Higgs physics

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Lecture II
Understanding a new force

- A new force has been discovered, the first elementary of Yukawa type ever seen.
- Its mediator looks a lot like the SM scalar: H-universality of the couplings
- No sign of…..New Physics (from the LHC)!
- We have no bullet-proof theoretical argument to argue for the existence of New Physics accessible at 13 TeV and even less so to prefer a NP model with respect to another.
Searching for new physics

Model-dependent
- SUSY, 2HDM, ED,…

Model-independent
- simplified models, EFT,…

Search for new states
- specific models, simplified models

Search for new interactions
- anomalous couplings, EFT,…

Exotic signatures
- precision measurements

Standard signatures
- rare processes
What about new physics?

The foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea.

The hedgehogs view the world through the lens of a single defining idea.
SM Portals

$$(\Phi^\dagger \Phi)$$ dim=2

$$(\bar{L}\Phi_c)$$ dim=5/2

$$B^{\mu\nu}$$ dim=2

Scalars and vectors

Sterile fermions

Dark photons
Searching for H to invisible

Immediate implications for any model with particles of mass $m < m_{H}/2$

\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} M^{2} \phi^{2} - c_{\phi} |H|^{2} \phi^{2} \]

Simplest extension of the SM: The Higgs portal
Searching for H to invisible

Important Dark Matter implications

\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} M^2 \phi^2 - c_\phi |H|^2 \phi^2 \]
Search for new interactions

• Such a programme is based on large set of measurements, both in the exploration and in the precision phases:

  • **PHASE I (EXPLORATION):**
    Bound Higgs couplings

  • **PHASE II (DETERMINATION):**
    Stress test the SM: Look for deviations wrt dim=4 SM (rescaling factors)

  • **PHASE III (PRECISION):**
    Interpret measurements in terms the dim=6 SM parameters (SMEFT)

• Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.

• For interactions with vector boson and third generation fermions we are ready to move to phase II.
Phase I (exploration) : examples

COUPLINGS to SM particles

• H self-interactions

• Second generation Yukawas: ccH, µµH

• Flavor off-diagonal int.s : tqH, ll’H, …

• HZγ

• Top self-interactions : 4top interactions

• Top neutral gauge interactions

• Top FCNC’s

• Top CP violation

COUPLINGS to non-SM particles

• H portals
Second generation

Using kinematic distributions i.e. the Higgs pT

Inclusive Higgs decays i.e. VH + flavour tagging (limited by c-tagging) gives a limit of 5.5 x SM expectation. (VZ has been observed!)

ZH (H → c¯c)
Baryogenesis

Remember that to generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.
Baryogenesis

Remember that to generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.

A trilinear coupling above 1.5*SM value allows a 1st order transition.
Phase I: Higgs self-coupling

At 14 TeV from gg fusion:

\[ \sigma_H = 55 \text{ pb} \]
\[ \sigma_{HH} = 44 \text{ fb} \]
\[ \sigma_{HHH} = 110 \text{ ab} \]

As in single Higgs many channels contribute in principle. Cross sections for HH(H) increase by a factor of 20(60) at a FCC.
Phase I: Higgs self-coupling

Many channels, but small cross sections.

Current limits are on $\sigma_{SM} (gg\to HH)$ channel in various $H$ decay channels:

- CMS: $\sigma/\sigma_{SM} < 3.4 (2.5)$
- ATLAS: $\sigma/\sigma_{SM} < 2.4 (2.9)$

Remarks:
1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of $\lambda_3$ which leads to a change in $\sigma$ as well as of distributions:

$$\sigma = \sigma_{SM} [1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

Note: due to shape changes, it is not straightforward to infer a bound on $\lambda_3$ from $\sigma(HH)$, even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

[Frederix et al. '14]
Phase I: Higgs self-coupling

Currently limits on $k_\lambda$ from H and HH are comparable and will stay so at the HL-LHC. Borderline sensitivity to say something about EW baryogenesis…
Phase II: couplings

\[ \mu_i^f = \frac{\sigma_i \cdot B_f^f}{(\sigma_i)_{SM} \cdot (B_f^f)_{SM}} = \mu_i \cdot \mu^f \]
Phase II : Legacy Run II results

