Summary of ggF measurements using bosonic channels

Alessandra Cappati
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On behalf of ATLAS and CMS Collaborations

Higgs Couplings 2018
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The Gluon-Gluon Fusion production mode

- ggF is the main production mechanism of the SM Higgs boson at hadron colliders
- ggF cross-section proportional to $\alpha_S^2$
- Main contribution to ggH comes from top quark
- ggF cross-section prediction (LHC HIGGS XS WG CERN Report4 2016) for $m_H = 125.09$ GeV/c$^2$ at 13 TeV: 48.52 pb (N3LO)
Higgs boson bosonic decay channels

Review of recent results obtained in pp collisions in LHC Run2 (13 TeV) by the ATLAS and CMS Collaborations

Results from the following papers will be presented:

**$H \rightarrow WW \rightarrow 2\ell 2\nu$:**

**$H \rightarrow ZZ \rightarrow 4\ell$:**
- ATLAS: ATLAS-CONF-2018-018 (data 80 fb$^{-1}$)
- CMS: JHEP11(2017)047 (data 36 fb$^{-1}$) + CMS-PAS-HIG-18-001 (data 41 fb$^{-1}$)

**$H \rightarrow \gamma\gamma$:**
- ATLAS: ATLAS-CONF-2018-028 (data 80 fb$^{-1}$)

Combination of bosonic and fermionic channels (**snippets**, see other talks during the conference):
\[ H \rightarrow WW \rightarrow 2\ell 2\nu: \text{datasets} \]

- Large branching ratio \( (\sim 2 \times 10^{-1} \times (10^{-1})^2) \)
- Main backgrounds: non-resonant \( WW, t\bar{t}, \text{single-top-quark}, \text{Drell-Yan} \) (mainly \( \text{DY} \rightarrow \tau^+\tau^- \)), di-boson processes (\( WZ, ZZ, W\gamma \)), \( W+jets, \text{multi-jet production} \)

Datasets:
- **ATLAS**
  - Data: 36 fb\(^{-1}\) at 13 TeV
  - MC:
    - \textbf{ggH signal} generated with POWHEG-BOX v2 NNLOPS and PDF set PDF4LHC15 NNLO;
    - \textbf{MC backgrounds}: \( q\bar{q} \rightarrow WW \) (SHERPA 2.2.2 with NNPDF3.0NNLO); \( gg \rightarrow WW \) and di-boson (SHERPA 2.1 with CT10); \( t\bar{t} \) (POWHEG-BOX v2 with NNPDF3.0NLO); single-top (POWHEG-BOX v2 with CT10)
    - \textbf{Other backgrounds}: \( W+jets, \text{multi-jet production} \) due to misidentified leptons from heavy quarks decays or jets faking leptons → estimate by data-driven technique

- **CMS**
  - Data: 36 fb\(^{-1}\) at 13 TeV
  - MC:
    - \textbf{ggH signal} generated with POWHEG v2 NLO, reweighted to match POWHEG NNLOPS and PDF set NNPDF 3.0;
    - \textbf{MC backgrounds}: \( q\bar{q} \rightarrow WW, t\bar{t} \) and single-top (POWHEG v2 with NNPDF 3.0); \( gg \rightarrow WW \) (MCFM v7.0 with NNPDF 3.0); \( \text{DY and di-boson} \) (MADGRAPH5_aMC@NLO with NNPDF 3.0)
    - \textbf{Other backgrounds}: \( W+jets, \text{multi-jet production} \) due to misidentified leptons from heavy quarks decays or jets faking leptons → estimate by data-driven technique
**$H \to WW \to 2\ell 2\nu$: event selection and categorization**

**Event preselection:**
- 2 different-flavour (e,μ) opposite-charge leptons with $p_T^{\ell_1} > 22$ GeV/c and $p_T^{\ell_2} > 15$ GeV/c
- $p_T^{jets} > 20$ GeV/c; MET > 20 GeV; b-tagged jet with $p_T > 20$ GeV/c vetoed to suppress top quark bkg

**Event categorization:** based on the number of jets with $p_T > 30$ GeV/c (seen the different bkg composition as function of jet multiplicity)
- 2 categories target ggF (0jet or 1jet)
- 1 category target VBF

Dedicated BDT to discriminate ggF from VBF

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**Event preselection:**
- 2 opposite-charge leptons with $p_T^{\ell_1} > 25$ GeV/c and $p_T^{\ell_2} > 10$ (13) GeV/c for e(μ)
- $p_T^{jets} > 30$ GeV/c; MET > 20 GeV ; b-tagged jet with $p_T > 20$ GeV/c vetoed to suppress top quark bkg

**Event categorization:** based on number of leptons and jets, and lepton flavour
- 5 categories target ggF (0jet, 1jet or 2jets, same-flavour (SF) or different-flavour (DF) leptons)
- 4 categories target other production modes

