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B-physics anomalies: The bridge between R-parity violating Supersymmetry and flavoured Dark Matter

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[T.] 1904.12940

Outline

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- **Background and Motivation**
- RPV and DM interactions under the $U(2)^2$ flavour symmetry
- Constraints from low-energy observables and numerical fit
- Conclusions & Future outlook

B-Physics anomalies

1. An overall 2.5 σ deviation from μ/e universality in natural current $b \to s$ transition:

$$R_{K^*}^{\mu/e}\Big|_{q^2\in[1.1,6]\ \mathrm{GeV}^2} = \frac{BR(B\to K^*\mu^+\mu^-)_{\mathrm{exp}}}{BR(B\to K^*e^+e^-)_{\mathrm{exp}}} = 0.69^{+0.11}_{-0.07}\pm 0.05$$

$$R_K^{\mu/e} = \frac{BR(B\to K\mu^+\mu^-)_{\mathrm{exp}}}{BR(B\to Ke^+e^-)_{\mathrm{exp}}} = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

[LHCb] 1903.09252
1705.05802

2. An overall 3.1 σ deviation from τ/μ universality in charged current $b \to c$ transition:

$$R_{D^*}^{\tau/l} = \frac{BR(B\to D^*\tau^-\overline{\nu_\tau})_{\mathrm{exp}} \big/ BR(B\to D^*\tau^-\overline{\nu_\tau})_{\mathrm{SM}}}{BR(B\to D^*l^-\overline{\nu_l})_{\mathrm{exp}} \big/ BR(B\to D^*l^-\overline{\nu_l})_{\mathrm{SM}}} = 1.151\pm 0.062$$

$$R_D^{\tau/l} = \frac{BR(B\to D\tau^-\overline{\nu_\tau})_{\mathrm{exp}} \big/ BR(B\to D\tau^-\overline{\nu_\tau})_{\mathrm{SM}}}{BR(B\to Dl^-\overline{\nu_l})_{\mathrm{exp}} \big/ BR(B\to Dl^-\overline{\nu_l})_{\mathrm{SM}}} = 1.117\pm 0.104$$

[BaBar] 1303.0571,
[Belle] 1612.00529,
Morriond
[LHCb] 1711.02505,
1506.08614

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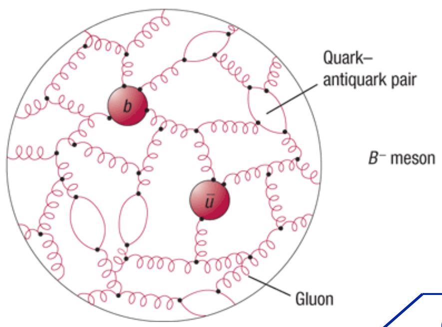
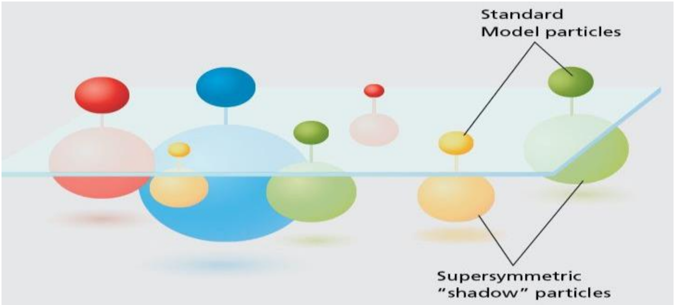
EFT acting as the pathfinder





[Altmannshofer et al] 1704.06659

EFT Analysis:

B-physics anomalies + flavor structure

NP couples to 3rd generation

Supersymmetry

RPV interactions

[Greljo et al] 1506.01705

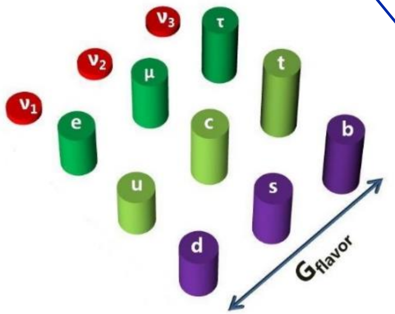
[Barbieri et al] 1105.2296

$U(2)$ flavor symmetries

$b \longrightarrow s\ell\ell$ anomaly: NP in muonic WC $\delta C_9 = - \delta C_{10}$

