIA8 tune 1 | Diffractive jets only |

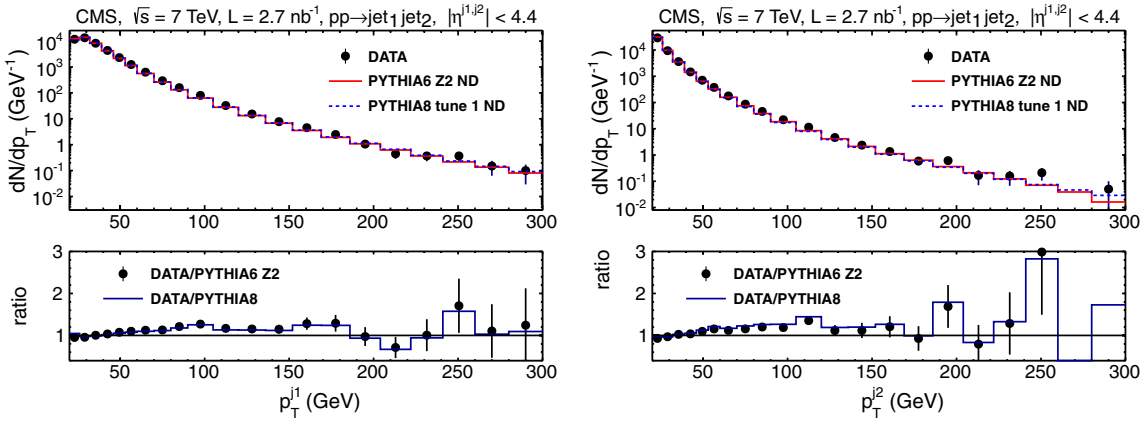


FIG. 3 (color online). Reconstructed transverse-momentum distributions of the leading (left panel) and second-leading (right panel) jets (black dots) compared to detector-level MC simulations (histograms) generated with two nondiffractive models (PYTHIA6 Z2 and PYTHIA8 tune 1). The error bars indicate the statistical uncertainty. The MC distributions are normalized to the number of events in the corresponding distributions for the data. The ratios of the data and MC distributions are also shown.

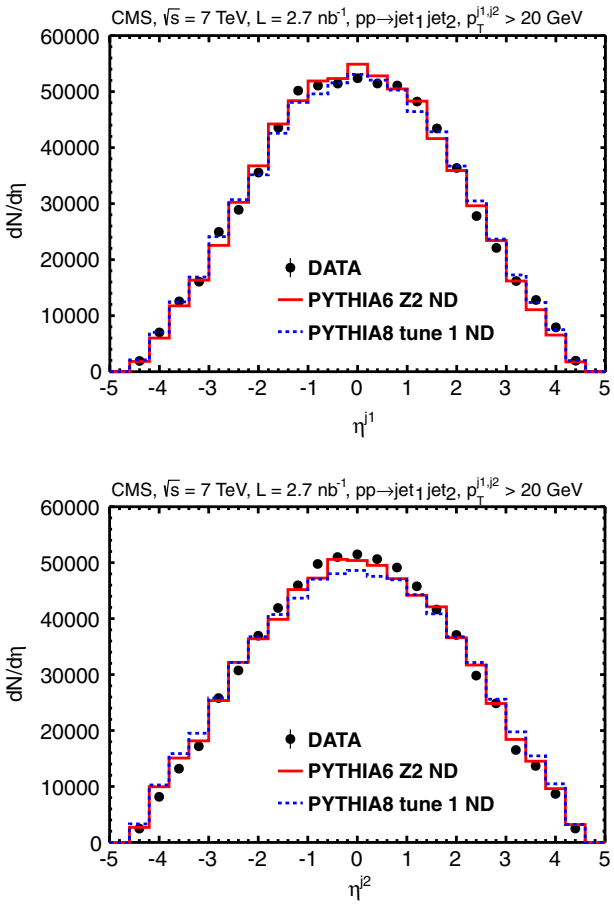


FIG. 4 (color online). Reconstructed pseudorapidity distributions of the leading (top panel) and second-leading (bottom panel) jets (black dots) compared to detector-level MC simulations (histograms) generated with two nondiffractive models (PYTHIA6 Z2 and PYTHIA8 tune 1). The statistical uncertainties are smaller than the data points. The MC distributions are normalized to the number of events in the corresponding distributions for the data.

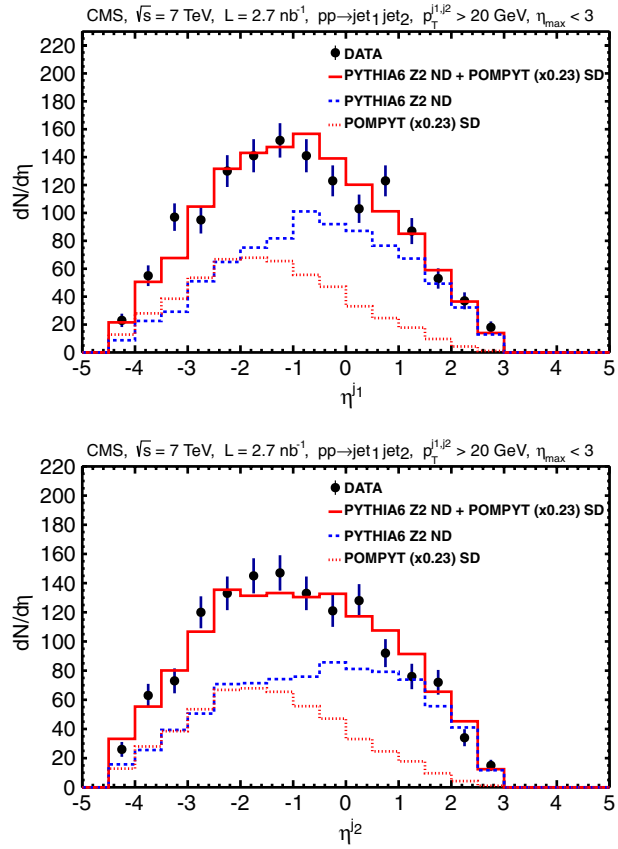


FIG. 5 (color online). Reconstructed pseudorapidity distributions of the leading (top panel) and second-leading (bottom panel) jets after the $\eta_{\max} < 3$ selection (black dots) compared to three detector-level MC simulations (histograms). Events with the $\eta_{\min} > -3$ condition are also included in the figure with $\eta^{j1,j2} \to -\eta^{j1,j2}$. The error bars indicate the statistical uncertainty. The predictions of the nondiffractive (PYTHIA6 Z2) and diffractive (POMPYT, scaled by the value quoted in the legend) contributions and their sum are also shown. The sum of the predictions of the two MC simulations is normalized to the number of events in the corresponding distributions for the data.

Also here, the MC distributions are normalized to the number of events in the data. Data are better described by PYTHIA6 tune Z2 than by PYTHIA8 tune 1.

The pseudorapidity distributions of the two leading jets for events selected with the $\eta_{\max} < 3$ requirement are presented in Fig. 5. Events with the $\eta_{\min} > -3$ condition are also included in Fig. 5 with $\eta^{j1,j2} \to -\eta^{j1,j2}$. The pseudorapidity gap condition enhances the diffractive component in the data, and selects events with the jets mainly in the hemisphere opposite to that of the gap. A combination of PYTHIA6 Z2 and POMPYT events reproduces the data reasonably well; the relative normalization of the models is optimized with the procedure described in Sec. VA.

### A. Reconstructed $\tilde{\xi}$ distributions and determination of the relative POMPYT and PYTHIA6 normalization

The reconstructed $\tilde{\xi}$ distribution is shown in Fig. 6 before the $\eta_{\max}$, $\eta_{\min}$ selections. Here again, the shape of the distribution can be described by the combination of diffractive and nondiffractive MC models. The best combination was obtained by minimizing the difference between the $\tilde{\xi}$ distributions of the data and of the sum of nondiffractive and diffractive models. The relative contribution of diffractive dijet production and the overall normalization of the sum were found in this fit, and the diffractive contribution was scaled accordingly. The overall normalization of the fit result is not relevant. The effect of the calorimeter energy scale uncertainty, estimated by varying by $\pm 10\%$ the energy of all PF objects not associated with the leading jets, is shown by the band. The solid line in Fig. 6(a) indicates the result of the fit, according to which the diffractive dijet cross section predicted by POMPYT should be multiplied by a factor $\simeq 0.23$ to match the data. The uncertainty of this correction factor was estimated by changing the fitting procedure and was found to be $\sim 20\%$. Figure 6(b) presents the same data compared to PYTHIA6 D6T + POMPYT; here the fit requires the POMPYT normalization to be scaled by a factor of $\simeq 0.17$.

Figure 6(c) compares the data to PYTHIA8 tune 1; both the single-diffractive and the double-diffractive components are added to the nondiffractive part, all simulated by PYTHIA8. The result of the fit is very different from that for POMWIG and PYTHIA6: the normalization of the diffractive components of PYTHIA8 needs to be multiplied by a factor $\simeq 2.5$ to match the data. This large difference is a consequence of the different implementation of the pomeron flux in PYTHIA8 and POMPYT.

In all three cases, after normalization, the shape of the reconstructed $\tilde{\xi}$ distribution in the data is described satisfactorily by the MC models (PYTHIA6 Z2 + POMPYT resulting in the best description). However, the predicted nondiffractive component in the lowest $\tilde{\xi}$ bin varies from about 0.1% for PYTHIA6 D6T to as much as 10%–20% for PYTHIA6 Z2 and PYTHIA8.

The effect of the $\eta_{\max} < 3$ ($\eta_{\min} > -3$) requirement is illustrated in Fig. 7, where the reconstructed $\tilde{\xi}$ distributions with and without the $\eta_{\max} < 3$ ($\eta_{\min} > -3$) condition are compared to MC simulations. These pseudorapidity gap selections reject events at high values of $\tilde{\xi}$. The region of low $\tilde{\xi}$, where the diffractive contribution dominates, is only marginally affected. The data and MC simulations are in

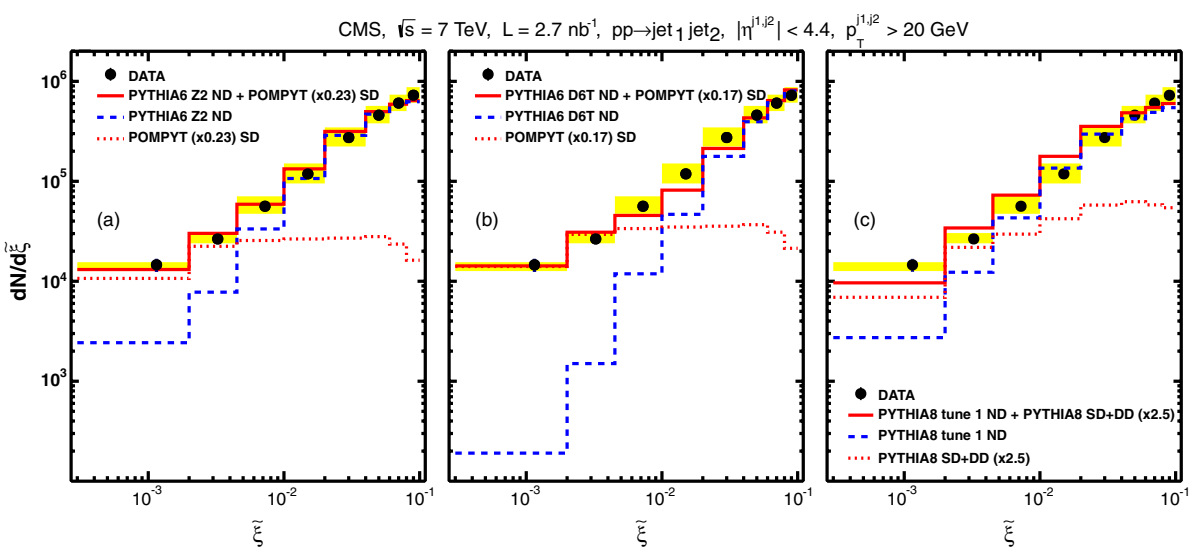


FIG. 6 (color online). Reconstructed $\tilde{\xi}$ distribution compared to detector-level MC predictions with and without diffractive dijet production. The predictions of (a) PYTHIA6 Z2 + POMPYT, (b) PYTHIA6 D6T + POMPYT, and (c) PYTHIA8 tune 1 are shown (in all the cases the relative diffractive contributions from the MC simulation are scaled by the values given in the legend). The error bars indicate the statistical uncertainty; the band represents the calorimeter energy scale uncertainty. The sum of the predictions of the two MC simulations is normalized to the number of events in the corresponding distributions for the data.

