CPTGA Precision Calculations Meeting, Annecy, 19 November 2019

Standard Model EFT at one-loop and beyond

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Outline

1. Motivation from flavour physics
2. The global SMEFT likelihood
3. Overview of the SMEFT framework
4. Conclusions

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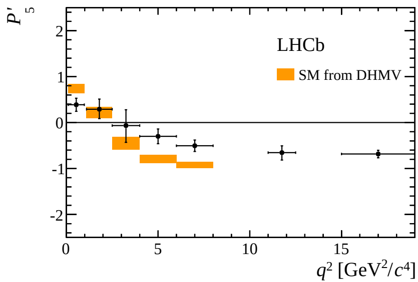
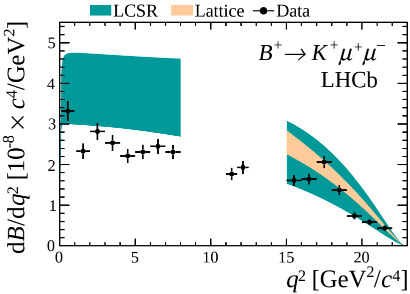
$b \to s\,\mu^+\mu^-$ anomaly

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

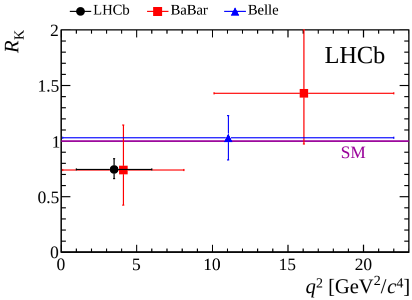


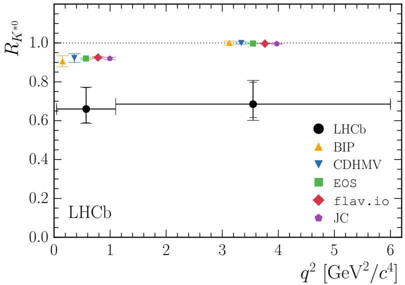


Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ showed deviations from SM by about 2.5σ each. LHCb, arXiv:1406.6482, arXiv:1705.05802

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

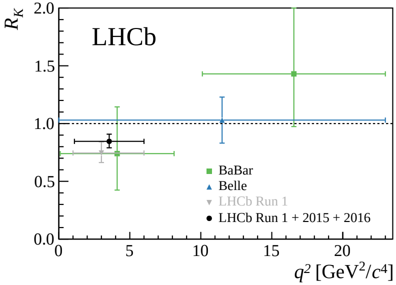


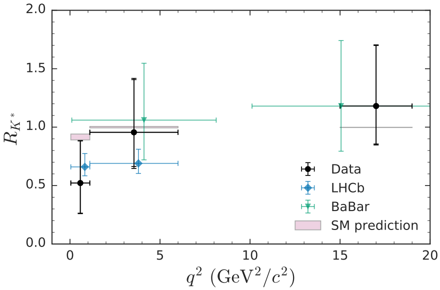


Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

New results at Moriond 2019

- Updated measurement of $\mathbf{R_K}$ **by LHCb** — LHCb, arXiv:1903.09252
- New measurement of $\mathbf{R_{K^*}}$ **by Belle** — Belle, arXiv:1904.02440





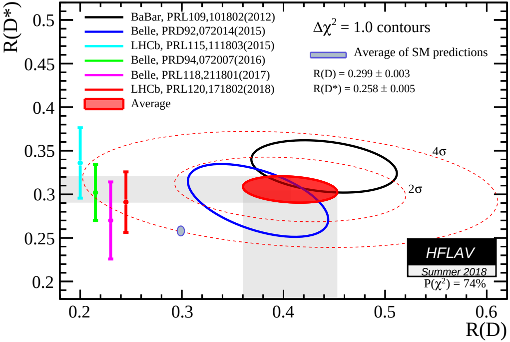
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb showed combined deviation from SM by 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

