PSI Summer School “Particle Flavour Fever”, Zuoz

Implications of *B* Anomalies

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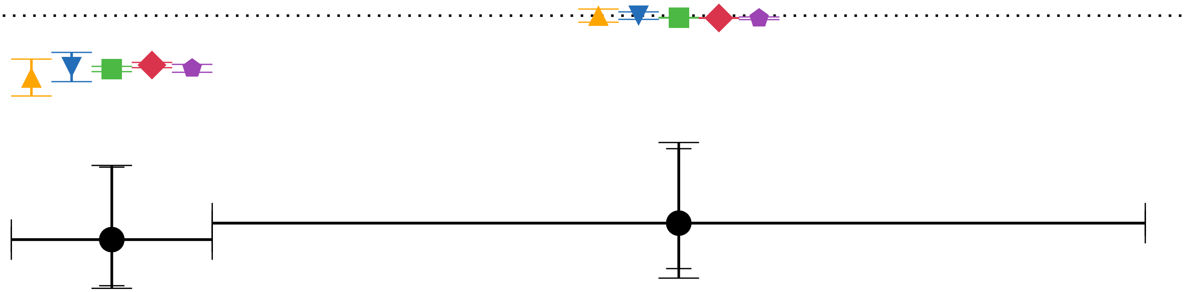
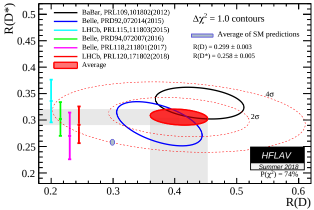
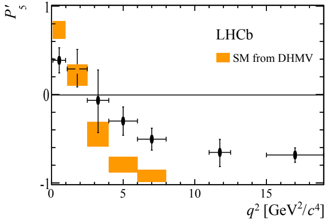


B "anomalies"

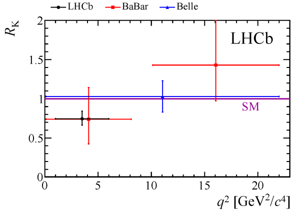
R_D & R_D^* anomalies

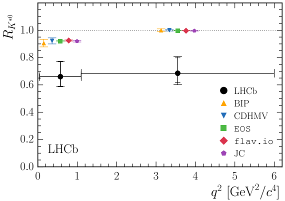


$B \to K^* \mu\mu$ anomalies



R_K & R_K^* anomalies





Outline

1. Introduction
   - What's an anomaly?
   - The need for theory hypotheses
2. $b \to c\tau\nu$ anomalies
   - $B \to D^{(*)}\tau\nu$ in the SM
   - EFT analysis of $R_{D^{(*)}}$
   - Simplified models to explain $R_{D^{(*)}}$

1. $b \to s\mu\mu$ anomalies
   - $B \to K^* \mu^+\mu^-$ angular observables
   - SM predictions: challenges
   - EFT analysis of $b \to s\mu\mu$ anomalies
   - Simplified models for $b \to s\mu\mu$ anomlies
2. R_K and R_{K^*} anomalies
   - EFT analysis of $R_{K^{(*)}}$ anomalies
3. Combined explanations
   - Simplified models
   - Model-building directions
   - Outlook

Lecture I

Introduction & charged-current anomalies

1. Introduction
   - What's an anomaly?
   - The need for theory hypotheses

2. $b \to c\tau\nu$ anomalies

Anomaly, evidence, discovery?

Simplest case: measurement with purely statistical, normally distributed uncertainty, no theory uncertainties

$$\mu_{\text{exp}} = 0.5 \pm 0.1 \qquad \mu_{\text{th}} = 1.0$$

Particle physics convention:

- Evidence: $3\sigma, p = 1.3 \times 10^{-3}$
- Discovery: $5\sigma, p = 2.9 \times 10^{-7}$

Issues of the 5σ criterion

- Systematic uncertainties:

$$\mu_{\text{exp}} = 0.5 \pm 0.01_{\text{stat}} \pm 0.1_{\text{sys}} \qquad \mu_{\text{th}} = 1.0$$

  - Systematic uncertainty underestimated by factor of 2 $\Rightarrow$ significance reduces by factor 2 $\Rightarrow$ p-value increases by factor 2×10^4
- Theory uncertainties:

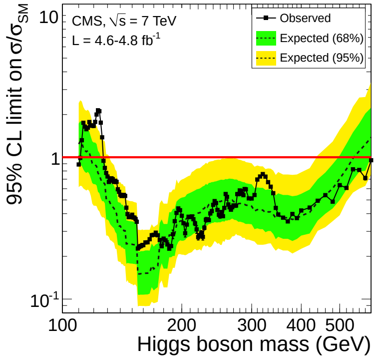
$$\mu_{\text{exp}} = 0.5 \pm 0.01 \qquad \mu_{\text{th}} = 1.0 \pm 0.1$$

  - Usually systematic in nature, often based on (educated) guesses, unclear probability distribution

On the "look elsewhere effect" (LEE)

Much discussed especially since the Higgs discovery, the LEE refers to measurements of a local excess in a distribution where the location of the excess is not clear a priory

- Probability of observing such a fluctuation at $m = 125$ GeV? "Local" significance 3.1σ
- Probability of observing such a fluctuation *anywhere* in the mass range? "Global" significance 1.5σ



In flavour physics, the LEE usually plays little role since deviations do not show up as local excess but as correlated shifts in multiple observables based on the same partonic process

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Dealing with multiple observables: R_D and R_{D^*} example

- both sensitive to the same partonic process, $b \to c\tau\nu$
- both deviate from the SM:

$$(R_D/R_D^{\text{SM}}) = 1.36 \pm 0.11 \qquad (R_{D^*}/R_{D^*}^{\text{SM}}) = 1.19 \pm 0.05$$

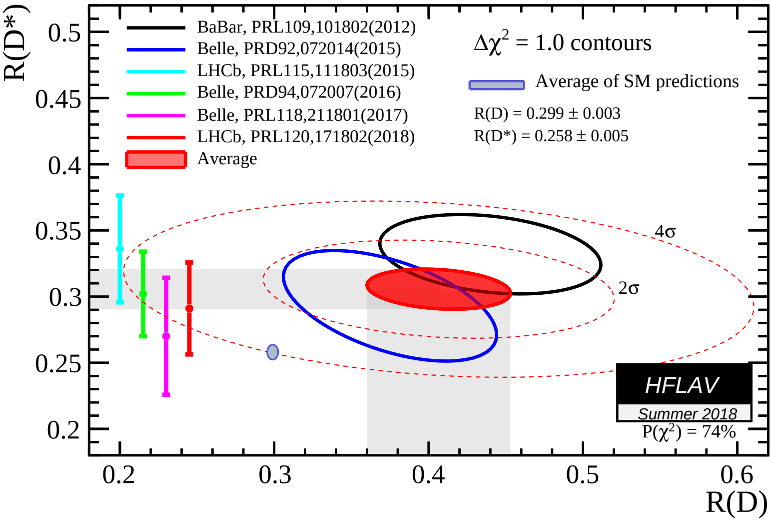
- 2.3σ and 3.0σ, respectively. How to combine this?
  - Option 1: simultaneous enhancement $\to$ 1 degree of freedom, weighted average

$$(R_{D^{(*)}}/R_{D^{(*)}}^{\text{SM}}) = 1.22 \pm 0.05 \qquad (3.7\sigma)$$

  - Option 2: independent enhancement, 2 degrees of freedom: 3.8σ
  - What if theory predicts anticorrelation of R_D and R_D^*?

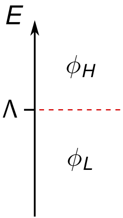
General fact: combining significances in more than 1 observable requires a *theory hypothesis*!

Theory vs. experiment



Effective field theory

We want to study physics at energies much lower than some scale Λ in a theory where particles lighter and heavier than Λ are present.



To this end, we can replace the complicated Lagrangian of the "full" theory by an **effective Lagrangian** containing only the light fields and a series of local operators built out of the light fields

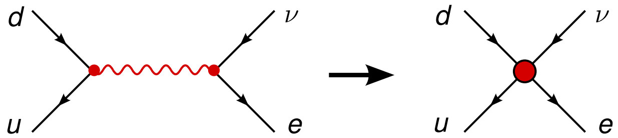
$$\mathcal{L}(\varphi_L, \varphi_H) \to \mathcal{L}(\varphi_L) + \mathcal{L}_{\text{eff}} = \mathcal{L}(\varphi_L) + \sum_i C_i Q_i(\varphi_L)$$

This expansion is called the **operator product expansion**

Example: modern view of Fermi theory

In Fermi's model of β decay, the full weak Lagrangian (that he didn't know of course) is effectively replaced by the low-energy (QED) Lagrangian plus a single operator

$$\mathcal{L}_{\text{ew}} \to \mathcal{L}_{\text{QED}} + \frac{G_F}{\sqrt{2}}(\bar{u}d)(e\bar{\nu})$$



Local operator $\equiv$ effective vertex!

Interpretation of anomalies: theory hypotheses

- Effective field theory
  - In observables based on the same partonic process (e.g. $b \to c\tau\nu$) only a handful of operators in the operator product expansion are relevant
  - Significance can be defined in the space of Wilson coefficients
- Simplified models
  - Models with a single (or a few) multiplet of new particles allow to study "typical" pattern of Wilson coefficients and correlations with other processes, e.g. direct searches
- UV complete models
  - Allow to investigate whether successful simplified models can be embedded in a consistent theory

Summary: anomaly caveats

- When observing sizable discprepancies, we need to pay attention to the dominant source of uncertainty (statistical, systematic, theory)
- When we can measure multiple observables sensitive to the same short-distance physics, we need a theory hypothesis to quote a combined significance
- The combined significance depends on the number of degrees of freedom (that is somewhat arbitrary in a pure EFT analysis)

How to deal with anomalies (as a theorist)

1. Scrutinize SM predictions & uncertainties (but don't inflate your errors without physics reason)
2. Try to find an EFT solution and investigate correlation with other observables
3. Try to realize your EFT solution in a simplified model and investigate signals and investigate correlation with other observables, direct searches
4. Try to embed your simplified model in a reasonable theory

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Let's discuss 1.-3. for $R_{D^{(*)}}$

1 Introduction

2 $b \to c\tau\nu$ anomalies

- $B \to D^{(*)}\tau\nu$ in the SM
- EFT analysis of $R_{D^{(*)}}$
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Lepton flavour universality (LFU) in the SM

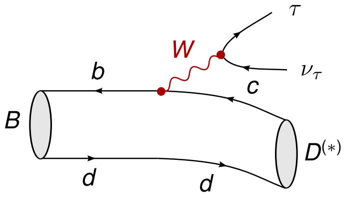
$$\mathcal{L}_{\text{SM}} = -\sum_F \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_\psi \bar{\psi} i \not{D} \psi$$
$$+ |D_\mu H|^2 + \mu^2 |H|^2 - \lambda |H|^4$$
$$- \bar{l}_L Y_l H e_R - \bar{q}_L Y_d H d_R - \bar{q}_L Y_u \widetilde{H} i_R$$

