Theory of Rare Decays and Lepton Flavor Universality Violation and Lepton Flavor Violation

Wolfgang Altmannshofer (UCSC)

loosely based on Whitepapers in preparation:

Rare decays of b and c hadrons: F. Archilli, WA
LFUV and LFV in b and c decays: D. Guadagnoli, P. Koppenburg

(personal selection of topics, apologies for omissions)

Snowmass Rare and Precision Frontier Meeting

Cincinnati, May 16 - 19, 2022

Flavor in the Standard Model and Beyond

CC problem — Hierarchy problem — Vacuum stability? — Strong CP problem

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

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

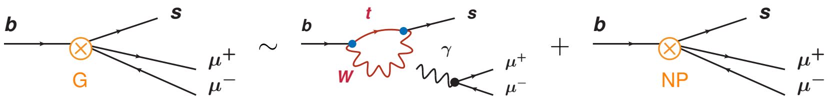
$$+ Y H \bar{\Psi}\Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{\rm dim6} + \ldots$$

SM flavor puzzle — Neutrino masses — 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 Rare Decays



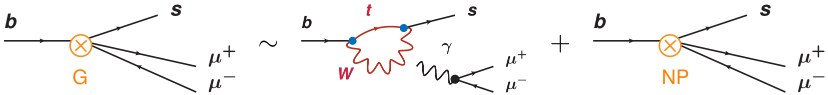
$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

New Physics in Rare Decays

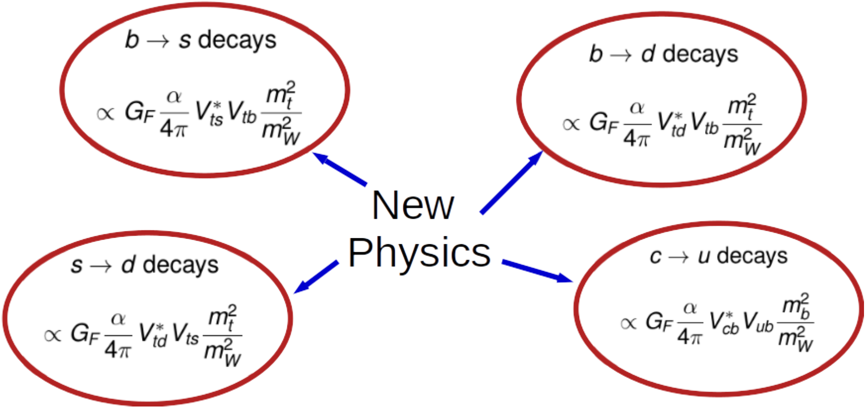


$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

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

To establish new physics in rare decays we need
high precision experimental results and theory calculations

Complementarity of Rare Decays



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

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

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

neutrino final states

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

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

semileptonic decays

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

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

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

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

The Effective Hamiltonian Framework

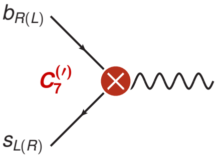
Useful setup to frame the discussion of b and c decays.

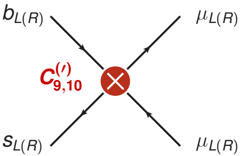
(Works as long as the new physics is heavy compared to b and c quarks.
In the presence of light new physics, one needs dedicated studies.)

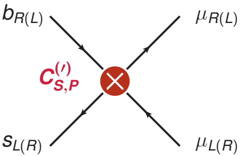
Here: example of effective Hamiltonian for $b \to s\ell\ell$

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

magnetic dipole operators | semileptonic operators | scalar operators







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

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

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)

$B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

SM Prediction

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

SM Prediction

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

- Decay constants known from lattice QCD with sub-percent precision!

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

$$f_{B^0} = (190.0 \pm 1.3)\ \text{MeV}$$

SM Prediction

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

- Decay constants known from lattice QCD with sub-percent precision!

