Search for lepton flavour violating decays of heavy resonances and quantum black holes to an $e\mu$ pair in proton–proton collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration
CERN, 1211 Geneva 23, Switzerland

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Abstract A search for narrow resonances decaying to an electron and a muon is presented. The $e\mu$ mass spectrum is also investigated for non-resonant contributions from the production of quantum black holes (QBHs). The analysis is performed using data corresponding to an integrated luminosity of 19.7 fb$^{-1}$ collected in proton-proton collisions at a centre-of-mass energy of 8 TeV with the CMS detector at the LHC. With no evidence for physics beyond the standard model in the invariant mass spectrum of selected $e\mu$ pairs, upper limits are set at 95% confidence level on the product of cross section and branching fraction for signals arising in theories with charged lepton flavour violation. In the search for narrow resonances, the resonant production of a $\tau$ sneutrino in R-parity violating supersymmetry is considered. The $\tau$ sneutrino is excluded for masses below 1.28 TeV for couplings $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$, and below 2.30 TeV for $\lambda_{132} = \lambda_{231} = 0.07$ and $\lambda'_{311} = 0.11$. These are the most stringent limits to date from direct searches at high-energy colliders. In addition, the resonance searches are interpreted in terms of a model with heavy partners of the Z boson and the photon. In a framework of TeV-scale quantum gravity based on a renormalization of Newton’s constant, the search for non-resonant contributions to the $e\mu$ mass spectrum excludes QBH production below a threshold mass $M_{\text{th}}$ of 1.99 TeV. In models that invoke extra dimensions, the bounds range from 2.36 TeV for one extra dimension to 3.63 TeV for six extra dimensions. This is the first search for QBHs decaying into the $e\mu$ final state.

1 Introduction

Several extensions of the standard model (SM) predict the existence of heavy, short-lived states that decay to the $e\mu$ final state, and motivate the search for lepton flavour violating (LFV) signatures in interactions involving charged leptons. This paper reports a search for phenomena beyond the SM in the invariant mass spectrum of $e\mu$ pairs. The analysis is based on data with an integrated luminosity of 19.7 fb$^{-1}$ collected in proton-proton (pp) collisions at $\sqrt{s} = 8$ TeV with the CMS detector at the CERN LHC [1]. The results are interpreted in terms of three theoretically predicted objects: a $\tau$ sneutrino ($\tilde{\nu}_\tau$) lightest supersymmetric particle (LSP) in R-parity violating (RPV) supersymmetry (SUSY) [2], interfering LFV $Z'$ and $\gamma'$ bosons [3], and quantum black holes (QBHs) [4–6].

In RPV SUSY, lepton number can be violated at tree level in interactions between fermions and sfermions, and the $\tilde{\nu}_\tau$ may be the LSP [7]. For the resonant $\tilde{\nu}_\tau$ signal, the following trilinear RPV part of the superpotential is considered: $W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i E_j T_k + \lambda'_{ijk} L_i Q_j \tilde{T}_k$, where $i, j, k \in \{1, 2, 3\}$ are generation indices, $L$ and $Q$ are the $SU(2)_L$ doublet superfields of the leptons and quarks, and $\tilde{E}$ and $\tilde{T}$ are the $SU(2)_L$ singlet superfields of the charged leptons and down-like quarks. We assume that all RPV couplings vanish, except for $\lambda_{132}, \lambda_{231},$ and $\lambda'_{311}$, and consider a SUSY mass hierarchy with a $\tilde{\nu}_\tau$ LSP. In this model, the $\tilde{\nu}_\tau$ can be produced resonantly in pp collisions via the $\lambda'_{311}$ coupling and it can decay either into an $e\mu$ pair via the $\lambda_{132}$ and $\lambda_{231}$ couplings, or into a $d\bar{D}$ pair via the $\lambda'_{311}$ coupling. In this analysis we consider only the $e\mu$ final state and, for simplicity, we assume $\lambda_{132} = \lambda_{231}$.

The LFV $Z'$ signal is based on a model with two extra dimensions [3, 8], where the three generations of the SM arise from a single generation in higher-dimensional space-time. Flavour changing processes are introduced through the Kaluza–Klein modes of gauge fields that are not localised on a brane. In four-dimensional space-time, an effective Lagrangian can be obtained that contains two complex vector fields $Z'$ and $\gamma'$. These vector fields generate transitions between the families in which the generation number changes by unity, such as the process $d + \bar{s} \rightarrow Z'/\gamma' \rightarrow e^- + \mu^+$. 

*e-mail: cms-publication-committee-chair@cern.ch
and its charge conjugate. The structure of the terms in the Lagrangian for the production and decay of the $Z'$ and $\gamma'$ bosons is analogous to that describing the interactions of the $Z$ boson and the photon with quarks and charged leptons, respectively. The coupling strengths $g_{12}$ and $e_{12}$ are related to their SM counterparts through a multiplicative coupling modifier $\kappa$. For simplicity, the masses $M_{Z'}$ and $M_{\gamma'}$ are assumed to be equal, and the model is referred to as the LFV $Z'$ model. It is characterized by the two independent parameters $M_{Z'}$ and $\kappa$.

Theories that have a fundamental Planck scale of the order of a TeV [9–13] offer the possibility of producing microscopic black holes [14–16] at the LHC. In contrast to semiclassical, thermal black holes, which would decay to high-multiplicity final states, QBHs are non-thermal objects expected to decay predominantly to pairs of particles. We consider the production of a spin-0, colourless, neutral QBH in a model with lepton flavour violation, in which the cross section for QBH production is extrapolated from semiclassical black holes and depends on the threshold mass $M_{th}$ for QBH production and the number of extra dimensions $n$. For $n = 0$, it corresponds to a 3+1-dimensional model with low-scale quantum gravity, where a renormalization of Newton’s constant leads to a Planck scale at the TeV scale [13,17,18]; $n = 1$ corresponds to the Randall–Sundrum (RS) brane world model [9,10]; and $n > 1$ to the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [11,12].

We consider flat-space black holes (black holes that are spherical both in the brane and in the bulk dimensions) and, in the case of RS-type black holes ($n = 1$), consider only the regime in which almost flat five-dimensional space is an applicable metric. This is the case for $r_S \ll 1/(ke^{-k r_c})$, where $r_S$ is the Schwarzschild radius, $k$ denotes the Anti-de Sitter curvature, and $r_c$ is the size of the extra dimension. The threshold $M_{th}$ is assumed to be at the Planck scale in the definition of the Particle Data Group [19] for $n = 0$ and $n > 1$, whereas for $n = 1$ both the PDG and RS definitions [4] are adopted. In this model, the branching fraction of QBH decays to the $e^\pm \mu^\mp$ final state is 1.1 %, which is twice that of the dimuon or dielectron decay modes, making the $e^\pm \mu^\mp$ signature the most promising lepton decay channel. While the resonant $\tilde{\nu}_\tau$ and LFV $Z'$ signals result in a narrow peak in the invariant mass spectrum of the $e\mu$ pair, the mass distribution of the QBH signal is characterized by an edge at the threshold for QBH production, and a monotonically decreasing tail.

