TPPC seminar, King’s College London, 26 May 2021

The global SMEFT likelihood and applications to new physics interpretations

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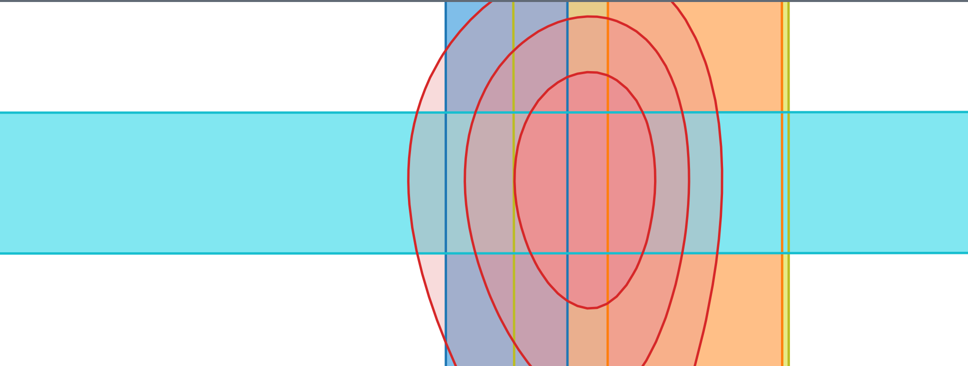
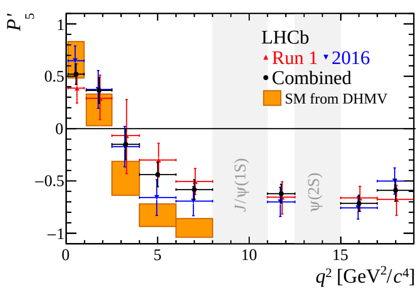


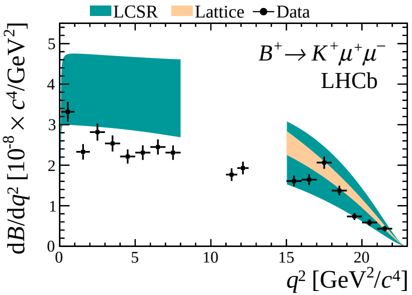
Motivation: The flavor anomalies

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

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

- Angular observables in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:2003.04831, arXiv:2012.13241
- 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



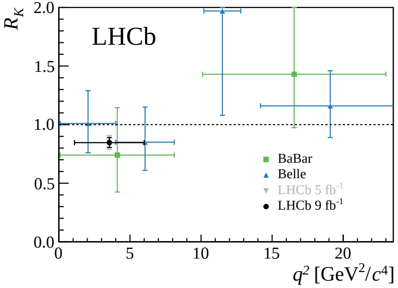


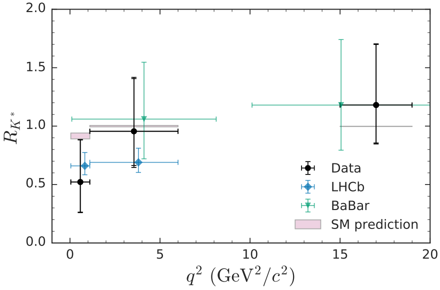
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavor universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ show deviations from SM by 2.3, 2.5, and 3.1σ.

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

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

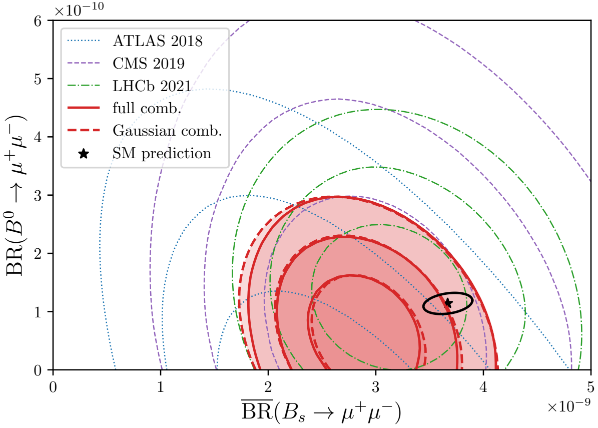




Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

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

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb seminar 23 March 2021
Altmannshofer, PS, arXiv:2103.13370



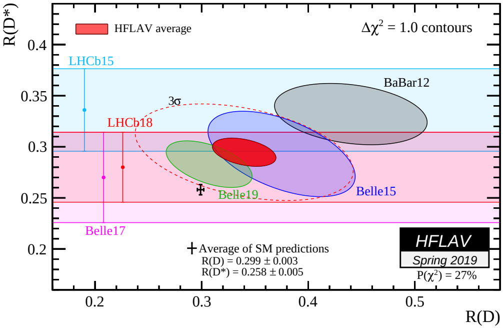
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3-4σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794

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

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



HFLAV, hflav.web.cern.ch

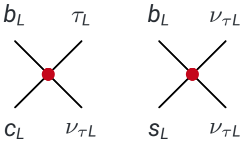
Model building - lessons learned

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

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

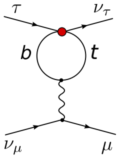
  Constrained by $B \to K \nu \bar{\nu}$ searches

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



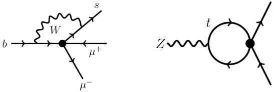
- Model explaining $R_{D^{(*)}}$ and $R_{K^{(*)}}$ using mostly 3rd gen. couplings
  Modifies LFU in τ and Z decays, strongly constrained

  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



What one would have to do

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

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

- Take into account loop / RGE effects

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

- Compare to experiment

$$\vec{\mathcal{O}}(\vec{\xi}) \to \underbrace{L_{\text{exp}}(\vec{\mathcal{O}}(\vec{\xi}))}_{\text{Likelihood}}$$

Tedious to do this for each model...

