A Global Likelihood for Precision Constraints and Flavour Anomalies

Presented by Peter Stangl

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Outline

Based on:

Jason Aebischer, Jacky Kumar, PS, David M. Straub [arXiv:1810.07698]
Jason Aebischer, Wolfgang Altmannshofer, Diego Guadagnoli, Méril Reboud, PS, David M. Straub [arXiv:1903.10434]

Outline

1. Flavour anomalies and a global likelihood
2. Applications: EWPOs
3. Applications: Fitting anomalies
4. Conclusions

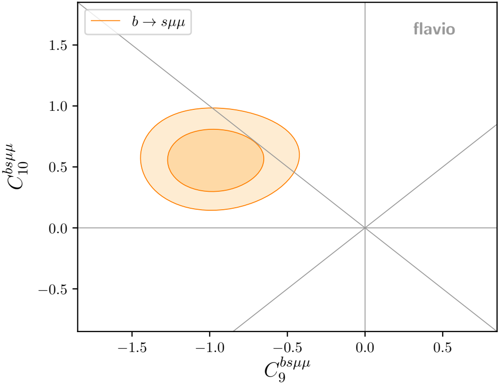
$b \to s\,\mu^+\mu^-$ anomaly

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

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



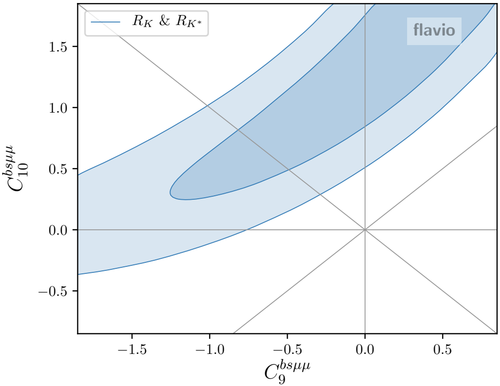
see also fits by other groups:
Capdevila et al., arXiv:1704.05340
D'Amico et al., arXiv:1704.05438
Geng et al., arXiv:1704.05446
Ciuchini et al., arXiv:1704.05447
Mahmoudi et al.. arXiv:1611.05060

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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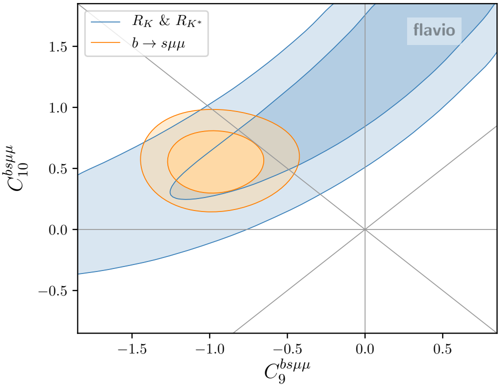

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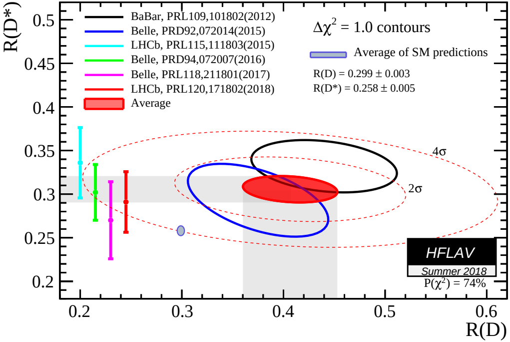
Hints for LFU violation in charged current decays

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

Hurdles for model building

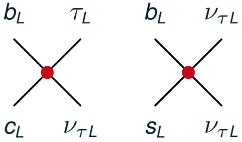
Hurdles for model building

- Model explaining $R_{D^{(*)}}$ using $b_L \to c_L \tau_L \nu_{\tau L}$

$$b_L \to c_L \tau_L \nu_{\tau L} \xrightarrow{\mathrm{SU}(2)_L} b_L \to s_L \nu_{\mu L} \nu_{\tau L}$$

