

Search for exclusive or semi-exclusive $\gamma\gamma$ production and observation of exclusive and semi-exclusive e^+e^- production in pp collisions at $\sqrt{s} = 7$ TeV



The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: A search for exclusive or semi-exclusive $\gamma\gamma$ production, $pp \rightarrow p^{(*)} + \gamma\gamma + p^{(*)}$ (where p^* stands for a diffractively-dissociated proton), and the observation of exclusive and semi-exclusive e^+e^- production, $pp \rightarrow p^{(*)} + e^+e^- + p^{(*)}$, in proton-proton collisions at $\sqrt{s} = 7$ TeV, are presented. The analysis is based on a data sample corresponding to an integrated luminosity of 36 pb^{-1} recorded by the CMS experiment at the LHC at low instantaneous luminosities. Candidate $\gamma\gamma$ or e^+e^- events are selected by requiring the presence of two photons or a positron and an electron, each with transverse energy $E_T > 5.5$ GeV and pseudorapidity $|\eta| < 2.5$, and no other particles in the region $|\eta| < 5.2$. No exclusive or semi-exclusive diphoton candidates are found in the data. An upper limit on the cross section for the reaction $pp \rightarrow p^{(*)} + \gamma\gamma + p^{(*)}$, within the above kinematic selections, is set at 1.18 pb at 95% confidence level. Seventeen exclusive or semi-exclusive dielectron candidates are observed, with an estimated background of 0.85 ± 0.28 (stat.) events, in agreement with the QED-based prediction of 16.3 ± 1.3 (syst.) events.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

In central exclusive (hereafter referred to as “exclusive”, for brevity) production in pp collisions, $pp \rightarrow p+X+p$, the colliding protons emerge intact from the interaction, carrying small transverse momentum ($\lesssim 2$ GeV), and all the energy transferred from the protons goes into a color-singlet system at central rapidities. No other particles are produced aside from the central system, and large rapidity gaps, i.e. wide regions of rapidity devoid of particles, are present. The three main types of exclusive processes are due to $\gamma\gamma$ interactions (e.g. exclusive e^+e^- or $\mu^+\mu^-$ production [1]), $\gamma\mathbb{P}$ fusion (e.g. exclusive Υ production [2]) and $\mathbb{P}\mathbb{P}$ exchange (e.g. exclusive $\gamma\gamma$ or Higgs boson production [3]), where \mathbb{P} denotes the pomeron, a strongly interacting color-singlet t -channel exchange with the vacuum quantum numbers [4, 5].

At the Large Hadron Collider (LHC), exclusive $\gamma\gamma$ (hereafter referred to as “diphoton”) events can be produced by means of $\mathbb{P}\mathbb{P}$ exchange, interpreted in partonic terms as $gg \rightarrow \gamma\gamma$

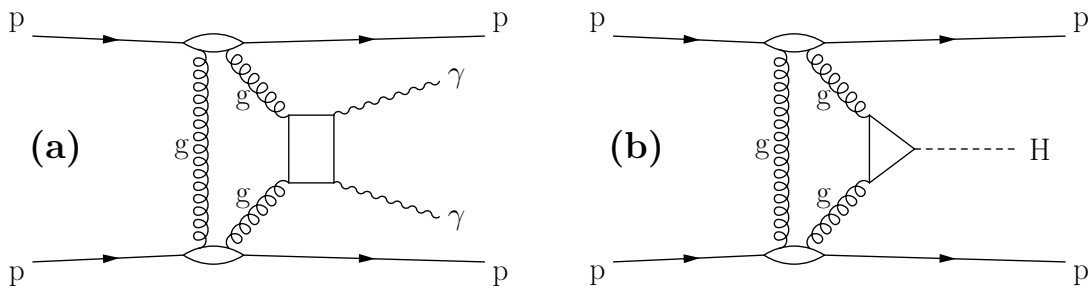


Figure 1. The dominant diagrams for (a) exclusive diphoton production and (b) exclusive Higgs boson production in pp collisions. Note the screening gluon that cancels the color flow from the interacting gluons and therefore allows the protons to stay intact. For exclusive $\gamma\gamma$ production, the contributions from $q\bar{q} \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow \gamma\gamma$ are both theoretically estimated to be less than 1% of $gg \rightarrow \gamma\gamma$ [6].

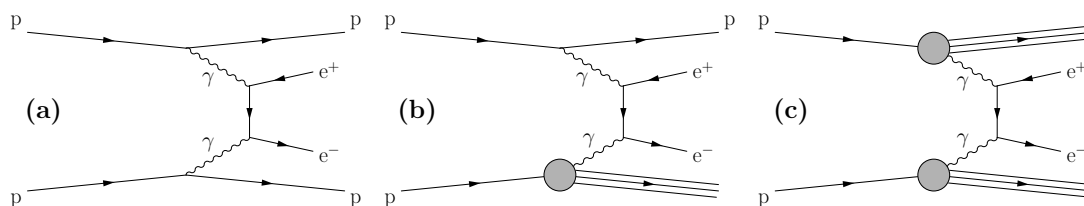


Figure 2. The Feynman diagrams for (a) exclusive e^+e^- production and semi-exclusive e^+e^- production with (b) either or (c) both protons dissociating in pp collisions.

via a quark loop, with an additional “screening” gluon exchanged to cancel the color of the interacting gluons, as shown in figure 1(a). The quantum chromodynamics (QCD) calculation of this diagram is difficult because the screening gluon has low four-momentum-transfer squared, Q^2 . Furthermore, additional inelastic interactions between the protons may produce particles that destroy the rapidity gaps; this effect is taken into account by introducing the so-called rapidity-gap survival probability [7], which is poorly known theoretically. The study of exclusive diphoton production may shed light on diffraction and the dynamics of pomeron exchange. In addition, exclusive diphoton production is closely related to exclusive Higgs boson production (figure 1(b)), where the Higgs boson is produced via gg fusion dominantly through a top-quark loop [8–15]. Since the QCD part of the calculation, from which most theoretical uncertainties originate, is the same for H and $\gamma\gamma$ production, and only the calculable matrix elements $gg \rightarrow \gamma\gamma$ and $gg \rightarrow H$ are different, exclusive $\gamma\gamma$ production provides an excellent test of the theoretical predictions for exclusive Higgs boson production.

