

# EFT same-sign WW studies

Michał Szleper (NCBJ Warsaw)

Based on arXiv:1802.02366

“Same-sign WW scattering at the LHC:  
can we discover BSM effects before discovering new states?”

work in collaboration with

Jan Kalinowski, Paweł Kozów, Stefan Pokorski, Janusz Rosiek, (University of Warsaw),  
Sławek Tkaczyk (Fermilab)

ΑΡΙΣΤΟΤΕΛΗΣ

2<sup>nd</sup> VBSCan annual meeting  
Θεσσαλονίκη, June 20, 2018

# The main topic of this study: practical usefulness of the EFT approach to describe future VBS data

## Working assumptions:

- focus on the same-sign WW channel, with purely leptonic decays,
- luminosity target:  $3 \text{ ab}^{-1}$  at 14 TeV (HL-LHC).

## Two possible approaches for the EFT:

1. Global fits to many EW processes – need a full basis of operators, available for dim-6 only. Will VBS processes make a significant impact on such fits?
2. Try to explore what is unique to VBS: the quartic couplings and associated dim-8 operators. Vary dim-8 operators one by one or in groups.

**The rest of the talk has to do with the latter option.**

**Working scenario 1:** we observe a significant deviation from SM predictions, but no other hints from elsewhere – can we interpret the results in the EFT framework so that we really learn something about the underlying BSM physics?

**Working scenario 2:** 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 “models”

1. Provides an in-principle-model-independent parameterization of BSM interactions between SM particles

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

$$f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^2}, \quad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \dots$$

2. In principle an infinite expansion – but there is no way one can fit an infinite number of parameters to any data.

3. We always need a truncation. What truncation is a good one? E.g. dim-6 vs dim-8?

There is no obvious answer! (see, e.g., *Liu et al.* 1603.03064, *Contino et al.* 1604.06444, *Azatov et al.* 1607.05236, *Franceschini et al.* 1712.01310, *Biekter et al.* 1406.7320, *Falkowski et al.* 1609.06312)

4. For practical reasons, one needs **a choice** of the operators to consider.

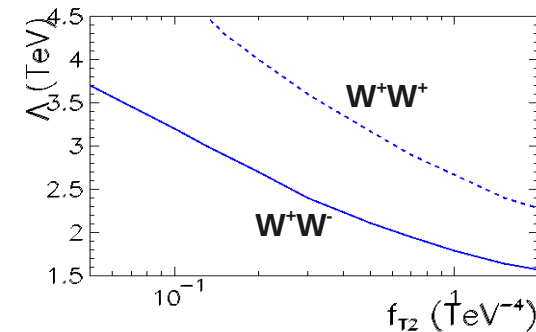
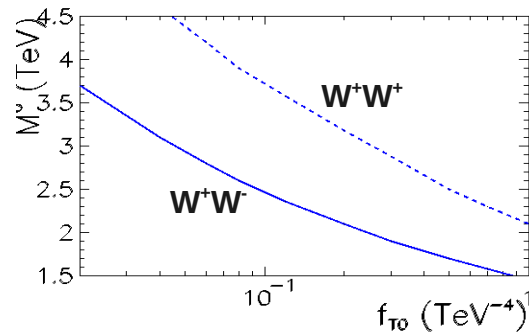
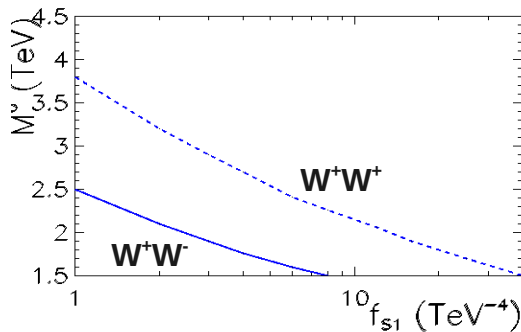
E.g., common *choice* for VBS: consider only variations of single dim-8 operators at a time.

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  $\Lambda$

# EFT cutoff

1. **EFT validity stops at  $M_{VV}=\Lambda$ , the scale of new physics.**  $\Lambda$  can be *maximally* equal to the lowest relevant unitarity limit,  $\Lambda \leq M^U$ .
2.  $\Lambda$  is one for a given operator, it applies to all affected amplitudes, even if they are still far from their individual unitarity limits.
3.  $\Lambda$  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  $f$ ),  $\mathcal{O}_{T2}$ ,  $\mathcal{O}_{M0}$ ,  $\mathcal{O}_{M1}$ ,  $\mathcal{O}_{M6}$  and  $\mathcal{O}_{M7}$ .



