PROSPECTS FOR HIGGS BOSON MEASUREMENTS AT THE HL-LHC

Nicola De Filippis
Politecnico & INFN, Bari and LPC-FNAL, Batavia

On behalf of the CMS collaboration
LHC experiments confirm that the SM is robust but it should not be the ultimate theory of particle physics, because of many questions:

- why is the Higgs boson so light (“naturalness”/fine-tuning/hierarchy problem)?
- what is the nature of the dark part (96%!) of the universe?
- what is the origin of the matter-antimatter asymmetry?
- why is gravity so weak?
- Is supersymmetry realized in Nature?
- Inflation

No excess in data for direct signs of new physics:

- Supersymmetry
- Long-lived particles
- New heavy resonances
- Dark Matter and its nature

Doing Precision measurements (Couplings, Cross Sections, Width, Differential Distributions,...) which might be an indirect sign of BSM physics
LHC and HL-LHC schedule

Luminosity

Nominal scenario: \( \mathcal{L} = 5 \times 10^{34} \text{ cm}^{-1}\text{s}^{-1} \) for 3000/fb; Pile-up = 140

Ultimate Scenario: \( \mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-1}\text{s}^{-1} \) for 4000/fb; Pile-up = 200

\( \Rightarrow 25\% \) increase in integrated lum.
CMS Phase 2 upgrade

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to $\eta \sim 3$
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

Barrel HCAL
- Replace HPD by SiPM
- Replace inner layers scint. tiles?

New Endcap Calorimeters
- Radiation tolerant
- High granularity (HGCAL)

Trigger/DAQ
- L1 (hardware) with tracks and rate up $\sim 750$ kHz
- L1 Latency 12.5 $\mu$s
- HLT output rate 7.5 kHz
- New DAQ hardware

Timing layer
- Timing resolution $\sim 10$ ps
- Space resolution $\sim 10$'s of $\mu$m

New all Al beam pipe with smaller cone angle and cyl. central pipe
Strategy for Higgs physics @ HL-LHC

Phase II Detector Upgrades:
- Radiation hardness
- Mitigate physics impact of high pileup
- Object reconstruction efficiencies, resolutions and fake rates are assumed to be similar in the Run-2 and HL-LHC environments

Higgs@HL-LHC:
- Precision Measurements (Couplings, Cross Sections, Width, differential Distributions,…) → looking for deviations from the SM
- BSM Higgs direct searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VBS scattering
- Rare decays and couplings: $H \rightarrow \mu\mu$, $H \rightarrow ee$, $H \rightarrow cc$, $H \rightarrow Z\gamma$
- Di-Higgs production → Higgs self coupling
Analysis approaches for HL-LHC

- **Method 1: Full simulation (CMS):** use of the most advanced geometry, algorithms and tuning, PU simulation

- **Method 2: Full analysis with parameterized detector performance (CMS):** use DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)

- **Method 3: truth + smearing (ATLAS):** truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from MC truth+overlay and smear their energy and $p_T$ using appropriate smearing functions $\rightarrow$ cross checked with some of the ‘real’ data analyses

- **Method 4: projections (mostly CMS and LHCb):**
  - Existing signal and background samples (simulated at 13 TeV) scaled to higher lumi and $\sqrt{s} = 14$ TeV. Analysis steps (cuts) from present analyses.
  - **2 scenarios** for uncertainties:
    - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
    - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by 1/$\sqrt{L}$
Modeling the projections for HL-LHC

Experimental uncertainties:
- Estimates of **ultimately achievable accuracy** based on the upgraded Phase-2 detectors studies (TDRs).
- Assumption that **sufficiently large simulation samples** will be available

