Higgs Physics - Theory
Lecture 2

Higgs-boson physics at the LHC

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Outline of these lectures

- **Lecture 1: the Standard-Model Higgs boson.**
  - EW gauge symmetry, Higgs mechanism.
  - Higgs-boson interactions.
  - Quantum constraints.

- **Lecture 2: Higgs-boson physics at the LHC.**
  - Production and decay modes, what do they probe.
  - Theoretical predictions and their accuracy.

- **Lecture 3: from Higgs-boson properties to new physics.**
  - Probing specific extensions of the SM.
  - Probing classes of interactions within SM boundaries.
Testing EWSB: precision physics at the energy frontier

- Precision is intrinsic to having a **predictive theory** like the **Standard Model** of particle physics.

- Precision is effective when both theory and experiments have a way to reach comparable accuracy and improve it systematically.

- Particle physics has a very successful history of constraining **new physics** through precision measurements in:
  - Precision fits of electroweak observables (LEP, SLD, Tevatron, LHC)
  - Indirectly constrained $M_H$

- From Run 1 to Run 2 and beyond: crucial to develop the LHC Higgs precision program:
  - Precision measurement of Higgs properties (mass, couplings, width)
  - Constraints on anomalous interactions

Explore indirect evidence of new physics while searching for direct one.
Higgs boson: a remarkable prediction of precision EW fits

Spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$ via the SM Higgs mechanism + SM renormalizability imply:

$\rightarrow$ systematic control of $M_H$ dependence in renormalized parameters.

$M_H$ only free parameter of the SM:

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$m_t = 173.2 \pm 0.90 \text{ GeV}$$

$$M_H = 94^{+29}_{-24} \text{ GeV}$$

$$M_H < 152 \text{ (171)} \text{ GeV}$$

Measured in Run 1 of the LHC: $M_H = 125.09 \pm 0.24$ GeV
Example: $M_H$-dependence in $M_W$ quantum corrections

\[
\Pi_{VV}^{\mu\nu}(q^2) \leftarrow \begin{array}{c}
\text{W} \\
\text{H} \\
\text{W}
\end{array} \quad \begin{array}{c}
\text{Z} \\
\text{H} \\
\text{Z}
\end{array}
\]

where $(V = W, Z)$

\[
\Pi_{VV}^{\mu\nu}(q^2) = \Pi_{VV}(q^2) g^{\mu\nu} + \Sigma_{VV}(q^2) q^\mu q^\nu
\]

and

\[
M_{V,0}^2 = M_V^2 + \Pi_{VV}(M_V^2)
\]

**State of the art** (full EW 2-loop + leading 3-loop + some 4-loop)


\[
M_W = M_{W,0} - c_1 \text{dh} - c_2 \text{dh}^2 - c_3 \text{dh}^4 + \ldots
\]

where \( \text{dh} = \ln(M_H/100 \text{GeV}) \).
**EW precision fits, strategy**

Having a variety of measurement for different observables, test the SM by comparing theory and experiment.

- Pick a set of input parameters, typical choice:
  \[ \alpha_s, \alpha, G_F, M_Z, M_H, m_t, m_f, \ldots \]

- Compute theoretical predictions for all available electroweak precision observables (EWPO), including radiative corrections, in a given renormalization scheme treating the best measured parameters as inputs (typically \( \alpha, G_F \)), i.e. as fixed parameters.

- Perform a best fit to the electroweak data, defined by a \( \chi^2 \) test

\[
\chi^2(\alpha, G_F, \ldots) = \sum_i \left( \frac{(\hat{O}_i^{\text{exp}} - O_i^{\text{th}}(\alpha, G_F, \ldots))^2}{(\Delta \hat{O}_i^{\text{exp}})^2} \right)
\]

This results in a best fit of the non-fixed or floating parameters. Compare best-fit values to measurements if available (ex.: \( M_W, m_t, \alpha_s, M_H ! \))

- For the best-fit values of all input parameters, quote the SM theoretical prediction for each observable and compare with the experimental measurements. “Tensions” may signal new physics …
Fully stress-testing the SM consistency

→ Very good agreement between indirect determination of EWPO and experimental measurements

→ Very strong constraint on any physics beyond the SM.
LHC Run 1+Run 2: promoted $M_H$ to EW precision observable

