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

The CMS Collaboration\*

## Abstract

A search for heavy narrow resonances decaying into four-lepton final states from cascade decays of a  $Z'$  boson has been performed using proton-proton collision data at  $\sqrt{s} = 8$  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 TeV within the benchmark model. This is the first result to constrain a leptophobic  $Z'$  resonance in the four-lepton channel.

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## 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], and  $t\bar{t}$  [18–21] 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 backgrounds 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 in Ref. [22]. 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 ( $\varphi$ ) each of which subsequently decays to pairs of leptons ( $\varphi \rightarrow \ell\ell'$ , where  $\ell$  and  $\ell' = e$  or  $\mu$ ). Figure 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  $\varphi$  bosons in the dilepton channel is inefficient because the two daughter leptons are highly collimated. In the following sections we describe a technique to increase the selection efficiency.

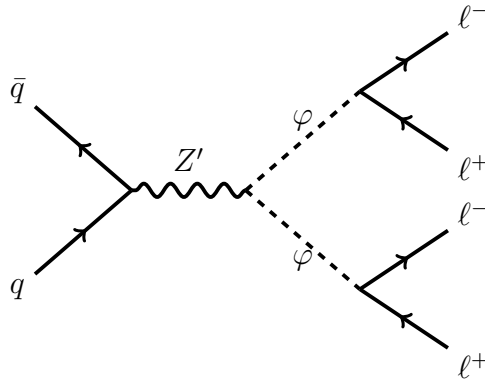


Figure 1: Leading order Feynman diagram for the production and cascade decay of a  $Z'$  resonance to a four-lepton final state.

The analysis is a search for heavy narrow resonances decaying into four isolated final state leptons. The benchmark model [22] 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:  $\mu\mu\mu\mu$ ,  $\mu\mu\mu e$ ,  $\mu\mu e e$ ,  $\mu e e e$ , and  $e e e e$ . In particular,  $\mu\mu e e$ ,  $\mu\mu\mu e$  and  $\mu e e e$  channels are included to allow for the possibility of lepton flavor violation (LFV) [23–25] 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 [22].

## 2 The CMS detector and signal simulation

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 [26].

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 in the barrel region to 4.5% for showering electrons in the endcaps [27].

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. [28].

## 3 The Monte Carlo samples

The Monte Carlo (MC) samples for the benchmark model are produced using the CALCHEP 3.4.1 generator [29] interfaced with PYTHIA 6.4.24 [30]. 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  $\varphi$  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  $\varphi$  mass ( $m_\varphi$ ), with  $m_\varphi = 50$  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  $m_\varphi$ . In addition, samples are generated with  $m_\varphi$  masses of 5, 10, 20, 30 and 40% of the  $m_{Z'}$ , 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  $\varphi \rightarrow \ell\ell'$  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 [31]. Additional backgrounds from diboson production ( $WW$  and  $WZ$ ) are generated with PYTHIA, and from top quark production ( $t\bar{t}$ ,  $tW$ , and  $tW$ ) are generated with POWHEG 1.0 [32]. Other processes, such as  $t\bar{t}Z$  and triboson produc-

tion ( $WW\gamma$ ,  $WWZ$ ,  $WZZ$ , and  $ZZZ$ ), are generated with MADGRAPH 5.1.3.30, rescaled by the next-to-leading order (NLO) K-factors [33]. Simulated event samples are normalized using the integrated luminosity and higher order theoretical cross sections: next-to-next-to-leading order for  $t\bar{t}$  [34] and NLO for  $ZZ$  [35] and the other backgrounds.

The MC samples are generated using the CTEQ6L [36] set of parton distribution functions (PDFs) and the PYTHIA Z2\* tune [37, 38] 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 [39, 40], 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 ( $\mu e e e$ ,  $e e e e$ ) requires two clusters of energy deposits in the ECAL with transverse energy  $E_T > 33$  GeV each. For the  $\mu\mu e e$  channel, the trigger requires  $p_T > 22$  GeV for both the muon and the electron.