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**CMS Simulation**

<table>
<thead>
<tr>
<th>Signal fraction</th>
<th>Events</th>
<th>35.9 fb$^{-1}$ (13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>509.4 events</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>240.3 events</td>
<td></td>
</tr>
<tr>
<td>WH</td>
<td>313.3 events</td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>92.7 events</td>
<td></td>
</tr>
<tr>
<td>b\bar{b}H</td>
<td>103.3 events</td>
<td></td>
</tr>
<tr>
<td>t\bar{t}H</td>
<td>31.2 events</td>
<td></td>
</tr>
<tr>
<td>2-lepton VH-tagged</td>
<td>19.6 events</td>
<td></td>
</tr>
<tr>
<td>4-lepton ZH-tagged</td>
<td>2.7 events</td>
<td></td>
</tr>
</tbody>
</table>

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Alessandra Cappati (University and INFN Torino)
\[ H \rightarrow WW \rightarrow 2\ell 2\nu: ATLAS \text{ results} \]

- Signal extracted with a simultaneous fit in all categories
- Different variables used to discriminate signal from background in different categories \((m_{\ell \ell}, m_T)\)

Results:

- observed (expected) significance of \(ggF\) signal: \(6.3\sigma\) (5.2\(\sigma\))
- cross section x Branching ratio:
  - \(\sigma_{ggF} \times B_{H\rightarrow WW} = 12.6^{+2.3}_{-2.1} \text{ pb} = 12.6 \pm 1.0(\text{stat.}) \pm 1.1(\text{th. syst})^{+1.6}_{-1.5}(\text{exp. syst.})\) (consistent with expectations 10.4\pm0.6 \text{ pb})
  - \(\sigma_{VBF} \times B_{H\rightarrow WW} = 0.5^{+0.30}_{-0.29} \text{ pb} \) (consistent with expectations 0.81\pm0.02 \text{ pb})
  - signal strength parameter (measured yield/ yield predicted by SM): \(\mu_{ggF} = 1.21^{+0.22}_{-0.21} = 1.21 \pm 0.1(\text{stat.})^{+0.13}_{-0.12}(\text{th. syst}) \pm 0.15(\text{exp. syst.})\)
• Signal extracted with a simultaneous template fit in all categories
• Different variables used to discriminate signal from background in different categories ($m_{\ell\ell}, m_T$)

Results:

> Higgs boson signal observed (expected) significance $9.1\sigma$ ($7.1\sigma$);
> signal strength modifier: inclusive $\mu = 1.28^{+0.18}_{-0.17}$, ggF $\mu_{ggF} = \sigma_{ggF}/\sigma_{SM} = 1.38^{+0.21}_{-0.24}$
> production mode cross section ratios measured in the fiducial phase space $|y_H| < 2.5$
> Higgs boson coupling to fermions ($\mu_F$) and vector bosons ($\mu_V$)

CMS

$\sigma_{ggF}/\sigma_{SM} = 1.24^{+0.20}_{-0.20}$

$\sigma_{VH}/\sigma_{SM} = 0.24^{+0.24}_{-0.24}$

$|y_H| < 2.5$

$\sigma_{ZH}/\sigma_{SM} = 1.80^{+1.00}_{-1.00}$

$\sigma_{ZZ}/\sigma_{SM} = 0.71^{+1.40}_{-0.71}$

$\sigma_{WH}/\sigma_{SM} = 12.88^{+9.95}_{-4.90}$

$\mu_F = 1.37^{+0.21}_{-0.20}$

$\mu_V = 0.78^{+0.60}_{-0.57}$
$H \rightarrow ZZ \rightarrow 4l$: datasets

- Small branching ratio ($\sim 2.64 \times 10^{-2} \times (6.72 \times 10^{-2})^2 \sim 1.2 \times 10^{-4}$)
- But large signal/bkg ratio ($\sim 2/1$), good mass resolution and possibility to fully reconstruct the decay kinematics
- Main backgrounds: irreducible: $q\bar{q} \rightarrow ZZ, gg \rightarrow ZZ$, reducible: $Z$+jets (multi-jet due to misidentified leptons from heavy quarks decays or jets faking leptons)

Datasets:

- **ATLAS**
  - Data: $80 \text{ fb}^{-1}$ at $13 \text{ TeV}$
  - MC:
    - $ggH$ signal generated with POWHEG-BOX v2 NNLOPS and PDF set PDF4LHC NNLO;
    - MC backgrounds: $q\bar{q} \rightarrow ZZ$ (SHERPA 2.2.2 at NLO, NLO EW corrections applied); $gg \rightarrow ZZ$ (GG2VV at LO, rescaled with k-factors to higher order); $Z$+jets modelled with SHERPA 2.2.1 and normalized to data-driven estimate

