An EFT analysis of Vector Boson Scattering at the LHC

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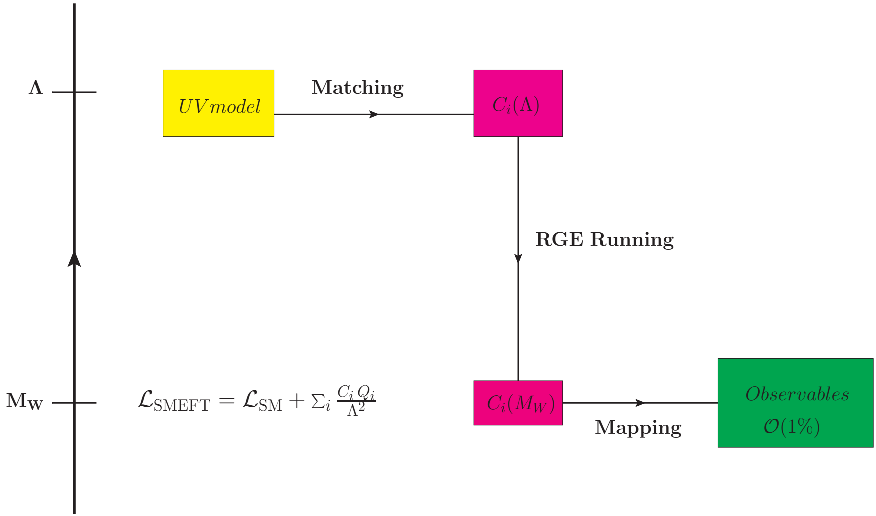
Outline

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

The EFT picture[1]



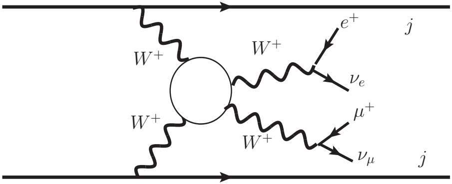
[1] B. Henning, X. Lu and H. Murayama, arXiv:1412.1837

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

My focus will be on like-sign-Ws

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

Example diagram:



- Has been confirmed[2] at LHC far above 5σ
- Only recently the full 1-loop SM has been completed[3]

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

[4] M. 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.

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3. Heavy particles' decoupling: **SM EFT results in a growth of cross-sections at energies straight after the electroweak scale.**

[4] M. 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 $W^+W^+ \to W^+W^+$ amplitudes

(usually dimension-8 operators are employed)

Our aim was to study[5] the effect of dimension-6 operators

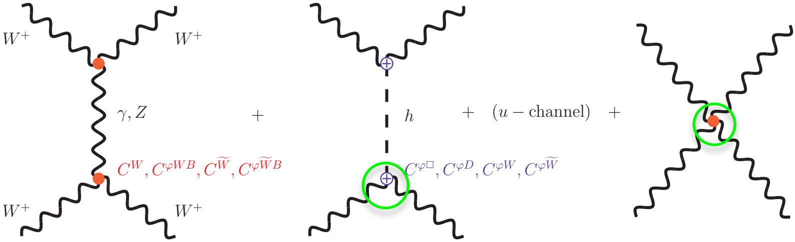
$$\mathcal{L} \;=\; \mathcal{L}_{SM} \;+\; \sum_i \frac{C^i}{\Lambda^2}\, Q_i \;+\; \ldots \;\equiv\; \mathcal{L}_{SM} + \sum_i f_i\, Q_i \;+\; \ldots$$

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

[5] A. Dedes, P. Kozów and M. Szleper, arXiv:2011.07367, in Phys. Rev. D

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

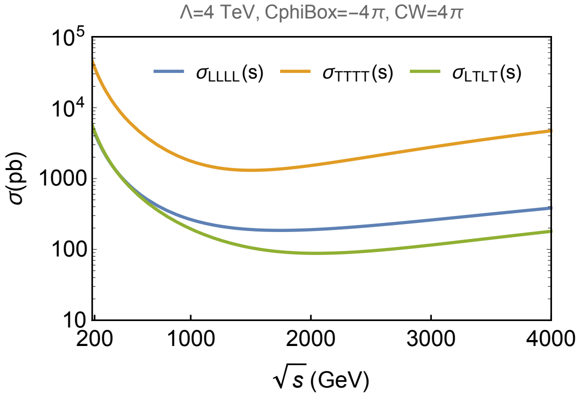
t, u-channel mediated by γ, Z, h plus a contact graph



