Interpreting Flavor and Electroweak Puzzles

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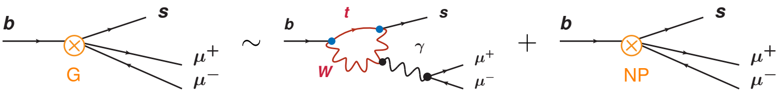
Basic Idea Behind Indirect Probes of New Physics

Example: Rare B decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

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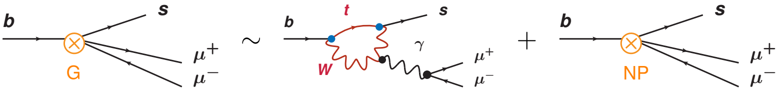

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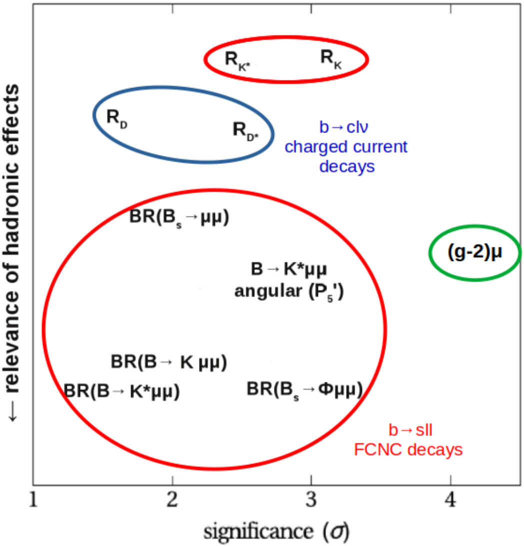
calculate precisely the SM contribution

get information on NP coupling and scale

Anomalies at low energies can establish a new scale in particle physics
⇒ “no-loose theorems”, “guaranteed” discoveries at colliders, ...

(at least in principle)

Anomalies and Puzzles in 2022



see talks by:

Asutosh Kotwal

Martin Fertl

Soeren Prell

Carla Marin Benito (Fr)

(plot inspired by

Zoltan Ligeti)

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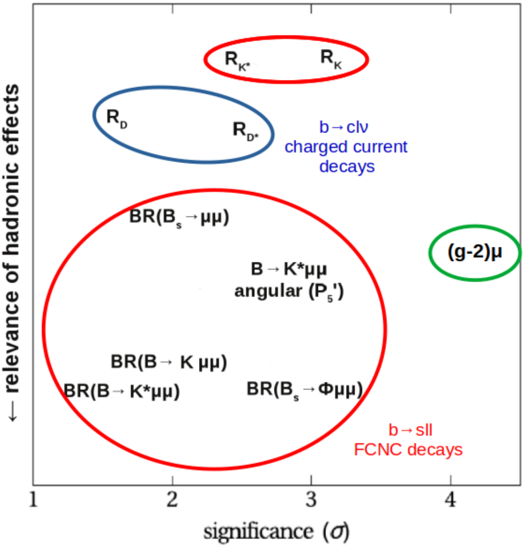

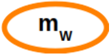

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Bottom-Up Approach to the Anomalies

theory input / bias

'motivated' models — address other open questions: hierarchy problem, SM flavor puzzle,...
ensure the model is renormalizable, UV complete, ...

simplified models — introduce new particles in the simplest way possible
(e.g. a single lepto-quark or a single Z' boson)

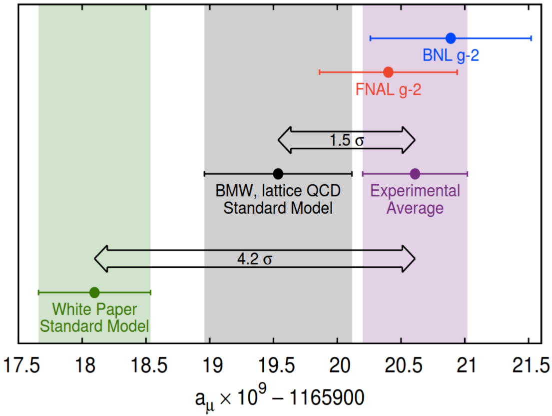
effective field theory (SMEFT / LEFT) — parameterize new physics model independently
(need to make minimal assuptions, e.g. new physics is heavy)

experimental input

(inspired by Marco Nardecchia)

Implications of the muon g-2

Anomalous Magnetic Moment of the Muon



4.2 σ discrepancy between the experimental average (Fermilab g-2, 2104.03281) and the SM consensus (Aoyama et al. 2006.04822)