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 and the two subleading leptons to have  $p_T > 30$  GeV. 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 tracker and muon detectors (“global muons”) [26]. Global muons are required to pass the following criteria: 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, excluding the identified muon candidates, within a cone of  $\Delta R < 0.3$  around the muon does not exceed 10% of the muon  $p_T$ , where  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ . We remove the contribution of the second lepton candidate if it is within a cone of  $\Delta R < 0.3$ .

An electron candidate is identified by matching a cluster in the ECAL to a track in the silicon tracker [27]. 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: the  $p_T$  sum of all other tracks in a cone of  $\Delta R < 0.3$  around the track of the electron candidate 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”) [26], if the two muons are as close as  $\Delta R < 0.4$ . In such exceptional cases, the requirement of at least one muon chamber hit and at least two muon detector planes with the 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 the 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 to 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. 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.

A typical 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 entire  $m_{Z'}$  range at  $m_\varphi = 50$  GeV. The heavier  $m_\varphi$  values correspond to a less boosted signature and therefore are selected with a higher efficiency. For  $m_{Z'} > 2$  GeV, 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  $m_{Z'}$ .

## 5 Background estimation

Most of the SM backgrounds are suppressed by requiring four isolated high-quality lepton candidates. As discussed above, the dominant backgrounds are  $ZZ$  events decaying into four leptons. Other background originates from top quark events with two genuine leptons and

two lepton candidates arising from misidentified jets. The WW (WZ) events can also pass the signal selection if they contain two (one) misidentified or nonprompt leptons from jets. In the case of triboson production, there may be four genuine leptons associated with jets or missing transverse energy. 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.

Figure 2 shows the four-lepton invariant mass ( $m_{4\ell}$ ) distribution for selected events. The observed events and estimated backgrounds are summarized in Table 1. As shown in the figure and table, the observed events are 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.

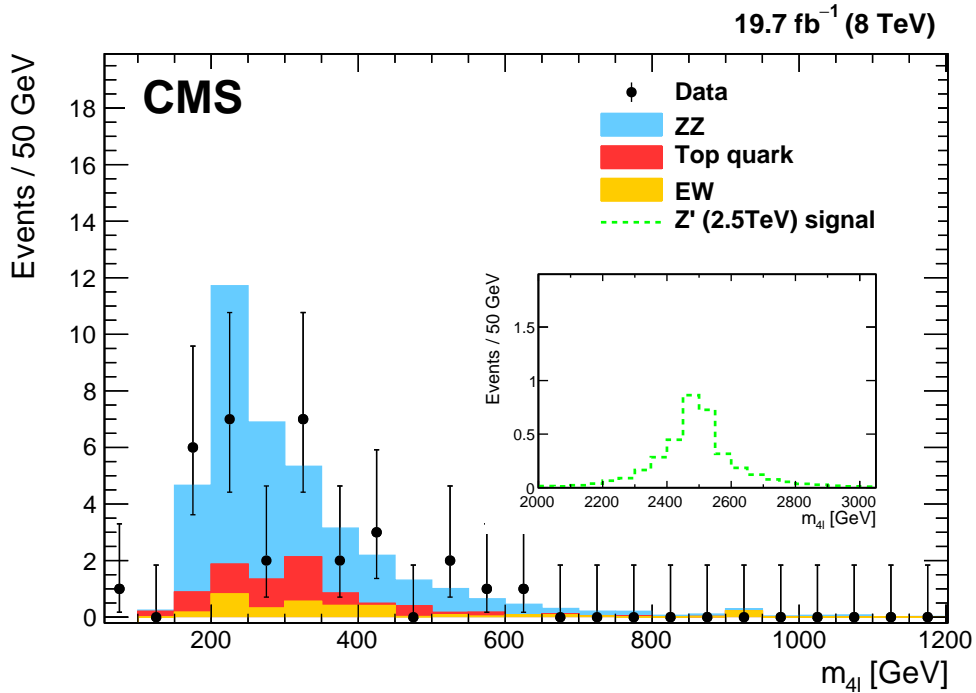


Figure 2: The  $m_{4\ell}$  spectrum for the combination of the five studied channels. The points with vertical bars represent the data with their statistical uncertainties; the histograms represent the expectations from SM processes; “Top quark” denotes the sum of the events for  $t\bar{t}$ ,  $tW$ ,  $t\bar{W}$ ,  $t\bar{t}Z$  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  $m_\phi = 50$  GeV.