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

$$f_{B^0} = (190.0 \pm 1.3)\ \text{MeV}$$

- Precision of the SM prediction is limited by the CKM input

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

$$\text{BR}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

- Note: the above SM predictions use the inclusive value for $|V_{cb}|_{\text{incl.}} \simeq 42 \times 10^{-3}$. Using instead the exclusive value, the B_s branching ratio is lower by $\sim 10\%$

  (e.g. Bobeth, Buras 2104.09521; WA, Lewis 2112.03437)

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)

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

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

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

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)

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

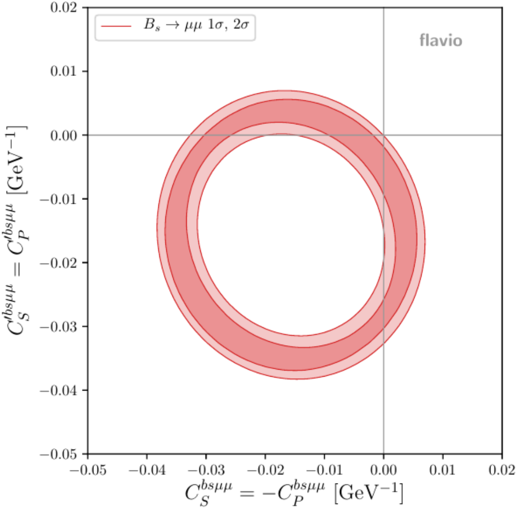
$$\text{with}\;\; y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.068 \pm 0.004 \quad \text{HFLAV}$$

- In the SM, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu} = 1$, but in the presence of new physics it can take any value $-1 < \mathcal{A}_{\Delta\Gamma}^{\mu\mu} < 1$
- Want precision measurement of $\tau_{\rm eff}$ to access $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$

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

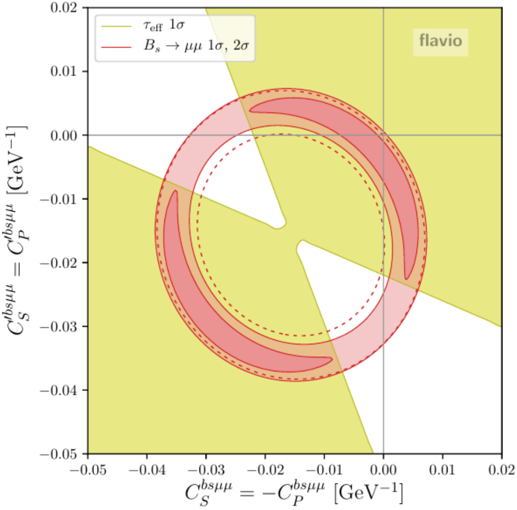
$$\tau_{\rm eff} = (1.70^{+0.61}_{-0.44})\ \text{ps} \quad \text{CMS 1910.12127}$$

Sensitivity to New Physics



WA, Stangl 2103.13370

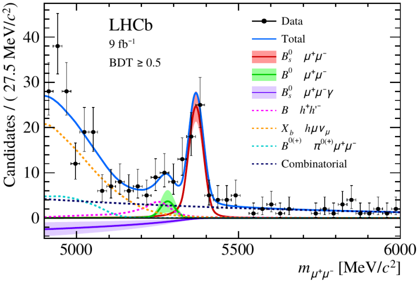
- scalar new physics is strongly constrained. (certain leptoquarks, or additional Higgs bosons from the MSSM)
- branching ratio data alone leaves degeneracy in the allowed parameter space



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
- latest results on the effective lifetime already start having impact (despite the sizable uncertainties)

- The $B_s \to \mu^+\mu^-\gamma$ decay is sensitive to additional terms in the effective Hamiltonian
- For theory predictions, need $B_s \to \gamma^{(*)}$ form factors.
- Not yet observed, but might become accessible at HL-LHC.



- Can perform lepton flavor universality tests, where form factor uncertainties largely cancel (Guadagnoli, Reboud, Zwicky 1708.02649)

$$R_\gamma = \frac{BR(B_s \to \mu^+\mu^-\gamma)}{BR(B_s \to e^+e^-\gamma)}$$

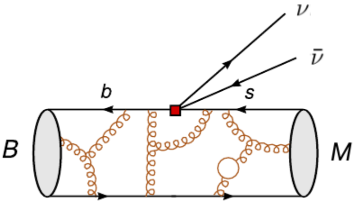
- Also the effective lifetime of $B_s \to \mu^+\mu^-\gamma$ is an interesting observables sensitive to new physics

  (Carvunis, Dettori, Gangal, Guadagnoli, Normand 2102.13390)

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

$$B_s \to \phi\nu\bar{\nu},\ \Lambda_b \to \Lambda\nu\bar{\nu}$$

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

Sensitivity to New Physics

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)

For $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$ need Z-pole machines FCC-ee, CEPC

