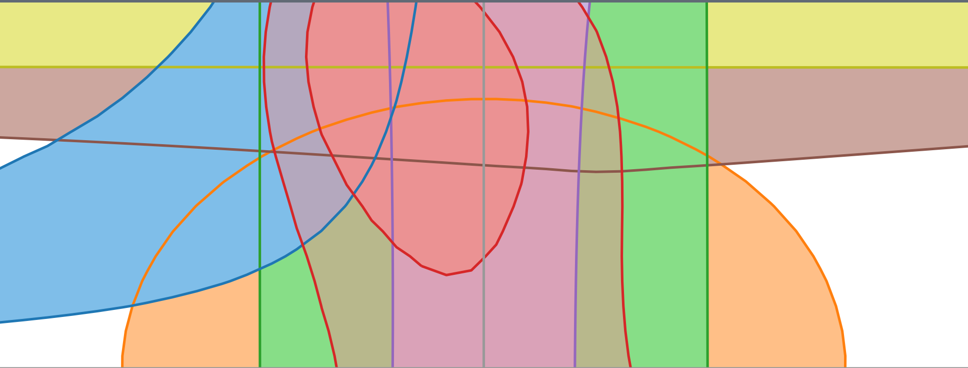
EFT Foundations and Tools 2023, MITP, Mainz, 7 September 2023

