Toward off-the-shelf flavour constraints for your SMEFT fit

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Motivation

- overwhelming amount of data from both direct and indirect searches for physics beyond the Standard Model (BSM)
- absence of obvious "bumps" at $\lesssim$ 2TeV suggests the absence of new particles at or below these scales
  - expect the Standard Model Effective Field Theory (SMEFT) to describe data well
  - constructed from SM fields and SM gauge group
  - "only" 2499 operators at mass dimension 6
  - reducing # of operators, e.g. via imposing flavour symmetries, is essential to make parameter space manageable!
- approach: simultaneously fit reduced set of SMEFT parameters to constraints from direct and indirect searches

[Bißmann,Erdmann,Grunwald,Hiller,Kröninger 1909.13632&1912.06090]

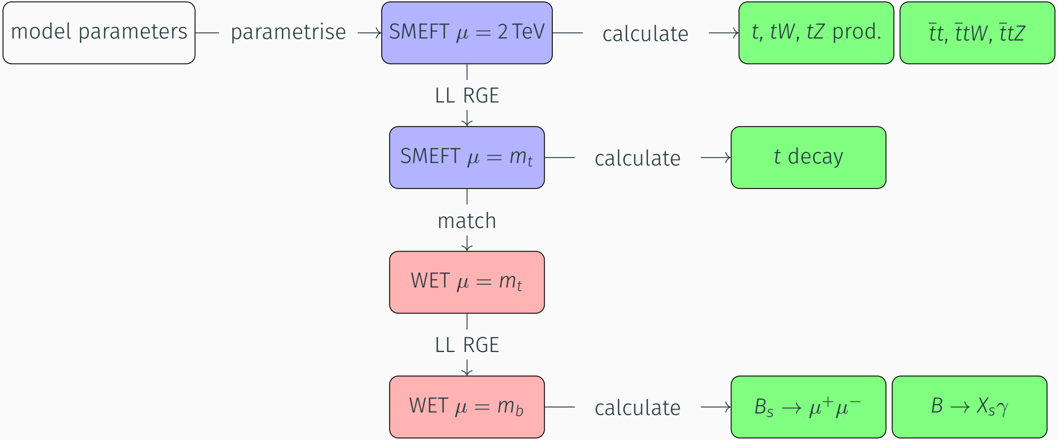
[Aoude,Hurth,Renner,Shephard 2003.05432]

[Bißmann,Grunwald,Hiller,Kröninger 2012.10456]

[Bruggisser,Schäfer,DvD,Westhoff 2101.07273]

[Bruggisser,DvD,Westhoff 2212.02532]

[Grunwald,Hiller,Kröninger,Nollen 2304.12837]



[Bruggisser,DvD,Westhoff 2212.02532]

WET: Weak Effective Theory

$$\mathcal{L}^{\text{SMEFT}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \cdot O_i + \text{h.c.}$$

O_i: local operators C_i: Wilson coefficients

$C_i \cdot O_i$: inner product w.r.t. (hidden) flavour indices

- aim: elucidate flavour structure of SMEFT Wilson coefficients C_i [Bruggisser,DvD,Westhoff 2212.02532]
- here: use MFV building blocks to parametrize [D'Ambrosio et al. hep-ph/0207036]
- spurion expansion in Yukawa matrices Y_U and Y_D [ex. for left-handed currents $\overline{Q}\ldots Q$]

$$\mathcal{A}_{kl} = \left[a\,\mathbf{1} + b\,Y_U Y_U^\dagger + c\,Y_D Y_D^\dagger + \ldots\right]_{kl}$$

k,l: flavour indices

- expand in Yukawa couplings, only keep terms $\sim y_t \simeq 1$

two-quark ops

$$C_i^{kl} \to \mathcal{A}_{kl} = a\delta_{kl} + b\delta_{k3}\delta_{l3}$$

four-quark ops

$$\begin{aligned} C_i^{klmn} &\to \mathcal{A}_{kl}\mathcal{A}_{mn} + \tilde{\mathcal{A}}_{kn}\tilde{\mathcal{A}}_{ml} \\ &= (aa)\delta_{kl}\delta_{mn} + (ba)y_t^2\delta_{k3}\delta_{l3}\delta_{mn} + (ab)y_t^2\delta_{kl}\delta_{m3}\delta_{n3} \\ &+ (\widetilde{aa})\delta_{kn}\delta_{ml} + (\widetilde{ba})y_t^2\delta_{k3}\delta_{n3}\delta_{ml} + (\widetilde{ab})y_t^2\delta_{kn}\delta_{m3}\delta_{l3} \\ &+ [(bb) + (\widetilde{bb})]\delta_{k3}\delta_{l3}\delta_{m3}\delta_{n3} \end{aligned}$$

