New Physics Models for the Flavor Anomalies

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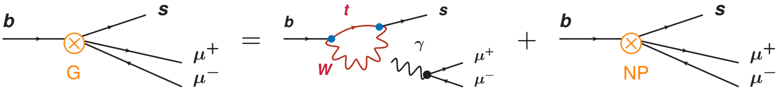
(partly based on whitepaper 2203.07726 with Jure Zupan)

Snowmass Summer Meeting 2022,

Seattle, July 17 - 26, 2022

Example: Rare B decays



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

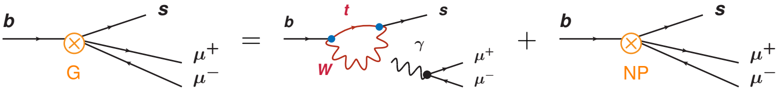
measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

Basic Idea Behind Indirect Probes of New Physics

Example: Rare B decays



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measure precisely

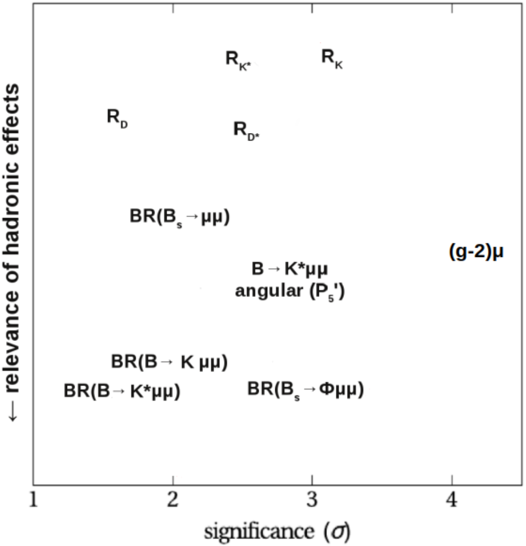
calculate precisely the SM contribution

get information on NP coupling and scale

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

(at least in principle)

Summary of Flavor Anomalies



(inspired by
Zoltan Ligeti)

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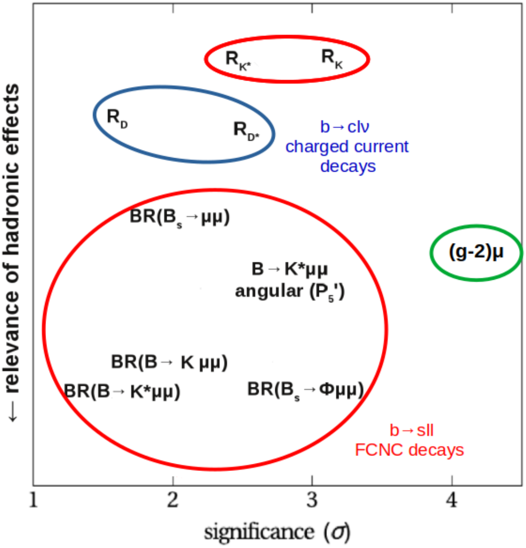

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Bottom-Up Approach to the Anomalies

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

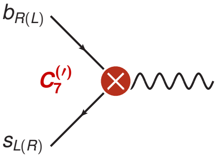
(inspired by Marco Nardecchia)

New Physics Models for the $b \to s\ell\ell$ Anomalies (R_K , R_{K^*} and Friends)

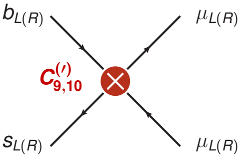
Model Independent Analysis

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

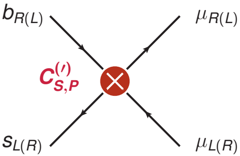
magnetic dipole operators



semileptonic operators



scalar operators



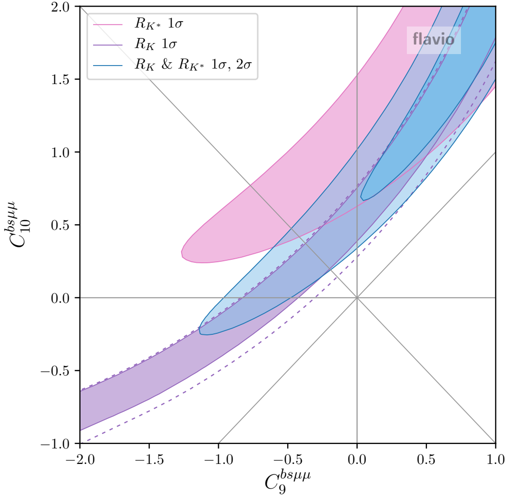
$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

