Higgs and Effective Field Theory - HEFT 2022, Granada, 16 June 2022

Towards a global SMEFT likelihood

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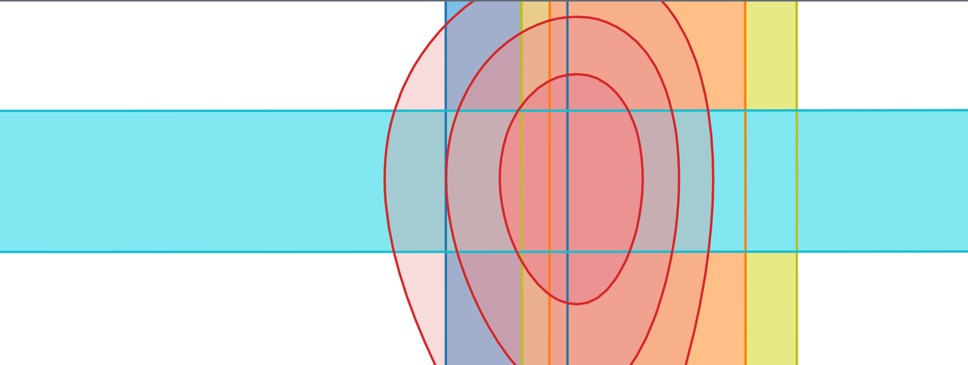


EFT phenomenology: two approaches

EFT phenomenology: two approaches

- **Top-Down approach**: start with (renormalizable) UV model
  - Integrate out heavy particles with masses $m \approx \Lambda$
  - Obtain EFT containing non-renormalizable operators suppressed by powers of Λ
  - Wilson coefficients are expressed in terms of parameters of UV model
  - Observables are predicted in terms of Wilson coefficients
  - Parameters of UV model are constrained by experimental measurements

- **Bottom-Up approach**: start with field content & symmetries at low energy
  - Construct all operators from field content that are allowed by symmetries
  - Non-renormalizable operators are suppressed by powers of cutoff Λ
  - Observables are predicted in terms of Wilson coefficients
  - Wilson coefficients are constrained by experimental measurements

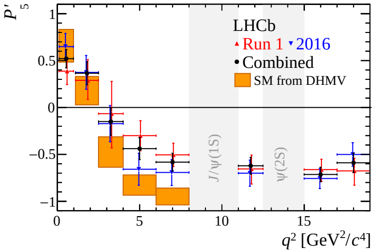
EFT phenomenology: two approaches – pros and cons

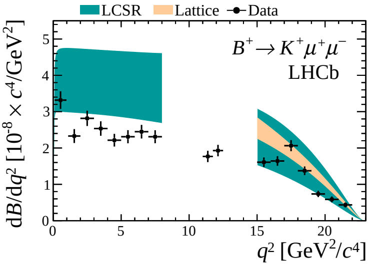
- **Top-Down approach**:
  - (+) Correlations between EFT parameters fixed by UV model
  - (+) Small number of model parameters
  - (-) Requires UV model
  - (-) Parameter fits are specific to the given model

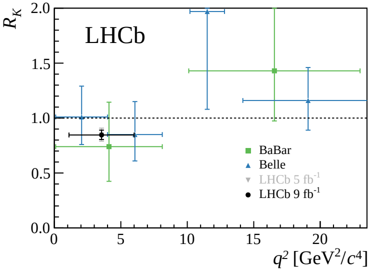
- **Bottom-Up approach**:
  - (+) Parameterization of generic UV completions
  - (+) Suitable for model-independent interpretation of experimental data
  - (+) Patterns of non-zero Wilson coefficients in EFT fits hint at possible UV models
  - (-) Very large number of parameters
  - (-) EFT fits require simplifying assumptions (e.g. flavor structure, vanishing coefficients, etc.)
  - (-) EFT fits can in general not be used to constrain UV models

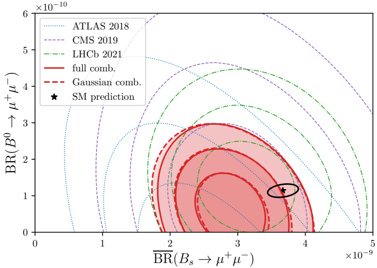
Lessons learned from B anomalies

The $b \to s\ell\ell$ anomalies



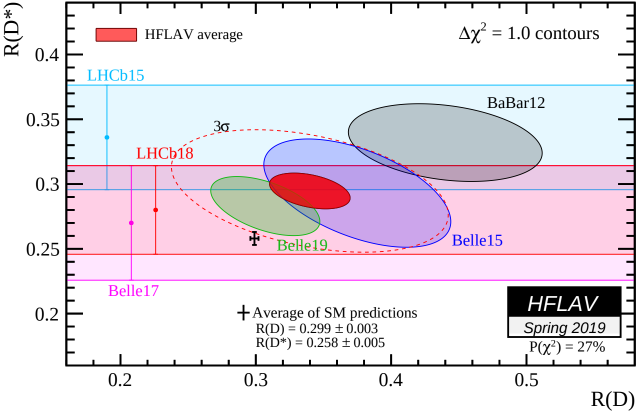






LHCb: arXiv:2003.04831, arXiv:2012.13241, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, arXiv:2105.14007, arXiv:1705.05802, arXiv:2103.11769, arXiv:2108.09283, arXiv:2108.09284
ATLAS: arXiv:1812.03017, CMS: arXiv:1910.12127, Altmannshofer, PS: arXiv:2103.13370

The $b \to c\ell\nu$ anomalies

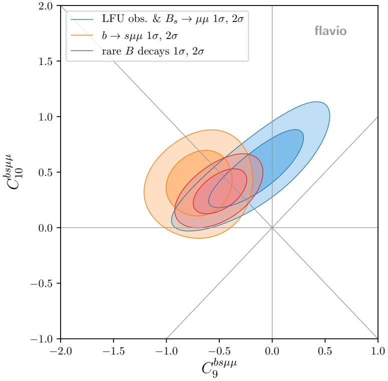


HFLAV, hflav.web.cern.ch
BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794

EFT fits in weak effective theory (WET/LEFT)

$b \to s\ell\ell$

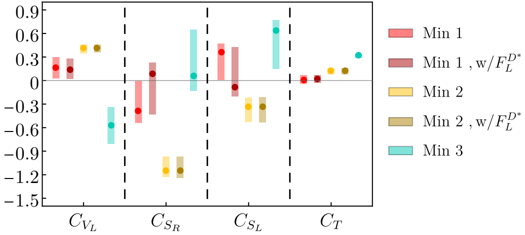
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



Altmannshofer, PS, arXiv:2103.13370

$b \to c\ell\nu$

$$O_{V_L} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)\,,$$
$$O_{S_R} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)\,,$$
$$O_{S_L} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)\,,$$
$$O_T = (\bar{c}\sigma_{\mu\nu} P_L b)(\bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau)\,.$$



Murgui, Peñuelas, Jung, Pich, arXiv:1904.09311

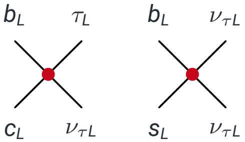
Model building - lessons learned

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

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

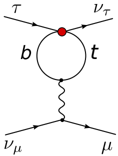
  Constrained by $B \to K \nu \bar{\nu}$ searches

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



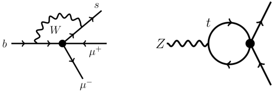
- Model explaining $R_{D^{(*)}}$ and $R_{K^{(*)}}$ using mostly 3rd gen. couplings
  Modifies LFU in τ and Z decays, strongly constrained

  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...

SMEFT top-down approach

- 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 and matching:

see talks by Pablo Olgoso, Anders Eller Thomsen, and Alejo Nahuel Rossia

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

  - *Model-independent* pheno:

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

  - **SMEFT likelihood** $L_{\text{exp}}(\vec{C})$ can tremendously simplify analyses of NP models

SMEFT: two approaches

Top-Down approach	**Bottom-Up approach**
NP model $\mathcal{L}_{\text{NP}}(\vec{\xi})$, Parameters $\vec{\xi}$	
$\downarrow$ Matching	
SMEFT Wilson coefficients $\vec{C}(\vec{\xi})$	SMEFT Wilson coefficients $\vec{C}$ (with restricting assumptions)
$\downarrow$	$\downarrow$
Observable predictions $\vec{\mathcal{O}}(\vec{C})$	Observable predictions $\vec{\mathcal{O}}(\vec{C})$
$\downarrow$	$\downarrow$
Likelihood function $L_{\text{exp}}(\vec{\mathcal{O}})$	Likelihood function $L_{\text{exp}}(\vec{\mathcal{O}})$
$\Downarrow$	$\Downarrow$
Analysis of NP model	EFT fit

SMEFT: two approaches

Top-Down approach

NP model $\mathcal{L}_{\text{NP}}(\vec{\xi})$, Parameters $\vec{\xi}$

$\downarrow$ Matching

SMEFT Wilson coefficients $\vec{C}(\vec{\xi})$

$\downarrow$

Observable predictions $\vec{\mathcal{O}}(\vec{C})$

$\downarrow$

Likelihood function $L_{\text{exp}}(\vec{\mathcal{O}})$

$\Downarrow$

Analysis of NP model

Bottom-Up approach

SMEFT Wilson coefficients $\vec{C}$
(with restricting assumptions)

$\downarrow$

Observable predictions $\vec{\mathcal{O}}(\vec{C})$

$\downarrow$

Likelihood function $L_{\text{exp}}(\vec{\mathcal{O}})$

$\Downarrow$

EFT fit

SMEFT: two approaches

Top-Down approach

NP model $\mathcal{L}_{\text{NP}}(\vec{\xi})$, Parameters $\vec{\xi}$

$\downarrow$ Matching

SMEFT Wilson coefficients $\vec{C}(\vec{\xi})$

$\downarrow$

SMEFT Likelihood $L_{\text{exp}}(\vec{C})$

$\Downarrow$

Analysis of NP model

Bottom-Up approach

SMEFT Wilson coefficients $\vec{C}$
(with restricting assumptions)

$\downarrow$

SMEFT Likelihood $L_{\text{exp}}(\vec{C})$

$\Downarrow$

EFT fit

The global SMEFT likelihood

The global SMEFT likelihood

- Several likelihood functions have been considered in the context of EFT fits in the **bottom-up** approach

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

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 in the **top-down** approach 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
SMEFT RGE: Alonso, Jenkins, Manohar, Trott, arXiv:1308.2627, arXiv:1310.4838, arXiv:1312.2014
(ported from DsixTools: Celis, Fuentes-Martin, Vicente, Virto, arXiv:1704.04504)
SMEFT$\rightarrow$ WET matching: Jenkins, Manohar, Stoffer, arXiv:1709.04486
WET RGE: Jenkins, Manohar, Stoffer, arXiv:1711.05270

Implementing the global SMEFT likelihood

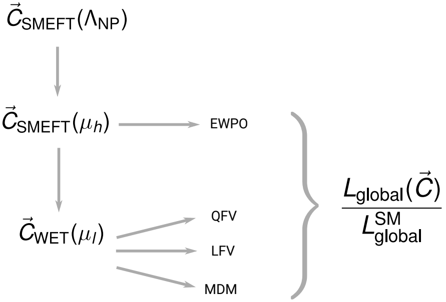
- Based on these tools, we have started building the **SME**FT **L**ike**LI**hood
  - **smelli** `https://github.com/smelli/smelli`

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- $L(\vec{C}) \approx \prod_i L^i_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0)) \times \tilde{L}_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0))$

