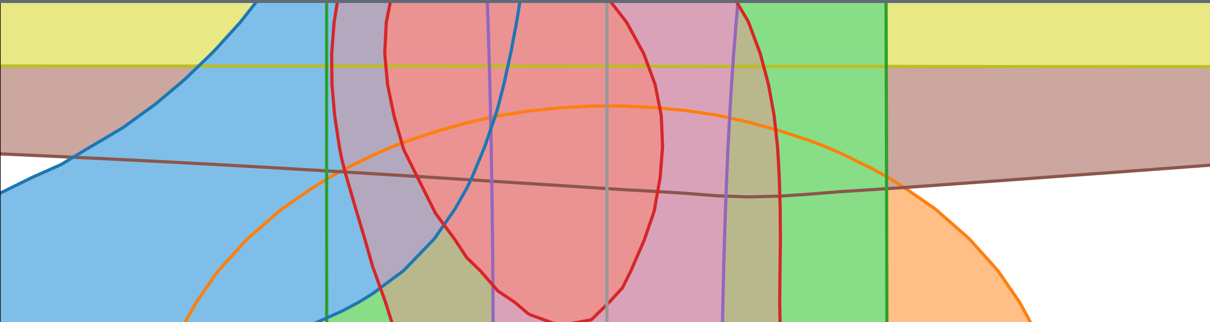
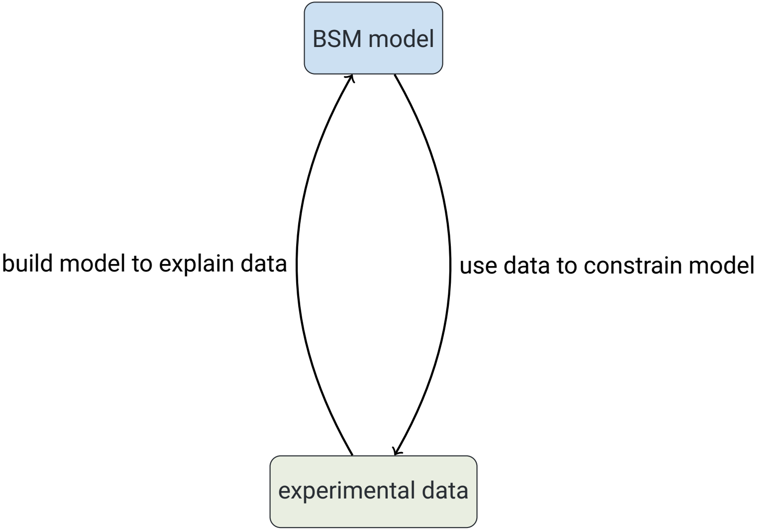
Higgs and Effective Field Theory - HEFT 2024, Bologna, 14 June 2024

