BSM discovery vs EFT validity

in same-sign WW scattering

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Based on studies reported in:
arXiv:1802.02366, arXiv:1905.03354 and arXiv:1906.10769

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The main topic of this study: practical usefulness of the EFT approach to describe BSM physics

Working scenario:

- collected 3 ab^{-1} of data at 14 TeV (HL-LHC target),
- no new particles or resonances found,
- maybe even worse: no clear indirect BSM hints from other processes,
- but: disagreement observed in VBS processes wrt. SM predictions.

Two complementary approaches for the EFT:

1. Global fits to many EW processes – need a full basis of operators, available for dim-6 only. Description of VBS processes is not complete without dim-8.

2. Try to focus on what is unique to VBS: the quartic couplings and associated dim-8 operators. Standard procedure used in CMS and ATLAS: vary dim-8 operators one by one.

This talk is about the latter option.

Q1: can we successfully describe the observed deviation in the EFT language?
Q2: can we learn something about the underlying BSM physics using the EFT framework?

Related Q I will not address in this talk: if we observe agreement with the SM – how to correctly set limits on dim-8 operators so that our numbers are really useful to the theory community?

EFT and model independence

1. EFT provides an in-principle-model-independent parameterization of BSM interactions between SM particles, e.g. in SMEFT:

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \Sigma_i \frac{C_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \ldots$$

$$f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^2}, \qquad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \ldots.$$

2. Infinite expansion – but there is no way one can fit an infinite number of parameters to the data.

3. We always need a truncation. What truncation is a good one? Not obvious.

(For dim-6 vs dim-8 considerations see, e.g., *Liu et al.* 1603.03064, *Contino et al.* 1604.06444, *Azatov et al.* 1607.05236, *Franceschini et al.* 1712.01310, *Biektter et al.* 1406.7320, *Falkowski et al.* 1609.06312)

4. For practical reasons, one needs ***a choice*** of the operators to consider.
E.g., considering only single dim-8 operators at a time is one such *choice*.

This effectively means testing only a (rather narrow) class of BSM extensions for which such choice is a good approximation for the studied process in the kinematic range of the LHC.

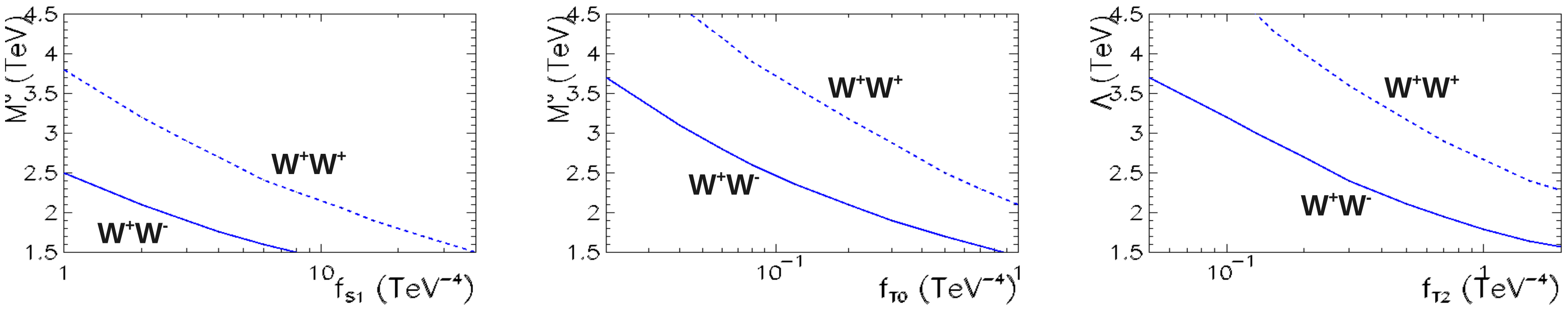
EFT "model": attempt at description of the data using a single f and a value of Λ

EFT validity cutoff

1. **EFT validity stops at $M_{VV}=\Lambda$, the scale of new physics.** Λ can be *maximally* equal to the lowest relevant unitarity limit, $\Lambda \leq M^U$.

2. For a given operator Λ is one value, it applies to all affected amplitudes, even if they are still far from their individual unitarity limits – see next slide for details.

3. Λ must be common to different processes if they probe the same set of higher dimension operators. For instance, the W^+W^- scattering process reaches unitarity limit *before* W^+W^+ for most dim-8 operators: $\mathcal{O}_{S1}$, $\mathcal{O}_{T0}$, $\mathcal{O}_{T1}$ (positive f), $\mathcal{O}_{T2}$, $\mathcal{O}_{M0}$, $\mathcal{O}_{M1}$ and $\mathcal{O}_{M7}$.



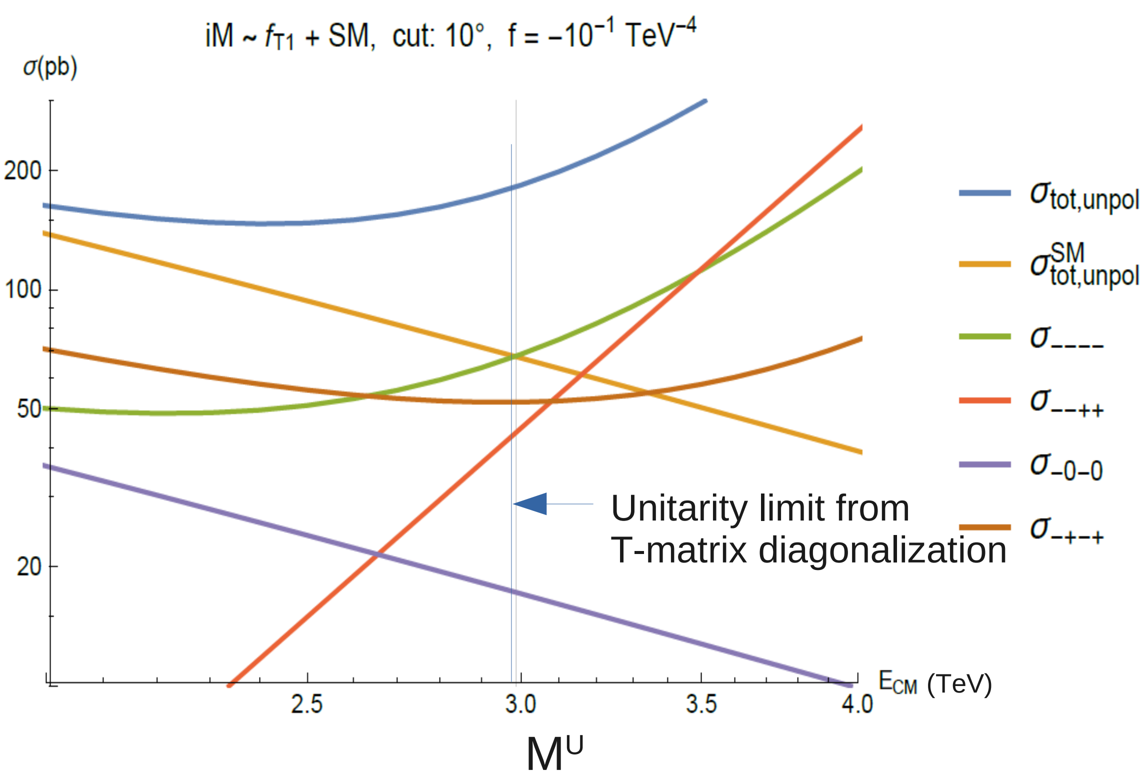
4. But Λ can also be much lower than *any* unitarity bound (lesson learned from the Higgs boson!). **The actual value of Λ must be deduced from the data.**

Helicities and unitarity limits

The case of f_{T1}

Total **W^+W^+** → **W^+W^+** cross section (on shell) for f_{T1} = -0.1/TeV^4
split into initial & final state helicity combinations

13 independent combinations



Unitarity limits M^U (in TeV)
for individual amplitudes

Hel. \ f_{T1} =	−0.01	−0.1	−1.	−10.
−−−−	5.3	3.0	1.7	0.96
−−−0	7.5×10^7	7.5×10^6	7.5×10^5	7.5×10^4
−−−+	1.7×10^3	530.	170.	53.
−−00	440.	140.	44.	14.
−−0+	74.	34.	16.	7.4
−−++	5.5	3.1	1.7	0.99
−0−0	2.5×10^3	800.	250.	80.
−0−+	69.	32.	15.	6.9
−000	3.7×10^7	3.7×10^6	3.7×10^5	3.7×10^4
−00+	2.3×10^3	740.	230.	74.
−+−+	10.	5.6	3.2	1.8
−+00	1.7×10^3	530.	170.	53.
0000	x	x	x	x

EFT signal vs total BSM signal

- The full process is $pp \rightarrow jj\, \ell^+\ell^+\nu\nu$ - ``gold-plated channel''

- **M_{WW} is not accessible experimentally.** We don't know a priori what part of the signal comes from the EFT-controlled range.

D – distribution of some physical observable, BSM signal: $D^{BSM} - D^{SM}$, EFT signal: D^{EFT} - D^{SM}

Realistically modeled total signal with regularized tail:

$$D^{BSM} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM_{WW}}\bigg|_{EFT\ \ model} dM_{WW}}_{\text{EFT controlled region}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM_{WW}}\bigg|_{regularized} dM_{WW}}_{\text{the tail}}$$

The EFT-controlled part of the signal is given by:

$$D^{EFT} = \int_{2M_W}^{\Lambda} \frac{d\sigma}{dM_{WW}}\bigg|_{EFT\ \ model} dM_{WW} + \int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM_{WW}}\bigg|_{SM} dM_{WW}$$

EFT in its range of validity *Only SM contribution*

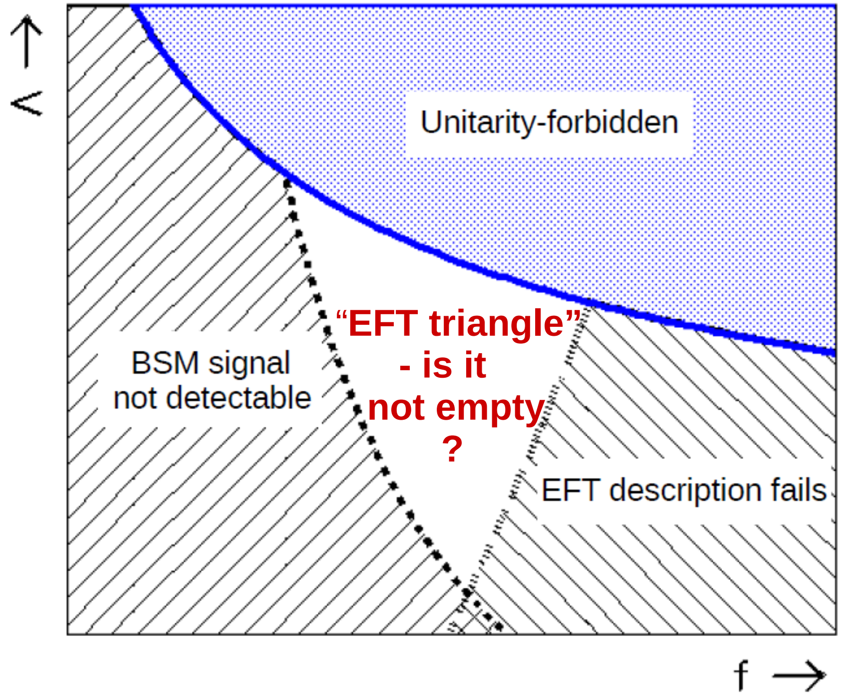
EFT triangle: unitarity vs. BSM discoverability vs. EFT validity

