



# Search for leptophobic $Z'$ bosons decaying into four-lepton final states in proton–proton collisions at $\sqrt{s} = 8\text{ TeV}$



The CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 5 January 2017  
Received in revised form 30 April 2017  
Accepted 24 August 2017  
Available online 6 September 2017  
Editor: M. Doser

### Keywords:

LHC  
CMS  
Physics  
Exotica  
 $Z'$   
Four leptons

## ABSTRACT

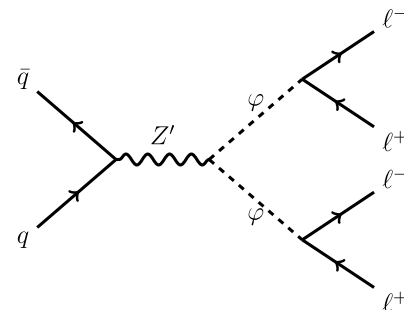
A search for heavy narrow resonances decaying into four-lepton final states has been performed using proton–proton collision data at  $\sqrt{s} = 8\text{ TeV}$  collected by the CMS experiment, corresponding to an integrated luminosity of  $19.7\text{ fb}^{-1}$ . No excess of events over the standard model background expectation is observed. Upper limits for a benchmark model on the product of cross section and branching fraction for the production of these heavy narrow resonances are presented. The limit excludes leptophobic  $Z'$  bosons with masses below  $2.5\text{ TeV}$  within the benchmark model. This is the first result to constrain a leptophobic  $Z'$  resonance in the four-lepton channel.

© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

Extensions of the standard model (SM) that incorporate one or more extra Abelian gauge groups predict the existence of one or more neutral gauge bosons [1,2]. These occur naturally in most grand unified theories. Heavy neutral bosons are also predicted in models with extra spatial dimensions [3,4], e.g. Randall–Sundrum models [5,6], where these resonances may arise from Kaluza–Klein excitations of a graviton. Searches for heavy neutral resonances at hadron colliders, and most recently at the CERN LHC, are typically performed using the dijet [7–10], dilepton [11–14], diphoton [15–17], diboson [18–24], and  $t\bar{t}$  [25–28] final states. The dilepton channel provides a clean signal compared with the dijet and  $t\bar{t}$  channels. However, in leptophobic  $Z'$  models, where the  $Z'$  does not couple to SM leptons, the dilepton limits are not applicable. Although searches based on the dijet final state remain applicable, they suffer from large dijet background produced by quantum chromodynamics (QCD) subprocesses. We extend the search for heavy neutral vector bosons by considering possible  $Z'$  decays into new particles predicted by various theoretical extensions of the SM.

In this Letter, we report on a search for a leptophobic  $Z'$  resonance that decays into four leptons via cascade decays as described



**Fig. 1.** Leading order Feynman diagram for the production and cascade decay of a  $Z'$  resonance to a four-lepton final state.

in Ref. [29]. In this model, the  $Z'$  is coupled to quark pairs but not to lepton pairs, and can be produced with a large cross section at the LHC. These non-standard  $Z'$  resonances also decay to pairs of new scalar bosons ( $\phi$ ) each of which subsequently decays to pairs of leptons ( $\phi \rightarrow \ell\ell'$ , where  $\ell$  and  $\ell' = e$  or  $\mu$ ). Fig. 1 shows the leading-order Feynman diagram for the production of four-lepton final states via a  $Z'$  resonance at a hadron collider. The reconstruction of the  $\phi$  bosons in the dilepton channel is inefficient if the difference between  $Z'$  and  $\phi$  masses is large and the two daughter leptons are consequently highly collimated. In the following sections we describe a technique to increase the selection efficiency.

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

The analysis is a search for heavy narrow resonances decaying into four isolated final state leptons. The benchmark model [29] assumes ( $\Gamma/M < 1\%$ ), corresponding to a natural width of the  $Z'$  resonance that is much smaller than the detector resolution. The following final states are considered:  $\mu\mu\mu\mu$ ,  $\mu\mu\mu e$ ,  $\mu\mu ee$ ,  $\mu eee$ , and  $eeee$ . The  $\mu\mu ee$ ,  $\mu\mu\mu e$  and  $\mu eee$  channels are included to allow for the possibility of lepton flavor violation (LFV) [30–32] in the decays of the new scalar bosons. In this Letter, we set limits on the product of the cross section and branching fraction for production and decay to four leptons, and interpret the results in the context of the benchmark model described above [29].

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Each detector is composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

Muons are measured in the range  $|\eta| < 2.4$  with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100$  GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The  $p_T$  resolution in the barrel is better than 10% for muons with  $p_T$  up to 1 TeV [33].

The ECAL consists of 75 848 crystals that provide coverage in pseudorapidity  $|\eta| < 1.48$  in a barrel region (EB) and  $1.48 < |\eta| < 3.00$  in two endcap regions (EE). The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with transverse momentum  $p_T \approx 45$  GeV from  $Z \rightarrow e^+e^-$  decays ranges from 1.7% for nonshowering electrons (approximately 30%) in the barrel region to 4.5% for showering electrons (approximately 60%) in the endcaps [34].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [35].

## 3. The simulated event samples

The Monte Carlo (MC) generator program used to produce the simulated event samples for the benchmark model is CALCHEP 3.4.1 [36] interfaced with PYTHIA 6.4.24 [37]. These samples are divided into five decay channels ( $\mu\mu\mu\mu$ ,  $\mu\mu\mu e$ ,  $\mu\mu ee$ ,  $\mu eee$ ,  $eeee$ ) for different  $Z'$  boson masses ( $m_{Z'}$ ) ranging from 250 to 3000 GeV in increments of 250 GeV. The benchmark model assumes that new particles other than  $Z'$  and  $\phi$  are heavy enough not to affect the production and decay of the  $Z'$  boson. Signal MC samples are produced with six different values of the  $\phi$  mass ( $m_\phi$ ), with  $m_\phi = 50$  GeV used as the reference mass value in the interpretation of the results. An important feature of this analysis is the presence of a “boosted signature” associated with the collimation of the two leptons coming from the same parent particle and resulting from the large difference between  $m_{Z'}$  and  $m_\phi$ . In addition, samples are generated with  $m_\phi$  masses of 5, 10, 20, 30 and 40% of  $m_{Z'}$ , for which, in most cases, the contribution from the boosted signature is less important. The product of the leading order (LO) signal cross section and branching fraction in each channel varies with  $m_{Z'}$  (from 250 to 3000 GeV) as follows:  $\mu\mu\mu\mu$  and  $eeee$

from 0.8 pb to  $3.0 \times 10^{-6}$  pb,  $\mu\mu ee$  from 12.3 pb to  $4.7 \times 10^{-5}$  pb, and  $\mu\mu\mu e$  and  $\mu eee$  from 3.1 pb to  $1.2 \times 10^{-5}$  pb. The branching fraction of  $\phi \rightarrow \ell\ell'$  is set to 1 and therefore only the leptonic decay channels are considered. These signal MC samples are used to optimize event selection, evaluate signal efficiencies and calculate exclusion limits.

