Planck 2019, Granada, June 4 2019

B-decay discrepancies after Moriond 2019

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Excellence Cluster
Technische Universität München

Outline

1. Motivation
2. Numerical tools
3. Fitting anomalies
4. Summary

Based on:

JA, Jacky Kumar, Peter Stangl, David M. Straub [arXiv:1810.07698]
JA, Wolfgang Altmannshofer, Diego Guadagnoli, Méril Reboud, Peter Stangl, David M. Straub [arXiv:1903.10434]

Outline

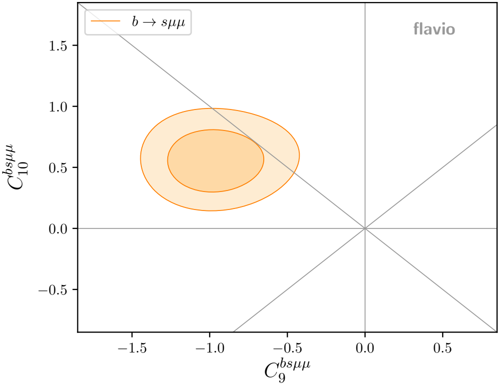
$b \to s\,\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



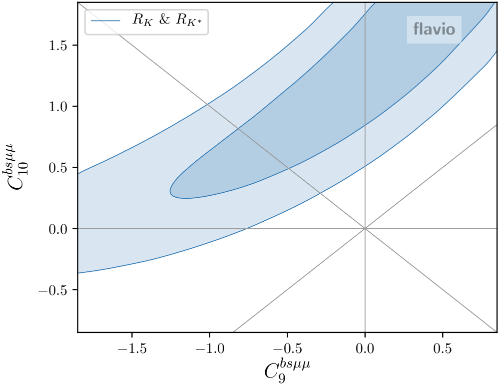
see also fits by other groups:
Capdevila et al., arXiv:1704.05340
D'Amico et al., arXiv:1704.05438
Geng et al., arXiv:1704.05446
Ciuchini et al., arXiv:1704.05447
Mahmoudi et al., arXiv:1611.05060

Hints for LFU violation in neutral current decays

Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each.

LHCb, arXiv:1406.6482, arXiv:1705.05802

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



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(this slide: excluding results from Moriond 2019)

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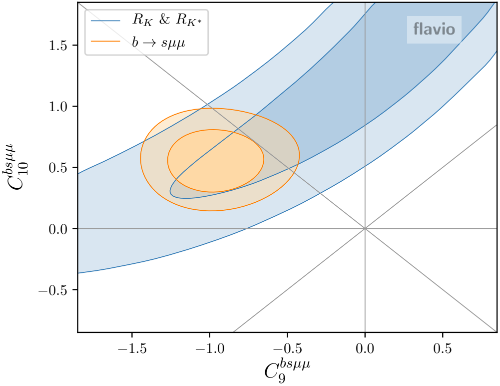

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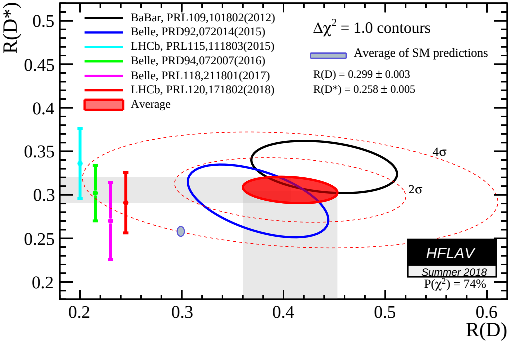
Hints for LFU violation in charged current decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by 3.6-3.8σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529

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

$$\ell \in \{e, \mu\}$$



HFLAV, arXiv:1612.07233

Outline

Tools for the numerical analysis

- Computing hundreds of relevant flavour observables properly accounting for theory uncertainties
  - **flavio** `https://flav-io.github.io` Straub, arXiv:1810.08132
- Representing and exchanging thousands of Wilson coefficient values, different EFTs, possibly different bases
  - **Wilson coefficient exchange format (WCxf)** `https://wcxf.github.io/` JA et al., arXiv:1712.05298
- RG evolution above* and below the EW scale, matching from SMEFT to the weak effective theory (WET)
  - **wilson** `https://wilson-eft.github.io` JA, Kumar, Straub, arXiv:1804.05033