Exclusive e^+e^- (hereafter referred to as “dielectron”) production via $\gamma\gamma$ interactions is a quantum electrodynamics (QED) process (figure 2(a)), and the cross section is known with an accuracy better than about 1%; the uncertainty is dominated by that on the proton electromagnetic form factor [16–18]. Detailed theoretical studies have shown that in this case the correction due to the rapidity-gap survival probability is well below 1% and can be safely neglected [19]. Exclusive e^+e^- events provide an excellent control sample for other exclusive processes with less certain theoretical predictions, such as exclusive $\gamma\gamma$ production.

Semi-exclusive $\gamma\gamma$ and e^+e^- production, involving single- or double-proton dissociation (figures 2(b) and 2(c) for the dielectron case), is also considered as signal in this analysis, as long as no particles from the proton dissociation have pseudorapidity $|\eta| < 5.2$. The pseudorapidity η is defined as $\eta = -\ln(\tan \frac{\theta}{2})$, where θ is the polar angle. This process has larger theoretical uncertainties. In the rest of this paper, exclusive events will be referred to as “el-el” events, while semi-exclusive events with either or both protons dissociated will be referred to as “inel-el” and “inel-inel” events, respectively. The term “non-exclusive events” will be used to indicate all other events with two photons or two electrons and additional activity.

Results on exclusive $\gamma\gamma$ production in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV were obtained by the CDF collaboration [20, 21], and the measured cross sections are consistent with the KMR [22] predictions. The CDF experiment also measured the exclusive e^+e^- and $\mu^+\mu^-$ production cross sections [23–25], and the results are in agreement with theory. Exclusive $\mu^+\mu^-$ production, which proceeds via the same mechanisms as exclusive e^+e^- production, was also measured by the Compact Muon Solenoid (CMS) experiment in pp collisions at $\sqrt{s} = 7$ TeV [26], and the result agrees with the QED-based prediction.

This paper presents a search for exclusive or semi-exclusive $\gamma\gamma$ production, and the observation of exclusive and semi-exclusive e^+e^- production in pp collisions at $\sqrt{s} = 7$ TeV. Since any other inelastic pp collision occurring in the same bunch crossing as the exclusive interaction (“pileup” events) would destroy the rapidity gaps and make the exclusive interaction unobservable, only a data sample with low pileup contamination is used. The data sample was collected in 2010 by the CMS experiment at the LHC, and corresponds to an integrated luminosity of 36 pb^{-1} . The signal diphoton or dielectron event selection requires the presence of two photons or two electrons of opposite charge, each with transverse energy $E_T > 5.5 \text{ GeV}$ and pseudorapidity $|\eta| < 2.5$, and no other particles in the region $|\eta| < 5.2$. The two photons or electrons are expected to be balanced in E_T ($\Delta E_T \sim 0$) and to be back-to-back in azimuthal angle ϕ ($\Delta\phi \sim \pi$), a consequence of the very small Q^2 of the exchanged pomerons or photons.

2 The CMS detector

A detailed description of the CMS detector can be found in ref. [27]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors made by using three technologies: drift tubes (DT), cathode strip chambers (CSC), and resistive plate chambers. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, ϕ , is measured

in the x - y plane. The inner tracker measures charged particle trajectories with transverse momentum p_T from less than 100 MeV, and within the pseudorapidity range $|\eta| < 2.5$. The ECAL provides coverage in the pseudorapidity range $|\eta| < 1.479$ in the barrel region (EB) and $1.479 < |\eta| < 3.0$ in the two endcap regions (EE). The HCAL provides coverage for $|\eta| < 1.3$ in the barrel region (HB) and $1.3 < |\eta| < 3.0$ in the two endcap regions (HE). The two hadronic forward calorimeters (HF) cover the region of $2.9 < |\eta| < 5.2$. The CMS experiment selects data by using a two-level trigger system. The first level consists of custom hardware processors and uses information from the calorimeters and muon systems. The high-level trigger processor farm further decreases the event rate before data storage.

3 Simulation and reconstruction

The ExHUME 1.34 Monte Carlo (MC) event generator [28] is used to simulate exclusive diphoton events and to calculate their production cross section σ . The ExHUME package is an implementation of the KMR model [22]. In this model, the two gluons couple perturbatively to the protons, and produce the $\gamma\gamma$ system through a quark loop. The calculation includes the Sudakov factor, which accounts for the probability that no partons are emitted by the interacting gluons in the evolution up to the hard scale. The cross section is further suppressed by the rapidity-gap survival probability. A variety of parton distribution function (PDF) sets have been used, so as to assess the sensitivity of the cross section calculation to the low- x gluon density $g(x)$ ($\sigma \sim [g(x)]^4$, where x is the gluon fractional momentum) [29], which changes significantly in different PDF sets. Semi-exclusive diphoton production is not well known theoretically, and is not simulated in this analysis.

The LPAIR 4.0 event generator [30] is used to simulate both exclusive and semi-exclusive e^+e^- events and to calculate their production cross sections. For exclusive events, the cross section depends on the proton electromagnetic form factor. In the case of proton dissociation, the cross section calculation requires the knowledge of the proton structure function and the rapidity-gap survival probability. The latter is not included in LPAIR and is taken as 1 in this analysis. In order to simulate the fragmentation of the excited protons, LPAIR is interfaced to the JETSET 7.408 package [31], where the LUND fragmentation model [32] is implemented.

The generated events are further processed through a detailed simulation of the CMS detector based on GEANT4 [33] and are reconstructed in the same way as the collision data.

Photon candidates are reconstructed [34] from clusters of ECAL channels around significant energy deposits, which are merged into so-called superclusters. The clustering algorithm results in an almost complete recovery of the energy of photons converting in the material in front of the ECAL. In the barrel region, superclusters are formed from 5-crystal-wide strips in η centered on the locally most energetic crystal (seed), and have a variable extension in ϕ (up to ± 17 crystals from the seed). In the endcap, matrices of 5×5 crystals (which may partially overlap) around the most energetic crystals are merged if they lie within a narrow road in η ($\Delta\eta = 0.14$, $\Delta\phi = 0.6$ rad).

