B Decay Anomalies and Future Colliders

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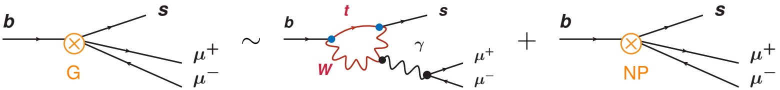
New Physics in Rare B Decays



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

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

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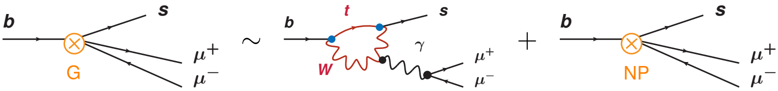

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measure precisely

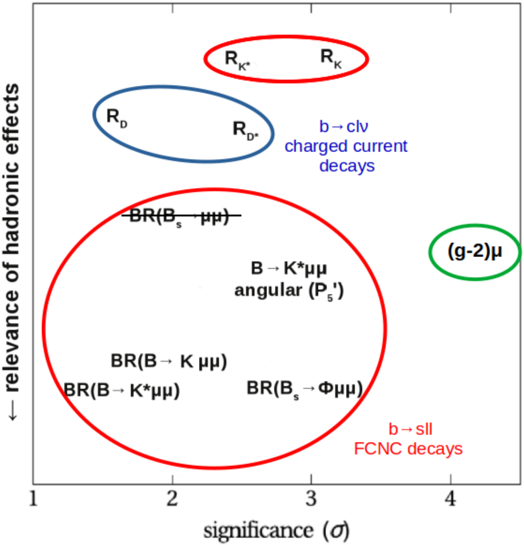
calculate precisely the SM contribution

get information on NP coupling and scale

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

(at least in principle)

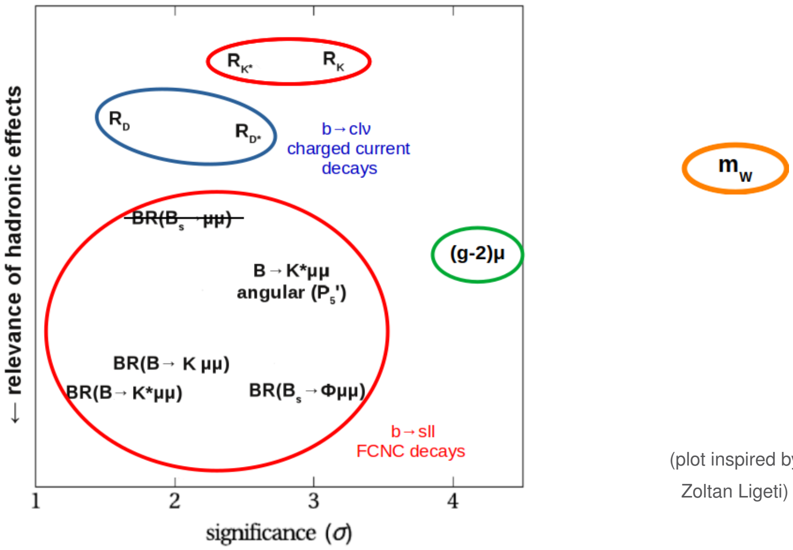
Anomalies and Puzzles in 2022



(plot inspired by

Zoltan Ligeti)

Anomalies and Puzzles in 2022



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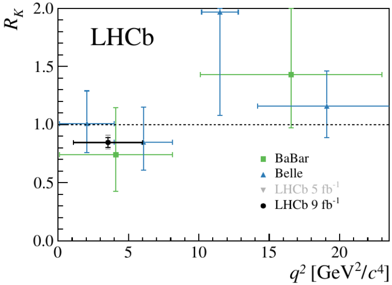
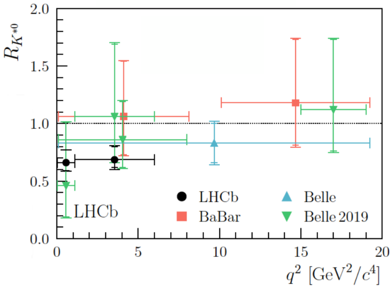
Evidence for Lepton Flavor Universality Violation





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

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

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

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

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

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

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

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

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

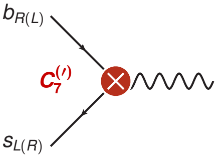
(inspired by Marco Nardecchia)