Direct searches for resonances in the $e\mu$ invariant mass spectrum with interpretations in terms of $\tilde{\nu}_\tau$ production have been carried out by the CDF [20] and D0 [21] collaborations at the Fermilab Tevatron and most recently by the ATLAS collaboration [22] using pp collision data at a centre-of-mass energy of 8 TeV at the LHC. For couplings $\lambda_{132} = 0.07$ and $\lambda_{311} = 0.11$, the most stringent of these limits stems from the search performed by the ATLAS collaboration, excluding at 95 % confidence level (CL) a $\tilde{\nu}_\tau$ below a mass of 2.0 TeV. Low-energy muon conversion experiments [23] yield strong limits as a function of the $\tau$ sneutrino mass on the product of the two RPV couplings $\lambda_{132}\lambda_{311} < 3.3 \times 10^{-7}$ $(M_{\tilde{\nu}_\tau}/1$ TeV)$^2$ at 90 % CL [24]. In the case of the $Z'$ signal, searches for $K^0_L \rightarrow e\mu$ decays constrain the coupling modifier $\kappa$. For the choice $M_{Z'} = M_{\gamma'}$, a bound of $\kappa \lesssim M_{Z'}/100$ TeV is obtained at 90 % CL [3,25].

There have been searches for QBHs decaying hadronically, by the CMS [26–28] and ATLAS [29,30] collaborations, and in the photon plus jet, lepton plus jet, dimuon, and dielectron final states, by the ATLAS collaboration [31–34]. This is the first search for QBH decays into the $e\mu$ final state.

The search for the phenomena beyond the SM described above is carried out for invariant masses of the $e\mu$ pair of $M_{e\mu} \geq 200$ GeV, which is the relevant region in light of existing constraints from other direct searches. Using the same event selection, the $e\mu$ invariant mass spectrum is searched for two different signal shapes: the shape associated with a narrow resonance that may be interpreted in terms of any model involving a resonance decaying promptly into an electron and a muon, and the more model-specific QBH signal shape. With a relative $e\mu$ invariant mass resolution ranging from 1.6 % at $M_{e\mu} = 200$ GeV to 6 % at $M_{e\mu} = 3$ TeV, the CMS detector is a powerful tool for searches for new physics in the $e\mu$ invariant mass spectrum.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules and measures charged particles within the pseudorapidity range $|\eta| < 2.5$. The ECAL consists of 75 848 lead tungstate crystals and provides coverage for $|\eta| < 1.479$ in a barrel region and $1.479 < |\eta| < 3.0$ in two endcap regions. Muons are measured in the range $|\eta| < 2.4$, with detection planes using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A two-level trigger system is used by the CMS experiment. The first level is composed of custom hardware processors and uses information from the calorimeters and muon detectors to select interesting events and to reduce the event rate from the initial bunch crossing frequency of 20 MHz to a.
maximum of 100 kHz. The high-level trigger processor farm further decreases the event rate to 400 Hz before data storage. A 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 Event selection

The search is designed in a model-independent way by requiring only one prompt, isolated muon and one prompt, isolated electron in the event selection. This minimal selection allows for a reinterpretation of the results in terms of models with more complex event topologies than the single $e\mu$ pair present in the signals considered in this paper.

The data sample is selected using a single-muon trigger with a minimum transverse momentum ($p_T$) requirement of $p_T > 40$ GeV. In order to allow the trigger to remain unprescaled, the pseudorapidity of the muons is constrained to values $|\eta| < 2.1$. Offline, each event is required to have a reconstructed $pp$ collision vertex with at least four associated tracks, located less than 2 cm from the centre of the detector in the plane transverse to the beam and less than 24 cm from it in the direction along the beam. The primary vertex is defined as the vertex with the largest sum of squared transverse momenta of its associated tracks.

The reconstruction and identification of electrons and muons is carried out using standard CMS algorithms, described in more detail in Refs. [36–40]. Reconstruction of the muon track starts from two tracks, one built in the silicon tracker and one built in the muon system. Hits used to reconstruct the tracks in the two systems are then used to reconstruct a track spanning over the entire detector [36]. Muon candidates are required to have a transverse momentum of $p_T > 45$ GeV with a measured uncertainty of $\delta(p_T)/p_T < 0.3$ and must fall into the acceptance of the trigger [36]. The candidate’s track must have transverse and longitudinal impact parameters with respect to the primary vertex position of less than 0.2 and 0.5 cm, respectively. At least one hit in the pixel detector, six or more hits in silicon-strip tracker layers, and matched segments in at least two muon detector planes are required to be associated with the reconstructed track. In order to suppress backgrounds from muons with jets, the scalar $p_T$ sum of all other tracks within a cone of size 0.3 in $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ (where $\phi$ is the azimuthal angle in radians) around the muon candidate’s track is required to be less than 10 % of the candidate’s $p_T$.

In the electron reconstruction, ECAL clusters are matched to silicon pixel detector hits, which are then used as seeds for the reconstruction of tracks in the tracker. Electron candidates are built from clusters with associated tracks and must lie within the barrel or endcap acceptance regions, with pseudorapidity of $|\eta| < 1.442$ and $1.56 < |\eta| < 2.5$, respectively, with a transverse energy $E_T > 35$ GeV. The transverse energy is defined as the magnitude of the projection on the plane perpendicular to the beam of the electron momentum vector normalized to the electron energy measured in the ECAL. Misidentification of jets as electrons is suppressed by requiring that the scalar sum of the $p_T$ of all other tracks in a cone of size 0.3 in $\Delta R$ around the electron candidate’s track is less than 5 GeV. In addition, the sum of the $E_T$ of calorimeter energy deposits in the same cone that are not associated with the electron candidate must be less than 3 % of the candidate’s $E_T$ (plus a small $\eta$-dependent offset). To minimise the impact of additional pp interactions in the same bunch crossing (pileup) on the selection efficiency, the calorimeter isolation is corrected for the average energy density in the event [41]. Further reduction of electron misidentification is achieved by requiring the transverse profile of the energy deposition in the ECAL to be consistent with the expected electron profile, and the sum of HCAL energy deposits in a cone of size 0.15 in $\Delta R$ to be less than 5 % of the electron’s ECAL energy. The transverse impact parameter of the electron candidate’s track with respect to the primary vertex must not exceed 0.02 cm and 0.05 cm, for barrel and endcap candidates, respectively, and the track must not have more than one missing hit in the layers of the pixel detector it crossed.