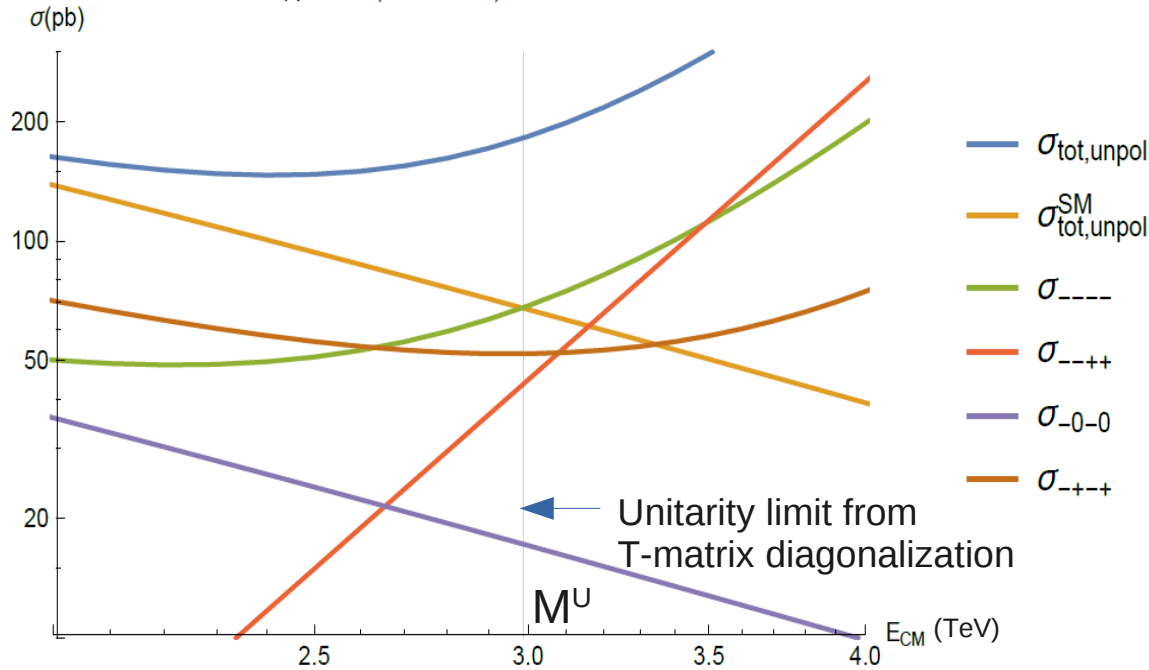
4. But  $\Lambda$  can also be much lower than *any* unitarity bound (lesson learned from the Higgs boson!). **The actual value of  $\Lambda$  must be deduced from the data.**

# Helicities and unitarity limits

## The case of $f_{T1}$

### $W^+W^+$ - 13 independent helicity combinations

$iM \sim f_{T1} + \text{SM}, \text{ cut: } 10^\circ, f = -10^{-1} \text{ TeV}^{-4}$



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	$7.5 \times 10^7$	$7.5 \times 10^6$	$7.5 \times 10^5$	$7.5 \times 10^4$
---+	$1.7 \times 10^3$	530.	170.	53.
--00	440.	140.	44.	14.
--0+	74.	34.	16.	7.4
--++	5.5	3.1	1.7	0.99
-0-0	$2.5 \times 10^3$	800.	250.	80.
-0-+	69.	32.	15.	6.9
-000	$3.7 \times 10^7$	$3.7 \times 10^6$	$3.7 \times 10^5$	$3.7 \times 10^4$
-00+	$2.3 \times 10^3$	740.	230.	74.
+-++	10.	5.6	3.2	1.8
++00	$1.7 \times 10^3$	530.	170.	53.
0000	x	x	x	x

Total  $W^+W^+ \rightarrow W^+W^+$  cross section for  $f_{T1} = -0.1/\text{TeV}^4$   
split into initial & final state helicity combinations

# EFT signal vs total BSM signal

- The full process is  $pp \rightarrow jj \ell^+ \ell^- \nu \nu$
- $M_{\nu\nu}$  is not accessible experimentally. We don't know a priori what part of the signal comes from the EFT-controlled range.

$D_i$  – physical observable, BSM signal:  $S = D_i^{model} - D_i^{SM}$

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

$$D_i^{model} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM} |_{model} dM}_{\text{EFT in its range of validity}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM} |_{SM} dM}_{\text{Only SM contribution}}$$

**EFT can be applied to describe the full measured  $D_i$  distribution only so long as the  $M > \Lambda$  tail does not significantly distort it.**

1. The condition  $M < \Lambda$  effectively translates into a limit in the plane  $(f, \Lambda)$  for which the contribution from  $M > \Lambda$  is small enough,
2. We need to control the contribution above  $\Lambda$ , it can be estimated within certain limits from general physics principles.