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

neglecting tensor operators and additional scalar operators

(they are dimension 8 in SMEFT: Alonso, Grinstein, Martin Camalich 1407.7044)

Wilson Coefficient Fits



WA, Stangl 2103.13370

(+ many others)

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

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

- LFU ratios prefer non-standard C_{10}, but large degeneracy

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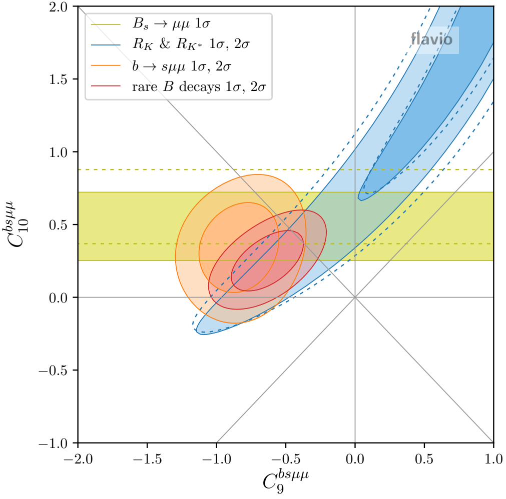

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- LFU ratios prefer non-standard C_{10}, but large degeneracy
- $B_s \to \mu^+\mu^-$ branching ratio shows slight preference for non-standard C_{10}
  (with latest CMS update probably compatible with SM-like C_{10})
- $b \to s\mu\mu$ observables prefer non-standard C_9
- 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	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$

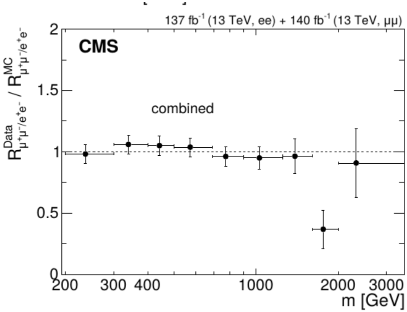
(MFV = Minimal Flavor Violation)

Model Independent Approach at the LHC

even if the new degrees of freedom
are not accessible at the LHC,
high energy tails of di-lepton spectra
are in principle 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

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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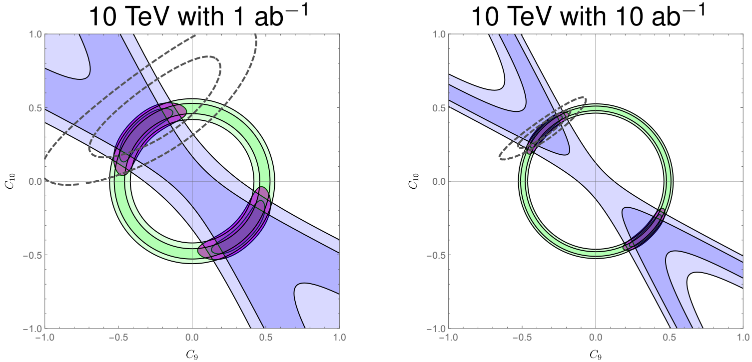
Forward backward asymmetry is sensitive to the chirality strcuture

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

Need charge tagging to measure the forward backward asymmetry

Sensitivity Projections

WA, Gadam, Profumo 2203.07495 and in preparation

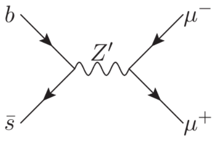


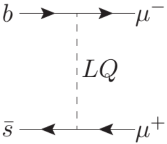
- branching ratio (green) and forward backward asymmetry (blue) are highly complementary
- 10 TeV muon collider has better sensitivity than the current and projected rare B decay results (dashed)

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

Azatov et al. 2205.13552 for related studies) possible tree level explanations:

- *Z′* Bosons
- Leptoquarks





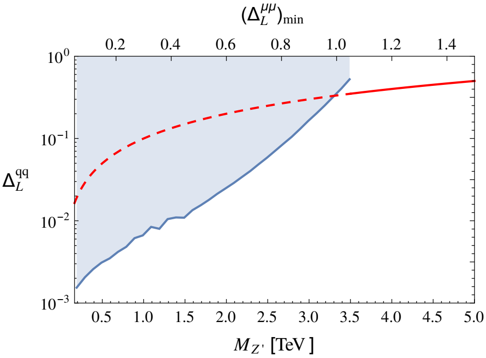
upper bounds on flavor violating couplings from B_s mixing imply upper bounds on the particle masses (e.g. Di Luzio et al. 1909.11087)

