The beginning of a new era
Combined results: the excess

Maximum excess observed at $m_H = 126.5$ GeV
Local significance (including energy-scale systematics) 5.0 $\sigma$
Probability of background up-fluctuation $3 \times 10^{-7}$
Expected from SM Higgs $m_H = 126.5$ 4.6 $\sigma$

4th July 2012
Figure 3: The expected and observed four-lepton invariant mass distribution for the selected Higgs boson candidates with a constrained Z boson mass, shown for an integrated luminosity of 36.1 fb⁻¹ and at $p_s = 13$ TeV assuming the SM Higgs boson signal with a mass $m_H = 125.09$ GeV.

Table 6: The expected and observed numbers of signal and background events in the four-lepton decay channels for an integrated luminosity of 36.1 fb⁻¹ and at $p_s = 13$ TeV, assuming the SM Higgs boson signal with a mass $m_H = 125.09$ GeV. The second column shows the expected number of signal events for the full mass range while the subsequent columns correspond to the mass range of $118 < m_{4l} < 129$ GeV. In addition to the $ZZ^*$ background, the contribution of other backgrounds is shown, comprising the data-driven estimate from Table 4 and the simulation-based estimate of contributions from rare triboson and $t\bar{t}V$ processes. Statistical and systematic uncertainties are added in quadrature.
2013 Nobel Prize in Physics

François Englert
Peter W. Higgs

2013 Nobel Prize in Physics

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs “for the theoretical discovery of a mechanism that contributes to our understanding of the weakness of the electromagnetic interaction in the standard model of particle physics.”

What Happened after the Big Bang?

Announcements of the 2013 Nobel Prizes

Physiology or Medicine:
Announced Monday 7 October

Physics:
Tuesday 8 October, 11:45 a.m. CET at the earliest

Chemistry:
Wednesday 9 October, 11:45 a.m. CET at the earliest

Literature:
Thursday 10 October 1.00 p.m. CET

Peace:
The conception: 1964
Electroweak symmetry breaking
The Higgs potential

\[ V(H) = -\mu^2 |H|^2 + \lambda |H|^4 \]

Who ordered that?

🔗 see talk by Mangano at Higgs Hunting 2019
The Higgs potential does not follow from first principles!

See talk by Mangano at Higgs Hunting 2019
The Higgs mechanism

- The **wonder**: the Higgs discovery confirmed the mechanism of spontaneous symmetry breaking postulated by Brout, Englert and Higgs almost fifty years before

- The **beauty** of this discovery is that the underlying idea (and mathematics) is incredibly simple

- The **power** of the idea: the Higgs mass fixes everything in the Standard Model
The Higgs is special

It is the only fundamental scalar with spin 0 we have seen so far

• Yukawa couplings (new type of interaction)
• Scalar-Gauge boson interactions
• Higgs potential: cornerstone of BEH mechanism, not yet probed experimentally

Discovery allows to access a new sector in the Lagrangian:

\[
\mathcal{L} = -\frac{1}{4} F_{\mu} F^{\mu} + i F \bar{D} \gamma \psi + \mathcal{L}_{\text{Higgs}}
\]
An incredibly rich program

Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

Tool for discovery
- portal to BSM
- portal to hidden sector
- portal to DM

Rare / beyond SM decays
- $H \rightarrow Z\gamma$
- $H \rightarrow \mu\mu$
- $H \rightarrow c\bar{c}$
- $H \rightarrow \tau\mu, \tau e, e\mu$
- $H \rightarrow J/\Psi\gamma, \Upsilon\gamma, \ldots$

... and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- ...