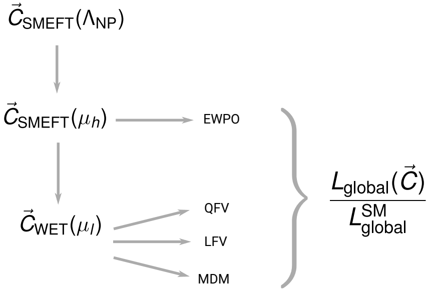
* based on DsixTools Celis, Fuentes-Martin, Vicente, Virto, arXiv:1704.04504

Global SMEFT likelihood

JA, Kumar, PS, Straub, arXiv:1810.07698

- Based on tools above, builds a **SME**FT **Like****Li**hood
  - **smelli** `https://github.com/smelli`

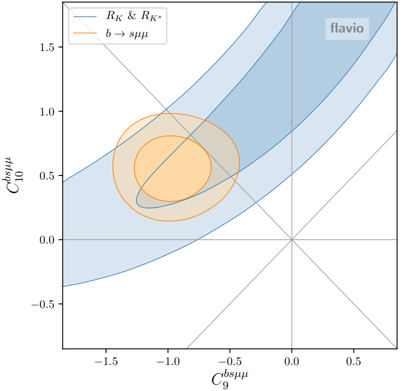
- So far, 265 observables included
  - Rare *B* decays
  - Semi-leptonic *B* and *K* decays
  - Meson-antimeson mixing
  - FCNC *K* decays
  - (LFV) tau and muon decays
  - *Z* and *W* pole EWPOs
  - $g-2$



- Real *global* likelihood is work in progress and open to everybody: `smelli` is **open source**

Outline

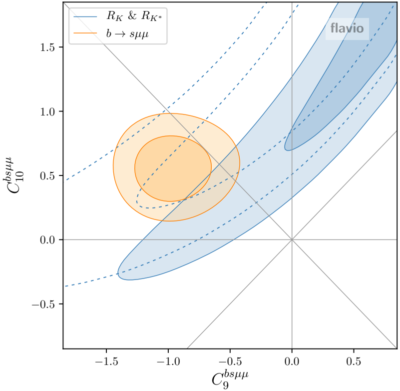
Fitting anomalies in the WET



WET at 4.8 GeV

- **Before Moriond 2019**:
  Very good agreement between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*}

Fitting anomalies in the WET

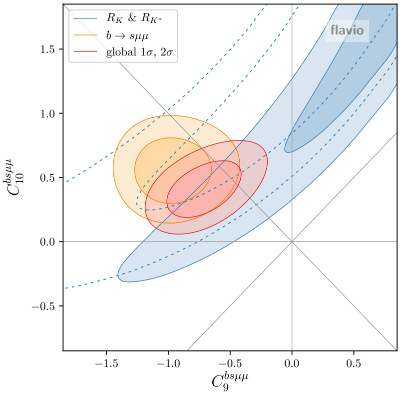


WET at 4.8 GeV

- **Before Moriond 2019**:
  Very good agreement between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*}
- **After Moriond 2019**:
  Updated R_K measurement by LHCb and new R_{K^*} measurement by Belle closer to SM value LHCb, arXiv:1903.09252 Belle, arXiv:1904.02440

  Tension between fits to R_K & R_{K^*} and $b \to s\mu\mu$ observables in C_9 direction

Fitting anomalies in the WET



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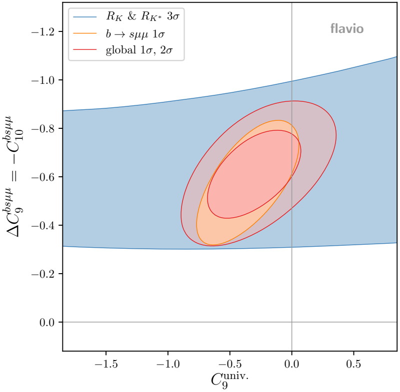
  Tension between fits to R_K & R_{K^*} and $b \to s\mu\mu$ observables in C_9 direction
- **Global likelihood**:
  Contribution to purely left-handed $\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$ yields very good fit to experimental data