(Li et al. 2201.07374)

Sensitivity to New Physics

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)

For $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$ need Z-pole machines FCC-ee, CEPC

(Li et al. 2201.07374)

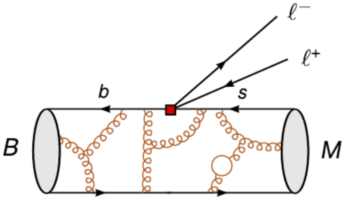
Role of $b \to s\nu\bar{\nu}$ in probing New Physics

- 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 → 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)

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

SM Predictions

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

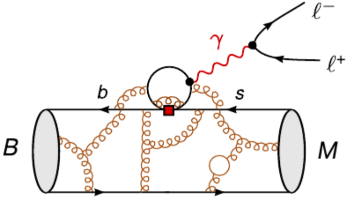
    (Bharucha, Straub, Zwicky 1503.05534; Gubernari, Kokulu, van Dyk 1811.00983)
- typical uncertainties $\lesssim$ 10%

(recent progress in $\Lambda_b \to \Lambda$ form factors Blake, Meinel, Rahimi, van Dyk 2205.06041)

SM Predictions

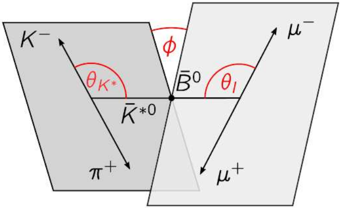
amplitudes $\sim$ Wilson coefficients $\times$ form factors

$+$ 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%?

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

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect
independent on q^2	could be q^2 dependent

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect
independent on q^2	could be q^2 dependent
might involve RH currents	mainly affect LH currents

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect
independent on q^2	could be q^2 dependent
might involve RH currents	mainly affect LH currents
might be CP violating	CP conserving

Distinguishing New Physics from Hadronic Effects

(heavy) New Physics	Hadronic Contributions
described by local four fermion operator	a non-local and non-perturbative effect
independent on q^2	could be q^2 dependent
might involve RH currents	mainly affect LH currents
might be CP violating	CP conserving
might violate lepton flavor universality	lepton flavor universal

Lepton Flavor Universality Tests

SM predictions for b hadron decays require non-perturbative input

1. form factors ($\rightarrow$ lattice QCD)
2. non-factorizable effects (need to be modeled)

Lepton Flavor Universality Tests

SM predictions for b hadron decays require non-perturbative input

1. form factors ($\rightarrow$ lattice QCD)
2. non-factorizable effects (need to be modeled)

clever way to reduce/eliminate hadronic uncertainties:
lepton flavor universality (LFU) tests

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

LFU ratios of
charged current decays

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

LFU ratios of
neutral current decays

$$Q_5 = D_{P_5'} = P_5'(\mu) - P_5'(e)$$

LFU differences of angular observables

How Robust Are the Predictions for R_K and R_{K^*}?

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha_{\rm em}}{\pi}\log^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space (tiny effect)

hadronic corrections (tiny effect)

QED corrections (soft and collinear photon emission)

- QED corrections seem to be under control at the level of the total rate, given the experimental cuts on e.g. the reconstructed B meson mass

  Bordone, Isidori, Pattori 1605.07633, Isidori, Nabeebaccus, Zwicky 2009.00929

$$R_K^{[1,6]} = 1.00 \pm 0.01 \;,\quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \;,\quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

- potentially larger QED effects at the differential level (?)

Even Cleaner Observables

- In the SM with neutrino masses, lepton flavor violating decays are suppressed by the tiny neutrino mass splittings

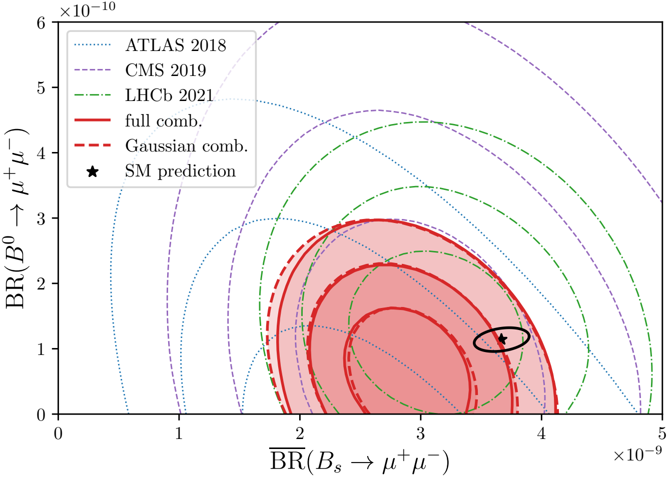
$$\text{e.g.} \quad \text{BR}(B \to K\mu e) \sim \text{BR}(B \to K\mu\mu) \times \left(\frac{m_\nu^2}{m_W^2}\right)^2 \sim 10^{-50}$$