The key aspect of our approach is that the predictions for all the available production and decay channels depend on a single parameter (Ref. [5]), we ignore correlations between the different uncertainties of a single process normalised to the SM. Since different uncertainties of a single process normalised to the SM can be measured experimentally, this information can be used by anybody to test BSM scenarios that lead to different patterns of Higgs coupling changes.

\[
\mu_i^f = \frac{\sigma_i \cdot B_f}{(\sigma_i)_{\text{SM}} \cdot (B_f)_{\text{SM}}} = \mu_i \cdot \mu^f
\]

\[
\mu_i = 1 + \delta\sigma\lambda_3(i)
\]

\[
\mu^f = 1 + \delta\text{BR}\lambda_3(f)
\]
Phase II: Prospects

\[(\sigma \cdot BR)(i \rightarrow H \rightarrow f) = \frac{\sigma^{SM}_i \cdot \Gamma^{SM}_f \cdot \kappa^{2}_i}{\Gamma^{SM}_H \cdot \kappa^{2}_H} \rightarrow \mu^f_i = \frac{\sigma \cdot BR}{\sigma^{SM} \cdot BR^{SM}_i} = \frac{\kappa^2_i \cdot \kappa^2_f}{\kappa^2_H}\]
Phase II : Legacy Run II results

\[ \mu = 1.05 \pm 0.06 \]

\[ = 1.05 \pm 0.03 \text{(stat.)} \pm 0.03 \text{(exp.)} \pm 0.04 \text{(sig. th.)} \pm 0.02 \text{(bkg. th.)}. \]
Phase III: SMEFT

\[ \mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \frac{1}{\Lambda} \mathcal{L}^{(5)} + \frac{1}{\Lambda^2} \mathcal{L}^{(6)} + \ldots \]

- \( m_h^2 \approx \Lambda^2 \)
- \( m_v = 0 \)
- \( U(1)_L^3 \times U(1)_B \)
- GIM
- \( Y_u, Y_d, Y_\ell \Rightarrow \text{Flavor} \& \mathcal{CP} \)

\( \Rightarrow \Lambda \geq 10^{14} \text{ GeV} \)
\( \Rightarrow \Lambda \geq 10^6 \text{ GeV} \)
\( \Rightarrow \Lambda \geq 10^{15} \text{ GeV} \)
\( \Rightarrow \Lambda \geq 10^3 \text{ GeV} \)
Phase III : SMEFT

The matter content of SM has been experimentally verified and evidence for new light states has not yet emerged.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

\[ \mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in as simple as powerful way in terms of one statement:

“BSM goal” of the SM LHC Run II programme:

determination of the couplings of the SM@DIM6
The matter content of SM has been experimentally verified and evidence for new light states has not yet emerged.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

Phase III: SMEFT
The idea of an EFT

SM  \Lambda  New Physics

\Lambda

Energy
The idea of an EFT
The idea of an EFT

\[ \Lambda \]

\[ \text{SM} \quad \text{New Physics} \]

Energy
The idea of an EFT

New Physics

Energy

Λ
The idea of an EFT

\[ \Lambda = M \]

New Physics

Energy
The idea of an EFT

\[ \Lambda = M \]

New Physics

Energy
The idea of an EFT

\[ \frac{g^2}{M^2} \times \]

\[ L_{\text{eff}} = L_{SM} + \frac{g^2}{M^2} \bar{\psi} \psi \bar{\psi} \psi \]

\[ M^2 = g^2 v^2 \Rightarrow \Lambda = v \]

\( \Lambda \) is an upper bound on the scale of new physics
The idea of an EFT

\[ \hat{h} = c = 1 \]
\[ \dim A^\mu = 1 \]
\[ \dim \phi = 1 \]
\[ \dim \psi = 3/2 \]

\[ \frac{g^2}{M^2} \times \]

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\dim=6} \]

