Prospects for Higgs Physics at the (HL-)LHC

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XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Santiago de Compostela
2-6 May 2022
10 years after the Higgs boson discovery

- All main production modes observed
  - couplings measured with 10-50% precision

Spin/parity: $J^{PC} = 0^{++}$
- spin 1 and 2 excluded at > 99% CL

Mass: precision < 0.2% (140 MeV)
**Context**

- Only **5%** of total LHC dataset delivered
  - already ~8 million Higgs bosons per experiment

- Prospects studies done by the ATLAS and CMS collaborations in the past years

- **European Strategy** for Particle Physics 2018-2020
  - CERN Yellow Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC ([link](#))
  - symposium in 2019 + briefing book ([link](#)) + conclusions ([link](#))

- **US Snowmass process** 2020-2022
  - to identify the most important questions in HEP and the tools and infrastructure required to address them
  - meeting in July 2022, book end of 2022
  - White paper by ATLAS and CMS ([link](#))
Run 3 of the LHC

♦ First beam on the 22\textsuperscript{nd} of April!

♦ Expected integrated luminosity: \(~350\ \text{fb}^{-1}\)
  - pile-up similar to Run 2 + upgraded muons system, but generally radiation damaged detectors

♦ Centre-of-mass energy: 13.6 TeV
Higgs boson at Run 3

- Increase in Higgs boson production cross-section from the centre of $\sqrt{s}$:

<table>
<thead>
<tr>
<th>Process</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>+7.5%</td>
</tr>
<tr>
<td>VBF</td>
<td>+7.9%</td>
</tr>
<tr>
<td>WH</td>
<td>+6.2%</td>
</tr>
<tr>
<td>ZH</td>
<td>+6.9%</td>
</tr>
<tr>
<td>ttH</td>
<td>+12.6%</td>
</tr>
<tr>
<td>HH</td>
<td>+11%</td>
</tr>
</tbody>
</table>

- In general: measurements that are still statistically limited with Run 2 dataset

- **Differential** cross-section measurements

- Couplings to 2\textsuperscript{nd} generation
  - $H \rightarrow \mu\mu$: first evidence by the CMS collaboration with Run 2 dataset:
    - observed (expected) signal significance of 3.0$\sigma$ (2.5$\sigma$)
    - ATLAS Run2: observed (expected) signal significance of 2.0$\sigma$ (1.7$\sigma$)
    - projected CMS analysis: 5$\sigma$ can be achieved with $L \approx 300$ fb\textsuperscript{−1} of data (at = 14 TeV)
    - also sensitivity to $VH(\rightarrow c\bar{c})$

- Rare decay: $H \rightarrow Z(\rightarrow ee/\mu\mu)\gamma$ : $\text{BR} = 0.1 \times 10^{-3}$
  - full Run 2 significance:
    - ATLAS: 2.2$\sigma$ (expected 1.2$\sigma$)
    - CMS: 2.7$\sigma$ (expected 1.2$\sigma$)
  - 5$\sigma$ expected at HL-LHC ⇒ evidence could be expected by the end of Run 3
♦ From 2029 to ~2040
♦ Total integrated luminosity: 3000 fb\(^{-1}\) /experiment
  - peak luminosity *5-7 wrt Run 2-3
♦ Center-of-mass energy: 14 TeV

♦ **Upgrades** of ATLAS and CMS to cope with aging, pile-up, radiation
  - possible to maintain (or even improve!) Run 2 performance (reconstruction efficiencies, calibration, etc) despite harder environment
HL-LHC analyses

♦ Extrapolated from Run-2, or dedicated analyses with parameterised performance

♦ Assumption on systematics: Run 2 or ‘YR2018’:
  - statistics-driven sources: data $\rightarrow \sqrt{L}$, simulation $\rightarrow 0$
  - theory uncertainties typically halved
  - intrinsic detector limitations stay $\sim$constant
  - luminosity uncertainty 1%
  - PDF uncertainties: pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets, etc
    ● optimistic (A) and conservative (C) scenarios
      
