Probes of new physics in final states with two taus and two muons

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Overview

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Introduction

- The recent experimental results of muon $g-2$ (from the Fermilab) and the lepton flavor universality violation in rare B-meson decays (from the LHCb, Belle, BaBar) could be the hints ($> 3\sigma$ anomalies) of new physics beyond the Standard Model.
- RPV3: Assuming the mass of third generation sfermions lighter than the other two generations, RPV3 preserves gauge coupling unification and has the usual attribute of naturally addressing the Higgs radiative stability. Altmannshofer, Dev, Soni (PRD 2017).
- Under a minimal RPV3 SUSY framework, there exist some scenarios that can simultaneously address all these flavor anomalies, while being consistent with the existing low-energy constraints and the high-energy collider limits. Altmannshofer, Dev, Soni, Sui (PRD 2020); Dev, Soni, Xu (PRD 2022).

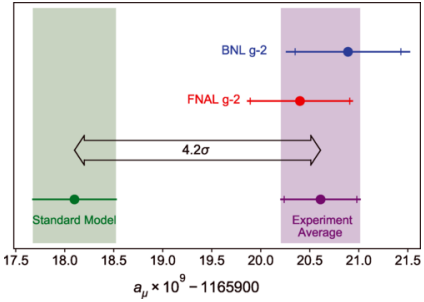
Introduction

$$\mathcal{L}_{LQD} = \lambda'_{ijk}(\widetilde{\nu}_{i\mathrm{L}}\overline{d}_{k\mathrm{R}}d_{j\mathrm{L}} + \widetilde{d}_{j\mathrm{L}}\overline{d}_{k\mathrm{R}}\nu_{i\mathrm{L}} + \widetilde{d}^*_{k\mathrm{R}}\overline{\nu}^c_{i\mathrm{L}}d_{j\mathrm{L}} - \widetilde{e}_{i\mathrm{L}}\overline{d}_{k\mathrm{R}}u_{j\mathrm{L}} - \widetilde{u}_{j\mathrm{L}}\overline{d}_{k\mathrm{R}}e_{i\mathrm{L}} - \widetilde{d}^*_{k\mathrm{R}}\overline{e}^c_{i\mathrm{L}}u_{j\mathrm{L}}) + \mathrm{H.c.} \tag{1}$$

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\widetilde{\nu}_{i\mathrm{L}}\overline{e}_{k\mathrm{R}}e_{j\mathrm{L}} + \widetilde{e}_{j\mathrm{L}}\overline{e}_{k\mathrm{R}}\nu_{i\mathrm{L}} + \widetilde{e}^*_{k\mathrm{R}}\overline{\nu}^c_{i\mathrm{L}}e_{j\mathrm{L}} - (i \leftrightarrow j)\right] + \mathrm{H.c.} \tag{2}$$

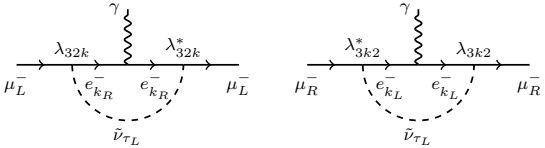
- A distinct feature of our RPV3 scenarios is the orthogonality between the sbottom and the sneutrino parameter spaces: the sneutrino with LLE interactions gives the main contribution to muon $g-2$ anomaly and the sbottom with LQD interactions accounts for $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies. Dev, Soni, Xu (PRD 2022)
- Focusing on the muon $g-2$ anomaly, we propose another scenario in the sneutrino parameter space that leads to a better and specific collider signal $\tau^+\tau^-\mu^+\mu^-$ from the sneutrino pair production.

$(g-2)_\mu$ anomaly



B. Abi et al. (PRL 2021)

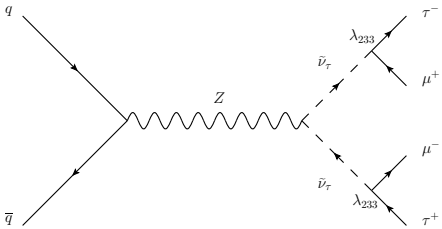
$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$ has a significance of 4.2σ.