- **CMS**
  - Data: $36 \text{ fb}^{-1}$ (2016) and $41 \text{ fb}^{-1}$ (2017) at $13 \text{ TeV}$
  - MC:
    - $ggH$ signal generated with POWHEG 2.0 NLO and PDF set NNPDF30_nlo_as_0118 (2016), NNPDF31_nlo_hessian_pdfas (2017);
    - MC backgrounds: $q\bar{q} \rightarrow ZZ$ (POWHEG 2.0 at NLO, rescaled with k-factors to higher order); $gg \rightarrow ZZ$ (MCFM at LO, rescaled with k-factors to higher order);
    - $Z$+jets estimated with data-driven technique
Event selection:

- Leptons: \( p_{Te} > 7 \text{ GeV/c}, p_{T\mu} > 5 \text{ GeV/c} \) (15 GeV/c for calorimeter tagged \( \mu \))
- \( Z \) candidates: 2 same-flavour opposite-charge lepton pairs with \( p_{T1} > 20 \text{ GeV/c} \), \( p_{T2} > 15 \text{ GeV/c} \), \( p_{T3} > 10 \text{ GeV/c} \) and \( 50 < m_{12} < 106 \text{ GeV/c}^2 \), \( m_{\text{min}} < m_{12} < 115 \text{ GeV/c}^2 \) (\( m_{\text{min}} = 12 - 50 \text{ GeV/c}^2 \) when \( m_{4\ell} = 140-190 \text{ GeV/c}^2 \), \( m_{\text{min}} = 50 \text{ GeV/c}^2 \) if \( m_{4\ell} > 190 \text{ GeV/c}^2 \)), and \( m_{e^-\ell^+} > 5 \text{ GeV/c}^2 \), FSR photon accounted in \( Z \) decays
- \( H \to 4\ell \) candidates: \( 115 < m_{4\ell} < 130 \text{ GeV/c}^2 \)

Event selection:

- Leptons: \( p_{Te} > 7 \text{ GeV/c}, p_{T\mu} > 5 \text{ GeV/c} \)
- \( Z \) candidates: 2 same-flavour opposite-charge lepton pairs with \( 12 < m_{\ell\ell} < 120 \text{ GeV/c}^2 \)
- \( H \to 4\ell \) candidates: \( m_{Z1} > 40 \text{ GeV/c}^2 \), \( p_{T1} > 20 \text{ GeV/c} \), \( p_{T2} > 10 \text{ GeV/c} \), \( m_{l^+l^-} > 4 \text{ GeV/c}^2 \), candidates are discarded 4\( \mu \) and 4\( e \) if the alternative combination \( Z_aZ_b \) satisfies \( |m(Z_a) - m(Z)| < |m(Z_1) - m(Z)| \) and \( m(Z_b) < 12 \text{ GeV/c}^2 \); \( m_{4\ell} > 70 \text{ GeV/c}^2 \)
- If more than one \( H \to 4\ell \) candidate survives per event, the one with the highest value of \( D_{bkg}^{\text{kin}} \) is chosen.
Event categorization: based on the number of additional leptons, jets, and BDT discriminants
- 4 categories target ggF
- 7 categories target other production modes

Event categorization: based on number of additional leptons, jets, and kinematic discriminants
- 1 category targets ggF
- 6 categories target other production modes
Fiducial inclusive and differential cross sections measured using a binned profile-likelihood-ratio fit in all categories, fitting the $m_{4\ell}$ distribution in each channel and bin:

- Inclusive fiducial production cross section of $H \to ZZ \to 4\ell$ computed for individual final state
- Total cross-section obtained extrapolating the fiducial cross-section to the total phase space (results compared to NNLOPS, MADGRAPH5_AMC@NLO-FXFX and HRES for ggF)
- Differential production cross-section data compared to SM expectation for the ggF prediction of NNLOPS and MADGRAPH5_AMC@NLO-FXFX
• Production cross sections measured using a binned profile-likelihood-ratio fit in all categories, fitting the BDT distributions and observed yields in each category
• Production xsec measured in the fiducial phase space $|y_H| < 2.5$
• Inclusive signal strength: $\mu = 1.19 \pm 0.12 \text{ (stat.)} \pm 0.06 \text{ (exp.)} ^{+0.09}_{-0.07} \text{ (th.)} = 1.19^{+0.16}_{-0.15}$
• Dominant systematics: lepton efficiency, integrated luminosity measurement, theoretical uncertainty of ggF signal yield due to QCD scale variation
• bbH production process is treated as a part of ggF production bin
Cross-section for $H \rightarrow ZZ \rightarrow 4\ell$ is computed in fiducial phase space performing a maximum-likelihood fit of $m_{4\ell}$ distribution without event categorization. Fit preformed simultaneously in all final states.

