Phenomenology, but fast

Aleks Smolkovic

Jožef Stefan Institute

Now:

Advisor: There's this cool model I have, it would be great if you could make these plots for our awesome paper.

PhD student: Sure no problem, give me a few weeks!

Soon:

Advisor: There's this cool model I have, it would be great if you could make these plots for our awesome paper.

PhD student: Sure no problem, give me a few ~~weeks~~ seconds!*

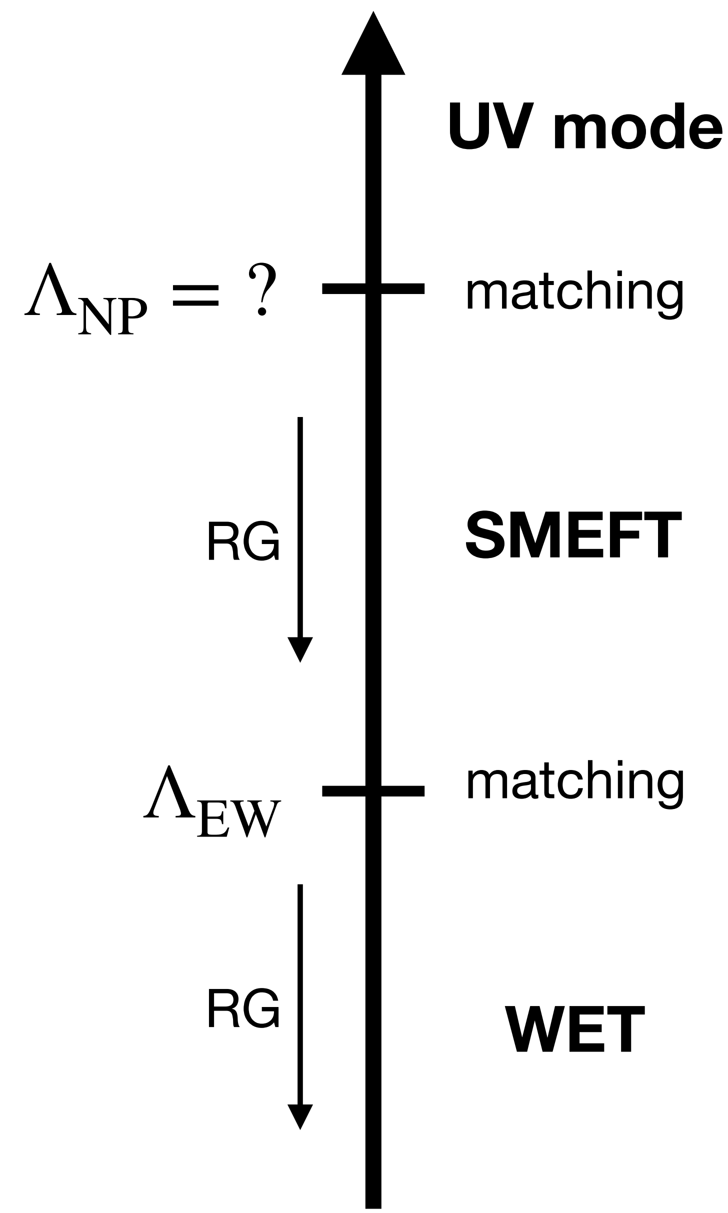
*(slight) exaggeration for dramatic purposes

SMEFT

Nucl.Phys.B 268 (1986) 621-653
Phys.Rept. 793 (2019) 1-98
Rev.Mod.Phys. 96 (2024) 1, 015006

- SM fields and symmetries
- Scale separation, linearly realized EWSB
- Higher-dimensional operators encode short-distance NP

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{Q} \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$



- No preferred BSM model-building direction
- SM works well as a low-energy limit
- Experiments headed towards the precision era
- A global SMEFT likelihood can be ‘recycled’ for reinterpretation in concrete models

Challenge:

Large number of parameters (2499@dim 6 (dB=dL=0) for 3 gen, flavor!)

SMEFT operators will impact observables from vastly different classes

The Warsaw basis

JHEP 10 (2010) 085

One-loop anomalous dimension matrix

JHEP 10 (2013) 087, *JHEP* 01 (2014) 035, *JHEP* 04 (2014) 159

One-loop matching onto LEFT

JHEP 03 (2018) 016, *JHEP* 10 (2019) 197

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

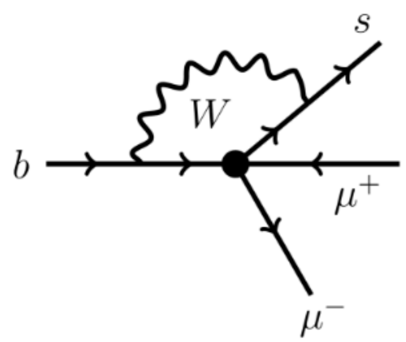
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

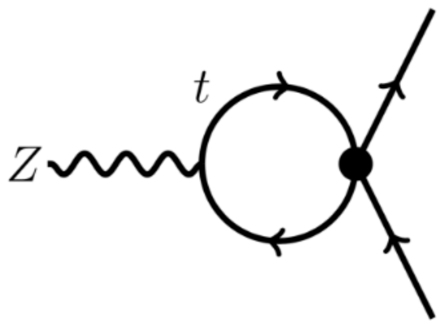
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

Side note: Renormalization Group effects are essential

Some recent examples:

Anomalies in $b \to s\mu\mu$ from NP in Top





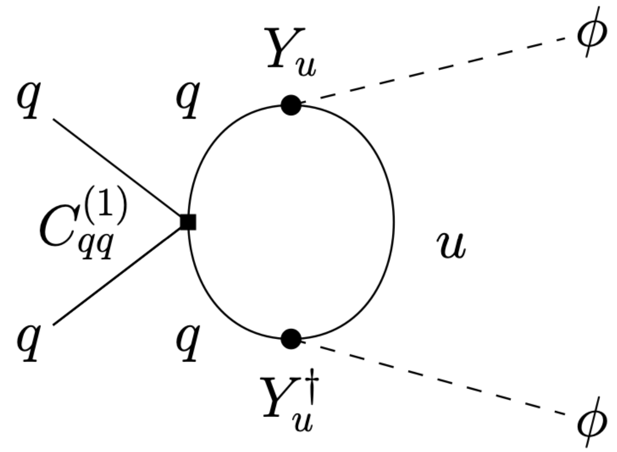
Celis, Fuentes-Martin, Vicente, Virto, 1704.05672
Kamenik, Soreq, Zupan, 1704.06005
Camargo-Molina, Celis, Faroughy, 1805.04917