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Run 2 uncertainty</th>
<th>Projection minimum uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID</td>
<td></td>
<td>1-2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron ID</td>
<td></td>
<td>1-2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>0.5–2%</td>
<td>0.25–1%</td>
</tr>
<tr>
<td>Hadronic tau ID</td>
<td></td>
<td>6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Absolute</td>
<td>0.5%</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>0.1–3%</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>Pileup</td>
<td>0–2%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>Method and sample</td>
<td>0.5–5%</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>Jet flavour</td>
<td>1.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td></td>
<td>Time stability</td>
<td>0.2%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet energy res.</td>
<td></td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td>MET scale</td>
<td></td>
<td>Varies with analysis selection</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td>b-Tagging</td>
<td>b-/c-jets (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>b-/c-jets (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td></td>
<td>2.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Theoretical uncertainties:
- Build upon existing/recent TH progress/studies
- Assume a scaling down by a constant factor
- **QCD calculations (1/2), understanding of PDFs (1/3), top $p_T$ (1/2), etc.**

ID and isolation efficiencies for electrons and muons reduced to approximately 0.5%.
hadronic $\tau$ lepton ID uncertainty reduced to approximately 2.5%.
uncertainty in the overall jet energy scale (JES) reduced to 1% precision for jets with $p_T > 30$ GeV, driven primarily by improvements in the absolute scale and jet flavour calibrations.
**Projections** for:
- $H \rightarrow \gamma \gamma$ (ggH, VBF, VH, ttH)

Two isolated photon candidates passing good quality requirements in the precision regions of the detectors.

Expected $\pm 1\sigma$ uncertainties

- $\sigma_{ggH}^{\gamma \gamma}$
- $\sigma_{VBF}^{\gamma \gamma}$
- $\sigma_{WH}^{\gamma \gamma}$
- $\sigma_{ZH}^{\gamma \gamma}$
- $\sigma_{ttH}^{\gamma \gamma}$

Achievable precision @3000 fb$^{-1}$: less than 10% (VH dominated by stat uncert.)

The main systematic uncertainties are the background modeling uncertainty, missing higher order uncertainties causing event migrations between the bins, photon isolation efficiencies and jet uncertainties.
Projections for:
- $H \rightarrow ZZ \rightarrow 4l$ (ggH, VBF, VH, ttH)

- at least two same-flavor opposite-sign di-lepton pairs, chosen from isolated $e$ and $\mu$ candidates passing good quality requirements in acceptance

Dominant systematic uncertainties:
- for ggH: on the lepton reconstruction and identification efficiencies, and pile-up modeling uncertainties.
- for VBF and VH: on the jet energy scale and resolution, and by the missing higher order uncertainties + the parton shower modelling for ttH.
**Projections for:**
- $VH$, $H \rightarrow bb$ and boosted $H \rightarrow bb$
- Leptonic decays of the vector boson for triggering and to reduce the multi-jet background
- Final states: two $b$-jets and either zero, one or two electrons or muons.

The largest component of the systematic uncertainty is theoretical. This arises from the uncertainty in the gluon-induced ZH ($gg \rightarrow ZH$) production cross section due to QCD scale variations.

**Projections for:**
- $H \rightarrow \tau\tau$ ($ggH$, VBF)

Three sub-channels ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) are defined by requirements on the number of hadronically decayed $\tau$-leptons candidates and leptons (electrons or muons).

The dominant contributions to the systematic uncertainty come from:
- the experimental and background modeling errors
- the uncertainties on jet calibration and resolution, on the reconstruction of the $E_T^{miss}$
- the determination of the background normalization from signal and control region
Rare decays: $H\to\mu\mu$

- **Signature**: 2 OS isolated muons, resonant peak at the Higgs mass over a falling background
- **$\text{BR}(H\to\mu\mu)=0.022$**. Only visible at HL-LHC
- di-muon invariant mass width is reduced in order to match the expected increase in performances due to the upgrade in the tracking system