SM minimal or not?
- 2HDM
- MSSM, NMSSM
- extra Higgs states, doubly-charged Higgs
Higgs couplings

SM predictions for the couplings of heavier particles (gauge bosons, 3rd generation fermions) tested to about 10%

No stringent tests for lighter particles yet (1st and 2nd generation fermions)

Footprint of SM Higgs: mass versus coupling correlation

Electron, light quarks, neutrinos
Largest contribution from theory

Given the detailed projections from the experiments substantial further progress will be needed from theory calculations if these are not to become a limiting factor in interpreting a wide range of High-Luminosity LHC (HL-LHC) data.
Looking at the present:

- $H \rightarrow ZZ^* \rightarrow 4\ell$
  - Still statistics limited with 140 fb$^{-1}$
  - ggF measurement precision reaches precision of SM prediction
ggf Higgs at $N^3$LO

Dominant uncertainties (PDF & $\alpha_s$) will be reduced by new data and new input from lattice for $\alpha_s$ (PDG error on $\alpha_s$ already reduced from 0.015 to 0.011)

$\Rightarrow$ A reduction of the uncertainty by a factor 2 seems realistic
Rapidity at $N^3LO$

**New at $N^3LO$:**
Higgs rapidity (using a threshold expansion)

All ingredients available to have fully differential Higgs production at $N^3LO$ accuracy

⇒ Remarkable stability of perturbative expansion

Dulat, Mistlberger, Pelloni 1810.09462
VBF Higgs at $N^3$LO

Inclusive Vector Boson Fusion Higgs cross-section (DIS approx.)

Dreyer & Karlberg 1606.00840

NB: NNLO non-factorizable effects sub-percent

Liu et al. 1906.10899
N^3LO: future prospects?

In the two cases where N^3LO results are known, the series shows a remarkable convergence and stability:

• it will be interesting to see whether the same pattern holds for e.g. associated Higgs production and other Higgs background processes (WW, ZZ, etc)

• it will be interesting to see how stable the picture is with realistic LHC fiducial cuts (e.g. Higgs cross-section with jet-veto)
Higgs transverse momentum

quark couplings

new heavy particles

N^3\text{LL}

b,c mass effects

transverse momentum

EW effects

NNLO (large m_t)

NLO (finite m_t)
Higgs transverse momentum

Today impressive level of sophistication (NNLO+N^3LL at low pt and NLO exact at high pt), still theory uncertainty about 20%
Higgs transverse momentum

Low transverse momentum: sensitivity to light Yukawa coupling (b and 2nd generation)
Higgs transverse momentum

High transverse momentum: sensitivity to New Physics (resolve heavy particles circulating in loops)

HEFT: $m_t \rightarrow \infty$ limit

NLO loop-induced: different scaling behaviour at large $p_T$

Similarly to top-loops, new particles will largely affect the shape at high $p_T$
**H(→4l)+jet @ NNLO**

Chen, Gehrmann, Glover, Huss 1905.13738

Good agreement with ATLAS and CMS data (within their larger errors)

ATLAS lepton isolation: removal of non-isolated jet

CMS lepton isolation: removal of non-isolated lepton → worse convergence of acceptance at fixed-order
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Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)
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Good agreement with ATLAS and CMS data (within their larger errors)

Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)

But example also illustrates shortcomings of NNLO calculations, where only 2 leptons from the Higgs decay are present

ATLAS

CMS lepton isolation: removal of non-isolated lepton → worse convergence of acceptance at fixed-order
NNLO or PS?

**NNLO:**
good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only

**Parton shower:**
less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects
NNLO or PS?

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less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects

Matching of NLO & parton shower achieved in seminal papers about 15y ago


Today: NLO+PS codes (MC@NLO, POWHEG, Sherpa) well-established and used in all advanced LHC analyses
Matching of NNLO and parton shower (=NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final states.

**NNLOPS:** currently three methods exist (UNNLOPS, Geneva, MiNLO) but very hard to extend to generic $2 \rightarrow 2$ processes.

