The SM EFT & new physics

LHC indirect searches for BSM

Alex Pomarol UAB & IFAE (Barcelona)
What’s the SM EFT?

Effective Field Theory
Similarly as in Classical mechanics

Expanding around the minimum:

\[ V(x) = \frac{k x^2}{2} + \ldots \]
Similarly as in Classical mechanics

Expanding around the minimum:

$$V(x) = k \frac{x^2}{2} + \ldots$$

universal behaviour:

$$F = -k x$$

Hooke’s law

(valid only for small oscillations)
Assuming only the SM states below some Λ:

\[
\begin{align*}
&\text{only SM states} \\
&\{ m_t,h,W \} \\
&\Lambda \sim 100 \text{ GeV}
\end{align*}
\]

New states (susy, compositeness,…)

We can then Taylor expand (SM fields and derivative over Λ):

\[
\mathcal{L}_{\text{eff}} = \frac{\Lambda^4}{g_*^2} \mathcal{L} \left( \frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{f_{L,R} f_{L,R}}}{\Lambda^{3/2}}, \frac{g_{F_{\mu\nu}}}{\Lambda^2} \right) \sim \mathcal{L}_4 + \cdots
\]

dimension-4 terms:

The SM \(\rightarrow\) predictive model (but not fundamental)

(e.g. universal gauge couplings)
Assuming only the SM states below some $\Lambda$: 

\[ \Lambda \]

\begin{align*}
\text{only SM states} & \quad \{ \text{New states (susy, compositeness, \ldots)} \} \\
& \quad \begin{aligned}
\text{m}_{t,h,W} & \approx 100 \text{ GeV} \\
\end{aligned}
\end{align*}

We can then Taylor expand (SM fields and derivative over $\Lambda$):

\[ \mathcal{L}_{\text{eff}} = \frac{\Lambda^4}{g_*^2} \mathcal{L} \left( \frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{fL,R} f_{L,R}}{\Lambda^{3/2}}, \frac{g_{F \mu \nu}}{\Lambda^2} \right) \approx \mathcal{L}_4 + \cdots \]

dimension-4 terms:

The SM \quad \rightarrow \text{predictive model (but not fundamental)}

Valid for $E \leq \Lambda$!

(e.g. universal gauge couplings)
Similarly as in Classical mechanics

Expanding around the minimum:

\[ V(x) = \frac{k x^2}{2} + \frac{c_1 x^3}{3} + \ldots \]

\[ F = -k x - c_1 x^2 \]

leading deviations from Hooke’s law
1 Introduction

Let us consider a sector beyond the SM (BSM) characterised by a new mass-scale $\Lambda$ much larger than the electroweak scale $m_{t,h,W}$. We will assume, among other requirements to be specified later, that this sector preserves lepton and baryon number. By integrating out this sector and performing an expansion of SM fields and their derivatives $D_\mu$ over $\Lambda$, we can obtain an effective Lagrangian made of local operators:

$$L_{\text{eff}} = \frac{\Lambda^4}{g_*^2} L \left( \frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{f,L,R} f_{L,R}}{\Lambda^{3/2}}, \frac{g_{F\mu\nu}}{\Lambda^2} \right) \sim L_4 + L_6 + \cdots$$

We can then Taylor expand (SM fields and derivative over $\Lambda$):

(assuming lepton & baryon number)

Assuming only the SM states below some $\Lambda$:

- **New states** (susy, compositeness, …)
- **only SM states**
- **m_{t,h,W} \sim 100 \text{ GeV}**