further reduced in case of adjoint ops/identical currents

Weak Effective Theory (WET)

$$\mathcal{L}^{\text{WET}} = \mathcal{L}^{\text{QCD}\times\text{QED}} + \frac{4G_F}{\sqrt{2}} \sum_\alpha \mathcal{C}_\alpha \mathcal{O}_\alpha + \text{h.c.}$$

$\mathcal{O}_\alpha$: local dim-6 operators
$\mathcal{C}_\alpha$: WET Wilson coefficients

[Aebischer,Fael,Greub,Virto 1704.06639] [Jenkins,Manohar,Stoffer 1709.04486&1711.05270] [Dekens,Stoffer 1908.05295]

- dim-6 operators $\mathcal{O}_\alpha$ constructed from SM field except for W, Z, ϕ, and t
- expansion in Fermi's constant $G_F \sim 1/M_W^2$
- operators have fixed flavour quantum numbers

anatomy of low-energy flavour observables

$$\Gamma = \sum_{\alpha,\beta} \mathcal{C}_\alpha \mathcal{C}_\beta^* \Gamma^{\alpha\beta} + \mathcal{O}\left(\frac{m_b^2}{M_W^2}\right)$$

conceptionally different from SMEFT

- dim-6 Wilson coefficients $\mathcal{C}_\alpha$ also encode SM contributions
- low-energy flavour observables constrain sesquilinear combinations of the WET Wilson coefficients

- we retain SM contribution to the WET at up to two-loop accuracy
- we use complete one-loop matching between dim-6 WET and dim-6 SMEFT

  [Dekens,Stoffer 1908.05295]

  - "single insertions": WET Wilson coefficients are linear in the SMEFT Wilson coefficients
  - "double insertions" of dim-6 SMEFT ops would compete with SM/dim-8 interference terms; neither are available in the literature

⇒ flavour-observables constrain sesquilinear combinations of the dim-6 SMEFT Wilson coefficients

- BSM contributions within the WET are then parametrized by means of the MFV SMEFT parameters $(a, b, (aa), \ldots, (\widetilde{bb}))$

our analysis includes

- $\mathcal{B}(B_s \to \mu^+\mu^-)$: effectively constrains tree-level FCNCs through $b^{(1)}_{\phi q}$ and $b^{(3)}_{\phi q}$
  - theoretically clean, only a single hadronic nuisance parameter
- $\mathcal{B}(B \to X_s\gamma)$: creates interplay with $b^{(-)}_{\phi q} \equiv b^{(1)}_{\phi q} - b^{(3)}_{\phi q}$
- Δm_s: B_s—$\overline{B}_s$ mixing constrains a lineary combination of $b^{(1)}_{\phi q}$ and $b^{(3)}_{\phi q}$ complementary to $\mathcal{B}(B_s \to \mu^+\mu^-)$
- $\mathcal{B}(Z \to \bar{b}b)$: mainly constrains $b^{(1,3)}_{\phi q}$ at tree level
  - at one-loop, constrains $\overline{(bb)}^{(-)} \equiv (bb)^{(-)} + (\widetilde{bb})^{(-)}$, which is only loosely constrained by $b\bar{b}t\bar{t}$ production