A simultaneous fit in all production modes

**Expected precision on the signal strength measurement**

<table>
<thead>
<tr>
<th>Experiment Process</th>
<th>CMS Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>S1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>13%</td>
</tr>
<tr>
<td>Statistical uncert.</td>
<td>9%</td>
</tr>
<tr>
<td>Experimental uncert.</td>
<td>8%</td>
</tr>
<tr>
<td>Theory uncer.</td>
<td>5%</td>
</tr>
</tbody>
</table>

CMS detector will be able to reach in the best category a di-muon mass resolution down to 0.65%
Higgs boson cross section

Projections for:
- $H \rightarrow ZZ \rightarrow 4l$ (ggH, VBF, VH, ttH)
- $H \rightarrow WW \rightarrow 2\ell 2\nu$ (ggH, VBF, VH)
- $H \rightarrow \gamma\gamma$ (ggH, VBF, VH, ttH)
- $H \rightarrow \tau\tau$ (ggH, VBF)
- VH, $H \rightarrow bb$ and boosted $H \rightarrow bb$
- $H \rightarrow \mu\mu$ (ggH and VBF)
- ttH, $H \rightarrow$ leptons, $H \rightarrow bb$
  + studies about tH

Systematic uncertainties will dominate, in particular theoretical uncertainties on signal and background are the main component for S2 scenario

CMS: S2 uncertainties range from 3–4%, with the exception of that on $\mu \mu \mu$ at 10%.
Higgs couplings formalism

LHC Higgs Xsection WG

- Single resonance with mass of 125 GeV.
- Zero-width approximation
  \[ \sigma \cdot B (i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \]
  - the tensor structure of the lagr. is the SM one → observed $0^+$
- coupling scale factors $K_i$ are defined in such a way that:
  - the cross sections $s_i$ and the partial decay widths $\Gamma_i$
    scale with $K_i^2$ compared to the SM prediction
- deviations of $K_i$ from unity → new physics BSM
- Results from fits to the data using the profile likelihood ratio with $\kappa_i$ couplings
  - as parameters of interest or as nuisance parameters

Production modes

- $\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \kappa^2_F(\kappa_b, \kappa_t, m_H)$
- $\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$
- $\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa^2_W$
- $\frac{\sigma_{Z}^{ZH}}{\sigma_{Z}^{ZH}^{SM}} = \kappa^2_Z$
- $\frac{\sigma_{t}^{ttH}}{\sigma_{t}^{ttH}^{SM}} = \kappa^2_t$

arXiv:1307.1347v2
Higgs boson couplings

- Results for couplings in $\kappa$-framework
- Six coupling modifiers corresponding to the tree-level Higgs boson couplings are defined: $\kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_Z (\pm \kappa_g, \kappa_Y, \kappa_{Z\gamma})$ and $\text{BR}_{BSM} = 0$

Uncertainties on the $\kappa$’s 2-5%, apart from $\kappa_\mu$ and $\kappa_{Z\gamma}$ mostly limited by statistical/theoretical uncertainties
Looking at distortions of $p_T^H$ differential distributions as potential new physics may reside in the tails of the distribution, which cannot be measured in inclusive measurements.

Combined differential cross sections using:
• $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ \rightarrow 4l$
• + boosted $H \rightarrow bb$ in the high $p_T^H$ tail

The uncertainties at 3000 fb$^{-1}$:
• in the higher $p_T^H$ region are about a factor of ten smaller (statistically dominated) w.r.t. S1
• in the lower $p_T^H$ region the reduced systematic uncertainties in S2 yield a reduction in the total uncertainty of up to 25% w.r.t. S1 (and are no longer statistically dominated)
The Higgs potential

Higgs potential:

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

Expanding about minimum: \( V(\phi) \rightarrow V(v + h) \)

\[
V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4
= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4
\]

Why is it relevant?

- the strength of the triple and quartic couplings is fully fixed by the potential shape.
- It has implications on the stability of the Vacuum
- it could make the Higgs boson a good inflation field
Double Higgs production

Main probe for trilinear Higgs coupling $\lambda_{HHH}$. Diagrams interfere destructively in SM

$ggF-hh$: sensitive to possible BSM contribution.

<table>
<thead>
<tr>
<th>Production mode</th>
<th>Cross section (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF-hh$</td>
<td>$\sim$ 40 fb</td>
</tr>
<tr>
<td>$VBF-hh$</td>
<td>$\sim$ 2 fb</td>
</tr>
<tr>
<td>$V-hh$</td>
<td>$\sim$ 1 fb</td>
</tr>
<tr>
<td>$tt-hh$</td>
<td>$\sim$ 1 fb</td>
</tr>
</tbody>
</table>

Not enough data in Run 2 to approach the SM sensitivity

A large matrix of final states

BR $HH\rightarrow xy yy$ ($m_H = 125$ GeV)

$bttttt$ largest statistics

$bb(gg, \tau\tau)$ good compromise between statistics and $S/B$
Prospects for HH measurements

Search of Higgs boson pair (HH) production and the measurement of the Higgs boson self-coupling ($\lambda_{HHH}$)

Decay channels: $HH \rightarrow bbbb$, $bb\tau\tau$, $bbWW(\rightarrow ll\nu\nu)$, $bb\gamma\gamma$ (most sensitive), $bbZZ(\rightarrow 4l)$

Measurement of the $k_\lambda = \lambda_{HHH}/\lambda_{SMHHH}$ in the range $[0.4, 1.9]$ at the 68% CL
Differential XS and constraint on self coupling

Alternative approach: exploiting radiative corrections to inclusive and differential Higgs boson production rates → at NLO single Higgs boson production modes include contributions involving the $\lambda_3$ → sizeable contribution from ttH, tH, VH

Focus in ttH (+tH), $H \rightarrow \gamma\gamma$ using Delphes simulation and a strategy similar to the Run2

At 68% C.L.: -1.9 $< \kappa_\lambda <$ 5.3 → complementary to the stronger constraints from direct Higgs production

The dependence of the single-Higgs boson differential xs is parameterised as a function of $\kappa_\lambda$

The $p_T^H$ allows to disentangle the effects of modified Higgs boson self-coupling values from other effects such as the presence of anomalous top–Higgs couplings.
Limits on the Higgs width

Comparison of on-shell and off-shell rate in $H \rightarrow ZZ \rightarrow 4l$ constrain the Higgs boson width

- current constraint: $\Gamma < 9.16$ MeV @ 95% CL

**Off-peak to on-peak ratio**

Systematic uncertainty:

- theoretical uncertainties dominant over experimental ones - dominant effect comes from the uncertainty in the NLO EW correction on the $qq \rightarrow 4l$ simulation above the $2m_Z$ threshold
- approximate S2 in which the experimental uncertainties not reduced, while the theoretical uncertainties halved w.r.t S1
- 10% additional uncertainty applied on the QCD NNLO K factor on the $gg$

Precision reachable combining CMS and ATLAS predictions with 3000 fb$^{-1}$

\[ 4.1^{+0.7}_{-0.8} \text{ MeV} \quad @68\% \text{ C.L.} \]
Several studies on probing the BSM effects in the Higgs physics:

- Probe for anomalous interactions & rare/exotic decays:
  - $H \rightarrow$ invisible
    $B_{\text{INV}} < 3.8\%$ (compare to 22% @Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - $B_{\text{BSM}} < 6\%$ from couplings combination
      (compare to 34% @Run2) [FTR-18-011]
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl.
      Width: $\Gamma_H \subset [2,6\] \text{MeV} @ 95\%\text{CL}$ [FTR-18-011]

- Search for additional Higgs bosons and/or scalars:
  - MSSM $H \rightarrow \tau\tau$ search [FTR-18-017]
  - High mass search $X \rightarrow ZZ \rightarrow 2l2q$
    [FTR-18-040]
Summary/Conclusions

**HL-LHC**: potential for new physics discoveries and precision measurements in the Higgs sector:

- Few per-cent level precision on most Higgs cross sections and couplings
- Significance of about $2.6\sigma$ for HH production → triple self coupling
- Higgs width measurable to within 1 MeV
- Sensitivity to BSM effects in Higgs physics derived

Many inclusive measurements limited by systematic uncertainties → work needed from theoretical and experimental side

An exciting journey ahead!
Backup
SM Higgs production at the LHC

- **ggF**: dominant, larger initial state radiation from gluons
- **VBF**: two forward jets with high mass and large rapidity gap
- **VH**: vector boson (lv, ll', qq')
- **ttH**: many b-jets, leptons, $E_t^{miss}$

Total cross-section = 56 pb at 13 TeV
Higgs decay channels

At $m_H = 125$ GeV:

- $H(bb) = 57.8\%$
- $H(WW) = 21.4\%$
- $H(gg) = 8.19\%$
- $H(\tau\tau) = 6.27\%$
- $H(ZZ) = 2.62\%$
- $H(cc) = 2.89\%$
- $H(\gamma\gamma) = 0.23\%$
- $H(Z\gamma) = 0.15\%$
- $H(\mu\mu) = 0.02\%$
Detector performance for Phase 2 upgrade

Detector performance after Phase-2 upgrades:
- Effective pileup mitigation
- Overall performance similar or better than during Run 2
- Extended capabilities with new algorithms

**Pile-up suppression**

**Mass resolution**

**B-tagging**

**LHCb Vertex Locator**

N. De Filippis

Sept 30 - Oct 4, Higgs couplings 2019
The measurement of the $ggH$ cross section by branching fraction is dominated by theoretical PDF uncertainty, followed by experimental uncertainties affecting the signal acceptance, including uncertainties on the jet energy scale and flavour composition, and lepton mis-identification.
Higgs boson cross section

---

ATLAS and CMS

$\sigma_{ggH}$

$\sigma_{VBF}$

$\sigma_{WH}$

$\sigma_{ZH}$

$\sigma_{ttH}$

Expected relative uncertainty

---

3000 fb$^{-1}$

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ggH}$</td>
<td>$\sigma_{ggH}$</td>
</tr>
<tr>
<td>$\sigma_{VBF}$</td>
<td>$\sigma_{VBF}$</td>
</tr>
<tr>
<td>$\sigma_{WH}$</td>
<td>$\sigma_{WH}$</td>
</tr>
<tr>
<td>$\sigma_{ZH}$</td>
<td>$\sigma_{ZH}$</td>
</tr>
<tr>
<td>$\sigma_{ttH}$</td>
<td>$\sigma_{ttH}$</td>
</tr>
</tbody>
</table>

Total uncertainty [%]

---

3000 fb$^{-1}$

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ggH}$</td>
<td>$\sigma_{ggH}$</td>
</tr>
<tr>
<td>$\sigma_{VBF}$</td>
<td>$\sigma_{VBF}$</td>
</tr>
<tr>
<td>$\sigma_{WH}$</td>
<td>$\sigma_{WH}$</td>
</tr>
<tr>
<td>$\sigma_{ZH}$</td>
<td>$\sigma_{ZH}$</td>
</tr>
<tr>
<td>$\sigma_{ttH}$</td>
<td>$\sigma_{ttH}$</td>
</tr>
</tbody>
</table>

---

N. De Filippis
For the combined ATLAS-CMS extrapolation
• uncertainty range from 2 to 4%, with the exception of that on $B(\mu\mu)$ at 8% and on $B(Z\gamma)$ at 19%.
Higgs couplings formalism

arXiv:1307.1347v2

Contributions from new physics through $\Gamma_{\text{BSM}}$ and loop processes
### Differential Higgs cross sections

Relative uncertainties on the projected $p_T$ H spectrum measurements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>6.5%</td>
<td>5.9%</td>
<td>6.2%</td>
<td>6.0%</td>
<td>6.5%</td>
<td>6.7%</td>
<td>6.0%</td>
<td>5.4%</td>
<td>6.3%</td>
<td>9.5%</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>9.0%</td>
<td>8.1%</td>
<td>8.9%</td>
<td>6.9%</td>
<td>6.3%</td>
<td>6.8%</td>
<td>6.8%</td>
<td>6.2%</td>
<td>6.7%</td>
<td>13.2%</td>
<td>24.3%</td>
</tr>
<tr>
<td>Combination</td>
<td>5.5%</td>
<td>4.8%</td>
<td>5.0%</td>
<td>4.7%</td>
<td>5.0%</td>
<td>5.1%</td>
<td>4.6%</td>
<td>4.4%</td>
<td>5.4%</td>
<td>8.7%</td>
<td></td>
</tr>
</tbody>
</table>

3000 fb$^{-1}$ CMS

<table>
<thead>
<tr>
<th>$p_T^H$ [GeV]</th>
<th>0-15</th>
<th>15-30</th>
<th>30-45</th>
<th>45-80</th>
<th>80-120</th>
<th>120-200</th>
<th>200-350</th>
<th>350-600</th>
<th>600-∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>5.1%</td>
<td>6.8%</td>
<td>7.1%</td>
<td>6.9%</td>
<td>7.1%</td>
<td>6.7%</td>
<td>7.1%</td>
<td>9.9%</td>
<td>32.5%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>5.4%</td>
<td>5.7%</td>
<td>5.0%</td>
<td>5.5%</td>
<td>9.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>none</td>
<td>38.2%</td>
<td>37.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>4.7%</td>
<td>4.4%</td>
<td>5.0%</td>
<td>4.7%</td>
<td>4.7%</td>
<td>5.2%</td>
<td>8.5%</td>
<td>25.4%</td>
<td></td>
</tr>
</tbody>
</table>

6000 fb$^{-1}$

| Combination | 4.0% | 3.7% | 4.0% | 3.9% | 4.0% | 4.0% | 4.3% | 6.3% | 18.3% |

3000 fb$^{-1}$ ATLAS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>5.3%</td>
<td>4.6%</td>
<td>4.9%</td>
<td>4.7%</td>
<td>5.4%</td>
<td>5.7%</td>
<td>4.9%</td>
<td>4.2%</td>
<td>5.1%</td>
<td>8.7%</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>8.3%</td>
<td>7.6%</td>
<td>8.3%</td>
<td>6.3%</td>
<td>5.7%</td>
<td>6.2%</td>
<td>6.3%</td>
<td>5.7%</td>
<td>6.4%</td>
<td>13.1%</td>
<td>23.2%</td>
</tr>
<tr>
<td>Combination</td>
<td>4.5%</td>
<td>3.8%</td>
<td>3.9%</td>
<td>3.6%</td>
<td>4.1%</td>
<td>4.2%</td>
<td>3.7%</td>
<td>3.5%</td>
<td>4.5%</td>
<td>8.2%</td>
<td></td>
</tr>
</tbody>
</table>

3000 fb$^{-1}$ CMS

<table>
<thead>
<tr>
<th>$p_T^H$ [GeV]</th>
<th>0-15</th>
<th>15-30</th>
<th>30-45</th>
<th>45-80</th>
<th>80-120</th>
<th>120-200</th>
<th>200-350</th>
<th>350-600</th>
<th>600-∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>5.1%</td>
<td>4.6%</td>
<td>5.1%</td>
<td>4.8%</td>
<td>4.9%</td>
<td>4.5%</td>
<td>5.1%</td>
<td>8.6%</td>
<td>32.2%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>5.4%</td>
<td>4.8%</td>
<td>4.1%</td>
<td>4.7%</td>
<td>9.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>none</td>
<td>31.4%</td>
<td>36.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>3.7%</td>
<td>3.3%</td>
<td>4.2%</td>
<td>3.7%</td>
<td>4.0%</td>
<td>3.8%</td>
<td>4.4%</td>
<td>8.0%</td>
<td>24.5%</td>
</tr>
</tbody>
</table>