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

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

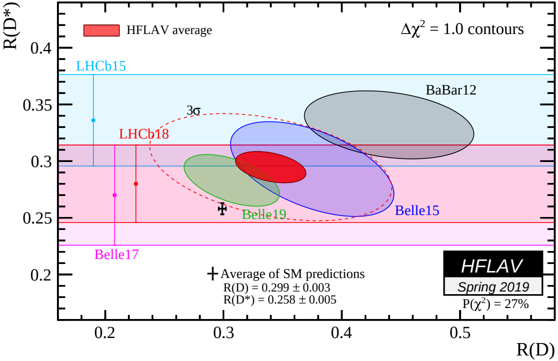


HFLAV, arXiv:1612.07233

Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

New results at Moriond 2019

- Updated measurements of $\mathbf{R_D}$ **and** $\mathbf{R_{D^*}}$ **by Belle** — Belle, arXiv:1904.08794

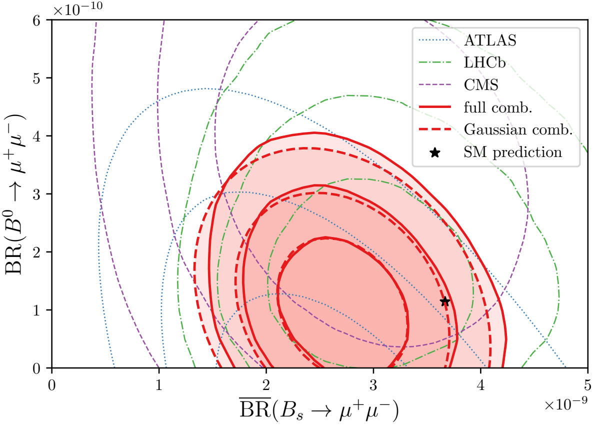


HFLAV, hflav.web.cern.ch

Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

Measurements of $\text{BR}(B_{s,d} \to \mu^+\mu^-)$ by LHCb, CMS, and ATLAS show combined deviation from SM by about 2σ.

LHCb, arXiv:1703.05747
CMS, arXiv:1307.5025
ATLAS, arXiv:1812.03017



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Hurdles for model building

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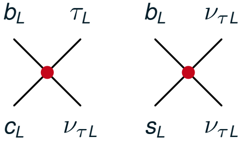
- Model explaining $R_{D^{(*)}}$ using $b_L \to c_L \tau_L \nu_{\tau L}$

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

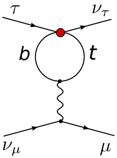
  Constrained by $B \to K \nu \bar{\nu}$ searches

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



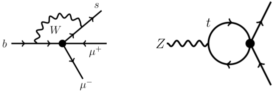
- Model explaining $R_{D^{(*)}}$ and $R_{K^{(*)}}$ using mostly 3rd gen. couplings
  Modifies LFU in τ and Z decays, strongly constrained

  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 $\Lambda_{\text{NP}} \gg v$, NP effects in flavour, EWPO, Higgs, top,... can be expressed in terms of Standard Model Effective Field Theory (SMEFT) Wilson coefficients

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

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:

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

  - *Model-independent* pheno:

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

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

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

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

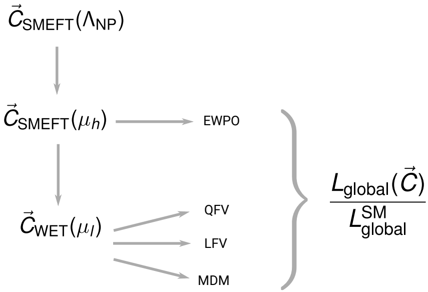
Building the global SMEFT likelihood

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

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

- So far, 280 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 work in progress
  Soon: Higgs physics, beta decays, ...



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Matching a new physics model to the SMEFT

- **Tree-level:** Full tree-level matching of new physics model with general **scalar**, **spinor**, and **vector** field content and **arbitrary interactions** is known.

  de Blas, Criado, Perez-Victoria, Santiago, arXiv:1711.10391

- **One-loop:**
  - **Diagrammatic methods**: `MatchMaker` code built using `Python`, `FeynRules`, `QGRAF`, `FORM`, `Mathematica`.