Bad News: 59 operators [Buchmuller, Wyler, 1986]
Good News: an handful are unconstrained and can significantly contribute to top phenomenology!
### SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

<table>
<thead>
<tr>
<th>( X^3 )</th>
<th>( \phi^6 ) and ( \phi^4 D^2 )</th>
<th>( \psi^2 \phi^3 )</th>
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<tbody>
<tr>
<td>( Q_G )</td>
<td>( f^{ABC} G^{A}<em>{\mu} G^{B}</em>{\nu} G^{C}_{\rho} )</td>
<td>( Q_{\phi} )</td>
</tr>
<tr>
<td>( Q_{\bar{G}} )</td>
<td>( f^{ABC} \tilde{G}^{A}<em>{\mu} \tilde{G}^{B}</em>{\nu} \tilde{G}^{C}_{\rho} )</td>
<td>( Q_{\phi\tilde{\phi}} )</td>
</tr>
<tr>
<td>( Q_W )</td>
<td>( \epsilon^{IJK} W^{I}<em>{\mu} W^{J}</em>{\nu} W^{K}_{\rho} )</td>
<td>( Q_{\phi D} )</td>
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<td>( Q_{\phi W} )</td>
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<td>( \phi^\dagger \phi W^{I}<em>{\mu} W^{I}</em>{\mu} )</td>
<td>( Q_{\phi u} )</td>
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### SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

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<tbody>
<tr>
<td>( Q_{ll} )</td>
<td>( l_p \gamma_\mu l_r (\bar{\ell}<em>s \gamma</em>\mu \ell_t) )</td>
<td>( q_{ve} )</td>
<td>( q_{le} )</td>
</tr>
<tr>
<td>( Q_{qq}^{(1)} )</td>
<td>( q_p \gamma_\mu q_r (\bar{q}<em>s \gamma</em>\mu q_t) )</td>
<td>( q_{uu} )</td>
<td>( q_{le} )</td>
</tr>
<tr>
<td>( Q_{qq}^{(3)} )</td>
<td>( q_p \gamma_\mu \tau^I q_r (\bar{q}<em>s \gamma</em>\mu \tau^I q_t) )</td>
<td>( q_{dd} )</td>
<td>( (\bar{q}<em>p \gamma</em>\mu q_r (\bar{d}<em>s \gamma</em>\mu d_t) )</td>
</tr>
<tr>
<td>( Q_{1q}^{(1)} )</td>
<td>( (\bar{q}<em>p \gamma</em>\mu l_r (\bar{\ell}<em>s \gamma</em>\mu q_t) )</td>
<td>( Q_{eq} )</td>
<td>( Q_{qu} )</td>
</tr>
<tr>
<td>( Q_{1q}^{(3)} )</td>
<td>( (\bar{q}<em>p \gamma</em>\mu \tau^I l_r (\bar{\ell}<em>s \gamma</em>\mu \tau^I q_t) )</td>
<td>( Q_{qd} )</td>
<td>( Q_{qu}^{(8)} )</td>
</tr>
</tbody>
</table>

\[
(\tilde{L}R)(\tilde{R}L) \text{ and } (\tilde{L}R)(\tilde{L}R)
\]