The reconstruction of electrons [35] combines the ECAL and inner-tracker information. It starts with clusters of energy deposits in the ECAL, which include the energy due to

electron-induced electromagnetic showers and that of the bremsstrahlung photons emitted along the electron trajectory. The clusters drive the search for hits in the pixel detector, which are then used to seed electron tracks. This is complemented by the usage of the tracker for the seeding, to improve the reconstruction efficiency at low p_T and in the transition regions between the ECAL detector elements. Trajectories in the tracker volume are reconstructed by using a dedicated model of the electron energy loss, and are fitted with a Gaussian sum filter (GSF) [35]. The four-momenta of electrons are obtained by using the angle from the associated GSF track and the energy from the combination of the tracker and ECAL information.

4 Event selection

The selection of signal events proceeds in three steps. Exactly two photons or two electrons of opposite charge, each with $E_T > 5.5$ GeV and $|\eta| < 2.5$, are required to be present in the triggered events. Then, the events are required to satisfy the cosmic-ray rejection criteria. Finally, the exclusivity selection is performed, based on the information from the tracker, the electromagnetic calorimeter, the hadron calorimeter, and the muon chambers; this selection requires no additional particles reconstructed in these subdetectors, and thus suppresses the contribution from semi-exclusive events and rejects non-exclusive events as well as pileup events.

4.1 Photon and electron selection

Both diphoton and dielectron candidate events were selected online by two different triggers corresponding to two subsequent data acquisition periods. Both triggers required the presence of two electromagnetic showers with $E_T > 5$ GeV. In the second data acquisition period with higher instantaneous luminosities, the two showers were also required to be separated in azimuthal angle by at least 2.5 rad, and a low-activity requirement of less than 10 hadronic towers with energy above 5 GeV and $|\eta| < 5.2$ was applied.

The first offline selection step is to require the presence of exactly two photon candidates or two electron candidates of opposite charge, each with $E_T > 5.5$ GeV and $|\eta| < 2.5$, for the diphoton and the dielectron analyses, respectively. These photon or electron candidates are subsequently required to satisfy the identification criteria described below.

For photons, the energy detected in the HCAL behind the photon cluster is required to be less than 2% of the ECAL energy, and the ECAL cluster-shape parameter [34] is required to be consistent with that of a photon. The photons are required to be isolated from other activity in the detector. The isolation parameter is defined as the scalar sum of the transverse energies of tracks or calorimeter deposits within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ of the direction of the photon, after excluding the contribution from the candidate itself. The isolation parameter is required to be less than $0.001 \times E_T + 1.0$ GeV, $0.006 \times E_T + 2.5$ GeV, and $0.0025 \times E_T + 2.0$ GeV for the tracker, ECAL, and HCAL, respectively, where E_T is the photon transverse energy in GeV. The absence of any hit patterns in the pixel tracker consistent with those of an electron track is also required in order to discriminate photons

from electrons. No explicit attempt is made to distinguish between photons and neutral pions when the showers of the two decay photons merge.

For electrons, the same requirements on the HCAL energy and the cluster shape are applied as in the photon case. The ratio between the isolation parameter described above (but with $\Delta R = 0.3$) and the electron p_T is required to be less than 0.05, 0.3, and 0.2 (barrel) or 0.1 (endcap), for the tracker, ECAL, and HCAL, respectively. The difference between the azimuthal angle of the cluster and that of the direction of the electron track at its vertex is required to be less than 0.3 rad; the corresponding difference in pseudorapidity is required to be less than 0.02 (EB) or 0.03 (EE). The number of missing hits in front of the first valid hit of the electron track is required to be ≤ 1 in order to reject electrons from photon conversions.

4.2 Cosmic-ray rejection

In order to remove cosmic-ray events, the timing of the two photons or electrons, as measured by the ECAL, is required to be consistent with that of particles originating from a collision, i.e. $|t_1| < 2$ ns, $|t_2| < 2$ ns, and $|t_1 - t_2| < 2$ ns, where t_i is the timing of the i -th photon or electron. Furthermore, the two photon or electron candidates are required to be separated by more than 2.5 rad in ϕ , in order to reject the remaining cosmic-ray events in which the cosmic ray is far away from the interaction point in the x - y plane.

4.3 Exclusivity selection

Exclusivity selection criteria are designed to reject events with particles in the range $|\eta| < 5.2$ not associated with the two photon or electron candidates. More specifically, it is required that there should be no additional tracks in the tracker, no additional towers above the noise thresholds in the calorimeters (EB, EE, HB, HE, and HF), and no track segments in the DTs and CSCs. An additional track is defined as any track outside a region of $\Delta\eta < 0.15$ and $\Delta\phi < 0.7$ rad of the photons or the electrons. An additional tower in the EB is defined as a tower above the noise threshold and outside a region of $\Delta\eta < 0.15$ and $\Delta\phi < 0.7$ rad of the photons or the electrons, while in the EE the region is $\Delta\eta < 0.15$ and $\Delta\phi < 0.4$ rad. An additional tower in the HB, HE, and HF is defined as any tower above the noise thresholds. The noise thresholds are determined from non-interaction events. The values of the noise thresholds are 0.52 GeV, 2.18 GeV, 1.18 GeV, 1.95 GeV, and 9.0 GeV for the EB, EE, HB, HE, and HF, respectively, and are applied in energy rather than E_T .

The numbers of diphoton and dielectron candidates in the data sample remaining after each selection step are listed in table 1.

5 Efficiencies

The overall selection efficiency ε is defined as $\varepsilon = \varepsilon_{\gamma\gamma(e+e-)} \cdot \varepsilon_{\text{cos}} \cdot \varepsilon_{\text{fsr}} \cdot \varepsilon_{\text{exc}}$, where $\varepsilon_{\gamma\gamma(e+e-)}$ is the efficiency for identifying the two photons or electrons; ε_{cos} is the efficiency for a signal event to pass the cosmic-ray rejection criteria; ε_{fsr} is the probability for a signal event not to be rejected by the exclusivity selection criteria because of final-state radiation; and ε_{exc}

Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Table 1. Numbers of diphoton and dielectron candidates remaining after each selection step.

is the probability for a signal event not to be rejected by the exclusivity selection criteria because of pileup, calorimeter noise, or beam background.

