Beyond Top EFT Veronica Sanz

with André Lessa (2312.00670, JHEP (2024))



EFT WG workshop '24

Outline

SMEFT Validity of the EFT expansion Going beyond SMEFT An example with Top physics

SMEFT



How well we know SMEFT? = how well we know the SM

Standard Model Total Production Cross Section Measurements

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nn	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb (data) COMPETE HPR1R2 (theory)		1 4	4
РР	$\sigma = 95.35 \pm 0.38 \pm 1.3 \text{ mb}$ (data)	ATI AS Preliminary	6	•
	$\sigma = 190.1 \pm 0.2 \pm 6.4 \text{ nb (data)}$	AILAO I Iommary	<u> </u>	h
۱۸/	$\sigma = 112.69 \pm 3.1 \text{ nb (data)}$, [→]	L L
vv	DYNNLO + CT14NNLO (theory) $\sigma = 98.71 \pm 0.028 \pm 2.191$ nb (data)	$\sqrt{s} = 7.8.13$ TeV	T T	1 Î
	$DYNNLO + CT14NNLO (theory)$ $T = 58.43 \pm 0.03 \pm 1.66 \text{ pb} (data)$	• • • •	Ŷ	P
_	DYNNLO+CT14 NNLO (theory)		, P	I P I
Ζ	$\sigma = 34.24 \pm 0.03 \pm 0.92$ hb (data) DYNNLO+CT14 NNLO (theory)		<u></u>	
	$\sigma = 29.53 \pm 0.03 \pm 0.77$ nb (data) DYNNLO+CT14 NNLO (theory)		o	0
	$\sigma = 826.4 \pm 3.6 \pm 19.6 \text{ pb (data)}$ top++ NNLO+NNLL (theory)	¢.		Ö
+Ŧ	$\sigma = 242.9 \pm 1.7 \pm 8.6 \text{ pb (data)}$	Δ		
	$\sigma = 182.9 \pm 3.1 \pm 6.4 \text{ pb} (\text{data})$	<u>ь'</u>		
	$\sigma = 247 \pm 6 \pm 46 \text{ pb (data)}$, The second sec		
+ .	$\sigma = 89.6 \pm 1.7 + 7.2 - 6.4 \text{ pb} \text{ (data)}$, F		
∙t–chan	NLO+NLL (theory) $\sigma = 68 + 2 + 8 \text{ pb} (\text{data})$	<u>_</u>		1
	NLO+NLL (theory) $\sigma = 94 \pm 10 \pm 28 = 23 \text{ pb} (data)$	Q		0
	NLO+NNLL (theory)			
VVt	$0 = 23 \pm 1.3 \pm 3.4 \pm 3.7$ pb (data) NLO+NLL (theory)	^		▲ I
	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb (data) NLO+NLL (theory)	0		
	$\sigma = 55.4 \pm 3.1 \pm 3 \text{ pb} \text{ (data)}$ LHC-HXSWG YR4 (theory)	¢		•
н	$\sigma = 27.7 \pm 3 + 2.3 - 1.9 \text{ pb (data)}$ LHC-HXSWG YB4 (theory)	<u> </u>		
	$\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7 \text{ pb} (data)$	ä		
	$\sigma = 130.04 \pm 1.7 \pm 10.6 \text{ pb (data)}$	<u> </u>	Ineory	Ġ.
\\/\\/	$\sigma = 68.2 \pm 1.2 \pm 4.6 \text{ pb (data)}$	▲ [—]		T T
~~~~	$\sigma = 51.9 \pm 2 \pm 4.4$ pb (data)	<u> </u>	$I HC pp \sqrt{s} = 13 TeV$	
	NNLO (theory) $\sigma = 51 \pm 0.8 \pm 2.3$ pb (data)	¥		- F
14/7	MATRIX (NNLO) (theory) $\sigma = 24.3 \pm 0.6 \pm 0.9$ pb (data)	, <del>,</del> ,	Data	L L L
vvz	MATRIX (NNLO) (theory) $\sigma = 19 \pm 1.4 \pm 1.3 \pm 1.$ pb (data)	4	stat	<b>1</b>
	MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.8$ pb (data)	O L		<b>P</b>
	Matrix (NNLO) & Sherpa (NLO) (theory)	- <b>P</b>	LHC pp $\sqrt{s} = 8$ TeV	P
ZZ	$v = 7.3 \pm 0.4 \pm 0.4 = 0.3 \text{ pb (data)}$ NNLO (theory)	<b>A</b>	Dete	
	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb} (\text{data})$ NNLO (theory)	<b>O</b>		•
t _{s-chan}	$\sigma = 4.8 \pm 0.8 + 1.6 - 1.3 \text{ pb} \text{ (data)}$ NLO+NNL (theory)	<b></b>	Siai	
+=>^/	$\sigma = 870 \pm 130 \pm 140$ fb (data) Madgraph5 + aMCNLO (theory)		siai ⊕ sysi	
ττνν	$\sigma = 369 + 86 - 79 \pm 44$ fb (data) MCFM (theory)		LHC pp $\sqrt{s} = 7$ TeV	
	$\sigma = 990 \pm 50 \pm 80 \text{ fb} \text{ (data)}$ Madgraph5 + aMCNLO (theory)		Data	
ttZ	$\sigma = 176 + 52 - 48 \pm 24 \text{ fb} \text{ (data)}$			