- Integrated fiducial xsec: $\sigma_{\text{fid}} = 2.92^{+0.48}_{-0.44}\text{(stat.)}^{+0.26}_{-0.24}\text{(syst.)} \text{ fb}$ (expected: $\sigma_{\text{fid}}^{\text{SM}} = 2.76 \pm 0.14 \text{ fb}$)
- Differential xsec: data compared to SM expectation for the $ggF$ prediction of NNLOPS and POWHEG
- Dominant systematics: lepton identification efficiency, integrated luminosity measurement, theoretical sources of uncertainty are subdominant
$H \rightarrow ZZ \rightarrow 4\ell$: CMS results

- Production cross sections measured performing a multi-dimensional simultaneous fit in all categories, 2D likelihood $L_{2D}(m_{4\ell}, D_{bkg}^{\text{kin}})$ unbinned in the $m_{4\ell}$ dimension
- Combination of 2016 and 2017 results: theoretical and experimental uncertainties considered fully correlated
- bbH production process is treated as a part of ggF production bin
This channel has:
• Small branching ratio ($\sim 2 \times 10^{-3}$)
• But clean final state with invariant mass peak that can be reconstructed with high precision
• Dominant background: irreducible prompt diphoton production. Reducible background: $\gamma$+jets, di-jet events, $W\gamma$, $Z\gamma$

Datasets:
• Data: 80 fb$^{-1}$ at 13 TeV
• MC:
  • ggH signal generated with POWHEG and PDF set PDF4LHC15;
  • MC backgrounds: continuum $\gamma\gamma$, $W\gamma$ and $Z\gamma$ (SHERPA 2.2.4 with PDF CT10); $t\bar{t}\gamma\gamma$ (MADGRAPH5_aMC@NLO with PDF PDF4LHC15); bkg determined directly from the fit to data distribution (sidebands)

Datasets:
• Data: 36 fb$^{-1}$ at 13 TeV
• MC:
  • ggH signal generated with MADGRAPH5_aMC@NLO at NLO v2.2.2, reweighted to match prediction from NNLOPS; PDF set used: NNPDF3.0
  • MC backgrounds: di-photon bkg (SHERPA v2.2.1); $\gamma$+jets and multi-jet processes (PYTHIA); $W\gamma$ and $Z\gamma$ (MADGRAPH5_aMC@NLO at LO); bkg determined directly from the fit to data distribution (sidebands)
Event selection:
- $\gamma$ candidate reconstructed in $|\eta| < 2.37$, excluding the range $1.37 < |\eta| < 1.52$ (barrel-endcap ECAL transition)
- $\gamma$ separated from jet bkg using identification criteria based on calorimeter shower shape variables
- At least 2 $\gamma$ in the event associated to a di-photon primary vertex
- 2 highest-$p_T$ $\gamma$ chosen as candidate for di-photon system
- Neural network to determine the correct primary vertex
- Leading $\gamma$ s.t. $p_T/m_{\gamma\gamma} > 0.35$; sub-leading $\gamma$ s.t. $p_T/m_{\gamma\gamma} > 0.25$
- $105 < m_{\gamma\gamma} < 160$ GeV/c$^2$

Event categorization: based on jet $p_T$ and BDT discriminants
- 10 category targets ggF
- 19 categories target other production modes
Event selection:
- $\gamma$ candidate reconstructed in $|\eta| < 2.5$, excluding the range $1.44 < |\eta| < 1.57$ (barrel-endcap ECAL transition)
- $p_T^{\gamma_1} > 30$ GeV/c, $p_T^{\gamma_2} > 20$ GeV/c
- Condition on ECAL and HCAL deposits to separate $\gamma$ from jet bkg
- BDT used to separate $\gamma$ from misidentified jets
- BDT used to determine the primary vertex
- Event selection: 2 $\gamma$ candidates with $p_T^{\gamma_1} > m_{\gamma\gamma}/3$ and $p_T^{\gamma_2} > m_{\gamma\gamma}/4$
- $100 < m_{\gamma\gamma} < 180$ GeV/c$^2$

Event categorization: based on dedicated BDT
- 4 category targets ggF
- 10 categories target other production modes
  - xsec measurement (CMS-HIG-17-025) events categorized according to their mass resolution → 3 categories
H → γγ: ATLAS results

- Fiducial inclusive and differential cross sections measured using a likelihood fit on the $m_{γγ}$ distribution
  - Inclusive fiducial $\sigma \times BR (H → γγ)$ is measured to be: $\sigma_{fid} = 60.4 \pm 6.1\text{(stat.)} \pm 6.0\text{(exp.)} \pm 0.3\text{(theo.)}\text{ fb}$ (expected: $63.5 \pm 3.3\text{ fb}$)
  - Differential fiducial xsec reported as function of $p_T^{γγ}$, $|γγ|$, $N_{b-jets}$
- Dominant systematics: photon energy scale and resolution, bkg modeling
H → γγ: ATLAS results

