Possible BSM Interpretations of Flavor & $g-2$ Anomalies

Bhupal Dev

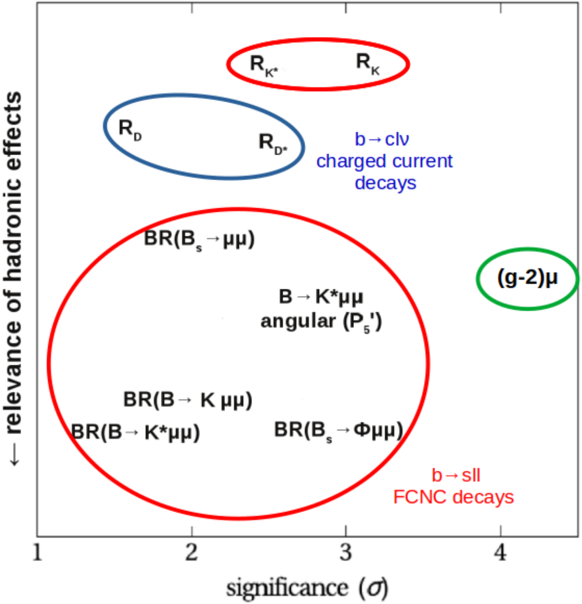
Washington University in St. Louis

DWQ@25

BNL-HET & RBRC Joint Workshop

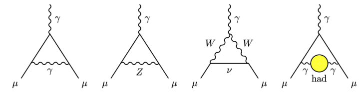
December 15, 2021

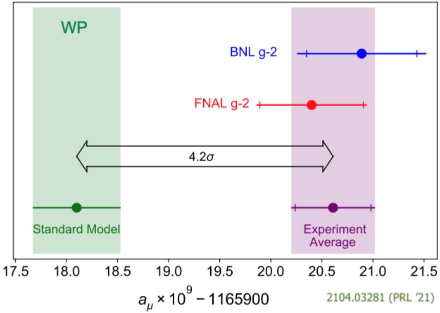
Flavor Anomalies

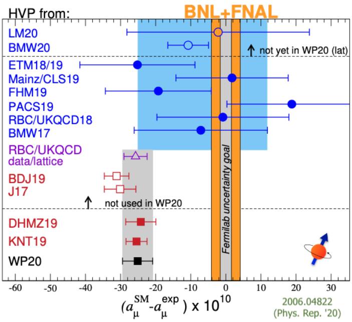


[from W. Altmannshofer's talk at *Anomalies 2021*]

Lepton Anomalous Magnetic Moment







[see A. El-Khadra's talk]

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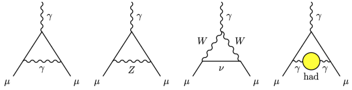

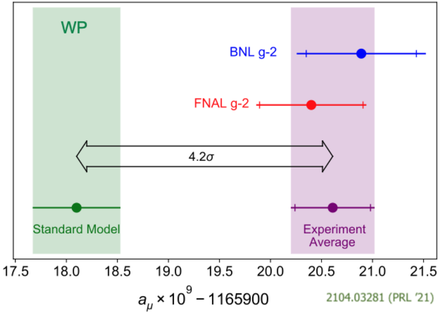

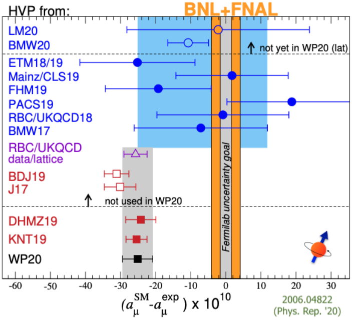

[see A. El-Khadra's talk]

- If a change in HVP brought $a_\mu^{\rm SM}$ closer to $a_\mu^{\rm exp}$, problems in the global EW fit? [Crivellin, Hoferichter, Manzari, Montull, 2003.04886 (PRL '20); see also rebuttal in Borsanyi et al., 2002.12347 (Nature '21)]

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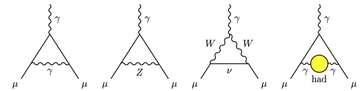

