

An EFT analysis of Vector Boson Scattering at the LHC

Athanasios Dedes

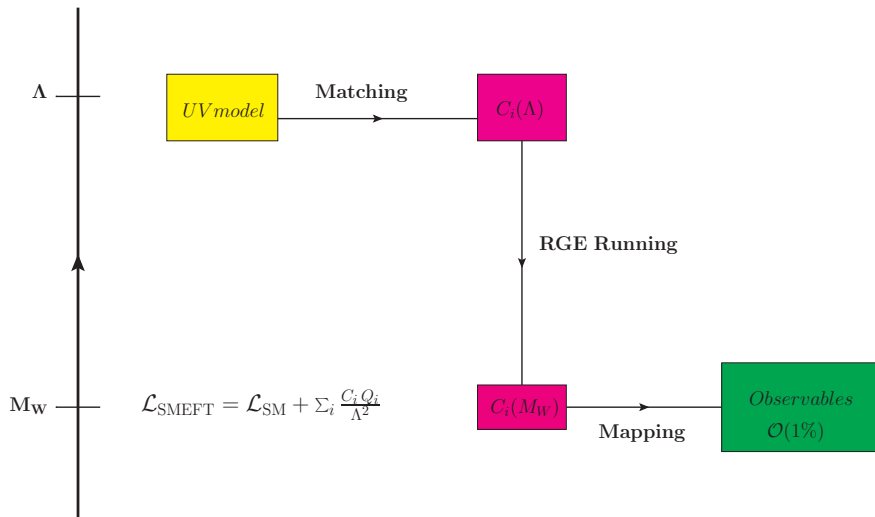
University of Ioannina

HEP-2021, Thessaloniki

Outline

- A very brief intro to SM EFT
- Vector-Boson Scattering at LHC
- Conclusions

The EFT picture¹



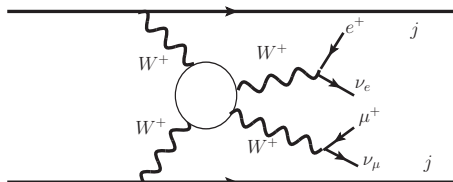
¹B. Henning, X. Lu and H. Murayama, arXiv:1412.1837

Vector Boson Scattering at the (HL)-LHC with SM EFT

My focus will be on like-sign-Ws

$pp \rightarrow 2 \text{ jets} + W^{+*} W^{+*} \rightarrow 2 \text{ jets} + 2 \text{ charged-leptons} + 2 \text{ neutrinos}$

Example diagram:



- Has been confirmed² at LHC far above 5σ
- Only recently the full 1-loop SM has been completed³

²A. M. Sirunyan *et al.* [CMS], Phys. Lett. B **809** (2020), 135710 2005.01173

³B. Biedermann, A. Denner and M. Pellen, arXiv:1611.02951

Why VBS is interesting?

1. VBS processes are directly related to the mechanism of electroweak symmetry breaking (**Goldstone Boson Equivalence Theorem**)⁴

⁴M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261** (1985) 379;
G. J. Gounaris, R. Kogerler and H. Neufeld, Phys. Rev. D **34** (1986) 3257.

Why VBS is interesting?

1. VBS processes are directly related to the mechanism of electroweak symmetry breaking (**Goldstone Boson Equivalence Theorem**)⁴
2. In the SM, even when next-to-leading order corrections are included, VBS processes feature particularly slow **slope with energy** in comparison to other electroweak processes

⁴M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261** (1985) 379;
G. J. Gounaris, R. Kogerler and H. Neufeld, Phys. Rev. D **34** (1986) 3257.

Why VBS is interesting?

1. VBS processes are directly related to the mechanism of electroweak symmetry breaking (**Goldstone Boson Equivalence Theorem**)⁴
2. In the SM, even when next-to-leading order corrections are included, VBS processes feature particularly slow **slope with energy** in comparison to other electroweak processes
3. Heavy particles' decoupling: **SM EFT results in a growth of cross-sections at energies straight after the electroweak scale.**

⁴M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261** (1985) 379;
G. J. Gounaris, R. Kogerler and H. Neufeld, Phys. Rev. D **34** (1986) 3257.