Indirect constraints on top operators

EW/Higgs coeff.		TeV-scale coefficient
$\delta g_L^{Z\ell}$	$\longleftarrow$	$C_{uB},\ C_{uW}, C_{Hu},\ C_{Hq}^{(1,3)},\ C_{lq}^{(1,3),\ell\ell},\ C_{lu}^{\ell\ell},\ \ldots$
$\delta g_L^{W\ell}$	$\longleftarrow$	$C_{uB},\ C_{uW},\ C_{Hu},\ C_{Hq}^{(1,3)},\ C_{lq}^{(3),\ell\ell},\ \ldots$
$\delta g_R^{Z\ell}$	$\longleftarrow$	$C_{uB},\ C_{uW},\ C_{Hu},\ C_{Hq}^{(1,3)},\ C_{eu}^{\ell\ell},\ C_{qe}^{\ell\ell},\ \ldots$
δg_L^{Zb}	$\longleftarrow$	$C_{Hq}^{(1,3)},\ C_{Hu},\ C_{qq}^{(1,3)},\ \ldots$
δg_R^{Zb}	$\longleftarrow$	$C_{Hq}^{(1)},\ C_{Hu},\ C_{qq}^{(1,3)},\ C_{uB},\ C_{uW},\ \ldots$
$c_{\gamma\gamma}$	$\longleftarrow$	$C_{uB},\ C_{uW},\ C_{uG}$
c_{gg}	$\longleftarrow$	C_{uG}
$[C_{eH}]_{\alpha\alpha}$	$\longleftarrow$	$C_{lequ}^{(1),\alpha\alpha}$
$[C_{uH}]_{33}$	$\longleftarrow$	$C_{uH},\ C_{uG},\ C_{Hq}^{(1,3)},\ C_{qu}^{(1,8)},\ \ldots$

Garosi, Marzocca, Rodriguez-Sanchez, Stanzione, 2310.00047

Indirect constraints on universal NP directions



Greljo, Palavric, AS, 2312.09179

Efficient BSM phenomenology

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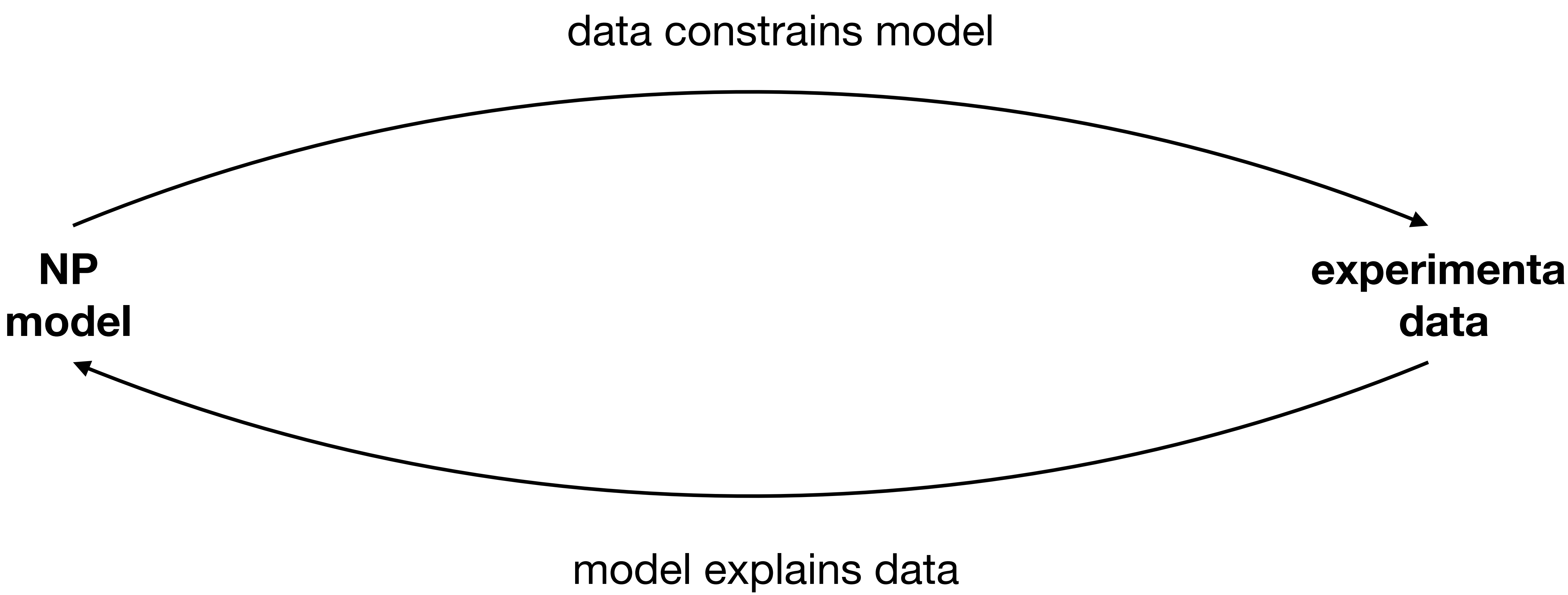
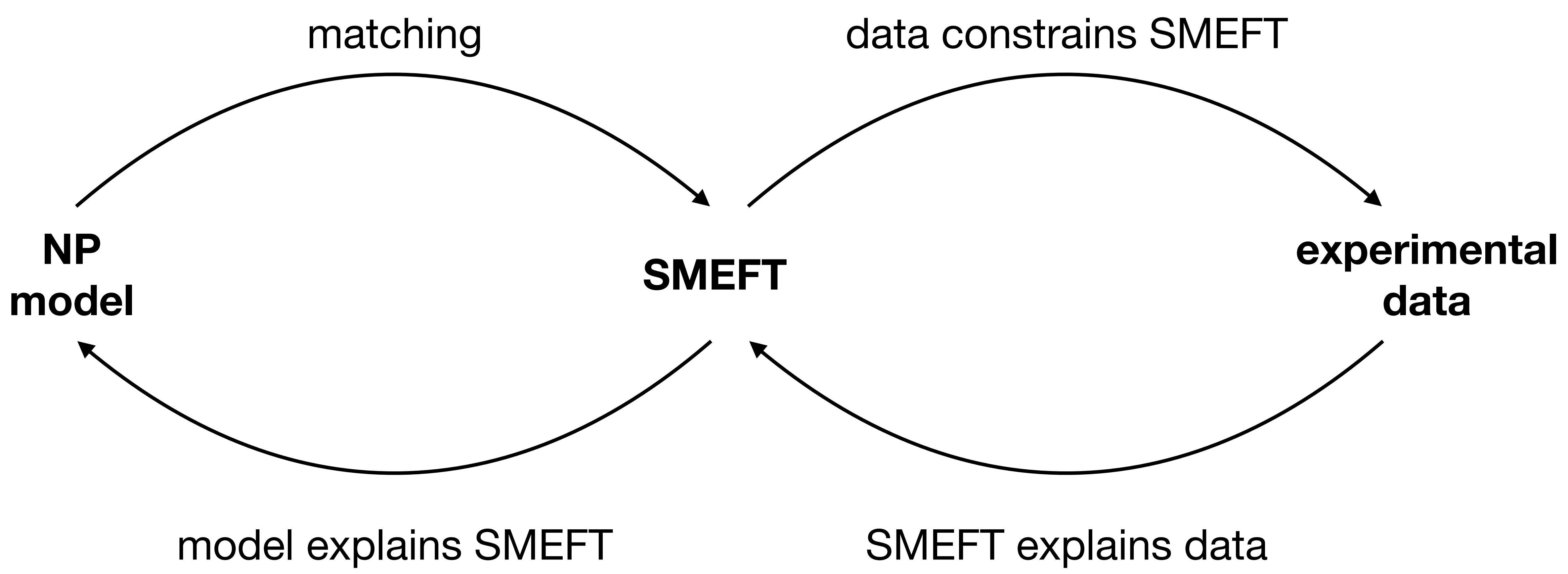
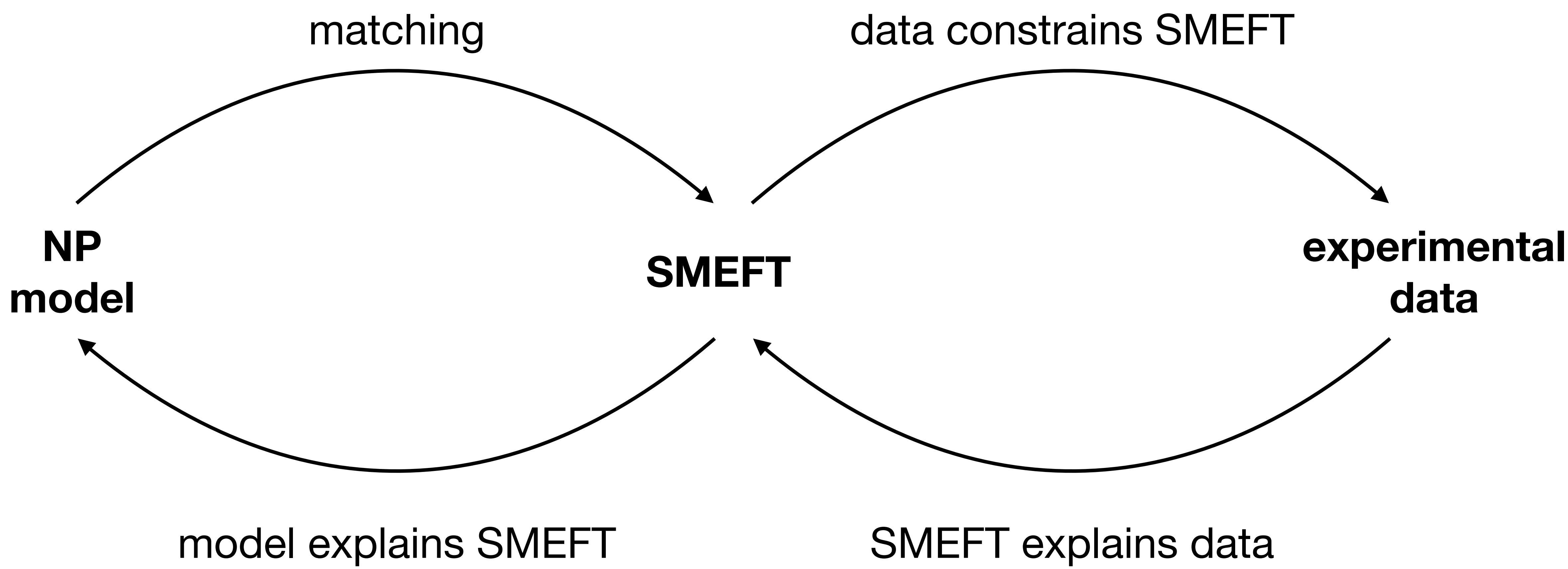