Model Independent Studies

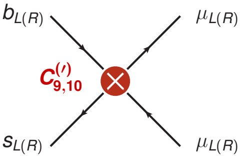
Model Independent Analysis

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

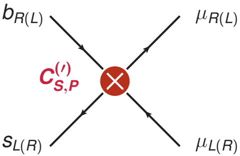
magnetic dipole operators



semileptonic operators



scalar operators



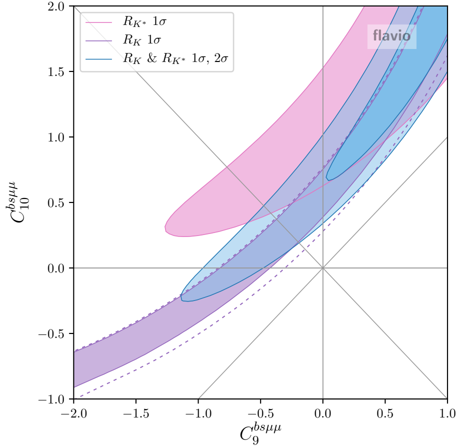
$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

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

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



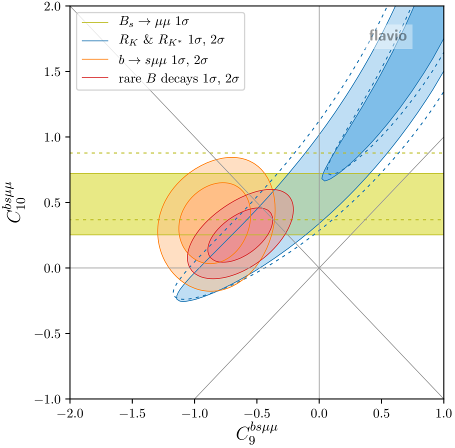
$$C_9^{bs\mu\mu} (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

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

- LFU ratios

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)

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



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

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

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

(if one is only interested in the LFU ratios, one can also put the NP into operators with electrons)

The New Physics Scale

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

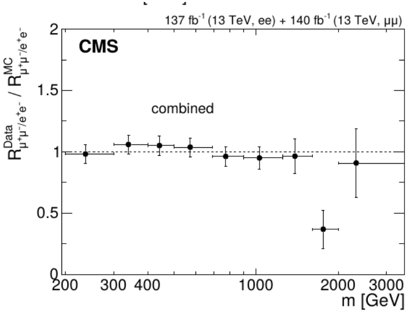
(MFV = Minimal Flavor Violation)

Model Independent Approach at the LHC

Even 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

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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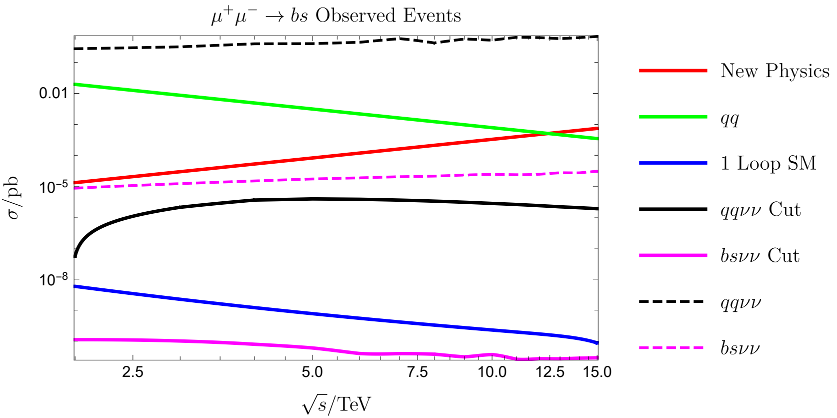
Forward backward asymmetry is sensitive to the chirality strcuture

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

Need charge tagging to measure the forward backward asymmetry

Backgrounds

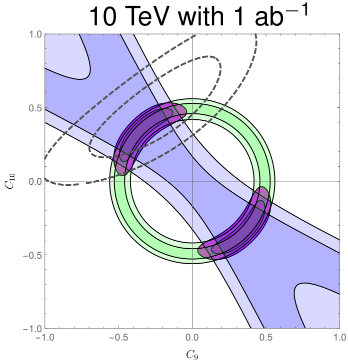
WA, Gadam, Profumo 2203.07495 and in preparation

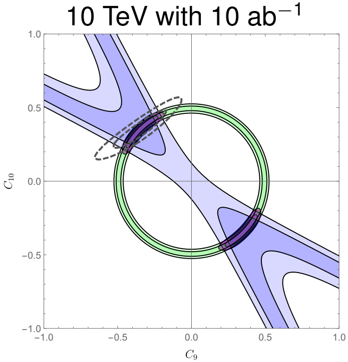


- backgrounds fall with c.o.m. energy; new physics signal increases
- $S/B \sim 1$ for a c.o.m. energy of ~ 10 TeV.

