$R_{D^{(*)}}$ Anomaly: A Model-Independent Collider Signature and Possible Hint for R-parity Violating Supersymmetry

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W. Altmannshofer, BD and A. Soni, Phys. Rev. D **96**, 095010 (2017) [arXiv:1704.06659 [hep-ph]] and in preparation.

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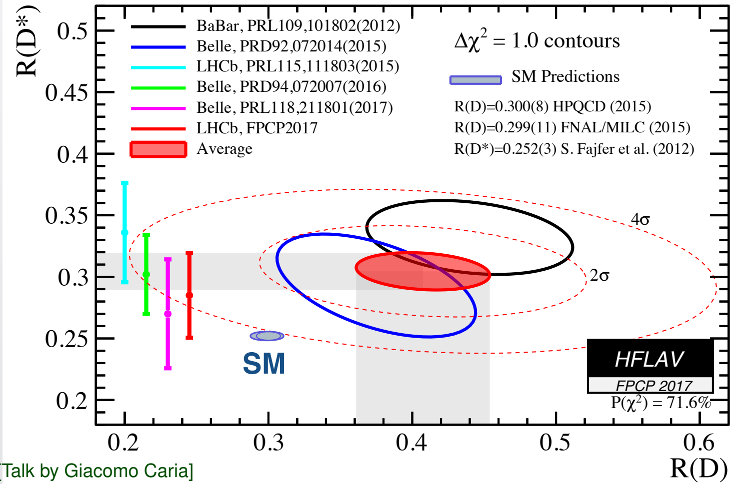
$R_{D^{(*)}}$ Anomaly

$$R_D = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}, \quad R_{D^*} = \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)} \qquad \text{(where } \ell = e, \mu\text{)}.$$



[Talk by Giacomo Caria]

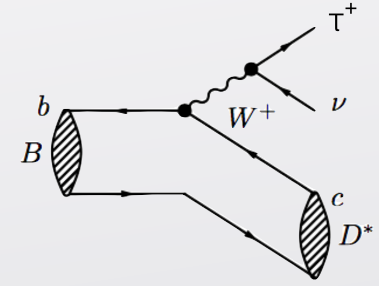
Outline

- 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: $b \to c\tau\nu$.
- This necessarily implies by **crossing symmetry** an analogous anomaly in $g + c \to b\tau\nu$.
- Leads to a model-independent collider probe: $pp \to b\tau\nu$.

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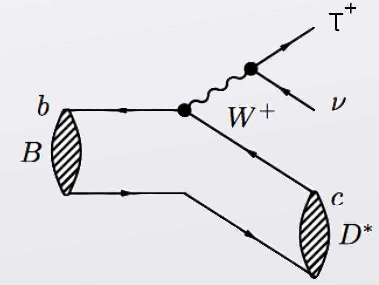

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Effective Operators

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

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

- Same Lagrangian gives rise to $pp \to b\tau\nu$, 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)]

$$\begin{aligned}
\mathcal{O}_{V_{R,L}} &= \left(\bar{c}\gamma^\mu P_{R,L} b\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right) \\
\mathcal{O}_{S_{R,L}} &= \left(\bar{c} P_{R,L} b\right)\left(\bar{\tau} P_L \nu\right) . \\
\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 $pp \to b\tau\nu$ is suppressed by $|V_{cb}|^2$.
- In a realistic hadron collider environment, however, there are other potentially dangerous backgrounds.
  - $pp \to jW \to j\tau\nu$ (j misidentified as b)
  - $pp \to W \to \tau\nu$, with an ISR gluon $\to b\bar{b}$ and one b is lost
  - $pp \to tj \to b\tau\nu j$ and $pp \to tW \to b\tau\nu jj$, where the jet(s) are lost
  - $pp \to b\bar{b}j$, where one b is misidentified as a τ 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, $\not{E}_T > 20$ GeV, $|\eta^{j,b,\ell}| < 2.5$ and $\Delta R^{\ell j,\ell b,jb} > 0.4$, we find the dominant contribution comes from $pp \to Wj$ and $pp \to b\bar{b}j$.
- $\sigma_{\rm SM}(pp \to b\tau\nu \to b\ell + \not{E}_T) \sim 50$ pb at $\sqrt{s} = 13$ TeV LHC.

