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

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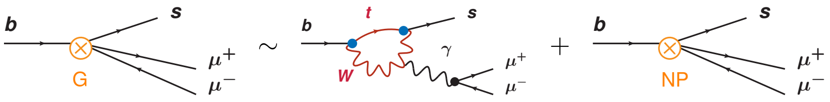
Rare B Decays as a Probe of New Physics

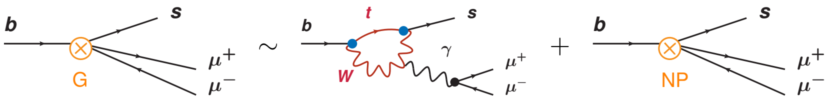


$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale



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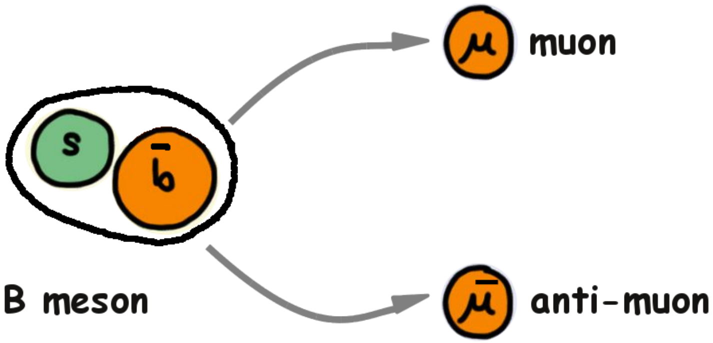
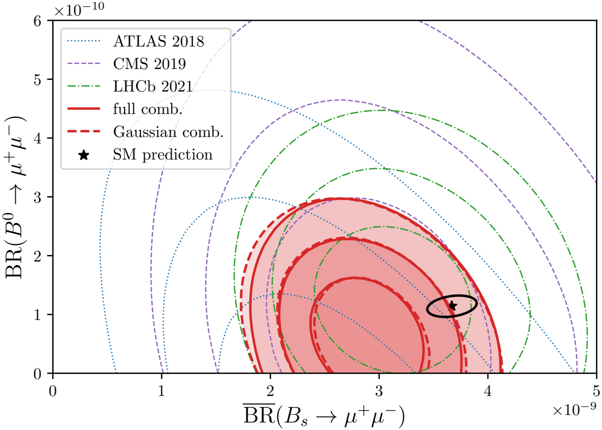
Anomalies in rare decays could establish a new scale in particle physics!

Overview of the Rare B Decay Anomalies


s
b̄
B meson
μ
muon
μ̄
anti-muon

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

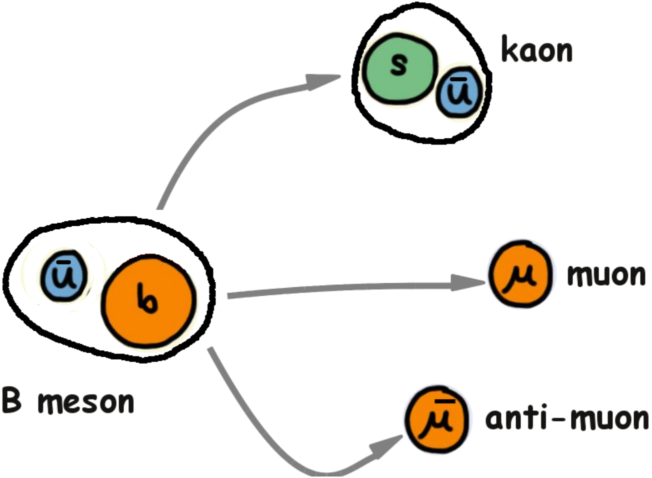
WA, Stangl 2103.13370; combination of LHCb 2108.09284, CMS 1910.12127, ATLAS 1812.03017



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

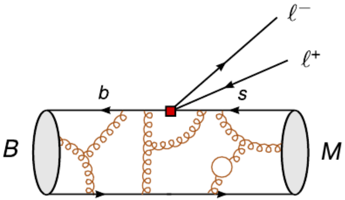
(Hadronic physics is under good control. Largest uncertainty is from CKM input.)