The global SMEFT likelihood

Effective field theories to the rescue

- 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

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \sum_{i} \frac{C_i}{\Lambda_{\text{NP}}^{n-4}} O_i$$

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

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

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

  - *Model-independent* pheno:

$$\vec{C} \xrightarrow{\Lambda_{\text{NP}} \to \Lambda_{\text{IR}}} \vec{\mathcal{O}}(\vec{C}) \to L_{\text{exp}}(\vec{\mathcal{O}}(\vec{C}))$$

Effective field theories to the rescue

- **SMEFT likelihood function** $L(\vec{C})$ can 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
Ellis, Madigan, Mimasu, Sanz, You, arXiv:2012.02779
...

- But these likelihood functions should **not be considered separately** since RG (loop) effects mix different sectors and UV models match to several sectors
- We need to consider the **global** SMEFT likelihood

Basis for implementation

- Computing hundreds of relevant flavour observables properly accounting for theory uncertainties
  - **flavio** `https://flav-io.github.io` Straub, arXiv:1810.08132
  - Already used in $\mathcal{O}(100)$ 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

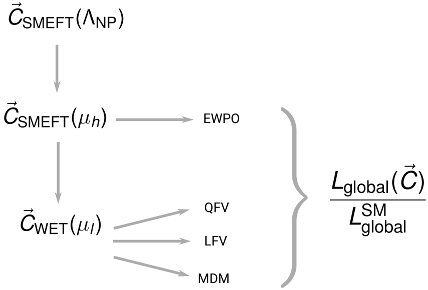
* based on DsixTools Celis, Fuentes-Martin, Vicente, Virto, arXiv:1704.04504

Implementing the global SMEFT likelihood

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

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- More than 400 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
  - $g - 2$
  - beta decays *new*
  - Higgs physics *new* Falkowski, Straub arXiv:1911.07866



- Real *global* likelihood work in progress

New physics in rare B decays

Setup

- Global likelihood from **smelli**
- Quantify agreement between theory and experiment by likelihood L, $\Delta\chi^2$, and pull

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

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

- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

$b \to s\ell\ell$ 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

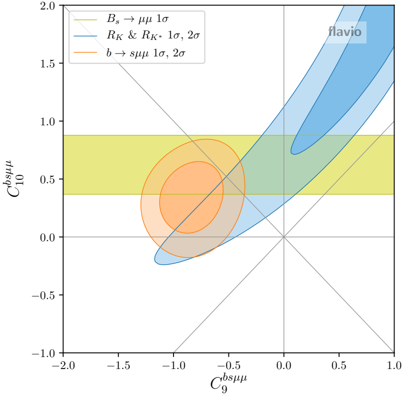
Wilson coefficient	$b \to s\mu\mu$ best fit	pull	LFU, $B_s \to \mu\mu$ best fit	pull	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Only small pull for

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

see also similar fits by other groups:
Geng et al., arXiv:2103.12738 Algueró et al., arXiv:2104.08921 Hurth et al., arXiv:2104.10058
Ciuchini et al., arXiv:2011.01212 Datta et al., arXiv:1903.10086 Kowalska et al., arXiv:1903.10932

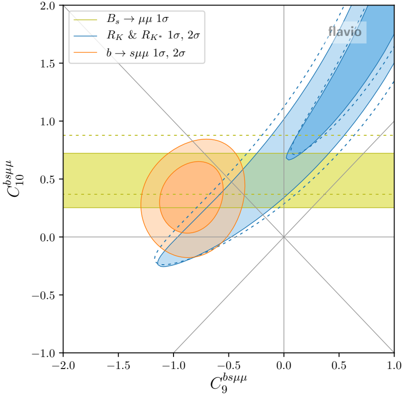
Scenarios with two Wilson coefficients



- **Before Moriond 2021**

WET at 4.8 GeV

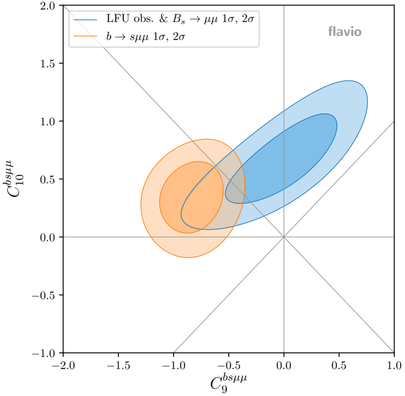
Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **After Moriond 2021**:
  - R_K: smaller uncertainty
  - $B_s \to \mu\mu$: smaller uncertainty, better agreement with $b \to s\mu\mu$

Scenarios with two Wilson coefficients



Combination of $B_s \to \mu^+\mu^-$ and NC LFU observables ($R_K, R_{K^*}, D_{P_{4',5'}}$)

- NCLFU obs. & $B_s \to \mu\mu$: very clean theory prediction, insensitive to universal $C_9^{\text{univ.}}$
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.