## 6 Results

No excess of events is observed in the data sample compared to the SM expectations. Exclusion limits at 95% confidence level (CL) are calculated in the context of the benchmark model with

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	$0.1 < m_{4\ell} < 1.0 \text{ TeV}$					$m_{4\ell} > 1.0 \text{ TeV}$	
	$N_{\text{obs}}$	SM backgrounds			$N_{\text{tot}}$	$N_{\text{obs}}$	$N_{\text{tot}}$
		$N_{ZZ}$	$N_t$	$N_{EW}$			
$Z' \rightarrow \mu\mu\mu\mu$	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	$0.4 \pm 0.2$

a Bayesian approach. The signal region ( $0.1 < m_{4\ell} < 3.0 \text{ TeV}$ ) consists of four leptons (e or  $\mu$ ) with  $|\eta| < 2.4$ : two leading (subleading) leptons are required to have  $p_T > 45$  (30) GeV. The likelihood function is defined with a signal strength modifier, a prior probability, and a set of nuisance parameters that are used to incorporate systematic uncertainties. This method is based on interpreting the likelihood as a probability distribution, with log-normal distributions used for nuisance parameters [41]. Integrating over the latter we obtain a limit on the signal contribution.

The systematic uncertainties are dominated by the uncertainty in the background estimates and in the lepton selection efficiencies. A 30% uncertainty in the total background cross section ( $ZZ$  and  $t\bar{t}$ ) is used to account for uncertainties arising from PDFs and higher-order QCD corrections in the measured 8 TeV cross sections. The systematic uncertainty in the muon selection including reconstruction, identification, and isolation is 0.5% [26]. The uncertainties in the electron selection 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% 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% [26]. The uncertainty in the integrated luminosity is assigned to be 2.6% [42]. 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 mass resolution of the detector is assumed to be larger than the natural width of the  $Z'$  resonance in all channels. 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. Figure 3 shows the upper limit on the product of the cross section and branching fraction, for the combination of all five channels. Using the benchmark model of Ref. [22] 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  $m_\phi = 50$  GeV. This theoretical cross section is calculated under the benchmark model assumption that the branching fraction  $\mathcal{B}(\phi \rightarrow \ell\ell') = 100\%$ . In the region above the 1–1.5 TeV, the bands are not visible since backgrounds are negligible here.