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

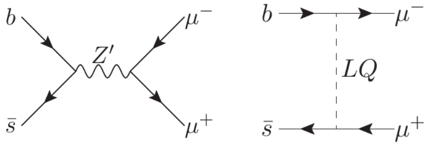
Azatov et al. 2205.13552 for related studies)

(Simplified) Models

Simplified Models for R_K and R_{K^*}

possible tree level explanations:

- Z' Bosons
- Lepto-Quarks



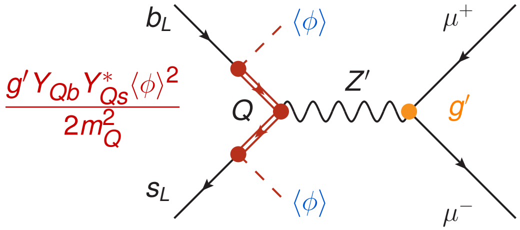
upper bounds on flavor violating couplings from B_s mixing imply upper bounds on the particle masses (e.g. Di Luzio et al. 1909.11087)

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

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

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 $L_\mu - L_\tau$

My Favorite Z' Model

Z' based on gauged $L_\mu - L_\tau$ (He, Joshi, Lew, Volkas PRD 43, 22-24)
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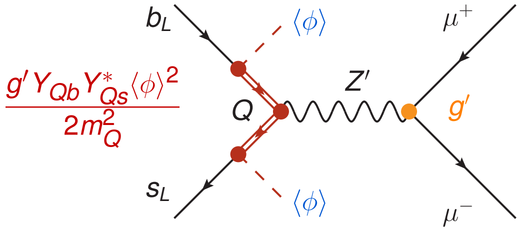
WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



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

$(g-2)_\mu$

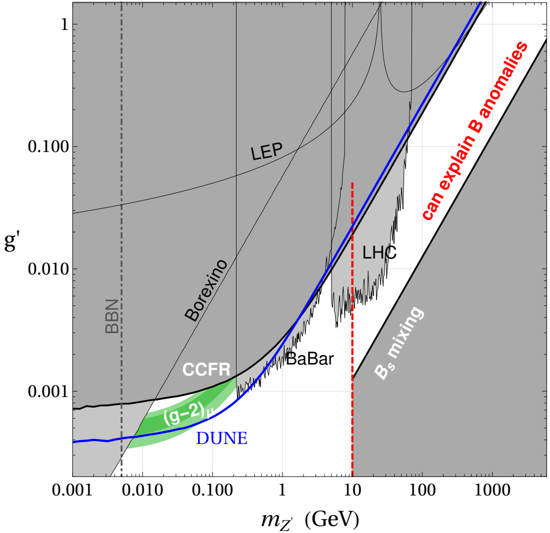
νe scattering

$Z \to \ell\ell$

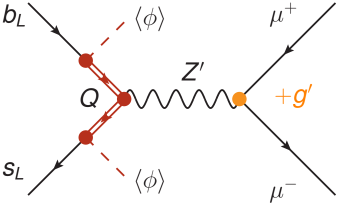
$Z \to 4\mu$

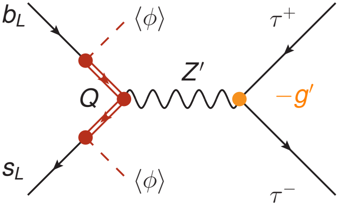
$e^+e^- \to 4\mu$

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



$L_\mu - L_\tau$ and Lepton Flavor Universality





the Z' model based on gauged $L_\mu - L_\tau$ predicts:

1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state

2) no effect in the e^+e^- final state

Rare $b \to s\tau\tau$ Decays

- Rare b decays with taus in the final state are very weakly constrained at the moment.
- Expected sensitivities at LHCb and Belle II still far from the SM predictions.