[Bhattacharyy] hep-ph/9707297

[Aebischer et al] 1903.10434



Lessons from [T.] 1807.01638

- The $U(2)^2$ flavor symmetry naturally suppresses the RPV couplings within the experimental bounds and still allows for an improvement over the SM fit for $R_{D^{(*)}}$, at least as good as the generic RPV scenario.
- With respect to a combined explanation of the $R_{K^{(*)}}$ anomaly, the model without the leptonic interactions is equivalent at the EFT level with the $(\mathbf{3},\mathbf{1},1/3)$ scalar leptoquark studied in [Bauer et al] 1511.01900 ($\approx 0\%$ improvement to $R_{K^{(*)}}$).
- Involving the leptonic trilinear couplings, we can achieve at max a 30% improvement! (but with a $\tilde{\tau}_R$ significantly heavier than $\tilde{b}_R$)
- The possibility to provide a complete solution is severely limited by the strict bounds on Z boson decay to leptons and tree-level, LFV τ decays.

Tension in the leptonic interactions already anticipated by the EFT analysis

[Bordone et al] 1702.07238

RPV → Dark Matter → B-physics anomalies?

- The RPV setup preserves all the attractive features of SUSY, but one, namely the candidacy of the LSP as Dark Matter. → We need a new WIMP!
- Among the numerous WIMP models, we are interested in those that:
  - DM couples to specific SM fermions directly (= distinguished collider signatures),
  - the apparent suppression of the interactions with the lighter generations from direct detection limits is explained from a flavour symmetry rationale,
  - exhibit a supersymmetric structure.

  extended bibliography…
- As long as the nature of DM remains a mystery, it is important to investigate any possible connection with other anomalous observations. To this end, there have been attempts to link mostly the $R_{K^{(*)}}$ discrepancy with DM.
- **<u>GOAL</u>**: Address both anomalies by introducing a supersymmetric hidden sector that features the most economical BMSSM particle content, is controlled by the $U(2)^2$ flavour symmetry and satisfies the rich flavour and DM Pheno!

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R-parity violating and Dark Matter superpotential

- The motivation for an exact R-parity is no longer theoretically strong. We consider the **R-parity odd** and gauge-invariant **superpotential**:

$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c U_j^c D_k^c$$

[Brust et al] 1110.6670
[Buckley et al] 1610.08059

- The low-energy spectrum is simplified according to SUSY SSB conditions and bottom-up approaches. It contains only $\tilde{b}_R$ and $\tilde{\tau}_R$.

- We extend the matter content by adding two Z_2-odd superfields; a gauge singlet, flavour multiplet X and a $SU(2)_L$ doublet, flavour singlet mediator Y. The most general, **superpotential** relevant to the new fields is,

$$W_{\mathrm{DM}} = \hat{M}_X X\overline{X} + \hat{M}_Y Y\overline{Y} + \hat{\lambda}_{ij} X_i Y L_j$$

scalar χ in X_3 = DM candidate!

- Due to the **holomorphicity** of W_{DM}, no other term is allowed at renormalizable level! The problematic Higgs-Portal is thus absent.
- Non-holomorphic terms in the Kähler potential may account for a large mass splitting between X_3 and the degenerate X_1 and X_2.

[Batell et al] 1309.4462

Flavour structure

- We adopt a version of $U(2)^2$ that is compatible with gauge coupling unification. In terms of the $\mathbf{10}_i(T_i) \oplus \bar{\mathbf{5}}_i(\bar{F}_i)$ reps of $SU(5)$, the plausible choice is $\mathcal{G}_f = U(2)_T \times U(2)_{\bar{F}}$ with the transformation properties:

$$\mathbf{T} = (T_1, T_2) \sim (\mathbf{2},\mathbf{1}), \quad T_3 \sim (\mathbf{1},\mathbf{1}), \quad \bar{\mathbf{F}} = (\bar{F}_1, \bar{F}_2) \sim (\mathbf{2},\mathbf{1}), \quad \bar{F}_3 \sim (\mathbf{1},\mathbf{1}).$$