The dominant SM background is the production of ZZ decaying into four leptons. The  $q\bar{q}$ -induced ZZ production is generated using the PYTHIA event generator and the gg-induced production using the GG2ZZ program [38]. Additional backgrounds from diboson production (WW and WZ) are generated with PYTHIA, and from top quark production ( $t\bar{t}$ ,  $tW$ , and  $\bar{t}W$ ) are generated with POWHEG 1.0 [39]. Other processes, such as  $t\bar{t}Z$  and triboson production ( $WW\gamma$ ,  $WWZ$ ,  $WZZ$ , and  $ZZZ$ ), are generated with MADGRAPH 5.1.3.30 [40]. Simulated event samples are normalized using the integrated luminosity and higher order theoretical cross sections: next-to-next-to-leading order for  $t\bar{t}$  [41] and next-to-leading order for ZZ [42] and the other backgrounds.

The MC samples are generated using the CTEQ6L [43] set of parton distribution functions (PDFs) and the PYTHIA Z2\* tune [44,45] in order to model the proton structure and the underlying event. The samples are then processed with the full CMS detector simulation software, based on GEANT4 [46,47], which includes trigger simulation and event reconstruction.

## 4. Event selection

The 2012 data set of proton–proton collisions at  $\sqrt{s} = 8$  TeV, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ , is used for the analysis. Data are collected with lepton triggers with various  $p_T$  thresholds. The trigger used for the muon-enriched channels ( $\mu\mu\mu\mu$ ,  $\mu\mu\mu e$ ) requires the presence of at least one muon candidate with  $p_T > 40$  GeV and  $|\eta| < 2.1$ . The trigger used for the electron-enriched channels ( $\mu eee$ ,  $eeee$ ) requires two clusters of energy deposits in the ECAL with transverse energy  $E_T > 33$  GeV each. For the  $\mu\mu ee$  channel, the trigger requires both an electron and a muon with  $p_T > 22$  GeV.

In the subsequent analysis, events are required to contain a reconstructed primary vertex (PV) with at least four associated tracks, and its  $r(z)$  coordinates are required to be within 2(24) cm of the nominal interaction point. The PV is defined as the vertex with the highest sum of  $p_T^2$  for the associated tracks. We select the events with four leptons in the final state, where the leptons are identified by the selection criteria described below. The two leading leptons are required to have  $p_T > 45$  GeV to ensure that the trigger is fully efficient for the selected events. This requirement has a negligible effect on the signal acceptance. The two subleading leptons are required to have  $p_T > 30$  GeV. This choice balances loss of efficiency against increased misidentification probability. All four leptons must satisfy  $|\eta| < 2.4$ . No charge requirement is applied to the lepton selection.

Muon candidates are reconstructed by a combined fit including hits in both tracking and muon detectors (“global muons”) [33]. The tracks associated with global muons are required to have the following properties: at least one pixel detector hit, at least six strip tracker layers with hits, at least one muon chamber hit, at least two muon detector planes with muon segments, a transverse impact parameter of the tracker track  $|d_{xy}| < 0.2$  cm with respect to the PV, a longitudinal distance of the tracker track  $|d_z| < 0.5$  cm with respect to the PV, and  $\delta p_T/p_T < 0.3$  where  $\delta p_T$  is the uncertainty in the measured  $p_T$  of the track. All muon candidates are required to be isolated. A muon is considered isolated if the scalar  $p_T$  sum of all tracks within a cone of  $\Delta R < 0.3$  around the muon, excluding the muon candidate itself, does not exceed 10% of the

muon  $p_T$ , where  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ . If there is a second lepton candidate within a cone  $\Delta R < 0.3$ , we remove its contribution.

An electron candidate is identified by matching a cluster in the ECAL to a track in the silicon tracker [34]. Identification criteria are applied to suppress jets misidentified as electrons. Electrons are required to pass the following criteria: the profile of energy deposition in the ECAL should be consistent with an electron, the sum of HCAL energy deposits behind the ECAL cluster should be less than 10% of the associated ECAL deposit, the track associated with the cluster should have no more than one hit missing in the pixel detector layers and  $|d_{xy}|$  should be less than 0.02 cm with respect to the selected PV. All electron candidates are required to be isolated using the following definition: within a cone  $\Delta R < 0.3$  around the track of the electron candidate, the  $p_T$  sum of all other tracks is required to be less than 5 GeV and the  $E_T$  sum of the energies of the calorimeter deposits that are not associated with the candidate is required to be less than 5% of the candidate's  $E_T$ . This differs from the isolation requirement of 3% in Ref. [13], because of the inefficiency (of approximately 6% at electron  $E_T = 1$  TeV) caused by overlapping electrons due to the high Lorentz boost of the  $\varphi$  boson ( $m_\varphi = 50$  GeV). In addition, if the direction of the second lepton candidate falls within the isolation cone of the first ( $\Delta R < 0.3$ ), the contributions it makes to both  $p_T$  and  $E_T$  are subtracted when imposing the isolation requirements.

The kinematic distributions of the final-state particles are similar for all five channels. The final state consists of two leading leptons with high  $p_T$  and two subleading leptons with relatively low  $p_T$ . The two leptons from the same parent  $\varphi$  boson can be highly Lorentz boosted if  $m_\varphi$  is significantly smaller than  $m_{Z'}$ . This feature is generally found for high-mass ( $m_{Z'} > 1$  TeV) samples in the case of  $m_\varphi = 50$  GeV. This boosted signature introduces a significant inefficiency for the event selection except for the LFV case ( $\varphi$  decaying into  $e\mu$ ). To take into account the boosted signature for  $\varphi$  decaying into  $\mu\mu$ , one of the muon candidates selected by the above criteria is allowed to be reconstructed only as a tracker muon, a track in the tracker matched to track segments in the muon system (“tracker muons”) [33], if the two muons are as close as  $\Delta R < 0.4$ . In such exceptional cases, the requirements of at least one muon chamber hit and at least two muon detector planes with muon segments are not applied to the tracker muon.

The boosted signature for a  $\varphi$  decaying into  $ee$  is much more complicated since the electrons can easily merge into a single cluster in the ECAL. In this case, only one electron candidate is reconstructed from the two original electrons. The probability for having a merged candidate is about 50% with  $m_{Z'} = 3$  TeV and  $m_\varphi = 50$  GeV. These events would be rejected by the four-lepton requirement, introducing a large signal inefficiency. To select such events, an electron candidate having a ratio of ECAL cluster energy to track momentum larger than 1.5 and a second track with  $p_T > 30$  GeV within a cone of  $\Delta R(\text{electron, track}) < 0.25$ , is considered as a “merged electron”. Events are accepted with three (two) leptons if they contain one (two) merged electron(s), since each merged electron is considered to contribute two electrons to the total. In order to avoid significant misidentification, merged electrons are only considered if the ECAL cluster energy is bigger than 500 GeV.