      - reduction of PDF uncertainties by almost a factor 4 in the optimistic scenario in the gg channel, and around a factor 3 in the q\bar{q} and qq channels
  - VH($\rightarrow$ bb) and H($\rightarrow$ $\tau\tau$) studies for Snowmass2021 showed that ‘YR2018’ assumptions could be achieved
**Mass**: new projection of CMS measurements
- $H \to \gamma\gamma$: $20 \text{ (stat)} \oplus 70 \text{ (syst)}$ MeV
- $H \to ZZ \to 4l$: $30 = 22 \text{ (stat)} \oplus 20 \text{ (syst)}$ MeV
- reach of 10-20 MeV precision plausible goal, dependent on future improvements of muon momentum measurements

**Width** (SM = 4.07 MeV): Direct measurement will be challenging also with HL-LHC statistics.
- new CMS 4lepton onshell: upper limit of 177 MeV at 95% CL
- 4lepton onshell+offshell: 20% precision at 68% CL combining CMS+ATLAS (assumption that ratio from SM)
- from couplings: $\Gamma_H$ 5% precision at 95% CL, but model dependent
- diphoton interference study, only weaker constraints
 Modification of CP-structure to the couplings to τ leptons could account for the observed baryon asymmetry of the universe in certain baryogenesis models
  - described in terms of an effective mixing angle α_{Hττ}:
    • 0° = pure scalar coupling, 90° = pure pseudoscalar coupling
    • any other value = mixed couplings between CP-even and CP-odd components

If α_{Hττ} = 0°, expected uncertainty of 5%  
  - ~independent from the systematic uncertainty assumptions  
  - 20% uncertainty with Run-2 data
Precision on cross-sections and $\kappa$ modifiers between 2 and 4%

- limited by experimental and mostly theoretical systematics
  - except for $\kappa_\mu$ and $\kappa_{Z\gamma}$

Importance of systematic uncertainties, example of $t\bar{t}H(\rightarrow b\bar{b},\text{dilepton})$ channel:

$\mu_i = \frac{\sigma_i \cdot \text{BR}_{i}}{\sigma_{\text{SM}} \cdot \text{BR}_{\text{SM}}} = \frac{\kappa_i^2}{\kappa_H^2}$

$(\sigma \cdot \text{BR})(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$

more information on the $\kappa$ framework in the talk by P. Windischhofer
Higgs couplings at HL-LHC (2)

♦ 2nd generation: Coupling to muons through $H \rightarrow \mu\mu$

♦ Extrapolations of Run 2 analyses
  - improvement of the acceptance and resolution thanks to the extension of the coverage of the CMS muon system ($|\eta| < 2.8$) and ATLAS inner tracker ($|\eta| < 4$)

♦ Expected precision on signal strength (YR2018 uncertainties):

<table>
<thead>
<tr>
<th></th>
<th>Statistical</th>
<th>Experimental</th>
<th>Theoretical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS YR2018</td>
<td>+12%</td>
<td>2.00%</td>
<td>+5%</td>
<td>13%</td>
</tr>
<tr>
<td>CMS Snowmass2013</td>
<td></td>
<td></td>
<td></td>
<td>14%</td>
</tr>
<tr>
<td>CMS YR2018</td>
<td>9%</td>
<td>2%</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>CMS Snowmass2021</td>
<td>6%</td>
<td>2%</td>
<td>2%</td>
<td>7%</td>
</tr>
</tbody>
</table>

expected precision on $\kappa_\mu$ (CMS Snowmass2021): 3.5%

2\textsuperscript{nd} generation: Coupling to \textit{charm} through VH (H\rightarrow c\bar{c})

CMS Run2 (most stringent limits up to date):
- both resolved and boosted jets, and new c-taggers
- observed (expected) upper limit on cross-section: 14 (7.6^{+3.4}_{-2.3}) times the SM
- observed limit on $\kappa_c$: $1.1 < |\kappa_c| < 5.5$ (expected $|\kappa_c| < 3.4$)

CMS HL-LHC:
- 3 $c\bar{c}$-enriched categories and 3 $b\bar{b}$-enriched categories
- expected best fit values:
  - $\mu_{VH(H\rightarrow b\bar{b})} = 1.00 \pm 0.03 \text{ (stat)} \pm 0.04 \text{ (syst)}$
  - $\mu_{VH(H\rightarrow c\bar{c})} = 1.00 \pm 0.60 \text{ (stat)} \pm 0.5 \text{ (syst)}$

Also ATLAS HL-LHC projection but less sensitive
- only resolved jets in this extrapolation
- boosted H(bb) analyses using substructure methods, developed in Run 2
Higgs couplings at HL-LHC (4)