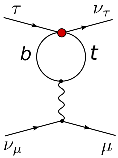
Constrained by $B \to K \nu \bar{\nu}$ searches

Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557



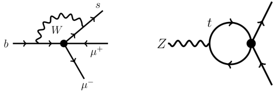
- Model explaining $R_{D^{(*)}}$ and $R_{K^{(*)}}$ using mostly 3rd gen. couplings
Modifies LFU in τ and Z decays, strongly constrained

Feruglio, Paradisi, Pattori, arXiv:1705.00929



- Model explaining $b \to s\mu\mu$ using $tt\mu\mu$ interaction
Modifies $Z \to \mu\mu$, constrained by LEP

Camargo-Molina, Celis, Faroughy, arXiv:1805.04917



Hurdles for model building

Leaping the hurdles

- Compute *all relevant* observables $\vec{O}$ (flavour, EWPO, ...) in terms of Lagrangian parameters $\vec{\theta}$

$$\mathcal{L}_{\text{NP}}(\vec{\theta}) \to \vec{O}(\vec{\theta})$$

- Take into account loop / RGE effects

$$\mathcal{L}_{\text{NP}}(\vec{\theta}) \xrightarrow{\Lambda_{\text{NP}} \to \Lambda_{\text{IR}}} \vec{O}(\vec{\theta})$$

- Compare to experiment

$$\vec{O}(\vec{\theta}) \to \underbrace{L(\vec{O}(\vec{\theta}), \vec{O}_{\text{exp}})}_{\text{Likelihood}}$$

Tedious to do this for each model...

Leaping the hurdles

- Assuming $\Lambda_{NP} \gg v$, NP effects in flavour, EWPO, Higgs, top,... can be expressed in terms of SMEFT Wilson coefficients

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n>4} \sum_{i} \frac{c_i}{\Lambda^{n-4}} O_i$$

Buchmuller, Wyler, Nucl. Phys. B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak, Rosiek, arXiv:1008.4884

- Powerful tool to connect model-building to phenomenology without needing to recompute hundreds of observables in each model
  - Model building:

$$\mathcal{L}_{NP}(\vec{\theta}) \rightarrow \vec{C}(\vec{\theta}) \;\; @ \;\; \Lambda_{NP}$$

  - *Model-independent* pheno:

$$\vec{C} \xrightarrow{\Lambda_{NP} \to \Lambda_{IR}} \vec{O}(\vec{C}) \rightarrow L(\vec{O}(\vec{C}), \vec{O}_{exp})$$

Leaping the hurdles

- Having this *SMEFT likelihood function* $L(\vec{C}) = L(\vec{O}(\vec{C}), \vec{O}_{\text{exp}})$ at hand would tremendously simplify analyses of NP models
- Several likelihood functions have been considered

see talks by Anke Biekötter, Alexander Josef Grohsjean, Chris Hays, Juan Rojo

$$L(\vec{C}) = L_{\text{EW + Higgs}}(\vec{C}_{\text{EW + Higgs}}) \times \ldots$$

$$L(\vec{C}) = L_{\text{top physics}}(\vec{C}_{\text{top physics}}) \times \ldots$$

$$L(\vec{C}) = L_{B\,\text{physics}}(\vec{C}_{B\,\text{physics}}) \times \ldots$$

$$L(\vec{C}) = L_{\text{LFV}}(\vec{C}_{\text{LFV}}) \times \ldots$$

cf. eg. Falkowski, Mimouni, arXiv:1511.07434
Falkowski, González-Alonso, Mimouni, arXiv:1706.03783
Ellis, Murphy, Sanz, You, arXiv:1803.03252
Biekötter, Corbett, Plehn, arXiv:1812.07587
Hartland et al., arXiv:1901.05965
...