Relevant contribution to the $(g-2)_\mu$ from $\widetilde{\nu}_\tau$ and λ couplings

$$\Delta a_\mu = \frac{m_\mu^2}{96\pi^2}\sum_{k=1}^{3}\left(\frac{2(|\lambda_{32k}|^2+|\lambda_{3k2}|^2)}{m^2_{\widetilde{\nu}_\tau}} - \frac{|\lambda_{3k2}|^2}{m^2_{\widetilde{\tau}_L}} - \frac{|\lambda_{k23}|^2}{m^2_{\widetilde{\tau}_R}} + \frac{3|\lambda'_{2k3}|^2}{m^2_{\widetilde{b}_R}}\right)$$

Collider signal $\tau^+\tau^-\mu^+\mu^-$



Signal: $\widetilde{\nu}_\tau$ pair production with $\widetilde{\nu}_\tau \to \tau^-\mu^+$ through λ_{233} coupling

Cannot have $\tau^\pm\tau^\pm\mu^\mp\mu^\mp$ $\Leftarrow$ the structure of LLE interactions

$(\frac{1}{2}\lambda_{ijk}[\widetilde{\nu}_{i\mathrm{L}}\overline{e}_{k\mathrm{R}}e_{j\mathrm{L}} - (i \leftrightarrow j)] + \mathrm{H.c.},$
$\widetilde{\nu}_\tau \to \tau^+\mu^-$ not allowed)

Two dominant decay modes in our scenario: BR($\widetilde{\nu}_\tau \to \tau^-\mu^+$) and BR($\widetilde{\nu}_\tau \to \widetilde{\chi}_1^0\nu_\tau$)

Cannot produce $\widetilde{\nu}_\tau$ through quark lines in our scenario $\Leftarrow$ orthogonality (switching off λ'_{3ij} couplings) or focusing on $(g-2)_\mu$ only (switching off the entire LQD interactions)

Otherwise, would have a strong single production of $\widetilde{\nu}_\tau$

$\Leftarrow$ constraints

Dev, Soni, Xu (PRD 2022) for detailed analysis

Event selection and background

- We set limits on our model using existing analysis done by the ATLAS collaboration in ATLAS Collaboration•Aaboud et al. (PRD 2018), using the data recorded during Run-2 of the LHC with a center-of-mass energy of $\sqrt{s} = 13$ TeV and integrated luminosity of 36.1 fb^{-1}, and show that the sensitivity can be enhanced with dedicated selections.

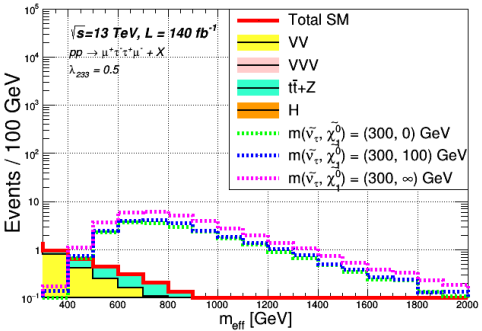
Selection	SR2	SR2-$\mu\mu$
N_ℓ	$= 2$	$= 2$
N_μ	0-2	$= 2$
N_e	0-2	$= 0$
$N_{\tau_{\text{had}}^{\text{vis}}}$	≥ 2	
$m_{\ell\ell}^{\text{OSSF}}$ [GeV]	< 81.2 & > 101.2	
$m_{\ell\ell\ell}^{\text{OSSF}}$ [GeV]	< 81.2 & > 101.2	
m_{eff} [GeV]	> 650	

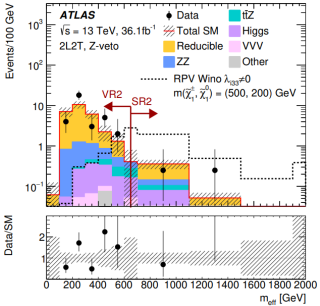
Selections for the analysis. SR2 defined in ATLAS Collaboration•Aaboud et al. (PRD 2018), which contains two light leptons (electrons or muons) and at least two $\tau_{\text{had}}^{\text{vis}}$.
SR2-$\mu\mu$ applies similar selections, with muons only as the light leptons.

Effective mass distribution

OSSF: opposite-sign and same-flavor to reduce events with a Z-boson decaying to a pair of leptons.

Effective mass: the scalar sum of the p_{T} of all light leptons, all tau leptons, the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of all jets with $p_{\mathrm{T}} > 40$ GeV.



