SM Higgs prospects in ATLAS and CMS

G. Ortona (LLR) for the CMS and ATLAS collaborations
Outline

Introduction

Golden channels and coupling to bosons
• $H \rightarrow ZZ$, $H \rightarrow \gamma \gamma$, $H \rightarrow WW$

Yukawa couplings
• bottom, taus, muons

The big picture
• Overview of couplings and signal strengths for production and decay mode

Summary and conclusions
The existence of (at least one) Higgs boson well established
No deviations from SM so far
A few exceptions aside, we are not yet at the level of precision
we need to probe small deviations from the SM and narrow
down NP. For precision Higgs coupling we need HL/HE-LHC
Strategy

CMS extrapolation scenarios:

• S1: Systematic uncertainties constant, unchanged detector performances
• S2: Theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a floor)
• S1/S2+: Includes higher PU and detector upgrades effects

ATLAS extrapolation scenarios:

• Includes programmed detector upgrades, with extended $\eta$ coverage of the tracker up to $|\eta|<4.0$ ("reference" scenario)
• PU and upgrades taken into account for projections
• Theoretical uncertainties scaled by 1, 0.5 or 0
Golden channels: ZZ

Main contributor to the H mass measurement at LHC-Run2
Upgraded detectors bring significant improvements:
  • Increased CMS/ATLAS tracker acceptances up to $|\eta|<4$, new EM trigger, improved $\mu$ triggers, higher reco efficiency and momentum resolution in Phase2
  • Strong sensitivity to ggH, and good (but limited) sensitivity to VBF and VH
**ATLAS** Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int Ldt=300$ fb$^{-1}$ ; $\int Ldt=3000$ fb$^{-1}$

- Expected uncertainties below 15% (5% for gluon fusion) with 3 ab$^{-1}$ for the signal strengths measurement
ZZ: Differential distributions

Measured in a fiducial phase space close to experiment acceptance

Statistical uncertainties are still dominating at high $p_T$ even at 3 ab$^{-1}$ (4-9%)

Improved signal modelling needed before 300 fb$^{-1}$

Some sensitivity to the shape at low (high) $p_T$: gives sensitivity to $k_b$, $k_c$ ($k_t$)

Important to extend coverage (bins, range, variables) in the future
**Anomalous ZZ couplings**

\[
A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2^{VV} f_{\mu\nu}^{* (1)} f_{\mu\nu}^{* (2), \mu\nu} + a_3^{VV} f_{\mu\nu}^{* (1)} f_{\mu\nu}^{* (2), \mu\nu}
\]

**O(1%) precision** on anomalous HVV couplings at HL-LHC

Different notations in CMS and ATLAS. Both probe tensor-structure and the CP violation in the H→VV coupling:

\( f_{a3} = \) fraction of CP violation; \( f_{g3} (f_{g4}) = \) fraction of CP-even(odd) contributions

Significant improvement when including production-level information (HIG-17-011)

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**CMS Projection**

Expected limits on Higgs Boson anomalous couplings

- ECFA16 S1 (300 fb⁻¹)
- ECFA16 S1+ (300 fb⁻¹)

\( H \rightarrow ZZ^* \rightarrow 4\ell \)

\( m_H = 125 \text{ GeV} \)

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**ATLAS Simulation**

Preliminary

- 3000 fb⁻¹: 68%-95% CL
- 300 fb⁻¹: 68%-95% CL

8D Fit

\[
a_1 = g_1 \frac{m_V^2}{m_H^2} + \frac{s}{m_H^2} \left( 2g_2 + g_3 \frac{s}{\Lambda^2} \right) \; ; \; \; a_2 = - \left( 2g_2 + g_3 \frac{s}{\Lambda^2} \right) \; ; \; \; a_3 = g_2 - 2g_4,
\]
Golden channels: $\gamma\gamma$

Resolution mostly driven by photon energy and vertexing resolutions

For the projections assumed reduced photon ID, vertex efficiency

CMS Projection

3000 fb$^{-1}$ (13 TeV)

fiducial volume :