# Estimating the signal above $\Lambda$

- Expected asymptotic behavior for the total WW  $\rightarrow$  WW cross section above  $\Lambda$  is  $\sim 1/s$ , e.g. amplitudes remain asymptotically constant.
- A conservative estimate is given by freezing all the amplitudes at their respective values they reach at  $\Lambda$ .

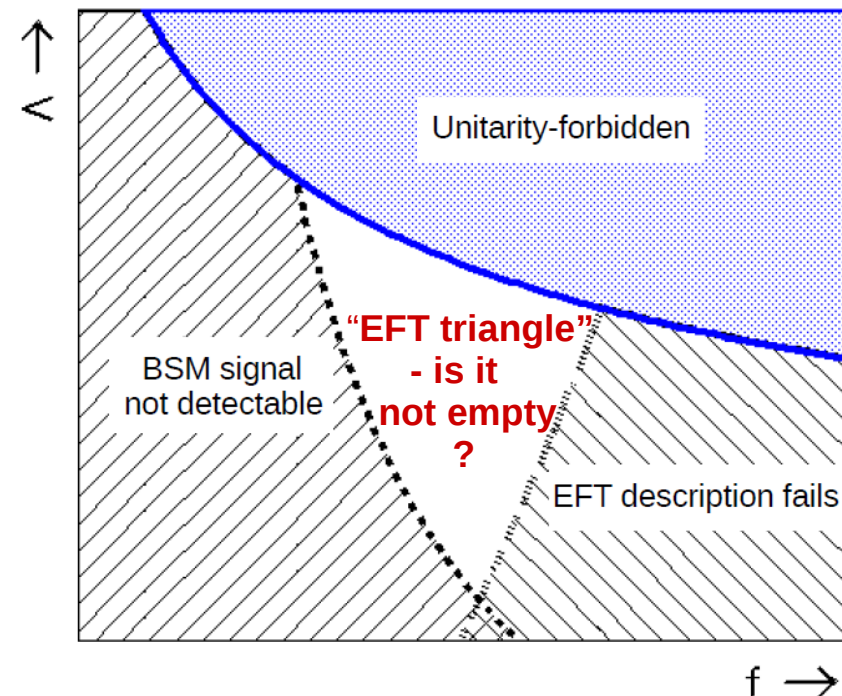
**Total measured BSM signal** – a reasonable(?) estimate:

$$D_i^{model} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM} \big|_{model} dM}_{\text{EFT in its range of validity}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM} \big|_{A=const} dM}_{\text{Some physically plausible additional contribution}}$$

- We want BSM signal significance at 5 sigma  
+ we want the signal be driven by the EFT-controlled part rather than by the  $M > \Lambda$  tail:  
BSM signal and EFT signal must remain in statistical consistency, e.g., within 2 sigma.
- This puts a lower and upper bound on  $f$  for every value of  $\Lambda$ .

# Data analysis strategy: what if we see a deviation from the SM and would like to interpret it in the EFT framework?

1. Measure the most sensitive distribution  $D$  from data,
2. Fit values of  $(f, \Lambda)$  using simulated distributions that include estimated BSM contributions from the region  $M > \Lambda$ ,
3. Fixing  $(f, \Lambda)$  to the fit values recalculate distribution  $D$  using the EFT signal only (only SM left for  $M > \Lambda$ ),
4. Check statistical consistency between the simulated distributions of the BSM signal and the EFT signal for this  $(f, \Lambda)$ .
5. Obtained values of  $(f, \Lambda)$  make sense if such consistency is found, otherwise data description in terms of the studied operator is not possible.
6. Check stability of the result against different regularization methods.