Hoeche, Li, Prestel [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh [Geneva]
NNLOPS

Example: associated HW production with cuts used by HXSWG

- PS and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables

<table>
<thead>
<tr>
<th>BIN 1 (no jets)</th>
<th>BIN 2 (no jets)</th>
<th>BIN 3 (no jets)</th>
<th>BIN 1 (with jets)</th>
<th>BIN 2 (with jets)</th>
<th>BIN 3 (with jets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.95</td>
<td>7.51</td>
<td>2.02</td>
<td>58.65</td>
<td>10.65</td>
<td>3.97</td>
</tr>
<tr>
<td>77.93</td>
<td>8.20</td>
<td>2.34</td>
<td>56.52</td>
<td>10.05</td>
<td>3.65</td>
</tr>
<tr>
<td>80.13</td>
<td>8.46</td>
<td>2.43</td>
<td>54.33</td>
<td>9.79</td>
<td>3.57</td>
</tr>
</tbody>
</table>

Bizon et al. 1603.01620
NNLOPS without reweighing

**MiNNLOPS**: NNLO at generation time (no additional) reweighing

\[
\frac{d\sigma}{d\Phi_{FJ}} = \exp[-\tilde{S}(p_T)] \left\{ \frac{\alpha_s(p_T)}{2\pi} \left[ \frac{d\sigma_{FJ}}{d\Phi_{FJ}} \right]^{(1)} \left( 1 + \frac{\alpha_s(p_T)}{2\pi} [\tilde{S}(p_T)]^{(1)} \right) \\
+ \left( \frac{\alpha_s(p_T)}{2\pi} \right)^2 \left[ \frac{d\sigma_{FJ}}{d\Phi_{FJ}} \right]^{(2)} + \left( \frac{\alpha_s(p_T)}{2\pi} \right)^3 [D(p_T)]^{(3)} F_{\text{corr}}(\Phi_{FJ}) \right\} \\
\times \left\{ \Delta_{\text{wg}}(\Lambda) + \int d\Phi_{\text{rad}} \Delta_{\text{wg}}(p_{T,\text{rad}}) \frac{R(\Phi_{FJ}, \Phi_{\text{rad}})}{B(\Phi_{FJ})} \right\} + O(\alpha_s^3)
\]

Monni, Nason, Re, Wiesemann, GZ 1908.06987
**MC uncertainty: example ttH**

Dominant background from ttbb:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Tool</th>
<th>$\sigma_{NLO}$ [fb]</th>
<th>$\sigma_{NLO+PS}$ [fb]</th>
<th>$\sigma_{NLO+PS}/\sigma_{NLO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_b \geq 1$</td>
<td>SHERPA+OPENLOOPS</td>
<td>12820$^{+35%}_{-28%}$</td>
<td>12939$^{+30%}_{-27%}$</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>MadGRAPH5_AMC@NLO</td>
<td>13833$^{+37%}_{-29%}$</td>
<td>10073$^{+45%}_{-29%}$</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>PowHel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_b \geq 2$</td>
<td>SHERPA+OPENLOOPS</td>
<td>2268$^{+30%}_{-27%}$</td>
<td>2413$^{+21%}_{-24%}$</td>
<td>1.06</td>
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<tr>
<td></td>
<td>MadGRAPH5_AMC@NLO</td>
<td>3192$^{+38%}_{-29%}$</td>
<td>2570$^{+35%}_{-28%}$</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>PowHel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Shower effects large and MC dependent in Higgs region!*

Recoil effect? Bin migration? b-definition? $g \rightarrow bb$ contamination… ?

Resummed calculations crucial to validate logarithmic accuracy of parton showers

*Needs to be understood!*

☞ see talk by Caola at Higgs Hunting 2019
Resummations

Current status: in several cases, the accuracy of all-order resummed predictions pushed to NNLL or even $N^3\text{LL}$, properly matched to fixed order
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3) NNLO QCD computations work in “hard kinematic regions”. For an object with the invariant mass $O(100)$ GeV, “hard” means down to transverse momenta $O(30)$ GeV. This requires NNLO. Resummations are important but with NNLO results available, they become relevant at low(er) transverse momenta;
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Both points seem to imply that resummations are not quite that useful. I want to argue that this is not true.
Resummations

Even if the hard scale is $O(100 \text{ GeV})$, fiducial cuts can push all the kinematics at low transverse momentum values, e.g., for Higgs production the bulk of the cross section lies well below 30 GeV.

