Hints for New Physics in Rare B Decays and How to Test Them at a Muon Collider

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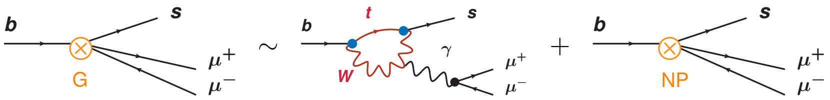
Rare B Decays as a Probe of New Physics

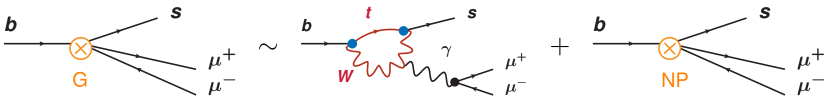


$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale



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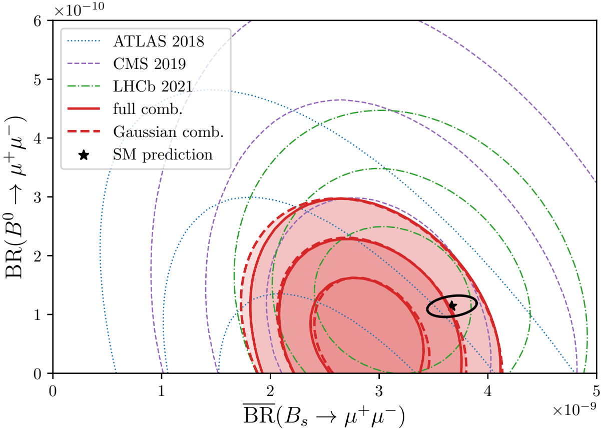
Anomalies in rare decays could establish a new scale in particle physics!

Overview of the Rare B Decay Anomalies

The $B_s \to \mu^+\mu^-$ Branching Ratio

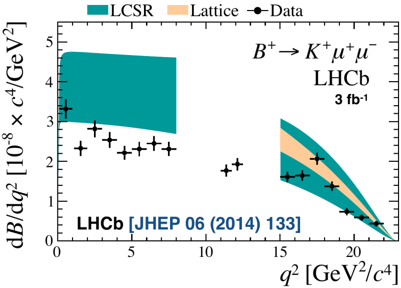
WA, Stangl 2103.13370; combination of LHCb 2108.09284, CMS 1910.12127, ATLAS 1812.03017

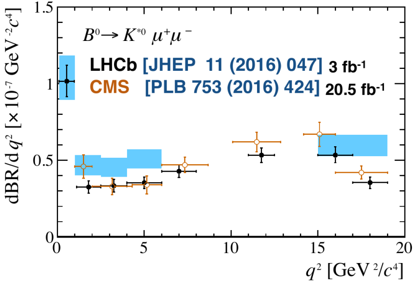


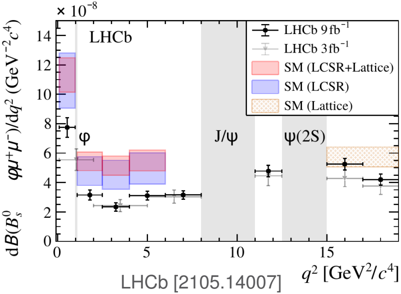
$\sim 2\sigma$ tension between SM and experiment

(Hadronic physics is under good control. Largest uncertainty is from CKM input.)

Semileptonic Branching Ratios

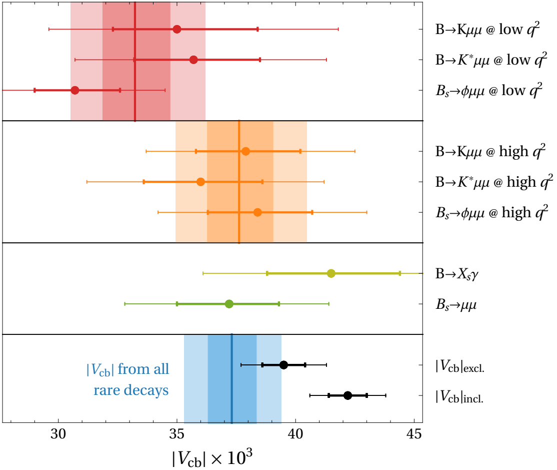






Experimental results for
$\text{BR}(B \to K\mu\mu)$
$\text{BR}(B \to K^*\mu\mu)$
$\text{BR}(B_s \to \phi\mu\mu)$
are consistently low
across many q^2 bins

