Progress in Theory on Rare Decays

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UC SANTA CRUZ

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$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi$$

Flavor in the Standard Model and Beyond

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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SM flavor puzzle

Neutrino masses

Flavorful new physics?

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SM flavor puzzle

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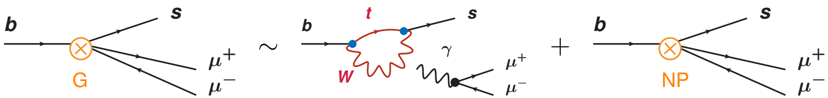
Flavorful new physics?

Q1: What is the origin of the hierarchies in the SM sources of flavor violation?

Q2: Are there other sources of flavor violation beyond the SM?

New Physics in FCNC Decays

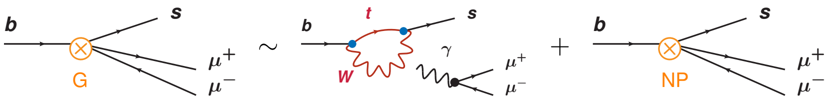


$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely (→ G)

calculate precisely the SM contribution (→ SM term)

get information on NP coupling and scale (→ C_{NP}/Λ_{NP}^2)



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measure precisely

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

A Wealth of Rare $b \to s$ Decays

radiative decays

$B \to X_s \gamma$

$B \to K^* \gamma$

$B_s \to \phi \gamma$

leptonic decays

$B_s \to \ell^+ \ell^-$

baryon decays

$\Lambda_b \to \Lambda \ell^+ \ell^-$

semileptonic decays

$B \to X_s \ell^+ \ell^-$

$B \to K \ell^+ \ell^-$

$B \to K^* \ell^+ \ell^-$

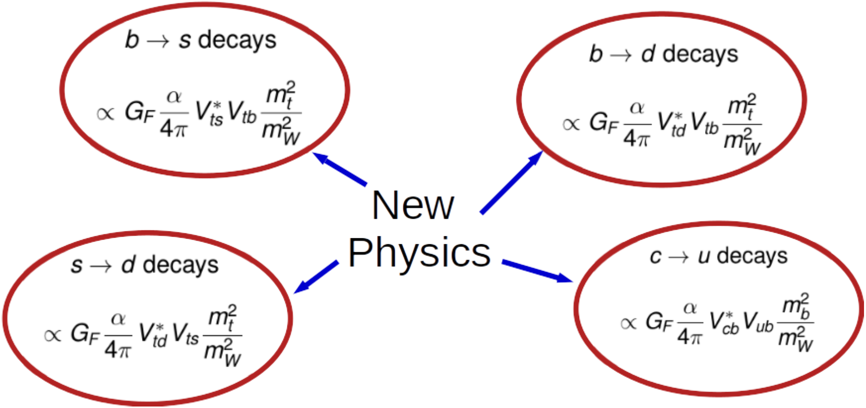
$B_s \to \phi \ell^+ \ell^-$

neutrino final states

$B \to K \nu \bar{\nu}$

$B \to K^* \nu \bar{\nu}$

Complementarity of Rare Decays



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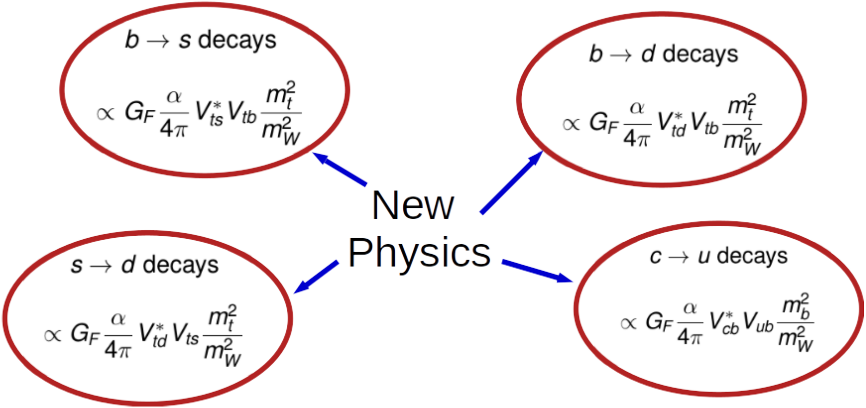