- Signal strength, production mode cross sections and STXS measured performing a likelihood fit to $m_{γγ}$ simultaneously in the 29 categories
  - Global signal strength: $μ = 1.06^{+0.14}_{-0.12} = 1.06 ± 0.08$ (stat.)$^{+0.08}_{-0.07}$ (exp.)$^{+0.07}_{-0.06}$ (theo.)
  - Production mode $σ × BR (H → γγ)$ in the region $|y_H| < 2.5$

<table>
<thead>
<tr>
<th>Process</th>
<th>Result [fb]</th>
<th>Uncertainty [fb]</th>
<th>SM prediction [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1/80)</td>
<td>98</td>
<td>$+15^-14_0$</td>
<td>$+11^-9_8$</td>
</tr>
<tr>
<td>$+4^-3_0$</td>
<td>102$^-7_0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$
$H → γγ$, $|y_H| < 2.5$

ATLAS-CONF-2018-028
$H \to \gamma\gamma$: CMS results

- Fiducial inclusive and differential cross section obtained with a maximum likelihood fit to $m_{\gamma\gamma}$ simultaneously in the 3 categories
  - Inclusive $\sigma \times BR(H \to \gamma\gamma)$ is measured to be: $\sigma_{\text{fid}} = 84 \pm 11(\text{stat}) \pm 7(\text{syst}) \text{fb} = 84 \pm 13(\text{stat} + \text{syst}) \text{fb}$ (expected: $73 \pm 4 \text{fb}$)
  - Differential fiducial xsec reported as function of $p_T^{\gamma\gamma}$, $|y^{\gamma\gamma}|$, $N_{b-jets}$
Signal strength and STXS measured performing a binned maximum-likelihood fit to $m_{\gamma\gamma}$ in all the categories:

- Global signal strength: $\mu = 1.18^{+0.17}_{-0.14} = 1.18^{+0.12}_{-0.11} (\text{stat.})^{+0.09}_{-0.07} (\text{exp.})^{+0.07}_{-0.06} (\text{theo.})$; $ggF: \mu = 1.10^{+0.20}_{-0.18}$
- STXS stage-0
- Higgs boson coupling to fermions ($\mu_{ggF,t\bar{t}H}$) and vector bosons ($\mu_{VBF,VH}$)

- $\mu_{ggF,t\bar{t}H} = 1.19^{+0.22}_{-0.18}$
- $\mu_{VBF,VH} = 1.21^{+0.58}_{-0.51}$
Combination

- Channels: γγ, ZZ, WW, ττ, μμ, b̅b̅
- Datasets: 80 fb⁻¹ at 13 TeV

CMS

CMS-CONF-2018-031

ATLAS

ATLAS Preliiminary

Total = 13 TeV, 36.1 - 79.8 fb⁻¹

m_H = 125.09 GeV, |y_H| < 2.5

ATLAS-CONF-2018-031

μ_ggH

μ_VBF

μ_WH

μ_ZH

μ_{ttH + tH}

CMS

CMS-HIG-17-031

μ_{ggF} = 1.22 ± 0.14 (± 0.08 (stat) ± 0.12 (syst))

Higgs Couplings 2018
Summary

- ggF is the main production mechanism of the SM Higgs boson at hadron colliders
- $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$ are good channels to investigate the Higgs boson main production mode
- Results presented found to be in general in agreement with SM predictions
Back-up
$H \rightarrow ZZ \rightarrow 4\ell$ CMS: discriminants

$$D_{2\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{H+JJ}(\Omega_{H+JJ}^H|m_{4\ell})}{\mathcal{P}_{VBF}(\Omega_{H+JJ}^H|m_{4\ell})} \right]^{-1}$$

$$D_{WH} = \left[ 1 + \frac{\mathcal{P}_{H+JJ}(\Omega_{H+JJ}^H|m_{4\ell})}{\mathcal{P}_{WH}(\Omega_{H+JJ}^H|m_{4\ell})} \right]^{-1}$$

$$D_{1\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{H+J}(\Omega_{H+JJ}^H|m_{4\ell})}{\int d\eta J \mathcal{P}_{VBF}(\Omega_{H+JJ}^H|m_{4\ell})} \right]^{-1}$$

$$D_{ZH} = \left[ 1 + \frac{\mathcal{P}_{H+JJ}(\Omega_{H+JJ}^H|m_{4\ell})}{\mathcal{P}_{ZH}(\Omega_{H+JJ}^H|m_{4\ell})} \right]^{-1}$$
\[ H \to ZZ \to 4\ell \] ATLAS: categorization and STXS
$H \to ZZ \to 4\ell$ CMS: 2016 categorization

![CMS categorization diagram](chart.png)

JHEP11(2017)047
$H \rightarrow ZZ \rightarrow 4\ell$: fiducial phase space

Table 2: List of event selection requirements which define the fiducial phase space for the cross section measurement. SFOS lepton pairs are same-flavour opposite-sign lepton pairs.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptons and jets</strong></td>
<td></td>
</tr>
<tr>
<td>Leptons:</td>
<td>$p_T &gt; 5 \text{ GeV},</td>
</tr>
<tr>
<td>Jets:</td>
<td>$p_T &gt; 30 \text{ GeV},</td>
</tr>
<tr>
<td>remove jets with:</td>
<td>$\Delta R(\text{jet, } \ell) &lt; 0.1$</td>
</tr>
<tr>
<td><strong>Lepton selection and pairing</strong></td>
<td></td>
</tr>
<tr>
<td>Lepton kinematics:</td>
<td>$p_T &gt; 20, 15, 10 \text{ GeV}$</td>
</tr>
<tr>
<td>Leading pair ($m_{12}$):</td>
<td>SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td>Subleading pair ($m_{34}$):</td>
<td>remaining SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td>Event selection (at most one quadruplet per event)</td>
<td></td>
</tr>
<tr>
<td>Mass requirements:</td>
<td>$50 \text{ GeV} &lt; m_{12} &lt; 106 \text{ GeV}$ and $12 \text{ GeV} &lt; m_{34} &lt; 115 \text{ GeV}$</td>
</tr>
<tr>
<td>Lepton separation:</td>
<td>$\Delta R(\ell_i, \ell_j) &gt; 0.1$</td>
</tr>
<tr>
<td>$J/\psi$ veto:</td>
<td>$m(\ell_i, \ell_j) &gt; 5 \text{ GeV}$ for all SFOS lepton pairs</td>
</tr>
<tr>
<td>Mass window:</td>
<td>$115 \text{ GeV} &lt; m_{4\ell} &lt; 130 \text{ GeV}$</td>
</tr>
<tr>
<td>If extra leptons with $p_T &gt; 12 \text{ GeV}$:</td>
<td>Quadruplet with the largest ME</td>
</tr>
</tbody>
</table>

Table 4: Summary of requirements and selections used in the definition of the fiducial phase space for the $pp \rightarrow H \rightarrow 4\ell$ cross section measurements.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton kinematics and isolation</strong></td>
<td></td>
</tr>
<tr>
<td>Leading lepton $p_T$</td>
<td>$p_T &gt; 20 \text{ GeV}$</td>
</tr>
<tr>
<td>Subleading lepton $p_T$</td>
<td>$p_T &gt; 10 \text{ GeV}$</td>
</tr>
<tr>
<td>Additional electrons (muons) $p_T$</td>
<td>$p_T &gt; 7 \text{ (5) GeV}$</td>
</tr>
<tr>
<td>Pseudorapidity of electrons (muons)</td>
<td>$</td>
</tr>
<tr>
<td>Sum $p_T$ of all stable particles within $\Delta R &lt; 0.3$ from lepton</td>
<td>$&lt;0.35 p_T$</td>
</tr>
<tr>
<td><strong>Event topology</strong></td>
<td></td>
</tr>
<tr>
<td>Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above</td>
<td></td>
</tr>
<tr>
<td>Invariant mass of the $Z_1$ candidate</td>
<td>$40 &lt; m_{Z_1} &lt; 120 \text{ GeV}$</td>
</tr>
<tr>
<td>Invariant mass of the $Z_2$ candidate</td>
<td>$12 &lt; m_{Z_2} &lt; 120 \text{ GeV}$</td>
</tr>
<tr>
<td>Distance between selected four leptons</td>
<td>$\Delta R(\ell_i, \ell_j) &gt; 0.02$ for any $i \neq j$</td>
</tr>
<tr>
<td>Invariant mass of any opposite-sign lepton pair</td>
<td>$m_{\ell^+\ell^-} &gt; 4 \text{ GeV}$</td>
</tr>
<tr>
<td>Invariant mass of the selected four leptons</td>
<td>$105 &lt; m_{4\ell} &lt; 140 \text{ GeV}$</td>
</tr>
</tbody>
</table>
# $H \rightarrow \gamma\gamma$: ATLAS categorization