# Are there any “EFT triangles” for dim-8 operators? – simulation work

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

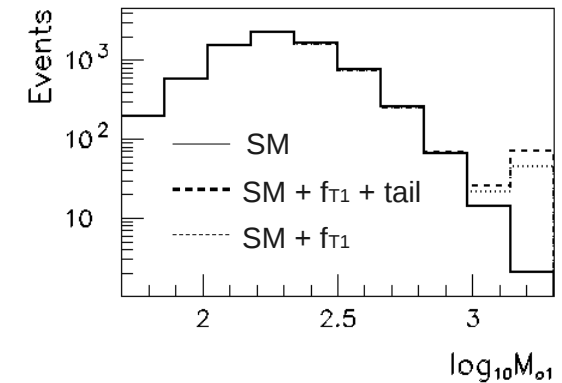
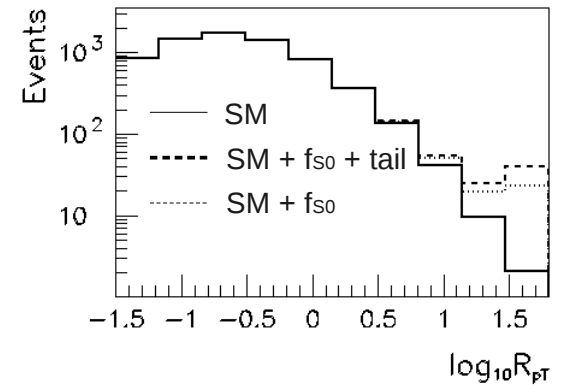
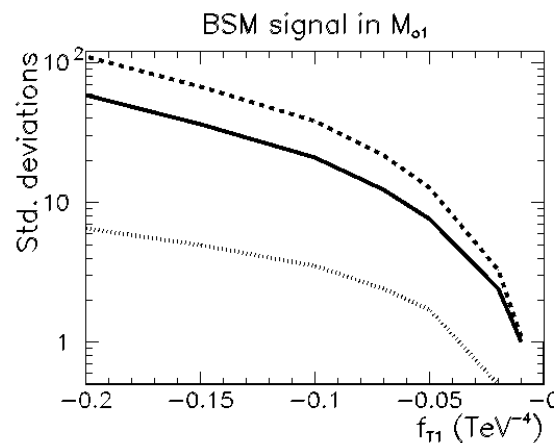
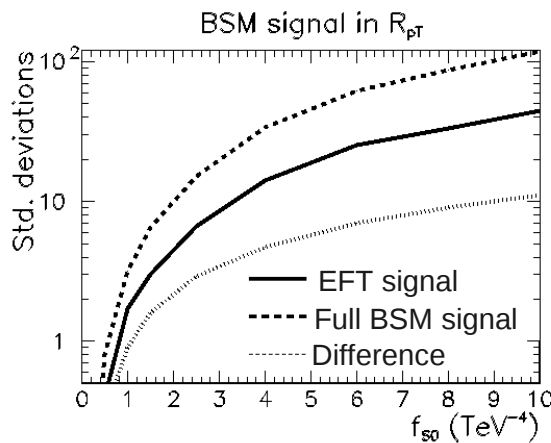
- Tails  $M > \Lambda$  modeled by applying additional weights  $(\Lambda/M)^4$ ,

- Standard VBS cuts, signal significances calculated from different kinematic distributions, the most sensitive variables:

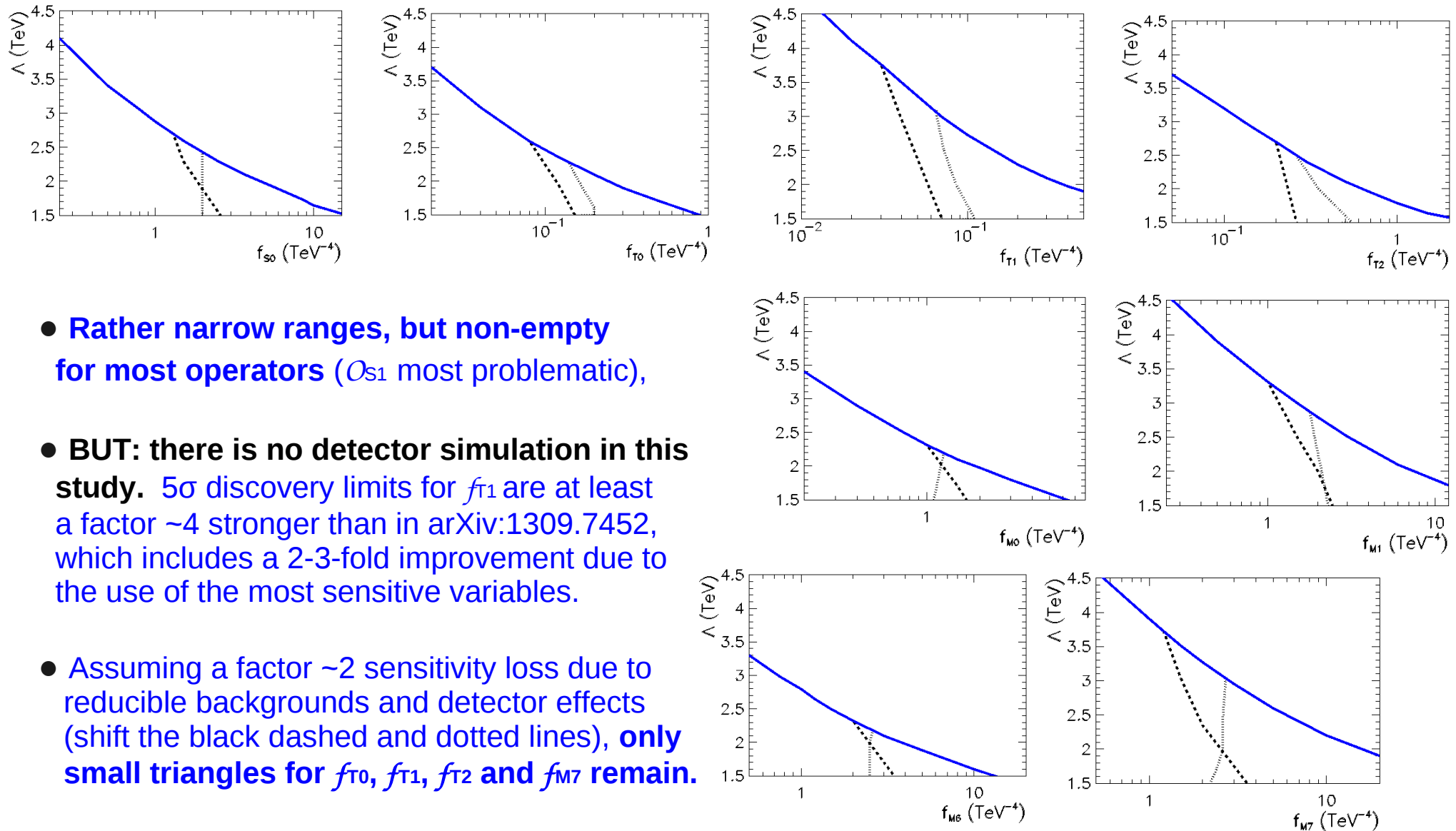
$$R_{p_T} \equiv p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2}) \quad \text{for } O_{S0} \text{ and } O_{S1}, \text{ and}$$