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Signal Rate

- We consider the dimension-6 NP operators $\mathcal{O}_{V_{R,L}}$ and $\mathcal{O}_{S_{R,L}}$.
- For a typical choice $g_{\rm NP}/\Lambda^2 = (1\ {\rm TeV})^{-2}$, the signal cross section for $pp \to b\tau\nu \to b\ell + \not{E}_T$ of $\sigma_V \simeq 1.1$ pb (vector case) and $\sigma_S \simeq 1.8$ pb (scalar case), both at $\sqrt{s} = 13$ TeV LHC.
- Can directly probe mediator masses up to around 2.4 (2.6) TeV at 3σ CL in the vector (scalar) operator case with $\mathcal{O}(1)$ couplings at $\sqrt{s} = 13$ TeV LHC with $\mathcal{L} = 300\ {\rm fb}^{-1}$.
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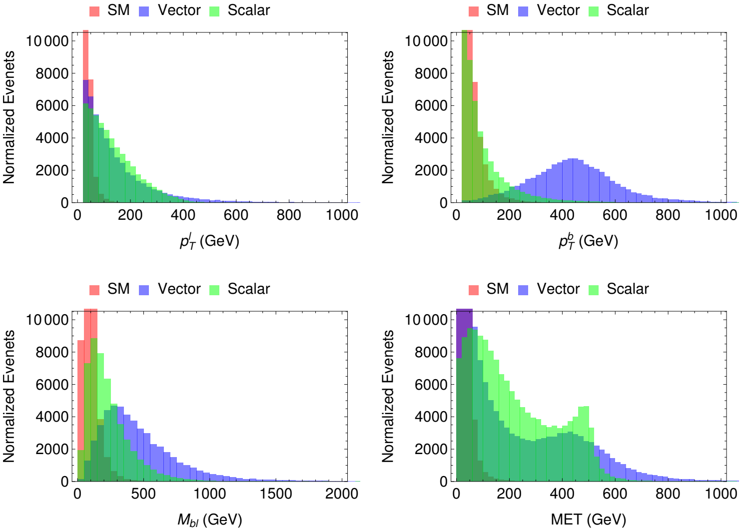
Kinematic Distributions

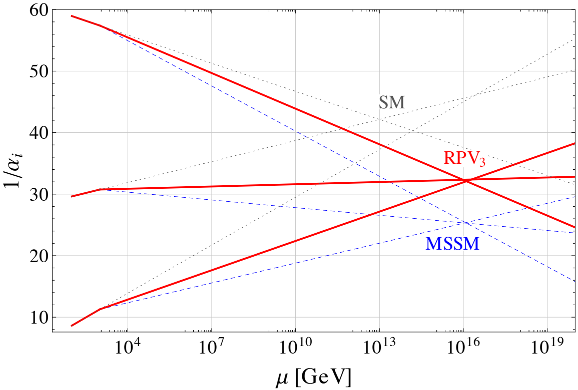


Cut Efficiency

Observable	Cut value (GeV)	Efficiency		
		SM background	Signal (Vector case)	Signal (Scalar case)
p_T^ℓ	100	0.01	0.52	0.56
	50	0.10	0.78	0.82
	30	0.44	0.92	0.94
p_T^b	100	0.13	0.99	0.33
	50	0.47	1.00	0.62
	30	0.75	1.00	0.84
$M_{b\ell}$	100	0.18	0.96	0.76
	50	0.63	0.99	0.94
	30	0.88	1.00	0.98
$\not{E}_T$	100	0.01	0.54	0.70
	50	0.09	0.70	0.86
	30	0.29	0.79	0.92

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.