- But actually the likelihood *does not factorize* since RG effects mix different sectors
- We need to consider the *global* SMEFT likelihood

Tools for leaping the hurdles

Tools for leaping the hurdles

- Computing hundreds of relevant flavour observables properly accounting for theory uncertainties
  - **flavio** `https://flav-io.github.io` Straub, arXiv:1810.08132
  - Already used in $O(20)$ papers since 2016
- Representing and exchanging thousands of Wilson coefficient values, different EFTs, possibly different bases
  - **Wilson coefficient exchange format (WCxf)** `https://wcxf.github.io/` Aebischer 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` Aebischer, Kumar, Straub, arXiv:1804.05033

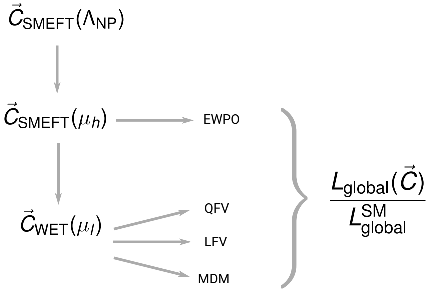
* based on DsixTools Celis, Fuentes-Martin, Vicente, Virto, arXiv:1704.04504

Building a global SMEFT likelihood

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- Based on these tools, we have started building the **SME**FT **Like**L**I**hood
  - **smelli** `https://github.com/smelli`

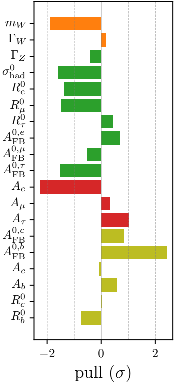
- So far, 265 observables included
  - Rare *B* decays
  - Semi-leptonic *B* and *K* decays
  - Meson-antimeson mixing
  - FCNC *K* decays
  - (LFV) tau and muon decays
  - *Z* and *W* pole EWPOs
  - $g-2$



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

Outline

Electroweak precision observables



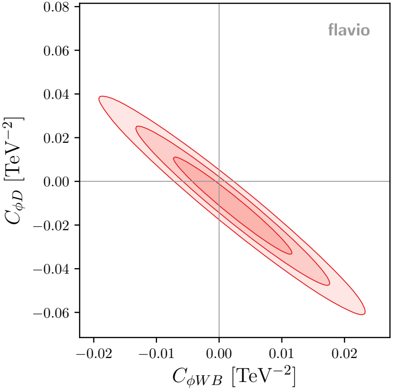
- We have implemented all the relevant Z and W pole observables, not assuming LFU, in `flavio`

  Efrati, Falkowski, Soreq, arXiv:1503.07872
  Brivio, Trott, arXiv:1706.08945

- SM pulls in good agreement e.g. with Gfitter

  Baak et al., arXiv:1407.3792

Oblique parameters

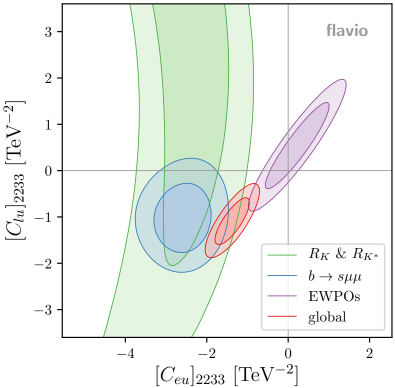


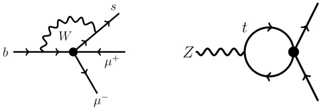
- Reproducing the EWPO constraint on the electrowewak S and T parameters

$$S \propto C_{\phi WB}, \quad T \propto -C_{\phi D}$$

$$O_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$$
$$O_{\phi WB} = \phi^\dagger \tau^I \phi W^I_{\mu\nu} B^{\mu\nu}$$

B anomalies from NP in top





- $[C_{eu}]_{2233}$, i.e. RH $tt\mu\mu$ operator, suggested as solution to $b \to s\ell\ell$ anomalies in Celis et al., arXiv:1704.05672
  - see Z' model in Kamenik et al., arXiv:1704.06005
- Later realized that there are strong constraints from $Z \to \mu\mu$ Camargo-Molina, Celis, Faroughy, arXiv:1805.04917
- Plot: SMEFT at 1 TeV