# The global SMEFT likelihood

Peter Stangl CERN

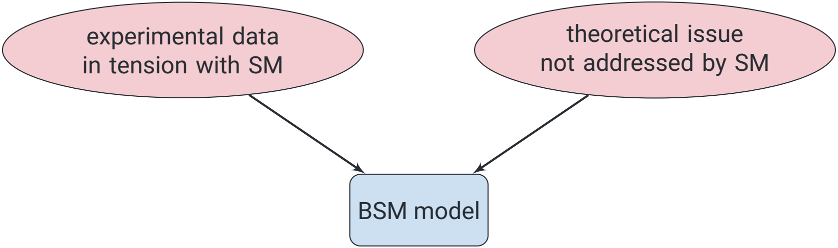


# BSM phenomenology

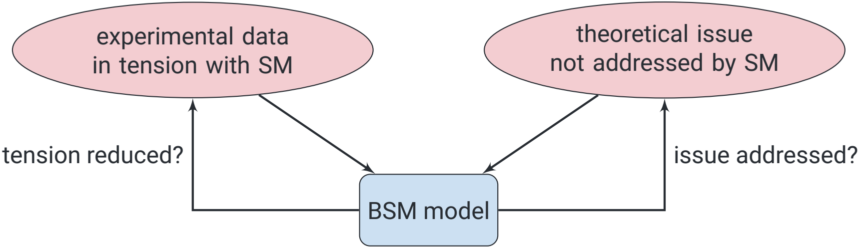
experimental data
in tension with SM

theoretical issue
not addressed by SM

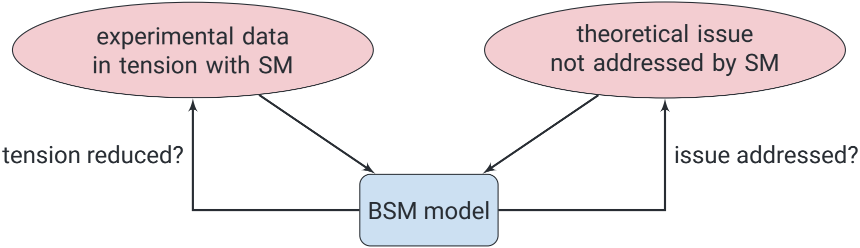
# BSM phenomenology



# BSM phenomenology

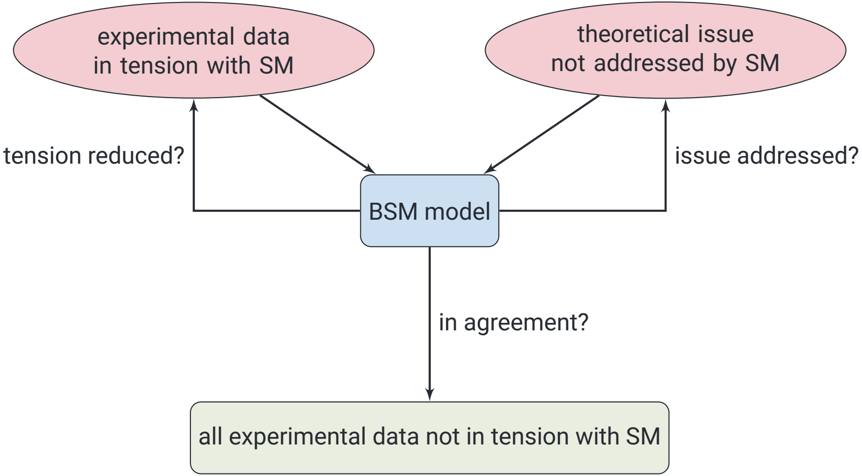


# BSM phenomenology



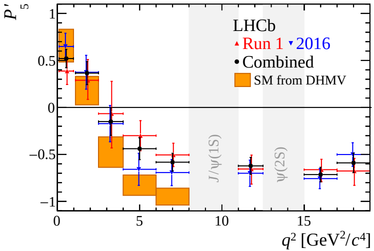

all experimental data not in tension with SM

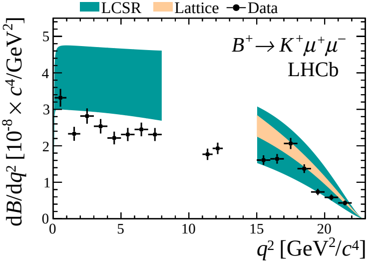
# BSM phenomenology

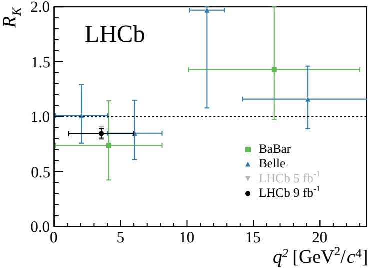


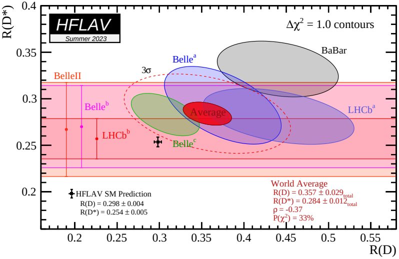
# Example:
# Lessons learned from *B* anomalies

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



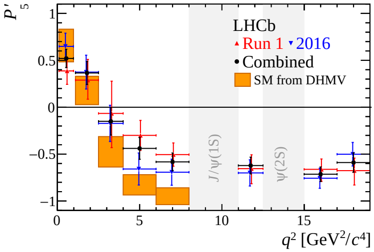



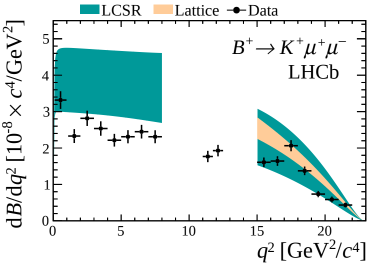



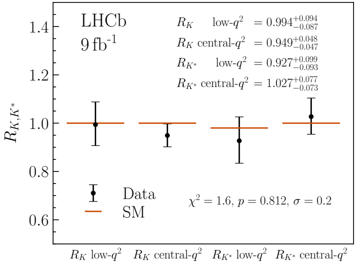



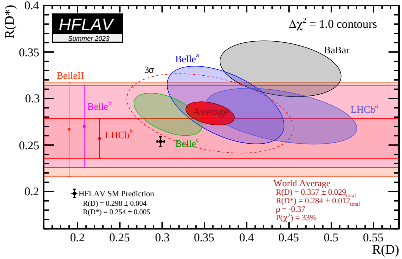

LHCb: arXiv:2003.04831, arXiv:2012.13241, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, arXiv:2105.14007, arXiv:1705.05802, arXiv:2103.11769, arXiv:2108.09283, arXiv:2108.09284, arXiv:2212.09153
HFLAV, hflav.web.cern.ch

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

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HFLAV, hflav.web.cern.ch

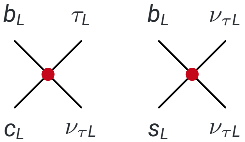
# Model building - lessons learned

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

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

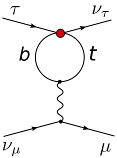
  Constrained by $B \to K \nu \bar{\nu}$ searches

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



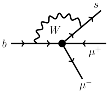

- Model explaining $B$ anomalies using mostly 3rd generation couplings
  Modifies $\tau$ and $Z$ decays, strongly constrained

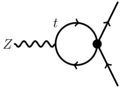
  Feruglio, Paradisi, Pattori, arXiv:1705.00929




- 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



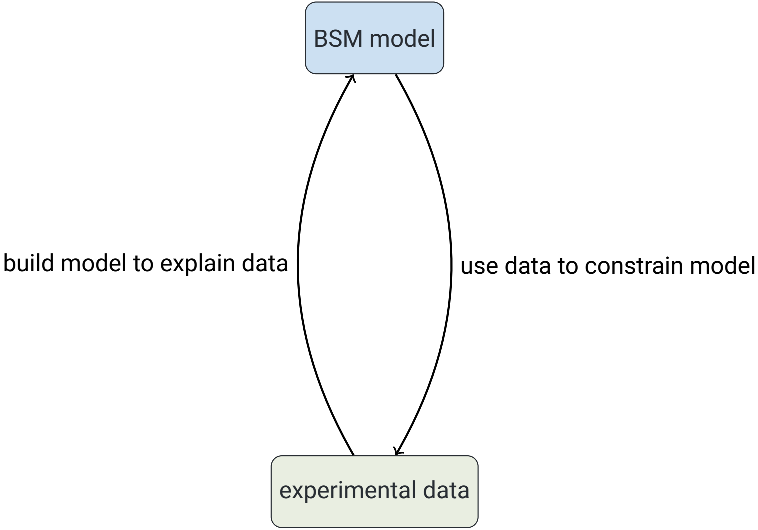
# What one would have to do

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

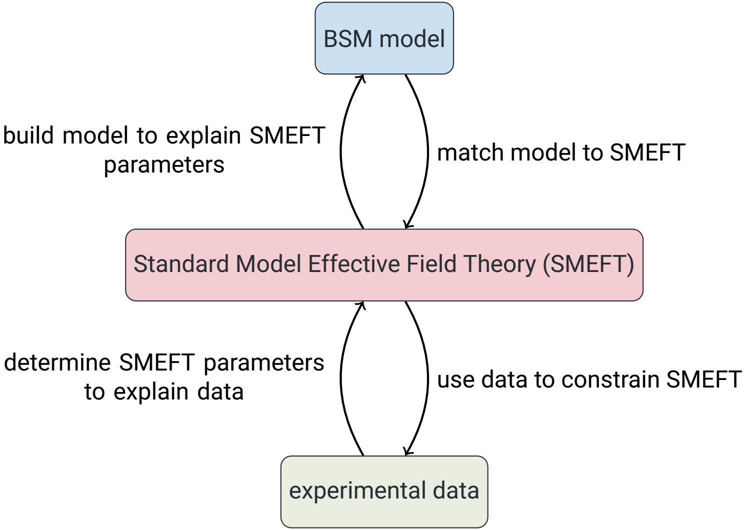
Has to be done **repeatedly** (for each model) taking into account a **large number** of observables $\Rightarrow$ This calls for **automation**!