$$\mathrm{BR}(B_s \to \tau\tau)_{\mathrm{SM}} = (7.7 \pm 0.5) \times 10^{-7}$$ (Bobeth et al. 1311.0903)

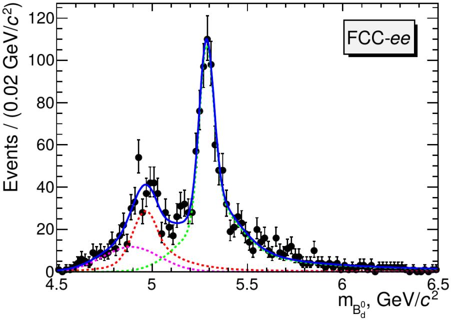
$$\mathrm{BR}(B \to K\tau\tau)_{\mathrm{SM}} = (1.2 \pm 0.1) \times 10^{-7}$$ (Du et al. 1510.02349)

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–

(Belle II Physics Book 1808.10567)

- Z vertex from primary tracks
- B vertex from $K\pi$
- tau vertices from 3 prong tau decays

$\Rightarrow$ decay can be fully reconstructed



(Kamenik, Monteil, Semkiv, Silva 1705.11106)

- with 3×10^{12} Z bosons can expect up to O(100) reconstructed $B \to K^* \tau\tau$ events
- Important to control backgrounds from D mesons faking taus

(Li, Liu 2012.00665)

More Predictions Based on $L_\mu - L_\tau$

(a) Lepton Yukawas and Z' couplings are aligned due to $L_\mu - L_\tau$
$\Rightarrow$ no lepton flavor violating couplings of the Z'
$\Rightarrow$ negligible rates of $B_s \to \tau\mu$, $B \to K^{(*)}\tau\mu$, etc
(in contrast to many other models)

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(c) $B \to K^{(*)}\nu_\mu\bar{\nu}_\mu$ suppressed, $B \to K^{(*)}\nu_\tau\bar{\nu}_\tau$ enhanced,
$B \to K^{(*)}\nu_e\bar{\nu}_e$ unaffected
neutrino flavor cannot be measured in experiment
$\Rightarrow$ $B \to K^{(*)}\nu\bar{\nu}$ is SM-like to a very good approximation
(in contrast to many other models)

Lepton Universality in Z Decays

- Most models that address the anomalies in $R_{K^{(*)}}$ (and $R_{D^{(*)}}$) predict lepton flavor universality violation in Z decays
- Lepton universality in Z decays established at LEP at permille level (hep-ex/0509008)

$$\frac{\text{BR}(Z \to \mu\mu)}{\text{BR}(Z \to ee)} = 1.0009 \pm 0.0028$$

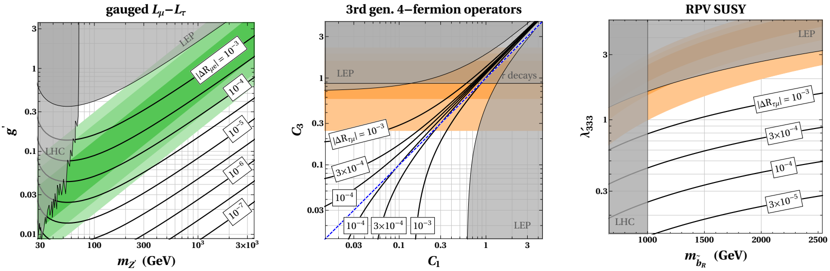
$$\frac{\text{BR}(Z \to \tau\tau)}{\text{BR}(Z \to ee)} = 1.0019 \pm 0.0032$$

- Systematic uncertainties are non-negligible.
- Measurements already constrain many models that are motivated by the hints of LFU violation in B decays.
  e.g. Feruglio, Paradisi, Pattori 1606.00524, ...

$\to$ Improved results would be very important!

Expected Sensitivities at Future Z Factories

- With 3×10^{12} Z bosons, statistics is not an issue.
- Key is the control of systematic uncertainties ($e/\mu/\tau$ efficiencies).
- relative BR measurements with 10^{-4} could probe essentially all parameter space of many models that explain R_K, R_{K^*}, R_D, R_{D^*}.



