Couplings and properties measurements (Spin/Parity, mass and width) with ATLAS + CMS in bosonic Higgs decay modes

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on behalf of the ATLAS and CMS Collaborations

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Introduction

- Higgs boson plays a fundamental role in the Standard Model (SM)
- Bosonic decay channels ($H \rightarrow \gamma\gamma, ZZ, WW$) have excellent sensitivities at LHC
  - Leading channels for Higgs boson discovery
  - Crucial for high precision Higgs boson property measurements
- This presentation: latest ATLAS & CMS Run 2 Higgs boson property measurement results in bosonic decay channels

* Results labeled as “new” in this presentation are produced after LHCP2018
Bosonic channels @ 13 TeV

- \( m_H = 125.09 \) GeV (Run 1 ATLAS+CMS)

<table>
<thead>
<tr>
<th>Channel</th>
<th>H→γγ</th>
<th>H→ZZ→4l</th>
<th>H→WW→lνlν</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR [%]</td>
<td>0.23</td>
<td>0.013</td>
<td>0.98</td>
</tr>
</tbody>
</table>

- N(Higgs) in 1 fb\(^{-1}\) of pp collisions at 13 TeV: 130, 7, 550

\~56k Higgs boson produced in every fb\(^{-1}\) of 13 TeV data

- **Small BRs!** For WW and ZZ, stick to leptonic (e, \( \mu \)) decay of vector boson to suppress large bkg.

- \( γγ \) and ZZ→4l can reconstruct Higgs boson invariant mass with high resolution

- WW→lνlν has MET in the final states: rely on other observables (\( m_T \), \( m_\parallel \) etc.)
Coupling measurements

This talk will focus on ggF and VBF production modes

VH results will be covered by L. Mastrolorenzo

ttH results will be covered by J. Keller

Gluon-fusion

\[ \text{ggF (\sim 87\%)} \]

Vector boson

\[ \text{fusion (VBF) (\sim 7\%)} \]
Run 2 dataset in each channel

ATLAS-CONF-2018-028
Up to 2017

ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 79.8 fb⁻¹

ATLAS-CONF-2018-018
Up to 2017

H → γγ
77.4 fb⁻¹ (13 TeV)

PLB 789 (2019) 508
Up to 2016

ATLAS
H → WW → llνν
Nₜₚ ≤ 1
13 TeV, 36.1 fb⁻¹

CMS-PAS-HIG-18-001
New

CMS
H → γγ
7.4 fb⁻¹ (13 TeV)

CMS-PAS-HIG-18-029
New

CMS-PAS-HIG-19-001
New

PLB 791 (2019) 96
Up to 2016

H → WW → llνν
35.9 fb⁻¹ (13 TeV)

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Simplified template cross-section (STXS)

- Measure cross-section per production mode in different phase-space regions (more discussions in C. Kato’s talk)
  - Reduce model dependence and maximize sensitivity to BSM effects
  - Support kinematic-dependent interpretations (EFT etc.)
- Within each region, use the SM predicted signal templates to fit data
  - Can still exploit powerful analysis techniques (e.g. MVA)

Les Houches'15, Yellow Report 4
**H→γγ inclusive production cross-sections & STXS**

**Inclusive**

- Reaching 15% level precision for inclusive ggF cross-section, 30~40% level for VBF with ~80 fb$^{-1}$
- Data in good agreement with SM within uncertainties

**STXS**

- Reaching 15% level precision for inclusive ggF cross-section, 30~40% level for VBF with ~80 fb$^{-1}$
- Data in good agreement with SM within uncertainties
H→ZZ→4l: inclusive production cross-sections

- Reaching 10% precision for ggF with full Run 2 stats
- Good agreement with SM. 2σ tension from SM in ATLAS VBF result not confirmed by CMS
H→ZZ→4l: STXS cross-sections

- CMS use “Stage 1.1”. Current ATLAS results based on “Stage 1” granularity (will move to “Stage 1.1” in the next step)
- Choice of binning: balance between granularity and sensitivity/correlation
$H \rightarrow WW \rightarrow l\nu l\nu$