(see, however, the lattice results 2002.12347, 2206.06582, 2206.15084, 2207.04765)

$$\Delta a_\mu = (251 \pm 59) \times 10^{-11}$$

Model Independent Analysis and New Physics Scale

The leading effective operator that modifies the anomalous magnetic moment of the muon and that respects $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{\rm eff} = \frac{C}{\Lambda_{\rm NP}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta} \quad \Rightarrow \quad \Delta a_\mu \simeq \frac{4 m_\mu v C}{e\sqrt{2}\Lambda_{\rm NP}^2}$$

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strong coupling	$\frac{1}{\Lambda_{\text{NP}}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta}$	$\Lambda_{\text{NP}} \simeq 290$ TeV
weak coupling	$\frac{e}{16\pi^2}\frac{1}{\Lambda_{\text{NP}}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta}$	$\Lambda_{\text{NP}} \simeq 14$ TeV
weak coupling + MFV	$\frac{e y_\mu}{16\pi^2}\frac{1}{\Lambda_{\text{NP}}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta}$	$\Lambda_{\text{NP}} \simeq 280$ GeV

(MFV = Minimal Flavor Violation)

New Physics Models for $(g-2)_\mu$

- In the strongly coupled case, the new physics scale could be extremely high, outside the reach of current and future colliders. (However, I am not aware of any actual model)

- Most explanations of $(g-2)_\mu$ predict:

new physics not far above the electroweak scale
("heavy new physics": SUSY, leptoquarks, Z', ...)

or

new physics considerably below the electroweak scale
("light new physics": dark photons, axions, light Z', ...)

Heavy New Physics Example: SUSY

- It is very well known that the MSSM can give sizeable contributions to $(g-2)_\mu$ via $\tan\beta$ enhanced slepton chargino/neutralino loops

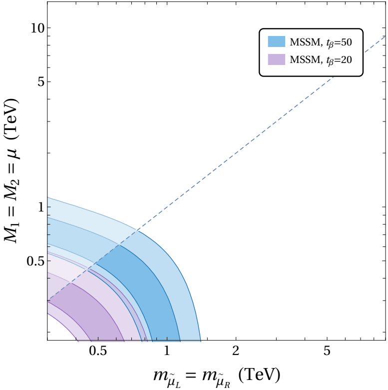
  Athron et al. 2104.03691 + many others

  (apologies for the omission)

- Sleptons, charginos, neutralinos need to be pretty light

- Compressed spectra to avoid exising LHC constraints

- Good discovery prospects at the high luminosity LHC and e^+e^- colliders (ILC, CLIC)



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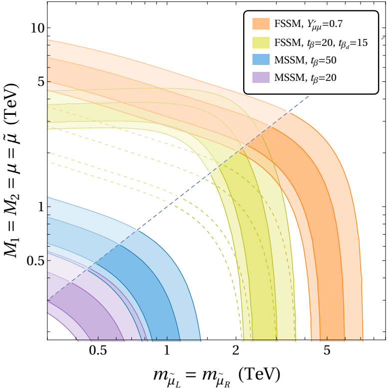


- In non-minimal SUSY scenarios, sleptons, charginos, neutralinos can be significantly heavier

  WA, Gadam, Gori, Hamer 2104.08293

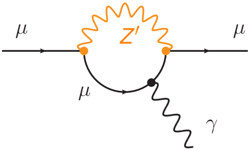
Light New Physics Example: $L_\mu - L_\tau$

New gauge bosons are well known candidates to explain $(g-2)_\mu$

(e.g. Greljo et al. 2203.13731)

Dark photons have been ruled out for quite a while

Gauged $L_\mu - L_\tau$ is one of the least constrained options



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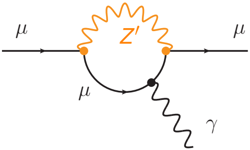
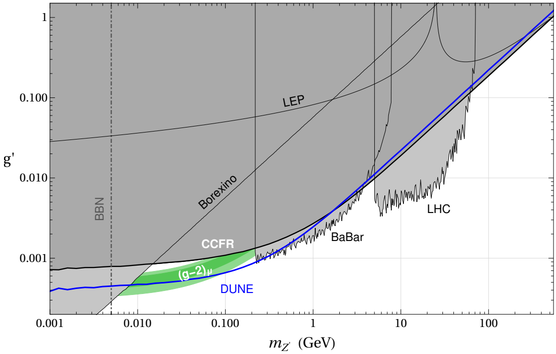


