Theory challenges and issues in SMEFT fits

Ilaria Brivio

ITP Heidelberg

SMEFT global analyses @LHC

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

describes new physics
- nearly decoupled $\boldsymbol{\Lambda \gg v, E}$
- matching onto **SM fields** + symmetries

Goals

measure as many SMEFT parameters as possible.
find **evidence** for NP — $C_i \neq 0$
and hints about its **nature** — *which* C_i*?*

⇝ **Ken**'s talk

Needs

1. being **sensitive** to indirect BSM effects

in bulk $\sim \frac{v^2}{\Lambda^2} \to$ 1.5%

on tails $\sim \frac{E^2}{\Lambda^2} \to$ 10%

2. making sure that, if we observe one, we **interpret it correctly**

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Theory challenges

minimize bias and maximize reinterpretability

Many parameters

- retaining all **relevant contributions**
  NLO, higher orders, SMEFT in PDFs...
- correct understanding of **uncertainties and correlations**
- correct **mapping to BSM models**

Many measurements

- **combining** is crucial
  remove flat directions, ensure basis independence...
- larger and larger combinations. eventually across exp and sectors.
  LEP + EW + Higgs + top + LHCb + non-LHC flavor + ...

  → different E scales
  → complementary components of theory structure (EWSB, flavor,...)

Many issues already solved / under control

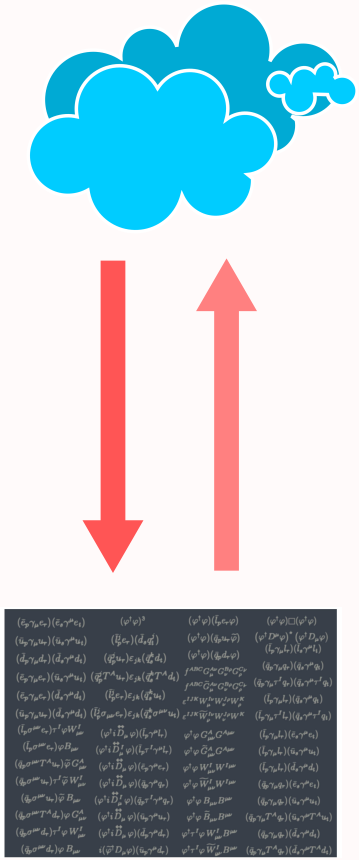
- ✅ ∼common conventions for bases, tools for translation
- ✅ consistent formulation with/without flavor symmetries
- ✅ correct treatment of input parameters
- ✅ LO predictions fully automated (any operator in any process), NLO QCD to a good extent
- ✅ understanding of NLO EW improved substantially
- ✅ 1-loop RGE running well understood and automated
- ✅ 1-loop matching to BSM models automated
- ✅ 1-loop matching to LEFT/WET
- ✅ good understanding of measurements' constraining power
- ✅ global analyses with up to ~ 30 free parameters
- ✅ strategies to handle unconstrained directions (PCA) and understand fit structure (Fisher info)

Theory issues for the (near) future

(those that fit in today's talk)

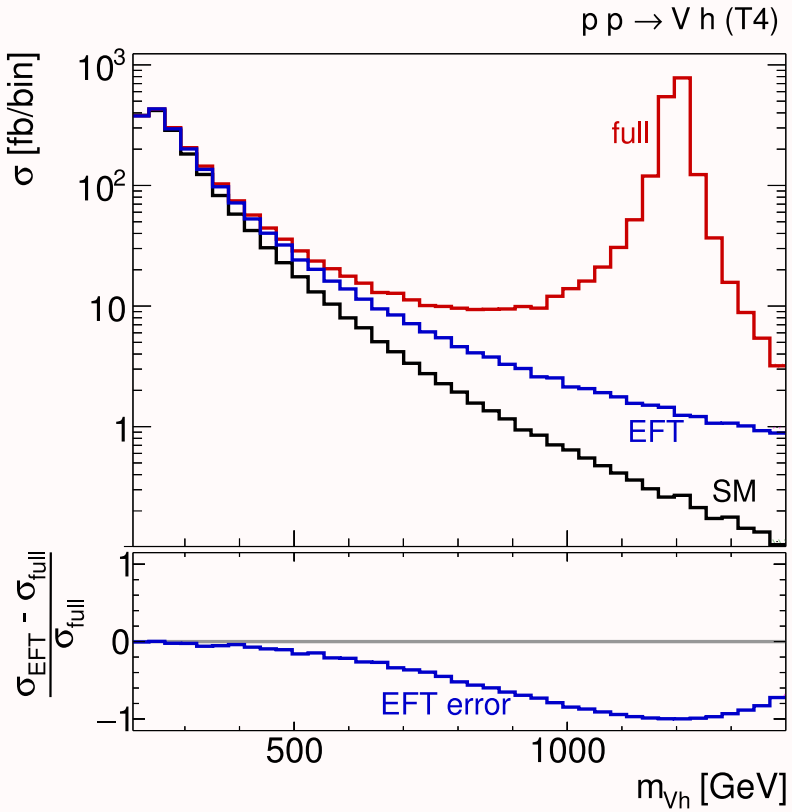
EFT validity, interpretation in terms of BSM models

- impact of higher orders in EFT
- which EFT?
- which terms are relevant?
- RG mixing effects
- matching scale uncertainties
- ...

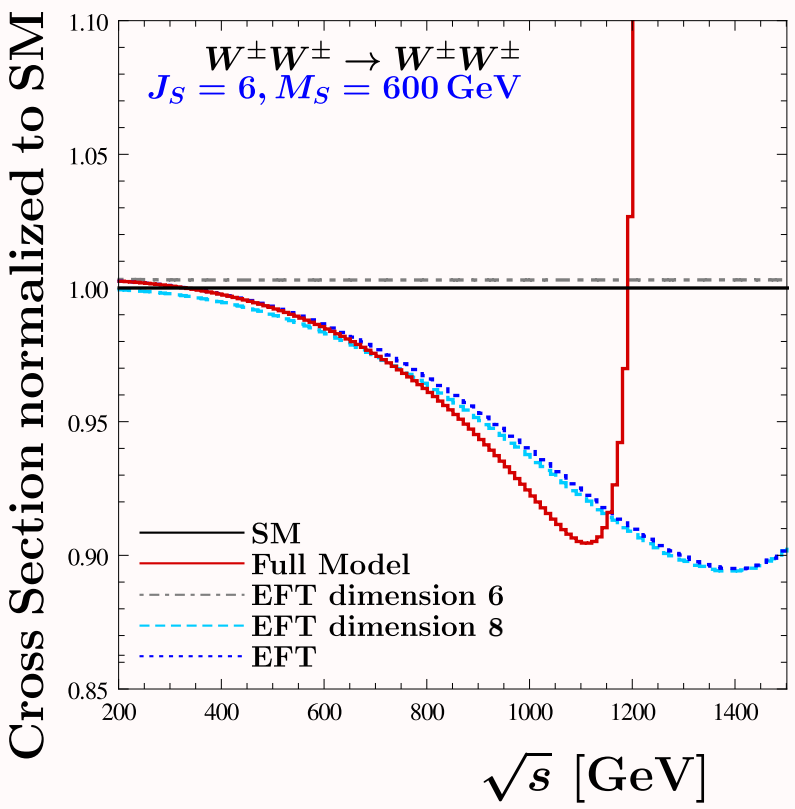


Missing higher EFT orders

EFT obtained from matching to full model



adapted from Brehmer, Freitas, López-Val, Plehn 1510.03443



adapted from Lang, Liebler, Schäfer-Siebert, Zeppenfeld 2103.16517

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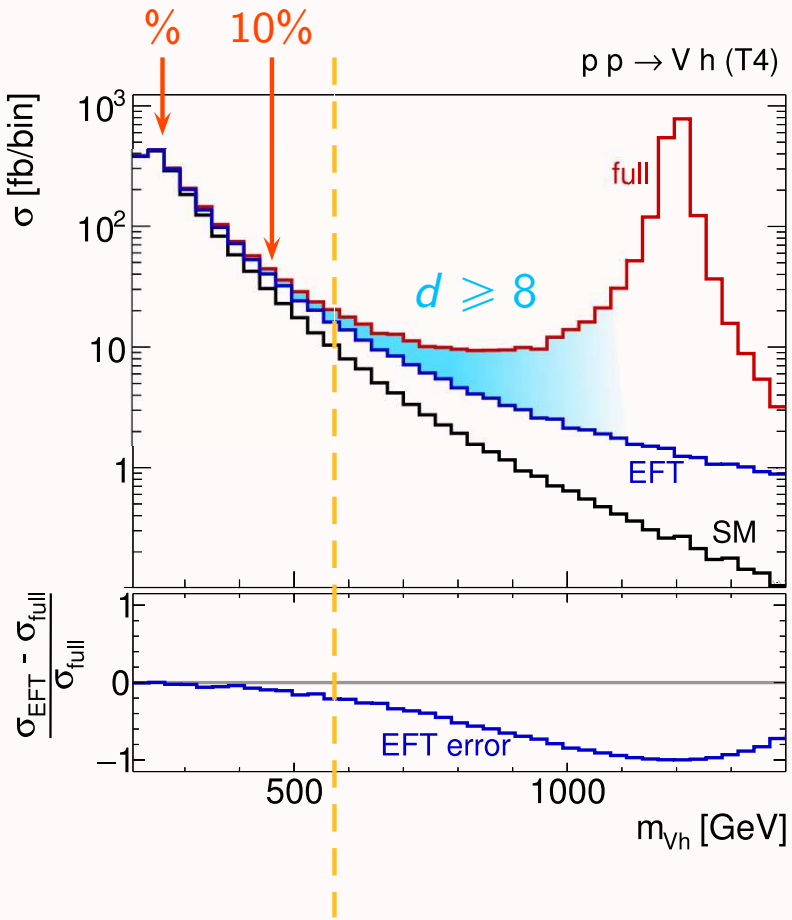

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$d = 6$ breaks down

Missing higher EFT orders

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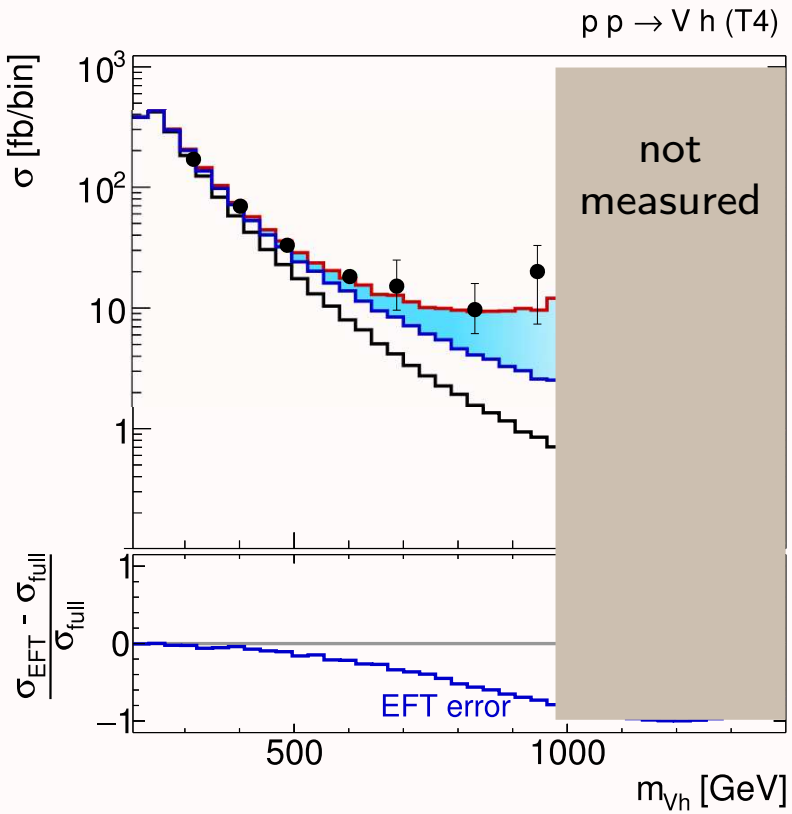

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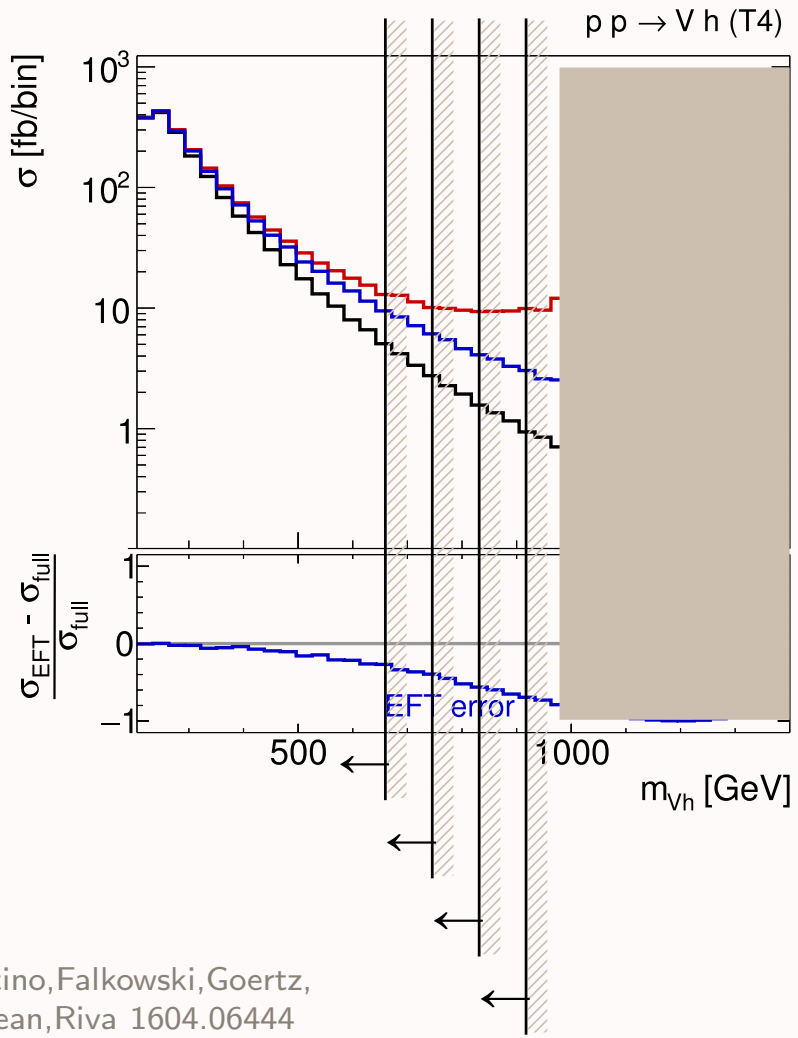
top-down: C_i fixed by matching
→ EFT not valid in high-E region

bottom-up: fit C_i to data
tends to make EFT match full result
→ find wrong values of C_i

how to keep this into account?