- The $SU(5)$- and flavour-invariant Yukawa sector can be expressed as,

$$\mathcal{L}_Y = y_t T_3 T_3 H_5 + y_t x_t \mathbf{T}\mathbf{V}_T T_3 H_5 + \mathbf{T}\Delta_T \mathbf{T} H_5 + y_b T_3 \bar{F}_3 H_{\bar{5}} + y_b x_b \mathbf{T}\mathbf{V}_T \bar{F}_3 H_{\bar{5}} + \mathbf{T}\Delta_{T\times\bar{F}} \bar{\mathbf{F}} H_{\bar{5}}$$

The masses and the mixings are reproduced with the following spurion alignment: $\mathbf{V}_T = (0 \;\; \epsilon)^T, \quad \Delta_T = \begin{pmatrix} 0 & \epsilon' \\ -\epsilon' & \epsilon\rho \end{pmatrix}, \quad \Delta_{T\times\bar{F}} = \begin{pmatrix} 0 & \epsilon' \\ -\epsilon' & \epsilon \end{pmatrix},$

where $\epsilon \approx 0.025, \;\; \epsilon' \approx 0.006,$ and $\rho \approx 0.02.$

[Barbieri et al] 1506.09201, hep-ph/9610449

- All trilinear terms in the superpotential can be converted to holomorphic flavour singlets by contracting the superfields with the above spurions and $\mathbf{V}_{\bar{F}} = (0 \;\; \epsilon_{\bar{F}})^T$ transforming as $(\mathbf{1},\bar{\mathbf{2}})$.

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Contributions to $B \to D^{(*)}\tau\bar{\nu}$ and $B \to K^{(*)}\ell\bar{\ell}$

- The RPV contribution to charged-current decays occurs at tree-level:

$$\mathcal{L}(b \to c\ell\bar{\nu}_\ell) = -\frac{4G_F}{\sqrt{2}} V_{cb}(\delta_{ii'} + \Delta^c_{ii'})\bar{\ell}^{i'}_L \gamma^\mu \nu^i_L \bar{c}_L \gamma_\mu b_L, \quad \Delta^c_{ii'} = \sum_{j'=s,b} \frac{\sqrt{2}}{4G_F} \frac{\lambda'_{i33}\lambda'_{i'j'3}}{2m^2_{\tilde{b}_R}} \frac{V_{cj'}}{V_{cb}}.$$

We examine then the NP effects in the ratio:

$$r_{D^{(*)}} = \frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = \frac{\left|1+\Delta^c_{33}\right|^2 + \left|\Delta^c_{23}\right|^2}{\frac{1}{2}\left(1+\left|1+\Delta^c_{22}\right|^2 + \left|\Delta^c_{32}\right|^2\right)}.$$

Large $\lambda'_{323}\ \lambda'_{333}$
Small $\lambda'_{223}\ \lambda'_{233}$

[Deshpande et al] 1608.04817

- For the FCNC transition , we regard the NP modification of the WC in:

$$\mathcal{L}(b \to s\ell\bar{\ell}) = \frac{4G_F}{\sqrt{2}} \frac{\alpha_e}{4\pi} V_{tb}V^*_{tb} \left[(C^\ell_9 + \delta C^\ell_9)\bar{\ell}^{i'}\gamma^\mu \ell^i \bar{s}_L \gamma_\mu b_L + (C^\ell_{10} + \delta C^\ell_{10})\bar{\ell}^{i'}\gamma^\mu\gamma_5 \ell^i \bar{s}_L \gamma_\mu b_L\right]$$

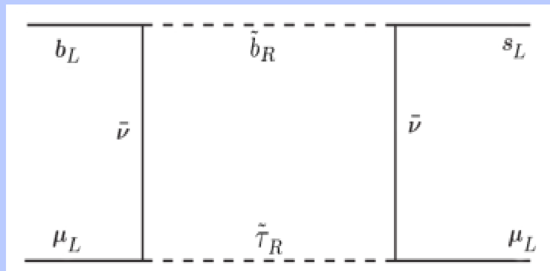
- At one-loop order, one gets:

[Das et al] 1705.09188

$$\delta C^\mu_9 = -\delta C^\mu_{10} = \frac{m_t^2}{16\pi\alpha} \frac{(\lambda'_{233})^2}{m^2_{\tilde{b}_R}} - \frac{\lambda'_{i23}\lambda'_{i33}\lambda'_{2j3}\lambda'_{2j3}}{64\sqrt{2}G_F \pi V_{tb}V^*_{ts}\alpha m^2_{\tilde{b}_R}} - \frac{\lambda'_{323}\lambda'_{333}(\lambda_{323})^2}{64\sqrt{2}G_F \pi V_{tb}V^*_{ts}\alpha} \frac{\log\left(m^2_{\tilde{b}_R} / m^2_{\tilde{\tau}_R}\right)}{m^2_{\tilde{b}_R} - m^2_{\tilde{\tau}_R}}$$

Small due to tree-level $B \to K^{(*)}\nu\bar{\nu}$

New!



With (leptophilic, scalar) DM

Can LLE^c interactions save the day? ... YES!

- A tree-level $\tilde{\tau}_R$ exchange affect the strictly bounded τ decays. Additionally, RGE effects driven by the top Yukawa y_t contribute via one-loop diagrams. At leading order, one gets:

[Feruglio et al] 1606.00524

$$R_{\tau}^{\tau/\ell} \simeq 1 + \frac{\sqrt{2}}{4G_F}\frac{(\lambda_{323})^2}{m_{\tilde{\tau}_R}^2} - \frac{3m_t^2}{16\pi^2}\frac{(\lambda'_{333})^2}{m_{\tilde{b}_R}^2}\left(\log\left(\frac{m_{\tilde{b}_R}^2}{m_t^2}\right) - \frac{1}{2}\right) - \frac{\hat{\lambda}_{33}\hat{\lambda}_{32}}{8\pi^2}\left(\frac{m_\chi^2}{m_\psi^2}\log\left(\frac{m_\chi^2}{m_\psi^2}\right) + 1\right)$$

- Opportunity for a **cancellation mechanism**? In the absence of DM, this

scenario is restricted due to the NP modification of the $Z \to \ell\bar{\ell}'$ coupling, induced by triangle diagrams proportional to coupling λ'_{333}. In particular,

$$\frac{a_\tau}{a_e} = 1 - \frac{3m_t^2}{16\pi^2}\frac{(\lambda'_{333})^2}{m_{\tilde{b}_R}^2}\left(\log\left(\frac{m_{\tilde{b}_R}^2}{m_t^2}\right) - 1\right) + (1 - 4s_W^2)\frac{(\hat{\lambda}_{33})^2}{16\pi^2}\left(\frac{m_\chi^2}{m_\psi^2}\log\left(\frac{m_\chi^2}{m_\psi^2}\right) + 1\right)$$

- If we include the DM interaction the cancellation is invoked naturally in both processes.
- Additional LFV processes become relevant at one-loop: $\tau \to 3\mu$ and $\tau \to \mu\gamma$.

DM Phenomenology

- The main self-annihilation channels are $\bar{\chi}\chi \to \bar{\ell}\ell(\bar{\nu}_\ell \nu_\ell)$. The effective cross-section is p-wave suppressed,

$$\frac{1}{2}\langle \sigma v \rangle = \frac{1}{2}\left[\frac{(\hat{\lambda}_{32}^2 + \hat{\lambda}_{33}^2) m_\chi^2}{48\pi (m_\psi^2 + m_\chi^2)^2} v^2\right] \equiv p v^2$$

[Bai et al] 1402.6696

- The dominant contribution for DM scattering off nucleons is generated by the **charge-radius operator**,