    Anastasiou, Carmona, Lazopoulos, Santiago, to appear soon, see arXiv:1910.11003

  - **Functional methods**: Covariant Derivative Expansion (CDE) and Universal One-Loop Effective Action (UOLEA). Loop integrals and UV-specific parts are factorized. Only partial results available.

    Henning, Lu, Murayama, arXiv:1412.1837
    Drozd, Ellis, Quevillon, You, arXiv:1512.03003
    Das Bakshi, Chakrabortty, Patra, arXiv:1808.04403
    Krämer, Summ, Voigt, arXiv:1908.04798

Renormalization group equations in SMEFT

- **One-loop:**
  - **Diagrammatic methods**: Anomalous dimensions are known for all operators up to dimension-six.
    Jenkins, Manohar, Trott, arXiv:1308.2627
    Jenkins, Manohar, Trott, arXiv:1310.4838
    Alonso, Jenkins, Manohar, Trott, arXiv:1312.2014
    Implemented in `smelli`
  - **Functional methods**: Master formula for bosonic dimension-six operators using super-heat-kernel expansion. Buchalla, Celis, Krause, Toelstede, arXiv:1904.07840
- **Beyond one-loop**: Two- and three-loop anomalous dimensions of CP-violating gluonic operator. de Vries, Falcioni, Herzog, Ruijl, arXiv:1907.04923

Matching of the SMEFT to the WET/LEFT

Phenomenology at energies below the electroweak scale:
Integrate out W, Z, H, t $\Rightarrow$ **Weak Effective Theory (WET)** / Low-energy EFT (LEFT)

- **Tree-level:** Full operator basis and tree-level matching from SMEFT to WET are known.
  Jenkins, Manohar, Stoffer, arXiv:1709.04486
  Implemented in `smelli`

- **One-loop:** Recently, full one-loop matching computed.
  Dekens, Stoffer, arXiv:1908.05295
  Implemented in `smelli`

Renormalization group equations in WET/LEFT

- **One-loop:** Anomalous dimensions are known for all operators up to dimension-six.

  Jenkins, Manohar, Stoffer, arXiv:1711.05270

  Implemented in `smelli`

- **Beyond one-loop**: Partial results of anomalous dimensions up to four-loops.

  Buchalla, Buras, Lautenbacher, arXiv:hep-ph/9512380
  Misiak, Steinhauser, arXiv:hep-ph/0401041
  Czakon, Haisch, Misiak, arXiv:hep-ph/0612329
  ...

Tools for the SMEFT

Many public tools available for analyses in SMEFT or general EFTs

- Construction and change of EFT Bases
- Feynman Rules for the SMEFT
- Matching calculators
- Generic Matching+Running codes
- Fitters/Likelihoods
- Observables and Monte Carlo enablers

"Computing Tools for the SMEFT",
Aebischer, Fael, Lenz, Spannowsky, Virto, Brivio, Criado, Dedes, Kumar, Misiak, Passarino, Pruna, Renner, Santiago, Scott, Slade, PS, Stoffer, Straub, Sutherland, van Dyk, Vicente,
arXiv:1910.11003

Current accuracy

<table>
<tr><th></th><th>leading-log</th><th>one-loop</th><th>next-to-leading log</th></tr>
<tr><td>Matching to SMEFT</td><td>✓</td><td colspan="2">✓</td></tr>
<tr><td>RGEs in SMEFT</td><td colspan="2">✓</td><td>✓ ✗</td></tr>
<tr><td>Matching to WET</td><td>✓</td><td colspan="2">✓</td></tr>
<tr><td>RGEs in WET</td><td colspan="2">✓</td><td>✓ ✗</td></tr>
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Conclusions