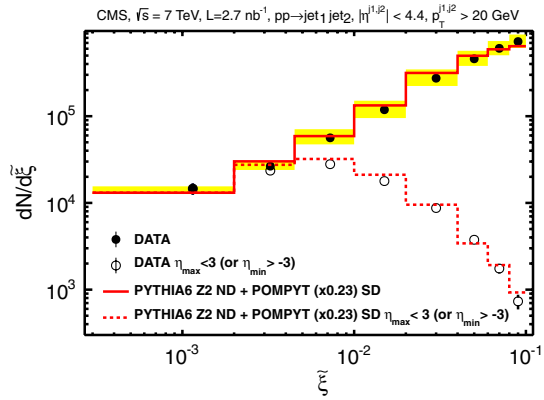


FIG. 7 (color online). Reconstructed $\tilde{\xi}$ distributions with (open symbols) and without (closed symbols) the $\eta_{\max} < 3$ (or $\eta_{\min} > -3$) condition are compared to detector-level MC predictions including diffractive dijet production (PYTHIA6 Z2 + POMPYT). The error bars indicate the statistical uncertainty; the band represents the calorimeter energy scale uncertainty. The relative diffractive dijet contribution from the MC simulation has been scaled by the factor 0.23. The sum of the predictions of the two MC simulations is normalized to the number of events in the corresponding distributions for the data.

agreement at low $\tilde{\xi}$. The relative normalization of PYTHIA6 Z2 and POMPYT in the figure is the same as in Fig. 6.

## VI. CROSS SECTION DETERMINATION AND SYSTEMATIC UNCERTAINTIES

The differential cross section for dijet production as a function of $\tilde{\xi}$ is evaluated as

$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N_{jj}^{i}}{L \cdot \epsilon \cdot A^{i} \cdot \Delta\tilde{\xi}^{i}}, \tag{4}$$

where $N_{jj}^{i}$ is the measured number of dijet events in the $i$th $\tilde{\xi}$ bin, $A^{i}$ is the correction factor defined as the number of reconstructed MC events in that bin divided by the number of generated events in the same bin, $\Delta\tilde{\xi}^{i}$ is the bin width, $L$ is the integrated luminosity, and $\epsilon$ is the trigger efficiency. The factors $A^{i}$ include the effects of the geometrical acceptance of the apparatus, and that of all the selections listed in Sec. IV, as well as the unfolding corrections to account for the finite resolution of the reconstructed variables used in the analysis. Various unfolding techniques (bin-by-bin, singular value decomposition [36] and Bayesian [37]) yield consistent results and the bin-by-bin correction was kept. In addition, the measured number of events, $N_{jj}^{i}$, is corrected for the effect of pileup. This correction takes into account the probability of single pp interactions, evaluated on a run-by-run basis, as well as the probability that pileup interactions do not destroy the visible gap, estimated with the minimum-bias MC samples (PYTHIA6 Z1 and PYTHIA8 tune 1); the average correction is 1.07. The cross section is measured for dijets with the axes in the pseudorapidity range $|\eta^{j1,j2}| < 4.4$ and $p_{T}^{j1,j2} > 20$ GeV in the $\tilde{\xi}$ bins $0.0003 < \tilde{\xi} < 0.002$, $0.002 < \tilde{\xi} < 0.0045$, and $0.0045 < \tilde{\xi} < 0.01$. The cross section results for $\tilde{\xi}^{+}$ and $\tilde{\xi}^{-}$ are averaged, yielding the cross section as a function of $\tilde{\xi}$.

The systematic uncertainties are estimated by varying the selection criteria and by modifying the analysis procedure as follows:

(1) The uncertainty on the jet energy scale varies between 2% and 9% depending on the jet $p_{T}$ and $\eta$ [23]. It decreases with the jet $p_{T}$ and is typically higher at high $\eta$. The energy of the reconstructed jets is varied accordingly.

(2) The effect of the uncertainty on the jet energy resolution is studied by changing the resolution by up to $\pm 10\%$ in the central region ($|\eta| < 2.3$) and by up to $\pm 20\%$ in the forward regions ($|\eta| > 2.3$) [23].

(3) The systematic uncertainty related to the $\tilde{\xi}$ reconstruction is determined as follows: (i) the effect of the calorimeter energy scale uncertainty is estimated by varying the energy of all PF objects not associated with the leading jets by $\pm 10\%$; (ii) the $p_{T}$ threshold for tracks is increased from 200 to 250 MeV; (iii) the correction factor $C$ is varied by $\pm 3\%$, i.e. by its uncertainty (as discussed in Sec. IV).

(4) The uncertainty on the correction factor $A^{i}$ in Eq. (4) is estimated by changing the MC models used to evaluate it. In addition, the relative fraction of diffraction is changed by $\pm 20\%$, i.e. by the uncertainty of the scaling factors obtained in the fits discussed in Sec. VA.

(5) The sensitivity to pileup is studied by restricting the analysis to events with only one reconstructed vertex.

(6) The sensitivity to the jet reconstruction procedure is studied by repeating the analysis with jets reconstructed only with calorimetric information instead of particle-flow objects. This affects the results by 4% at most.

(7) The difference in the results obtained for the cross section as a function of $\tilde{\xi}^{+}$ and $\tilde{\xi}^{-}$ is found to be less than 11% and is included in the systematic uncertainty.

(8) The uncertainty on the trigger efficiency is estimated from the comparison of the turn-on curves as a function of the jet $p_{T}$ in the minimum-bias data and the MC simulation. The resulting uncertainty is 3%.

(9) The uncertainty on the integrated luminosity is estimated to be 4% [38,39].

The total systematic uncertainty is calculated as the quadratic sum of the individual contributions. The resulting

TABLE II. Contributions to the systematic uncertainty on the dijet cross section in the three lowest $\tilde{\xi}$ bins considered. The total systematic uncertainty calculated as the quadratic sum of the individual contributions is given in the last row.

| Uncertainty source | $0.0003 < \tilde{\xi} < 0.002$ | $0.002 < \tilde{\xi} < 0.0045$ | $0.0045 < \tilde{\xi} < 0.01$ |
|---|---|---|---|
| 1. Jet energy scale | $(+26; -19)\%$ | $(+21; -20)\%$ | $(+28; -16)\%$ |
| 2. Jet energy resolution | $(+6; -4)\%$ | $(+4; -3)\%$ | $(+3; -2)\%$ |
| 3. PF energy, $p_T$ threshold, C | $(+7; -15)\%$ | $(+14; -8)\%$ | $(+12; -11)\%$ |
| 4. MC model uncertainty | $(+5; -3)\%$ | $(+2; -14)\%$ | $(+3; -1)\%$ |
| 5. One-vertex selection | $(+6; -0)\%$ | $(+0; -1)\%$ | $(+1; -0)\%$ |
| 6. Jet objects (Calorimeter, PF) | $(+0; -4)\%$ | $(+0; -4)\%$ | $(+2; -4)\%$ |
| 7. $\tilde{\xi}^+$, $\tilde{\xi}^-$ difference | $\pm 8\%$ | $\pm 8\%$ | $\pm 11\%$ |
| 8. Trigger efficiency | $\pm 3\%$ | $\pm 3\%$ | $\pm 3\%$ |
| 9. Luminosity | $\pm 4\%$ | $\pm 4\%$ | $\pm 4\%$ |
| Total error | $(+30; -26)\%$ | $(+27; -29)\%$ | $(+33; -23)\%$ |

uncertainty of the cross section measurement is ~30%, dominated by the jet energy scale. The effect of each systematic check on the cross section uncertainty is given in Table II.

## VII. RESULTS

Table III and Fig. 8 present the differential cross section for dijet production as a function of $\tilde{\xi}$. The data are compared to the predictions of nondiffractive (PYTHIA6 Z2 and PYTHIA8 tune 1) and diffractive (POMPYT SD, POMWIG SD, PYTHIA8 SD + DD, and POWHEG) models. The normalization of the predictions is absolute, unlike in Fig. 6.

The following conclusions can be drawn from Fig. 8:

(i) The generators PYTHIA6 Z2 and PYTHIA8 tune 1, without hard diffraction, cannot by themselves describe the low-$\tilde{\xi}$ data, especially in the first bin, $0.0003 < \tilde{\xi} < 0.002$.

(ii) It was noted already in Sec. VA that the contribution of SD MC models, e.g. POMWIG and POMPYT, is needed to describe the low-$\tilde{\xi}$ data, reflecting the presence of hard diffractive events in this region. However, these MC models predict more events than are observed, by a factor of about 5 in the lowest $\tilde{\xi}$ bin.

(iii) The ratio of the measured cross section to that expected from the POMPYT and POMWIG simulations is $0.21 \pm 0.07$ in the first $\tilde{\xi}$ bin, where the nondiffractive contribution is small. This ratio can be taken as an upper limit of the rapidity gap survival probability (not simulated by the event generators considered). This is an upper limit because the measured cross section includes a contribution from proton-dissociative events in which the scattered proton is excited into a low mass state, which escapes undetected in the forward region; the dPDFs also include a proton-dissociative contribution. If the amount of proton-dissociative events in the data is assumed to be 41%, as estimated at particle level with PYTHIA8, and that in the dPDFs is taken to be 23% [7], then this upper limit can be turned into an estimate of the rapidity gap survival probability of $0.12 \pm 0.05$.

(iv) POMPYT and POMWIG are LO MC generators. If POWHEG is used to predict the diffractive cross section at NLO in the first $\tilde{\xi}$ bin and PYTHIA8 tune 1 is used for hadronization, the ratio between data and predictions becomes $0.14 \pm 0.05$. With the assumptions just discussed on the proton-dissociative contribution, the rapidity gap survival probability becomes $0.08 \pm 0.04$.

(v) Figure 8 also shows that the normalization of the SD + DD PYTHIA8 prediction disagrees with that of POMPYT and POMWIG, and would have to be scaled up by a factor of about 2 to match the data. This is a consequence of the different modeling of diffraction in these generators: while they all use the same H1 dPDFs, the parametrization of the pomeron flux in PYTHIA8 is different—and, notably, not the one used in the H1 fit. Because of this, PYTHIA8 (version 8.135) cannot be used to extract the rapidity gap survival probability.

TABLE III. Differential cross section for inclusive dijet production as a function of $\tilde{\xi}$ for jets with $p_T^{j1,j2} > 20$ GeV and jet axes in the pseudorapidity range $|\eta^{j1,j2}| < 4.4$.

| $\tilde{\xi}$ bin | $d\sigma_{jj}/d\tilde{\xi}$ ($\mu$b) |
|---|---|
| $0.0003 < \tilde{\xi} < 0.002$ | $5.0 \pm 0.9(\text{stat})^{+1.5}_{-1.3}(\text{syst})$ |
| $0.002 < \tilde{\xi} < 0.0045$ | $8.2 \pm 0.9(\text{stat})^{+2.2}_{-2.4}(\text{syst})$ |
| $0.0045 < \tilde{\xi} < 0.01$ | $13.5 \pm 0.9(\text{stat})^{+4.5}_{-3.1}(\text{syst})$ |

While the rapidity gap survival probability measured at the Tevatron [5,6] is close to that found in the present analysis, the two measurements cannot be directly compared because of the different kinematic regions they cover: $0.035 < \xi < 0.095$ for the CDF data and $0.0003 < \tilde{\xi} < 0.002$ for the present CMS data. This difference is

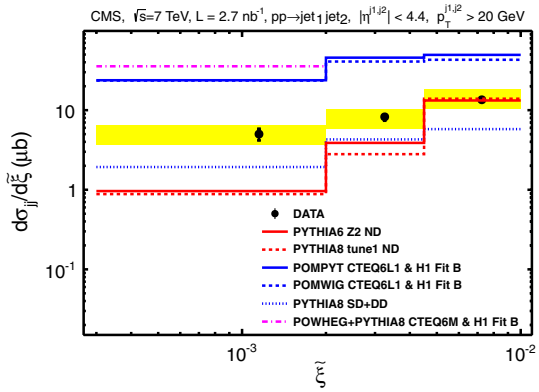


FIG. 8 (color online). The differential cross section for inclusive dijet production as a function of $\tilde{\xi}$ for jets with axes in the range $|\eta^{j1,j2}| < 4.4$ and $p_T^{j1,j2} > 20$ GeV. The points are plotted at the center of the bins. The error bars indicate the statistical uncertainty and the band represents the systematic uncertainties added in quadrature. The predictions of nondiffractive (PYTHIA6 Z2 and PYTHIA8 tune 1) and diffractive (POMPYT SD, POMWIG SD and PYTHIA8 SD + DD) MC generators are also shown, along with that of the NLO calculation based on POWHEG (first bin only). The predictions of POMPYT and POMWIG in the first $\tilde{\xi}$ bin are identical.

relevant because the rapidity gap survival probability depends on the parton momentum $x$ and is expected to increase with decreasing $x$ (and hence $\xi$): from about 0.05 at $x = 10^{-1}$ to about 0.3 for $x = 10^{-3}$ according to Ref. [40].

