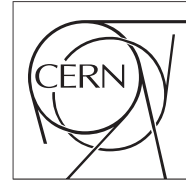


The Compact Muon Solenoid Experiment

# Conference Report

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## Search for R-parity violating supersymmetry and quantum black-holes in $e\mu$ final state in CMS

Swagata Mukherjee for the CMS Collaboration

### Abstract

A search for narrow resonances decaying to an electron and a muon is performed using an integrated luminosity of  $2.7 \text{ fb}^{-1}$  of 13 TeV proton-proton collision data recorded with the CMS detector at the LHC. The  $e\mu$  mass spectrum is also investigated for non-resonant contributions from the production of quantum black holes (QBH). 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 1.0 TeV for couplings  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$  and below 3.3 TeV for  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.2$ . In a framework of TeV-scale quantum gravity, for models that invoke extra dimensions, the observed exclusion limits for the threshold mass of QBH production range from 2.5 TeV for one extra dimension to 4.5 TeV for six extra dimensions.

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# Search for R-parity violating supersymmetry and quantum black-holes in $e\mu$ final state in CMS

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**Abstract.** A search for narrow resonances decaying to an electron and a muon is performed using an integrated luminosity of  $2.7 \text{ fb}^{-1}$  of 13 TeV proton-proton collision data recorded with the CMS detector at the LHC. The  $e\mu$  mass spectrum is also investigated for non-resonant contributions from the production of quantum black holes (QBH). 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 1.0 TeV for couplings  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$  and below 3.3 TeV for  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.2$ . In a framework of TeV-scale quantum gravity, for models that invoke extra dimensions, the observed exclusion limits for the threshold mass of QBH production range from 2.5 TeV for one extra dimension to 4.5 TeV for six extra dimensions.

## 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 document reports a search for phenomena beyond the SM in the invariant mass spectrum of  $e\mu$  pairs. The analysis [1] is based on data with an integrated luminosity of  $2.7 \text{ fb}^{-1}$  collected in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  with the CMS detector [2] at the CERN LHC. The results are interpreted in terms of two theoretical models: a  $\tau$  sneutrino, which is assumed to be the lightest supersymmetric particle (LSP) in R-parity violating (RPV) supersymmetry (SUSY) and another interpretation comes from quantum black holes (QBH) with models that invoke extra spatial dimensions.

In RPV SUSY, lepton number can be violated at tree level in interactions between fermions and sfermions. We assume that all R-parity violating couplings are zero, except for  $\lambda_{132}$ ,  $\lambda_{231}$  and  $\lambda'_{311}$ , which are connected to the production and decay of the  $\tau$  sneutrino. In this model, the  $\tau$  sneutrino can decay either into the final state under study, an  $e\mu$  pair, via the couplings  $\lambda_{132}$  and  $\lambda_{231}$  or into  $d\bar{d}$

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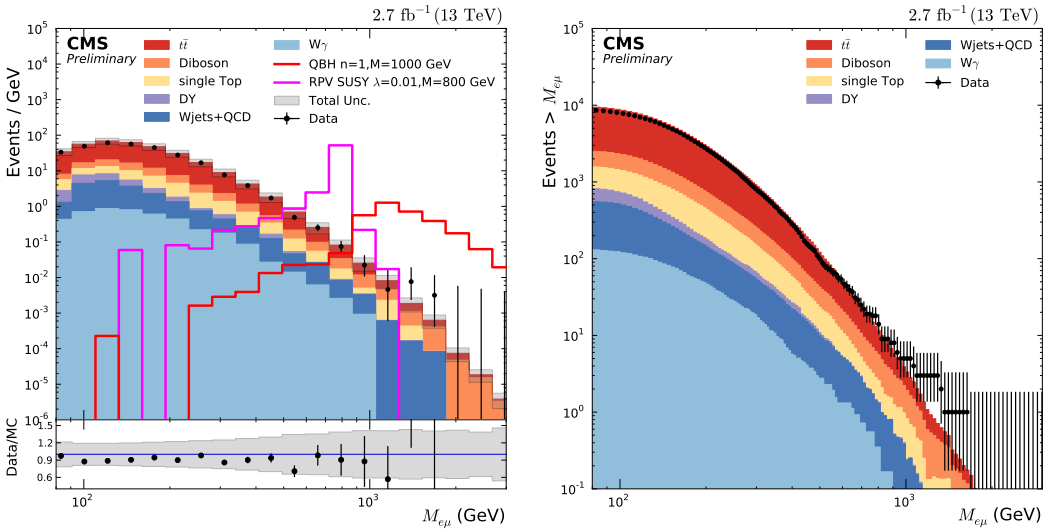
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via the coupling  $\lambda'_{311}$ . For simplicity, we assume  $\lambda_{132} = \lambda_{231}$  in all the presented results. Also, we consider a SUSY mass hierarchy where the  $\tau$  sneutrino is the LSP.

