$R_D(*)$ Anomaly: A Model-Independent Collider Signature and Possible Hint for $R$-parity Violating Supersymmetry

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$R_D(\ast)$ Anomaly

$$R_D = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)} , \quad R_D^\ast = \frac{\mathcal{B}(B \to D^\ast\tau\nu)}{\mathcal{B}(B \to D^\ast\ell\nu)} \quad \text{(where } \ell = e, \mu) .$$
A model-independent way to test the anomaly using ATLAS and CMS

A possible correlation of the anomaly with the Higgs naturalness

$R$-parity violating Supersymmetry with light 3rd generation
Model-independent Collider Analysis

- In a nut-shell, the anomalous behavior is in the basic process: \( b \rightarrow c \tau \nu \).
- This necessarily implies by crossing symmetry an analogous anomaly in \( g + c \rightarrow b \tau \nu \).
- Leads to a model-independent collider probe: \( pp \rightarrow b \tau \nu \).
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This necessarily implies by **crossing symmetry** an analogous anomaly in $g + c \rightarrow b \tau \nu$.

Leads to a model-independent collider probe: $pp \rightarrow b \tau \nu$. 
Effective Operators

The effective 4-fermion Lagrangian for $b \rightarrow c \tau \nu$ in the SM is given by

$$-\mathcal{L}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} (\bar{c} \gamma_\mu P_L b) (\bar{\tau} \gamma^\mu P_L \nu_\tau) + \text{H.c.}$$

Same Lagrangian gives rise to $pp \rightarrow b \tau \nu$, but the rate is CKM-suppressed.

Need not be the case in a generic NP scenario, which might be observable above the SM background at the LHC.

Various dimension-6 four-fermion operators possible: [Freytsis, Ligeti, Ruderman (PRD '15)]

$$\mathcal{O}_{V_{R,L}} = (\bar{c} \gamma^\mu P_{R,L} b) (\bar{\tau} \gamma_\mu P_L \nu)$$
$$\mathcal{O}_{S_{R,L}} = (\bar{c} P_{R,L} b) (\bar{\tau} P_L \nu) .$$
$$\mathcal{O}_T = (\bar{c} \sigma^{\mu \nu} P_L b)(\bar{\tau} \sigma_{\mu \nu} P_L \nu) .$$
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SM Backgrounds

- The direct $pp \rightarrow b\tau\nu$ is suppressed by $|V_{cb}|^2$.
- In a realistic hadron collider environment, however, there are other potentially dangerous backgrounds.
  - $pp \rightarrow jW \rightarrow j\tau\nu$ (j misidentified as b)
  - $pp \rightarrow W \rightarrow \tau\nu$, with an ISR gluon $\rightarrow b\bar{b}$ and one b is lost
  - $pp \rightarrow tj \rightarrow b\tau\nu j$ and $pp \rightarrow tW \rightarrow b\tau\nu jj$, where the jet(s) are lost
  - $pp \rightarrow b\bar{b}j$, where one b is misidentified as a $\tau$ and the light jet is lost (i.e. misidentified as MET).
- The mis-ID rates at the LHC typically are at the level of $\sim 1\%$.
- With basic trigger cuts $p_{T}^{j,b,\ell} > 20$ GeV, $E_{T} > 20$ GeV, $|\eta^{j,b,\ell}| < 2.5$ and $\Delta R^{\ell j,\ell b,jb} > 0.4$, we find the dominant contribution comes from $pp \rightarrow Wj$ and $pp \rightarrow b\bar{b}j$.
- $\sigma_{SM}(pp \rightarrow b\tau\nu \rightarrow b\ell + E_{T}) \sim 50$ pb at $\sqrt{s} = 13$ TeV LHC.
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We consider the dimension-6 NP operators $O_{V_{R,L}}$ and $O_{S_{R,L}}$.

For a typical choice $g_{NP}/\Lambda^2 = (1 \text{ TeV})^{-2}$, the signal cross section for $pp \rightarrow b\tau\nu \rightarrow b\ell + \not{E}_T$ of $\sigma_V \simeq 1.1 \text{ pb}$ (vector case) and $\sigma_S \simeq 1.8 \text{ pb}$ (scalar case), both at $\sqrt{s} = 13 \text{ TeV}$ LHC.

Can directly probe mediator masses up to around 2.4 (2.6) TeV at 3$\sigma$ CL in the vector (scalar) operator case with $O(1)$ couplings at $\sqrt{s} = 13 \text{ TeV}$ LHC with $\mathcal{L} = 300 \text{ fb}^{-1}$.