Efficient BSM phenomenology



Efficient BSM phenomenology

MatchMakerEFT, Matchete
2112.10787, 2212.04510



Tree-level, one-loop dictionaries
1711.10391, 2207.13714, 2303.16965

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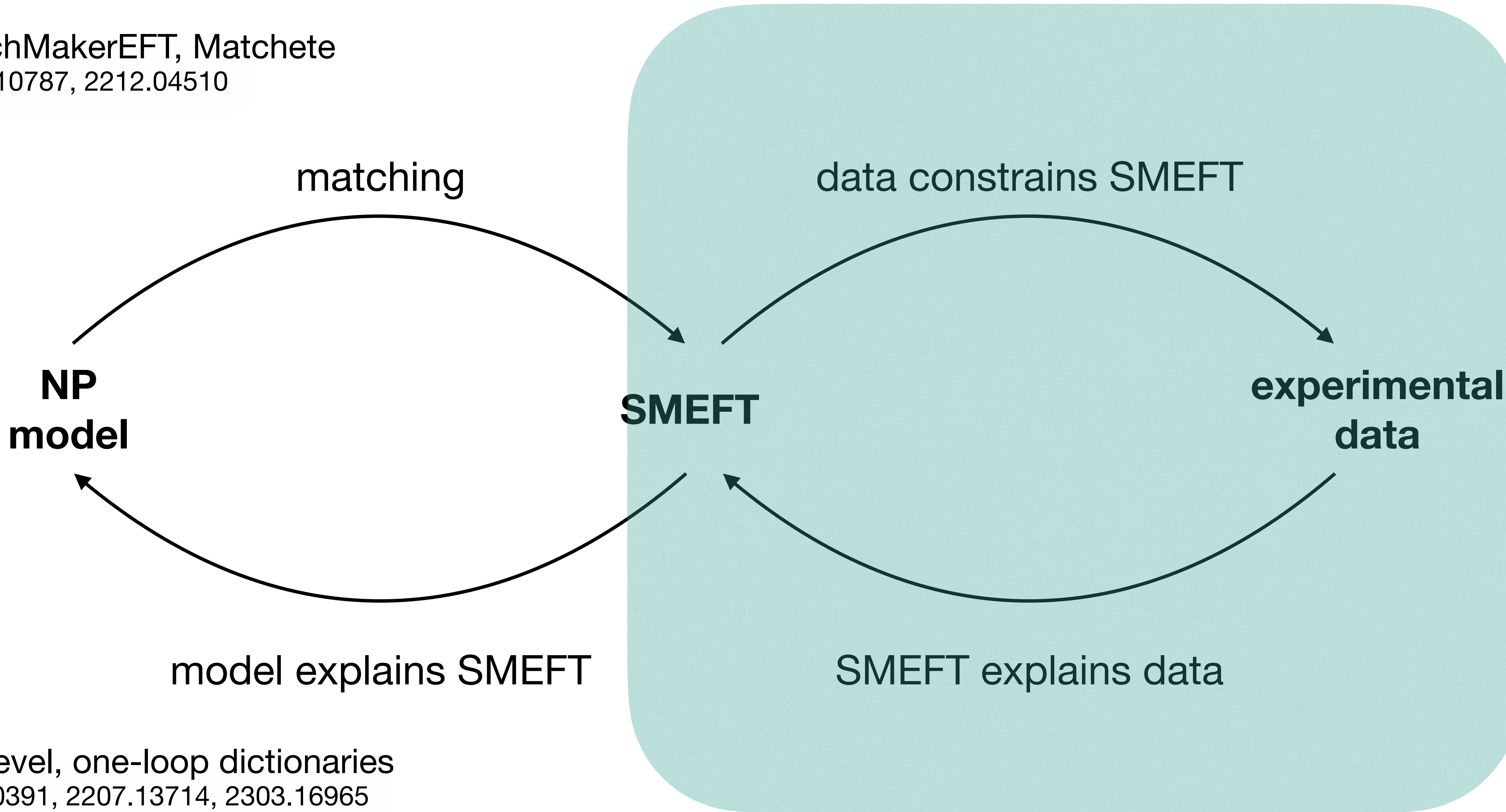

Tree-level, one-loop dictionaries
1711.10391, 2207.13714, 2303.16965

Global (flavorful) SMEFT likelihood

How can we make it as efficient as possible?