$P_T^{\text{gen}}(\gamma_1, \gamma_2) > \frac{1}{3} \left( \frac{1}{4} \right) m_\gamma$
$H_T^{\text{gen}}(\gamma_1, \gamma_2) < 2.5$
$\text{Iso}_{R=0.3}(\gamma_{1,2}) < 10 \text{ GeV}$

S/(S+B)-weighted signal models

CMS Phase-2 Simulation Preliminary

14 TeV, 200 PU

All H-$\gamma\gamma$ photons

- 300 fb$^{-1}$ $\sigma_{\text{eff}}=2.8$ GeV
- 1000 fb$^{-1}$ $\sigma_{\text{eff}}=2.9$ GeV
- 3000 fb$^{-1}$ $\sigma_{\text{eff}}=4.3$ GeV
- 4500 fb$^{-1}$ $\sigma_{\text{eff}}=5.6$ GeV

$\text{CMS-TDR-17-002}$

$\text{ATL-PHYS-PUB-2016-0}$
Fiducial cross-section measurement to be dominated by systematic uncertainties already at 300 fb⁻¹
**γγ: couplings**

- Similar expected sensitivities between the two experiments
- Precision higher than 5-10%

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}: \int \text{Ldt}=300 \text{ fb}^{-1}; \int \text{Ldt}=3000 \text{ fb}^{-1} \]

**γγ → H**

- (comb.)
  - (0j)
  - (1j)
  - (VBF-like)
  - (WH-like)
  - (ZH-like)
  - (ttH-like)

**CMS Projection**

- Standard Model
  - 300 fb\(^{-1}\) (13 TeV)
  - 3000 fb\(^{-1}\) (13 TeV)
Even in worst case scenario we should be able to observe $H \rightarrow WW$ production.

$\eta$ acceptance important for signal efficiency (VBF topology)
- $82\%$ efficiency in $|\eta|<4.0$
- $26\%$ in $|\eta|<2.7$

<table>
<thead>
<tr>
<th>Scoping scenario</th>
<th>$\Delta_{\mu}$</th>
<th>Significance ($\sigma$)</th>
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<tbody>
<tr>
<td></td>
<td>Full</td>
<td>1/2</td>
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<tr>
<td>Reference</td>
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<td>0.16</td>
</tr>
<tr>
<td>Middle</td>
<td>0.25</td>
<td>0.21</td>
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<tr>
<td>Low</td>
<td>0.39</td>
<td>0.32</td>
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</table>
Yukawa couplings: bottom

Projections from Run1 legacy from ATLAS: from $3.9\sigma$ (300fb$^{-1}$) to $8.8\sigma$ (3000fb$^{-1}$). 15% uncertainty on the signal strength

With current statistics, first evidence for (V)H→bb from CMS (3.3σ, arXiv: 1709.07497) and ATLAS (3.5σ, arXiv:1708.03299)

5-10% uncertainty from CMS projections from Run1

$ggH\rightarrow bb$ could probe high $p_T$ region, can be within reach
Reasonable separation of the H and Z peaks
Mass resolution at HL-LHC almost the same as in Run2, even when factoring in ageing of the detectors (1ab⁻¹)
Precision at the 5-8% level (3 ab⁻¹)
2 OS sign isolated muons, resonant peak at the Higgs mass, very clear signature

\[ \text{BR}(H \rightarrow \mu\mu) = 0.022. \] Only visible at HL-LHC

CMS and ATLAS projections from Run1:

40% (16%) signal strength precision at 300 (3000) fb\(^{-1}\)

With Phase2 detector:

- mass resolution <1%, uncertainty on \( H \rightarrow \mu\mu \) coupling <5%

\[ \text{BR}(H \rightarrow \mu\mu) = 0.022. \] Only visible at HL-LHC
• Tight constraints could be set on NP and Higgs properties from $H \rightarrow$ invisible branching fraction (constrained to the $\sim$10% level)
The big picture: $\mu$

**CMS Projection**

Expected uncertainties on Higgs boson signal strength

- 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV Scenario 1
- 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV Scenario 2

**Higgs boson signal strength**

- $H \rightarrow \gamma \gamma$
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow bb$
- $H \rightarrow \tau \tau$