Missing higher EFT orders

EFT WG: note, comments
meetings 1, 2



adapted from
Brehmer,Freitas,López-Val,Plehn 1510.03443

Contino,Falkowski,Goertz,
Grojean,Riva 1604.06444

A sliding upper-cut

→ C-fit changes with the cut

→ choose *a posteriori* which limit applies

→ can be easily un-done

👎 how to choose the E variable to cut?

👎 how to cut consistently across processes?

👎 throwing away information?

Missing higher EFT orders

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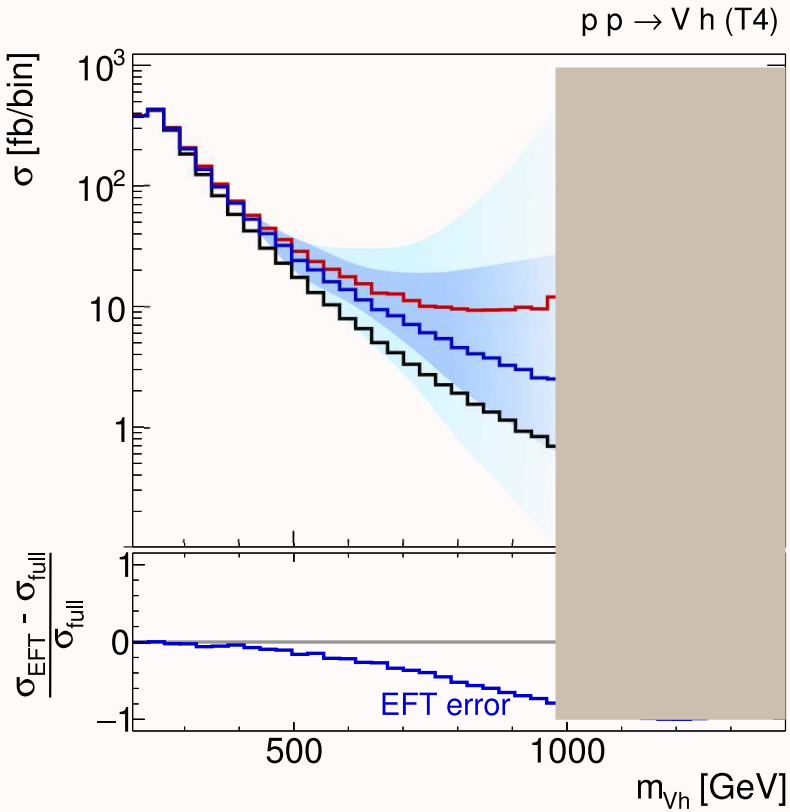

B error band

→ C-fit consistent within uncertainties

→ damps impact of high-E bins

👎 how to choose the E variable?

$(d = 6)^2$ as proxy or full $(d = 8)$

👎 how to determine growth?

benchmark Λ, prior on # and values of $C_i^{(8)}$

👎 embedded in measurement. hard to undo

(Berthier),Trott 1508.05060,2106.13794
Hays,Martin,Sanz,Setford 1808.00442
Alte,König,Shepherd 1812.07575
Keilmann,Shepherd 1907.13160
Hays,Helset,Martin,Trott 2007.00565

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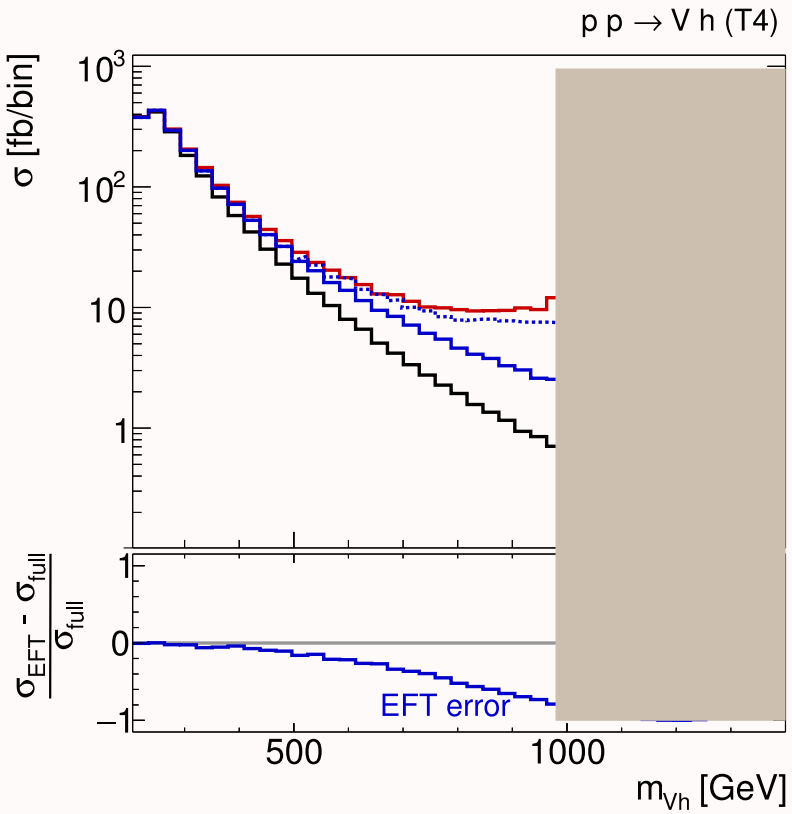