Q3: Are there hierarchies in the new physics sources of flavor violation?
If yes, what is their origin?

$$B_s \to \mu^+\mu^-$$

SM Prediction

amplitude $\sim$ Wilson coefficient $\times$ decay constant

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- Decay constant is known from lattice QCD with sub-percent precision!

$$f_{B_s} = (230.3 \pm 1.3)\ \text{MeV}$$ FLAG review 2021, 2111.09849

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- Precision of the SM prediction is limited by the CKM element V_{cb}

$$\text{BR}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$ Beneke, Bobeth, Szafron 1908.07011

- Note: the above SM prediction uses the inclusive value for $|V_{cb}|_{\text{incl.}} \simeq 42 \times 10^{-3}$. Using instead the exclusive value, the branching ratio is lower by $\sim 10\%$ (e.g. Bobeth, Buras 2104.09521)
- A precision measurement of $\text{BR}(B_s \to \mu^+\mu^-)$ could be used to give a precise value for V_{cb} (assuming the absence of new physics...)

The Effective $B_s \to \mu^+\mu^-$ Lifetime

- The sizeable width difference of the B_s mesons gives the opportunity to test new physics in a complementary way through measurements of the effective lifetime (De Bruyn et al. 1204.1737)

$$\tau_{\text{eff}} = \frac{\int_0^\infty dt\; t\; \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle}{\int_0^\infty dt\; \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle} = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma}^{\mu\mu} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} y_s} \right)$$

$$\text{with} \quad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.068 \pm 0.004 \quad \text{HFLAV}$$

- In the SM, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu} = 1$, but in the presence of new physics it can take any value $-1 < \mathcal{A}_{\Delta\Gamma}^{\mu\mu} < 1$

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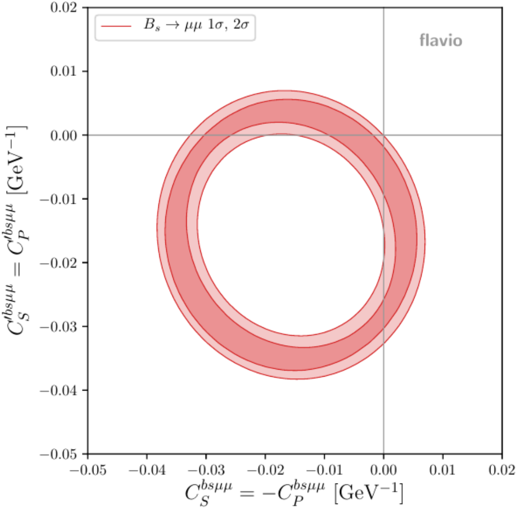
- In the SM, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}=1$, but in the presence of new physics it can take any value $-1<\mathcal{A}_{\Delta\Gamma}^{\mu\mu}<1$

- Want precision measurement of $\tau_{\rm eff}$ to access $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$

$$\tau_{\rm eff} = (2.07\pm 0.29\pm 0.03)\ \text{ps} \quad \text{LHCb 2108.09284}$$

$$\tau_{\rm eff} = (1.70^{+0.61}_{-0.44})\ \text{ps} \quad \text{CMS 1910.12127}$$

Sensitivity to New Physics



WA, Stangl 2103.13370

- scalar new physics is strongly constrained. (certain leptoquarks, or additional Higgs bosons from the MSSM)
- branching ratio data alone leaves degeneracy in the allowed parameter space

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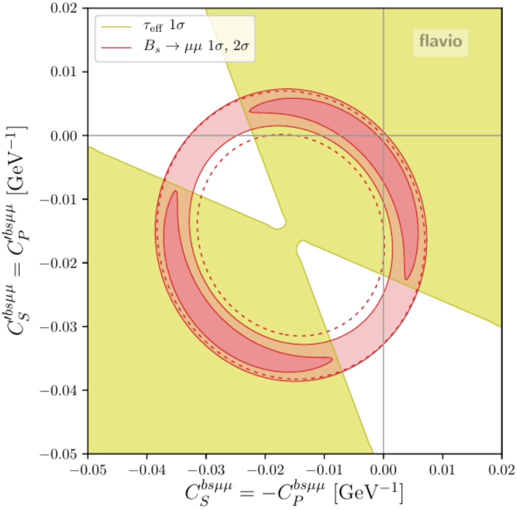