The Role of V_{cb}



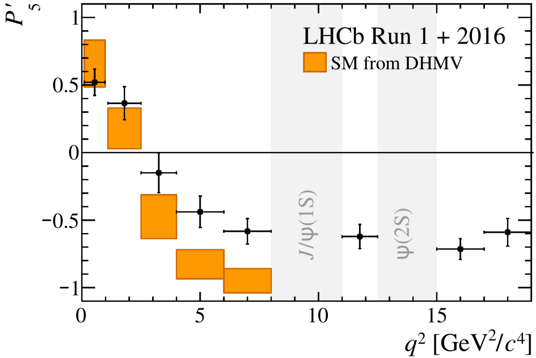
WA, Lewis 2112.03437

- Predictions for $b \to s\mu\mu$ rates depend sensitively on $|V_{cb}|$.
- For many years there are tensions between inclusive and exclusive determinations of V_{cb}.
- The rare B decay rates could be partially explained by a (very) low $|V_{cb}|$.
- Emphasizes the importance of precision CKM determinations.

The P_5' Anomaly

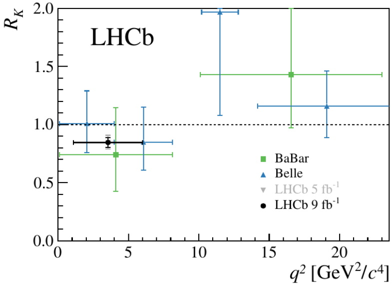
$P_5' \sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

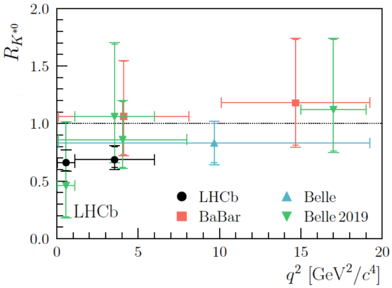
LHCb 2003.04831



$\sim 2\sigma - 3\sigma$ anomaly persists in the latest update of $B^0 \to K^{*0} \mu^+ \mu^-$.
(Anomaly also seen in $B^\pm \to K^{*\pm} \mu^+ \mu^-$ LHCb 2012.13241)

Evidence for Lepton Flavor Universality Violation





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

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

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

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

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

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

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

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

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios

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underestimated hadronic effects?	✗	✓	✓	✗

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	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?
statistical fluctuations?	√	√	√	√
parametric uncertainties?	√	√	×	×
underestimated hadronic effects?	×	√	√	×
New Physics?	√	√	√	√

Bottom-Up Approach to the Flavor 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

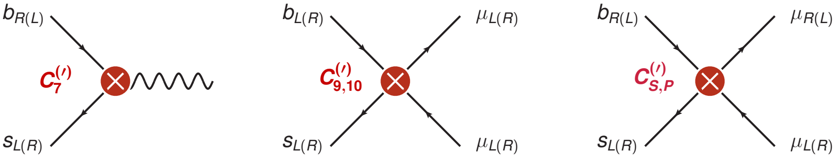
(inspired by Marco Nardecchia)

Model Independent Fits

Model Independent New Physics 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



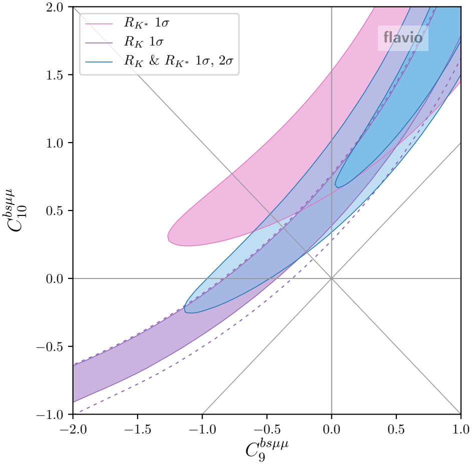
$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

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

neglecting tensor operators and additional scalar operators

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

Fits of Pairs of Wilson Coefficients



WA, Stangl 2103.13370

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

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

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

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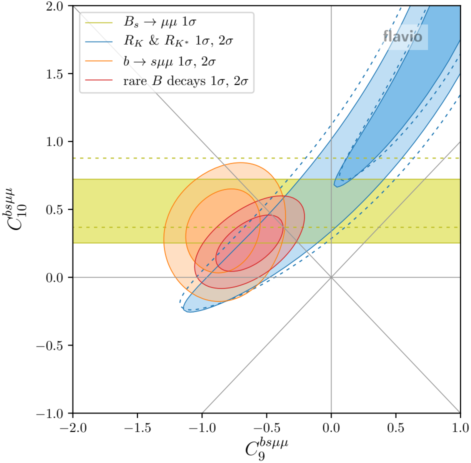