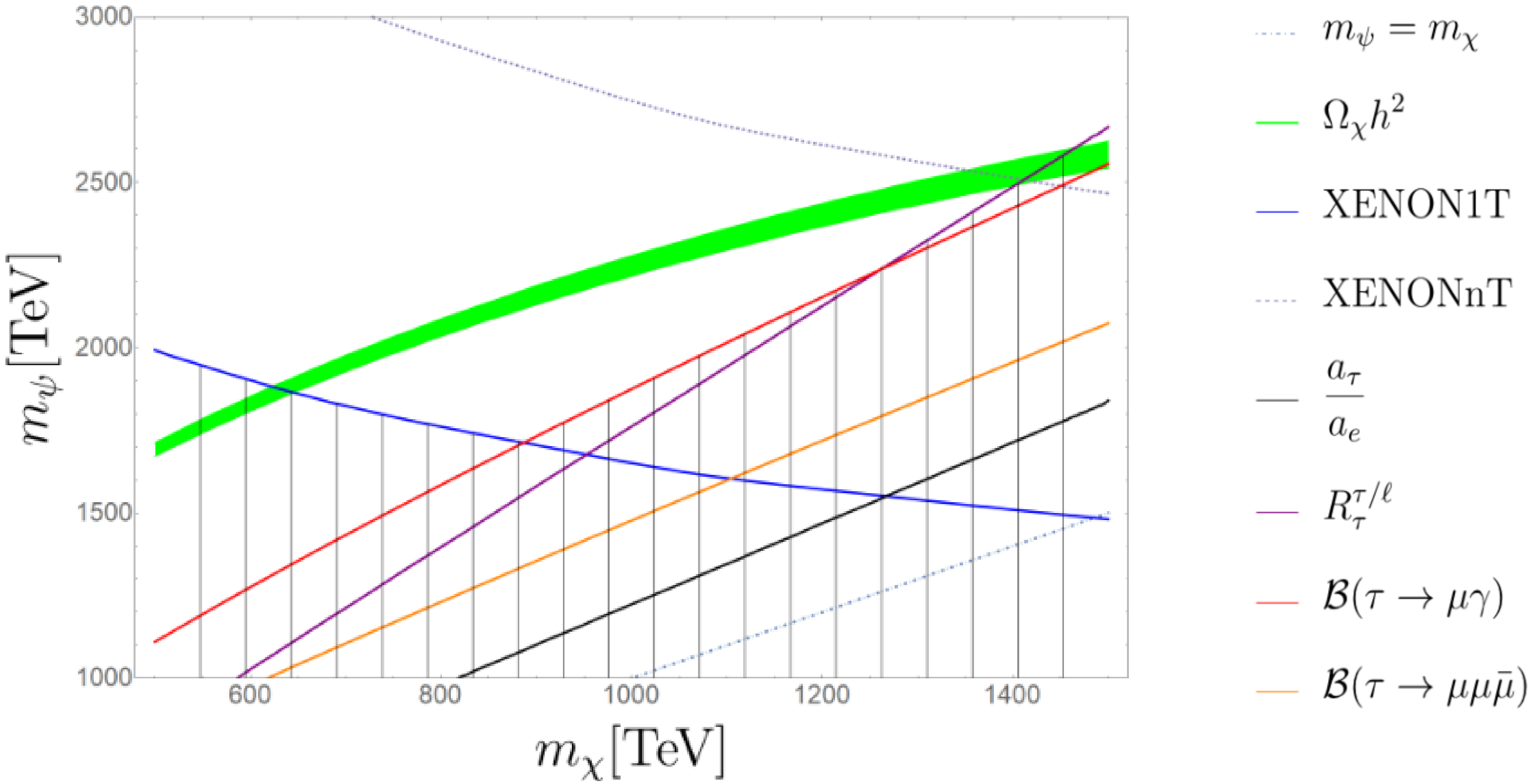
$$\mathcal{L}_{\text{charge-radius}} = i b_\chi \partial_\mu \chi^* \partial_\nu \chi F^{\mu\nu}, \qquad b_\chi = \sum_{\ell=\mu,\tau} \frac{\hat{\lambda}_{3\ell}^2 e}{16\pi^2 m_\psi^2}\left(1 - \frac{2}{3}\log\left(\frac{m_\ell^2}{m_\psi^2}\right)\right)$$

- The spin-independent, DM-nucleus $\frac{d\sigma}{dE_R}$ has the same E_R- and υ^2-profile as the ordinary contact interaction. With a Z^2/A^2 rescaling (isospin violation), one can map the latest exclusion limits onto limits on the parameter space.