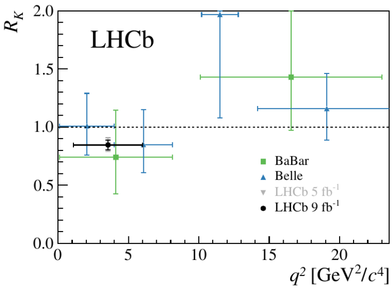
WA, Gori, Pospelov, Yavin, 1406.2332;

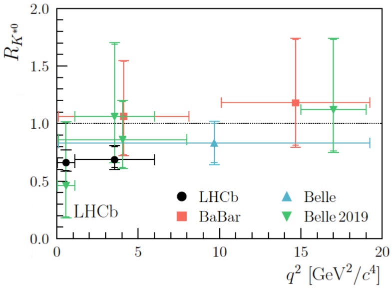
WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



Implications of the $b \to s\ell\ell$ Anomalies (R_K , R_{K^*} and Friends)

Evidence for Lepton Flavor Universality Violation





$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)} \overset{\text{SM}}{\simeq} 1$$

$$R_{K^+}^{[1,6]} = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012}\ (3.1\sigma)$$

$$R_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03\ (\sim 2.5\sigma)$$

$$R_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05\ (\sim 2.5\sigma)$$

$$R_{K_S}^{[1.1,6]} = 0.66^{+0.20}_{-0.14}{}^{+0.02}_{-0.04}\ (\sim 1.5\sigma)$$

$$R_{K^{*+}}^{[0.045,6]} = 0.70^{+0.18}_{-0.13}{}^{+0.03}_{-0.04}\ (\sim 1.5\sigma)$$

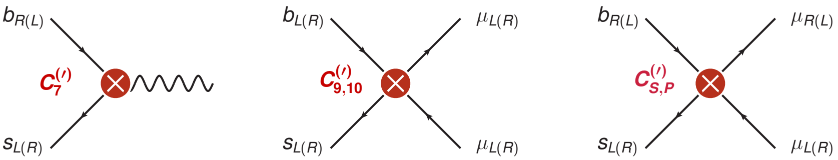
$$R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05\ (\sim 1\sigma)$$

LHCb 2103.11769, LHCb 1705.05802, 1912.08139, 2110.09501; also Belle 1904.02440, 1908.01848

Model Independent Analysis

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators | semileptonic operators | scalar operators

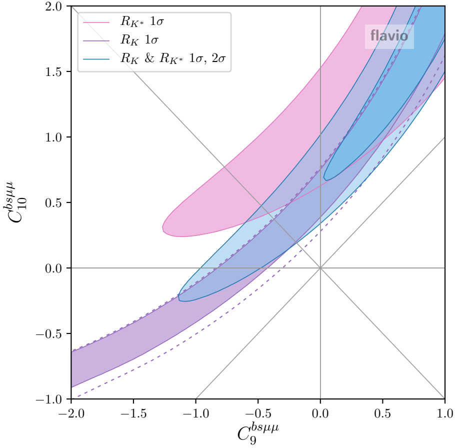


$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

$$C_{10}^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

neglecting tensor operators and additional scalar operators
(they are dimension 8 in SMEFT: Alonso, Grinstein, Martin Camalich 1407.7044)

Global Fits of Rare $b \to s\ell\ell$ Decays



WA, Stangl 2103.13370 (other recent fits: Geng et al. 2103.12738; Cornella et al. 2103.16558; Alguero et al. 2104.08921; Hurth et al. 2104.10058; Gubernari et al. 2206.03797)

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios

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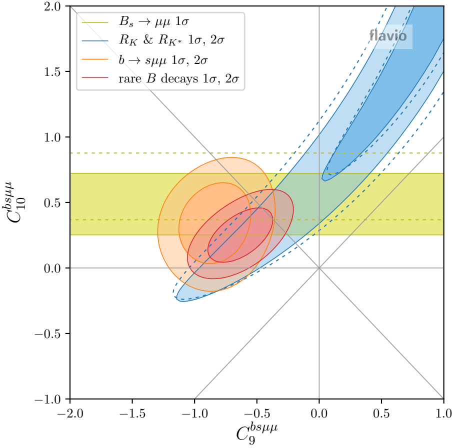

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- LFU ratios
- $B_s \to \mu^+\mu^-$ branching ratio (with latest CMS update probably compatible with SM-like C_{10})
- $b \to s\mu\mu$ observables
- overall remarkable consistency

The New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu\mu)$	$\Lambda_{\rm NP} \simeq 120\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu\mu)$	$\Lambda_{\rm NP} \simeq 35\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu\mu)$	$\Lambda_{\rm NP} \simeq 7\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu\mu)$	$\Lambda_{\rm NP} \simeq 3\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu\mu)$	$\Lambda_{\rm NP} \simeq 0.6\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$