$\sqrt{s} = 13$ TeV, $36.1 \text{ fb}^{-1}$

$\sigma_{ggF} \cdot B_{H \rightarrow WW^*} \, [\text{pb}]$

- $\mu_{ggF} = 1.10^{+0.10}_{-0.09}(\text{stat})^{+0.13}_{-0.11}(\text{theory})^{+0.14}_{-0.13}(\text{exp})$
- $\mu_{VBF} = 0.62^{+0.29}_{-0.27}(\text{stat})^{+0.12}_{-0.13}(\text{theory}) \pm 0.15(\text{exp})$

- Good sensitivity for ggF (20% level precision) and VBF (50% level precision) with $\sim 36 \text{ fb}^{-1}$ (about a quarter of full Run 2 data)

- Two processes well separated, yielding small correlation between them
Mass, width, and CP results
Higgs boson mass measurement

- ATLAS ($\gamma\gamma$+4l): $m_H = 124.97 \pm 0.16$ (stat.) $\pm 0.18$ (syst.) GeV
- CMS (4l): $m_H = 125.26 \pm 0.20$ (stat.) $\pm 0.08$ (syst.) GeV
- Syst. uncertainty dominated by experimental ones (energy/momentum scale and resolution)
Off-shell analysis (new)

- $\Gamma_H < 14.4 \text{ MeV} @ 95\% \text{ CL} (<15.2 \text{ MeV exp.})$

- $\Gamma_H^{\text{SM}} = 4 \text{ MeV}$ for $m_H = 125.09 \text{ GeV}$: far below detector resolution!

- Use off-shell production in $H \rightarrow ZZ \rightarrow 4l/ll\nu\nu$ channels to constrain Higgs boson total width, assuming same couplings for on-shell/off-shell regions

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**ATLAS**

$H^* \rightarrow ZZ \rightarrow 4l, 2l2\nu$

13 TeV, 36.1 fb$^{-1}$

$\kappa_{g/V, \text{on-shell}} = \kappa_{g/V, \text{off-shell}}$

$\Gamma_H < 14.4 \text{ MeV} @ 95\% \text{ CL} (<15.2 \text{ MeV exp.})$

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**CMS**

5.1 fb$^{-1}$ (7 TeV) + 19.7 fb$^{-1}$ (8 TeV) + 77.5 fb$^{-1}$ (13 TeV)

$\Gamma_H < 9.16 \text{ MeV} @ 95\% \text{ CL} (<13.7 \text{ MeV exp.})$

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$\Gamma_H^{\text{SM}} = 4 \text{ MeV}$ for $m_H = 125.09 \text{ GeV}$: far below detector resolution!

Use off-shell production in $H \rightarrow ZZ \rightarrow 4l/ll\nu\nu$ channels to constrain Higgs boson total width, assuming same couplings for on-shell/off-shell regions
CP studies: CMS results

- Spin-0 nature established in Run 1
- CP admixture as well as other BSM interactions still possible: use Run 2 data to study HVV couplings
CP studies: ATLAS results

ATLAS

$H \rightarrow ZZ^* \rightarrow 4l$

13 TeV, 36.1 fb$^{-1}$

$\kappa_{Hgg} = 1$, $\kappa_{SM}$ free

$\tilde{c}_{HB} = \tilde{c}_{HW}$

$\tilde{c}_{HB} = \tilde{c}_{HW}$

- ATLAS use Higgs characterization model or Wilson coefficients etc. to probe CP even and odd BSM interactions

$H \rightarrow \gamma\gamma$, $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$, $m_H = 125.09$ GeV

68% CL
95% CL

Run 1 95% CL
Run 1 68% CL

Standard Model
Conclusions

- Bosonic decay channels continue leading Run 2 measurements of ggF (reaching 10% precision) and VBF (reaching 30% level precision) cross-sections
  - Also measured phase-space regions within production modes using STXS framework

- Higgs boson mass measurement updated with Run 2 data

- Off-shell analysis (for total width) and HVV CP studies did not show deviation from SM

- Many analyses to be updated to full Run 2 dataset, ATLAS and CMS dataset to be combined. Stay tuned for more results!

