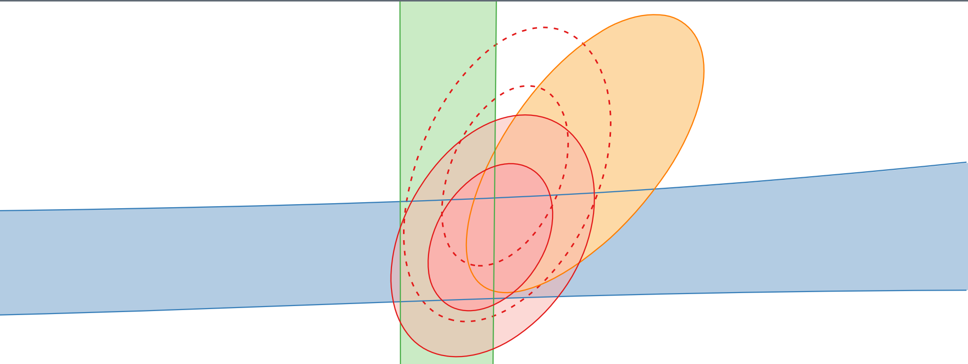
2019-03-22, Moriond EW Session, La Thuile

Status of Lepton Flavour Universality and other Discrepancies in *B* Physics

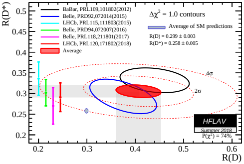
David M. Straub Universe Cluster/TUM, Munich



Discrepancies in B physics

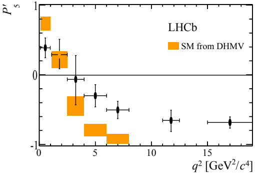
R_D & R_D^* anomalies

- $b \to c\tau\nu$ vs. $c\mu\nu$
- theoretically clean



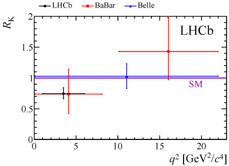
$B^* \mu\mu$ anomalies

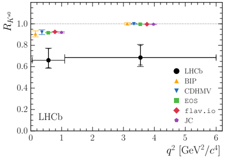
- $b \to s\mu\mu$
- hadronic uncertainties comparable to exp.



R_K & R_K^* anomalies

- $b \to s\mu\mu$ vs. see
- theoretically very clean





News this week

1. Updated Belle measurement of R_{K^*} Talk by M. Prim

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu\mu)}{\mathrm{BR}(B \to K^* ee)} = \begin{cases} 0.90^{+0.27}_{-0.21} \pm 0.10\,, & \text{for } 0.1\,\mathrm{GeV}^2 < q^2 < 8\,\mathrm{GeV}^2 \\ 1.18^{+0.52}_{-0.32} \pm 0.10\,, & \text{for } 15\,\mathrm{GeV}^2 < q^2 < 19\,\mathrm{GeV}^2 \end{cases}$$

2. Updated LHCb measurement of R_K Talk by T. Humair

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} = 0.846\,{}^{+0.060}_{-0.054}\,{}^{+0.016}_{-0.014}\,, \qquad \text{for } 1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$$

3. Update of $R_{D^{(*)}}$ by Belle Talk by G. Caria

$$R_D = ?? \qquad R_{D^*} = ??$$

This talk: updated global analysis using 1. & 2.

Credits

- Thanks to the **organizers**!
- Congratulations to **Belle** and **LHCb** …

Credits

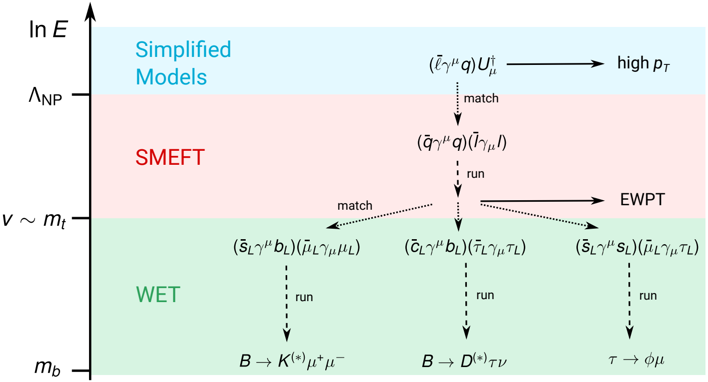
- Thanks to the **organizers**!
- Congratulations to **Belle** and **LHCb** …

… and thanks for ruining my afternoon ;-)

- Thanks to my hard-working **collaborators**: J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl
- Thanks to the Computing Center for Particle and Astrophysics (**C2PAP**) for swift number crunching
- Apologies for typos and missing references due to lack of time!