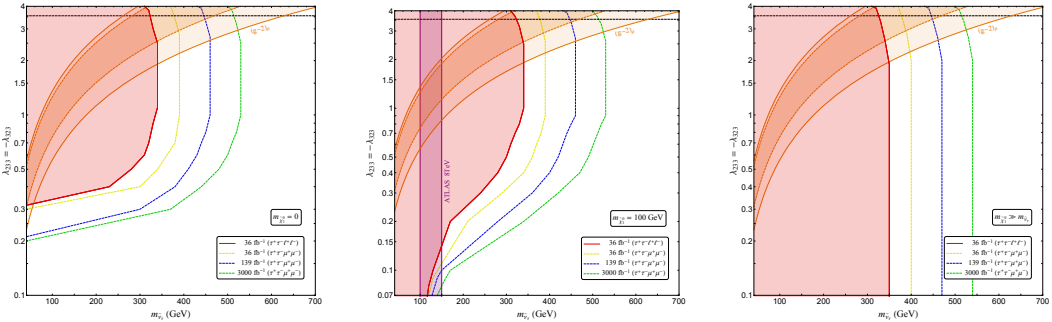


ATLAS Collaboration•Aaboud et al. (PRD 2018)

The dominant SM backgrounds are ZZ, $t\bar{t}Z$, VVV $(V = W, Z)$ and Higgs production. All of those processes can have four leptons in the final state.

Reducible background (fakes) is a significant contribution $\Rightarrow$ conservatively scaling

Results (Preliminary)

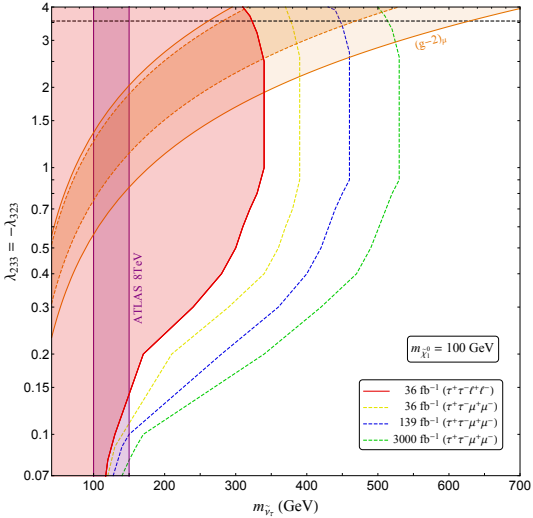


(a) $m_{\tilde{\chi}_1^0} = 0$ (b) $m_{\tilde{\chi}_1^0} = 100$ GeV (c) $m_{\tilde{\chi}_1^0} \gg m_{\tilde{\nu}_\tau}$

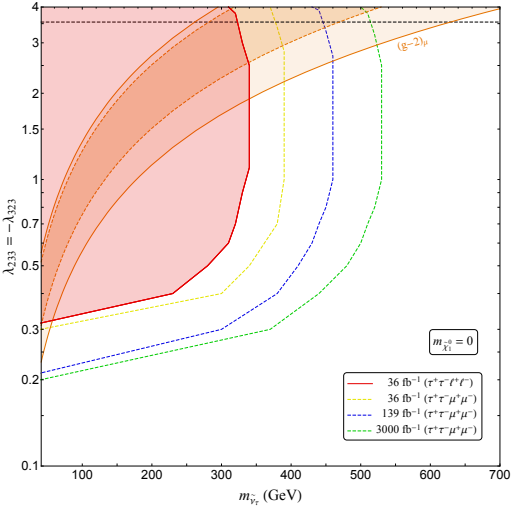
- The red solid curves: current bounds, 36.1 fb^{-1}, 13 TeV
- The yellow, blue and green dashed curves: expected improved bounds, 36.1 fb^{-1}, 139.0 fb^{-1} and 3000.0 fb^{-1}, 13 TeV
- The orange-shaded region: explains the $(g-2)_\mu$ anomaly at 3σ (2σ) CL