- All interactions in $\mathcal{L}_{\text{SM}}$ are flavour-blind (large $U(3)^5$ flavour symmetry) except for the Yukawa terms
- In the SM (without RH neutrinos), only the 3 diagonal elements of Y_l are physical

$\Rightarrow$ Gauge interactions are *lepton flavour universal*, only lepton masses and lepton-Higgs couplings (tiny!) distinguish between flavours

Testing LFU in $B \to D^{(*)}\tau\nu$

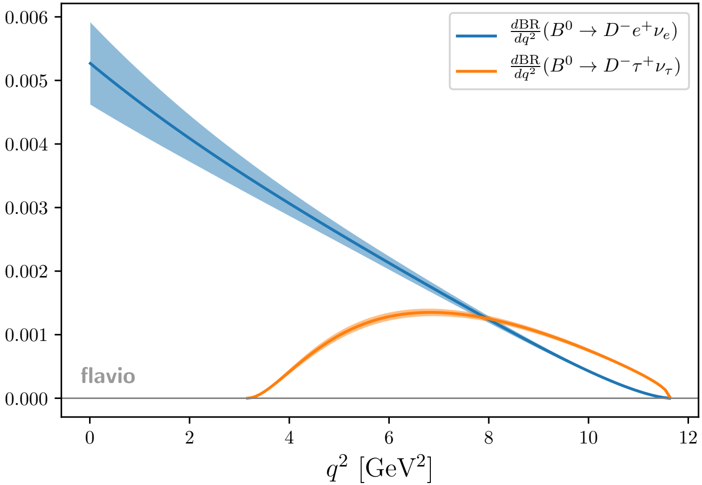
- The decays $B \to D^{(*)}\ell\nu$ with $\ell = e, \mu$ are used to measure the $V_{\rm CKM}$ element V_{cb}
  - Not a *rare* B decay! $\text{BR}(B \to X_c(e+\mu)\nu) \sim 20\%$
  - μ-e universality confirmed at the 4% level
- $R_{D^{(*)}} = \frac{\text{BR}(B\to D^{(*)}\tau\nu)}{\text{BR}(B\to D^{(*)}\ell\nu)}$ tests μ-τ (e-τ) universality



- Two sources for $R_{D^{(*)}} \neq 1$:
  - Phase-space due to $m_\tau \gg m_{e,\mu}$
  - m_ℓ-dependent terms in the amplitude, in particular multiplying the scalar form factors, e.g.

$$\frac{d\Gamma_D}{dq^2} \propto O(1) \times f_+^2(q^2) + O(m_\ell^2/q^2) \times f_0^2(q^2)$$

$B \to D\ell\nu$ vs. $B \to D\tau\nu$



$B \to D^{(*)}$ form factors and $R_{D^{(*)}}$

- Due to the m_ℓ-dependent terms, $R^{\text{SM}}_{D^{(*)}}$ require knowledge of form factors
    - Vector form factors can be fitted from measurements of $B \to D^{(*)}\ell\nu$ with $\ell = e, \mu$ assuming them to be SM-like
    - Scalar form factors need to be predicted by theory: in particular lattice QCD (LQCD) or heavy quark effective theory (HQET)
- Status of $B \to D$
    - LQCD calculations of both form factors extrapolated to the full kinematic range Bailey et al. 1503.07237,Na et al. 1505.03925
- Status of $B \to D^*$
    - LQCD calculations restricted to zero recoil (q^2_{max}), vector form factor Bailey et al. 1403.0635, Harrison et al. 1711.11013. Need HQET for scalar, non-zero recoil Caprini et al. hep-ph/9712417

$R_{D^{(*)}}^{\text{SM}}$: *status*

- R_D
  - Lattice QCD: 0.299 ± 0.11 Bailey et al. 1503.07237, 0.300 ± 0.008 Na et al. 1505.03925
  - Lattice + Fit to $B \to D(e,\mu)\nu$: 0.299 ± 0.003 Bernlochner et al. 1703.05330, Bigi et al. 1707.09509
- R_{D^*}
  - Slight controversy over how conservative to estimate HQET uncertainties
  - 0.257 ± 0.003 Bernlochner et al. 1703.05330, 0.260 ± 0.008 Bigi et al. 1707.09509,
  - this should be settled soon by LQCD
- In both cases, much smaller than experimental uncertainty!

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Effective theory for $b \to c\tau\nu$

Assuming no light particles except the SM ones:

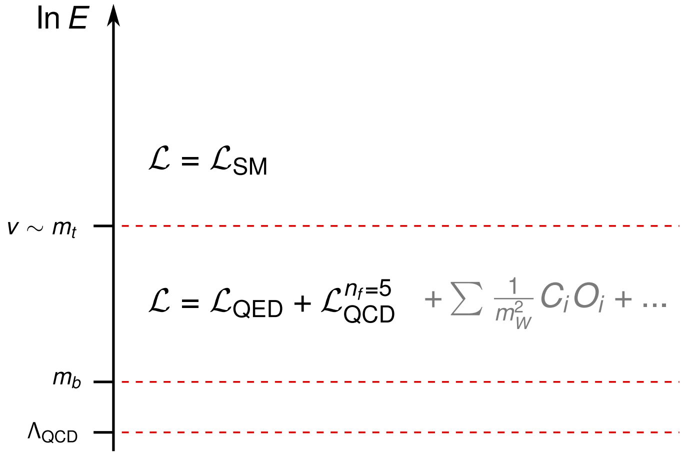
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(O_{V_L} + \sum_i C_i O_i + \text{h.c.} \right)$$

$$O_{V_L} = (\bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \nu_{\tau L}) \qquad O_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\tau L}) \qquad O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\tau L})$$

$$O_{V_R} = (\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_{\tau L}) \qquad O_{S_L} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\tau L})$$

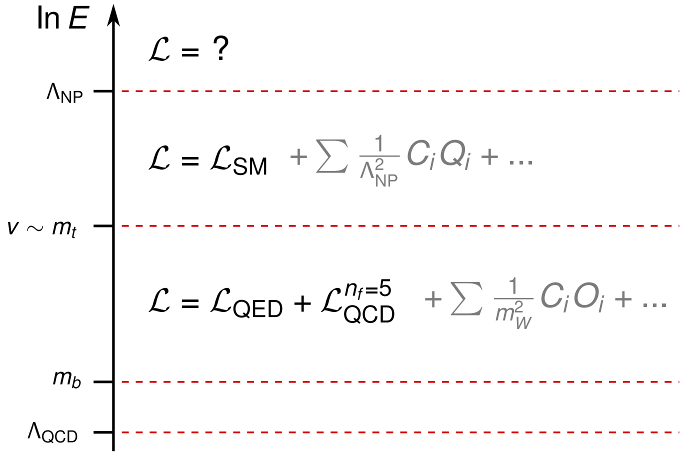
(Strictly speaking, we also have to distinguish between operators with different neutrino flavours. In particular, the ones with $\nu_{\mu,eL}$ do not interfere with the SM. Neglected here for simplicity.)

Hierarchy of effective theories



- $m_b \ll v$: weak effective Hamiltonian

Hierarchy of effective theories

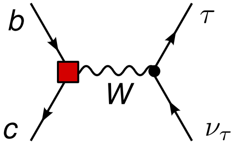


- $m_b \ll v$: weak effective Hamiltonian
- $v \ll \Lambda_{\text{NP}}$: "SMEFT"

Implications of SMEFT

- The Wilson coefficients of O_{V_L}, O_{S_R}, O_{S_L}, O_T receive a direct matching contribution from a $SU(2)_L \times U(1)_Y$ invariant semi-leptonic operator in SMEFT
- $O_{V_R} = (\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_{\tau L})$ does not have a direct counterpart in SMEFT: it violates hypercharge $(-\frac{2}{3} - \frac{1}{3} + \frac{1}{2} - \frac{1}{2} = -1)$
- Additional dimension-6 contributions to C_{V_L} and C_{V_R} from modified W couplings, but these are *lepton flavour universal*

$\Rightarrow C_{V_R}$ cannot modify $R_{D^{(*)}}$!



New physics in C_{V_L}

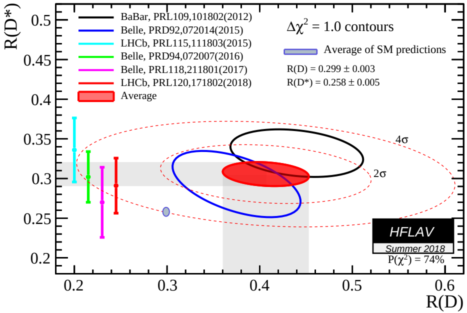
- O_{V_L} is the SM operator
- Modifying C_{V_L} leads to universal rescaling,

$$(R_D/R_D^{\text{SM}}) = (R_{D^*}/R_{D^*}^{\text{SM}})$$

- Preferred value

$$(R_{D^{(*)}}/R_{D^{(*)}}^{\text{SM}}) = 1.22 \pm 0.05$$

implies $C_{V_L} = 0.10 \pm 0.02$

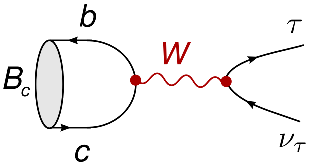


Scalar operators in $R_{D^{(*)}}$

- $B \to D\tau\nu$ only probes $C_{S_R} + C_{S_L}$
- $B \to D^*\tau\nu$ only probes $C_{S_R} - C_{S_L}$

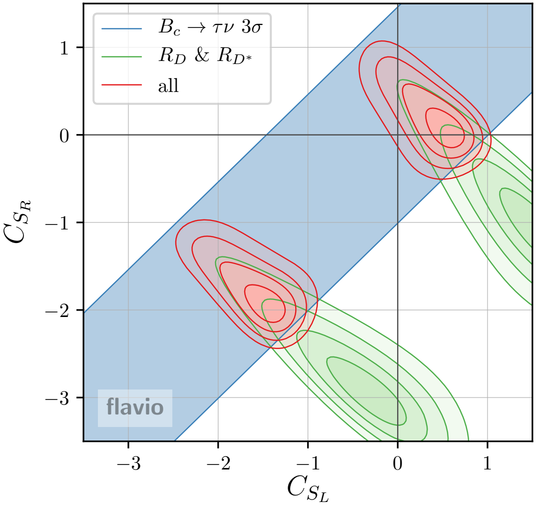
cf. Crivellin et al. 1206.2634

Constraint from $B_c \to \tau\nu$

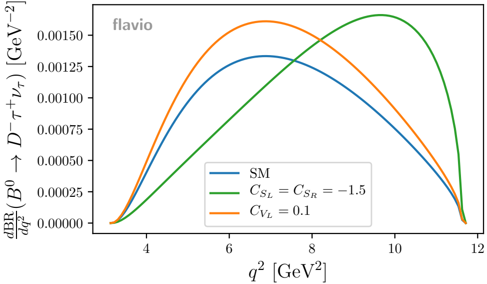


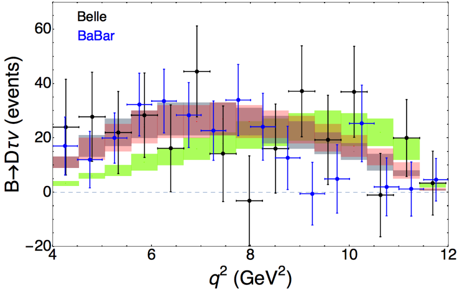
- Can be strongly enhanced by scalar operators
- sensitive to $C_{S_R} - C_{S_L}$
- Even though the decay has not been measured or searched for, theoretical arguments allow to constrain $\text{BR}(B_c \to \tau\nu) \lesssim 0.3$ Li et al. 1605.09308, Alonso et al. 1611.06676
- Reinterpreting an old LEP1 search for $B^+ \to \tau\nu$ allows to constrain $\text{BR}(B_c \to \tau\nu) \lesssim 0.1$ Akeroyd and Chen 1708.04072