- Discrepancies in
  - $b \to s\mu\mu$ observables
  - Neutral current ($b \to s\ell\ell$) LFU ratios $R_{K^{(*)}}$
  - Charged current ($b \to c\ell\nu$) LFU ratios $R_{D^{(*)}}$
- Models explaining discrepancies generically predict effects in other observables
- Global likelihood open source package `smelli`
  - Test models
  - Interpret data model-independently in WET and SMEFT
  - Currently 280 flavour and electroweak precision observables included
  - Other sectors to be added
    $\to$ Coming soon: higgs production & decay, nuclear & neutron beta decay
- Phenomenological studies using SMEFT and WET
  at leading-log and one-loop accuracy
  (Full two-loop anomalous dimensions of SMEFT and WET missing for
  next-to-leading-log accuracy)

Backup slides

Setup

- Global likelihood from **smelli** python package for comparing theory predictions to experimental data
- Quantify agreement between theory and experiment by likelihood L, $\Delta\chi^2$, and pull

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

$$\text{pull}_{2\text{D}} = 1\sigma, 2\sigma, 3\sigma, \ldots \quad \text{for} \quad \Delta\chi^2 \approx 2.3, 6.2, 11.8, \ldots$$

- Model-independent new physics scenarios in
  - Weak Effective Theory (WET) at scale m_b
  - Standard Model Effective Field Theory (SMEFT) at scale 2 TeV
- Simplified model matched to SMEFT at 2 TeV

$b \to s\ell\ell$ in the weak effective theory

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, SM}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, NP}}^{bs\ell\ell}$

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

- Operators considered here ($\ell = e, \mu$)

$$\begin{aligned}
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,\\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, & O_{10}'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,\\
O_S^{bs\ell\ell} &= m_b(\bar{s} P_R b)(\bar{\ell}\ell)\,, & O_S'^{bs\ell\ell} &= m_b(\bar{s} P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bs\ell\ell} &= m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P'^{bs\ell\ell} &= m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5\ell)\,.
\end{aligned}$$

- Not considered here
  - Dipole operators: strongly constrained by radiative decays. e.g. [arXiv:1608.02556]
  - Four quark operators: dominant effect from RG running above m_B.
    Jäger, Leslie, Kirk, Lenz [arXiv:1701.09183]

Scenarios with a single Wilson coefficients

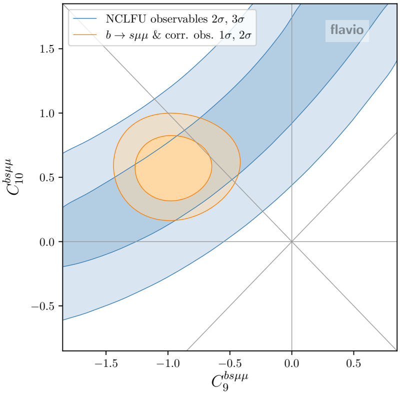
Coefficient	type	best fit	1σ	$\text{pull}_{1D} = \sqrt{\Delta\chi^2}$
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.97	$[-1.12, -0.81]$	**5.9σ**
$C_9'^{bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.03, +0.32]$	0.8σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.75$	$[+0.62, +0.89]$	**5.7σ**
$C_{10}'^{bs\mu\mu}$	$R \otimes A$	-0.24	$[-0.36, -0.12]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.06, +0.36]$	1.4σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.53	$[-0.61, -0.45]$	**6.6σ**

Only small pull for

- Coefficients with $\ell = e$ (cannot explain $b \to s\mu\mu$ anomaly)
- Scalar coefficients (can only reduce tension in $B_s \to \mu\mu$)

see also similar fits by other groups:
Algueró et al., arXiv:1903.09578 Ciuchini et al., arXiv:1903.09632 Datta et al., arXiv:1903.10086
Kowalska et al., arXiv:1903.10932 Arbey et al., arXiv:1904.08399