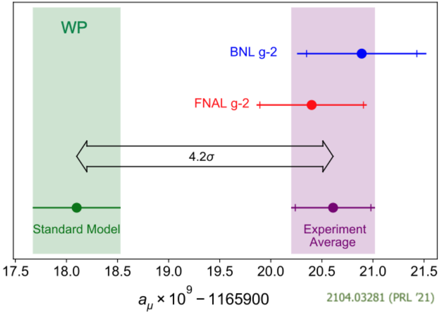

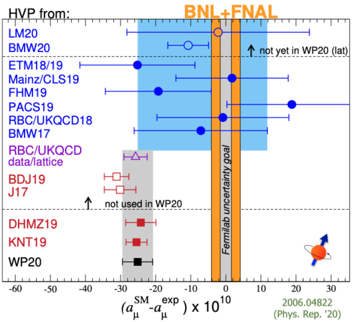

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- Electron $g-2$: 5.4σ tension between Cs and Rb [Parker, Yu, Zhong, Estey, Mueller, 1812.04130 (Science '19); Morel, Yao, Clade, Guellati-Khelifa (Nature '20)]; 4.8σ tension between numerical evaluations of 5-loop coefficients [Aoyama, Kinoshiya, Nio (Atoms '19); Volkov, 1909.08015 (PRD '19)]

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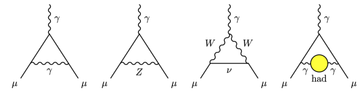

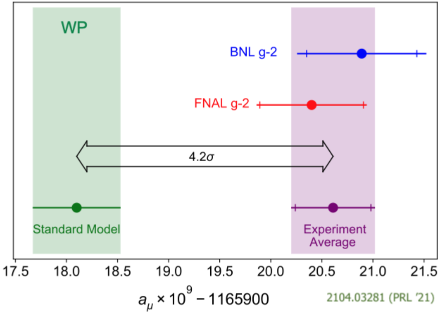

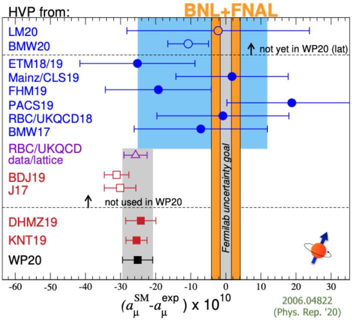

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- Tau $g-2$: Limits too weak. Possible improvement from $e^+e^- \to \tau^+\tau^-$ at Υ resonance in Belle II. [Bernabeu, Gonzalez-Sprinberg, Vidal, 0807.2366 (JHEP '09)]

BSM Solutions to $(g-2)_\mu$ Anomaly

Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL #1

Muon g-2 Collaboration • G.W. Bennett (Brookhaven) et al. (Feb, 2006)

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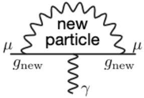
- Need $\Delta a_\mu = 251(59) \times 10^{-11}$ which is coincidentally at the same level as $a_\mu^{\rm EW} = 153.6(1.0) \times 10^{-11}$.

$$\Delta a_\mu \sim \frac{g_{\rm new}^2}{16\pi^2} \frac{(\text{muon mass} \sim 0.1\ \text{GeV})^2}{(\text{new particle mass})^2}$$

$$\sim a_\mu^{\rm EW} \quad \text{when} \quad \begin{cases} g_{\rm new} \sim W \text{ boson coupling} \\ m_{\rm new} \sim W \text{ boson mass} \end{cases}$$



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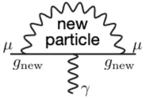
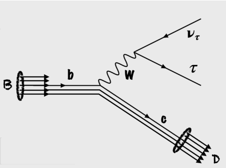


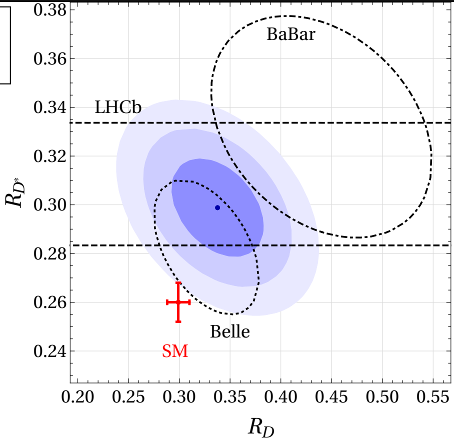
- Essentially two choices:
  - Superweak interaction, small mass (e.g., ALP, dark photon, light Z')
  - $\mathcal{O}(1)$ interaction, large mass (e.g. 2HDM, SUSY, leptoquark)
- New particle(s) in the loop can be anything: neutral/charged spin 0, 1/2, 1. [Lindner, Platscher, Queiroz, 1610.06587 (Phys. Rep. '18)]
- Need to be careful about the sign of the BSM contribution.
- Also often need flavor non-universal couplings to avoid other experimental constraints (mostly involving electron/quark sector).