# Approach to automating BSM phenomenology

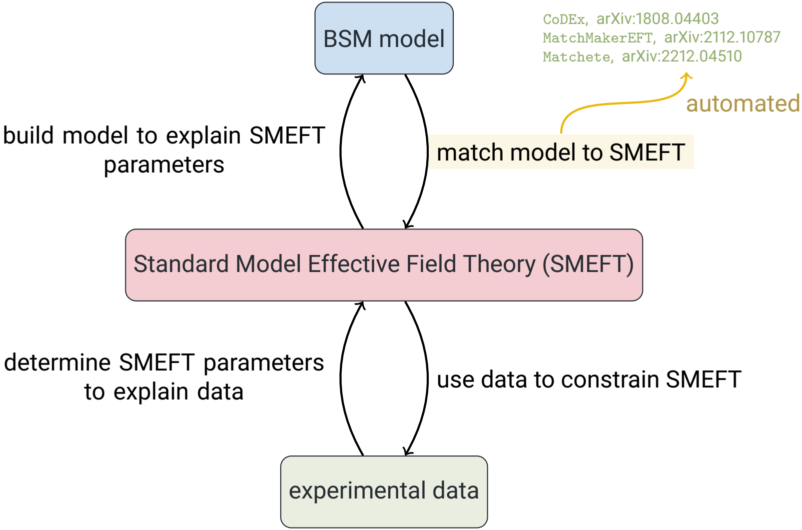
# Approach to automating BSM phenomenology



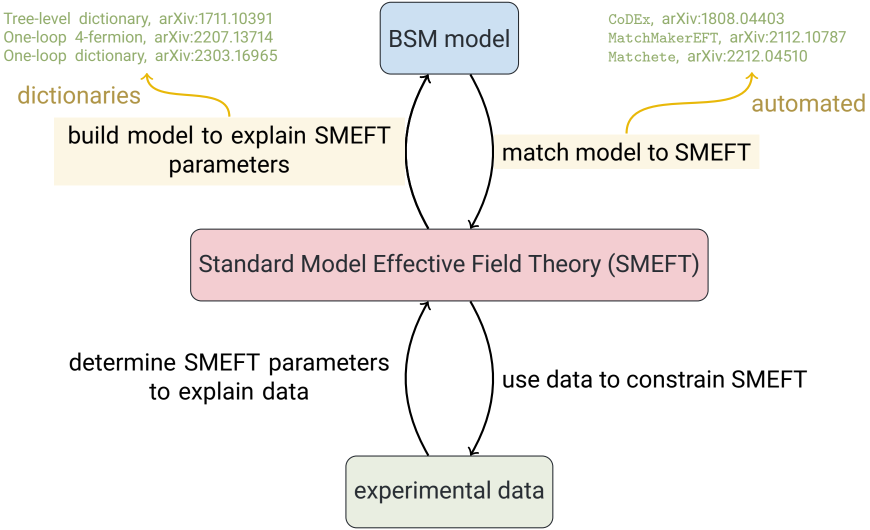
# Approach to automating BSM phenomenology



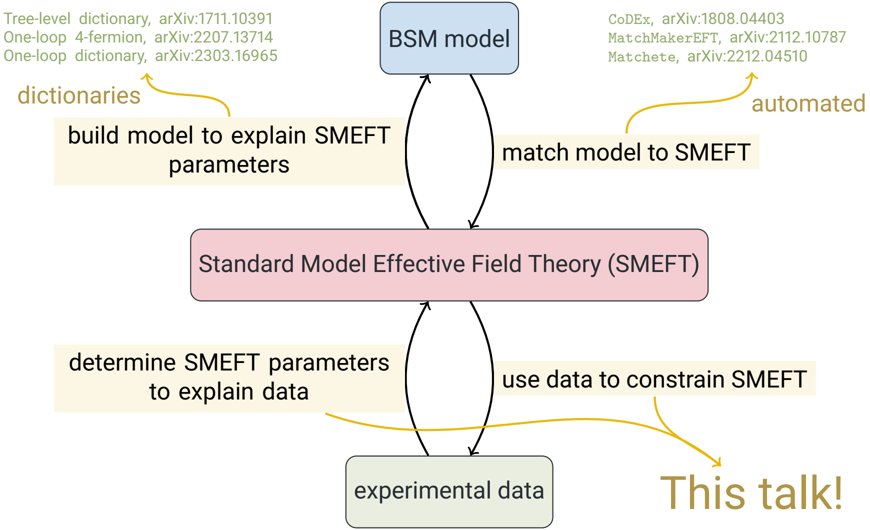
# Approach to automating BSM phenomenology



# Approach to automating BSM phenomenology



# Approach to automating BSM phenomenology




see also talk by Lukas Allwicher

# SMEFT 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:

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

  - *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

# Tools

- **flavio**: Theory predictions, Database of measurements, Likelihoods
- **wilson**: RG evolution in SMEFT and WET, matching from SMEFT to WET
- **Wilson coefficient exchange format (WCxf)**
- **smelli** - the **SME**FT **Like****LI**hood: WET and SMEFT likelihood function

# **flavio**: what can it do for me?

# flavio: main features

**1. Computing theory predictions**

for a huge number of observables (flavour physics, electroweak precision observables, Higgs physics, ...)

- **Standard Model** (SM) predictions
- Predictions in the presence of **new physics** (NP) (parameterized by Wilson coefficients)
- Theory **uncertainties** for SM and NP

# flavio: main features

**2. Database of experimental data**

for all implemented observables that have been measured

- provided in terms of YAML file
- easy to update and extend

# flavio: main features

**3. Likelihoods**

Combining predictions with experimental data allows constructing likelihoods

- Likelihoods in parameters (e.g. CKM parameters) or Wilson coefficients
- Possibility to use Gaussian approximation for **fast likelihood** estimates
- Use external fitters to perform Bayesian or frequentist statistics with `flavio` likelihoods
- Basis for **smelli** - the **SME**FT **Like****LI**hood

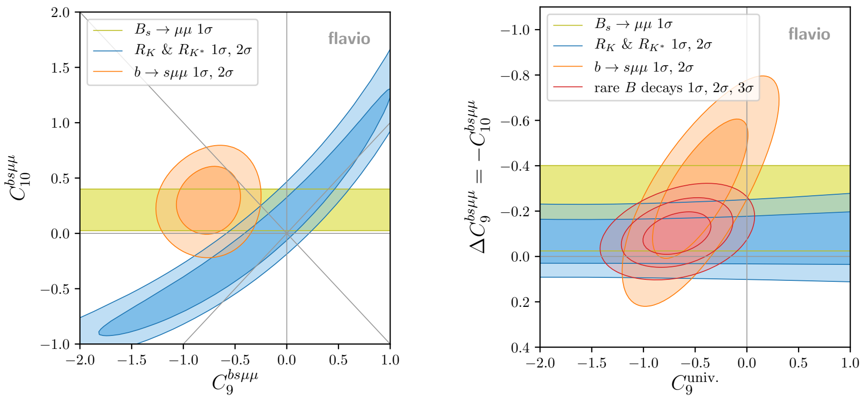
# flavio: main features

**4. Plots**

- Visualize experimental measurements & theory predictions
- Visualize your likelihoods

# flavio: showcase

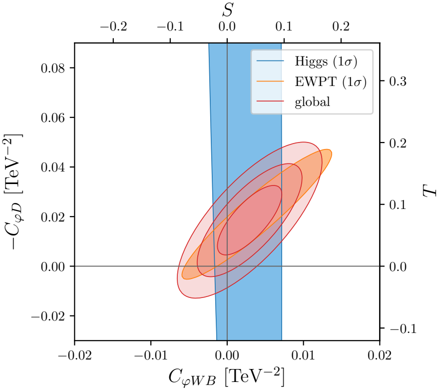
New physics in *B*-decays in Weak effective theory Wilson coefficients @ 4.8 GeV




Greljo, Salko, Smolkovič, PS, arXiv:2212.10497

# flavio: showcase

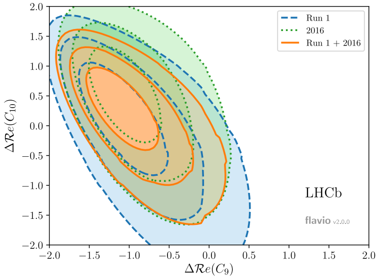
S-T fit using combined Higgs and electroweak likelihood in SMEFT

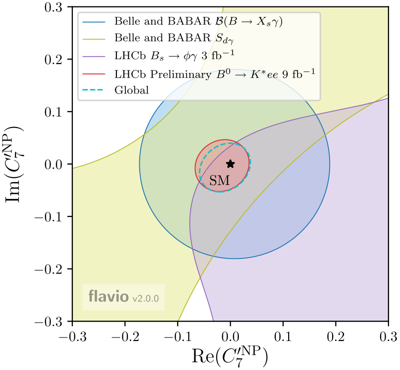



Falkowski, Straub, arXiv:1911.07866

# flavio: showcase

Fits to new physics Wilson coefficients from recent LHCb analyses




LHCb-PAPER-2020-002
LHCb-TALK-2020-155

# flavio: observables

See `https://flav-io.github.io/docs/observables.html`

- $B$ physics: $B \to (V, P, X)(\ell\ell, \ell\nu)$, $B \to (\ell\ell, \ell\nu)$, $B \to (V, X)\gamma$, $\Lambda_b \to \Lambda\ell\ell$, mixing
- $K$ physics: $K \to \pi\nu\nu$, $K \to \ell\ell$, $K \to \ell\nu$, $K \to \pi\ell\nu$, $\varepsilon_K$, $\varepsilon'/\varepsilon$
- $D$ physics: $D \to \ell\nu$, CPV in mixing
- $\mu$ physics: $\mu \to e\gamma$, $\mu \to 3e$, $\mu$-$e$ conversion, $\nu$ trident
- $\tau$ physics: $\tau \to 3\ell$, $\tau \to \ell\gamma$, $\tau \to (P, V)(\ell, \nu)$, $\tau \to \ell\nu\nu$
- EWPT: All LEP-1 $Z$ and $W$ pole observables
- Dipole moments: $(g-2)_{e,\mu,\tau}$, $d_n$
- Higgs production and decay new in flavio v2.0 Falkowski, Straub, arXiv:1911.07866
- Nuclear and neutron $\beta$ decays new in flavio v2.0
- Atomic and molecular EDMs new in flavio v2.0
- High-mass Drell-Yan tails: $pp \to e\nu, \mu\nu$ and $pp \to e^+e^-, \mu^+\mu^-$ new in flavio v2.5 Greljo, Salko, Smolkovič, PS, arXiv:2212.10497
- LEP 2: $e^+e^- \to \ell^+\ell^-$ soon in flavio Allanach, Mullin, arXiv:2306.08669

# **flavio**: setup & documentation

- Requires **Python 3.7** and pip (Python package manager)
- Installation

```
python3 -m pip install flavio --user
```

  (automatically downloads `flavio` and all dependencies)
- **Introductory documentation**: `https://flav-io.github.io/`
- Detailed **API documentation** of all functions and classes: `https://flav-io.github.io/apidoc/flavio/`
- **GitHub repository**: `https://github.com/flav-io/flavio`
- Paper: D. Straub, arXiv:1810.08132 (not a manual)

# wilson & WCxf

# wilson & WCxf

**flavio** depends on:

- **wilson** `https://wilson-eft.github.io` Aebischer, Kumar, Straub, arXiv:1804.05033
  - RG evolution above* and below the EW scale
    SMEFT RGE: Alonso, Jenkins, Manohar, Trott, arXiv:1308.2627, arXiv:1310.4838, arXiv:1312.2014
    WET/LEFT RGE: Aebischer, Fael, Greub, Virto, arXiv:1704.0663
    Jenkins, Manohar, Stoffer, arXiv:1711.05270
  - Matching from SMEFT to the weak effective theory (WET) aka LEFT
    Jenkins, Manohar, Stoffer, arXiv:1709.04486
    Dekens, Stoffer: arXiv:1908.05295
  - Basis translation
- **Wilson coefficient exchange format (WCxf)** `https://wcxf.github.io/` Aebischer et al., arXiv:1712.05298
  - Representing and exchanging Wilson coefficient values
  - Different EFTs, different bases
  - Interface between codes

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

# **smelli** - the **SME**FT **L**ike**LI**hood

# smelli: implementation

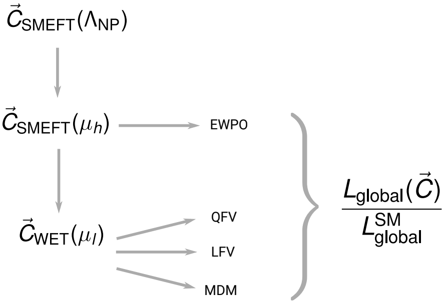
- Based on **flavio**, **wilson**, and **WCxf**, we have started building the global **SME**FT **LikeLI**hood **smelli** `https://github.com/smelli/smelli`

Aebischer, Kumar, PS, Straub, arXiv:1810.07698
PS, arXiv: 2012.12211

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

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: setup & documentation

- Requires **Python 3.7** and pip (Python package manager)
- Installation

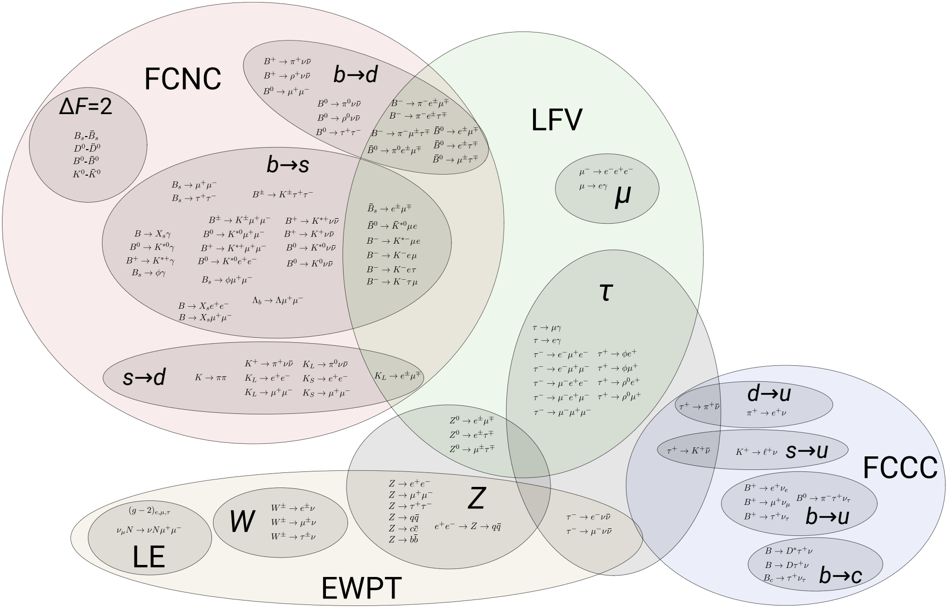
```
python3 -m pip install smelli --user
```

  (automatically downloads `smelli` and all dependencies)
- Detailed **API documentation** of all functions and classes: `https://smelli.github.io/`
- **GitHub repository**: `https://github.com/smelli/smelli`
- Original paper: Aebischer, Kumar, PS, Straub, arXiv:1810.07698 (containing brief user manual)
- Recent article: PS, arXiv:2012.12211 (up-to-date usage examples)

# **smelli**: observables and features

# 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
  - $\boldsymbol{K \to \pi\ell\nu}$: 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 $\delta$)
  - Determine **effective CKM** matrix in presence of SMEFT operators

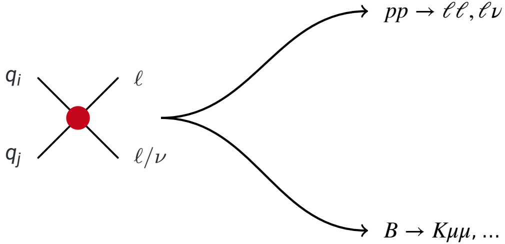
see also talk by Lukas Allwicher on Drell-Yan tails

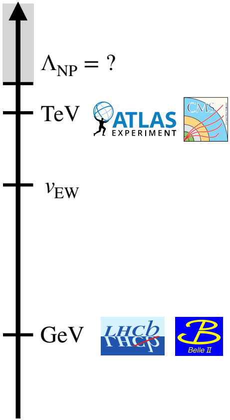
# Recent development: Drell-Yan tails meet rare $b$ decays

# 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)



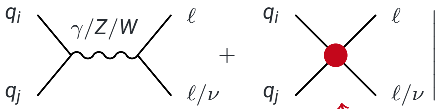




- **Rare *B* decays** ($B \to (M)\ell^+\ell^-$ for $\ell = e, \mu$) sensitive to
  - **semi-leptonic four-fermion operators**
  - $\boldsymbol{b \to s}$ and $\boldsymbol{b \to d}$ flavor changing interactions

# Implementation of Drell-Yan: Theory prediction

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

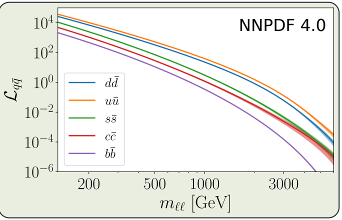
$$\sigma^{q_i q_j}_{\text{part.}} \sim \sum_{\substack{\text{chiralities} \\ \text{Lorentz structures}}} \left| \; \cdots \; + \; \cdots \; \right|^2$$




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

- **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 ($\sim 140\ \mathrm{fb}^{-1}$) 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** $\Delta_{\text{th}}$
- **Likelihood** of $\boldsymbol{R}_{\text{DY}}$:

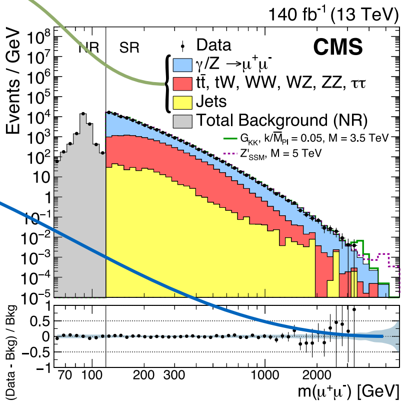
$$L(\boldsymbol{R}_{\text{DY}}) = (L_{\mathcal{P}} * \mathcal{N}_{\Delta_{\text{th}}})\left(N_{\text{exp}}^{\text{SM+NP}}(\boldsymbol{R}_{\text{DY}})\right)$$

as convolution of

- Likelihood of Poisson distributed data

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

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

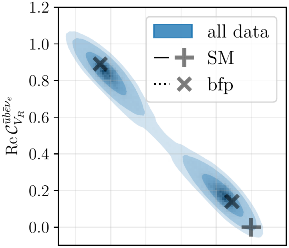


## **smelli** usage example:

## 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

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

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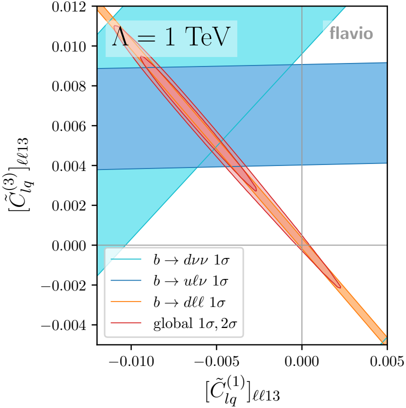
ABSTRACT: We fit the available data on exclusive semileptonic $b \to u\ell^-\bar{\nu}$ decays within the Standard Model and in the Weak Effective Theory. Assuming Standard Model dynamics, we find $|V_{ub}| = 3.59^{+0.13}_{-0.12} \times 10^{-3}$. Lifting this assumption, we obtain stringent constraints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

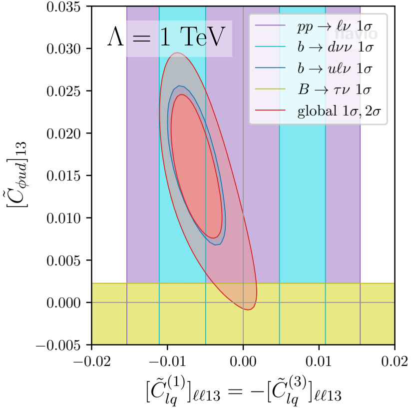
# New physics in $b \to u\ell\nu$ is strongly constrained!

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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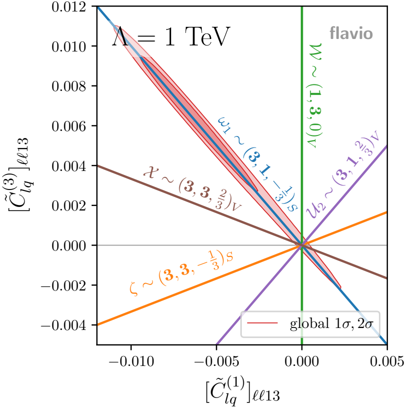


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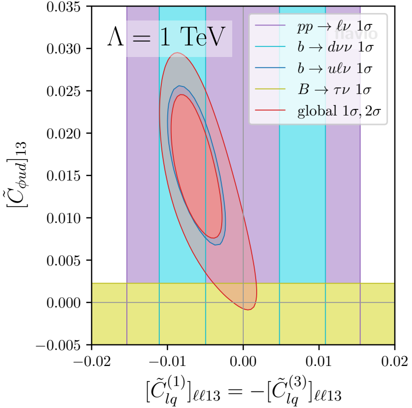