(WA, unpublished)

Summary

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

- would have a transformative impact:

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

- Implications of $R_{K^{(*)}}$ for CEPC:

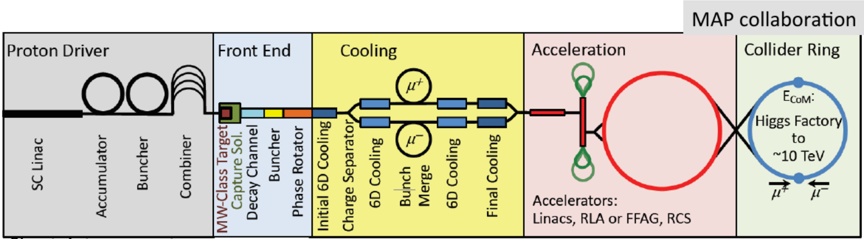
$\rightarrow$ look for enhancements of $b \to s\tau\tau$ decays

$\rightarrow$ look for LFUV in Z decays at the 10^{-4} level

Back Up

A Muon Collider?

Muon collider design is driven by finite muon lifetime



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

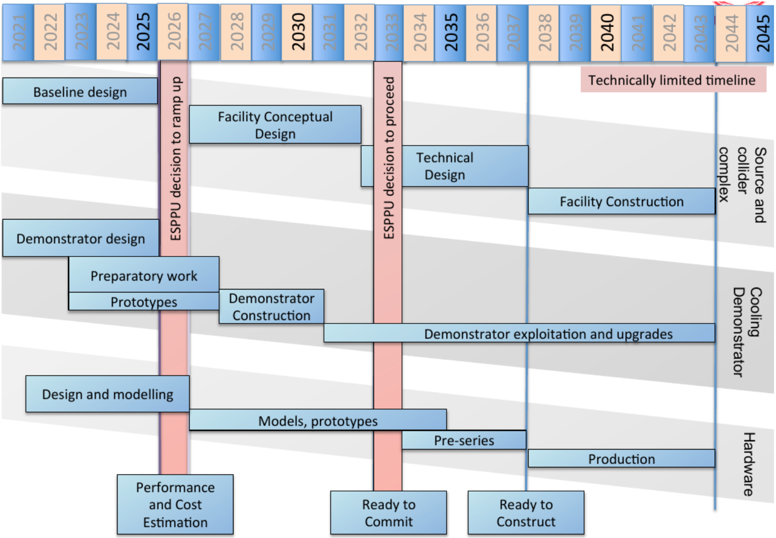
Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

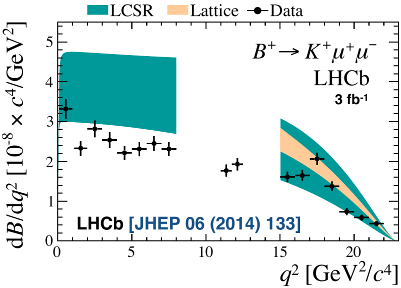
talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

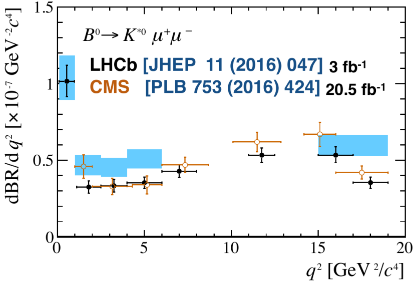
A Muon Collider!

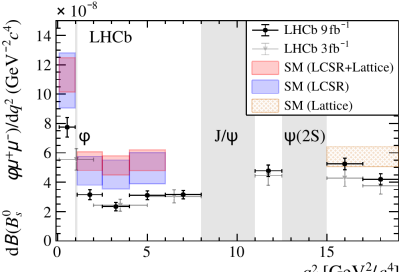


talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

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





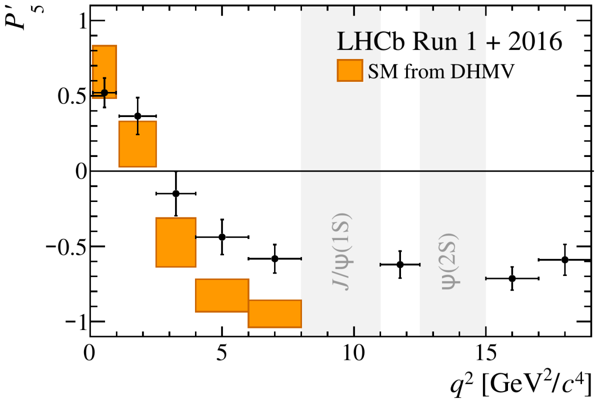


LHCb [2105.14007]

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)