Building blocks of a global likelihood

- A diverse set of observables $\overrightarrow{O}$
- State-of-the-art theory predictions $\overrightarrow{O}_{\mathrm{th}}(\overrightarrow{C}, \vec{\theta})$
- Latest experimental measurements, defining $\mathscr{L}_{\mathrm{exp}}$

$\overrightarrow{C}$ - Wilson coefficients
$\vec{\theta}$ - nuisance parameters

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Likelihood:

$$\mathscr{L}(\vec{C}, \vec{\theta}) = \prod_i \mathscr{L}^i_{\rm exp}\left(\vec{O}_{\rm exp}, \vec{O}_{\rm th}(\vec{C}, \vec{\theta})\right) \times \mathscr{L}_\theta(\vec{\theta})$$

1810.07698

- Various $\vec{O}$ should be treated consistently

E.g. flavor observables in terms of WET WCs at low-energy scales

various high-energy observables in terms of SMEFT WCs at various scales

Crucially relies on RGE&matching computations

- Obtaining a nuisance-free likelihood $\mathscr{L}(\vec{C})$ for parameter estimation, hypothesis testing:

Marginalization/profiling computationally expensive

With clever approximations we can speed things up

Building blocks of a global likelihood

flavio:
1810.08132

- Theory predictions: flavor, EWPO, Higgs, beta decays, EDMs, DY tails, …
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wilson + WCxf
1712.05298, 1804.05033

- SMEFT RG evolution
- SMEFT to WET matching
- WET RG evolution
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1712.05298, 1804.05033

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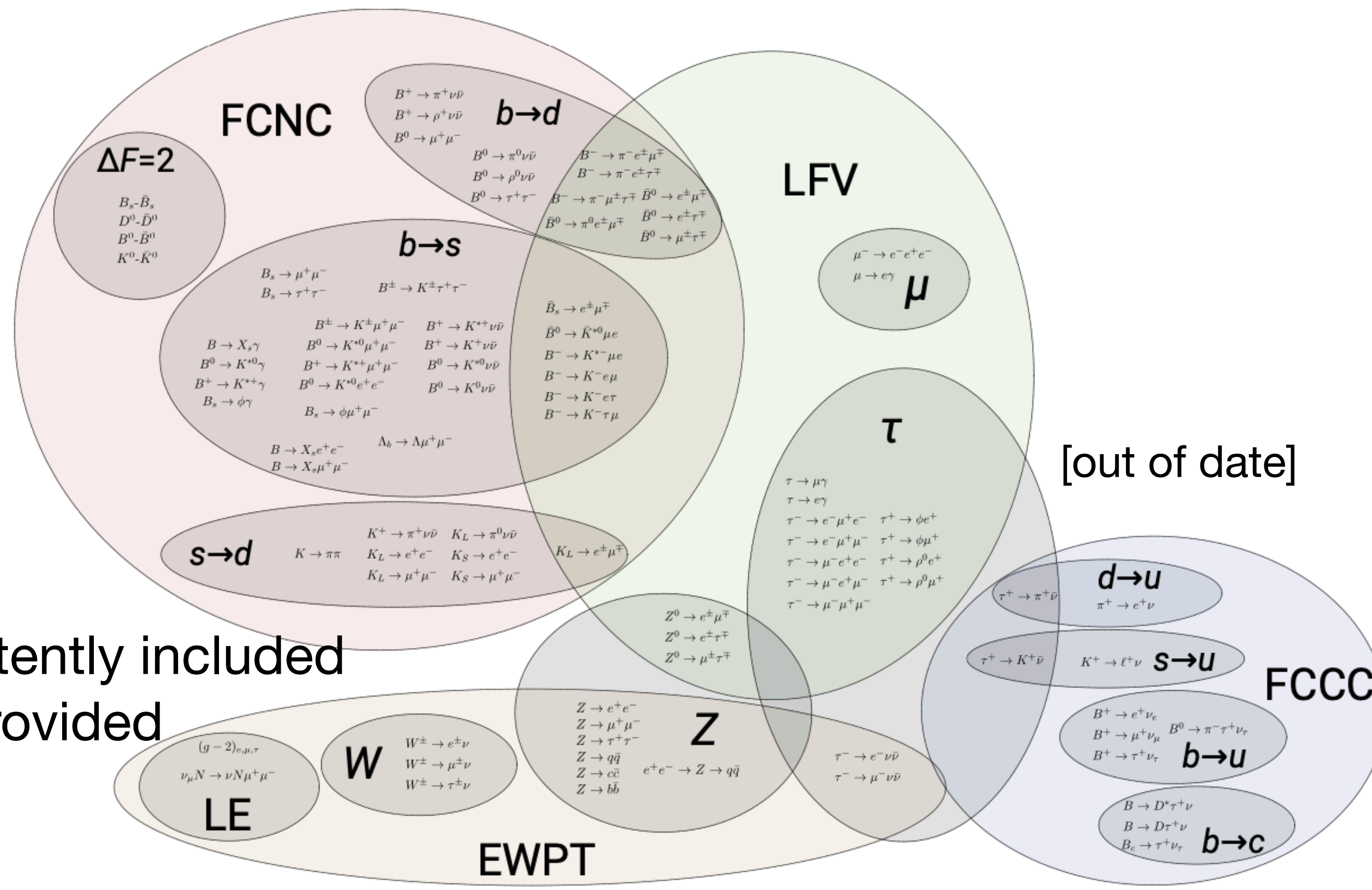
smelli - the **SME**FT **li**keli**hood**
1810.07698, 2012.12211

- Observables and measurements consistently included
- Approximate nuisance-free likelihood provided



Observables split into two categories:

1. Negligible theory uncertainties (can be non-Gaussian exp. likelihood)
2. Gaussian approximation
   -> covariances computed “once and for all”, but SM th. unc. assumed

introducing

jelli

JAX-based **E**FT **l**ike**li**hood

AS, P. Stangl, 241x.xxxxx

Data:

- observables
- measurements
- RGs+matching

→

jelli

→

Highly optimized likelihood

Data:

- observables
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jelli

Highly optimized likelihood

- open-source python package
- built from scratch, using JAX
- uses Just-In-Time (**JIT**) compilation
- **autodiff:** differentiable likelihood
- **backwards compatible** with the smelli **user interface**
- many new features
- **fast**: **few ms** per parameter point
- takes any data in predefined format

jax.readthedocs.io

- can be any data in predefined format
- from now on we discuss a *jellified* smelli

Data:
- observables
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jelli

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smelli 3.0 - a *jellified* version with new features and observables