Fitting anomalies in the WET

- **LFU contribution** only affects $b \to s\mu\mu$ observables
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$
- Perform two-parameter fit in space of $\boldsymbol{C_9^{\text{univ.}}}$ and $\boldsymbol{\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$:

$$
\begin{aligned}
C_9^{bsee} &= C_9^{\text{univ.}} & \qquad C_{10}^{bsee} &= 0 \\
C_9^{bs\mu\mu} &= C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu} & \qquad C_{10}^{bs\mu\mu} &= -\Delta C_9^{bs\mu\mu} \\
C_9^{bs\tau\tau} &= C_9^{\text{univ.}} & \qquad C_{10}^{bs\tau\tau} &= 0
\end{aligned}
$$

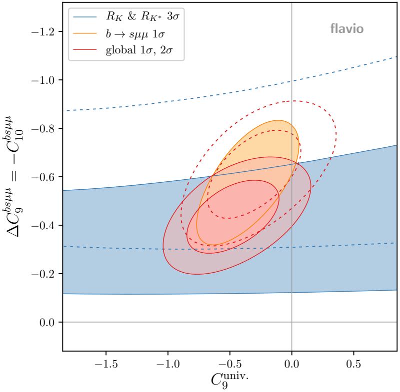
Fitting anomalies in the WET



WET at 4.8 GeV

- **Before Moriond 2019**: Fit compatible with $C_9^{\text{univ.}} = 0$ and only contribution to $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

Fitting anomalies in the WET



WET at 4.8 GeV

- **Before Moriond 2019**: Fit compatible with $C_9^{\text{univ.}} = 0$ and only contribution to $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$
- **After Moriond 2019**: Preference for **non-zero $C_9^{\text{univ.}}$**

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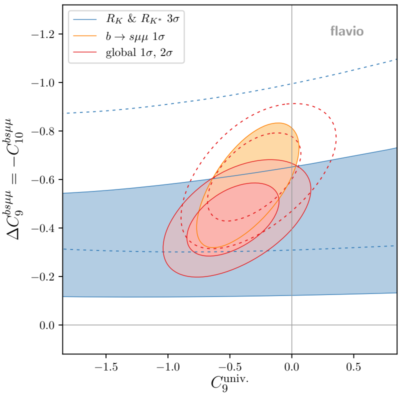
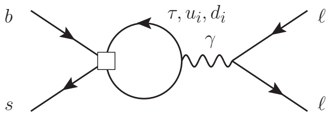


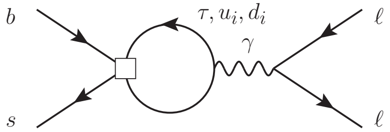
WET at 4.8 GeV

- **Before Moriond 2019**:
  Fit compatible with $C_9^{\text{univ.}} = 0$ and only contribution to $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$
- **After Moriond 2019**:
  Preference for **non-zero $C_9^{\text{univ.}}$**
- $C_9^{\text{univ.}}$ can arise from RG effects:



Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

Fitting anomalies in the SMEFT



RG effects require scale separation

- Consider **SMEFT at 2 TeV**

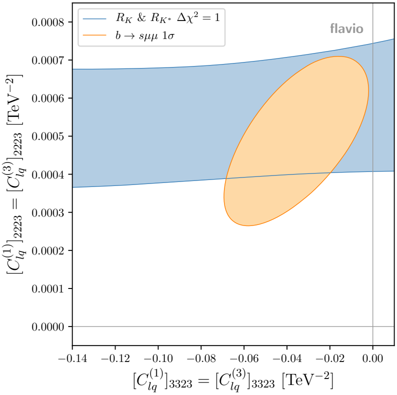
Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3 \gamma_\mu \tau^I l_3)(\bar{q}_2 \gamma^\mu \tau^I q_3)$:
  Can also **explain $R_{D^{(*)}}$ anomalies!**
- $[O_{lq}^{(1)}]_{3323} = (\bar{l}_3 \gamma_\mu l_3)(\bar{q}_2 \gamma^\mu q_3)$:
  Strong constraints from $B \to K\nu\nu$ require $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$