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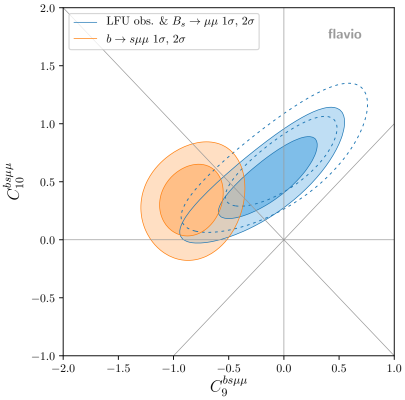

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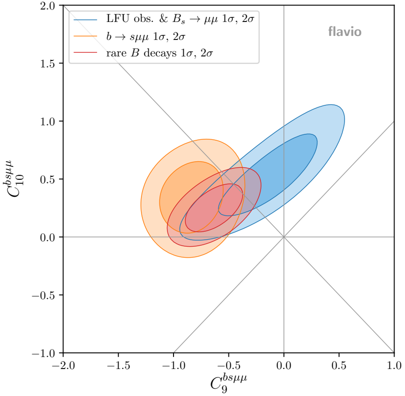
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.

- **After Moriond 2021**:
  - **LFU obs. & $B_s \to \mu\mu$**: smaller uncertainty, better agreement with $b \to s\mu\mu$

WET at 4.8 GeV

Scenarios with two Wilson coefficients

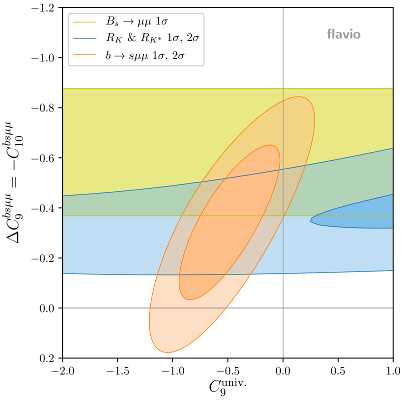


WET at 4.8 GeV

- Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$

Scenarios with two Wilson coefficients

- **Before Moriond 2021**



WET at 4.8 GeV

- Perform two-parameter fit in space of $C_9^{\text{univ.}}$ and $\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$:

$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ.}}$$
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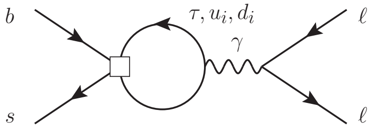
scenario first considered in
Algueró et al., arXiv:1809.08447

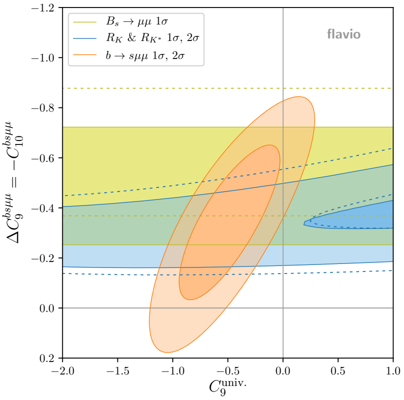
- Preference for **non-zero $C_9^{\text{univ.}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



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

Scenarios with two Wilson coefficients

- **After Moriond 2021**:
  smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \to \mu\mu$



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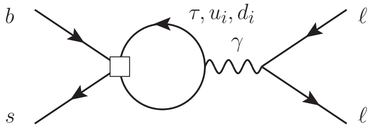

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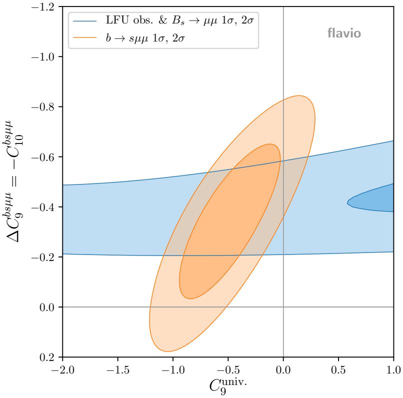

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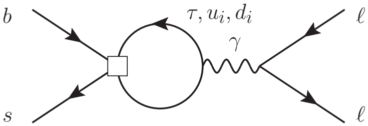

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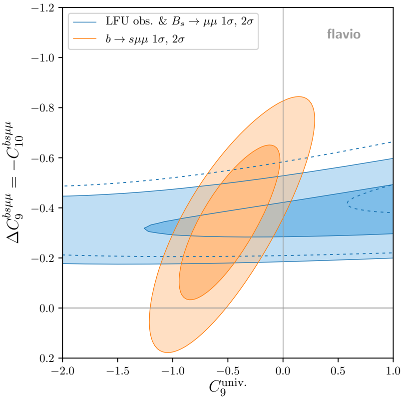
Scenarios with two Wilson coefficients

- **After Moriond 2021**:
  smaller uncertainty, better agreement



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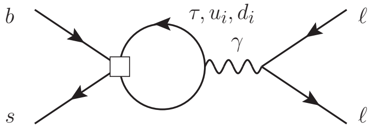