Combined fit to scalar operators



Differential $B \to D\tau\nu$ rate vs. scalar operators

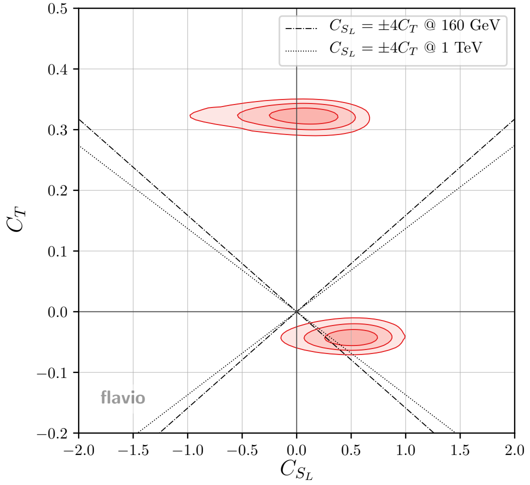




Celis et al. 1612.07757

Solution with large scalar Wilson coefficients is disfavoured Freytsis et al. 1506.08896, Celis et al. 1612.07757

Scalar vs. tensor operator



- Fit to $R_D, R_{D^*}, B_c \to \tau\nu$

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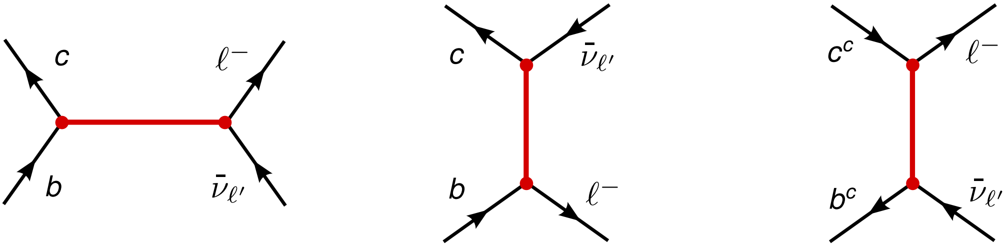
New physics: naive dimensional analysis

- The SM amplitude is
$$\propto \frac{4G_F}{\sqrt{2}} V_{cb} = \frac{2}{v^2} V_{cb} \approx 870\,\text{GeV}$$
where $V_{cb} \approx 0.04$ and $v = 246$ GeV is the Higgs VEV
- Tree-level mediator would need $O(1)$ couplings with mass of 2 TeV to get 20% effect
- Lessons:
  - we need fairly light mediators potentially accessible at LHC
  - we cannot afford a loop suppression

Tree-level models to explain $R_{D^{(*)}}$

- 3 ways to connect the 4 fermions keeping gauge invariance

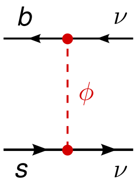


Tree-level models to explain $R_{D^{(*)}}$

Spin	Rep.	Name	C_{V_L}	C_{S_R}	C_{S_L}	C_T	Comments
0	$(1,2)_{\frac{1}{2}}$	$H^\pm$		$\times$	$\times$		
1	$(1,3)_0$	W'	$\times$				
0	$(\bar{3},1)_{\frac{1}{3}}$	S_1	$\times$		$\times$	$\times$	$C_{S_L} = -4C_T$
0	$(\bar{3},3)_{\frac{1}{3}}$	S_3	$\times$				
0	$(\bar{3},2)_{\frac{7}{6}}$	R_2			$\times$	$\times$	$C_{S_L} = 4C_T$
1	$(\bar{3},1)_{\frac{2}{3}}$	U_1	$\times$	$\times$			
1	$(\bar{3},3)_{\frac{2}{3}}$	U_3	$\times$				
1	$(\bar{3},2)_{\frac{5}{6}}$	V_2		$\times$			

Correlation with $b \to s\nu\bar\nu$

- $SU(2)_L$ symmetry relates the processes $b_L \to c_L \tau_L \bar\nu_{\tau_L}$ and $b_L \to s_L \nu_{\tau_L} \bar\nu_{\tau_L}$.
  - SMEFT: $O_{lq}^{(1)} = (\bar l_i \gamma_\mu l_j)(\bar q_k \gamma^\mu q_l)$ $O_{lq}^{(3)} = (\bar l_i \gamma_\mu \tau^I l_j)(\bar q_k \gamma^\mu \tau^I q_l)$
  - $\mathcal{H}_\text{eff}$: $O_{V_L} = (\bar c_L \gamma^\mu b_L)(\bar\ell_L \gamma_\mu \nu_{\tau L})$ $O_L^{\nu\nu} = (\bar s_L \gamma^\mu b_L)(\bar\nu_{\tau L} \gamma_\mu \nu_{\tau L})$
  - Matching: $C_{V_L} \propto V_{ci}[C_{lq}^{(3)}]_{33i3}$ $C_L^{\nu\nu} \propto [C_{lq}^{(1)}]_{3323} - [C_{lq}^{(3)}]_{3323}$
- Need $i = 2$ (V_{cs}) to avoid CKM suppression. Resulting correlation: $C_L^{\nu\nu} = a\, C_{V_L}$



	S_1	S_3	U_1	U_3
a	-2	2	0	-4

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

- $B \to K\nu\bar{\nu}$ is a flavour-changing neutral current (FCNC) and thus *rare* in the SM:

$$\mathrm{BR}(B \to K\nu\bar{\nu})_{\mathrm{SM}} \approx 5 \times 10^{-5}$$

- B factories BaBar & Belle have looked for the decay and set a limit

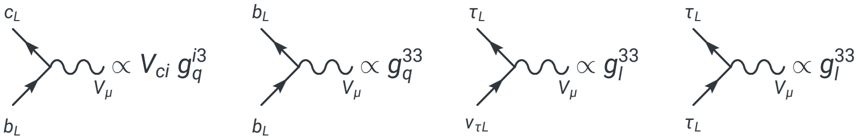
$$\mathrm{BR}(B \to K\nu\bar{\nu})_{\mathrm{exp}} \lesssim 15 \times 10^{-5}$$

- S_1, S_3, U_3 leptoquarks disfavoured as solution to $R_{D^{(*)}}$ anomalies!
- Possible to suppress using cancellation between S_1 and S_3 contribution Crivellin et al. 1703.09226 but this is not renormalization group invariant $\to$ fine-tuning

W' solution: direct searches

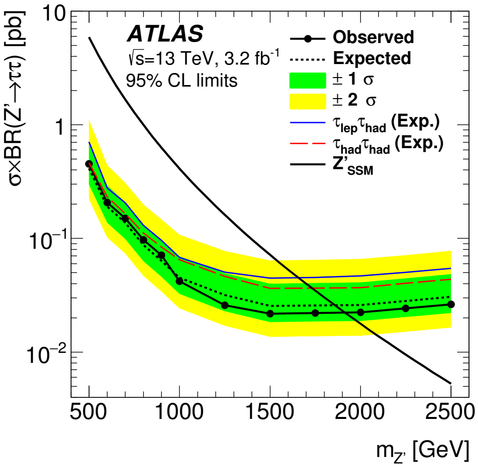
- The W' needs to come as $SU(2)_L$ triplet, i.e. degenerate $W^{\pm\prime}$ and $Z^{0\prime}$
- Couplings to up/down-type quarks and charged leptons/neutrinos related by $SU(2)_L$:

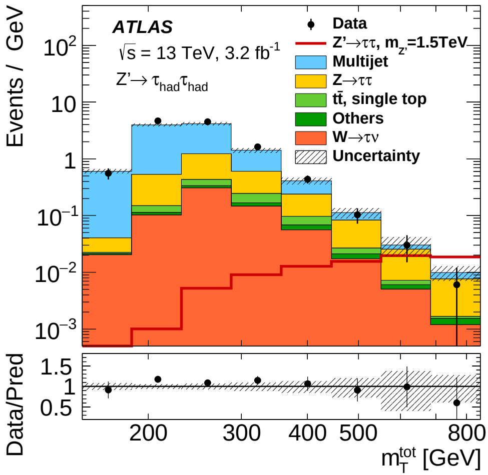
$$\mathcal{L} \supset g_q^{ij}\, \bar{q}_L^i \gamma^\mu q_L^j\, V_\mu + g_l^{ij}\, \bar{l}_L^i \gamma^\mu l_L^j\, V_\mu$$



- g_q^{13} and g_q^{23} strongly constrained by B^0-$\bar{B}^0$ and B_s-$\bar{B}_s$ mixing $\to$ large g_q^{33} required!
- Sizable cross-section $b\bar{b} \to \tau^+\tau^-$ predicted

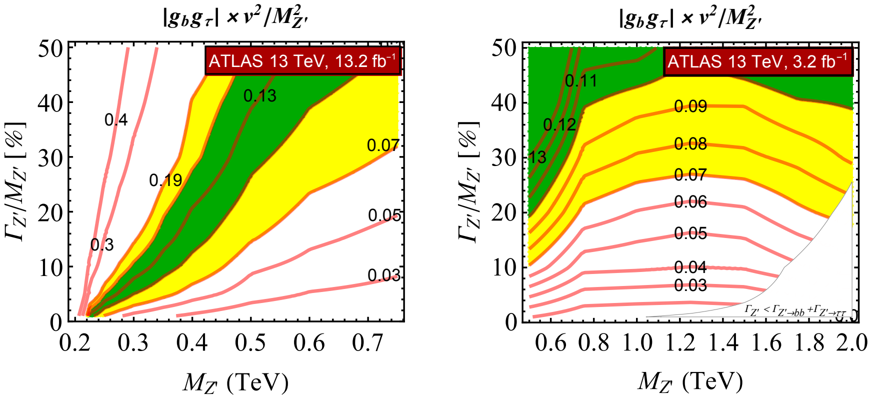
The $pp \to \tau^+\tau^-$ constraint





Aaboud et al. 1608.00890

Constraint on W'/Z' scenario



- W' only allowed if light ($M < 500$ GeV) or broad ($\Gamma/M > 30\%$)
- Similarly tight constraints on $H^{\pm,0}$ (2HDM) scenario