♦ Higgs invisible width

♦ Current ATLAS and CMS Run 2:
  - global coupling fit $\text{BR}(H\rightarrow\text{inv}) < 4.2\%$ @ 95% CL if $\text{BR}(\text{BSM}) \geq 0$ (any invisible or undetected states)
  - direct searches: $\text{BR}(H\rightarrow\text{inv}) < 10\%$ at 95% CL

♦ Prospects of direct searches @14TeV:
  - VH: ATLAS, 2013: <8% @ 95%CL
  - VBF: CMS, 2018: <3.8% @ 95%CL
    - full reoptimization of the analysis at 200 pile-up to study how to handle the impact of pile-up in $E_T^{\text{miss}}$
  - combination: $\text{BR}(H\rightarrow\text{inv}) < 2.5\%$ @ 95% CL
Differential cross-sections at HL-LHC (1)

- Sensitive to $\kappa_b/\kappa_c$ at low $p_T^H$ and $\kappa_t / \text{BSM}$ at high $p_T^H$

![Graph showing CMS projection](image)

- Expected precision of $\sim 10\%$ for $p_T^H > 350 \text{ GeV}$, statistically limited
♦ For Snowmass2021: couplings in Simplified Template Cross Section framework for
  - measurements into bins of key variables such as Higgs transverse momentum ($p_T^H$), jet multiplicity (Njets), and dijet invariant mass (mjj)
♦ VH$(\rightarrow b\bar{b})$ and $H \rightarrow \tau\tau$

- $p_T^H > 250$-300 GeV (sensitive to BSM) could be measured with a precision of $\sim 10\%$
  - better than theoretical uncertainties for $H \rightarrow \tau\tau$
Through the HH production
- rare process of the Standard Model ($\sigma(HH)/\sigma(H) = 0.1\%$)
- destructive interference between triangle and box diagrams

Summary of channels/methods for the YR2018 studies:

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| bbbb         | extrapolation | parametric | Largest BR ☺
|              |           |         | Large multijet and tt bkg ☹               |
| bbπ          | extrapolation | parametric | Sizeable BR ☺
|              |           |         | Relatively small bkg ☻                      |
| bbγγ         | smearing  | parametric | Small BR ☹
|              |           |         | Good diphoton resolution ☺                 |
| bbVV (→ lνlν)| parametric |         | Large BR ☻
|              |           |         | Large bkg ☹                                |
| bbZZ (→ 4l)  | parametric |         | Very small BR ☹                            |
|              |           |         | Very small bkg ☻                            |

New for Snowmass 2021:

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWγγ+τγγ</td>
<td>parametric</td>
<td></td>
<td>Clean channel ☻</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Large bkg ☹</td>
</tr>
<tr>
<td>ttHH</td>
<td>parametric</td>
<td></td>
<td>Very small cross-section ☹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Highly sensitive to BSM ☻</td>
</tr>
</tbody>
</table>
Expected significance for SM HH production in YR2018 (→ Snowmass2021):

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( HH \to b\bar{b}b\bar{b} )</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
<td>0.95</td>
</tr>
<tr>
<td>( HH \to b\bar{b}\tau\tau )</td>
<td>2.5→4.0</td>
<td>1.6</td>
<td>2.1→2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>( HH \to b\bar{b}\gamma\gamma )</td>
<td>2.1→2.3</td>
<td>1.8</td>
<td>2.0→2.2</td>
<td>1.8  →2.2</td>
</tr>
<tr>
<td>( HH \to b\bar{b}VV(ll\nu\nu) )</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>( HH \to b\bar{b}ZZ(4l) )</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Combined:

- ATLAS: 3.5 → 2.8
- CMS: 3.0 → 3.2

Combined:

- ATLAS: 4.5
- CMS: 4.0

... as a function of int. luminosity:

\( \text{t}\bar{t}HH \): upper limit of 3.14^{+1.27}_{-0.9} \text{SM}
Measurement of $\kappa_\lambda$:

- **YR2018 (ATLAS+CMS):** [0.5; 1.5] at 68% CL
- **Snowmass2021 (ATLAS $b\bar{b}\tau\tau+b\bar{b}\gamma\gamma$ only!):** [0.5; 1.6]

