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

A R T I C L E   I N F O

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

A B S T R A C T

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 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], 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 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.
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: \(\mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu\) and \(\mu\mu\mu\mu\) 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 magnet of 6.5 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 \((\mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu)\) 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 \(\psi\) 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 \(\mu\) mass \((m_\mu)\), with \(m_\mu = 50\) 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 \(m_\mu\) and \(m_\psi\). In addition, samples are generated with \(m_\psi\) 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 \(\mu\mu\mu\mu\) from 0.8 pb to 3.0 \(\times 10^{-6}\) pb, \(\mu\mu\mu\mu\) from 12.3 pb to 4.7 \(\times 10^{-5}\) pb, and \(\mu\mu\mu\mu\) and \(\mu\mu\mu\mu\) from 3.1 pb to 1.2 \(\times 10^{-5}\) pb. The branching fraction of \(\psi \rightarrow e^+e^-\) 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 \(Z\) decaying into four leptons. The QCD-induced \(Z\) 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 t\(\bar{t}\)W) are generated with PowHEG 1.0 [39]. Other processes, such as t\(\bar{t}\)Z and triboson production (WW\(\gamma\), WWZ, WZZ, and ZZ\(\gamma\)), 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 Z\(\gamma\) 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 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 \((\mu\mu\mu\mu, \mu\mu\mu\mu)\) 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 \((\mu\mu\mu\mu, \mu\mu\mu\mu)\) requires two clusters of energy deposits in the ECAL with transverse energy \(E_T > 33\) GeV each. For the \(\mu\mu\mu\mu\) 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 \(|d_0| < 0.2 \text{ cm}\) with respect to the PV, a longitudinal distance of the tracker track \(|d_1| < 0.5 \text{ cm}\) 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 $\psi$ boson ($m_\psi = 50$ GeV). In addition, if the direction of the second lepton candidate falls within the 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 $\psi$ boson can be highly Lorentz boosted if $m_\psi$ is significantly smaller than $m_{Z_2}$. This feature is generally found for high-mass ($m_{Z_2} > 1$ TeV) samples in the case of $m_\psi = 50$ GeV. This boosted signature introduces a significant inefficiency for the event selection except for the LFV case ($\psi$ decaying into $e\mu$). To take into account the boosted signature for $\psi$ decaying into $e\mu$, 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 $\psi$ 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 $m_{Z_2} = 3$ TeV and $m_\psi = 50$ 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 $\Delta R$ (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 85–93 GeV. The Z mass window is made as narrow as possible in order to minimize degradation of the signal efficiency in the case of $m_{Z_2} = m_Z$. This requirement results in negligible signal efficiency loss for $m_{Z_2} > 500$ GeV. At lower masses, the efficiency loss increases and is approximately 20 (7)% at $m_{Z_2} = 250$ GeV for the eee ($\mu\mu\mu\mu$) 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% ($\mu\mu\mu\mu$ and $\mu\mu\mu\mu$) and 45–65% (eee and eeee) throughout the range $m_{Z_2} > 1$ TeV for $m_\psi = 50$ GeV. Below $m_{Z_2} = 1$ TeV, the efficiency decreases rapidly because of the effect on the acceptance of the kinematic requirements. Heavier $m_\psi$ values correspond to a less boosted signature and therefore are selected with a higher efficiency. For $m_{Z_2} > 2$ TeV, the efficiency for the other $m_\psi$ samples is approximately 10–15% (1–5%) higher in the electron (muon) channels than for the $m_\psi = 50$ GeV scenario, where the range of values reflects the variation with $m_{Z_2}$. For $m_{Z_2} < 1$ TeV, the contribution from boosted events is not significant and the efficiency is similar for all values of $m_\psi$ 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 ($m_4$) 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 $m_{Z_2} > 1$ 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.
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 channel) 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 eee 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 ±1(2) standard deviation uncertainty in the expected limits, and the blue dashed line shows the theoretical $Z'$ cross section for $m_{\gamma} = 50$ GeV. This theoretical cross section is calculated under the benchmark model assumption that the branching fraction

![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, tZ processes; "EW" denotes the sum of the events from WW, WZ, WW\(\gamma\), WZ, and ZZ processes. The inset shows the expectation from the benchmark model for a signal at $m_{Z'} = 2.5$ TeV with $m_{\gamma} = 50$ GeV.](image-url)
the scenarios with \( m_\phi/m_Z = 5, 10, 20, 30 \) and 40\% of \( m_Z \), give slightly higher limits than the \( m_\phi = 50 \text{GeV} \) 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 \( \phi \to \ell\ell \) \((\ell = e \text{ or } \mu)\) is set to 1. These results are based on a sample of proton–proton collision data at \( \sqrt{s} = 8 \text{ TeV} \), corresponding to an integrated luminosity of 19.7 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 \( m_\phi = 50 \text{GeV} \), and for five different assumptions for the ratio \( m_\phi/m_Z \) \((m_\phi/m_Z = 5, 10, 20, 30 \text{ and } 40\%)\). Five decay channels \((\mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu, \mu\mu\mu\mu)\) 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: BMWFV and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COFECUB (Colombia); CSF (Croatia); DFG and HDF (Germany); INFN (Italy); CNRS; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSE (Croatia); RPI (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); PPARC (UK); and NSF (USAF).