<table>
<thead>
<tr>
<th>Observable</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 1+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow 4l$</td>
<td>125.51 ± 0.52 (± 0.52) GeV</td>
<td>124.93 ± 0.40 (± 0.21) GeV</td>
<td>124.79 ± 0.37 (± 0.36) GeV</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>126.02 ± 0.51 (± 0.43) GeV</td>
<td>124.93 ± 0.40 (± 0.21) GeV</td>
<td>124.30 ± 0.35 (± 0.19) GeV</td>
</tr>
<tr>
<td>$l_4 \rightarrow H$</td>
<td>125.38 ± 0.41 (± 0.37) GeV</td>
<td>125.32 ± 0.35 (± 0.19) GeV</td>
<td>125.30 ± 0.35 (± 0.19) GeV</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow H$</td>
<td>125.86 ± 0.27 (± 0.18) GeV</td>
<td>124.97 ± 0.24 (± 0.16) GeV</td>
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</tr>
<tr>
<td>ATLAS + CMS Run 1</td>
<td>125.09 ± 0.24 (± 0.21) GeV</td>
<td>124.97 ± 0.24 (± 0.16) GeV</td>
<td>124.97 ± 0.24 (± 0.16) GeV</td>
</tr>
</tbody>
</table>

[ATLAS-CONF-2019-005]

Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings $\leftrightarrow$ probing EWSB

Moreover, from decays ($H \rightarrow VV$ and $H \rightarrow f\bar{f}$)

$\rightarrow$ Spin: highly constrained to be $s = 0$

$\rightarrow$ Parity: scalar vs pseudoscalar, from structure of decay amplitudes.
LHC Run 1+Run 2: first measurements of Higgs couplings

$\kappa_i = g_{Hi}/g_{H_i}^{SM}$

$\kappa_i$ | ATLAS | CMS | HL-LHC
--- | --- | --- | ---
$\kappa_Z$ | $1.10^{+0.08}_{-0.08}$ | $0.99^{+0.11}_{-0.12}$ | 2.4%
$\kappa_W$ | $1.05^{+0.08}_{-0.08}$ | $1.10^{+0.12}_{-0.17}$ | 2.2%
$\kappa_t$ | $1.02^{+0.11}_{-0.10}$ | $1.11^{+0.12}_{-0.10}$ | 3.4%
$\kappa_b$ | $1.06^{+0.19}_{-0.18}$ | $-1.10^{+0.33}_{-0.23}$ | 3.7%
$\kappa_{t'}$ | $1.07^{+0.15}_{-0.15}$ | $1.01^{+0.16}_{-0.20}$ | 1.9%
$\kappa_{\mu}$ | < 1.51 at 95% CL. | $0.79^{+0.58}_{-0.79}$ | 4.3%

$\kappa_i$ = $g_{Hi}/g_{H_i}^{SM}$

→ Higgs couplings to gauge bosons measured to 10-15% level.
→ Higgs couplings to 3rd-generation fermions measured at 20-30% level.
→ First bound on Higgs self-coupling ($\kappa_\lambda = \lambda_3/\lambda_3^{SM}$).
Extracted from production and decay strength measurements

[The Higgs XS WG, arXiv:1610.07922]
... where theoretical systematics plays a substantial role

\[
\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}} \\
\mu = 1.11^{+0.09}_{-0.08} \text{ (combined)}
\]

by production channel:

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>4.4</td>
</tr>
<tr>
<td>Systematic</td>
<td>6.2</td>
</tr>
<tr>
<td>Theory uncertainties</td>
<td>1.8</td>
</tr>
<tr>
<td>Signal</td>
<td>4.2</td>
</tr>
<tr>
<td>Background</td>
<td>2.6</td>
</tr>
<tr>
<td>Experimental (excl. MC stat.)</td>
<td>4.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.0</td>
</tr>
<tr>
<td>Background modeling</td>
<td>1.6</td>
</tr>
<tr>
<td>Jets, $E_{T}^{miss}$</td>
<td>1.4</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>1.1</td>
</tr>
<tr>
<td>Electrons, photons</td>
<td>2.2</td>
</tr>
<tr>
<td>Muons</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau$-lepton</td>
<td>0.4</td>
</tr>
<tr>
<td>Other</td>
<td>1.6</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>1.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainties</td>
<td>7.6</td>
</tr>
</tbody>
</table>

-2 ln $\Lambda$}

[ATLAS-CONF-2019-005]
Anatomy of theoretical predictions for hadronic collisions ...

Structure mainly **QCD dominated**

![Diagram](image)

- **red blob**: hard collision (partons)
- **blue radiation**: initial-state radiation (PS)
- **red radiation**: final-state radiation (PS)
- **purple blobs**: secondary scattering events
- **light green blobs**: parton to hadron transitions
- **dark green blobs**: hadron decays

Theoretical uncertainty affects predictions at multiple levels. Relevance of each is process dependent.
Starting point, schematically . . .