| \( Q_{ledq} \) | \( (\bar{l}_p \gamma_\mu e_r (\bar{d}_s q_t) \) | \( Q_{duq} \) | \( \varepsilon^{\alpha \beta \gamma} \varepsilon_{jk} \left[ (d_\alpha^\gamma)^T C u_\beta \right] \left[ (q_\gamma^j)^T C l_j^\gamma \right] \) |
| \( Q_{qqu}^{(1)} \) | \( q_{pu} \) | \( Q_{qqu} \) | \( \varepsilon^{\alpha \beta \gamma} \varepsilon_{jk} \left[ (q_\alpha^\gamma)^T C q_\delta \right] \left[ (u_\gamma^j)^T C e_i \right] \) |
| \( Q_{qu}^{(8)} \) | \( (\bar{q}_p \gamma_\mu T^A q_r \varepsilon_{jk} (\bar{q}_s^k)^T T^A d_t) \) | \( Q_{qu}^{(1)} \) | \( \varepsilon^{\alpha \beta \gamma} \varepsilon_{jk} \varepsilon_{mn} \left[ (q_\alpha^\gamma)^T C q_\delta \right] \left[ (q_\gamma^m)^T C l_j^\gamma \right] \) |
| \( Q_{lequ}^{(1)} \) | \( (\bar{\ell}_p \gamma_\mu \tau^I e_r \varepsilon_{jk} (\bar{q}_s^k)^T \) | \( Q_{qu}^{(3)} \) | \( \varepsilon^{\alpha \beta \gamma} \varepsilon_{jk} \varepsilon_{mn} \left[ (q_\alpha^\gamma)^T C q_\delta \right] \left[ (q_\gamma^m)^T C l_j^\gamma \right] \) |
| \( Q_{qu}^{(3)} \) | \( (\bar{l}_p \gamma_\mu \tau^I \sigma_{\mu \nu} e_r \varepsilon_{jk} (\bar{q}_s^k)^T \) | \( Q_{duu} \) | \( \varepsilon^{\alpha \beta \gamma} \varepsilon_{jk} \varepsilon_{mn} \left[ (d_\alpha^\gamma)^T C l_j^\gamma \right] \left[ (q_\gamma^m)^T C e_i \right] \) |
The way of SMEFT

One can satisfy all the previous requirements, by building an EFT on top of the SM that respects the gauge symmetries:

\[
\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2} \sum_i N_i c_i \mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4} \sum_j N_j c_j \mathcal{O}_j^{(8)} + \ldots
\]

With the “only” assumption that all new states are heavier than energy probed by the experiment \( \sqrt{s} < \Lambda \).

The theory is renormalizable order by order in \( 1/\Lambda \), perturbative computations can be consistently performed at any order, and the theory is predictive, i.e., well defined patterns of deviations are allowed, that can be further limited by adding assumptions from the UV. Operators can lead to larger effects at high energy (for different reasons).
The master equation of an EFT approach has three key elements:

\[
\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}(\mu)c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)
\]

- Most precise/accurate experimental measurements with uncertainties and correlations
- Most precise SM predictions for observables: NLO, NNLO, N3LO...
- Most precise EFT predictions

\[\Rightarrow\] increased NP Sensitivity
\[\Rightarrow\] increased UV identification power

EFT \rightarrow UV

current measurements
future measurements
EFT picture: Matching

\[ \mathcal{L}_{\text{EFT}}(\phi_{\text{SM}}, \mu = \Lambda) \xleftrightarrow{\text{M}} \mathcal{L}_{\text{UV}}(\phi_{\text{SM}}, \phi_{\text{BSM}}) \]

Energy

\[ \mathcal{L}_{\text{EFT}}(\phi_{\text{SM}}, \mu = \nu) \]
Running

Operators run and mix under RGE

\[ O_{t\phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q}t) \bar{\phi}, \]
\[ O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G_{\mu \nu}^A G^{A \mu \nu}, \]
\[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu \nu} T^A t) \bar{\phi} G_{\mu \nu}^A. \]

\[
\frac{dC_i(\mu)}{d \log \mu} = \frac{\alpha_s}{\pi} \gamma_{ij} C_j(\mu), \quad \gamma = \begin{pmatrix}
-2 & 16 & 8 \\
0 & -7/2 & 1/2 \\
0 & 0 & 1/3
\end{pmatrix}
\]

At \( = 1 \text{ TeV} \): \( C_{tG} = 1, C_{t\phi} = 0 \);

At \( = 173 \text{ GeV} \): \( C_{tG} = 0.98, C_{t\phi} = 0.45 \)

Scale corresponds to the change from \( m_t \) to 2 TeV.
Loop effects

New operators arise at one loop

The SMEFT is as renormalizable as the SM when QCD and EW corrections are calculated.