EFT Operators for $W^+ W^+ \rightarrow W^+ W^+$ amplitudes

(usually dimension-8 operators are employed)

Our aim was to study⁵ the effect of dimension-6 operators

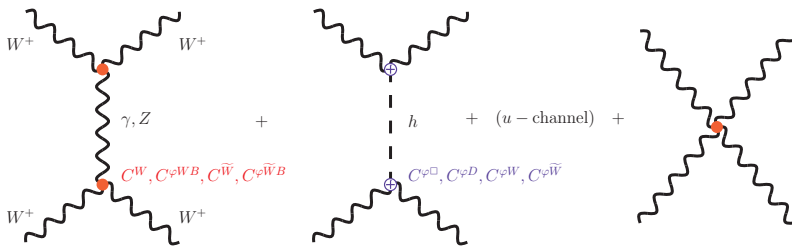
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} Q_i + \dots \equiv \mathcal{L}_{SM} + \sum_i f_i Q_i + \dots$$

X^3	$\varphi^4 D^2$	$X^2 \varphi^2$
$Q_W = \epsilon^{IJK} W_\mu^{\nu I} W_\nu^{\rho J} W_\rho^{\mu K}$	$Q_{\varphi\Box} = (\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$ $Q_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{\varphi W} = \varphi^\dagger \varphi W_{\mu\nu}^I W^{\mu\nu I}$
$Q_{\widetilde{W}} = \epsilon^{IJK} \widetilde{W}_\mu^{\nu I} W_\nu^{\rho J} W_\rho^{\mu K}$		$Q_{\varphi \widetilde{W}} = \varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{\mu\nu I}$

⁵A. Dedes, P. Kozów and M. Szleper, [arXiv:2011.07367](https://arxiv.org/abs/2011.07367), in Phys. Rev. D

Feynman diagrams for $W^+ W^+ \rightarrow W^+ W^+$

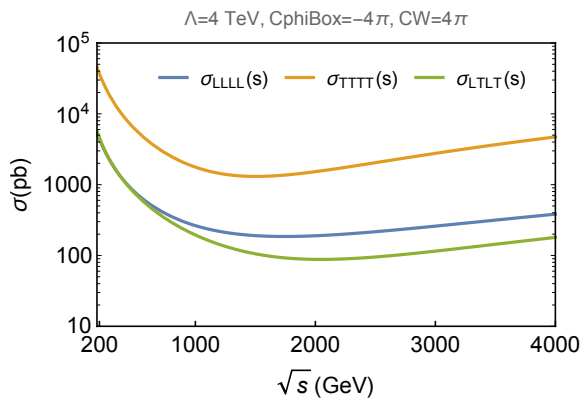
t, u -channel mediated by γ, Z, h plus a contact graph



Polarized Cross sections for $W^+W^+ \rightarrow W^+W^+$

$$\sigma_{TTTT}(s) \approx \frac{\bar{g}^4}{s} \left[\frac{A_T}{1-c^2} + B_T \cdot 0 + \Gamma_T \bar{g}^2 \left(\frac{|C^W|}{\bar{g}^2} \right)^2 \left(\frac{s}{\Lambda^2} \right)^2 + \dots \right],$$

$$\sigma_{LLLL}(s) \approx \frac{\bar{g}^4}{s} \left[\frac{A_L}{1-c^2} + B_L \left(\frac{C^{\varphi\Box}}{\bar{g}^2} \right) \left(\frac{s}{\Lambda^2} \right) + \Gamma_L \left(\frac{C^{\varphi\Box}}{\bar{g}^2} \right)^2 \left(\frac{s}{\Lambda^2} \right)^2 + \dots \right],$$



Consistency bounds

Tree-Unitarity of the S-matrix:⁶

Partial wave expansion:

$$\mathcal{M}_{\lambda_a \lambda_b; \lambda_1 \lambda_2} = 16\pi \sum_{J=0}^{\infty} (2J+1) \mathcal{T}_{\lambda_a \lambda_b; \lambda_1 \lambda_2}^{(J)}(s) D_{\lambda_1 - \lambda_2, \lambda_a - \lambda_b}^{(J)*}(\Omega_{\mathbf{p}(ab)})$$

For $W^+ W^+ \rightarrow W^+ W^+$ it must be:

$$\left| \mathcal{T}_{\lambda_a \lambda_b; \lambda_1 \lambda_2}^{(J)}(s) \right| \leq 1 .$$

This sets (sometimes severe) bounds on $\frac{c}{\Lambda^2} s$

⁶J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. D **10**, 1145 (1974);
B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. D **16**, 1519 (1977);
C. E. Vayonakis, Lett. Nuovo Cim. **17**, 383 (1976).

Unitarization procedure and checks

Q: what to do above perturbative unitarity violating scale ($\sqrt{s^U}$)?

In order for the amplitude to be at the most constant we employ two different unitarization scenarios and compare them.