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C just add d=8 to the fit

→ extends validity range

→ helps determining the correct range for $d = 6$

👎 $d = 8$ prohibitive for some processes (no automation in sight)

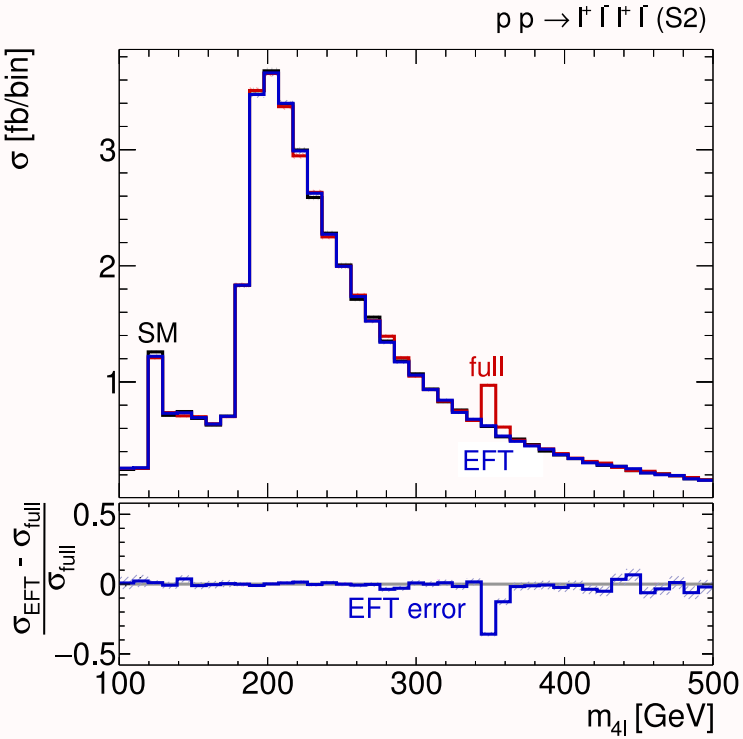
👎 just moving the problem up?

Boughezal,Mereghetti,Petriello
2106.05337

safe scenarios ↔ no energy growth ↔ small effects

typical cases where $d = 6$ works well **across the whole visible spectrum**:

- observables w/o E dependence ($1 \to 2$ decays)
- BSM scenarios with very narrow and/or heavy states



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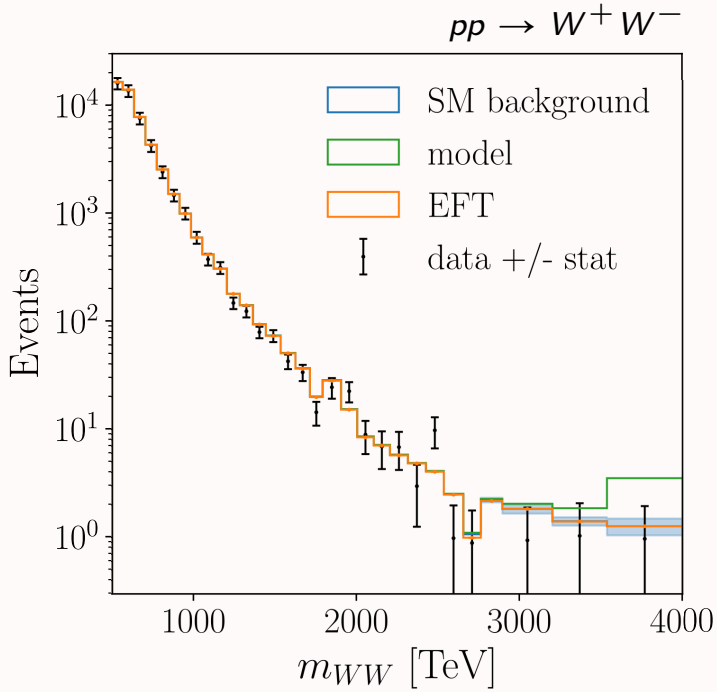