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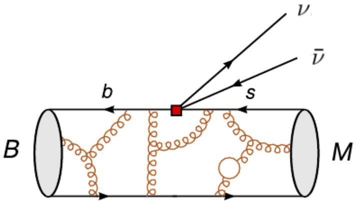
- scalar new physics is strongly constrained. (certain leptoquarks, or additional Higgs bosons from the MSSM)
- branching ratio data alone leaves degeneracy in the allowed parameter space
- latest results on the effective lifetime already start having impact (despite the sizable uncertainties)

$B \to K^{(*)}\nu\bar{\nu}$

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%

$\text{BR}(B^+ \to K^+ \nu\bar{\nu}) = (4.23 \pm 0.56) \times 10^{-6}$ Bause et al. 2109.01675

$\text{BR}(B^0 \to K^{*0} \nu\bar{\nu}) = (8.24 \pm 0.99) \times 10^{-6}$ Bause et al. 2109.01675

SM rates of $B \to K^{(*)}\nu\bar{\nu}$ can be observed at Belle II

(first limit on $B \to K\nu\bar{\nu}$ from Belle II: 2104.12624)

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ ($0.12\,\mathrm{ab}^{-1}$)	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%

(Belle II Physics Book 1808.10567)

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Role of $b \to s\nu\bar{\nu}$ in probing New Physics

- modification of $b \to s\nu\bar{\nu}$ rates by heavy new physics, e.g. leptoquarks, Z', ... (e.g. Browder et al. 2107.01080; Bause et al. 2109.01675)
- neutrino flavor is summed over in the measurement $\to$ indirect sensitivity to new physics in $b \to s\tau\tau$ because of $SU(2)_L$
- new invisible decay modes into light dark sector particles $b \to sX$, $b \to sX_1X_2$, ... (e.g. Hostert et al. 2005.07102; Felkl et al. 2111.04327)

$$B \to K^{(*)}\ell^+\ell^-$$
$$B_s \to \phi\ell^+\ell^-$$

SM Predictions

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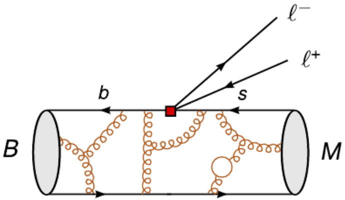

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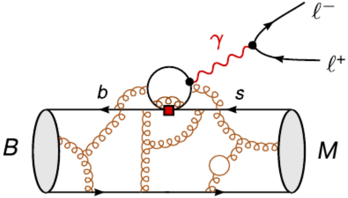
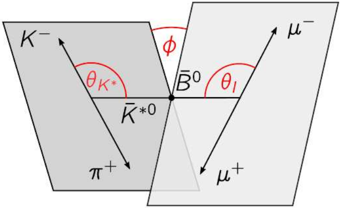
$+$ non-local terms (aka "charm loops")



- 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)
- dominant uncertainty ($\sim$ 10%?)

Angular Distributions



$$\frac{1}{\frac{d}{dq^2}(\Gamma + \bar{\Gamma})} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2\, d\vec{\Omega}} =$$

$$\begin{aligned}
= \;& \frac{3}{4}(1 - F_L)\sin^2\theta_{K^*} + F_L \cos^2\theta_{K^*} \\
& + \frac{1}{4}(1 - F_L)\sin^2\theta_{K^*}\cos 2\theta_\ell - F_L\cos^2\theta_{K^*}\cos 2\theta_\ell \\
& + S_3 \sin^2\theta_{K^*}\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_{K^*}\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_{K^*}\sin\theta_\ell\cos\phi \\
& + \frac{4}{3}A_{FB}\sin^2\theta_{K^*}\cos\theta_\ell + S_7\sin 2\theta_{K^*}\sin\theta_\ell\sin\phi \\
& + S_8\sin 2\theta_{K^*}\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_{K^*}\sin^2\theta_\ell\sin 2\phi
\end{aligned}$$