The trigger efficiency has been measured using the “tag-and-probe” technique in dimuon events from $Z$ decays described in [36,38,39]. The trigger efficiency for muons that pass the selection requirements is 92.9 % within $|\eta| < 0.9$, 83.1 % within $0.9 < |\eta| < 1.2$, and 80.3 % within $1.2 < |\eta| < 2.1$. The muon identification efficiency, including the isolation requirement, is measured with the tag-and-probe technique applied to muons from $Z$ boson decay using tracks in the inner silicon tracker as probes. The same efficiency of $95 \pm 1$ % (syst) is obtained in the three pseudorapidity regions $|\eta| < 0.9$, $0.9 < |\eta| < 1.2$, and $1.2 < |\eta| < 2.1$, with corresponding efficiency ratios between data and the simulation of $0.990 \pm 0.005$ (syst), $0.992 \pm 0.005$ (syst), and $0.995 \pm 0.005$ (syst). A $p_T$ range up to 300 GeV has been probed with the tag-and-probe method and the muon identification efficiencies remain constant within the statistical precision, as do the corresponding efficiency ratios between data and simulation. The evolution of the muon reconstruction and identification efficiencies and the muon trigger efficiency for muon $p_T > 300$ GeV is based on simulation. Using dielectron events from $Z$ boson decays [37], the total efficiency to reconstruct and select electrons with $p_T^e > 100$ GeV is found to be $88 \pm 2$ % (syst) in the barrel region and $84 \pm 4$ % (syst) in the endcaps. According to Monte Carlo (MC) simulation, the variation of these efficiencies with electron $p_T$ is less than $\pm 1$ % in the barrel and $\pm 2$ % in the endcaps. The corresponding efficiency ratios for $p_T^e > 100$ GeV between data and simulation are $0.985 \pm 0.014$ (syst) in the barrel and $0.981 \pm 0.004$ (syst)
in the endcaps. These efficiencies and efficiency ratios have been measured up to an electron $p_T$ of 1 TeV in the barrel and 500 GeV in the endcap regions.

In the event selection, at least one isolated muon and one isolated electron that both pass the identification criteria described above are required. After the application of all efficiency scale factors that correct the simulation to the efficiencies measured in data, the combined dilepton reconstruction and identification efficiency for RPV $\nu_{\tau}$ signal events within the detector acceptance is expected to be 80.6 % at $M_{\tilde{\nu}} = 200$ GeV and the full selection efficiency including the trigger requirement is 71.2 %. The MC simulation predicts that this efficiency is constant within 3 % for masses between 200 GeV and 3 TeV. The electron and the muon are not required to have opposite charge, in order to avoid a loss in signal efficiency due to possible electron charge misidentification at high electron $p_T$. Since highly energetic muons can produce bremsstrahlung resulting in an associated supercluster in the calorimeter in the direction of the muon’s inner track, they can be misidentified as electrons. Therefore, an electron candidate is rejected if there is a muon with $p_T$ greater than 5 GeV within $\Delta R < 0.1$ of the candidate. Only one $e\mu$ pair per event is considered. For about 1 % of the events passing the event selection there is more than one $e\mu$ pair in the event, in which case the pair with the highest invariant mass is selected.

## 4 Signal simulation

The RPV and QBH signal samples are generated with the CALCHEP (v. 3.4.1) event generator [42]. A cross section calculation at next-to-leading order (NLO) in perturbative QCD is used for the RPV signal [43], in which the factorization and renormalization scales are set to $M_{\tilde{\nu}}$, and the CTEQ6M [44] set of parton distribution functions (PDF) is used. The invariant mass distributions of reconstructed $e\mu$ pairs from simulated QBH signal samples are presented in Fig. 1 for different signal masses and numbers of extra dimensions. A more detailed description of the implemented QBH model including the dependence of the $M_{e\mu}$ spectrum from QBH decays on the model parameters is presented in Ref. [45]. The LFV $Z'$ signal events are produced with the MADGRAPH (v. 5.1.5.9) generator [46]. The effects of the interference resulting from the $M_{Z'} = M_{\gamma'}$ mass degeneracy on the cross section and signal acceptance are taken into account, and the coupling parameters of the model are taken to be the same as in Ref. [3]. All signal samples use the CTEQ6L1 [44] PDF, PYTHIA (v. 6.426) [47] for hadronization with the underlying event tune Z2*, and are processed through a simulation of the full CMS detector based on GEANT4 (v. 9.4) [48]. The PYTHIA Z2* tune is derived from the Z1 tune [49], which uses the CTEQ5L PDF set, whereas Z2* adopts CTEQ6L.

![Fig. 1 Invariant mass distributions of reconstructed $e\mu$ pairs from simulated QBH signal events that pass the event selection, normalized to unit area. The steps at the threshold masses $M_{\tilde{\nu}}$ are smeared out by the detector resolution.](image_url)

### Table 1

| $M_{\tilde{\nu}}$ (TeV) | $A$    | $A\epsilon$ | $M_{Z'}$ (TeV) | $A$    | $A\epsilon$ |
|-------------------------|-------|-------------|----------------|-------|-------------|
| 0.2                     | 0.59  | 0.42        | 0.25           | 0.57  | 0.39        |
| 0.5                     | 0.80  | 0.58        | 0.5            | 0.72  | 0.51        |
| 1.0                     | 0.89  | 0.64        | 1.0            | 0.83  | 0.59        |
| 1.5                     | 0.91  | 0.65        | 1.5            | 0.87  | 0.61        |
| 2.0                     | 0.92  | 0.65        | 2.0            | 0.89  | 0.62        |

The total acceptance times efficiency for each of the three signal models considered in this analysis is determined using MC simulation with selection efficiencies corrected to the values measured in data. The signal acceptance, as defined by the selection on the lepton $p_T$ and $\eta$ applied to the generated leptons in the signal simulation, and the product of acceptance and selection efficiency, are shown in Tables 1 and 2, evaluated for selected signal masses. The acceptance of the RPV $\nu_{\tau}$ model is that of a generic spin-0 resonance. In the case of the LFV $Z'$ model, the acceptance is more model-specific due to the interference between the $Z'$ and the $\gamma'$. This interference shapes the $\eta$ distributions of the leptons in the final state, which leads to a smaller acceptance compared to a generic spin-1 resonance. Table 3 lists the parameterizations of the acceptance times efficiency as a function of signal mass for the RPV $\nu_{\tau}$ and LFV $Z'$ resonance signals, resulting from fits in the mass range from 200 GeV to 2.5 TeV. These parameterizations are used later in the statistical interpretation of the resonance search.
Table 2 Signal acceptance (A) and the product of acceptance and efficiency (Aε) for different threshold masses $M_{th}$ for the QBH models with $n = 0$ and $n = 6$ extra dimensions. The acceptance is defined as the fraction of signal events in the simulation passing the selection on lepton $p_T$ and $η$ applied to the generated leptons.