## VIII. SUMMARY

The differential cross section for dijet production as a function of $\tilde{\xi}$, a variable that approximates the fractional momentum loss of the proton in single-diffractive processes, has been measured with the CMS detector for events with at least two jets with $p_T^{j1,j2} > 20$ GeV in the pseudorapidity region $|\eta^{j1,j2}| < 4.4$. The results are compared to diffractive (POMPYT, POMWIG, and PYTHIA8 SD + DD) and nondiffractive (PYTHIA6 Z2, D6T, and PYTHIA8 tune 1) MC models. The low-$\tilde{\xi}$ data show a significant contribution from diffractive dijet production, observed for the first time at the LHC. The associated rapidity gap survival probability is estimated. Leading-order diffractive generators (POMPYT and POMWIG), based on dPDFs from the HERA experiments, overestimate the measured cross section and their normalization needs to be scaled down by a factor of ~5. This factor can be interpreted as the effect of the rapidity gap survival probability. The results are also compared with NLO predictions. The rapidity gap survival probability, estimated from the comparison of the cross section measured in the first bin, $0.0003 < \tilde{\xi} < 0.002$, with LO and NLO diffractive MC models, ranges from $0.08 \pm 0.04$ (NLO) to $0.12 \pm 0.05$ (LO).

## ACKNOWLEDGMENTS

We would like to thank M. Diehl, M. G. Ryskin, and L. Trentadue for their valuable suggestions. 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 BMWF and FWF (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); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEP, IPST and NECTEC (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Austrian Science Fund (FWF); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); and the HOMING PLUS programme of the Foundation for Polish Science, cofinanced by the European Union, Regional Development Fund.

[1] P. D. B. Collins, *An Introduction to Regge Theory and High-Energy Physics* (Cambridge University Press, Cambridge, England, 1977).
[2] A. Brandt, S. Erhan, A. Kuzucu, M. Medinnis, N. Ozdes, P. E. Schlein, M. T. Zeyrek, J. G. Zweizig, J. B. Cheze, and J. Zsembery (UA8 Collaboration), Phys. Lett. B **297**, 417 (1992).
[3] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **79**, 2636 (1997).
[4] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **531**, 52 (2002).
[5] T. Affolder *et al.* (CDF Collaboration), Phys. Rev. Lett. **84**, 5043 (2000).
[6] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **86**, 032009 (2012).
[7] A. Aktas *et al.* (H1 Collaboration), Eur. Phys. J. C **48**, 715 (2006).
[8] S. Chekanov *et al.* (ZEUS Collaboration), Nucl. Phys. **B816**, 1 (2009).
[9] S. Chekanov *et al.* (ZEUS Collaboration), Nucl. Phys. **B831**, 1 (2010).
[10] F. D. Aaron *et al.* (H1 Collaboration), Eur. Phys. J. C **70**, 15 (2010).
[11] L. Trentadue and G. Veneziano, Phys. Lett. B **323**, 201 (1994).
[12] J. C. Collins, Phys. Rev. D **57**, 3051 (1998).
[13] M. Grazzini, L. Trentadue, and G. Veneziano, Nucl. Phys. **B519**, 394 (1998).
[14] J. D. Bjorken, Phys. Rev. D **47**, 101 (1993).
[15] M. Ryskin, A. D. Martin, and V. A. Khoze, Eur. Phys. J. C **60**, 265 (2009).
[16] E. Gotsman, E. Levin, U. Maor, and J. S. Miller, Eur. Phys. J. C **57**, 689 (2008).
[17] J. R. Cudell, A. Dechambre, O. F. Hernandez, and I. P. Ivanov, Eur. Phys. J. C **61**, 369 (2009).
[18] L. Frankfurt, C. E. Hyde, M. Strikman, and C. Weiss, Phys. Rev. D **75**, 054009 (2007).
[19] S. Chatrchyan *et al.* (CMS Collaboration), JINST **3**, S08004 (2008).
[20] T. Sjöstrand, S. Mrenna, and P. Skands, Comput. Phys. Commun. **178**, 852 (2008).
[21] M. Cacciari, G. P. Salam, and G. Soyez, J. High Energy Phys. 04 (2008) 063.
[22] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-PFT-09-001, 2009.
[23] S. Chatrchyan *et al.* (CMS Collaboration), JINST **6**, P11002 (2011).
[24] V. Khachatryan *et al.* (CMS Collaboration), J. High Energy Phys. 02 (2010) 041.
[25] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
[26] R. Field, arXiv:1010.3558.
[27] R. Field, Acta Phys. Pol. B **39**, 2611 (2008).
[28] R. Corke and T. Sjöstrand, J. High Energy Phys. 03 (2011) 032.
[29] P. Bruni and G. Ingelman, Report No. DESY 93-187, 1993; a modified version of POMPYT 2.6 was used.
[30] B. E. Cox and J. R. Forshaw, Comput. Phys. Commun. **144**, 104 (2002).
[31] G. Ingelman and P. Schlein, Phys. Lett. **152B**, 256 (1985).
[32] S. Navin, arXiv:1005.3894.
[33] G. Corcella, I. G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M. H. Seymour, and B. R. Webber, J. High Energy Phys. 01 (2001) 010.
[34] S. Alioli, K. Hamilton, P. Nason, C. Oleari, and E. Re, J. High Energy Phys. 04 (2011) 081.
[35] S. Agostinelli and others (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[36] A. Hoecker and W. Kartvelishvili, Nucl. Instrum. Methods Phys. Res., Sect. A **372**, 469 (1996).
[37] G. D'Agostini, Nucl. Instrum. Methods Phys. Res., Sect. A **362**, 487 (1995).
[38] CMS Collaboration, CMS Physics Analysis Summary Report No. CMS-PAS-EWK-10-004, 2010.
[39] CMS Collaboration, CMS Detector Performance Summary Report No. CERN-CMS-DP-2011-002, 2011.
[40] M. Klasen and G. Kramer, Phys. Rev. D **80**, 074006 (2009).



S. Chatrchyan,[1] V. Khachatryan,[1] A. M. Sirunyan,[1] A. Tumasyan,[1] W. Adam,[2] E. Aguilo,[2] T. Bergauer,[2] M. Dragicevic,[2] J. Erö,[2] C. Fabjan,[2,b] M. Friedl,[2] R. Frühwirth,[2,b] V. M. Ghete,[2] J. Hammer,[2] N. Hörmann,[2] J. Hrubec,[2] M. Jeitler,[2,b] W. Kiesenhofer,[2] V. Knünz,[2] M. Krammer,[2,b] I. Krätschmer,[2] D. Liko,[2] I. Mikulec,[2] M. Pernicka,[2,a] B. Rahbaran,[2] C. Rohringer,[2] H. Rohringer,[2] R. Schöfbeck,[2] J. Strauss,[2] A. Taurok,[2] W. Waltenberger,[2] G. Walzel,[2] E. Widl,[2] C.-E. Wulz,[2,b] V. Mossolov,[3] N. Shumeiko,[3] J. Suarez Gonzalez,[3] S. Bansal,[4] T. Cornelis,[4] E. A. De Wolf,[4] X. Janssen,[4] S. Luyckx,[4] L. Mucibello,[4] S. Ochesanu,[4] B. Roland,[4] R. Rougny,[4] M. Selvaggi,[4] Z. Staykova,[4] H. Van Haevermaet,[4] P. Van Mechelen,[4] N. Van Remortel,[4] A. Van Spilbeeck,[4] F. Blekman,[5] S. Blyweert,[5] J. D'Hondt,[5] R. Gonzalez Suarez,[5] A. Kalogeropoulos,[5] M. Maes,[5] A. Olbrechts,[5] W. Van Doninck,[5] P. Van Mulders,[5] G. P. Van Onsem,[5] I. Villella,[5] B. Clerbaux,[6] G. De Lentdecker,[6] V. Dero,[6] A. P. R. Gay,[6] T. Hreus,[6] A. Léonard,[6] P. E. Marage,[6] A. Mohammadi,[6] T. Reis,[6] L. Thomas,[6] G. Vander Marcken,[6] C. Vander Velde,[6] P. Vanlaer,[6] J. Wang,[6] V. Adler,[7] K. Beernaert,[7] A. Cimmino,[7] S. Costantini,[7] G. Garcia,[7] M. Grunewald,[7] B. Klein,[7] J. Lellouch,[7] A. Marinov,[7] J. Mccartin,[7] A. A. Ocampo Rios,[7] D. Ryckbosch,[7] N. Strobbe,[7] F. Thyssen,[7] M. Tytgat,[7] P. Verwilligen,[7] S. Walsh,[7] E. Yazgan,[7] N. Zaganidis,[7] S. Basegmez,[8] G. Bruno,[8] R. Castello,[8] L. Ceard,[8] C. Delaere,[8] T. du Pree,[8] D. Favart,[8] L. Forthomme,[8] A. Giammanco,[8,c] J. Hollar,[8] V. Lemaitre,[8] J. Liao,[8] O. Militaru,[8] C. Nuttens,[8] D. Pagano,[8] A. Pin,[8] K. Piotrzkowski,[8] N. Schul,[8] J. M. Vizan Garcia,[8] N. Beliy,[9] T. Caebergs,[9] E. Daubie,[9] G. H. Hammad,[9] G. A. Alves,[10] M. Correa Martins Junior,[10]