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

for the remaining operators



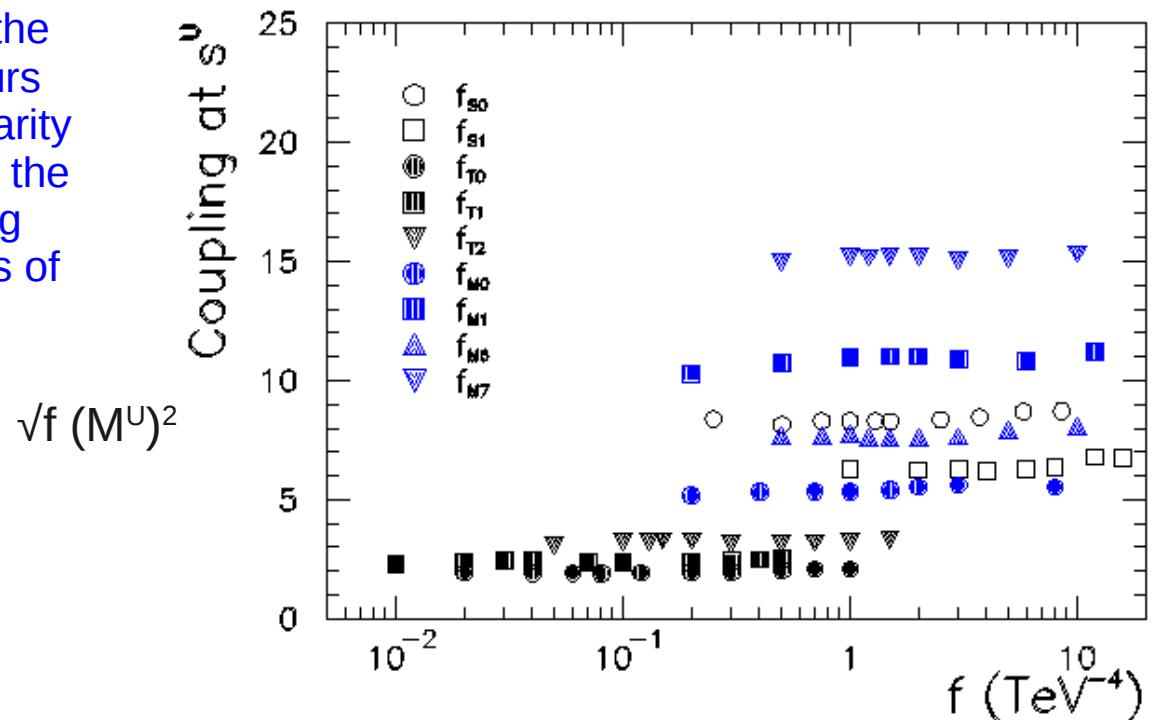
# Results: examples of “EFT triangles” (regions of BSM discovery describable by an EFT “model”)



- **Rather narrow ranges, but non-empty for most operators** ( $O_{S1}$  most problematic),
- **BUT: there is no detector simulation in this study.**  $5\sigma$  discovery limits for  $f_{t1}$  are at least a factor  $\sim 4$  stronger than in arXiv:1309.7452, which includes a 2-3-fold improvement due to the use of the most sensitive variables.
- Assuming a factor  $\sim 2$  sensitivity loss due to reducible backgrounds and detector effects (shift the black dashed and dotted lines), **only small triangles for  $f_{t0}$ ,  $f_{t1}$ ,  $f_{t2}$  and  $f_{M7}$  remain.**

# A hint on BSM couplings

- $C = f \Lambda^4$
- In models with one BSM scale and one BSM coupling,  $\sqrt{C}$  has the interpretation of the coupling constant (*Giudice et al. hep-ph/0703164*).
- Obtained “EFT triangles” correspond to  $\Lambda > 2$  TeV and  $C$  very close to the strong coupling limit for M operators, and a somewhat wider range for T operators.
- For every dim-8 operator, the maximum value of  $\sqrt{C}$  occurs when  $\Lambda$  is equal to the unitarity limit and is generally within the range  $\sqrt{(4\pi) - 4\pi}$  (= strong interaction limit), regardless of the actual value of  $f$ .



## Working scenario 2: setting limits on higher-dim operators

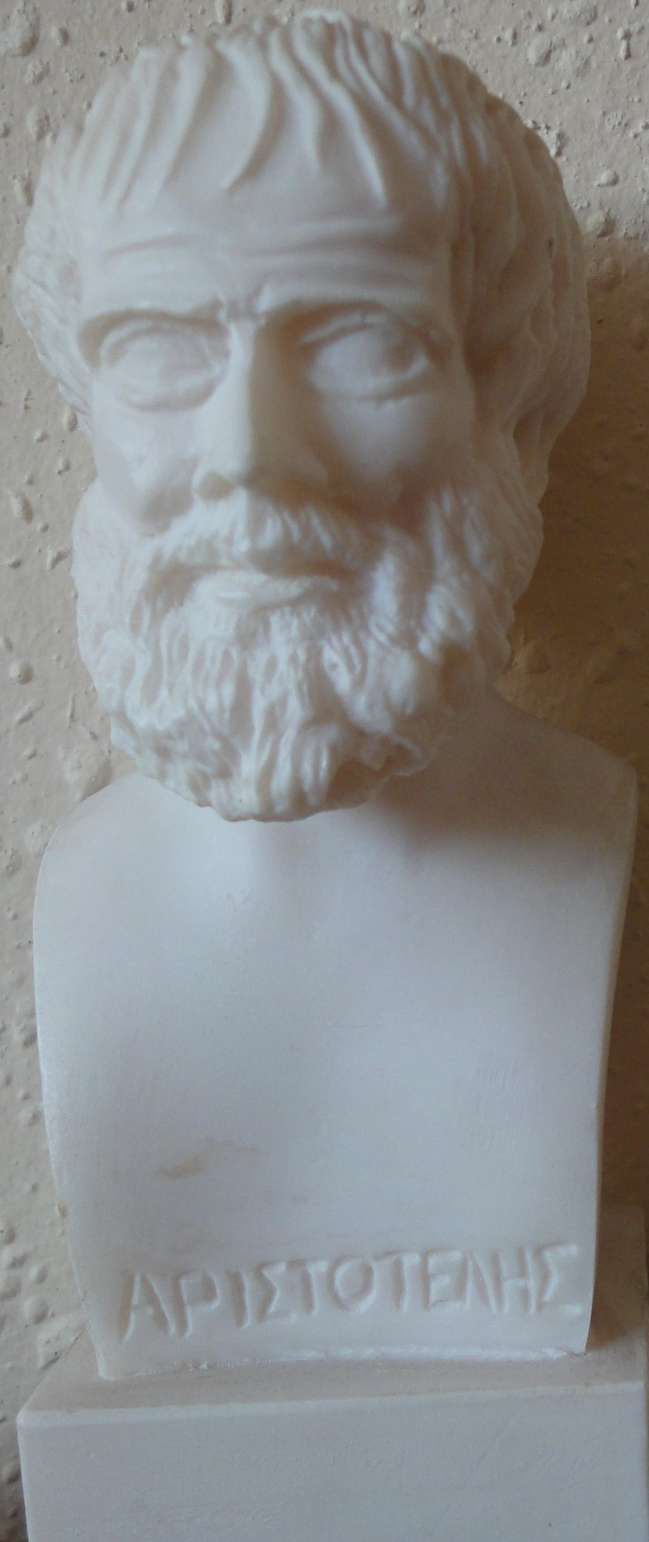
- If agreement with the SM is found, any mathematical parameterizations are OK to quantify the precision of the data and the degree of agreement with the SM.
- But physically useful limits on dim-8 operators are only those that strictly respect their regions of validity.
  - the value of  $\Lambda$  must be varied as well,
  - limits can only be determined in 2 dimensions:  $f$  vs.  $\Lambda$   
(note: if  $\Lambda$  is very low, the limit on  $f$  goes to infinity!),
  - **no additional BSM signal above  $\Lambda$  should be assumed, only SM contribution**
    - only the most conservative signal estimate gives a true experimental bound on the value of  $f$ .

