Concluding remarks and a look to the future

Fabiola Gianotti (CERN), 4 July 2022
Initial remarks

1. Experimental verification of the Brout-Englert-Higgs mechanism through the discovery of the Higgs boson: monumental step forward in our understanding of fundamental physics, with wide-ranging implications for particle physics and beyond.

2. Higgs boson discovery is the culmination of a long journey (completion of the Standard Model!) and the beginning of a new era:
   - the Higgs boson is profoundly different from all elementary particles discovered previously (first elementary scalar?)
   - brings new interactions (Yukawa, self-interaction)
   - is related to the most obscure sector of the Standard Model and linked to some of the deepest structural questions (flavour, naturalness/hierarchy, vacuum, ...)

Higgs boson discovery opens new paths of exploration, provides a unique door into new physics, and calls for a compelling and broad experimental programme which will extend for decades at the LHC and beyond.

3. Nature has been kind to us: $m_H = 125 \text{ GeV}$ !!
   - all production and large number of decay modes accessible, allowing a vast, detailed and robust portrait of the new particle.
A relatively quick discovery …

- Fast ramp up of the LHC achieving $\sim 7 \times 10^{33}$ in 2012 and excellent availability in Spring/Summer 2012
- Detector performance close to (or better than) target; fast development of methods to mitigate the impact of pile-up
- Excellent performance of the WLCG → data processed and distributed quickly to the worldwide community for analysis
- Nature: actual Higgs production cross-section (N3LO) is $\sim 3$ larger than predictions used in the past (LO)

2.5-3 times larger cross-sections at 14-16 TeV than at 8 TeV ~ offset by cross-section increase from LO to N3LO
In the last 10 years we have come a long way ...
Superb performance of the accelerator complex $\rightarrow$ > 30 times more Higgs bosons available than in 2012

Superb (understanding of) performance of ATLAS and CMS detectors (despite aging, huge pile-up, ...)

Superb performance of WLCG in handling floods of data (storage, simulation, reconstruction, distribution, analysis, ...)

Much improved analysis methods (machine learning, statistical treatment, etc.) boosting detector performance and physics sensitivity

Very fruitful theory-experiments collaboration (e.g. in the framework of LHC Higgs XS WG and LPCC)

Lots of new ideas have made “impossible at hadron colliders” channels become accessible

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TODAY (numbers below are per experiment):

- All main Higgs boson production modes (ggF, VBF, VH, ttH+tH) established at > 5$\sigma$
- Couplings to gauge bosons (established in Run 1) measured to 6-8%
  - Couplings to 3$^{rd}$ generation fermions (established in Run 2) measured to 7-11%
  - Couplings to 2$^{nd}$ generation fermions: 3$\sigma$ evidence for $H \rightarrow \mu\mu$; first constraints on $H \rightarrow cc$
- Rare decays (e.g. $H \rightarrow Z\gamma$; $H \rightarrow ll\gamma$ at ~ 3$\sigma$ level)
- Limits on invisible and exotic decays
- HH production: sensitivity x 3 SM cross-section
- Mass measured to ~ 0.1%
- Width measurement from off-shell/on-shell production demonstrated (3.6$\sigma$ evidence for H off-shell production)
- $J^{CP=0^{++}}$ (large number of alternative hypotheses excluded > 99.9% C.L.)
- Inclusive studies complemented by increasing variety of differential/exclusive measurements (useful to constrain theory; provide additional constraints on couplings; sensitive to new physics in quantum loops affecting kinematic distributions)
- Searches for additional Higgs bosons (no sign yet ...)
- Etc. etc.

Note: some of the above measurements were not expected to be possible in Run 2
Accelerator complex and luminosity

~ 90% of delivered luminosity used by the experiments (high data-taking efficiency and excellent data quality)

Peak $L \sim 7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
~ $12$ fb$^{-1}$ at $\sqrt{s} = 7$-8 TeV
~ 250 000 Higgs bosons produced per experiment

Peak $L \sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
~ $189$ fb$^{-1}$ (~$160$ fb$^{-1}$ at $\sqrt{s} = 13$ TeV)
~ 9 M Higgs bosons produced per experiment

July 2012

Today

2011 vs = 7 TeV
2012 vs = 8 TeV
2015 - 2018 vs = 13 TeV

Integrated luminosity [fb$^{-1}$]
Evolution of the performance for several objects in CMS from 2012 to 2022

- Tau energy scale
- Luminosity uncertainty
- Photon energy scale contribution in Hgg
- Jet Energy Scale (low pt)
- Jet Energy Scale (high pt)
- bTag efficiency @1% mistag
- Tau tagging efficiency @0.5% mistag
- Jet energy resolution @30 GeV, PU=25
Detector performance

Light jet rejection - $b$ tagging efficiency $\varepsilon = 70\%$

- **JetProb 2010**
  Initial tagger based on track impact parameter
  ATLAS-CONF-2011-102

- **IP3D-JetFitter/SV1 2011-2012**
  Impact Parameter (IP) and Secondary Vertex (SV) tagger
  ATLAS, JINST 11 (2016) P04008

- **MV1 2014**
  Tagger combination based on MultiVariate method (MV)
  ATLAS, JINST 11 (2016) P04008

- **MV2c20 - IBL 2018**
  MV tagger after IBL insertion at Run 2
  ATLAS, JINST 13 T09008 (2018)

- **DL1r* 2019**
  Deep Learning Neural Network tagger

- **GN1 2021**
  Graph Neural Network tagger
  ATL-PHYS-PUB-2022-027

* Variation in efficiency due to lower jet threshold and improved charm rejection
Computing - WLCG

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0 → T1 transfer rate (GB/s, peak)</td>
<td>5.7</td>
<td>33.4</td>
</tr>
<tr>
<td>Global WLCG transfer rate (GB/s, peak)</td>
<td>15</td>
<td>80 (during data challenges)</td>
</tr>
<tr>
<td>Total processing power (HS06 hours/month)</td>
<td>1.6 B</td>
<td>9.1 B</td>
</tr>
<tr>
<td>Number of cores in use (WLCG only)</td>
<td>~ 250 k</td>
<td>~ 1 M</td>
</tr>
<tr>
<td>Total disk space (PB)</td>
<td>170</td>
<td>750</td>
</tr>
<tr>
<td>Total tape (PB)</td>
<td>170</td>
<td>1200</td>
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The big success of the Worldwide LHC Computing Grid: outstanding performance right from the beginning of the LHC operation, thanks also to the strong support of the Funding Agencies.