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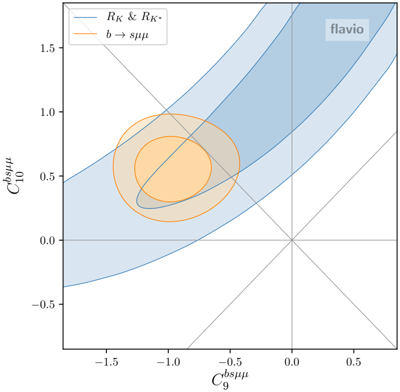
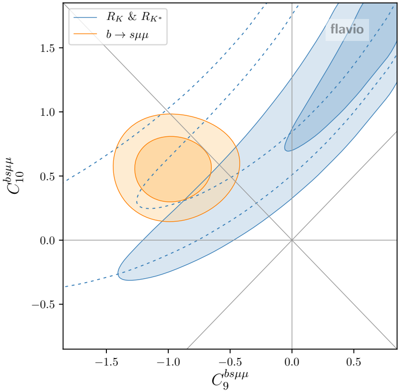
Fitting anomalies in the WET



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



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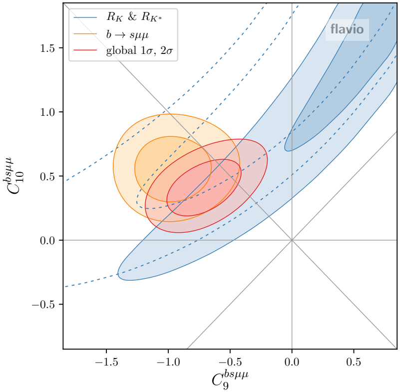
- **After Moriond 2019**:
  Updated R_K measurement by LHCb and new R_{K^*} measurement by Belle closer to SM value LHCb, arXiv:1903.09252
  Belle, arXiv:1904.02440

  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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- **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
- **Global likelihood**:
  Contribution to purely left-handed $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ yields very good fit to experimental data

Fitting anomalies in the WET

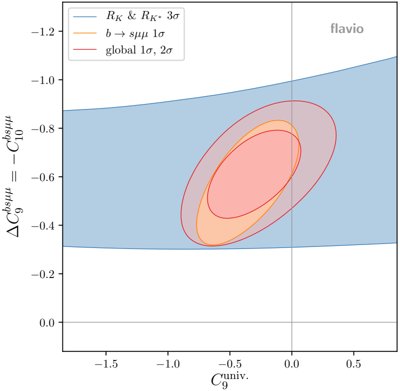
- **LFU contribution** only affects $b \to s\mu\mu$ observables
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$
- Perform two-parameter fit in space of $\boldsymbol{C_9^{\text{univ.}}}$ and $\boldsymbol{\Delta C_9^{bs\mu\mu}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

$$C_9^{bsee} = C_9^{\text{univ.}} \qquad C_{10}^{bsee} = 0$$

$$C_9^{bs\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu} \qquad C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu}$$

$$C_9^{bs\tau\tau} = C_9^{\text{univ.}} \qquad C_{10}^{bs\tau\tau} = 0$$

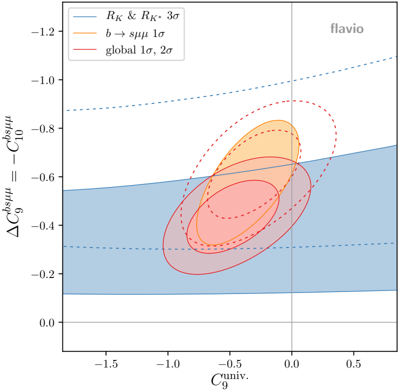
Fitting anomalies in the WET



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



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- **After Moriond 2019**:
  Preference for **non-zero $\boldsymbol{C_9^{\text{univ.}}}$**