Interpretation: hierarchy of (effective) theories

- Example: the $U_1 \sim (3,1)_{2/3}$ vector leptoquark



- WET is completely general
- SMEFT allows studying correlations between CC & NC, flavour & EWPT
- Simplified Models allow studying constraints by direct searches

The global EFT likelihood

- All processes below Λ_{NP} (flavour, EWPT, …) can be expressed in terms of SMEFT Wilson coefficients
- Comparison with experimental measurements leads to *global EFT likelihood*

$$L(\vec{C}) = L(\vec{O}(\vec{C}), \vec{O}_{\mathrm{exp}})$$

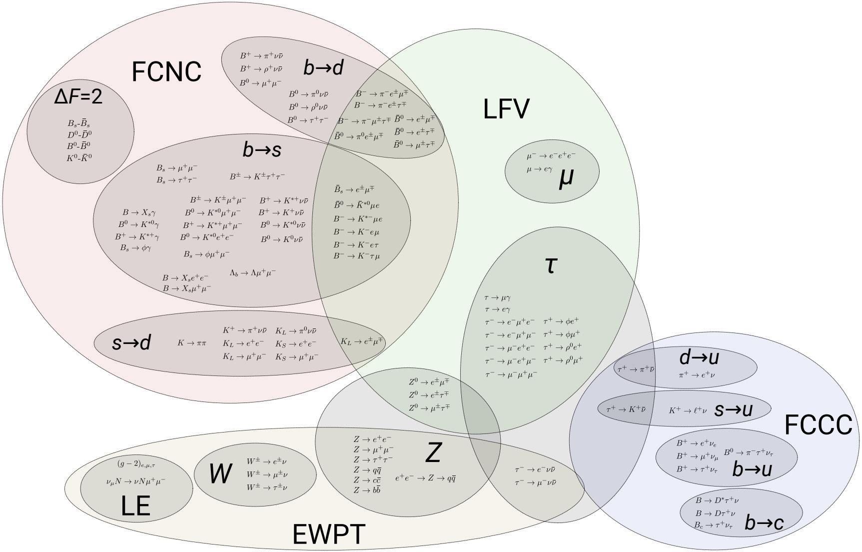
- Separates model-independent pheno from model building:

$$L(\vec{\theta}_{\mathrm{NP}}) = L(\vec{C}(\vec{\theta}_{\mathrm{NP}}))$$

  greatly simplifies analyses of NP models!
- Public code providing this likelihood and used in the following:
  - “smelli” https://github.com/smelli/smelli Aebischer et al. 1810.07698

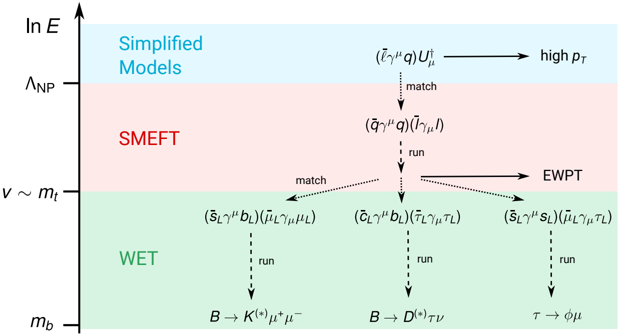
Observables included in the global likelihood

So far, 265 Observables Aebischer et al. 1810.07698



Interpretation of discrepancies: strategy

1. $b \to s\ell\ell$ observables in WET
2. $b \to s\ell\ell$ & $b \to c\tau\nu$ in SMEFT
3. Simplified models



$b \to s\ell\ell$ in WET

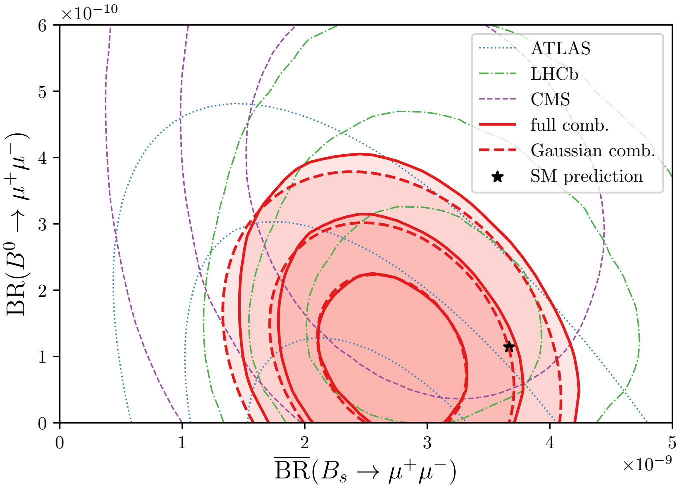
Effective Hamiltonian with operators contributing at LO at $\mu \sim m_b$:

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\mathcal{N}\left(C_7^{bs}O_7^{bs} + C_7^{\prime bs}O_7^{\prime bs}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P}\left(C_i^{bs\ell\ell}O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell}O_i^{\prime bs\ell\ell}\right)\right) + \text{h.c.}$$

$$\begin{aligned}
O_7^{bs} &= \tfrac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}\,, & O_7^{\prime bs} &= \tfrac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}\,,\\
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell)\,, & O_9^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\ell)\,,\\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, & O_{10}^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,\\
O_S^{bs\ell\ell} &= (\bar{s}P_R b)(\bar{\ell}\ell)\,, & O_S^{\prime bs\ell\ell} &= (\bar{s}P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bs\ell\ell} &= (\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P^{\prime bs\ell\ell} &= (\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)\,.
\end{aligned}$$

Will focus on $O_9^{(\prime)}$, $O_{10}^{(\prime)}$ here!

$B_q \to \mu^+\mu^-$: combination of LHCb, ATLAS, CMS



- Including new ATLAS measurement Talk by O. Igonkina
- $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$ roughly 2σ below the SM prediction

Pulls in single-coefficient scenarios

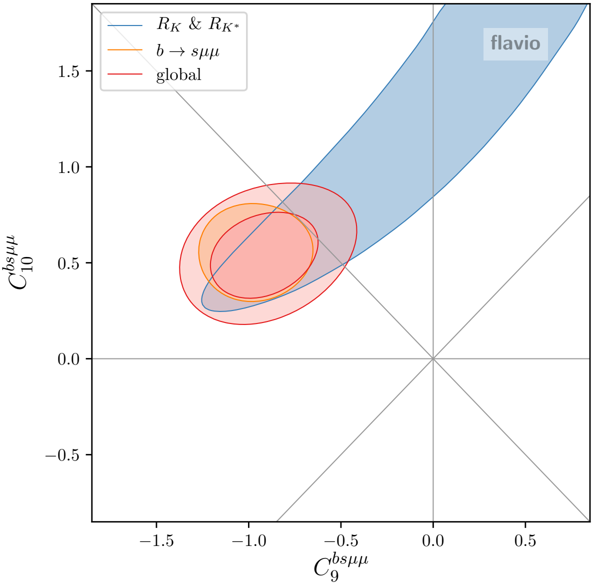
- First step: maxima of the global likelihood along 1D directions given by $b \to s\mu\mu$ WET operators

Coeff.	Dirac structure	best fit	1σ	pull
$C_9^{bs\mu\mu}$	$L \otimes V$	-0.95	$[-1.10, -0.79]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.09$	$[-0.07, +0.24]$	0.5σ
$C_{10}^{bs\mu\mu}$	$L \otimes A$	$+0.73$	$[+0.59, +0.87]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.19	$[-0.30, -0.07]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.05, +0.35]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$L \otimes L$	-0.53	$[-0.62, -0.45]$	6.5σ

$$\text{pull} = \sqrt{\Delta x^2}\,, \qquad \text{where } -\frac{1}{2}\Delta - x^2 = \ln L(\vec{0}) - \ln L(\vec{C}_{\text{best fit}})\,.$$

- Strong improvement of fit compared to SM! (But not “discovery”)
- For the first time, $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$, predicted by LQ et al., fits better than $C_9^{bs\mu\mu}$

Muonic C_9 vs. C_{10}



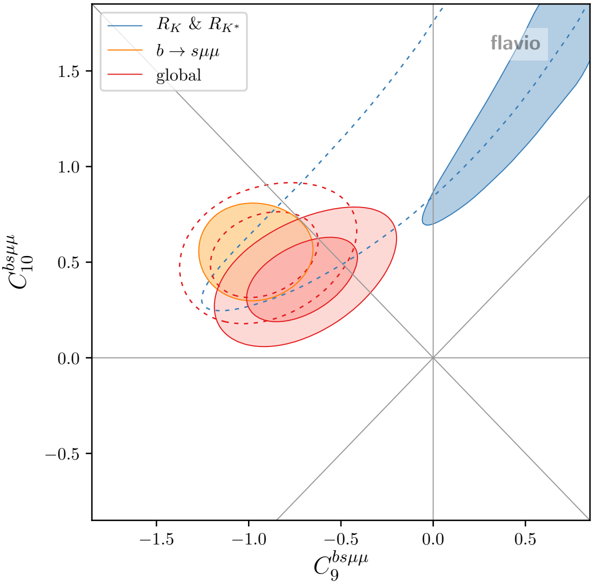
$C_9^{bs\mu\mu}\ (\bar{s}_L \gamma^\mu b_L)(\mu \gamma_\mu \mu)$