| $M_{th}$ (TeV) | $n = 0$ | $n = 6$ |
|---------------|---------|---------|
|               | $A$     | $Aε$    | $M_{th}$ (TeV) | $A$     | $Aε$ |
| 0.5           | 0.85    | 0.61    | 0.5           | 0.82    | 0.60 |
| 1.0           | 0.90    | 0.63    | 1.0           | 0.89    | 0.64 |
| 2.0           | 0.93    | 0.64    | 2.0           | 0.93    | 0.65 |
| 3.0           | 0.94    | 0.63    | 3.0           | 0.94    | 0.64 |
| 4.0           | 0.94    | 0.62    | 4.0           | 0.94    | 0.63 |

Table 3 Parametrization of the product of signal acceptance and efficiency (Aε) as a function of signal mass M, for the RPV $\tilde{v}_τ$ and LFV $Z'$ models. The value of M is expressed in units of GeV.

| Model          | Functional form of Aε                               |
|----------------|-----------------------------------------------------|
| RPV $\tilde{v}_τ$ | $0.76 - 86.9/(61.4 + M) - 3.3 \times 10^{-5} M$    |
| LFV $Z'$         | $0.74 - 141.3/(165.6 + M) - 2.7 \times 10^{-5} M$ |

5 Background estimation

The SM backgrounds contributing to the $eμ$ final state can be divided into two classes of events. The first class comprises events with at least two prompt, isolated leptons. The second class consists of events with either jets or photons that are misidentified as isolated leptons, and events with jets containing non-prompt leptons. This second class of background is referred to as “non-prompt background” in this paper. The expected SM background from processes with two prompt leptons is obtained from MC simulations. It consists mostly of events from $t\bar{t}$ production and WW production; the former process is dominant at lower masses and the latter becomes equally important above $M_{ee} \sim 1$ TeV. Other background processes estimated from MC simulation are the additional diboson processes WZ and ZZ, single top $tW$ production, and Drell–Yan (DY) $ττ$ events with subsequent decay of the $τ$ pair into an electron and a muon. The $t\bar{t}$, $tW$, and WW simulated samples are generated using POWHEG (v. 1.0) [50–52] with the CT10 PDF [53], and the DY, WZ, and ZZ background samples are generated using the MADGRAPH (v. 5.1.3.30) event generator with the CTEQ6L1 PDF. All background samples use PYTHIA (v. 6.426) for hadronization with the underlying event tune Z2*. The generated events are processed through a full simulation of the CMS detector based on GEANT4 (v. 9.4). Pileup interactions are included in the simulation and event-dependent weights are applied in order to reproduce the number of pp interactions expected for the measured instantaneous luminosity. After this procedure, the distribution of the number of vertices per event observed in data is well described by the simulation. The simulated samples are normalized to the integrated luminosity of the data sample, 19.7 fb$^{-1}$. The cross sections are calculated to next-to-next-to-leading order (NNLO) accuracy in perturbative QCD for $t\bar{t}$ [54] and DY [55] and to NLO accuracy for the $tW$ [56], WW, WZ, and ZZ [57] processes.

The main sources of non-prompt background in the $eμ$ selection arise from W+jet and $Wγ$ production with a jet or photon that are misidentified as an electron. The Z+jet, QCD multijet, and $t\bar{t}$ processes yield subleading contributions to the background with non-prompt leptons. The $Wγ$ background is estimated from simulation based on the MADGRAPH (v. 5.1.3.30) event generator. A background estimation based on control samples in data, using the jet-to-electron misidentification rate (MR) method explained below, is used to determine the $M_{eeγ}$ distributions from W+jet and QCD multijet production. The measurement of the jet-to-electron misidentification rate has been carried out in the context of Ref. [40]. It starts from a sample collected using a prescaled single electromagnetic cluster trigger, in which the presence of an electron candidate with relaxed electron identification criteria is required. The events of the sample must have no more than one reconstructed electron with $E_T > 10$ GeV, in order to suppress the contribution from $Z$ decays. The misidentification measurement can be biased by selecting genuine electrons from W+jet events or converted photons from $γ$+jet events. Processes that can give a single electron, such as $t\bar{t}$, $tW$, WW, WZ, $Z \rightarrow ττ$, and $Z \rightarrow ee$ where, if a second electron is produced, it fails to be reconstructed, give another less significant source of contamination. Simulated samples are used to correct for this contamination and its effect on the MR. After these corrections, the electron MR, measured in bins of $E_T$ and $η$, is the number of electrons passing the full selection over the number of electron candidates in the sample.

Using the measured electron MR, the W+jet and QCD multijet contributions can be estimated from a sample with a muon passing the single-muon trigger and the full muon selection, and an electron candidate satisfying the relaxed selection requirements but failing the full electron selection. Each event in the sample is weighted by the factor MR/(1 − MR) to determine the overall contribution of the jet backgrounds. Contributions from processes other than W+jet and QCD multijet are subtracted from the sample to which the MR is applied, to avoid double counting. This subtraction is based on MC simulated background samples. A systematic uncertainty of 30% is applied to the jet background estimate, based on cross-checks and closure tests. An uncertainty of 50% is assigned to the background estimate for the $Wγ$ process, which is taken from simulation at leading order (LO) in perturbative QCD.
Results

After the event selection, 28 925 events are observed in data. The $e\mu$ invariant mass distribution is shown in Fig. 2, together with the corresponding cumulative distribution. A comparison of the observed and expected event yields is given in Table 4. The dominant background process is $t\bar{t}$, which contributes 69 % of the total background yield after selection, followed by $WW$ production, contributing 11 %. The two selected leptons carry opposite measured electric charge in 26 840 events and carry the same charge in 2085 events. According to the background estimation, 2100 ± 360 events with same-charge $e\mu$ pairs are expected, most of which stem from the $W$+jet process, followed by $t\bar{t}$ and diboson production $WZ/ZZ$.

The systematic uncertainties assigned to backgrounds obtained from simulation include the integrated luminosity (2.6 %) [58] and the acceptance times efficiency (5 %). The latter is based on the uncertainties in the various efficiency scale factors that correct the simulation to the efficiencies measured in data. According to simulation, the evolution of the lepton selection efficiencies from the $Z$ pole, where they are measured, to high lepton $p_T$ is covered within this uncertainty. The uncertainty in the muon momentum scale is 5 %.