**This method is already known as “clipping”!**

- how does this change the results of published analyses (ATLAS, CMS)? Probably much weaker limits...

# Conclusions and outlook

- Lack of experimental access to the VV invariant mass is a crucial issue if one wants to correctly apply the EFT to describe VBS data – ZZ may turn out effectively the best channel to look at,
- Varying one dim-8 operator at a time has rather slim chances of being useful as a description of potential new physics,
- More hopeful should be varying many dim-8 operators at a time, but this may be difficult due to strong kinematic correlations,
- A solution may be a simultaneous fit to different VBS processes, including WZ, ZZ and semi-leptonic decay channels,



**“The most exact of the sciences are those that are connected with primary things.”**

Aristotle, *The Metaphysics*

**Backup  
slides**

## Definitions of dim-8 operators

$$\mathcal{O}_{S0} = \left[ (D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[ (D^\mu \Phi)^\dagger D^\nu \Phi \right],$$

$$\mathcal{O}_{S1} = \left[ (D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[ (D_\nu \Phi)^\dagger D^\nu \Phi \right],$$

$$\mathcal{O}_{M0} = \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[ (D_\beta \Phi)^\dagger D^\beta \Phi \right],$$

$$\mathcal{O}_{M1} = \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[ (D_\beta \Phi)^\dagger D^\mu \Phi \right],$$

$$\mathcal{O}_{M6} = \left[ (D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right],$$

$$\mathcal{O}_{M7} = \left[ (D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right],$$

$$\mathcal{O}_{T0} = \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right],$$

$$\mathcal{O}_{T1} = \text{Tr} \left[ \hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[ \hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right],$$

$$\mathcal{O}_{T2} = \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[ \hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right].$$

$$D_\mu \equiv \partial_\mu + i \frac{g'}{2} B_\mu + i g W_\mu^i \frac{\tau^i}{2}$$

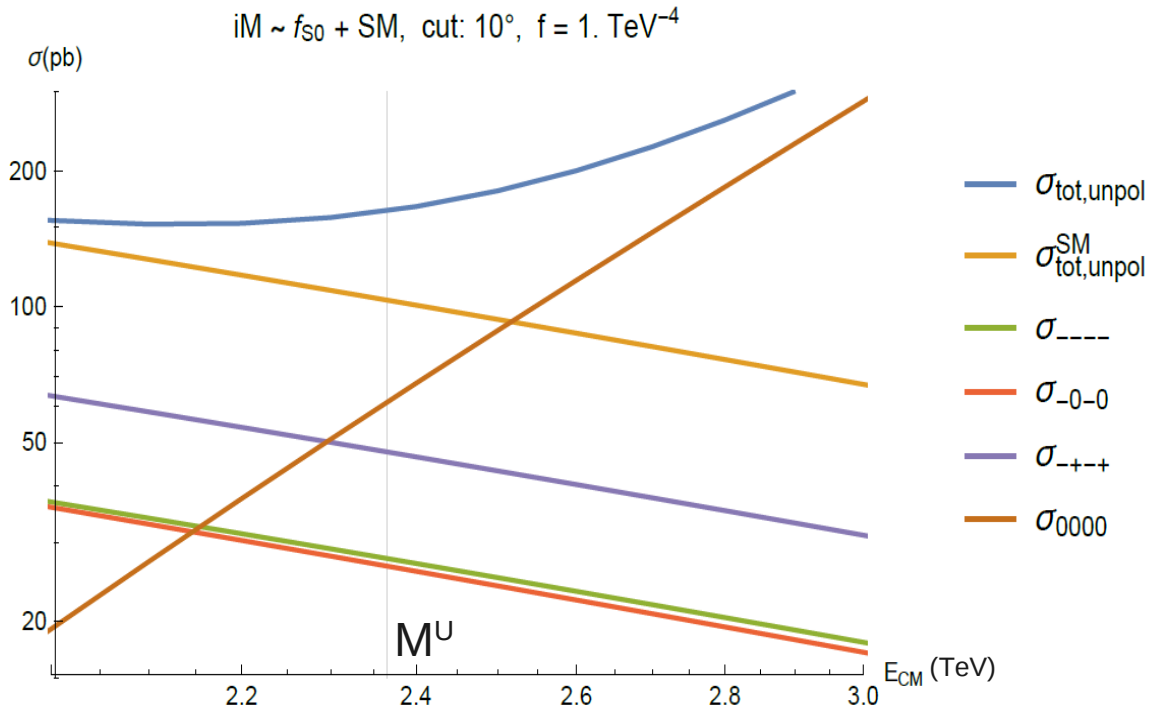
$$W_{\mu\nu} = \frac{i}{2} g \tau^i (\partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g \epsilon_{ijk} W_\mu^j W_\nu^k)$$

