Impact of Muon $g-2$ and Flavor Anomalies on the Energy Frontier

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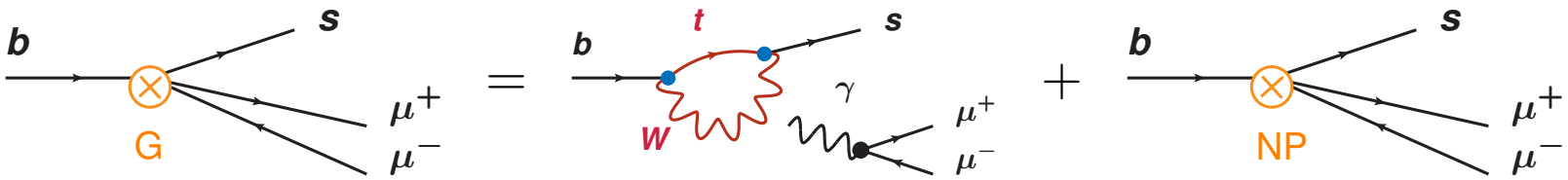
Basic Idea behind Indirect Probes of New Physics

Example: Rare B decays



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

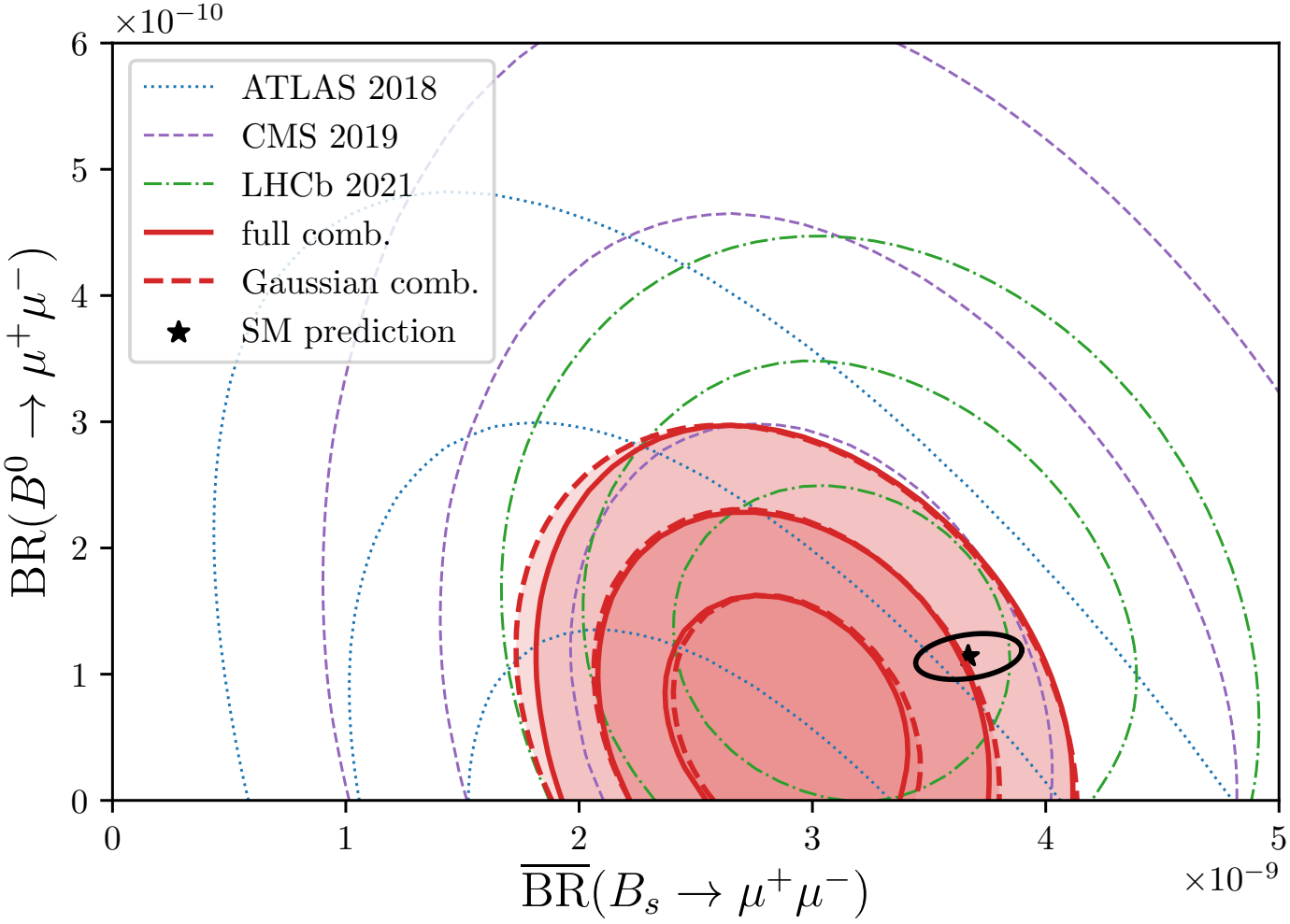
measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

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

Overview of the Anomalies

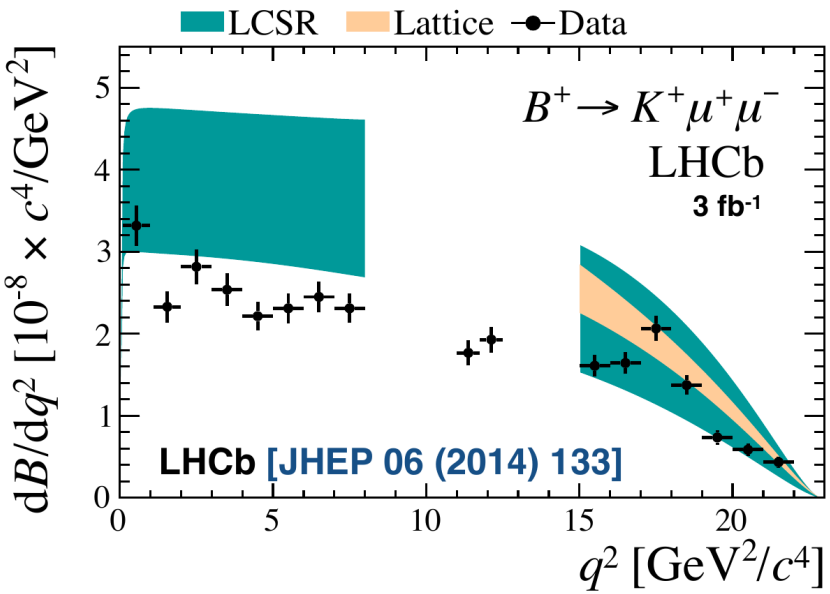
The $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ Decays

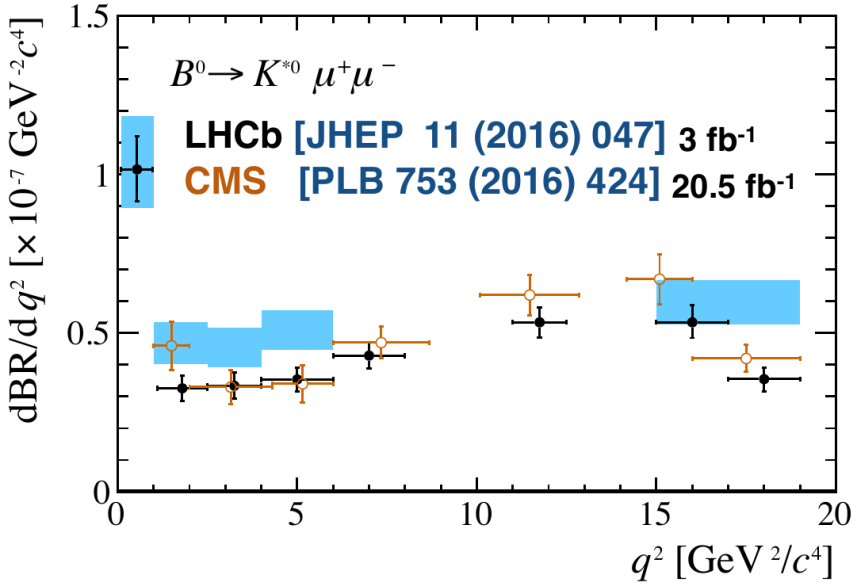
WA, Stangl 2103.13370; combination of LHCb-paper-2021-007, CMS 1910.12127, ATLAS 1812.03017