Total BSM signal (or "Kink") method:

$$A_i(s) \rightarrow A_i(s) \begin{cases} 1, & M_{WW}^2 \leq s^U \\ \left(\frac{s^U}{M_{WW}^2}\right)^{-\xi_i}, & M_{WW}^2 > s^U \end{cases}$$

EFT-controlled method: [J. Kalinowski et.al, 1802.02366](#)

$$A_i(s) \rightarrow \begin{cases} A_i^{\text{EFT}}, & M_{WW}^2 \leq s^U \\ A_i^{\text{SM}}, & M_{WW}^2 > s^U \end{cases}$$

The conclusions based on EFT are reliable only if bulk of the BSM signal is in the EFT controlled region \rightarrow **within 2σ agree in the plots below**

The realistic study: $pp \rightarrow jjW^+W^+$ at the LHC

	f_W	$f_{\varphi\Box}$	$f_{\varphi D}$	$f_{\varphi W}$
“individual”	[-0.15,+0.36]	[-0.44,+0.52]	[-0.025,+0.0015]	[-0.014,+0.0068]
“global”	[-1.3,+1.1]	[-3.4,+2.4]	[-2.7,+1.2]	[-0.14,+1.6]

Experimental constraints on the subset of operators modifying the process $W^+W^+ \rightarrow W^+W^+$: based on the individual-operator-at-a-time or global marginalized fit analyses; from⁷ and⁸

⁷S. Dawson, S. Homiller and S. D. Lane, Phys. Rev. D **102** (2020) no.5, 055012 2007.01296 .

⁸J. Ellis, C. W. Murphy, V. Sanz and T. You, JHEP **06** (2018), 146 1803.03252

The realistic study: $pp \rightarrow jjW^+W^+$ at the LHC

We studied many kinematic observables

$$m^{jjl}, m^l, m^{jj}, p_T^{j1}, p_T^{j2}, p_T^{l1}, p_T^{l2}, \rightarrow \mathbf{C}_W$$

$$\eta^{j1}, \eta^{j2}, \eta^{l1}, \eta^{l2}, d\eta^j, d\phi^j, d\phi^l,$$

$$\mathbf{R}_{p_T} \equiv p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2}), \rightarrow \mathbf{C}_{\varphi\Box}, \mathbf{C}_{\varphi D}$$

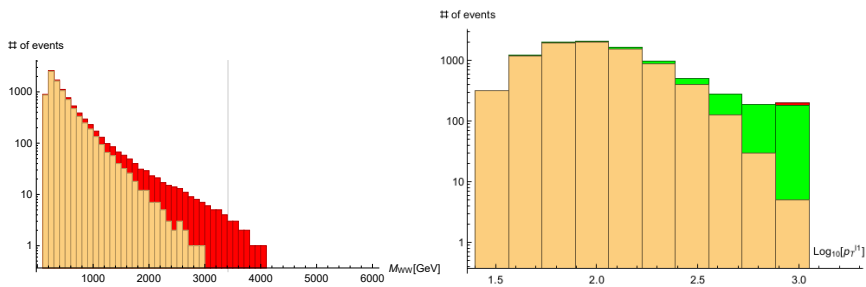
$$\mathbf{M}_{o1} \equiv \sqrt{(|\tilde{p}_T^{l1}| + |\tilde{p}_T^{l2}| + |\tilde{p}_T^{\text{miss}}|)^2 - (\tilde{p}_T^{l1} + \tilde{p}_T^{l2} + \tilde{p}_T^{\text{miss}})^2}, \rightarrow \mathbf{C}_{\varphi W}$$

$$M_{1T}^2 = \dots$$

Use SmeftFR⁷ \rightarrow MadGraph \rightarrow MadAnalysis, FastJet, Pythia

⁷ <http://www.fuw.edu.pl/smeft>

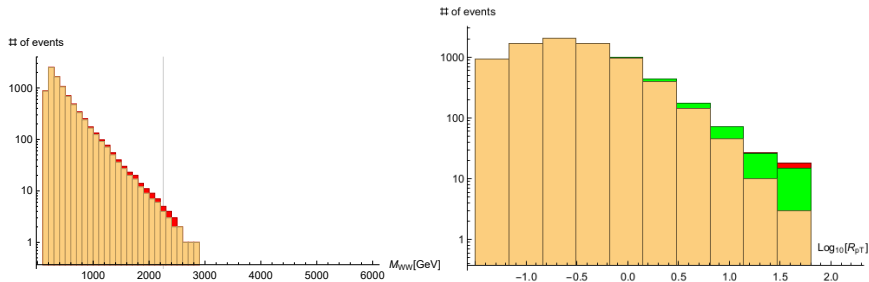
Effects on Transverse W_T (from Q_W operator)



Distributions in WW pair invariant mass M_{WW} (left) and the most sensitive observable (right, here p_T^4), for $f_W = +0.36 \text{ TeV}^{-2}$ compared to the SM case. Normalized to HL-LHC.