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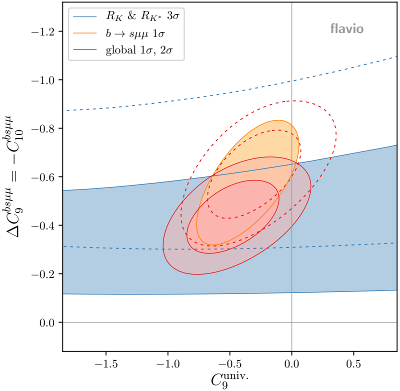
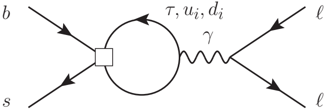


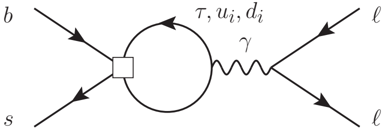
WET at 4.8 GeV

- **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

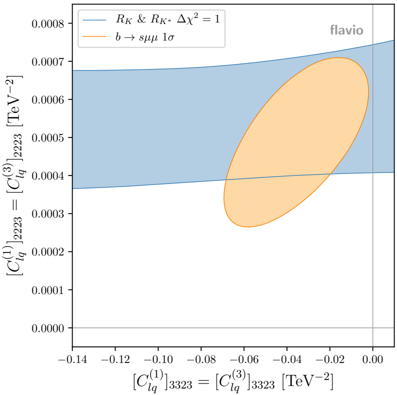
- Consider **SMEFT at 2 TeV**

Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3 \gamma_\mu \tau^a l_3)(\bar{q}_2 \gamma^\mu \tau^a q_3)$:
  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

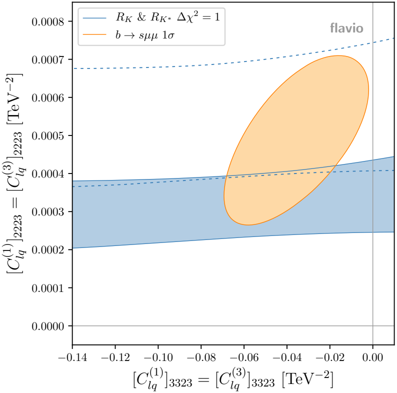


- **Before Moriond 2019**:
  Fit compatible with $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} = 0$ and only contribution to $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$

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

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

Fitting anomalies in the SMEFT



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

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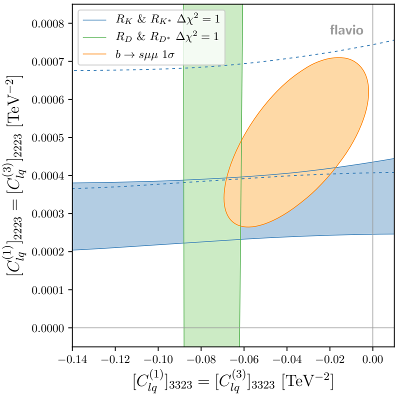
Fitting anomalies in the SMEFT



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

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

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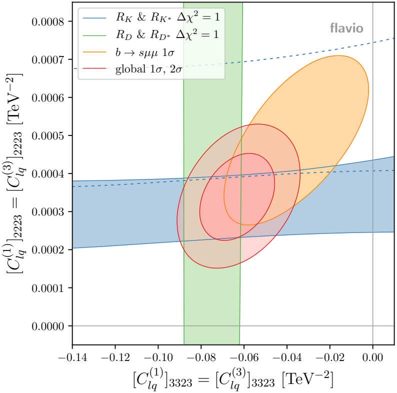
Fitting anomalies in the SMEFT



- **Before Moriond 2019**:
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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