The hard cross section is calculated perturbatively

\[ \hat{\sigma}(ij \rightarrow X) = \alpha_s^k \alpha_e^h \sum_{m=0}^{n} \sum_{l=0}^{n-m} \hat{\sigma}_{ij}^{(m,l)} \alpha_s^m \alpha_e^l \]

\( n=0 \) : Leading Order (LO), or tree level or Born level

\( n=1 \) : Next to Leading Order (NLO), include \( O(\alpha_s) \) and \( O(\alpha_e) \) corrections

.....

and convoluted with initial state parton densities at the same order.

Renormalization and factorization scale dependence left at any fixed order \( (\mu: \mu_{R,F}) \)

\[ \sigma(pp, p\bar{p} \rightarrow X) = \sum_{ij} \int dx_1 dx_2 f_i^P(x_1, \mu) f_j^{\bar{P}}(x_2, \mu) \hat{\sigma}_{ij}(\mu, Q^2) \]

Systematic theoretical error from:

▷ PDF and \( \alpha_s(\mu) \);

▷ left over scale dependence;

▷ input parameters.

\( \leftarrow \) After which the parton shower takes over.
EW+Higgs precision physics in the LHC era: What does it imply for theory?

Q1: How accurate?

- Experimental errors on inclusive and exclusive observables will be significantly reduced to below 10%
  - \(\text{NNLO QCD}\) known for all processes (except \(t\bar{t}H\)), \(N^3\text{LO QCD}\) known for \(gg \rightarrow H\) and \(b\bar{b} \rightarrow H\).
  - \(\text{NLO EW+QCD corrections}\) known for all processes.
  - \(\text{Resummation}\) of specific kinematic- or cut-induced large (logarithmic) need to be included.
  - Effects previously neglected need to be reconsidered (mass effects, ...).
- Higher statistics gives access to distributions
  - Need at least \(\text{NLO accuracy}\), for both signal and background.
  - Need systematic control in matching to parton-shower Monte Carlo event generators.
  - Need to assure validity of theory predictions in all kinematic regimes (ex.: high \(p_T\), low \(p_T\), ...).

⇒ Illustrated with several examples in the following
Q2: How to interpret deviations from SM prediction?

- Disentangling evidence of new physics.
  - Model-specific approach: more stringent, yet arbitrary.
  - NP can just rescale the Higgs-boson couplings: \( \kappa_i = g_{Hi}/g_{H_i}^{SM} \): limited scope.
  - NP can introduce new structures in Higgs couplings: how to explore?
  - Effective Field Theory approach: less arbitrary, systematic, but less prone to simple prescriptions.

↓

Tomorrow’s Lecture
$gg \to H$ calculated at $N^3\text{LO}$

Fundamental building block of the whole Higgs-boson physics program: overall signal normalization.


dominated by soft-dynamics: cannot resolve Higgs coupling to gluons $(z \to 1, z = M_H^2/\hat{s})$.

HEFT: $m_t \to \infty$ limit

\[ \mathcal{L}_{\text{eff}} = \frac{H}{4v} C(\alpha_s) G_{\mu\nu} G_{\mu\nu} \]
ggH@N³LO: why is this a meaningful accuracy?

Dramatically improves theoretical accuracy to 5-6%:

\[ \sigma(13 \text{ TeV}) = 48.58^{+2.22}_{-3.27}(\text{th}) + 1.56(\alpha_s + \text{PDF}) \text{ pb} \]

where:

\[ 48.58 \text{ pb} = 16.00 \text{ pb} \ (\pm 32.9\%) \ (\text{LO, rEFT}) \]
\[ + 20.84 \text{ pb} \ (\pm 42.9\%) \ (\text{NLO, rEFT}) \]
\[ - 2.05 \text{ pb} \ (\pm 4.2\%) \ ((t, b, c), \text{exact NLO}) \]
\[ + 9.56 \text{ pb} \ (\pm 19.7\%) \ (\text{NNLO, rEFT}) \]
\[ + 0.34 \text{ pb} \ (\pm 0.2\%) \ (\text{NNLO, } 1/m_t) \]
\[ + 2.40 \text{ pb} \ (\pm 4.9\%) \ (\text{EW, QCD-EW}) \]
\[ + 1.49 \text{ pb} \ (\pm 3.1\%) \ (\text{N³LO, rEFT}) \]

Also, sensitive to other production modes:

\[ \sigma_{pp-H} \]

sensitive to

\[ \rightarrow m_t \text{ effects } (m_t \rightarrow \infty). \]
\[ \rightarrow \ldots \text{ but also } m_b, m_c \text{ effects.} \]
\[ \rightarrow \text{EW and EW-QCD corrects.} \]

[ATLAS-CONF-2017-047]
$H + j$ calculated at NNLO in HEFT ($m_t \rightarrow \infty$)

[Bhoughezal et al., arXiv:1504.07922] [Chen et al., arXiv:1408.5325]

← Extra jets present in all Higgs signatures: used to improve S/B ratios.

