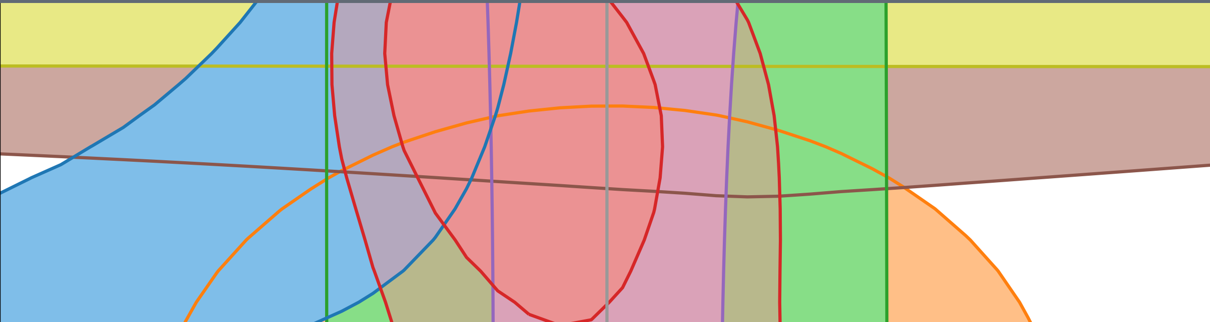
CERN-Annecy-Geneva-EPFL (CAGE) BSM Workshop, CERN, 13 February 2024