D. De Jesus Damiao,[10] T. Martins,[10] M. E. Pol,[10] M. H. G. Souza,[10] W. L. Aldá Júnior,[11] W. Carvalho,[11] A. Custódio,[11] E. M. Da Costa,[11] C. De Oliveira Martins,[11] S. Fonseca De Souza,[11] D. Matos Figueiredo,[11] L. Mundim,[11] H. Nogima,[11] V. Oguri,[11] W. L. Prado Da Silva,[11] A. Santoro,[11] L. Soares Jorge,[11] A. Sznajder,[11] T. S. Anjos,[12,d] C. A. Bernardes,[12,d] F. A. Dias,[12,e] T. R. Fernandez Perez Tomei,[12] E. M. Gregores,[12,d] C. Lagana,[12] F. Marinho,[12] P. G. Mercadante,[12,d] S. F. Novaes,[12] Sandra S. Padula,[12] V. Genchev,[13,f] P. Iaydjiev,[13,f] S. Piperov,[13] M. Rodozov,[13] S. Stoykova,[13] G. Sultanov,[13] V. Tcholakov,[13] R. Trayanov,[13] M. Vutova,[13] A. Dimitrov,[14] R. Hadjiiska,[14] V. Kozhuharov,[14] L. Litov,[14] B. Pavlov,[14] P. Petkov,[14] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15] C. H. Jiang,[15] D. Liang,[15] S. Liang,[15] X. Meng,[15] J. Tao,[15] J. Wang,[15] X. Wang,[15] Z. Wang,[15] H. Xiao,[15] M. Xu,[15] J. Zang,[15] Z. Zhang,[15] C. Asawatangtrakuldee,[16] Y. Ban,[16] S. Guo,[16] Y. Guo,[16] W. Li,[16] S. Liu,[16] Y. Mao,[16] S. J. Qian,[16] H. Teng,[16] D. Wang,[16] L. Zhang,[16] B. Zhu,[16] W. Zou,[16] C. Avila,[17] J. P. Gomez,[17] B. Gomez Moreno,[17] A. F. Osorio Oliveros,[17] J. C. Sanabria,[17] N. Godinovic,[18] D. Lelas,[18] R. Plestina,[18,g] D. Polic,[18] I. Puljak,[18,f] Z. Antunovic,[19] M. Kovac,[19] V. Brigljevic,[20] S. Duric,[20] K. Kadija,[20] J. Luetic,[20] S. Morovic,[20] A. Attikis,[21] M. Galanti,[21] G. Mavromanolakis,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21] P. A. Razis,[21] M. Finger,[22] M. Finger, Jr.,[22] Y. Assran,[23,h] S. Elgammal,[23,i] A. Ellithi Kamel,[23,j] S. Khalil,[23,i] M. A. Mahmoud,[23,k] A. Radi,[23,l,m] M. Kadastik,[24] M. Müntel,[24] M. Raidal,[24] L. Rebane,[24] A. Tiko,[24] P. Eerola,[25] G. Fedi,[25] M. Voutilainen,[25] J. Härkönen,[26] A. Heikkinen,[26] V. Karimäki,[26] R. Kinnunen,[26] M. J. Kortelainen,[26] T. Lampén,[26] K. Lassila-Perini,[26] S. Lehti,[26] T. Lindén,[26] P. Luukka,[26] T. Mäenpää,[26] T. Peltola,[26] E. Tuominen,[26] J. Tuominiemi,[26] E. Tuovinen,[26] D. Ungaro,[26] L. Wendland,[26] K. Banzuzi,[27] A. Karjalainen,[27] A. Korpela,[27] T. Tuuva,[27] M. Besancon,[28] S. Choudhury,[28] M. Dejardin,[28] D. Denegri,[28] B. Fabbro,[28] J. L. Faure,[28] F. Ferri,[28] S. Ganjour,[28] A. Givernaud,[28] P. Gras,[28] G. Hamel de Monchenault,[28] P. Jarry,[28] E. Locci,[28] J. Malcles,[28] L. Millischer,[28] A. Nayak,[28] J. Rander,[28] A. Rosowsky,[28] I. Shreyber,[28] M. Titov,[28] S. Baffioni,[29] F. Beaudette,[29] L. Benhabib,[29] L. Bianchini,[29] M. Bluj,[29,n] C. Broutin,[29] P. Busson,[29] C. Charlot,[29] N. Daci,[29] T. Dahms,[29] L. Dobrzynski,[29] R. Granier de Cassagnac,[29] M. Haguenauer,[29] P. Miné,[29] C. Mironov,[29] I. N. Naranjo,[29] M. Nguyen,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. Salerno,[29] Y. Sirois,[29] C. Veelken,[29] A. Zabi,[29] J.-L. Agram,[30,o] J. Andrea,[30] D. Bloch,[30] D. Bodin,[30] J.-M. Brom,[30] M. Cardaci,[30] E. C. Chabert,[30] C. Collard,[30] E. Conte,[30,o] F. Drouhin,[30,o] C. Ferro,[30] J.-C. Fontaine,[30,o] D. Gelé,[30] U. Goerlach,[30] P. Juillot,[30] A.-C. Le Bihan,[30] P. Van Hove,[30] F. Fassi,[31] D. Mercier,[31] S. Beauceron,[32] N. Beaupere,[32] O. Bondu,[32] G. Boudoul,[32] J. Chasserat,[32] R. Chierici,[32,f] D. Contardo,[32] P. Depasse,[32] H. El Mamouni,[32] J. Fay,[32] S. Gascon,[32] M. Gouzevitch,[32] B. Ille,[32] T. Kurca,[32] M. Lethuillier,[32] L. Mirabito,[32] S. Perries,[32] V. Sordini,[32] Y. Tschudi,[32] P. Verdier,[32] S. Viret,[32] Z. Tsamalaidze,[33,p] G. Anagnostou,[34] S. Beranek,[34] M. Edelhoff,[34] L. Feld,[34] N. Heracleous,[34] O. Hindrichs,[34] R. Jussen,[34] K. Klein,[34] J. Merz,[34] A. Ostapchuk,[34] A. Perieanu,[34] F. Raupach,[34] J. Sammet,[34] S. Schael,[34] D. Sprenger,[34] H. Weber,[34] B. Wittmer,[34] V. Zhukov,[34,q] M. Ata,[35] J. Caudron,[35] E. Dietz-Laursonn,[35] D. Duchardt,[35] M. Erdmann,[35] R. Fischer,[35] A. Güth,[35] T. Hebbeker,[35] C. Heidemann,[35] K. Hoepfner,[35] D. Klingebiel,[35] P. Kreuzer,[35] C. Magass,[35] M. Merschmeyer,[35] A. Meyer,[35] M. Olschewski,[35] P. Papacz,[35] H. Pieta,[35] H. Reithler,[35] S. A. Schmitz,[35] L. Sonnenschein,[35] J. Steggemann,[35] D. Teyssier,[35] M. Weber,[35] M. Bontenackels,[36] V. Cherepanov,[36] G. Flügge,[36] H. Geenen,[36] M. Geisler,[36] W. Haj Ahmad,[36] F. Hoehle,[36] B. Kargoll,[36] T. Kress,[36] Y. Kuessel,[36] A. Nowack,[36] L. Perchalla,[36] O. Pooth,[36] P. Sauerland,[36] A. Stahl,[36] M. Aldaya Martin,[37] J. Behr,[37] W. Behrenhoff,[37] U. Behrens,[37] M. Bergholz,[37,r] A. Bethani,[37] K. Borras,[37] A. Burgmeier,[37] A. Cakir,[37] L. Calligaris,[37] A. Campbell,[37] E. Castro,[37] F. Costanza,[37] D. Dammann,[37] C. Diez Pardos,[37] G. Eckerlin,[37] D. Eckstein,[37] G. Flucke,[37] A. Geiser,[37] I. Glushkov,[37] P. Gunnellini,[37] S. Habib,[37] J. Hauk,[37] G. Hellwig,[37] H. Jung,[37] M. Kasemann,[37] P. Katsas,[37] C. Kleinwort,[37] H. Kluge,[37] A. Knutsson,[37] M. Krämer,[37] D. Krücker,[37] E. Kuznetsova,[37] W. Lange,[37] W. Lohmann,[37,r] B. Lutz,[37] R. Mankel,[37] I. Marfin,[37] M. Marienfeld,[37] I.-A. Melzer-Pellmann,[37] A. B. Meyer,[37] J. Mnich,[37] A. Mussgiller,[37] S. Naumann-Emme,[37] J. Olzem,[37] H. Perrey,[37] A. Petrukhin,[37] D. Pitzl,[37] A. Raspereza,[37] P. M. Ribeiro Cipriano,[37] C. Riedl,[37] E. Ron,[37] M. Rosin,[37] J. Salfeld-Nebgen,[37] R. Schmidt,[37,r] T. Schoerner-Sadenius,[37] N. Sen,[37] A. Spiridonov,[37] M. Stein,[37] R. Walsh,[37] C. Wissing,[37] C. Autermann,[38] V. Blobel,[38] J. Draeger,[38] H. Enderle,[38] J. Erfle,[38] U. Gebbert,[38] M. Görner,[38] T. Hermanns,[38] R. S. Höing,[38] K. Kaschube,[38] G. Kaussen,[38] H. Kirschenmann,[38] R. Klanner,[38] J. Lange,[38] B. Mura,[38] F. Nowak,[38] T. Peiffer,[38] N. Pietsch,[38] D. Rathjens,[38] C. Sander,[38] H. Schettler,[38] P. Schleper,[38] E. Schlieckau,[38] A. Schmidt,[38] M. Schröder,[38] T. Schum,[38] M. Seidel,[38] V. Sola,[38] H. Stadie,[38] G. Steinbrück,[38] J. Thomsen,[38] L. Vanelderen,[38] C. Barth,[39] J. Berger,[39] C. Böser,[39] T. Chwalek,[39] W. De Boer,[39] A. Descroix,[39] A. Dierlamm,[39] M. Feindt,[39] M. Guthoff,[39,f] C. Hackstein,[39] F. Hartmann,[39] T. Hauth,[39,f] M. Heinrich,[39] H. Held,[39] K. H. Hoffmann,[39] S. Honc,[39] I. Katkov,[39,q] J. R. Komaragiri,[39] P. Lobelle Pardo,[39] D. Martschei,[39] S. Mueller,[39]

Th. Müller,[39] M. Niegel,[39] A. Nürnberg,[39] O. Oberst,[39] A. Oehler,[39] J. Ott,[39] G. Quast,[39] K. Rabbertz,[39] F. Ratnikov,[39] N. Ratnikova,[39] S. Röcker,[39] A. Scheurer,[39] F.-P. Schilling,[39] G. Schott,[39] H. J. Simonis,[39] F. M. Stober,[39] D. Troendle,[39] R. Ulrich,[39] J. Wagner-Kuhr,[39] S. Wayand,[39] T. Weiler,[39] M. Zeise,[39] G. Daskalakis,[40] T. Geralis,[40] S. Kesisoglou,[40] A. Kyriakis,[40] D. Loukas,[40] I. Manolakos,[40] A. Markou,[40] C. Markou,[40] C. Mavrommatis,[40] E. Ntomari,[40] L. Gouskos,[41] T. J. Mertzimekis,[41] A. Panagiotou,[41] N. Saoulidou,[41] I. Evangelou,[42] C. Foudas,[42,f] P. Kokkas,[42] N. Manthos,[42] I. Papadopoulos,[42] V. Patras,[42] G. Bencze,[43] C. Hajdu,[43,f] P. Hidas,[43] D. Horvath,[43,s] F. Sikler,[43] V. Veszpremi,[43] G. Vesztergombi,[43,t] N. Beni,[44] S. Czellar,[44] J. Molnar,[44] J. Palinkas,[44] Z. Szillasi,[44] J. Karancsi,[45] P. Raics,[45] Z. L. Trocsanyi,[45] B. Ujvari,[45] M. Bansal,[46] S. B. Beri,[46] V. Bhatnagar,[46] N. Dhingra,[46] R. Gupta,[46] M. Kaur,[46] M. Z. Mehta,[46] N. Nishu,[46] L. K. Saini,[46] A. Sharma,[46] J. B. Singh,[46] Ashok Kumar,[47] Arun Kumar,[47] S. Ahuja,[47] A. Bhardwaj,[47] B. C. Choudhary,[47] S. Malhotra,[47] M. Naimuddin,[47] K. Ranjan,[47] V. Sharma,[47] R. K. Shivpuri,[47] S. Banerjee,[48] S. Bhattacharya,[48] S. Dutta,[48] B. Gomber,[48] Sa. Jain,[48] Sh. Jain,[48] R. Khurana,[48] S. Sarkar,[48] M. Sharan,[48] A. Abdulsalam,[49] R. K. Choudhury,[49] D. Dutta,[49] S. Kailas,[49] V. Kumar,[49] P. Mehta,[49] A. K. Mohanty,[49,f] L. M. Pant,[49] P. Shukla,[49] T. Aziz,[50] S. Ganguly,[50] M. Guchait,[50,u] M. Maity,[50,v] G. Majumder,[50] K. Mazumdar,[50] G. B. Mohanty,[50] B. Parida,[50] K. Sudhakar,[50] N. Wickramage,[50] S. Banerjee,[51] S. Dugad,[51] H. Arfaei,[52] H. Bakhshiansohi,[52,w] S. M. Etesami,[52,x] A. Fahim,[52,w] M. Hashemi,[52] H. Hesari,[52] A. Jafari,[52,w] M. Khakzad,[52] M. Mohammadi Najafabadi,[52] S. Paktinat Mehdiabadi,[52] B. Safarzadeh,[52,y] M. Zeinali,[52,x] M. Abbrescia,[53a,53b] L. Barbone,[53a,53b] C. Calabria,[53a,53b,f] S. S. Chhibra,[53a,53b] A. Colaleo,[53a] D. Creanza,[53a,53c] N. De Filippis,[53a,53c,f] M. De Palma,[53a,53b] L. Fiore,[53a] G. Iaselli,[53a,53c] L. Lusito,[53a,53b] G. Maggi,[53a,53c] M. Maggi,[53a] B. Marangelli,[53a,53b] S. My,[53a,53c] S. Nuzzo,[53a,53b] N. Pacifico,[53a,53b] A. Pompili,[53a,53b] G. Pugliese,[53a,53c] G. Selvaggi,[53a,53b] L. Silvestris,[53a] G. Singh,[53a,53b] R. Venditti,[53a] G. Zito,[53a] G. Abbiendi,[54a] A. C. Benvenuti,[54a] D. Bonacorsi,[54a,54b] S. Braibant-Giacomelli,[54a,54b] L. Brigliadori,[54a,54b] P. Capiluppi,[54a,54b] A. Castro,[54a,54b] F. R. Cavallo,[54a] M. Cuffiani,[54a,54b] G. M. Dallavalle,[54a] F. Fabbri,[54a] A. Fanfani,[54a,54b] D. Fasanella,[54a,54b,f] P. Giacomelli,[54a] C. Grandi,[54a] L. Guiducci,[54a,54b] S. Marcellini,[54a] G. Masetti,[54a] M. Meneghelli,[54a,54b,f] A. Montanari,[54a] F. L. Navarria,[54a,54b] F. Odorici,[54a] A. Perrotta,[54a] F. Primavera,[54a,54b] A. M. Rossi,[54a,54b] T. Rovelli,[54a,54b] G. P. Siroli,[54a,54b] R. Travaglini,[54a,54b] S. Albergo,[55a,55b] G. Cappello,[55a,55b] M. Chiorboli,[55a,55b] S. Costa,[55a,55b] R. Potenza,[55a,55b] A. Tricomi,[55a,55b] C. Tuve,[55a,55b] G. Barbagli,[56a] V. Ciulli,[56a,56b] C. Civinini,[56a] R. D'Alessandro,[56a,56b] E. Focardi,[56a,56b] S. Frosali,[56a,56b] E. Gallo,[56a] S. Gonzi,[56a,56b] M. Meschini,[56a] S. Paoletti,[56a] G. Sguazzoni,[56a] A. Tropiano,[56a,f] L. Benussi,[57] S. Bianco,[57] S. Colafranceschi,[57,z] F. Fabbri,[57] D. Piccolo,[57] P. Fabbricatore,[58a] R. Musenich,[58a] S. Tosi,[58a,58b] A. Benaglia,[59a,59b,f] F. De Guio,[59a,59b] L. Di Matteo,[59a,59b,f] S. Fiorendi,[59a,59b] S. Gennai,[59a,f] A. Ghezzi,[59a,59b] S. Malvezzi,[59a] R. A. Manzoni,[59a,59b] A. Martelli,[59a,59b] A. Massironi,[59a,59b,f] D. Menasce,[59a] L. Moroni,[59a] M. Paganoni,[59a,59b] D. Pedrini,[59a] S. Ragazzi,[59a,59b] N. Redaelli,[59a] S. Sala,[59a] T. Tabarelli de Fatis,[59a,59b] S. Buontempo,[60a] C. A. Carrillo Montoya,[60a] N. Cavallo,[60a,aa] A. De Cosa,[60a,60b,f] O. Dogangun,[60a,60b] F. Fabozzi,[60a,aa] A. O. M. Iorio,[60a] L. Lista,[60a] S. Meola,[60a,bb] M. Merola,[60a,60b] P. Paolucci,[60a,f] P. Azzi,[61a] N. Bacchetta,[61a,f] P. Bellan,[61a,61b] D. Bisello,[61a,61b] A. Branca,[61a,f] R. Carlin,[61a,61b] P. Checchia,[61a] T. Dorigo,[61a] F. Gasparini,[61a,61b] A. Gozzelino,[61a] K. Kanishchev,[61a,61c] S. Lacaprara,[61a] I. Lazzizzera,[61a,61c] M. Margoni,[61a,61b] A. T. Meneguzzo,[61a,61b] J. Pazzini,[61a] N. Pozzobon,[61a,61b] P. Ronchese,[61a,61b] F. Simonetto,[61a,61b] E. Torassa,[61a] M. Tosi,[61a,61b] A. Triossi,[61a] S. Vanini,[61a,61b] P. Zotto,[61a,61b] G. Zumerle,[61a,61b] M. Gabusi,[62a,62b] S. P. Ratti,[62a,62b] C. Riccardi,[62a,62b] P. Torre,[62a,62b] P. Vitulo,[62a,62b] M. Biasini,[63a,63b] G. M. Bilei,[63a] L. Fanò,[63a,63b] P. Lariccia,[63a,63b] A. Lucaroni,[63a,63b,f] G. Mantovani,[63a,63b] M. Menichelli,[63a] A. Nappi,[63a,63b] F. Romeo,[63a,63b] A. Saha,[63a] A. Santocchia,[63a,63b] A. Spiezia,[63a,63b] S. Taroni,[63a,63b,f] P. Azzurri,[64a,64c] G. Bagliesi,[64a] T. Boccali,[64a] G. Broccolo,[64a,64c] R. Castaldi,[64a] R. T. D'Agnolo,[64a,64c] R. Dell'Orso,[64a] F. Fiori,[64a,64b,f] L. Foà,[64a,64c] A. Giassi,[64a] A. Kraan,[64a] F. Ligabue,[64a,64c] T. Lomtadze,[64a] L. Martini,[64a,cc] A. Messineo,[64a,64b] F. Palla,[64a] A. Rizzi,[64a,64b] A. T. Serban,[64a,dd] P. Spagnolo,[64a] P. Squillacioti,[64a,f] R. Tenchini,[64a] G. Tonelli,[64a,64b,f] A. Venturi,[64a,f] P. G. Verdini,[64a] L. Barone,[65a,65b] F. Cavallari,[65a] D. Del Re,[65a,65b,f] M. Diemoz,[65a] C. Fanelli,[65a] M. Grassi,[65a,65b,f] E. Longo,[65a,65b] P. Meridiani,[65a,f] F. Micheli,[65a,65b] S. Nourbakhsh,[65a,65b] G. Organtini,[65a,65b] R. Paramatti,[65a] S. Rahatlou,[65a,65b] M. Sigamani,[65a] L. Soffi,[65a,65b] N. Amapane,[66a,66b] R. Arcidiacono,[66a,66c] S. Argiro,[66a,66b] M. Arneodo,[66a,66c] C. Biino,[66a] N. Cartiglia,[66a] M. Costa,[66a,66b] N. Demaria,[66a] C. Mariotti,[66a,f] S. Maselli,[66a] E. Migliore,[66a,66b] V. Monaco,[66a,66b] M. Musich,[66a,f] M. M. Obertino,[66a,66c] N. Pastrone,[66a] M. Pelliccioni,[66a] A. Potenza,[66a,66b] A. Romero,[66a,66b] M. Ruspa,[66a,66c] R. Sacchi,[66a,66b] A. Solano,[66a,66b] A. Staiano,[66a] A. Vilela Pereira,[66a] S. Belforte,[67a] V. Candelise,[67a,67b] F. Cossutti,[67a] G. Della Ricca,[67a,67b] B. Gobbo,[67a] M. Marone,[67a,67b,f] D. Montanino,[67a,67b,f] A. Penzo,[67a] A. Schizzi,[67a,67b]