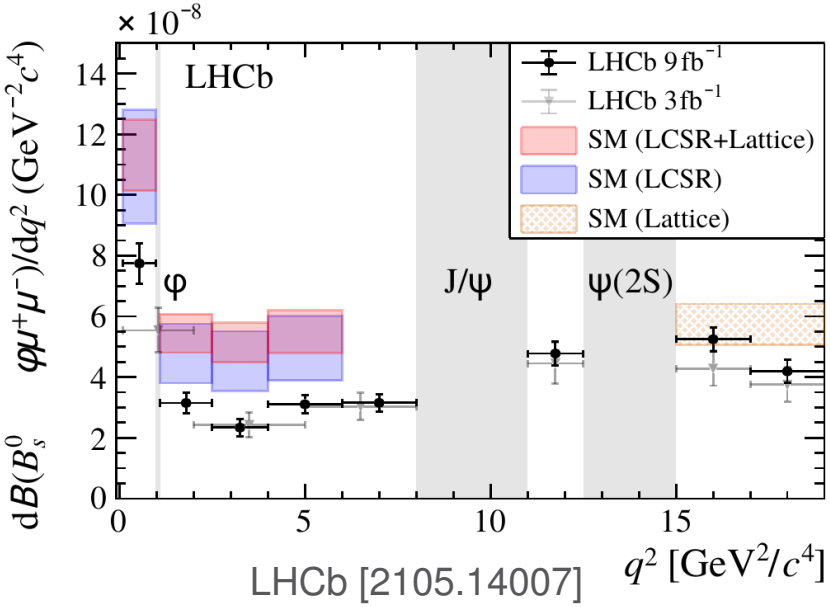


$\sim 2\sigma$ tension between SM and experiment

Semileptonic Branching Ratios





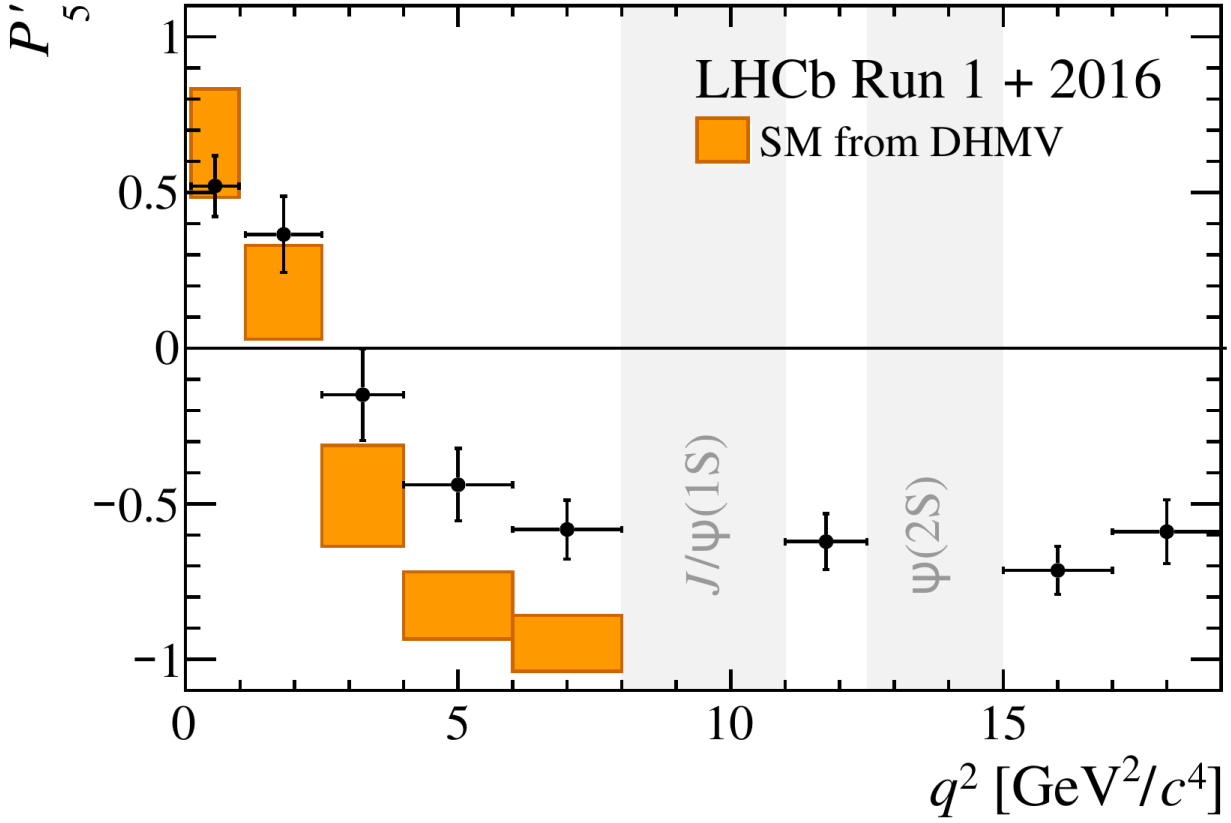


Experimental results for
$\mathrm{BR}(B \to K\mu\mu)$
$\mathrm{BR}(B \to K^*\mu\mu)$
$\mathrm{BR}(B_s \to \phi\mu\mu)$
are consistently low
across many q^2 bins

The P_5' Anomaly

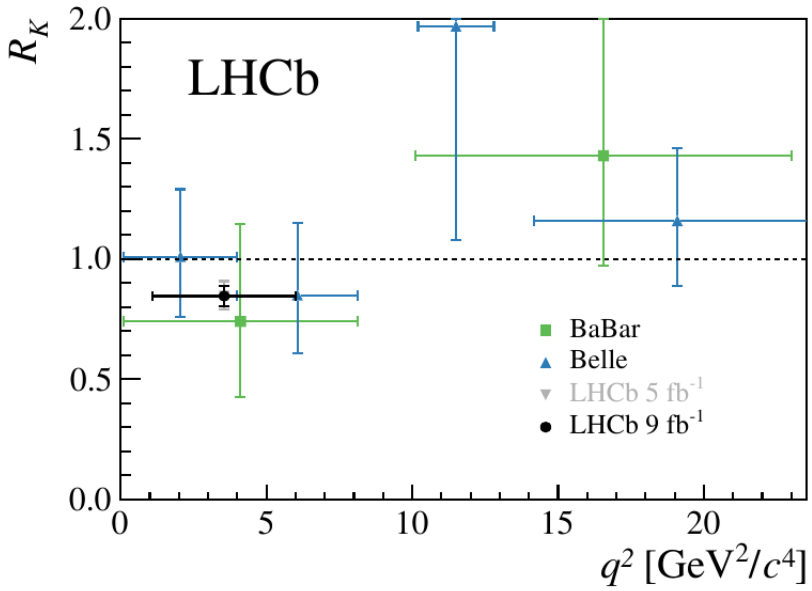
$P_5' \sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

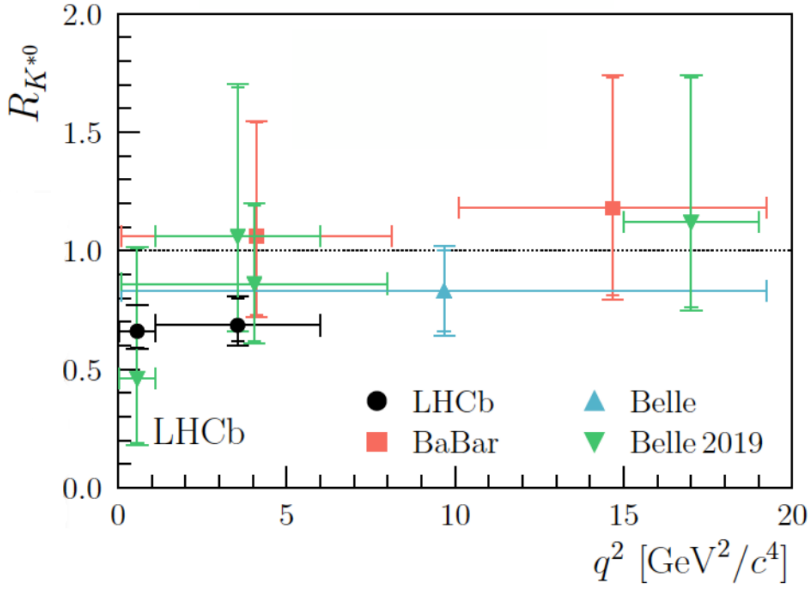
LHCb 2003.04831



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)

Evidence for Lepton Flavor Universality Violation





$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

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

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

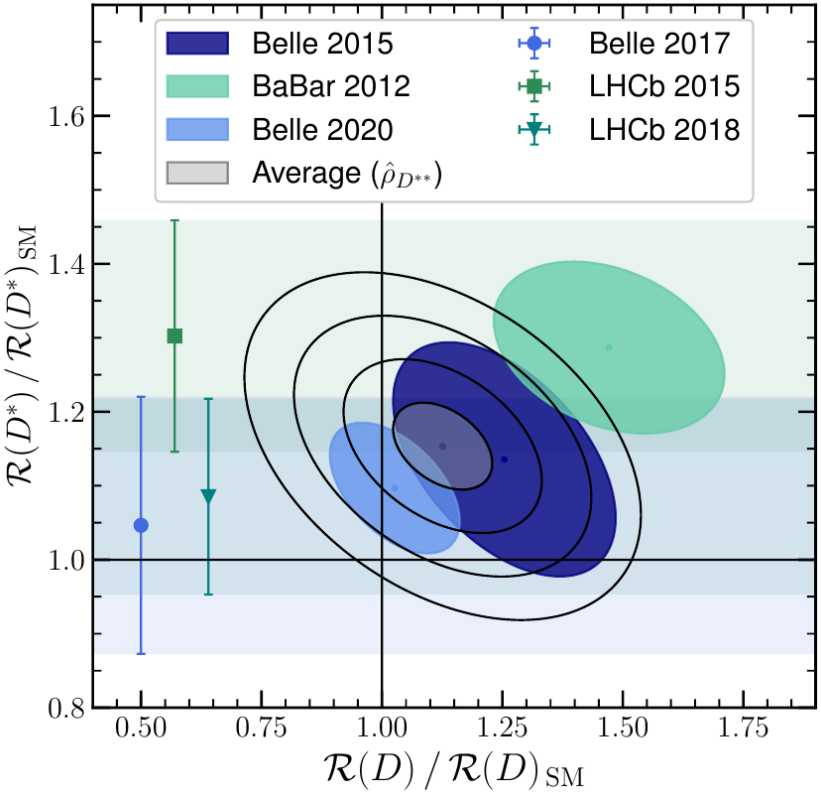
$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

R_K update, LHCb 2103.11769
deviation by 3.1σ
from the SM prediction

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

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

Bernlochner, Franco Sevilla, Robinson, 2101.08326



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

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

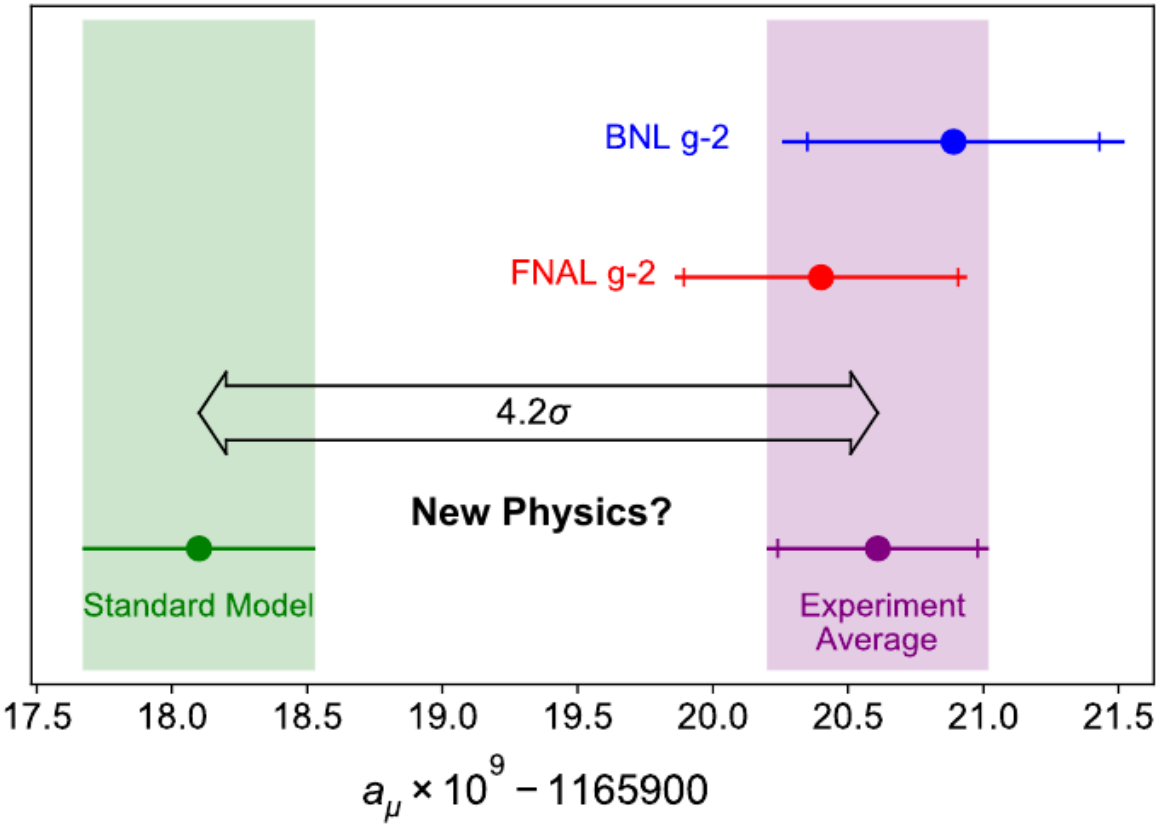
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