angular observables have (somewhat) reduced theory uncertainties

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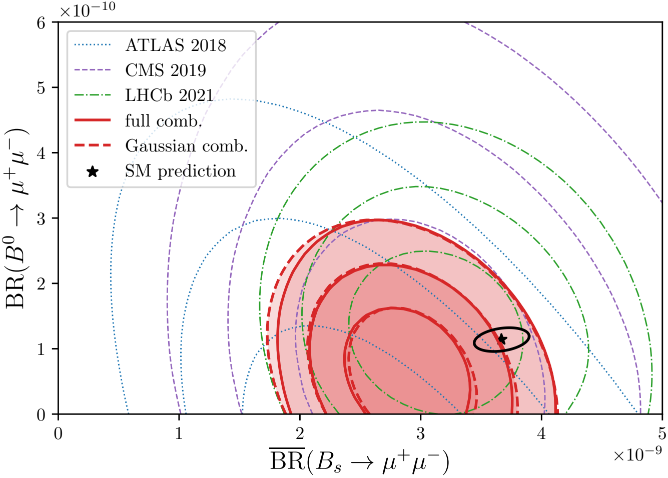
might violate lepton flavor universality	lepton flavor universal

Overview of the Flavor Anomalies

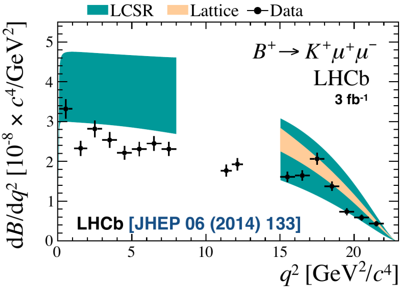
The $B_s \to \mu^+\mu^-$ Branching Ratio

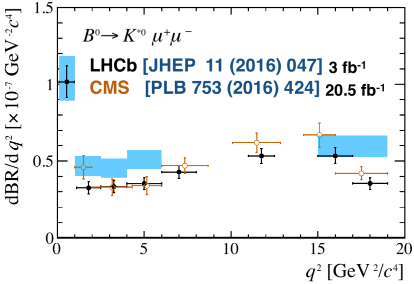
WA, Stangl 2103.13370; combination of LHCb 2108.09284, CMS 1910.12127, ATLAS 1812.03017

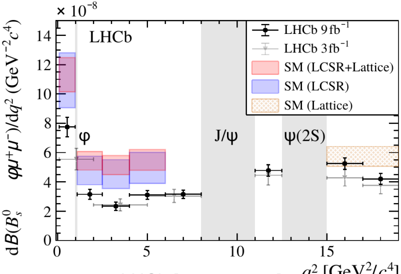


$\sim 2\sigma$ tension between SM and experiment

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







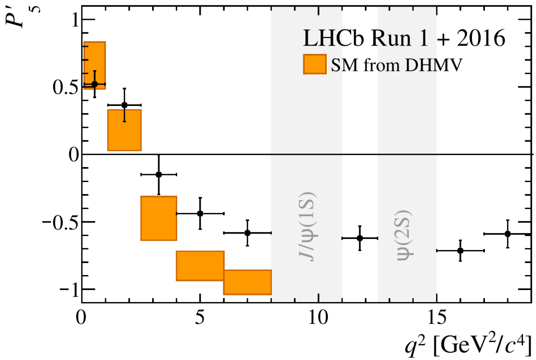
LHCb [2105.14007]

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
$(\sim 2\sigma - 3\sigma)$

The P_5' Anomaly

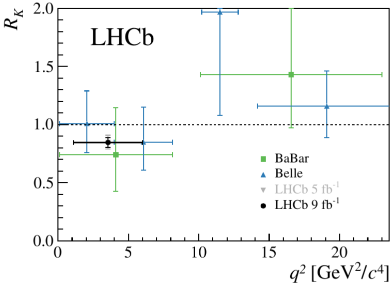
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