The dominant background in this analysis arises from ZZ events decaying into four leptons. To suppress this background, events with two oppositely charged same-flavor lepton pairs are rejected if the mass of the lepton pair,  $m_{\ell\ell}$ , is in the range 89–93 GeV. The Z mass window is made as narrow as possible in order to minimise degradation of the signal efficiency in the case of  $m_\varphi \approx m_Z$ . This requirement results in negligible signal efficiency loss for  $m_{Z'} > 500$  GeV. At lower masses, the efficiency loss increases and is approximately 20 (7)% at  $m_{Z'} = 250$  GeV for the  $eeee$  ( $\mu\mu\mu\mu$ )

channel. More than 70% (30%) of the ZZ background is rejected by the mass window veto requirement in the muon (electron) channel. This requirement is not applied to the merged electron case, thus accounting for the difference in rejection efficiency for the two channels.

The event selection efficiency is 50–70% ( $\mu\mu\mu\mu$ ), 55–65% ( $\mu\mu\mu e$  and  $\mu\mu ee$ ) and 45–65% ( $\mu eee$  and  $eeee$ ) throughout the range  $m_{Z'} > 1$  TeV for  $m_\varphi = 50$  GeV. Below  $m_{Z'} = 1$  TeV, the efficiency decreases rapidly because of the effect on the acceptance of the kinematic requirements. Heavier  $m_\varphi$  values correspond to a less boosted signature and therefore are selected with a higher efficiency. For  $m_{Z'} > 2$  TeV, the efficiency for the other  $m_\varphi$  samples is approximately 10–15% (1–5%) higher in the electron (muon) channels than for the  $m_\varphi = 50$  GeV scenario, where the range of values reflects the variation with  $m_{Z'}$ . For  $m_{Z'} < 1$  TeV, the contribution from boosted events is not significant and the efficiency is similar for all values of  $m_\varphi$  considered.

## 5. Background estimation

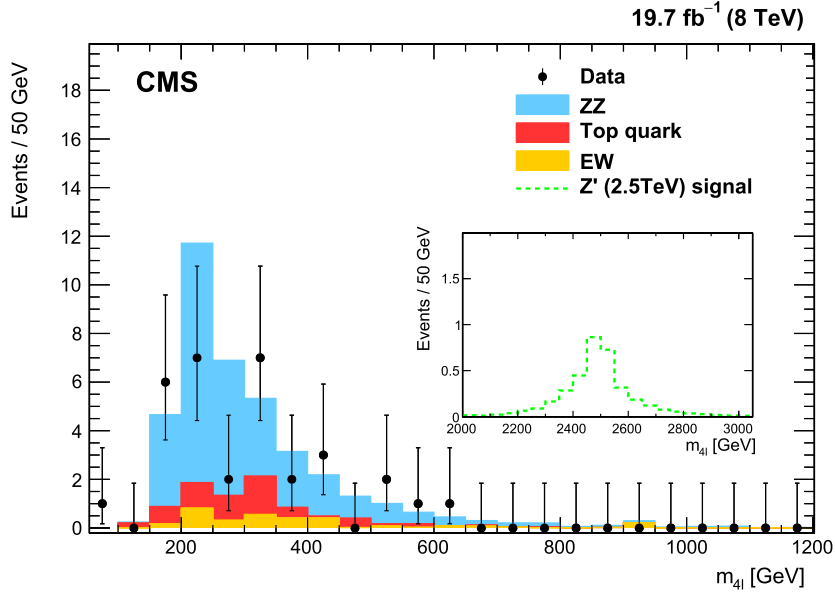
Most of the SM backgrounds are suppressed by requiring four isolated high-quality lepton candidates. As discussed above, the dominant background is from ZZ events decaying into four leptons. Other backgrounds originate from top quark events with two genuine leptons and two lepton candidates arising from misidentified jets, and from WW (WZ) events that contain two (one) misidentified or nonprompt leptons from jets. In the case of triboson production, there may be four genuine leptons in the event. These backgrounds are estimated using MC simulation.

The contribution from events with more than two leptons arising from misidentified jets is expected to be small because this analysis requires four isolated leptons in the final state. This background is estimated using the “misidentification rate” method described in Ref. [13]. The misidentification rate measured as a function of electron  $E_T$  in the barrel and endcap is applied to events with electron candidates passing the trigger but failing the full selection. The contribution from jet backgrounds estimated using this procedure is found to be negligible.

Fig. 2 shows the four-lepton invariant mass ( $m_{4\ell}$ ) distribution for selected events. The number of observed events and estimated backgrounds are summarized in Table 1. As shown in the figure and table, the distribution of observed events is in agreement with the expected backgrounds. The table shows two different mass ranges. In the region  $m_{4\ell} > 1$  TeV, the backgrounds from SM processes are very small, typically less than one event.

## 6. Results

No excess of events is observed in the data sample compared to the SM expectations and exclusion limits at 95% confidence level (CL) are calculated in the context of the benchmark model. The signal region consists of events with four leptons (e or  $\mu$ ) with  $|\eta| < 2.4$ : the two leading (subleading) leptons are required to have  $p_T > 45$  (30) GeV. A Bayesian approach is adopted with a likelihood function defined with a signal strength modifier, a prior probability, and a set of nuisance parameters. The prior probability distribution for the signal cross section is positive and uniform, since this is known to result in good frequentist coverage properties. The systematic uncertainties associated with the backgrounds, selection efficiency and luminosity are treated as nuisance parameters with log-normal prior distributions [48]. A limit on the signal contribution is derived by interpreting the likelihood function as a probability distribution and integrating over this. The coverage of the 95% CL assigned to the limit has been checked using a Markov chain Monte Carlo method.



**Fig. 2.** The  $m_{4\ell}$  spectrum for the combination of the five studied channels. The points with vertical bars represent the data and the associated statistical uncertainties; the histograms represent the expectations from SM processes; “Top quark” denotes the sum of the events for  $t\bar{t}$ ,  $tW$ ,  $t\bar{t}Z$  processes; “EW” denotes the sum of the events from  $WW$ ,  $WZ$ ,  $WW\gamma$ ,  $WWZ$ ,  $WZZ$ , and  $ZZZ$  processes. The inset shows the expectation from the benchmark model for a signal at  $m_{Z'} = 2.5$  TeV with  $m_\varphi = 50$  GeV.