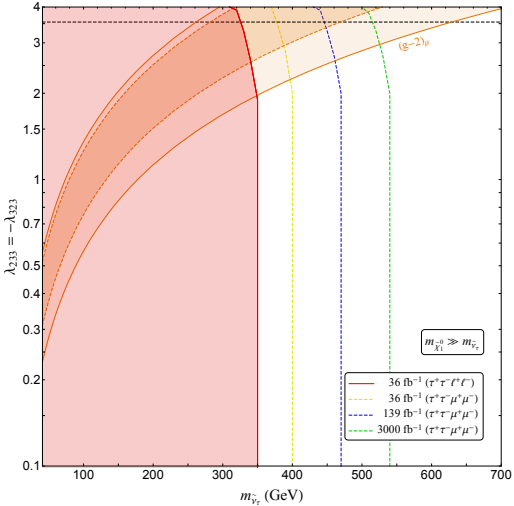
Features of the bounds

- Nearly vertical when λ_{233} is large or $m_{\tilde{\nu}_\tau} \ll m_{\tilde{\chi}_1^0}$
  $\Leftarrow$ $\mathrm{BR}(\tilde{\nu}_\tau \to \tau^- \mu^+)$ is dominant in these regions.
- Bending to the horizontal direction as $\lambda_{233} \downarrow$
  $\Leftarrow$ $\mathrm{BR}(\tilde{\nu}_\tau \to \tilde{\chi}_1^0 \nu_\tau) \sim \mathrm{BR}(\tilde{\nu}_\tau \to \tau^- \mu^+)$.
- Asymptotically to the line $m_{\tilde{\nu}_\tau} = m_{\tilde{\chi}_1^0}$
  $\Leftarrow$ $\tilde{\nu}_\tau$ cannot decay into $\tilde{\chi}_1^0 \nu_\tau$ when $m_{\tilde{\nu}_\tau} \leq m_{\tilde{\chi}_1^0}$ and $\mathrm{BR}(\tilde{\nu}_\tau \to \tau^- \mu^+)$ is dominant again.



Features of the bounds





Other constraints

- Model independent mass limit: $m_{\widetilde{\nu}} > 41$ GeV $\Leftarrow \Gamma(Z \to \text{invisible})$

  Decamp et al. (Phys. Rept. 1992)
- LHC 8 TeV multi-lepton search: depends on the relation between $m_{\widetilde{\chi}_1^0}$ and $m_{\widetilde{\nu}_\tau}$, not valid for $m_{\widetilde{\chi}_1^0} = 0$ and $m_{\widetilde{\chi}_1^0} \gg m_{\widetilde{\nu}_\tau}$

  Aad et al. (PRD 2014)
- LEP Z-pair search: $\lesssim$ 100 GeV, completely included in the red curves $\Leftarrow$ similar signal diagram (changing $q\bar{q}$ to e^+e^-); not shown

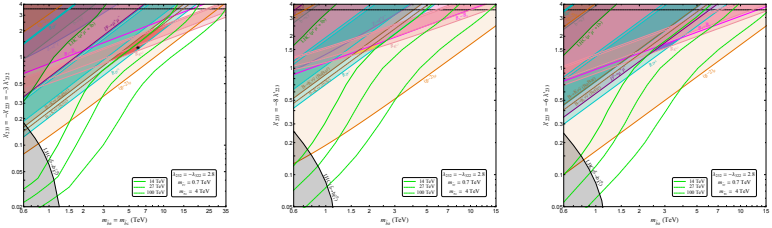
  the SLD Electroweak for the collaborations (hep-ex/0312023)
- LEP mono-photon: Weaker ($\Leftarrow$ uncertainty of xs large) than the model independent limit even at BR($\widetilde{\nu}_\tau \to \widetilde{\chi}_1^0 \nu_\tau$) = 100% ($\lambda_{233} = 0$); not shown

  Achard et al. (PLB 2004)
- LHC 13 TeV mono-jet: Weaker ($\Leftarrow$ scenario $\lambda'_{3ij} = 0$) than the model independent limit even at BR($\widetilde{\nu}_\tau \to \widetilde{\chi}_1^0 \nu_\tau$) = 100% ($\lambda_{233} = 0$); not shown

  Aad et al. (PRD 2021)

$R_{D^{(*)}}$ and $R_{K^{(*)}}$?

- $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies are automatically satisfied in the whole $(m_{\tilde{\nu}_\tau}, \lambda_{233})$ space as long as $(m_{\tilde{b}_R}, \lambda') \in$ red, yellow or blue shaded regions. Partly testable at HL-LHC through $pp \to \bar{t}\mu^+\mu^-$; $B \to K\nu\bar{\nu}$ is the most important constraint for this scenario.



Dev, Soni, Xu (PRD 2022)

- New feature: introduce $\tilde{\tau}_R$ which is not involved in our previous work. $\Rightarrow \tau \to \mu\nu\bar{\nu}$ (tree level diagram through $(m_{\tilde{\tau}_R}, \lambda_{233})$) $\Rightarrow \tau$ lifetime $(m_{\tilde{\tau}_R} \gtrsim 2.0$ TeV) & the $e-\mu$ universality in τ decays $(m_{\tilde{\tau}_R} \gtrsim 5.6$ TeV).