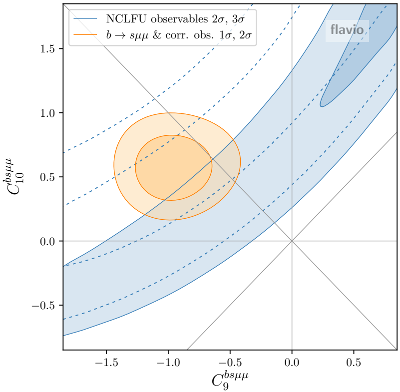
Scenarios with two Wilson coefficients



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^*}

Scenarios with two Wilson coefficients



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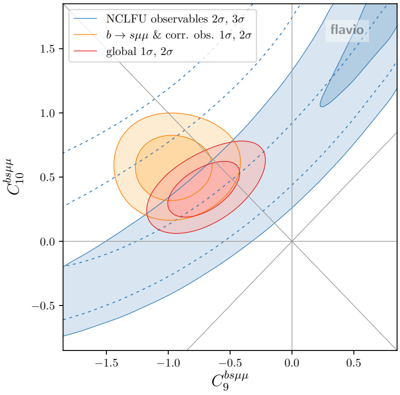
- **After Moriond 2019**:
  Updated R_K measurement by LHCb and new R_{K^*} measurement by Belle closer to SM value LHCb, arXiv:1903.09252 Belle, arXiv:1904.02440

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

Scenarios with two Wilson coefficients



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  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

Scenarios with two Wilson coefficients

- **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 $\boldsymbol{\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$:

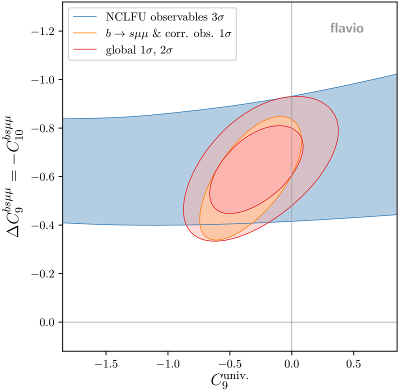
$$C_9^{bsee} = C_9^{\text{univ.}} \qquad C_{10}^{bsee} = 0$$

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

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

scenario first considered in
Algueró et al., arXiv:1809.08447

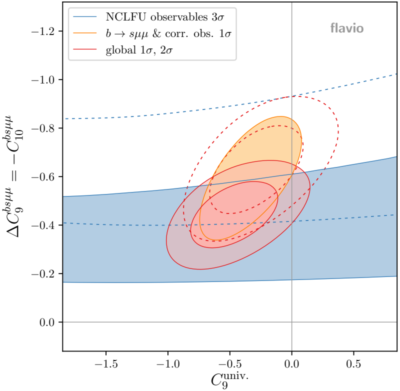
Scenarios with two Wilson coefficients



WET at 4.8 GeV

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

Scenarios with two Wilson coefficients



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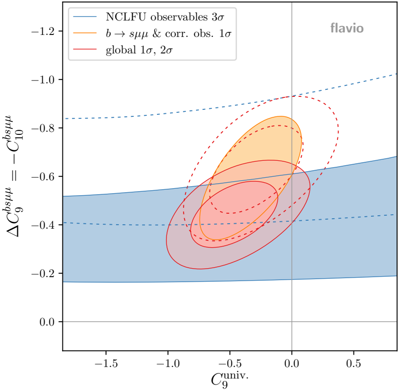
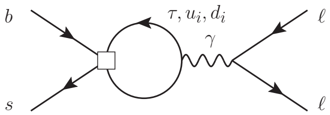
- **After Moriond 2019**: Preference for **non-zero $C_9^{\text{univ.}}$**

Scenarios with two Wilson coefficients



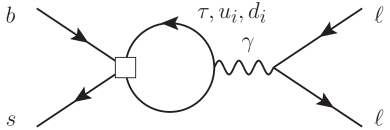
WET at 4.8 GeV

- **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** $\boldsymbol{C_9^{\text{univ.}}}$
- $\boldsymbol{C_9^{\text{univ.}}}$ can arise from RG effects:



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

The global picture in the SMEFT



RG effects require scale separation

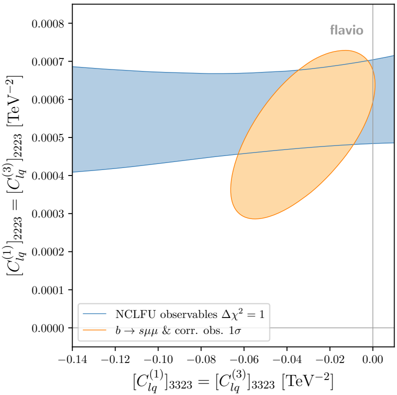
- Consider **SMEFT at 2 TeV**

Possible operators:

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

  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

The global picture in the SMEFT

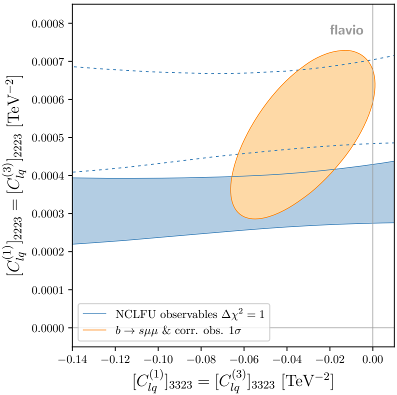


- **Before Moriond 2019**: Fit compatible with $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} = 0$ and only contribution to $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$

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

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

The global picture in the SMEFT



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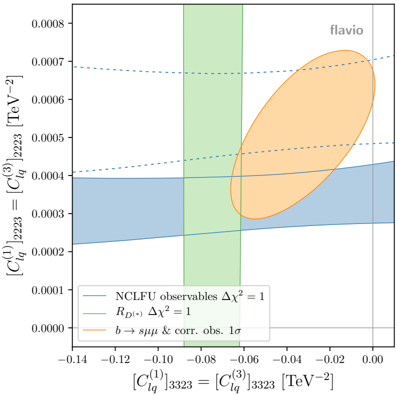

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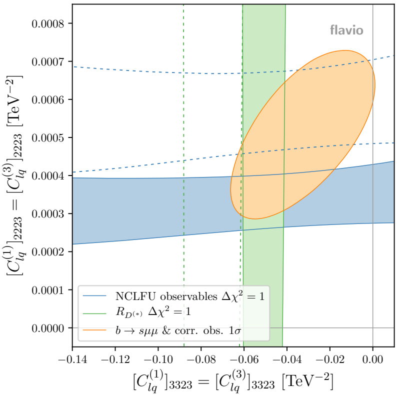

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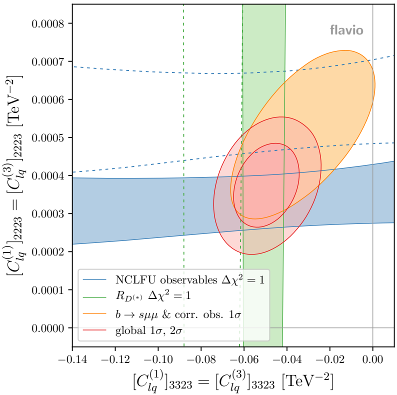

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Simplified U_1-leptoquark model

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

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

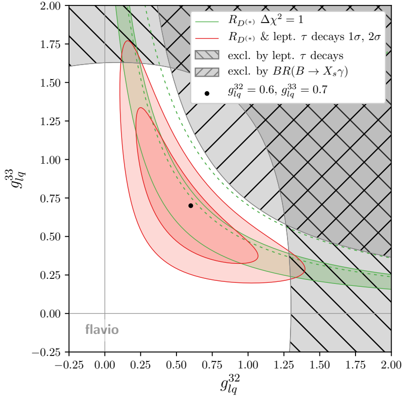
- Generates **semi-leptonic operators at tree-level**