Buras et al., arXiv:1409.4557

- $[O_{qe}]_{2333} = (\bar{q}_2 \gamma_\mu q_3)(\bar{e}_3 \gamma^\mu e_3)$ cannot explain $R_{D^{(*)}}$
- Four-quark operators cannot explain $R_{D^{(*)}}$, models yielding large enough contributions already in tension with data

Fitting anomalies in the SMEFT

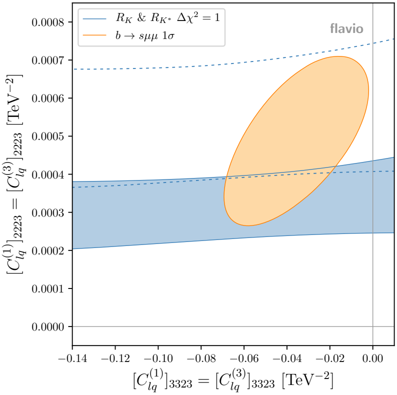


- **Before Moriond 2019**: Fit compatible with $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} = 0$ and only contribution to $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$

$$[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} \quad \Rightarrow \quad C_9^{\text{univ.}} \quad \text{(RG effect)}$$

$$[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223} \quad \Rightarrow \quad \Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$$

Fitting anomalies in the SMEFT



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  Fit compatible with $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} = 0$ and only contribution to $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$

- **After Moriond 2019**:
  Clear preference for **non-zero $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$**

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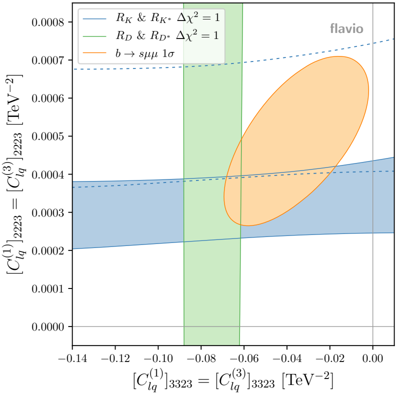
Fitting anomalies in the SMEFT



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- **After Moriond 2019**:
  Clear preference for **non-zero $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$**
- **$R_{D^{(*)}}$ explanation**:
  Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved

$$[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} \quad \Rightarrow \quad C_9^{\text{univ.}} \quad \text{(RG effect)}$$

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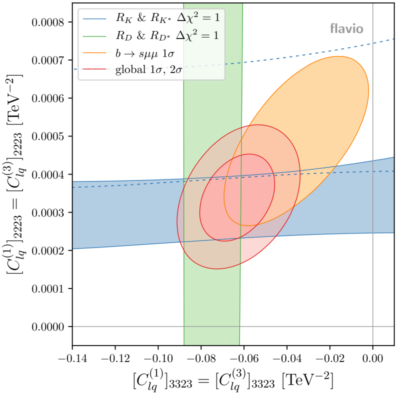
Fitting anomalies in the SMEFT



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- **After Moriond 2019**:
  Clear preference for **non-zero** $[\boldsymbol{C_{lq}^{(1)}}]_{3323} = [\boldsymbol{C_{lq}^{(3)}}]_{3323}$

- $\boldsymbol{R_{D^{(*)}}}$ **explanation**:
  Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved

$$[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} \quad \Rightarrow \quad C_9^{\text{univ.}} \quad \text{(RG effect)}$$

$$[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223} \quad \Rightarrow \quad \Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$$

Fitting anomalies in a U_1-leptoquark model

- **U_1 vector leptoquark** $(\mathbf{3},\mathbf{1})_{2/3}$ couples quarks and leptons