[XENON1T] 1805.12562

- Indirect detection signals of scalar DM are too small to be observed due to the p-wave suppression

DM Parameter space (at 2σ exclusion)



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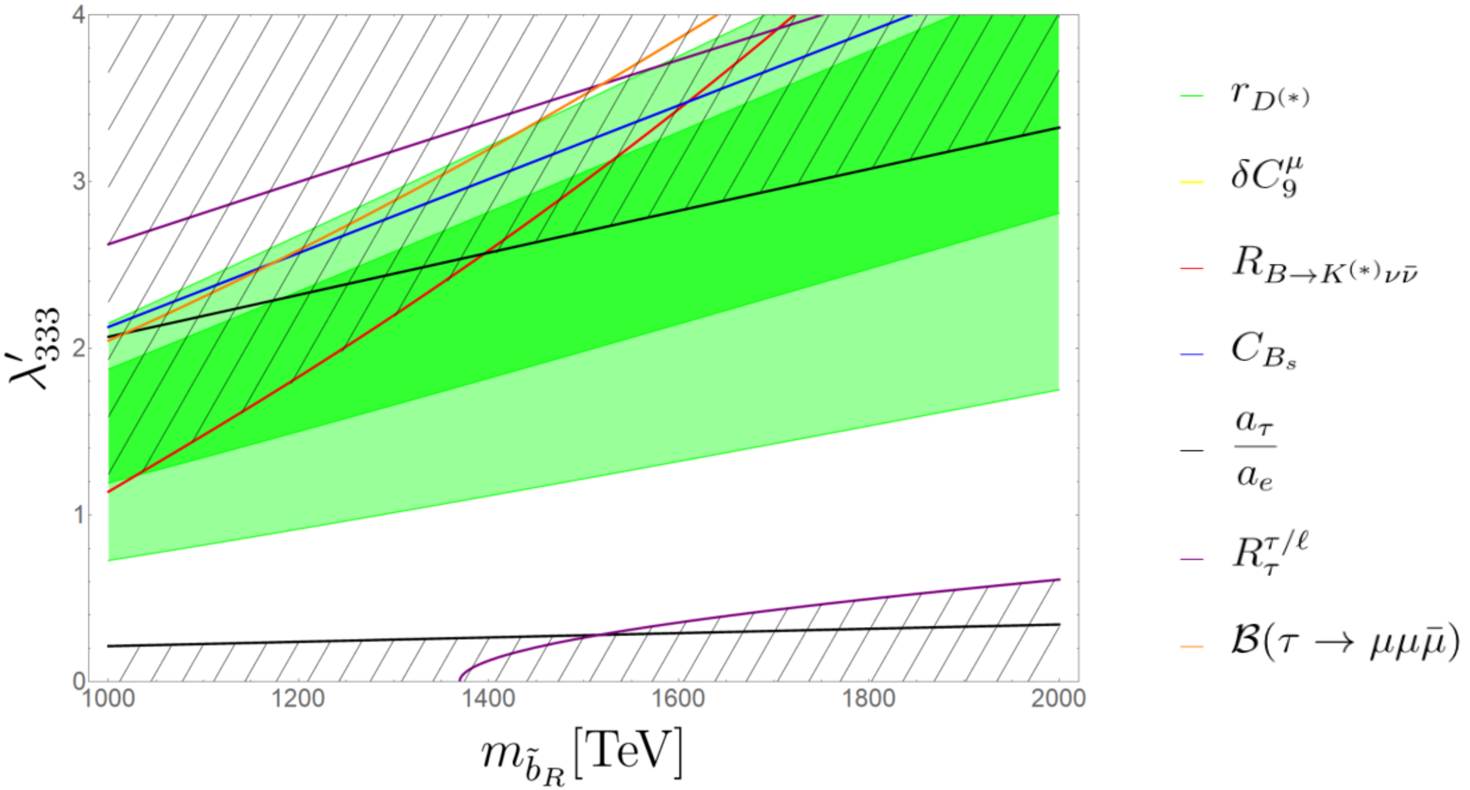
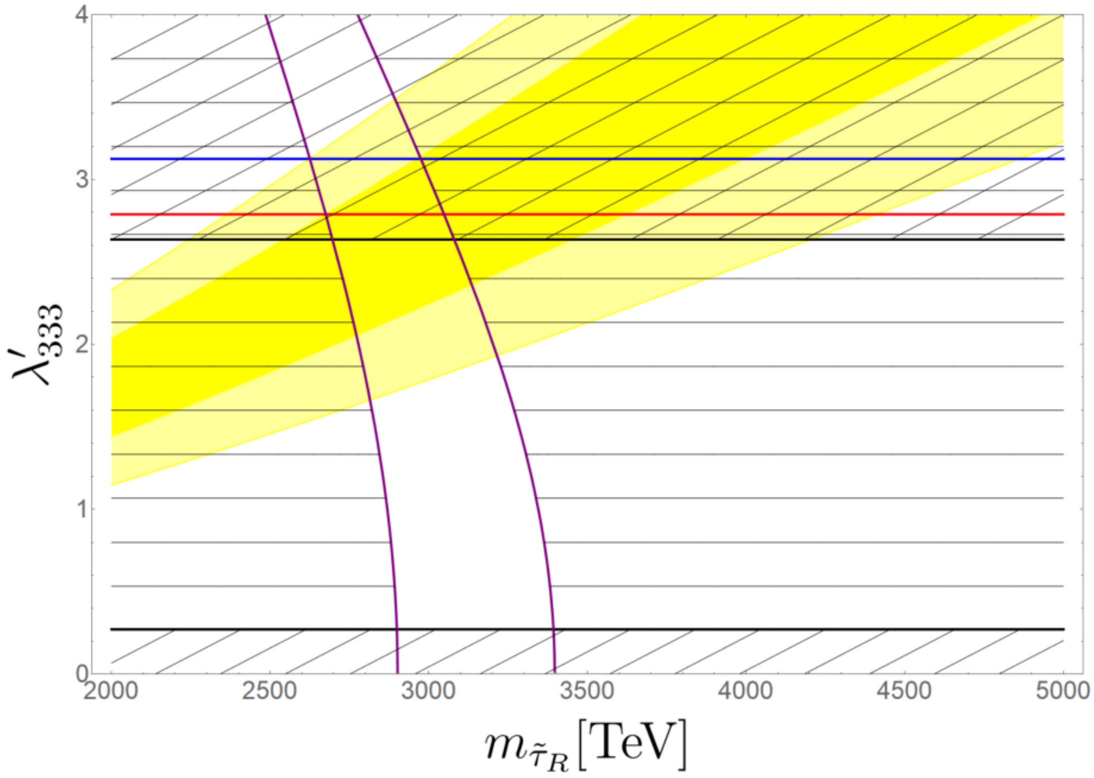
RPV Parameter space (at 2σ exclusion)

