Theoretical implications of the LHC Higgs measurements

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CERN TH

LHCP2018
Bologna
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LHC: the story so far

Higgs couplings

Good agreement with the SM predictions
How to look for new physics?

**Model-dependent**

- SUSY, 1HSM, 2HDM…

**Model-Independent**

- anomalous couplings, EFT

**New particles**

**New Interactions**

Resonance peaks

Deviations in tails
How to look for new physics?

**Model-dependent**

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**New Interactions**

- Deviations in tails

A lot to learn

Plethora of measurements and searches

CMS Preliminary

35.9 fb⁻¹ (13 TeV)

Events/(25.0 GeV)

M(jjyy) [GeV]

Data
Knowns and Unknowns

\[ c, u, d, s, e? \]
Knowns and Unknowns

A? H? H\(^{+/-}\)?
Knowns and Unknowns

ATLAS and CMS LHC Run 1

Particle mass [GeV]

ATLAS+CMS

SM Higgs boson

[M, $\epsilon$] fit

68% CL

95% CL

$u, d, s, e$?

$A$?

$H$?

$H^{\pm/-}$?
Knowns and Unknowns

A?  H?  H±/-?

u,d,s,e?

c?

X?

h?
Outline

I. Higgs couplings
II. Searching for new states
III. The Higgs potential
I. Higgs couplings
The big news: Top-Higgs interaction

~20% accuracy

First observation of \( ttH \)

Heavy particles in the loops?
The big news: Top-Higgs interaction

~20% accuracy

First observation of $ttH$

Heavy particles in the loops?

Direct evidence of the coupling of the top to the Higgs
Probing the top-Higgs interaction

Current limits using LHC measurements

Combination:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

Azatov et al arXiv:1608.00977

Maltoni, EV, Zhang arXiv:1607.05330

14TeV projection 3000 fb⁻¹

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Probing the top-Higgs interaction

Current limits using LHC measurements

impact of recent ttH observation

Combination:
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Going beyond…

ttH is more than just the top Yukawa
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Going beyond…

$t\bar{t}H$ is more than just the top Yukawa

The SMEFT

A model independent framework for parametrising deviations from the SM in the absence of light states
Going beyond…

A gigantic effort lies ahead: determining the couplings of the dim-6 Lagrangian

\[ \mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4}) \]

The SMEFT

A model independent framework for parametrising deviations from the SM in the absence of light states

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Towards EFT global fits

The future of global fits

Inclusive

Differential

Using differential information will be crucial

Ellis et al arXiv:1803.03252

Englert, Kogler, Spannowsky arXiv:1511.05170

See more in Veronica’s talk
Higgs couplings beyond the 3rd generation

Run I and II results indicate that vector bosons and third generation fermions get their masses from the Higgs

Is this the case for the 1st and 2nd generation? Do they get their masses from the same scalar doublet?

An opportunity to test flavour models which predict deviations from the SM
Light quark Yukawas (1)
A challenge and an opportunity:

Rare radiative decays to vector mesons:

Direct: sensitive to the quark Yukawa

Indirect

SM predictions:
\[ \mathcal{B}(H \to J/\psi \gamma) \sim 3 \times 10^{-6} \]
\[ \mathcal{B}(H \to Y(1S)\gamma) \sim 5 \times 10^{-9} \]
\[ \mathcal{B}(H \to \rho \gamma) \sim 2 \times 10^{-5} \]
\[ \mathcal{B}(H \to \phi \gamma) \sim 2 \times 10^{-6} \]

First LHC results:
\[ \mathcal{B}(H \to J/\psi \gamma) < 1.5 \times 10^{-3} = 500 \times \text{SM} \]
\[ \mathcal{B}(H \to \phi \gamma) < 4.8 \times 10^{-4} = 208 \times \text{SM} \]
\[ \mathcal{B}(H \to \rho \gamma) < 8.8 \times 10^{-4} = 52 \times \text{SM} \]


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Light quark Yukawas (1)
A challenge and an opportunity:

Rare radiative decays to vector mesons:

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Indirect

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Lots of room for BSM deviations
Great opportunity for HL-LHC
New idea: Using kinematic distributions i.e. the Higgs pT

Inclusive Higgs decays i.e. VH + flavour tagging (limited by c-tagging)

(1st generation)

To be fully explored
II. Searching for new states
Searching for the invisible

CMS HIG-16-016 [JHEP 02 (2017) 135]

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

Immediate implications for any model with particles of mass \( m < m_H/2 \)

Simplest extension of the SM:
- The Higgs portal
- A window to the Dark Sector

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\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} M^2 \phi^2 - c_\phi |H|^2 \phi^2 \]
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Based on HP of arXiv:1112.3299

90% CL limits

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Simplest extension of the SM:
The Higgs portal

A window to the Dark Sector

Important Dark Matter implications

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Casas et al arXiv:1701.08134
Searching for the visible

LHC constrains extended scalar sectors using:
• Resonant searches VV, ZH, HH, tt, bb, ττ etc
• Single Higgs measurements:
  • Coupling strengths
  • Higgs exotic decays
  • Higgs width
The example of the 2HDM

Second Higgs doublet $\rightarrow h, H, A, H^\pm$ + modifications of the 125 GeV Higgs couplings

SM-like Higgs $\rightarrow$ approaching the alignment limit:

$$|\cos(\beta - \alpha)| \ll 1$$

Is decoupling avoidable? Or is $m_h \ll m_H, m_A, m_{H^\pm}$?