reminder: MFV model parameters

$$C_i^{kl} \to \mathcal{A}_{kl} = a\delta_{kl} + b\delta_{k3}\delta_{l3}$$

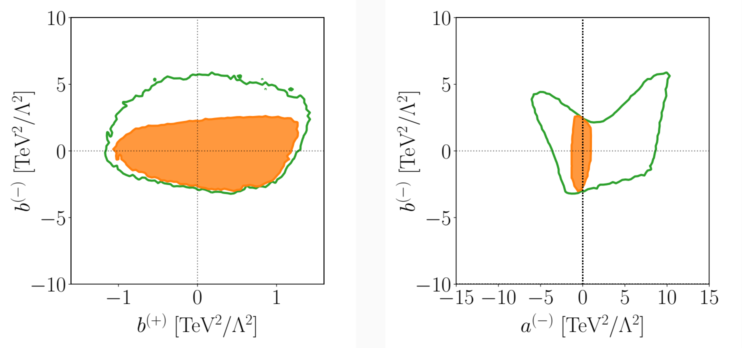
$$\begin{aligned} C_i^{klmn} \to\ & \mathcal{A}_{kl}\mathcal{A}_{mn} + \tilde{\mathcal{A}}_{kn}\tilde{\mathcal{A}}_{ml} \\ =\ & (aa)\delta_{kl}\delta_{mn} + (ba)y_t^2\delta_{k3}\delta_{l3}\delta_{mn} + (ab)y_t^2\delta_{kl}\delta_{m3}\delta_{n3} \\ & + (\widetilde{aa})\delta_{kn}\delta_{ml} + (\widetilde{ba})y_t^2\delta_{k3}\delta_{n3}\delta_{ml} + (\widetilde{ab})y_t^2\delta_{kn}\delta_{m3}\delta_{l3} \\ & + [(bb) + (\widetilde{bb})]\delta_{k3}\delta_{l3}\delta_{m3}\delta_{n3} \end{aligned}$$

Implementation

our analysis combines three existing codes to carry out the fits

- global SMEFT fit carried out with the `sfitter` software
  - fit to t observables follows a previous work [Brivio et al. 1910.03606]
  - frequentist fit, `Rfit` scheme for handling theory uncertainties
  - N.B.: `sfitter` recently adapted for Bayesian fits [Brivio et al. 2208.08454]
- SMEFT/WET matching and RGE running carried out with `wilson` [Aebischer,Kumar,Straub 1804.05033]
  - 1-loop matching [Deken,Stoffer 1908.05295]
  - running of BSM contributions currently at leading log accuracy only!
- flavour observables evaluated using EOS [DvD et al. 2111.15428]
  - interfacing to `wilson` via `wcxf` [Aebischer et al. 1712.05298]

Selected results



green top + flavor + dijet constraints

orange adds Z pole constraints

regions correspond to $\Delta\chi^2 = 5.99$

- Z-pole observables are not sensitive to $b_{\phi q}^{(-)}$ at tree level
- nevertheless, adding Z−pole constraints in a stronger bound on $b_{\phi q}^{(-)}$
  - global fit benefits from theory correlations amongst the various observables

Hadronic Nuisance Parameters

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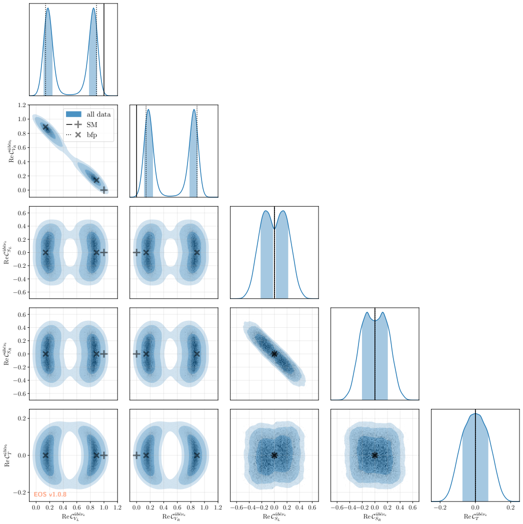
- constraining basis of 5 LFU WET coeffs in exclusive $b \to u\ell^-\bar{\nu}$ processes requires ≥ 50 hadronic nuisance parameters

[Leljak,Melic,Novak,Reboud,DvD 2302.05268]



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- proof of concept: use normalizing flows to provide evaluation of the likelihood & a χ^2 test statistic based on the marginal posterior