- We perform a χ^2 **minimization** with the flavour and DM data and mass lower bounds set by collider searches: $m_{\tilde{b}_R} > 1\,\text{TeV}$, $m_{\tilde{\tau}_R} > 400\,\text{GeV}$, $m_\chi > 400\,\text{GeV}$ and $m_\psi > 500\,\text{GeV}$.



RPV Parameter space (at 2σ exclusion)



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Conclusions & Future outlook

- The model provides an explanation for the B-physics anomalies without raising significant tensions with other low-energy observables.
- The required destructive amplitude interference between the RPV and DM interactions occurs for natural choice of parameters and mass spectrum.
- All newly introduced ingredients are in accordance with the spirit of gauge coupling unification.
- The flavour symmetry controls consistently the strength of SM Yukawa, RPV and DM interactions.
- Regarding the **testability** of the model: With the new world average of $R_{D^{(*)}}$ (after Moriond), there is no guarantee of finding the scalar leptoquark after the LH-LHC phase. The same holds for the DM sector at LHC.

[Greljo et al] 1811.07920

- DM direct detection proves to be much more promising! The bulk of the parameter space is expected to be probed by XENONnT (and similar experiments)

Thank you!!!!

QUESTIONS ???

Backup slides

Field Content

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(2)_T$	$U(2)_{\bar{F}}$
(Q_1, Q_2)	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{2}$	$\mathbf{1}$
Q_3	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{1}$	$\mathbf{1}$
(U_1^c, U_2^c)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{2}$	$\mathbf{1}$
U_3^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{1}$	$\mathbf{1}$
(D_1^c, D_2^c)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\mathbf{1}$	$\mathbf{2}$
D_3^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\mathbf{1}$	$\mathbf{1}$
(L_1, L_2)	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$\mathbf{2}$
L_3	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$
(E_1^c, E_2^c)	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{2}$	$\mathbf{1}$
E_3^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$
(X_1, X_2)	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$
X_3	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$
Y	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$

Expanded Lagrangians & Best-fit point

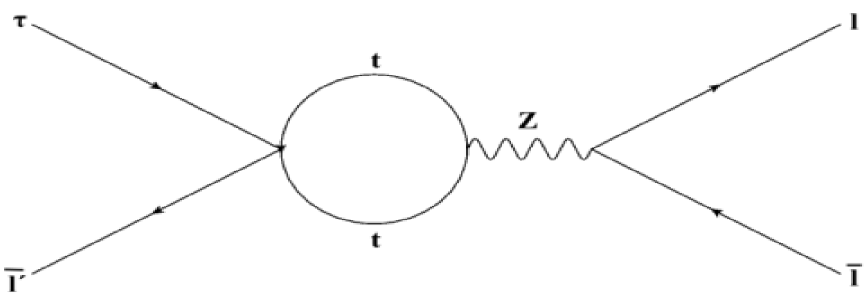
$$\mathcal{L}_{\lambda} = -\frac{1}{2}\lambda_{ijk}\left(\tilde{\nu}_{Li}\overline{\ell}_{Rk}\ell_{Lj} + \tilde{\ell}_{Lj}\overline{\ell}_{Rk}\nu_{Li} + \tilde{\ell}^{*}_{Rk}\overline{\nu}^{c}_{Ri}\ell_{Lj} - (i \leftrightarrow j)\right) + \text{h.c.} \quad \mathcal{L}_{\hat{\lambda}} = \hat{\lambda}_{3j}\overline{\ell}_{Lj}\chi\psi + \text{h.c.}$$

$$\mathcal{L}_{\lambda'} = -\lambda'_{ijk}\left(\tilde{\nu}_{Li}\overline{d}_{Rk}d_{Lj} + \tilde{d}_{Lj}\overline{d}_{Rk}\nu_{Li} + \tilde{d}^{*}_{Rk}\overline{\nu}^{c}_{Ri}d_{Lj} - \tilde{\ell}_{Li}\overline{d}_{Rk}u_{Lj} - \tilde{u}_{Lj}\overline{d}_{Rk}\ell_{Li} - \tilde{d}^{*}_{Rk}\overline{\ell}^{c}_{Ri}u_{Lj}\right) + \text{h.c.}$$

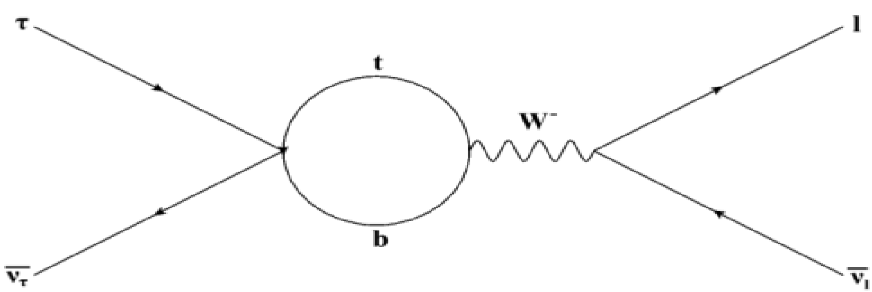
RPV & DM couplings	best-fit point	Flavour Suppression	Total value
λ_{323}	3.5	$\epsilon_{\bar{F}}$	3.5
λ'_{223}	$1^{\dagger}$	$\epsilon_{\bar{F}}\epsilon$	0.03
λ'_{233}	0.7	$\epsilon_{\bar{F}}$	0.7
λ'_{323}	2.4	ϵ	0.07
λ'_{333}	2.3	1	2.3
$\hat{\lambda}_{32}$	$1^{\dagger}$	$\epsilon_{\bar{F}}$	1
$\hat{\lambda}_{33}$	3.5	1	3.5

Masses	best-fit point [TeV]
$m_{\tilde{b}_R}$	1450
$m_{\tilde{\tau}_R}$	2900
m_{χ}	700
m_{ψ}	1950

NP loop contribution to *Z* boson/*τ* decays



(a)



(b)