- Any observation of lepton flavor violating decays in the foreseeable future would be an unambiguous sign of new physics.

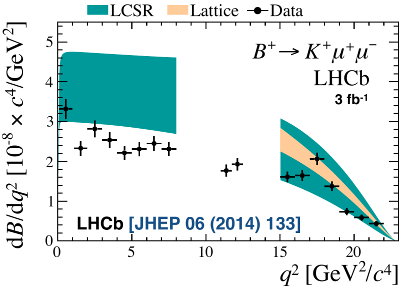
Overview of the Flavor Anomalies

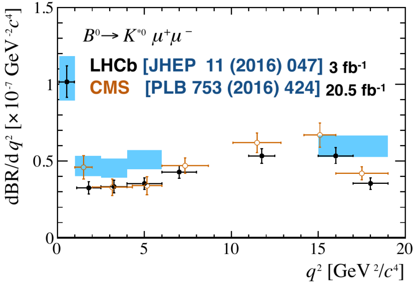
The $B_s \to \mu^+\mu^-$ Branching Ratio

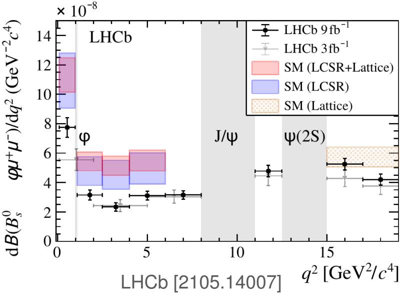
WA, Stangl 2103.13370; combination of LHCb 2108.09284, CMS 1910.12127, ATLAS 1812.03017



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



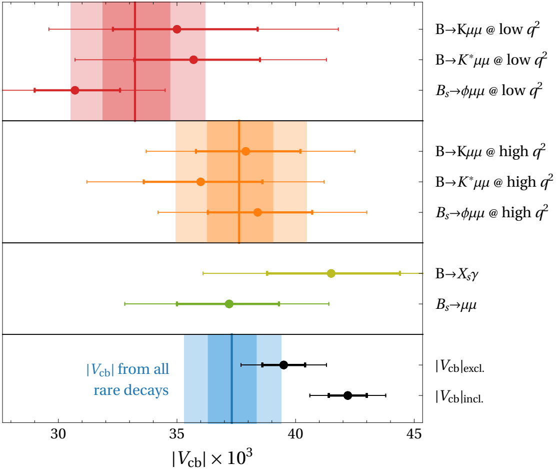




LHCb [2105.14007]

Experimental results for
BR($B \to K\mu\mu$)
BR($B \to K^*\mu\mu$)
BR($B_s \to \phi\mu\mu$)
are consistently low
across many q^2 bins
($\sim 2\sigma - 3\sigma$)

The Role of V_{cb}



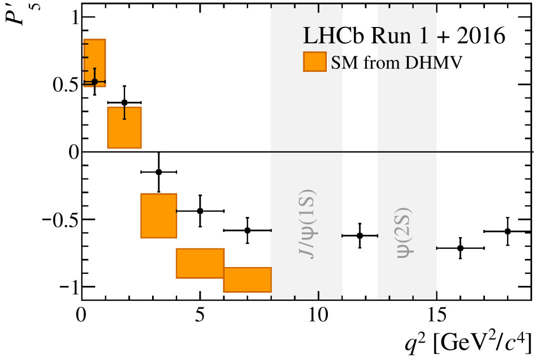
WA, Lewis 2112.03437

- 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

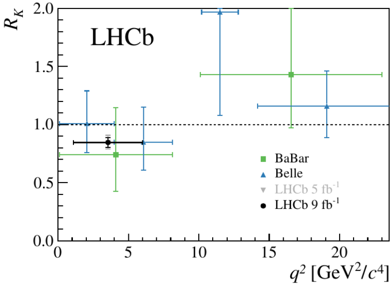
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