Theories that allow for a fundamental Planck scale at the TeV scale offer the possibility of the production of microscopic black holes at the LHC. In contrast to semiclassical, thermal black holes, which would decay to high-multiplicity final states, QBHs are non-thermal objects which are expected to decay predominantly into two-particle final states. We consider the production of a spin-0, colourless, charge-neutral QBH in a model with lepton flavour violation, in which the cross section for QBH production is extrapolated from the semiclassical case and depends on the threshold mass for QBH production,  $M_{th}$ , and the number of extra dimensions  $n$ . The  $n = 1$  case corresponds to the Randall-Sundrum (RS) [3] brane world model and  $n > 1$  to the Arkani-Hamed-Dimopoulos-Dvali (ADD) [4] model.

## 2 Analysis Strategy

The search is designed in a model-independent way by only requiring one prompt muon and one prompt electron in the event selection. The data sample is selected using a single-muon trigger. In the offline analysis, muon candidates are required to have a transverse momentum of  $p_T > 53$  GeV and must fall into the acceptance region  $|\eta| < 2.4$ . The muon and electron candidates are required to



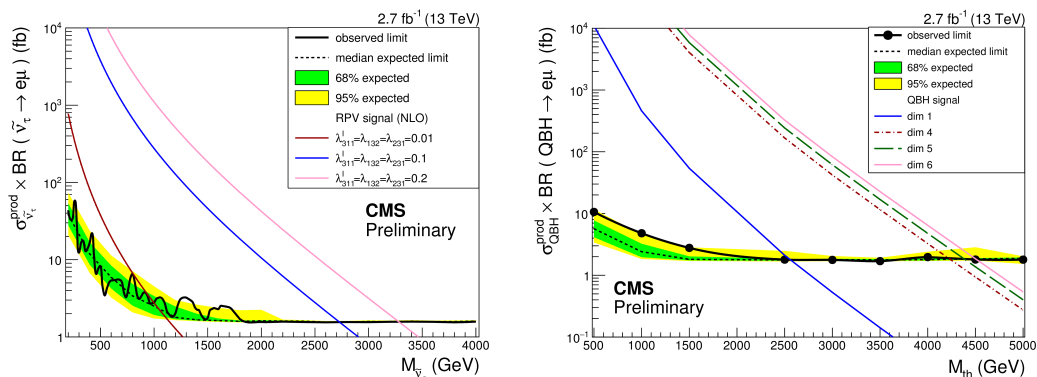
**Figure 1.** Left: The invariant mass distribution of selected  $e\mu$  pairs [1]. The black points with error bars represent data and the stacked histograms represent the expectations from SM processes. The combined statistical and systematic uncertainty is labeled total uncertainty. Right: The cumulative distribution of the invariant mass of selected  $e\mu$  pairs [1], where all events above the mass value on the X-axis are summed up.

pass the high  $p_T$  identification criteria. 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  $E_T$ . Since highly energetic muons can produce bremsstrahlung and an associated supercluster in the calorimeter in the direction of the muons 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 electron candidate. Only one  $e\mu$  pair per event is considered. If there is more than one  $e\mu$  pair in the event, the pair with the highest invariant mass is selected.