![Fig. 2](image-url) The invariant mass distribution of selected $e\mu$ pairs (left), and the corresponding cumulative distribution, where all events above the mass value on the $x$-axis are summed (right). The points with error bars represent the data and the stacked histograms represent the expectations from SM processes. The label ‘Jets’ refers to the estimate of the $W$+jet and QCD multijet backgrounds from data. The ratio of the data to the background for each bin is shown at the bottom. The horizontal lines on the data points indicate the bin width.

| Total   | $<200$ | $200–400$ | $400–600$ | $600–1000$ | $>1000$ |
|---------|--------|-----------|-----------|------------|---------|
| $t\bar{t}$ | 20100 ± 1800 | 15800 ± 1400 | 4050 ± 450 | 260 ± 44 | 30 ± 7 | 0.9 ± 0.4 |
| $WW$    | 3150 ± 260 | 2400 ± 200 | 670 ± 64 | 68 ± 8 | 13 ± 2 | 0.9 ± 0.2 |
| $tW$    | 2000 ± 160 | 1550 ± 120 | 430 ± 40 | 30 ± 3 | 4 ± 0.5 | <0.2 |
| Jets    | 1570 ± 470 | 1250 ± 400 | 280 ± 83 | 30 ± 9 | 5 ± 2 | 0.6 ± 0.3 |
| DY      | 960 ± 100 | 910 ± 100 | 40 ± 15 | 5 ± 5 | <1 | <0.1 |
| WZ/ZZ   | 940 ± 80 | 670 ± 60 | 240 ± 20 | 27 ± 3 | 5 ± 0.6 | 0.3 ± 0.1 |
| $W\gamma$ | 480 ± 240 | 360 ± 180 | 100 ± 50 | 12 ± 6 | 3 ± 1.5 | 0.6 ± 0.3 |
| Total bkg | 29200 ± 2300 | 22900 ± 1800 | 5800 ± 560 | 430 ± 53 | 60 ± 9 | 3.5 ± 0.6 |
| Data    | 28925 | 22736 | 5675 | 448 | 65 | 1 |
per TeV. Electron energy scale uncertainties are 0.6 % in the barrel and 1.5 % in the endcap. These momentum and energy scale uncertainties cumulatively lead to an uncertainty in the total background yield of 2 % at $M_{\text{ej}} = 500$ GeV and 3.5 % at $M_{\text{ej}} = 1$ TeV. Uncertainties in the electron $E_T$ and muon $p_T$ resolutions have a negligible impact on the total background yield. The uncertainty associated with the choice of PDF in the background simulation is evaluated according to the PDF4LHC prescription [59, 60] and translates into an uncertainty in the total background yield of up to 13 % at $M_{\text{ej}} = 1$ TeV. Among the uncertainties in the cross sections used for the normalization of the various simulated background samples, the 5 % uncertainty in the NNLO QCD cross section of the dominant $t\bar{t}$ background [54] is the most relevant. Further uncertainties associated with the modelling of the shape of the $e\mu$ invariant mass distribution are taken into account for the two leading backgrounds: $t\bar{t}$ (higher-order corrections on the top-$p_T$ description discussed in [61]) and WW (scale uncertainties studied with the POWHEG generator). These lead to an uncertainty in the total background yield of up to 13 % at $M_{\text{ej}} = 1$ TeV. A further systematic uncertainty arises from the limited sizes of the simulated background samples at high invariant mass, where the background expectation is small. Taking all systematic uncertainties into account, the resulting uncertainty in the background yield ranges from 9 % at $M_{\text{ej}} = 200$ GeV to 18 % at $M_{\text{ej}} = 1$ TeV.

As shown in the cumulative invariant mass distribution in Fig. 2, we observe a deficit in data compared to the background expectation for $M_{\text{ej}} \geq 700$ GeV. In this invariant mass region, 17 events are observed and the background estimate yields 27 ± 4 (syst) events. Combining the systematic and statistical uncertainties, the local significance of this discrepancy is below 2$\sigma$.

No significant excess with respect to the expectation is found in the measured $e\mu$ invariant mass distribution, and we set limits on the product of signal cross section and branching fraction for signal mass hypotheses above 200 GeV. Two types of signal shapes are considered for the limit setting: a narrow resonance and the broader $e\mu$ invariant mass spectrum from QBH decays. The RPV $\tilde{\nu}_\tau$ and $Z'$ signals both result in a narrow resonance. For coupling values not excluded by existing searches, the QBH signal exhibits a broader shape with a sharp edge at the threshold mass $M_{\text{th}}$ and a tail towards higher masses (Fig. 1). The QBH signal shapes are obtained directly from simulated samples.

The systematic uncertainties in the signal entering the limit calculation are the 2.6 % uncertainty in the integrated luminosity, the 5 % uncertainty in the product of acceptance and efficiency, and the relative uncertainty in the mass resolution, which ranges from 5 % at $M_{\text{es}} = 200$ GeV to 10 % at $M_{\text{es}} = 1$ TeV. These uncertainties in the cross sections used for the normalization of the various simulated background samples, the 5 % uncertainty in the NNLO QCD cross section of the dominant $t\bar{t}$ background [54] is the most relevant. Further uncertainties associated with the modelling of the shape of the $e\mu$ invariant mass distribution are taken into account for the two leading backgrounds: $t\bar{t}$ (higher-order corrections on the top-$p_T$ description discussed in [61]) and WW (scale uncertainties studied with the POWHEG generator). These lead to an uncertainty in the total background yield of up to 13 % at $M_{\text{ej}} = 1$ TeV. A further systematic uncertainty arises from the limited sizes of the simulated background samples at high invariant mass, where the background expectation is small. Taking all systematic uncertainties into account, the resulting uncertainty in the background yield ranges from 9 % at $M_{\text{ej}} = 200$ GeV to 18 % at $M_{\text{ej}} = 1$ TeV.