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

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

Simplified Z' Models

- “minimalistic” Z' setups are very hard to probe (need only *bs* and $\mu\mu$ coupling to explain the anomalies)
- direct searches at the LHC can be used to constrain couplings to light quark generations (WA, Straub 1411.3161)



- simple MFV ansatz for quark couplings already excluded by LHC searches (Greljo, Marzocca 1704.09015)

Origin of the Z'

1) Z' could be a vector resonance of a composite sector

$\rightarrow$ composite Higgs models

- to explain the rare B decay anomalies, need a large amount of muon compositeness. Unusual, but not excluded.

for an extensive list of references see WA, Zupan 2203.07726

(let us know if your favorite model is missing ...)

Origin of the Z'

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- to explain the rare B decay anomalies, need a large amount of muon compositeness. Unusual, but not excluded.

2) Z' could be the gauge boson of a spontaneously broken gauge symmetry

- want to couple the Z' to muons

$\rightarrow$ most obvious choice is a $U(1)$ that includes muon number
e.g. $B_3 - L_\mu$, $L_\mu - L_\tau$, ...

(note: if generation specific baryon number is gauged, some quark Yukawa couplings are not allowed at the renormalizable level; connection to SM flavor puzzle?)

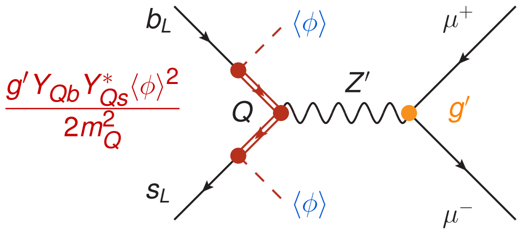
for an extensive list of references see WA, Zupan 2203.07726

(let us know if your favorite model is missing ...)

My Favorite Z' Model

Z' based on gauging $L_\mu - L_\tau$ (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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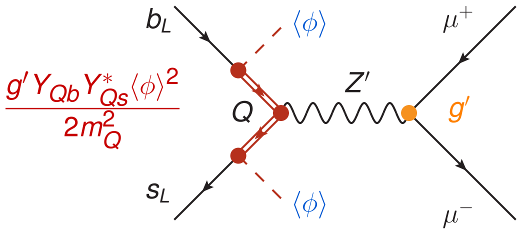


predicted Lepton Universality Violation!

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

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

Neutrino Tridents

B_s mixing

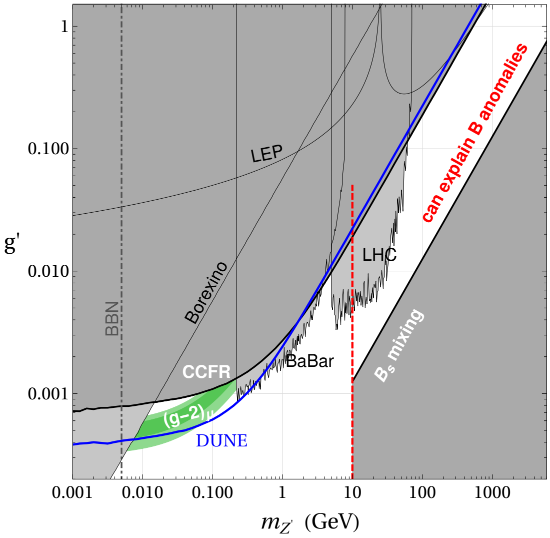
$(g-2)_\mu$

νe scattering

$Z \to \ell\ell$

$Z \to 4\mu$

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



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

Neutrino Tridents

B_s mixing

$(g-2)_\mu$

νe scattering

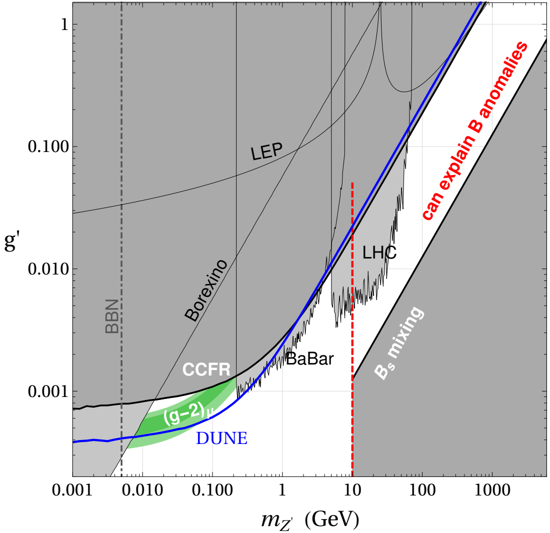
$Z \to \ell\ell$

$Z \to 4\mu$

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

would be hard to miss at a muon collider (Huang, Jana, Queiroz, Rodejohann 2101.04956)