5.1 Photon and electron efficiency

The diphoton efficiency $\varepsilon_{\gamma\gamma}$ is split into three parts: the reconstruction efficiency $\varepsilon_{\text{reco}}$, the identification efficiency ε_{id} , and the trigger efficiency $\varepsilon_{\text{trig}}$, i.e. $\varepsilon_{\gamma\gamma} = \varepsilon_{\gamma\gamma, \text{reco}} \cdot \varepsilon_{\gamma, \text{id}}^2 \cdot \varepsilon_{\gamma\gamma, \text{trig}}$. The reconstruction and trigger efficiencies are both denoted by the subscript “ $\gamma\gamma$ ”, rather than just “ γ ”, to reflect the fact that these efficiencies must be calculated per event, rather than per photon, due to the strong E_T and ϕ correlations between the two photons (balanced in E_T and back-to-back in ϕ). All these efficiencies are calculated by using signal MC samples. The systematic uncertainty of the reconstruction efficiency is evaluated by shifting the E_T threshold by $\pm 5\%$, motivated by the energy scale uncertainty for low- E_T photons and electrons. The systematic uncertainty of the identification efficiency is evaluated by shifting the thresholds of the identification parameters by $\pm 10\%$. The systematic uncertainty of the trigger efficiency is estimated from the difference of the single-photon trigger efficiency calculated from interaction (minimum-bias) events in the data and in the MC samples. A summary of the photon efficiencies for exclusive diphoton events is listed in table 2.

For the dielectron analysis, the same procedure as in the diphoton analysis is used to determine the electron efficiencies and the corresponding systematic uncertainties. The results are listed in table 2 for both exclusive and semi-exclusive e^+e^- events.

5.2 Cosmic-ray rejection efficiency

For exclusive $\gamma\gamma$ and e^+e^- events, since the efficiency for the requirement of $\Delta\phi > 2.5$ rad is 100%, the cosmic-ray rejection efficiency ε_{cos} is equal to the efficiency for the timing requirements mentioned in section 4.2. This efficiency is determined by applying the timing requirements to a data sample of $J/\psi \rightarrow e^+e^-$ events with invariant mass $3.0 < M(e^+e^-) < 3.2$ GeV, which has a negligible cosmic-ray contamination. This yields $\varepsilon_{\text{cos}} = 0.979 \pm 0.009$ for exclusive $\gamma\gamma$ and e^+e^- events. The quoted systematic uncertainty is evaluated by shifting the thresholds of the timing requirements by $\pm 5\%$, motivated by the uncertainty of the timing measurement of less than 100 ps. For semi-exclusive e^+e^- events, the efficiency

Diphoton analysis		Dielectron analysis			
			el-el	inel-el	inel-inel
$\varepsilon_{\gamma\gamma, \text{reco}}$	0.724 ± 0.087	$\varepsilon_{e^+e^-, \text{reco}}$	0.606 ± 0.055	0.663 ± 0.050	0.683 ± 0.045
$\varepsilon_{\gamma, \text{id}}$	0.941 ± 0.003	$\varepsilon_{e, \text{id}}$	0.967 ± 0.005	0.966 ± 0.005	0.960 ± 0.005
$\varepsilon_{\gamma\gamma, \text{trig}}$	0.757 ± 0.050	$\varepsilon_{e^+e^-, \text{trig}}$	0.655 ± 0.024	0.708 ± 0.018	0.683 ± 0.013
$\varepsilon_{\gamma\gamma}$	0.485 ± 0.067	$\varepsilon_{e^+e^-}$	0.371 ± 0.037	0.438 ± 0.035	0.430 ± 0.030

Table 2. Summary of the photon and electron efficiencies with systematic uncertainties.

for the $\Delta\phi$ requirement is determined from MC to be 0.858 and 0.701 for inel-el and inel-inel events, respectively. A correction factor of 0.979 and 0.932 is subsequently applied for inel-el and inel-inel e^+e^- events in order to take into account the $\Delta\phi$ requirement at the trigger level. The cosmic-ray rejection efficiency for inel-el and inel-inel e^+e^- events is then estimated to be 0.822 ± 0.008 and 0.639 ± 0.006 , respectively.

5.3 Final-state-radiation efficiency

As a consequence of the exclusivity requirements, signal diphoton events with either or both photons converting into e^+e^- pairs, as well as events that produce electrons in the tracker detector by Compton scattering, are vetoed if there are energy deposits above the noise thresholds outside the regions defined in section 4.3. The corresponding efficiency is the final-state-radiation efficiency ε_{fsr} , and is estimated by applying the exclusivity selection criteria to simulated signal events. The systematic uncertainty is evaluated by shifting the noise thresholds of the exclusivity selection criteria by the energy scale uncertainty for each subdetector. The uncertainty due to the tracker-material budget is negligible and is evaluated by using a set of realistic tracker-material modifications [36] in the simulation.

Likewise, for both exclusive and semi-exclusive dielectron production, if a final-state electron emits a high-energy bremsstrahlung photon, the event is vetoed by the exclusivity selection criteria. For the semi-exclusive case, the probability that a semi-exclusive event is not vetoed because of the particles from the proton dissociation is also folded into this efficiency, which results in a much lower final-state-radiation efficiency than for the exclusive case. The same procedure as in the diphoton analysis is used to determine the efficiencies and the uncertainties due to the energy scale. For the semi-exclusive case, the additional uncertainty coming from the proton fragmentation model is dominant, and is evaluated by using different programs to simulate the dissociation of the excited protons. The programs considered are PHOJET 1.12 [37, 38], PYTHIA 6.422 [39], PYTHIA 8.142 [40], and PYTHIA 8.165 with MBR [41].