Three conditions that restrict the (f, Λ) space of practical interest:

1. Unitarity: sets maximum Λ for a given f,

2. BSM signal significance: defines minimum f as a function of Λ,

3. In addition, we need the bulk of BSM signal originate from the EFT-controlled region. Consistency of the (measured) total BSM signal with the EFT-controlled signal defines a maximum f for a given Λ



Recommended data analysis strategy:

- Fit simultaneously f and Λ to a measured distribution,

- Check statistical consistency between the simulated distributions of the BSM signal and the EFT signal for this (f, Λ).

Generator level study – technical details

- MG5 (LO) + Pythia samples (500k-1M) of the process $pp \to jj\, \ell^+\ell^+\nu\nu$ @ 14 and 27 TeV for each dim-8 operator, f scan done using event reweight (including f=0 for SM),

- Tails M>Λ modeled by applying additional weights $(\Lambda/M)^4$ to approximate a 1/s total cross section fall,

- Standard VBS cuts,

- Signal significances calculated from different kinematic distributions

  BSM signal significance: $\chi^2 = \sum_i (N_i^{BSM} - N_i^{SM})^2 / N_i^{SM}$ $\quad (\sqrt{\chi^2} \geq 5)$

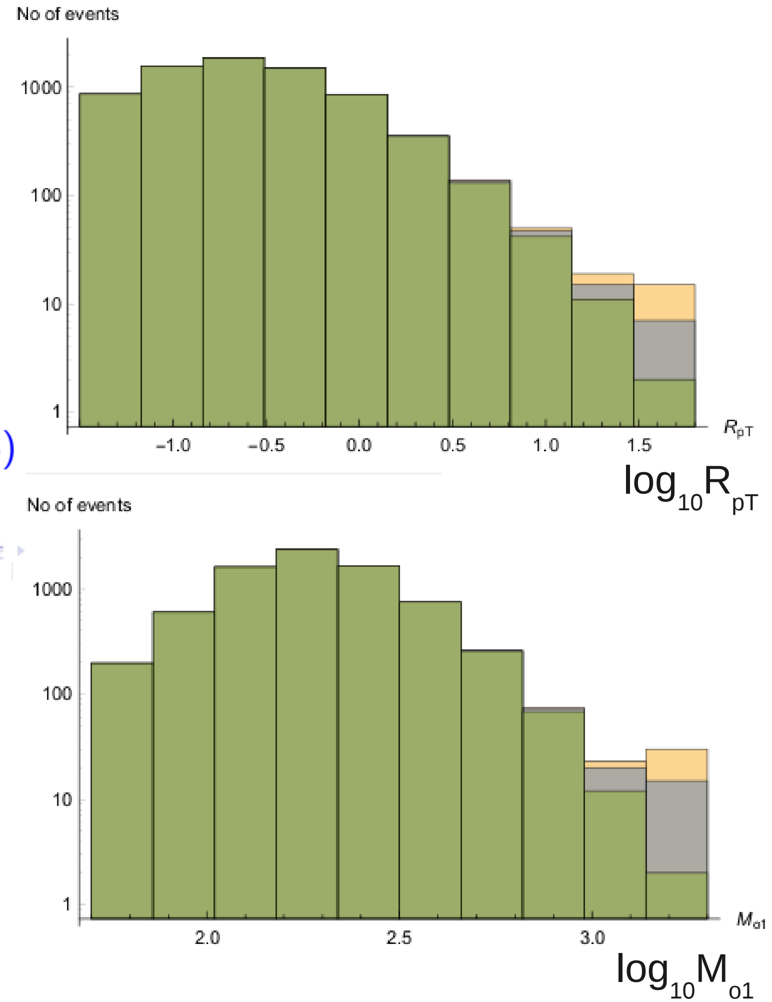
  EFT consistency: $\chi^2_{add} = \sum_i (N_i^{BSM} - N_i^{EFT})^2 / N_i^{BSM}$ $\quad (\sqrt{\chi^2_{add}} \leq 2)$

- The most sensitive variables:

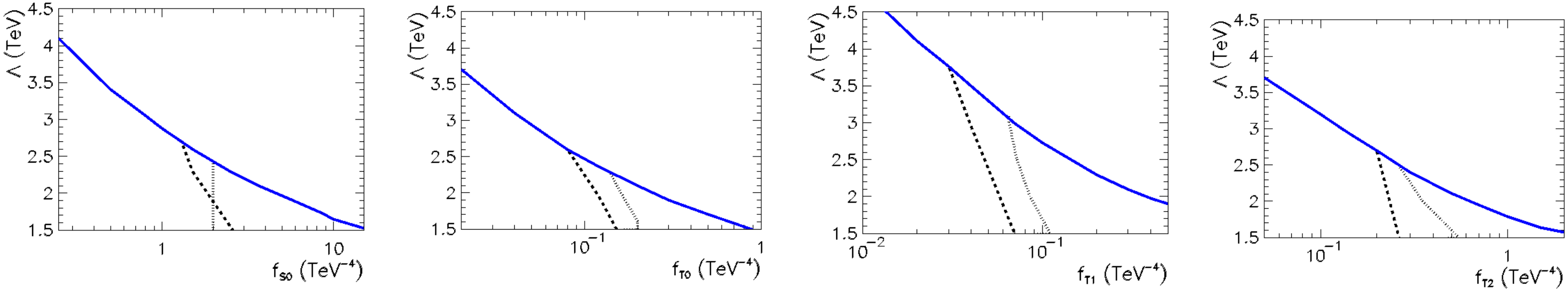
$$R_{p_T} \equiv p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2})$$ for $\mathcal{O}_{S0}$ and $\mathcal{O}_{S1}$, and

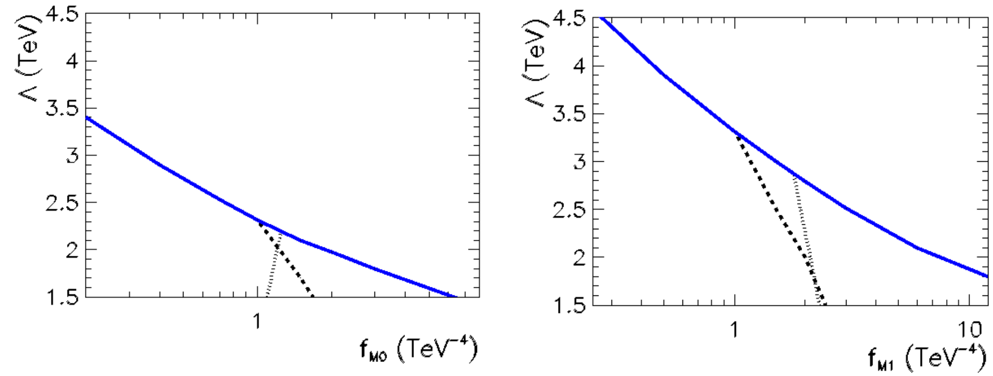
$$M_{o1} \equiv \sqrt{(|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,miss}|)^2 - (\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,miss})^2}$$

for the remaining operators



EFT triangles at HL-LHC, 14 TeV (SMEFT)

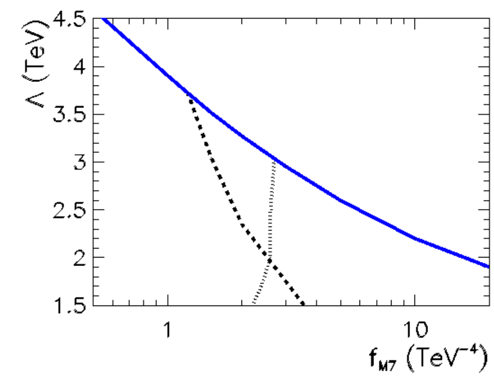




- Rather narrow ranges, totally empty in one case ($\mathcal{O}_{S1}$),

- **Caution: there is no detector simulation and reducible background treatment in this study.** Sensitivity loss due to reducible backgrounds and detector effects is at least a factor 2 in f (can be inferred from earlier works, e.g., arXiv:1309.7452).

- Realistically, **only small triangles for f_{T0}, f_{T1}, f_{T2} and f_{M7} are likely to remain.**



EFT triangles at HE-LHC, 27 TeV (SMEFT)

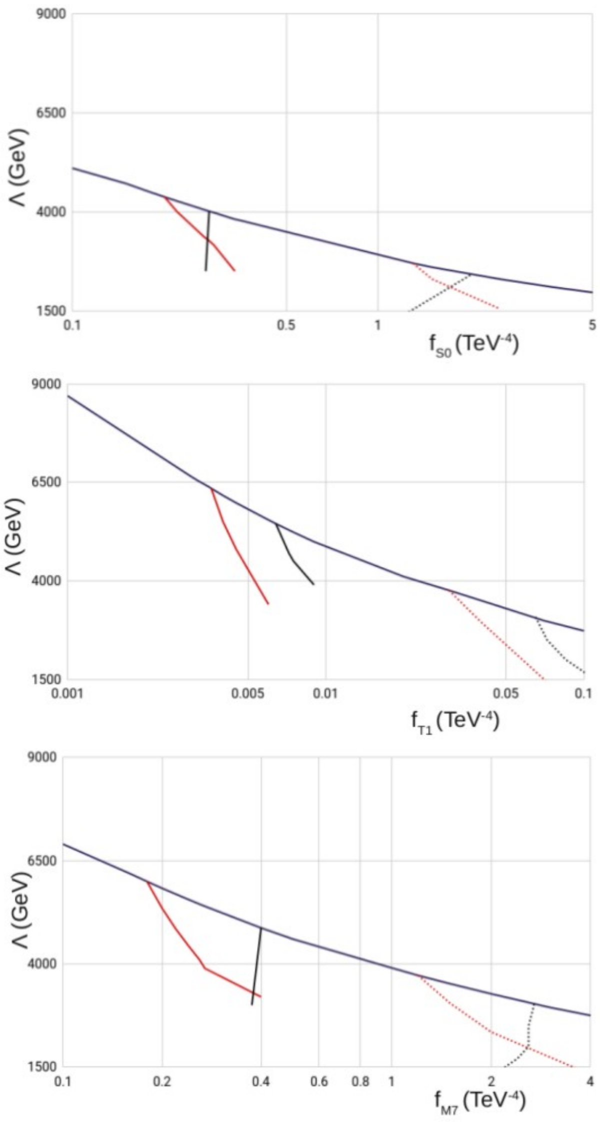
- Still narrow ranges, not much larger than at 14 TeV, $\mathcal{O}_{S1}$ still empty.