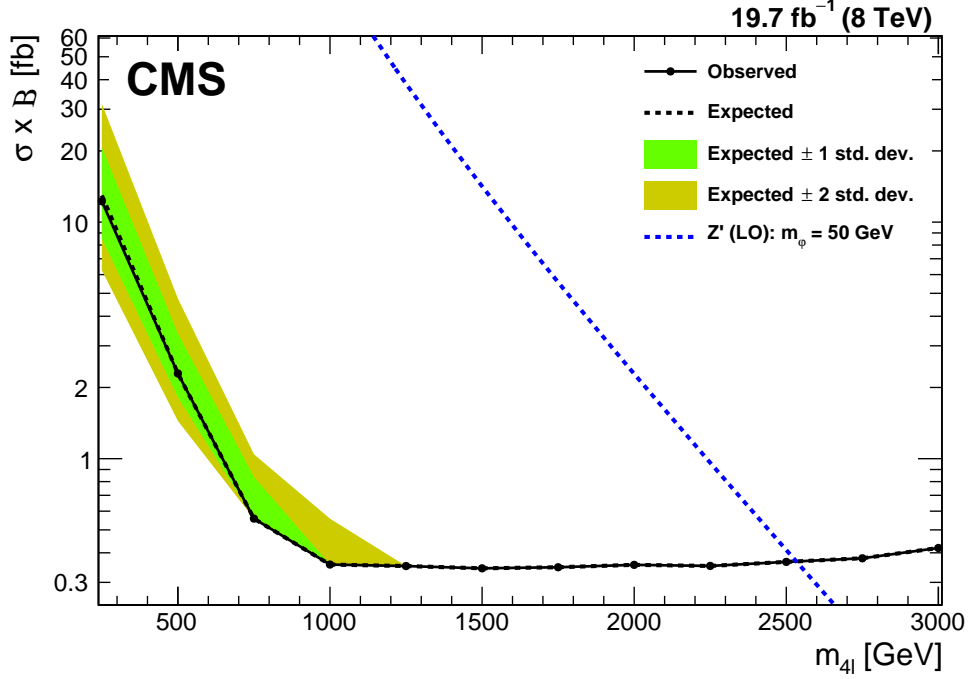


Figure 3: The 95% CL upper limit on the cross section times branching fraction as a function of  $m_{4\ell}$  for the combination of the five channels. The shaded green (yellow) band indicates the one (two) sigma uncertainty in the expected limits. The blue dashed line represents the theoretical predictions for the benchmark model [22] for  $m_\phi = 50$  GeV.

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  $m_\phi/m_{4\ell}$  assumed for the generated signal samples, taking into account the event selection efficiencies described above. The predicted cross sections decrease as the ratio  $m_\phi/m_{4\ell}$  increases. The contribution of the merged lepton signature also decreases, resulting in an overall efficiency increase. Therefore the scenarios with  $m_\phi/m_{4\ell} = 5, 10, 20, 30$  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

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

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.

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

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

### Institut für Hochenergiephysik, Wien, Austria

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. Rabadý, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

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

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

### Universiteit Antwerpen, Antwerpen, Belgium

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

### Vrije Universiteit Brussel, Brussel, 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

### Université Libre de Bruxelles, Bruxelles, 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>

### Ghent University, Ghent, Belgium

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

### Université Catholique de Louvain, Louvain-la-Neuve, 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. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

### Université de Mons, Mons, Belgium

N. Bely

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

### Universidade do Estado do Rio de Janeiro, 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 Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, 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

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

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

**University of Sofia, Sofia, Bulgaria**

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

**Beihang University, Beijing, China**

W. Fang<sup>6</sup>

**Institute of High Energy Physics, 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

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

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

**Universidad de Los Andes, Bogota, Colombia**

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

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

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

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

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

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

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

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

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin

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

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

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

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

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

P. Eerola, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, 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



**Lappeenranta University of Technology, Lappeenranta, Finland**

J. Talvitie, T. Tuuva

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

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

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

**Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3**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**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, 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**Georgian Technical University, Tbilisi, Georgia**T. Toriashvili<sup>16</sup>**Tbilisi State University, Tbilisi, Georgia**Z. Tsamalaidze<sup>8</sup>**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**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, III. Physikalisches Institut A, 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 B, 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>**Deutsches Elektronen-Synchrotron, Hamburg, 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

**University of Hamburg, 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

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, 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

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

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

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

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

**University of Ioánnina, Ioánnina, Greece**

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

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

N. Filipovic

**Wigner Research Centre for Physics, 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

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

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

**Institute of Physics, University of Debrecen**

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

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

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

**Panjab University, Chandigarh, 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

**University of Delhi, Delhi, 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

**Saha Institute of Nuclear Physics, Kolkata, 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

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera

**Bhabha Atomic Research Centre, Mumbai, 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

**Tata Institute of Fundamental Research-A, 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-B, 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>

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

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

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

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

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

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>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, 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. Navarra<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>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, 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>

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, 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>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>17</sup>**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, 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>**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, 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>**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, 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**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, 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>**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, 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>**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, 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>**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**K. Androsov<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, 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>**INFN Sezione di Roma <sup>a</sup>, Università di Roma <sup>b</sup>, Roma, 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>**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, 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>**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, 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>

**Kyungpook National University, Daegu, Korea**

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

**Chonbuk National University, Jeonju, Korea**

A. Lee

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

H. Kim

**Hanyang University, Seoul, Korea**

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

**Korea University, Seoul, 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

**Seoul National University, Seoul, 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

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

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

**Vilnius University, Vilnius, Lithuania**

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

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

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

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

**Universidad Iberoamericana, Mexico City, Mexico**

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

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

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

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler

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

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

**National Centre for Nuclear Research, Swierk, Poland**

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

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

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

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

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. Vadrucchio, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