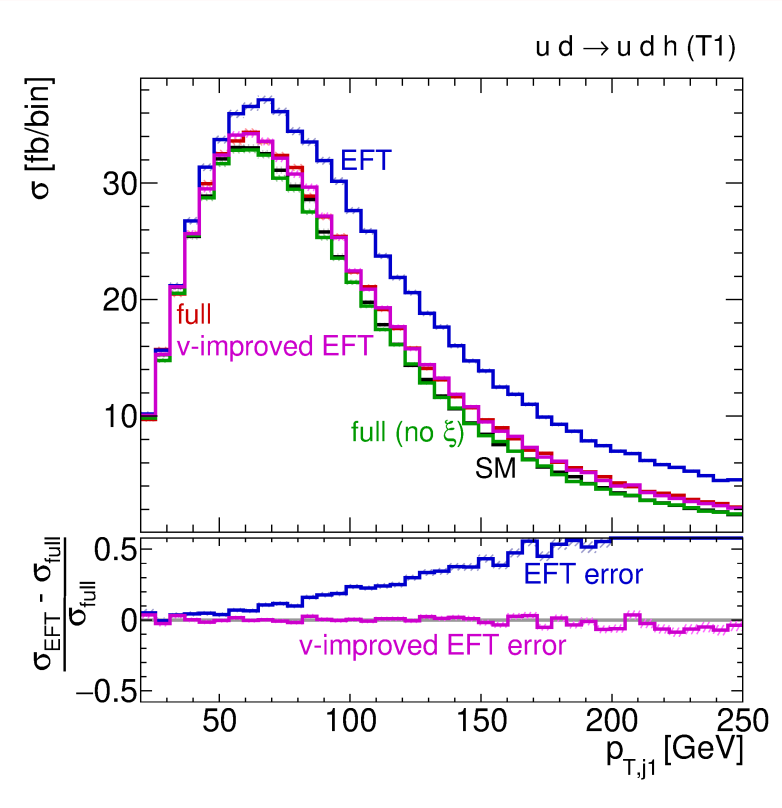
Brivio,Bruggisser,Geoffray,Kilian,Krämer,
Luchmann,Plehn,Summ 2108.01094

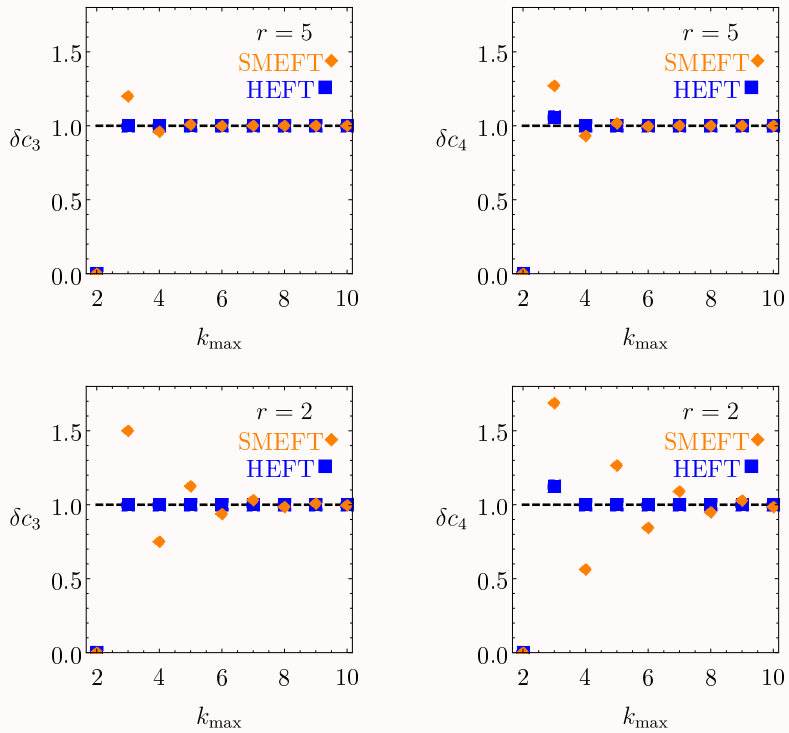
price to pay: % effects only
→ most sensitivity from lowest error region (∼ bulk)

SMEFT or HEFT?

a component of the $d = 6$ vs model discrepancy can be removed by reabsorbing higher powers of v within $d = 6$ coefficients instead of leaving them to $d \geqslant 8$