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0.25 fb. For a comparison with earlier searches at hadron colliders [20,22], the two coupling benchmarks \( \lambda_{132} = \lambda_{231} = 0.07 \), \( \lambda'_{311} = 0.11 \) and \( \lambda_{132} = \lambda_{231} = 0.05 \), \( \lambda'_{311} = 0.10 \) are considered. For RPV couplings \( \lambda_{132} = \lambda_{231} = 0.07 \) and \( \lambda'_{311} = 0.11 \), we set a mass limit of 2.30 TeV, and improve the lower bound of 2.0 TeV previously set [22]. The lower bound on the signal mass for \( \lambda_{132} = \lambda_{231} = 0.05 \) and \( \lambda'_{311} = 0.10 \) is 2.16 TeV. In the narrow width approximation, the cross section times branching fraction scales with the RPV couplings as:

\[
\sigma B \sim \left( \lambda'_{311} \right)^2 \left( (\lambda_{132})^2 + (\lambda_{231})^2 \right) / (3 (\lambda'_{311}))^2 + (\lambda_{132})^2 + (\lambda_{231})^2).
\]

Using this relation and the observed upper cross section bounds, we derive the limit contour in the \((M_{\tilde{\nu}_\tau}, \lambda'_{311})\) parameter plane as a function of a fixed value of \( \lambda_{132} = \lambda_{231} \). For the results presented in Fig. 3 (right), values of the couplings \( \lambda'_{311} \) and \( \lambda_{132} = \lambda_{231} \) up to 0.2 and 0.07 are considered, respectively. The ratio of decay width to mass of the \( \tau \) sneutrino is less than 0.5 % for these coupling values and finite-width effects are small. Searches for resonant dijet production [27,29] that cover the \( \tau \) sneutrino decay to a \( \text{d}\bar{\text{d}} \) pair via the coupling \( \lambda'_{311} \) do not exclude this region of parameter space. In the model considered here with resonant production of the \( \tilde{\nu}_\tau \), we do not reach the sensitivity of muon conversion experiments, which lead to a bound on the coupling product of \( \lambda_{132} \lambda'_{311} < 3.3 \times 10^{-7} (M_{\tilde{\nu}_\tau}/1 \text{ TeV})^2 \) at 90 % CL, assuming \( \lambda_{132} = \lambda_{231} \). For comparison, with a signal mass of \( M_{\tilde{\nu}_\tau} = 1 \text{ TeV} \) and the assumption \( \lambda_{132} = \lambda_{231} = \lambda'_{311} \), we obtain a limit of \( \lambda_{132} \lambda'_{311} < 4.1 \times 10^{-5} \) at 90 % CL. We present results in terms of the product of the production cross section and branching fraction of the \( \tilde{\nu}_\tau \) that do not depend on a specific production mechanism of the sneutrino.

The 95 % CL limits on the signal cross section times branching fraction for the \( Z' \) signal, which exhibits a different acceptance from the spin-0 resonance in the RPV model, are presented in Fig. 4 (left). For the coupling modifier \( \kappa = 0.05 \), a lower bound on the signal mass \( M_{Z'} = M_{\nu'_{\tau}} \) of 1.29 TeV is obtained. Figure 4 (right) shows the corresponding limit contour in the \((M_{Z'}, \kappa)\) parameter plane. Since this resonance is produced dominantly in the \( \text{d}\bar{\text{d}} \) initial state, the bound from searches for muon conversion is not as strong as for the RPV \( \tilde{\nu}_\tau \) signal, but searches for \( K^0_L \rightarrow \mu^+ \mu^- \) decays yield a stringent exclusion limit of \( \kappa < M_{Z'}/100 \text{ TeV} \) at 90 % CL. This can be compared to our bound of \( \kappa = 0.031 \) at 90 % CL for \( M_{Z'} = M_{\nu'_{\tau}} = 1 \text{ TeV} \).

In the QBH search, we set limits on the mass threshold for QBH production, \( M_{\text{threshold}} \), in models with \( n = 0 \) to \( n = 6 \) extra dimensions. The 95 % CL limits on the signal cross section times branching fraction for the QBH signal are shown in Fig. 5. For \( n = 0 \) in a model with a Planck scale at the TeV scale from a renormalization of the gravitational constant, we exclude QBH production below a threshold mass \( M_{\text{threshold}} \) of 1.99 TeV. For \( n = 1 \), two signal cross sections are considered with the Schwarzschild radius evaluated in the RS and PDG conventions. The resulting limits on \( M_{\text{threshold}} \) are 2.36 TeV and 2.81 TeV, respectively. For ADD-type black holes with \( n > 1 \), we obtain lower bounds on \( M_{\text{threshold}} \) ranging from 3.15 TeV for \( n = 2 \) to 3.63 TeV for \( n = 6 \). A summary of the 95 %
Fig. 4 Left The 95% CL exclusion limit on the product of signal cross section and branching fraction for the $Z'$ signal as a function of the mass $M_{Z'}$. Right The 95% CL limit contour for the $Z'$ signal in the $(M_{Z'}, \kappa)$ parameter plane.

Fig. 5 The 95% CL exclusion limit on the product of signal cross section and branching fraction for the QBH signal as a function of the threshold mass $M_{th}$. The limits have been calculated using the signal shape of the QBH model without extra dimensions ($n=0$). For signal masses $M_{th} \geq 1$ TeV, the change in the QBH signal shape for different numbers of extra dimensions has a negligible impact on the limit.

Table 5 The 95% CL observed and expected lower bounds on the signal masses of $\tau$ sneutrinos in RPV SUSY, resonances in the LFV $Z'$ model, and QBHs, each with subsequent decay into an $e\mu$ pair. For the QBH signal with $n=1$, two signal cross sections are considered with the Schwarzschild radius evaluated in either the Randall–Sundrum (RS) or the Particle Data Group (PDG) convention.

| Signal model | Lower limit signal mass (TeV) |
|--------------|-------------------------------|
|              | Observed | Expected |
| RPV $\tilde{\nu}_\tau$ ($\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$) | 1.28 | 1.24 |
| RPV $\tilde{\nu}_\tau$ ($\lambda_{132} = \lambda_{231} = 0.05, \lambda'_{311} = 0.10$) | 2.16 | 2.16 |
| RPV $\tilde{\nu}_\tau$ ($\lambda_{132} = \lambda_{231} = 0.07, \lambda'_{311} = 0.11$) | 2.30 | 2.30 |
| LFV $Z'$ ($\kappa = 0.05$) | 1.29 | 1.25 |
| QBH $n=0$ | 1.99 | 1.99 |
| QBH $n=1$ (RS) | 2.36 | 2.36 |
| QBH $n=1$ (PDG) | 2.81 | 2.81 |
| QBH $n=2$ | 3.15 | 3.15 |
| QBH $n=3$ | 3.34 | 3.34 |
| QBH $n=4$ | 3.46 | 3.46 |
| QBH $n=5$ | 3.55 | 3.55 |
| QBH $n=6$ | 3.63 | 3.63 |

CL lower mass limits set for all signal models is presented in Table 5.