5.4 Exclusivity efficiency

The exclusivity efficiency is the probability that a signal event is not rejected by the exclusivity selection criteria because of pileup, calorimeter noise, or beam background in the same bunch crossing, and is determined by using zero-bias events. Zero-bias events

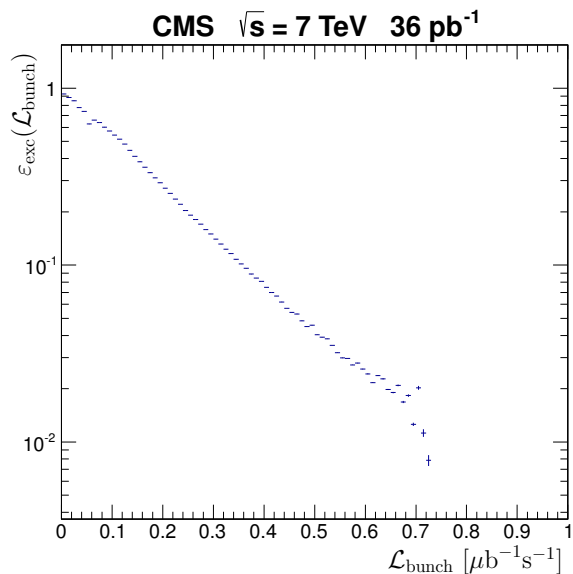


Figure 3. Exclusivity efficiency as a function of the bunch-by-bunch luminosity.

are those triggered solely on the bunch-crossing time. Since the number of inelastic proton-proton interactions in a given bunch crossing follows a Poisson distribution and the exclusivity efficiency is approximately equal to the probability of having no inelastic collision, the exclusivity efficiency is an exponential function of the bunch-by-bunch instantaneous luminosity:

$$\varepsilon_{\text{exc}}(\mathcal{L}_{\text{bunch}}) = \frac{N_{\text{zero-bias}}^{\text{exc}}(\mathcal{L}_{\text{bunch}})}{N_{\text{zero-bias}}(\mathcal{L}_{\text{bunch}})} \approx e^{-\bar{n}} = e^{-\mathcal{L}_{\text{bunch}} \cdot \sigma_{\text{inelastic}}/f}$$

where $N_{\text{zero-bias}}^{(\text{exc})}$ is the number of zero-bias events with (exc) or without the exclusivity requirements, \bar{n} is the average number of inelastic interactions per bunch crossing for a given bunch-by-bunch luminosity $\mathcal{L}_{\text{bunch}}$, and $f = 11\,246$ Hz is the LHC revolution frequency. The exclusivity efficiency is shown in figure 3 as a function of the bunch-by-bunch luminosity, calculated with a zero-bias data sample taken during the same data acquisition period as that of the signal sample.

The average exclusivity efficiency is calculated by using the following equation [23]:

$$\varepsilon_{\text{exc}} = \frac{\int \frac{dN_{\text{zero-bias}}}{d\mathcal{L}_{\text{bunch}}} \cdot \mathcal{L}_{\text{bunch}} \cdot \varepsilon_{\text{exc}}(\mathcal{L}_{\text{bunch}}) \cdot d\mathcal{L}_{\text{bunch}}}{\int \frac{dN_{\text{zero-bias}}}{d\mathcal{L}_{\text{bunch}}} \cdot \mathcal{L}_{\text{bunch}} \cdot d\mathcal{L}_{\text{bunch}}}$$

where the weight $\mathcal{L}_{\text{bunch}}$ in the integrations reflects the fact that the probability of a process taking place in a given bunch crossing is proportional to the corresponding bunch-by-bunch luminosity. The average exclusivity efficiency is $\varepsilon_{\text{exc}} = 0.145 \pm 0.008$, where the uncertainty is evaluated by varying the noise thresholds of the exclusivity selection criteria by $\pm 5\%$. This efficiency is dominated by the losses due to pileup.

Table 3 lists a summary of the efficiencies for both the diphoton and the dielectron analyses.

Diphoton analysis		Dielectron analysis			
			el-el	inel-el	inel-inel
$\varepsilon_{\gamma\gamma}$	0.485 ± 0.067	$\varepsilon_{e^+e^-}$	0.371 ± 0.037	0.438 ± 0.035	0.430 ± 0.030
ε_{cos}	0.979 ± 0.009	ε_{cos}	0.979 ± 0.009	0.822 ± 0.008	0.639 ± 0.006
ε_{fsr}	0.972 ± 0.005	ε_{fsr}	0.927 ± 0.005	0.666 ± 0.049	0.299 ± 0.041
ε_{exc}	0.143 ± 0.008	ε_{exc}	0.143 ± 0.008	0.143 ± 0.008	0.143 ± 0.008
ε	0.0660 ± 0.0099	ε	0.0481 ± 0.0055	0.0343 ± 0.0042	0.0117 ± 0.0019

Table 3. Summary of the efficiencies for both the diphoton and the dielectron analyses. The quoted uncertainties are systematic.

6 Backgrounds

For diphoton production, the following background processes are considered: non-exclusive events, exclusive e^+e^- production, cosmic-ray events, and exclusive $\pi^0\pi^0$ production.

The non-exclusive background consists of non-exclusive events with particles passing through the cracks between the calorimeter elements, or with energy deposits below the noise thresholds, so that they appear exclusive. In order to estimate the amount of this background, the two-dimensional distribution of the numbers of additional tracks and additional towers for diphoton events, with all selection criteria applied except the exclusivity requirements, is fitted and then extrapolated to the signal region, i.e. the bin with no additional tracks or towers. This yields a non-exclusive background of 1.68 ± 0.40 events.

Exclusive e^+e^- events can be misidentified as diphoton events if neither electron track is reconstructed or both electrons undergo hard bremsstrahlung. This contribution is estimated by assuming a single-electron misidentification probability of 8%, as determined from simulated exclusive e^+e^- events, for the 17 e^+e^- candidates found in the data (table 1), which results in a background of 0.11 ± 0.03 events.

The background from cosmic-ray events is evaluated by measuring the density of cosmic-ray events outside the signal region described in section 4.2 and then extrapolating that density into the signal region. This results in a probability of 0.46% that a diphoton candidate is due to a cosmic ray.