CPU Delivered: HS06 hours per month

July 2012: few hundred thousand cores in use all time

July 2022: ~ 1 M WLCG cores in use all time
Reducible backgrounds from Z+jets, Zbb, tt giving 2 genuine + 2 fake leptons measured using background-enriched, signal-depleted control regions in data.

Typical control regions:
- leading lepton pair (l1,l2) satisfies all selections
- sub-leading pair (l1,l2): no isolation nor impact parameter requirements applied

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwidth, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment.

Data well described by MC within uncertainties (ZZ excess at high mass ...)

- Samples of Z^+Z^- and Z^+e^- used to compare efficiencies of isolation and impact parameter cuts between data and MC → good agreement → MC used to estimate background contamination in signal region
- Several cross-checks made with different control regions → consistent results
Huge theoretical progress (N3LO-QCD, NNLO Monte Carlos with PS matching, N3LL resummations matched to fixed order, etc.)

Challenge: theoretical uncertainties on signal and backgrounds already important today, will become dominant in many cases with increased Run 3 and HL-LHC statistics
Current precision on inclusive cross-sections: typically few percent over almost 14 orders of magnitude!
H → 4 leptons

July 2012

Today

Peak at $m_{4l} \sim 90$ GeV from $Z \rightarrow 4l$ production
Higgs boson production and decay measurements

July 2012

Overall signal strength normalised to SM expectation:

\[ \mu = 0.87 \pm 0.23 \]

Today

Overall signal strength normalised to SM expectation:

\[ \mu = 1.002 \pm 0.057 \]
A look to the future
Higher peak luminosity and larger pile-up (from ~ 30-40 to 140-200 events/interaction) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwidth, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment.

→ Major upgrades of ATLAS and CMS

Event with 78 reconstructed vertices (CMS Run 2 data)
Note: ~ 20 expected when detectors were designed

New timing detectors with resolution ~ 30 ps in both experiments for 4-dimensional identification of primary vertex

For illustration, adapted from Chris Tully (courtesy André David).
Higgs boson at HL-LHC

Factor ~ 20 larger data sample than today (3000 fb\(^{-1}\), ~180 M Higgs produced per experiment) and improved detectors $\rightarrow$ significant increase in sensitivity to new physics and precise measurements, e.g. rare production and decay modes, differential distributions, searches for additional H, etc.

Global fit assuming no BSM contributions to $\Gamma_H$.
- 3-4 times more precise than today
- first 5$\sigma$ observation of $H \rightarrow Z\gamma$ ($H \rightarrow \mu\mu$ already in Run 3)
- experimental precision challenges theory

First observation of HH production (~ 5$\sigma$ level)

\[ \mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4 \]

Today:
- ATLAS : cross-section < 2.4 $\times$ SM (2.9 expected), $-0.6 < k_\lambda < 6.6$ 95% C.L.
- CMS : cross-section < 3.4 $\times$ SM (2.5 expected), $-1.24 < k_\lambda < 6.49$ 95% C.L.
Higgs boson(s) at HL-LHC

$p^H_T$ spectrum (sensitive to new physics) can be measured to few percent up to 600 GeV by combining ATLAS and CMS

Additional MSSM Higgs bosons can be excluded from direct searches or H (125) measurements well into the several TeV region.

Branching ratio into invisible: $B_{\text{inv}} < 2.5\%$ at 95% C.L.

Coupling to charm-quark: $|k_c| < 1-2$

$\Gamma_H$ to 20% from off-shell $H \rightarrow ZZ$ cross-section and 5% from coupling fits (assuming $|k_V| \leq 1$)

Addressing increasingly challenging final states (e.g. charm tagging, $E_T^{\text{miss}}$ at very high pile-up) requiring ingenuity and analysis improvements.
Higgs boson measurements at future colliders

Future Circular Collider (FCC): input from FCC-ee (e.g. HZZ coupling and ttZ cross-section) removes model-dependence of several couplings that are best measured at FCC-hh (e.g. $H \rightarrow \mu\mu$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$, $ttH$)
The Higgs boson discovery in 2012 opened a new era of exploration at the LHC, HL-LHC and future colliders.

The fundamental questions surrounding the Higgs boson (naturalness, origin of flavor and masses, CP-violation and baryogenesis, vacuum stability, existence of additional Higgs bosons, portal to dark sector, etc.) make it an extraordinary discovery tool.

Progress in accelerator, detector and computing technologies, theory, and analysis techniques, as well as lot of ingenuity, will be needed to fully exploit the discovery power of this special particle at current and future colliders.
A bright future ahead for generations of scientists!

The Higgs boson discovery, and the many beautiful accomplishments since then at the LHC, demonstrate the talent, competence, perseverance and determination of the worldwide high-energy physics community, and its ability to deliver beyond expectation. These are crucial assets for future, even more ambitious projects.
Many thanks to

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