7 Summary

A search has been reported for heavy states decaying promptly into an electron and a muon using 19.7 fb$^{-1}$ of proton-proton collision data recorded with the CMS detector at the LHC at a centre-of-mass energy of 8 TeV. Agreement is observed between the data and the standard model expectation with new limits set on resonant production of $\tau$ sneutrinos in R-parity violating supersymmetry with subsequent decay into $e\mu$ pairs. For couplings $\lambda_{132} = \lambda_{231} = 0.01$ and $\lambda'_{311} = 0.01$, $\tau$ sneutrino lightest supersymmetric particles for masses $M_{\tilde{\nu}}$ below 1.28 TeV are excluded at 95% CL. For couplings $\lambda_{132} = \lambda_{231} = 0.07$ and $\lambda'_{311} = 0.11$, masses $M_{\tilde{\nu}}$ below 2.30 TeV are excluded. These are the most stringent
limits from direct searches at high-energy colliders. For the $Z'$
signal model, a lower mass limit of $M_{Z'} = M_{\gamma'} = 1.29$ TeV
is set at 95 % CL for the coupling modifier $\kappa = 0.05$. This
direct search for resonant production of an $e\mu$ pair at the
TeV scale does not reach the sensitivity of dedicated low-
energy experiments, but complements such indirect searches
and can readily be interpreted in terms of different signals
of new physics involving a heavy state that decays promptly
into an electron and a muon. Lower bounds are set on the
mass threshold for the production of quantum black holes
with subsequent decay into an $e\mu$ pair in models with zero
to six extra dimensions, assuming the threshold mass to be at
the Planck scale, ranging from $M_{\text{BH}} = 1.99$ TeV ($n = 0$)
to 3.63 TeV ($n = 6$). These are the first limits on quantum
black holes decaying into $e\mu$ final states.

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References

1. L. Evans, P. Bryant, LHC Machine, JINST 3, S08001 (2008). doi:10.1088/1748-0221/3/08/S08001
2. R. Barbieri et al., R-parity violating supersymmetry. Phys. Rep. 420, 1 (2005). doi:10.1016/j.physrep.2005.08.006.
    arXiv:hep-ph/0406039
3. J.M. Frere, M.V. Libanov, E.Y. Nugaev, S.V. Troitsky, Searching for family number conserving neutral gauge bosons from extra
dimensions. JETP Lett. 79, 598 (2004). doi:10.1134/1.1790014. arXiv:hep-ph/0404139
4. P. Meade, L. Randall, Black holes and quantum gravity at the LHC. JHEP 05, 003 (2008). doi:10.1088/1126-6708/2005/05/003.
    arXiv:0708.3017
5. X. Calmet, W. Gong, S.D.H. Hsu, Colorful quantum black holes at the LHC. Phys. Lett. B 668, 20 (2008). doi:10.1016/j.physletb.
    2008.08.011. arXiv:0806.4605
6. D.M. Gingrich, Quantum black holes with charge, colour, and spin at the LHC. J. Phys. G 37, 105008 (2010). doi:10.1088/0954-3899/
    37/10/105008. arXiv:0912.0820
7. M.A. Bernhardt, S.P. Das, H.K. Dreiner, S. Grab, Snuetrino as lightest supersymmetric particle in $B_3$ mSUGRA models and signals at
the LHC. Phys. Rev. D 79, 035003 (2009). doi:10.1103/PhysRevD.79.035003. arXiv:0810.3423
8. J.M. Frere, M.V. Libanov, E.Y. Nugaev, S.V. Troitsky, Fermions in the vortex background on a sphere. JHEP 06, 009 (2003). doi:10.1088/
    1126-6708/2003/06/009. arXiv:hep-ph/0304117
9. L. Randall, R. Sundrum, Large mass hierarchy from a small extra dimension. Phys. Rev. Lett. 83, 3370 (1999). doi:10.1103/
    PhysRevLett.83.3370. arXiv:hep-ph/9905221
10. L. Randall, R. Sundrum, An alternative to compactification. Phys. Rev. Lett. 83, 4690 (1999). doi:10.1103/PhysRevLett.83.4690.
    arXiv:hep-th/9906064
11. N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, The hierarchy problem and new dimensions at a millimeter. Phys. Lett. B 429, 263
(1998). doi:10.1016/S0370-2693(98)00466-3. arXiv:hep-ph/9803315
12. N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phenomenology, astrophysics, and cosmology of theories with submil-
limeter dimensions and TeV scale quantum gravity. Phys. Rev. D 59, 086004 (1999). doi:10.1103/PhysRevD.59.086004.
    arXiv:hep-ph/9807344
13. X. Calmet, S.D.H. Hsu, D. Reeb, Quantum gravity at a TeV and the renormalization of Newton’s constant. Phys. Rev. D 77, 125015
(2008). doi:10.1103/PhysRevD.77.125015. arXiv:0803.1836
14. T. Banks, W. Fischler, A model for high-energy scattering in quantum gravity (1999). arXiv:hep-th/9906038
15. S. Dimopoulos, G.L. Landsberg, Black holes at the LHC. Phys. Rev. Lett. 87, 161602 (2001). doi:10.1103/PhysRevLett.87.161602.
    arXiv:hep-ph/0106295
16. S.B. Giddings, S.D. Thomas, High-energy colliders as black hole factories: the end of short distance physics. Phys. Rev. D 65, 056010
(2002). doi:10.1103/PhysRevD.65.056010. arXiv:hep-ph/0106219
17. X. Calmet, A review of quantum gravity at the Large Hadron Collider. Mod. Phys. Lett. A 25, 1553 (2010). doi:10.1142/
    S0217732310033591. arXiv:1005.1805
55. Y. Li, F. Petriello, Combining QCD and electroweak corrections to dilepton production in the framework of the FEWZ simulation code. Phys. Rev. D 86, 094034 (2012). doi:10.1103/PhysRevD.86.094034. arXiv:1208.5967
56. N. Kidonakis, Differential and total cross sections for top pair and single top production (2012). arXiv:1205.3453
57. J.M. Campbell, R.K. Ellis, MCFM for the Tevatron and the LHC. Nucl. Phys. Proc. Suppl. 205–206, 10 (2010). doi:10.1016/j.nuclphysbps.2010.08.011. arXiv:1007.3492
58. CMS Collaboration, CMS luminosity based on pixel cluster counting—summer 2013 update. CMS Physics Analysis Summary CMS-PAS-LUM-13-001 (2013)
59. S. Alekhin et al., The PDF4LHC Working Group interim report (2011). arXiv:1101.0536
60. M. Botje et al., The PDF4LHC Working Group interim recommendations (2011). arXiv:1101.0538
61. N. Kidonakis, NNLO soft-gluon corrections for the top-quark \( p_T \) and rapidity distributions. Phys. Rev. D 91, 031501 (2015). doi:10.1103/PhysRevD.91.031501. arXiv:1411.2633
62. ATLAS and CMS Collaborations, Procedure for the LHC Higgs boson search combination in Summer 2011. Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-011 (2011)
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, A. Vilela Pereira