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

combined discrepancy with the SM: 3.6σ

(the heavy flavor averaging group quotes 3.1σ)

Anomalous Magnetic Moment of the Muon

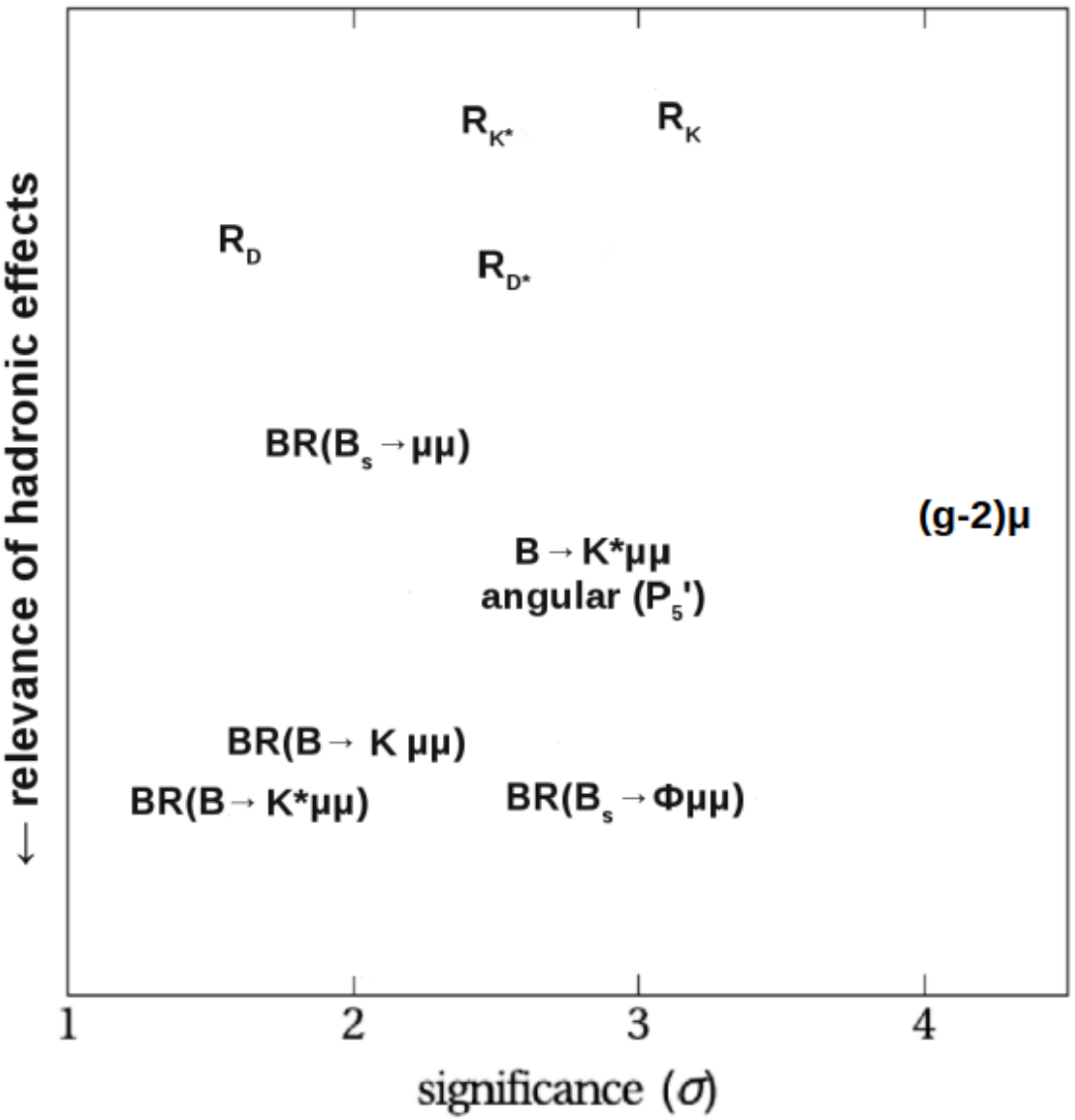


4.2 σ discrepancy between the experimental average (Fermilab g-2, 2104.03281) and the SM consensus (Aoyama et al. 2006.04822)

(see, however, the lattice results from BMW 2002.12347)

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

(Selection of) Anomalies in 2021



(inspired by Zoltan Ligeti)

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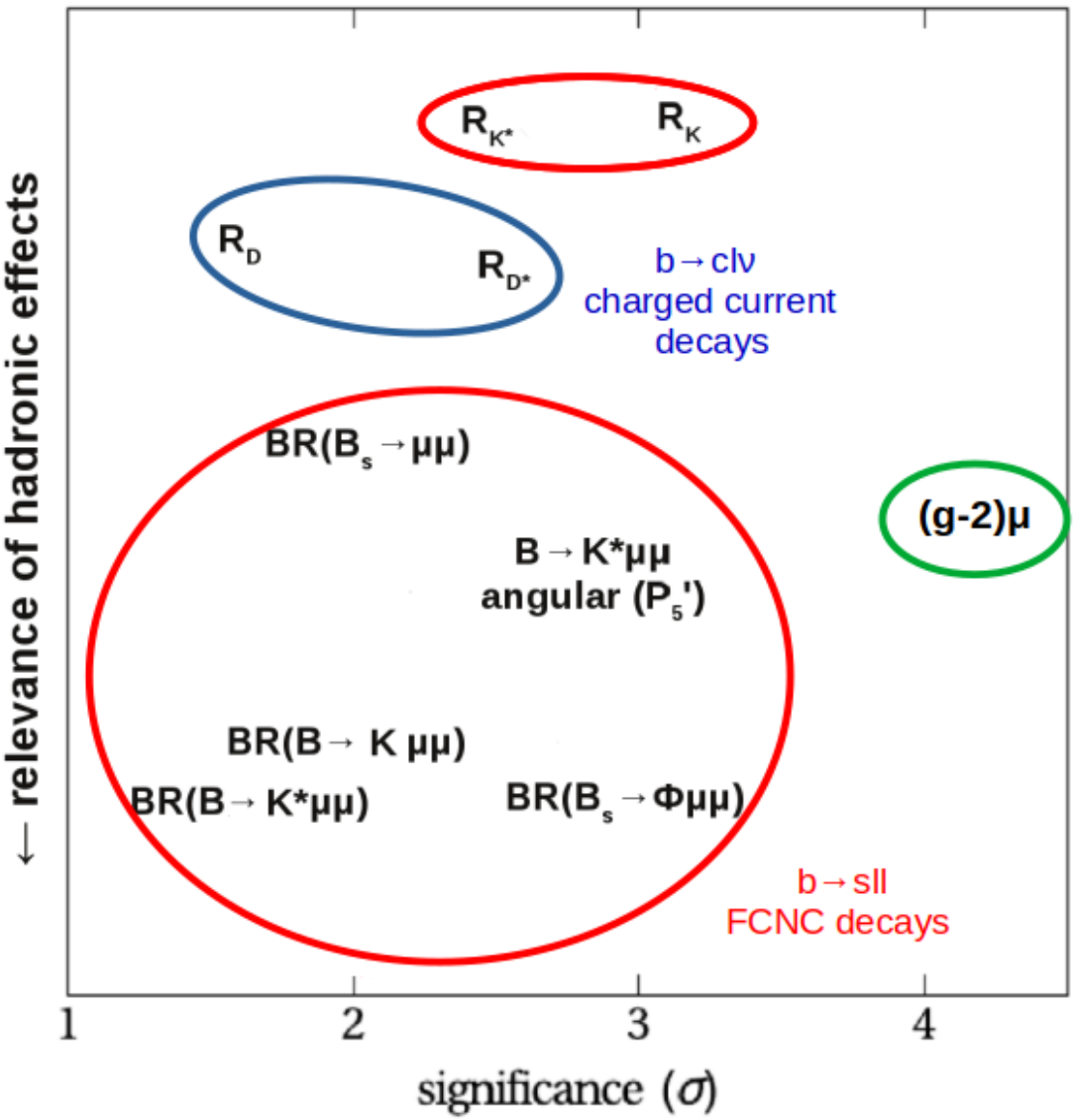

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Bottom-Up Approach to the Anomalies

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

Model Independent Analysis and New Physics Scale

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

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

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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)

Probing $(g-2)_\mu$ at a Muon Collider

- In the strongly coupled case, the new physics scale might be too high to be probed directly anytime soon. But there is a model independent signature at a muon collider, Buttazzo, Paradisi 2012.02769

$$\sigma(\mu\mu \to h\gamma) \simeq 0.7\text{ab} \times \left(\frac{\sqrt{s}}{30\text{ TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^9}\right)^2$$

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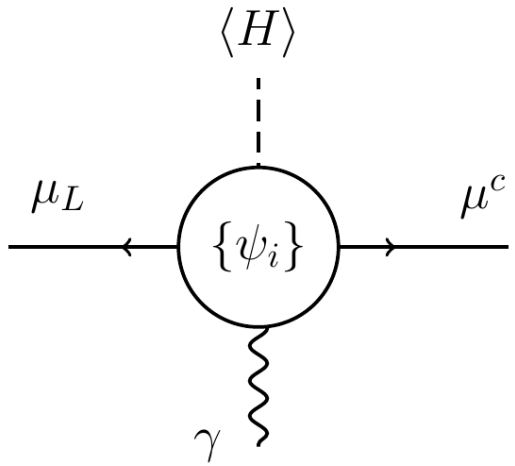
- Weakly coupled simplified models are essentially guaranteed to be discovered at a muon collider.