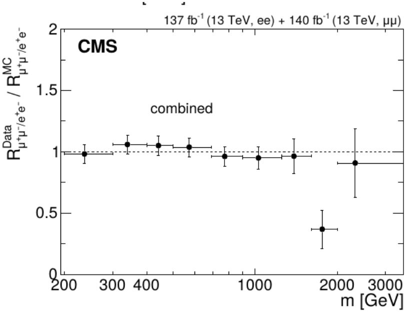
(MFV = Minimal Flavor Violation)

Model Independent Approach at the LHC

If the new physics is not accessible directly at the LHC,
high energy tails of di-lepton spectra are in principle still affected

(Greljo, Marzocca 1704.09015)

$$R = \frac{\sigma(pp \to \mu\mu)}{\sigma(pp \to ee)}$$



CMS 2103.02708 (also ATLAS 2105.13847)

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) \qquad C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

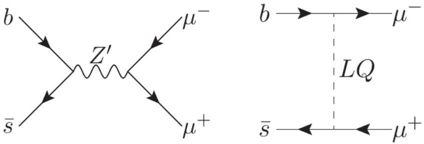
- flavor changing operators are probed up to scales of few TeV
- order of magnitude is missing to probe the $b \to s\ell\ell$ anomalies

$\to$ would need a 100 TeV collider

Simplified Models for R_K and R_{K^*}

possible tree level explanations:

- Z' Bosons
- Lepto-Quarks



upper bounds on flavor violating couplings from B_s mixing imply upper bounds on the particle masses (e.g. Di Luzio et al. 1909.11087)

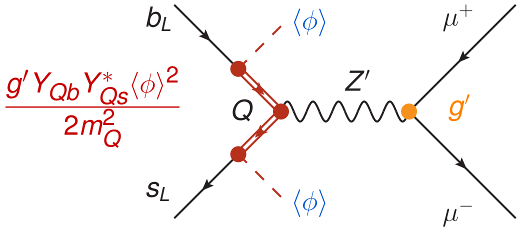
- $m_{Z'} \lesssim g_\mu \times 5\text{TeV}$
- $m_{\text{LQ}} \lesssim (30 - 60)\text{TeV}$ (depending on the lepto-quark representation)

$\rightarrow$ a weakly coupled Z' might be in reach of the LHC

My Favorite Z' Model

Z' based on gauged $L_\mu - L_\tau$ (He, Joshi, Lew, Volkas PRD 43, 22-24)
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

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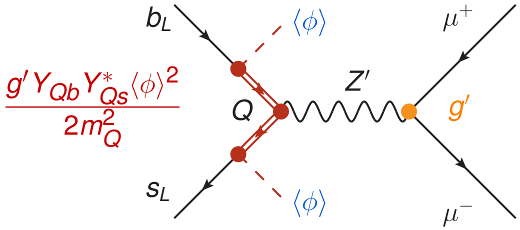


predicted Lepton Universality Violation!

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Probing the $L_\mu - L_\tau$ Parameter Space

Neutrino Tridents

B_s mixing

$(g-2)_\mu$

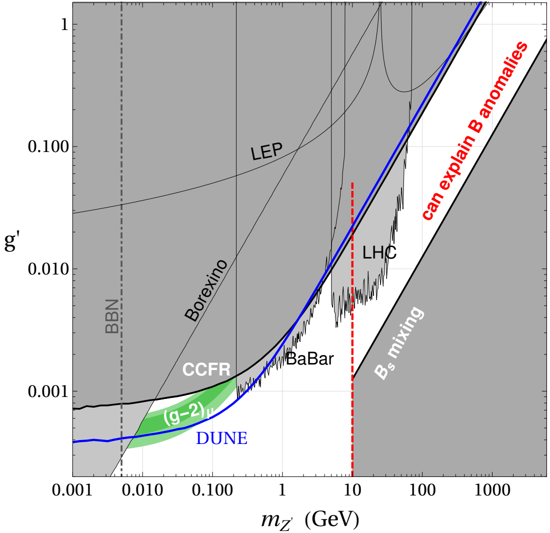
νe scattering

$Z \to \ell\ell$

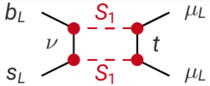
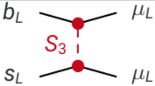
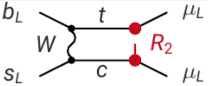
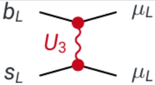
$Z \to 4\mu$