### 3 Results

After the event selection, 9608 events are observed in data in the complete mass spectrum, where the expectation from SM background is 10379. The  $e\mu$  invariant mass distribution is shown in

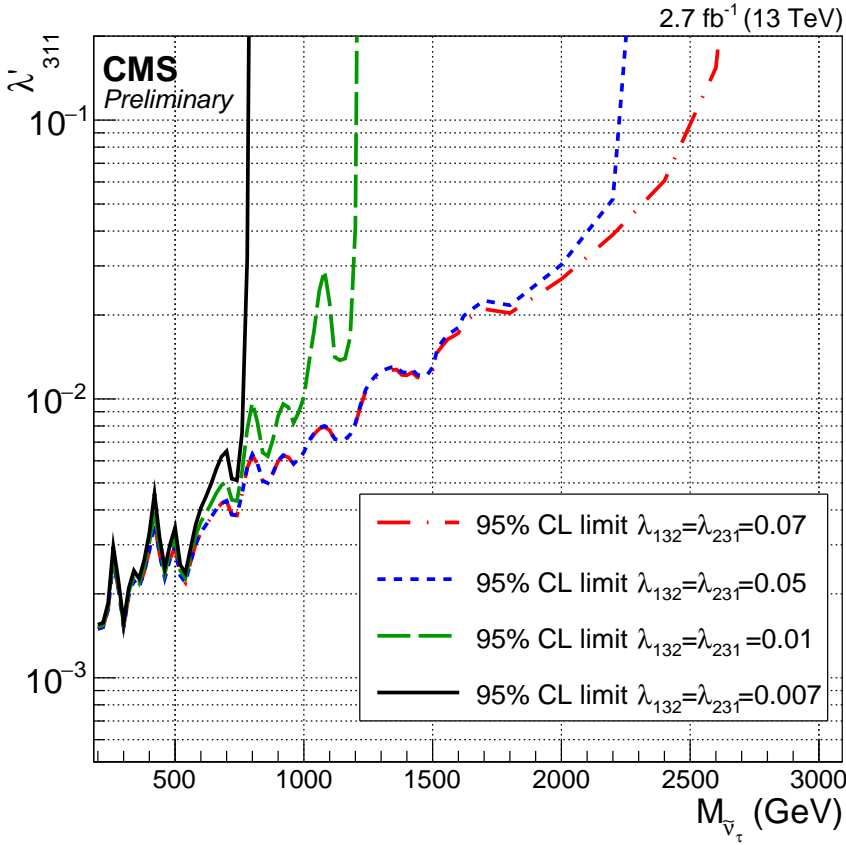


**Figure 2.** Left: 95% CL upper limit on the signal cross section times branching fraction for the RPV  $\tau$  sneutrino signal as a function of the mass of the resonance [1]. Right: 95% CL upper limit on the signal cross section times branching fraction for the QBH signal as a function of the threshold mass [1].

Fig. 1, together with the corresponding cumulative distribution. The lower panel of Fig. 1-left shows the combined statistical and systematic uncertainty as grey band. Shape of  $t\bar{t}$  background leads to the dominant systematic uncertainty in the total background yield of up to 26% at  $M_{e\mu} = 1$  TeV. Other important sources of systematic uncertainties include integrated luminosity, background cross section, muon and electron momentum scale and resolution, choice of PDF etc. Taking all systematic uncertainties into account, the resulting uncertainty on the background yield ranges from 15% at  $M_{e\mu} = 200$  GeV to 31% at  $M_{e\mu} = 2$  TeV.

No significant excess with respect to the SM expectation is found in the measured  $e\mu$  invariant mass distribution, and limits are set on the signal cross section times branching fraction. The RPV SUSY and QBH signal samples have been generated with the CALCHEP [5] and the QBH 2.0 [6] event generators respectively. All simulated samples use PYTHIA 8 [7] for hadronization. The generated events are processed through a full simulation of the CMS detector based on GEANT 4 [8]. The full selection efficiency of RPV  $\tau$  sneutrino signal is 65.8% at  $M_{\tilde{\nu}_\tau} = 1$  TeV and that of QBH signal is 66.6% at  $M_{th} = 1$  TeV. The SM backgrounds contributing to the  $e\mu$  final state can be divided into two categories:

- **Real lepton:** Backgrounds with at least two prompt, isolated leptons. The expected SM background from processes with two prompt leptons is obtained from MC simulations. It consists mostly of events from  $t\bar{t}$  and WW production. Other background processes estimated from MC simulation are WZ, ZZ, single top, and Drell-Yan (DY) production.
- **Fake lepton:** Backgrounds where jets or photons are misidentified as leptons. The main sources of non-prompt background in the  $e\mu$  selection arise from W+jets and QCD production, where a