Universidade Estadual Paulista\textsuperscript{a}, Universidade Federal do ABC\textsuperscript{b}, São Paulo, Brazil
S. Ahuja\textsuperscript{a}, C. A. Bernardes\textsuperscript{b}, A. De Souza Santos\textsuperscript{b}, S. Dogra\textsuperscript{a}, T. R. Fernandez Perez Tome\textsuperscript{a}, E. M. Gregores\textsuperscript{b}, P. G. Mercadante\textsuperscript{b}, C. S. Moon\textsuperscript{a,7}, S. F. Novaes\textsuperscript{a}, Sandra S. Padula\textsuperscript{a}, D. Romero Abad\textsuperscript{b}, 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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, T. Cheng, R. Du, C. H. Jiang, D. Leggat, R. Plestina\textsuperscript{8}, F. Romeo, S. M. Shaheen, A. Spiezja, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogotá, Colombia
C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, B. Gomez Moreno, J. C. Sanabria

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano

Faculty of Science, University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

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. Bodlak, M. Finger\textsuperscript{9}, M. Finger Jr.\textsuperscript{9}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran\textsuperscript{10,11}, S. Elgamal\textsuperscript{10}, A. Ellithi Kamel\textsuperscript{12}, M. A. Mahmoud\textsuperscript{10,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kัดastik, M. Murumaa, 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, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malec, J. Rander, A. Rosowsky, M. Titov, A. Zghiche
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Fresch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann, S. M. Heindl, U. Husemann, I. Katkov, A. Kornmayer, P. Lobelle Pardo, B. Maier, H. Mildner, M. U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, 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. Geralis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, 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, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horváth, F. Sikler, V. Veszprémi, G. Vesztergombi, A. J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary
M. Bartok, A. Makovec, P. Raics, Z. L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S. Choudhury, P. Mal, K. Mandal, D. K. Sahoo, N. Sahoo, S. K. Swain

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, 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. Malhotra, M. Namuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty, L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik, R. M. Chatterjee, R. K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu, Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity, G. Majumder, K. Mazumdar, S. Mitra, G. B. Mohanty, B. Parida, T. Sarkar, N. Sur, B. Sutar, N. Wickr merge

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S. M. Etesami, A. Fahim, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald
INFN Sezione di Torino$^a$, Università di Torino$^b$, Turin, Italy, Università del Piemonte Orientale$^c$, Novara, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c,2}$, S. Arigo$^{a,b}$, M. Arneodo$^{a,c}$, R. Bellan$^{a,b}$, C. Biino$^a$, N. Cartiglia$^a$, M. Costa$^{a,b}$, R. Covarelli$^{a,b}$, P. De Remigis$^a$, A. Degano$^{a,b}$, N. Demaria$^a$, L. Finco$^{a,b,2}$, C. Mariotti$^a$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, E. Monteli$^{a,b}$, M. M. Obertino$^{a,b}$, L. Pacher$^{a,b}$, N. Pastrone$^a$, M. Pelliccioni$^a$, G. L. Pinna Angioni$^{a,b}$, F. Ravera$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, A. Staiano$^a$

INFN Sezione di Trieste$^a$, Università di Trieste$^b$, Trieste, Italy
S. Belforte$^a$, V. Candelise$^{a,b}$, M. Casarsa$^a$, F. Cossutti$^a$, G. Della Ricca$^{a,b}$, B. Gobbo$^a$, C. La Licata$^{a,b}$, M. Marone$^{a,b}$, A. Schizzi$^{a,b}$, A. Zanetti$^a$

Kangwon National University, Chunchon, Korea
A. Kropivnitskaya, S. K. Nam

Kyungpook National University, Daegu, Korea
D. H. Kim, G. N. Kim, M. S. Kim, D. J. Kong, S. Lee, Y. D. Oh, A. Sakharov, D. C. Son

Chonbuk National University, Jeonju, Korea
J. A. Brochero Cifuentes, H. Kim, T. J. Kim

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

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

Seoul National University, Seoul, Korea
H. D. Yoo

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, D. Kim, E. Kwon, 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$^{33}$, F. Mohamad Idris$^{34}$, W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz$^{35}$, A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H. A. Salazar Ibarguen, 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, S. Qazi, M. Shoaib, M. Waqas
CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, G. M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D’Alfonso, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M. J. Kortelainen, K. Kousouris, K. Krajezcar, P. Lecoq, C. Lourenço, M. T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijsers, S. Mersi, E. Meschi, F. Morogtang, S. Morovic, M. Mulders, M. V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrunciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwieck, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G. I. Veres, N. Wardle, H. K. Wöhri, A. Zagozdzinska, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Himlicher, 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. Dossertoni, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoff, G. Kasieczka, P. Lecomte, W. Lüstermann, 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, L. Perrozzi, M. Quitin, M. Rossini, M. Schönenberger, D. Starodumov, M. Takahashi, V. R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T. K. Aarrestad, C. Amsler, L. Caminada, M. F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K. H. Chen, 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, U. Grundler, W.-S. Hou, Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Petracou, J. P. Tsai, Y. M. Tseng

Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci, S. Damarseckin, Z. S. Demiroglu, C. Dozen, D. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hoss, E. Kanga, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, B. Tali, H. Topakli, C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey
B. Bilin, B. Bilmis, B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmey, M. Kaya, O. Kaya, E. A. Yetkin, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen, F. I. Vardarlı

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 Rochester, Rochester, USA
B. Betchart, A. Bodek, F. de Barbaro, R. Demina, Y. Eshaq, 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
J. P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, 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, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali70, A. Castaneda Hernandez70, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon71, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer2

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S. W. Lee, T. Li, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A. G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M. W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hierosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P. E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin-Madison, Madison, WI, USA
D. A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W. H. Smith, D. Taylor, P. Verwilligen, N. Woods

† Deceased

1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at Centre National de la Recherche Scientifique (CNRS)-IN2P3, Paris, France
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Joint Institute for Nuclear Research, Dubna, Russia
10: Also at British University in Egypt, Cairo, Egypt
11: Now at Suez University, Suez, Egypt
12: Also at Cairo University, Cairo, Egypt
13: Also at Fayoum University, El-Fayoum, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, USA
32: Now at Hanyang University, Seoul, Korea
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
39: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at California Institute of Technology, Pasadena, USA
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Università di Roma, Rome, Italy
44: Also at National Technical University of Athens, Athens, Greece
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
48: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Mersin University, Mersin, Turkey
51: Also at Cag University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Yildiz Technical University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, UK
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, USA
65: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
66: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
67: Also at Argonne National Laboratory, Argonne, USA
68: Also at Erzincan University, Erzincan, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea