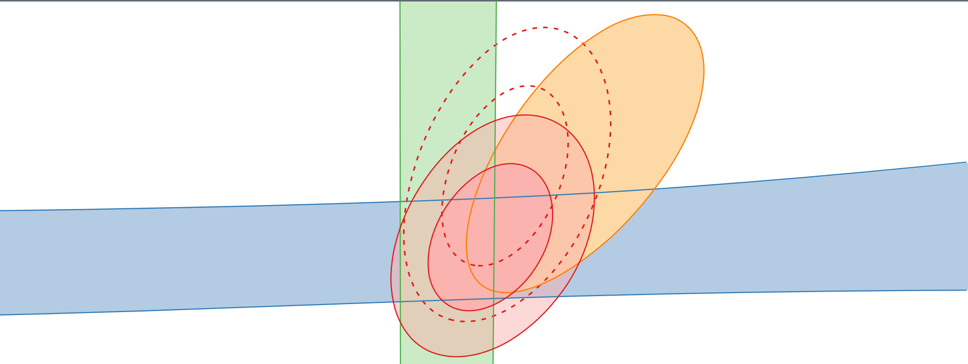
$b \to s\ell\ell$ within the global SMEFT likelihood

David M. Straub Universe Cluster/TUM, Munich



Motivation

- The Weak Effective Theory (WET) is a very useful *tool* because it allows a **general parametrization of NP** in $b \to s\ell\ell$ (apart from some crazy models).
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So should we abandon the WET?

Of course not, but we should not consider it in isolation when interpreting anomalies in terms of NP.

B anomalies: lessons learned

When constructing models to solve the neutral- or charged-current B anomalies, new effects in different sectors pop up, e.g.

- neutrino trident production Altmannshofer, Gori, Pospelov, and Yavin 1406.2332
- Shift in ΔM_s Altmannshofer and DMS 1308.1501
- $B_s \to \tau\tau$ ...
- $B \to K\tau\mu$ Glashow, Guadagnoli, and Lane 1411.0565
- $\tau \to \varphi\mu$ Kumar, London, and Watanabe 1806.07403
- $\tau \to \ell\nu\nu$ Feruglio, Paradisi, and Pattori 1606.00524
- $b \to s\mu\mu$ loop-induced by $b \to s\tau\tau$ Crivellin, Greub, Müller, and Saturnino 1807.02068
- ...

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Some of these effects took the community years to realize!

How to solve this “once and for all” without commiting to a model?

1 Global SMEFT likelihood

- Introduction
- Inputs
- Differences to traditional approach to $b \to s\ell\ell$

2 Applications

- Charged- vs. neutral-current B anomalies in SMEFT
- U_1 leptoquark
- LFU C_9 from charming NP

3 CKM elements in the global SMEFT likelihood

4 Conclusions

SMEFT: *lingua franca* for new physics from flavour to Higgs

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D>4} \sum_i \frac{1}{\Lambda_{\text{NP}}^{D-4}} C_i^{(D)} O_i^{(D)}$$

Buchmuller and Wyler; Grzadkowski, Iskrzynski, Misiak, and Rosiek 1008.4884

Model-independent parametrization of new physics in

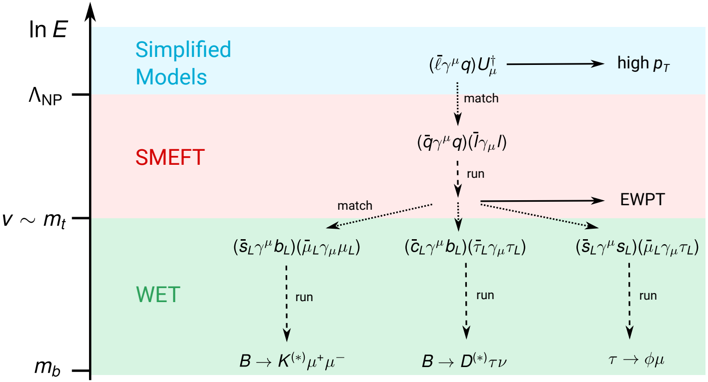
- low-energy processes (quark flavour, lepton flavour, magnetic moments, ...)
- EW & Higgs physics
- top physics
- high-p_T processes as long as $E \ll \Lambda_{\text{NP}}$