A flavourful global SMEFT likelihood: `smelli v3.0`

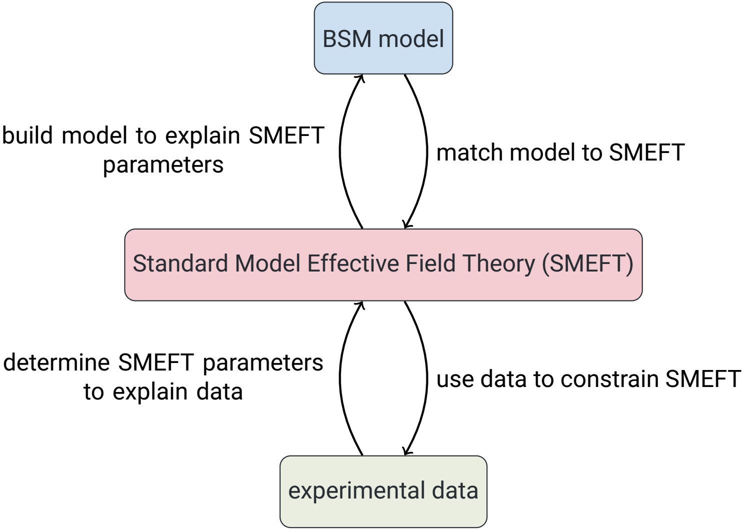
Peter Stangl CERN



Automating BSM phenomenology

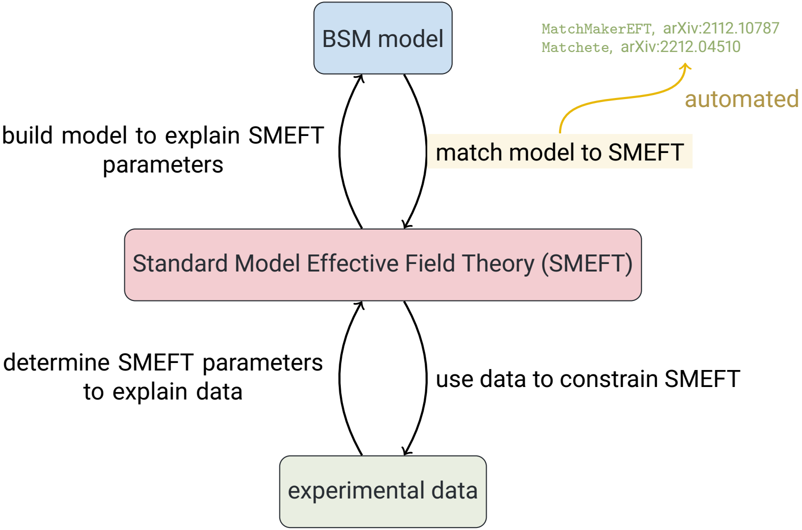


Automating BSM phenomenology



Automating BSM phenomenology

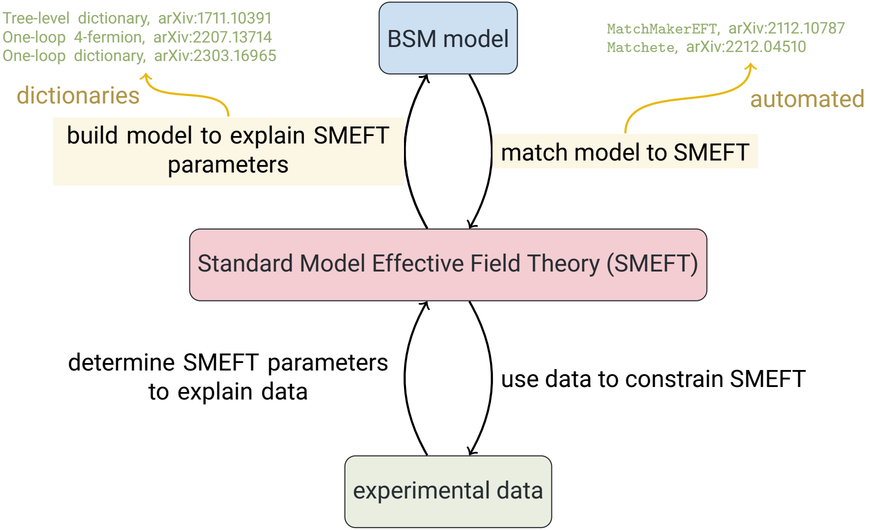
see also talk by Javier Fuentes-Martin



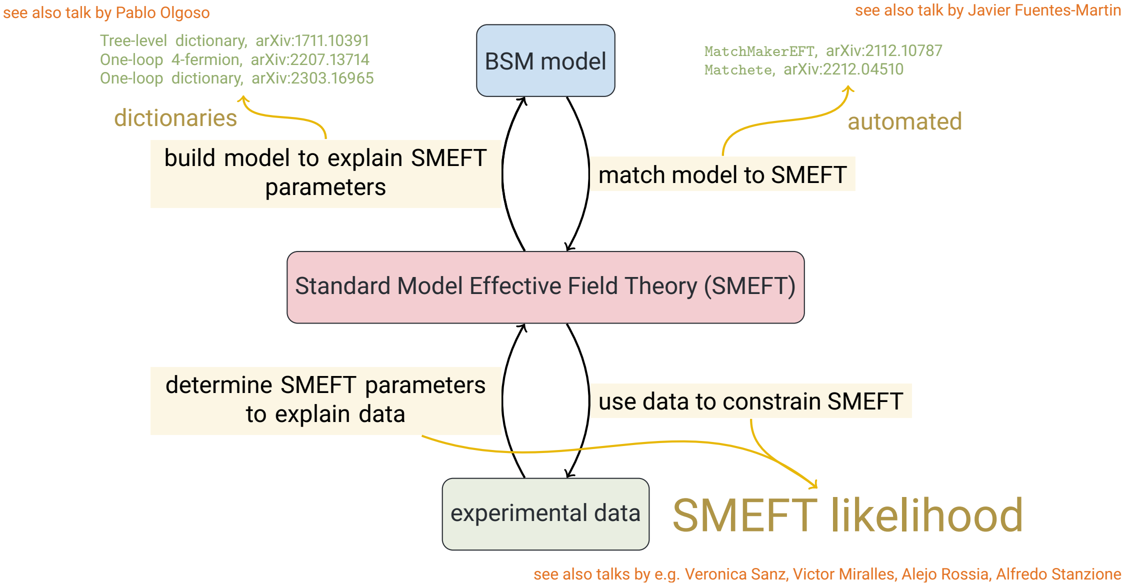
Automating BSM phenomenology

see also talk by Pablo Olgoso

see also talk by Javier Fuentes-Martin



Automating BSM phenomenology



Remark:
Lessons learned from model building — RG effects

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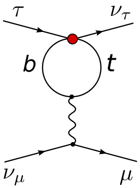
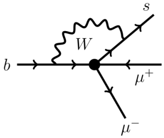


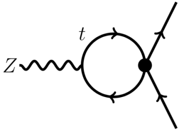
- Model explaining $\boldsymbol{b \to c\ell\nu}$ anomalies using mostly 3rd generation couplings
  Modifies τ **and** $\boldsymbol{Z}$ **decays**, strongly constrained