The LHC is doing its best to tell us

Constraints from:

$A/H/h \rightarrow \tau\tau,$
$H \rightarrow WW/ZZ,$
$H \rightarrow hh,$
$A \rightarrow Zh$ + Light Higgs couplings
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- $H \rightarrow WW/ZZ$
- $H \rightarrow hh$
- $A \rightarrow Zh$
+ Light Higgs couplings

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LHC impact on global 2HDM fits

Signal strengths clearly pointing towards the alignment limit: more stringent for type II

A plethora of searches are being used to constrain the model

Allowed windows remain
III. The Higgs potential
The Higgs potential

Higgs potential:

\[ V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4 \]

Fixed values in the SM:

\[ \lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2} \]

Measuring \( \lambda_{HHH} \) and \( \lambda_{HHHH} \) tests the SM

What can measuring \( \lambda_{HHH} \) tell us?

Electroweak baryogenesis requires a first order strong EWPT

\[ \frac{\phi_c}{T_c} \gtrsim 1 \]


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\[ \frac{\phi_c}{T_c} \gtrsim 1 \]

\( \lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1 \)

EW baryogenesis is disfavoured

\( \lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1 \)

EW baryogenesis is favoured

Constraining the Higgs self-coupling

**Theory constraints:** How large can $\lambda_{hhh}$ be (in particular given Higgs couplings measurements)?

**Experimental prospects:** Which measurements can be used to constrain $\lambda_{hhh}$?
Theoretical constraints on $\lambda_{\text{HHH}}$

Perturbativity:
- Partial wave unitarity: $|\text{Re} \, a_{h_h \to h_h}^0| < 1/2$, $|\lambda_{h_h h}/\lambda_{h_h h}^{\text{SM}}| \lesssim 6.5$
- Loop-corrections to $\lambda$ smaller than $\lambda$, $|\lambda_{h_h h}/\lambda_{h_h h}^{\text{SM}}| \lesssim 6$

Di Luzio, Grober, Spannowsky arXiv:1704.02311

Specific UV complete models:
Scalar extensions:

<table>
<thead>
<tr>
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See also Di Vita et al. 1704.01953: Fine-tuned Higgs portal $|\lambda_{h_h h}/\lambda_{h_h h}^{\text{SM}}| \lesssim 6$

Di Luzio, Grober, Spannowsky arXiv:1704.02311
How to extract $\lambda_{HHH}$: 1) HH

Current limits:
CMS: $\sigma/\sigma_{SM} < 19(bb\gamma\gamma)$
ATLAS: $\sigma/\sigma_{SM} < 30(bbbb)$
CMS: $\sigma/\sigma_{SM} < 28(bb\tau\tau)$

SM cross sections

\[
\begin{array}{c|c|c|c|c}
\sqrt{s} & 13 \text{ TeV} & 14 \text{ TeV} & 27 \text{ TeV} & 100 \text{ TeV} \\
\sigma(HH) [fb] & 31.05^{+2.2}_{-5.0} & 36.69^{+2.1}_{-4.9} & 139.9^{+1.3}_{-3.9} & 1224^{+0.9}_{-3.2} \\
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\]

Grazzini et al arXiv:1803.02463

Projections for HL-LHC:

\[
\begin{align*}
bbbb & \quad 0.2 < \lambda/\lambda_{SM} < 7.0 \text{ (stat)} \\
bb\gamma\gamma & \quad -0.8 < \lambda/\lambda_{SM} < 7.7 \text{ (stat)}
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ATL-PHYS-PUB -2015-046

ATL-PHYS-PUB -2016-024

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- $bb\gamma\gamma$ -0.8 < $\lambda/\lambda_{SM}$ < 7.7 (stat)
- $bbbb$ 0.2 < $\lambda/\lambda_{SM}$ < 7.0 (stat)

ATL-PHYS-PUB -2015-046

ATL-PHYS-PUB -2016-024

Frederix et al. arXiv:1401.7340

Dolan et al arXiv:1206.5001

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$bb\bar{b}\bar{b}$ $0.2 < \lambda/\lambda_{SM} < 7.0$ (stat)

ATL-PHYS-PUB -2016-024

$bb\gamma\gamma$ $-0.8 < \lambda/\lambda_{SM} < 7.7$ (stat)

ATL-PHYS-PUB -2015-046

A challenge even for the HL-LHC
How to extract $\lambda_{HHHH}$ from HH?

Other couplings enter in the same process:
- top Yukawa, ggh(h) coupling,
- top-gluon interaction
How to extract $\lambda_{\text{HHH}}$ from HH?

**The present**

Given the current constraints on $\sigma(\text{HH})$, $\sigma(\text{H})$ 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.
How to extract $\lambda_{HHH}$ from HH?

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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 be necessary
How to extract $\lambda_{HHH}$: 2) Indirectly

Higgs observables: production and decay at NLO (EW)

Run I single Higgs results: $\kappa_{2\sigma}^{2\sigma} = [-9.4, 17.0]$  
c.f. HH: $\kappa_{2\sigma}^{2\sigma} = [-8.82, 15.04]$

Future prospects:
- Synergy between H and HH production
- Differential distributions crucial to break degeneracies at HL-LHC

Degrassi et al. arXiv:1607.04251
See also: Gorbahn, Haisch 1607.03773, Bizon et al 1610.05771, Maltoni et al 1709.08649
Di Vita et al. arXiv:1704.01953

EWPO:
- $\kappa_\lambda \in [-11.1, 14.6]$

Degrassi et al 1702.01737
Kribs et al 1702.07678
LHC Higgs measurements are exploring Higgs couplings to all SM particles and frantically searching for new physics in the scalar sector

No sign of deviation from the SM prediction, yet

But the exploration has just begun
Lots of questions will be answered over the coming years of the LHC
Thanks for your attention