Exclusive $\pi^0\pi^0$ production ($\pi^0 \rightarrow \gamma\gamma$) [42] can be a background to diphoton production if the two pions are both misidentified as photons. A simulation carried out with the SUPERCHIC 1.41 event generator [43] is used to calculate the cross section and derive the selection efficiency. Fewer than 10^{-4} exclusive diphoton candidates are expected to originate from $\pi^0\pi^0$ events. Therefore, the background from exclusive $\pi^0\pi^0$ production, even with conservative theoretical uncertainties, is negligible. The background from exclusive pair production of other mesons, e.g. $pp \rightarrow p + \eta\eta + p$ ($\eta \rightarrow \gamma\gamma$), is also estimated to be negligible because of the low production cross sections (which are similar to that of exclusive $\pi^0\pi^0$ production). Exclusive $\gamma\pi^0$ or $\gamma\eta$ production is forbidden by C-parity conservation. Exclusive single-meson production, e.g. $pp \rightarrow p + \eta + p \rightarrow p + \gamma\gamma + p$, is completely removed

Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive $\Upsilon(1S,2S,3S) \rightarrow e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28

Table 4. Background event yields expected for both the diphoton and the dielectron analyses. The quoted uncertainties are statistical.

by the requirement $E_T(\gamma) > 5.5 \text{ GeV}$, complemented by $\Delta\phi(\gamma\gamma) > 2.5 \text{ rad}$, which selects events with $M(\gamma\gamma) \gtrsim 11 \text{ GeV}$.

For dielectron production, the following background processes are considered: non-exclusive events, exclusive Υ production, cosmic-ray events, and exclusive $\pi^+\pi^-$ production.

The non-exclusive background is estimated by using the distribution of the numbers of additional tracks and additional towers for dielectron events with all selection criteria applied except the exclusivity requirements, after subtracting the contributions from both exclusive and semi-exclusive e^+e^- production expected from the simulation. This background is estimated to be of 0.80 ± 0.28 events.

The background from exclusive Υ production via γIP fusion ($\gamma\text{IP} \rightarrow \Upsilon(1S,2S,3S) \rightarrow e^+e^-$) [2] is completely removed by the $E_T > 5.5 \text{ GeV}$ requirement on the electrons, which corresponds to $M(e^+e^-) \gtrsim 11 \text{ GeV}$, well above the $\Upsilon(3S)$ mass (10.36 GeV) even taking into account the e^+e^- mass resolution of $\sim 150 \text{ MeV}$.

The cosmic-ray background contamination, estimated with the same method as for the diphoton analysis, is 0.3%, i.e. 0.05 ± 0.01 events.

Exclusive $\pi^+\pi^-$ production via IPIP exchange [42] can be a background to e^+e^- production if the two pions are both misidentified as electrons. The cross section, calculated with SUPERCHIC, is less than 0.1% of that for exclusive e^+e^- production, which translates into a negligible background. This is consistent with the fact that no additional candidates are found, after removing the requirement of no HCAL energy behind the electron shower (a high-energy deposit in the HCAL is the signature of a pion).

A summary of the background processes for both the diphoton and the dielectron analyses is listed in table 4. The non-exclusive background is the largest contribution in both analyses.

7 Results

No diphoton events survive the selection criteria. An upper limit on the production cross section is set employing a CL_s approach [44, 45], taking into account the integrated lu-

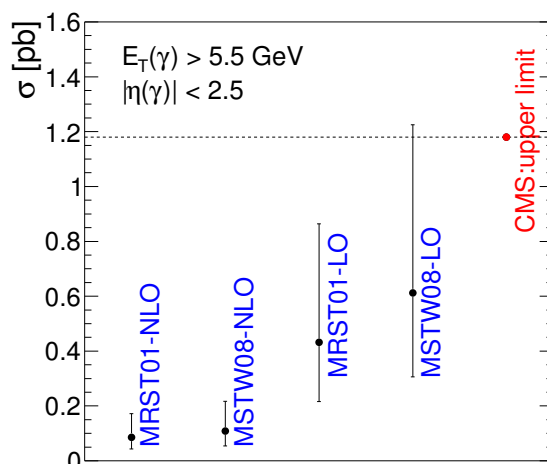


Figure 4. Comparison of the upper limit (at 95% CL) derived with the present data and four theoretical predictions. The upper limit is on the sum of the exclusive and semi-exclusive $\gamma\gamma$ production cross sections (where it is required that no particles from the proton dissociation have $|\eta| < 5.2$), while the theoretical predictions are for exclusive $\gamma\gamma$ production only. If the contributions from semi-exclusive production are included, the predictions increase by a factor of ~ 2 [49].

minosity, the selection efficiency, the background contributions, and their uncertainties. A log-normal prior is used for the integration over the nuisance parameters. This gives an upper limit on the production cross section at 95% confidence level (CL):

$$\sigma(E_T(\gamma) > 5.5 \text{ GeV}, |\eta(\gamma)| < 2.5) < 1.18 \text{ pb.}$$

The upper limit is on the sum of the exclusive (el-el) and semi-exclusive (inel-el and inel-inel) $\gamma\gamma$ production cross sections, with no particles from the proton dissociation having $|\eta| < 5.2$ for the semi-exclusive case. Figure 4 shows the comparison between the present upper limit and the predicted cross sections (el-el only) calculated with the ExHUME generator. Two different PDF sets, MRST01 [46, 47] and MSTW08 [48], from both leading-order (LO) and next-to-leading-order (NLO) fits, are considered. The difference between LO and NLO predictions reflects mostly the difference in the low- x gluon density. The uncertainties in these theoretical predictions (in addition to those due to the PDFs) are estimated to be a factor of about 2 [49], as shown in figure 4. The upper limit measured in this analysis is an order of magnitude above the predicted cross sections with NLO PDFs, while it provides some constraint on the predictions with LO PDFs. If the MSTW08-LO PDF is used, the probability of finding no candidate in the present data is less than 23%. The semi-exclusive $\gamma\gamma$ production cross section has larger theoretical uncertainties, but is expected to be of magnitude similar to that of the fully exclusive process [49].