\\/\////	$\sigma = 0.848 \pm 0.008 \pm 0.081 \text{ pb (data)}$		Stat ⊕ syst	
	$\sigma = 0.55 \pm 0.14 + 0.15 - 0.13 \text{ pb (data)}$			
	$\sigma = 24 \pm 4 \pm 5 \text{ fb (data)}$			
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10	-5 10-4 10-3 10-2 10	-1 1 101 102 103	104 105 106 1011	0510152025
TC	10 10 10 10 10 10	$1 10^{-} 10^{-} 10^{\circ}$	10, 10, 10, 10,	0.5 1.0 1.5 2.0 2.5
			$\sigma$ [nh]	data/theory
				Gala/ LIGOLY

# How well we know SMEFT? = how well we know the SM



# Run3 and beyond

The LHC is a hadron machine, a **discovery** machine yet it had to re-invent itself to become a **precision** machine



**Precision LHC-> new opportunity** 

#### Traditional **resonant searches** have been so far unfruitful

On the other hand, more statistics and better understanding of the experiment allows diving into extreme kinematic regions

## State-of-the-art

Global EFT analyses nowadays use EWPT, LEP WW, LHC di/tri-boson Higgs, Top, HTop, 4F from LEP, Tevatron, LHC Run1 and Run2 inclusive and differential and even flavour in some cases

So it's a game of matching hundreds of observables with a very large parameter space, and give a **consistent view** when all EFT directions are taken into account

This is very tricky, theoretically and experimentally

# The issue of validity



### Differential information is key

Models offer richer kinematics than the kappa-formalism and the EFT approach captures them

$$-\frac{1}{4}h\,g_{hVV}^{(1)}V_{\mu\nu}V^{\mu\nu} -h\,g_{hVV}^{(2)}V_{\nu}\partial_{\mu}V^{\mu\nu} -\frac{1}{4}h\,\tilde{g}_{hVV}V_{\mu\nu}\tilde{V}^{\mu\nu}$$



$$\begin{split} &i\eta_{\mu\nu}\left(g_{hVV}^{(1)}\left(\frac{\hat{s}}{2}-m_V^2\right)+2g_{hVV}^{(2)}m_V^2\right)\\ &-ig_{hVV}^{(1)}p_3^{\mu}p_2^{\nu} \quad -i\tilde{g}_{hVV}\epsilon^{\mu\nu\alpha\beta}p_{2,\alpha}p_{3,\beta}\\ &+ \textit{off-shell pieces} \end{split}$$

exploited in searches for anomalous **TGCs** 



## Too much of anything is bad



In these regions our theoretical/experimental understanding is weaker e.g. WW at high-pT (large EW corrections) e.g. Higgs+jet at high-pTH and the **EFT validity** needs to be taken into account

## Validity is model-dependent



We place limits on *number of events* 

$$\sigma_{NP} \propto c_{NP}^2 \left(\frac{\hat{s}}{\Lambda^2}\right)^n$$
  
We require  $\sqrt{\hat{s}} \gg \Lambda$   
but there is a *coupling* in between  
 $c_{NP} = \left(\frac{1}{16\pi^2}\right)^l \dots \mathcal{O}(1)$ 

limits then depend on the choice of c



# Beyond SMEFT

Further use of precise SM measurements to search for new physics

#### Non-resonant ALP

#### Gavela, No, VS, Troconiz PRL 2020



 $\sigma_{V_1V_2} \propto g_{agg}^2 g_{aV_1V_2}^2 \hat{s} \sim \frac{\hat{s}}{f_a^4},$ 





here we also have to deal with the validity issue: limit on f_a needs to be above the kinematic region we use to set the limit we had to discard channels and certain bins

# +Beyond SMEFT?

Is there something in between resonant and non-resonant searches?



#### localized excess



# Going beyond SMEFT: example with top SM measurements

### Dark Matter scenario

Let's study a simple scenario Z2 symmetry, DM candidate, colored top partner yDM=coupling SM to BSM

$$\mathcal{L}_{BSM} = \bar{\chi} \left( i \partial \!\!\!/ - \frac{1}{2} m_{\chi} \right) \chi + |D_{\mu} \varphi_T|^2 - m_T^2 |\varphi_T|^2 - \left( y_{\text{DM}} \varphi_T^{\dagger} \bar{\chi} t_R + h.c. \right)$$