Automating BSM Phenomenology

Peter Stangl CERN

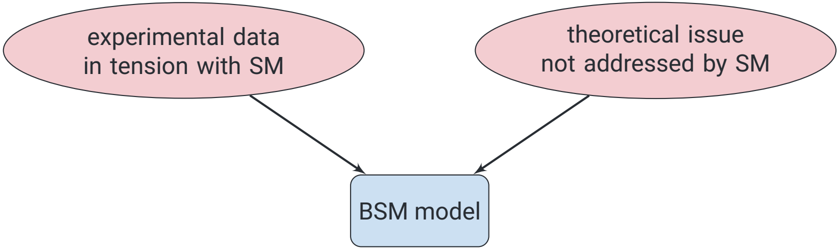


BSM phenomenology

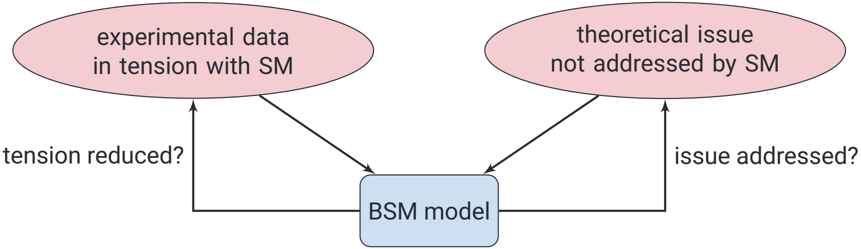
experimental data
in tension with SM

theoretical issue
not addressed by SM

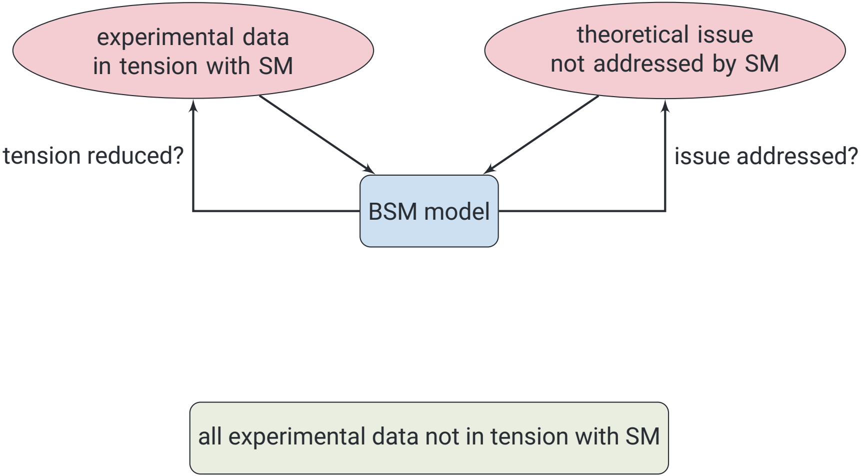
BSM phenomenology



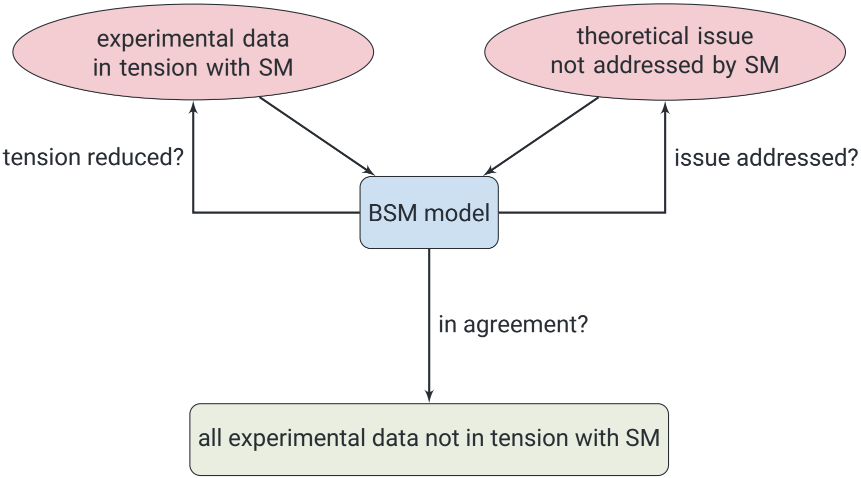
BSM phenomenology



BSM phenomenology

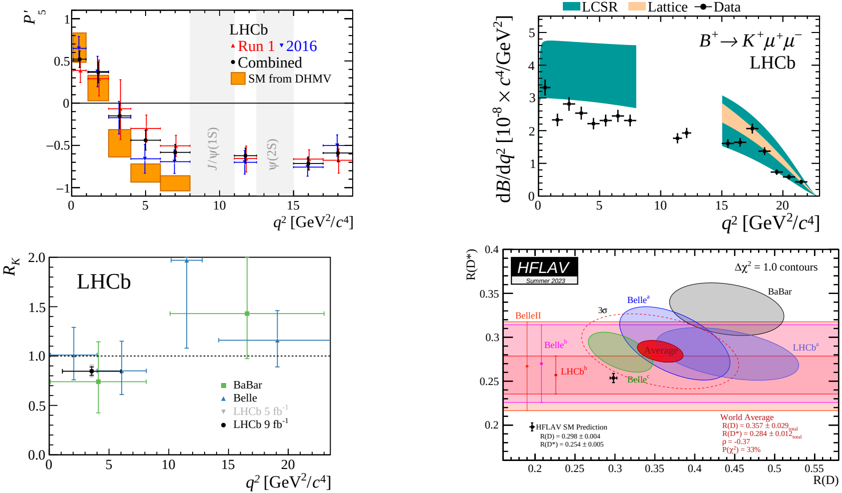


BSM phenomenology



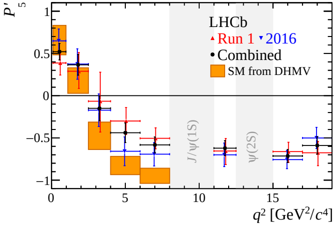
Example:
Lessons learned from B anomalies

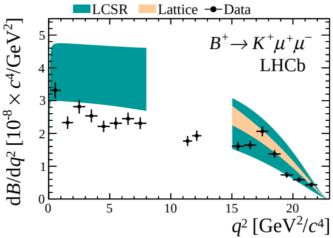
The B anomalies ($b \to s\ell\ell$ and $b \to c\ell\nu$)

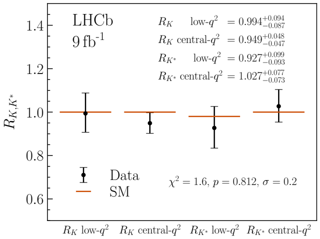


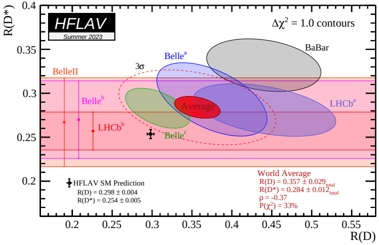
LHCb: arXiv:2003.04831, arXiv:2012.13241, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, arXiv:2105.14007, arXiv:1705.05802, arXiv:2103.11769, arXiv:2108.09283, arXiv:2108.09284, arXiv:2212.09153
HFLAV, hflav.web.cern.ch

The B anomalies ($b \to s\ell\ell$ and $b \to c\ell\nu$)









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HFLAV, hflav.web.cern.ch

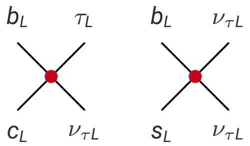
Model building - lessons learned

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

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

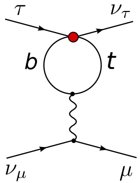
  Constrained by $B \to K \nu \bar{\nu}$ searches

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



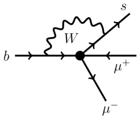
- Model explaining B anomalies using mostly 3rd generation couplings
  Modifies τ and Z decays, strongly constrained

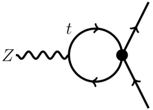
  Feruglio, Paradisi, Pattori, arXiv:1705.00929



- 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 $\vec{\xi}$

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

- Take into account loop / RGE effects

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

- Compare to experiment

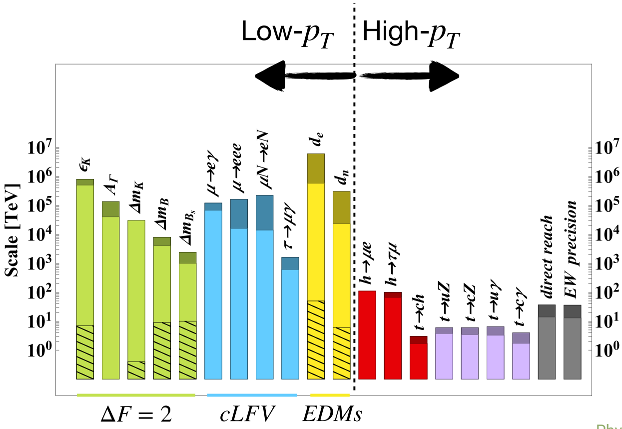
$$\vec{\mathcal{O}}(\vec{\xi}) \to \underbrace{L_{\rm exp}(\vec{\mathcal{O}}(\vec{\xi}))}_{\text{Likelihood}}$$

Has to be done **repeatedly** (for each model) taking into account a **large number** of observables
$\Rightarrow$ This calls for **automation**!

Approach to automating BSM phenomenology

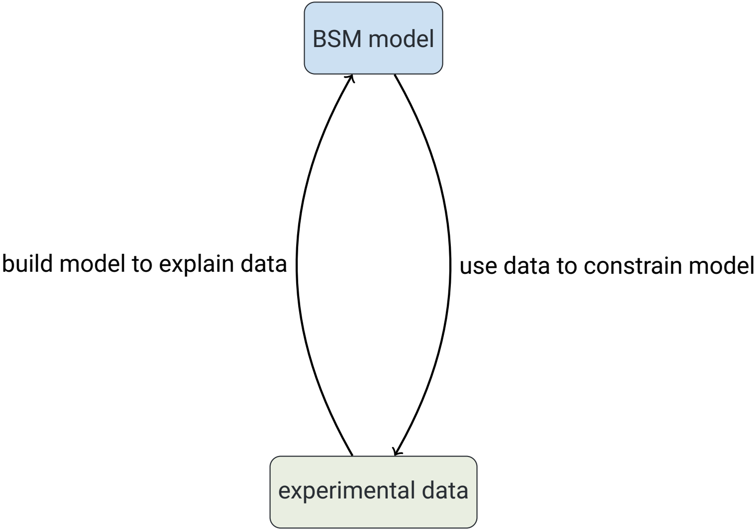
Precision observables and flavour physics: indirect searches for new physics

Precision measurements at **low energy** can indirectly probe scales far above the reach of direct searches

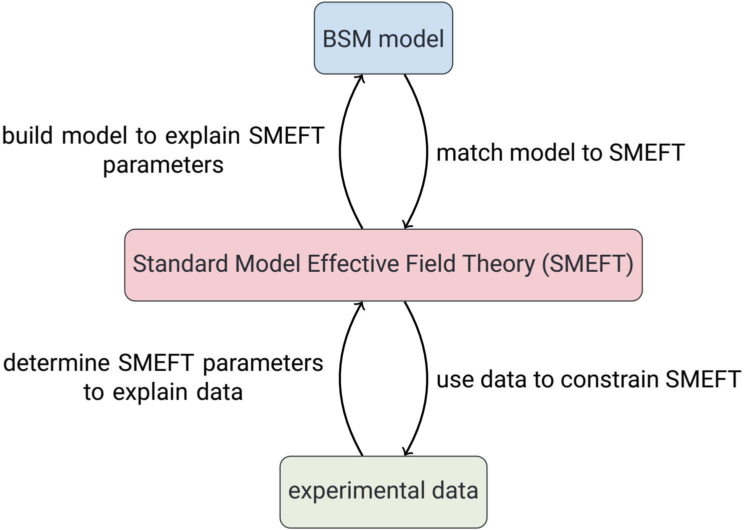


Physics Briefing Book, arXiv:1910.11775
annotations from Admir Greljo @ ICHEP 2022

Approach to automating BSM phenomenology



Approach to automating BSM phenomenology



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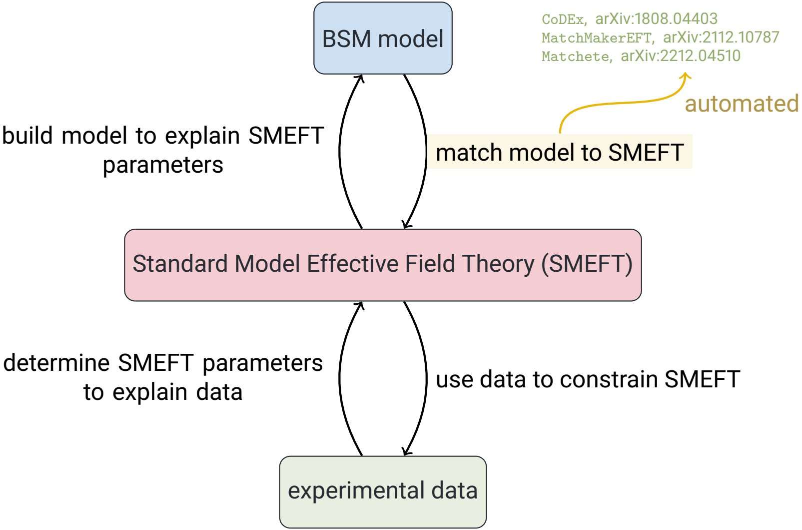

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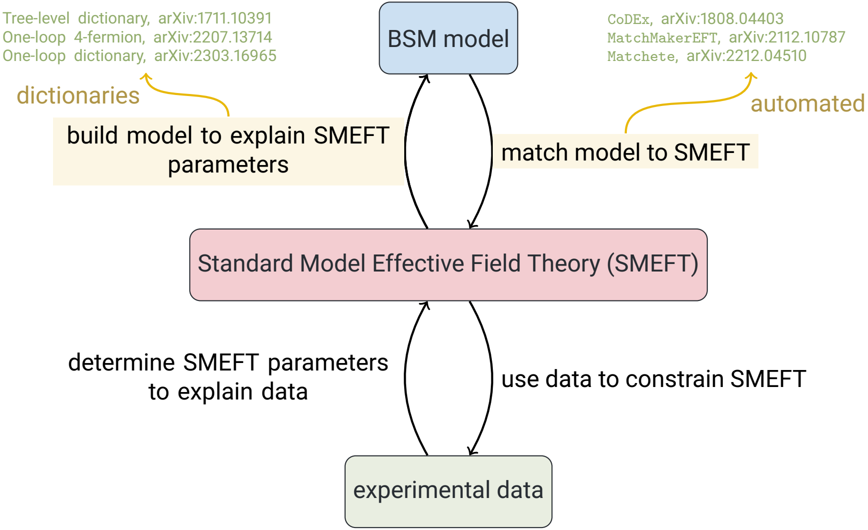
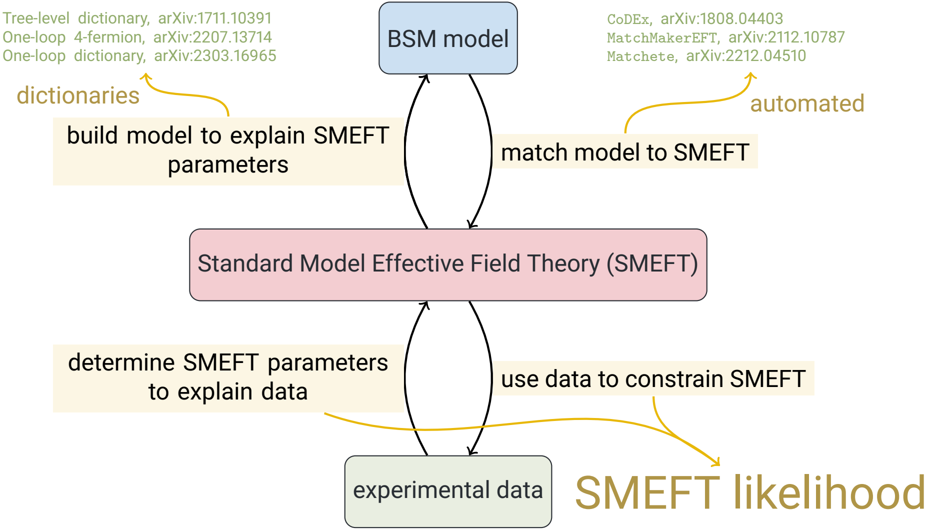


Approach to automating BSM phenomenology



SMEFT likelihood

- Assuming $\Lambda_{\text{NP}} \gg v$, new physics (NP) effects in flavour, EWPO, Higgs, top,…can be expressed in terms of SMEFT Wilson coefficients

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

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:

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

  - *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

The global SMEFT likelihood

- Several likelihood functions have been considered in the context of EFT fits

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

$$L(\vec{C}) = L_{\text{top physics}}(\vec{C}_{\text{top physics}}) \times \ldots$$

$$L(\vec{C}) = L_{B\text{ physics}}(\vec{C}_{B\text{ physics}}) \times \ldots$$

$$L(\vec{C}) = L_{\text{LFV}}(\vec{C}_{\text{LFV}}) \times \ldots$$

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
...

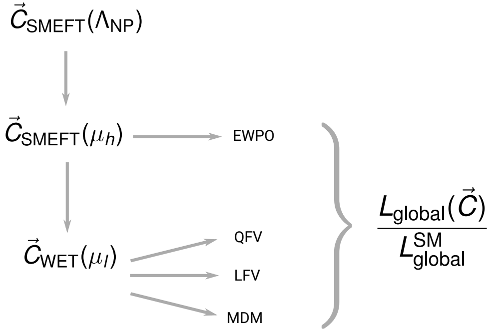
- But these likelihood functions should **not be considered separately** since RG (loop) effects mix different sectors and UV models match to several sectors

- We need to consider the **global SMEFT likelihood**

Implementation and tools

Implementation and tools

- **flavio** `https://flav-io.github.io`
  - Theory predictions: flavour physics and many other observables (EWPO, Higgs, β-decays, EDMs, DY tails, . . .)
  - Database of measurements
  - Constructing likelihoods
- **wilson** `https://wilson-eft.github.io`
  - Matching from SMEFT to Weak Effective Theory (WET)
  - One-loop RG evolution in SMEFT and WET
- **smelli** - the **SME**FT **Like**L**I**hood
  `https://github.com/smelli/smelli`
  - SMEFT and WET likelihood function

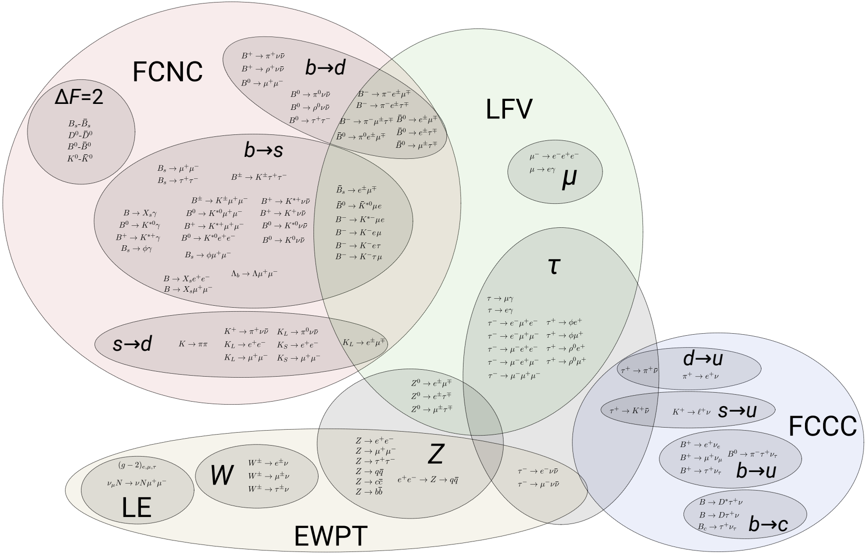


smelli v1.1.1: Flavour + EWPT

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

SMEFT parameters @ dim-6:

- No flavour (1-gen): **84**
- Flavour (3-gen): **3045**



smelli: recent developments

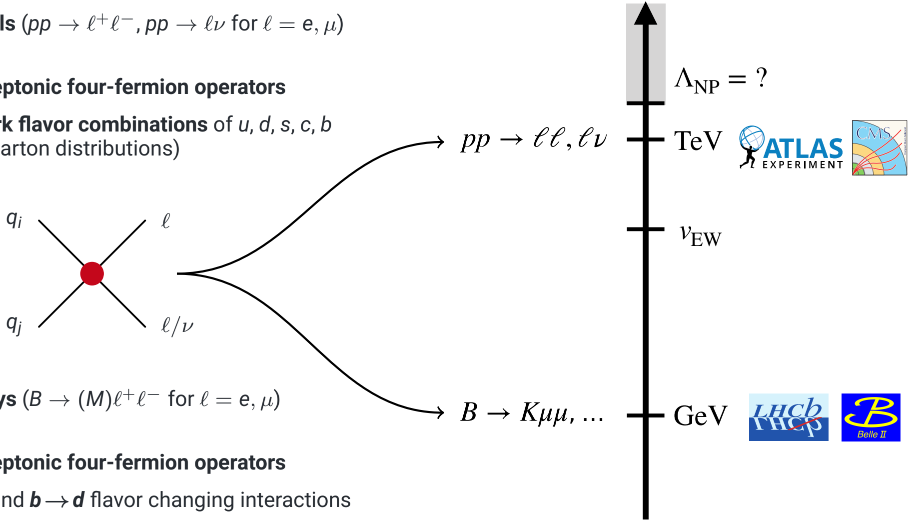
- **smelli v2.0**: Higgs physics and beta decays
  - **Higgs physics**: signal strengths for various decay ($h \to \gamma\gamma$, $Z\gamma$, ZZ, WW, bb, cc, $\tau\tau$, $\mu\mu$) and production (gg, VBF, Zh, Wh, $t\bar{t}h$) channels
    Falkowski, Straub, arXiv:1911.07866
  - **Beta decays**: lifetime and correlation coefficients of neutron beta decay, superallowed nuclear beta decays
    based on Gonzalez-Alonso, Naviliat-Cuncic, Severijns, arXiv:1803.08732
- Outlook to **smelli v3.0** (work in progress)
  - New physics dependence of correlated theory uncertainties
    Altmannshofer, PS, arXiv:2103.13370
  - **Major speed improvement** (orders of magnitude) and **automatic differentiation** ($\to$ e.g. Hamiltonian MC)
  - Interface to `MatchMakerEFT` and `Matchete` one-loop UV to SMEFT matching
  - **EDMs**: neutron, atomic, and molecular (already available in `flavio`)
  - LEP 2: $\mathbf{e^+e^-} \to \ell^+\ell^-$ (soon in `flavio`)
  - High-mass **Drell-Yan tails**: $pp \to e^+e^-$, $\mu^+\mu^-$, $e\nu$, $\mu\nu$ (already available in `flavio`)
    Greljo, Salko, Smolkovič, PS, arXiv:2212.10497

Recent development:
Drell-Yan tails meet rare *b* decays

Drell-Yan tails meet rare *b* decays

Greljo, Salko, Smolkovič, PS, arXiv:2212.10497

- **Drell-Yan tails** ($pp \to \ell^+\ell^-$, $pp \to \ell\nu$ for $\ell = e, \mu$) sensitive to
  - **semi-leptonic four-fermion operators**
  - **all quark flavor combinations** of *u*, *d*, *s*, *c*, *b* (from parton distributions)

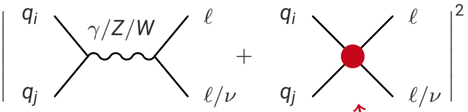


- **Rare *B* decays** ($B \to (M)\ell^+\ell^-$ for $\ell = e, \mu$) sensitive to
  - **semi-leptonic four-fermion operators**
  - $\boldsymbol{b \to s}$ and $\boldsymbol{b \to d}$ flavor changing interactions

Implementation of Drell-Yan: Theory prediction

- **Partonic cross section**, including all relevant SMEFT four-fermion operators

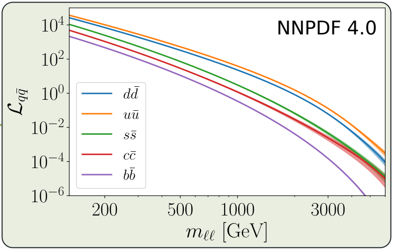
$$\sigma^{q_i q_j}_{\text{part.}} \sim \sum_{\substack{\text{chiralities} \\ \text{Lorentz structures}}} \left| \ \ldots \ \right|^2$$



$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

- **Hadronic cross section**, integrated over parton luminosities

$$\sigma_{\text{hadr.}} \sim \int \frac{d\hat{s}}{s} \sum_{q_i q_j} \mathcal{L}_{q_i q_j}(\hat{s}) \ \sigma^{q_i q_j}_{\text{part.}}(\hat{s})$$



- **Drell-Yan ratio of NP+SM and SM contributions,** cancelling higher order corrections and uncertainties

$$R_{\text{DY}} = \frac{\sigma^{\text{SM+NP}}_{\text{hadr.}}}{\sigma^{\text{SM}}_{\text{hadr.}}}$$

Implementation of Drell-Yan: Experimental data

We implement data ($\sim 140\ \text{fb}^{-1}$) from latest ATLAS and CMS searches:

	$pp \to \ell\ell$	$pp \to \ell\nu$
CMS	2103.02708	2202.06075
ATLAS	2006.12946	1906.05609

- **Expected # of events** in SM $N_{\text{exp}}^{\text{SM}} = N_{\text{DY}}^{\text{SM}} + N_{\text{bkg}}$ including $N_{\text{DY}}^{\text{SM}}$ @ NNLO QCD, NLO EW
- **In presence of NP**:

$$N_{\text{exp}}^{\text{SM+NP}}(\boldsymbol{R}_{\text{DY}}) = \boldsymbol{R}_{\text{DY}}\, N_{\text{DY}}^{\text{SM}} + N_{\text{bkg}}$$