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

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

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

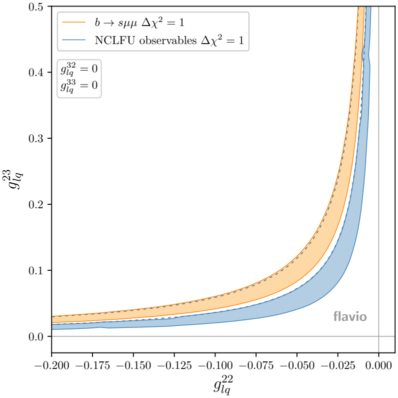
Simplified U_1-leptoquark model



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

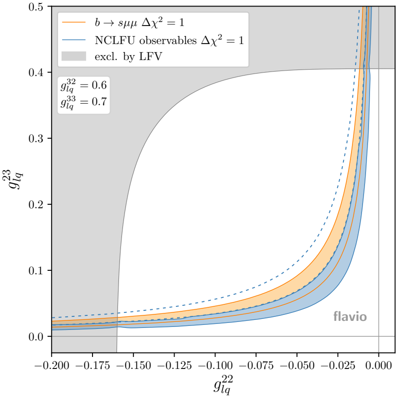
$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.7$$

Simplified U_1-leptoquark model



- $R_{K^{(*)}}$ can be explained by **muonic couplings g_{lq}^{22}, g_{lq}^{23}**
- **Vanishing tauonic couplings**: Tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables after Moriond 2019

Simplified U_1-leptoquark model



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- **Vanishing tauonic couplings**: Tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables after Moriond 2019
- Benchmark point explaining $R_{D^{(*)}}$,

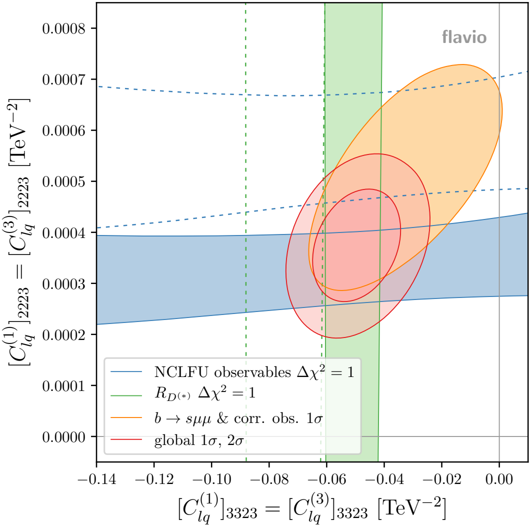
$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.7,$$

  implies non-zero $C_9^{\text{univ.}}$, $R_{K^{(*)}}$ and $b \to s\mu\mu$ in good agreement after Moriond 2019
- Constraint from **LFV observables**

New physics in individual Wilson coefficients

Coefficient	type	best fit	1σ	pull
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.97	$[-1.12, -0.81]$	$\boldsymbol{5.9\sigma}$
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.03, +0.32]$	0.8σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.75$	$[+0.62, +0.89]$	$\boldsymbol{5.7\sigma}$
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.24	$[-0.36, -0.12]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.06, +0.36]$	1.4σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.53	$[-0.61, -0.45]$	$\boldsymbol{6.6\sigma}$
C_9^{bsee}	$L \otimes V$	$+0.93$	$[+0.66, +1.17]$	3.5σ
$C_9^{\prime bsee}$	$R \otimes V$	$+0.39$	$[+0.05, +0.65]$	1.2σ
C_{10}^{bsee}	$L \otimes A$	-0.83	$[-1.05, -0.60]$	3.6σ
$C_{10}^{\prime bsee}$	$R \otimes A$	-0.27	$[-0.57, -0.02]$	1.1σ
$C_9^{bsee} = C_{10}^{bsee}$	$L \otimes R$	-1.49	$[-1.79, -1.18]$	3.2σ
$C_9^{bsee} = -C_{10}^{bsee}$	$L \otimes L$	$+0.47$	$[+0.33, +0.59]$	3.5σ
$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$	$\bar{L}R \otimes \bar{R}L$	-0.006	$[-0.009, -0.003]$	2.8σ
$\left(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}\right) \times \text{GeV}$	$\bar{R}L \otimes \bar{L}R$	-0.006	$[-0.009, -0.003]$	2.8σ