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- LFU ratios prefer non-standard C_{10}, but large degeneracy
- $B_s \to \mu^+\mu^-$ branching ratio shows slight preference for non-standard C_{10}
- $b \to s\mu\mu$ observables prefer non-standard C_9
- overall remarkable consistency

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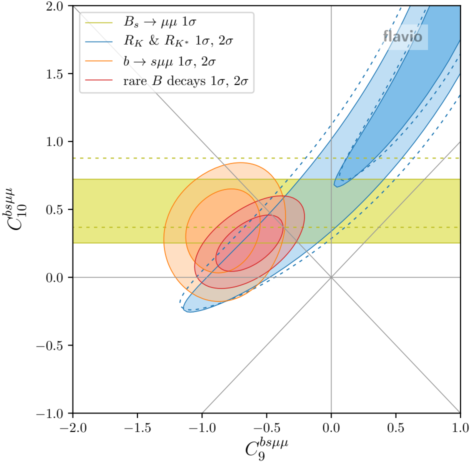

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- Note: LFU ratios could also be explained by new physics in electrons

Comparison of Global Fits

(B. Capdevilla, M. Fedele, S. Neshatpour, P. Stangl @ Flavour Anomaly Workshop, CERN, Oct. 20 2021)

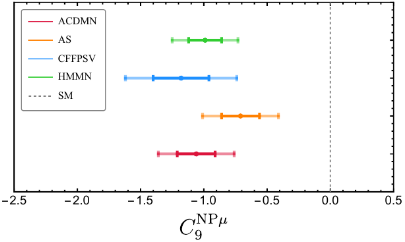
- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` arXiv:2103.13370
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` arXiv:2011.01212
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso` arXiv:2104.10058

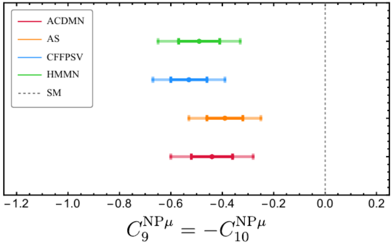
See also similar fits by other groups:
Geng et al., arXiv:2103.12738, Alok et al., arXiv:1903.09617, Datta et al., arXiv:1903.10086, Kowalska et al., arXiv:1903.10932, D'Amico et al., arXiv:1704.05438, Hiller et al., arXiv:1704.05444, ...

- Global fits have reached a high level of sophistication. Are done by many groups with different statistical approaches, different treatment of theory uncertainties, different selection of observables, ...

Fits of One Single Wilson Coefficient

(B. Capdevilla, M. Fedele, S. Neshatpour, P. Stangl @ Flavour Anomaly Workshop, CERN, Oct. 20 2021)





- small differences among the groups due to different approaches, but overall remarkable agreement
- NP scenarios are preferred over SM with pulls $> 5\sigma$
- Warning: pull $\neq$ global significance.
- Global significance $\simeq 4.3\sigma$ determined in Isidori et al. arXiv:2104.05631

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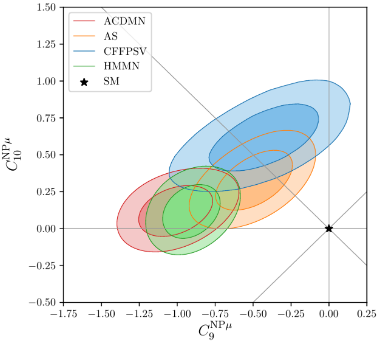
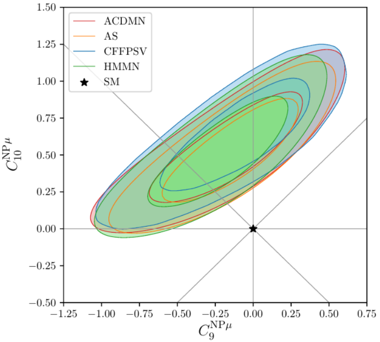


global fit



fit to LFU observables + $B_s \to \mu\mu$

- Perfect agreement if only theoretically clean observables are used.

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

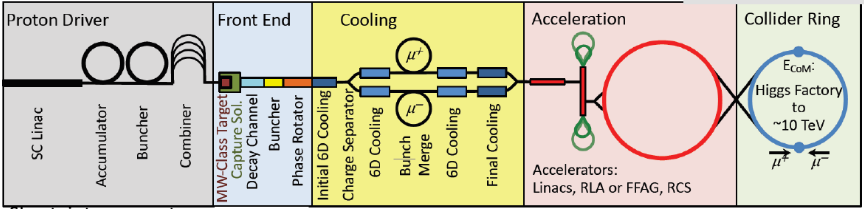
(MFV = Minimal Flavor Violation)

Testing the Anomalies at a Muon Collider

A Muon Collider?