$C_{10}^{bs\mu\mu}\ (\bar{s}_L \gamma^\mu b_L)(\mu \gamma_\mu \gamma_5 \mu)$

Pre-Moriond

- Perfect agreement between $R_{K^{(*)}}$ & $b \to s\mu\mu$
- Pull towards $C_{10} > 0$ mostly from $B_s \to \mu^+\mu^-$
- Excellent for models with LH leptons ($C_9 = -C_{10}$)

Muonic C_9 vs. C_{10}



$C_9^{bs\mu\mu}\,(\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\mu)$
$C_{10}^{bs\mu\mu}\,(\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\gamma_5\mu)$

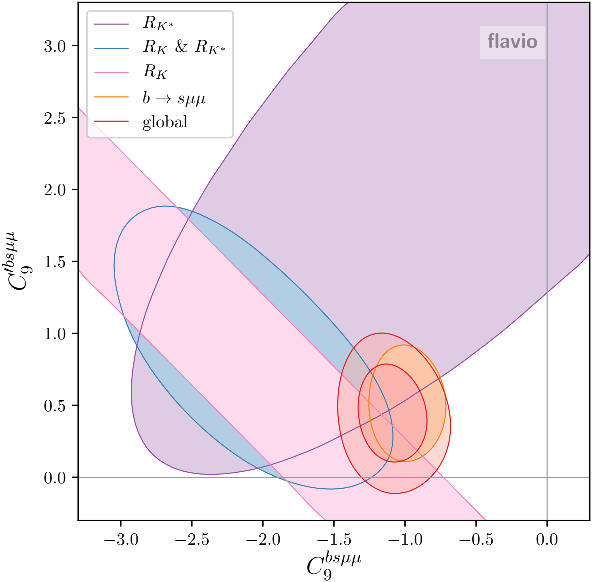
Pre-Moriond

- Perfect agreement between $R_{K^{(*)}}$ & $b \to s\mu\mu$
- Pull towards $C_{10} > 0$ mostly from $B_s \to \mu^+\mu^-$
- Excellent for models with LH leptons ($C_9 = -C_{10}$)

Now

- Agreement between $R_{K^{(*)}}$ & $b \to s\mu\mu$ no longer perfect
- Fit closer to SM, $C_9 = -C_{10}$ still preferred

Muonic C_9 vs. C_9'



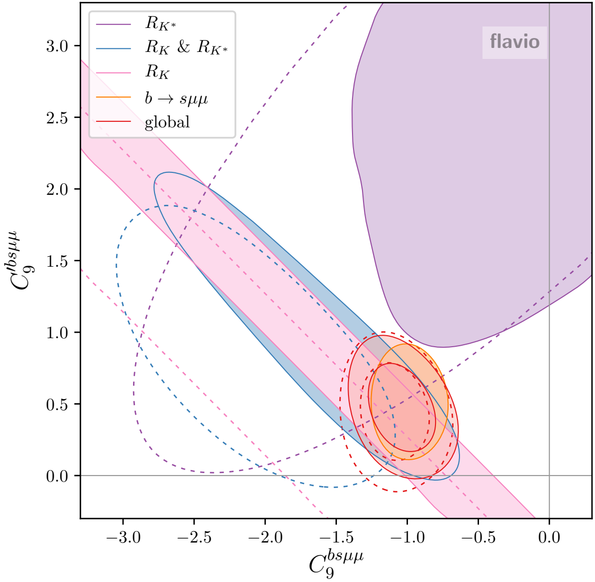
$C_9^{bs\mu\mu}\ (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\mu)$

$C_9'^{bs\mu\mu}\ (\bar{s}_R\gamma^\mu b_R)(\mu\gamma_\mu\mu)$

Pre-Moriond

- No preference for $C_9' \neq 0$

Muonic C_9 vs. C_9'