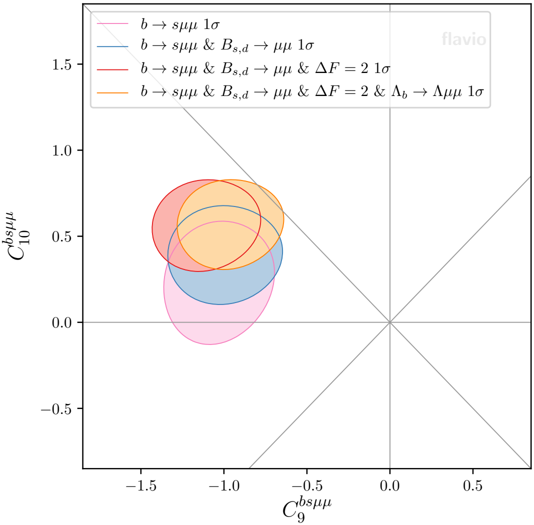
Predictions from global likelihood in SMEFT scenario



Predictions from global likelihood in SMEFT scenario

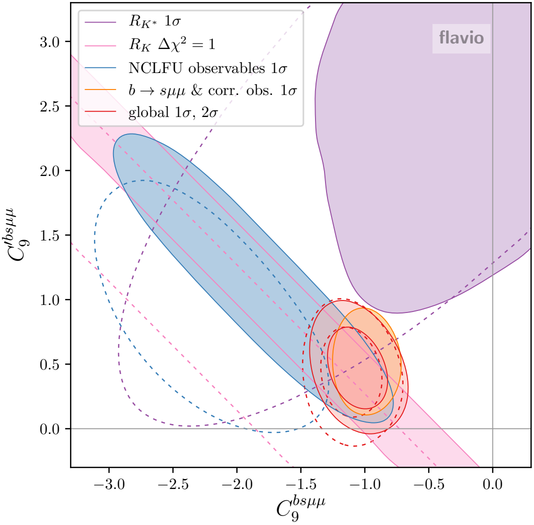
Observable	1σ	SM
$R_{K^*}^{[0.045,1.1]}$	$0.88\,^{+0.01}_{-0.01}$	0.926 ± 0.004
$R_{K^*}^{[1.1,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	0.9964 ± 0.0006
$R_{K^*}^{[0.1,8.0]}$	$0.83\,^{+0.04}_{-0.03}$	0.995 ± 0.002
$R_{K^*}^{[15,19]}$	$0.79\,^{+0.04}_{-0.04}$	0.99807 ± 0.00004
$R_{K}^{[1.0,6.0]}$	$0.80\,^{+0.04}_{-0.04}$	1.0008 ± 0.0003
$R_{\phi}^{[1.0,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	0.9970 ± 0.0003
$\langle P_5' \rangle^{[4.0,6.0]}$	$-0.58\,^{+0.13}_{-0.12}$	-0.763 ± 0.072
R_D	$0.34\,^{+0.01}_{-0.01}$	0.303 ± 0.006
R_{D^*}	$0.29\,^{+0.01}_{-0.01}$	0.255 ± 0.004
$\overline{\text{BR}}(B_s \to \mu^+\mu^-)$	$2.98\,^{+0.20}_{-0.19} \times 10^{-9}$	$(3.67 \pm 0.16) \times 10^{-9}$
$\text{BR}(B^\pm \to K^\pm\tau^+\tau^-)$	$3.05\,^{+1.78}_{-1.06} \times 10^{-5}$	$(1.66 \pm 0.19) \times 10^{-7}$
$\overline{\text{BR}}(B_s \to \tau^+\tau^-)$	$1.41\,^{+0.80}_{-0.47} \times 10^{-4}$	$(7.78 \pm 0.33) \times 10^{-7}$

C_9 vs. $C_9 = -C_{10}$



$b \to s\mu\mu$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ & $\Delta F = 2$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ & $\Delta F = 2$ & $\Lambda_b \to \Lambda\mu\mu$ 1σ
flavio
1.5
1.0
0.5
0.0
−0.5
$C_{10}^{bs\mu\mu}$
−1.5
−1.0
−0.5
0.0
0.5
$C_9^{bs\mu\mu}$

New physics in right-handed quark current



Direct contraints on U_1 leptoquark