Faroughy et al. 1609.07138

Summary of single-particle solutions

Spin	Rep.	Name	C_{V_L}	C_{S_R}	C_{S_L}	C_T	Comments
0	$(1,2)_{\frac{1}{2}}$	$H^\pm$		$\times$	$\times$		
1	$(1,3)_0$	W'	$\times$				
0	$(\bar{3},1)_{\frac{1}{3}}$	S_1	$\times$		$\times$	$\times$	$C_{S_L} = -4C_T$
0	$(\bar{3},3)_{\frac{1}{3}}$	S_3	$\times$				
0	$(\bar{3},2)_{\frac{7}{6}}$	R_2			$\times$	$\times$	$C_{S_L} = 4C_T$ *
1	$(\bar{3},1)_{\frac{2}{3}}$	U_1	$\times$	$\times$			
1	$(\bar{3},3)_{\frac{2}{3}}$	U_3	$\times$				
1	$(\bar{3},2)_{\frac{5}{6}}$	V_2		$\times$			

* requires imaginary couplings Becirevic 1806.07298

New light particles: right-handed neutrino

- Allowing new particles that are *not* heavy, an interesting possibility is to add a RH neutrino, that is a SM singlet, $N_R \sim (1,1)_0$
- This leads to new dimension-6 operators, e.g.

$$(\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_R \gamma^\mu N_R)$$

- Possible UV completion: $W' \sim (1,1)_1$

Asadi et al. 1804.04135, Greljo et al. 1804.04642

Outlook

- Theory
  - $B \to D^*$ LQCD form factors for non-zero recoil will further reduce SM uncertainties
  - Direct searches for LQ scenarios will further cut into parameter space
- Experiment
  - LHCb measurement of R_D?
  - Further modes: $\Lambda_b \to \Lambda_c\tau\nu$, $B_c \to J/\psi\tau\nu$, ...
  - More observables (e.g. τ polarization in $B \to D^*\tau\nu$)
  - Belle II!

Advertisement: `flavio`

- A Python package for flavour phenomenology in the SM & beyond
  - repository: `http://github.com/flav-io/flavio`
  - documentation: `http://flav-io.github.io`
- Features
  - SM predictions with uncertainties
  - NP predictions for arbitrary Wilson coefficients (weak EFT or SMEFT)
  - Fitting SM parameters and Wilson coefficients to data (Bayesian or frequentist)
  - Plotting library to visualize fit results

Lecture II

Neutral-current anomalies and combined explanations

1. $b \to s\mu\mu$ anomalies
   - $B \to K^* \mu^+ \mu^-$ angular observables
   - SM predictions: challenges
   - EFT analysis of $b \to s\mu\mu$ anomalies
   - Simplified models for $b \to s\mu\mu$ anomlies
2. R_K and R_{K^*} anomalies
3. Combined explanations

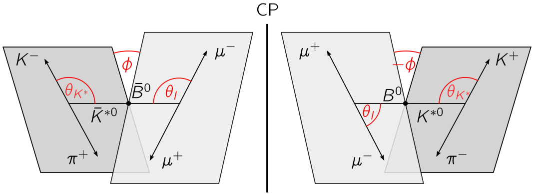
$b \to s$ transitions

- Loop- & CKM-suppressed $\Rightarrow$ *rare* decays with branching ratios around 10^{-6}
- Many decay modes

non-leptonic	$B \to \varphi K$, $B \to \eta' K$, $B_s \to \varphi\varphi$, $B \to K\pi$, $B_s \to KK$, …
radiative	$B \to X_s\gamma$, $B \to K^*\gamma$, $B_s \to \varphi\gamma$, …
semi-leptonic	$B \to X_s\ell\ell$, $B \to K\ell\ell$, $B \to K^*\ell\ell$, $B_s \to \varphi\ell\ell$, …
leptonic	$B_s \to \mu\mu$
neutrino	$B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$

- Not only branching ratios but also angular distributions, CP asymmetries, …

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular distribution



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\varphi} = \frac{9}{32\pi} \times$$

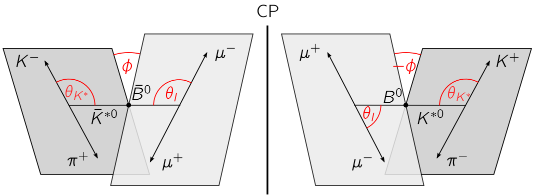
$$\Big\{ I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l$$

$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\varphi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\varphi$$

$$+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\varphi + \left(I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}\right) \cos\theta_l$$

$$+ I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\varphi + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\varphi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\varphi \Big\}$$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular distribution



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\varphi} = \frac{9}{32\pi} \times$$

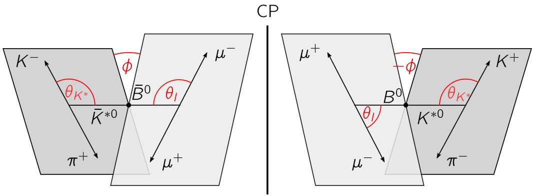
$$\Big\{ + I_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - I_2^c 2\cos^2\theta_{K^*}\sin^2\theta_l$$

$$+ I_3 \sin^2\theta_{K^*}\sin^2\theta_l\cos 2\varphi + I_4 \sin 2\theta_{K^*}\sin 2\theta_l \cos\varphi$$

$$+ I_5 \sin 2\theta_{K^*}\sin\theta_l\cos\varphi + I_6 \sin^2\theta_{K^*}\cos\theta_l$$

$$+ I_7 \sin 2\theta_{K^*}\sin\theta_l\sin\varphi + I_8 \sin 2\theta_{K^*}\sin 2\theta_l\sin\varphi + I_9 \sin^2\theta_{K^*}\sin^2\theta_l\sin 2\varphi \Big\}$$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular distribution



$$\frac{d^4\bar{\Gamma}}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\varphi} = \frac{9}{32\pi} \times \Big\{ + \bar{I}_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - \bar{I}_2^c\, 2\cos^2\theta_{K^*}\sin^2\theta_l + \bar{I}_3 \sin^2\theta_{K^*}\sin^2\theta_l\cos 2\varphi + \bar{I}_4 \sin 2\theta_{K^*}\sin 2\theta_l\cos\varphi - \bar{I}_5 \sin 2\theta_{K^*}\sin\theta_l\cos\varphi - \bar{I}_6 \sin^2\theta_{K^*}\cos\theta_l + \bar{I}_7 \sin 2\theta_{K^*}\sin\theta_l\sin\varphi - \bar{I}_8 \sin 2\theta_{K^*}\sin 2\theta_l\sin\varphi - \bar{I}_9 \sin^2\theta_{K^*}\sin^2\theta_l\sin 2\varphi \Big\}$$

Basis of observables

- CP-averaged angular coefficients Altmannshofer et al. 0811.1214

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

- CP asymmetries Kruger et al. hep-ph/9907386

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

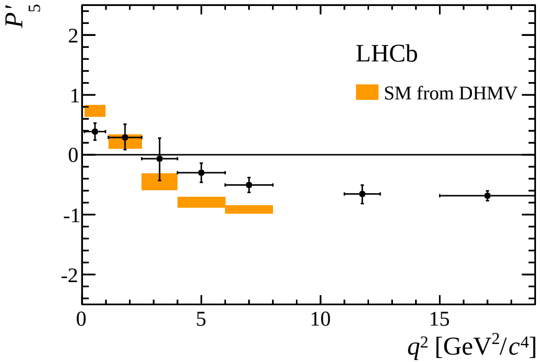
- Alternative basis Sebastien Descotes-Genon et al. 1303.5794

$$P_4' = \frac{S_4}{\sqrt{F_L(1-F_L)}} \qquad P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}} \qquad \ldots$$

Form factors drop out in heavy quark limit ($m_b/\Lambda_{\text{QCD}} \to \infty$)

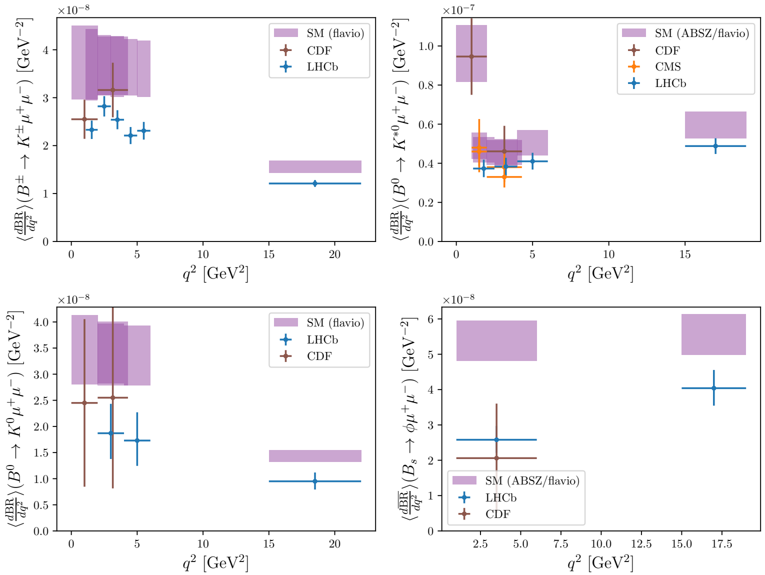
- Beware of various different conventions! See Gratrex et al. 1506.03970

LHCb 3 fb^{-1} measurement of P_5'



- How reliable is the SM prediction?
- How to combine different bins, other angular observables? ($\to$ theory hypothesis!)

