Same-sign WW scattering as a test of Beyond the SM (BSM) physics: Effective Field Theory (EFT) approach, HL-, HE-LHC

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Plan of the talk:

1. brief characterization of the EFT approach
2. brief description of discovery regions in the EFT approach to same-sign WW scattering
3. discussion of two EFT: SMEFT and HEFT
4. 1905.03354; PK, L. Merlo, S. Pokorski, M. Szleper
   (the HEFT context, HL-LHC)
5. 1906.10769; G. Chaudhary, J. Kalinowski, M. Kaur, PK, K. Sandeep, M. Szleper, S. Tkaczyk
   (27 TeV study)

$$pp \to 2j + W^+W^+ \to 2j + 2(l\,\nu_l), \qquad l = e^+, \mu^+$$

with particular emphasis on EFT validity

Characterization of the EFT approach:

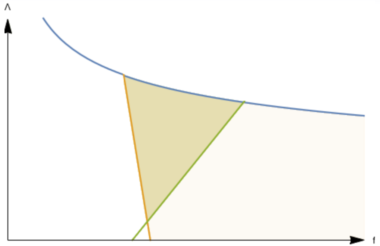
- EFT: existence of a new heavy particle manifests itself at energies $E << \Lambda$ as deviations suppressed as $(E/\Lambda)^n$
- these effects are parametrizable by non-renormalizable operators added to $\mathcal{L}_{SM}$
- each concrete model, after decoupling of heavy fields:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \Sigma_i f_i \cdot \mathcal{O}_i, \qquad f_i = \frac{g_*}{\Lambda}$$

- the strength of EFT: one can investigate the experimental reach for NP discovery without specifying concrete models
- choice of $\mathcal{O}_i, f_i$ defines an "EFT model" to be tested for its discovery potential

the goal: to examine discovery reach of the HL, HE-LHC in $W^\pm W^\pm$ scattering, using EFT by studying discovery regions for a class of "EFT models",

The problem of EFT validity (1802.02366, see also talk by M. Szleper at VBScan, Thessaloniki, 2018)



- the discovery regions should be reported in the (f_i, Λ) space
- Λ bounded from above from unitarity; the bound is a function of f_i (blue curve)
- for fixed f_i different assumptions on Λ can be considered
- for BSM signal estimate, the EFT amplitudes are regularized $M_{WW} > \Lambda$
- orange contour: lower bound on f_i from the condition $> 5\sigma$ BSM discrepancy
- green contour: contribution to the discrepancy from $M_{WW} > \Lambda$ in the regularized amplitudes must be negligible
- since $f = f(g_*/\Lambda)$ one obtains the region in (g_*, Λ) that can be discovered via EFT in the future LHC data

Two ways of constructing $\mathcal{L}_{eff}$, depending on how the scalar sector SM global symmetry breaking

$$SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V, \qquad g_V : g_L = g_R \tag{1}$$

is realized:

1. the linear realization on the Φ Higgs doublet; parametrization of Φ in the broken phase:

$$\exp\{i\pi^a T^a/v\} \begin{pmatrix} 0 \\ v+h \end{pmatrix}, \qquad T^a |0\rangle \neq 0 \tag{2}$$

   $\rightarrow$ the physical Higgs boson h is a component of the doublet
   Standard Model Effective Field Theory (SMEFT)
   the expansion is in $1/\Lambda$
   an EFT realization for the unbroken phase

2. non-linear realization of (1) on the 3 Goldstone Bosons (GB) ($\equiv W_L^{\pm}, Z_L$) described by the matrix:

$$U = \exp\{i\pi^a T^a/v\}, \qquad U \to g_L \cdot U \cdot g_R \tag{3}$$

- expansion in $\#\partial U$
- the physical Higgs h is a singlet of the global group (1)
- construction for the broken phase
- Higgs Effective Field Theory (HEFT) the most general EFT assuming (1): includes SM, SMEFT, ...[1]
- particularly suitable as the effective description of Composite Higgs (CH) scenarios[2]
- interesting question: discovery potential depending on the EFT construction used

[1] see e.g. 1212.3305, 1406.6367, 1307.5017

[2] see e.g. 1409.1589, 1904.00026 and references therein

The results of 1905.03354:

- main goal: to determine discovery potential of HEFT approach to HL-LHC data by finding discovery reach in (f_i, Λ) of several "EFT models" defined as SM + single effective operator at a time
- operators choice: modify VVVV quartic vertex, but not triple gauge and Higgs-to-gauge; start at dimension (D)=8 in the SMEFT
- start at primary dimension (d_p)=8 in HEFT (d_p= leading D after U expanded)
- operators of the same d_p have similar pheno impact[3]

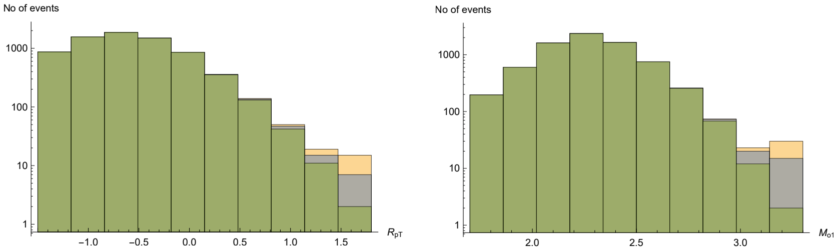
[3] see 1601.07551

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

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

We performed a generator level study:

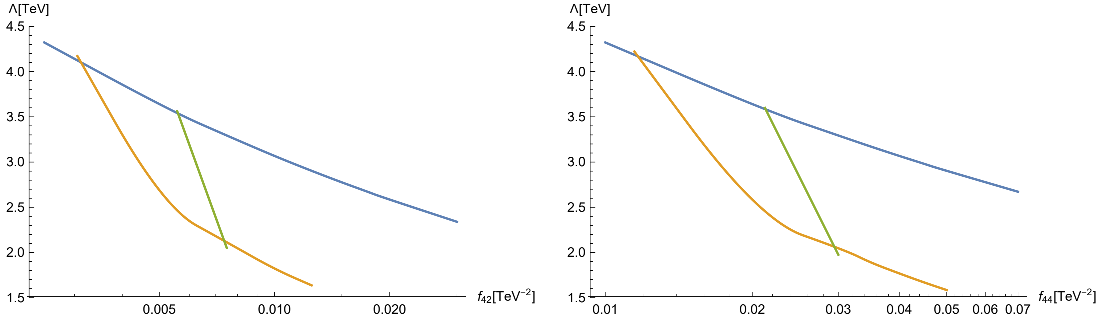
- the SM process $pp \to 2j + W^+W^+ \to 2j + 2(l\,\nu_l)$ is treated as the irreducible background
- "signal" is defined as the enhancement of over the SM prediction
- event selection: $M_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, $p_T^j > 30$ GeV, $|\eta_j| < 5$, p_T^ℓ >25 GeV and $|\eta_\ell| < 2.5$



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

- SMEFT analyzed in 1802.02366; except for $\mathcal{O}_{S1}$ ($LL \to LL$) all discovery regions non-empty
- most HEFT operators have their equivalents in SMEFT (Lorentz structure)
- correspondingly all discovery regions in HEFT found non-empty, except for $\mathcal{P}_{11}$ ($LL \to LL$)

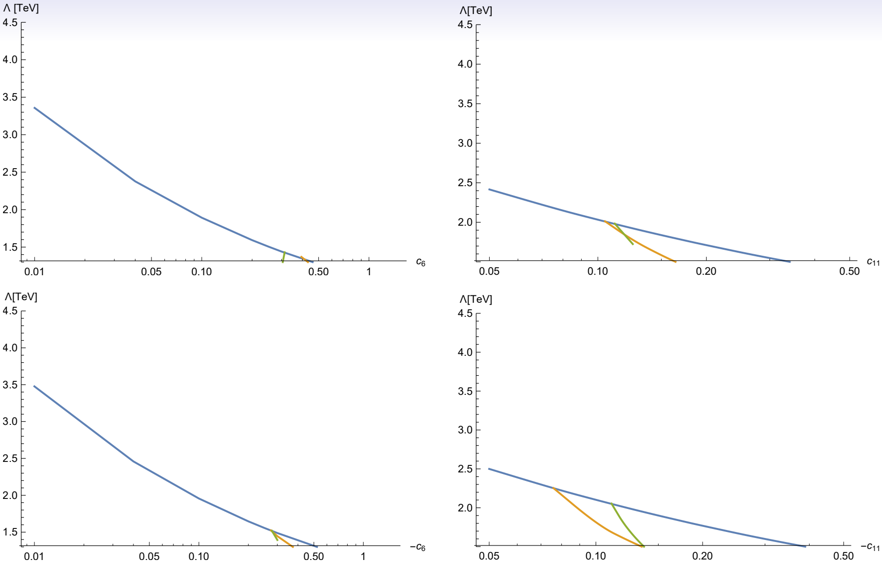
The discovery regions for $\mathcal{T}_{42}, \mathcal{T}_{44}$:



- dominating helicity amplitudes at $M_{WW} \lesssim \Lambda$ for $\mathcal{T}_{42}, \mathcal{T}_{44}$ are different than those found for the SMEFT operators (on-shell study)
- polarization studies in WW for SMEFT vs HEFT disentangling

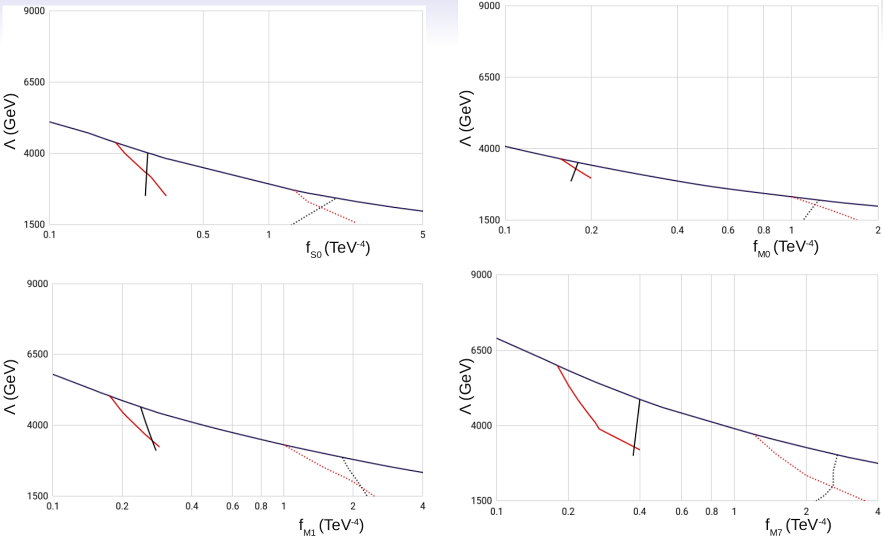
- The results for $\mathcal{P}_6$ and $\mathcal{P}_{11}$ also interesting: in the literature, the coefficients c_6 and c_{11} (typically labelled a_5 and a_4, respectively) may vary within a large range of values providing hypothetically visible signals at colliders

- we found, instead, that chances to find a signal of NP in the $W_L W_L \to W_L W_L$ scattering, described in a consistent HEFT framework $\mathcal{P}_6$ and $\mathcal{P}_{11}$, are present essentially only for negative c_{11}


Λ [TeV]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
0.01
0.05
0.10
0.50
1
c_6
Λ[TeV]
0.05
0.10
0.20
0.50
c_{11}
Λ[TeV]
$-c_6$
Λ[TeV]
$-c_{11}$

The results of 1906.10769:

- the goal: to examine what the gain in the EFT discovery potential can be, when increasing the pp energy
- We applied the analysis chain to the events generated at 27 TeV pp energy
- and compared the discovery reach with the HL-LHC case



shifts to lower values of f_i, but the overall discovery potential (total area) does not get larger at 27 TeV

only $i = S0, S1$ in perturbative regime, but close to strong interaction regime

Conclusions:

- $W^{\pm}W^{\pm}$ scattering with its purely leptonic W decays features severe restrictions in describing the data in terms of the EFT
- The reason: lack of experimental access to the M_{WW}
  $\rightarrow$ extra bound: bulk of the BSM signal must be in the EFT controlled region
- Moreover, we found that going to higher pp energies (e.g. 27 TeV) does not make the EFT discovery reach larger
- also, interpretation of the SMEFT discovery regions unclear for most operators and close to strongly interacting regime for $W_L W_L \rightarrow W_L W_L$

on the other hand: interesting HEFT discovery regions non-empty and our study indicates that projections onto (concrete) WW helicity combinations could be a sensitive test of (non)linearity of the Higgs (sector)...

back up

The problem of EFT validity (1802.02366, see also talk by M. Szleper at VBScan, Thessaloniki, 2018)