$R_{D^{(*)}}$ Anomaly ($b \to c\tau\nu$)

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \quad (\text{with } \ell = e, \mu)$$



Experiment	Tag method	τ decay mode	R_D	R_{D^*}	$R_{J/\psi}$
Babar (2012) [1]	hadronic	$\ell\nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015) [2]	hadronic	$\ell\nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015) [5]	hadronic	$\ell\nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016) [2]	semileptonic	$\ell\nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017) [3]	hadronic	$\pi(\rho)\nu$	-	$0.270 \pm 0.035 \pm 0.027$	
LHCb (2017) [6]	hadronic	$3\pi\nu$	-	$0.291 \pm 0.019 \pm 0.029$	
Belle (2019) [4]	semileptonic	$\ell\nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb (2016) [67]	hadronic	$\ell\nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011 [63]	0.260 ± 0.008 [64]	0.26 ± 0.02 [68]



[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

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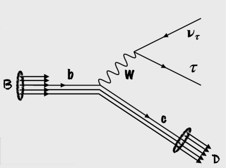

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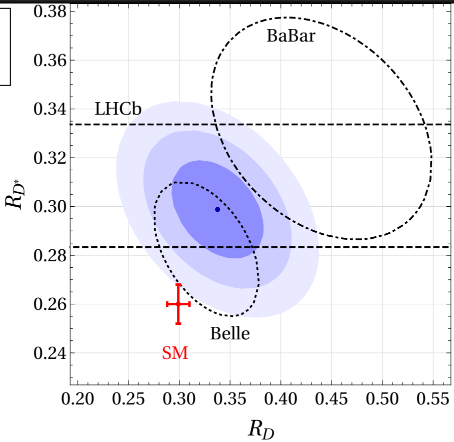
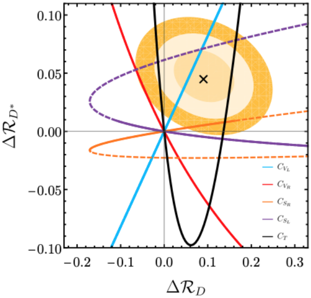


[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

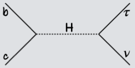
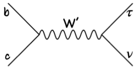
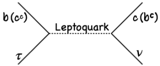
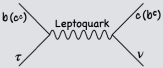
- Flavor Changing Charged Current – tree-level in the SM (only CKM-suppressed).
- *All* experimental measurements to date are consistently *above* the SM prediction.
- 3.3σ discrepancy (HFLAV gives 3.1σ) $\longrightarrow$ **Lattice can improve SM prediction.**
- BSM effect has to be large $\Longrightarrow \lesssim \mathcal{O}$(TeV)-scale new particle.

BSM Solutions to $R_{D^{(*)}}$ Anomaly

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb}\mathcal{O}_{V_L} + \frac{1}{\Lambda^2}\sum_i C_i^{(\prime,\prime\prime)}\mathcal{O}_i^{(\prime,\prime\prime)}$$



[Murgui, Peñuelas, Jung, Pich, 1904.09311 (JHEP '19)]

2HDM	 $\mathcal{O}_{S_L}: (\bar c\, P_L b)(\bar\tau P_L \nu)$ $\mathcal{O}_{S_R}: (\bar c\, P_R b)(\bar\tau P_L \nu)$	**W'**	 $\mathcal{O}_{V_L}: (\bar c\gamma_\mu P_L b)(\bar\tau\gamma^\mu P_L \nu)$
Scalar Leptoquark	 $\mathcal{O}'_{S_L}: (\bar\tau P_L b)(\bar c P_L \nu)$ $\mathcal{O}''_{S_L}: (\bar\tau P_L c^c)(\bar b^c P_L \nu)$ $\mathcal{O}''_{S_R}: (\bar\tau P_R c^c)(\bar b^c P_L \nu)$	**Vector Leptoquark**	 $\mathcal{O}'_{V_L}: (\bar\tau\gamma_\mu P_L b)(\bar c\gamma^\mu P_L \nu)$ $\mathcal{O}'_{V_R}: (\bar\tau\gamma_\mu P_R b)(\bar c\gamma^\mu P_L \nu)$ $\mathcal{O}''_{V_R}: (\bar\tau\gamma_\mu P_R c^c)(\bar b^c\gamma^\mu P_L \nu)$