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Theory predictions:

- All (100s) observables expressed as (functions of) polynomials of WCs - precomputation
- Predictions turn into fast linear algebra operations
- We precompute these from flavio with internal code, will be public in future

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- The category with theory uncertainties now additionally supports efficient NP dependence

Altmannshofer, Stangl, 2103.13370

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New and recently updated observables

- neutral and charged current Drell-Yan tails *Greljo, Salko, AS, Stangl, 2212.10497*
- updates of $b \to s\ell\ell$ observables *Altmannshofer, Stangl, 2103.13370*
- updates of $b \to d\ell\ell$ observables *Greljo, Salko, AS, Stangl, 2212.10497*
- updates of $b \to u\ell\nu$ observables *Greljo, Salko, AS, Stangl, 2306.09401*
- updates of D decays, beta decays *Crivellin, Kirk, Kitahara, Mescia, 2212.06862*

and more

smelli 3.0 - a *fast* version

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```
plotdata_smelli = gls.plot_data_2d(
    wc_func,
    scale=1000.0,
    x_min=-4.0, x_max=1.0,
    y_min=-2.0, y_max=1.5,
    steps=20
)
```

✓ 60m 48.8s

- **Goal:** scan over 2 directions in the SMEFT parameter space
- The directions are defined in wc_func
- The **UV scale** is set to 1 TeV
- The **range and step** of the two dimensions is set
- The result is the **sampled global likelihood** (and sublikelihoods)
- In the background this means RG evolving and matching to all the relevant EFTs and scales for observables, computing predictions, computing all the likelihoods

smelli 3.0 - a *fast* version

(preliminary version!)

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✓ 1.5s

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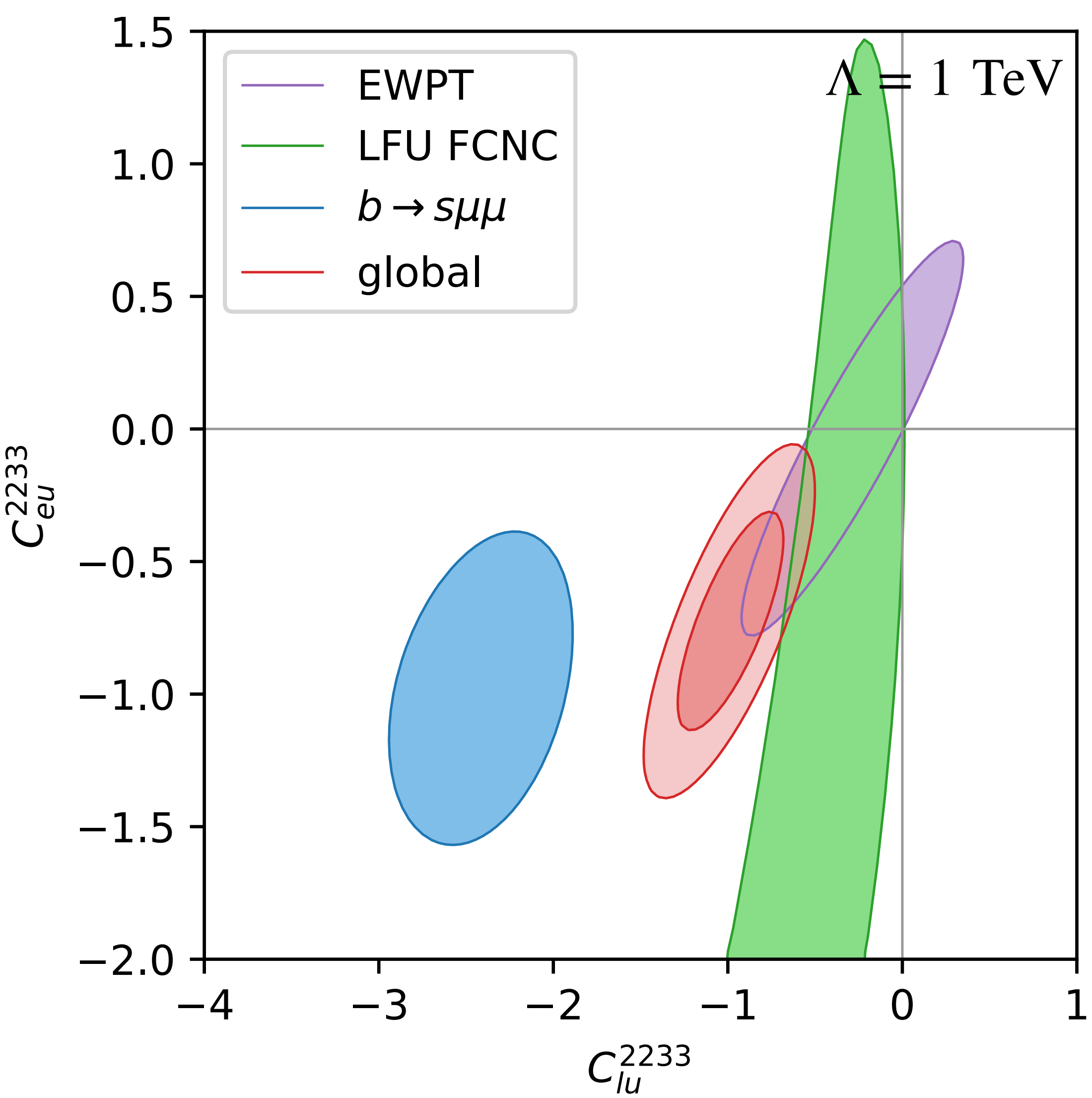