**Table 1**

Summary of the observed yield and expected backgrounds for all channels, where  $N_{\text{obs}}$  is the number of observed events in data. The total background ( $N_{\text{tot}}$ ) is the sum of three different backgrounds that are estimated using MC simulations;  $N_{ZZ}$  refers to the background from ZZ events;  $N_t$  is the background from  $t\bar{t}$ , single top quark, and  $t\bar{t}Z$  production;  $N_{EW}$  is the background from WW and WZ, and triple gauge boson production. The quoted uncertainties are statistical only.

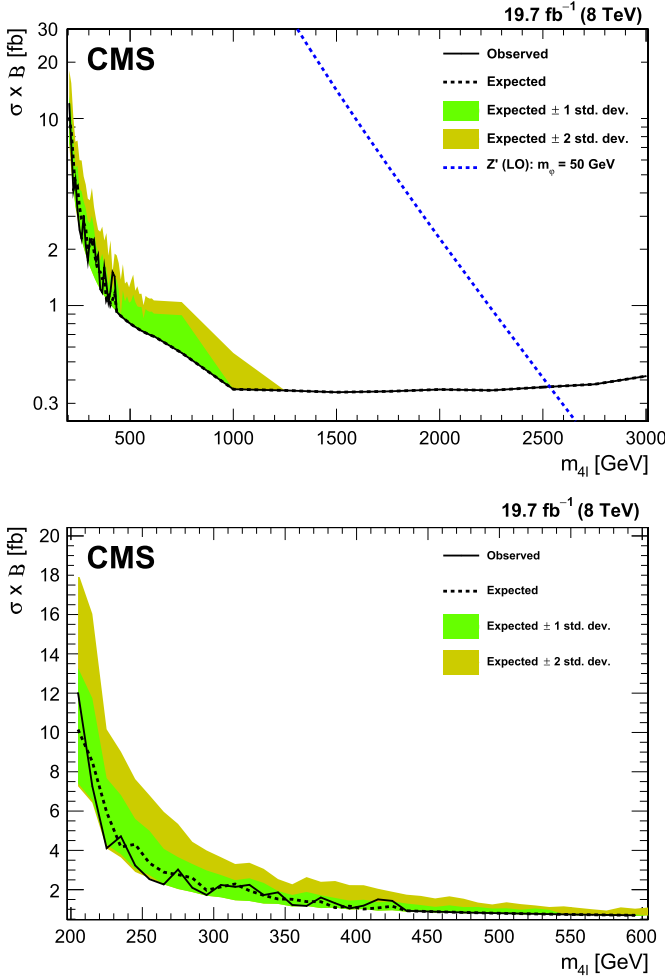
Channel	$0.1 < m_{4\ell} < 1.0$ TeV					$m_{4\ell} > 1.0$ TeV	
	$N_{\text{obs}}$	SM backgrounds				$N_{\text{obs}}$	$N_{\text{tot}}$
		$N_{ZZ}$	$N_t$	$N_{EW}$	$N_{\text{tot}}$		
$Z' \rightarrow \mu\mu\mu\mu$	3	$4.9 \pm 0.3$	$0.9 \pm 0.5$	–	$5.9 \pm 0.6$	0	–
$Z' \rightarrow \mu\mu\mu e$	6	$0.4 \pm 0.1$	$1.3 \pm 0.6$	$1.2 \pm 0.3$	$2.9 \pm 0.7$	0	–
$Z' \rightarrow \mu\mu ee$	12	$9.3 \pm 0.4$	$3.0 \pm 1.5$	$1.2 \pm 0.3$	$13.5 \pm 1.6$	0	$0.1 \pm 0.1$
$Z' \rightarrow \mu eee$	2	$0.2 \pm 0.1$	$0.4 \pm 0.1$	$0.6 \pm 0.2$	$1.2 \pm 0.2$	0	$0.1 \pm 0.1$
$Z' \rightarrow eeee$	9	$15.0 \pm 0.5$	$0.2 \pm 0.1$	$0.2 \pm 0.1$	$15.4 \pm 0.5$	0	$0.2 \pm 0.1$
Combined	32	$29.9 \pm 0.7$	$5.7 \pm 1.9$	$3.3 \pm 0.5$	$38.9 \pm 2.1$	0	$0.4 \pm 0.2$

The systematic uncertainties are dominated by the uncertainties in the background estimates and in the lepton selection efficiencies. The uncertainty in the MC estimation of the main background cross section (ZZ and  $t\bar{t}$ ) arising from higher-order QCD corrections and choice of PDFs is 15%. In order to be conservative, we choose to double this figure and assign an uncertainty of 30% from this source. The systematic uncertainty in the muon selection efficiency including reconstruction, identification, and isolation is 0.5% [33]. The uncertainties in the electron selection efficiency are 0.7% (0.6%) for electrons below 100 GeV in EB (EE) and 1.4% (0.4%) for electrons above 100 GeV in EB (EE) [13]. The uncertainties due to the lepton efficiency in both signal and background yields vary between 2.2% and 2.7% as a function of  $m_{4\ell}$ . Including the effect of the merged lepton signature, a total uncertainty of 10% in the event selection efficiency is assigned for each channel. The impact of the uncertainty in the electron energy scale on signal (background) yield is 1% (0.5%) [13]. Uncertainties in the muon momentum scale and mass resolutions are below 0.1% [33]. The uncertainty in the integrated luminosity is assigned to be 2.6% [49]. In this analysis, the statistical uncertainties are dominant and the systematic uncertainties have a small impact on the results. We tested the robustness of the limits by doubling the values assumed for the systematic uncertainties. We observed a negligible

change in the calculated limits, and conclude that the limits are insensitive to any underestimation of the systematic uncertainties.

Limits on the product of cross section and branching fraction are set in the context of the benchmark model as a function of  $m_{4\ell}$ . The natural width of the  $Z'$  resonance is assumed to be smaller than the mass resolution of the detector in all channels. The detector resolution in the  $\mu\mu\mu\mu$  channel varies from 1.1% at  $m_{4\ell} = 250$  GeV to 7.5% at  $m_{4\ell} = 3$  TeV, and it has a constant value of about 0.6% over this range in the eeee channel. In the limit calculation, we set the mass window to be six times the mass resolution centred around the signal mass point considered. A counting experiment is performed for the limit calculation. Fig. 3 shows the upper limits on the product of the cross section and branching fraction, for the combination of all five channels, for the mass range considered in the benchmark model of Ref. [29]. In the framework of this model, we translate these cross section upper limits into lower limits on the  $Z'$  boson mass. For the combination of the five channels, the value obtained for this lower mass limit is 2.5 TeV. The black solid (dashed) line indicates the observed (expected) 95% CL upper limits, the inner (outer) band indicates the  $\pm 1$  (2) standard deviation uncertainty in the expected limits, and the blue dashed line shows the theoretical  $Z'$  cross section for  $m_\varphi = 50$  GeV. This theoretical cross section is calculated under the benchmark model assumption that the branching fraction





**Fig. 3.** The 95% CL upper limit on the cross section times branching fraction as a function of  $m_{4\ell}$  for the combination of the five channels: full mass range (top) and expanded view of the low mass region (bottom). The shaded green (yellow) band indicates the one (two) sigma uncertainty in the expected limits. The blue dashed line represents the theoretical predictions for the benchmark model [29] for  $m_\phi = 50$  GeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**

The 95% CL lower limits (in TeV) on  $m_{Z'}$  for the five separate channels and for their combination. Results are presented for the benchmark assumption  $m_\phi = 50$  GeV, and for the five different values of the ratio  $m_\phi/m_{Z'}$ .