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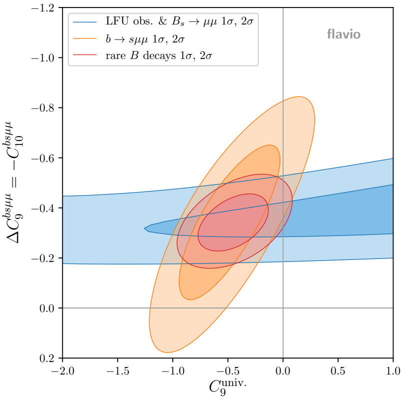

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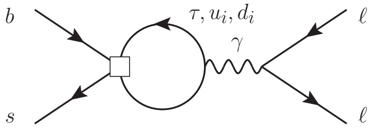
$$C_9^{bs\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu}$$
$$C_{10}^{bsee} = C_{10}^{bs\tau\tau} = 0$$
$$C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu}$$

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

- Preference for **non-zero $C_9^{\text{univ.}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



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

Analysis of an explicit model

An explicit model

Model setup:

- Effect in $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ can be generated at tree level by scalar leptoquark $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ Hiller, Schmaltz, arXiv:1408.1627
- Generic S_3 couples to all lepton generations $\Rightarrow$ **Lepton Flavour Violation** (LFV)
- Generic S_3 has di-quark couplings $\Rightarrow$ **proton decay**
- **Strong experimental constraints** on LFV and proton decay

Idea:

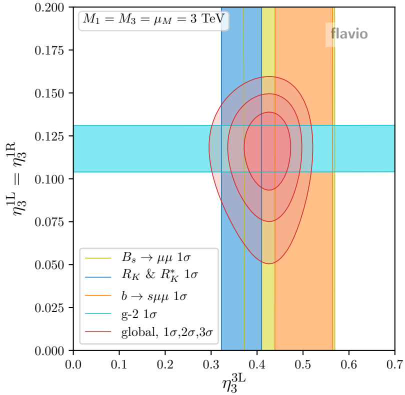
- Charge S_3 and muon under **new U(1) gauge symmetry** such that
  - S_3 cannot couple to two quarks $\Rightarrow$ prevents proton decay
  - Muon is only lepton that couples to S_3 $\Rightarrow$ prevents LFV

Hambye, Heeck, arXiv:1712.04871
Davighi, Kirk, Nardecchia, arXiv:2007.15016

- Second leptoquark $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ charged under **same U(1)** gauge symmetry receives same protection (only coupling to muons, no LFV, no proton decay) $\Rightarrow$ "**Muoquark**" models **explaining** $\mathbf{R_{K^{(*)}}}$ and $(\mathbf{g}-\mathbf{2})_\mu$

Greljo, PS, Thomsen, arXiv:2103.13991

A model for muon anomalies



$$\eta_i^{3L} = (V_{td},\ V_{ts},\ 1)\,\eta_3^{3L}$$
$$\eta_i^{1L} = (V_{td},\ V_{ts},\ 1)\,\eta_3^{1L}$$
$$\eta_i^{1R} = (0,\ 0,\ 1)\,\eta_3^{1R}$$

- Model for muon anomalies:
  $\mathcal{L} \supset \eta_i^{3L}\,\overline{q}_L^{c\,i}\ell_L^2\,S_3 + \eta_i^{1L}\overline{q}_L^{c\,i}\ell_L^2\,S_1 + \eta_i^{1R}\overline{u}_R^{c\,i}\mu_R S_1$
- One-loop matching to SMEFT
  Gherardi, Marzocca, Venturin, arXiv:2003.12525
- Interface to **smelli** using SMEFT Wilson coefficients
- Likelihood in space of model parameters
- Excellent fit to data with best fit point at $(\eta_3^{3L}, \eta_3^{1L} = \eta_3^{1R}) \simeq (0.43, 0.12)$ and $\Delta\chi^2 \simeq 62$ compared to SM point $(0, 0)$
- Compatible with all measurements included in smelli (>400 observables)

Conclusions

Conclusions

- Discrepancies between SM and experimental data, e.g. in B decays, $(g-2)_\mu$
- Models explaining them generically predict effects in other observables
- **Global likelihood** package `smelli`
  - Test models
  - Interpret data model-independently in WET and SMEFT
  - Currently more than 400 flavour and other precision observables included
  - Real *global* likelihood is work in progress
  - Completely open source!
    You are welcome to participate → `https://github.com/smelli/smelli`
- Application to rare B decays
  - New physics in the single muonic Wilson coefficients $\boldsymbol{C_9^{bs\mu\mu}}$, $\boldsymbol{C_{10}^{bs\mu\mu}}$, and $\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$ gives clearly better fit to data than SM ($\text{pull}_{1D} \gtrsim 5\sigma$).
  - Slight tension between $R_{K^{(*)}}$ and $b \to s\mu\mu$ in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ scenario can be reduced by **lepton flavor universal $\boldsymbol{C_9^{\text{univ.}}}$**.
- Analysis of a model
  - S_3 model can be protected from proton decay and LFV by new $U(1)$ gauge symmetry that makes the S_3 a **muoquark** (coupling only to 2nd gen. leptons).
  - Same mechanism can be used for S_1 muoquark explaining $(g-2)_\mu$.