Assumptions

- $\Lambda_{\text{NP}} \gg v$ (as hinted by LHC unfortunately)
- No new light particles (but can be extended)
- Approximately linearly realized EWSB (but OK if $f \gg v$)

Hierarchy of (effective) theories

- Example: the $U_1 \sim (3,1)_{2/3}$ vector leptoquark



- WET is completely general
- SMEFT allows studying correlations between CC & NC, flavour & EWPT
- Simplified Models allow studying constraints by direct searches

Global SMEFT likelihood

- Express all measurements as likelihoods in observable space

$$\ln L(\vec{\mathcal{O}})$$

- Express all observables as functions of SMEFT WCs (at an appropriate scale)

$$\mathcal{O}(\vec{C}_{\text{SMEFT}}, \vec{n})$$

- Get rid of nuisance parameters $\vec{n}$
  - we use the “SM covariance” approach known (to you) from $b \to s\ell\ell$ fits, no marginalization/profiling necessary!
- Outcome:

$$\ln L(\vec{C}_{\text{SMEFT}}) = \ln L(\mathcal{O}(\vec{C}_{\text{SMEFT}}, \vec{n}_0))$$

Building a global SMEFT likelihood: requirements

1. An agreed upon convention and exchange format for thousands of WCs (ideally supported by multiple tools)
2. Implementation of RG running and matching of *all* dimension-6 WCs above and below the EW scale
3. Expression of all relevant observables in terms of WCs at appropriate scale

Building a global SMEFT likelihood: requirements

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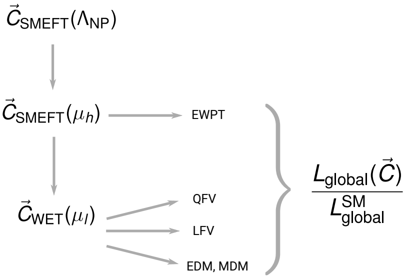
1. **Wilson coefficient exchange format (WCxf)** Aebischer et al. 1712.05298 `https://wcxf.github.io/`
   - Authored by developers of 10 public SMEFT-related codes
2. **wilson** Aebischer, Kumar, and DMS 1804.05033 `https://wilson-eft.github.io`
   - Based on series of papers by Alonso, Jenkins, Manohar, Stoffer, Trott
   - SMEFT running inherited from DsixTools Celis, Fuentes-Martin, Vicente, and Virto 1704.04504
3. **flavio** DMS 1810.08132 `https://flav-io.github.io`
   - Extended beyond flavour physics

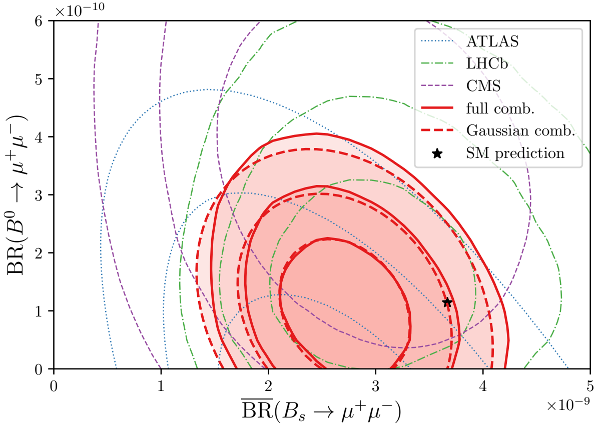
Building a global SMEFT likelihood Aebischer, Kumar, Stangl, and DMS 1810.07698

- Based on this toolbox, we have started building the **SME**FT **Like****LI**hood
  - **smelli** `https://github.com/smelli/smelli`
- So far, 265 observables included
  - Rare B and K Decays
  - LFU tests in charged-current B and K decays
  - Meson-antimeson mixing
  - ε'/ε
  - $(g-2)_{e,\mu,\tau}$
  - LFV & LFC τ and μ decays
  - Z and W pole EWPT



Updated inputs: $B_s \to \mu^+\mu^-$

- Combination of LHCb, ATLAS, CMS
- This is an update of the combination first done in Altmannshofer, Niehoff, and DMS 1702.05498



- $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$ roughly 2σ below the SM prediction