$C_9^{bs\mu\mu}$ $(\bar{s}_L \gamma^\mu b_L)(\mu \gamma_\mu \mu)$

$C_9'^{bs\mu\mu}$ $(\bar{s}_R \gamma^\mu b_R)(\mu \gamma_\mu \mu)$

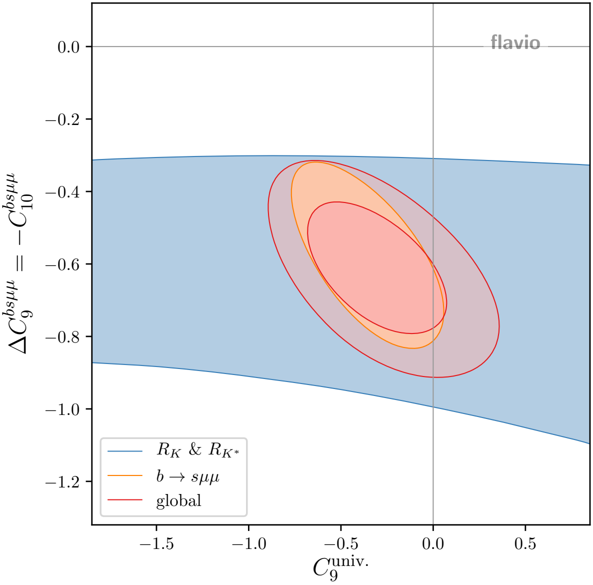
Pre-Moriond

- No preference for $C_9' \neq 0$

Now

- Slight preference for $C_9' > 0$ driven by interplay between R_K and $b \to s\mu\mu$

LF *universal* vs. purely muonic NP



$C_9^{univ.}\ (\bar{s}_L\gamma^\mu b_L)\sum_\ell(\ell\gamma_\mu\ell)$

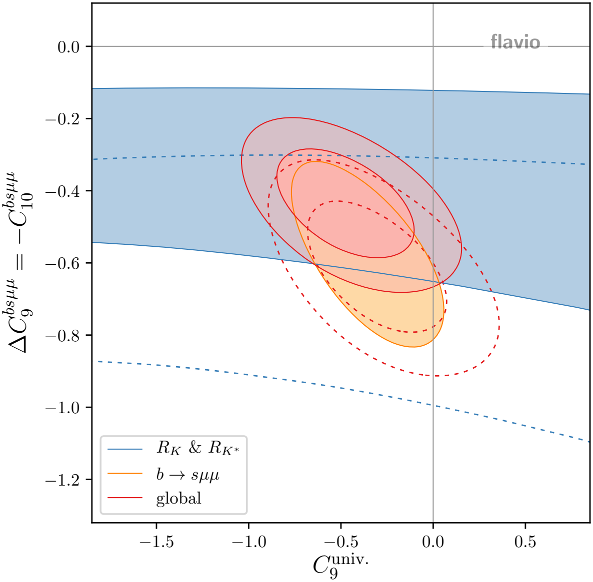
$\Delta C_9^{bs\mu\mu}\ (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\mu)$

$C_{10}^{bs\mu\mu}\ (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\gamma_5\mu)$

Pre-Moriond

- NP solution compatible with $C_9^{univ.} = 0$, i.e. purely muonic NP

LF *universal* vs. purely muonic NP



$C_9^{univ.}\ (\bar{s}_L\gamma^\mu b_L)\sum_\ell(\ell\gamma_\mu\ell)$

$\Delta C_9^{bs\mu\mu}\ (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\mu)$

$C_{10}^{bs\mu\mu}\ (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\gamma_5\mu)$

Pre-Moriond

- NP solution compatible with $C_9^{univ.} = 0$, i.e. purely muonic NP

Now

- Interplay between $R_{K^{(*)}}$ & $b \to s\mu\mu$ leads to preference for $C_9^{univ.} < 0$

$b \to s\ell\ell$ in SMEFT

- Generating $C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$ in SMEFT is simple:

$$O_{lq}^{(1)} = (\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma^\mu q)$$
$$O_{lq}^{(3)} = (\bar{\ell}\gamma^\mu \tau^a \ell)(\bar{q}\gamma^\mu \tau^a q)$$

  Matching:

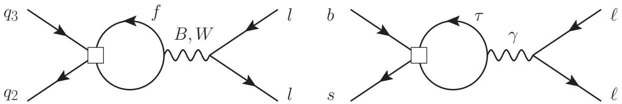
$$C_9^{bs\ell_i\ell_i} \propto \quad [C_{lq}^{(1)}]_{ii23} + [C_{lq}^{(3)}]_{ii23} + \dots$$
$$C_{10}^{bs\ell_i\ell_i} \propto -[C_{lq}^{(1)}]_{ii23} - [C_{lq}^{(3)}]_{ii23} + \dots$$