Backup slides

Effective Field Theory (EFT)

EFT example: Fermi Theory for muon decay

$$\mathcal{L}_{\text{EFT}} \supset \frac{4\,G_F}{\sqrt{2}}\,(\bar{\nu}_\mu \gamma^\alpha \mu_L)(\bar{e}_L \gamma_\alpha \nu_e)$$

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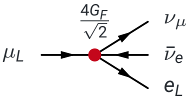

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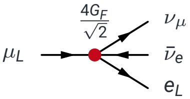

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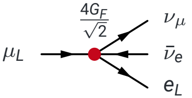

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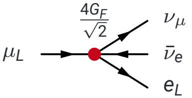

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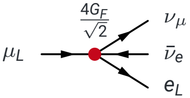

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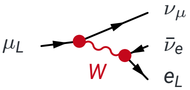

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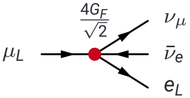

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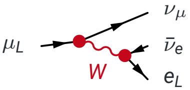

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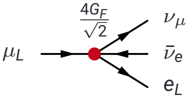

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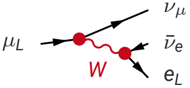

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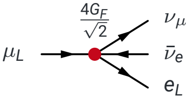

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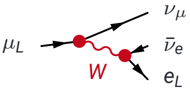

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- Going from UV theory to EFT, heavy W is removed: "integrated out"

EFT: Two approaches

- **Top-Down approach**: start with UV theory
  - Integrate out heavy particles with masses $m \approx \Lambda$
  - Obtain EFT containing non-renormalizable operators suppressed by powers of Λ
  - Wilson coefficients calculable from UV theory

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  - Integrate out heavy particles with masses $m \approx \Lambda$
  - Obtain EFT containing non-renormalizable operators suppressed by powers of Λ
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- **Bottom-Up approach**: start with field content & symmetries at low energy
  - Consider all operators allowed by symmetries constructed from fields
  - Non-renormalizable operators are suppressed by powers of cutoff Λ
  - Wilson coefficients constrained by experimental data

EFT from Standard Model

- Top-Down: **Weak Effective Theory (WET)**
  - Integrate out W, Z, h, t
  - Effective theory below the electroweak (EW) scale

EFT from Standard Model

- Top-Down: **Weak Effective Theory (WET)**
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- Bottom-Up: **Standard Model Effective Field Theory (SMEFT)**
  - Consider all operators invariant under SM gauge group constructed from SM fields

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \sum_{i} \frac{C_i}{\Lambda_{\text{NP}}^{n-4}} O_i$$

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

  - If new physics (NP) scale Λ_{NP} well above EW scale, series can be truncated
  - Here we consider SMEFT for $n \leq 6$
  - SMEFT parameterises *any* NP model with particles well above EW scale
  - SMEFT Wilson coefficients can be computed for a given NP model
  - Observables can be computed in SMEFT and Wilson coefficients can be constrained/estimated using experimental data

Likelihood

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- Likelihood $L(\vec{\theta})$ *is not* the probability of $\vec{\theta}$ given some data $\vec{d}$. It is still the probability of observing the data $\vec{d}$ for a given $\vec{\theta}$ but considered as a function of $\vec{\theta}$ for fixed $\vec{d}$.

Likelihood

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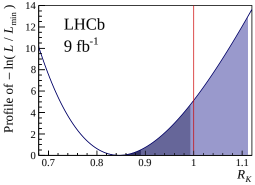
$$L(\vec{\mathcal{O}}) = L(\vec{\mathcal{O}}|\vec{d})$$



LHCb, arXiv:2103.11769

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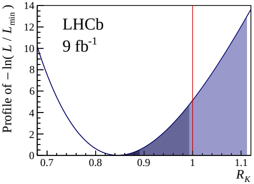

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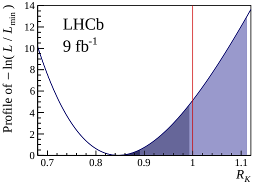

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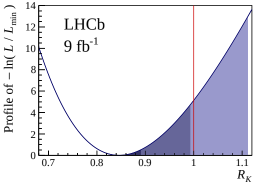

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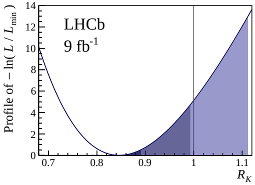

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- Estimate Wilson coefficients $\vec{C}$ by maximizing $L(\vec{C})$
- Compare different points in Wilson coefficient space $\vec{C}_1$ and $\vec{C}_2$ by Likelihood ratio

$$\frac{L(\vec{C}_1)}{L(\vec{C}_2)}$$

More on the Likelihood

The likelihood

Construct **likelihood** that quantifies the agreement between **experimental data** and **theoretical predictions**

- Experimental data of measurement *i* yields **experimental likelihood** for **observables $\vec{O}$**

$$\mathcal{L}^i_{\text{exp}}(\vec{O})$$

  - non-trivial likelihood function for one or several correlated observables
  - uniform likelihood for observables not measured by measurement *i*

- In SM or NP model, **theory predictions** in terms of theory parameters $\vec{C}$ and $\vec{\theta}$

$$\vec{O}_{\text{th}}(\vec{C}, \vec{\theta})$$

  $\vec{C}$: NP Wilson coefficients, defined such that SM is given by $\vec{C} = \vec{0}$
  $\vec{\theta}$: model-independent theory parameters (e.g. particle masses, hadronic form factors, ...)