BSM Solutions to $R_{D^{(*)}}$ Anomaly

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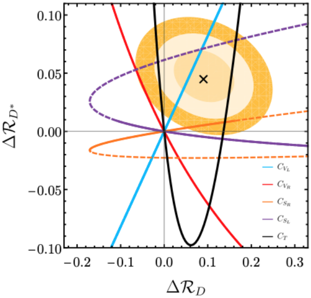

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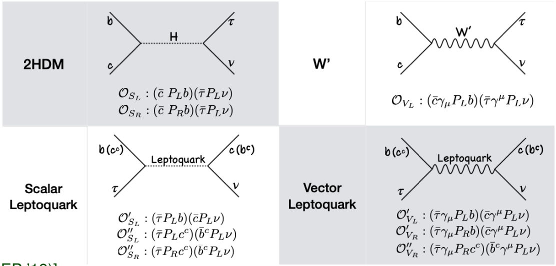

- Charged Higgs solution in type-II 2HDM (MSSM-type) goes in the wrong direction [BaBar, 1303.0571 (PRD '13); Belle, 1906.06871].
- In general, tension with LHC mono-τ data [Greljo, Camalich, Ruiz-Alvarez, 1811.07920 (PRL '19)] and induces a large $\text{BR}(B_c \to \tau\nu) > 50\%$ which is problematic [Alonso, Grinstein, Camalich, 1611.06676 (PRL '17); Akeroyd, Chen, 1708.04072 (PRD '17); Aebischer, Grinstein, 2105.02988]
- W' solution is challenged by LHC di-tau data [Faroughy, Greljo, Kamenik, 1609.07138 (PLB '17)] and by precision Z-pole observables [Feruglio, Paradisi, Pattori, 1606.00524 (PRL '17)].

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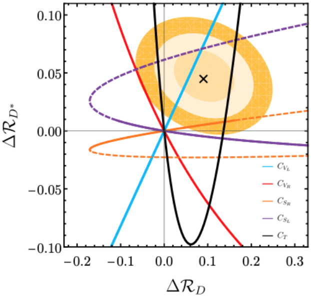

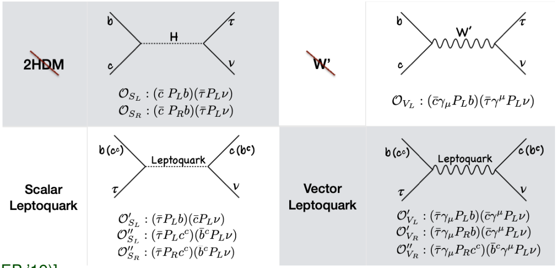

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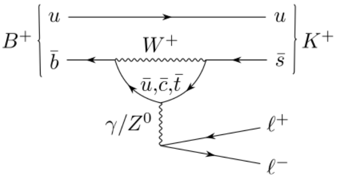
$R_{K^{(*)}}$ Anomaly ($b \to s\ell^+\ell^-$)

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$



- Flavor Changing Neutral Current $\longrightarrow$ loop-suppressed in the SM.
- New physics can be heavy (multi-TeV).

$$R_{K^+}^{[1,6]} = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$$

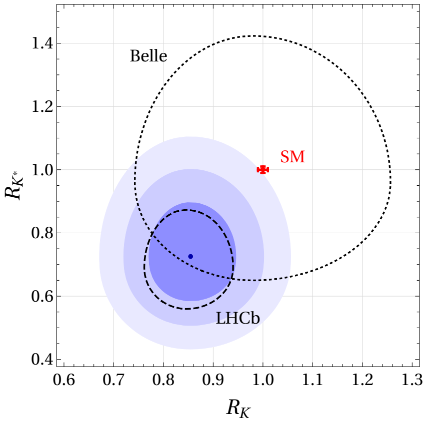
$$R_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

$$R_{K_S}^{[1.1,6]} = 0.66^{+0.20\,+0.02}_{-0.14\,-0.04}$$

$$R_{K^{*+}}^{[0.045,6]} = 0.70^{+0.18\,+0.03}_{-0.13\,-0.04}$$

$$R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05$$



[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

- 3.4σ net discrepancy.
- All measurements are consistently below the SM.
- Recent result from LHCb [2103.11769] didn't change the central value.