<table>
<thead>
<tr>
<th>Category label</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$ BDT1</td>
<td>$N_{\text{lep}} \geq 1$, $N_{\text{jet}} \geq 1$, $\text{BDT}_{\text{lep}} &gt; 0.987$</td>
</tr>
<tr>
<td>$t\bar{t}H$ BDT2</td>
<td>$N_{\text{lep}} \geq 1$, $N_{\text{jet}} \geq 1$, $0.942 &lt; \text{BDT}_{\text{lep}} &lt; 0.987$</td>
</tr>
<tr>
<td>$t\bar{t}H$ BDT3</td>
<td>$N_{\text{lep}} \geq 1$, $N_{\text{jet}} \geq 1$, $0.705 &lt; \text{BDT}_{\text{lep}} &lt; 0.942$</td>
</tr>
<tr>
<td>$t\bar{t}H$ had BDT1</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{jet}} \geq 1$, $\text{BDT}_{\text{had}} &gt; 0.996$</td>
</tr>
<tr>
<td>$t\bar{t}H$ had BDT2</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{jet}} \geq 1$, $0.991 &lt; \text{BDT}_{\text{had}} &lt; 0.996$</td>
</tr>
<tr>
<td>$t\bar{t}H$ had BDT3</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{jet}} \geq 1$, $0.971 &lt; \text{BDT}_{\text{had}} &lt; 0.991$</td>
</tr>
<tr>
<td>$t\bar{t}H$ had BDT4</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{jet}} \geq 1$, $0.911 &lt; \text{BDT}_{\text{had}} &lt; 0.971$</td>
</tr>
<tr>
<td>VH diphotons</td>
<td>$N_{\text{lep}} \geq 2$, $70 \text{ GeV} &lt; m_{\gamma\gamma} &lt; 110 \text{ GeV}$</td>
</tr>
<tr>
<td>VH lep High</td>
<td>$N_{\text{lep}} = 1$, $</td>
</tr>
<tr>
<td>VH lep Low</td>
<td>$N_{\text{lep}} = 1$, $</td>
</tr>
<tr>
<td>VH MET High</td>
<td>$150 \text{ GeV} &lt; E_{\text{T}}^{\gamma\gamma} &lt; 250 \text{ GeV}$, $E_{\text{T}}^{\gamma\gamma}$ significance &gt; 0 or $E_{\text{T}}^{\gamma\gamma}$ &gt; 250 GeV</td>
</tr>
<tr>
<td>VH MET Low</td>
<td>$80 \text{ GeV} &lt; E_{\text{T}}^{\gamma\gamma} &lt; 150 \text{ GeV}$, $E_{\text{T}}^{\gamma\gamma}$ significance &gt; 8</td>
</tr>
<tr>
<td>q/tt BSM</td>
<td>$m_{t\bar{t}} &gt; 2$, $p_{T,t} &gt; 200 \text{ GeV}$</td>
</tr>
<tr>
<td>VH had BDT tight</td>
<td>$60 \text{ GeV} &lt; m_{jj} &lt; 120 \text{ GeV}$, $\text{BDT}_{\text{VT}} &gt; 0.78$</td>
</tr>
<tr>
<td>VH had BDT loose</td>
<td>$60 \text{ GeV} &lt; m_{jj} &lt; 120 \text{ GeV}$, $0.35 &lt; \text{BDT}_{\text{VT}} &lt; 0.78$</td>
</tr>
<tr>
<td>VBF high-$H^{\ast}\gamma$</td>
<td>$</td>
</tr>
<tr>
<td>VBF low-$H^{\ast}\gamma$</td>
<td>$</td>
</tr>
<tr>
<td>ggf $2\gamma$ BSM</td>
<td>$N_{\text{jets}} = 2$, $p_{T,\gamma} &gt; 200 \text{ GeV}$</td>
</tr>
<tr>
<td>ggf $2\gamma$ High</td>
<td>$N_{\text{jets}} = 2$, $p_{T,\gamma} = (120, 200)$ GeV</td>
</tr>
<tr>
<td>ggf $2\gamma$ Med</td>
<td>$N_{\text{jets}} = 2$, $p_{T,\gamma} = (60, 120)$ GeV</td>
</tr>
<tr>
<td>ggf $2\gamma$ Low</td>
<td>$N_{\text{jets}} = 2$, $p_{T,\gamma} = (0, 60)$ GeV</td>
</tr>
<tr>
<td>ggf $1\gamma$ BSM</td>
<td>$N_{\text{jets}} = 1$, $p_{T,\gamma} &gt; 200 \text{ GeV}$</td>
</tr>
<tr>
<td>ggf $1\gamma$ High</td>
<td>$N_{\text{jets}} = 1$, $p_{T,\gamma} = (120, 200)$ GeV</td>
</tr>
<tr>
<td>ggf $1\gamma$ Med</td>
<td>$N_{\text{jets}} = 1$, $p_{T,\gamma} = (60, 120)$ GeV</td>
</tr>
<tr>
<td>ggf $1\gamma$ Low</td>
<td>$N_{\text{jets}} = 1$, $p_{T,\gamma} = (0, 60)$ GeV</td>
</tr>
<tr>
<td>ggf $0\gamma$ $\text{FWD}$</td>
<td>$N_{\text{jets}} = 0$, one photon with $</td>
</tr>
<tr>
<td>ggf $0\gamma$ $\text{CEN}$</td>
<td>$N_{\text{jets}} = 0$, two photons with $</td>
</tr>
</tbody>
</table>
The fiducial phase space for the analysis is defined by requiring that the generator-level ratio between the $p_T$ of the $p_T$-leading ($p_T$-subleading) photon and $m_{\gamma\gamma}$, $p_T^{\gamma_1}/p_T^{\gamma_2}$ ($m_{\gamma\gamma}$/$p_T^{\gamma_1}$), be greater than $1/3$ ($1/4$), and that the absolute pseudorapidity of both photons be less than 2.5.