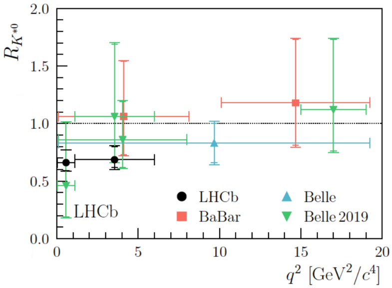
LHCb 2003.04831



$\sim 2\sigma - 3\sigma$ 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





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

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

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

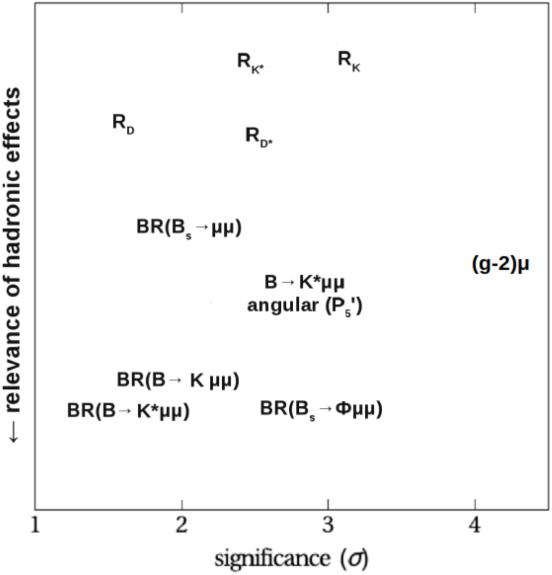
$$R_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05 \; (\sim 2.5\sigma)$$

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

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

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

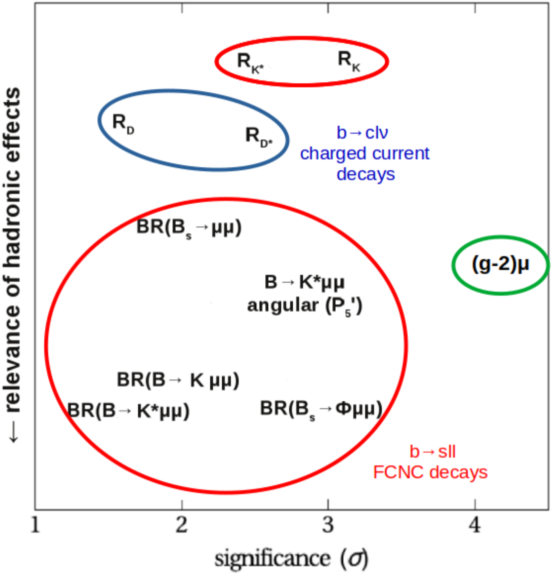
LHCb 2103.11769, LHCb 1705.05802, 1912.08139, 2110.09501; also Belle 1904.02440, 1908.01848



(inspired by

Zoltan Ligeti)

Flavor Anomalies in 2021



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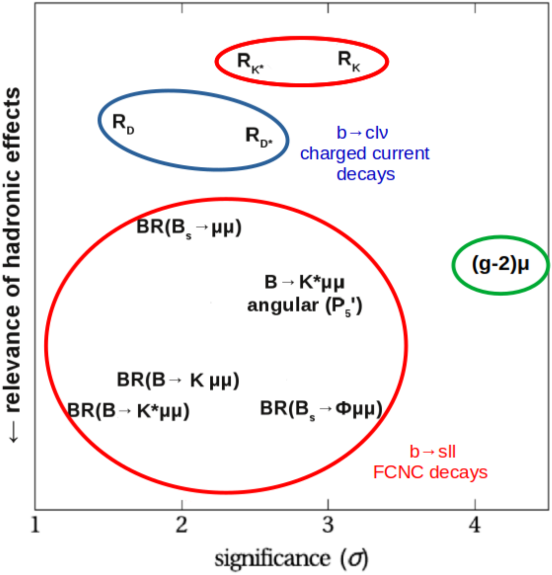

plus several others:

- inclusive vs. exclusive V_{cb}?
- inclusive vs. exclusive V_{ub}?
- first row CKM unitarity?
- ...