*Double differential resummed predictions*, e.g., NNLL resummed predictions for the Higgs transverse momentum with a veto on jets.

Reminder: jet-veto is required in the WW decay channel to suppress top background

Monni et al. ’19
Other joint resummations

Increasing interest in resummations in more exclusive regions

- $p_{t,H}$ and small-$x$  
  Lustermans et 1605.027400; Muselli et al. 1701.01464
- $p_{t,H}$ and large-$x$  
  Marzani 1511.06039; Forte and Muselli 1511.05561
- small-$x$ and large-$x$  
  Bonvini and Marzani 1802.07758
- $p_{t,H}$ and jet-radius  
  Banfi et al. 1511.02886
- $p_{t,V}$ and 0-jettiness  
  Lustermans et al. 1901.03331
- 2 angularities  
  Larkoski et al. 1501.4458; Procura et al. 1806.10622

Resummations no longer limited to inclusive observables

$\rightarrow$ closer connection between resummed predictions and measurements
Our Higgs factory

Higgs discovery: $N_{\text{Higgs}} \sim 0.6 \text{ mio.}$

Today: $N_{\text{Higgs}} \sim 7 \text{ mio.}$

Long Shutdown 1: 2011-2015
- Experiment beam pipes
- 7 TeV
- 30 fb$^{-1}$

Long Shutdown 2: 2016-2018
- Experiment upgrade phase 1
- 13 TeV
- 150 fb$^{-1}$

- HL-LHC installation
- 14 TeV
- 300 fb$^{-1}$

Run 1: 2011-2015
- 7 TeV

Run 2: 2015-2018
- 13 TeV

Run 3: 2019-2023
- 14 TeV

Run 4-5: 2024-2026
- 14 TeV

Total: 300 fb$^{-1}$

Long Shutdown 3: 2024-2026
- Experiment upgrade phase 2
- Integrated luminosity
- 3000 fb$^{-1}$

Run 4-5: 2024-2026
- 14 TeV

$N_{\text{Higgs}} \sim 16 \text{ mio.}$

$N_{\text{Higgs}} \sim 164 \text{ mio.}$
Did you know that? About $10^6$ Higgs bosons are produced every year from proton cosmic rays in our atmosphere! We just don’t have detectors to see them…
Beyond the Standard Model

Many open questions imply physics Beyond the Standard Model:

- The hierarchy problem
- Neutrinos are not massless
- Dark matter is not accounted for
- No explanation for the baryon asymmetry in the universe
- Solution to the strong CP problem?
- Gauge-coupling unification does not work (is it a hint?)
- No explanation for the inflationary period of the early universe
- Gravity not included in the picture
Beyond the Standard Model

Many open questions imply physics Beyond the Standard Model:

- dark matter
- neutrino masses
- inflation
- baryogenesis
- strong CP problem
- hierarchy problem

Only the hierarchy problem suggest a scale for New Physics
Precision and energy reach

New physics likely heavy $\Rightarrow$ use effective field theory (EFT)

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6} \]

- At low energy, e.g. Higgs couplings

\[ g = g_{\text{SM}} \left( 1 + c \frac{v^2}{\Lambda^2} \right) \]

- At high energy ($E$), e.g. oblique parameters in $V_LV_L$ scattering ($V=W, Z, h$)

\[ g = g_{\text{SM}} \left( 1 + c \frac{E^2}{\Lambda^2} \right) \]
Precision and energy reach

New physics likely heavy ⇒ use effective field theory (EFT)