conceptually similar to using **HEFT** instead





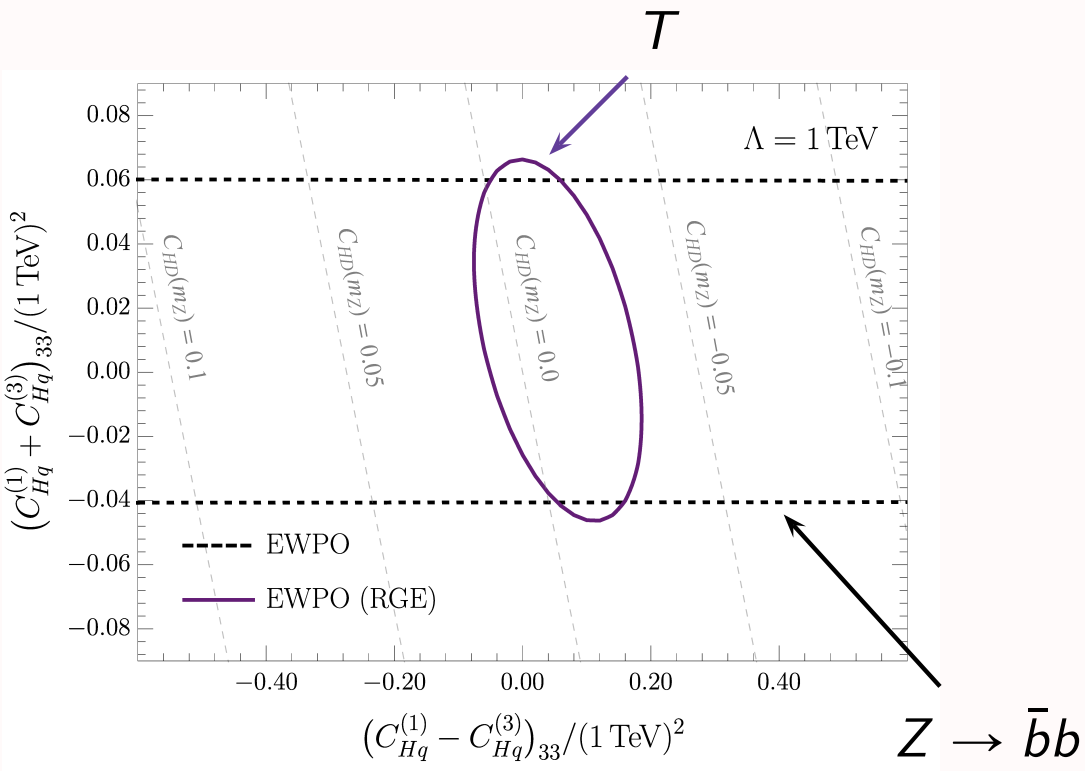
Brehmer,Freitas,López-Val,Plehn 1510.03443

Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient? $\rightsquigarrow$ other theory issues, not covered today

Lessons from UV matching

- RG running matters, even for low-ish cutoffs (~ 1 TeV) Dawson,Homiller,Lane 2007.01296



RG generates new operators

via **mixing**

↓

more constraints apply

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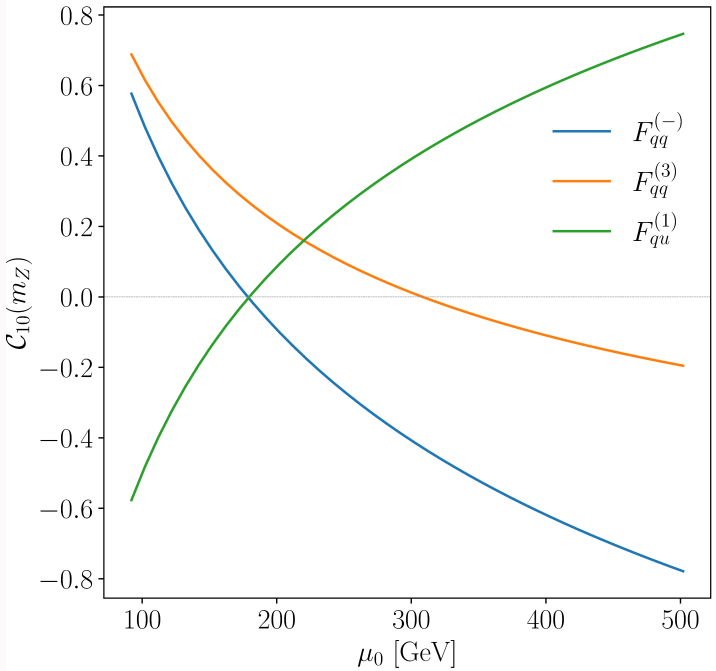

important also matching to WET/LEFT

impact of $(\bar{q}q\bar{q}q)$ operators on $(\bar{s}b)(\bar{\mu}\mu)$ amplified by mixing with $(\bar{q}q)$ op.

Bruggisser,Schäfer,van Dyk,Westhoff 2101.07273

Lessons from UV matching

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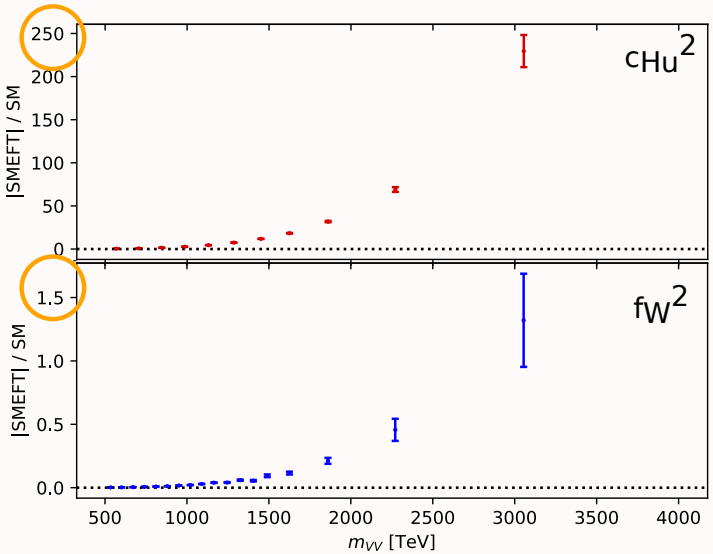
- **hierarchies** between coefficients easily induced, even 2-3 orders of mag.
  $\longrightarrow$ size at $C_i = 1$ is not fully representative of impact

e.g. $W^\pm W^\mp$ production high-m_{WW} Brivio,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094