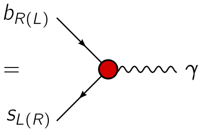
Branching ratio deviations



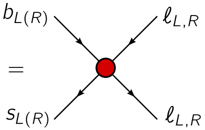
Effective theory for $b \to s\mu\mu$ in the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \text{h.c.}$$

$\mathcal{O}_7^{(\prime)} =$



$\mathcal{O}_{9,10}^{(\prime)} =$



$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu} \qquad O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

$B \to K^* \ell\ell$ amplitude

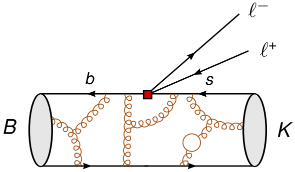
- "Transversity amplitudes"

$$A_\lambda^{L,R} \propto (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{2M_B^2}{q^2} \mathcal{H}_\lambda(q^2)$$

- $\mathcal{F}_\lambda^{(T)}(q^2)$: $B \to K^*$ form factors
- $\mathcal{H}_\lambda(q^2)$: "non-factorizable" hadronic contributions

$B \to K^*$ form factors

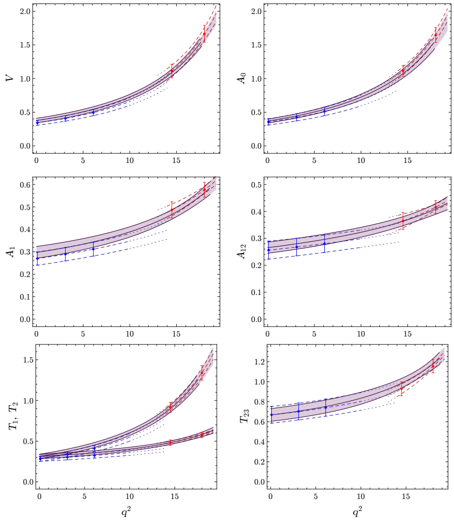
- Lattice calculation available, valid at high q^2 (low recoil) in the limit of stable K^* Horgan et al. 1501.00367
- Light-cone sum rules currently necessary for predictions at low q^2 Ball and Zwicky hep-ph/0412079, Khodjamirian et al. 1006.4945, Bharucha et al. 1503.05534
- Uncertainties around 10% $\to$ 20% on branching ratios
- For P_i' observables, only corrections to form factors in the heavy quark limit required (“soft form factors”), sometimes called “factorizable power corrections” see e.g. Sébastien Descotes-Genon et al. 1407.8526



LCSR vs. LCQCD form factors Bharucha et al. 1503.05534

- Results are complementary
- Results are compatible
- Combined fit valid in the whole kinematic region

Nevertheless, an improved LQCD calculation without assuming the K^* to be stable would be very desirable



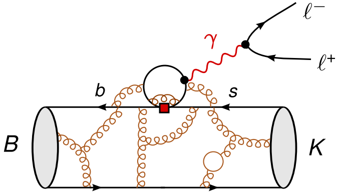
Hadronic contributions

$$A_\lambda^{L,R} \propto (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{2M_B^2}{q^2}\mathcal{H}_\lambda(q^2)$$

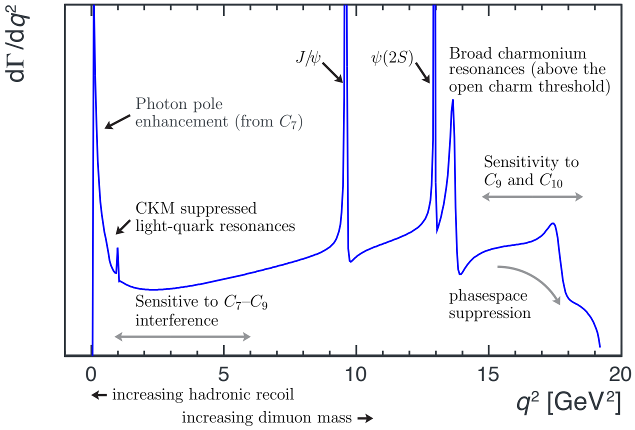
- *Hadronic* operators contribute via virtual photon exchange
- Particularly important: "charm loop" induced by the current-current operators

$$Q_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

  that arise from tree-level W exchange (and QCD corrections to it) in the SM!
- Partly calculable (e.g. QCD factorization Beneke et al. hep-ph/0106067)
- Incalculable contributions enter error estimate

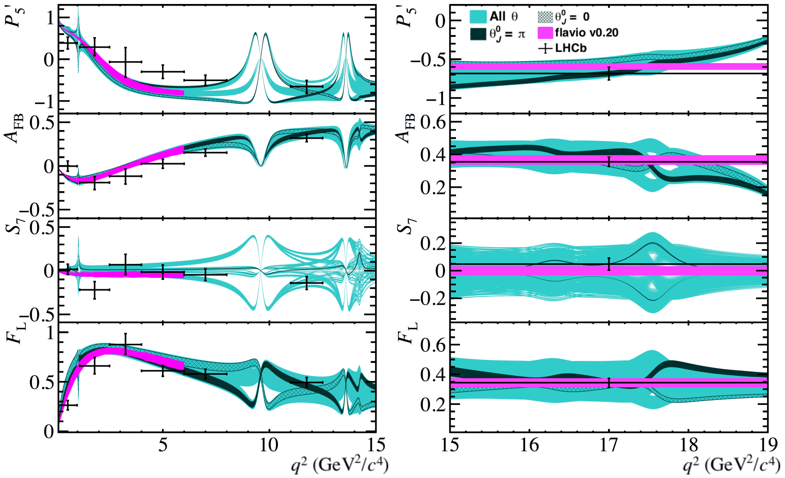


Cartoon: q^2 dependence of $B \to K^*\ell^+\ell^-$



Blake et al. 1606.00916

Importance of determining hadronic contribution



Blake et al. 1709.03921

- Measurements of $B \to J/\psi K^*$ and $B \to \psi(2S)K^*$ allow to constrain the magnitude of the hadronic contribution
- Feed-down to low q^2 relies on extrapolation

Bobeth et al. 1707.07305, Blake et al. 1709.03921

Numerics

Examplary error bars (using flavio):

$$\langle P_5' \rangle (B^0 \to K^{*0} \mu^+ \mu^-)_{[4,6]} = -0.756 \pm 0.025_{\text{FF}} \pm 0.070_{\text{had}}$$

$$\text{LHCb:} \quad -0.3\,^{+0.158}_{-0.159}\text{stat} \pm 0.023_{\text{sys}}$$

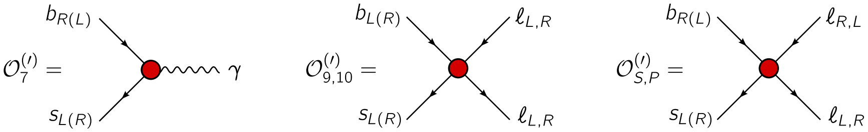
$$\left\langle \frac{d\text{BR}}{dq^2} \right\rangle (B^0 \to K^{*0} \mu^+ \mu^-)_{[1,6]} = (4.80 \pm 0.65_{\text{FF}} \pm 0.17_{\text{CKM}} \pm 0.14_{\text{had}}) \times 10^{-8}$$

$$\text{LHCb:} \;\; (3.42 \pm 0.17_{\text{stat}} \pm 0.09_{\text{sys}} \pm 0.23_{\text{norm}}) \times 10^{-8}$$

(“norm”: uncertainty on the normalization channel $B \to J/\psi(\to \mu\mu)K^*$)

Effective theory for $b \to s\mu\mu$ beyond the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$



$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu} \qquad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\ell) \qquad O_P^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma_5\ell)$$

In the SM, $C_i' = C_S^{(\prime)} = C_P^{(\prime)} = 0$ and $C_{9,10}$ are LFU

Parenthesis: operators omitted

The following operators have been omitted since they are irrelevant for the BSM discussion:

- Four-quark operators. Their matrix elements are small; if affected by NP, RG-induced contributions to the semi-leptonic Wilson coefficients dominate
- Chromomagnetic operator. Only enters via RG mixing into $C_7^{(\prime)}$
- Tensor operators

$$O_T^{(\prime)\ell} = (\bar{s}\sigma_{\mu\nu}P_{L(R)}b)(\bar{\ell}\sigma^{\mu\nu}P_{L(R)}\ell)$$

  violate hypercharge and thus do not arise at dimension 6 in SMEFT

Sensitivity to Wilson coefficients

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s \gamma$	X			
$B \to K^* \gamma$	X			
$B \to X_s \ell^+ \ell^-$	X	X	X	
$B \to K^{(*)} \ell^+ \ell^-$	X	X	X	
$B_s \to \mu^+ \mu^-$			X	X

- Different observables are complementary in constraining NP
- For semi-leptinic $b \to s\mu\mu$ transitions, we can restrict ourselves to NP in $C_{7,9,10}^{(\prime)}$

Global fit of $b \to s\mu\mu$ observables

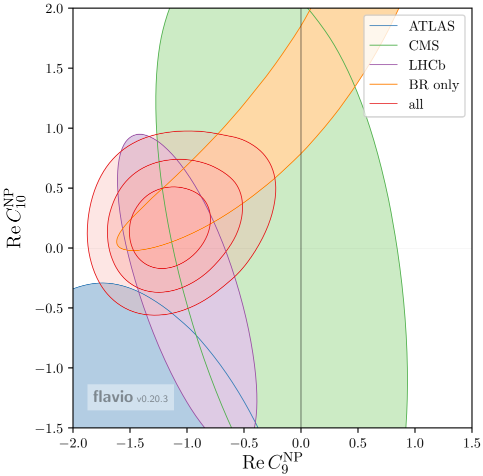
- Fit $C_{9,10}^{(\prime)\mu}$, 1 or 2 at a time
- Observables included:
  - Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ (CDF, LHCb, ATLAS, CMS)
  - $B^{0,\pm} \to K^{*0,\pm}\mu^+\mu^-$ branching ratios (CDF, LHCb, CMS)
  - $B^{0,\pm} \to K^{0,\pm}\mu^+\mu^-$ branching ratios (CDF, LHCb)
  - $B_s \to \varphi\mu^+\mu^-$ branching ratio (CDF, LHCb)
  - $B_s \to \varphi\mu^+\mu^-$ angular observables (LHCb)
  - $B \to X_s\mu^+\mu^-$ branching ratio (BaBar)
- Performed in Altmannshofer et al. 1703.09189 using flavio
- NB, R_K & R_{K^*} not used as constraints (yet)!

1D results

Coeff.	best fit	1σ	2σ	pull
C_9^{NP}	-1.21	$[-1.41, -1.00]$	$[-1.61, -0.77]$	5.2σ
C_9'	$+0.19$	$[-0.01, +0.40]$	$[-0.22, +0.60]$	0.9σ
C_{10}^{NP}	$+0.79$	$[+0.55, +1.05]$	$[+0.32, +1.31]$	3.4σ
C_{10}'	-0.10	$[-0.26, +0.07]$	$[-0.42, +0.24]$	0.6σ
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.30	$[-0.50, -0.08]$	$[-0.69, +0.18]$	1.3σ
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.67	$[-0.83, -0.52]$	$[-0.99, -0.38]$	4.8σ
$C_9' = C_{10}'$	$+0.06$	$[-0.18, +0.30]$	$[-0.42, +0.55]$	0.3σ
$C_9' = -C_{10}'$	$+0.08$	$[-0.02, +0.18]$	$[-0.12, +0.28]$	0.8σ

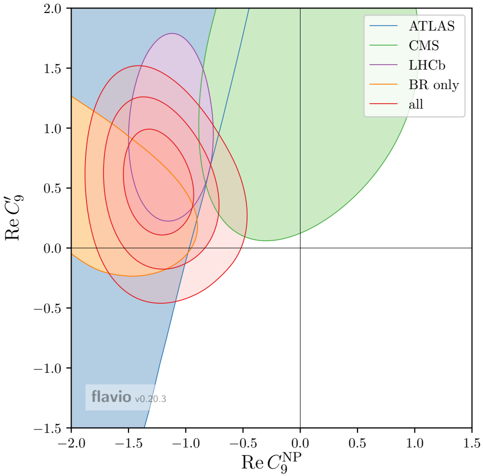
$$\text{pull} \equiv \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best fit}}} \qquad \text{(for 1D)}$$