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^2} O_i^{D=6} \]

scale of new physics

per-mille accuracy at LEP \( \approx \) 10% accuracy at 1 TeV
1% accuracy at 1 TeV \( \approx \) 10% accuracy at 3 TeV
0.1% accuracy at 1 TeV \( \approx \) 10% accuracy at 10 TeV

\[ g = g_{\text{SM}} \left( 1 + c \frac{v^2}{\Lambda^2} \right) \]

\[ g = g_{\text{SM}} \left( 1 + c \frac{E^2}{\Lambda^2} \right) \]
Higgs without the Higgs

With more and more precise LHC measurements and future collider programs, start to see clearly the connection between different sectors. It is then useful to think what we can learn from them.

- What can be learnt on the Higgs from measurements in other sectors?
- What can be learnt on other sectors from Higgs measurements?
Higgs without the Higgs

\[ \kappa_t \quad |H|^2 Q \tilde{H} t_R \]
\[ \sim \text{const} \]

\[ \kappa_G \quad |H|^2 G_{\mu\nu}^a G^{a \mu\nu} \]
\[ \sim E^2 \]

\[ \kappa_{\gamma} \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \]
\[ \kappa_{Z\gamma} \quad |H|^2 W_{\mu\nu}^a W^{a \mu\nu} \]

\[ \kappa_V \quad |H|^2 \partial_\mu H^\dagger \partial^\mu H \]
Possible future colliders

From Ursula Bassler, Granada 2019
Possible future constraints

$\kappa_W$ (%)

$\kappa_Z$ (%)

$\kappa_\tau$ (%)

$\kappa_\tau$ (%)

$\kappa_b$ (%)

$\kappa_g$ (%)

$\kappa_\gamma$ (%)

$\kappa_\eta$ (%)

$\kappa_\mu$ (%)

$\kappa_{\gamma\gamma}$ (%)

Br$_{inv}$ (<%, 95% C.L.)

Br$_{unt}$ (<%, 95% C.L.)

**Higgs@FC WG**

- FCC-ee+FCC-eh+FCC-hh
- FCC-ee365+FCC-ee240
- FCC-ee240
- CEPC
- CLIC3000+CLIC1500+CLIC380
- CLIC1500+CLIC380

All future colliders combined with HL-LHC

Kappa-3, May 2019
- CLIC380
- ILC500+ILC350+ILC250
- ILC250
- LHeC (|\kappa_\gamma| < 1)
- HE-LHC (|\kappa_\gamma| < 1)
- HL-LHC (|\kappa_\gamma| < 1)
Deep learning for Higgs

Additional amount of data needed to reach the ML-sensitivity without ML

About 15-125% gain on LHC running. Further improvements?
Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.
New opportunities

Examples of where precision and theoretical ingenuity brought in new opportunities:

- Higgs width from ratio off-shell to on-shell cross-section
- Constraints on light Yukawa from Higgs $p_T$ spectrum
- Constraints on Higgs-self coupling from single Higgs production modes

All theoretical ideas implemented in experimental analyses and provided new experimental bounds
Your proposal is innovative. Unfortunately, we won’t be able to use it because we’ve never tried something like this before.”
Your proposal is innovative. Unfortunately, we won’t be able to use it because we’ve never tried something like this before.”
New ideas wanted!!
Conclusions

❖ Higgs studies are just out of their infancy. So far, the Higgs looks very much Standard Model like

❖ The scalar sector is connected to profound questions (naturalness, vacuum stability, flavour)

❖ The discovery allows us to explore a new sector with a broad experimental program that will extend over decades

❖ There is much more, fundamental to learn about the Higgs sector in the years to come
Stay healthy and live long

Grojean EPS 2019
Stay healthy and live long

Grojean EPS 2019

Sharpen your axe!

Give me six hours to chop down a tree and I will spend the first four sharpening the axe.

A. Lincoln