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

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

Fitting anomalies in a U_1-leptoquark model

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

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

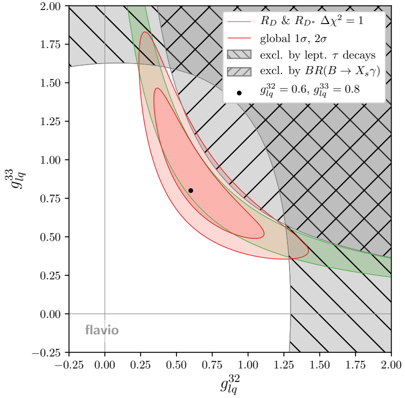
- Generates **semi-leptonic operators at tree-level**

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

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

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

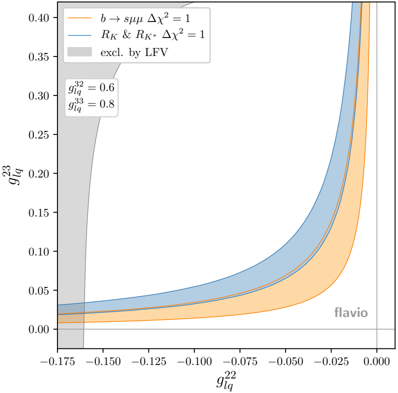
Fitting anomalies in a U_1-leptoquark model



- $R_{D^{(*)}}$ 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



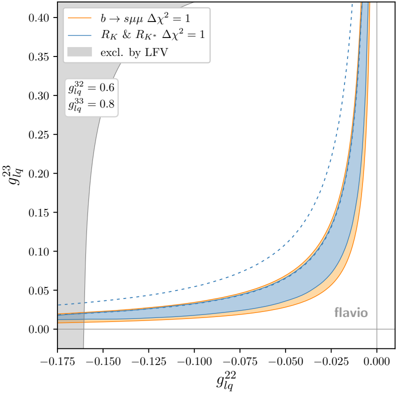
- Benchmark point explaining $R_{D^{(*)}}$,

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

  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



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

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

Outline

Conclusions

- New likelihood function in space of dim-6 SMEFT Wilson coeffcients
- Inlcudes 265 observables from
  - Rare *B* decays
  - Semi-leptonic *B* and *K* decays
  - Meson-antimeson mixing
  - FCNC *K* decays
  - (LFV) tau and muon decays
  - EWPOs
  - $g-2$
- Other sectors of observables to be added
  - Higgs production & decay
  - top physics
  - low-energy precision tests (atomic parity violation etc.)
  - high-p_T contact interaction searches
  - diboson production
  - ...
- Completely open source!
  You are welcome to participate → `https://github.com/smelli`

Backup slides

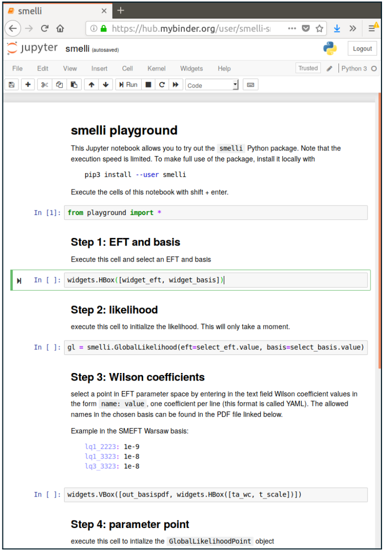
Installing `smelli`

- 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)

Using `smelli`



As any Python package, **smelli** can be used

- as library imported from other scripts
- directly in the command line interpreter
- in an interactive session
  $\rightarrow$ we recommend the **Jupyter notebook**

Try out **smelli** in a Jupyter notebook at
`https://github.com/smelli/smelli-playground`

Using smelli

- Step 1:
  Import package and initalize `GlobalLikelihood` class

```
import smelli
gl = smelli.GlobalLikelihood()
```

possible arguments are

- `eft='WET'` to use Wilson coefficients in weak effective theory (no EWPOs) (default: `eft='SMEFT'`)
- `basis='...'` to select different WCxf basis (default: `basis='Warsaw'` for SMEFT, `basis='flavio'` for WET)