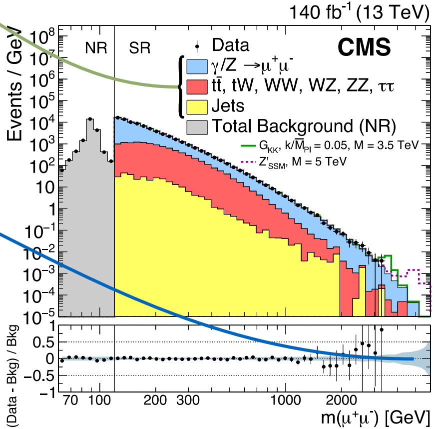
- **Theory uncertainties** Δ_{th}
- **Likelihood** of $\boldsymbol{R}_{\text{DY}}$:

$$L(\boldsymbol{R}_{\text{DY}}) = (L_{\mathcal{P}} * \mathcal{N}_{\Delta_{\text{th}}}) \left(N_{\text{exp}}^{\text{SM+NP}}(\boldsymbol{R}_{\text{DY}})\right)$$

  as convolution of
  - Likelihood of Poisson distributed data

$$L_{\mathcal{P}}(N_{\text{exp}}^{\text{SM+NP}}) = \frac{(N_{\text{exp}}^{\text{SM+NP}})^{N_{\text{obs}}}\ e^{-N_{\text{exp}}^{\text{SM+NP}}}}{N_{\text{obs}}!}$$

  - Normal distributed theory uncertainties with standard devation Δ_{th}: $\mathcal{N}_{\Delta_{\text{th}}}(N_{\text{exp}})$

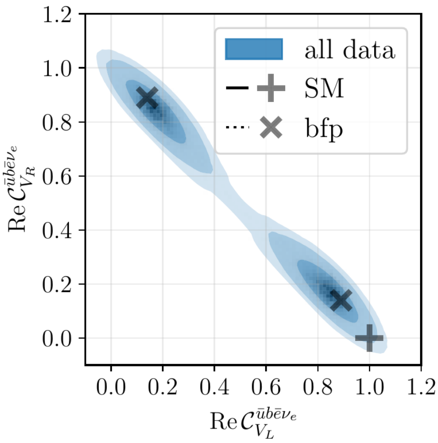


smelli usage example:

New physics in $b \to u\ell\nu$?

New physics in $b \to u\ell\nu$?

Leljak, Melić, Novak, Reboud, van Dyk, arXiv:2302.05268



Toward a complete description of $b \to u\ell^-\bar{\nu}$ decays within the Weak Effective Theory

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[b] *Physik Department T31, Technische Universität München, 85748 Garching, Germany*

[c] *Institute for Particle Physics Phenomenology and Department of Physics, Durham University, Durham DH1 3LE, U.K.*

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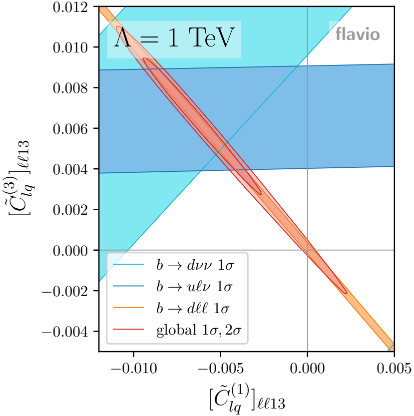
Abstract: We fit the available data on exclusive semileptonic $b \to u\ell^-\bar{\nu}$ decays within the Standard Model and in the Weak Effective Theory. Assuming Standard Model dynamics, we find $|V_{ub}| = 3.59^{+0.13}_{-0.12} \times 10^{-3}$. Lifting this assumption, we obtain stringent constraints on the coefficients of the $ub\ell\nu$ sector of the Weak Effective Theory. Performing a Bayesian model comparison, we find that a beyond the Standard Model interpretation is favoured over a Standard Model interpretation of the available data. We provide a Gaussian mixture model that enables the efficient use of our fit results in subsequent analyses beyond the Standard Model, within and beyond the framework of the Standard Model Effective Field Theory.

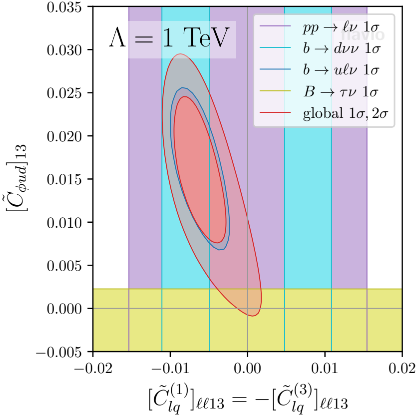
New physics in $b \to u\ell\nu$ is strongly constrained!