S. G. Heo,[68] T. Y. Kim,[68] S. K. Nam,[68] S. Chang,[69] D. H. Kim,[69] G. N. Kim,[69] D. J. Kong,[69] H. Park,[69] S. R. Ro,[69] D. C. Son,[69] T. Son,[69] J. Y. Kim,[70] Zero J. Kim,[70] S. Song,[70] S. Choi,[71] D. Gyun,[71] B. Hong,[71] M. Jo,[71] H. Kim,[71] T. J. Kim,[71] K. S. Lee,[71] D. H. Moon,[71] S. K. Park,[71] M. Choi,[72] J. H. Kim,[72] C. Park,[72] I. C. Park,[72] S. Park,[72] G. Ryu,[72] Y. Cho,[73] Y. Choi,[73] Y. K. Choi,[73] J. Goh,[73] M. S. Kim,[73] E. Kwon,[73] B. Lee,[73] J. Lee,[73] S. Lee,[73] H. Seo,[73] I. Yu,[73] M. J. Bilinskas,[74] I. Grigelionis,[74] M. Janulis,[74] A. Juodagalvis,[74] H. Castilla-Valdez,[75] E. De La Cruz-Burelo,[75] I. Heredia-de La Cruz,[75] R. Lopez-Fernandez,[75] R. Magaña Villalba,[75] J. Martínez-Ortega,[75] A. Sánchez-Hernández,[75] L. M. Villasenor-Cendejas,[75] S. Carrillo Moreno,[76] F. Vazquez Valencia,[76] H. A. Salazar Ibarguen,[77] E. Casimiro Linares,[78] A. Morelos Pineda,[78] M. A. Reyes-Santos,[78] D. Krofcheck,[79] A. J. Bell,[80] P. H. Butler,[80] R. Doesburg,[80] S. Reucroft,[80] H. Silverwood,[80] M. Ahmad,[81] M. H. Ansari,[81] M. I. Asghar,[81] H. R. Hoorani,[81] S. Khalid,[81] W. A. Khan,[81] T. Khurshid,[81] S. Qazi,[81] M. A. Shah,[81] M. Shoaib,[81] H. Bialkowska,[82] B. Boimska,[82] T. Frueboes,[82] R. Gokieli,[82] M. Górski,[82] M. Kazana,[82] K. Nawrocki,[82] K. Romanowska-Rybinska,[82] M. Szleper,[82] G. Wrochna,[82] P. Zalewski,[82] G. Brona,[83] K. Bunkowski,[83] M. Cwiok,[83] W. Dominik,[83] K. Doroba,[83] A. Kalinowski,[83] M. Konecki,[83] J. Krolikowski,[83] N. Almeida,[84] P. Bargassa,[84] A. David,[84] P. Faccioli,[84] P. G. Ferreira Parracho,[84] M. Gallinaro,[84] J. Seixas,[84] J. Varela,[84] P. Vischia,[84] I. Belotelov,[85] P. Bunin,[85] M. Gavrilenko,[85] I. Golutvin,[85] I. Gorbunov,[85] A. Kamenev,[85] V. Karjavin,[85] G. Kozlov,[85] A. Lanev,[85] A. Malakhov,[85] P. Moisenz,[85] V. Palichik,[85] V. Perelygin,[85] S. Shmatov,[85] V. Smirnov,[85] A. Volodko,[85] A. Zarubin,[85] S. Evstyukhin,[86] V. Golovtsov,[86] Y. Ivanov,[86] V. Kim,[86] P. Levchenko,[86] V. Murzin,[86] V. Oreshkin,[86] I. Smirnov,[86] V. Sulimov,[86] L. Uvarov,[86] S. Vavilov,[86] A. Vorobyev,[86] An. Vorobyev,[86] Yu. Andreev,[87] A. Dermenev,[87] S. Gninenko,[87] N. Golubev,[87] M. Kirsanov,[87] N. Krasnikov,[87] V. Matveev,[87] A. Pashenkov,[87] D. Tlisov,[87] A. Toropin,[87] V. Epshteyn,[88] M. Erofeeva,[88] V. Gavrilov,[88] M. Kossov,[88,f] N. Lychkovskaya,[88] V. Popov,[88] G. Safronov,[88] S. Semenov,[88] V. Stolin,[88] E. Vlasov,[88] A. Zhokin,[88] A. Belyaev,[89] E. Boos,[89] M. Dubinin,[89,e] A. Ershov,[89] A. Gribushin,[89] L. Khein,[89] V. Klyukhin,[89] O. Kodolova,[89] I. Lokhtin,[89] A. Markina,[89] S. Obraztsov,[89] M. Perfilov,[89] S. Petrushanko,[89] A. Popov,[89] A. Proskuryakov,[89] L. Sarycheva,[89,a] V. Savrin,[89] V. Andreev,[90] M. Azarkin,[90] I. Dremin,[90] M. Kirakosyan,[90] A. Leonidov,[90] G. Mesyats,[90] S. V. Rusakov,[90] A. Vinogradov,[90] I. Azhgirey,[91] I. Bayshev,[91] S. Bitioukov,[91] V. Grishin,[91,f] V. Kachanov,[91] D. Konstantinov,[91] A. Korablev,[91] V. Krychkine,[91] V. Petrov,[91] R. Ryutin,[91] A. Sobol,[91] L. Tourtchanovitch,[91] S. Troshin,[91] N. Tyurin,[91] A. Uzunian,[91] A. Volkov,[91] P. Adzic,[92,ee] M. Djordjevic,[92] M. Ekmedzic,[92] D. Krpic,[92,ee] J. Milosevic,[92] M. Aguilar-Benitez,[93] J. Alcaraz Maestre,[93] P. Arce,[93] C. Battilana,[93] E. Calvo,[93] M. Cerrada,[93] M. Chamizo Llatas,[93] N. Colino,[93] B. De La Cruz,[93] A. Delgado Peris,[93] D. Domínguez Vázquez,[93] C. Fernandez Bedoya,[93] J. P. Fernández Ramos,[93] A. Ferrando,[93] J. Flix,[93] M. C. Fouz,[93] P. Garcia-Abia,[93] O. Gonzalez Lopez,[93] S. Goy Lopez,[93] J. M. Hernandez,[93] M. I. Josa,[93] G. Merino,[93] J. Puerta Pelayo,[93] A. Quintario Olmeda,[93] I. Redondo,[93] L. Romero,[93] J. Santaolalla,[93] M. S. Soares,[93] C. Willmott,[93] C. Albajar,[94] G. Codispoti,[94] J. F. de Trocóniz,[94] H. Brun,[95] J. Cuevas,[95] J. Fernandez Menendez,[95] S. Folgueras,[95] I. Gonzalez Caballero,[95] L. Lloret Iglesias,[95] J. Piedra Gomez,[95] J. A. Brochero Cifuentes,[96] I. J. Cabrillo,[96] A. Calderon,[96] S. H. Chuang,[96] J. Duarte Campderros,[96] M. Felcini,[96,ff] M. Fernandez,[96] G. Gomez,[96] J. Gonzalez Sanchez,[96] A. Graziano,[96] C. Jorda,[96] A. Lopez Virto,[96] J. Marco,[96] R. Marco,[96] C. Martinez Rivero,[96] F. Matorras,[96] F. J. Munoz Sanchez,[96] T. Rodrigo,[96] A. Y. Rodríguez-Marrero,[96] A. Ruiz-Jimeno,[96] L. Scodellaro,[96] M. Sobron Sanudo,[96] I. Vila,[96] R. Vilar Cortabitarte,[96] D. Abbaneo,[97] E. Auffray,[97] G. Auzinger,[97] P. Baillon,[97] A. H. Ball,[97] D. Barney,[97] J. F. Benitez,[97] C. Bernet,[97,g] G. Bianchi,[97] P. Bloch,[97] A. Bocci,[97] A. Bonato,[97] C. Botta,[97] H. Breuker,[97] T. Camporesi,[97] G. Cerminara,[97] T. Christiansen,[97] J. A. Coarasa Perez,[97] D. D'Enterria,[97] A. Dabrowski,[97] A. De Roeck,[97] S. Di Guida,[97] M. Dobson,[97] N. Dupont-Sagorin,[97] A. Elliott-Peisert,[97] B. Frisch,[97] W. Funk,[97] G. Georgiou,[97] M. Giffels,[97] D. Gigi,[97] K. Gill,[97] D. Giordano,[97] M. Giunta,[97] F. Glege,[97] R. Gomez-Reino Garrido,[97] P. Govoni,[97] S. Gowdy,[97] R. Guida,[97] M. Hansen,[97] P. Harris,[97] C. Hartl,[97] J. Harvey,[97] B. Hegner,[97] A. Hinzmann,[97] V. Innocente,[97] P. Janot,[97] K. Kaadze,[97] E. Karavakis,[97] K. Kousouris,[97] P. Lecoq,[97] Y.-J. Lee,[97] P. Lenzi,[97] C. Lourenço,[97] T. Mäki,[97] M. Malberti,[97] L. Malgeri,[97] M. Mannelli,[97] L. Masetti,[97] F. Meijers,[97] S. Mersi,[97] E. Meschi,[97] R. Moser,[97] M. U. Mozer,[97] M. Mulders,[97] P. Musella,[97] E. Nesvold,[97] T. Orimoto,[97] L. Orsini,[97] E. Palencia Cortezon,[97] E. Perez,[97] L. Perrozzi,[97] A. Petrilli,[97] A. Pfeiffer,[97] M. Pierini,[97] M. Pimiä,[97] D. Piparo,[97] G. Polese,[97] L. Quertenmont,[97] A. Racz,[97] W. Reece,[97] J. Rodrigues Antunes,[97] G. Rolandi,[97,gg] C. Rovelli,[97,hh] M. Rovere,[97] H. Sakulin,[97] F. Santanastasio,[97] C. Schäfer,[97] C. Schwick,[97] I. Segoni,[97] S. Sekmen,[97] A. Sharma,[97] P. Siegrist,[97] P. Silva,[97] M. Simon,[97] P. Sphicas,[97,ii] D. Spiga,[97] A. Tsirou,[97] G. I. Veres,[97,t] J. R. Vlimant,[97] H. K. Wöhri,[97] S. D. Worm,[97,jj] W. D. Zeuner,[97] W. Bertl,[98] K. Deiters,[98] W. Erdmann,[98] K. Gabathuler,[98] R. Horisberger,[98]