- VBF, ZH, WH at LHC
- ZH, WWF, ZZF at $e^+e^-$
- H decay to $\gamma\gamma, \gamma Z, ZZ, Wl$, $b\bar{b}, \tau\tau, \mu\mu$
- ggH is known

Possible deviations using current constraints on the relevant operators
Higgs potential modifications

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

\[ V^{\text{BSM}}(\Phi) = -\mu^2(\Phi^\dagger \Phi) + \lambda(\Phi^\dagger \Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}} (\Phi^\dagger \Phi - \frac{v^2}{2})^n \]

so that the basic relations remain the same as in the SM:

\[
\begin{align*}
& m_H^2 = 2v^2 \\
& v^2 = \frac{\mu^2}{\lambda} \\
& \lambda_3 = \kappa_3 \lambda_3^{\text{SM}} \\
& \lambda_4 = \kappa_4 \lambda_4^{\text{SM}}
\end{align*}
\]

So for example: adding \(c_6\) only \[
\begin{align*}
& \kappa_3 = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \\
& \kappa_4 = 1 + \frac{6c_6 v^2}{\lambda \Lambda^2} = 6\kappa_3 - 5
\end{align*}
\]

Adding \(c_8\) makes \(\lambda_3\) and \(\lambda_4\) independent (full unlocking).

This is a general feature of dim=6 vs dim=8 in the SMEFT. In the HEFT three and four point (with Higgs couplings) are disentangled from the start=>more parameters. Equivalence can be established on a process by process basis between HEFT and dim=n EFT.
EFT analysis of HH

Other couplings enter in the same process: top Yukawa, ggh(h) coupling, top-gluon interaction, which can constrained by other processes. 1-1 correspondence between d.o.f and new constraint.

The present
Given the current constraints on $\sigma(HH)$, $\sigma(H)$ and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings.

The future
Precise knowledge of other Wilson coefficients will be needed to bound $\lambda$ as the bound gets closer to SM. Differential distributions will also
Unlocking with the EFT

dim=4 (SM)

⇒

dim=6

⇒

dim=8

⇒
EFT analysis of HH

Unlocking the SM

\[ \mathcal{L}_{SM}^{(4)} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi} i \slashed{D} \psi + (y_{ij} \bar{\psi}_L^i \phi \psi_R^j + \text{h.c.}) + |D_\mu \phi|^2 - V(\phi) \]

\[ \mathcal{A}(V_L V_L \rightarrow hh) \sim \frac{\hat{S}}{v^2} (c_{2V} - c_{V}^2). \]

Seagull vertex of scalar SU(2) or \((\phi^+ \phi)^2\)

- \(k_{2V} \leq 0\) excluded with 6.6\(\sigma\) assuming otherwise SM couplings

This can be interpreted as a dim=8 operator change in the SMEFT
SMEFT global fits at dim=6

- Measurements:
  - Total as well as differential, unfolded and/or fiducial, including uncertainties and correlations.
  - Reference SMEFT interpretations done by the experimental collaboration for best sensitivity targets.

- Theoretical predictions:
  - SM at the best possible accuracy
  - SMEFT at least at NLO in QCD

- Fitting:
  - Robust and scalable fitting technology
  - Combination with low/energy, flavour and LEP measurements
A powerful approach

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW, ...)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A LHC EFT WG is working hard to move things forward in a joint TH/EXP effort (thanks to all contributing!!)

Complementary!
First explorations: EWPO+H+EW+Top

- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits:

  - **Fitmaker** [J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You 2012.02779]
  - **HEPfit** [de Blas, et al. 2019]

- 30+ operators at dim=6, linear and/or quadratic fits, Higgs/Top/EW at LHC, WW at LEP and EWPO.
First explorations: EWPO+H+EW+Top

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

317 data points: Top: ttbar, single-top, associated top production, distributions.
Higgs production and decay, differential distributions, STXS.
Diboson production, distributions

Global EW/Top/Higgs SMEFT fit

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added

Methodology

Output
How do all these operators enter?
Global EW(PO)+H+Top

[Ellis et al. 2012.02779]

34 operators, $SU(2)^2 \times SU(3)^3$

EWPO fitted, 341 data points

[Either et al. (SMEFiT) 2105.00006]

36 operators, $SU(2)^2 \times SU(3)^3$

EWPO fixed, 317 data points
Global EW(PO)+H+Top

Linear vs quadratic

Posterior distributions

Significant impact for most operators in particular 4-fermion operators
Global EW(PO) + H + Top

LO vs NLO: linear

Posterior distributions for Wilson coefficients

Significant impact of NLO for some operators

NLO resolves non-interference problem for colour singlet 4F operators
Where is most information from?