The likelihood

- Define individual likelihoods in theory parameters

$$\mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) = \mathcal{L}^i_{\text{exp}}(\vec{O} = \vec{O}_{\text{th}}(\vec{C},\vec{\theta}))$$

- Define full likelihood taking into account parametric theory uncertainties

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta})$$

- Assumptions:
  - Measurements are independent of each other
  - Measurements do not explicitly depend on theory parameters (only through $\vec{O}_{\text{th}}$)

The New Physics likelihood

In the New Physics likelihood, all parameters $\vec{\theta}$ are **nuisance parameters**

- How do we get a “nuisance-free” likelihood?

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \overset{?}{\rightarrow} \quad \mathcal{L}(\vec{C})$$

- **Bayesian approach**:
  Interpret $\mathcal{L}_{\text{th}}(\vec{\theta})$ as *prior* and $\mathcal{L}(\vec{C})$ as *posterior*, marginalise over nuisance parameters
- **Frequentist approach**:
  Interpret $\mathcal{L}_{\text{th}}(\vec{\theta})$ as *likelihood of pseudo-experiments* and $\mathcal{L}(\vec{C})$ as *profiled likelihood*

For large numbers of nuisance parameters $\vec{\theta}$ and NP parameters $\vec{C}$, both approaches are **computationally expensive**.

What special cases exist that allow obtaining a “nuisance-free” likelihood **computationally *in*expensive** and that could serve as reasonable approximations?

Approximations: Case 1

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \overset{?}{\rightarrow} \quad \mathcal{L}(\vec{C})$$

Special case 1:

$$\mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \approx \mathcal{L}^i_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \qquad \text{for } \vec{\theta} \text{ sampled from } \mathcal{L}_{\text{th}}(\vec{\theta})$$

this is the case for **small parametric uncertainty of theory prediction** compared to experimental uncertainty e.g.

- Ratios of branching ratios like $R_{K^{(*)}}$, $R_{D^{(*)}}$
- Electroweak precision observables
- LFV decays
- ...

$$\Rightarrow \qquad \mathcal{L}(\vec{C}) \approx \prod_{i \in \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \times \mathcal{L}'(\vec{C})$$

Approximations: Case 2

$$\mathcal{L}'(\vec{C},\vec{\theta}) = \prod_{i\notin \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \overset{?}{\to} \quad \mathcal{L}'(\vec{C})$$

Special case 2:

- Theoretical **prediction likelihood** of subset of observables $\vec{O}^k$ can be approximated as multivariate **normal distribution** for given $\vec{C}$

$$-2\ln \mathcal{L}_{\text{th}}(\vec{O}^k,\vec{C}) = \left(\vec{O} - \vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}})\right)^T \Sigma_{\text{th}}^{-1} \left(\vec{O} - \vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}})\right) \,,$$

  with **covariance matrix** Σ_{th} determined for $\vec{C} = \vec{0}$ and (approximately) **independent of $\vec{C}$**

- Approximate **experimental likelihoods** for measurements of observables $\vec{O}^k$ as multivariate **normal distributions**

$$-2\ln \mathcal{L}^i_{\text{exp}}(\vec{O}^k) = (\vec{O}^k - \hat{\vec{O}}^{k,i})^T (\Sigma^i_{\text{exp}})^{-1} (\vec{O}^k - \hat{\vec{O}}^{k,i}) \,,$$

  $\hat{\vec{O}}^{k,i}$ exp. central value, Σ^i_{exp} covariance matrix

Approximations: Case 2

- Combine $\mathcal{L}^i_{\text{exp}}(\vec{O}^k)$ ($i \in$ case 2) in terms of **weighted averaged** covariance matrix Σ_{exp} and mean $\hat{\vec{O}}^k$

- Define **modified experimental likelihood** $\tilde{\mathcal{L}}_{\text{exp}}(\vec{O}^k)$

$$-2\ln\tilde{\mathcal{L}}_{\text{exp}}(\vec{O}^k) = (\vec{O}^k - \hat{\vec{O}}^k)^T(\Sigma_{\text{exp}} + \Sigma_{\text{th}})^{-1}(\vec{O}^k - \hat{\vec{O}}^k)\,,$$

  Takes into account theoretical uncertainties and correlations in terms of covariance matrix Σ_{th}, treated as additional experimental uncertainties

- Express in terms of $\vec{C}$ and $\hat{\vec{\theta}}$

$$-2\ln\tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) = \left(\vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}}) - \hat{\vec{O}}^k\right)^T(\Sigma_{\text{exp}} + \Sigma_{\text{th}})^{-1}\left(\vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}}) - \hat{\vec{O}}^k\right)\,,$$

$$\Rightarrow \qquad \mathcal{L}'(\vec{C}) \approx \tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \times \mathcal{L}''(\vec{C})$$

The New Physics likelihood

The (approximative) **global New Physics likelihood** Aebischer, Kumar, PS, Straub, arXiv:1810.07698

$$\mathcal{L}(\vec{C}) \approx \prod_{i \in \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C}, \hat{\vec{\theta}}) \times \tilde{\mathcal{L}}_{\text{exp}}(\vec{C}, \hat{\vec{\theta}})$$