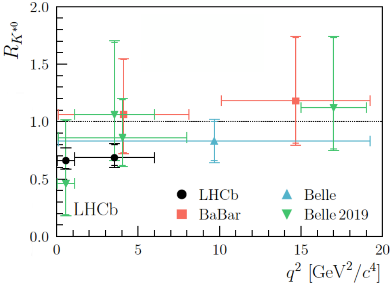
LHCb 2003.04831



$\sim 2\sigma - 3\sigma$ 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





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

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

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

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

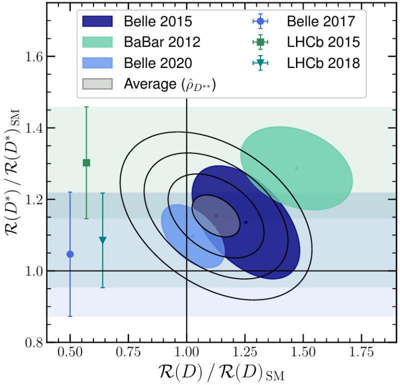
$$R_{K_S}^{[1.1,6]} = 0.66^{+0.20}_{-0.14}{}^{+0.02}_{-0.04} \; (\sim 1.5\sigma)$$

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

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

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

Bernlochner, Franco Sevilla, Robinson, 2101.08326



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

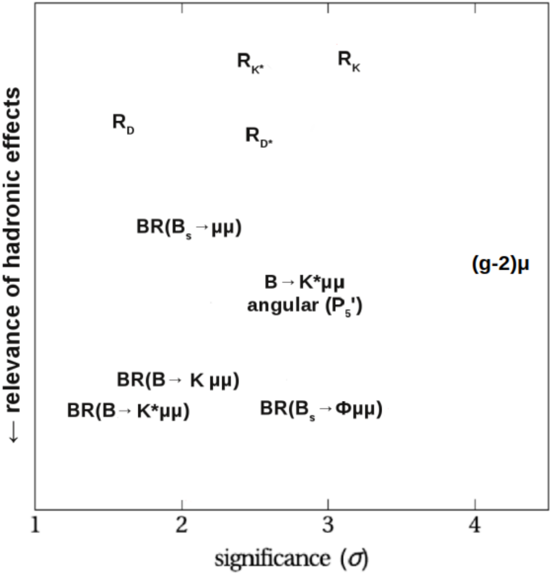
$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

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

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

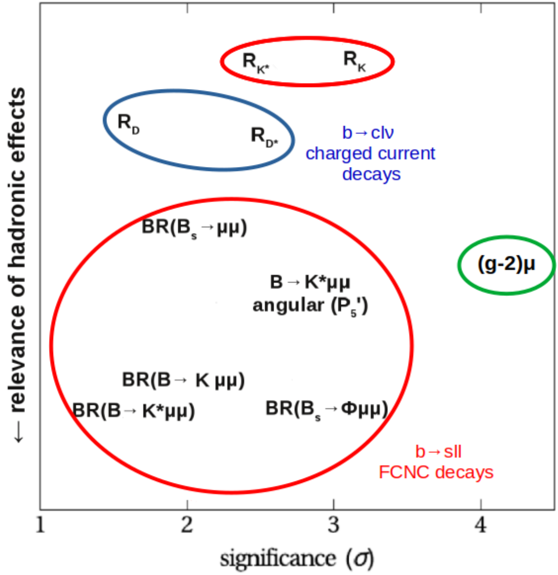
combined discrepancy with the SM: 3.6σ

(the heavy flavor averaging group quotes 3.1σ)



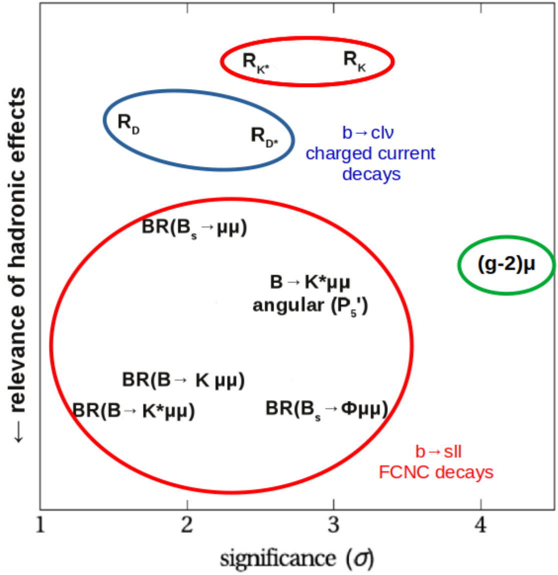
(inspired by Zoltan Ligeti)

Flavor Anomalies in 2022



(inspired by

Zoltan Ligeti)



plus several others:

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

(inspired by Zoltan Ligeti)

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, ...