(inspired by Zoltan Ligeti)

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios	$(g-2)_\mu$

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underestimated hadronic effects?	✗	✓	✓	✗	✓

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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

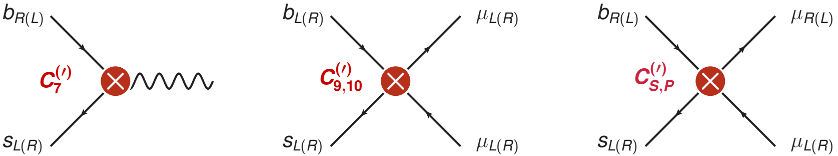
(inspired by Marco Nardecchia)

Implications for New Physics

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)

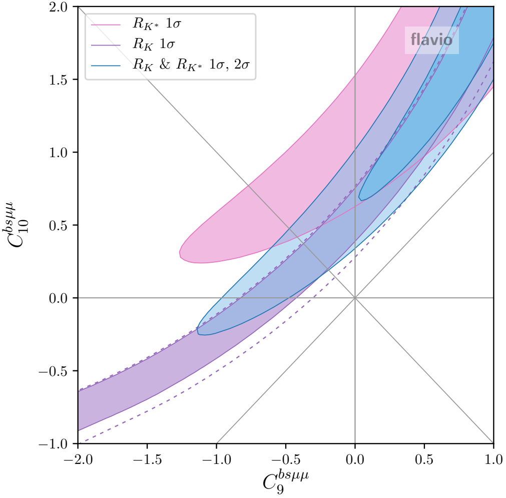
Complementary Sensitivity

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S'
$B \to (X_s, K^*)\gamma$	★			
$B_s \to \phi\gamma$	★			
$B \to (X_s, K, K^*)\ \ell^+\ell^-$	★	★	★	⋆
$B_s \to \phi\ \ell^+\ell^-$	★	★	★	⋆
$\Lambda_b \to \Lambda\ \ell^+\ell^-$	★	★	★	⋆
$B_s \to \ell^+\ell^-$			★	★
$B \to (K, K^*)\nu\bar{\nu}$ *		★	★	

(* SU(2) invariance implies that the neutrino modes are sensitive to $C_9 - C_{10}$ and $C_9' - C_{10}'$.

Measurements sum over all neutrino flavors)

Fits of Pairs of Wilson Coefficients



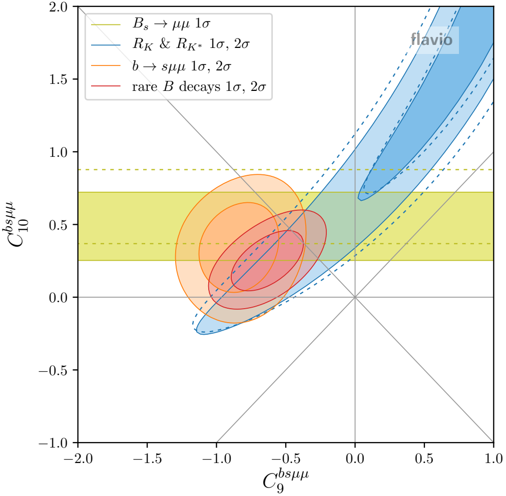
WA, Stangl 2103.13370

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

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

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

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

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

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

Comparison of Global Fits

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

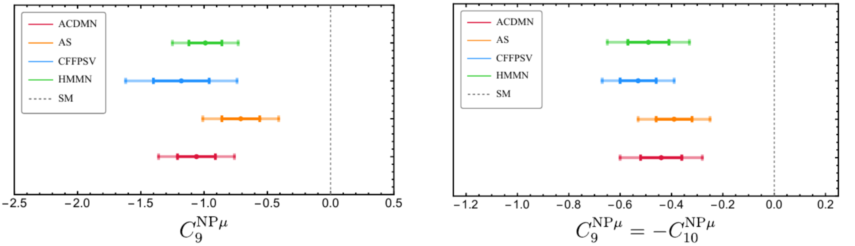
- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code — arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` — arXiv:2103.13370
- CFFPSV (M. Ciuchini, M. 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)

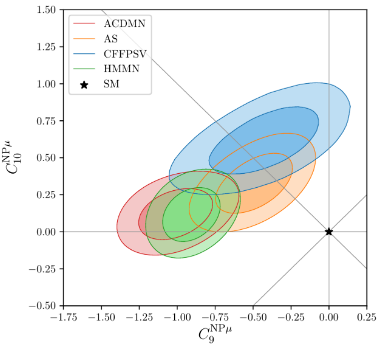


- small differences among the groups due to different approaches, but overall remarkable agreement
- NP scenarios are preferred over SM with pulls $> 5\sigma$