4F mostly top

- Top Yukawa
- Top Chromomagnetic
- ttV couplings

Tree-loop interface
Higgs and top interplay

Top measurements break the degeneracy between Higgs operators
Breaking degeneracies

Top and Higgs

\[ \mathcal{O}_{\varphi t} \quad \text{cpt} \quad i(\varphi^\dagger \bar{D}_\mu \varphi)(\bar{t} \gamma^\mu t) \]

\[ \mathcal{O}_{\varphi W} \quad \text{cpW} \quad (\varphi^\dagger \varphi - \frac{v^2}{2}) W^\mu_\nu W^\nu_\mu \]

\[ \mathcal{O}_{\tau W} \quad i(\bar{Q}^\rho_\tau \tau_i t) \bar{\varphi} W^I_\mu W^I_\nu + \text{h.c.} \]

\[ \mathcal{O}_{\tau B} \quad i(Q^\rho_\tau \tau_i t) \bar{\varphi} B^I_\mu + \text{h.c.} \]

[Either et al. (SMEFiT) 2105.00006]
Learning points

1. Current fits are at an exploratory state, yet prove feasibility.

2. Dedicated EFT studies/observables needed to improve sensitivity.

3. Shift towards combinable measurements is needed.

4. Major change in the way experimental analyses are planned and published
Outlook

• The Higgs LHC precision physics programme has set clear and very challenging goals for the next years.

• A universal and very powerful approach to the interpretation of Higgs (and more) precision measurements is that of the SMEFT which provides many challenges pushing us out of our confort zone, beyond our current TH/EXP workflows and value system.

• First explorations of the constraining power of present data in a global EW(PO)+Higgs+Top fit have appeared.

• A wonderful realm of opportunities and large room for improvement ⇒ many ways to contribute and learn about SM(EFT) physics.
TRUE or FALSE?

[Contino et al., 1604.06444] [Aguilar-Saavedra, 1802.07237] [Many discussions…]
Lambda is the scale of New Physics

Consider the case of the Fermi theory of the muon decay:

From the measured value of the Fermi constant $G_F$

$$\frac{G_F}{\sqrt{2}} = \left( \frac{g}{2\sqrt{2}} \right)^2 \frac{1}{m_W^2} = \frac{1}{2v^2}$$

So $(4\pi)v$ is the upper bound on the scale of New Physics. If the theory is weakly interacting the first massive state will have mass of the order $g v << v$. If the theory is strongly interacting, $g \sim 4\pi$, $(4\pi)v$ will coincide with the scale of NP.
Note: Reinstating dimensions

\[ \mathcal{L}^{\text{dim}=6} = \frac{g^{n_i-4}}{\Lambda^2} \mathcal{O}_i \]

loop factor = \( \frac{g^2 \hbar}{(4\pi)^2} \)

\[ M = g \Lambda = \text{GeV} \]

\[ [G_{\mu \nu}] = \sqrt{\hbar} \text{ GeV}^2 \]

\[ [\phi] = [\nu] = [\Lambda] = \sqrt{\hbar} \text{ GeV} \]

\[ [A_\mu] = \sqrt{\hbar} \text{ GeV} \]

\[ [\psi] = \sqrt{\hbar} \text{ GeV}^{3/2} \]

\[ [g] = [\sqrt{\lambda}] = 1/\sqrt{\hbar} \]
The SMEFT is model independent

The aim of an EFT is to reproduce the IR behaviour of (a possibly) wide set of UV theories. However, it always relies on (generic) assumptions on the UV dynamics. The SMEFT@dim6, for examples, assumes:

1. The upper bound on the scale of new physics is $\Lambda$.
2. The SU(2)$\times$U(1) symmetry is linearly realised.
3. The expansion in $1/\Lambda$ is well-behaved, i.e. effects of dimension-8 operators are parametrically suppressed with respect to the dimension-6.
In the SMEFT, the operator normalisation is meaningful. Associating a “natural" normalisation to (class of) operators implies a UV bias, either some scaling rules and/or already an interpretation in mind. This is certainly legitimate, yet not necessary at the data analysis stage, if maximal flexibility/generality is desired.

At the SMEFT@dim6 one can work leaving the normalisation arbitrary (i.e. fixing the simplest convention) and just using data to constrain the coefficients. At the end only relations between observables as implied by the model are physically meaningful. And these do not depend on the normalisation.
The SMEFT is a non-renormalizable QFT and therefore it has no predictive power.

Order by order in the $1/\Lambda$ expansion, the SMEFT is renormalisable, i.e. higher-order contributions can be computed as perturbative series in the gauge couplings. For example., amplitudes with one operator insertion (at order $1/\Lambda^2$) can be renormalised using a finite number of counter-terms at all order in PT.
Truncating the SMEFT at the dim=6 is always correct

The usefulness of the up to $1/\Lambda^2$ approximation will depend:

1. On the assumptions (explicit and implicit) on the UV model.

2. On the specific observables/interactions which might not be sensitive to dim=6 effects. For example a $ZZZ$ vertex appears only at dim=8:

$$ie\Gamma_{Z\bar{Z}V}^{\alpha\beta\mu}(q_1, q_2, q_3) = \frac{-e(q_3^2 - m_V^2)}{M_Z^2} \left[ f_4^V (q_3^\alpha g^{\mu\beta} + q_3^\beta g^{\mu\alpha}) - f_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho \right]$$

$$f_4^Z = \frac{M_Z^2 v^2}{2 c_w s_w} \left( c_w^2 \frac{C_{WW}}{\Lambda^4} + 2 c_w s_w \frac{C_{BW}}{\Lambda^4} + 4 s_w^2 \frac{C_{BB}}{\Lambda^4} \right)$$

$$f_4^\gamma = -\frac{M_Z^2 v^2}{4 c_w s_w} \left( -c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4} (c_w^2 - s_w^2) + 4 c_w s_w \frac{C_{BB}}{\Lambda^4} \right)$$

[Degrunde, 1308.6323]
The question on the validity/perturbativity of an EFT is moot.

A necessary condition for the EFT to be consistent is the $E < \Lambda$. However, predictions depend on $c_i/\Lambda^2$.

* Provide information on the energy scales probed by the process *

Figure 1: Illustration of the limit set on an EFT parameter as function of a cut on the characteristic energy scale of the process considered (see item 6). Qualitatively, one expects the limits to be progressively degraded as $E_{\text{cut}}$ is pushed towards lower and lower values. At high cut values, beyond the energy directly accessible in the process considered, a plateau should be reached. The regions excluded when the dimension-six EFT is truncated to linear and quadratic orders are delimited by solid lines (see item 5c). The hatched regions indicate where the dimension-six EFT loses perturbativity (see item 7). In practice, curves will not be symmetric with respect to $C_i/\Lambda^2 = 0$. 
Squared terms are not uniquely defined and should not be employed in pheno analyses

At the amplitude level:

\[ A = A_{SM} + \sum_{i} \tilde{c}_i^6 A_i^6 + \sum_{k} \tilde{c}_k^8 A_k^8 + \ldots \]

At \( 1/\Lambda^2 \) level, the dim=6 term is uniquely defined. One can change the basis, perform field redefinitions, use the EOM, yet the full blue sum remains the same, generating however, corrections of order \( 1/\Lambda^4 \), feeding into the red term. This means that

\[ |A|^2 = |A_{SM}|^2 + \sum_{i} \tilde{c}_i^6 |A_i^6|^2 \]

\[ = |A_{SM}|^2 + 2 \sum_{i} \tilde{c}_i^6 \text{Re} \left[ A_{SM}^* A_i^6 \right] + \sum_{i,j} \tilde{c}_i^6 \tilde{c}_j^{6*} A_i^{6*} A_j^6 \]

is parametrisation invariant. The last term is order \( 1/\Lambda^4 \), yet uniquely defined.
Squared terms are not uniquely defined and should not be employed in pheno analyses.