DM pheno: studied in Garny et al. 1802.00814, PRD

Would be produced **directly** and contribute at one-loop in **top** SM measurements



#### Direct searches



q

 $arphi_T$ 

Decays top partner to top and DM Using recasting tool SModelS scan for relevant analyses compressed spectrum: ISR, limited coverage

# Contributions to Top EFT

Compute explicitly all the one-loop integrals leading momentum expansion, generates EFT Lagrangian

 $\mathcal{L}_{EFT} = m_t C_g \ G^A_{\mu\nu} \left( \bar{t} T^A \sigma^{\mu\nu} t \right) + C_q \left( \bar{t}_R T^A \gamma^\mu t_R \right) \left( \bar{Q}_L T^A \gamma^\mu Q_L + \bar{u}_R T^A \gamma^\mu u_R + \bar{d}_R T^A \gamma^\mu d_R \right)$  $+ C_q \left( \bar{t}_R T^A \gamma^\mu t_R \right) \left( \bar{Q}_{3,L} T^A \gamma^\mu Q_{3,L} \right) + C_{tR} \left( \bar{t}_R T^A \gamma^\mu t_R \right) \left( \bar{t}_R T^A \gamma^\mu t_R \right)$ 

Relations among the EFT coefficients

Translation to SMEFT in the Warsaw basis

$$C_{g} = y_{t}^{-1} \frac{C_{tG}}{\Lambda^{2}},$$
  
 $C_{q} = \frac{C_{tq}^{(8)}}{\Lambda^{2}} = \frac{C_{t(u/d)}^{(8)}}{\Lambda^{2}}$   
 $C_{tR} = \frac{C_{tt}^{(8)}}{\Lambda^{2}},$ 

In the degenerate limit:

$$C_g \simeq -rac{1}{2} rac{g_s y_{DM}^2}{384\pi^2} rac{1}{m_T^2} , \ C_q \simeq rac{3}{2} rac{g_s^2 y_{DM}^2}{576\pi^2} rac{1}{m_T^2} , \ C_{tR} \simeq -rac{1}{3} rac{y_{DM}^4}{128\pi^2} rac{1}{m_T^2} \ (m_T \simeq m_\chi)$$

# Matching and form factors

Want to compare the full loop predictions and the EFT equivalent In practice one has to compute this matching Not so trivial, becomes a bit technical: counterterms... (all code and details in Zenodo)



#### Contributions to ttbar final states

 $\mathcal{L}_{FF} = \pi^2 g_s y_{DM}^2 G_{\mu} \bar{t} \left[ \mathcal{F}^{\mu} \left( p_t, p_{\bar{t}} \right) \right] t + \pi^2 g_s^2 y_{DM}^2 G_{\mu} G_{\nu} \bar{t} \left[ \mathcal{F}^{\mu\nu} \left( p_g, p_t, p_{\bar{t}} \right) \right] t$ 



The kinematic behaviour at parton level shows a *broad bump* beyond sensitivity of resonant searches Two form factors contribute to ttbar





#### Invariant mass distribution: low mT



When convoluted with PDFs, the bump behaviour remains

And it is quite different from the SMEFT "equivalent"

#### Invariant mass distribution: high mT



Even at relatively high masses, the difference 1loop to SMEFT is noticeable

Depends on the kinematic reach on mtt

# The money plot



*Qualitative features, should carry over other cases* **Direct vs indirect: compression of spectrum, MET Loop vs EFT: gain in knowledge of the full form factor** 

#### Conclusions

The SM EFT is a very active area of research at the LHC motivated by the lack of direct evidence for new physics and increased precision in SM observables

The state-of-the-art in our understanding of SMEFT: global analyses including hundreds of observations and dozens of possible EFT deviations

Alternative interpretations on non-resonant phenomena, e.g. ALPs, provide a different view on the same data

With the same SM precision measurements, we can look at different kinematic regions (~broad bumps) that would be missed in resonant searches and in SMEFT tails search and are motivated by e.g. scenarios of DM