Higgs physics

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain

Lecture II
New Physics

- 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 between 8 and 13 TeV and even less so to prefer a NP model with respect to another.
New Physics

Statement #1

Look for NP at the LHC by covering the widest range of TH- and/or EXP-motivated searches.

Searches should aim at being sensitive to the highest-possible scales of energy
New Physics

Statement #2

The Higgs provides a privileged searching ground

- It has just been discovered. Some of its properties are either just been measured or completely unknown.
- A plethora of production and decay modes available.
- First “elementary” scalar ever: carrier of a new Yukawa force, whose effects still need to be measured.
- \((\Phi^\dagger . \Phi)\) dim=2 singlet object \(\Rightarrow\) Higgs portal to a new sector.
- Several motivations to have a richer scalar sector with more doublets or higher representations \(\Rightarrow\) Higgs might be the first of many new scalar states.
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
Search for new physics via the Higgs
Search for new physics via the Higgs
SM Portals

$$(\Phi^\dagger \Phi)$$  \hspace{1cm} $$(\bar{L} \Phi_c)$$  \hspace{1cm} $$B^{\mu \nu}$$

\text{dim=2} \hspace{1cm} \text{dim=5/2} \hspace{1cm} \text{dim=2}

Scalars and vectors  \hspace{1cm} Sterile fermions  \hspace{1cm} Dark photons
Searching for H to invisible

\[ B(H \rightarrow \text{inv.}) < 0.24 \ (0.23) \ \text{at a 95\% CL} \]
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

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

\[ \text{B}(H \rightarrow \text{inv.}) < 0.24 \ (0.23) \text{ at a 95% CL} \]

Casas et al arXiv:1701.08134
Searching for H to invisible

Important Dark Matter implications

$B(H \rightarrow \text{inv.}) < 0.24 (0.23)$ at a 95% CL

$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} M^2 \phi^2 - c_\phi |H|^2 \phi^2$
Search for new physics via the Higgs

ATLAS and CMS LHC Run 1

ATLAS+CMS

SM Higgs boson

[M, ε] fit

68% CL

95% CL

Particle mass [GeV]
Direct vs indirect searches

Adopting a simple model one can compare the reach for direct vs indirect measurements: Again adding a singlet:

\[ V(\Phi, S) = -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2 \]

\[ m_h, m_H, \sin \alpha, \tan \beta, v. \]

Heavy Higgs searches

vs

Light Higgs signal strengths
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
Phase I (exploration) : examples

COUPLINGS to SM particles

• H self-interactions
• Second generation Yukawas: $ccH$, $\mu\mu H$
• Flavor off-diagonal int.s : $tqH$, $ll'H$, …
• $Hz\gamma$
• Top self-interactions : $4\text{top}$ 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

Higgs potential 101

A low-energy parametrisation of the Higgs potential

\[ V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots \]

In the Standard Model:

\[ V^{\text{SM}}(\Phi) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 \]

\[ \Rightarrow \begin{cases} v^2 = \mu^2 / \lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \]

\[ \begin{cases} \lambda_3^{\text{SM}} = \lambda \\ \lambda_4^{\text{SM}} = \lambda \end{cases} \]

i.e., fixing $v$ and $m_H$, uniquely determines both $\lambda_3$ and $\lambda_4$.

That means that by measuring $\lambda_3$ and $\lambda_4$ one can test the SM, yet to interpret deviations, one needs to “deform it”, i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.
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.
Baryogenesis

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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 $\sigma_{\text{SM}}$ ($gg\rightarrow HH$) channel in various H decay channels:

**CMS**: $\sigma/\sigma_{\text{SM}} < 19$ ($bb\gamma\gamma$) [EPS2017]

**ATLAS**: $\sigma/\sigma_{\text{SM}} < 13$ ($bbbb$). [Moriond18]

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:

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

Note: due to shape changes, it is not straightforward to infer a bound on $\lambda_3$ from $\sigma(HH)$, even when $\sigma_{\text{BSM}} = \sigma(\lambda_3)$ only is assumed.
Phase II: CMS/ATLAS Higgs couplings combination

Data points agree with SM hypothesis at the 20-30% level
Phase II : CMS/ATLAS Higgs couplings combination

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

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

\[ \mu^f = 1 + \delta BR \lambda_3 (f) \]

This information can be used by anybody to test BSM scenarios that lead to different patterns of Higgs coupling changes.
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:

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

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 idea of an EFT

SM \quad \Lambda \quad \text{New Physics} \quad \text{Energy}
The idea of an EFT
The idea of an EFT