$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S \;\Rightarrow\; [Q_{lq}^{(3)}]_{\ell\ell 13} = -[Q_{lq}^{(1)}]_{\ell\ell 13}$

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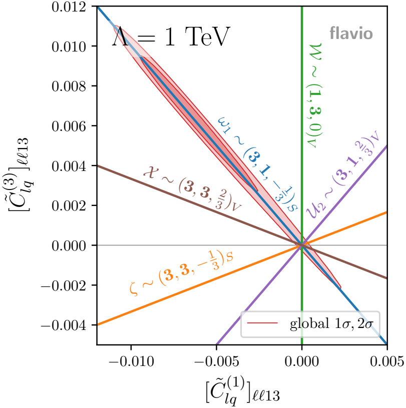


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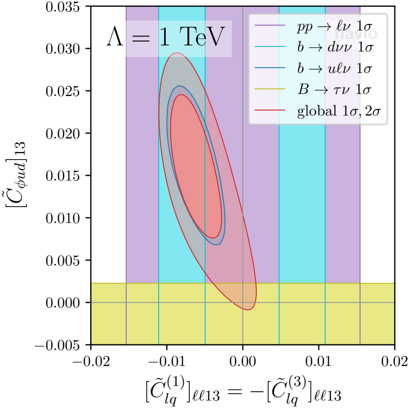


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$Q_1 \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_F \;\Rightarrow\; [Q_{\phi ud}]_{13}$

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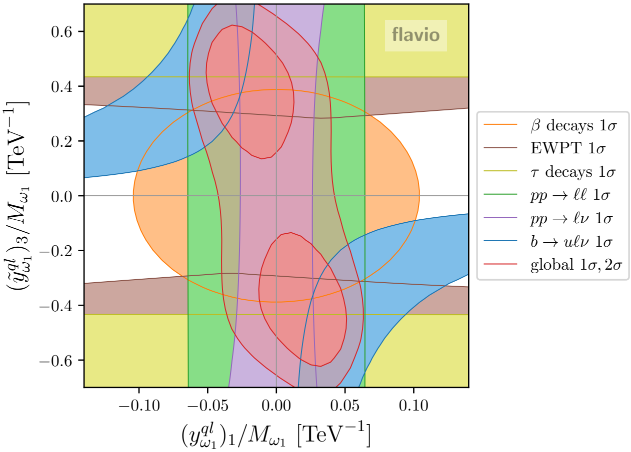
Greljo, Salko, Smolkovič, PS, arXiv:2306.09401




$\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S \;\Rightarrow\; [Q_{lq}^{(3)}]_{\ell\ell 13} = -[Q_{lq}^{(1)}]_{\ell\ell 13}$ $\qquad$ $Q_1 \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_F \;\Rightarrow\; [Q_{\phi ud}]_{13}$

# 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: $e^+e^- \to \ell^+\ell^-$ (soon in `flavio`)
  - EDMs: neutron, atomic, and molecular (already available in `flavio`)
  - Major speed improvement (orders of magnitude)
  - 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`

# Backup slides

# The likelihood

Construct **likelihood** that quantifies the agreement between **experimental data** and **theoretical predictions**

- Experimental data of measurement *i* yields **experimental likelihood** for **observables $\vec{O}$**

$$\mathcal{L}^i_{\text{exp}}(\vec{O})$$

  - non-trivial likelihood function for one or several correlated observables
  - uniform likelihood for observables not measured by measurement *i*

- In SM or NP model, **theory predictions** in terms of theory parameters $\vec{C}$ and $\vec{\theta}$

$$\vec{O}_{\text{th}}(\vec{C}, \vec{\theta})$$

  $\vec{C}$: NP Wilson coefficients, defined such that SM is given by $\vec{C} = \vec{0}$
  $\vec{\theta}$: model-independent theory parameters (e.g. particle masses, hadronic form factors, ...)

# The likelihood

- Define individual likelihoods in theory parameters

$$\mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) = \mathcal{L}^i_{\text{exp}}(\vec{O} = \vec{O}_{\text{th}}(\vec{C},\vec{\theta}))$$

- Define full likelihood taking into account parametric theory uncertainties

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta})$$

- Assumptions:
  - Measurements are independent of each other
  - Measurements do not explicitly depend on theory parameters (only through $\vec{O}_{\text{th}}$)

# The New Physics likelihood

In the New Physics likelihood, all parameters $\vec{\theta}$ are **nuisance parameters**

- How do we get a "nuisance-free" likelihood?

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \stackrel{?}{\to} \quad \mathcal{L}(\vec{C})$$

- **Bayesian approach**:
  Interpret $\mathcal{L}_{\text{th}}(\vec{\theta})$ as *prior* and $\mathcal{L}(\vec{C})$ as *posterior*, marginalise over nuisance parameters
- **Frequentist approach**:
  Interpret $\mathcal{L}_{\text{th}}(\vec{\theta})$ as *likelihood of pseudo-experiments* and $\mathcal{L}(\vec{C})$ as *profiled likelihood*

For large numbers of nuisance parameters $\vec{\theta}$ and NP parameters $\vec{C}$, both approaches are **computationally expensive**.

What special cases exist that allow obtaining a "nuisance-free" likelihood **computationally *in*expensive** and that could serve as reasonable approximations?