- UV completions: Z', Talks by B. Allanach, S. King leptoquarks Talks by A. Angelescu, J. Heeck
- Interesting connection:

$$[O_{lq}^{(3)}]_{3323} \supset (\bar{c}_L \gamma^\mu b_L)(\tau_L \gamma_\mu \nu_{\tau L})$$

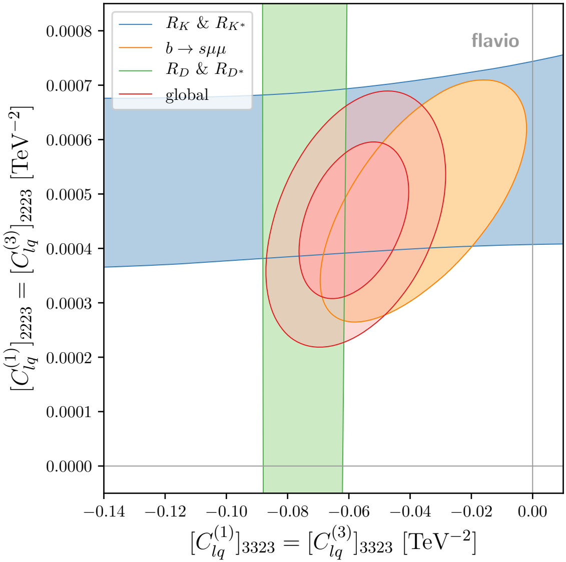
  - Common origin for $b \to s\ell\ell$ & $b \to c\tau\nu$ anomalies
  - NB: need $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$ to avoid strong constraint from B factory searches for $B \to K\nu_\tau\bar{\nu}_\tau$ Buras et al. 1409.4557
  - Radiatively induces LFU effect in $C_9^{\text{univ.}}$!

Semitauonic NP & lepton flavour *universal* C_9



- A semitauonic operator *unavoidably generates* a LFU contribution to C_9 through RG running above and below the EW scale Bobeth and Haisch 1109.1826
- This effect has the right sign and rough size to explain the $b \to s\mu\mu$ data (except $R_{K^{(*)}}$)! Crivellin et al. 1807.02068

Semitauonic vs. semimuonic NP



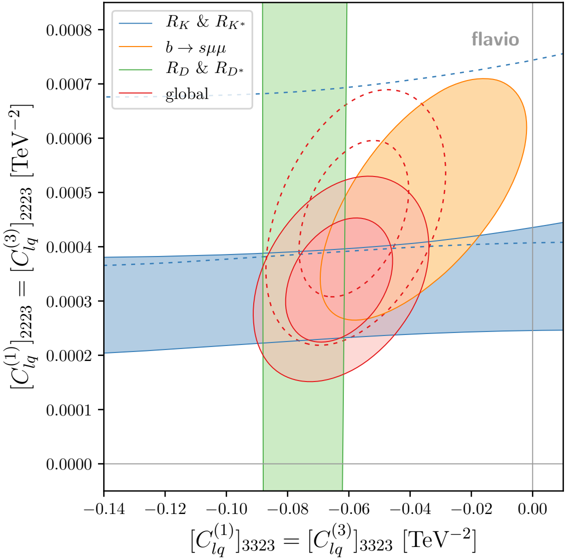
$[C_{lq}^{(1)}]_{ii23}(\bar{\ell}_i\gamma^\mu\ell_i)(\bar{q}_2\gamma^\mu q_3)$

$[C_{lq}^{(3)}]_{ii23}(\bar{\ell}_i\gamma^\mu\tau^a\ell_i)(\bar{q}_2\gamma^\mu\tau^a q_3)$

Pre-Moriond

- $R_{K^{(*)}}$ & $b \to s\mu\mu$ compatible with $[C_{lq}^{(a)}]_{3323} = 0$

Semitauonic vs. semimuonic NP



$$[C_{lq}^{(1)}]_{ii23}(\bar{\ell}_i\gamma^\mu\ell_i)(\bar{q}_2\gamma^\mu q_3)$$
$$[C_{lq}^{(3)}]_{ii23}(\bar{\ell}_i\gamma^\mu\tau^a\ell_i)(\bar{q}_2\gamma^\mu\tau^a q_3)$$