**ATLAS Simulation Preliminary**

\[ \sim 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1} ; \int L dt = 3000 \text{ fb}^{-1} \]

**Higgs Boson Signal Strength**

- $H \rightarrow \gamma \gamma$
  - (comb.)
  - (0j)
  - (1j)
  - (VBF-like)
  - (WH-like)
  - (ZH-like)
  - (ttH-like)

- $H \rightarrow ZZ$
  - (comb.)
  - (VH-like)
  - (ttH-like)
  - (VBF-like)
  - (ggF-like)

- $H \rightarrow WW$
  - (comb.)
    - (0j)
    - (1j)
    - (VBF-like)

- $H \rightarrow b\bar{b}$
  - (comb.)
    - (WH-like)
    - (ZH-like)

- $H \rightarrow \tau \tau$
  - (VBF-like)

- $H \rightarrow \mu \mu$
  - (comb.)
    - (incl.)
    - (ttH-like)

- $H \rightarrow ZZ$
  - (incl.)
The big picture: couplings

• Expected sensitivity on coupling modifiers $\lesssim 5\%$ in all channels for $3\text{ ab}^{-1}$
A large amount of integrated luminosity is required in order to observe this extremely rare process. Projections for the HL-LHC indicate that SM di-Higgs production can be observed by CMS with a significance of 1.9 standard deviations with a data set corresponding to an integrated luminosity of 3000 fb⁻¹. The cross section for production of Higgs boson pairs via gluon fusion at a centre-of-mass energy of 14 TeV has been calculated at next-to-next-to-leading-order to be 40 fb [89].

Higgs pair production can occur through its trilinear self-coupling or through a box diagram. In the SM the two processes interfere destructively, resulting in a near minimal Higgs boson pair production cross section. If the Higgs boson decays can be completely reconstructed and identified as a mass peak on top of the background, the prospects for Higgs coupling measurements by CMS show an uncertainty of about 5% for couplings to muons [13].

The observation of this process is an important objective of the HL-LHC program. Higgs pair production can occur through Higgs boson and the nature of electroweak symmetry breaking. The analysis [88], the three

<table>
<thead>
<tr>
<th>L (fb⁻¹)</th>
<th>κγ</th>
<th>κW</th>
<th>κZ</th>
<th>κb</th>
<th>κt</th>
<th>κτ</th>
<th>κZγ</th>
<th>κμμ</th>
<th>BRSM</th>
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<td>[2, 5]</td>
<td>[2, 5]</td>
<td>[2, 4]</td>
<td>[3, 5]</td>
<td>[7, 10]</td>
<td>[2, 5]</td>
<td>[10, 12]</td>
<td>[8, 8]</td>
<td>[7, 11]</td>
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\[ \Delta \lambda_{XY} = \Delta \left( \frac{\kappa_X}{\kappa_Y} \right) \]
Summary & Conclusions

Projections and studies were performed by the ATLAS and CMS collaborations from Run1/2 extrapolations or parametrised simulation.

Potential to reach the percentage level in precision on the Higgs coupling modifiers and signal strengths.

Covering most of the Higgs production and decay channels.

Latest projections confirm previous assumptions (Snowmass).

Recent improvement in Run2 analyses not yet propagated to HL-LHC projections.
BACKUP
Anomalous ZZ couplings

Recent CMS results (HIG-17-011) show that exploiting the production-level information can significantly improve the sensitivity to anomalous couplings towards 3000fb-1
Yukawa couplings: top

- Top Yukawa coupling can be measured from:
  - ttH-like categories in H->gg, H->ZZ, H->mm
  - And searches for ttH production, with different H decays

- tHq production can probe FCNC down to BR(t->Hq~10^{-4})
Yukawa couplings: charm

- ATLAS H→j/ψi

- Very difficult to see it even at HL-LHC
• (Explain assumptions, RB*, mu->width etc.)
• If off-shell and on-shell couplings are the same, it is possible to translate the off-shell production in a measurement on the width
• With 3 ab\(^{-1}\): 30-50% uncertainty: \(\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \) MeV (stat+sys).