More details in C. Kato’s talk!
References

- ATLAS Collaboration, “Constraints on off-shell Higgs boson production and the Higgs boson total width in ZZ→4ℓ and ZZ→2ℓ2ν final states with the ATLAS detector”, PLB 786 (2018) 223
- Measurements of Higgs boson properties in the diphoton decay channel with 36 fb⁻¹ of pp collision data at √s = 13 TeV with the ATLAS detector, PRD 98 (2018) 052005
- CMS Collaboration, “Measurements of Higgs boson production via gluon fusion and vector boson fusion in the diphoton decay channel at √s = 13 TeV”, CMS-PAS-HIG-18-029
- CMS Collaboration, “Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state”, arXiv:1901.00174, accepted by PRD
Backup
SM Higgs boson production at LHC

Main

- Gluon-fusion: $ggF$ (~87%)
- Vector boson fusion (VBF) (~7%)
- VH (~4%)
- $ttH$ (~1%)

Rare

- $bbH$ (~1%) 0.49 pb
- $tH$ (~0.1%) 0.09 pb

- Distinct topology from each production mode
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios
- Improved accuracy from theory calculations: inclusive $\sigma(ggF)$ now calculated at $N^3$LO in QCD and NLO in EW, with 5% uncertainty

LHC Higgs XS WG Yellow Report 4

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Stage 1 STXS framework

- **ggF**
  - = 0-jet
  - = 1-jet (+)
  - ≥ 2-jet
  - \( p_T^{H} [0, 60] \)
  - \( p_T^{H} [60, 120] \)
  - \( p_T^{H} [120, 200] \)
  - \( p_T^{H} [200, \infty] \)

- **VBF**
  - \( (\text{EW} qqH \text{ incl.} \ V H \rightarrow qqH) \)
  - \( p_T^{j1} [0, 200] \)
  - \( p_T^{j1} [200, \infty] \)

- **VH**
  - \( (H + \text{leptonic } V) \)
  - \( q \bar{q} \rightarrow VH \)
  - \( W \rightarrow \ell \nu \)
  - \( p_T^{V} [0, 150] \)
  - \( p_T^{V} [150, 250] \)
  - \( p_T^{V} [250, \infty] \)

- **tH+tH**
  - \( ttH+tH \)
  - \( p_T^{H} < 200 \)
  - \( p_T^{H} [0, 120] \)
  - \( p_T^{H} [120, 200] \)
  - \( p_T^{H} [200, \infty] \)

- **Rest**
  - \( ≥ 2\text{-jet } VH \text{ cuts} \)
  - \( p_T^{Hjj} [0, 25] \)
  - \( p_T^{Hjj} [25, \infty] \)

- **gg \rightarrow ZH**
  - \( p_T^{V} [0, 150] \)
  - \( p_T^{V} [150, \infty] \)
  - \( = 0\text{-jet} \)
  - \( ≥ 1\text{-jet} \)

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Stage 1.1 STXS framework

- **gg → H**
  - $p_T^H$ [0, 200]
  - $m_{jj}$ [0, 350]
  - $m_{jj}$ [350, ∞]

- **EW qqH**
  - $= VBF + V(\rightarrow qq)H$

- **qqH-rest**
  - $m_{jj}$ [0, 350]
  - $m_{jj}$ [350, ∞]

- **VH**
  - $= V(\rightarrow$ leptons)H

- **ttH+tH**
  - $q\bar{q}' \rightarrow WH$
  - $q\bar{q} \rightarrow ZH$
  - $gg \rightarrow ZH$

- VH/pTV[0-150]
- VH/pTV>150
$H \rightarrow \gamma \gamma$: signal fractions

**ATLAS Simulation Preliminary**
$H \rightarrow \gamma \gamma$, $\sqrt{s} = 13$ TeV, $m_{H} = 125.09$ GeV

**CMS Simulation Preliminary**
$H \rightarrow \gamma \gamma$, 13 TeV (2017)

Fraction of signal process / Category

Category signal composition (%)

STXS process

Event category

Reconstruction Category

ttH
VH
VBF

Fraction of signal process / Category

ATLAS Simulation Preliminary
$H \rightarrow \gamma \gamma$
$\sqrt{s} = 13$ TeV

Higgs boson signals

- ggH 1J med
- ggH 1J high
- ggH 1J BSM
- ggH 2J low
- ggH 2J med
- ggH 2J high
- ggH 2J BSM
- ggF 1J med
- ggF 1J high
- ggF 1J BSM
- ggF 0J Fwd
- ggF 0J Cen

VBF signals

- VBF rest
- VBF BSM
- VBF VH-like
- VBF 3J-like
- VBF 2J-like
- VBF 1J-like
- VBF 2J-med
- VBF 1J-med
- VBF 0J

ttH signals

- ttH had BDT1
- ttH had BDT2
- ttH lep BDT1
- ttH lep BDT2
- ttH had BDT3
- ttH had BDT4