$e^+e^- \to 4\mu$

WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



Simplified Leptoquark Models

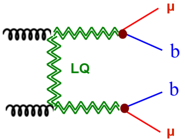
Spin	G_{SM}	Name	Characteristic process	First time used for $b \to s\mu\mu$
0	$(\bar{3},1)_{1/3}$	S_1		Bauer, Neubert, arXiv:1511.01900
0	$(\bar{3},3)_{1/3}$	S_3		Hiller, Schmaltz, arXiv:1408.1627
0	$(3,2)_{7/6}$	R_2		Bečirević, Sumensari, arXiv:1704.05835
1	$(3,1)_{2/3}$	U_1		Barbieri et al., arXiv:1512.01560
1	$(3,3)_{2/3}$	U_3		Fajfer, Košnik, arXiv:1511.06024

from talk by Peter Stangl LF(U)V workshop, Zurich, July 4

(the loop level leptoquarks struggle to accommodate the anomalies) e.g. Allanach, Gripaios, You 1710.06363, Hiller, Loose, Nisandzic 1801.09399

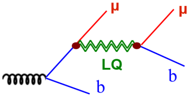
- Leptoquarks are pair produced through QCD interactions

$$pp \to \text{LQ LQ} \to j(b)\mu^+ \, j(b)\mu^-$$



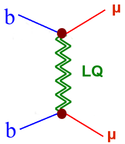
- Leptoquarks can be singly produced through their couplings to quarks/leptons

$$pp \to \text{LQ}\ \mu \to j(b)\mu^+\mu^-$$



- Leptoquarks contribute to di-muon production

$$pp \to \mu^+\mu^-$$



Leptoquark Signatures at the LHC

e.g. Allanach, Gripaios, You 1710.06363, Hiller, Loose, Nisandzic 1801.09399

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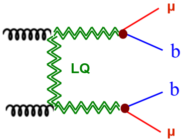

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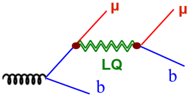

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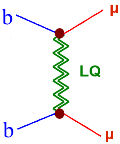


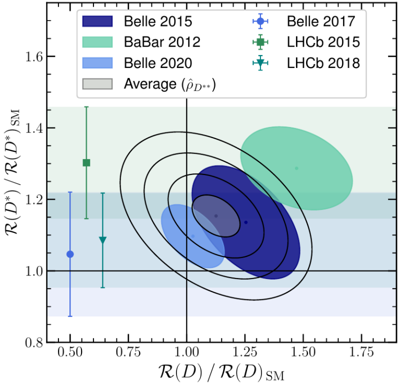
Also: excellent prospects to see these leptoquarks at a muon collider

Huang, Jana, Queiroz, Rodejohann 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720

Implications of the $b \to c\tau\nu$ Anomalies (R_D , R_{D^*})

LFU in Charged Current Decays: R_D and R_{D^*}

Bernlochner, Franco Sevilla, Robinson, 2101.08326



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

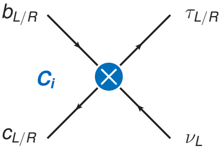
$$R_D^{\rm exp} / R_D^{\rm SM} = 1.13 \pm 0.10 \ , \quad R_{D^*}^{\rm exp} / R_{D^*}^{\rm SM} = 1.15 \pm 0.06$$

combined discrepancy with the SM: 3.6σ

(the heavy flavor averaging group quotes 3.1σ)

Model Independent Analysis

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



$\mathcal{O}_i$ = contact interactions
with vector, scalar
or tensor currents

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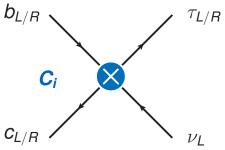

$\mathcal{O}_i$ = contact interactions
with vector, scalar
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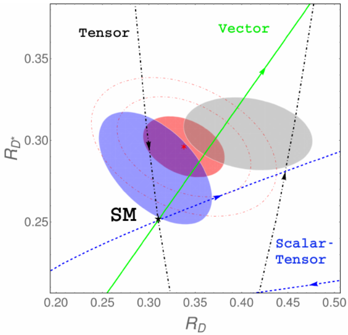
rescaling of the SM vector operator fits the data best

combinations of operators are also possible

Shi et al. 1905.08498



(also Murgui et al. 1904.09311, Asadi, Shih 1905.03311, Cheung et al. 2002.07272, ...)