See the exhaustive survey of all particles that can show up in the loop by Capdevilla et al. 2006.16277, 2101.10334



Probing New Physics Models (MSSM)

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

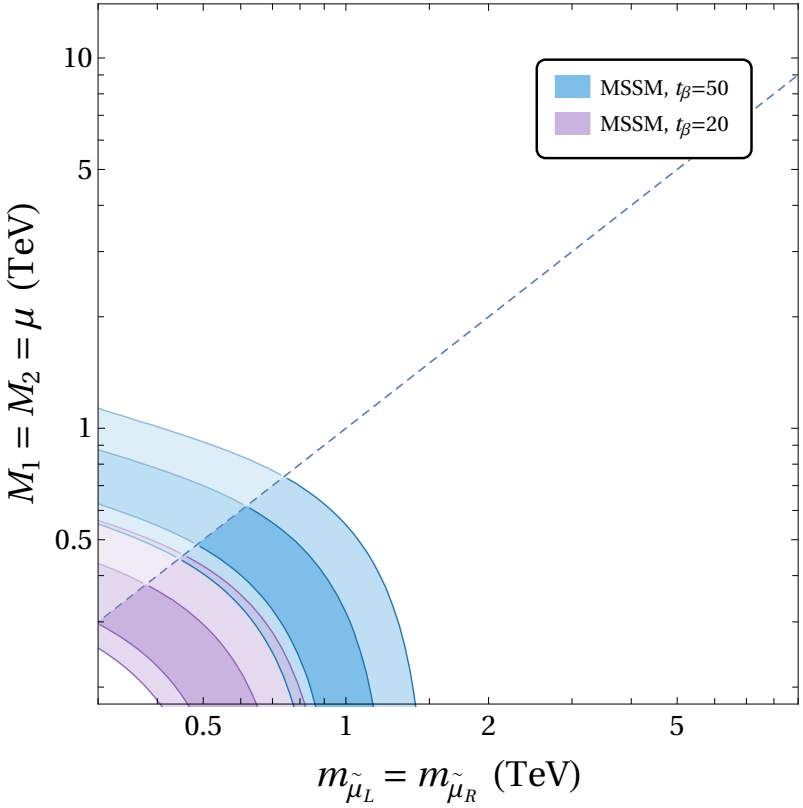
  many many recent references

  (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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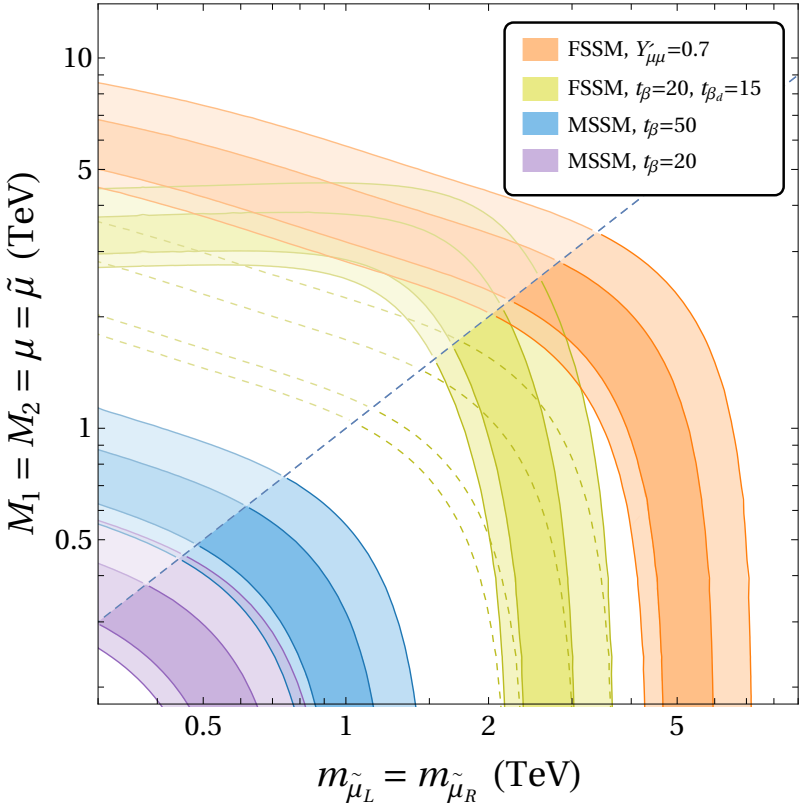


- In non-minimal SUSY scenarios, sleptons, charginos, neutralinos can be significantly heavier

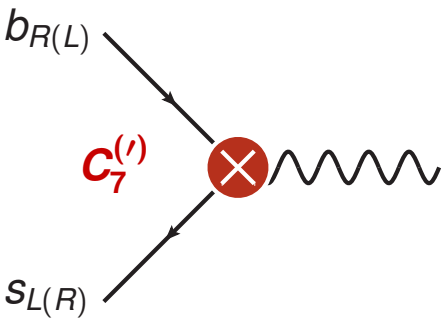
  WA, Gadam, Gori, Hamer 2104.08293

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

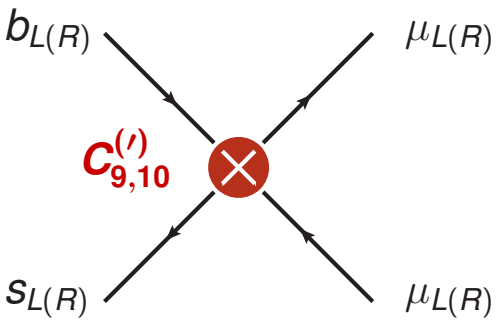
Model Independent Analysis

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

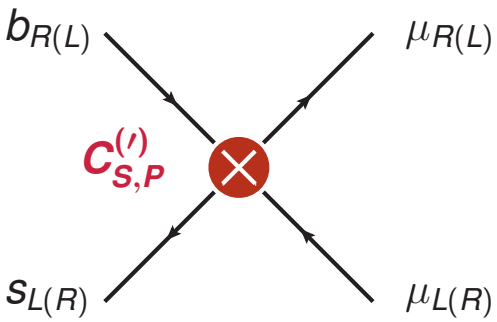
magnetic dipole operators



semileptonic operators



scalar operators



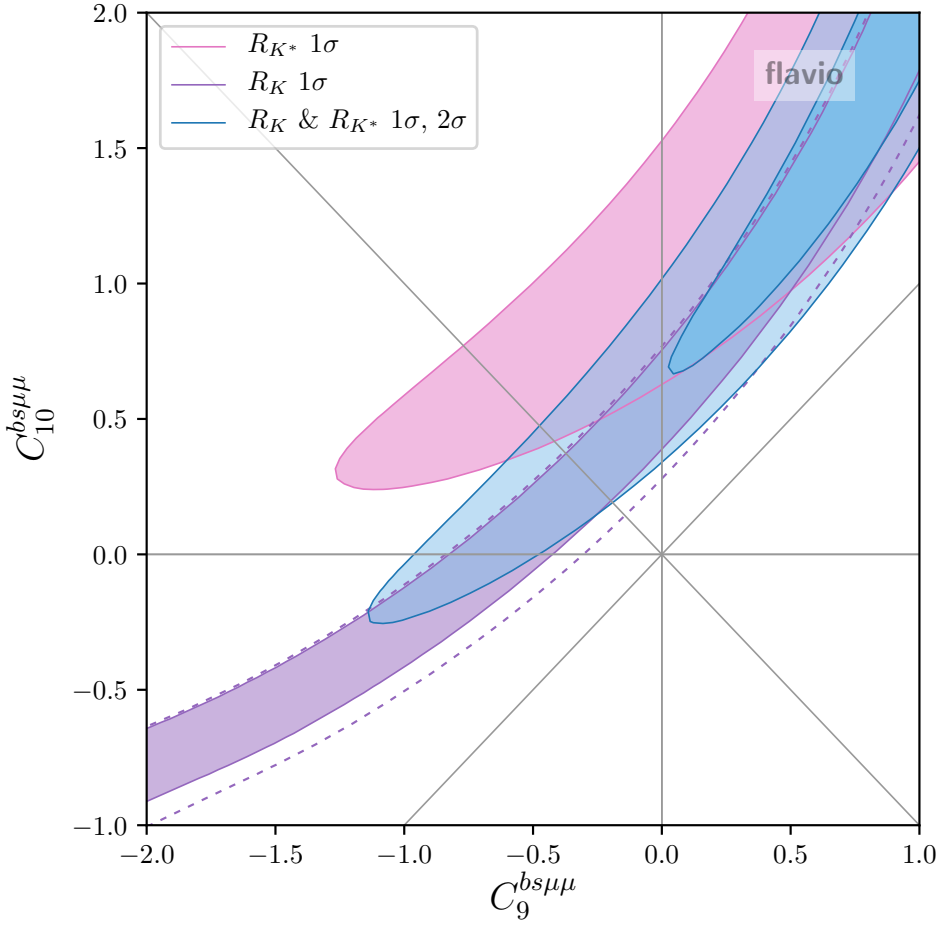
$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