VH signals

- VH dilep
- VH lep Low
- VH MET High
- VH MET Low
- VH had BDT tight
- VH had BDT loose
- VH had BDT tight
- VH had BDT loose

ttH had BDT1
ttH had BDT2
ttH had BDT3
ttH had BDT4

VH dilep
VH lep Low
VH MET High
VH MET Low
VH had BDT tight
VH had BDT loose

VBF signals

- VBF BSM
- VBF VH-like
- VBF 2J-like
- VBF 2J-med
- VBF 2J-high
- VBF 1J-like
- VBF 1J-med
- VBF 0J

ggF signals

- ggF 2J BSM
- ggF 2J High
- ggF 2J Med
- ggF 1J BSM
- ggF 1J Low
- ggF 0J Fwd
- ggF 0J Cen

STXS Region

Higgs boson signals

- ggF 1J med
- ggF 1J high
- ggF 1J BSM
- ggF 2J low
- ggF 2J med
- ggF 2J high
- ggF 2J BSM
- ggF 0J Fwd
- ggF 0J Cen

VBF signals

- VBF rest
- VBF BSM
- VBF VH-like
- VBF 3J-like
- VBF 2J-like
- VBF 1J-like
- VBF 2J-med
- VBF 1J-med
- VBF 0J
H→γγ: correlation matrices for STXS

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \)
H→γγ, m_h = 125.09 GeV

CMS Supplementary H→γγ

77.4 fb⁻¹ (13 TeV)
H → ZZ → 4l: correlation matrices for STXS

13 TeV, 79.8 fb⁻¹
$H \rightarrow Z\gamma/\gamma\gamma^* \rightarrow ll\gamma$

ATLAS

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

- Data
- Background fit
- Signal $\times 20$

$m_H = 125$ GeV

CMS

H → Zγ → μμγ

Untagged 1

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

- Data
- Background model
- ±1 st. dev.
- ±2 st. dev.
- Expected signal $\times 10$

JHEP 10 (2017) 112

95% CL limit

<table>
<thead>
<tr>
<th></th>
<th>Obs. [xSM]</th>
<th>Exp. [xSM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (Zγ)</td>
<td>6.6</td>
<td>5.2</td>
</tr>
<tr>
<td>CMS (Zγ+γγ*)</td>
<td>3.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Prospect for off-shell constraint on $\Gamma_H$

**CMS Projection**

- w/ YR18 syst. uncert. ($f_{ai}=0$)
- w/ Run 2 syst. uncert. ($f_{ai}=0$)
- w/ Stat. uncert. only ($f_{ai}=0$)

**ATLAS Simulation**

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

- No systematics
- Norm systematics
- Norm+shape systematics
Theory model for HVV anomalous coupling studies

CMS:

\[
A \sim \left[ a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} - \frac{\kappa_3^{VV} (q_1 + q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{VV} f^{*(1)}_{\mu \nu} f^{*(2)}_{\mu \nu} + a_3^{VV} f^{*(1)}_{\mu \nu} \tilde{f}^{*(2)}_{\mu \nu}
\]

ATLAS:

\[
\mathcal{L}_0^V = \left\{ \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^-_{\mu} \right] \right.
\]

\[
- \frac{1}{4} \left[ \kappa_{Hgg} g_{Hgg} G_{\alpha, \mu \nu} G^a_{\alpha, \mu \nu} + \tan \alpha \kappa_{A_{gg}} g_{A_{gg}} G_{\alpha, \mu \nu} \tilde{G}^a_{\alpha, \mu \nu} \right]
\]

\[
- \frac{1}{4} \frac{1}{\Lambda} \left[ \kappa_{HZZ} Z_{\mu \nu} Z^{\mu \nu} + \tan \alpha \kappa_{A_{ZZ}} Z_{\mu \nu} \tilde{Z}^{\mu \nu} \right]
\]

\[
- \frac{1}{2} \frac{1}{\Lambda} \left[ \kappa_{HWW} W_{\mu \nu}^+ W^{-\mu \nu} + \tan \alpha \kappa_{A_{WW}} W_{\mu \nu}^+ \tilde{W}^{-\mu \nu} \right] \left\} X_0. \right.
\]