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

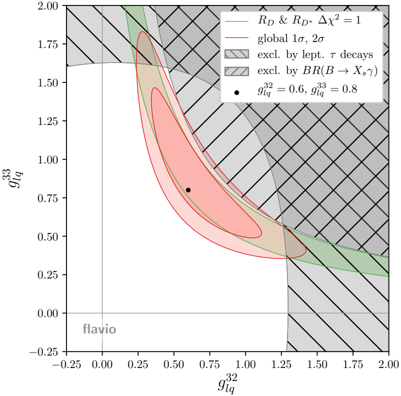
- Generates **semi-leptonic operators at tree-level**

$$[C_{lq}^{(1)}]_{ijkl} = [C_{lq}^{(3)}]_{ijkl} = -\frac{g_{lq}^{jk}\, g_{lq}^{il*}}{2M_U^2}.$$

- And **dipole operators at one-loop**, e.g.
  $[O_{dV}]_{ij} = (\bar{q}_i \sigma^{\mu\nu} V_{\mu\nu} d_j)\varphi, \quad V \in \{W, B, G\}$:

$$[C_{dV}]_{23} = \kappa_V \frac{Y_b}{16\pi^2} \sum_i \frac{g_{lq}^{i2}\, g_{lq}^{i3*}}{M_U^2}, \qquad \kappa_W = \tfrac{g}{6}, \quad \kappa_B = \tfrac{-4\,g'}{9}, \quad \kappa_V = \tfrac{-5\,g_s}{12}$$

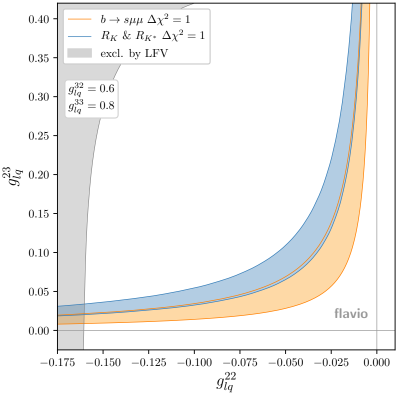
Fitting anomalies in a U_1-leptoquark model



- $R_{D^{(*)}}$ mostly depends on **tauonic couplings g_{lq}^{32}, g_{lq}^{33}**
- Dipole operators contribute to **BR$(B \to X_s\gamma)$**
- RG running contributes to **leptonic τ decays**
- Well defined allowed region for explaining $R_{D^{(*)}}$, select **benchmark point**

$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.8$$

Fitting anomalies in a U_1-leptoquark model

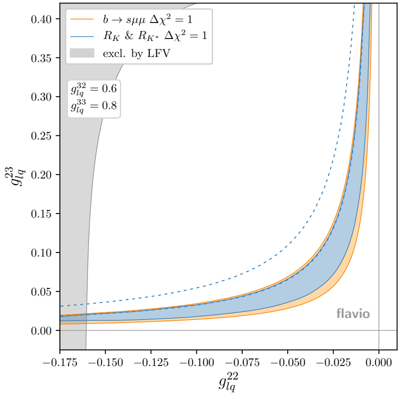


- Benchmark point explaining $R_{D^{(*)}}$,

  $$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.8,$$

  implies non-zero $C_9^{\text{univ.}}$
- $R_{K^{(*)}}$ can be explained by additional **muonic couplings g_{lq}^{22}, g_{lq}^{23}**
- Constraint from **LFV observables**
- **Before Moriond 2019**:
  Given non-zero $C_9^{\text{univ.}}$, tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables

Fitting anomalies in a U_1-leptoquark model



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- **Before Moriond 2019**:
  Given non-zero $C_9^{\text{univ.}}$, tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables
- **After Moriond 2019**:
  Non-zero $C_9^{\text{univ.}}$ preferred, $R_{K^{(*)}}$ and $b \to s\mu\mu$ in good agreement

Outline

Summary

Solving the anomalies in

- WET: $\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ and $C_9^{univ.}$
- SMEFT: $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$ and $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$
- U_1 LQ: g_{lq}^{32}, g_{lq}^{33} and g_{lq}^{22}, g_{lq}^{23}

Backup slides

Installing `smelli`

- Prerequisite: working installtion of **Python** version **3.5** or above
- Installation from the command line:

```
python3 -m pip install smelli --user
```

  - downloads `smelli` with all dependencies from Python package archive (PyPI)
  - installs it in user's home directory (no need to be root)