- In fact, not much difference between 14 and 27 TeV, except for a shift in f by a factor corresponding to the difference between the respective cross sections,

- Similarly, only a shift can be expected with increasing statistics,

- Possible differences we have neglected:
  - reducible backgrounds and detector resolutions
    - can only make things worse,
  - NLO vs. LO – not much different between 14 and 27 TeV (see arXiv:1902.04070)
  - optimization of selection criteria – marginal.

- **Conclusions:**
  - **doing one operator at a time has slim potential for being successful to describe BSM discovery,**
  - **increasing proton energy does not solve the problem.**



The HEFT approach

- Most general, non-linear realization of the Higgs sector via matrix $U = exp(i\sigma_a \pi^a / v)$
- Expansion in U derivatives, 10 operators at primary dimension d_p=8.

SMEFT	HEFT
$\mathcal{O}_{S_0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]\left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$	$\mathcal{P}_6 = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{V}_\nu\mathbf{V}^\nu)$
$\mathcal{O}_{S_1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right]\left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$	$\mathcal{P}_{11} = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\mathrm{Tr}(\mathbf{V}^\mu\mathbf{V}^\nu)$
	$\mathcal{T}_{42} = \mathrm{Tr}(\mathbf{V}_\alpha W_{\mu\nu})\mathrm{Tr}(\mathbf{V}^\alpha W^{\mu\nu})$
$\mathcal{O}_{M_7} = (D_\mu\Phi)^\dagger W_{\alpha\nu} W^{\alpha\mu} D^\nu\Phi$	$\mathcal{T}_{43} = \mathrm{Tr}(\mathbf{V}_\alpha W_{\mu\nu})\mathrm{Tr}(\mathbf{V}^\nu W^{\mu\alpha})$
	$\mathcal{T}_{44} = \mathrm{Tr}(\mathbf{V}^\nu W_{\mu\nu})\mathrm{Tr}(\mathbf{V}_\alpha W^{\mu\alpha})$
$\mathcal{O}_{M_0} = W^a_{\mu\nu} W^{a\mu\nu}\left[(D_\alpha\Phi)^\dagger D^\alpha\Phi\right]$	$\mathcal{T}_{61} = W^a_{\mu\nu} W^{a\mu\nu}\mathrm{Tr}(\mathbf{V}_\alpha\mathbf{V}^\alpha)$
$\mathcal{O}_{M_1} = W^a_{\mu\nu} W^{a\nu\alpha}\left[(D_\alpha\Phi)^\dagger D^\mu\Phi\right]$	$\mathcal{T}_{62} = W^a_{\mu\nu} W^{a\mu\alpha}\mathrm{Tr}(\mathbf{V}_\alpha\mathbf{V}^\nu)$
$\mathcal{O}_{T_0} = W^a_{\mu\nu} W^{a\mu\nu} W^b_{\alpha\beta} W^{b\alpha\beta}$	$\mathcal{O}_{T_0} = W^a_{\mu\nu} W^{a\mu\nu} W^b_{\alpha\beta} W^{b\alpha\beta}$
$\mathcal{O}_{T_1} = W^a_{\alpha\nu} W^{a\mu\beta} W^b_{\mu\beta} W^{b\alpha\nu}$	$\mathcal{O}_{T_1} = W^a_{\alpha\nu} W^{a\mu\beta} W^b_{\mu\beta} W^{b\alpha\nu}$
$\mathcal{O}_{T_2} = W^a_{\alpha\mu} W^{a\mu\beta} W^b_{\beta\nu} W^{b\nu\alpha}$	$\mathcal{O}_{T_2} = W^a_{\alpha\mu} W^{a\mu\beta} W^b_{\beta\nu} W^{b\nu\alpha}$