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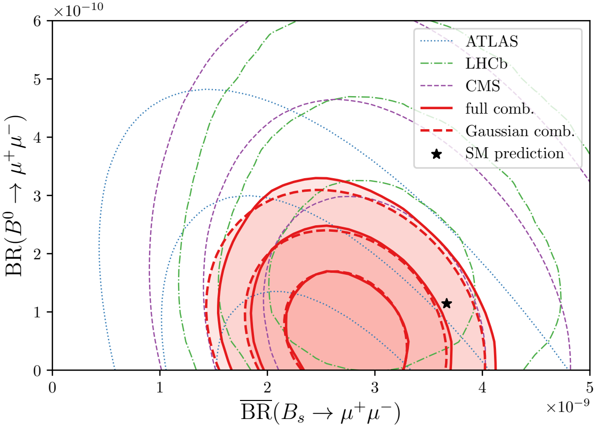
- Combination of LHCb, ATLAS, CMS
- **Update using CMS 2019 measurement** (not yet used in fits)



- $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$ roughly 2σ below the SM prediction

$b \to s\ell\ell$ Wilson coefficients: subtleties

- When considering the likelihood in a 2D WC subspace (e.g. C_9^μ-C_{10}^μ), one might think that there is no difference between using the global (WET) likelihood and the "traditional" approach of using only $b \to s\ell\ell$ observables.
- But this would only be true if the likelihood factorized:

$$L(\mathcal{O}(\vec{C})) = L(\mathcal{O}_{bs\ell\ell}(\vec{C}_{bs\ell\ell})) \cdot L(\mathcal{O}_{\text{other}}(\vec{C}_{\text{other}}))$$

- However it **does not factorize** since there are strong **correlations** among theory uncertainties, e.g. with $\Delta F = 2$ processes, stemming e.g. from
  - CKM elements
  - lattice decay constants
  - …

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Dealing with uncertainties correlated beyond $b \to s\ell\ell$

Possibilities:

1. Profile/marginalize over WCs of non-$b \to s\ell\ell$ operators.
    - Definitely the most well-defined and informative option, but highly expensive $\Rightarrow$ nobody does it!
2. Only consider $b \to s\ell\ell$ observables
    - assumption: presence/absence of NP in other observables does not affect $b \to s\ell\ell$ likelihood in a significant way
    - Done in most fits so far (including ours)
3. Only consider $b \to s\ell\ell$ Wilson coefficients
    - assumption: other observables are free from NP
    - Done in our most recent work based on the global likelihood

Comments

- All options should give results similar if the other correlated observables (e.g. $\Delta F = 2$) are well under control (which they are not: cf. ΔM tensions, V_{cb} tensions, …)
- 2 and 3 correspond to different assumptions, so should not be expected to give exactly the same results
- **All options are only useful for illustration**, not for actually comparing to NP models, because for NP models we need the **global likelihood** anyway

Comment on comment on ...

In v3 of their paper, Alguerò et al. added the comment:

”After discussion with [Aebischer et al.], this difference comes from their inclusion of B_s-$\bar{B}_s$ mixing and the assumption that $\Delta F = 2$ observables are purely governed by the SM, which helps them sharpening the prediction for $\mathrm{BR}(B_s \to \mu^+\mu^-)$ and increase the weight of this observable in the fit.

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We slightly disagree.

Neglecting the correlation is actually equivalent to assuming that all $\Delta F = 2$ observables sit on top of the experimental central values. Is that a weaker assumption? I think not. We should agree that 2-WC plots are only good for illustration and there are several choices what to assume about the other directions.

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What do we *actually* learn from “the fact that most models invoked to explain $b \to s\ell\ell$ anomalies typically affect also $\Delta F = 2$ observables”? That we need a **global likelihood** including all WCs.

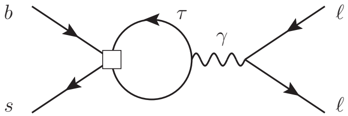
$b \to s\ell\ell$ & $b \to c\tau\nu$ in SMEFT

- Dimension-6 operators of interest:

$$O_{lq}^{(1)} = (\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma^\mu q)$$
$$O_{lq}^{(3)} = (\bar{\ell}\gamma^\mu \tau^a \ell)(\bar{q}\gamma^\mu \tau^a q)$$