2D results



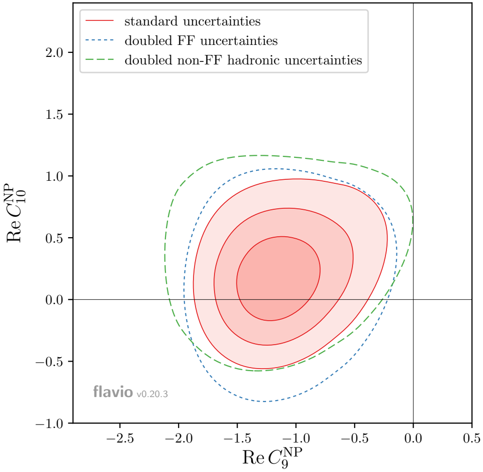
- best fit $(C_9^{NP}, C_{10}^{NP}) = (-1.15, +0.26)$
- pull 5.0σ

2D results



- best fit $(C_9^{\text{NP}}, C_9') = (-1.25, +0.59)$
- pull 5.3σ

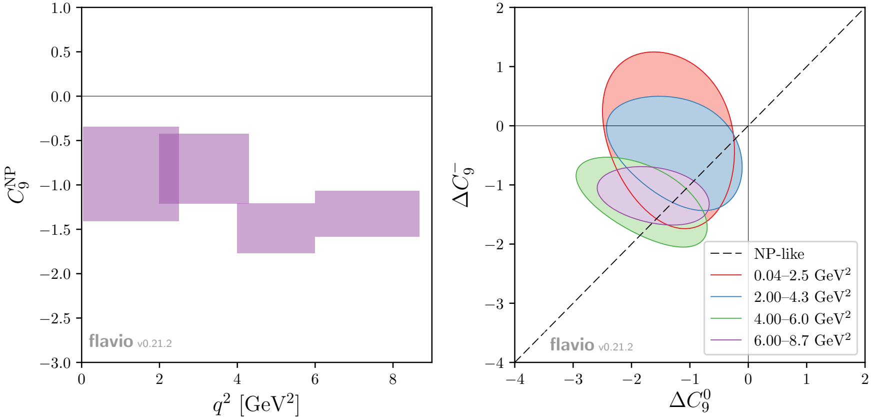
Impact of enlarging uncertainties



Doubling form-factor *or* “non-factorizable” hadronic uncertainties:

- Significance decreases but stays well above 3σ
- best-fit point hardly affected

q^2 dependence of C_9 best-fit



- NP in C_9 would give helicity and q^2 independent effect
- hadronic effect could be helicity and q^2 dependent
- current data not conclusive

SMEFT operators matching on $C_{9,10}$

$$O_{lq}^{(1)} = (\bar{l}_i \gamma_\mu l_j)(\bar{q}_k \gamma^\mu q_l)$$
$$O_{lq}^{(3)} = (\bar{l}_i \gamma_\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l)$$
$$O_{qe} = (\bar{q}_i \gamma_\mu q_j)(\bar{e}_k \gamma^\mu e_l)$$

$$C_{ql}^{(1)} \to C_9^\mu = -C_{10}^\mu$$
$$C_{ql}^{(3)} \to C_9^\mu = -C_{10}^\mu$$
$$C_{qe} \to C_9^\mu = C_{10}^\mu$$
$$C_{Hq}^{(1,3)} \to C_9^\mu \ll C_{10}^\mu$$

$\Rightarrow$ Succesful models need $C_{ql}^{(1,3)}$ (and possibly in addition C_{qe})

New physics: naive dimensional analysis

- The size of the required effect is

$$\frac{4G_F}{\sqrt{2}}|V_{tb}V_{ts}^*|\frac{\alpha_e}{4\pi} \times 1.0 \approx (34\text{ TeV})^{-2}$$

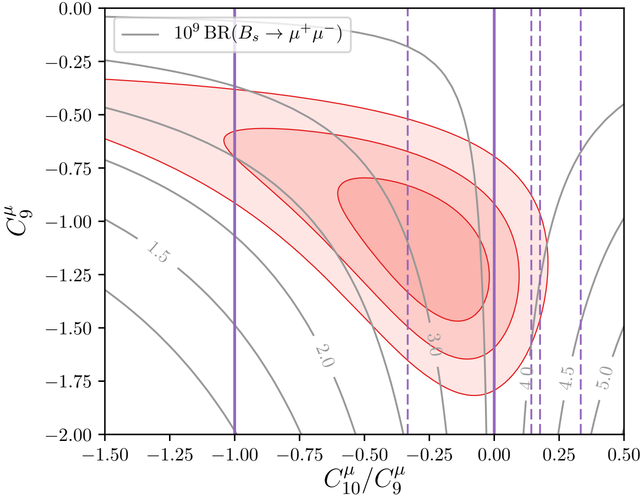
- In contrast to the $b \to c\tau\nu$ anomalies, could well be a loop effect or weakly coupled model
- Nevertheless, let's look at possible tree-level mediators for simplicity

Tree-level models for $b \to s\mu\mu$

Spin	Rep.	Name	$C_{lq}^{(1)}$	$C_{lq}^{(3)}$	C_{qe}
1	$(1,1)_0$	Z'	×		×
1	$(1,3)_0$	V'		×	
0	$(\bar{3},1)_{\frac{1}{3}}$	S_1	×	×	
0	$(\bar{3},3)_{\frac{1}{3}}$	S_3	×	×	
0	$(\bar{3},2)_{\frac{7}{6}}$	R_2			×
1	$(\bar{3},1)_{\frac{2}{3}}$	U_1	×	×	
1	$(\bar{3},3)_{\frac{2}{3}}$	U_3	×	×	
1	$(\bar{3},2)_{\frac{5}{6}}$	V_2			×

- Except singlet Z', all models appeared also for $R_{D^{(*)}}$
- R_2 and V_2 by themselves disfavoured since $C_9^\mu = +C_{10}^\mu$
- S_1 has $C_{lq}^{(1)} = -C_{lq}^{(3)} \Rightarrow C_{9,10} = 0$ at tree-level. Can be produced at 1-loop Bauer and Neubert 1511.01900
- Except Z', all 1-particle simplified models predict $C_9^\mu = -C_{10}^\mu$

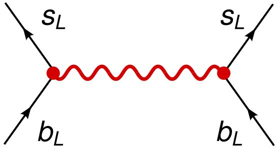
Discriminating models



$\frac{C_{10}^\mu}{C_9^\mu} =$: special cases

- 1: LQ or V' models
- 0: Z' models involving L_μ
- $\frac{3}{17}$ or $\frac{1}{3}$ Z' Celis et al. 1505.03079
- $-\frac{1}{3}$ or $\frac{1}{7}$ Z' Ellis et al. 1705.03447
- ...

Z' constraints: B_s mixing



- Dangerous contribution to mass difference ΔM_s in the B_s-$\bar{B}_s$ system
- Forces Z' (or vector triplet) models into regime with strong coupling to muons - Results in *upper* bound on Z' mass:

$$m_{Z'} \lesssim g_\mu^{Z'} \times 800 \text{ GeV}$$

Altmannshofer and DMS 1308.1501

- Lepton flavour *universal* coupling on the verge of being excluded by LEP-2 4-lepton contact interaction searches ($e^+e^- \to \ell^+\ell^-$)
- Lepton flavour *non-universal* models more successful e.g. Altmannshofer et al. 1403.1269

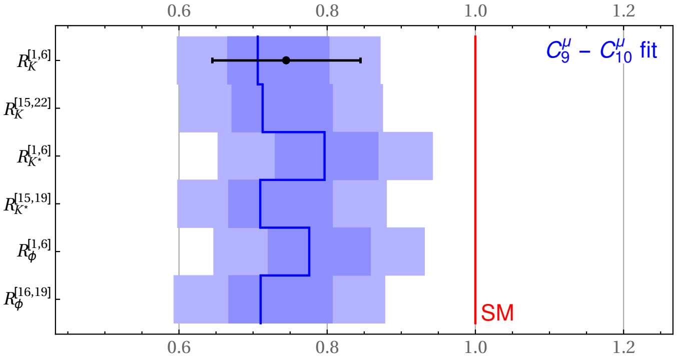
Predictions for LFU tests

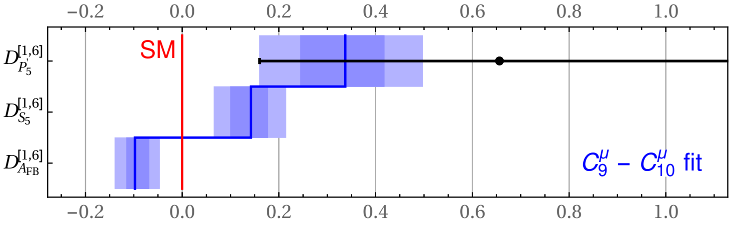
Using the model-independent fit to $b \to s\mu^+\mu^-$ observables and *assuming* the corresponding $b \to se^+e^-$ observables to be free from NP, can *predict* LFU ratios/differences

$$R_X = \frac{\text{BR}(B \to X\mu\mu)}{\text{BR}(B \to Xee)}$$

$$D_{\mathcal{O}} = \mathcal{O}(B \to K^*\mu\mu) - \mathcal{O}(B \to K^*ee)$$

Predictions for LFU tests



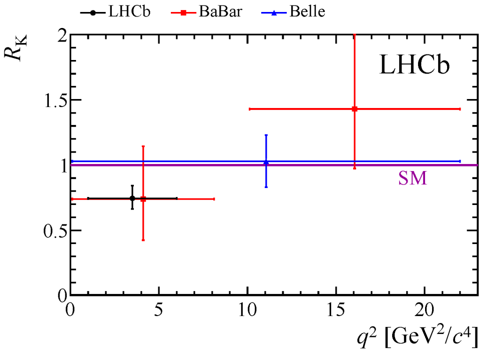


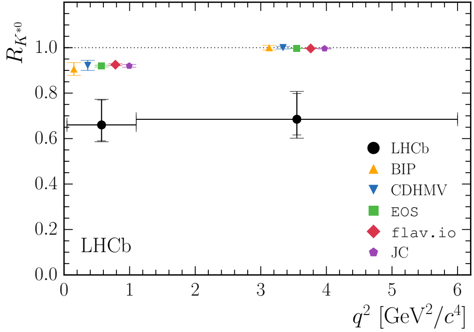
1. $b \to s\mu\mu$ anomalies

2. R_K and R_{K^*} anomalies
   - EFT analysis of $R_{K^{(*)}}$ anomalies

3. Combined explanations

R_K & R_{K^*}





$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$$

SM predictions

$$R_K = 1.000 \pm 0.001 \qquad R_{K^*}^{\text{low}} = 0.926 \pm 0.004 \qquad R_{K^*}^{\text{high}} = 0.996 \pm 0.001$$

- QED corrections can be sizable, but are reduced by appropriate cuts and are well simulated by experiments' Monte Carlos Bordone et al. 1605.07633

These are extremely clean null tests of the SM!