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

neglecting tensor operators and additional scalar operators

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

Global Fits



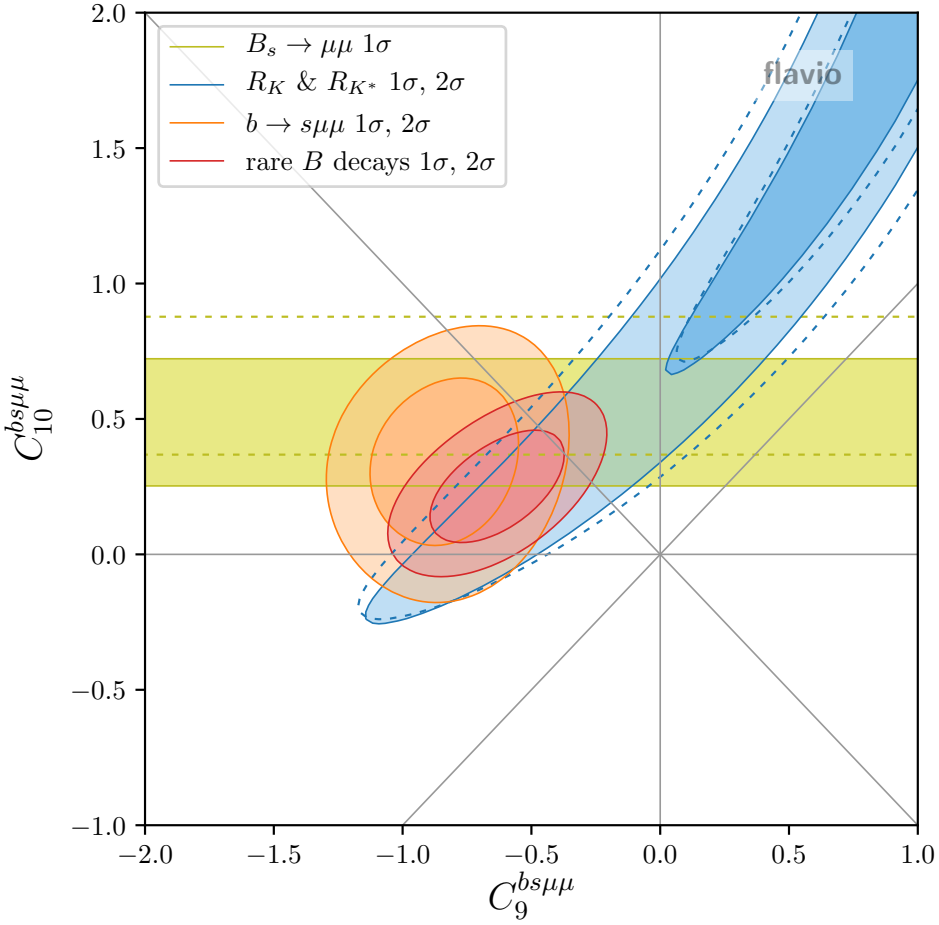
$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

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

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

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)

Global Fits



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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}
- $b \to s\mu\mu$ observables prefer non-standard C_9
- best fit point

$$C_9^{bs\mu\mu} \simeq -0.63$$

$$C_{10}^{bs\mu\mu} \simeq +0.25$$

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	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$

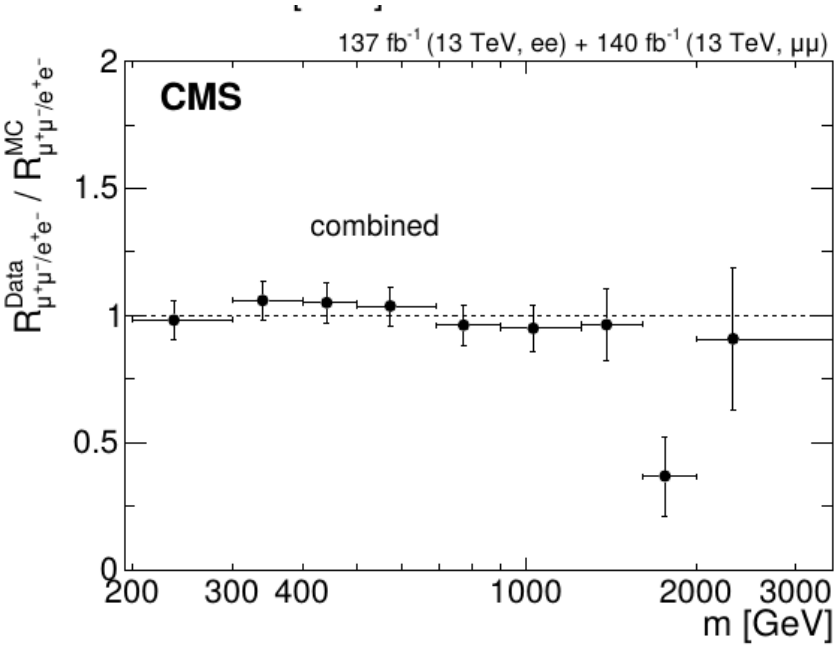
(MFV = Minimal Flavor Violation)

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

Model Independent Approach at a Muon Collider

[WA, Gadam, Profumo, in progress]

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

- At a muon collider look for $\mu^+\mu^- \to bs$
- Main background from $\mu^+\mu^- \to bb$ and $\mu^+\mu^- \to qq$ with misidentified jets. Mis-ID rate $\mathcal{O}(1\%)$?
- (Background from $\mu\mu \to bs$ negligible(?) GIM suppression m_t^4/s^2)
- Very naive estimate for signal over background

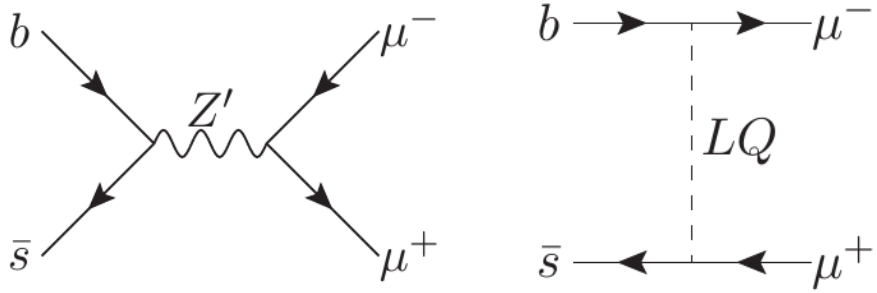
$$\frac{S}{B} \sim \frac{s^2}{g^4 \Lambda_{\text{NP}}^4} \frac{1}{\epsilon_{\text{mis-ID}}} \sim \left(\frac{\sqrt{s}}{10\ \text{TeV}}\right)^4$$

- Because of $SU(2)_L$ also expect operators with top quarks Search for single top production $\mu^+\mu^- \to tc$?
- Polarized beams to identify the chirality structure of operators?

Simplified Models

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)

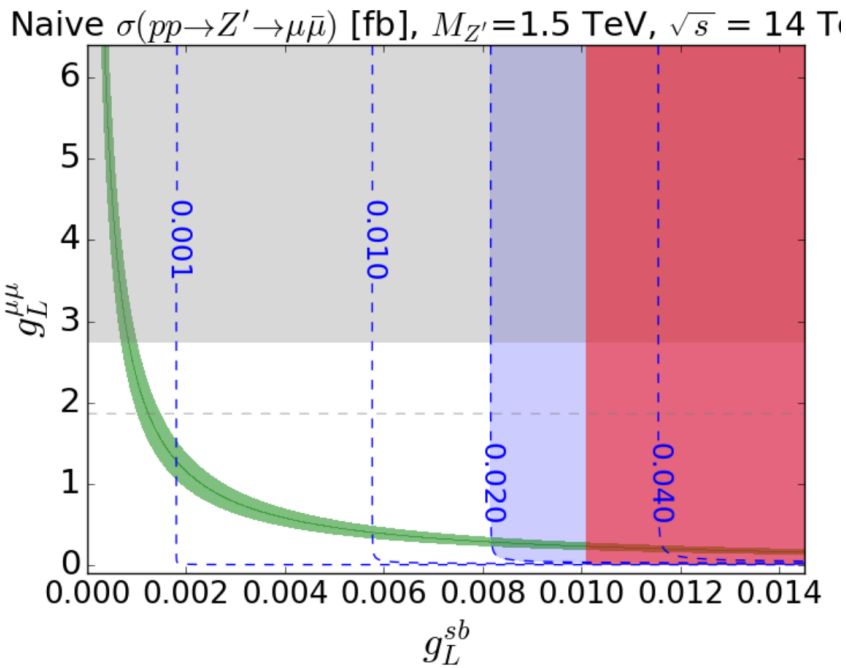
- $m_{Z'} \lesssim g_\mu \times 5\text{TeV}$
- $m_{\text{LQ}} \lesssim (30 - 60)\text{TeV}$ (depending on the lepto-quark representation)

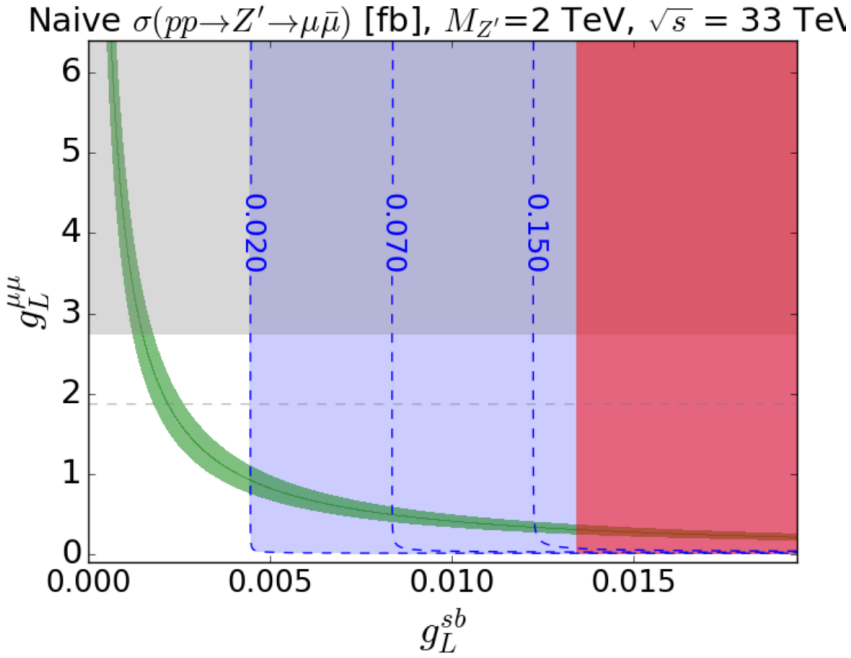
$\rightarrow$ a weakly coupled Z' might be in reach of the LHC