Seventeen exclusive or semi-exclusive e^+e^- candidates are observed, with an expected background of 0.85 ± 0.28 (stat.) events, consistent with the theoretical prediction for the combined el-el, inel-el and inel-inel e^+e^- yield of 16.3 ± 1.3 (syst.) events (table 5). Figure 5 shows the comparison of the measured and simulated invariant-mass and p_T distributions of the e^+e^- pairs, while figure 6 shows that for the Δp_T and $\Delta\phi$ distributions. Both the

Process	\mathcal{L} (pb^{-1})	σ (pb)	ε	Yield (events)
el-el	36.2 ± 1.4	3.74	0.0481 ± 0.0055	6.51 ± 0.79 (syst.)
inel-el		6.68	0.0343 ± 0.0042	8.29 ± 1.07 (syst.)
inel-inel		3.52	0.0117 ± 0.0019	1.49 ± 0.25 (syst.)
Total				16.3 ± 1.3 (syst.)

Table 5. Predicted e^+e^- yields for both exclusive and semi-exclusive e^+e^- production. The relative uncertainty of the integrated luminosity \mathcal{L} is 4% [50]. The production cross sections σ are calculated with the LPAIR generator.

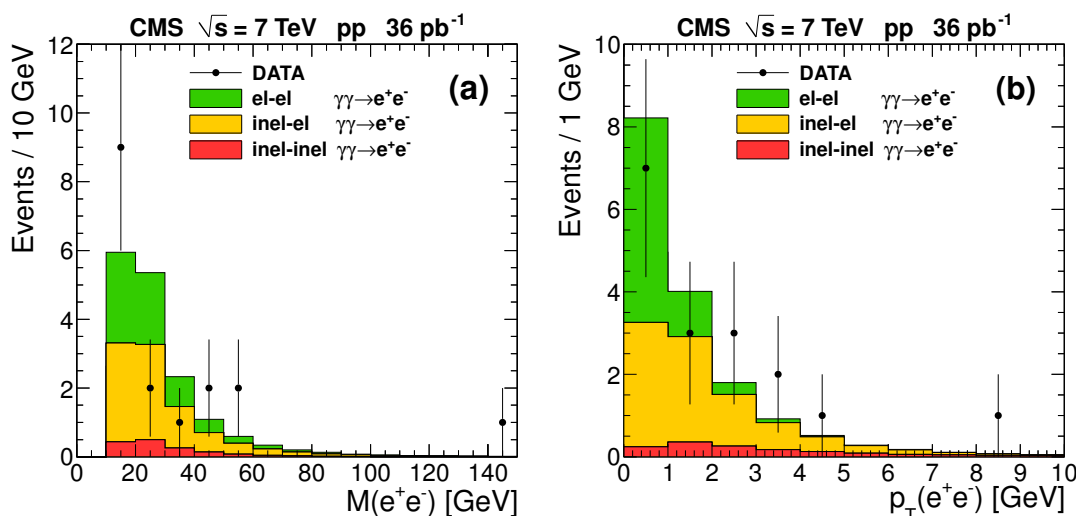


Figure 5. Distributions of (a) the invariant mass and (b) the transverse momentum of the e^+e^- pairs, compared to the LPAIR predictions (histograms) for the three processes contributing to exclusive and semi-exclusive $\gamma\gamma \rightarrow e^+e^-$ production, passed through the full detector simulation and reconstruction. The simulation is normalized to the integrated luminosity of the data sample (36 pb^{-1}), and does not include the estimated 0.85 ± 0.28 background events.

yield and the kinematic distributions are consistent with the assumption of exclusive and semi-exclusive e^+e^- production via the $\gamma\gamma \rightarrow e^+e^-$ process, which validates the analysis technique, notably the exclusivity selection.

8 Summary

A search for exclusive or semi-exclusive $\gamma\gamma$ production and the observation of exclusive and semi-exclusive e^+e^- production have been presented, based on a sample of pp collisions at $\sqrt{s} = 7 \text{ TeV}$ corresponding to an integrated luminosity of 36 pb^{-1} . Exclusive $\gamma\gamma$ production helps improve the understanding of diffraction and provides a test of the theoretical predictions for exclusive Higgs boson production. Exclusive e^+e^- production is dominantly a QED process and provides a means to check the selection procedure for other exclusive processes. No diphoton events satisfy the selection criteria. An upper limit on the cross

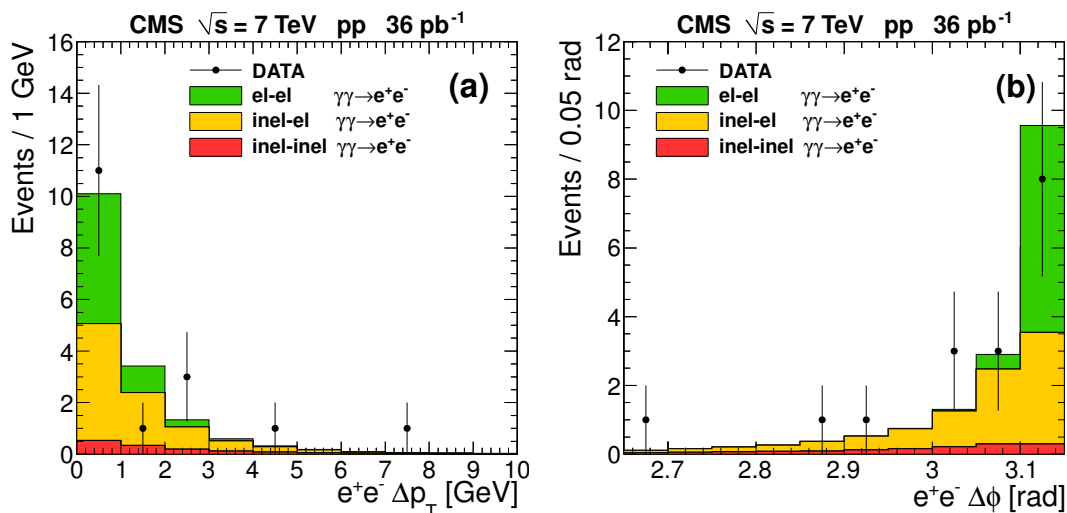


Figure 6. Distributions of the difference of (a) the transverse momentum and (b) the azimuthal angle of the e^+e^- pairs, compared to the LPAIR predictions (histograms) for the three processes contributing to exclusive and semi-exclusive $\gamma\gamma \rightarrow e^+e^-$ production, passed through the full detector simulation and reconstruction. The simulation is normalized to the integrated luminosity of the data sample (36 pb^{-1}), and does not include the estimated 0.85 ± 0.28 background events.