SMEFT



SMEFT reduced w/ model

$c_{Hu} = 0$

f_W well-constrained

Model

no constraint

$$\frac{f_W}{\Lambda^2} = 4.76 \frac{\tilde{g}_H \tilde{g}_l}{m_V^2}$$

$\tilde{g}_H$, $\tilde{g}_l$ better constrained through other WC

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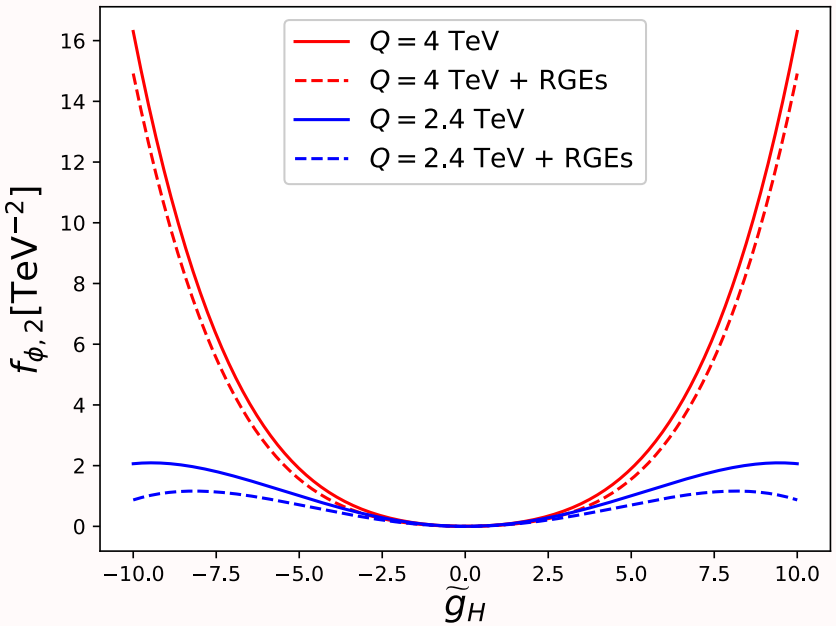
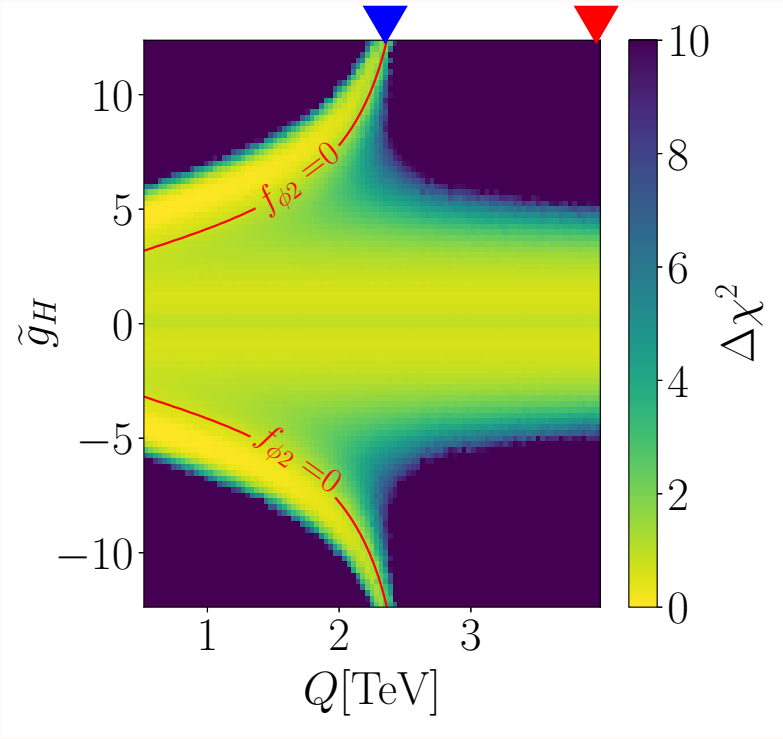
- **hierarchies** between coefficients easily induced, even 2-3 orders of mag.
  $\longrightarrow$ size at $C_i = 1$ is not fully representative of impact
- matching scale can lead to large TH uncertainties. Brivio,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094
  $\longrightarrow$ understand origin + include in fits

$$f_{\phi 2} = f_0 + f_2(Q)\tilde{g}_H^2 + f_4(Q)\,\tilde{g}_H^4, \quad \Lambda = 4 \text{ TeV}$$





Other theory issues

- Inclusion of CP violating terms
- Unified flavor treatment → combination with low-E
- Streamlining/automating NLO EW calculations in SMEFT
- 2-loop RGE running (consistency with 1-loop matching)
- Treatment of scale uncertainties in NLO SMEFT calculations
- Implementation of unitarity constraints & positivity bounds
- Handling fits with 50+ parameters → bayesian?
- Interplay with direct searches
- SMEFT in non-perturbative effects? PDF, hadronization...
- ...