Z' at HL/HE LHC

green: $R_{K^{(*)}}$ explanation, gray: low scale Landau pole

red: B_s mixing constraint, blue: LHC sensitivity



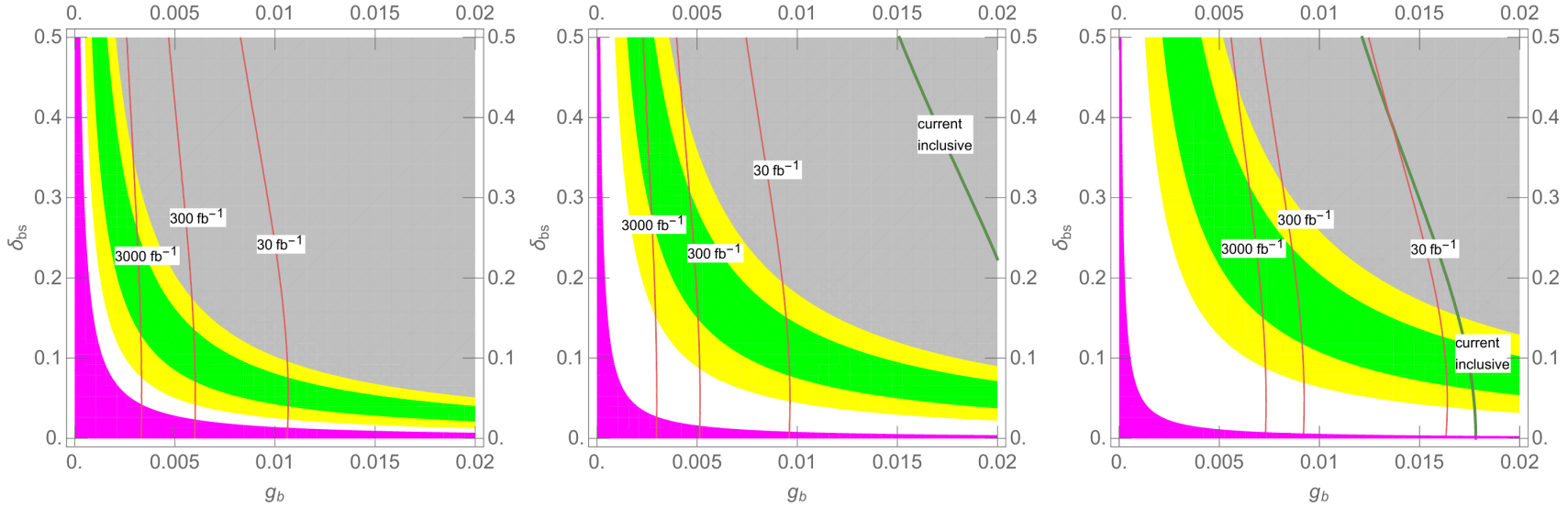


"minimalistic" Z' setups cannot be fully covered at the HL/HE LHC (3/ab) even for rather light Z' of O(TeV)

Allanach, Gripaios, You 1710.06363; also Chivukula et al. 1706.06575

Z' at HL/HE LHC

sensitivity increases in the presence of a sizable $Z'bb$ coupling



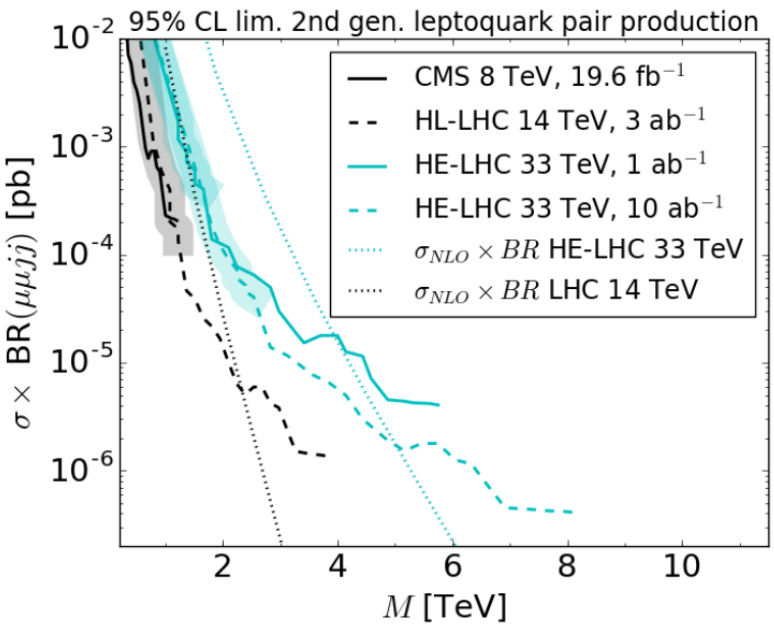
$m_{Z'} = 200\ GeV$ $m_{Z'} = 350\ GeV$ $m_{Z'} = 500\ GeV$

Dalchenko, Dutta, Eusebi, Huang, Kamon, Rathjens 1707.07016

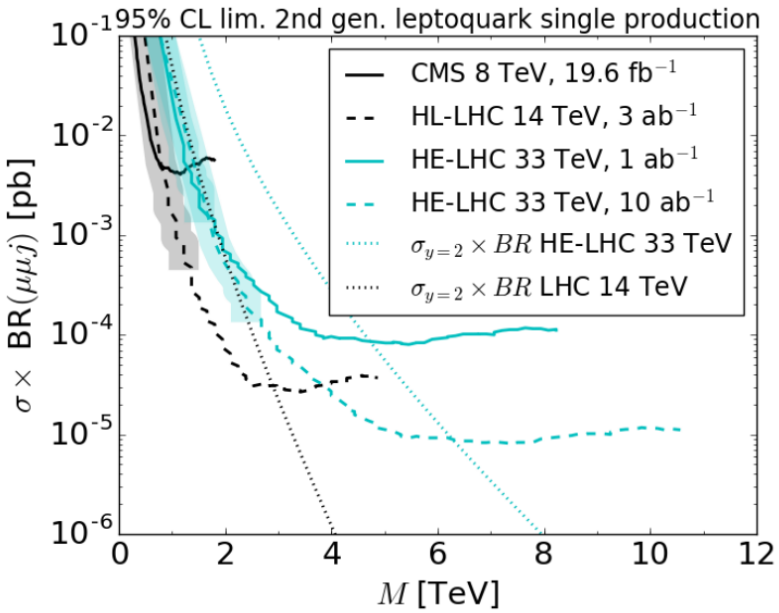
also Kohda, Modak, Soffer 1803.07492

Leptoquarks at the HL/HE LHC

pair production



single production



Allanach, Gripaios, You 1710.06363

also Hiller, Loose, Nisandzic 1801.09399

Leptoquarks could be significantly beyond the LHC reach

Leptoquarks at a Muon Collider

- pair production

$$\mu^+\mu^- \to LQ\ LQ$$

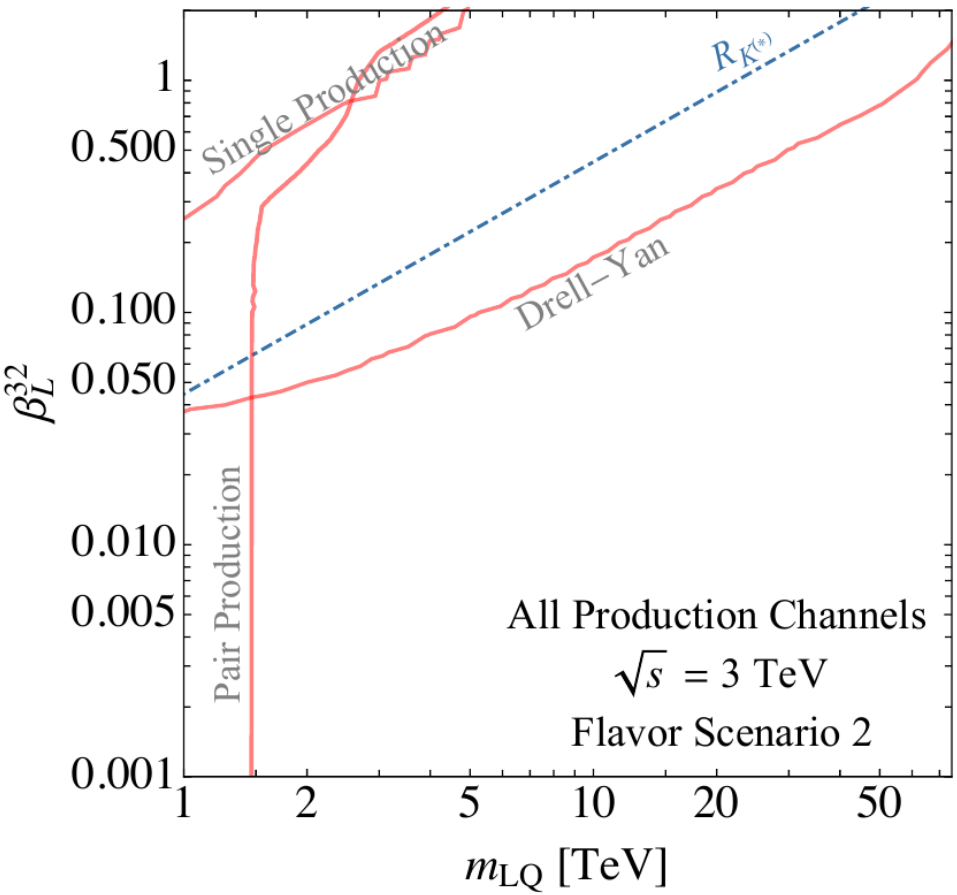
- single production

$$\mu V \to LQ + jet$$

- Drell-Yan with t-channel LQ

$$\mu^+\mu^- \to bb$$

$$\mu^+\mu^- \to ss$$



Asadi, Capdevilla, Cesarotti, Homiller 2104.05720

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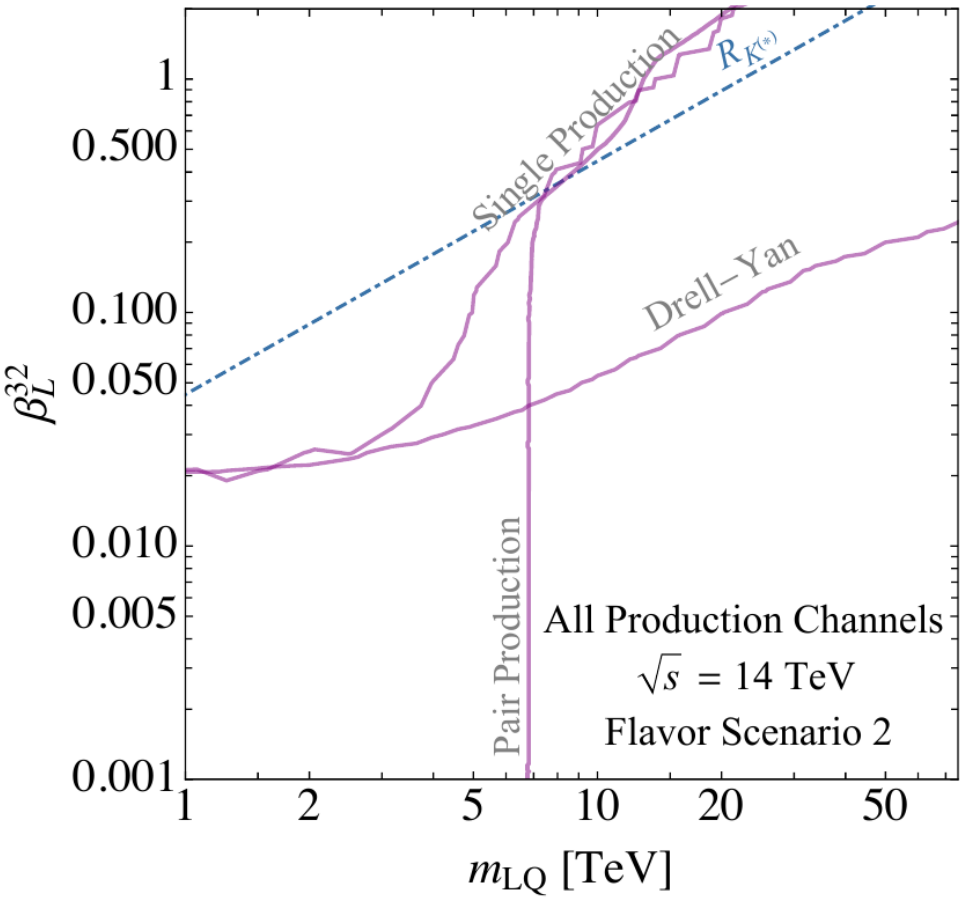