6000 fb$^{-1}$

| Combination | 2.9% | 2.6% | 3.2% | 2.9% | 3.0% | 2.9% | 3.2% | 5.8% | 17.9% |
Higgs boson properties

Projections based on Run-2 combined differential XS (HIG-17-028):
• Channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, boosted $H \rightarrow bb$ (in the high $p_T^H$ tail)
• Constraints on effective $k_b$, $k_c$, $k_t$, $c_g$ couplings (competitive with direct probes).

Expected 2D limits in $(c_g, k_t)$

Expected 2D limits in $(k_b, k_c)$

Reduction of uncertainties @3ab$^{-1}$:
• High-$p_T^H$ region: x10
• Low-$p_T^H$ region: x4

N. De Filippis

Sept 30 - Oct 4, Higgs couplings 2019
Anomalous HVV interactions

Performance to be estimated using the $H \rightarrow 4\ell$ analysis @13 TeV.

- Parameterisation of decay amplitude:

$$A = \frac{1}{v} \left[ \text{SM} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{2} + \frac{\kappa_3^{VV} (q_1 + q_2)^2}{2} \right] \quad \text{leading momentum expansion}$$

Higher order cp-even and cp-odd

$\text{powerful constraints on anomalous couplings:}$

- Exploiting information from:
  - H decay (on-shell)
  - H on-shell production
  - H off-shell production:

Sensitivity driven by on-shell production-level info. Some model dependance from assumption on HWW/HZZ relation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Information from</th>
<th>95% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{a3}$</td>
<td>decay</td>
<td>$\pm 120 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$f_{a3}$</td>
<td>decay &amp; production</td>
<td>$\pm 1.8 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$f_{a3}$</td>
<td>decay &amp; production &amp; off-shell</td>
<td>$\pm 1.6 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Constraints on fractional CP-odd presence $< 1.6 \cdot 10^{-4}$
HH: CMS and ATLAS combined

<table>
<thead>
<tr>
<th></th>
<th>Statistical-only</th>
<th></th>
<th>Statistical + Systematic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
<td>ATLAS</td>
<td>CMS</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b} b\bar{b}$</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
<td>0.95</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b} \tau\bar{\tau}$</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b} \gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b} VV (llll\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b} ZZ (4l)$</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{SM HHH}}$$

**ATLAS and CMS HL-LHC prospects**

**SM HH significance:** $4\sigma$

*0.1 < $\kappa_\lambda$ < 2.3 [95% CL]*

*0.5 < $\kappa_\lambda$ < 1.5 [68% CL]*
Constraints on the trilinear coupling
Constraint on the $\Gamma_H$ from $H^*(126) \to ZZ$

Off-shell $H^*(126) \to VV$ \hspace{1cm} (V=W,Z)

- In N. Kauer and G. Passarino, JHEP 08 (2012) 11 it has been shown that the off-shell production cross section is sizeable at high ZZ invariant mass
- that comes from a peculiar cancellation between BW trend and $\Gamma(H \to VV)$
- Enhancement of $7.6\%$ of total cross section in the ZZ final state

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma$ [pb]</th>
<th>$M_{ZZ} &gt; 2 M_Z$ [pb]</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H \to all$</td>
<td>19.146</td>
<td>0.1525</td>
<td>0.8</td>
</tr>
<tr>
<td>$gg \to H \to ZZ$</td>
<td>0.5462</td>
<td>0.0416</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ$