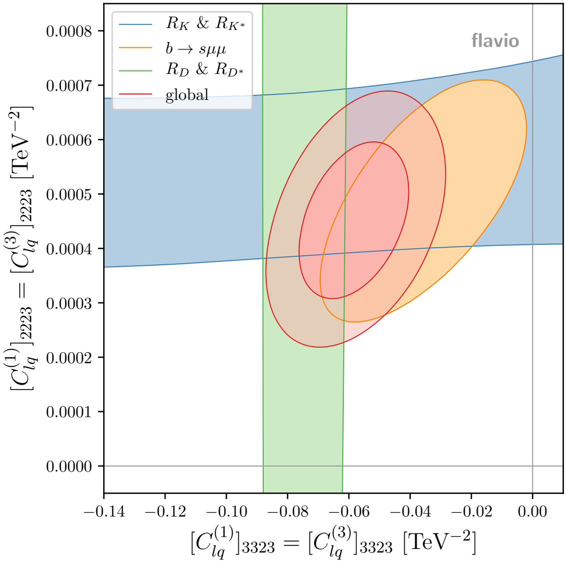
- $[C_{lq}^{(1)}]_{ii23} + [C_{lq}^{(3)}]_{ii23}$ matches onto $C_9^{bs\ell_i\ell_i} = -C_{10}^{bs\ell_i\ell_i}$
- $[C_{lq}^{(3)}]_{3323}$ induces $b_L \to c_L \tau_L \bar{\nu}_{\tau L}$, but also $b_L \to s_L \tau_L^+ \tau_L^-$

Semitauonic NP & lepton flavour *universal* C_9



- A semitauonic operator *unavoidably generates* a LFU contribution to C_9 through RG running above and below the EW scale Bobeth and Haisch 1109.1826
- This effect has the right sign and rough size to explain the $b \to s\mu\mu$ data (except $R_{K^{(*)}}$)! Crivellin, Greub, Müller, and Saturnino 1807.02068

Semitauonic vs. semimuonic NP



$[C_{lq}^{(1)}]_{ii23}(\bar{\ell}_i\gamma^\mu\ell_i)(\bar{q}_2\gamma^\mu q_3)$

$[C_{lq}^{(3)}]_{ii23}(\bar{\ell}_i\gamma^\mu\tau^a\ell_i)(\bar{q}_2\gamma^\mu\tau^a q_3)$

Pre-Moriond

- $R_{K^{(*)}}$ & $b \to s\mu\mu$ compatible with $[C_{lq}^{(a)}]_{3323} = 0$

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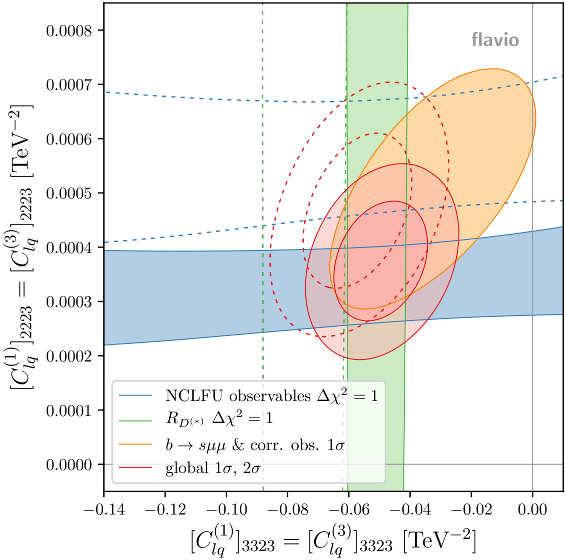

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Pre-Moriond

- $R_{K^{(*)}}$ & $b \to s\mu\mu$ compatible with $[C_{lq}^{(a)}]_{3323} = 0$

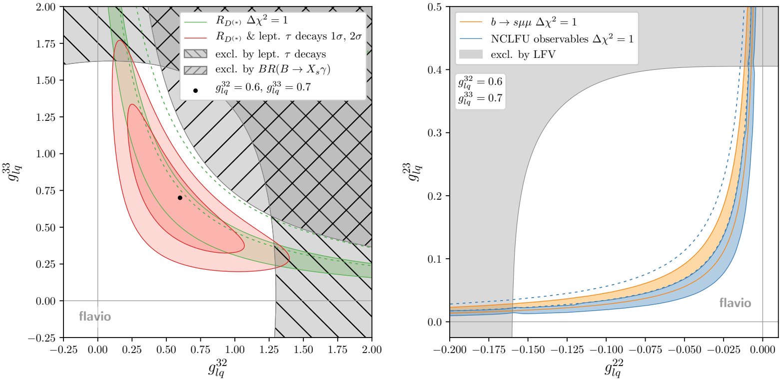
Now

- Where $R_{K^{(*)}}$ & $b \to s\mu\mu$ agree at 1σ: non-zero semitauonic WCs
- Solution coincides with semitauonic WCs that generate right size of $R_{D^{(*)}}$!
- Agreement better than before
- Lower $R_{D^{(*)}}$ makes agreement even better!