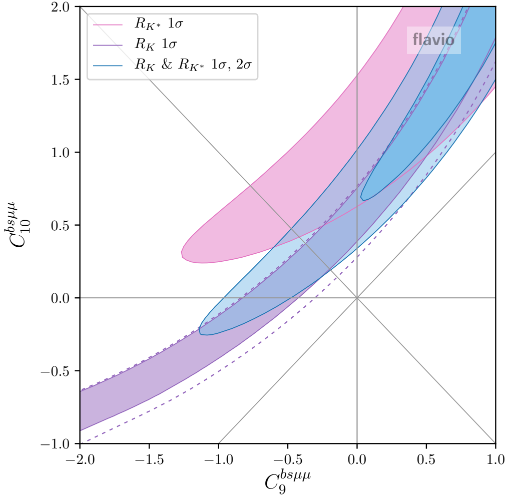
simplified models — introduce new particles in the simplest way possible (e.g. a single lepto-quark or a single Z' boson)

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)

Fits of Pairs of Wilson Coefficients



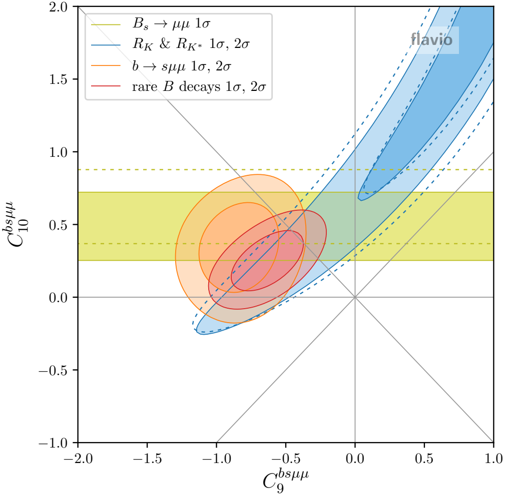
WA, Stangl 2103.13370

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

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

- 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
- overall remarkable consistency

Comparison of Global Fits

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

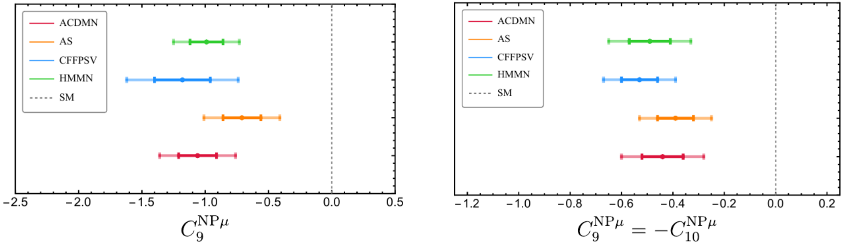
- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code — arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` — arXiv:2103.13370
- CFFPSV (M. Ciuchini, M.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

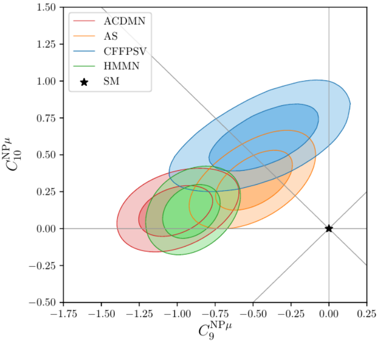
Fits of One Single Wilson Coefficient

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

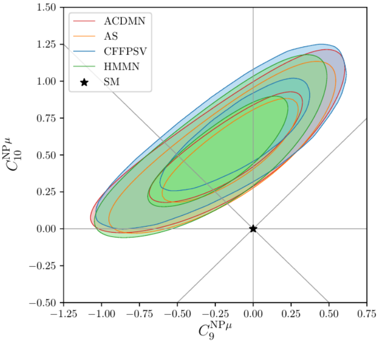


- small differences among the groups due to different approaches, but overall remarkable agreement
- NP scenarios are preferred over SM with pulls $> 5\sigma$
- Warning: pull $\neq$ global significance.
- Global significance $\simeq 4.3\sigma$ determined in Isidori et al. arXiv:2104.05631

(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.