The New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar c \gamma_\nu P_L b)(\bar\tau \gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 8.4$ TeV
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar c \gamma_\nu P_L b)(\bar\tau \gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 2.4$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2} V_{cb} (\bar c \gamma_\nu P_L b)(\bar\tau \gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 0.5$ TeV

(MFV = Minimal Flavor Violation)

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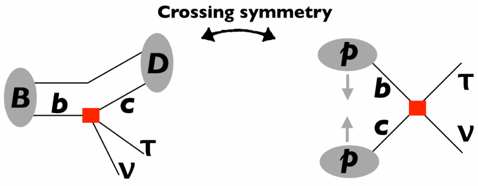
(MFV = Minimal Flavor Violation)

rather low scale $\rightarrow$ model building is non-trivial

Model Independent Approach at the LHC

Expect non-standard
mono-tau production
at the LHC

(possibly in association
with b-jets)



WA, Dev, Soni 1704.06659; Greljo et al. 1811.07920;
Marzocca et al. 2008.07541; ...

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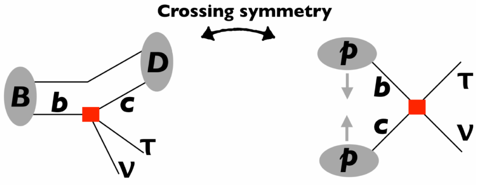

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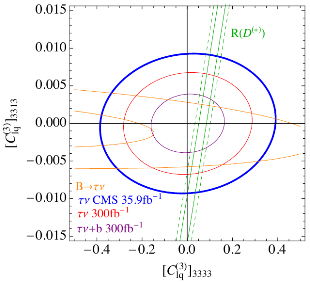


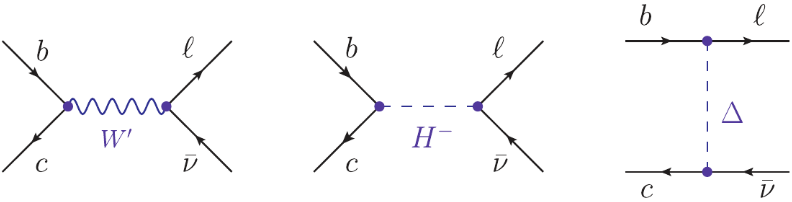
- Collider and low energy sensitivities are complementary
- High-luminosity LHC can probe relevant parts of parameter space

Need a tree level mediator: 3 options

1) *W′* bosons excluded by direct searches

2) Charged Higgs bosons strongly constrained by $B_c \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ kinematic distributions

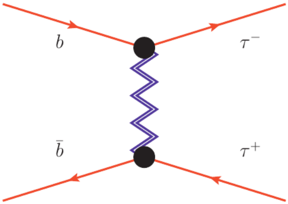
3) Leptoquarks that couple dominantly to the 3rd generation can work.



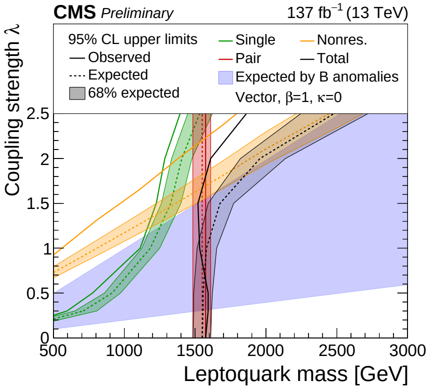
Collider Signature of the Leptoquarks

- Robust collider signature of leptoquarks that explain R_D and R_{D^*}: non-standard di-tau production at high invariant mass

  Faroughy et al. 1609.07138



CMS-PAS-EXO-19-016



Combined Explanations of the B anomalies

- U_1 leptoquark can simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ (recent studies: Cornella et al. 2103.16558; Angelescu et al. 2103.12504)
- U_1 could be the remnant of an extended gauge group: "4321 models", (Pati-Salam)^3 models (Di Luzio et al. 1708.08450; Bordone et al. 1712.01368, ...)

Model		$R_{K^{(*)}}$	$R_{D^{(*)}}$
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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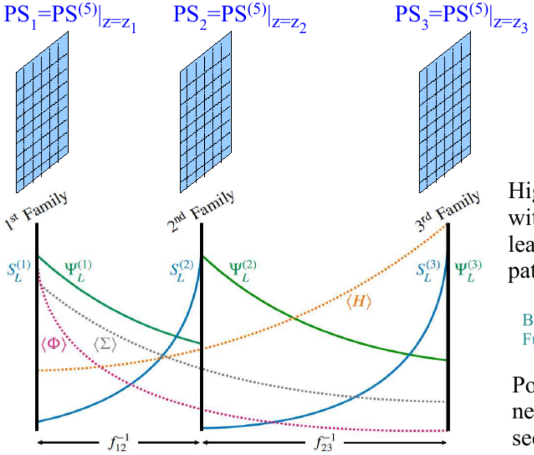
U_1	$(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓
U_3	$(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗

- also attempts for simultaneous explanations in RPV SUSY
  Deshpande, He, 1608.04817; WA, Dev, Soni 1704.06659; Earl, Gregoire 1806.01343; Trifinopoulos 1807.01638; WA, Dev, Soni, Sui 2002.12910; Dev, Soni, Xu 2106.15647; ...