BSM Solutions to $R_{K^{(*)}}$ Anomaly

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

Altmannshofer, Stangl, 2103.13370 (EPJC '21)

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.75^{+0.22}_{-0.23}$	3.4σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.73^{+0.15}_{-0.15}$	5.2σ
$C_{10}^{bs\mu\mu}$	$+0.42^{+0.23}_{-0.24}$	1.7σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.7σ
$C_9^{\prime bs\mu\mu}$	$+0.24^{+0.27}_{-0.26}$	0.9σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.18^{+0.13}_{-0.14}$	1.4σ
$C_{10}^{\prime bs\mu\mu}$	$-0.16^{+0.16}_{-0.16}$	1.0σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.02^{+0.10}_{-0.10}$	0.2σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.20^{+0.15}_{-0.15}$	1.3σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$+0.05^{+0.12}_{-0.12}$	0.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.53^{+0.13}_{-0.13}$	3.7σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.6σ

BSM Solutions to $R_{K^{(*)}}$ Anomaly

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

Altmannshofer, Stangl, 2103.13370 (EPJC '21)

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.75^{+0.22}_{-0.23}$	3.4σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.73^{+0.15}_{-0.15}$	5.2σ
$C_{10}^{bs\mu\mu}$	$+0.42^{+0.23}_{-0.24}$	1.7σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.7σ
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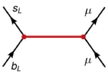
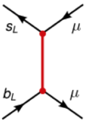
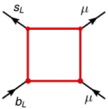
➢ Possible BSM models



- Heavy Z' model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...



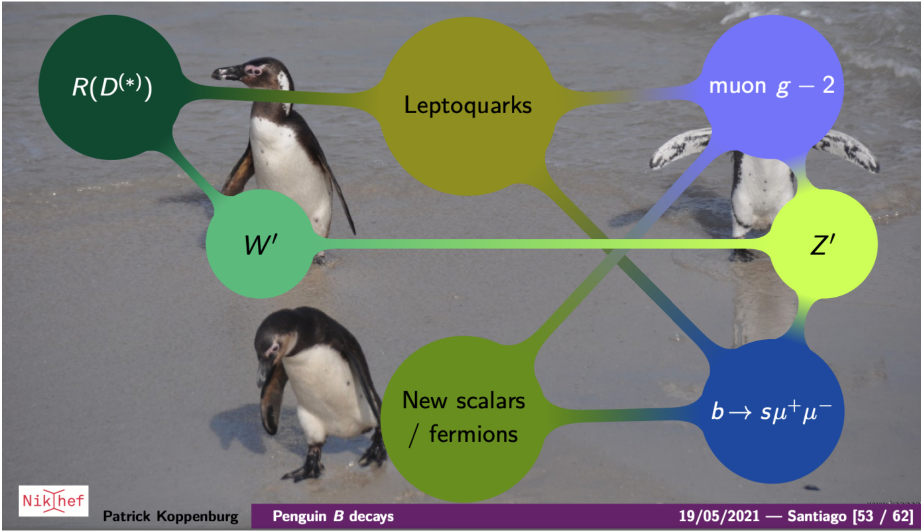
- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...



- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

arXiv:1706.07808

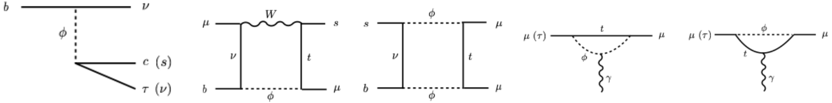
BSM Solutions to All Flavor Anomalies



Leptoquarks emerge as the winner! (or not too soon?)

Leptoquarks

- Single scalar leptoquark solution [Bauer, Neubert, 1511.01900 (PRL '16)]



- Now disfavored by global fits (including $b \to s\mu^+\mu^-$ observables, as well as LHC constraints). [Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504]

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

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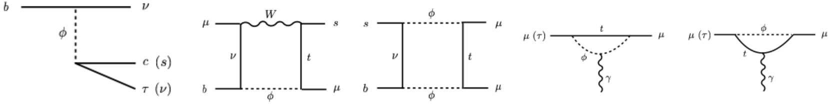

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U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
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- Vector LQ must be embedded into some UV-completion [e.g. Heeck, Teresi, 1808.07492]
- Solutions with more than one scalar LQ also possible. [Chen, Nomura, Okada, 1703.03251; Bigaran, Gargalionis, Volkas, 1906.01870); Saad, 2005.04352; Babu, BD, Jana, Thapa, 2009.01771]