Semileptonic Decays $b \to s\mu\mu$



SM Predictions for Exclusive $b \to s\ell\ell$ Decays

amplitudes $\sim$ Wilson coefficients $\times$ form factors



- form factors from
  - lattice QCD (high q^2)
  - light-cone sum rules (low q^2)
  - combined fits available

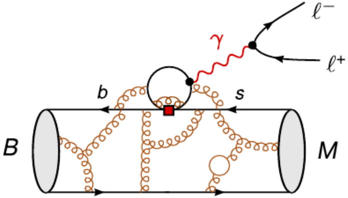
    (Bharucha, Straub, Zwicky 1503.05534;

    Gubernari, Kokulu, van Dyk 1811.00983)
- typical uncertainties $\lesssim 10\%$

SM Predictions for Exclusive $b \to s\ell\ell$ Decays

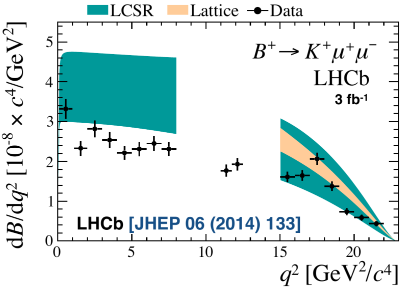
amplitudes $\sim$ Wilson coefficients $\times$ form factors

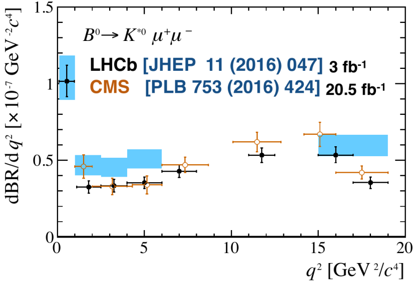
$+$ non-local terms (aka "charm loops")

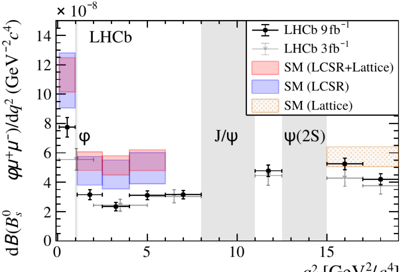


- various model approaches:
  - sum of resonances (Blake et al. 1709.03921)
  - polynomial fit to data (Ciuchini et al. 1512.07157)
  - LCSR estimates (Khodjamirian et al. 1006.4945; Gubernari et al. 2011.09813)
  - analytic function fit to data (Bobeth et al. arXiv:1707.07305; Gubernari et al. 2011.09813)
- uncertainties $\sim$ 10%?

Semileptonic Branching Ratios



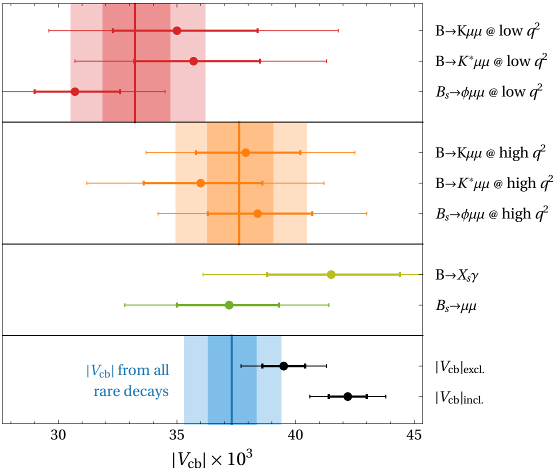




LHCb [2105.14007]

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

The Role of V_{cb}



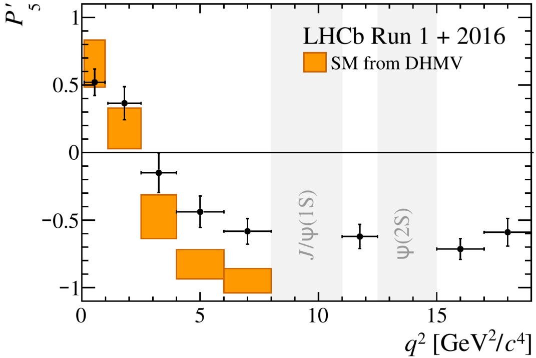
WA, Lewis 2112.03437

- 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 $|V_{cb}|$.
- Emphazises 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)

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect
universal for all processes	could be process dependent
universal for all final state helicities	could be helicity dependent
independent on q^2	could be q^2 dependent

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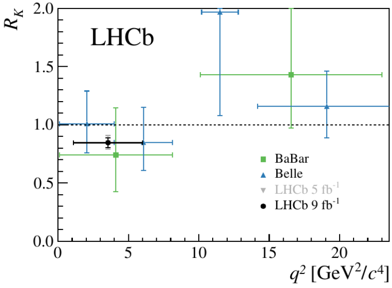
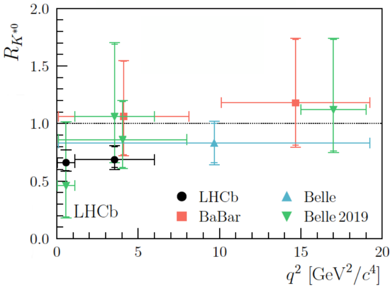
universal for all processes	could be process dependent
universal for all final state helicities	could be helicity dependent
independent on q^2	could be q^2 dependent
could be leptonic axial-vector current	leptonic vector current
could be RH quark current	LH quark current
could be CP violating	CP conserving
could violate lepton flavor universality	lepton flavor universal