$m_\phi$	50 GeV	$0.05m_{Z'}$	$0.1m_{Z'}$	$0.2m_{Z'}$	$0.3m_{Z'}$	$0.4m_{Z'}$
$\mu\mu\mu\mu$	1.7	1.6	1.7	1.7	1.7	1.7
$\mu\mu\mu e$	2.0	2.0	2.1	2.1	2.1	2.1
$\mu\mu ee$	2.4	2.4	2.5	2.5	2.5	2.5
$\mu eee$	2.0	2.0	2.1	2.1	2.1	2.1
$eeee$	1.7	1.7	1.7	1.7	1.7	1.7
Combined	2.5	2.6	2.6	2.6	2.6	2.6

$\mathcal{B}(\phi \rightarrow \ell\ell') = 100\%$ . In the region above the 1–1.5 TeV, the bands are not visible since backgrounds are negligible here.

Table 2 shows the exclusion limit on  $m_{Z'}$  for the five separate channels and for the combination. Results are presented for the benchmark assumption  $m_\phi = 50$  GeV, and for the five different values of the ratio  $m_\phi/m_{Z'}$  assumed for the generated signal samples, taking into account the event selection efficiencies described above. The predicted cross sections decrease as the ratio  $m_\phi/m_{Z'}$  increases. The contribution of the merged lepton signature also decreases, resulting in an overall efficiency increase. Therefore

the scenarios with  $m_\phi/m_{Z'} = 5, 10, 20, 30$  and 40% of  $m_{Z'}$ , give slightly higher limits than the  $m_\phi = 50$  GeV scenario.

## 7. Summary

Results have been presented from a search for heavy narrow resonances decaying into four-lepton final states via intermediate scalar particles  $\phi$ , where the branching fraction of  $\phi \rightarrow \ell\ell$  ( $\ell = e$  or  $\mu$ ) is set to 1. These results are based on a sample of proton–proton collision data at  $\sqrt{s} = 8$  TeV, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The four-lepton invariant mass spectra are consistent with the standard model predictions. Masses of  $Z'$  bosons have been excluded at 95% confidence level for a specific benchmark model with  $m_\phi = 50$  GeV, and for five different assumptions for the ratio  $m_\phi/m_{Z'}$  ( $m_\phi/m_{Z'} = 5, 10, 20, 30$  and 40%). Five decay channels ( $\mu\mu\mu\mu, \mu\mu\mu e, \mu\mu ee, \mu eee, eeee$ ) are considered in this analysis. Combining all channels, a lower limit on the  $Z'$  mass of 2.5 TeV is obtained for the benchmark model, and 2.6 TeV for each of the models assuming a fixed ratio between  $m_\phi$  and  $m_{Z'}$ . This is the first result to constrain a leptophobic  $Z'$  resonance in the four-lepton channel.

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; 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 the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the Thalís and Aristeia

programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

## References

- [1] A. Leike, The phenomenology of extra neutral gauge bosons, *Phys. Rep.* **317** (1999) 143, [http://dx.doi.org/10.1016/S0370-1573\(98\)00133-1](http://dx.doi.org/10.1016/S0370-1573(98)00133-1), arXiv:hep-ph/9805494.
- [2] J.L. Hewett, T.G. Rizzo, Low-energy phenomenology of superstring-inspired  $E_6$  models, *Phys. Rep.* **183** (1989) 193, [http://dx.doi.org/10.1016/0370-1573\(89\)90071-9](http://dx.doi.org/10.1016/0370-1573(89)90071-9).
- [3] K.R. Dienes, E. Dudas, T. Gherghetta, Extra spacetime dimensions and unification, *Phys. Lett. B* **436** (1998) 55, [http://dx.doi.org/10.1016/S0370-2693\(98\)00977-0](http://dx.doi.org/10.1016/S0370-2693(98)00977-0), arXiv:hep-ph/9803466.
- [4] T. Appelquist, H.-C. Cheng, B.A. Dobrescu, Bounds on universal extra dimensions, *Phys. Rev. D* **64** (2001) 035002, <http://dx.doi.org/10.1103/PhysRevD.64.035002>, arXiv:hep-ph/0012100.
- [5] L. Randall, R. Sundrum, An alternative to compactification, *Phys. Rev. Lett.* **83** (1999) 4690, <http://dx.doi.org/10.1103/PhysRevLett.83.4690>, arXiv:hep-ph/9906064.
- [6] L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension, *Phys. Rev. Lett.* **83** (1999) 3370, <http://dx.doi.org/10.1103/PhysRevLett.83.3370>, arXiv:hep-ph/9905221.
- [7] ATLAS Collaboration, Search for new phenomena in the dijet mass distribution using  $pp$  collision data at  $\sqrt{s} = 8$  TeV with the ATLAS detector, *Phys. Rev. D* **91** (2015) 052007, <http://dx.doi.org/10.1103/PhysRevD.91.052007>, arXiv:1407.1376.
- [8] ATLAS Collaboration, Search for new phenomena in dijet mass and angular distributions from  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *Phys. Lett. B* **754** (2016) 302, <http://dx.doi.org/10.1016/j.physletb.2016.01.032>, arXiv:1512.01530.
- [9] CMS Collaboration, Search for narrow resonances using the dijet mass spectrum in  $pp$  collisions at  $\sqrt{s} = 8$  TeV, *Phys. Rev. D* **87** (2013) 114015, <http://dx.doi.org/10.1103/PhysRevD.87.114015>, arXiv:1302.4794.
- [10] CMS Collaboration, Search for narrow resonances decaying to dijets in proton–proton collisions at  $\sqrt{s} = 13$  TeV, *Phys. Rev. Lett.* **116** (2016) 071801, <http://dx.doi.org/10.1103/PhysRevLett.116.071801>, arXiv:1512.01224.
- [11] ATLAS Collaboration, Search for high-mass dilepton resonances in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, *Phys. Rev. D* **90** (2014) 052005, <http://dx.doi.org/10.1103/PhysRevD.90.052005>, arXiv:1405.4123.
- [12] ATLAS Collaboration, Search for high-mass new phenomena in the dilepton final state using proton–proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *Phys. Lett. B* **761** (2016) 372, <http://dx.doi.org/10.1016/j.physletb.2016.08.055>, arXiv:1607.03669.
- [13] CMS Collaboration, Search for physics beyond the standard model in dilepton mass spectra in proton–proton collisions at  $\sqrt{s} = 8$  TeV, *J. High Energy Phys.* **04** (2015) 025, [http://dx.doi.org/10.1007/JHEP04\(2015\)025](http://dx.doi.org/10.1007/JHEP04(2015)025), arXiv:1412.6302.
- [14] CMS Collaboration, Search for narrow resonances in dilepton mass spectra in proton–proton collisions at  $\sqrt{s} = 13$  TeV and combination with 8 TeV data, *Phys. Lett. B* **768** (2017) 57, <https://doi.org/10.1016/j.physletb.2017.02.010>, arXiv:1609.05391, 2016.
- [15] ATLAS Collaboration, Search for resonances in diphoton events at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *J. High Energy Phys.* **09** (2016) 001, [http://dx.doi.org/10.1007/JHEP09\(2016\)001](http://dx.doi.org/10.1007/JHEP09(2016)001), arXiv:1606.03833.
- [16] CMS Collaboration, Search for resonant production of high-mass photon pairs in proton–proton collisions at  $\sqrt{s} = 8$  and 13 TeV, *Phys. Rev. Lett.* **117** (2016) 051802, <http://dx.doi.org/10.1103/PhysRevLett.117.051802>, arXiv:1606.04093.
- [17] CMS Collaboration, Search for high-mass diphoton resonances in proton–proton collisions at 13 TeV and combination with 8 TeV search, *Phys. Lett. B* **767** (2017) 147, <https://doi.org/10.1016/j.physletb.2017.01.027>, arXiv:1609.02507, 2016.
- [18] ATLAS Collaboration, Search for heavy resonances decaying to a Z boson and a photon in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *Phys. Lett. B* **764** (2017) 11, <http://dx.doi.org/10.1016/j.physletb.2016.11.005>, arXiv:1607.06363.
- [19] ATLAS Collaboration, Search for Higgs boson pair production in the  $hh \rightarrow b\bar{b}\tau\tau, \gamma\gamma WW^*, \gamma\gamma b\bar{b}, b\bar{b}b\bar{b}$  channels with the ATLAS detector, *Phys. Rev. D* **92** (2015) 092004, <http://dx.doi.org/10.1103/PhysRevD.92.092004>, arXiv:1509.04670.
- [20] ATLAS Collaboration, Search for WZ resonances in the fully leptonic channel using  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, *Phys. Lett. B* **737** (2014) 223, <http://dx.doi.org/10.1016/j.physletb.2014.08.039>, arXiv:1406.4456.
- [21] CMS Collaboration, Search for high-mass  $Z\gamma$  resonances in  $e^+e^- \gamma$  and  $\mu^+\mu^- \gamma$  final states in proton–proton collisions at  $\sqrt{s} = 8$  and 13 TeV, *J. High Energy Phys.* **01** (2017) 076, [http://dx.doi.org/10.1007/JHEP01\(2017\)076](http://dx.doi.org/10.1007/JHEP01(2017)076), arXiv:1610.02960.
- [22] CMS Collaboration, Search for high-mass  $Z\gamma$  resonances in proton–proton collisions at  $\sqrt{s} = 8$  and 13 TeV using jet substructure techniques, *Phys. Lett. B* (2017), <http://dx.doi.org/10.1016/j.physletb.2017.06.062>, in press, arXiv:1612.09516, 2016.
- [23] CMS Collaboration, Search for heavy resonances decaying to two Higgs bosons in final states containing four b quarks, *Eur. Phys. J. C* **76** (2016) 371, <http://dx.doi.org/10.1140/epjc/s10052-016-4206-6>, arXiv:1602.08762.
- [24] CMS Collaboration, Search for a massive resonance decaying into a Higgs boson and a W or Z boson in hadronic final states in proton–proton collisions at  $\sqrt{s} = 8$  TeV, *J. High Energy Phys.* **02** (2016) 145, [http://dx.doi.org/10.1007/JHEP02\(2016\)145](http://dx.doi.org/10.1007/JHEP02(2016)145), arXiv:1506.01443.
- [25] ATLAS Collaboration, Search for resonances decaying into top-quark pairs using fully hadronic decays in  $pp$  collisions with ATLAS at  $\sqrt{s} = 7$  TeV, *J. High Energy Phys.* **01** (2013) 116, [http://dx.doi.org/10.1007/JHEP01\(2013\)116](http://dx.doi.org/10.1007/JHEP01(2013)116), arXiv:1211.2202.
- [26] ATLAS Collaboration, Search for  $t\bar{t}$  resonances using lepton-plus-jets events in proton–proton collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, *J. High Energy Phys.* **08** (2015) 148, [http://dx.doi.org/10.1007/JHEP08\(2015\)148](http://dx.doi.org/10.1007/JHEP08(2015)148), arXiv:1505.0718.
- [27] CMS Collaboration, Search for anomalous  $t\bar{t}$  production in the highly-boosted all-hadronic final state, *J. High Energy Phys.* **09** (2012) 029, [http://dx.doi.org/10.1007/JHEP09\(2012\)029](http://dx.doi.org/10.1007/JHEP09(2012)029), arXiv:1204.2488.
- [28] CMS Collaboration, Search for resonant  $t\bar{t}$  production in proton–proton collisions at  $\sqrt{s} = 8$  TeV, *Phys. Rev. D* **93** (2016) 012001, <http://dx.doi.org/10.1103/PhysRevD.93.012001>, arXiv:1506.03062.
- [29] V. Barger, H.-S. Lee, Four-lepton resonance at the Large Hadron Collider, *Phys. Rev. D* **85** (2012) 055030, <http://dx.doi.org/10.1103/PhysRevD.85.055030>, arXiv:1111.0633.
- [30] Y. Kuno, Y. Okada, Muon decay and physics beyond the standard model, *Rev. Mod. Phys.* **73** (2001) 151, <http://dx.doi.org/10.1103/RevModPhys.73.151>, arXiv:hep-ph/9909265.
- [31] A. de Gouvea, P. Vogel, Lepton flavor and number conservation and physics beyond the standard model, in: *Fund. Sym. in the Era of the LHC*, in: *Prog. Part. Nucl. Phys.*, vol. 71, 2013, p. 75, arXiv:1303.4097.
- [32] D.K. Ghosh, P. Roy, S. Roy, Four lepton flavor violating signals at the LHC, *J. High Energy Phys.* **05** (2012) 067, [http://dx.doi.org/10.1007/JHEP05\(2012\)067](http://dx.doi.org/10.1007/JHEP05(2012)067), arXiv:1203.0187.
- [33] CMS Collaboration, Performance of CMS muon reconstruction in  $pp$  collision events at  $\sqrt{s} = 7$  TeV, *J. Instrum.* **7** (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [34] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at  $\sqrt{s} = 8$  TeV, *J. Instrum.* **10** (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [35] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* **3** (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [36] A. Belyaev, N. Christensen, A. Pukhov, CalChEP 3.4 for collider physics within and beyond the Standard Model, *Comput. Phys. Commun.* **184** (2013) 1729, <http://dx.doi.org/10.1016/j.cpc.2013.01.014>, arXiv:1207.6082.
- [37] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [38] T. Binoth, N. Kauerer, P. Mertsch, Gluon-induced QCD corrections to  $pp \rightarrow ZZ \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ , *Phys. Lett. B* **687** (2008) 0024, 2008.
- [39] S. Alioli, P. Nason, C. Oleari, E. Re, NLO vector-boson production matched with shower in POWHEG, *J. High Energy Phys.* **07** (2008) 060, <http://dx.doi.org/10.1088/1126-6708/2008/07/060>, arXiv:0805.4802.
- [40] J. Alwall, et al., Madgraph v5: going beyond, *J. High Energy Phys.* **06** (2011) 128, [http://dx.doi.org/10.1007/JHEP06\(2011\)128](http://dx.doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [41] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through  $\alpha_s^4$ , *Phys. Rev. Lett.* **110** (2013) 252004, <http://dx.doi.org/10.1103/PhysRevLett.110.252004>, arXiv:1303.6254.
- [42] J.M. Campbell, R.K. Ellis, C. Williams, Vector boson pair production at the LHC, *J. High Energy Phys.* **07** (2011) 018, [http://dx.doi.org/10.1007/JHEP07\(2011\)018](http://dx.doi.org/10.1007/JHEP07(2011)018), arXiv:1105.0020.
- [43] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* **07** (2002) 012, <http://dx.doi.org/10.1088/1126-6708/2002/07/012>, arXiv:hep-ph/0201195.
- [44] CMS Collaboration, Study of the underlying event at forward rapidity in  $pp$  collisions at  $\sqrt{s} = 0.9, 2.76$ , and 7 TeV, *J. High Energy Phys.* **04** (2013) 072, [http://dx.doi.org/10.1007/JHEP04\(2013\)072](http://dx.doi.org/10.1007/JHEP04(2013)072), arXiv:1302.2394.
- [45] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* **76** (2016) 155, <http://dx.doi.org/10.1140/epjc/s10052-016-3988-x>, arXiv:1512.00815.
- [46] S. Agostinelli, et al., GEANT4, GEANT4 – a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* **506** (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).