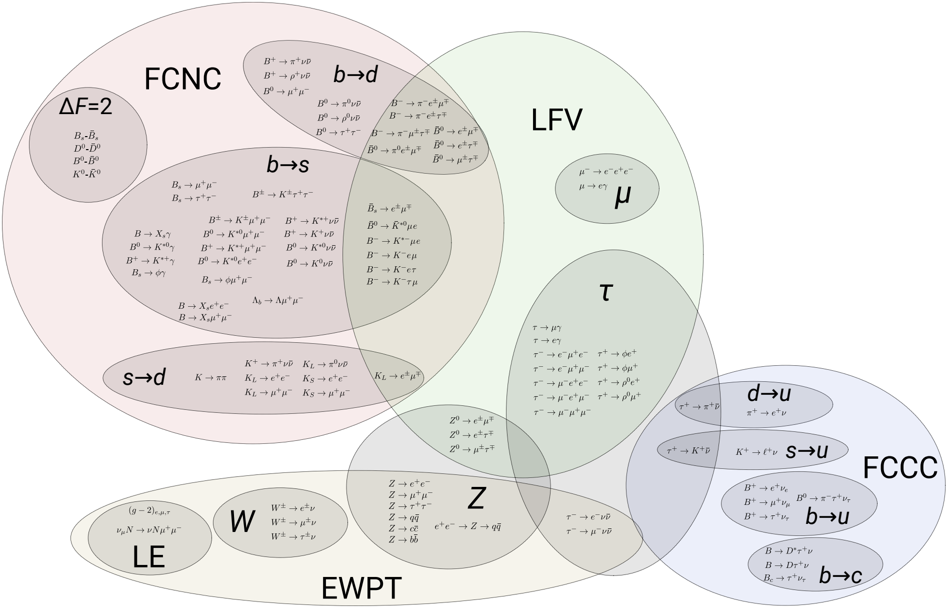
where

- $\vec{C}$ WET or SMEFT Wilson coefficients
- $\vec{\theta}_0$ fixed nuisance parameters
- $\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0)$ observable predictions
- $L^i_{\text{exp}}(\vec{O})$ experimental likelihood from measurement i for observables $\vec{O}$
- $\tilde{L}_{\text{exp}}(\vec{O})$ modified exp. likelihood: $-2\ln\tilde{L}_{\text{exp}}(\vec{O}) = \vec{D}^T(\Sigma_{\text{exp}}+\Sigma_{\text{th}})^{-1}\vec{D}$, with $\vec{D}=\vec{O}-\vec{O}_{\text{exp}}$ and covariance matrices $\Sigma_{\text{exp,th}}$ (Gaussian approx.)



smelli v1.1.1: Flavor + EWPT

Aebischer, Kumar, PS, Straub, arXiv:1810.07698



smelli v2.0: Higgs and beta decays, $K \to \pi\ell\nu$, $e^+e^- \to W^+W^-$

- **New observables**
  - **Higgs physics**: signal strengths for various decay ($h \to \gamma\gamma$, $Z\gamma$, ZZ, WW, bb, cc, $\tau\tau$, $\mu\mu$) and production (gg, VBF, Zh, Wh, $t\bar{t}h$) channels
    Falkowski, Straub, arXiv:1911.07866
  - **Beta decays**: lifetime and correlation coefficients of neutron beta decay, superallowed nuclear beta decays
    based on Gonzalez-Alonso, Naviliat-Cuncic, Severijns, arXiv:1803.08732
    see talk by Martín González-Alonso
  - $\boldsymbol{K \to \pi\ell\nu}$: total branching ratios of $K^+ \to \pi^0\ell^+\nu$, $K_{L,S} \to \pi^\pm\ell^\mp\nu$ ($\ell = e, \mu$), and $K^+ \to \pi^0\mu^+\nu$ effective scalar form factor $\ln C$ and tensor coupling R_T
  - $\boldsymbol{e^+e^- \to W^+W^-}$: total and differential cross sections for $e^+e^- \to W^+W^-$ pair production measured in LEP-2
- Proper treatment of the **CKM matrix in SMEFT**
  based on Descotes-Genon, Falkowski, Fedele, González-Alonso, Virto, arXiv:1812.08163
  - **CKM input scheme** using 4 observables to fix 4 CKM parameters:
    - $R_{K\pi} = \Gamma(K^+ \to \mu^+\nu)/\Gamma(\pi^+ \to \mu^+\nu)$ (mostly fixing V_{us})
    - $BR(B^+ \to \tau\nu)$ (fixing V_{ub})
    - $BR(B \to X_c e\nu)$ (fixing V_{cb})
    - $\Delta M_d/\Delta M_s$ (mostly fixing CKM phase δ)
  - Determine **effective CKM** matrix in presence of SMEFT operators

New developments related to `smelli`

- **New numerical methods** developed for $b \to s\ell^+\ell^-$ analyses

  Altmannshofer, PS, arXiv:2103.13370

  - numerical efficient implementation of **NP dependence of theory covariance matrix**
  - **computational speed increased** by orders of magnitude through numerical improvements ($\mathcal{O}$(s) $\to$ $\mathcal{O}$(ms) per parameter point)

    $\to$ makes `smelli` suitable for parameter scans of NP models and EFT fits with many parameters
  - will be implemented for all observables in `smelli`

- Neutral and charged current **Drell-Yan tails** ($pp \to \ell^+\ell^-$, $pp \to \ell\nu$ for $\ell = e, \mu$)

  Greljo, Šalko, Smolkovič, PS, work in progress

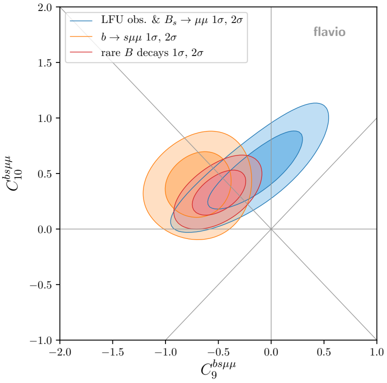
  see talks by Admir Greljo , Felix Wilsch, and Maeve Madigan

  - sensitivity to **all semi-leptonic four-fermion operators** with **all quark flavor combinations** of u, d, s, c, b (from parton distributions)
  - **complimentary to flavor physics** constraints
  - will be implemented in `smelli`