Fit to R_K and R_{K^*} Altmannshofer et al. 1704.05435

Fit Wilson coefficients of lepton flavour dependent operators:

$$O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Observables:

- R_K (LHCb)
- R_{K^*} (LHCb)
- $D_{P'_{4,5}} = P'_{4,5}(B \to K^* \mu\mu) - P'_{4,5}(B \to K^* ee)$ (Belle)

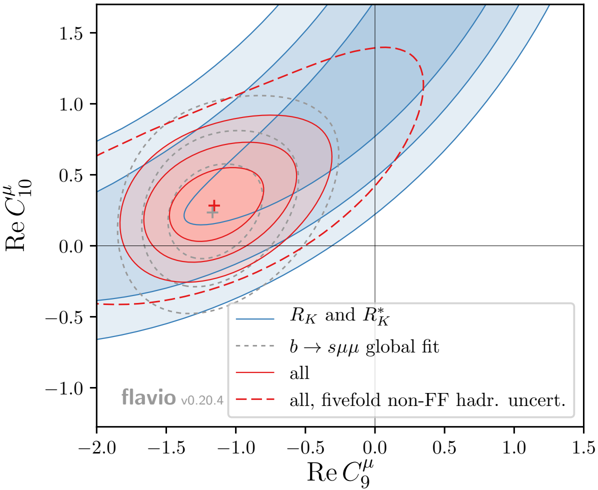
These observables/measurements are *disjoint* from the ones used in the $b \to s\mu\mu$ fit!

1D results

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	$[-2.90, -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	$[+0.60, +2.04]$	4.3σ
C_9^e	$+1.58$	$[+1.17, +2.03]$	$[+0.79, +2.53]$	4.4σ
C_{10}^e	-1.30	$[-1.68, -0.95]$	$[-2.12, -0.64]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	$[-1.00, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56, +1.02]$	$[+0.37, +1.31]$	4.3σ

$$\text{pull} \equiv \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best fit}}} \qquad \text{(for 1D)}$$

2D results: $R_{K^{(*)}}$ vs. $b \to s\mu\mu$



- Perfect agreement between $R_{K^{(*)}}$ and $b \to s\mu\mu$ when assuming NP to affect muonic modes only
- $R_{K^{(*)}}$ explanations involving enhancement of electronic modes only seem contrived

1. $b \to s\mu\mu$ anomalies

2. R_K and R_{K^*} anomalies

3. Combined explanations
   - Simplified models
   - Model-building directions
   - Outlook

Recap: SMEFT operators to solve B anomalies

$b \to s\mu^+\mu^-$

- $[C_{lq}^{(1)}]^{2223} \to C_9 = -C_{10}$
- $[C_{lq}^{(3)}]^{2223} \to C_9 = -C_{10}$
- $[C_{qe}]^{2322} \to C_9 = C_{10}$

$b \to c\tau\nu$

- $[C_{lq}^{(3)}]^{33i3} \to C_{V_L}$
- $[C_{ledq}]^{333i*} \to C_{S_R}$
- $[C_{lequ}^{(1)}]^{333i} \to C_{S_L}$
- $[C_{lequ}^{(3)}]^{333i} \to C_T$

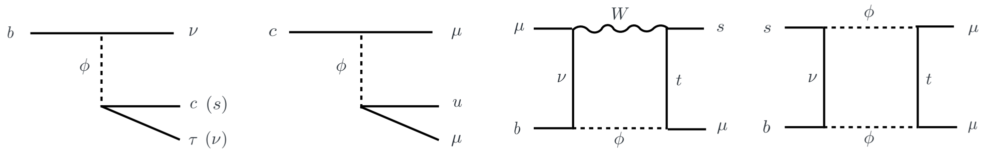
Single-multiplet solutions to B anomalies

Spin	Rep.	Name	C_{qe}	$C_{lq}^{(1)}$	$C_{lq}^{(3)}$	C_{ledq}	$C_{lequ}^{(1)}$	$C_{lequ}^{(3)}$	$b \to c$?	$b \to s$?
0	$(1,2)_{\frac{1}{2}}$	H'				×	×		$pp \to \tau\tau$	
1	$(1,1)_0$	Z'	×	×						
1	$(1,3)_0$	V'			×				$pp \to \tau\tau$	
0	$(\bar{3},1)_{\frac{1}{3}}$	S_1		×	×		×	×		
0	$(\bar{3},3)_{\frac{1}{3}}$	S_3		×	×				$B \to K\nu\bar{\nu}$	
0	$(\bar{3},2)_{\frac{7}{6}}$	R_2	×				×	×		$C_9 = C_{10}$
1	$(\bar{3},1)_{\frac{2}{3}}$	U_1		×	×	×				
1	$(\bar{3},3)_{\frac{2}{3}}$	U_3		×	×				$B \to K\nu\bar{\nu}$	
1	$(\bar{3},2)_{\frac{5}{6}}$	V_2	×			×				$C_9 = C_{10}$

NB: there is of course no strong reason to restrict to single-multiplet solutions, except for parsimony

A closer look at S_1

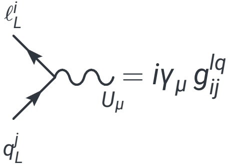
- Originally suggested in Bauer and Neubert 1511.01900
- Elegant idea: $b \to c\tau\nu$ at tree level, $b \to s\mu\mu$ at 1 loop ($C_{lq}^{(3)} = -C_{lq}^{(3)}$)



- Strong constraints from $B \to K\nu\nu$, violation of e-μ universality in $b \to c\ell\nu$, D decays
  Bauer and Neubert 1511.01900, Bečirević and Sumensari 1704.05835, Cai et al. 1704.05849
- Numerical scan shows: $R_{D^{(*)}}$ and $R_{K^{(*)}}$ can be explained individually, but not simultaneously Cai et al. 1704.05849

A closer look at U_1

- Originally suggested in Barbieri et al. 1512.01560
- Elegant idea: weakly broken $U(2)^5$ flavour symmetry acting on light generations explains hierarchy of effects in $b \to c\tau\nu$ vs. $b \to s\mu\mu$
- Relevant coupling:



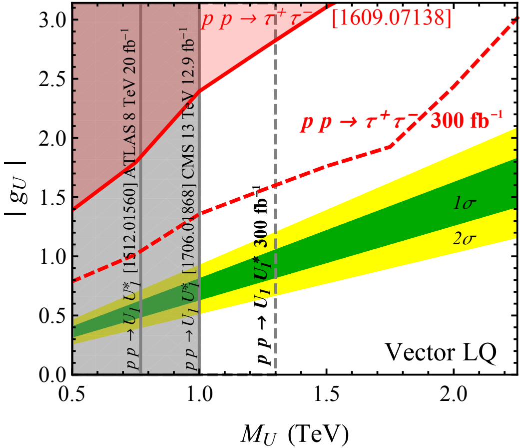
- Wilson coefficients:

$$C_{V_L}^{b\to c\tau\nu} \propto -\sum_{i=d,s,b} \frac{V_{ci}\, g_{\tau i}^{lq*} g_{\tau b}^{lq}}{2M_U} \qquad C_9^{b\to s\mu\mu} = -C_{10}^{b\to s\mu\mu} \propto -\frac{g_{\mu s}^{lq*} g_{\mu b}^{lq}}{2M_U}$$

- Need $g_{\tau s}^{lq*}$, otherwise large $g_{\tau b}^{lq*}$ coupling leads to excessive $pp \to \tau^+\tau^-$
  Faroughy et al. 1609.07138, Buttazzo et al. 1706.07808

U_1: evading direct searches

- Depending on the coupling structure, U_1 *could* show up at LHC, but there is no no-loose theorem Buttazzo et al. 1706.07808



1. $b \to s\mu\mu$ anomalies
   - $B \to K^* \mu^+ \mu^-$ angular observables
   - SM predictions: challenges
   - EFT analysis of $b \to s\mu\mu$ anomalies
   - Simplified models for $b \to s\mu\mu$ anomlies
2. R_K and R_{K^*} anomalies
   - EFT analysis of $R_{K^{(*)}}$ anomalies
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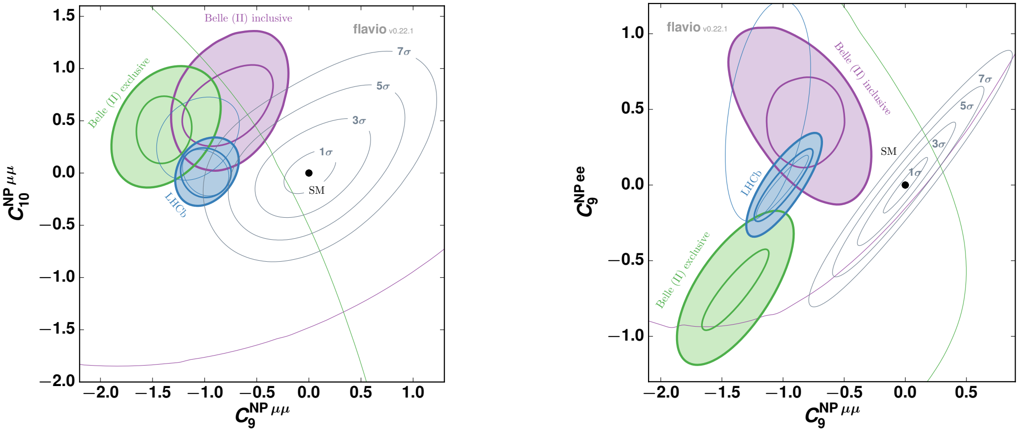
UV completions of the U_1 leptoquark

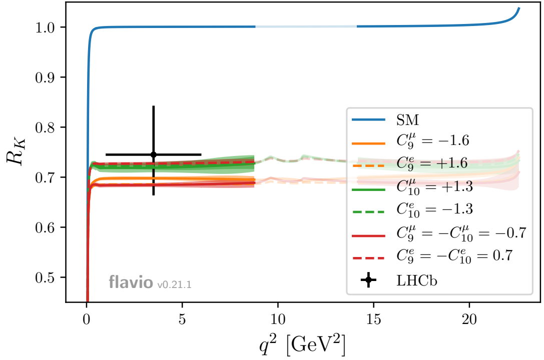
- U_1 is a massive *vector*: either gauge boson of a spontaneously broken gauge symmetry or composite resonance
- Interesting observation: the breaking of the Pati-Salam GUT group $SU(4) \times SU(2)_L \times SU(2)_R \to G_{\text{SM}}$ ("lepton number as the fourth colour") leads to $U_1 \sim (\bar{3}, 1)_{\frac{2}{3}}$ as one of the heavy coset gauge bosons (along with a heavy gluon $(8,1)_0$ and a Z' $(1,1)_0$) Barbieri et al. 1611.04930
- Practical problem: the Pati-Salam group needs to act flavour non-universally, otherwise excessive rates for processes like $K_L \to \mu e$ ($s \to d\mu e$)
- Realizations of this idea:
  - Composite PS resonance Barbieri et al. 1611.04930, Barbieri and Tesi 1712.06844
  - $SU(4) \times SU(3) \times SU(2) \times U(1)$ Di Luzio et al. 1708.08450, cf. v2 of Assad et al. 1708.06350
  - PS with additional vector-like fermions Calibbi et al. 1709.00692
  - Three-site PS Bordone et al. 1712.01368
  - PS in warped extra dimensions Blanke and Crivellin 1801.07256