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 Future Colliders!

What's Next?

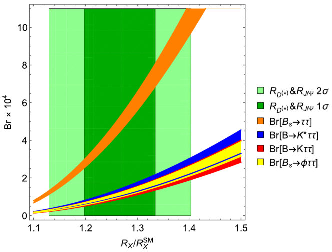
Rare Decays with Taus

- Combined explantions of the anomalies ($R_{K^{(*)}} + R_{D^{(*)}}$) typically predict large enhancements of semi-leptonic FCNC decays with taus in the final state

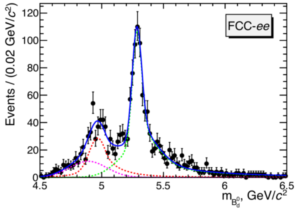
$$B_s \to \tau\tau\ , \quad B \to K^{(*)}\tau\tau\ , \quad \ldots$$

- To reach sensitivity to the SM rate, need a Z pole machine: e.g. expect O(100) - O(1000) reconstructed $B \to K^*\tau\tau$ events at FCC-ee/CEPC

Capdevilla et al. 1712.01919



Kamenik et al. 1705.11106; Li, Liu 2012.00665



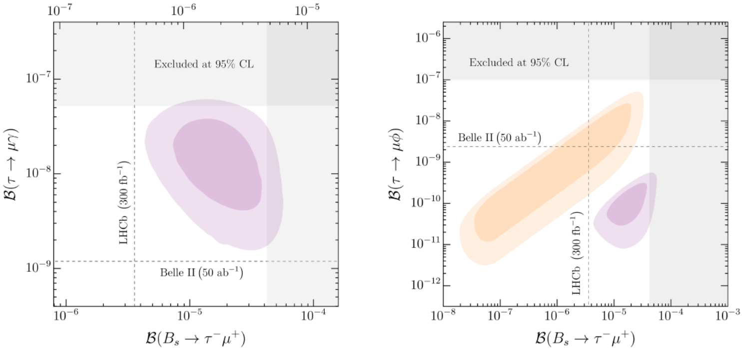
- Results on the tau modes would complete the picture of lepton universality in rare decays

Lepton Flavor Violating Decays

- Combined explantions of the anomalies ($R_{K^{(*)}} + R_{D^{(*)}}$) typically predict large rates of lepton flavor violating decays

$$B_s \to \tau\mu \,, \quad B \to K^{(*)}\tau\mu \,, \quad \ldots$$

- Complementarity with rare tau decays



Cornella et al. 2103.16558

We observe anomalies in $b \to s\ell\ell$ decays

2 options:

$b \to d\ell\ell$ Decays

We observe anomalies in $b \to s\ell\ell$ decays

2 options:

1) anomalies are due to new physics
$\Rightarrow$ want to study $b \to d\ell\ell$ transitions to find out if new physics shows up there as well

$b \to d\ell\ell$ Decays

We observe anomalies in $b \to s\ell\ell$ decays

2 options:

1) anomalies are due to new physics
   $\Rightarrow$ want to study $b \to d\ell\ell$ transitions to find out if new physics shows up there as well

2) anomalies are not due to new physics
   $\Rightarrow$ want to study $b \to d\ell\ell$ transitions to find out if new physics shows up there instead

Expect a $b \to d\ell\ell$ program that
parallels the effort for $b \to s\ell\ell$ decays

$b \to d\ell\ell$ Decays

Expect a $b \to d\ell\ell$ program that
parallels the effort for $b \to s\ell\ell$ decays

- this includes many processes:

$$B^0 \to \mu^+\mu^- \ , \quad B^+ \to \pi^+\ell^+\ell^- \ , \quad B^0 \to \pi^+\pi^-\ell^+\ell^- \ , \quad B_s \to K_S\ell^+\ell^-,$$

$$B_s \to K^*(\to K\pi)\ell^+\ell^- \ , \quad \Lambda_b \to p\pi\ell^+\ell^-$$

$b \to d\ell\ell$ Decays

Expect a $b \to d\ell\ell$ program that
parallels the effort for $b \to s\ell\ell$ decays