← Impact ubiquitously all Higgs searching channels (events binned by number of jets: H+0j, H+1j, ...).

← **High-$p_T$**: very important to improve by retrieving exact $m_t$ dependence $\rightarrow$ disentangle new-physics loop effects in $Hgg$ and $H\gamma\gamma$, and anomalous structures in Higgs couplings.

← **Low-$p_T$**: sensitive to light-quark masses in $ggH$ loop $\rightarrow$ measure $g_{Hb}$, $g_{Hc}$ [Bishara et al., arXiv:1606.09253]. Need to calculate it reliably $\rightarrow$ resummation of large logs. of $p_T/m_H$, $m_q/p_T$, and $m_q/m_H$. 

$\frac{\sigma}{d\sigma/dp_{T,H}} [\text{fb}/5\text{ GeV}]$

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$\frac{\sigma}{d\sigma/dp_{T,H}} [\text{fb}/5\text{ GeV}]$
Higgs $p_T$ spectrum: high $p_T$, exact $m_t$ dependence at NLO

> Important agreement: analytical result under the assumption $m_{t,H} \ll p_H^T$ (Kudashkin et al.) vs exact numerical result (Jones et al.)

> Large QCD effects ($K$ factor), but very similar to HEFT.

> Can combine with NNLO HEFT $K$ factor?

[Kudashkin et al., arXiv:1801.08226]  [Jones et al., arXiv:1802.00349]
Higgs $p_T$ spectrum: low $p_T$, resum large log. corrections

Resumming large logarithms for $p_T \ll M_H$.

Including mass corrections for $m_b \ll p_T \ll m_t$ (bottom-top interference).

Low-$p_T$ spectrum accuracy at 10-15% level.

[Caola et al., arXiv:1705.09127]

[Bizòn et al., arXiv:1804.07632]
$t\bar{t}H(H \rightarrow b\bar{b})$, NLO+PS validation

- crucial to measure $g_{Ht}$: discovered (5σ!) in Run II.
- Signal well understood (including NLO QCD+EW and PS).
- $t\bar{t} + b$ jets: dominant backgrounds for $t\bar{t}H(\rightarrow b\bar{b})$.
- NLO+PS tools: initially large discrepancies, being resolved by in depth studies of NLO PS tools plus NLO calculation of $t\bar{t}b\bar{b} + j$ [Pozzorini et al.], and NLO merging of $X + jj$ and $X + b\bar{b}$ [Siegert et al., arXiv:1904.09382]

[Pozzorini, et al., Higgs XS Working Group]
HH production at NNLO, full $m_t$ dependence

Measuring the Higgs-boson trilinear coupling

[14 TeV]

$\frac{d^2 \sigma}{d M_{hh} (fb/GeV)}$

$s = 14 \text{ TeV}$

$M_{hh} (GeV)$

$ratio to NLO$

$300 \leq M_{hh} \leq 800$

$0.8 \leq ratio \leq 1.4$

[100 TeV]

$\frac{d^2 \sigma}{d M_{hh} (fb/GeV)}$

$s = 100 \text{ TeV}$

$M_{hh} (GeV)$

$ratio to NLO$

$300 \leq M_{hh} \leq 800$

$0.8 \leq ratio \leq 1.4$

$\rightarrow$ above top threshold $m_t \rightarrow 0$ (EFT) cannot be trusted.

$\rightarrow$ Including full $m_t$ effects at NLO QCD:

$$\sigma_{\text{NLO}}(13 \text{ TeV}) = 27.78^{+13.8\%}_{-12.8\%} \quad \rightarrow \quad \sigma_{\text{NNLOFTapprox}}(13 \text{ TeV}) = 31.05^{+2.2\%}_{-5.0\%}$$

Most recent experimental result for $\kappa_{\lambda} = \lambda_3/\lambda_3^{\text{SM}}$,

$-11.8 \leq \kappa_{\lambda} \leq 18.8 \quad (95\% \text{ CL})$ \quad [CMS, PRL 122, 121803]

$-5.0 \leq \kappa_{\lambda} \leq 12.0 \quad (95\% \text{ CL})$ \quad [ATLAS, arXiv:1906.02025]

Or, extract trilinear coupling from indirect loop effects

[Degrassi et al., arXiv:1607.04251] $\to \kappa_\lambda > -14.3$

[Degrassi et al., arXiv:1702.01737] $\to -14 < \kappa_\lambda < 18$

[Kribs et al., arXiv:1702.07678] $\to -14 < \kappa_\lambda < 17.4$