The inclusive fiducial cross section is also measured in restricted fiducial phase spaces, defined using additional criteria as follows:

- at least one lepton, at least one b-tagged jet, referred to as the $\geq 1$-lepton, $\geq 1$-b-jet fiducial cross section ($\sim 1.7 \times 10^{-3}$ of the baseline phase space);
- exactly one lepton, $p_T^{\text{miss}} \geq 100$ GeV, referred to as the 1-lepton, high-$p_T^{\text{miss}}$ fiducial cross section ($\sim 1.5 \times 10^{-3}$ of the baseline phase space);
- exactly one lepton, $p_T^{\text{miss}} < 100$ GeV, referred to as the 1-lepton, low-$p_T^{\text{miss}}$ fiducial cross section ($\sim 7.4 \times 10^{-3}$ of the baseline phase space).

### Table 6: Definition of the particle-level objects and the fiducial measurement regions.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$</td>
</tr>
<tr>
<td>Jets</td>
<td>$k_T$, $R = 0.4$, $p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>– Central jets</td>
<td>$</td>
</tr>
<tr>
<td>– b-jets</td>
<td>$</td>
</tr>
<tr>
<td>Leptons, $\ell = e$ or $\mu$</td>
<td>electrons: $p_T &gt; 10$ GeV, $</td>
</tr>
</tbody>
</table>

### ATLAS-CONF-2018-028

Alessandra Cappati (University and INFN Torino)
### $H \to \gamma\gamma$: ATLAS STXS stage-1

<table>
<thead>
<tr>
<th>Measurement region</th>
<th>Result [fb]</th>
<th>Uncertainty [fb]</th>
<th>SM prediction [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>($</td>
<td>y_H</td>
<td>&lt; 2.5$)</td>
<td></td>
</tr>
<tr>
<td>ggF, 0 jet</td>
<td>58</td>
<td>$^{+15}_{-14}$</td>
<td>$^{+10}<em>{-8} -^{+2}</em>{-1}$</td>
</tr>
<tr>
<td>ggF, 1 jet, $p_T^H &lt; 60$ GeV</td>
<td>18</td>
<td>$^{+10}_{-9}$</td>
<td>$^{+8}<em>{-6} +^{1}</em>{-1}$</td>
</tr>
<tr>
<td>ggF, 1 jet, $60 \leq p_T^H &lt; 120$ GeV</td>
<td>9</td>
<td>±5</td>
<td>$^{+3}<em>{-2} +^{1}</em>{-0}$</td>
</tr>
<tr>
<td>ggF, 1 jet, $120 \leq p_T^H &lt; 200$ GeV</td>
<td>2.6</td>
<td>$^{+1.5}_{-1.3}$</td>
<td>$^{+1.2}<em>{-0.6} +^{0.3}</em>{-0.1}$</td>
</tr>
<tr>
<td>ggF, ≥2 jet</td>
<td>7</td>
<td>±6</td>
<td>$^{+5}<em>{-2} +^{2}</em>{-2}$</td>
</tr>
<tr>
<td>$q\bar{q} \to H q\bar{q}$, $p_T^j &lt; 200$ GeV</td>
<td>15</td>
<td>$^{+5}_{-4}$</td>
<td>$^{+4}<em>{-2} +^{2}</em>{-2}$</td>
</tr>
<tr>
<td>ggF + $q\bar{q} \to H q\bar{q}$, BSM-like</td>
<td>1.4</td>
<td>±0.9</td>
<td>$^{+0.8}<em>{-0.6} +^{0.4}</em>{-0.2}$</td>
</tr>
<tr>
<td>VH, leptonic</td>
<td>2.0</td>
<td>$^{+1.1}_{-1.0}$</td>
<td>$^{+1.0}<em>{-0.9} +^{0.4}</em>{-0.1}$</td>
</tr>
<tr>
<td>Top</td>
<td>1.5</td>
<td>$^{+0.6}_{-0.5}$</td>
<td>$^{+0.5}<em>{-0.2} +^{0.2}</em>{-0.2}$</td>
</tr>
</tbody>
</table>

Table 5: Best-fit values and uncertainties of the simplified template cross sections times the Higgs to diphoton branching ratio. The SM predictions [9] are shown for each region. The central values and uncertainties are rounded.
• STXS: current data not yet sensitive to all 31 region of stage-1 → stage-1 regions merged in 9 phase space regions