**We can then Taylor expand (SM fields and derivative over $\Lambda$):**

- **dimension-4 terms:** The SM
- **dimension-6 terms:** Leading deviations from the SM
Let us consider a sector beyond the SM (BSM) characterised by a new mass-scale $\Lambda$ much larger than the electroweak scale $m_W$. We will assume, among other requirements to be specified later, that this sector preserves lepton and baryon number. By integrating out this sector and performing an expansion of SM fields and their derivatives $D_\mu$ over $\Lambda$, we can obtain an effective Lagrangian made of local operators:

$$L = g_4 \delta g_{ZWW}$$

$$L = g_{ZuR}$$

$$L = g_{ZdR}$$

$$L = g_{ZuL}$$

$$L = g_{ZdL}$$

$$L = g_{ZeR}$$

$$L = g_{ZeL}$$

$$L = g_{ZvL}$$

where $L_4$ denotes the term in the expansion made of operators of dimension 4. By $g_4$ we denote an effective coupling of the BSM, while $g_{\Delta}$ and $g_{\Phi}$ are respectively the couplings of the Higgs-doublet $\Delta$ (of hypercharge $Y=1/2$) and SM fermion $\Phi$ to the BSM sector, and $g_f$ and $F_\mu$ are respectively the SM gauge couplings and field-strengths. The Lagrangian Eq. (1) is based on dimensional grounds where the dependence on the couplings is easily obtained when the Planck constant $\Lambda$ is put back in place. The dominant effects of the BSM sector are encoded in $L_6$, as $L_4$ leads only to an unphysical redefinition of the SM couplings. There are different bases used in the literature for the set of independent dimension-six operators appearing in $L_6$. Although physics is independent of the choice of basis, it is clear that some bases are better suited than others for extracting the relevant information for, for example, Higgs physics. A convenient basis can be that which capture in few operators the impact of different new-physics scenarios, at least for the most interesting cases. For example, in the basis of ref. [1], universal theories only generate 11 CP-conserving operators, but this number can be larger in other basis, as that of ref. [2], with the corresponding correlation in their coefficients. If only $ff \to ff$ processes are considered, only 4 operators can parametrize universal theories if we use the basis [1]. Another important consideration for the choice of basis is to avoid mixing operators whose coefficients are naturally expected to have different sizes (again, at least in main theories of interest). For example, it is convenient to keep separated operators that can be induced at tree-level from integrating weakly-coupled states from those that can only be generated at the one-loop level. This helps to determine what are the most relevant operators when dealing with a large class of the BSM such as supersymmetric, composite Higgs or little Higgs models among others. As shown in ref. [3] this criteria is also useful when considering one-loop operator mixing, since one finds that tree-level induced operators do not contribute to the RG flow of one-loop induced ones, independently, of course, of the origin of the operators. In this sense the basis of [3] is better suited than that of [1]. It is obvious that all the criteria given above are not at all in contradiction with being generic, that is also the propose of these analysis, as soon as we keep all operators, as we do in this analysis.

In our bases we broadly distinguish three classes of operators. The first two classes consist of operators that can in principle be generated at tree-level when integrating out heavy states

Small splittings $\sim v^2/\Lambda^2$ (visible if $\Lambda \sim \text{TeV}$)
Expansion seen at work already many times…

in the 30’: \( \mathcal{L}_{\text{EM}} + \mathcal{L}_{\text{Fermi}} + \cdots \)

\( \Upsilon \rightarrow \) p,e  
\( \) p,e  
\( \) p,e

\( n \rightarrow \) e  
\( p \rightarrow \) e  
\( v \rightarrow \) e

\( \propto \frac{1}{\Lambda^2} \)
Expansion seen at work already many times...

in the 30': \( \mathcal{L}_{EM} + \mathcal{L}_{Fermi} + \cdots \)
SM EFT:

$\mathcal{L}_4$ can fit in a t-shirt:

Dimension-4 operators

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4g^2} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4g^2} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4g_s^2} G^{\mu\nu} G_{\mu\nu} - \frac{1}{16\pi G_N} R$$

$$+ i\tilde{Q}_L^i \not{D} Q_L^i + i\tilde{u}_R^i \not{D} u_R^i + i\tilde{d}_R^i \not{D} d_R^i$$

$$+ i\tilde{e}_R^i \not{D} e_R^i + i\tilde{l}_L^i \not{D} l_L^i$$

$$+ Y_{u}^{ij} Q_L^i \tilde{H} u_R^j + Y_{d}^{ij} Q_L^i H d_R^j + Y_{e}^{ij} \tilde{l}_L^i H e_R^j$$

$$+ \frac{1}{2} m^2 \not{H}^2 - \lambda \not{H}^4$$

SM t-shirt
propose of these analysis, as soon as we keep all operators, as we do in this analysis.

mixing operators whose coe

only

in other basis, as that of ref. [\text{ref}]. with the corresponding correlation in their coe

suited than others for extracting the relevant information for, for example, Higgs physics.