  Feruglio, Paradisi, Pattori, arXiv:1705.00929

- Model explaining $\boldsymbol{b \to s\mu\mu}$ anomalies using $\boldsymbol{tt\mu\mu}$ interaction
  Modifies $\boldsymbol{Z} \to \mu\mu$, constrained by LEP

  Camargo-Molina, Celis, Faroughy, arXiv:1805.04917





Using SMEFT for **UV model phenomenology**:

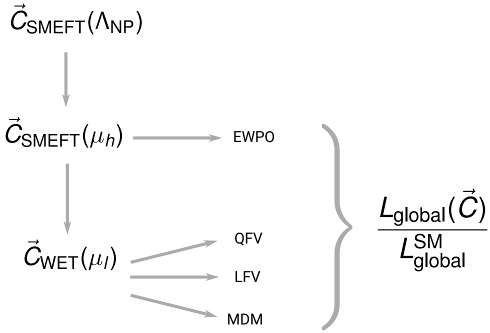
Renormalization Group effects are essential!

see also talk by Alfredo Stanzione, Uli Haisch

Implementation of the SMEFT likelihood

Implementation of the SMEFT likelihood

- **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
- **Wilson coefficient exchange format (WCxf)** `https://wcxf.github.io/`
- **smelli** - the **SME**FT **Like**L**I**hood `https://github.com/smelli/smelli`
  - SMEFT and WET likelihood function

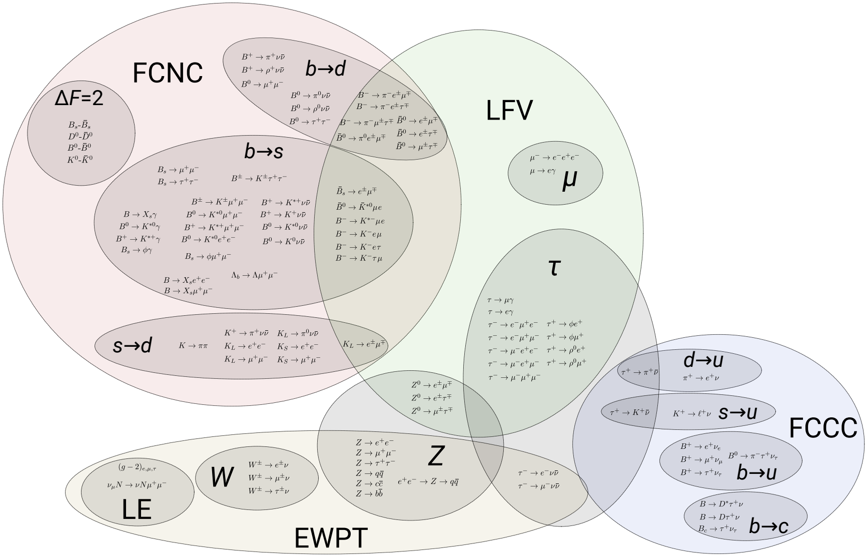


smelli v1.1.1: Flavour + EWPT

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

SMEFT parameters @ dim-6:

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



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

- **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

- $\boldsymbol{K \to \pi\ell\nu}$: 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

smelli v3.0

Smolkovič, PS, arXiv:240x.xxxxx

smelli v3.0: new observables

Greljo, Šalko, Smolkovič, PS, arXiv:2212.10497

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

- More new observables and updates
  - μ-e conversion in nuclei
  - $B_s \to \mu\mu$ effective lifetime, updates of $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ angular observables
    Altmannshofer, PS, arXiv:2103.13370
  - Updates of $b \to d\ell\ell$ observables Greljo, Šalko, Smolkovič, PS, arXiv:2212.10497
  - Updates of $b \to u\ell\nu$ observables Greljo, Šalko, Smolkovič, PS, arXiv:2306.09401
  - New D meson charged current decays, updated theory predictions of super-allowed beta decays
    Crivellin, Kirk, Kitahara, Mescia, arXiv:2212.06862

smelli v3.0: new features and improvements

- **Theory predictions**: Computational speed increased by 3 orders of magnitude through more efficient implementation
- **Theory uncertainties**: New efficient method to implement **new physics dependence** of theory uncertainties and correlations
  Altmannshofer, PS, arXiv:2103.13370
- **RG evolution and SMEFT-to-WET matching**: Fast RG evolution matrix formalism and matching as efficient linear algebra operations
- **Reimplemented SMEFT and WET likelihoods using `JAX` machine learning framework**:
  Just-In-Time (JIT) compilation and **automatic differentiation** (analytical differentiation of code)
  - **Fast likelihood**: $\mathcal{O}(10\,\text{ms})$ per parameter point on single CPU
  - Allows efficient use of **gradient based algorithms** (e.g. minimization using stochastic gradient descent, sampling using Hamiltonian Monte Carlo)
  - Fast computation of Hessian at minimum (= Gaussian approximation of likelihood) possible in high-dimensional parameter spaces

$\Rightarrow$ `smelli v3.0` codename “**jelli**” – a **J**AX-based **E**FT **L**ike**LI**hood

smelli v3.0 (jelli) preliminary demo

Conclusions & Outlook

Conclusions

- **smelli** - the **SME**FT **Like**L**I**hood Python package based on **flavio** and **wilson** can explore the **full flavourful dim-6 SMEFT and WET** including **RG effects** important for UV model phenomenology
- **smelli v3.0** – "**jelli**" – a JAX-based **E**FT **Like**L**I**hood has powerful new features (**just-in-time (JIT) compilation, automatic differentiation** based on `JAX`), includes **many additional observables** and implements efficient method to account for **new physics (NP) depends of theory uncertainties**
  To be released very soon!

Outlook: Work in progress

- New observables:
  - **EDMs**: neutron, atomic, and molecular (already in `flavio`), requires NP dependence of th. uncert.
  - LEP 2: $\mathbf{e}^+\mathbf{e}^- \to \ell^+\ell^-$ (soon in `flavio`)
  - ...
- **New interfaces to automatic matching tools**
  - Interface for importing one-loop matching results from **Matchete** and **MatchMakerEFT**
  - Evaluation of matching expressions based on `JAX` (**jit-compiled with gradients**)
  - **No restriction on flavour structure**
  - Allows exploration of **highly-dimensional UV model parameter spaces**

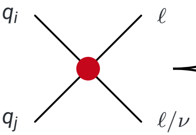
Backup slides

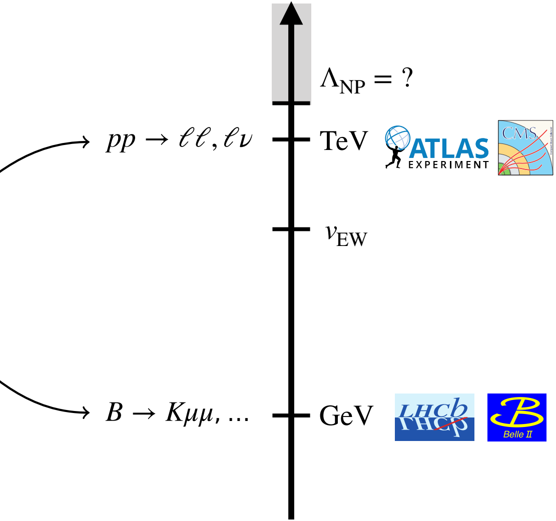
Recent development:
Drell-Yan tails meet rare *b* decays

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)



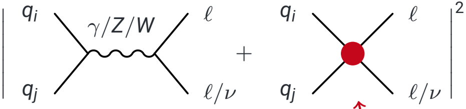


- **Rare *B* decays** ($B \to (M)\ell^+\ell^-$ for $\ell = e, \mu$) sensitive to
  - **semi-leptonic four-fermion operators**
  - $\boldsymbol{b \to s}$ and $\boldsymbol{b \to d}$ flavor changing interactions

Implementation of Drell-Yan: Theory prediction

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

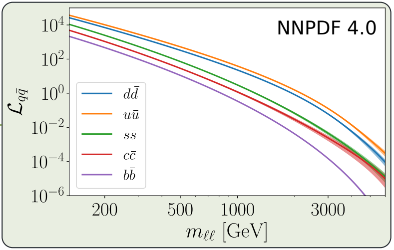
$$\sigma^{q_i q_j}_{\text{part.}} \sim \sum_{\substack{\text{chiralities}\\ \text{Lorentz structures}}}$$



$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
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 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**:

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

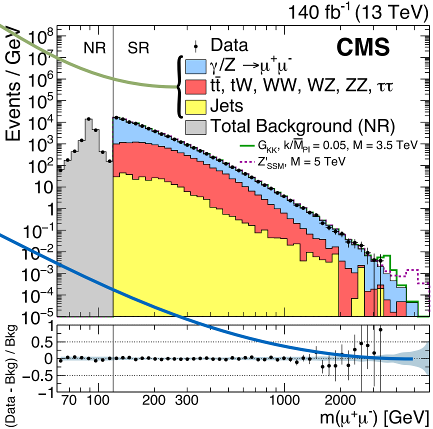
- **Theory uncertainties** Δ_{th}
- **Likelihood** of $\boldsymbol{R}_{\text{DY}}$:

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

  as convolution of
  - Likelihood of Poisson distributed data

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

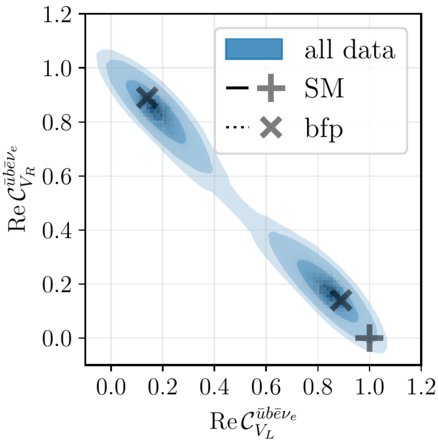
  - Normal distributed theory uncertainties with standard devation Δ_{th}: $\mathcal{N}_{\Delta_{\text{th}}}(N_{\text{exp}})$



smelli usage example:

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

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



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

Domagoj Leljak,[a] Blaženka Melić,[a] Filip Novak,[b] Méril Reboud[c] and Danny van Dyk[c]

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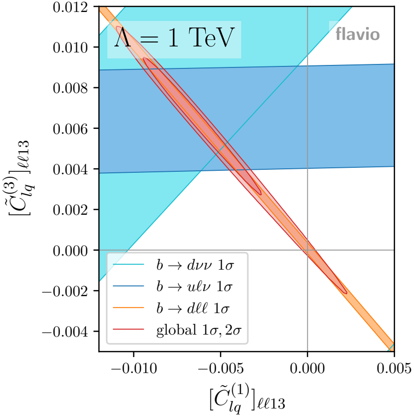
Abstract: We fit the available data on exclusive semileptonic $b \to u\ell^-\bar{\nu}$ decays within the Standard Model and in the Weak Effective Theory. Assuming Standard Model dynamics, we find $|V_{ub}| = 3.59^{+0.13}_{-0.12} \times 10^{-3}$. Lifting this assumption, we obtain stringent constraints 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.