# Approximations: Case 1

$$\mathcal{L}(\vec{C},\vec{\theta}) = \prod_i \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \stackrel{?}{\rightarrow} \quad \mathcal{L}(\vec{C})$$

Special case 1:

$$\mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \approx \mathcal{L}^i_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \qquad \text{for } \vec{\theta} \text{ sampled from } \mathcal{L}_{\text{th}}(\vec{\theta})$$

this is the case for **small parametric uncertainty of theory prediction** compared to experimental uncertainty e.g.

- Ratios of branching ratios like $R_{K^{(*)}}$, $R_{D^{(*)}}$
- Electroweak precision observables
- LFV decays
- ...

$$\Rightarrow \qquad \mathcal{L}(\vec{C}) \approx \prod_{i \in \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \times \mathcal{L}'(\vec{C})$$

# Approximations: Case 2

$$\mathcal{L}'(\vec{C},\vec{\theta}) = \prod_{i \notin \text{case 1}} \mathcal{L}^i_{\text{exp}}(\vec{C},\vec{\theta}) \times \mathcal{L}_{\text{th}}(\vec{\theta}) \quad \overset{?}{\rightarrow} \quad \mathcal{L}'(\vec{C})$$

Special case 2:

- Theoretical **prediction likelihood** of subset of observables $\vec{O}^k$ can be approximated as multivariate **normal distribution** for given $\vec{C}$

$$-2\ln \mathcal{L}_{\text{th}}(\vec{O}^k,\vec{C}) = \left(\vec{O} - \vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}})\right)^T \Sigma_{\text{th}}^{-1} \left(\vec{O} - \vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}})\right) ,$$

  with **covariance matrix** $\Sigma_{\text{th}}$ determined for $\vec{C} = \vec{0}$ and (approximately) **independent of $\vec{C}$**

- Approximate **experimental likelihoods** for measurements of observables $\vec{O}^k$ as multivariate **normal distributions**

$$-2\ln \mathcal{L}^i_{\text{exp}}(\vec{O}^k) = (\vec{O}^k - \hat{\vec{O}}^{k,i})^T (\Sigma^i_{\text{exp}})^{-1} (\vec{O}^k - \hat{\vec{O}}^{k,i}) ,$$

  $\hat{\vec{O}}^{k,i}$ exp. central value, $\Sigma^i_{\text{exp}}$ covariance matrix

# Approximations: Case 2

- Combine $\mathcal{L}^i_{\text{exp}}(\vec{O}^k)$ ($i \in$ case 2) in terms of **weighted averaged** covariance matrix $\Sigma_{\text{exp}}$ and mean $\hat{\vec{O}}^k$

- Define **modified experimental likelihood** $\tilde{\mathcal{L}}_{\text{exp}}(\vec{O}^k)$

$$-2\ln\tilde{\mathcal{L}}_{\text{exp}}(\vec{O}^k) = (\vec{O}^k - \hat{\vec{O}}^k)^T(\Sigma_{\text{exp}} + \Sigma_{\text{th}})^{-1}(\vec{O}^k - \hat{\vec{O}}^k)\,,$$

  Takes into account theoretical uncertainties and correlations in terms of covariance matrix $\Sigma_{\text{th}}$, treated as additional experimental uncertainties

- Express in terms of $\vec{C}$ and $\hat{\vec{\theta}}$

$$-2\ln\tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) = \left(\vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}}) - \hat{\vec{O}}^k\right)^T(\Sigma_{\text{exp}} + \Sigma_{\text{th}})^{-1}\left(\vec{O}^k_{\text{th}}(\vec{C},\hat{\vec{\theta}}) - \hat{\vec{O}}^k\right)\,,$$

$$\Rightarrow \qquad \mathcal{L}'(\vec{C}) \approx \tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \times \mathcal{L}''(\vec{C})$$

# The New Physics likelihood

The (approximative) **global New Physics likelihood** Aebischer, Kumar, PS, Straub, arXiv:1810.07698

$$\mathcal{L}(\vec{C}) \approx \prod_{i\in\text{case 1}} \mathcal{L}^{i}_{\text{exp}}(\vec{C},\hat{\vec{\theta}}) \times \tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}})$$

- $\prod_{i\in\text{case 1}} \mathcal{L}^{i}_{\text{exp}}(\vec{C},\hat{\vec{\theta}})$ : negligible parametric theory uncertainties

  e.g. EFT fits to electroweak precision tests:
  Efrati, Falkowski, Soreq, arXiv:1503.07872
  Falkowski, González-Alonso, Mimouni, arXiv:1706.03783

- $\tilde{\mathcal{L}}_{\text{exp}}(\vec{C},\hat{\vec{\theta}})$ : theoretical and experimental uncertainties combined at $\vec{C}=\vec{0}$ (SM)

  EFT fits of rare B decays first in: Altmannshofer, Straub, arXiv:1411.3161
  also used by other groups, e.g. Descotes-Genon, Hofer, Matias, Virto, arXiv:1510.04239

# Advantages and disadvantages of approximations

Disadvantages

- Theory uncertainties only weakly dependent on New Physics $\vec{C}$:
  **strong assumption**, validity has to be **checked explicitly**
  (e.g. by computing $\Sigma_{\rm th}(\vec{C} \neq \vec{0})$)
- **Not able to include certain observables**, e.g. electric dipole moments afflicted by sizable hadronic uncertainties for $\vec{C} \neq \vec{0}$ but negligible ones for $\vec{C} = \vec{0}$

Advantages

- Computationally expensive determination of $\Sigma_{\rm th}$
  - has to be done **only once**
  - is **independent of experimental data**
  - computing time is **independent of number of nuisance parameters**
- Computation of global likelihood **fast** enough for **phenomenological analysis of New Physics** models ($\sim$ 5 sec. per point on laptop)