Using smelli

- Step 2:
  Select point in Wilson coefficient space using `parameter_point` method
- Three possible input formats:
  - Python dictionary with Wilson coefficient name/value pair and input scale

```
glp = gl.parameter_point({'lq1_2223': 1e-8}, scale=1000)
```

fixes Wilson coefficient $[C_{lq}^{(1)}]_{2223}$ to 10^{-8} GeV^{-2} at scale 1 TeV

  - WCxf data file in YAML or JSON format (specified by file path)

```
glp = gl.parameter_point('my_wc.yaml')
```

  - instance of class `wilson.Wilson` from `wilson` package

```
glp = gl.parameter_point(wilson_instance)
```

Using `smelli`

- Step 3:
  Get results from `GlobalLikelihoodPoint` instance `glp` defined in step 2
- The most important methods are:

```
glp.log_likelihood_global()
```

returns $\ln \Delta L = \ln \left(\frac{L_{\text{global}}(\vec{C})}{L_{\text{global}}^{\text{SM}}} \right)$

```
glp.log_likelihood_dict()
```

returns Python dictionary with contributions to $\ln \Delta L$ from different sets of observables (EWPOs, charged current LFU, neutral current LFU,...)

```
glp.obstable()
```

returns table listing individual observables with their experimental and theoretical central values and uncertainties

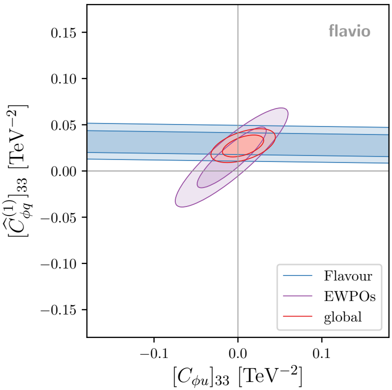
Using smelli

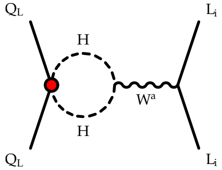
```
glp = gl.parameter_point({}, scale=1000)
glp.obstable(min_pull='2.35')
```

returns observables with highest pull in Standard Model (no Wilson coefficient set)

Observable	Prediction	Measurement	Pull
$\langle \frac{dBR}{dq^2} \rangle (B_s \to \phi\mu^+\mu^-)^{[1.0,6.0]}$	$(5.37 \pm 0.65) \times 10^{-8}\ \frac{1}{\text{GeV}^2}$	$(2.57 \pm 0.37) \times 10^{-8}\ \frac{1}{\text{GeV}^2}$	3.8σ
a_μ	$(1.1659182 \pm 0.0000004) \times 10^{-3}$	$(1.1659209 \pm 0.0000006) \times 10^{-3}$	3.5σ
$\langle P_5' \rangle (B^0 \to K^{*0}\mu^+\mu^-)^{[4,6]}$	-0.756 ± 0.074	-0.21 ± 0.15	3.3σ
$R_{\tau\ell}(B \to D^*\ell^+\nu)$	0.248	0.306 ± 0.018	3.3σ
$\langle A_{\text{FB}}^{\ell h} \rangle (\Lambda_b \to \Lambda\mu^+\mu^-)^{[15,20]}$	0.1400 ± 0.0075	0.250 ± 0.041	2.6σ
$\langle R_{\mu e} \rangle (B^\pm \to K^\pm\ell^+\ell^-)^{[1.0,6.0]}$	1.000	0.745 ± 0.098	2.6σ
ϵ'/ϵ	$(-0.3 \pm 6.0) \times 10^{-4}$	$(1.66 \pm 0.23) \times 10^{-3}$	2.6σ
$\text{BR}(W^\pm \to \tau^\pm\nu)$	0.1084	0.1138 ± 0.0021	2.6σ
$\langle R_{\mu e} \rangle (B^0 \to K^{*0}\ell^+\ell^-)^{[1.1,6.0]}$	1.00	0.68 ± 0.12	2.5σ
$R_{\tau\ell}(B \to D\ell^+\nu)$	0.281	0.406 ± 0.050	2.5σ
$\langle \frac{dBR}{dq^2} \rangle (B^\pm \to K^\pm\mu^+\mu^-)^{[15.0,22.0]}$	$(1.56 \pm 0.12) \times 10^{-8}\ \frac{1}{\text{GeV}^2}$	$(1.210 \pm 0.072) \times 10^{-8}\ \frac{1}{\text{GeV}^2}$	2.5σ
$A_{\text{FB}}^{0,b}$	10.31×10^{-2}	$(9.92 \pm 0.16) \times 10^{-2}$	2.4σ
$\langle \frac{dBR}{dq^2} \rangle (B^0 \to K^0\mu^+\mu^-)^{[15.0,22.0]}$	$(1.44 \pm 0.11) \times 10^{-8}\ \frac{1}{\text{GeV}^2}$	$(9.6 \pm 1.6) \times 10^{-9}\ \frac{1}{\text{GeV}^2}$	2.4σ
$\langle R_{\mu e} \rangle (B^0 \to K^{*0}\ell^+\ell^-)^{[0.045,1.1]}$	0.93	0.65 ± 0.12	2.4σ

