A Global Likelihood for Precision Constraints and Flavour Anomalies

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Outline

Based on:

Jason Aebischer, Jacky Kumar, PS, David M. Straub [arXiv:1810.07698]

Outline

Hurdles for model building

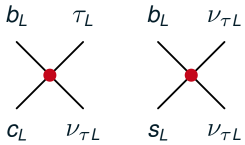
Hurdles for model building

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

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

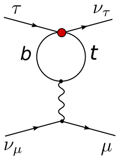
Constrained by $B \to K \nu \bar{\nu}$ searches

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

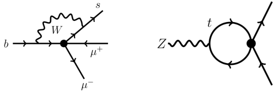
Feruglio, Paradisi, Pattori, arXiv:1705.00929



- 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

see talk by Darius Faroughy



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 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 a 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
- In practice we have considered

see talk by Martín González-Alonso

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

cf. eg. Falkowski, González-Alonso, Mimouni, arXiv:1706.03783
Ellis, Murphy, Sanz, You, arXiv:1803.03252

- 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

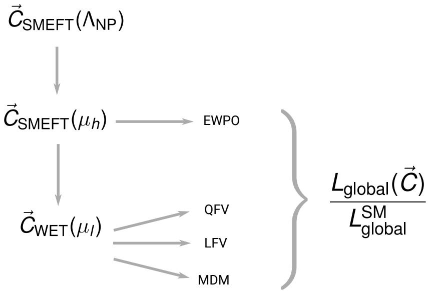
* based on DsixTools Celis, Fuentes-Martin, Vicente, Virto, arXiv:1704.04504

Building a global SMEFT likelihood

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

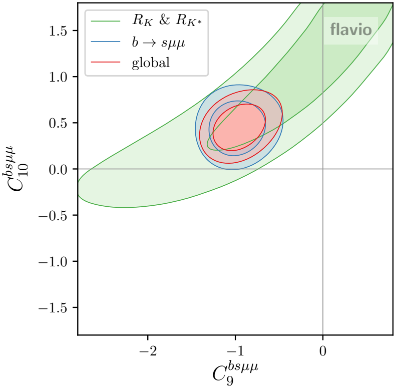
- Based on these tools, we have started building the **SME**FT **Like**L**I**hood
  - **smelli** `https://github.com/smelli`

- So far, 257 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
  - $g-2$



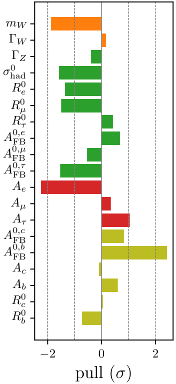
Outline

Likelihood maps: $b \to s\ell\ell$ anomalies



- Since *B* phyiscs constraints are included in the likelihood, the usual $b \to s\ell\ell$ Wilson coefficient are one example application (using WET WCs here)
- Disclaimer: this and the following two-coefficient plots are only meant for illustration – main point of the global likelihood is to *not* be restricted to 2D subspaces

Electroweak precision tests



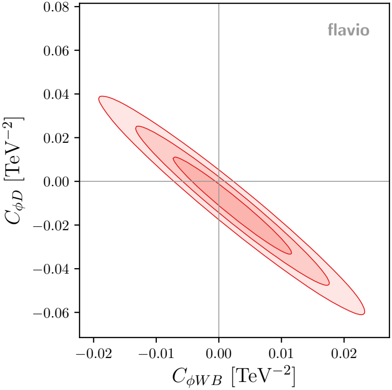
- We have implemented all the relevant Z and W pole observables, not assuming LFU, in `flavio`

  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



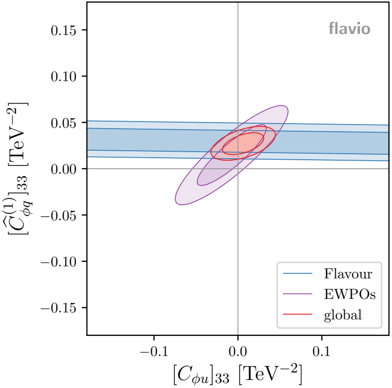
- Reproducing the EWPO constraint on the electrowewak S and T parameters

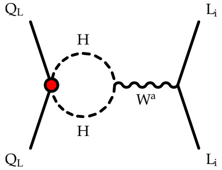
$$S \propto C_{\phi WB}, \quad T \propto -C_{\phi D}$$

$$O_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$$

$$O_{\phi WB} = \phi^\dagger \tau^I \phi W^I_{\mu\nu} B^{\mu\nu}$$

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

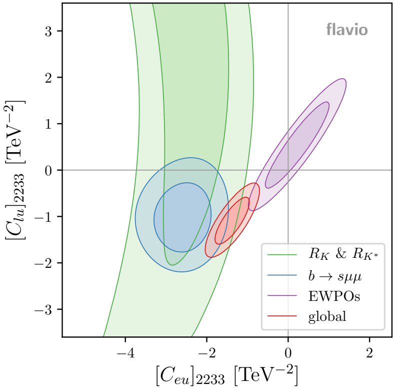


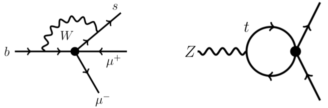


- Modfications of LH vs. RH $Zt\bar{t}$ couplings (in basis where up-type quark mass matrix is diagonal)
- Complementarity between flavour ($B_s \to \mu^+\mu^-$) and EW ($Z \to b\bar{b}$, T) constraints
  Brod, Greljo, Stamou, Uttayarat, arXiv:1408.0792
- Plot: WC at 1 TeV, up-aligned basis