Applications of `smelli`

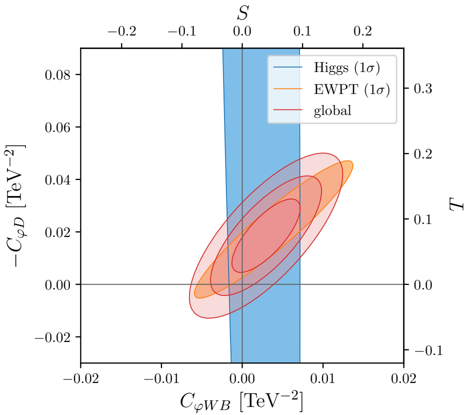
Bottom-Up approach: EFT fits

Global $b \to s\ell\ell$ fits



Altmannshofer, PS, arXiv:2103.13370

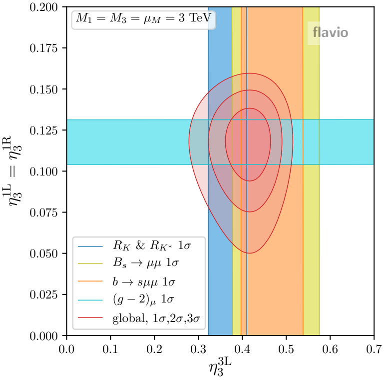
Higgs + EW fit



Falkowski, Straub, arXiv:1911.07866

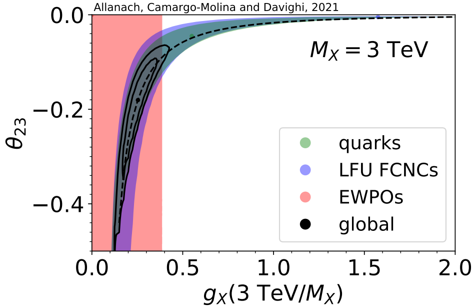
Top-Down approach: Analyses of NP models

$S_1 + S_3$ scalar leptoquarks
matched to SMEFT at 1 loop



Greljo, PS, Thomsen, arXiv:2103.13991
(matching: Gherardi, Marzocca, Venturini, arXiv:2003.12525)

Z' model from gauged $U(1)_X$
matched to SMEFT at tree level



Allanach, Camargo-Molina, Davighi, arXiv:2103.12056

Conclusion

Conclusions

- **Global SMEFT likelihood** can be used in
  - Bottom-Up approach: **global EFT fits**
  - Top-Down approach: **analyses of NP models**
- Python package **smelli** currently contains
  - FCNC flavor observables ($b \to s$, $b \to d$, $s \to d$, and meson mixing)
  - FCCC flavor observables ($b \to c$, $b \to u$, $s \to u$, $d \to u$)
  - LFV observables (μ, τ, Z, B-meson, and Kaon decays)
  - EWPT (W and Z pole observables, τ decays, $(g-2)_{e,\mu,\tau}$)
  - Higgs physics (signal strengths)
  - Beta decays (neutron and superallowed nuclear beta decays)
- `smelli` will be extended soon
  - New numerical methods to **improve accuracy** and **computational speed**
  - Implementation of **Drell-Yan tails**
- **Truly global likelihood** is work in progress
  - To be added: top physics, dijets, vector boson scattering, diboson production, ...
  - `smelli` is completely open-source
    You are welcome to participate $\to$ `https://github.com/smelli/smelli`

Backup slides

Using `smelli`

Installing smelli

- Prerequisite: working installtion of **Python** version **3.7** or above
- Installation from the command line:

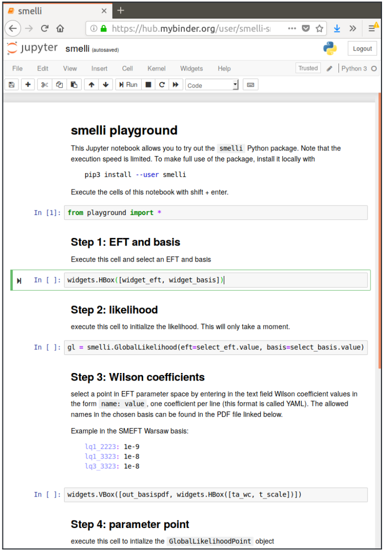
```
python3 -m pip install smelli --user

```

  - 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
  $\longrightarrow$ we recommend the **Jupyter notebook**



smelli tutorial in a Jupyter notebook at
`https://github.com/peterstangl/smelli-talk`

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

```
glp.log_likelihood_dict()

```

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

```
glp.obstable()

```

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

Using `smelli`

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

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

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