SM

New Physics

Energy

Λ
The idea of an EFT

New Physics

Energy

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The idea of an EFT

\[ \Lambda = M \]

New Physics

Energy
The idea of an EFT

\[ \Lambda = M \]
The idea of an EFT

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

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

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

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

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

Bad News: 59 operators [Buchmuller, Wyler, 1986]
Good News: an handful are unconstrained and can significantly contribute to top phenomenology!
Majorana neutrinos

• Consider the SM@dim5. There is only one such operator that can be added:

\[ \mathcal{L} = \frac{c}{\Lambda} (L^T \epsilon \phi) C (\phi^T \epsilon L) + h.c. \]

When the Higgs fields acquire a vev this term gives rise to a Majorana neutrino mass

\[ m_\nu = \frac{v^2}{\Lambda} \]

If I now calculate the amplitude \( v \nu \rightarrow hh \)

\[ a_0 \left( \frac{1}{\sqrt{2}} \nu_+ \nu_+ \rightarrow \frac{1}{\sqrt{2}} hh \right) \sim \frac{c \sqrt{s}}{16 \pi M} \sim \frac{m_\nu \sqrt{s}}{16 \pi v^2} \]

\[ \Rightarrow \quad \Lambda_{\text{Maj}} \equiv \frac{4 \pi v^2}{m_\nu} \quad \Rightarrow \quad \text{min mass for the neutrino} \quad \Rightarrow \quad \text{upper bound for} \ \Lambda \]

Majorana neutrino mass implies New Physics before \( 10^{15} \) GeV
Majorana neutrinos

An UV completion of the dim=5 operator (there are few) is well known: the see-saw model

\[ \mathcal{L} = -y_D \bar{L} \epsilon \phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \text{H.c.} \]

with a Dirac mass term and a Majorana one ($\nu_R$ is a singlet of SU(2)). One can diagonalise the mass matrix and obtains two mass eigenstates

\[ \nu \approx \nu_L \quad m_\nu \approx \frac{m_D}{M_R} \]

\[ N \approx \nu_R \quad M_R \]

and the amplitude $\nu \rightarrow hh$ does not grow anymore because the last term is not present anymore.
## SMEFT Lagrangian: Dim=6

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

<table>
<thead>
<tr>
<th>$X^3$</th>
<th>$\varphi^6$ and $\varphi^4D^2$</th>
<th>$\psi^2\varphi^3$</th>
</tr>
</thead>
</table>
| $Q_G$ | $f^{ABC}G^A_{\mu\nu}G^B_{\mu\nu}G^C_{\mu\nu}$ | $Q_{\varphi}$ | $(\varphi^4)^3$
| $Q_{\tilde{G}}$ | $f^{ABC}\tilde{G}^A_{\mu\nu}G^B_{\mu\nu}G^C_{\mu\nu}$ | $Q_{\varphi}^\Box$ | $(\varphi^4)\Box(\varphi^4)$
| $Q_W$ | $\varepsilon^{IJK}W^I_{\mu\nu}W^J_{\rho\sigma}W^K_{\lambda\rho}$ | $Q_{\varphi D}$ | $(\varphi^4 D^\mu \varphi)^\ast (\varphi^4 D_\mu \varphi)$
| $Q_{\tilde{W}}$ | $\varepsilon^{IJK}\tilde{W}^I_{\mu\nu}W^J_{\rho\sigma}W^K_{\lambda\rho}$ | |

<table>
<thead>
<tr>
<th>$X^2 \varphi^2$</th>
<th>$\psi^2X\varphi$</th>
<th>$\psi^2\varphi^2D$</th>
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</table>
| $Q_{\varphi G}$ | $\varphi^4 G^A_{\mu\nu}G^A_{\mu\nu}$ | $Q_{eW}$ | $(\tilde{l}_p \sigma^{\mu\nu}e_r)\tau^I \varphi W^I_{\mu\nu}$
| $Q_{\varphi \tilde{G}}$ | $\varphi^4 \tilde{G}^A_{\mu\nu}G^A_{\mu\nu}$ | $Q_{eB}$ | $(\tilde{l}_p \sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
| $Q_{\varphi W}$ | $\varphi^4 W^I_{\mu\nu}W^I_{\mu\nu}$ | $Q_{uG}$ | $(\tilde{q}_p \sigma^{\mu\nu}u_r)\tau^I \tilde{G}^A_{\mu\nu}$
| $Q_{\varphi \tilde{W}}$ | $\varphi^4 \tilde{W}^I_{\mu\nu}W^I_{\mu\nu}$ | $Q_{uB}$ | $(\tilde{q}_p \sigma^{\mu\nu}u_r)\varphi B_{\mu\nu}$
| $Q_{\varphi B}$ | $\varphi^4 B_{\mu\nu}B_{\mu\nu}$ | $Q_{dG}$ | $(\tilde{q}_p \sigma^{\mu\nu}d_r)\tau^I \varphi W^I_{\mu\nu}$
| $Q_{\varphi \tilde{B}}$ | $\varphi^4 \tilde{B}_{\mu\nu}B_{\mu\nu}$ | $Q_{dB}$ | $(\tilde{q}_p \sigma^{\mu\nu}d_r)\varphi B_{\mu\nu}$
| $Q_{\varphi WB}$ | $\varphi^4 \tau^I \varphi W^I_{\mu\nu}B_{\mu\nu}$ | $Q_{\varphi l}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{l}_p \gamma^\mu l_r)$
| $Q_{\varphi \tilde{W}B}$ | $\varphi^4 \tau^I \varphi \tilde{W}^I_{\mu\nu}B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{l}_p \gamma^\mu l_r)$
| | | $Q_{\varphi e}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{e}_p \gamma^\mu e_r)$
| | | $Q_{\varphi q}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{q}_p \gamma^\mu q_r)$
| | | $Q_{\varphi u}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{u}_p \gamma^\mu u_r)$
| | | $Q_{\varphi d}$ | $(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{d}_p \gamma^\mu d_r)$
| | | $i(\varphi^4 \tilde{D}_\mu \varphi)(\tilde{u}_p \gamma^\mu d_r)$

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# SMEFT Lagrangian: Dim=6

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

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<td>$Q_{le}$</td>
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<td>$Q_{lu}$</td>
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$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$

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EFT picture: Matching and Running

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

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

Energy

RGE
Running/Mixing

Operators run and mix under RGE

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

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

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

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

Scale corresponds to the change from mt to 2 TeV.
SMEFT Lagrangian: Dim=6

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself: $\Lambda > M_X$
- QCD and EW renormalisable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale $\Lambda : \sqrt{s} < \Lambda$
The EFT approach: managing unknown unknowns

- Very powerful model-independent approach.

- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable, signal as well as “backgrounds”. (LO, NLO,..)
  - find enough observables (cross sections, BR’s, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
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Higgs

Top

Jets

Decays

Flavor

CPV

Courtesy of Ken Mimasu
Example: Gauge-Higgs operators

Focus on a subset of 10 operators:

\[ \mathcal{O}_{GG} = \phi^{\dagger} \phi G_{\mu\nu}^{a} G^{a\mu\nu} \]
\[ \mathcal{O}_{W} = (D_{\mu} \phi)^{\dagger} \tilde{W}^{\mu\nu} (D_{\nu} \phi) \]
\[ \mathcal{O}_{c_{\phi,33}} = (\phi^{\dagger} \phi)(\bar{L}_{3} \phi e_{R,3}) \]
\[ \mathcal{O}_{WW} = \phi^{\dagger} \tilde{W}_{\mu\nu} \tilde{W}^{\mu\nu} \phi \]
\[ \mathcal{O}_{B} = (D_{\mu} \phi)^{\dagger} \tilde{B}^{\mu\nu} (D_{\nu} \phi) \]
\[ \mathcal{O}_{u_{\phi,33}} = (\phi^{\dagger} \phi)(\bar{Q}_{3} \phi u_{R,3}) \]
\[ \mathcal{O}_{BB} = \phi^{\dagger} \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} \phi \]
\[ \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^{\mu} (\phi^{\dagger} \phi) \partial_{\mu} (\phi^{\dagger} \phi) \]
\[ \mathcal{O}_{d_{\phi,33}} = (\phi^{\dagger} \phi)(\bar{Q}_{3} \phi d_{R,3}) \]

Constrain those modifying triple-gauge couplings by WW, WZ measurements.
Example: Gauge-Higgs operators

Add the Higgs strengths constraints:

arXiv:1803.03252
arXiv:1604.03105
Top-quark operators and processes

\[ O_{Q}^{(3)} = i \frac{1}{2} y_t^2 \left( \varphi^\dagger D^I_{\mu} \varphi \right) (\bar{Q} \gamma^\mu T^I Q) \]

\[ O_{Q}^{(1)} = i \frac{1}{2} y_t^2 \left( \varphi^\dagger D_{\mu} \varphi \right) (\bar{Q} \gamma^\mu Q) \]

\[ O_{\varphi t} = i \frac{1}{2} y_t^2 \left( \varphi^\dagger D_{\mu} \varphi \right) (\bar{t} \gamma^\mu t) \]

\[ O_{tW} = y_t g_w (\bar{Q} \sigma^{\mu\nu} T^I t) \varphi W_{\mu\nu}^I \]

\[ O_{tB} = y_t g_Y (\bar{Q} \sigma^{\mu\nu} t) \varphi B_{\mu\nu} \]

\[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \varphi G_{\mu\nu}^A \]

\[ O_{t\varphi} = y_t^3 (\varphi^\dagger \varphi) \bar{Q} \varphi t \]

+ four-fermion operators

+ operators that do not feature a top, but contribute to the procs…
Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO$^2$) and

<table>
<thead>
<tr>
<th>Process</th>
<th>$O_{tG}$</th>
<th>$O_{tB}$</th>
<th>$O_{tW}$</th>
<th>$O_{\varphi Q}^{(3)}$</th>
<th>$O_{\varphi Q}^{(1)}$</th>
<th>$O_{t\varphi}$</th>
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Top/Higgs operators and processes

Let’s take a simple example, i.e. Higgs production via top interactions and consider the relevant subset of operators.

Note that these operators mix into each others and therefore they NEED to be considered together.

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

\[ \gamma = \frac{2\alpha_s}{\pi} \left( \begin{array}{ccc} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{array} \right) \]
Top-Higgs interactions: constraints

From a global fit the coupling of the higgs to the top is poorly determined.

\[ \frac{\sigma_{ggh}}{\sigma_{SM}} \approx 1 + 237 c_{gg} + 2.06 \delta y_u - 0.06 \delta y_d. \]

\[ \mathcal{O}_{H_y} = H^\dagger H (H \bar{Q}_L) t_R \]

\[ \mathcal{O}_{HG} = \frac{1}{2} H^\dagger HG^a_{\mu \nu} G^{\mu \nu}_a \]

The loop could still be dominated by np.

The effect of the CM operator not included

[Belusca-Maite, Falkowski, 2013]
Top-Higgs interactions: high-pT

From a global fit the coupling of the Higgs to the top is poorly determined: the loop could still be dominated by NP.

\[ O_{Hy} = H^\dagger H (H \tilde{Q}_L) t_R \]
\[ O_{HG} = \frac{1}{2} H^\dagger H G_{\mu\nu}^a G_{a}^{\mu\nu} \]

EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision.
Top-Higgs interactions: high-pT

From a global fit the coupling of the Higgs to the top is poorly determined: the loop could still be dominated by NP.

\[
O_{Hy} = H^\dagger H (H\bar{Q}_L) t_R \\
O_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^a_{\mu\nu}
\]

EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision.

Grojean et al., 2013
Top-Higgs interactions: $ttH$

$$pp \rightarrow t\bar{t}h$$

$$\frac{\sigma(pp \rightarrow t\bar{t}h)}{fb} = 611^{+92}_{-110} + \left[457^{+127}_{-91} R_{chg} - 49^{+15}_{-10} c_G \right]$$

$$+ 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y \left( \frac{\text{TeV}}{\Lambda} \right)^2$$

$$+ \left[543^{+143}_{-123}(R_{chg})^2 + 132^{+323}_{-232} c_G^2 \right]$$

$$+ 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2$$

$$+ 233^{+81}_{-144} R_{chg} c_{HG} - 50^{+16}_{-14} R_{chg} c_y$$

$$- 3.2^{+83}_{-83} R_{cH} c_{HG} - 1.2^{+83}_{-83} c_H c_{HG} \right] \left( \frac{\text{TeV}}{\Lambda} \right)^4$$

[Degrande et al. 2012]
How to extract $\lambda_{HHH}$ from HH?

**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.

**Other couplings enter in the same process:** top Yukawa, ggh(h) coupling, top-gluon interaction.

**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 be necessary.
Constraints from ttH and Higgs production

Current limits using LHC measurements

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

14TeV projection
3000 fb-1
Conclusions

❖ The golden era for Higgs physics has just started
❖ We are moving in three main directions:
  ❖ exploiting the Higgs as a gateway to BSM sectors
  ❖ exploring uncharted sectors of the SM
  ❖ performing accurate measurements of the couplings and their interpretation through an EFT approach
❖ Exciting, challenging, rich and very promising physics program ahead of us!