Large deviations from the SM at HL-LHC

Effects on Longitudinal W_L (from $Q_{\varphi\Box}$ operator)

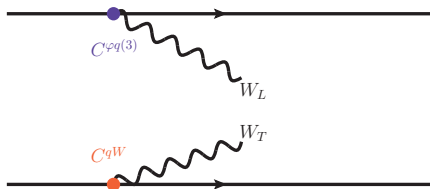


For $f_{\varphi\Box} = -3.4 \text{ TeV}^{-2}$

Large deviations from the SM at HL-LHC (but not as in Q_W)

Background Operators

Although LHC cuts on kinematic observables are focused on VBS, there are still effects from “background” operators e.g.



Effects from

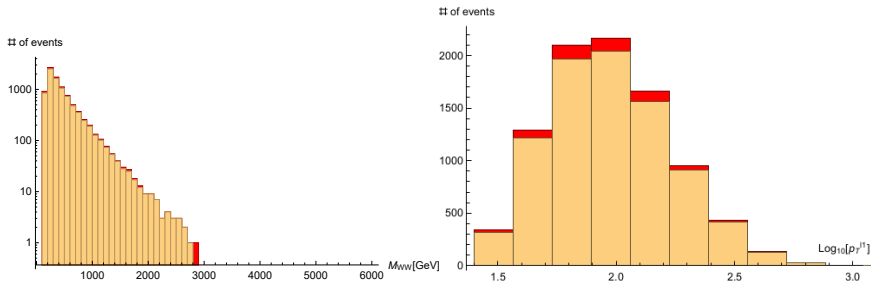
$$Q_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q} \tau^I \gamma^\mu q)$$

are significant, more the 5σ w.r.t. the SM at HL-LHC.

How do these affect $pp \rightarrow jj\ell\ell'\nu\nu'$?

Background Operators

How do these affect $pp \rightarrow jj\ell\ell'\nu\nu'$? In an interesting way!



$Q_{\varphi q}^{(3)}$: Equal distributions in $p_T^{\ell 1}$ bins !

Conclusions

- We have reasons to believe that the SM is an Effective Field Theory (**SM EFT**); a low energy part of unknown theories manifested at high energies. New phenomena may be accounted for within SM EFT.

Conclusions

- We have reasons to believe that the SM is an Effective Field Theory (**SM EFT**); a low energy part of unknown theories manifested at high energies. New phenomena may be accounted for within SM EFT.
- **A message to take home:** within current experimental bounds, $d = 6$ SM EFT effects in VBS can be large at (HL-)LHC especially for transversely polarized W s.

Conclusions

- We have reasons to believe that the SM is an Effective Field Theory (**SM EFT**); a low energy part of unknown theories manifested at high energies. New phenomena may be accounted for within SM EFT.
- **A message to take home:** within current experimental bounds, $d = 6$ SM EFT effects in VBS can be large at (HL-)LHC especially for transversely polarized W s.
- The EFT approach to BSM interactions is very useful and robust. Ideally, it will account for anomalies in LHC data that point across another “stair landing” towards our trip to a more fundamental theory.

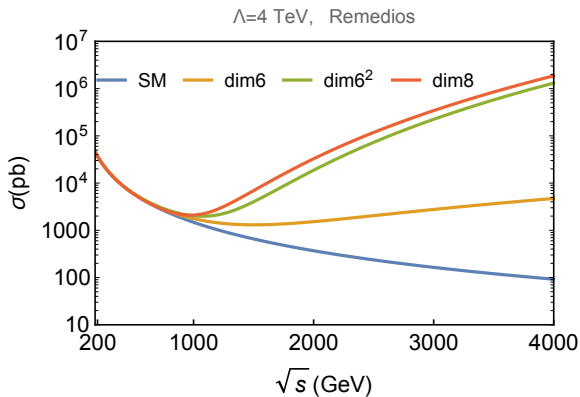
Conclusions

- We have reasons to believe that the SM is an Effective Field Theory (**SM EFT**); a low energy part of unknown theories manifested at high energies. New phenomena may be accounted for within SM EFT.
- **A message to take home:** within current experimental bounds, $d = 6$ SM EFT effects in VBS can be large at (HL-)LHC especially for transversely polarized W s.
- The EFT approach to BSM interactions is very useful and robust. Ideally, it will account for anomalies in LHC data that point across another “stair landing” towards our trip to a more fundamental theory.