Greljo, Salko, Smolkovič, PS, arXiv:2306.09401

$C_{V_L}^{(\ell)} \propto [C_{lq}^{(3)}]_{\ell\ell 13}$



$C_{V_R}^{(\ell)} \propto [C_{\phi ud}]_{13}$



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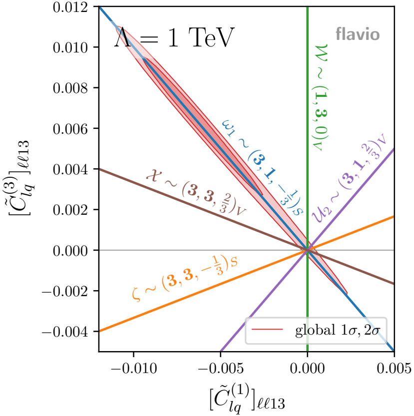

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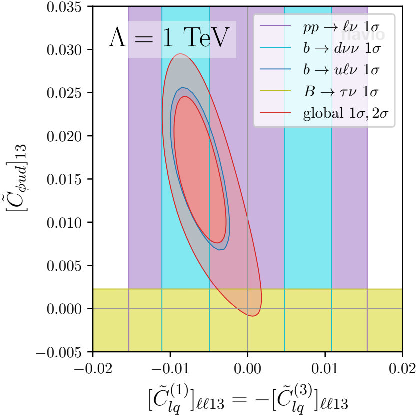

$$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3})_S \;\Rightarrow\; [Q_{lq}^{(3)}]_{\ell\ell 13} = -[Q_{lq}^{(1)}]_{\ell\ell 13}$$

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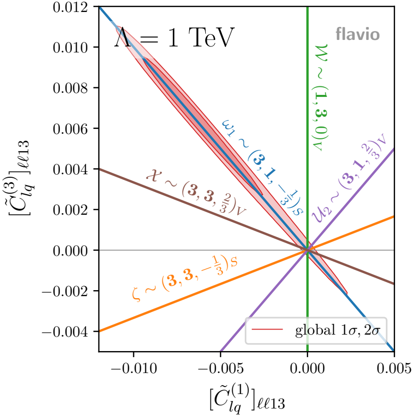

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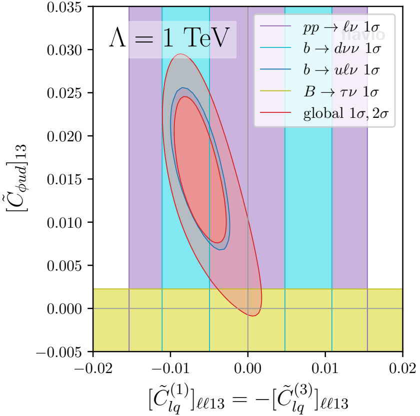

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$Q_1 \sim (\mathbf{3},\mathbf{2},\tfrac{1}{6})_F \;\Rightarrow\; [Q_{\phi ud}]_{13}$

New physics in $b \to u\ell\nu$ is strongly constrained!

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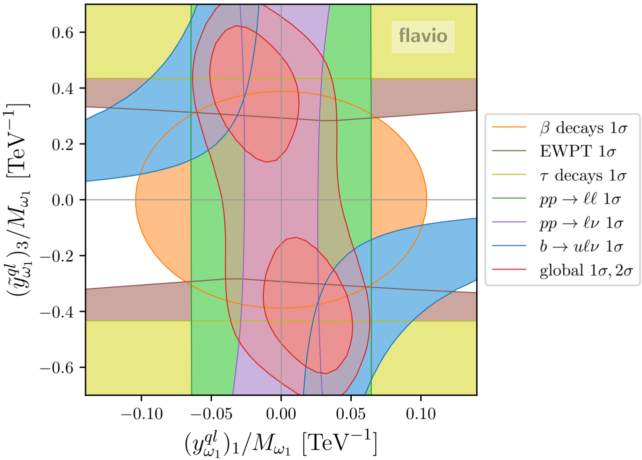

$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S \;\Rightarrow\; [Q^{(3)}_{lq}]_{\ell\ell 13} = -[Q^{(1)}_{lq}]_{\ell\ell 13}$

$Q_1 \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_F \;\Rightarrow\; [Q_{\phi ud}]_{13}$

Conclusions & Outlook

Conclusions & Outlook

- Lessons learned from Flavor Anomalies
  - Models that **explain anomalies** generically predict **effects in other observables**
  - Important to consider **all relevant bounds** and **loop effects**
- Automating BSM phenomenology using the SMEFT
  - Python package **smelli** based on **flavio** and **wilson** implements a **Global SMEFT likelihood**
  - Recent development: implementation of **Drell-Yan Tails** in `flavio v2.5`
- Outlook to **smelli v3.0** (work in progress)
  - High-mass **Drell-Yan tails**: $pp \to e^+e^-, \mu^+\mu^-, e\nu, \mu\nu$ (already available in `flavio`)
  - LEP 2: $\mathbf{e^+e^-} \to \ell^+\ell^-$ (soon in `flavio`)
  - **EDMs**: neutron, atomic, and molecular (already available in `flavio`)
  - **Major speed improvement** (orders of magnitude) and **automatic differentiation**
  - Interface to **MatchMakerEFT** and **Matchete**
- **Truly global likelihood** is work in progress
  - Open-source development (contributions welcome!)
    `https://github.com/smelli/smelli`
    `https://github.com/flav-io/flavio`