Explaining the $R_{D^{(*)}}$ Anomaly

- Consider a minimal RPV SUSY setup with the λ'-couplings.

$$\begin{aligned}\mathcal{L} \; &= \lambda'_{ijk}\big[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} \\ &\quad -\tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\big] + \text{H.c.}\end{aligned}$$

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

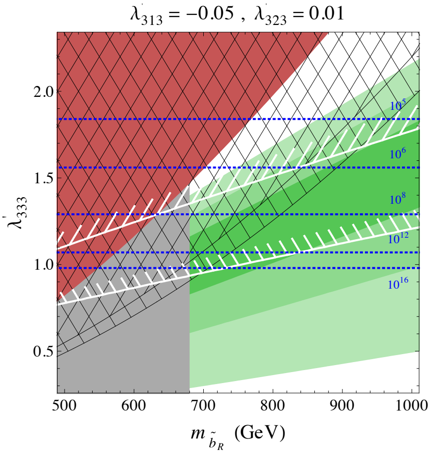
$$\begin{aligned}\mathcal{L}_{\text{eff}} \supset \frac{\lambda'_{ijk}\lambda'^*_{mnk}}{2m^2_{\tilde{d}_{kR}}}\Big[&\bar{\nu}_{mL}\gamma^\mu\nu_{iL}\bar{d}_{nL}\gamma_\mu d_{jL} \\ &+ \bar{e}_{mL}\gamma^\mu e_{iL}\left(\bar{u}_L V_{\text{CKM}}\right)_n\gamma_\mu\left(V^\dagger_{\text{CKM}}u_L\right)_j \\ &- \nu_{mL}\gamma^\mu e_{iL}\bar{d}_{nL}\gamma_\mu\left(V^\dagger_{\text{CKM}}u_L\right)_j + \text{h.c.}\Big] \\ &- \frac{\lambda'_{ijk}\lambda'^*_{mjn}}{2m^2_{\tilde{u}_{jL}}}\bar{e}_{mL}\gamma^\mu e_{iL}\bar{d}_{kR}\gamma_\mu d_{nR}\ ,\end{aligned}$$

- Contributes to $R_{D^{(*)}}$ at tree-level: $b \to \widetilde{b}\nu \to c\tau\nu$.

Allowed Parameter Space

$$\frac{R_D}{R_D^{\mathrm{SM}}} = \frac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}} = \left| 1 + \frac{v^2}{2m_{\tilde{b}_R}^2} X_c \right|^2 ,$$

$$X_c = |\lambda'_{333}|^2 + \lambda'_{333}\lambda'_{323}\frac{V_{cs}}{V_{cb}} + \lambda'_{333}$$



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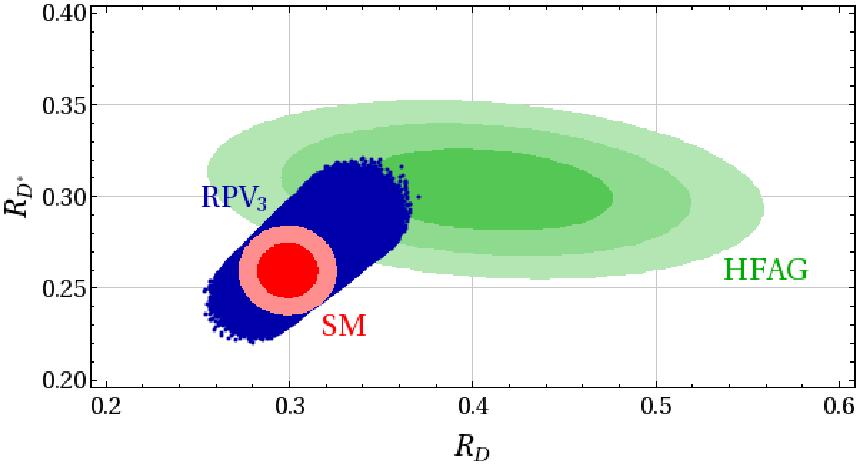

Conclusion and Outlook

- 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 $R_{K^{(*)}}$?