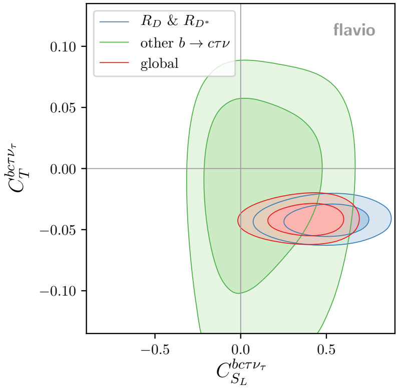
EWPT vs. *B* constraints on modified *t* couplings





- Modfications of LH vs. RH $Zt\bar{t}$ couplings (in basis where up-type quark mass matrix is diagonal)
- Complementarity between flavour ($B_s \to \mu^+\mu^-$) and EW ($Z \to b\bar{b}$, T) constraints
  Brod, Greljo, Stamou, Uttayarat, arXiv:1408.0792
- Plot: WC at 1 TeV, up-aligned basis

Scalar and tensor operator explanation of $R_{D^{(*)}}$

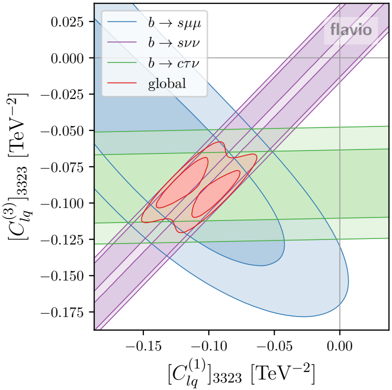


- This combination is generated with $C_{S_L}^{bc\tau\nu_\tau} = -4C_T^{bc\tau\nu_\tau}$ at matching scale in S_1 leptoquark scenario

  Becirevic, Sumensari, arXiv:1704.05835

- New result:
  second, disjoint solution with large tensor Wilson coefficient excluded by new, preliminary Belle measurement of longitudinal polarization fraction F_L in $B \to D^* \tau\nu$ Nishida, Talk given at CKM 2018

LLLL solutions to B anomalies



- Using models that generate $C_{lq}^{(3)}$ with flavour $\tau\tau sb$ are prime candidates to explain $R_{D^{(*)}}$
- Strong constraint from bounds on $B \to K\nu\nu$ probing $b \to s\nu_\tau\bar{\nu}_\tau$ unless $C_{lq}^{(1)} \approx C_{lq}^{(3)}$ Buras et al., arXiv:1409.4557
- Radiatevely induced lepton flavour *universal* conntribution to $b \to s\mu\mu$ and thus also explain $B \to K^*\mu\mu$ anomalies Bobeth, Haisch, arXiv:1109.1826 Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068
- (Explaining $R_{K^{(*)}}$ possible by directly coupling to muons)
- Plot: WC at 1 TeV