Flavor anomalies from the U_1 leptoquark of (Pati-Salam)^3



Flavor ↔ special position (*topological defect*) in an extra (compact) space-like dimension

Dvali & Shifman, '00

Higgs and SU(4)-breaking fields with oppositely-peaked profiles, leading to the desired flavor pattern for masses & anomalies

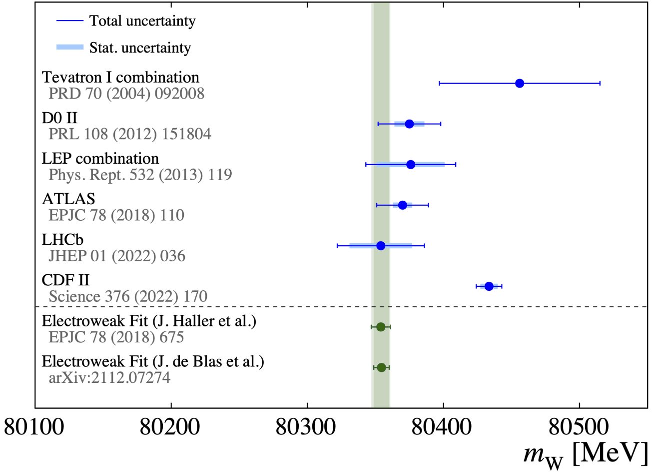
Bordone, Cornella, Fuentes-Martin, GI '17
Fuentes-Martin, GI, Pages, Stefanek '20

Possible to implement anarchic neutrino masses via an inverse see-saw mechanism

(talk by Gino Isidori @ Beyond the Anomalies workshop, Durham 2021)

Implications of the W Mass

W Mass Measurements



CDF measurement is 7σ away from the SM prediction !?!

The W Mass and New Physics

- The SM predicts a relation between the *W* mass, the *Z* mass, and weak mixing angle (precise relation is subject to higher order correction, choice of renormalization scheme, ...)

$$\frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = \rho \simeq 1$$

The W Mass and New Physics

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New physics could enter by:

- changing the mass of the W (e.g. mixing of W with a W')

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- changing the weak mixing angle (e.g. by modifying Z couplings)

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$$\frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \rho \simeq \frac{\sum_i (I_i(I_i+1) - Y_i^2) v_i^2}{\sum_i 2 Y_i^2 v_i^2}$$

New physics could enter by:

- changing the mass of the W (e.g. mixing of W with a W')
- changing the mass of the Z (e.g. mixing of Z with a Z')
- changing the weak mixing angle (e.g. by modifying Z couplings)
- changing the relation itself (e.g. exotic Higgs sectors)

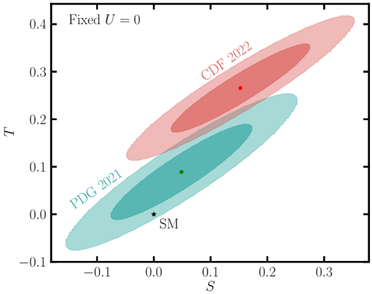
Model Independent Approach

- New physics is often model independently described by oblique corrections

$$S \frac{gg'}{16\pi}\frac{1}{v^2}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$

$$T \frac{e^2}{8\pi}\frac{1}{v^2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$$

$$+\ldots$$



Lu et al. 2204.03796

(also de Blas et al. 2204.04204; Strumia 2204.04191;

... + many others, apologies for the omission)

- Need a generic new physics scale of a few TeV

Connection with the B Anomalies?

- Z' models that can explain the $b \to s\ell\ell$ anomalies might also explain shifts in the W mass
- Example 1: gauge a linear combination of hypercharge, baryon number, and individual lepton numbers

  WA, Davighi, Nardecchia 1909.02021

$$X = a_Y Y - a_e(B/3 - L_e) - a_\mu(B/3 - L_\mu) - a_\tau(B/3 - L_\tau)$$

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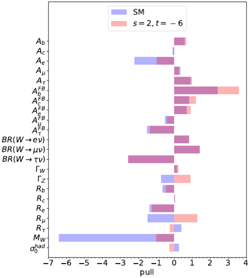
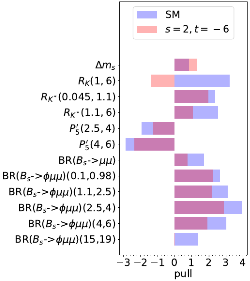
- Example 2: gauge a linear combination of third generation hypercharge, baryon number, and lepton number