Muon collider design is driven by finite muon lifetime

MAP collaboration



Short, intense proton bunches to produce hadronic showers

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

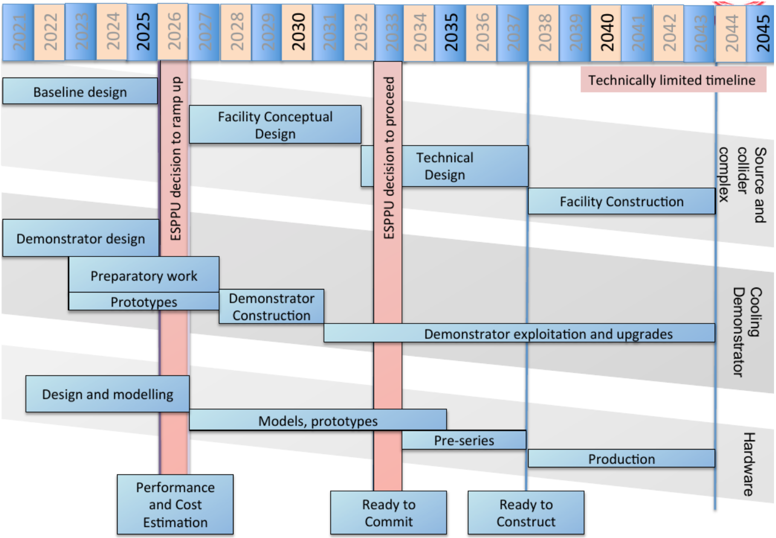
Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

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

A Muon Collider!



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

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

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

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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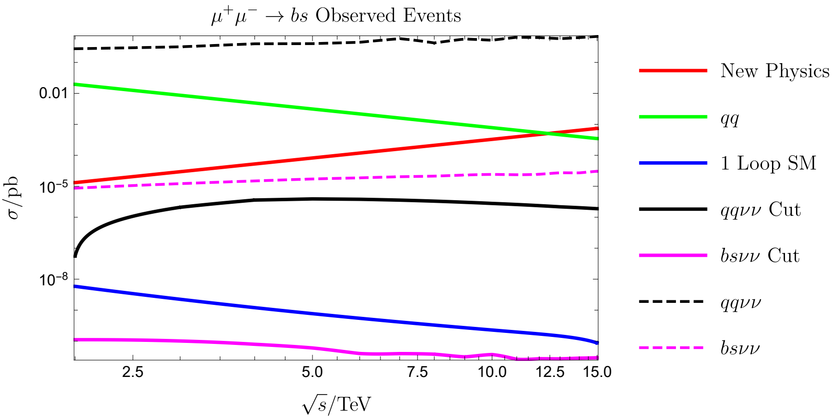
Forward backward asymmetry is sensitive to the chirality strcuture

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

Need charge tagging to measure the forward backward asymmetry

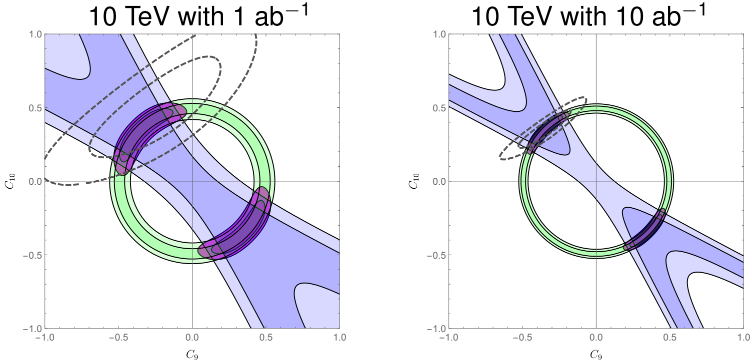
WA, Gadam, Profumo 2203.07495 and in preparation



- 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, Jana, Queiroz, Rodejohann 2103.01617;

Asadi, Capdevilla, Cesarotti, Homiller 2104.05720 for studies of Z' and leptoquark models)

Summary

- B decay data shows persistent discrepancies with SM predictions (almost a decade now!).
- If significance of LFU violation continues to grow with more statistics $\Rightarrow$ clear indication of new physics. (Last year's updates by LHCb are reassuring!)
- A 10 TeV muon collider would conclusively test explanations with 4 fermion operators.
- Looking forward to the next round of experimental updates!