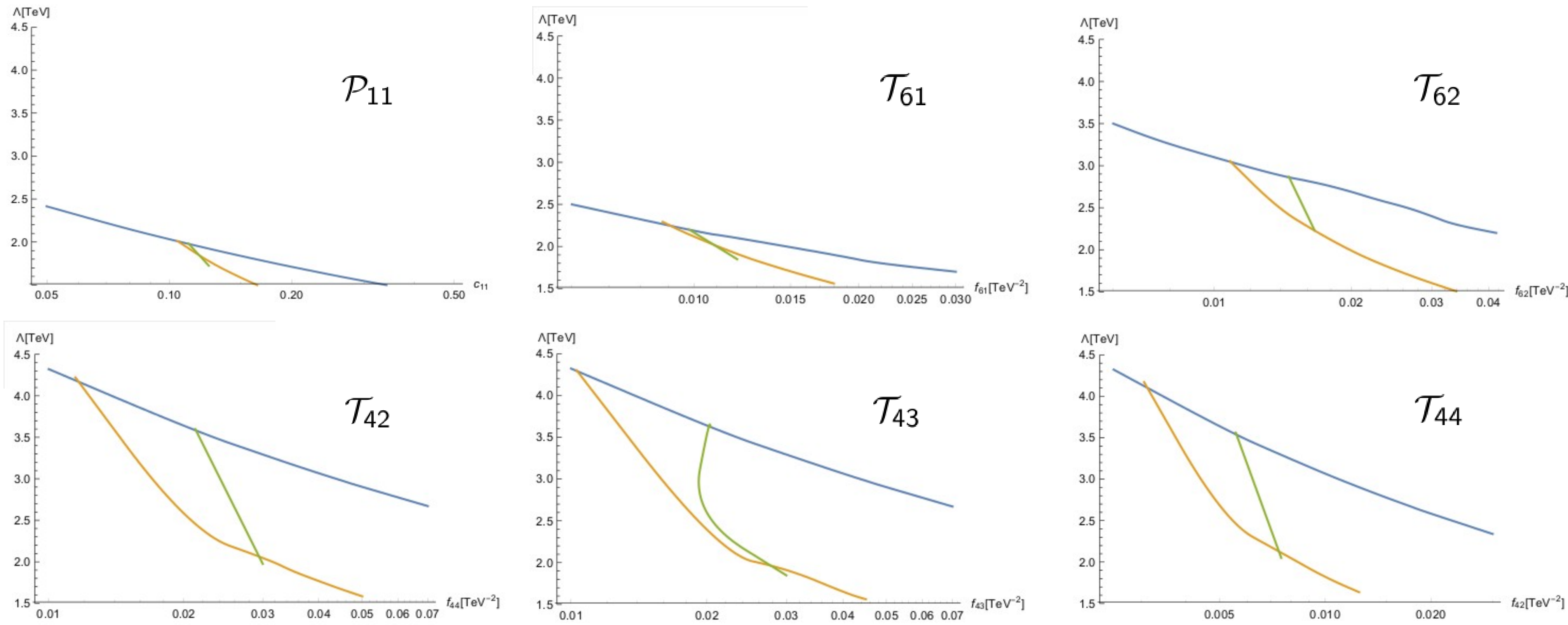
$\mathbf{V}_\mu \equiv (D_\mu U)U^\dagger$

- Correspondence between HEFT and SMEFT operators:

$$c_6\mathcal{P}_6 \iff c^{(8)}_{S_1}\mathcal{O}_{S_1}$$
$$c_{11}\mathcal{P}_{11} \iff c^{(8)}_{S_0}\mathcal{O}_{S_0} + c^{(8)}_{S_1}\mathcal{O}_{S_1}$$
$$c_{61}\mathcal{T}_{61} \iff c^{(8)}_{M_0}\mathcal{O}_{M_0}$$
$$c_{62}\mathcal{T}_{62} \iff c^{(8)}_{M_1}\mathcal{O}_{M_1}\,.$$

$\mathcal{T}_{42}$, $\mathcal{T}_{43}$ and $\mathcal{T}_{44}$ do not have SMEFT equivalents at or below dimension 8.

EFT triangles in the HEFT approach (HL-LHC, 14 TeV)

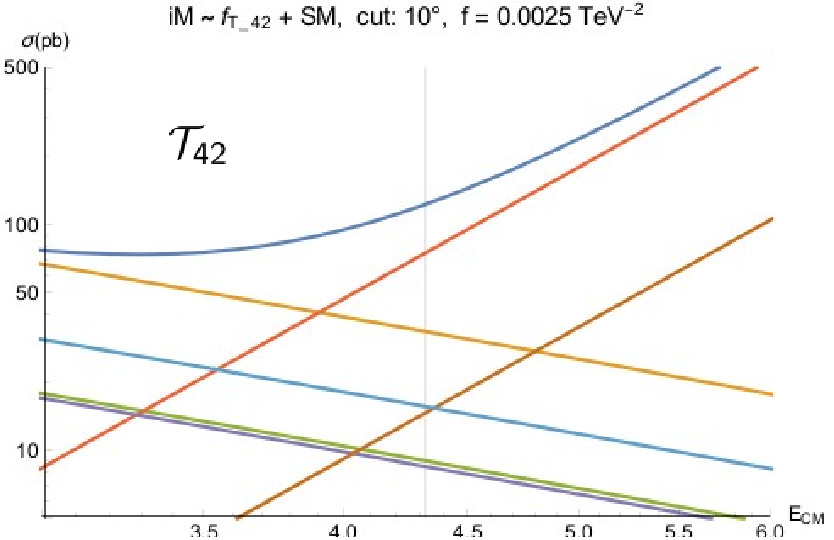


- Tiny or totally empty for $\mathcal{P}_6$, $\mathcal{P}_{11}$ and $\mathcal{T}_{61}$, similarly like in their SMEFT equivalents (nb. c_6 and c_{11} are usually denoted in literature as a_5 and a_4).

- Relatively largest (but not large) for the operators that have no equivalent in SMEFT
  - hint at a possibility to distinguish linear from non-linear Higgs realization from the data?