Conclusion

- We propose a new RPV3 scenario that can explain $(g-2)_\mu$ anomaly while being consistent with the low-energy constraints. The scenario is also compatible with $R_{D^{(*)}}$ and $R_{K^{(*)}}$ (positive or negative)
- For this scenario, we construct the LHC bounds using the data recorded during Run-2 of the LHC. We also show how would the bounds improve with a dedicated selection of only two muons as the light leptons.
- We use the $m_{\text{eff}} > 650$ GeV result from the ATLAS paper to make a general point, but the sensitivity can be improved by a dedicated optimization.
- We find that under the current data, there still exists some parameter space that can fit $(g-2)_\mu$ even at $< 1\sigma$ level. The allowed mass for $\widetilde{\nu}_\tau$ is $\gtrsim 350$ GeV with a relatively large coupling $\lambda_{233} \gtrsim 1.7$

Supplementary material

Backup

Choice of the couplings

- $(g-2)_\mu \Rightarrow$ candidates from Eq.(3): $\lambda_{312}, \lambda_{321}, \lambda_{322}, \lambda_{323}$ (λ'_{2k3} terms cannot contribute much). To get enough contribution, we have to let at least two λ couplings to be non-zero otherwise the magnitude of the λ need to be larger than $\sqrt{4\pi}$.
- ✓ $\lambda_{322} \neq 0$, contributes two times for $k = 2$ in Eq.(3)
- ✓ $\lambda_{323} \neq 0$, cannot have another coupling, because $\tau \to \overline{e}\mu\mu \Rightarrow \lambda_{323}\lambda_{312}$ small (propagator $\widetilde{\nu}_\tau$); $\tau \to e\mu\overline{\mu} \Rightarrow \lambda_{323}\lambda_{321}$ small (propagator $\widetilde{\nu}_\tau$); $\tau \to \mu\mu\overline{\mu} \Rightarrow \lambda_{323}\lambda_{322}$ small (propagator $\widetilde{\nu}_\tau$). $m_{\widetilde{\nu}_\tau}$ is then about 350 GeV - 600 GeV. Luckly, the LHC constraint is weaker compared with the previous case ($\gtrsim$ 650 GeV) because of τ
- ? $\lambda_{312} \neq 0$ and $\lambda_{321} \neq 0$, cannot let $\lambda_{322} \neq 0$ at the same time due to the constraint of $\mu \to e\gamma$
- × $\lambda'_{3ij} \neq 0$ moreover, because $(\overline{d}_i d_j) \to \mu\overline{\mu} \Rightarrow \lambda_{322}\lambda'_{3ij}$ small (propagator $\widetilde{\nu}_\tau$).

Choice of couplings

- $R_{K^{(*)}} \Rightarrow \lambda'_{233}\lambda'_{223} \neq 0$ since $\lambda'_{3ij} \approx 0$ and $\lambda_{323} \approx 0$
- ✓ $\lambda'_{233} \neq 0$ and $\lambda'_{223} \neq 0$. Only choice of $R_{K^{(*)}}$, also contribute to $R_{D^{(*)}}$
- $\lambda'_{ij3} \neq 0$ and $\lambda'_{i3j} \neq 0$ may cause some troubles because
  $(\overline{u}_j c) \to \overline{e}_i \mu \Rightarrow \lambda'_{223}\lambda'_{ij3}$ (propagator $\widetilde{b}_{\rm R}$) e.g. $D^0 \to \mu^+\mu^- \Rightarrow \frac{\lambda'_{213}}{m^2_{\widetilde{b}_{\rm R}}}$ small;
  $(\overline{d}_j b) \to \overline{e}_i \mu \Rightarrow \lambda'_{233}\lambda'_{i3j}$ (propagator $\widetilde{t}_{\rm L}$) e.g. $B_s \to \mu^+\mu^- \Rightarrow \frac{\lambda'_{232}}{m^2_{\widetilde{t}_{\rm L}}}$ small.
- In our case $\lambda'_{232} \neq 0$. But a small λ'_{232} may also be possible (but the cancellation term in $B_s - \overline{B}_s$ mixing is zero) and λ'_{232} will contribute to $B_s \to \mu^+\mu^-$, $(C'_9)^\mu$ and $(C'_{10})^\mu$. But λ'_{232} do not have to be small and prefer the relation $\lambda'_{223} \approx 3\lambda'_{232}$.
- Now, non-zero couplings are chosen to be λ_{232}, λ'_{233}, λ'_{223} and λ'_{232}.