Planck constant

e.g. coupling of the BSM, while the

sector and performing an expansion of SM fields and their derivatives

Introduction

L

as

4 operators can parametrize universal theories

processes are considered, only 4 operators can parametrize universal theories

Odd ones in Eqs. (2)

Table 1:

are respectively the couplings of the Higgs-

erent structure within a given class. There are, in addition, the 6 CP-odd

2

\begin{align*}
\mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\
\mathcal{O}_T &= \frac{1}{2}(H^\dagger D_\mu H)^2 \\
\mathcal{O}_6 &= \lambda |H|^6
\end{align*}

\begin{align*}
\mathcal{O}_W &= \frac{ig}{2} \left( H^\dagger \sigma^a D_\mu H \right) D^\nu W^a_{\mu\nu} \\
\mathcal{O}_B &= \frac{ig'}{2} \left( H^\dagger D_\mu H \right) \partial^\nu B_{\mu\nu} \\
\mathcal{O}_{2W} &= -\frac{1}{2}(D^\mu W_{\mu\nu}^a)^2 \\
\mathcal{O}_{2B} &= -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2 \\
\mathcal{O}_{2G} &= -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2
\end{align*}

\begin{align*}
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^A_{\mu\nu} G^A_{\mu\nu} \\
\mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \\
\mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
\mathcal{O}_{3W} &= \frac{1}{3!} g e_{abc} W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\rho\mu} \\
\mathcal{O}_{3G} &= \frac{1}{3!} g_s f_{ABC} G^A_{\mu\nu} G^B_{\nu\rho} G^C_{\rho\mu}
\end{align*}

Too many terms to understand the implications?
A more intuitive parametrization of leading BSM effects

Flavor & CP conserving

Which departures predict from the SM?
A more intuitive parametrization of leading BSM effects

Shifts from the SM couplings:

**Higgs couplings:**
- $hVV$, $hff$, $h^3$

**Z couplings:**
- $Zf_Lf_L$, $Zf_Rf_R$, $ZWW$

New type of couplings:

- $hγγ$, $hGG$, $hZγ$
- $Wd_{RuR}$

Dipole-type:
- $Wf_Lf_R$, $γWW$
- $WWW$, $GGG$

4-fermion contact-interactions (25 of them)

A more intuitive parametrization of leading BSM effects

Flavor & CP conserving

Shifts from the SM couplings:

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• $hVV$, $hff$, $h^3$

Z couplings:
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related! $\rightarrow$ $Wf_L f_L$

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Higgs couplings:
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New type of couplings:
- $h\gamma\gamma$, $hGG$, $hZ\gamma$
- $W_{dR}u_R$

From LEP $\rightarrow$ Z physics
From LHC $\rightarrow$ Higgs & top

almost all couplings measured $\sim$ few %

related! $W_{f_L}f_L'$

4-fermion contact-interactions
(25 of them)

A more intuitive parametrization of leading BSM effects

Flavor & CP conserving

Shifts from the SM couplings:

Higgs couplings:
- $hVV$, $hff$, $h^3$

Z couplings:

but (few) important couplings still to unravel

related! $Wf_L f_L'$

New type of couplings:

- $h\gamma\gamma$, $hGG$, $hZ\gamma$
- $Wd_{uR} u_R$

Dipole-type:

- $WWW$, $GGG$

4-fermion contact-interactions (25 of them)

A lot of effort to combine all data to place bounds on the coefficients of the new terms:

e.g.
A lot of effort to combine all data to place bounds on the coefficients of the new terms:

e.g.