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

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

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

**Institute for Nuclear Research, Moscow, Russia**

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

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

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

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

A. Bylinkin<sup>39</sup>

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

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

**P.N. Lebedev Physical Institute, 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

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

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

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

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

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

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

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

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

**Universidad Autónoma de Madrid, Madrid, Spain**

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

**Universidad de Oviedo, Oviedo, Spain**

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

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

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

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

**Paul Scherrer Institut, Villigen, Switzerland**

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

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

**Universität Zürich, 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

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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 Taiwan University (NTU), Taipei, 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

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

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

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

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

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

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

**Bogazici University, Istanbul, Turkey**

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

**Istanbul Technical University, Istanbul, Turkey**

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

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

B. Grynyov

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

L. Levchuk, P. Sorokin

**University of Bristol, Bristol, United Kingdom**

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

**Rutherford Appleton Laboratory, Didcot, 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

**Imperial College, London, 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



**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, USA**

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

**The University of Alabama, Tuscaloosa, USA**

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

**Boston University, Boston, USA**

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

**Brown University, Providence, 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

**University of California, Davis, Davis, 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, Los Angeles, USA**

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

**University of California, Riverside, Riverside, 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, San Diego, La Jolla, 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, Santa Barbara - Department of Physics, Santa Barbara, 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

**California Institute of Technology, Pasadena, 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

**Carnegie Mellon University, Pittsburgh, USA**

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

**University of Colorado Boulder, Boulder, USA**

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

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J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fairfield University, Fairfield, USA**

D. Winn

**Fermi National Accelerator Laboratory, Batavia, 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

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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

**Florida International University, Miami, USA**

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

**Florida State University, Tallahassee, 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 Institute of Technology, Melbourne, USA**

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

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

**The University of Iowa, Iowa City, 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

**Johns Hopkins University, Baltimore, 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

**The University of Kansas, Lawrence, 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

**Kansas State University, Manhattan, USA**

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

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, 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

**Massachusetts Institute of Technology, Cambridge, 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

**University of Minnesota, Minneapolis, 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

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J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, 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

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

**Northeastern University, Boston, 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

**Northwestern University, Evanston, 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

**University of Notre Dame, Notre Dame, 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

**The Ohio State University, Columbus, 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

**Princeton University, Princeton, 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

**University of Puerto Rico, Mayaguez, USA**

S. Malik

**Purdue University, West Lafayette, 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 Calumet, Hammond, USA**

N. Parashar, J. Stupak

**Rice University, Houston, 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

**University of Rochester, Rochester, 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

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

**University of Tennessee, Knoxville, USA**

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

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

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

**Vanderbilt University, Nashville, 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

**University of Virginia, Charlottesville, 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

**Wayne State University, Detroit, USA**

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

**University of Wisconsin - Madison, Madison, WI, 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

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- 3: Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Helwan University, Cairo, Egypt
- 10: Now at Zewail City of Science and Technology, Zewail, Egypt
- 11: Now at Fayoum University, El-Fayoum, Egypt
- 12: Also at British University in Egypt, Cairo, Egypt
- 13: Now at Ain Shams University, Cairo, Egypt
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 16: Also at Tbilisi State University, Tbilisi, Georgia
- 17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 19: Also at University of Hamburg, Hamburg, Germany
- 20: Also at Brandenburg University of Technology, Cottbus, Germany
- 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 23: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 24: Also at Indian Institute of Science Education and Research, Bhopal, India
- 25: Also at Institute of Physics, Bhubaneswar, India
- 26: Also at University of Visva-Bharati, Santiniketan, India
- 27: Also at University of Ruhuna, Matara, Sri Lanka
- 28: Also at Isfahan University of Technology, Isfahan, Iran
- 29: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 30: Also at Yazd University, Yazd, Iran
- 31: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 32: Also at Università degli Studi di Siena, Siena, Italy
- 33: Also at Purdue University, West Lafayette, USA
- 34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 38: Also at Institute for Nuclear Research, Moscow, Russia
- 39: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 41: Also at University of Florida, Gainesville, USA
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia

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