- this includes many processes:

$$B^0 \to \mu^+\mu^- \;,\quad B^+ \to \pi^+\ell^+\ell^- \;,\quad B^0 \to \pi^+\pi^-\ell^+\ell^- \;,\quad B_s \to K_S\ell^+\ell^-,$$

$$B_s \to K^*(\to K\pi)\ell^+\ell^- \;,\quad \Lambda_b \to p\pi\ell^+\ell^-$$

- and many observables:

branching ratios, angular distributions, LFU ratios

$$R_\pi = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \text{BR}(B \to \pi\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \text{BR}(B \to \pi e^+ e^-)}$$

$b \to d\ell\ell$ Decays

Expect a $b \to d\ell\ell$ program that
parallels the effort for $b \to s\ell\ell$ decays

- this includes many processes:

$$B^0 \to \mu^+\mu^- \;, \quad B^+ \to \pi^+\ell^+\ell^- \;, \quad B^0 \to \pi^+\pi^-\ell^+\ell^- \;, \quad B_s \to K_S\ell^+\ell^-,$$

$$B_s \to K^*(\to K\pi)\ell^+\ell^- \;, \quad \Lambda_b \to p\pi\ell^+\ell^-$$

- and many observables:

branching ratios, angular distributions, LFU ratios

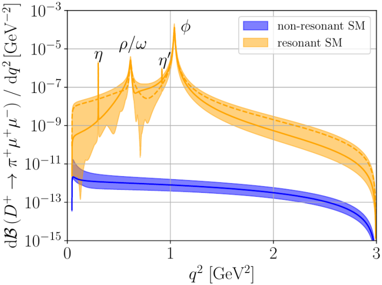
$$R_\pi = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, {\rm BR}(B \to \pi\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, {\rm BR}(B \to \pi e^+e^-)}$$

- already existing measurements of $b \to d$ processes can be used to probe new physics (Rusov 1911.12819)
- $b \to d$ will become the new $b \to s$ (after high-lumi phase, will have $\sim$ comparable statistics for $b \to d$ as there is now for $b \to s$)

Rare Charm Decays

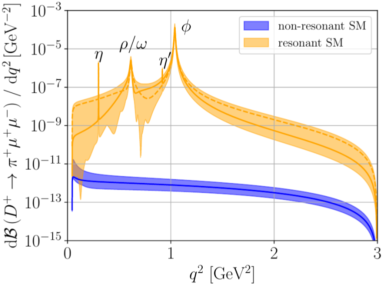
- Due to the strong GIM suppression, the sensitivity of rare charm decays to new physics is in principle even higher than the one of rare b decays. (de Boer, Hiller 1510.00311; Fajfer, Kosnik 1510.00965; ...)
- Challenge: control the long distance physics.

Bause et al. 1909.11108



Rare Charm Decays

Bause et al. 1909.11108



- Due to the strong GIM suppression, the sensitivity of rare charm decays to new physics is in principle even higher than the one of rare b decays. (de Boer, Hiller 1510.00311; Fajfer, Kosnik 1510.00965; ...)
- Challenge: control the long distance physics.

- focus on "null tests" (observables that are strongly suppressed in the SM due to exact or approximate symmetries) e.g. Bause et al. 2010.02225

  Examples: LFU ratios in $D \to \pi\ell\ell$, $D_s \to K\ell\ell$, lepton flavor violating decays, di-neutrino decays $D \to \pi\nu\nu$, $D_s \to K\nu\nu$, lepton forward backward asymmetry in $D \to \pi\pi\ell\ell$, also angular distributions in baryon decays (Golz et al. 2107.13010), ...
- Complementarity with LHC di-lepton spectra (Fuentes-Martin et al. 2003.12421)

Final Thoughts

- Rare decays have very high indirect sensitivity to new physics at very high scales.
- A comprehensive coverage of new physics parameter space requires the study of a large set of complementary rare decays.
  (too many to discuss them all in a 30min talk!)
- The expected experimental precision (see next talk) combined with improved theoretical predictions will allow us to probe uncharted new physics parameter space.
- The current “B anomalies” might be first indirect signs of new physics. If confirmed, they would imply a new mass scale in particle physics, potentially within reach of either the LHC or future colliders.
- In the absence of anomalies, the future rare decay program will quantitatively and qualitatively improve constraints on new physics and provide critical input for new physics model building.