Q. Ingram,[98] H. C. Kaestli,[98] S. König,[98] D. Kotlinski,[98] U. Langenegger,[98] F. Meier,[98] D. Renker,[98] T. Rohe,[98] J. Sibille,[98,kk] L. Bäni,[99] P. Bortignon,[99] M. A. Buchmann,[99] B. Casal,[99] N. Chanon,[99] A. Deisher,[99] G. Dissertori,[99] M. Dittmar,[99] M. Donegà,[99] M. Dünser,[99] J. Eugster,[99] K. Freudenreich,[99] C. Grab,[99] D. Hits,[99] P. Lecomte,[99] W. Lustermann,[99] A. C. Marini,[99] P. Martinez Ruiz del Arbol,[99] N. Mohr,[99] F. Moortgat,[99] C. Nägeli,[99,ll] P. Nef,[99] F. Nessi-Tedaldi,[99] F. Pandolfi,[99] L. Pape,[99] F. Pauss,[99] M. Peruzzi,[99] F. J. Ronga,[99] M. Rossini,[99] L. Sala,[99] A. K. Sanchez,[99] A. Starodumov,[99,mm] B. Stieger,[99] M. Takahashi,[99] L. Tauscher,[99,a] A. Thea,[99] K. Theofilatos,[99] D. Treille,[99] C. Urscheler,[99] R. Wallny,[99] H. A. Weber,[99] L. Wehrli,[99] C. Amsler,[100] V. Chiochia,[100] S. De Visscher,[100] C. Favaro,[100] M. Ivova Rikova,[100] B. Millan Mejias,[100] P. Otiougova,[100] P. Robmann,[100] H. Snoek,[100] S. Tupputi,[100] M. Verzetti,[100] Y. H. Chang,[101] K. H. Chen,[101] C. M. Kuo,[101] S. W. Li,[101] W. Lin,[101] Z. K. Liu,[101] Y. J. Lu,[101] D. Mekterovic,[101] A. P. Singh,[101] R. Volpe,[101] S. S. Yu,[101] P. Bartalini,[102] P. Chang,[102] Y. H. Chang,[102] Y. W. Chang,[102] Y. Chao,[102] K. F. Chen,[102] C. Dietz,[102] U. Grundler,[102] W.-S. Hou,[102] Y. Hsiung,[102] K. Y. Kao,[102] Y. J. Lei,[102] R.-S. Lu,[102] D. Majumder,[102] E. Petrakou,[102] X. Shi,[102] J. G. Shiu,[102] Y. M. Tzeng,[102] X. Wan,[102] M. Wang,[102] A. Adiguzel,[103] M. N. Bakirci,[103,nn] S. Cerci,[103,oo] C. Dozen,[103] I. Dumanoglu,[103] E. Eskut,[103] S. Girgis,[103] G. Gokbulut,[103] E. Gurpinar,[103] I. Hos,[103] E. E. Kangal,[103] T. Karaman,[103] G. Karapinar,[103,pp] A. Kayis Topaksu,[103] G. Onengut,[103] K. Ozdemir,[103] S. Ozturk,[103,qq] A. Polatoz,[103] K. Sogut,[103,rr] D. Sunar Cerci,[103,oo] B. Tali,[103,oo] H. Topakli,[103,nn] L. N. Vergili,[103] M. Vergili,[103] I. V. Akin,[104] T. Aliev,[104] B. Bilin,[104] S. Bilmis,[104] M. Deniz,[104] H. Gamsizkan,[104] A. M. Guler,[104] K. Ocalan,[104] A. Ozpineci,[104] M. Serin,[104] R. Sever,[104] U. E. Surat,[104] M. Yalvac,[104] E. Yildirim,[104] M. Zeyrek,[104] E. Gülmez,[105] B. Isildak,[105,ss] M. Kaya,[105,tt] O. Kaya,[105,tt] S. Ozkorucuklu,[105,uu] N. Sonmez,[105,vv] K. Cankocak,[106] L. Levchuk,[107] F. Bostock,[108] J. J. Brooke,[108] E. Clement,[108] D. Cussans,[108] H. Flacher,[108] R. Frazier,[108] J. Goldstein,[108] M. Grimes,[108] G. P. Heath,[108] H. F. Heath,[108] L. Kreczko,[108] S. Metson,[108] D. M. Newbold,[108,jj] K. Nirunpong,[108] A. Poll,[108] S. Senkin,[108] V. J. Smith,[108] T. Williams,[108] L. Basso,[109,ww] K. W. Bell,[109] A. Belyaev,[109,ww] C. Brew,[109] R. M. Brown,[109] D. J. A. Cockerill,[109] J. A. Coughlan,[109] K. Harder,[109] S. Harper,[109] J. Jackson,[109] B. W. Kennedy,[109] E. Olaiya,[109] D. Petyt,[109] B. C. Radburn-Smith,[109] C. H. Shepherd-Themistocleous,[109] I. R. Tomalin,[109] W. J. Womersley,[109] R. Bainbridge,[110] G. Ball,[110] R. Beuselinck,[110] O. Buchmuller,[110] D. Colling,[110] N. Cripps,[110] M. Cutajar,[110] P. Dauncey,[110] G. Davies,[110] M. Della Negra,[110] W. Ferguson,[110] J. Fulcher,[110] D. Futyan,[110] A. Gilbert,[110] A. Guneratne Bryer,[110] G. Hall,[110] Z. Hatherell,[110] J. Hays,[110] G. Iles,[110] M. Jarvis,[110] G. Karapostoli,[110] L. Lyons,[110] A.-M. Magnan,[110] J. Marrouche,[110] B. Mathias,[110] R. Nandi,[110] J. Nash,[110] A. Nikitenko,[110,mm] A. Papageorgiou,[110] J. Pela,[110,f] M. Pesaresi,[110] K. Petridis,[110] M. Pioppi,[110,xx] D. M. Raymond,[110] S. Rogerson,[110] A. Rose,[110] M. J. Ryan,[110] C. Seez,[110] P. Sharp,[110,a] A. Sparrow,[110] M. Stoye,[110] A. Tapper,[110] M. Vazquez Acosta,[110] T. Virdee,[110] S. Wakefield,[110] N. Wardle,[110] T. Whyntie,[110] M. Chadwick,[111] J. E. Cole,[111] P. R. Hobson,[111] A. Khan,[111] P. Kyberd,[111] D. Leggat,[111] D. Leslie,[111] W. Martin,[111] I. D. Reid,[111] P. Symonds,[111] L. Teodorescu,[111] M. Turner,[111] K. Hatakeyama,[112] H. Liu,[112] T. Scarborough,[112] O. Charaf,[113] C. Henderson,[113] P. Rumerio,[113] A. Avetisyan,[114] T. Bose,[114] C. Fantasia,[114] A. Heister,[114] J. St. John,[114] P. Lawson,[114] D. Lazic,[114] J. Rohlf,[114] D. Sperka,[114] L. Sulak,[114] J. Alimena,[115] S. Bhattacharya,[115] D. Cutts,[115] A. Ferapontov,[115] U. Heintz,[115] S. Jabeen,[115] G. Kukartsev,[115] E. Laird,[115] G. Landsberg,[115] M. Luk,[115] M. Narain,[115] D. Nguyen,[115] M. Segala,[115] T. Sinthuprasith,[115] T. Speer,[115] K. V. Tsang,[115] R. Breedon,[116] G. Breto,[116] M. Calderon De La Barca Sanchez,[116] S. Chauhan,[116] M. Chertok,[116] J. Conway,[116] R. Conway,[116] P. T. Cox,[116] J. Dolen,[116] R. Erbacher,[116] M. Gardner,[116] R. Houtz,[116] W. Ko,[116] A. Kopecky,[116] R. Lander,[116] T. Miceli,[116] D. Pellett,[116] F. Ricci-tam,[116] B. Rutherford,[116] M. Searle,[116] J. Smith,[116] M. Squires,[116] M. Tripathi,[116] R. Vasquez Sierra,[116] V. Andreev,[117] D. Cline,[117] R. Cousins,[117] J. Duris,[117] S. Erhan,[117] P. Everaerts,[117] C. Farrell,[117] J. Hauser,[117] M. Ignatenko,[117] C. Jarvis,[117] C. Plager,[117] G. Rakness,[117] P. Schlein,[117,a] P. Traczyk,[117] V. Valuev,[117] M. Weber,[117] J. Babb,[118] R. Clare,[118] M. E. Dinardo,[118] J. Ellison,[118] J. W. Gary,[118] F. Giordano,[118] G. Hanson,[118] G. Y. Jeng,[118,yy] H. Liu,[118] O. R. Long,[118] A. Luthra,[118] H. Nguyen,[118] S. Paramesvaran,[118] J. Sturdy,[118] S. Sumowidagdo,[118] R. Wilken,[118] S. Wimpenny,[118] W. Andrews,[119] J. G. Branson,[119] G. B. Cerati,[119] S. Cittolin,[119] D. Evans,[119] F. Golf,[119] A. Holzner,[119] R. Kelley,[119] M. Lebourgeois,[119] J. Letts,[119] I. Macneill,[119] B. Mangano,[119] S. Padhi,[119] C. Palmer,[119] G. Petrucciani,[119] M. Pieri,[119] M. Sani,[119] V. Sharma,[119] S. Simon,[119] E. Sudano,[119] M. Tadel,[119] Y. Tu,[119] A. Vartak,[119] S. Wasserbaech,[119,zz] F. Würthwein,[119] A. Yagil,[119] J. Yoo,[119] D. Barge,[120] R. Bellan,[120] C. Campagnari,[120] M. D'Alfonso,[120] T. Danielson,[120] K. Flowers,[120] P. Geffert,[120] J. Incandela,[120] C. Justus,[120] P. Kalavase,[120] S. A. Koay,[120] D. Kovalskyi,[120] V. Krutelyov,[120] S. Lowette,[120] N. Mccoll,[120] V. Pavlunin,[120] F. Rebassoo,[120] J. Ribnik,[120] J. Richman,[120] R. Rossin,[120] D. Stuart,[120] W. To,[120] C. West,[120] A. Apresyan,[121]

