Same-sign WW Scattering in the HEFT: Discoverability vs. EFT Validity

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- [1802.02366] J. Kalinowski, PK, S. Pokorski, J. Rosiek, M. Szleper and S. Tkaczyk
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- Our assumption: excess at $\geq 5\sigma$ in $W^+W^+ \to W^+W^+$ scattering at HL-LHC & no new resonances
- We assume EFT approach is then appropriate: $v << \Lambda$; the BSM deviations parametrized by a non-renormalizable $\mathcal{L}_{eff}$; the E/Λ suppression
- The goal: learn about the couplings and Λ using the EFT approach to WW scattering
- $\Rightarrow$ we particularly focus on the EFT description validity in the context of WW scattering at LHC

Two different EFTs: for the SM physical degrees of freedom have been constructed:

1. In the so-called SM Effective Field Theory (SMEFT) the $SU(2)_L \times SU(2)_R$ symmetry in the Higgs sector is realised linearly, with the Higgs field a $SU(2)_L \times SU(2)_R$ bi-doublet

2. In the so-called Higgs Effective Field Theory (HEFT) the $SU(2)_L \times SU(2)_R$ symmetry is realized non-linearly, on the three Goldstone bosons eaten up by the gauge fields;
   the Higgs field h is a real scalar field, singlet under the $SU(2)_L \times SU(2)_R$

Two main issues concerning the EFT validity in WW scattering at LHC:

1. non-renormalizable operators $\Rightarrow$ $iM \sim s^n$; lead to tree-level unitarity bound violation

$$\sqrt{s} > \sqrt{s^U} \qquad (\sqrt{s} \equiv M_{WW})$$

- $s^U = s^U(f_i)$
- in addition, the EFT description stops making sense for

$$\sqrt{s} > \Lambda$$

- Λ is unspecified even if we specify f_i of our EFT "model"
- since we assume that EFT is valid for $\sqrt{s} < \Lambda$, the following EFT region of validity emerges:

$$\sqrt{s} < \Lambda < \sqrt{s^U}$$

- Hence for each EFT "model" with specified f_i, one can consider different assumptions on Λ (according to the inequality);
- after Λ is fixed too, the EFT formulation should be valid for scattering energies $\sqrt{s} < \Lambda$

- Imagine we have the HL-LHC data and there is $\geq 5\sigma$ deviation from the SM
- and we want to fit simulated kinematic distributions to the data
- WW scattering is not directly accessible experimentally but one can use the reaction:however, in the full reaction at LHC

$$pp \rightarrow 2jets + WW \rightarrow 2jets + 2l + 2\nu_l$$

- since neutrinos in the final state, one has no access to M_{WW}
- one has to rely on kinematic variables that are observable
- in principle the variables have no correlation with M_{WW} and our fit distribution carries events that have $M_{WW} > \sqrt{s^U}$,
- hence we use "prediction" of the EFT Lagrangian that involves the region above the EFT validity

- To solve the problem, one could introduce the EFT signal estimate as follows

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

- $\Rightarrow$ It defines signal coming uniquely from the EFT in its range of validity

2 the second problem:

- the EFT fit can be considered sensible if and only if the tail in M_{WW} of the fitted distribution does not dominate the signal effect
- only then one can sensibly extract information about the BSM coupling and Λ
- with a single estimate (above) we cannot answer this question
- obviously the tail cannot be estimated using $\mathcal{L}_{eff}$

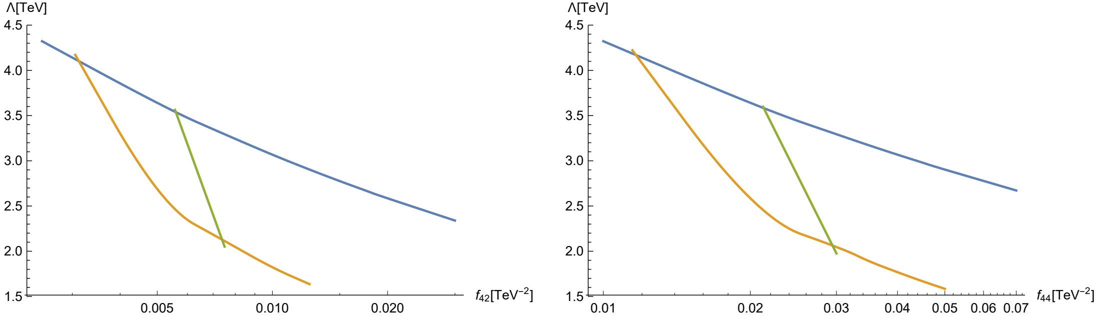
- to address this problem we introduce a physically plausible tail regularization of the EFT amplitude in which the amplitude above Λ is constant ($\equiv \sigma \sim 1/s$):