- [47] J. Allison, et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, <http://dx.doi.org/10.1109/TNS.2006.869826>.
- [48] Particle Data Group, K.A. Olive, et al., Review of particle physics, Chin. Phys. C 38 (2014) 090001, <http://dx.doi.org/10.1088/1674-1137/38/9/090001>.
- [49] CMS Collaboration, CMS Luminosity Based on Pixel Cluster Counting – Summer 2013 Update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013, <http://cdsweb.cern.ch/record/1598864>.

## The CMS Collaboration

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

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik, Wien, Austria*

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

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

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

*Universiteit Antwerpen, Antwerpen, Belgium*

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

*Vrije Universiteit Brussel, Brussel, Belgium*

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöffbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

H. Bakhshiansohi, C. Beluffi<sup>3</sup>, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

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

N. Beliy

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>4</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>5</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson,

D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>4</sup>, A. Vilela Pereira

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

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, C.S. Moon<sup>a</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

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

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

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>6</sup>

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen<sup>7</sup>, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

*Universidad de Los Andes, Bogota, Colombia*

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Finger<sup>8</sup>, M. Finger Jr.<sup>8</sup>

*Charles University, Prague, Czech Republic*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

A.A. Abdelalim<sup>9,10</sup>, Y. Mohammed<sup>11</sup>, E. Salama<sup>12,13</sup>

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



B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

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

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

*Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, France*

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>15</sup>, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

T. Toriashvili<sup>16</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>8</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov<sup>15</sup>

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

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, G. Flügge, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl<sup>17</sup>

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

M. Aldaya Martin, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras<sup>18</sup>, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>19</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>20</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>20</sup>, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>20</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>17</sup>, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Fries, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann<sup>17</sup>, S.M. Heindl, U. Husemann, I. Katkov<sup>15</sup>, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

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

*National and Kapodistrian University of Athens, Athens, Greece*

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

*University of Ioánnina, Ioánnina, Greece*

N. Filipovic

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>21</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>22</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>23</sup>, A. Makovec, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>22</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Hungary*

S. Bahinipati, S. Choudhury<sup>24</sup>, P. Mal, K. Mandal, A. Nayak<sup>25</sup>, D.K. Sahoo, N. Sahoo, S.K. Swain

*National Institute of Science Education and Research, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

*University of Delhi, Delhi, India*

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

*Saha Institute of Nuclear Physics, Kolkata, India*

P.K. Behera

*Indian Institute of Technology Madras, Madras, India*

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>17</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

*Tata Institute of Fundamental Research-A, Mumbai, India*

S. Banerjee, S. Bhowmik<sup>26</sup>, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>26</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>26</sup>, N. Wickramage<sup>27</sup>

*Tata Institute of Fundamental Research-B, Mumbai, India*

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

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

H. Behnamian, S. Chenarani<sup>28</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>28</sup>, A. Fahim<sup>29</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>30</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>31</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,17</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b,17</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a,b,17</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>17</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, M.R. Monge<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

L. Brianza<sup>17</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b,17</sup>, B. Marzocchi<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, G. De Nardo, S. Di Guida<sup>a,d,17</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,17</sup>, P. Paolucci<sup>a,17</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi<sup>a,17</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b,17</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Zanetti, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri<sup>a</sup>, A. Magnani<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

L. Alunni Solestizi<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsof<sup>a,32</sup>, P. Azzurri<sup>a,17</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,32</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a,c</sup>, G. Fedi<sup>a</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,32</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,33</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy



L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, M. Cipriani <sup>a,b</sup>, G. D'imperio <sup>a,b,17</sup>, D. Del Re <sup>a,b,17</sup>, M. Diemoz <sup>a</sup>, S. Gelli <sup>a,b</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, F. Preiato <sup>a,b</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c,17</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, N. Bartosik <sup>a</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>, N. Cartiglia <sup>a</sup>, M. Costa <sup>a,b</sup>, R. Covarelli <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, L. Finco <sup>a,b</sup>, B. Kiani <sup>a,b</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, G. Mazza <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, E. Monteil <sup>a,b</sup>, M.M. Obertino <sup>a,b</sup>, L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, G.L. Pinna Angioni <sup>a,b</sup>, F. Ravera <sup>a,b</sup>, A. Romero <sup>a,b</sup>, F. Rotondo <sup>a</sup>, M. Ruspa <sup>a,c</sup>, R. Sacchi <sup>a,b</sup>, V. Sola <sup>a</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, P. Traczyk <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte <sup>a</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, C. La Licata <sup>a,b</sup>, A. Schizzi <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim

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

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenias, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali <sup>34</sup>, F. Mohamad Idris <sup>35</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>36</sup>, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

S. Carpintheyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

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

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler

*University of Canterbury, Christchurch, New Zealand*

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

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

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszuk<sup>37</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

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

I. Belotelov, P. Bunin, I. Golutvin, I. Gorbunov, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev<sup>38,39</sup>, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim<sup>40</sup>, E. Kuznetsova<sup>41</sup>, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tisov, A. Toropin

*Institute for Nuclear Research, Moscow, Russia*

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

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

A. Bylinkin<sup>39</sup>

*Moscow Institute of Physics and Technology, Moscow, Russia*

R. Chistov<sup>42</sup>, M. Danilov<sup>42</sup>, V. Rusinov

*National Research Nuclear University, 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*

V. Andreev, M. Azarkin<sup>39</sup>, I. Dremin<sup>39</sup>, M. Kirakosyan, A. Leonidov<sup>39</sup>, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>43</sup>, L. Dudko, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, A. Snigirev

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

V. Blinov<sup>44</sup>, Y. Skovpen<sup>44</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic<sup>45</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco<sup>46</sup>, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer<sup>17</sup>, M.J. Kortelainen, K. Kousouris, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi<sup>47</sup>, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer,

C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas<sup>48</sup>, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns<sup>49</sup>, G.I. Veres<sup>22</sup>, N. Wardle, H.K. Wöhri, A. Zagozdinska<sup>37</sup>, W.D. Zeuner

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

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

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte<sup>†</sup>, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov<sup>50</sup>, V.R. Tavolaro, K. Theofilatos, R. Wallny

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

T.K. Aarrestad, C. Amsler<sup>51</sup>, L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

*Universität Zürich, Zurich, Switzerland*

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

*National Central University, Chung-Li, Taiwan*

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Adiguzel, S. Cerci<sup>52</sup>, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos, E.E. Kangal<sup>53</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>54</sup>, K. Ozdemir<sup>55</sup>, D. Sunar Cerci<sup>52</sup>, H. Topakli<sup>56</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Cukurova University, Physics Department, Science and Art Faculty, Turkey*

B. Bilin, S. Bilmis, B. Isildak<sup>57</sup>, G. Karapinar<sup>58</sup>, M. Yalvac, M. Zeyrek

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

E. Gülmez, M. Kaya<sup>59</sup>, O. Kaya<sup>60</sup>, E.A. Yetkin<sup>61</sup>, T. Yetkin<sup>62</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak, S. Sen<sup>63</sup>

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*

L. Levchuk, P. Sorokin

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



R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold<sup>64</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>65</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas<sup>64</sup>, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko<sup>50</sup>, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>66</sup>, T. Virdee<sup>17</sup>, J. Wright, S.C. Zenz

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

*Baylor University, Waco, USA*

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

*The University of Alabama, Tuscaloosa, USA*

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

*Boston University, Boston, USA*

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

*Brown University, Providence, USA*

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

*University of California, Davis, Davis, USA*

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

*University of California, Los Angeles, USA*

K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B.R. Yates

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, M. Tadel, A. Vartak, S. Wasserbaech<sup>67</sup>, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

*University of California, Santa Barbara, Department of Physics, Santa Barbara, USA*

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

M.B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

D. Winn

*Fairfield University, Fairfield, USA*

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir<sup>†</sup>, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes<sup>†</sup>, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>68</sup>, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

*Florida International University, Miami, USA*

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

*Florida State University, Tallahassee, USA*

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi<sup>69</sup>, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

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

B. Bilki<sup>70</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>71</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>72</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

*Johns Hopkins University, Baltimore, USA*

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

*The University of Kansas, Lawrence, USA*

A. Ivanov, K. Kaadze, S. Khalil, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, R. Bartek, K. Bloom, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

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

G. Alverson, E. Barberis, D. Baumgartel, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

*Northeastern University, Boston, USA*

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>38</sup>, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

*Princeton University, Princeton, USA*

S. Malik

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, USA*

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

*Rice University, Houston, USA*

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

*University of Rochester, Rochester, USA*

A. Agapitos, J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

*Rutgers, The State University of New Jersey, Piscataway, USA*

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>73</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon<sup>74</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

*Texas A&M University, College Station, USA*

N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P.R. Duerdo, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*



A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, USA*

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

*University of Wisconsin – Madison, Madison, WI, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

<sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France.

<sup>4</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>5</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>6</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>7</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

<sup>8</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>9</sup> Also at Helwan University, Cairo, Egypt.

<sup>10</sup> Now at Zewail City of Science and Technology, Zewail, Egypt.

<sup>11</sup> Now at Fayoum University, El-Fayoum, Egypt.

<sup>12</sup> Also at British University in Egypt, Cairo, Egypt.

<sup>13</sup> Now at Ain Shams University, Cairo, Egypt.

<sup>14</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>15</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>16</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>17</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>18</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>19</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>20</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>21</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>22</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>23</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>24</sup> Also at Indian Institute of Science Education and Research, Bhopal, India.

<sup>25</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>26</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>27</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>28</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>29</sup> Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

<sup>30</sup> Also at Yazd University, Yazd, Iran.

<sup>31</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>32</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>33</sup> Also at Purdue University, West Lafayette, USA.

<sup>34</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

<sup>35</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>36</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

<sup>37</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>38</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>39</sup> Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

<sup>40</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>41</sup> Also at University of Florida, Gainesville, USA.

<sup>42</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.

<sup>43</sup> Also at California Institute of Technology, Pasadena, USA.

<sup>44</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

<sup>45</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

<sup>46</sup> Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.

<sup>47</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

- <sup>48</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>49</sup> Also at Riga Technical University, Riga, Latvia.
- <sup>50</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>51</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>52</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>53</sup> Also at Mersin University, Mersin, Turkey.
- <sup>54</sup> Also at Cag University, Mersin, Turkey.
- <sup>55</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>56</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>57</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>58</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>59</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>60</sup> Also at Kafkas University, Kars, Turkey.
- <sup>61</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>62</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>63</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>64</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>65</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>66</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>67</sup> Also at Utah Valley University, Orem, USA.
- <sup>68</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>69</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- <sup>70</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>71</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>72</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>73</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>74</sup> Also at Kyungpook National University, Daegu, Korea.