To understand the impact on certain new physics, a small set of bounds on SM couplings is enough

(Not need of global fits)

Here I’ll present few examples of LHC best tests:

Higgs couplings + top couplings + High-energy probes
Higgs couplings

Still the main *destroyer* of BSM addressing the hierarchy problem

**Expected largest corrections to Higgs couplings:**

<table>
<thead>
<tr>
<th></th>
<th>hff</th>
<th>hVV</th>
<th>hγγ</th>
<th>hγZ</th>
<th>hGG</th>
<th>h³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MSSM</strong></td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td><strong>NMSSM</strong></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>PGB Composite</strong></td>
<td>√</td>
<td>√</td>
<td></td>
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<td>√</td>
</tr>
<tr>
<td><strong>SUSY Composite</strong></td>
<td>√</td>
<td>√</td>
<td>√</td>
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<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>SUSY partly-composite</strong></td>
<td>√</td>
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<td>√</td>
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<tr>
<td><strong>“Bosonic TC”</strong></td>
<td></td>
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<td></td>
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<td>√</td>
</tr>
<tr>
<td><strong>Higgs as a dilaton</strong></td>
<td>√</td>
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<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
In composite Higgs models the Higgs couplings to fermions generically deviate from their SM values. The contours are the scale of compositeness \( \kappa_F \) and fermion mass, \( \kappa_V \). The red part of the curves is for different curves corresponding to different values of the scale of compositeness.

No sign of Composite Higgs

scale of compositeness \( \approx 2-3 \) TeV

\[
\frac{g_{hff}}{g_{hff}^{SM}} \quad \frac{g_{hWW}}{g_{hWW}^{SM}}
\]
Figure 17. Limits from the global fit in the stop parameter plane, $(X_t m_{\tilde{t}}, m_{\tilde{t}})$. The two panels correspond to the low and high $\tan\beta$ choices, 1 and 20 respectively.

One sees in both panels of Fig. 17 that current LHC data constrain the stop mass scale to $\lesssim 300$ GeV, except for $|X_t| \ll 1$.5 [212], where partial cancellations reduce the sensitivity to the stop mass scale below 200 GeV. In these regions the SMEFT analysis gives only qualitative results. These blind directions could be eliminated with future measurements of the $H + \text{jets}$ differential distribution [213].

7.4 Survey of combinations of multiple operators

In general, new physics beyond the Standard Model could be expected to contribute to the SMEFT via exchanges of more than just a single massive particle, just as, e.g., $W$ and $Z$ exchanges both contribute to the Fermi 4-fermion EFT of the weak interactions, and various mesons including vectors $\pi$ and scalars $\sigma$ contribute to the low-energy pionic EFT.
Benchmark models MSSM:

- MSSM subgroup of LHC cross section working group:
  - 200 GeV
  - 300 GeV
  - 400 GeV
  - 1000 GeV
  - 2000 GeV

\[ A \]
\[ m \]
\[ \beta \]
\[ \tan \tau \]

- \[ 1 \rightarrow A/H \]
- \[ 13 \text{ TeV}, 139 \text{ fb} \]
- \[ \nu \tau \rightarrow +H \]
- \[ 13 \text{ TeV}, 36.1 \text{ fb} \]
- \[ t\bar{b} ightarrow +H \]
- \[ 13 \text{ TeV}, 36.1 \text{ fb} \]
- \[ \nu \nu 4l/ll \rightarrow ZZ \rightarrow H \]
- \[ 13 \text{ TeV}, 36.1 \text{ fb} \]
- \[ \nu
+l
\nu
+l
→ WW \rightarrow H \]
- \[ 13 \text{ TeV}, 36.1 \text{ fb} \]
- \[ 4b, \rightarrow hh \rightarrow H, \tau \tau /\gamma \gamma \]
- \[ 13 \text{ TeV}, 27.8 - 36.1 \text{ fb} \]
- \[ d\kappa, u\kappa, V\kappa h \] couplings
- \[ 13 \text{ TeV}, 36.1 - 79.8 \text{ fb} \]
- \[ \text{Phys. Lett. B 800 (2020) 135103} \]