$$\hat{W}_{\mu\nu} = \frac{1}{ig} W_{\mu\nu}$$

# Helicities and unitarity limits I

The easy case:  $f_{S0}$  – BSM in mainly one helicity combination

## $W^+W^+$ - 13 independent helicity combinations



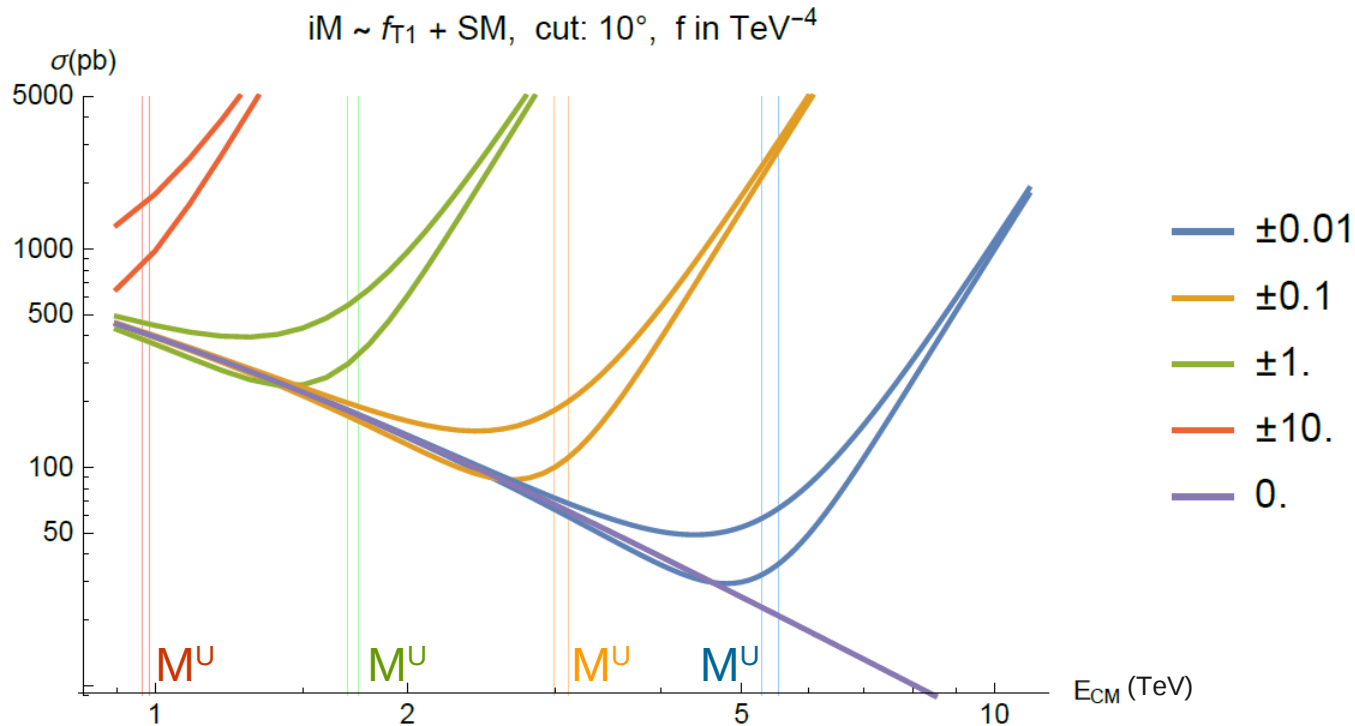
Unitarity limits  $M^U$  (in TeV)  
for individual amplitudes

Hel. \ $f_{S0} =$	0.01	0.1	1.	10.
----	X	X	X	X
---0	X	X	X	X
---+	X	X	X	X
--00	440.	140.	44.	14.
--0+	X	X	X	X
--++	X	X	X	X
-0-0	X	X	X	X
-0-+	X	X	X	X
-000	X	X	X	X
-00+	X	X	X	X
-+++	X	X	X	X
-+00	X	X	X	X
0000	7.5	4.2	2.4	1.3

Total  $W^+W^+ \rightarrow W^+W^+$  cross section for  $f_{S0} = 1/\text{TeV}^4$   
split into initial & final state helicity combinations

# Justification of high M tail modeling

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



- 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.

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  $M^U$ .

# “EFT triangles” for negative $f$