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

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

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



Consistency bounds

Tree-Unitarity of the S-matrix:[6]

Partial wave expansion:

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

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

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

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

[6] J. 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:

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

EFT-controlled method: J. Kalinowski et.al, 1802.02366

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

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

The realistic study: $pp \to jjW^+W^+$ 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 $W^+W^+ \to W^+W^+$: based on the individual-operator-at-a-time or global marginalized fit analyses; from[7] and[8]

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

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

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

We studied many kinematic observables

$$m^{jjll}, m^{ll}, m^{jj}, p_T^{j1}, p_T^{j2}, \mathbf{p_T^{l1}}, p_T^{l2}, \longrightarrow \mathbf{C_W}$$

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

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

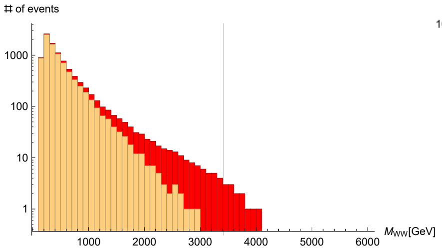
$$\mathbf{M_{o1}} \equiv \sqrt{(|\tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{l1}}| + |\tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{l2}}| + |\tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{miss}}|)^2 - (\tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{l1}} + \tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{l2}} + \tilde{\mathbf{p}}_\mathbf{T}^{\mathbf{miss}})^2}, \longrightarrow \mathbf{C}_{\varphi \mathbf{W}}$$

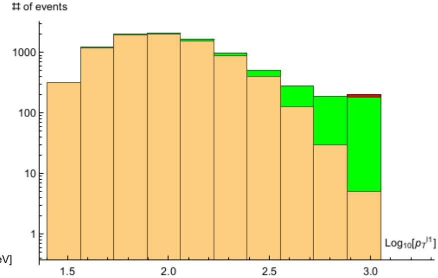
$$M_{1T}^2 = \ldots$$

Use `SmeftFR`[7] $\to$ `MadGraph` $\to$ `MadAnalysis, FastJet, Pythia`

[7] http://www.fuw.edu.pl/smeft

Effects on Transverse W_T (from Q_W operator)

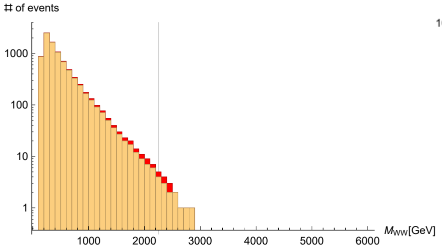


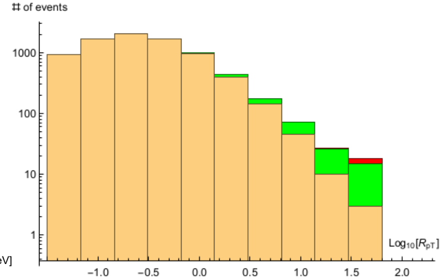


Distributions in WW pair invariant mass M_{WW} (left) and the most sensitive observable (right, here p_T^{l1}) , for $f_W = +0.36$ TeV^{-2} compared to the SM case. Normalized to HL-LHC.

Large deviations from the SM at HL-LHC

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



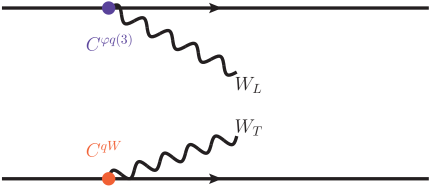


For $f_{\varphi\Box} = -3.4\ \mathrm{TeV}^{-2}$

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

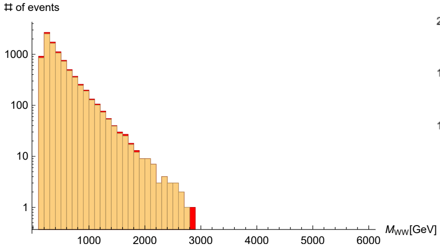
$$Q_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\tau^I \gamma^\mu q)$$

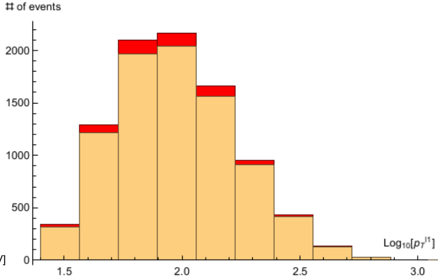
are significant, more the 5σ w.r.t. the SM at HL-LHC.