$U_1 \sim (3,1)_{2/3}$ vector leptoquark

- Minimal implementation of the semitauonic + -muonic scenario

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



- Main constraints: $\tau \to \ell\nu\nu$, $\tau \to \varphi\mu$, $B \to K\tau\mu$

cf. Barbieri, Isidori, Pattori, and Senia 1512.01560, Alonso, Grinstein, and Martin Camalich 1505.05164, Calibbi, Crivellin, and Ota 1506.02661, Fajfer and Košnik 1511.06024, Hiller, Loose, and Schönwald 1609.08895, Bhattacharya et al. 1609.09078, Buttazzo, Greljo,

Gedankenexperiment: what if the fits veer towards $C_9^{\text{univ.}}$?

How *not* to generate a LFU contribution to C_9:

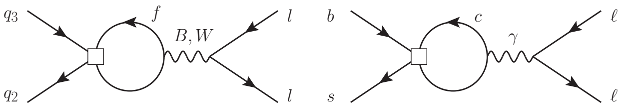
- Leptoquark coupling to e and μ
  - Leads to charged-lepton flavour violation!
- With a ditop operator via RG effects Camargo-Molina, Celis, and Faroughy 1805.04917
  - incompatible with EW precision tests

How to generate a LFU contribution to C_9:

- With a LFU Z' Altmannshofer and DMS 1308.1501
  - Difficult to avoid problems with LEP & ΔM_s
- With a semi-tauonic operator via RG effects Crivellin, Greub, Müller, and Saturnino 1807.02068
  - could be Z', V', leptoquark ...
- With a four-quark operator via RG effects Jäger, Leslie, Kirk, and Lenz 1701.09183

Leptophobic NP & lepton flavour *universal* C_9

- A four-quark operator can also generate a LFU contribution to C_9 through RG running above and below the EW scale Jäger, Leslie, Kirk, and Lenz 1701.09183



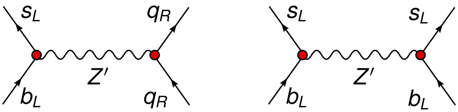
Which operators could work?

- Operators made of $q_L q_L q_L q_L$ do not work as they always lead to excessive effects in K^0 or D^0 mixing
- Operators with tops in the loop do not work as they induce a correction to the bsZ coupling and end up generating C_{10}, not C_9

Can we write down a model realizing this?

Simplified leptophobic models for LFU C_9

- Wilson coefficients of 4-quark operator must be of order $(2\,\mathrm{TeV})^{-2}$ $\to$ tree level
- Tree level spin-1 exchange (Z', G') does not work since $\Delta B = 1$ always implies $\Delta B = 2$ (which is strongly constrained)



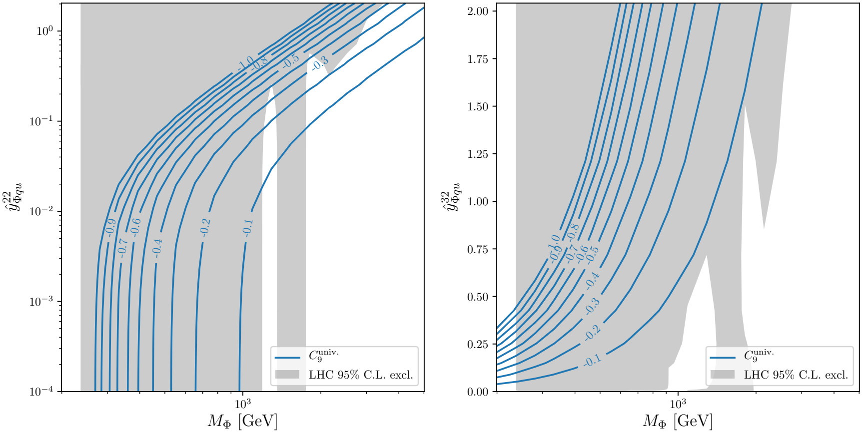
- Heavy uncouloured Higgs doublet generates operator that mixes into $b \to s\gamma$ at 2 loops Jäger, Leslie, Kirk, and Lenz 1701.09183 $\to$ excluded
- Only hope: colour-octet Higgs $\sim (\mathbf{8}, \mathbf{2})_{1/2}$

$$\mathcal{L}_\Phi \supset \hat{y}^{ij}_{\Phi qu}\, \bar{q}_i T^A u_j\, \tilde{\Phi}^A$$