- **importance of measurements sensitive to $m_{HH}$ to remove the second minimum** (degeneracy of the HH production cross-section)
Higgs boson studies at Future Colliders

- After HL-LHC: Electron-positron (FCC-ee, CEPC, CLIC, ILC), proton-proton (HE-LHC, FCC-hh), electron-proton (LHeC)
- Precision on $\kappa$ coupling modifiers:

- Precise measurements of Higgs couplings (large gain in $\kappa_W$, $\kappa_Z$, $\kappa_b$, access to $\kappa_c$), invisible decays and CP properties, and the opportunity to measure the Higgs width
- Several of the proposed FCs will establish the existence of the self-coupling at 5$\sigma$
Conclusion

♦ Already well defined physics program for the HL-LHC
  – mostly extrapolated from the Run-2 results
  – based on the foreseen detector improvements

♦ Higgs mass could be measured with an uncertainty of 10-20 MeV
♦ Higgs couplings will be measured with percent precision
♦ Higgs self-couplings could be measured with a precision better than 50%, expected significance for the HH process >4σ

♦ Already improvements between the YR2018 and Snowmass2021 projections
  – ex. uncertainty on κc:
    • Snowmass2013: 7.5%
    • YR2018: 5.0%
    • Snowmass2021: 3.5%
  – Stay tuned! Ultreia!
Back-up
Higgs couplings at HL-LHC (4)

- 2\textsuperscript{nd} generation: Coupling to charm through rare decays with quarkonium mesons
  - low branching ratios in the SM, can be largely enhanced by BSM
- $H \rightarrow J/\Psi + \gamma$ (BR = $2.9 \pm 0.2 \times 10^{-6}$)
  - \sim 3 expected signal events
  - expected 95% CL upper limits: 15*SM
- $H \rightarrow J/\Psi + Z$ (BR = $2.3 \times 10^{-6}$)
  - search in the 4 muon invariant mass
  - expected 95% CL upper limits: 126*SM
- $H \rightarrow \Upsilon(mS)\Upsilon(nS)$ (BR = $6.5 \times 10^{-5}$)
  - search in the 4 muon invariant mass
  - expected 95% CL upper limits: 0.2*SM
  - predicted background negligible
  \implies 1 event = evidence
  \implies 3 events = observation
Constraints of the HL–LHC pseudo-data on the PDF4LHC15 set by means of the Hessian Profiling method

- PDF4LHC15 set broadly represents the state-of-the-art understanding of the proton structure

- HL-LHC coverage of the large-x region, where current PDF fits exhibit large uncertainties, is markedly improved as compared to available LHC measurements

Example:

- expected precision of the HL-LHC measurements is rather higher than the current PDF uncertainties ⇒ marked improvement once they are included in PDF4LHC15 via the Hessian profiling
♦ Scenarios: reduction factor applied to the systematic errors of the reference 8 TeV or 13 TeV measurements
  - optimistic (C): reduction of the systematic errors by a factor 2.5 (5) as compared to the reference 8 TeV (13 TeV) measurements
  - conservative (A): no reduction in systematic errors with respect to the 8 TeV reference

♦ Results:
  - impact reasonably similar in both scenarios
    • use of processes which will benefit from a significant improvement in statistics
    • they tend to lie in kinematic regions where the PDFs themselves are generally less well determined
  - marked reduction of the PDF uncertainties in all cases
    • gluon PDF: improvement in the complete relevant range of momentum fraction $x$
Reduction of the PDF uncertainties as compared to the PDF4LHC15 baseline:

<table>
<thead>
<tr>
<th>Ratio to baseline</th>
<th>$10 \text{ GeV} \leq M_X \leq 40 \text{ GeV}$</th>
<th>$40 \text{ GeV} \leq M_X \leq 1 \text{ TeV}$</th>
<th>$1 \text{ TeV} \leq M_X \leq 6 \text{ TeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon-gluon</td>
<td>$0.50 \ (0.60)$</td>
<td>$0.28 \ (0.40)$</td>
<td>$0.22 \ (0.34)$</td>
</tr>
<tr>
<td>quark-quark</td>
<td>$0.74 \ (0.79)$</td>
<td>$0.37 \ (0.46)$</td>
<td>$0.43 \ (0.59)$</td>
</tr>
<tr>
<td>quark-antiquark</td>
<td>$0.71 \ (0.76)$</td>
<td>$0.31 \ (0.40)$</td>
<td>$0.50 \ (0.60)$</td>
</tr>
</tbody>
</table>

Predictions for SM Higgs production at $\sqrt{s} = 14 \text{ TeV}$:

Two caveats:
- only a subset of all possible measurements of relevance for PDF fits at HL–LHC
- possible data incompatibility has not been accounted for fully
Theoretical uncertainties (‘YR2018’)

- Theoretical uncertainties are assumed to be reduced by a factor of two with respect to the current knowledge
  - higher-order calculation
  - reduced parton distribution functions uncertainties

Gluon fusion:

Remove one source of uncertainty!