section for the exclusive reaction $pp \rightarrow p + \gamma\gamma + p$ and the corresponding semi-exclusive processes (in which either or both protons diffractively dissociate and no particles from the proton dissociation have $|\eta| < 5.2$), with $E_T(\gamma) > 5.5 \text{ GeV}$ and $|\eta(\gamma)| < 2.5$, is set at 1.18 pb at 95% confidence level. Using a similar technique, 17 exclusive or semi-exclusive e^+e^- candidates are observed, with an expected background of 0.85 ± 0.28 (stat.) events, consistent with the LPAIR prediction of 16.3 ± 1.3 (syst.) events. Both the number of candidates and the kinematic distributions are in agreement with the expectation for exclusive and semi-exclusive e^+e^- production via the $\gamma\gamma \rightarrow e^+e^-$ process.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

S. Basesmez, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

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

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

C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

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

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

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

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

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

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

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, FranceS. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France**

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**Z. Tsamalaidze¹⁵**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

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

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

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹⁶, J.R. Komaragiri, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas⁵, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

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

G. Bencze, C. Hajdu⁵, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

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

H. Arfaei, H. Bakhshiansohi²², S.M. Etesami²³, A. Fahim²², M. Hashemi, A. Jafari²², M. Khakzad, A. Mohammadi²⁴, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁵, M. Zeinali²³

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

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti, G. Zito^a

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

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, R. Travaglini^{a,b}

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

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

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropicano^{a,5}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁶, F. Fabbri, D. Piccolo

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

P. Fabbricatore^a, R. Musenich^a

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

A. Benaglia^{a,b,5}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^a, C.A. Carrillo Montoya^{a,5}, N. Cavallo^{a,27}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,27}, A.O.M. Iorio^a, L. Lista^a, S. Meola^{a,28}, M. Merola^{a,b}, P. Paolucci^{a,5}

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

P. Azzi^a, N. Bacchetta^{a,5}, D. Bisello^{a,b}, A. Branca^{a,b,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, M. Gulmini^{a,29}, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b,5}, S. Vanini^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

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

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

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

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,5}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, S. Taroni^{a,b,5}

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

P. Azzurri^{a,c}, G. Bagliesi^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b,5}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,30}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,31}, P. Spagnolo^a, P. Squillacioti^{a,5}, R. Tenchini^a, G. Tonelli^{a,b,5}, A. Venturi^{a,5}, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b,5}, M. Diemmoz^a, M. Grassi^{a,b,5}, E. Longo^{a,b}, P. Meridiani^{a,5}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b}, C. Mariotti^{a,5}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,5}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

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

S. Belforte^a, V. Candelise^{a,b}, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,5}, D. Montanino^{a,b,5}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

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

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

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

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

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

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

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

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

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

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

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilo, M. Kossov⁵, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic³², M. Djordjevic, M. Ekmedzic, D. Krpic³², J. Milosevic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³³, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Ro-

drigues Antunes, G. Rolandi³⁴, T. Rommerskirchen, C. Rovelli³⁵, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁶, D. Spiga, M. Spiropulu⁴, M. Stoye, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁷, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁸

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁹, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov⁴⁰, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴¹, S. Cerci⁴², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurbinar, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴³, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴², B. Tali⁴², H. Topakli⁴¹, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

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

Bogazici University, Istanbul, Turkey

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

Istanbul Technical University, Istanbul, Turkey

K. Cankocak

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁷, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴⁹, K.W. Bell, A. Belyaev⁴⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko⁴⁰, A. Papageorgiou, J. Pela⁵, M. Pesaresi, K. Petridis, M. Pioppi⁵⁰, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, C. Henderson, P. Rumerio

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵¹, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵², F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

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

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken,

K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵³, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁵, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁷, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen,

P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

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

Purdue University Calumet, Hammond, USA

S. Guragain, N. Parashar

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

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

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

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Dugan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, P.R. Duderov, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

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

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 3: Also at Universidade Federal do ABC, Santo Andre, Brazil
- 4: Also at California Institute of Technology, Pasadena, USA
- 5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at British University, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at National Centre for Nuclear Research, Swierk, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Shiraz University, Shiraz, Iran
- 25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 26: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 27: Also at Università della Basilicata, Potenza, Italy
- 28: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 29: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 30: Also at Università degli Studi di Siena, Siena, Italy
- 31: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania

- 32: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 33: Also at University of California, Los Angeles, Los Angeles, USA
- 34: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 35: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 36: Also at University of Athens, Athens, Greece
- 37: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 38: Also at The University of Kansas, Lawrence, USA
- 39: Also at Paul Scherrer Institut, Villigen, Switzerland
- 40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 41: Also at Gaziosmanpasa University, Tokat, Turkey
- 42: Also at Adiyaman University, Adiyaman, Turkey
- 43: Also at The University of Iowa, Iowa City, USA
- 44: Also at Mersin University, Mersin, Turkey
- 45: Also at Ozyegin University, Istanbul, Turkey
- 46: Also at Kafkas University, Kars, Turkey
- 47: Also at Suleyman Demirel University, Isparta, Turkey
- 48: Also at Ege University, Izmir, Turkey
- 49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 50: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 51: Also at University of Sydney, Sydney, Australia
- 52: Also at Utah Valley University, Orem, USA
- 53: Also at Institute for Nuclear Research, Moscow, Russia
- 54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 55: Also at Argonne National Laboratory, Argonne, USA
- 56: Also at Erzincan University, Erzincan, Turkey
- 57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- 58: Also at Kyungpook National University, Daegu, Korea