The signal-to-background ratio can be significantly improved by using specialized selection cuts, e.g. $p_T^b > 100 \text{ GeV}$, $M_{b\ell} > 100 \text{ GeV}$ and $\not{E}_T > 100 \text{ GeV}$.
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Kinematic Distributions

As for the NP contribution, we consider the following

\[ \Delta \rho = \frac{\sigma_{NP} - \sigma_{SM}}{\sigma_{SM}} \]

where the dominant contributions come from the dimension-6 four-fermion operators \([33]\):

\[ O^V, O^S \text{ (vector and scalar) operator case with} \]

\[ \Delta \rho \approx 10^{-3} \text{ for mediator masses up to} \]

\[ 2.4 \text{ (2.6) TeV in the vector (scalar) case with} \]

\[ g \text{ coupling at} \]

\[ 1 \text{ TeV LHC with an integrated luminosity of} \]

\[ 300 \text{ fb}^{-1}. \]

The amplitudes for the collider process may be directly probed at 3
## Cut Efficiency

<table>
<thead>
<tr>
<th>Observable</th>
<th>Cut value (GeV)</th>
<th>SM background</th>
<th>Efficiency</th>
<th>Signal (Vector case)</th>
<th>Signal (Scalar case)</th>
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<td>0.79</td>
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</table>
Possible Hint for Natural SUSY with RPV

- Anomaly involved 3rd generation of the SM.
- Speculation: May be related to Higgs naturalness?
- An obvious UV-complete candidate: **Natural SUSY** with light 3rd generation. [Brust, Katz, Lawrence, Sundrum (JHEP ’12); Papucci, Ruderman, Weiler (JHEP ’12)]
- Coupling unification still preserved, even with RPV.

![Graph showing RG evolution of gauge couplings in the SM, MSSM, SM, and RPV]

\[
\frac{1}{\alpha_i} = \frac{1}{\alpha_{SU(3)^c}} + \frac{1}{\alpha_{SU(2)^L}} + \frac{1}{\alpha_{U(1)}},
\]

\[\mu \text{ [GeV]} \]
Explaining the $R_D(\ast)$ Anomaly

- Consider a minimal RPV SUSY setup with the $\lambda'$-couplings.

$$\mathcal{L} = \lambda'_{ijk} \left[ \tilde{\nu}_{iL}\tilde{d}_{kR}d_{jL} + \tilde{d}_{jL}\tilde{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\tilde{\nu}_{iL}d_{jL} \\ - \tilde{\nu}_{iL}\tilde{d}_{kR}u_{jL} - \tilde{u}_{jL}\tilde{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\tilde{e}^c_{iL}u_{jL} \right] + \text{H.c.}$$

- Leads to the effective 4-fermion interactions: [Deshpande, He (EPJC '17)]

$$\mathcal{L}_{\text{eff}} \supset \frac{\lambda'_{ijk}\lambda'^*_{mnk}}{2m^2_{d_{kR}}} \left[ \tilde{\nu}_{mL}\gamma^\mu \nu_{iL}\tilde{d}_{nL}\gamma_\mu d_{jL} \\ + \tilde{e}_{mL}\gamma^\mu e_{iL} (\tilde{u}_{L}V_{\text{CKM}})_{n} \gamma_\mu \left( V^\dagger_{\text{CKM}}u_{L} \right)_{j} \\ - \nu_{mL}\gamma^\mu e_{iL}\tilde{d}_{nL}\gamma_\mu \left( V^\dagger_{\text{CKM}}u_{L} \right)_{j} + \text{h.c.} \right]$$

- Contributes to $R_D(\ast)$ at tree-level: $b \rightarrow \tilde{b}\nu \rightarrow c\tau\nu$. 
$$\frac{R_D}{R_D^{SM}} = \frac{R_D^*}{R_D^{SM}^*} = \left| 1 + \frac{v^2}{2m_{b_R}^2} X_c \right|^2,$$

$$X_c = \left| \lambda_{333}' \right|^2 + \lambda_{333}' \lambda_{323}' \frac{V_{cs}}{V_{cb}} + \lambda_{333}'^2 \lambda_{333}$$

$$\lambda_{313} = -0.05, \ \lambda_{323} = 0.01$$
Explaining the $R_D(\ast)$ Anomaly

The figure shows a plot with $R_D^\ast$ on the y-axis and $R_D$ on the x-axis. The graph includes data points and shaded regions representing different scenarios:

- **SM (Standard Model)**: A small, central region that likely corresponds to the SM predictions.
- **RPV$_3$** and **RPV$_4$**: Larger, blue and green shaded regions, respectively, indicating possible parameter spaces.
- **HFAG**: A green shaded region that overlaps with the RPV$_4$ region.

The figure highlights the $R_D(\ast)$ anomaly with respect to the SM predictions, showing how different models (RPV$_3$ and RPV$_4$) can accommodate this anomaly within their respective parameter spaces.
If the $R_D(*)$ anomaly is true, we should find an anomaly in the high-energy signal of $pp \to b\tau\nu$.

Provides a model-independent high-$p_T$ test of the $R_D(*)$ anomaly at the LHC.

Since it involves the 3rd generation, the origin of the anomaly might be related to the Higgs naturalness problem.

A specific scenario that addresses this issue: Natural SUSY with RPV.

Common explanation of $R_D(*)$ and $R_K(*)$?