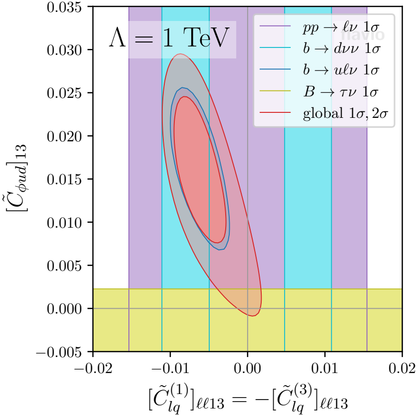
New physics in $b \to u\ell\nu$ is strongly constrained!

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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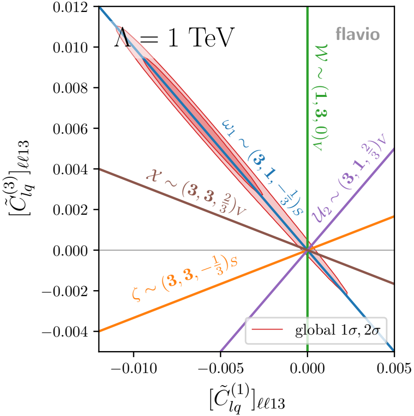

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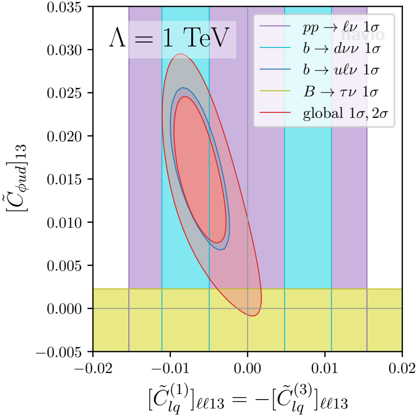

$$\omega_1 \sim (\mathbf{3},\mathbf{1},-\tfrac{1}{3})_S \;\Rightarrow\; [Q_{lq}^{(3)}]_{\ell\ell 13} = -[Q_{lq}^{(1)}]_{\ell\ell 13}$$

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

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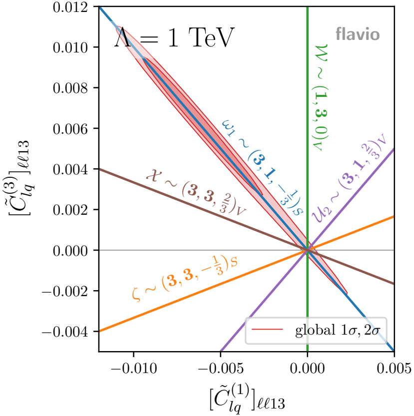

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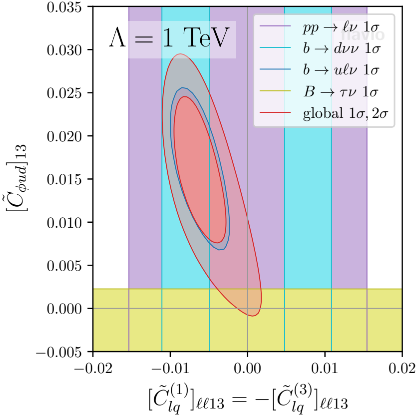

$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S \Rightarrow [Q_{lq}^{(3)}]_{\ell\ell 13} = -[Q_{lq}^{(1)}]_{\ell\ell 13}$

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

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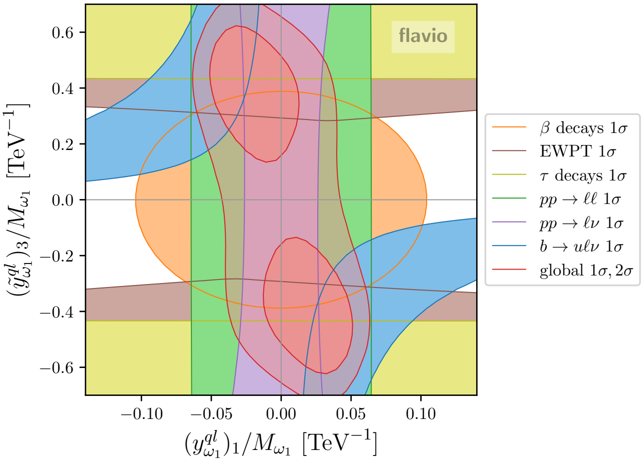

$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S \;\Rightarrow\; [Q^{(3)}_{lq}]_{\ell\ell 13} = -[Q^{(1)}_{lq}]_{\ell\ell 13}$

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