  Allanach, Davighi 2205.12252

$$X = sY_3 + t(B_3 - L_3)$$





Summary

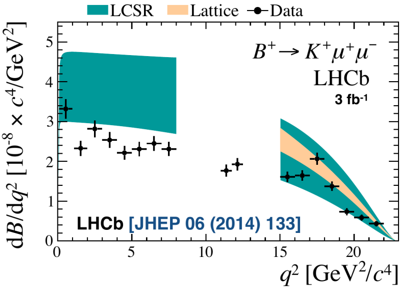
- Anomalies might be indirect signs of physics beyond the standard model.
- Anomalies could establish a new mass scale in particle physics

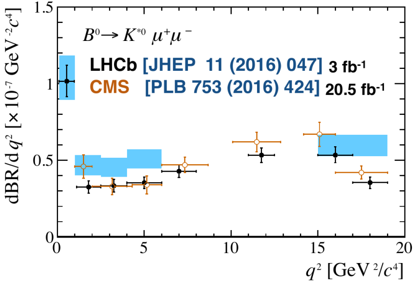
$\rightarrow$ would have a transformative impact:

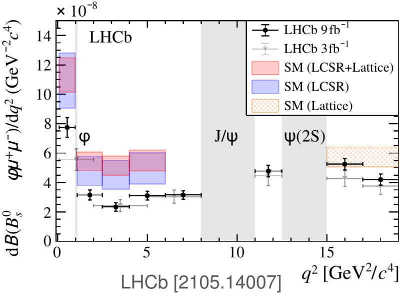
motivate a large new physics model building effort and provide targets for direct searches at the LHC and future colliders

Back Up

$b \to s\mu\mu$ Branching Ratios



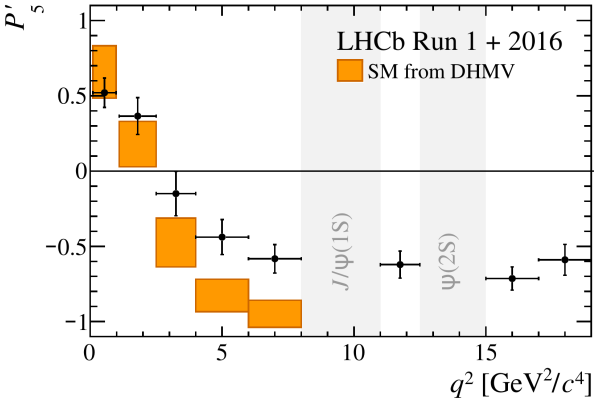




Experimental results for
$\text{BR}(B \to K\mu\mu)$
$\text{BR}(B \to K^*\mu\mu)$
$\text{BR}(B_s \to \phi\mu\mu)$
are consistently low
across many q^2 bins

$P_5' \sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

LHCb 2003.04831



Anomaly persists in the latest update of $B^0 \to K^{*0} \mu^+ \mu^-$ with 2016 data.
(Anomaly also seen in $B^\pm \to K^{*\pm} \mu^+ \mu^-$ LHCb 2012.13241)

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Total cross section increases with the center of mass energy

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\,\left(|C_9|^2 + |C_{10}|^2\right)$$

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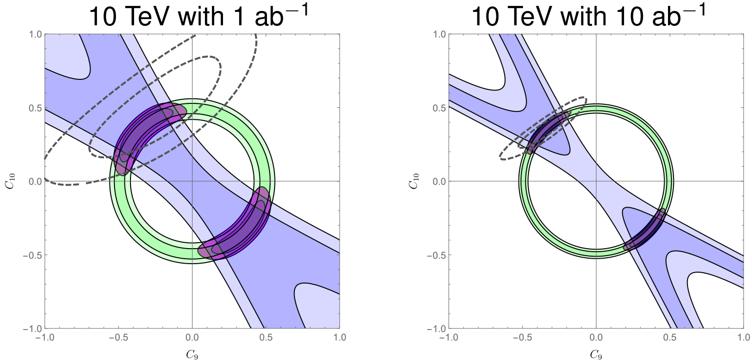
Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3{\rm Re}(C_9 C_{10}^*)}{2(|C_9|^2 + |C_{10}|^2)}$$

Need charge tagging to measure the forward backward asymmetry

Sensitivity Projections

WA, Gadam, Profumo 2203.07495 and in preparation



- branching ratio (green) and forward backward asymmetry (blue) are highly complementary
- 10 TeV muon collider has better sensitivity than the current and projected rare B decay results (dashed)

(see also Huang et al. 2103.01617; Asadi et al. 2104.05720

Azatov et al. 2205.13552 for related studies)