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024) and J. Campbell et al. (arXiv:1311.3589) showed how this feature can be turned into a constraint on the total Higgs width

\[
\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \propto g_{gH} g_{HZZ} \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}
\]

so measuring the ratio of $\sigma^{\text{off-peak}}$ and $\sigma^{\text{on-peak}} \rightarrow$ measurement of $\Gamma_H$

\[
\mu \equiv (\sigma / \text{BR})_{\text{SM}} \propto g_{gH} / g_{gH}^\text{SM}
\]

Once $\mu$ is fixed a determination of $r$ is obtained and so for $\Gamma_H$:

- “$\mu$ expected”: use expected signal strength
- “$\mu$ observed”: use observed signal strength

\[
\kappa_g = g_{gH} / g_{gH}^\text{SM}
\]

The interference with continuum $gg \rightarrow ZZ$ is taken into account at high mass $\rightarrow$ gg2VV/MCFM

VBF production is 10% at high mass $\rightarrow$ PHANTOM
Limits on the Higgs width

- Comparison of on- and off-shell rates in $H \rightarrow ZZ \rightarrow 4l$ can constrain the Higgs boson width. Current constraint: $\Gamma < 14.4$ MeV (ATLAS), $\Gamma < 9.2$ MeV (CMS)
- CMS projection: $4.1^{+1.0}_{-1.1}$ MeV, ATLAS projection: $4.1^{+1.5}_{-2.1}$ MeV
  - ATLAS projection based on Run I analysis, used large theoretical uncertainties that have been reduced in the meantime
- Assuming ATLAS analysis would have same sensitivity as CMS analysis at HL-LHC, combined constraint on the width $4.1^{+0.7}_{-0.8}$ MeV
Several studies on probing the BSM effects in the Higgs physics:

- **Probe for anomalous interactions & rare/exotic decays:**
  - $H \rightarrow \text{invisible}$
  - $B_{\text{inv}} < 3.8\%$ (compare to 22\% @ Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - $B_{\text{BSM}} < 6\%$ from couplings combination
      (compare to 34\% @ Run2) [FTR-18-011]
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl.
      Width: $\Gamma_{H} \subset [2,6] \text{ MeV} @ 95\%\text{CL}$ [FTR-18-011]

- Search for additional Higgs bosons and/or scalars:
  - MSSM $H \rightarrow \tau\tau$ search [FTR-18-017]
  - High mass search $X \rightarrow ZZ \rightarrow 2l2q$ [FTR-18-040]
Sensitivity to BSM effects in Higgs physics

Several studies on probing the BSM effects in the Higgs physics:

- Probe for anomalous interactions & rare/exotic decays:
  - $H \rightarrow$ invisible
    $\mathcal{B}_{\text{inv}} < 3.8\%$ (compare to 22% @Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - $\mathcal{B}_{\text{BSM}} < 6\%$ from couplings combination
      (compare to 34% @Run2) [FTR-18-011]
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl.
      Width: $\Gamma_H \subset [2,6]$ MeV @ 95%CL [FTR-18-011]

- Search for additional Higgs bosons and/or scalars:
  - MSSM $H \rightarrow \tau\tau$ search [FTR-18-017]
  - High mass search $X \rightarrow ZZ \rightarrow 2l2q$ [FTR-18-040]
Higgs to Invisible decays

- Current observed (expected) limits on $B_{\text{inv}}$ at 95% CL:
  - ATLAS: < 26% (17%)
  - CMS: < 22% (17%)

- VBF production mode dominates sensitivity $\rightarrow$ HL-LHC sensitivity studied using Delphes simulation

- With optimised selection: $B_{\text{inv}} < 3.8\%$ at 95% CL with 3000 fb$^{-1}$ at HL-LHC

- Degradation of $E_T^{\text{miss}}$ resolution does not impact the sensitivity significantly

- Combining with previous ATLAS projection of VH channel, and assuming both experiments would perform equally well in both channels: $B_{\text{inv}} < 2.5\%$ at 95% CL