Preliminary ATLAS hMSSM, 95% CL limits

\[ \sqrt{s} = 13 \text{ TeV}, 24.5 - 139 \text{ fb}^{-1} \]
\[ m_h = 125.09 \text{ GeV}, |y_h| < 2.5 \]

\[ M_{h,EFT}^{125} \] scenario

\[ \tan \beta \]
\[ m_A [\text{GeV}] \]

- \[ \text{Obs. 95\% CL} \]
- \[ \text{Exp. 95\% CL} \]

ATLAS Preliminary

- Ruled out
- No sign of extra Higgs (as in susy models)

Saskia Falke

EFT versus direct searches

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**htt, hbb & hTT** as a function of the parameters of the MSSM:

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \ 24.5 - 139 \text{ fb}^{-1} \]

\[ m_H = 125.09 \text{ GeV}, \ |y_H| < 2.5 \]

2HDM Type-II

Ruled out

Ruled out

\[ \cos(\beta - \alpha) = 0.001, \ \tan\beta = 25.4 \]
htt, hbb & hTT

as a function of the parameters of the MSSM:

Small regions left for the MSSM
Excluding the possibility of some flavor models:

- \( h \to \mu \tau \)

### Graphical Representation

- **Left Panel:**
  - Higgs to Lepton Flavor Violating
  - Common process in many BSM models
  - BR(H) < 0.16\%
  - BR(H) < 0.22\%
  - Expected ~same

- **Right Panel:**
  - Excluding the possibility of some flavor models
  - BR(h → μτ) > 1\%
Two modes for New Physics discovery: resonances & tails

Measuring couplings at high-energies where deviations can be larger

Possibility to do better than LEP even in Z physics

if you cannot get the resonance, try to get its tail
Two modes for New Physics discovery: resonances & tails

LHC main player

Measuring couplings at high-energies where deviations can be larger

Energy & accuracy needed to catch up different BSM!

if you cannot get the resonance, try to get its tail
Reasonable cross-sections
Clean if decay into lepton
BSM effects sensitive to EWSB

Large cross-sections
Clean for leptons
BSM effects not sensitive to EWSB
In the differential cross-sections \( q\bar{q} \rightarrow ll, l\bar{\nu} \):

- Can be sensitive to oblique-corrections or extra bosons:

  a) \( q\bar{q} \rightarrow q\bar{q} \) \( q^4/\Lambda^2 \) effects

  b) \( W', Z' \) effects can be seen in the differential cross-sections

\[
\frac{d\sigma}{dm_{ll}^2} \quad \text{at large inv. masses}
\]

\[
\frac{\delta M}{M_{\text{SM}}} \approx 1 + c \frac{\hat{s}}{\Lambda^2}
\]
bounds on oblique corrections

bounds on $Z'$

constraints of $O(10^{-4})$ on $q^4/\Lambda^2$ effects

$q\bar{q} \rightarrow V_LV_L(h)$

Shift of the SM WWZ-coupling

\[
\frac{\delta M_{LL}}{M_{LL}^{SM}} \simeq 1 - \frac{\hat{s}}{m_Z^2} \delta g_1^Z
\]

for $\hat{s} \gg m_Z^2$

New type of hZZ interaction: $hZ^{\mu\nu}Z_{\mu\nu}$
\[ q\bar{q} \rightarrow V_L V_L(h) \]

Shift of the SM WWZ-coupling

\[
\frac{\delta \mathcal{M}_{LL}}{\mathcal{M}_{LL}^{SM}} \simeq 1 - \frac{s}{m_Z^2} \delta g_1^Z
\]

for \( s \gg m_Z^2 \)

Shift of the SM WWZ-coupling

\[
\frac{\delta \mathcal{M}_{Zh}}{\mathcal{M}_{Zh}^{SM}} \simeq 1 - c_q \frac{s}{m_Z^2} \kappa_{ZZ}
\]

for \( s \gg m_Z^2 \)

TGC: EM dipole of a \( W \)

\((\delta \kappa_Y)\)

related

New type of \( hZZ \) interaction:

\[ hZ^{\mu\nu} Z_{\mu\nu} \]

prediction of the SM EFT!
The gray shaded area in figure 7 shows bounds from LEP2 [15]. These bounds depend also on the parameter $\delta$, which for simplicity we have taken to zero, a conservative choice in our comparison. Our analysis is instead insensitive to (small values of)$\delta$, because of the non-interference rules discussed before. This comparison allows us to conclude that, in the context of universal theories, LEP2 bounds will be order-of-magnitude improved by the HL-LHC, at least in the $gZ$ direction.

In section 2.2, we have further discussed explicit realizations of universal theories, which we can refer to as “general SILH theories” and include e.g. theories with extra gauge bosons or extra-dimensions, holographic versions of composite Higgs or little Higgs models. In these theories $\delta$ arises at the level, and therefore expected to be small. Similarly, for large $\delta$, $W$ and $Y$ are small, see for instance eq. (9). As a result, the only relevant parameters are $\hat{S}$ and $gZ$, that can be induced at tree-level. These parameters enter in the HEPs, eq. (7), and provide then a strong motivation for our analysis. The results are shown in the right panel of figure 7. Present limits on $\hat{S}$ come from LEP measurements on the $Z$-pole, and we do not expect that the LHC will improve them any further (such an improvement would require very accurate measurements of the $W/LW/Lh$ channels).

This result can be better appreciated in the specific context of composite Higgs models with $O(4)$ symmetry, where the two parameters are related according to eq. (9), $gZ = \hat{S}/2 \sqrt{W}$ (corresponding to $cB = cW$), as shown by a blue solid line in the plot. In this context it becomes remarkable that the size of the constraint on $\hat{S}$ from LEP (which is considered one of the most precise measurements of the EW sector) is comparable with that on $gZ$, obtained 26.
The allowed region after LEP bounds (taking the TGCs for the allowed region with 300 fb$^{-1}$) have been obtained from Ref. \[. Other parameters to zero.

TABLE IV: Comparison of the bounds obtained in this work with 300 (3000) fb$^{-1}$

<table>
<thead>
<tr>
<th>Shift of the SM WWZ-coupling</th>
<th>LEP Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_1 Z$</td>
<td>$\pm 0.04$ $\pm 0.02$ $0.00$ $0.02$ $0.04$</td>
</tr>
<tr>
<td>$\delta \kappa$</td>
<td>$-0.05$ $0.00$ $0.05$ $0.10$ $0.15$</td>
</tr>
</tbody>
</table>

The results are top left of the dashed line and weaker bounds to its right.

We see that, as we move further from the origin, the effect of the squared term becomes more pronounced.

EM dipole of a \( W \)

HL-LHC

S. Banerjee, C. Englert, R. Gupta, M. Spannowsky 1807.01796
Beating already LEP \((\delta g_1^Z \approx 0.05)\)

\[
\delta \kappa^Z = \delta g_1^Z - t_W^2 \delta \kappa^\gamma
\]

"tail" vs "bump" competition

No winners: Complementary of indirect and direct searches

\( t_R \): one of the less known state of the SM

Even that we produce a lot of top pairs, they do not provide much relevant information on the nature of \( t_R \)

**SM EFT** → BSM encoded in \( \delta g_{Zt_Rt_R} \) & \( t_Rt_Rt_Rt_R \) contact-int.

- \( Zt_Rt_R \) difficult to bound:
  - no growth with energy

- Best probe: 4 top contact-interaction:
  \[ pp \to t\bar{t}t\bar{t} \] effects grow with \( E \)

---

For the normalizations letting the normalizations

The ATLAS four-top measurement \[ \sigma_{t\bar{t}t\bar{t}} = 601 \text{ fb} \]

The CMS four-top analysis \[ \sigma_{t\bar{t}t\bar{t}} = 140 \text{ fb} \]