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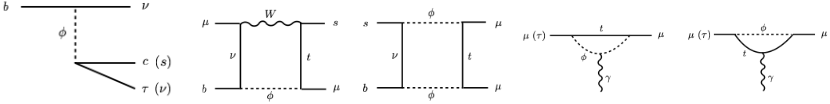

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U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
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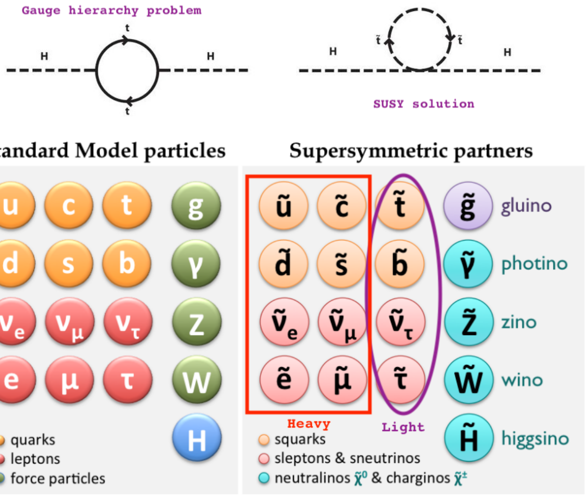
An alternative route: RPV-SUSY (not just another LQ model)

Why SUSY?



Natural SUSY

[Brust, Katz, Lawrence, Sundrum, 1110.6670 (JHEP ’12); Papucci, Ruderman, Weiler, 1110.6926 (JHEP ’12)]

MSSM with R-Parity Violation

- More natural to include RPV couplings, rather than imposing *R*-parity by hand.
  [Brust, Katz, Lawrence, Sundrum, 1110.6670 (JHEP '12)]
- LFUV arises naturally – á la Yang-Mills. [BD, Soni, Xu, 2106.15647]
- Third generation may be special. (LFUV in *B*-sector, but not in *D* nor in Λ)
- **RPV3**: RPV SUSY with light 3rd-generation sfermions.
  [Altmannshofer, BD, Soni, 1704.06659 (PRD '17)]

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- **RPV3**: RPV SUSY with light 3rd-generation sfermions. [Altmannshofer, BD, Soni, 1704.06659 (PRD '17)]
- Can naturally accommodate $R_{D^{(*)}}$ ($b \to c\tau\nu$) via LQD interactions. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); Trifinopoulos (EPJC '18); Hu, Li, Muramatsu, Yang (PRD '19)]

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

- Can *simultaneously* explain $R_{K^{(*)}}$ ($b \to s\ell\ell$) via LLE interactions, together with LQD. [Das, Hati, Kumar, Mahajan (PRD '17); Earl, Grégoire (JHEP '18); Trifinopoulos (EPJC '18); Hu, Huang (PRD '20); Altmannshofer, BD, Soni, Sui (PRD '20)]

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\widetilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \widetilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \widetilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)\right] + \text{H.c.}$$

- Muon $g-2$ from both LQD and LLE terms, but LLE more relevant.

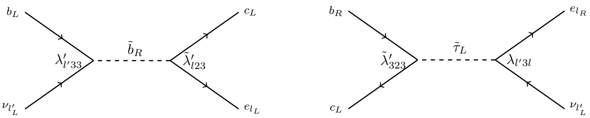


Figure: RPV3 contributions to $R_{D^{(*)}}$. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); · · ·]

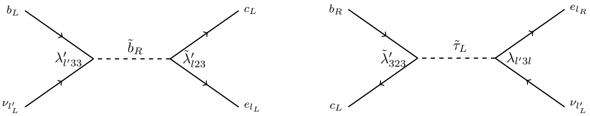
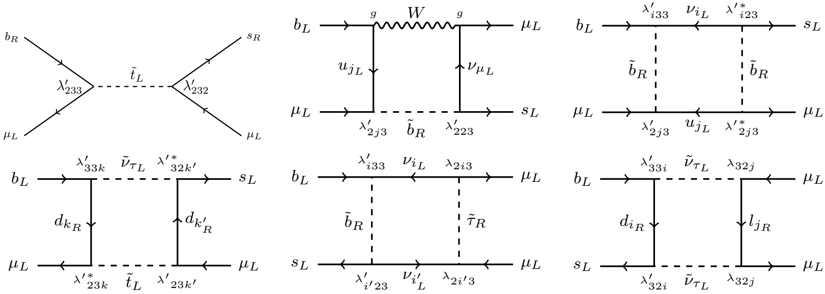