Asadi, Capdevilla, Cesarotti, Homiller 2104.05720

Leptoquarks at a Muon Collider

- pair production

$$\mu^+\mu^- \to LQ\ LQ$$

- single production

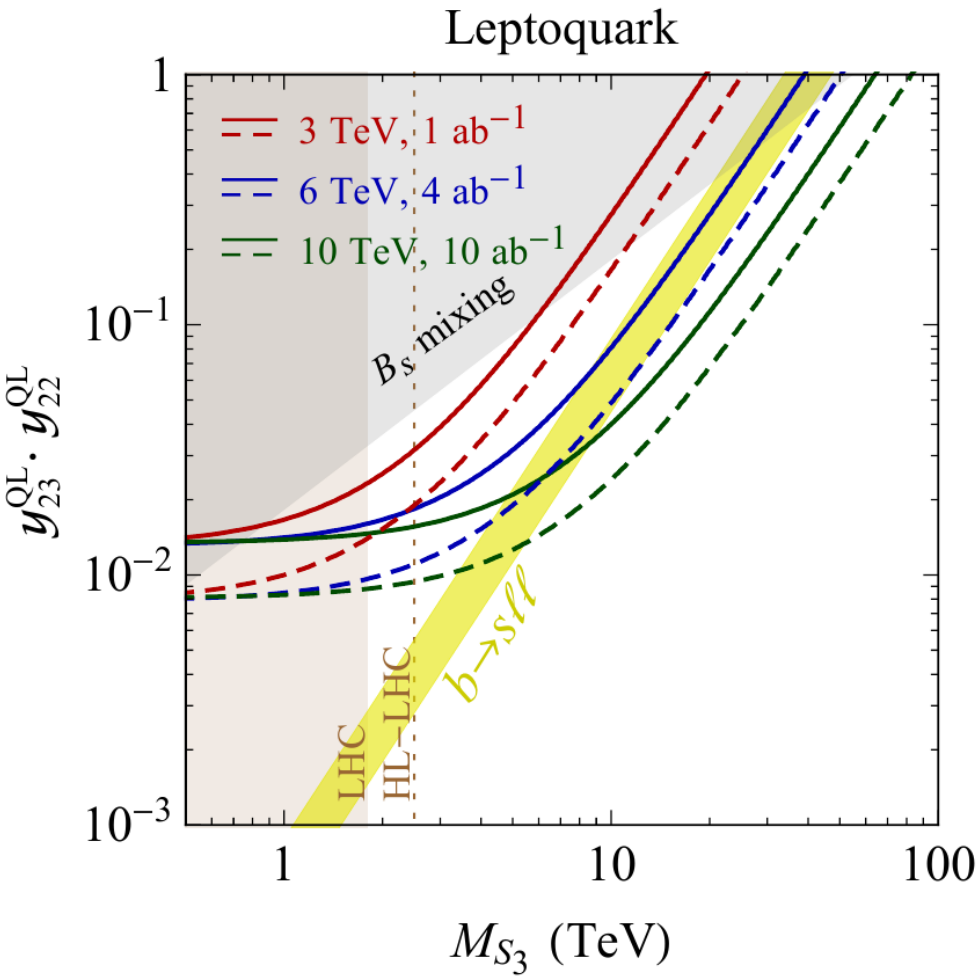
$$\mu V \to LQ + jet$$

- Drell-Yan with t-channel LQ

$$\mu^+\mu^- \to bb$$

$$\mu^+\mu^- \to ss$$

$$\mu^+\mu^- \to bs$$

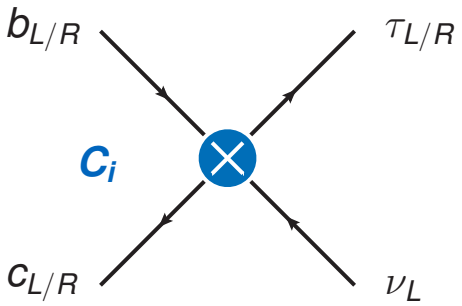


Huang, Jana, Queiroz, Rodejohann 2103.01617

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

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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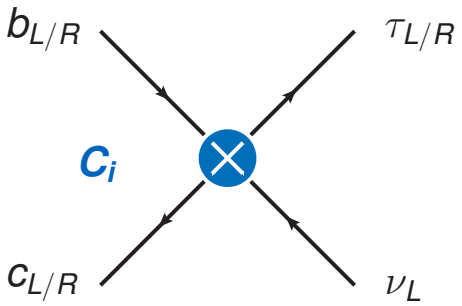
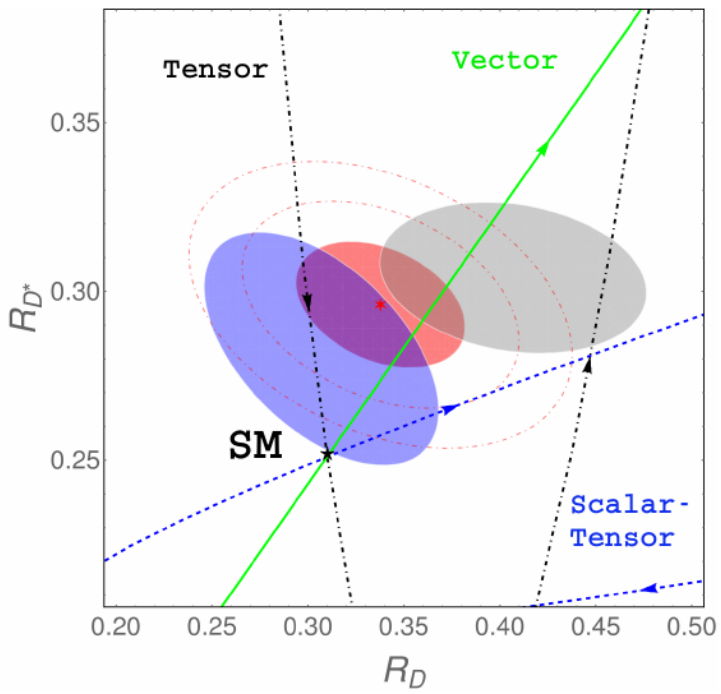


$\mathcal{O}_i$ = contact interactions with vector, scalar or tensor currents

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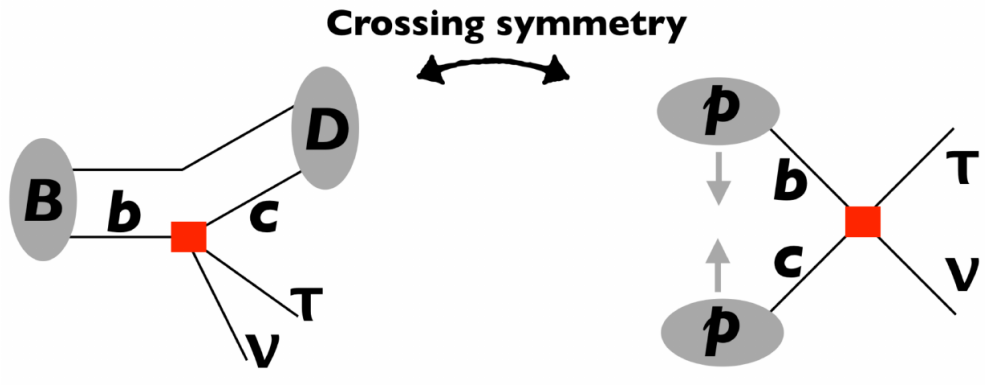
rather low scale $\rightarrow$ model building is non-trivial

Model Independent 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;
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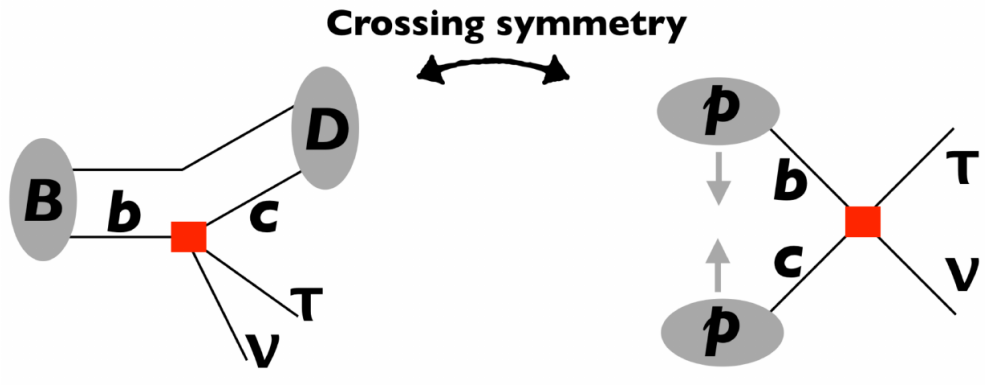