A. Bornheim,[121] Y. Chen,[121] E. Di Marco,[121] J. Duarte,[121] M. Gataullin,[121] Y. Ma,[121] A. Mott,[121] H. B. Newman,[121] C. Rogan,[121] M. Spiropulu,[121,e] V. Timciuc,[121] J. Veverka,[121] R. Wilkinson,[121] Y. Yang,[121] R. Y. Zhu,[121] B. Akgun,[122] V. Azzolini,[122] R. Carroll,[122] T. Ferguson,[122] Y. Iiyama,[122] D. W. Jang,[122] Y. F. Liu,[122] M. Paulini,[122] H. Vogel,[122] I. Vorobiev,[122] J. P. Cumalat,[123] B. R. Drell,[123] C. J. Edelmaier,[123] W. T. Ford,[123] A. Gaz,[123] B. Heyburn,[123] E. Luiggi Lopez,[123] J. G. Smith,[123] K. Stenson,[123] K. A. Ulmer,[123] S. R. Wagner,[123] J. Alexander,[124] A. Chatterjee,[124] N. Eggert,[124] L. K. Gibbons,[124] B. Heltsley,[124] A. Khukhunaishvili,[124] B. Kreis,[124] N. Mirman,[124] G. Nicolas Kaufman,[124] J. R. Patterson,[124] A. Ryd,[124] E. Salvati,[124] W. Sun,[124] W. D. Teo,[124] J. Thom,[124] J. Thompson,[124] J. Tucker,[124] J. Vaughan,[124] Y. Weng,[124] L. Winstrom,[124] P. Wittich,[124] D. Winn,[125] S. Abdullin,[126] M. Albrow,[126] J. Anderson,[126] L. A. T. Bauerdick,[126] A. Beretvas,[126] J. Berryhill,[126] P. C. Bhat,[126] I. Bloch,[126] K. Burkett,[126] J. N. Butler,[126] V. Chetluru,[126] H. W. K. Cheung,[126] F. Chlebana,[126] V. D. Elvira,[126] I. Fisk,[126] J. Freeman,[126] Y. Gao,[126] D. Green,[126] O. Gutsche,[126] J. Hanlon,[126] R. M. Harris,[126] J. Hirschauer,[126] B. Hooberman,[126] S. Jindariani,[126] M. Johnson,[126] U. Joshi,[126] B. Kilminster,[126] B. Klima,[126] S. Kunori,[126] S. Kwan,[126] C. Leonidopoulos,[126] J. Linacre,[126] D. Lincoln,[126] R. Lipton,[126] J. Lykken,[126] K. Maeshima,[126] J. M. Marraffino,[126] S. Maruyama,[126] D. Mason,[126] P. McBride,[126] K. Mishra,[126] S. Mrenna,[126] Y. Musienko,[126,aaa] C. Newman-Holmes,[126] V. O'Dell,[126] O. Prokofyev,[126] E. Sexton-Kennedy,[126] S. Sharma,[126] W. J. Spalding,[126] L. Spiegel,[126] P. Tan,[126] L. Taylor,[126] S. Tkaczyk,[126] N. V. Tran,[126] L. Uplegger,[126] E. W. Vaandering,[126] R. Vidal,[126] J. Whitmore,[126] W. Wu,[126] F. Yang,[126] F. Yumiceva,[126] J. C. Yun,[126] D. Acosta,[127] P. Avery,[127] D. Bourilkov,[127] M. Chen,[127] T. Cheng,[127] S. Das,[127] M. De Gruttola,[127] G. P. Di Giovanni,[127] D. Dobur,[127] A. Drozdetskiy,[127] R. D. Field,[127] M. Fisher,[127] Y. Fu,[127] I. K. Furic,[127] J. Gartner,[127] J. Hugon,[127] B. Kim,[127] J. Konigsberg,[127] A. Korytov,[127] A. Kropivnitskaya,[127] T. Kypreos,[127] J. F. Low,[127] K. Matchev,[127] P. Milenovic,[127,bbb] G. Mitselmakher,[127] L. Muniz,[127] R. Remington,[127] A. Rinkevicius,[127] P. Sellers,[127] N. Skhirtladze,[127] M. Snowball,[127] J. Yelton,[127] M. Zakaria,[127] V. Gaultney,[128] S. Hewamanage,[128] L. M. Lebolo,[128] S. Linn,[128] P. Markowitz,[128] G. Martinez,[128] J. L. Rodriguez,[128] T. Adams,[129] A. Askew,[129] J. Bochenek,[129] J. Chen,[129] B. Diamond,[129] S. V. Gleyzer,[129] J. Haas,[129] S. Hagopian,[129] V. Hagopian,[129] M. Jenkins,[129] K. F. Johnson,[129] H. Prosper,[129] V. Veeraraghavan,[129] M. Weinberg,[129] M. M. Baarmand,[130] B. Dorney,[130] M. Hohlmann,[130] H. Kalakhety,[130] I. Vodopiyanov,[130] M. R. Adams,[131] I. M. Anghel,[131] L. Apanasevich,[131] Y. Bai,[131] V. E. Bazterra,[131] R. R. Betts,[131] I. Bucinskaite,[131] J. Callner,[131] R. Cavanaugh,[131] C. Dragoiu,[131] O. Evdokimov,[131] L. Gauthier,[131] C. E. Gerber,[131] D. J. Hofman,[131] S. Khalatyan,[131] F. Lacroix,[131] M. Malek,[131] C. O'Brien,[131] C. Silkworth,[131] D. Strom,[131] N. Varelas,[131] U. Akgun,[132] E. A. Albayrak,[132] B. Bilki,[132,ccc] W. Clarida,[132] F. Duru,[132] S. Griffiths,[132] J.-P. Merlo,[132] H. Mermerkaya,[132,ddd] A. Mestvirishvili,[132] A. Moeller,[132] J. Nachtman,[132] C. R. Newsom,[132] E. Norbeck,[132] Y. Onel,[132] F. Ozok,[132] S. Sen,[132] E. Tiras,[132] J. Wetzel,[132] T. Yetkin,[132] K. Yi,[132] B. A. Barnett,[133] B. Blumenfeld,[133] S. Bolognesi,[133] D. Fehling,[133] G. Giurgiu,[133] A. V. Gritsan,[133] Z. J. Guo,[133] G. Hu,[133] P. Maksimovic,[133] S. Rappoccio,[133] M. Swartz,[133] A. Whitbeck,[133] P. Baringer,[134] A. Bean,[134] G. Benelli,[134] O. Grachov,[134] R. P. Kenny Iii,[134] M. Murray,[134] D. Noonan,[134] S. Sanders,[134] R. Stringer,[134] G. Tinti,[134] J. S. Wood,[134] V. Zhukova,[134] A. F. Barfuss,[135] T. Bolton,[135] I. Chakaberia,[135] A. Ivanov,[135] S. Khalil,[135] M. Makouski,[135] Y. Maravin,[135] S. Shrestha,[135] I. Svintradze,[135] J. Gronberg,[136] D. Lange,[136] D. Wright,[136] A. Baden,[137] M. Boutemeur,[137] B. Calvert,[137] S. C. Eno,[137] J. A. Gomez,[137] N. J. Hadley,[137] R. G. Kellogg,[137] M. Kirn,[137] T. Kolberg,[137] Y. Lu,[137] M. Marionneau,[137] A. C. Mignerey,[137] K. Pedro,[137] A. Peterman,[137] A. Skuja,[137] J. Temple,[137] M. B. Tonjes,[137] S. C. Tonwar,[137] E. Twedt,[137] A. Apyan,[138] G. Bauer,[138] J. Bendavid,[138] W. Busza,[138] E. Butz,[138] I. A. Cali,[138] M. Chan,[138] V. Dutta,[138] G. Gomez Ceballos,[138] M. Goncharov,[138] K. A. Hahn,[138] Y. Kim,[138] M. Klute,[138] K. Krajczar,[138,eee] W. Li,[138] P. D. Luckey,[138] T. Ma,[138] S. Nahn,[138] C. Paus,[138] D. Ralph,[138] C. Roland,[138] G. Roland,[138] M. Rudolph,[138] G. S. F. Stephans,[138] F. Stöckli,[138] K. Sumorok,[138] K. Sung,[138] D. Velicanu,[138] E. A. Wenger,[138] R. Wolf,[138] B. Wyslouch,[138] S. Xie,[138] M. Yang,[138] Y. Yilmaz,[138] A. S. Yoon,[138] M. Zanetti,[138] S. I. Cooper,[139] B. Dahmes,[139] A. De Benedetti,[139] G. Franzoni,[139] A. Gude,[139] S. C. Kao,[139] K. Klapoetke,[139] Y. Kubota,[139] J. Mans,[139] N. Pastika,[139] R. Rusack,[139] M. Sasseville,[139] A. Singovsky,[139] N. Tambe,[139] J. Turkewitz,[139] L. M. Cremaldi,[140] R. Kroeger,[140] L. Perera,[140] R. Rahmat,[140] D. A. Sanders,[140] E. Avdeeva,[141] K. Bloom,[141] S. Bose,[141] J. Butt,[141] D. R. Claes,[141] A. Dominguez,[141] M. Eads,[141] J. Keller,[141] I. Kravchenko,[141] J. Lazo-Flores,[141] H. Malbouisson,[141] S. Malik,[141] G. R. Snow,[141] U. Baur,[142] A. Godshalk,[142] I. Iashvili,[142] S. Jain,[142] A. Kharchilava,[142] A. Kumar,[142] S. P. Shipkowski,[142] K. Smith,[142] G. Alverson,[143] E. Barberis,[143] D. Baumgartel,[143] M. Chasco,[143] J. Haley,[143] D. Nash,[143] D. Trocino,[143] D. Wood,[143] J. Zhang,[143] A. Anastassov,[144] A. Kubik,[144] N. Mucia,[144] N. Odell,[144] R. A. Ofierzynski,[144] B. Pollack,[144] A. Pozdnyakov,[144] M. Schmitt,[144]

S. Stoynev,[144] M. Velasco,[144] S. Won,[144] L. Antonelli,[145] D. Berry,[145] A. Brinkerhoff,[145] M. Hildreth,[145] C. Jessop,[145] D. J. Karmgard,[145] J. Kolb,[145] K. Lannon,[145] W. Luo,[145] S. Lynch,[145] N. Marinelli,[145] D. M. Morse,[145] T. Pearson,[145] R. Ruchti,[145] J. Slaunwhite,[145] N. Valls,[145] M. Wayne,[145] M. Wolf,[145] B. Bylsma,[146] L. S. Durkin,[146] C. Hill,[146] R. Hughes,[146] R. Hughes,[146] K. Kotov,[146] T. Y. Ling,[146] D. Puigh,[146] M. Rodenburg,[146] C. Vuosalo,[146] G. Williams,[146] B. L. Winer,[146] N. Adam,[147] E. Berry,[147] P. Elmer,[147] D. Gerbaudo,[147] V. Halyo,[147] P. Hebda,[147] J. Hegeman,[147] A. Hunt,[147] P. Jindal,[147] D. Lopes Pegna,[147] P. Lujan,[147] D. Marlow,[147] T. Medvedeva,[147] M. Mooney,[147] J. Olsen,[147] P. Piroué,[147] X. Quan,[147] A. Raval,[147] B. Safdi,[147] H. Saka,[147] D. Stickland,[147] C. Tully,[147] J. S. Werner,[147] A. Zuranski,[147] J. G. Acosta,[148] E. Brownson,[148] X. T. Huang,[148] A. Lopez,[148] H. Mendez,[148] S. Oliveros,[148] J. E. Ramirez Vargas,[148] A. Zatserklyaniy,[148] E. Alagoz,[149] V. E. Barnes,[149] D. Benedetti,[149] G. Bolla,[149] D. Bortoletto,[149] M. De Mattia,[149] A. Everett,[149] Z. Hu,[149] M. Jones,[149] O. Koybasi,[149] M. Kress,[149] A. T. Laasanen,[149] N. Leonardo,[149] V. Maroussov,[149] P. Merkel,[149] D. H. Miller,[149] N. Neumeister,[149] I. Shipsey,[149] D. Silvers,[149] A. Svyatkovskiy,[149] M. Vidal Marono,[149] H. D. Yoo,[149] J. Zablocki,[149] Y. Zheng,[149] S. Guragain,[150] N. Parashar,[150] A. Adair,[151] C. Boulahouache,[151] K. M. Ecklund,[151] F. J. M. Geurts,[151] B. P. Padley,[151] R. Redjimi,[151] J. Roberts,[151] J. Zabel,[151] B. Betchart,[152] A. Bodek,[152] Y. S. Chung,[152] R. Covarelli,[152] P. de Barbaro,[152] R. Demina,[152] Y. Eshaq,[152] A. Garcia-Bellido,[152] P. Goldenzweig,[152] J. Han,[152] A. Harel,[152] D. C. Miner,[152] D. Vishnevskiy,[152] M. Zielinski,[152] A. Bhatti,[153] R. Ciesielski,[153] L. Demortier,[153] K. Goulianos,[153] G. Lungu,[153] S. Malik,[153] C. Mesropian,[153] S. Arora,[154] A. Barker,[154] J. P. Chou,[154] C. Contreras-Campana,[154] E. Contreras-Campana,[154] D. Duggan,[154] D. Ferencek,[154] Y. Gershtein,[154] R. Gray,[154] E. Halkiadakis,[154] D. Hidas,[154] A. Lath,[154] S. Panwalkar,[154] M. Park,[154] R. Patel,[154] V. Rekovic,[154] J. Robles,[154] K. Rose,[154] S. Salur,[154] S. Schnetzer,[154] C. Seitz,[154] S. Somalwar,[154] R. Stone,[154] S. Thomas,[154] G. Cerizza,[155] M. Hollingsworth,[155] S. Spanier,[155] Z. C. Yang,[155] A. York,[155] R. Eusebi,[156] W. Flanagan,[156] J. Gilmore,[156] T. Kamon,[156,fff] V. Khotilovich,[156] R. Montalvo,[156] I. Osipenkov,[156] Y. Pakhotin,[156] A. Perloff,[156] J. Roe,[156] A. Safonov,[156] T. Sakuma,[156] S. Sengupta,[156] I. Suarez,[156] A. Tatarinov,[156] D. Toback,[156] N. Akchurin,[157] J. Damgov,[157] P. R. Dudero,[157] C. Jeong,[157] K. Kovitanggoon,[157] S. W. Lee,[157] T. Libeiro,[157] Y. Roh,[157] I. Volobouev,[157] E. Appelt,[158] A. G. Delannoy,[158] C. Florez,[158] S. Greene,[158] A. Gurrola,[158] W. Johns,[158] C. Johnston,[158] P. Kurt,[158] C. Maguire,[158] A. Melo,[158] M. Sharma,[158] P. Sheldon,[158] B. Snook,[158] S. Tuo,[158] J. Velkovska,[158] M. W. Arenton,[159] M. Balazs,[159] S. Boutle,[159] B. Cox,[159] B. Francis,[159] J. Goodell,[159] R. Hirosky,[159] A. Ledovskoy,[159] C. Lin,[159] C. Neu,[159] J. Wood,[159] R. Yohay,[159] S. Gollapinni,[160] R. Harr,[160] P. E. Karchin,[160] C. Kottachchi Kankanamge Don,[160] P. Lamichhane,[160] A. Sakharov,[160] M. Anderson,[161] M. Bachtis,[161] D. Belknap,[161] L. Borrello,[161] D. Carlsmith,[161] M. Cepeda,[161] S. Dasu,[161] E. Friis,[161] L. Gray,[161] K. S. Grogg,[161] M. Grothe,[161] R. Hall-Wilton,[161] M. Herndon,[161] A. Hervé,[161] P. Klabbers,[161] J. Klukas,[161] A. Lanaro,[161] C. Lazaridis,[161] J. Leonard,[161] R. Loveless,[161] A. Mohapatra,[161] I. Ojalvo,[161] F. Palmonari,[161] G. A. Pierro,[161] I. Ross,[161] A. Savin,[161] W. H. Smith,[161] and J. Swanson[161]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12]*Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*Technical University of Split, Split, Croatia*