Figure: RPV3 contributions to $R_{D^{(*)}}$. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); $\cdots$]



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Muon $g-2$

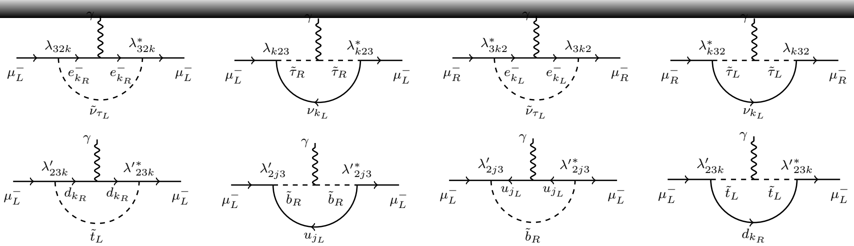

Figure: RPV3 contributions to $(g-2)_\mu$. [Kim, Kyae, Lee (PLB '01)]

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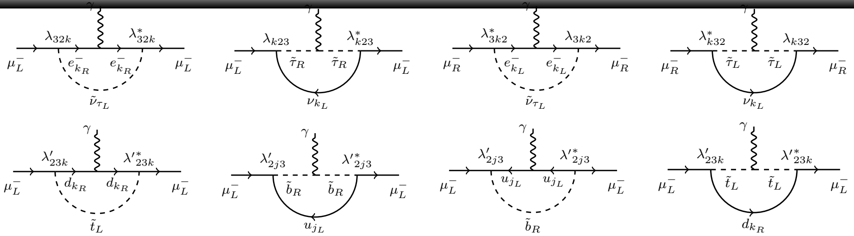

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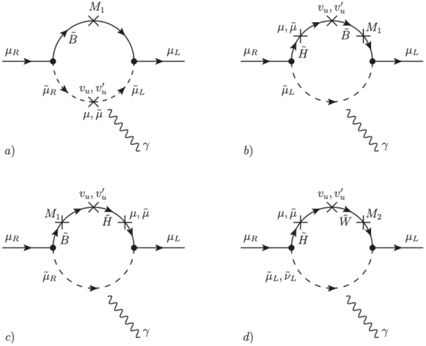
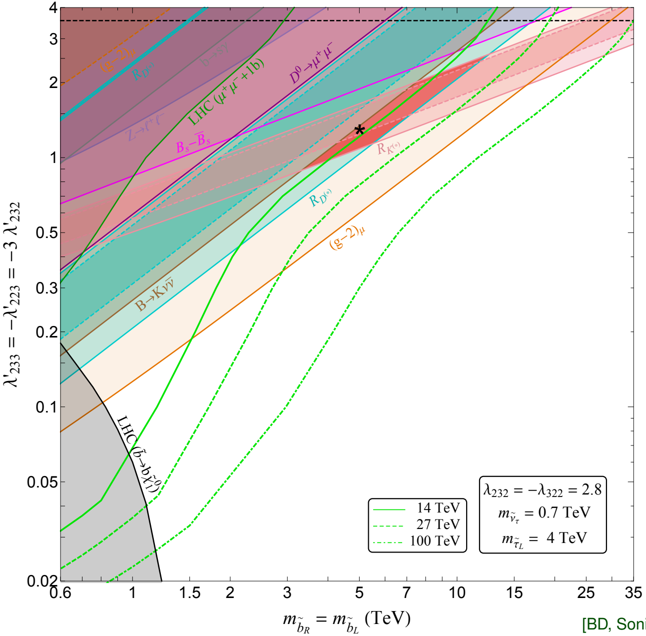


Figure: RPC contributions to $(g-2)_\mu$. [Moroi (PRD '96); Baum, Carena, Shah, Wagner (2104.03302)]

A Combined RPV3 Fit to All Flavor Anomalies



[BD, Soni, Xu (2106.15647)]