Pre-Moriond

- $R_{K^{(*)}}$ & $b \to s\mu\mu$ compatible with $[C_{lq}^{(a)}]_{3323} = 0$

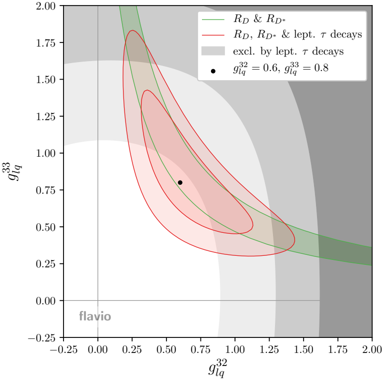
Now

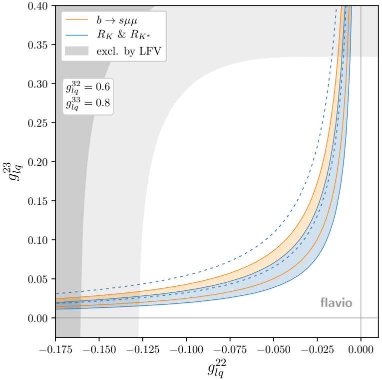
- Where $R_{K^{(*)}}$ & $b \to s\mu\mu$ agree at 1σ: non-zero semitauonic WCs
- Solution coincides with semitauonic WCs that generate right size of $R_{D^{(*)}}$!
- Agreement better than before
- $R_{D^{(*)}}$ slightler closer to the SM would be even better!

$U_1 \sim (3,1)_{2/3}$ vector leptoquark

- Minimal implementation of the semitauonic + -muonic scenario

$$\mathcal{L}_{U_1} \supset g_{lq}^{ji} \left(\bar{q}^i \gamma^\mu l^j \right) U_\mu + \text{h.c.}$$



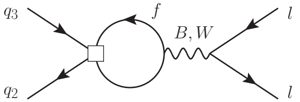


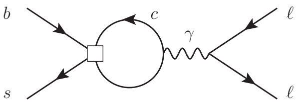
- Main constraints: $\tau \to \ell\nu\nu$, $\tau \to \varphi\mu$, $B \to K\tau\mu$

cf. Barbieri et al. 1512.01560, Alonso et al. 1505.05164, Calibbi et al. 1506.02661, Fajfer and Košnik 1511.06024, Hiller et al. 1609.08895, Bhattacharya et al. 1609.09078, Buttazzo et al. 1706.07808, Kumar et al. 1806.07403

Leptophobic NP & lepton flavour *universal* C_9

- A four-quark operator can also generate a LFU contribution to C_9 through RG running above and below the EW scale Jäger et al. 1701.09183





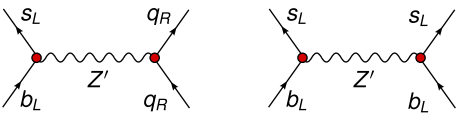
Which operators could work?

- Operators made of *qqqq* do not work as they always lead to excessive effects in K^0 or D^0 mixing
- Operators with tops in the loop do not work as they induce a correction to the *bsZ* coupling and end up generating C_{10}, not C_9

Can we write down a model realizing this?

Simplified leptophobic models for LFU C_9

- Wilson coefficients of 4-quark operator must be of order $(2\,\text{TeV})^{-2}$ $\to$ tree level
- Tree level spin-1 exchange (Z', G') does not work since $\Delta B = 1$ always implies $\Delta B = 2$ (which is strongly constrained)



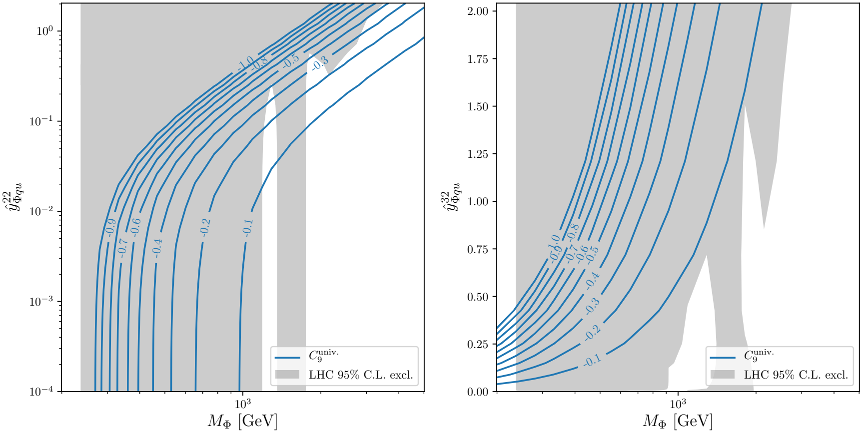
- Heavy uncouloured Higgs doublet generates operator that mixes into $b \to s\gamma$ at 2 loops Jäger et al. 1701.09183 $\to$ excluded
- Only hope: colour-octet Higgs $\sim (\mathbf{8}, \mathbf{2})_{1/2}$

$$\mathcal{L}_\Phi \supset \hat{y}^{ij}_{\Phi qu}\, \bar{q}_i T^A u_j\, \tilde{\Phi}^A$$