Back-up slides

d=6 vs. d=8 operators's effect

Important in magnitude e.g. $C_W = g_* = 4\pi$ and $C^{(8)} = g_*^2$ when $\frac{s}{\Lambda^2} \gg \frac{g}{g_*}$



In Remedios⁸ the cross-section **cannot be smaller** than the dim6-curve (orange curve) \rightarrow **Conservative analysis**

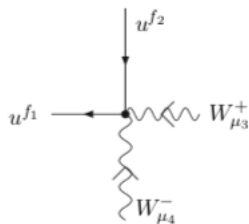
⁸D. Liu, A. Pomarol, R. Rattazzi and F. Riva, [arXiv:1603.03064].

SM EFT Feynman rules

In order to perform amplitude calculations in SM EFT we need the basic vertices in general quantization gauges. Our group performed this analysis.⁹

There are about 150 vertices in unitary gauge

For example, $u + u \rightarrow W^+ + W^-$



$$-\sqrt{2}\bar{g}v (\sigma^{\mu_3\mu_4} P_L C_{f_2 f_1}^{uW^*} + C_{f_1 f_2}^{uW} \sigma^{\mu_3\mu_4} P_R)$$

⁹A. D., W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, JHEP **1706**, 143 (2017), arXiv:1704.03888

The code SmeftFR

Plethora of vertices: we provide a code,¹⁰ called SmeftFR, containing the full set of Feynman rules in \LaTeX , in a Universal FeynRules Output (UFO) and in FeynArts.

It can feed various event generators, such as MadGraph, which perform amplitude calculations for colliders.

One may then perform serious analysis for the effect of operators on different LHC observables.

SmeftFR download web-page:

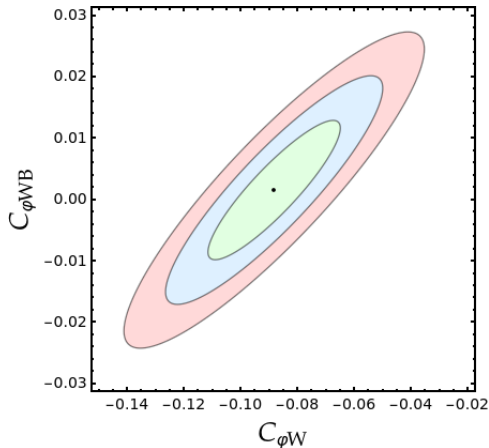
<http://www.fuw.edu.pl/smeft>

The program runs on *Mathematica* with FeynRules.

¹⁰A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, Comput.Phys.Commun. 247 (2020) 106931, 1904.03204

Three observables' fit in SM EFT

Three-observables' fit Fitting three Wilson-coefficients¹¹ for $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$ and S -parameter, from the LHC dataset ($\Lambda = 1$ TeV)



¹¹K. Mantzaropoulos, L. Trifyllis, unpublished

Positivity Bounds

Positivity Bounds¹² for elastic cross-sections:

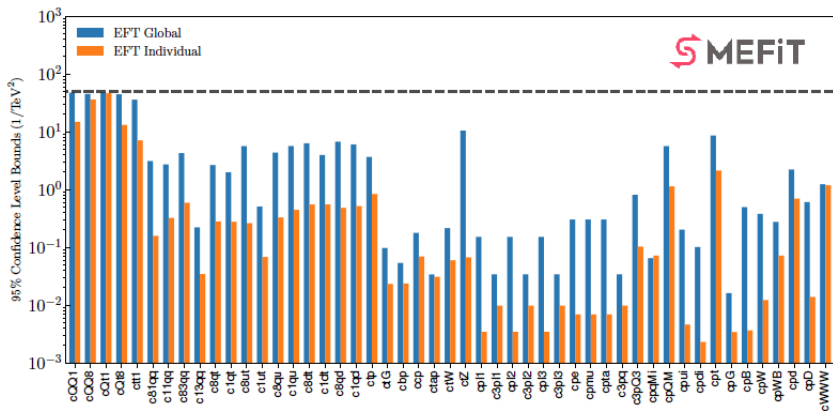
$$\mathcal{A}^{ij} = \frac{d^2}{ds^2} \mathcal{M}^{(ij \rightarrow ij)}(s, t = 0) \geq 0$$

This leads to (sometimes severe) constraints on the **d=8 coefficients**.

¹²K. Yamashita, C. Zhang and S. Y. Zhou, 2009.04490

Current state of observables' fit

LHC observables from Higgs, diboson and top-quark production and decays constrain 49 Wilson coefficients¹³



¹³ J. J. Ethier, F. Maltoni, et al, arXiv:2105.00006