Future:

- light-quark mass effects
  - large logs to resum?

Reduce uncertainty: $\sim 1\% \rightarrow 0.6\%$

Future:

- quark-induced EW contributions
- large $p_T$?
- $m_t$ dependence in QCD amplitude?

Sources of Uncertainties:

- $\delta(PDF + \alpha_s)$ — more data & accurate determinations
- $\delta(PDF – TH)$ — missing N$^3$LO PDFs (AP kernels)
Effect of $\kappa_c$ variations on $p_T^{Higgs}$:

![Graph showing differential cross-sections](https://example.com/graph.png)

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
*Higgs self-couplings*

- Higgs potential: \( V(\Phi) = \frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda \Phi^4 \)

- Approximation around the v.e.v:
  \[ V(\Phi) \approx \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 \]

  - mass term
  - self-coupling terms

- \( \lambda \) known from v.e.v and Higgs mass: \( \lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13 \)

- BSM effects could change \( \lambda \) ⇒ define deviation of tri-linear term: \( \kappa_\lambda = \frac{\lambda_{\text{HHH}}}{\lambda_{\text{SM}}} \)
  - no quartic terms considered here
Di-Higgs production at hadronic colliders (1)

- Main production mode: ggF
- Rare process of the Standard Model
  - destructive interference between triangle and box diagrams
  - \( \sigma(HH)/\sigma(H) = 0.1\% \)

- State of the art NNLO calculation with finite \( m_t \) effects at NLO
Self-couplings through
- total HH cross section
- differential cross section $d\sigma/dm_{HH}$

Degeneracy

HH production at 14 TeV LHC at (N)LO in QCD
$M_H=125$ GeV, MSTW2008 (N)LO pdf (68%cl)

$\sigma_{(N)LO}$ [fb]

$K_\lambda$
Di-Higgs production at hadronic colliders (3)

- Sensitivity to $\kappa_\lambda$ directly related to the acceptance, so to the $m_{HH}$ shape

- $\kappa_\lambda=0$: no triangle $\Rightarrow$ increase of cross-section above $2m_t$ + large tails

- $\kappa_\lambda=2$: max interference $\Rightarrow$ deficit between $2m_H$ and $2m_t$ + large tails

- $|\kappa_\lambda|>10$: trilinear dominant $\Rightarrow$ peaks at $2m_H$

- NB: most analyses optimised for $\kappa_\lambda=1$
Many decay channels!

It would be a very nice region for the Higgs to be accessible at LHC in $\gamma\gamma$, $4l$, $\ell\ell\ell\ell$, $b\bar{b}$, $\tau\tau$.

In practice consider channels with $b\bar{b}$ (BR = 59%) to maximise the rate.
Di-Higgs search

♦ Summary of channels/methods for HL-LHC studies:

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>extrapolation</td>
<td>Largest BR ☺ Large multijet and tt bkg ☹</td>
</tr>
<tr>
<td>bbττ</td>
<td>extrapolation</td>
<td>Sizeable BR ☻ Relatively small bkg ☺</td>
</tr>
<tr>
<td>bbγγ</td>
<td>smearing</td>
<td>Small BR ☹ Good diphoton resolution ☻ Relatively small bkg ☻</td>
</tr>
<tr>
<td>bbVV (→ lνlν)</td>
<td>parametric</td>
<td>Large BR ☺ Large bkg ☹</td>
</tr>
<tr>
<td>bbZZ (→ 4l)</td>
<td>parametric</td>
<td>Very small BR ☹ Very small bkg ☻</td>
</tr>
</tbody>
</table>

♦ Benefit from performance work of Technical design reports

♦ New analyses, either
  - extrapolations from Run-2 analyses
  - dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200