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

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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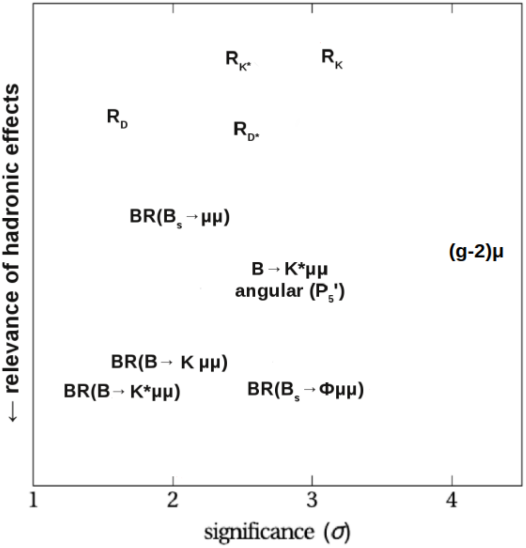
parametric uncertainties?	✓	✓	✗	✗
underestimated hadronic effects?	✗	✓	✓	✗
New Physics?	✓	✓	✓	✓

Summary of the Anomalies



(inspired by Zoltan Ligeti)

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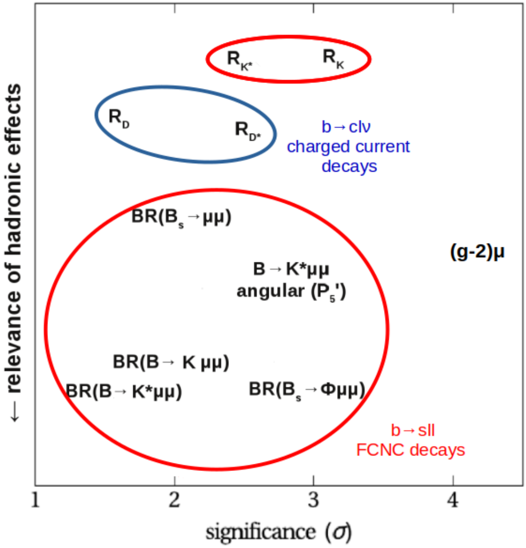

(inspired by

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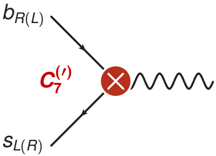
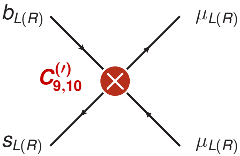
Model Independent Fits

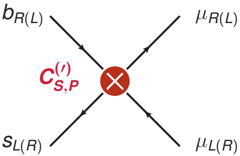
Model Independent New Physics Analysis

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

magnetic dipole operators | semileptonic operators | scalar operators







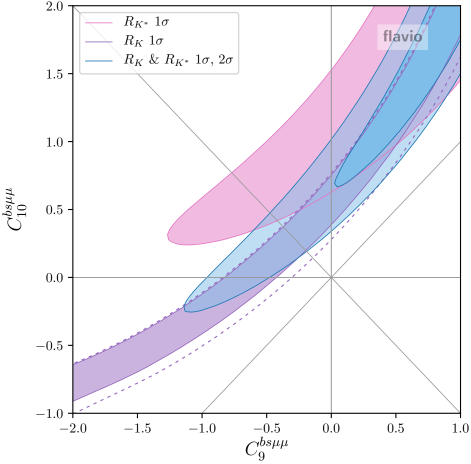
$C_7^{(\prime)}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$, $C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$, $C_S^{(\prime)}(\bar{s}P_{R(L)}b)(\bar{\mu}P_{L(R)}\mu)$

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

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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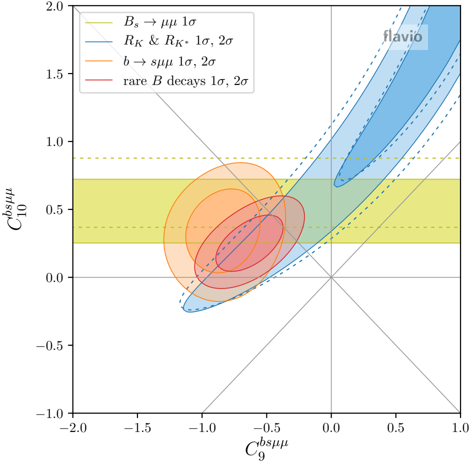