[19]University of Split, Split, Croatia
[20]Institute Rudjer Boskovic, Zagreb, Croatia
[21]University of Cyprus, Nicosia, Cyprus
[22]Charles University, Prague, Czech Republic
[23]Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
[24]National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
[25]Department of Physics, University of Helsinki, Helsinki, Finland
[26]Helsinki Institute of Physics, Helsinki, Finland
[27]Lappeenranta University of Technology, Lappeenranta, Finland
[28]DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
[29]Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
[30]Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
[31]Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
[32]Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
[33]Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
[34]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[35]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[36]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[37]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[38]University of Hamburg, Hamburg, Germany
[39]Institut für Experimentelle Kernphysik, Karlsruhe, Germany
[40]Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
[41]University of Athens, Athens, Greece
[42]University of Ioánnina, Ioánnina, Greece
[43]KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
[44]Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[45]University of Debrecen, Debrecen, Hungary
[46]Panjab University, Chandigarh, India
[47]University of Delhi, Delhi, India
[48]Saha Institute of Nuclear Physics, Kolkata, India
[49]Bhabha Atomic Research Centre, Mumbai, India
[50]Tata Institute of Fundamental Research—EHEP, Mumbai, India
[51]Tata Institute of Fundamental Research—HECR, Mumbai, India
[52]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[53a]INFN Sezione di Bari, Bari, Italy
[53b]Università di Bari, Bari, Italy
[53c]Politecnico di Bari, Bari, Italy
[54a]INFN Sezione di Bologna, Bologna, Italy
[54b]Università di Bologna, Bologna, Italy
[55a]INFN Sezione di Catania, Catania, Italy
[55b]Università di Catania, Catania, Italy
[56a]INFN Sezione di Firenze, Firenze, Italy
[56b]Università di Firenze, Firenze, Italy
[57]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[58a]INFN Sezione di Genova, Genova, Italy
[58b]Università di Genova, Genova, Italy
[59a]INFN Sezione di Milano-Bicocca, Milano, Italy
[59b]Università di Milano-Bicocca, Milano, Italy
[60a]INFN Sezione di Napoli, Napoli, Italy
[60b]Università di Napoli "Federico II", Napoli, Italy
[61a]INFN Sezione di Padova, Padova, Italy
[61b]Università di Padova, Padova, Italy
[61c]Università di Trento (Trento), Padova, Italy
[62a]INFN Sezione di Pavia, Pavia, Italy
[62b]Università di Pavia, Pavia, Italy
[63a]INFN Sezione di Perugia, Perugia, Italy
[63b]Università di Perugia, Perugia, Italy
[64a]INFN Sezione di Pisa, Pisa, Italy
[64b]Università di Pisa, Pisa, Italy

[64c]Scuola Normale Superiore di Pisa, Pisa, Italy
[65a]INFN Sezione di Roma, Roma, Italy
[65b]Università di Roma "La Sapienza", Roma, Italy
[66a]INFN Sezione di Torino, Torino, Italy
[66b]Università di Torino, Torino, Italy
[66c]Università del Piemonte Orientale (Novara), Torino, Italy
[67a]INFN Sezione di Trieste, Trieste, Italy
[67b]Università di Trieste, Trieste, Italy
[68]Kangwon National University, Chunchon, Korea
[69]Kyungpook National University, Daegu, Korea
[70]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[71]Korea University, Seoul, Korea
[72]University of Seoul, Seoul, Korea
[73]Sungkyunkwan University, Suwon, Korea
[74]Vilnius University, Vilnius, Lithuania
[75]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[76]Universidad Iberoamericana, Mexico City, Mexico
[77]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[78]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[79]University of Auckland, Auckland, New Zealand
[80]University of Canterbury, Christchurch, New Zealand
[81]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[82]National Centre for Nuclear Research, Swierk, Poland
[83]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[84]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[85]Joint Institute for Nuclear Research, Dubna, Russia
[86]Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
[87]Institute for Nuclear Research, Moscow, Russia
[88]Institute for Theoretical and Experimental Physics, Moscow, Russia
[89]Moscow State University, Moscow, Russia
[90]P.N. Lebedev Physical Institute, Moscow, Russia
[91]State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
[92]University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[93]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[94]Universidad Autónoma de Madrid, Madrid, Spain
[95]Universidad de Oviedo, Oviedo, Spain
[96]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[97]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[98]Paul Scherrer Institut, Villigen, Switzerland
[99]Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
[100]Universität Zürich, Zurich, Switzerland
[101]National Central University, Chung-Li, Taiwan
[102]National Taiwan University (NTU), Taipei, Taiwan
[103]Cukurova University, Adana, Turkey
[104]Middle East Technical University, Physics Department, Ankara, Turkey
[105]Bogazici University, Istanbul, Turkey
[106]Istanbul Technical University, Istanbul, Turkey
[107]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[108]University of Bristol, Bristol, United Kingdom
[109]Rutherford Appleton Laboratory, Didcot, United Kingdom
[110]Imperial College, London, United Kingdom
[111]Brunel University, Uxbridge, United Kingdom
[112]Baylor University, Waco, Texas, USA
[113]The University of Alabama, Tuscaloosa, Alabama, USA
[114]Boston University, Boston, Massachusetts, USA
[115]Brown University, Providence, Rhode Island, USA
[116]University of California, Davis, Davis, California, USA
[117]University of California, Los Angeles, Los Angeles, California, USA
[118]University of California, Riverside, Riverside, California, USA
[119]University of California, San Diego, La Jolla, California, USA
[120]University of California, Santa Barbara, Santa Barbara, California, USA

[121]*California Institute of Technology, Pasadena, California, USA*
[122]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[123]*University of Colorado at Boulder, Boulder, Colorado, USA*
[124]*Cornell University, Ithaca, New York, USA*
[125]*Fairfield University, Fairfield, Connecticut, USA*
[126]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[127]*University of Florida, Gainesville, Florida, USA*
[128]*Florida International University, Miami, Florida, USA*
[129]*Florida State University, Tallahassee, Florida, USA*
[130]*Florida Institute of Technology, Melbourne, Florida, USA*
[131]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[132]*The University of Iowa, Iowa City, Iowa, USA*
[133]*Johns Hopkins University, Baltimore, Maryland, USA*
[134]*The University of Kansas, Lawrence, Kansas, USA*
[135]*Kansas State University, Manhattan, Kansas, USA*
[136]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[137]*University of Maryland, College Park, Maryland, USA*
[138]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[139]*University of Minnesota, Minneapolis, Minnesota, USA*
[140]*University of Mississippi, Oxford, Mississippi, USA*
[141]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[142]*State University of New York at Buffalo, Buffalo, New York, USA*
[143]*Northeastern University, Boston, Massachusetts, USA*
[144]*Northwestern University, Evanston, Illinois, USA*
[145]*University of Notre Dame, Notre Dame, Indiana, USA*
[146]*The Ohio State University, Columbus, Ohio, USA*
[147]*Princeton University, Princeton, New Jersey, USA*
[148]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[149]*Purdue University, West Lafayette, Indiana, USA*
[150]*Purdue University Calumet, Hammond, Indiana, USA*
[151]*Rice University, Houston, Texas, USA*
[152]*University of Rochester, Rochester, New York, USA*
[153]*The Rockefeller University, New York, New York, USA*
[154]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[155]*University of Tennessee, Knoxville, Tennessee, USA*
[156]*Texas A&M University, College Station, Texas, USA*
[157]*Texas Tech University, Lubbock, Texas USA*
[158]*Vanderbilt University, Nashville, Tennessee, USA*
[159]*University of Virginia, Charlottesville, Virginia, USA*
[160]*Wayne State University, Detroit, Michigan, USA*
[161]*University of Wisconsin, Madison, Wisconsin, USA*

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[d]Also at Universidade Federal do ABC, Santo Andre, Brazil.
[e]Also at California Institute of Technology, Pasadena, California, USA.
[f]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[g]Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[h]Also at Suez Canal University, Suez, Egypt.
[i]Also at Zewail City of Science and Technology, Zewail, Egypt.
[j]Also at Cairo University, Cairo, Egypt.
[k]Also at Fayoum University, El-Fayoum, Egypt.
[l]Also at British University, Cairo, Egypt.
[m]Also at Ain Shams University, Cairo, Egypt.
[n]Also at National Centre for Nuclear Research, Swierk, Poland.
[o]Also at Université de Haute-Alsace, Mulhouse, Strasbourg, France.
[p]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[q]Also at Moscow State University, Moscow, Russia.

[r]Also at Brandenburg University of Technology, Cottbus, Germany.
[s]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[t]Also at Eötvös Loránd University, Budapest, Hungary.
[u]Also at Tata Institute of Fundamental Research—HECR, Mumbai, India.
[v]Also at University of Visva-Bharati, Santiniketan, India.
[w]Also at Sharif University of Technology, Tehran, Iran.
[x]Also at Isfahan University of Technology, Isfahan, Iran.
[y]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[z]Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
[aa]Also at Università della Basilicata, Potenza, Italy.
[bb]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[cc]Also at Università degli Studi di Siena, Siena, Italy.
[dd]Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
[ee]Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[ff]Also at University of California, Los Angeles, Los Angeles, California, USA
[gg]Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.
[hh]Also at INFN Sezione di Roma, Università di Roma ''La Sapienza'', Roma, Italy.
[ii]Also at University of Athens, Athens, Greece.
[jj]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[kk]Also at The University of Kansas, Lawrence, Kansas, USA.
[ll]Also at Paul Scherrer Institut, Villigen, Switzerland.
[mm]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[nn]Also at Gaziosmanpasa University, Tokat, Turkey.
[oo]Also at Adiyaman University, Adiyaman, Turkey.
[pp]Also at Izmir Institute of Technology, Izmir, Turkey.
[qq]Also at The University of Iowa, Iowa City, Iowa, USA.
[rr]Also at Mersin University, Mersin, Turkey.
[ss]Also at Ozyegin University, Istanbul, Turkey.
[tt]Also at Kafkas University, Kars, Turkey.
[uu]Also at Suleyman Demirel University, Isparta, Turkey.
[vv]Also at Ege University, Izmir, Turkey.
[ww]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[xx]Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
[yy]Also at University of Sydney, Sydney, Australia.
[zz]Also at Utah Valley University, Orem, Utah, USA.
[aaa]Also at Institute for Nuclear Research, Moscow, Russia.
[bbb]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[ccc]Also at Argonne National Laboratory, Argonne, Illinois, USA.
[ddd]Also at Erzincan University, Erzincan, Turkey.
[eee]Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[fff]Also at Kyungpook National University, Daegu, Korea.