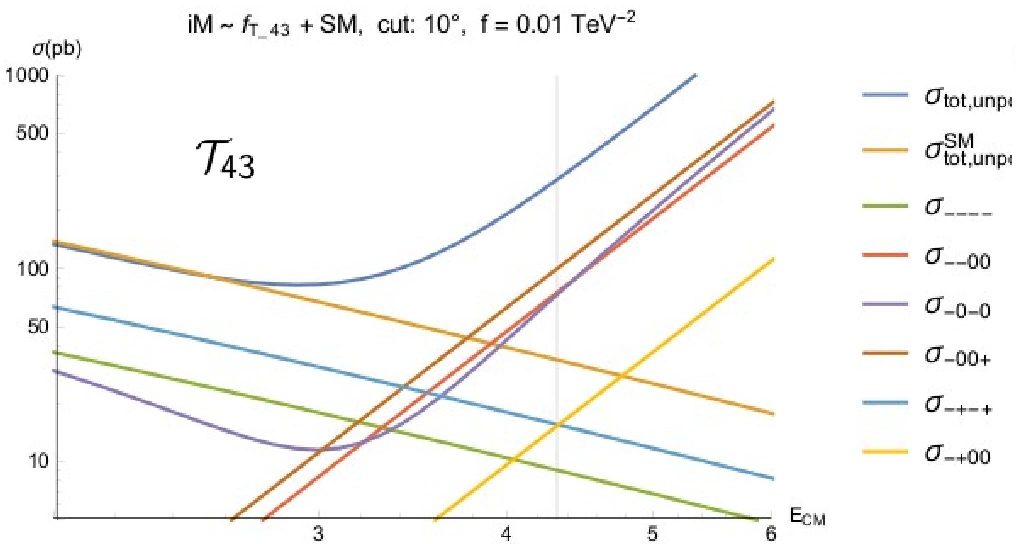
HEFT vs. SMEFT

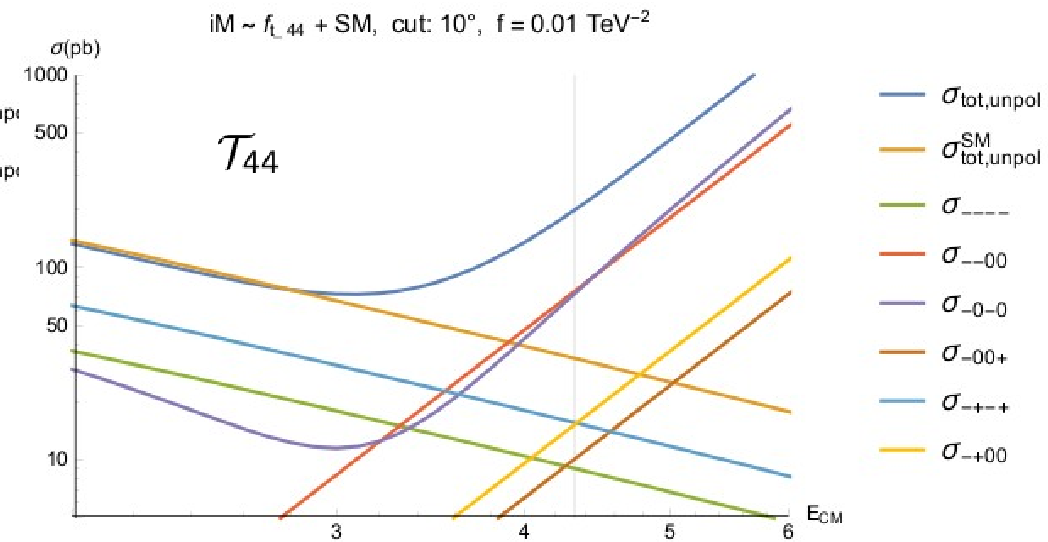
Total $W^+W^+ \rightarrow W^+W^+$ cross section (on shell) split into initial & final state helicity combinations



- For all these operators among the dominant amplitudes is --00 (TT → LL) !
  - negligible in the SM,
  - higher order (>8) in the SMEFT,
  - LL in the final state.

- Possible to disentangle based on event kinematics, e.g., p_T of tagging jets vs. p_T of leptons?





A look at BSM coupling constants

- Apply naive dimensional analysis (NDA) to relate discovery regions to BSM couplings
  The master formula for operator normalization (see **arXiv:1601.07551**):

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}$$

hence for us: $\left[\frac{\mathbf{V}_\mu}{\Lambda}\right]^{N\mathbf{v}_\mu}\left[\frac{4\pi}{\Lambda^2}W_{\mu\nu}\right]^{N_{W_{\mu\nu}}}$

Dimensionless constants c_i expected <1 for perturbativity

	$\mathcal{P}_6$	$\mathcal{P}_{11}$	$\mathcal{T}_{42}$	$\mathcal{T}_{43}$	$\mathcal{T}_{44}$
$c_i > 0$	-	0.11	$[0.033, 0.007]$	$[0.11, 0.27]$	$[0.13, 0.27]$
$c_i < 0$	0.3	$-[0.076, 0.14]$	$-[0.034, 0.070]$	$-[0.11, 0.27]$	$-[0.11, 0.28]$

	$\mathcal{T}_{61}$	$\mathcal{T}_{62}$	$\mathcal{O}_{T_0}$	$\mathcal{O}_{T_1}$	$\mathcal{O}_{T2}$
$c_i > 0$	$[0.045, 0.047]$	$[0.083, 0.120]$	$[0.0051, 0.0072]$	$[0.0026, 0.0110]$	-
$c_i < 0$	$-[0.044, 0.048]$	$-[0.072, 0.12]$	$-[0.003, 0.012]$	$-[0.0018, 0.0110]$	$-[0.0052, 0.032]$

OK!

- On the other hand, if W is elementary and couples via g, factor out g/4π for every W - trouble

$$\mathcal{L}_{SMEFT} \supset \quad f_i\mathcal{O}_i \equiv c_i \cdot 2\frac{g^2}{\Lambda^4}\mathcal{O}_i, \qquad i = M0, M1 \qquad \sim (D_\alpha\Phi)^2(W^i_{\mu\nu})^2$$

$$f_i\mathcal{O}_i \equiv c_i \cdot 2^2\frac{g^4}{16\pi^2\Lambda^4}\mathcal{O}_i, \qquad i = T0, T1, T2 \qquad \sim (W^i_{\mu\nu})^4$$

HL-LHC	$T0$	$T1$	$T2$	$M0$	$M1$	$M7$
c_{min}–c_{max}	137.–790.	76.–1300.	280.–2200.	23.-33.	38.-140.	24.-130.

Conclusions and outlook

- Lack of experimental access to the WW invariant mass is a crucial issue if one wants to correctly apply the EFT to describe VBS data,

- The same-sign WW (leptonic) process is still a very interesting channel to look for BSM physics, because of its experimental cleanness and small reducible background, but BSM interpretation in the EFT framework may be problematic
(ZZ, despite its low cross section, is the only process in which the invariant mass is measured to a good accuracy, and may be the best channel to study the nature of BSM physics),

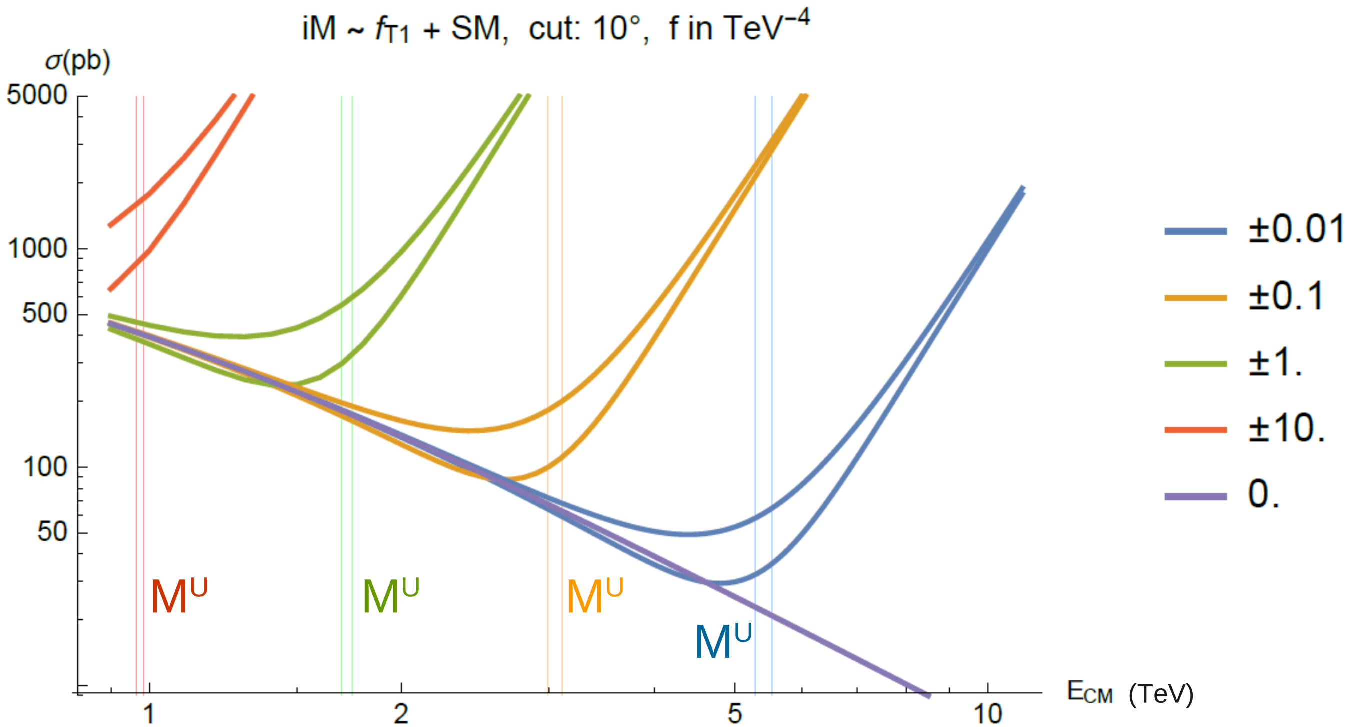
- Varying one dim-8 SMEFT operator at a time, widely practiced in ATLAS and CMS data analyses, has rather slim chances of being useful as a description of potential new physics; going to higher energy is not a solution; **multi-operator analysis and combination of different processes: ssWW, WZ, ZZ and WV is rather essential**,

- HEFT single-operator discovery regions are likewise small, but **existence of additional operators (42, 43 & 44) at lowest order may help distinguish between a linearly and non-linearly realized Higgs sector.**

Backups

Justification of high M tail modeling

- Asymptotically, every dim-8 operator produces a divergence ~s^3 in the total cross section.
- After regularization expected behavior ~1/s → reweight like $1/s^4$, i.e., $(\Lambda/M)^8$



Total $W^+W^+ \rightarrow W^+W^+$ cross section for different f_{T1}

- Of the simple power law scalings, $(\Lambda/M)^4$ fits best to the overall energy dependence around M^U.

- But we are mostly interested in the region just above $\Lambda \sim M^U$
- Around unitarity limit:
  - the highest power term is not dominant yet,
  - the fastest growing amplitude is not dominant yet.
- Hence the overall energy dependence is much less steep.