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 Thalis and Aristeia
programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarian-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


The CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia


Institut für Hochenergiephysik, Wien, Austria

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

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


Universiteit Antwerpen, Antwerpen, Belgium


Vrije Universiteit Brussel, Brussels, Belgium


Université Libre de Bruxelles, Bruxelles, Belgium


Ghent University, Ghent, Belgium


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

N. Beliy

Université de Mons, Mons, Belgium


Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil


D. Matos Figueiredо, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote, A. Vilela Pereira

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


Universidade Estadual Paulista, 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

Beihang University, Beijing, China


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


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


University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim, Y. Mohammed, E. Salama

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

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. Mohanty17, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar
Bhabha Atomic Research Centre, Mumbai, India

Tata Institute of Fundamental Research-A, Mumbai, India

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. Chenarani28, E. Eskandari Tadavani, S.M. Etesami28, A. Fahim29, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi30, F. Rezaei Hosseinabadi, B. Safarzadeh31, M. Zeinali
Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald
University College Dublin, Dublin, Ireland

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

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

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

a INFN Sezione di Bologna, Bologna, Italy
b Università di Bologna, Bologna, Italy
L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, M. Cipriani\textsuperscript{a,b}, G. D’imperio\textsuperscript{a,b,17}, D. Del Re\textsuperscript{a,b,17}, M. Diemoz\textsuperscript{a}, S. Gelli\textsuperscript{a,b}, E. Longo\textsuperscript{a,b}, F. Margaroli\textsuperscript{a,b}, P. Meridiani\textsuperscript{a}, G. Organtini\textsuperscript{a,b}, R. Paramatti\textsuperscript{a}, F. Preiato\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}

\textsuperscript{a} INFN Sezione di Roma, Roma, Italy
\textsuperscript{b} Università di Roma, Roma, Italy

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

\textsuperscript{a} INFN Sezione di Torino, Torino, Italy
\textsuperscript{b} Università di Torino, Torino, Italy
\textsuperscript{c} Università del Piemonte Orientale, Novara, Italy

S. Belforte\textsuperscript{a}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, C. La Licata\textsuperscript{a,b}, A. Schizzi\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Trieste, Trieste, Italy
\textsuperscript{b} Università di Trieste, Trieste, Italy


Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonja, 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


Korea University, Seoul, Republic of Korea


Seoul National University, Seoul, Republic of Korea


University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania


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


CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland


Institute for Particle Physics, ETH Zurich, Zurich, Switzerland


Universität Zürich, Zurich, Switzerland


National Central University, Chung-li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan

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

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


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

B. Bilin, B. Bilmis, B. Isildak57, G. Karapinar58, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya59, O. Kaya60, E.A. Yetkin61, T. Yetkin62

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen63

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

University of Bristol, Bristol, United Kingdom


Rutherford Appleton Laboratory, Didcot, United Kingdom


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


Brown University, Providence, USA


University of California, Davis, Davis, USA


University of California, Los Angeles, USA


University of California, Riverside, Riverside, USA


University of California, San Diego, La Jolla, USA

The University of Iowa, Iowa City, USA


Johns Hopkins University, Baltimore, USA


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


University of Maryland, College Park, USA


Massachusetts Institute of Technology, Cambridge, USA


University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA


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


Northeastern University, Boston, 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


University of Wisconsin – Madison, Madison, WI, USA

1 Deceased.
2 Also at Vienna University of Technology, Vienna, Austria.
3 Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
4 Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France.
5 Also at Universidade Estadual de Campinas, Campinas, Brazil.
6 Also at Universidade Federal de Pelotas, Pelotas, Brazil.
7 Also at Université Libre de Bruxelles, Bruxelles, Belgium.
8 Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
9 Also at Joint Institute for Nuclear Research, Dubna, Russia.
10 Now at Helwan University, Cairo, Egypt.
11 Now at Zewail City of Science and Technology, Zewail, Egypt.
12 Also at Ain Shams University, Cairo, Egypt.
13 Also at American University in Cairo, 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, Erzin, 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.