This amplitude will need max dim=6 operators for renormalisation.

This amplitude will generically need dim=8 operators for renormalisation.
Squared terms are not uniquely defined and should not be employed in pheno analyses

In many cases the squared term should be included and in any case can be included:

1) If the interference term is highly suppressed because of symmetries (such as absence of FCNC at the tree-level in the SM) or selection rules (helicity selection for VV productions, i.e. the GGG operator in gg→gg), the squared term is always the dominant contribution.

2) There are UV models, for which the squared terms are foreseen to be the dominant $1/\Lambda^4$ contributions:

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients
Squared terms are not uniquely defined and should not be employed in pheno analyses

At the fitting level the squared can have an important effect, as there are no flat directions in the fit with the squares:

[Brivio et al., 1910.03606]

In general without knowing the effect of the squares one is left in the dark about meaning/reliability of the fit.

*Provide constraints using i) linear and ii) linear+squared terms*
If a light resonance is found, the EFT approach is of no use

There are at least two cases where this will not be the case:

1. The new resonance is quite heavy with respect to the collider energy and no other states are found ⇒ it could be the first of particle of a new heavy sector. EFT can include it and search for indirect effects of other states/phenomena.

2. The new resonance is light and very weakly interacting (like an axion) so that it does not impact collider phenomenology.

\[
-\frac{g^2}{2M_W^2} + \frac{1}{r_a^2} \frac{q^2}{q^2 - m_a^2} = -\frac{2}{\nu^2} \left[1 + \frac{\nu^2}{2r_a^2} \frac{q^2 / m_a^2}{q^2 / m_a^2 - 1}\right]
\]

Ex. by Manohar

\[
v = 246 \text{ GeV}, \ r_a \sim 2 \times 10^{12} \text{ GeV}, \ \frac{\nu}{r_a} \sim 10^{-10}, \ m_a \sim 2 \mu \text{eV}. \text{ Need } \left|\frac{q^2}{m_a^2} - 1\right| \sim \frac{\nu^2}{r_a^2} \sim 10^{-20} \Rightarrow \Delta q \sim 10^{-25} \text{ GeV}
\]
A fit based on a single or a subset of parameters does not bring any useful information

It is true that the SMEFT approach is global in nature. This is due to RGE, reparametrisation invariance, and so on. However, individual constraints and constraints on subsets are extremely useful. For example:

1. To understand which process is the most constraining one (comparing the impact of an operator on different processes is normalisation independent) SENSITIVITY.

2. Using pairs or triplets to understand the correlations and the flat directions and how to break them.

3. Technically, it might be complicated to include all operators in an analysis. However, having previous knowledge about where the sensitivity of an operator comes from, bounds from other processes/experiments, RGE information and, if desired, also UV model dependent information, one can establish a hierarchy and make maximal use of experimental information.

* Provide individual (also by process) and global constraints *
NLO EFT is a necessary step

Understanding and quantifying the higher order effects in the SMEFT is needed because of many reasons:

1. The structure of the theory manifests itself when quantum corrections are known, such as for example mixing/running and relations between operators at different scales.

2. NLO brings more accurate central values (k-factors) and reduction of the uncertainties (which can be gauged with the scale dependence, including EFT).

3. NLO QCD effects are important at the LHC, due to the nature of the collision. Not only rates can be greatly affected but also distributions.

4. At NLO genuine new effects can come in, such as the appearance of other operators due to loops or real radiation.

5. NLO can reduce the impact of flat directions.