  - Forbid coupling to u to evade bounds from D mixing and reduce cross section $pp \to \Phi \to jj$

Colour-octet Higgs: Dijet constraints vs. C_9

Left: $\hat{y}^{32}_{\Phi qu} = -1$, right: $\hat{y}^{22}_{\Phi qu} = 0$



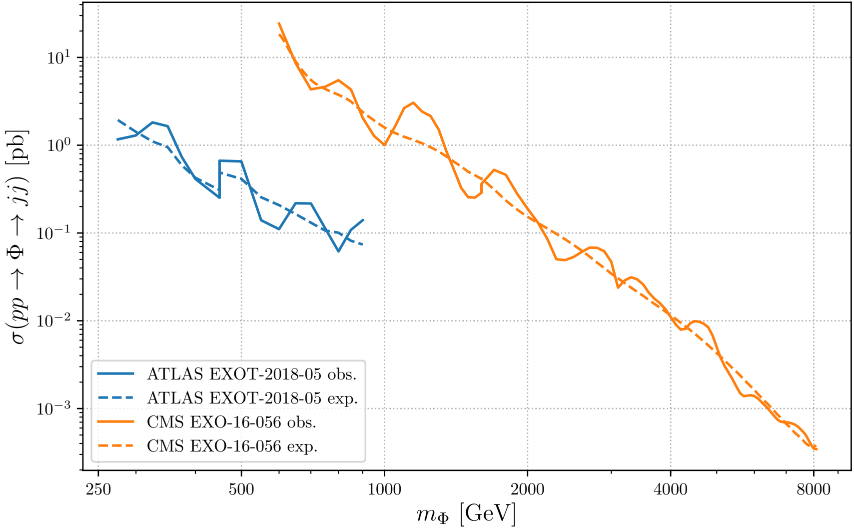
- LHC dijet resonance searches almost completely exclude this scenario from generating a visible contribution to $C_9^{\text{univ.}}$. Remaining space testable in Run 2!

Conclusions

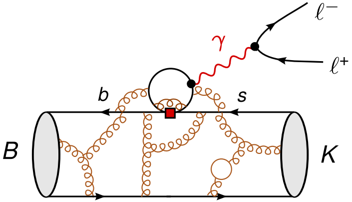
- Global WET fit to $b \to s\ell\ell$ observables still finds large pull for NP Wilson coefficients
  - $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ (LLLL) like in LQ models now gives better fit than $C_9^{bs\mu\mu}$-only
  - Small LFU contribution to C_9 improves the fit compared to muonic only
- SMEFT operators $O_{lq}^{(a)}$ with taus can explain all data including $R_{D^{(*)}}$ & $R_{K^{(*)}}$
  - LFU contribution of exactly the right size induced radiatively
- Popular U_1 leptoquark still giving excellent fit to the data
- Radiatively induced LFU contribution from 4-quark operators only possible with scalar mediator
  - On the brink of exclusion (or discovery …) by LHC dijet resonance searches

Backup

Dijet limits

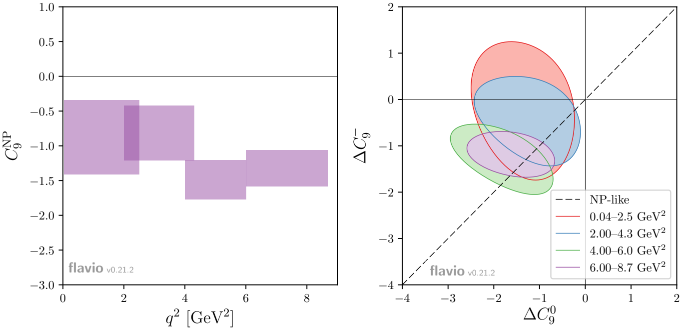


Hadronic uncertainties beyond form factors



- Partly calculable at low q^2 with QCDF Beneke et al. hep-ph/0106067
- Argued to have small impact on q^2-integrated observables at high q^2 Beylich et al. 1101.5118
- Remaining contributions enter error estimate

q^2 dependence of C_9 best-fit



Altmannshofer et al. 1703.09189

- NP in C_9 would give helicity and q^2 independent effect
- hadronic effect could be helicity and q^2 dependent

Using data to constrain hadronic contribution

- Use $b \to c\bar{c}s$ data & analyticity to extract/constrain the contribution

  Bobeth et al. 1707.07305