  - Forbid coupling to u to evade bounds from D mixing and reduce cross section $pp \to \Phi \to jj$

Colour-octet Higgs: Dijet constraints vs. C_9

Left: $\hat{y}^{32}_{\Phi qu} = -1$, right: $\hat{y}^{22}_{\Phi qu} = 0$



- LHC dijet resonance searches almost completely exclude this scenario from generating a visible contribution to $C_9^{\rm univ.}$. Remaining space testable in Run 2!

CKM elements in the SMEFT

- The original version of `smelli` used CKM elements from SM tree-level determinations (not the global fit!)
- This means that NP effects in tree-level semi-leptonic decays have to be negligible, otherwise inconsistent
- How to do this properly without costly marginalization? Sketched nicely in
  Descotes-Genon et al. 1812.08163

Simple example: Leptonic Tau decay

Consider using $\Gamma(\tau \to e\nu\bar{\nu})$ to constrain a Lepton-Universal BSM scenario:

$$\mathcal{L}_{BSM} = \sum_{i,j\in\{e,\mu,\tau\}} [C_{H\ell}^{(3)}](\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{\ell}_i \sigma^I \gamma^\mu \ell_i) + [C_{\ell\ell}](\bar{\ell}_i \gamma^\mu \ell_j)(\bar{\ell}_j \gamma_\mu \ell_i)$$

Then: $\mathcal{A}(\tau \to e\nu\bar{\nu}) \propto \dfrac{1}{v^2} + 2\, C_{H\ell}^{(3)} - C_{\ell\ell}$

Going to the PDG, $v = 246.21965(6)\text{GeV}$

A measurement of $\Gamma(\tau \to e\nu\bar{\nu})$ then constrains $[2\, C_{H\ell}^{(3)} - C_{\ell\ell}]$

WRONG : The PDG value of v comes from the measurement of τ_μ, which in this scenario is strictly speaking a determination of exactly $\tilde{v}$, with

$$\frac{1}{\tilde{v}^2} \equiv \frac{1}{v^2} + 2\, C_{H\ell}^{(3)} - C_{\ell\ell}$$

Simple example: Leptonic Tau decay

How to do it properly?

1. Reinterpret the PDG value: $\tilde{v} = 246.21965(6)\text{GeV}$

with $$\frac{1}{\tilde{v}^2} \equiv \frac{1}{v^2} + [C_{H\ell}^{(3)}]_{\mu\mu} + [C_{H\ell}^{(3)}]_{ee} - [C_{\ell\ell}]_{\mu ee\mu}$$

2. Rewrite the $\tau \to e\nu\bar{\nu}$ amplitude:

$$\begin{aligned}
\mathcal{A}(\tau \to e\nu\bar{\nu}) \quad &\propto \quad \frac{1}{v^2} + [C_{H\ell}^{(3)}]_{\tau\tau} + [C_{H\ell}^{(3)}]_{ee} - [C_{\ell\ell}]_{\tau ee\tau} \\
&= \quad \frac{1}{\tilde{v}^2} + [C_{H\ell}^{(3)}]_{\tau\tau} - [C_{H\ell}^{(3)}]_{\mu\mu} - [C_{\ell\ell}]_{\tau ee\tau} + [C_{\ell\ell}]_{\mu ee\mu}
\end{aligned}$$

3. Substitute $\tilde{v} = 246.21965(6)\text{GeV}$ and use $\Gamma(\tau \to e\nu\bar{\nu})$ to constrain C_i.

Fixing CKM couplings in the SMEFT

The procedure to fix the "SM" couplings in NP scenarios is well known and has been discussed extensively.

But... what about Quark Flavor transitions?

Imagine you want to predict

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto |V_{ts} V_{tb}|^2 f_{B_s} \times F(C_i)$$

In a general case with contributions to many SMEFT operators.

What shuold I use for V_{ij} ?