- perturbative partial wave unitarity condition:

$$|\mathrm{Re}\ \mathcal{T}_J| \leq 1/2 \tag{4}$$

- in the presence of non-renormalizable operators in EFT

$$A(VV \to VV) \sim E^n, \qquad A \equiv A(f_i)$$

- $\to$ EFT applicable at most for $E < E^U(f_i)$, where $|\mathrm{Re}\ \mathcal{T}_J(E^U)| = 1/2$
- the Λ sector 'protects' the unitarity of amplitudes:

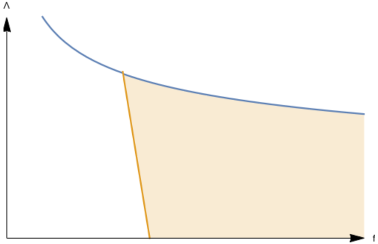
$$\Lambda < E^U$$

- hence the region of validity of an "EFT model"

$$E < \Lambda < E^U(f_i), \qquad E \equiv M_{WW} \tag{5}$$

- in particular, for a fixed f_i one should consider different assumptions on the cut-off Λ in the EFT analysis

- if access to M_{WW}, the EFT analysis more straightforward – apply cut-off at Λ in M_{WW} distribution both in data and simulated EFT prediction
- Discovery region of an "EFT model" : region in (Λ, f_i) for which deviation from the SM is $> 5\sigma$
- for a single operator



- since $f = f(g_*/\Lambda)$ one obtains the region in (g_*, Λ) that can be discovered via EFT in the future LHC data

- in the case of

$$pp \to 2j + W^+W^+ \to 2j + 2(l\,\nu_l), \qquad l = e^+, \mu^+ \tag{6}$$

$M_{WW} =?$

- one has necessarily rely on other (observable) distributions
- what are the consequences for the EFT analysis?

- generally, it may happen that for considered f_i the assumed scale Λ is within kinematic reach of WW collision energy

$$\Lambda < M_{max}$$

then one has to care about two aspects:

1. BSM signal as predicted by $\mathcal{L}_{EFT}$ must be necessarily regularized above Λ [4]

$$\underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM_{WW}}\bigg|_{EFT\ \ model} dM_{WW}}_{\text{EFT controlled region}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM_{WW}}\bigg|_{regularized} dM_{WW}}_{\text{the tail}} \quad (7)$$

2. any physics conclusions from the EFT analysis can be taken only if bulk of the signal is in the EFT controlled region $E < \Lambda$ and not in the tail $E > \Lambda$

$$\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM_{WW}}\bigg|_{EFT\ \ model} dM_{WW} + \int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM_{WW}}\bigg|_{SM} dM_{WW} \quad (8)$$

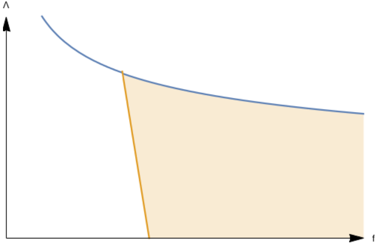
it defines signal coming uniquely from the EFT in its range of validity

EFT prediction sensible only if both (7) and (8) are statistically consistent at 2σ

[4] see 1907.06668 for study of impact on different popular regularizations

as a result one obtains smaller discovery regions

an extra contour (green) occurs which bounds the discovery regions ("from the right")



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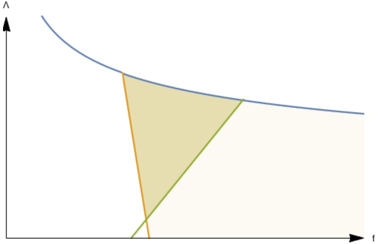

discovery regions $\equiv$ irregular "triangles"

Simple matching[5]:

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

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

$$f_i\mathcal{O}_i \equiv c_i \cdot 2^2\frac{g^2}{\Lambda^4}\mathcal{O}_i, \qquad i = M6, M7 \qquad \sim (D_\alpha\Phi)^2(W^i_{\mu\nu})^2$$

$|c_i| < 1$ in perturbative deeper completions, but instead e.g. for $c_i > 0$

27 *TeV*	$T0$	$T1$	$T2$	$M0$	$M1$	$M7$
c_{min}–c_{max}	130.–770.	120.–1300.	670.–2200.	23.–32.	45.–133.	33.–140.

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

[5]see 1601.07551