The growth with the energy of the four-top interaction will lead at the LHC to an enhancement

Similar expression holds for a composite

1.1 Subleading anomalous couplings

where consistency with precision data and minimal fine-tuning favor a strongly-coupled

Denoting with \( O \), only slightly stronger than the bound from

These observables can be

{ CMS: \[ \sigma_{t\bar{t}t\bar{t}} = 9.4^{+6.2}_{-5.6} \text{ fb} \] \[ \sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6} \text{ fb} \] } \[ \text{Present: } \Lambda \approx 0.75 \text{ TeV} \]

HL-LHC: \[ \Lambda \approx 1.3 \text{ TeV} \]

\[ \frac{1}{\Lambda^2} (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R) \]
Example of bounds on particles generating 4-tops:

Figure 8: 95% C.L. exclusions for two top-philic simplified models, presented in mass versus coupling planes and derived from the CMS-TOP-18-003 analysis (including the additional high-$H_T$ signal region of Sec. 3.2). We consider (a) $y^8_S$ as function of $M^8_S$ for a top-philic scalar octet simplified model and (b) $g^8_L = g^8_R$ as function of $M^8_V$ for a top-philic vector octet simplified model. Our results include the reinterpretation of the current CMS results (green lines) and their extrapolations at the HL-LHC (golden lines). The dotted lines represent the EFT-derived limits, while the solid and dashed lines represent the simplified model results. For the EFT limits, we use a $K$-factor of 1, while the simplified model ones are shown as bands obtained by varying the theoretical $K$-factor between 1 (top line) and 2 (bottom line). The grey regions in the top-right corner represent the parameter space regions in which the width of the top-philic particle is too large, making our approach unreliable.

We close this section by commenting further on the phenomenology associated with the low mass region. When the resonance is below the di-top threshold, four-top production from a pair of o-shell top-philic states dominates. However, the scaling of the top-philic state propagator is completely different from the one assumed when computing the EFT limit. Instead of the $1/M^2$ behaviour that would be expected for a large top-philic state mass, it exhibits a $1/s$ behaviour, with $s$ being typically around the invariant mass of the di-top system. We show in Fig. 9 the limits that we obtain by reinterpreting the CMS-TOP-18-003 results when the top-philic state mass varies in the 100 to 1000 GeV mass range, both for the scalar singlet and vector singlet simplified models. As expected from the above argument, the naive EFT approach overestimates the limits in this range. This is emphasised by the results shown in Sec. 2.3.2, from which we can observe that the signal efficiency would be drastically reduced after accounting for the fact that the EFT is used in a regime where it should not be used (see Fig. 4). Additionally, it is clear that the topology of the final state resembles closely the one expected from SM Higgs-induced four-top production, as verified directly by the CMS collaboration [4]. In this regime, we therefore consider the boosted decision tree (BDT) analysis of CMS [4] and extract limits directly from the measured signal cross section $NP + SM = 12.6^{+5.6}_{-5.4} + 1.2 + 0.5 + 0.2$. In order to derive projections for the HL-LHC, we use the last three BDT signal regions SR15 to SR17, that lead to $N_{bkd} = 8.1^{+1.3}_{-1.2}, N_{SM} = 8.2^{+3.1}_{-2.1}, N_{obs} = 14.7^{+3.1}_{-2.1}$. (4.1)
Conclusions

- The SM is an EFT: dimension-6 interactions are there waiting to be discovered (not clear though at which scale)

- LHC main strong impact:
  \[
  \text{Higgs couplings} \oplus \text{top couplings} \oplus \text{certain high-energy } 2 \rightarrow 2
  \]
  (e.g. di-lepton, di-bosons)

- No serious sign of deviations from the SM
  - Important BSM constraints (susy, compositeness, …)

- LHC legacy on SM tests will be very useful & essential to understand future strategies

  Null results are also important to make progress!
  (e.g. Michelson-Morley)
RESTRICTED AREA
NO UNAUTHORIZED PERSONNEL
BEYOND THIS POINT