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



Extending the $L_\mu - L_\tau$ Model

(self imposed) rules:

- Renormalizable SM Yukawa couplings are allowed.
- Absence of lepton flavor violation.
- At most 3 SM singlets (= RH neutrinos) to soak up gauge anomalies.

$\Rightarrow$ There is a 4 parameter family of possible $U(1)_X$ gauge symmetries

$$T_X = a_Y T_Y - a_e T_{B/3-L_e} - a_\mu T_{B/3-L_\mu} - a_\tau T_{B/3-L_\tau}$$

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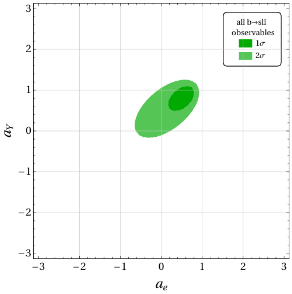
$$C_9^{bs\ell\ell} \propto a_\ell - \frac{3}{4} a_Y$$

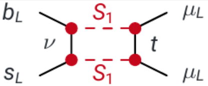
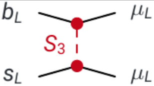
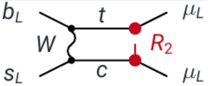
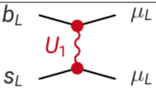
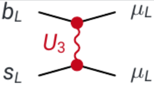
$$C_{10}^{bs\ell\ell} \propto -\frac{1}{4} a_Y$$

- Axial vector currents are necessarily lepton flavor universal
- Axial vector currents come with tree level Z-Z' mixing



WA, Davighi, Nardecchia 1909.02021

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

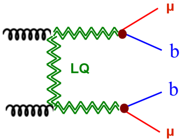
(the loop level leptoquarks struggle to accommodate the anomalies)

Leptoquark Signatures at the LHC

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

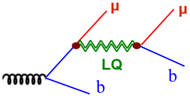
- Leptoquarks are pair produced through QCD interactions

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



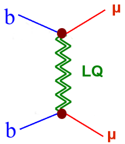
- Leptoquarks can be singly produced through their couplings to quarks/leptons

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



- Leptoquarks contribute to di-muon production

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



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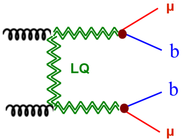

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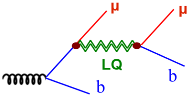

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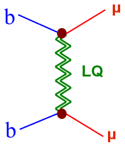


Also: excellent prospects to see these leptoquarks at a muon collider

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

Model Building Challenges for Leptoquarks

- Vector leptoquarks beg for a UV completion

→ Vector leptoquarks could be resonances of a composite sector

→ The U_1 vector leptoquark could be the gauge boson of an $SU(4)$ gauge symmetry (Di Luzio et al 1708.08450; Calibbi et al. 1709.00692; Bordone et al. 1712.01368; ...)

- The S_3 scalar leptoquark can couple to all lepton generations and also to di-quarks

→ strong constraints from LFV processes and proton decay

→ introduce a protection mechanism, like gauged muon number leptoquark → "muoquark"

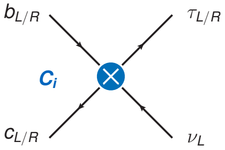
(Hambye, Heeck 1712.04871; Davighi, Kirk, Nardecchia 2007.15016; Greljo et al. 2103.13991, 2107.07518; ...)

for a much more extensive list of references see WA, Zupan 2203.07726

(let us know if your favorite model is missing ...)

New Physics Models for the $b \to c\tau\nu$ Anomalies (R_D , R_{D^*})

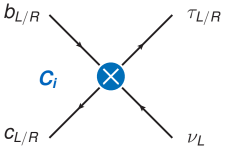
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i$$



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

Model Independent Analysis

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

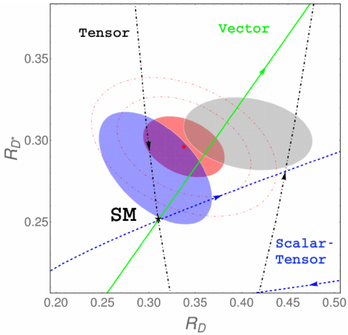


$\mathcal{O}_i$ = contact interactions with vector, scalar or tensor currents

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, ...)