The Strategy

We do:

1. Choose 4 “optimal” observables that depend on 4 orthogonal combinations of Wolfenstein parameters.
2. Absorb NP contributions into “effective” Wolfenstein parameters $\widetilde{W}_j$.
3. Extract numerical values for $\widetilde{W}_j$, and quote $W_j = \widetilde{W}_j - \delta W_j(C_k^{D=6})$.

$$O_i^{\text{exp}} \stackrel{!}{=} O_i^{\text{th}}(W_j) = \underbrace{O_i^{\text{SM}}(W_j)}_{\sim 1} + \underbrace{O_i^{\text{NP}}(W_j)}_{\sim 1/\Lambda^2} \equiv O_i^{\text{SM}}(\widetilde{W}_j) \quad \Rightarrow \quad \widetilde{W}_j = \#_j$$

You do:

4. To calculate your observables $P_i(W_j, C_k^{D=6})$, you substitute $W_j \to \widetilde{W}_j - \delta W_j(C_k^{D=6})$, and re-expand in $1/\Lambda$.

Why is this non-trivial?

- For $b \to u$ and $b \to c$, power counting does not guarantee NP contributions to be small w.r.t. SM: $V_{xb} \frac{1}{v^2}$ vs. $\frac{c}{\Lambda^2}$
  - NP is only small if c has the same CKM suppression (MFV-like, a very specific case) or if $\Lambda \gg v/\sqrt{V_{xb}}$
- For the CKM phase, we need at least one input observable based on a four-quark operator
  - NP matrix element poorly known except for $\Delta F = 2$

Why is this non-trivial?

- For $b \to u$ and $b \to c$, power counting does not guarantee NP contributions to be small w.r.t. SM: $V_{xb}\frac{1}{v^2}$ vs. $\frac{c}{\Lambda^2}$
  - NP is only small if c has the same CKM suppression (MFV-like, a very specific case) or if $\Lambda \gg v/\sqrt{V_{xb}}$
- For the CKM phase, we need at least one input observable based on a four-quark operator
  - NP matrix element poorly known except for $\Delta F = 2$

But it's doable and we implemented it in smelli now.

Implementation in smelli

1. User specifies $\vec{C}_{\text{SMEFT}}$
2. Automated extraction of "true" CKM elements from 4 input observables as function of $\vec{C}_{\text{SMEFT}}$
3. Computation of all SM contributions using these NP-dependent CKM elements

- No change from user perspective
- No assumption on smallness of NP in charged currents
- available in the public Github repository, will be part of next release

Comment on input parameters

- Choice in Descotes-Genon et al. 1812.08163

$$R_{K\pi}(P \to \mu\nu) \qquad \mathrm{BR}(B \to \tau\nu) \qquad \Delta M_d \qquad \Delta M_s$$

- smelli implementation allows to add arbitrary input sets but by default uses

$$R_{K\pi}(P \to \mu\nu) \qquad \mathrm{BR}(B \to \tau\nu) \qquad \mathrm{BR}(B \to X_c e\nu) \qquad \Delta M_d/\Delta M_s$$

  - Many more models (with high NP scale) that feature NP effects in $\Delta M_{d,s}$ than in $b \to ce\nu$. Makes it easier to trace likelihood contributions from these observables
  - Dependence of $\mathrm{BR}(B \to X_c e\nu)$ on CKM elements is simpler
  - $\Delta M_d/\Delta M_s$ is NP-free in CMFV models and known more precisely (ξ)
  - Meson mixing is FCNC and requires one loop order more: sensitive GIM cancellation absent in $b \to ce\nu$
- But in principle both are fine

Outlook on smelli 2.0

To appear in the next 2 months, featuring

- Complete Higgs production and decay
- Nuclear and neutron beta decays
- Some still secret things

Conclusions

- Global SMEFT likelihood likelihood is the tool of choice for model-independent NP analysis in flavour and beyond in the $\Lambda \gg v$ era
- We built – an are continuing to enlarge – a global likelihood built entirely on open source
  - Community effort?
- Looking at 2D $b \to s\ell\ell$ WC subspaces of the global likelihood is slightly different conceptionally than the "traditional" $b \to s\ell\ell$ fits, just be aware of them
- Global likelihood allows very easy & fast analysis of dynamical models automatically including EW RG effects etc.
- Treatment of CKM elements now also understood: way clear to include *all* charged-current semi-leptonic decay observables