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- $B_s \to \mu^+\mu^-$ branching ratio shows slight preference for non-standard C_{10}
- $b \to s\mu\mu$ observables prefer non-standard C_9
- overall remarkable consistency

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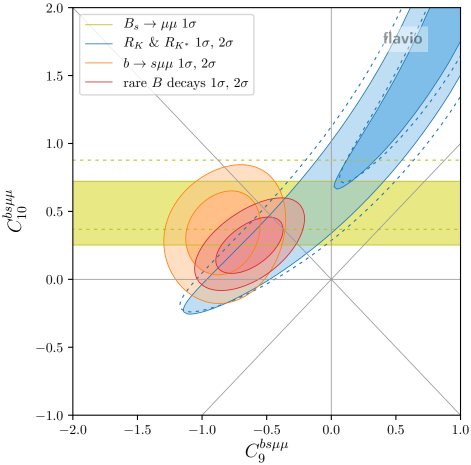

WA, Stangl 2103.13370

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- overall remarkable consistency
- 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)

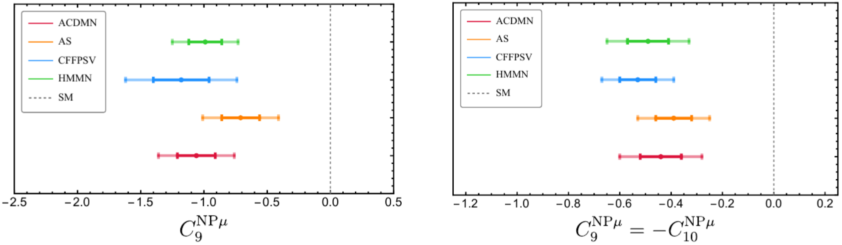
- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code — arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` — arXiv:2103.13370
- CFFPSV (M. Ciuchini, M. 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 very good agreement
- NP scenarios are preferred over SM with pulls $> 5\sigma$
- Warning: pull $\neq$ global significance.
- Global significance $\simeq 4.3\sigma$ estimated in Isidori et al. arXiv:2104.05631

Fits of Pairs of Wilson Coefficients

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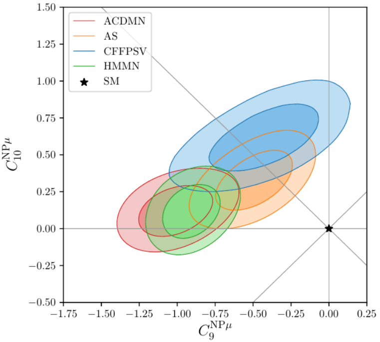
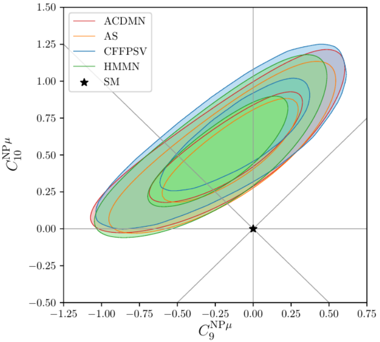


global fit



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

- Perfect agreement if only theoretically clean observables are used.

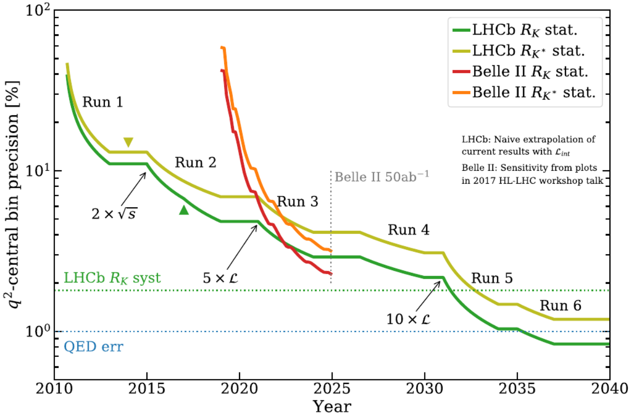
Implications for the New Physics Scale

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)

Future Prospects for R_K and R_{K^*}

- LHCb and Belle II can push uncertainties down to few percent
- (can ATLAS and CMS say something?)
- with sufficient statistics, LFU of angular distributions can be tested