B anomalies from NP in top

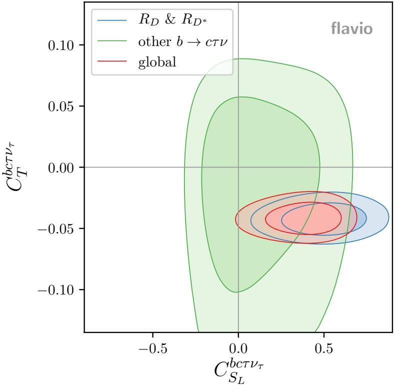
see talk by Darius Faroughy





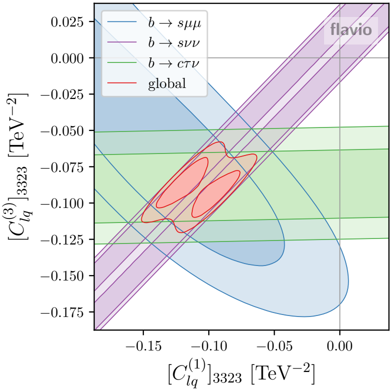
- $[C_{eu}]_{2233}$, i.e. RH $tt\mu\mu$ operator, suggested as solution to $b \to s\ell\ell$ anomalies in Celis et al., arXiv:1704.05672
  - see Z' model in Kamenik et al., arXiv:1704.06005
- Later realized that there are strong constraints from $Z \to \mu\mu$ Camargo-Molina, Celis, Faroughy, arXiv:1805.04917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

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 R_2 leptoquark scenario
  Becirevic, Sumensari, arXiv:1704.05835
  see talk by Olcyr Sumensari
- 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

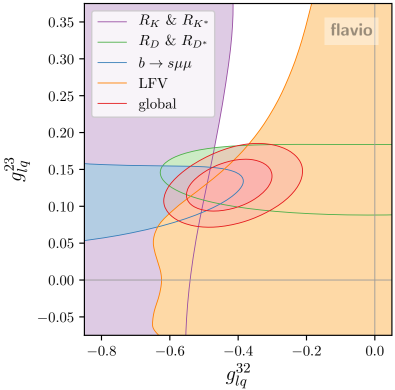
LLLL solutions to B anomalies



- 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

Vector leptoquark (U_1) solution to B anomalies

see talks by Luca Di Luzio and Javier Fuentes-Martin



- Suggested in Barbieri et al., arXiv:1512.01560
- Does not generate $B \to K\nu\nu$ at tree level
  Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557
- Couplings:

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

  - $b \to s\mu\mu$ requires $g_{lq}^{22} g_{lq}^{23*}$
  - $b \to c\tau\nu$ requires $g_{lq}^{32} g_{lq}^{33*}$
  - $\tau \to \phi\mu$ constrains $g_{lq}^{32} g_{lq}^{22*}$

$m_{U_1} = 1\,\text{TeV} \quad g_{lq}^{33} = 1 \quad g_{lq}^{22} = 0.04^2 \approx V_{cb}^2$

Outline

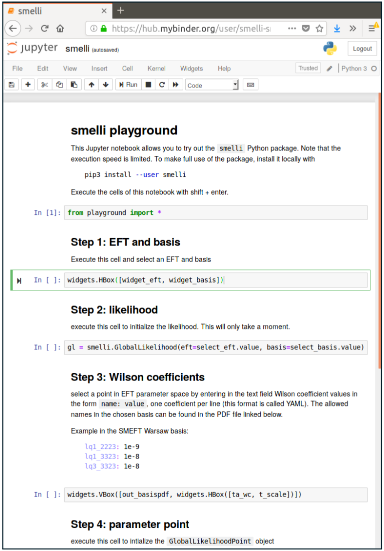
Installing `smelli`

- 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

Outline

Conclusions

- New likelihood function in space of dim-6 SMEFT Wilson coeffcients
- Inlcudes 257 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

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
$\langle \frac{dBR}{dq^2} \rangle (B_s \to \phi\mu^+\mu^-)^{[1.0,6.0]}$	$(5.37 \pm 0.65) \times 10^{-8}\ \frac{1}{\mathrm{GeV}^2}$	$(2.57 \pm 0.37) \times 10^{-8}\ \frac{1}{\mathrm{GeV}^2}$	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
$\langle A_{FB}^{\ell h} \rangle (\Lambda_b \to \Lambda\mu^+\mu^-)^{[15,20]}$	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
$\mathrm{BR}(W^\pm \to \tau^\pm\nu)$	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
$\langle \frac{dBR}{dq^2} \rangle (B^\pm \to K^\pm\mu^+\mu^-)^{[15.0,22.0]}$	$(1.56 \pm 0.12) \times 10^{-8}\ \frac{1}{\mathrm{GeV}^2}$	$(1.210 \pm 0.072) \times 10^{-8}\ \frac{1}{\mathrm{GeV}^2}$	2.5σ
$A_{FB}^{0,b}$	10.31×10^{-2}	$(9.92 \pm 0.16) \times 10^{-2}$	2.4σ
$\langle \frac{dBR}{dq^2} \rangle (B^0 \to K^0\mu^+\mu^-)^{[15.0,22.0]}$	$(1.44 \pm 0.11) \times 10^{-8}\ \frac{1}{\mathrm{GeV}^2}$	$(9.6 \pm 1.6) \times 10^{-9}\ \frac{1}{\mathrm{GeV}^2}$	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