- $\prod_{i \in \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C}, \hat{\vec{\theta}})$: negligible parametric theory uncertainties

  e.g. EFT fits to electroweak precision tests:
  Efrati, Falkowski, Soreq, arXiv:1503.07872
  Falkowski, González-Alonso, Mimouni, arXiv:1706.03783

- $\tilde{\mathcal{L}}_{\text{exp}}(\vec{C}, \hat{\vec{\theta}})$: theoretical and experimental uncertainties combined at $\vec{C} = \vec{0}$ (SM)

  EFT fits of rare B decays first in: Altmannshofer, Straub, arXiv:1411.3161
  also used by other groups, e.g. Descotes-Genon, Hofer, Matias, Virto, arXiv:1510.04239

Advantages and disadvantages of approximations

Disadvantages

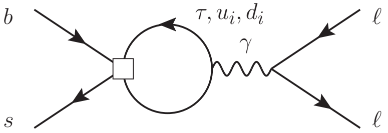
- Theory uncertainties only weakly dependent on New Physics $\vec{C}$: **strong assumption**, validity has to be **checked explicitly** (e.g. by computing $\Sigma_{\rm th}(\vec{C} \neq \vec{0})$)
- **Not able to include certain observables**, e.g. electric dipole moments afflicted by sizable hadronic uncertainties for $\vec{C} \neq \vec{0}$ but negligible ones for $\vec{C} = \vec{0}$

Advantages

- Computationally expensive determination of $\Sigma_{\rm th}$
  - has to be done **only once**
  - is **independent of experimental data**
  - computing time is **independent of number of nuisance parameters**
- Computation of global likelihood **fast** enough for **phenomenological analysis of New Physics** models ($\sim$ 5 sec. per point on laptop)

RG effects in SMEFT

RG effect in SMEFT

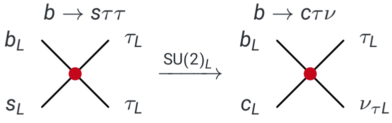


RG effects require scale separation

- Consider **SMEFT**

Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3\gamma_\mu\tau^a l_3)(\bar{q}_2\gamma^\mu\tau^a q_3)$:
  Might 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 $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$

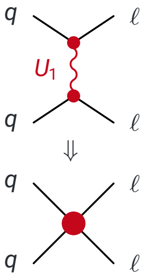
Buras et al., arXiv:1409.4557

- **U_1 vector leptoquark** $(\mathbf{3}, \mathbf{1})_{2/3}$ couples LH fermions

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

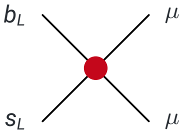
- Generates **semi-leptonic operators at tree-level**

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



Models for $b \to s\ell\ell$ anomalies

Models for $b \to s\ell\ell$ anomalies

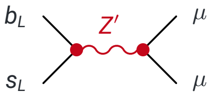


$$\sim \frac{C_9^\mu - C_{10}^\mu}{(34\,\text{TeV})^2}$$

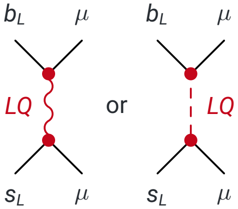
Global fits suggest

$$\boldsymbol{C_9^\mu - C_{10}^\mu \approx -0.9, \qquad 0 \gtrsim \frac{C_{10}^\mu}{C_9^\mu} \gtrsim -1}$$

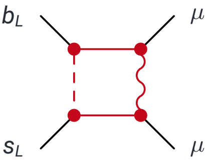
$$O_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)\,, \quad O_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2}$$

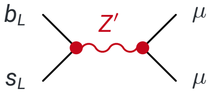


$$\sim \frac{g_{b\mu}\, g_{s\mu}}{m_{LQ}^2}$$

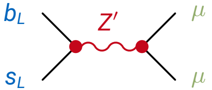


$$\sim \frac{g_b\, g_s\, g_{\mu,1}\, g_{\mu,2}}{16\,\pi^2\, m_{\text{NP}}^2}$$

Z'

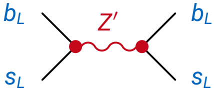


Z': Constraints from B_s-$\bar{B}_s$ mixing



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(36\,\text{TeV})^2}$$

$\rightarrow$



$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \Big/ 10\%}{(244\,\text{TeV})^2}$$

$$\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \approx 10\%$$

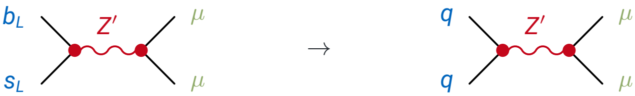
$$\Downarrow$$

$$\frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{5.3\,\text{TeV}}$$

Ways around:

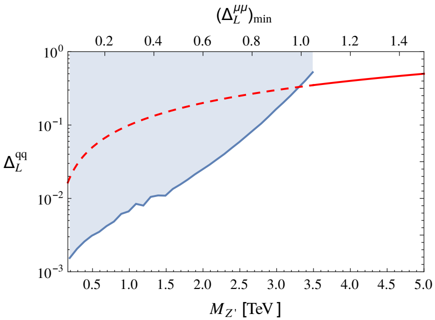
- imaginary part of g_{bs} $\rightarrow$ constraints from *CP* violating observables
- Z' coupling to $(\bar{s}\gamma_\mu P_R b)$ $\rightarrow$ constraint from $R_K \approx R_{K^*}$
- ...