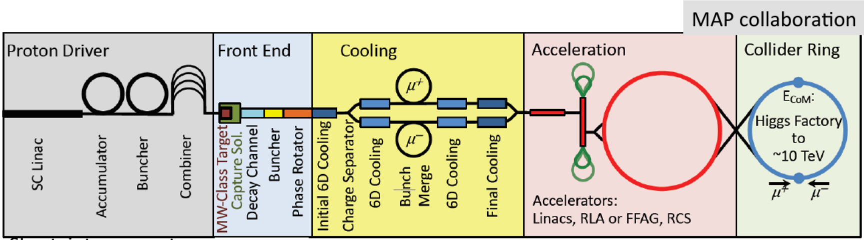
talk by Polci and Alvarez Cartelle @ Beyond the flavor anomalies workshop, Durham April 2020

- LHCb can cross check in other modes: R_ϕ , R_{pK} , ...

Testing the Anomalies at a Muon Collider

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

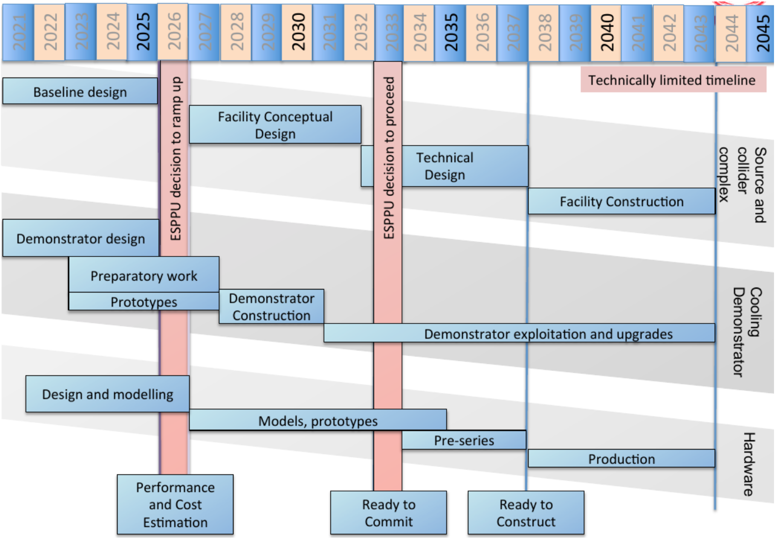
Collision

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

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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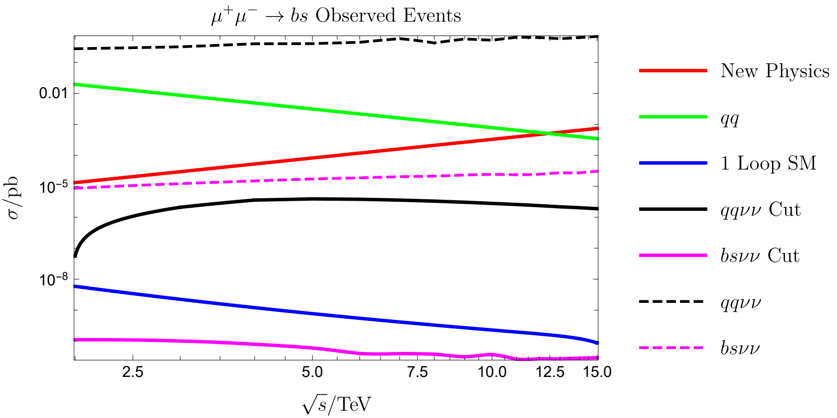
Forward backward asymmetry is sensitive to the chirality strcuture

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

Need charge tagging to measure the forward backward asymmetry

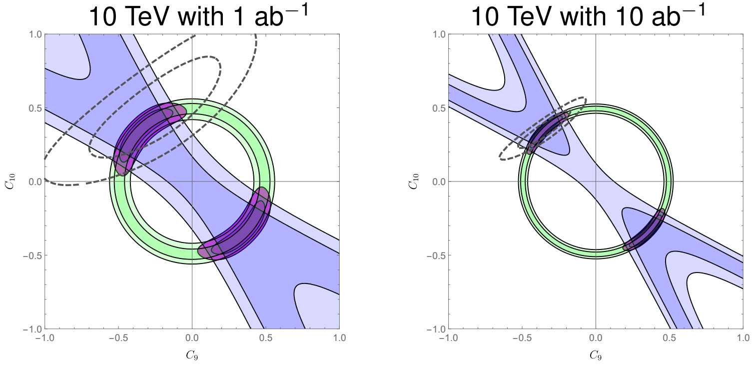
WA, Gadam, Profumo 2203.07495 and in preparation



- 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)

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.