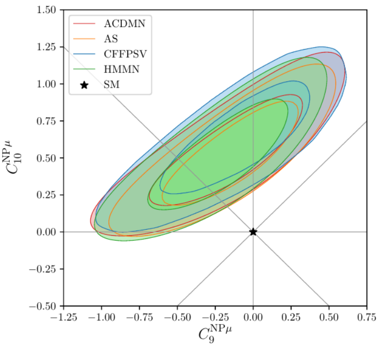
- Warning: pull $\neq$ global significance.
- Global significance $\simeq 4.3\sigma$ determined in Isidori et al. arXiv:2104.05631

Fits of Pairs of Wilson Coefficients

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



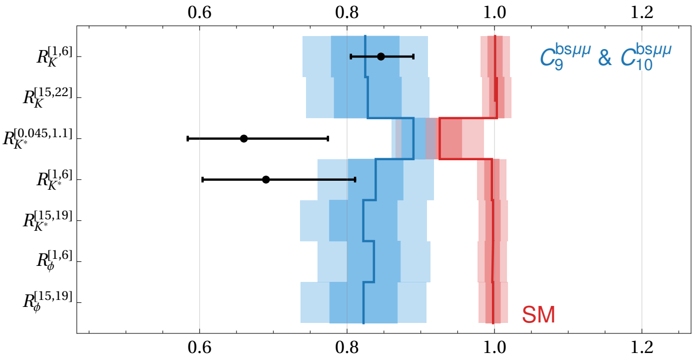
global fit



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

- Perfect agreement if only theoretically clean observables are used.

Predictions for Other LFU Ratios



WA, Stangl 2103.13370

LFU ratios of branching fractions are all predicted to show a similar devitation from the SM

$$R_K \simeq R_{K^*} \simeq R_\phi \simeq 0.8$$

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

Implications for the New Physics Scale

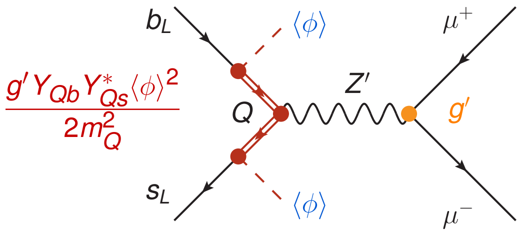
unitarity bound	$\frac{4\pi}{\Lambda_{NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 120$ TeV $\times (C_9^{NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{NP} \simeq 35$ TeV $\times (C_9^{NP})^{-1/2}$
MFV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

$\rightarrow$ Targets for Colliders!

My Favorite Model for R_K and R_{K^*}

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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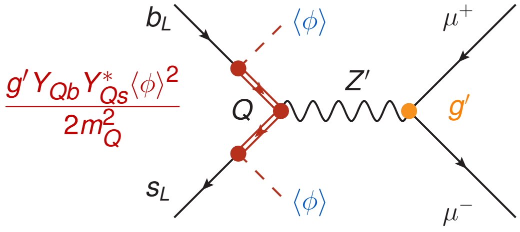


predicted Lepton Universality Violation!

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

Probing the Z' Parameter Space

Neutrino Tridents

B_s mixing

$(g-2)_\mu$

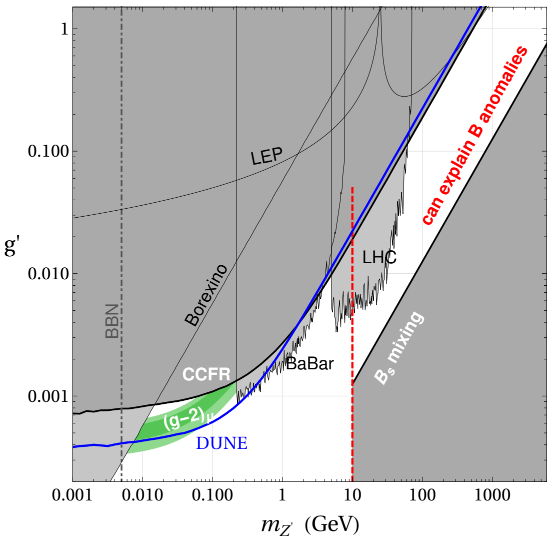
νe scattering

$Z \to \ell\ell$

$Z \to 4\mu$

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

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



No Summary

I look forward
to an exciting workshop!