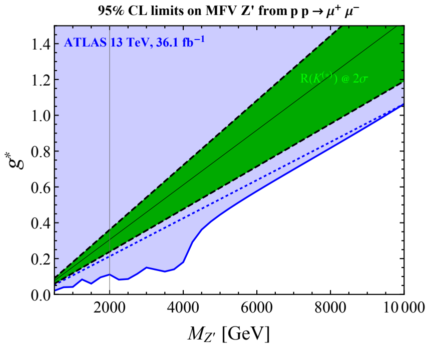
Z': Constraints from $pp \to \mu\mu$



- Direct searches for a Z' resonance
- Searches for quark-lepton contact interactions

Z': Constraints from $pp \to \mu\mu$



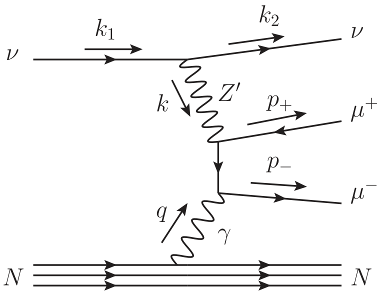


Altmannshofer, Straub, arXiv:1411.3161

Greljo, Marzocca, arXiv:1704.09015

- Couplings to light quarks must be suppressed for $m_{Z'} < 4.5$ TeV
- MFV-like Z'-quark couplings already excluded

Z': Constraints from neutrino trident production

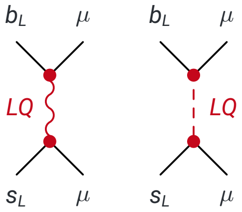


Altmannshofer, Gori, Pospelov, Yavin, arXiv:1406.2332

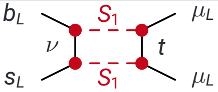
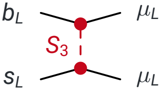
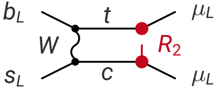
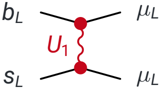
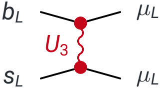
- $\mu^+\mu^-$ production induced by neutrino in Coulomb field of heavy nucleus
- Cross section with Z' contribution

$$\frac{\sigma}{\sigma_{SM}} \simeq \frac{1 + \left(1 + 4\, s_W^2 + 2\, v^2 \frac{g_{Z'}^2}{m_{Z'}^2}\right)^2}{1 + \left(1 + 4\, s_W^2\right)^2}$$

Leptoquarks

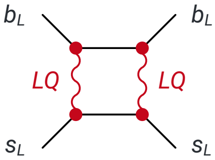


Leptoquarks: possible solutions for $b \to s\mu\mu$

Spin	$G_{\rm SM}$	Name	Characteristic process	
0	$(\bar{3}, 1)_{1/3}$	S_1		Bauer, Neubert, arXiv:1511.01900
0	$(\bar{3}, 3)_{1/3}$	S_3		Hiller, Schmaltz, arXiv:1408.1627
0	$(3, 2)_{7/6}$	R_2		Bečirević, Sumensari, arXiv:1704.05835
1	$(3, 1)_{2/3}$	U_1		Barbieri et al., arXiv:1512.01560
1	$(3, 3)_{2/3}$	U_3		Fajfer, Košnik, arXiv:1511.06024

Leptoquarks: B_s-$\bar{B}_s$ mixing loop-suppressed

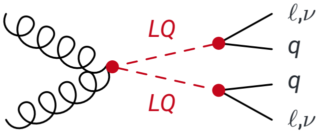
- Generic strong constraint on Z' models is loop-suppressed for leptoquark models



- Big advantage compared to Z'

Leptoquarks: direct constraints

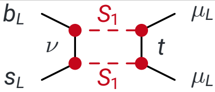
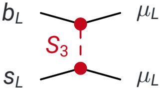
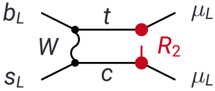
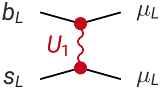
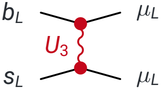
- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

Leptoquarks: still viable solutions for $b \to s\mu\mu$

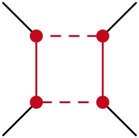
Spin	G_{SM}	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3},1)_{1/3}$	S_1		X	requires too large couplings
0	$(\bar{3},3)_{1/3}$	S_3		✓	
0	$(3,2)_{7/6}$	R_2		X	tension with LHC limits
1	$(3,1)_{2/3}$	U_1		✓	
1	$(3,3)_{2/3}$	U_3		✓	

cf. Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

Loop models

- New scalars and vector-like fermions

Gripaios, Nardecchia, Renner, arXiv:1509.05020
Arnan, Crivellin, Hofer, Mescia, arXiv:1608.07832



$\rightarrow$ ΔM_s always enhanced except with Majorana fermions

Blanke, Buras, arXiv:hep-ph/0610037
Arnan, Crivellin, Hofer, Mescia, arXiv:1608.07832

- Fundamental partial compositeness:
New scalars and vector-like fermions charged under new strong interaction

D'Amico et al., arXiv:1704.05438
Sannino, PS, Straub, Thomsen, arXiv:1712.07646