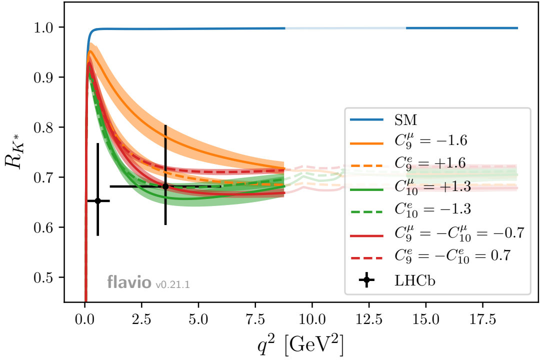
Future projections



Comparing LHCb (Run 4) and Belle-II reaches in the planes of $C_{9,10}^{\mu,e}$ Albrecht et al. 1709.10308

$R_{K^{(*)}}$ in different scenarios

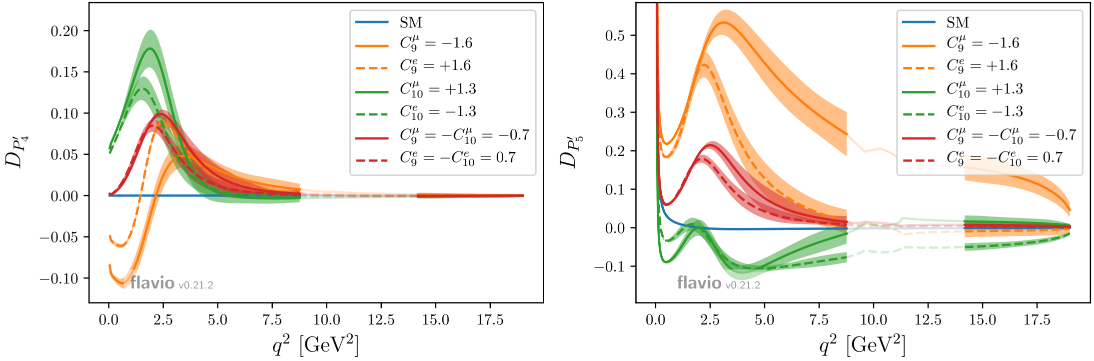




- Impossible to distinguish different best-fit scenarios on the basis of $R_{K^{(*)}}$ alone

Predictions for angular observables

$$D_{P'_{4,5}} = P'_{4,5}(B \to K^*\mu\mu) - P'_{4,5}(B \to K^*ee)$$



- Future measurement could unambiguously establish new physics and identify the

Conclusions

- Significant deviations from the SM in $b \to s\mu\mu$ transitions
  - $B \to K^*\mu\mu$ angular observables (unc. dominated by hadronic contribution)
  - $b \to s\mu\mu$ branching ratios (unc. dominated by form factors)
  - R_K & R_{K^*} (unc. purely experimental/stat.)
- Simultaneous EFT explanation very easy
- Combined explanation with $b \to c\tau\nu$ anomalies possible even with a single multiplet

Conclusions

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Near-future experiments have the power to unambiguously resolve the question whether this is new physics or not!

Backup

Could tensions be due to new *light* particle?

Sala and DMS 1704.06188

Need a new particle with mass below m_b leading to a suppression (destructive interference) of $B \to K^{(*)}\mu\mu$

- Can't be a scalar (would lead to negligible interference)
- Must be broad, i.e. have sizable Γ/m, since no narrow resonances seen

Minimal model

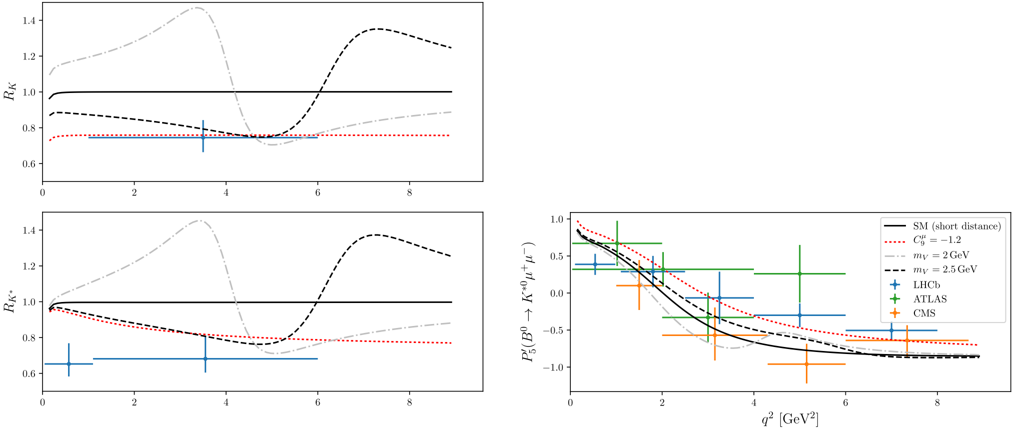
$$\mathcal{L} = \left[(g_{bs}\,\bar{s}_L\gamma_\nu b_L + \text{h.c.}) + g_{\mu V}\,\bar{\mu}\gamma_\nu\mu + g_{\mu A}\,\bar{\mu}\gamma_\nu\gamma_5\mu + g_x\,\bar{x}\gamma_\nu x\right]V^\nu + \frac{m_V^2}{2}V^\nu V_\nu$$

- Coupling to $\bar{s}b$ (could be loop-induced) and $\bar{\mu}\mu$
- Strong coupling to new "dark" fermion x to account for sizable width

On-shell exchange of broad V leads to q^2-dependent shift in $C_{9,10}^\mu$

$$C_{9,10}^V = \frac{g_{bs}g_{\mu V,A}/N}{q^2 - m_V^2 + i m_V \Gamma_V}$$

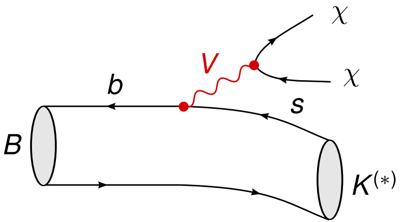
Impact on $b \to s\ell\ell$ observables



- Resonance with $m_V \approx 2.5$ GeV can explain R_K, R_{K^*}, and P'_5 anomalies similarly to "short-distance" C_9^μ
- Resonance with $m_V \approx 2$ GeV could explain P'_5 but not R_K & R_{K^*}

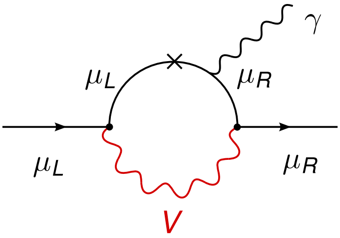
Main constraints & predictions

$B \to K^{(*)} V(\to xx)$



- has same signature as $B \to K^{(*)} \nu\bar{\nu}$ strongly constrained by BaBar & Belle
- leads to upper bound on g_{bs}/m_V

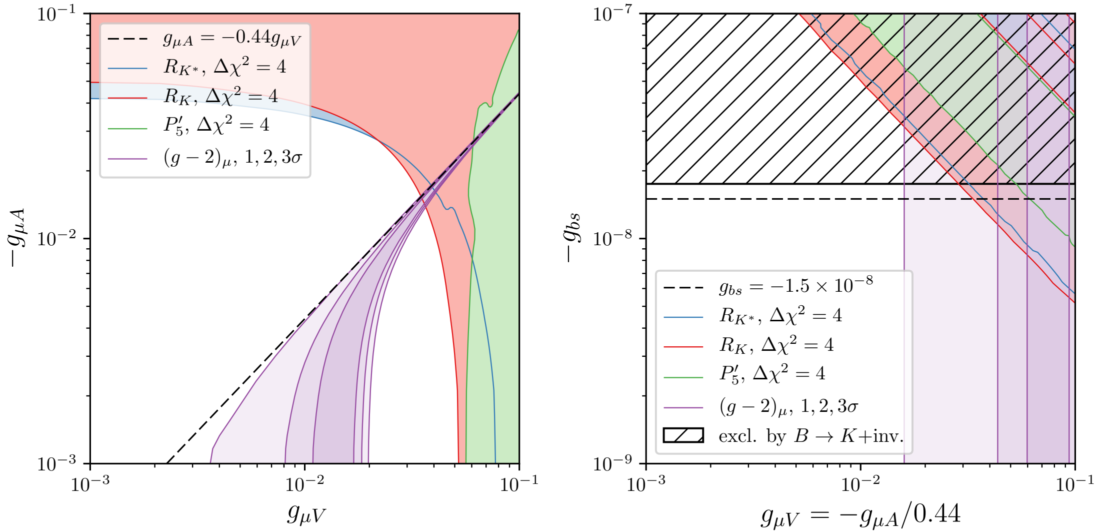
Muon anomalous magnetic moment



$$\delta a_\mu = \frac{g_{\mu V}^2 - 5 g_{\mu A}^2}{12\pi^2} \frac{m_\mu^2}{m_V^2} + O\left(\frac{m_\mu^2}{m_V^2}\right)$$

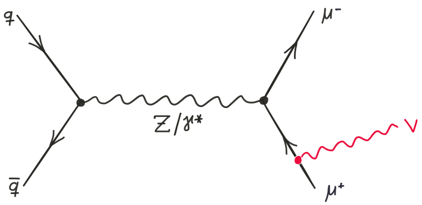
- Goes into the right direction to explain the long-standing anomaly for $g_{\mu V}^2 > 5 g_{\mu A}^2$
- Fine-tuning $g_{\mu A}$ vs. $g_{\mu V}$ can be invoked to avoid excessive contributions

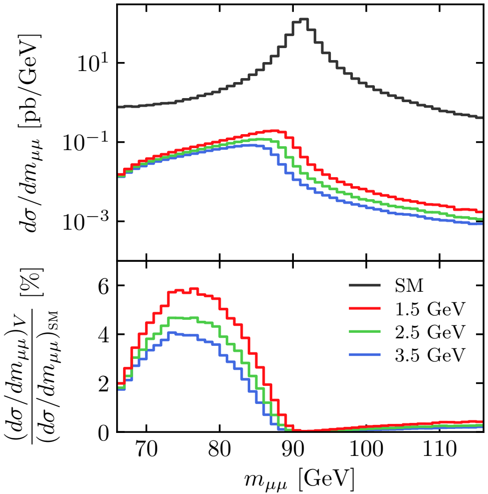
Summary of constraints



Additional constraint: $Z \to \mu\mu V$ Bishara et al. 1705.03465

- Modifies Z line shape in Drell-Yan at LHC





Impact of Drell-Yan constraint