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

Background Operators

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





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

Conclusions

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- 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.

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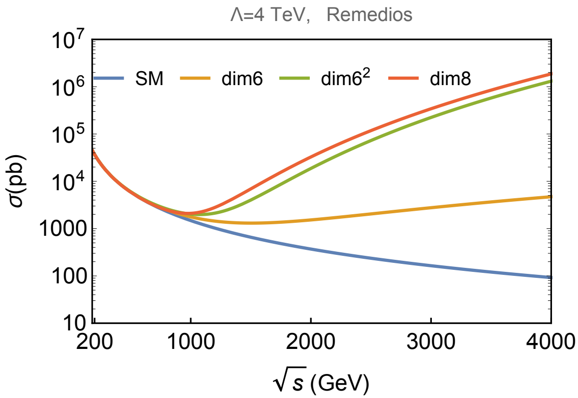
Back-up slides

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 Remedios[8] the cross-section **cannot be smaller** than the dim6-curve (orange curve) $\longrightarrow$ **Conservative analysis**

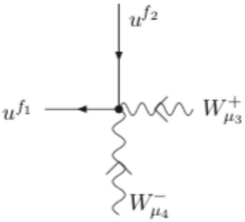
[8] D. Liu, A. Pomarol, R. Rattazzi and F. Riva, [arXiv:1603.03064].

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, $u + u \to W^+ + W^-$



$$-\sqrt{2}\bar{g}v\left(\sigma^{\mu_3\mu_4}P_L C^{uW*}_{f_2f_1} + C^{uW}_{f_1f_2}\sigma^{\mu_3\mu_4}P_R\right)$$

[9] A. 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`.

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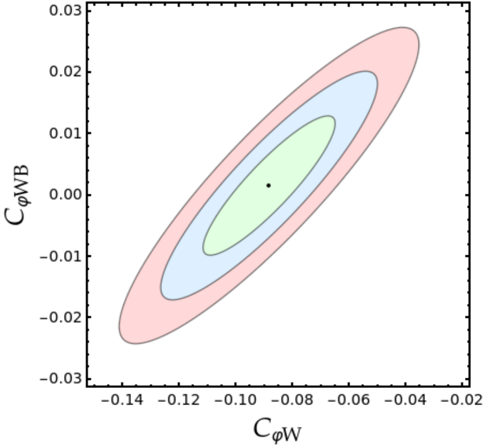
[10] A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, Comput.Phys.Commun. 247 (2020) 106931, 1904.03204

Three observables' fit in SM EFT

Three-observables' fit Fitting three Wilson-coefficients[11] for $h \to \gamma\gamma$ and $h \to Z\gamma$ and S-parameter, from the LHC dataset ($\Lambda = 1$ TeV)



[11]K. Mantzaropoulos, L. Trifyllis, unpuplished

Positivity Bounds

Positivity Bounds[12] for elastic cross-sections:

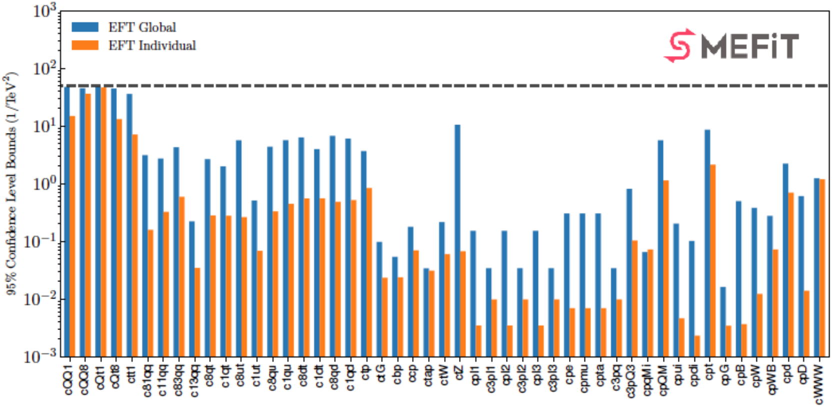
$$\mathcal{A}^{ij} = \frac{d^2}{ds^2}\mathcal{M}^{(ij\to ij)}(s, t=0) \geq 0$$

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

[12] K. 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 coefficients[13]



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