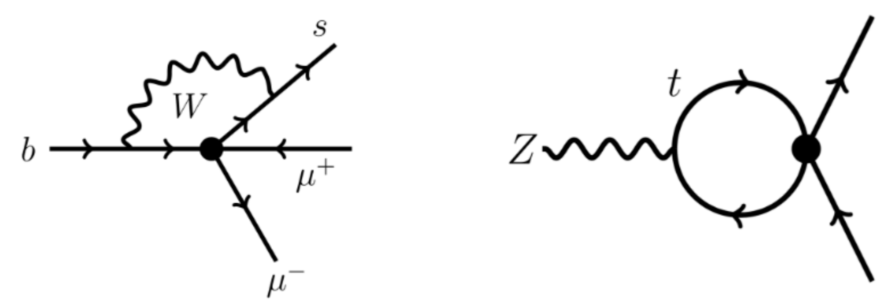


Anomalies in Bottom from new physics in Top

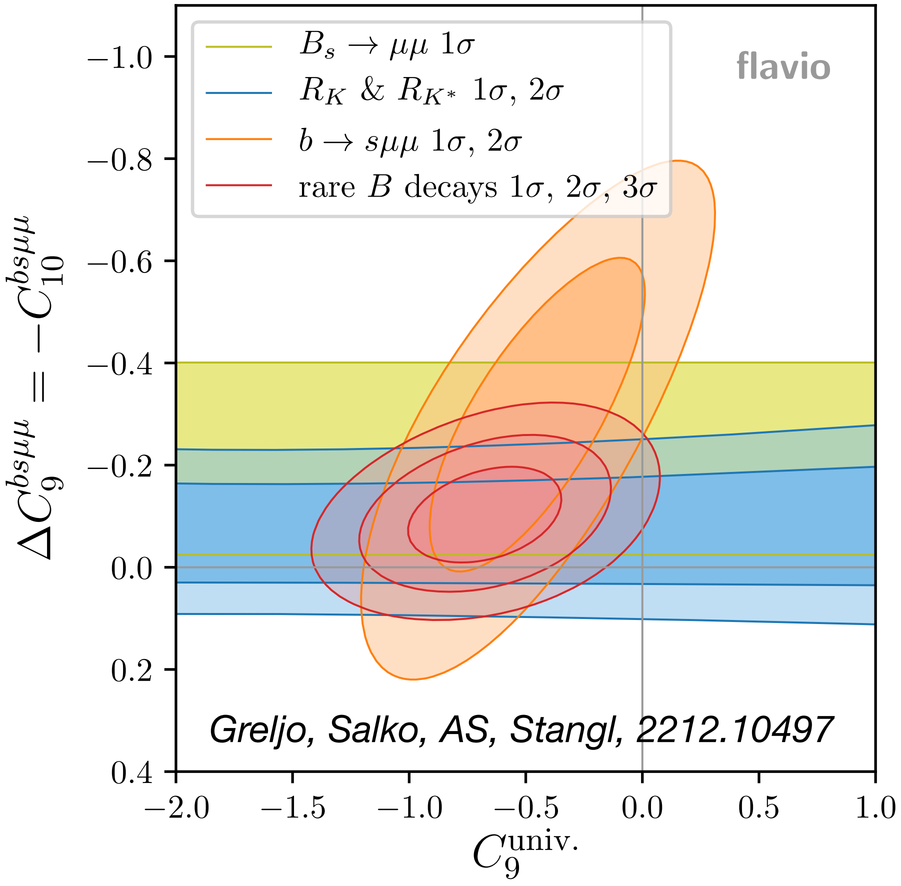


Celis, Fuentes-Martin, Vicente, Virto, 1704.05672
Kamenik, Soreq, Zupan, 1704.06005
Camargo-Molina, Celis, Faroughy, 1805.04917

$$(\bar{e}_2\gamma_\mu e_2)(\bar{u}_3\gamma^\mu u_3)$$
$$(\bar{\ell}_2\gamma_\mu \ell_2)(\bar{u}_3\gamma^\mu u_3)$$

Some recent usecases

Updated fits of $b \to s\ell\ell$



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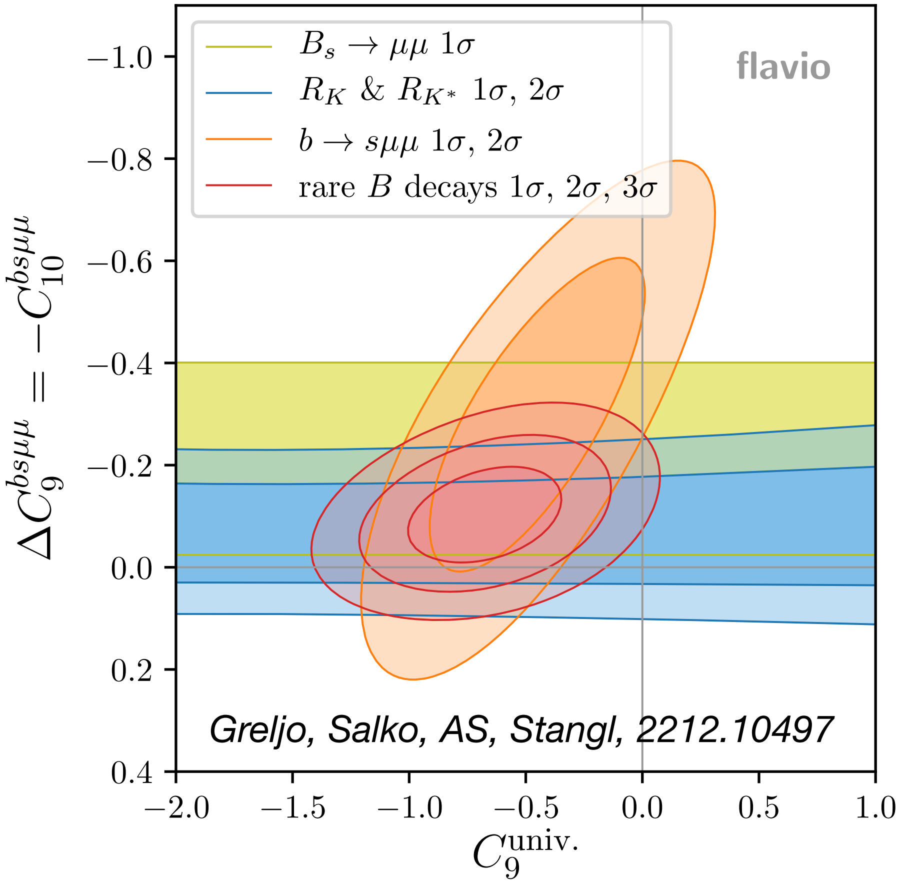
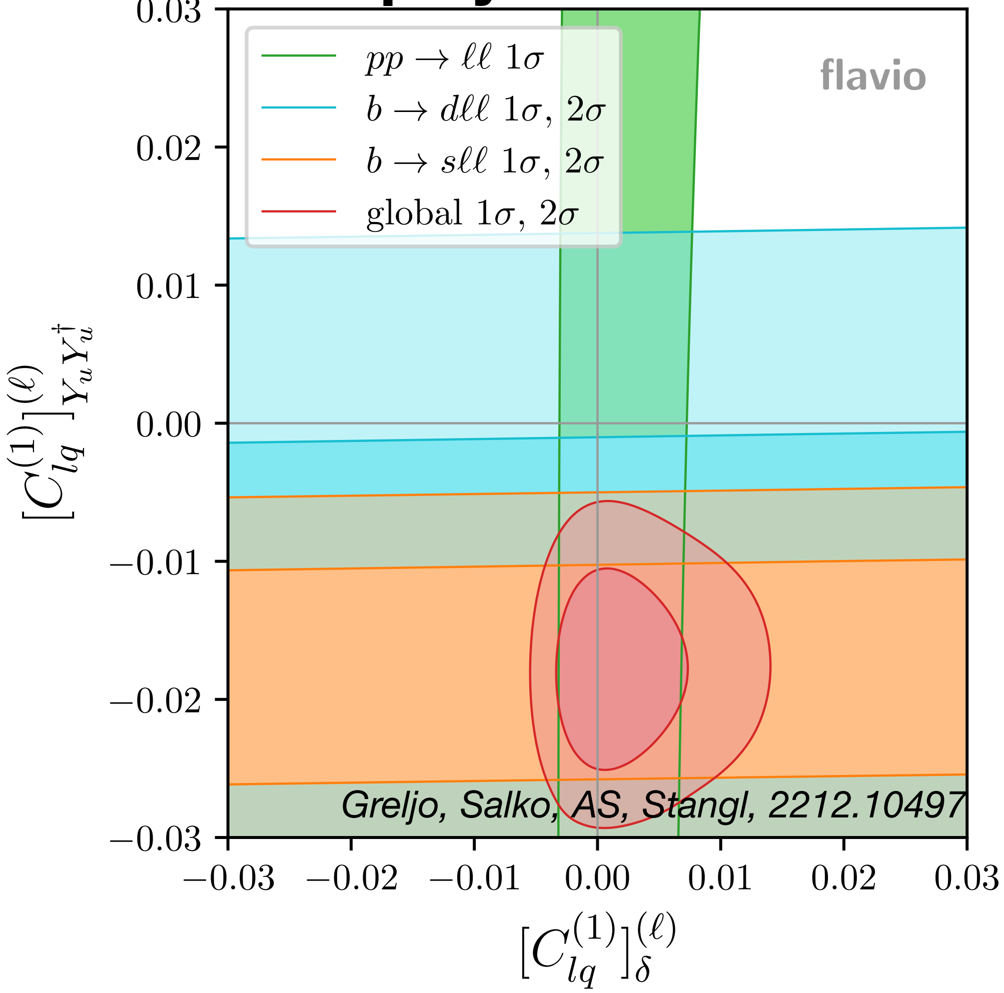


Interplay in MFV SMEFT



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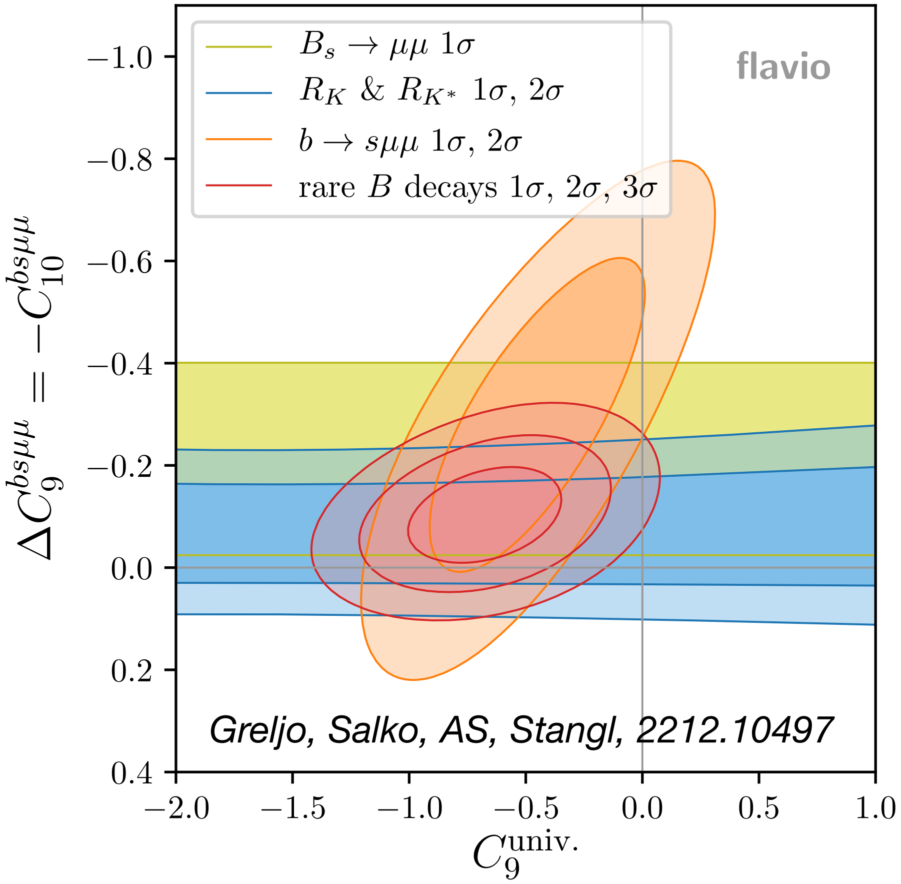
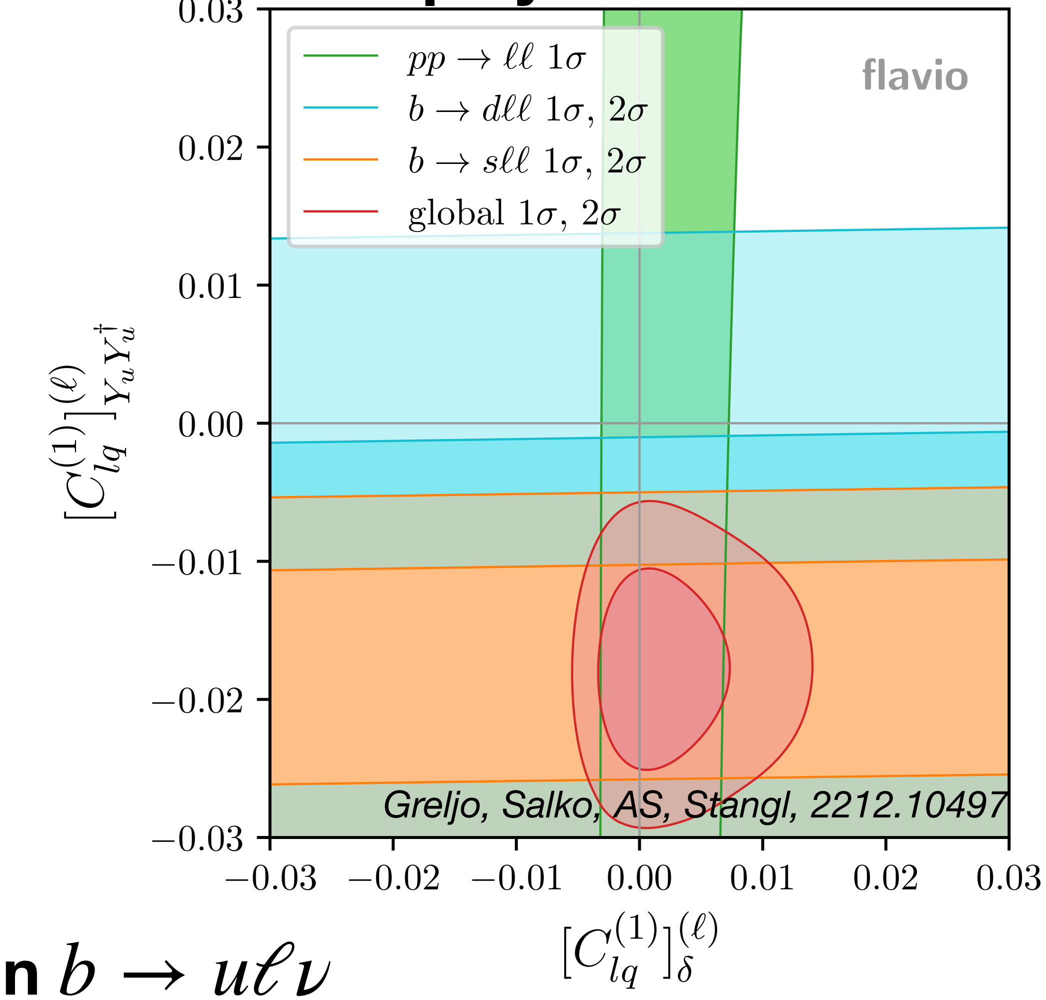
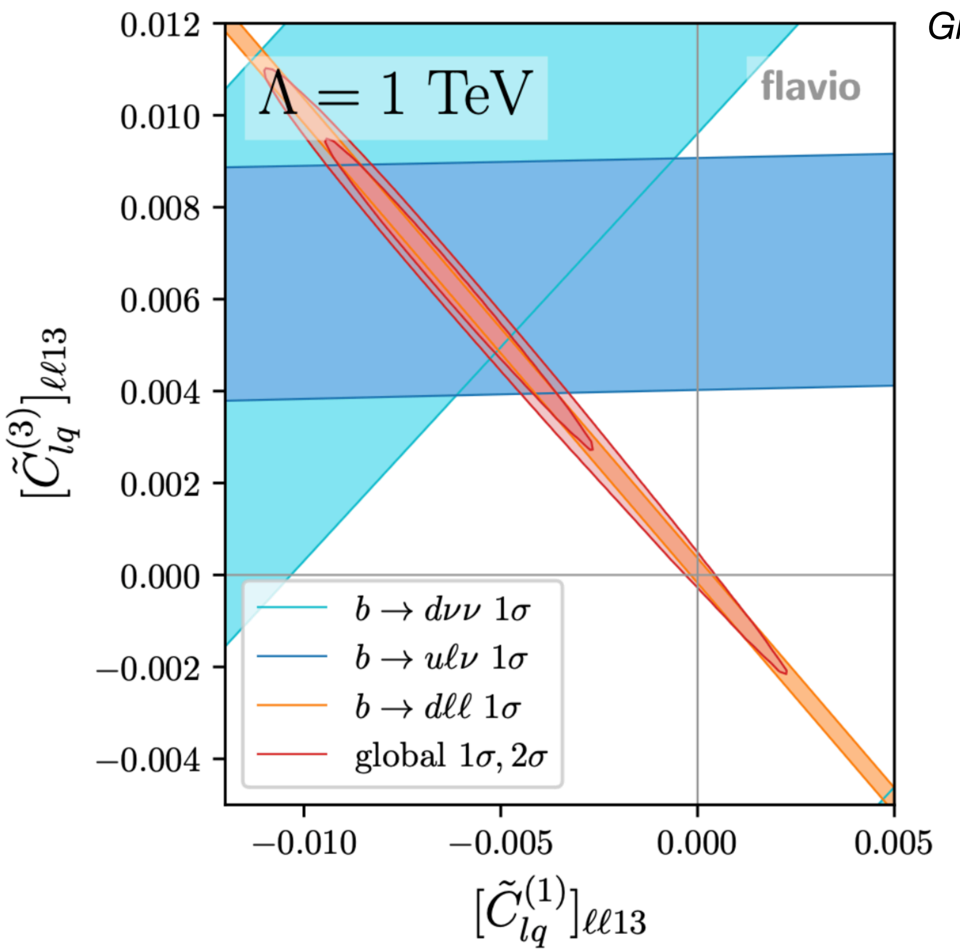


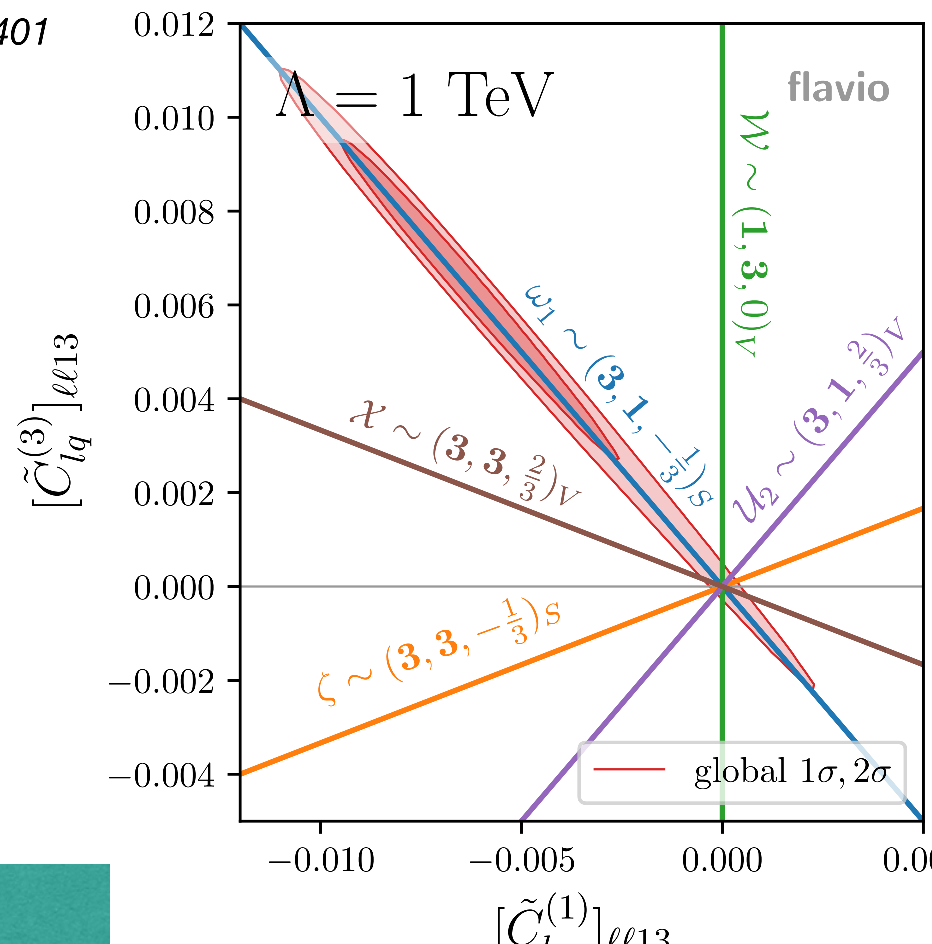
Interplay in MFV SMEFT



Not much room for NP in $b \to u\ell\nu$

Greljo, Salko, AS, Stangl, 2306.09401





Summary

- Model-independent approach to heavy NP
  -> tools for global analyses indispensable
  -> many are open-source, this is a community effort

- Complicated data analyses done in the SMEFT parameter space
  -> relative importance of data can be assessed
  -> high complementarity between various observables
  -> important RG effects captured
  -> efficient reinterpretation in concrete heavy NP models possible

- We introduce **jelli**: a **J**AX-based **E**FT **l**ike**li**hood
  -> built from scratch differentiable high-dim. EFT likelihood, fast, with powerful new features (JIT, autodiff, …)
  -> general, supports any data in proposed format
  -> **smelli v3.0** with new features, new and updated observables
  -> efficient interface with matching tools w.i.p.

to be released soon!

- Will allow for state-of-the-art (heavy BSM) phenomenology, but fast