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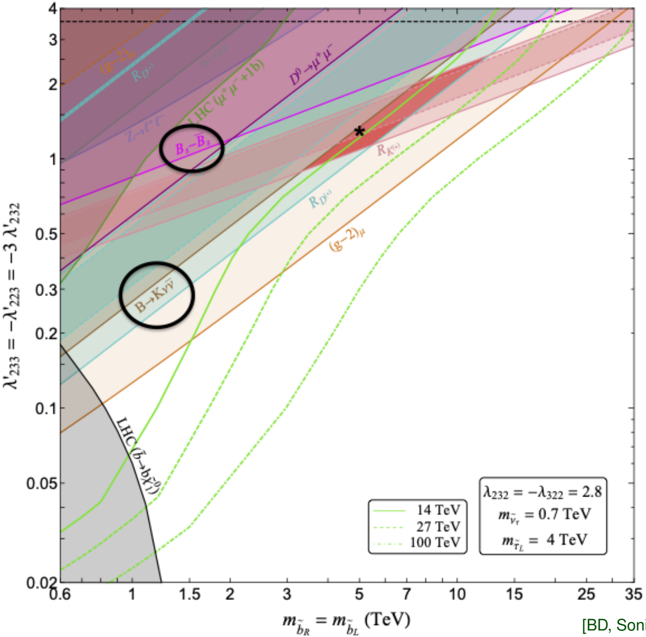

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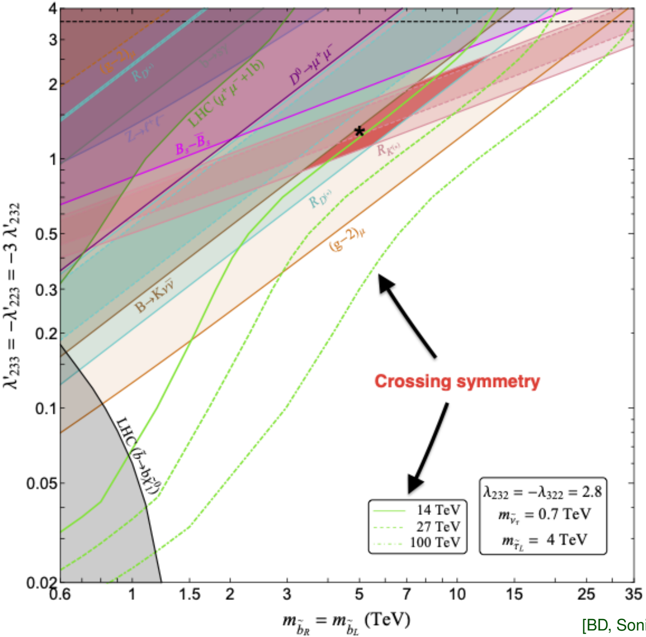

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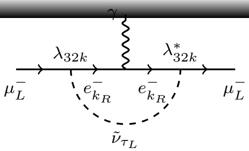
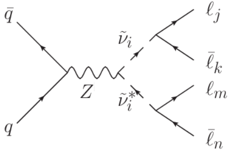
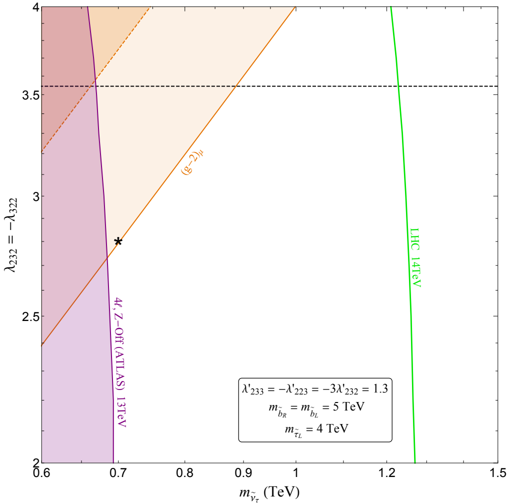
An LHC Test of Muon $g-2$







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Conclusion

- Mounting evidence for the violation of lepton flavor universality.
  [Crivellin, Hoferichter, 2111.1273 (Science '21)]
- Can be explained by invoking BSM physics.
- Leptoquarks and RPV-SUSY remain as the most attractive scenarios for a simultaneous explanation of B-anomalies and muon $g-2$.
- Personal choice: **RPV3** – motivated by Higgs naturalness and other beautiful features of SUSY, while being consistent with null searches at the LHC.
  - Removes the accidental flavor symmetry of the SM.
  - Same chiral structure as the SM $\Longrightarrow$ correct D^* and τ polarizations, as well as $R_K - R_{K^{(*)}}$ correlation come automatically.
  - Highly predictive and testable at Belle II, LHCb and high-p_T LHC experiments.
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Thank You.