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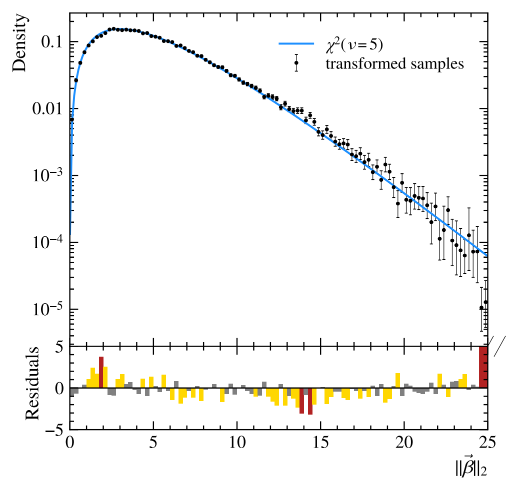

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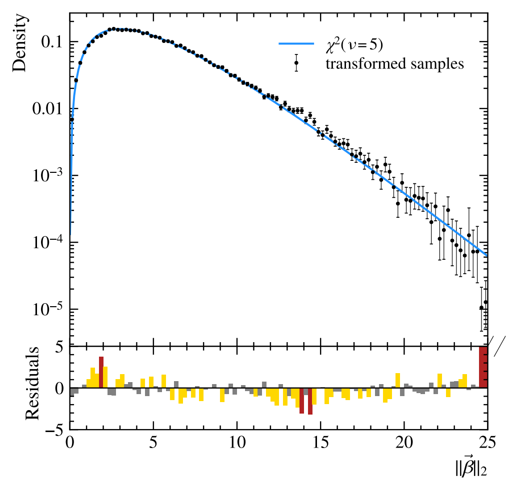
- aim: provide library of testable low-energy likelihoods, "off-the-shelf flavour constraints for your SMEFT fit"



Summary

- simultaneous SMEFT analyses of data t decay & production, flavour (incl. B_s-mixing) processes, Z-pole and dijet production observables [Bruggisser,DvD,Westhoff 2212.02532]
  - more constraining than individual analyses
  - flavour (WET) constraints important part of the overall puzzle
  - expansion to include more flavour constraints is not sustainable, due to proliferation of hadronic nuisance parameters

- to facilitate these types of analyses: divide and conquer
  - use constraints on WET Wilson coefficients directly by marginalizing the posterior w.r.t. hadronic nuisance parameters [example: Leljak,Melic,Novak,Reboud,DvD 2302.05268]
  - goal: provide library of testable low-energy likelihoods, to be used in BSM fits w/o need to deal with low-energy nuisance parameters [Beck,Reboud,DvD,Vos w.i.p.]

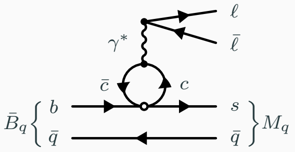
Backup Slides

Caveat for $4q$ operators

four-quark operators

- four-quark SMEFT operators play important role in $\bar{t}t$ observables
- low-energy $b \to s\{\gamma, \mu^+\mu^-\}$ observables currently assume SM-like four-quark WET operators except [Jäger,Kirk,Lenz,Leslie 1701.09183&1910.12924]

ϟ it is (currently) inconsistent to use both types of observables in joint analyses!



- further concern beyond c loop: effect of virtual b quark loops, strong connection to $\bar{t}t\bar{q}q$ operators in the SMEFT
- control of the full basis of $\bar{s}b\bar{q}q$ WET operators desirable!

Observables in the SMEFT vs WET

Using a $\bar{t}t$ production cross section as an example

$$\sigma(pp \to \bar{t}t) = \sigma_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i^{D=6} \sigma_i^{D=6} + \frac{1}{\Lambda^4} \left[\sum_{i,j} C_i^{D=6} C_j^{*,D=6} \sigma_{ij}^{D=6} + \sum_k C_k^{D=8} \sigma_k^{D=8} \right]$$

- we retain the SM and SM/dim-6 interference terms
- pure dim-6 and linear SM/dim-8 interference term are discarded

no such separation possible in flavour observables

- cannot disentangle SM from dim-6 SMEFT contribution to a WET Wilson coefficient

$\Rightarrow$ dim-6 SMEFT operators contribute identically to linear and quadratic dim-6 terms in the WET