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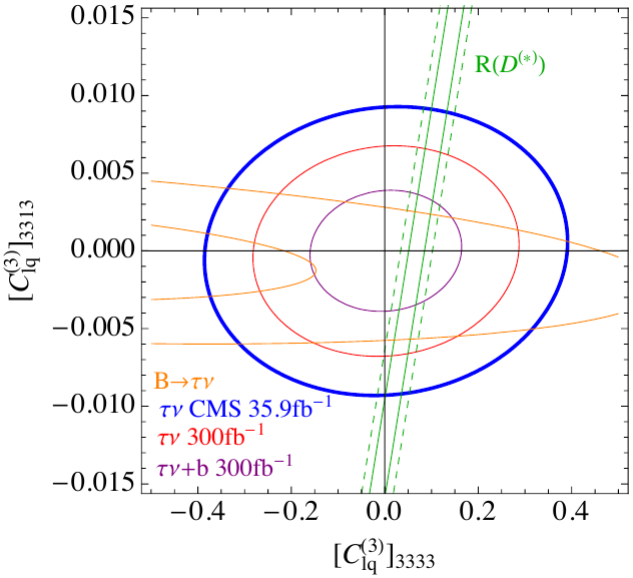
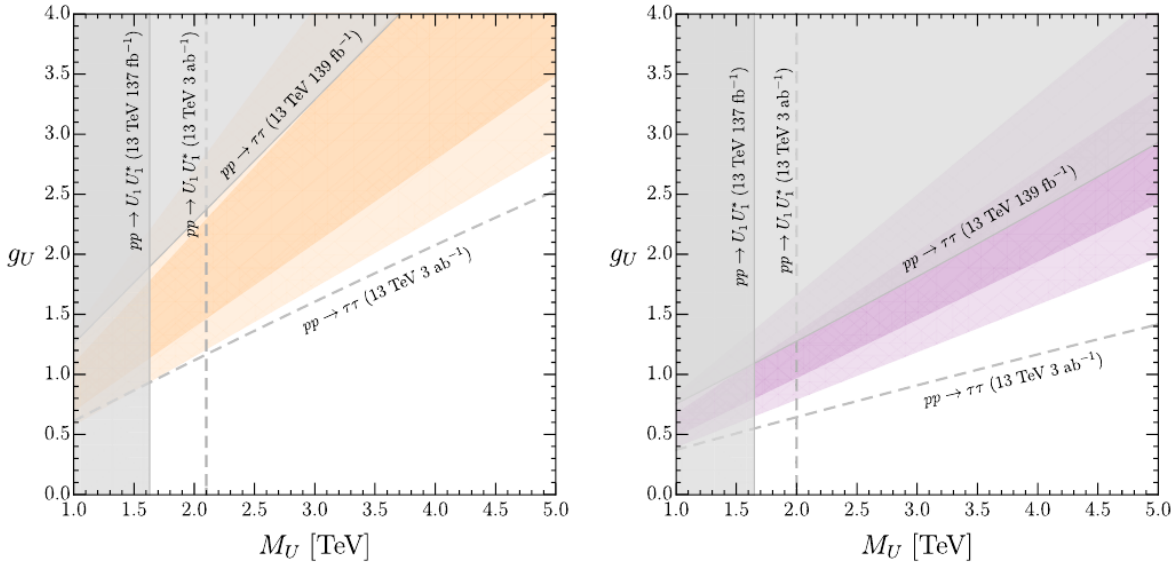


- Collider and low energy sensitivities are complementary
- High-luminosity LHC can probe large parts of parameter space

Simplified Models for $R_{D^{(*)}}$ at the LHC

- W' models excluded by direct searches
- Charged Higgs bosons strongly constrained by $B_c \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ kinematic distributions
- "3rd gen." leptoquarks can work. At colliders, look for pair production, single production, or modifications to $pp \to \tau\tau$



Cornella et al. 2103.16558

Preferred leptoquark parameter space can be covered at the high-luminosity LHC

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

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$U_3 \quad (\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗

- 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; ...
- look for sbottoms, stops, staus, sneutrinos with RPV couplings $pp \to t\mu\mu$, $pp \to b\mu\mu$, $pp \to b\tau\nu$, ...

Summary

The muon g-2 and the B decay anomalies could be
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R_D, R_{D^*}

- $\Lambda_{\rm NP} \lesssim 8$ TeV
- should have already seen something at the LHC
- new physics should be around the corner

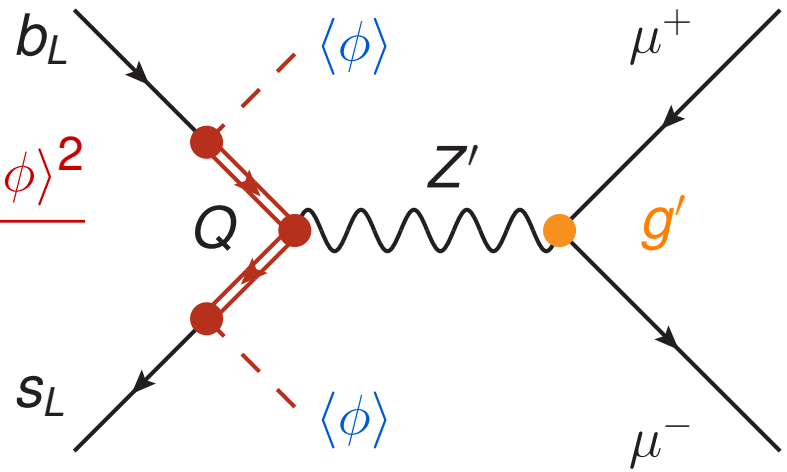
Back Up

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

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$



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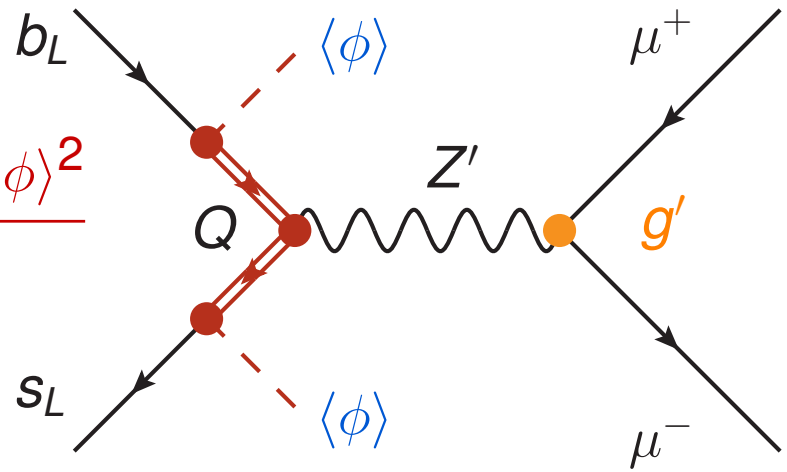

predicted Lepton Universality Violation!

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

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

Neutrino Tridents

B_s mixing

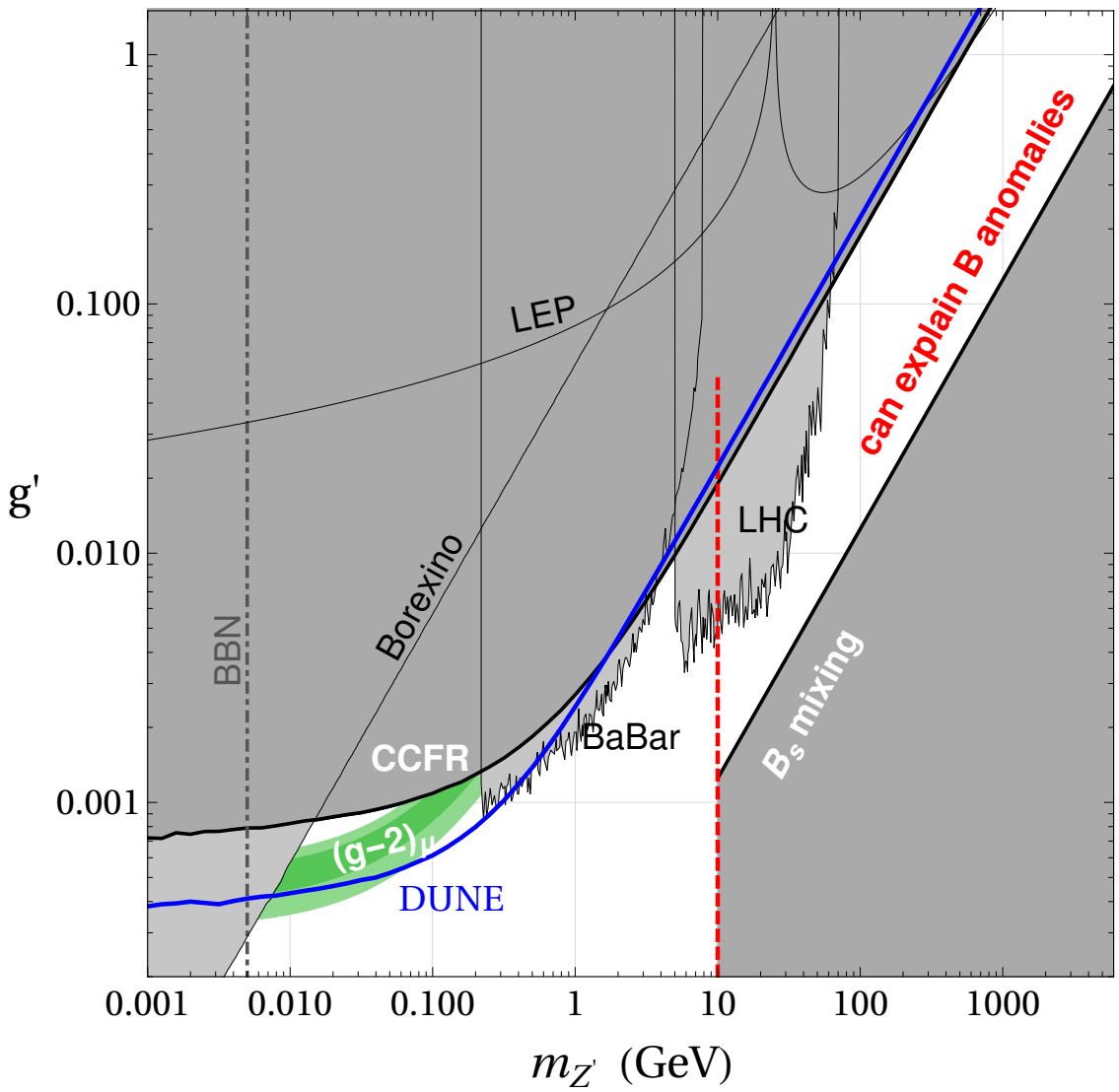
$(g-2)_\mu$

νe scattering

$Z \to \ell\ell$

$Z \to 4\mu$

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



$L_\mu - L_\tau$ at a Muon Collider

Huang, Jana, Queiroz, Rodejohann 2101.04956

- The Z' of gauged $L_\mu - L_\tau$ is hard to miss at a muon collider
- For heavy Z', look for 4μ contact interactions
- For light Z', look for $\mu\mu \to \gamma Z'$