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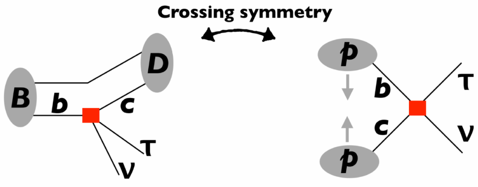
rather low scale $\rightarrow$ model building is non-trivial

Model Independent Tests 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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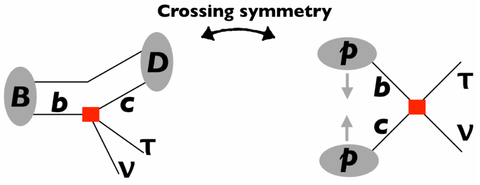

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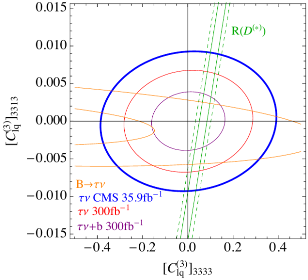


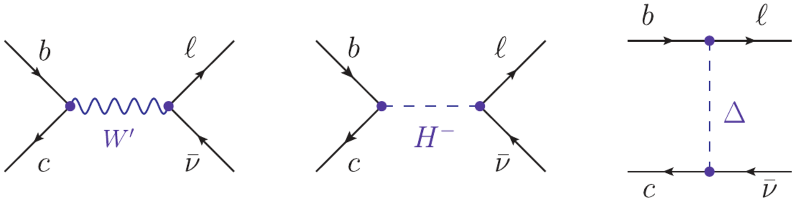
- Collider and low energy sensitivities are complementary
- High-luminosity LHC can probe large parts of parameter space

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

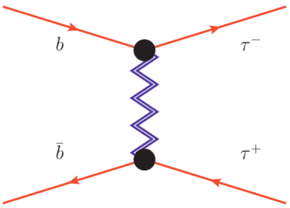
3) Leptoquarks that couple dominantly to the 3rd generation can work.



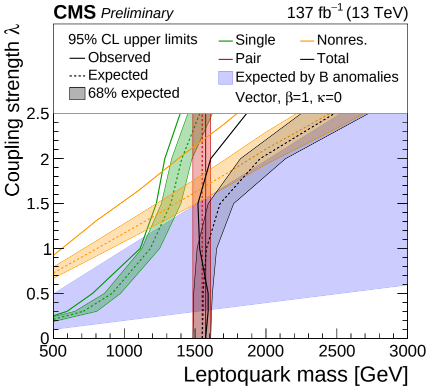
Collider Signature

- 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, ...)
- full models typically have many more collider accessible states: coloron, Z', vector-like fermions

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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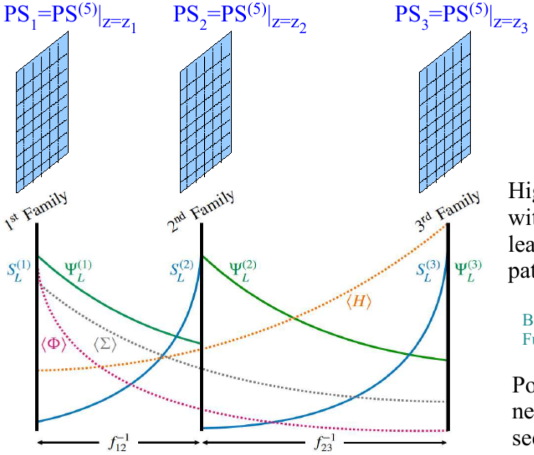
- also attempts for simultaneous explanations in RPV SUSY (several sfermions act like scalar leptoquarks)
  Deshpande, He, 1608.04817; WA, Dev, Soni 1704.06659; Earl, Gregoire 1806.01343; Trifinopoulos 1807.01638; WA, Dev, Soni, Sui 2002.12910; Dev, Soni, Xu 2106.15647; ...
- look for sbottoms, stops, staus, sneutrinos with RPV couplings

Fleshed Out (Pati-Salam)^3 Model

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)

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R_D, R_{D^*}

- $\Lambda_{\text{NP}} \sim 2$ TeV
- should have already seen something at the LHC
- new physics should be around the corner