**Figure 3.** 95% CL limit contours for the RPV  $\tau$  sneutrino signal in the  $(M_{\tilde{\tau}}, \lambda'_{311})$  parameter plane [1]. The values of the parameter  $\lambda_{132} = \lambda_{231}$  are fixed to 0.07 (red dashed and dotted), 0.05 (blue small-dashed), 0.01 (green dashed), and 0.007 (black solid). The regions above the curves are excluded.

jet is misidentified as a lepton; and  $W\gamma$  production, where a photon is misidentified as a lepton. The estimate of the  $W\gamma$  background is obtained from MC simulation. A data-driven background estimation based on control samples, using the jet-to-electron fake rate method, is used to determine the contribution from  $W$ +jets and QCD multijet production.

An upper limit of 95% confidence level on the cross section times branching ratio is determined using a binned likelihood Bayesian approach with a uniform prior for the signal cross section. The nuisance parameters associated with the systematic uncertainties are marginalised, and a Markov Chain Monte Carlo method is used for integration.

In RPV SUSY, the  $\tau$  sneutrino signal gives rise to a narrow resonance. For coupling values considered in this search, the intrinsic width of this signal is small compared to the detector resolution and a Gaussian is used to model the signal shape. For each probed resonance signal mass, the two parameters, acceptance times efficiency and invariant mass resolution, determine the normalization

and shape of the signal model respectively. The parameterization of the narrow resonance allows for a scan of the invariant mass spectrum with a fine spacing of the signal mass hypothesis. The QBH signal exhibits a broader shape with a sharp edge at the threshold mass  $M_{th}$  and a tail towards higher masses. The QBH signal shapes are obtained directly from simulated samples.

The 95% CL limits on the signal cross section times branching ratio for the RPV  $\tau$  sneutrino resonance signal are shown in Fig. 2-left. The corresponding mass limits are presented in table 1. The 95% CL limits on the signal cross section times branching ratio for the QBH non-resonant signal are shown in Fig. 2-right. The corresponding limits on threshold mass are presented in table 2. The limit contour is also derived in the  $(M_{\tilde{\tau}_\nu}, \lambda'_{311})$  parameter plane as a function of fixed values of  $\lambda_{132} = \lambda_{231}$ . The result is given in Fig. 3.

**Table 1.** The 95% CL observed and expected lower bounds on the signal masses of  $\tau$  sneutrinos in RPV SUSY

RPV coupling	Expected lower bound	Observed lower bound
$\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$	1.0 TeV	1.0 TeV
$\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.1$	2.7 TeV	2.7 TeV
$\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.2$	3.3 TeV	3.3 TeV

**Table 2.** The 95% CL observed and expected lower bounds on the threshold masses of QBH production in models with extra dimensions

Number of extra dimensions	Expected lower bound	Observed lower bound
$n = 1(\text{RS})$	2.5 TeV	2.5 TeV
$n = 4(\text{ADD})$	4.2 TeV	4.2 TeV
$n = 5(\text{ADD})$	4.3 TeV	4.3 TeV
$n = 6(\text{ADD})$	4.5 TeV	4.5 TeV

## 4 Conclusion

A search for a heavy resonance decaying into an  $e\mu$  pair has been carried out using  $2.7 \text{ fb}^{-1}$  of proton-proton collision data recorded with the CMS detector at the LHC at  $\sqrt{s} = 13 \text{ TeV}$ . Agreement between the data and the SM expectation is observed. We set limits on the resonant production of  $\tau$  sneutrinos in RPV SUSY with subsequent decay into  $e\mu$  pair. For couplings  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$ , a  $\tau$  sneutrino LSP is excluded for masses below 1.0 TeV, for couplings  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.1$  masses below 2.7 TeV are excluded and for couplings  $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.2$ , masses below 3.3 TeV are excluded. The corresponding expected limits are 1.0 TeV, 2.7 TeV and 3.3 TeV. Lower bounds are set on the mass thresholds for the production of quantum black holes with subsequent decay into  $e\mu$  pair in models with one to six extra dimensions, assuming the threshold mass to be at the Planck scale. The limits range from  $M_{th} = 2.5 \text{ TeV}$  ( $n = 1$ , RS model) to 4.5 TeV ( $n = 6$  ADD model).

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