$$\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM_{WW}}|_{model} dM_{WW} + \int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM_{WW}}|_{A=const} dM_{WW}$$

- different only in the tail region; the regularized amplitude does not violate perturbative unitarity bounds
- Therefore, the EFT fit is sensible if and only if both signal estimates are statistically consistent, at say 2σ
- it defines our proposition for WW data analysis strategy at LHC

- Both the facts that:
  - the "bare" EFT amplitudes violate the unitarity bounds
  - the EFT fit makes sense only if the tail in M_{WW} does not dominate the signal
- together with demanding $\geq 5\sigma$ deviation form the SM
- $\Rightarrow$ characterize a certain region in the (f_i, Λ) space of an EFT "model"
- it will be referred to as the discovery region
- it is the region that can be meaningfully fitted to the data, once available and feature $\geq 5\sigma$ deviation from SM
- for a single-at-a-time non-ren. operator addition to the SM Lagrangian, the discovery region is 2D

The discovery regions for $\mathcal{T}_{42}, \mathcal{T}_{44}$:



blue: the bound $\Lambda \leq \sqrt{s^U}$

yellow: 5σ contour

green: 2σ stat. consistency contour

Summary

- We proposed strategy for data analysis at LHC based on the EFT approach to WW scattering
- we focused on the EFT validity, which is limited by:
  - the fact that "bare" EFT amplitudes violate perturbative unitarity bounds above $M_{WW} > \sqrt{s^U}$
  - the tail $M_{WW} > \sqrt{s^U}$ cannot dominate the effect in the EFT fit
- we preliminarly examined the usefulness of the EFT approach by finding discovery regions for several SMEFT and HEFT EFT"models" defined as SM + single-at-a-time non-ren. operator
- we found most of the discovery regions non-empty
- $\Rightarrow$ same-sign WW channel is promising from the point of view of disentangling between the linear vs. non-linear EW symmetry realization anzatz

BACKUP

- both effective Lagrangians are renomalizable order by order in their expansions ($1/\Lambda$ and p^n)
- however, it has been argued that the so-called primary dimension d_p of operators should be counted in order to parametrize the strengths of signals measured by cross sections
- for SMEFT operators $d_p = D$;
- for HEFT it counts the canonical dimension D of the leading terms in the expansion of a given chiral operator
- Hence d_p counting links SMEFT and HEFT phenomenology: two operators of the same d_p are naively expected to contribute with similar strength to cross section

- we investigated EFT "models" that consisted in SM + a single at a time $d_p = 8$ operator
- we focused on $d_p = 8$ operators since:
    - $d_p = 6$ operators that affect WW scattering, modify tripple couplings;
    - deviations in the latter can be measured independently (in)
- we focused on $d_p = 8$ operators that do not affect tripple couplings (so-called gQGC operators)

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

- interestingly, there are 2 more operators in HEFT than in SMEFT at $d_p = 8$
- correspondingly there are 2 more distinct Lorentz structures for the WWWW vertex in HEFT
- moreover, the remaining HEFT operators have trivial correspondence to the SMEFT ones, at least concerning WW scattering
- Interestingly, the operators have somehow largest discovery regions among all the $d_p = 8$ operators
- Interestingly, the operators have somewhat largest discovery regions among all the $d_p = 8$ operators
- Therefore, our results suggests that same-sign WW scattering can be a sensitive channel in the context of disantangling between the linear vs. non-linear hypothesis of EWSB anzatz