Higgs fiducial and differential measurements at ATLAS and CMS

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Motivation and outline

The challenges of differential measurements...

- High statistics required
- Measurement limited to a subset of phase space
- Detectors warp the distribution, need to be accounted for by unfolding
  - Statistically delicate operation, comes with many considerations

...and their strengths

- Sensitive probes for BSM effects and precision benchmarks for the SM
- Directly measure the spectrum of an observable
- No need to specify a signal hypothesis a priori
  - Directly re-interpretable by theorists

Covered in this talk

- $H \rightarrow \tau \tau$
  - CMS: HIG-20-015
- $H \rightarrow b \bar{b}$
  - ATLAS: ATLAS–CONF–2021–010
  - CMS: JHEP12(2020)085
- $H \rightarrow WW$
  - CMS: JHEP03(2021)003
- $H \rightarrow ZZ \rightarrow 4\ell$
  - CMS: arXiv:2103.04956 (submitted to EPJC)
- $H \rightarrow \gamma \gamma$
  - CMS: JHEP01(2019)183
Measured observables

Wide range of observables giving sensitivity to several effects (including BSM)

- Higgs production-related quantities probe pQCD calculations, radiative corrections, choice of PDF, light quark couplings, CP-structure of the Higgs sector:
  - $p_T^H$, $\eta_H$, $N_{jets}$, $m_{jj}$, $|\Delta \eta_{jj}|$, $\Delta \phi_{jj}$

- Jet-related quantities probe radiative QCD quark and gluon emission patterns, QCD resummation effects
  - $p_T^{j_1}$, $p_T^{j_2}$, $N_{jets}$, $m_{jj}$

- Channel specific decay-related observables probe EW corrections and Higgs spin-parity properties
  - $m_{\ell_1 \ell_2}$, $m_{\ell_3 \ell_4}$, angular variables

Different channels have sensitivity to different variables
\[ H \rightarrow \tau \tau \]

HIG-20-015
The H → ττ channel

- The analysis measures $p_T^H$, $N_{jets}$ and $p_T^{\ell\ell}$ distributions
- Relatively large BR (≈ 6%) makes this channel competitive, especially in the high $p_T^H$, $N_{jets}$ regions
- All decay combinations of the ττ system considered, apart from $ee + 4\nu$ and $\mu\mu + 4\nu$
- First differential measurement in this channel!

Main backgrounds

- $Z \rightarrow \tau\tau, t\overline{t}$, di-boson production
  - Events with two τ leptons estimated with embedded samples
  - Di-muon events in data with muons replaced with simulated τ leptons
- Jets misidentified as $\tau_h$
  - Misidentification probability estimated in data

The fit is done on the mass of the ττ system ($m_{\tau\tau}$), reconstructed with a simplified matrix-element algorithm

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SM expectation

Fit result
Results

Measurement inclusive in production modes
Prediction from POWHEGv2@NLO reweighted to NNLOPS
Good agreement with expectation:
- \( p(p_T^H) = 17\% \), \( p(N_{jets}) = 71\% \), \( p(p_T^{1\text{j}}) = 45\% \)
- Fiducial cross section extracted from fit to \( N_{jets} \):
  \[ \sigma^{\text{fid}} = 426 \pm 102 \text{ fb} \ (\sigma_{SM}^{\text{fid}} = 408 \pm 27 \text{ fb}) \]

Fiducial cross section extracted from fit to \( N_{jets} \):
\[
\sigma_{\text{SM}}^{\text{fid}} = 408 \pm 27 \text{ fb}
\]

Regularization term (optional), Tikhonov scheme in this analysis

Migration matrix
Particle level signal strength

True for all analyses discussed except ALTAS \( H \to \gamma\gamma \) (bin by bin corrections)
H → b$b$
The $H \rightarrow b\bar{b}$ channel

- Very high multijet (QCD) background
- BR($H \rightarrow b\bar{b}$) = 58% → highest in the SM
- Mitigates natural cross section decrease at high $p_T^H$
- Both analyses target the boosted jet topology, i.e. a large radius jet with a 2 sub-jet structure

Signal extracted by fitting the jet mass distribution

- ATLAS: $p_T^{j_1} > 450$ GeV, $p_T^{j_2} > 250$ GeV, one compatible with 2 sub-jets
- CMS: $p_T^{j_1} > 450$ GeV, dedicated MVA tagger
Results

- Different approach for the two analyses (differential results):
  - ATLAS: inclusive in production modes
  - CMS: targets gluon fusion, other modes treated as background

- ATLAS: good agreement with SM
  - Predictions from POWHEG+MINLO (ggH), POWHEG-BOX v2 (VBF, gg → VH, t¯tH) and POWHEG-BOX v2+MINLO (qq → VH)

- CMS: 2.6σ excess in highest $p_T^H$ bin, reduced to 1.8σ when considering all bins simultaneously
  - Prediction from HJ-MINLO
  - Also compared to NNLO calculation from LHCHXSWG
H → WW

JHEP03(2021)003
Bosonic channels give good sensitivity on a wide range
Second highest total branching ratio, highest to a leptonic final state
Final state with 2 leptons and 2 neutrinos provides best sensitivity
No access to full kinematics of the diboson system
  - Neutrinos are undetected, resulting in missing transverse energy (MET)
  - The fit is done on the dilepton invariant mass and Higgs transverse mass

Main backgrounds

Non-resonant $WW$, $t\bar{t}$ (dominant):
  - Normalization measured in data
Lepton misidentification, $DY \rightarrow \tau\tau$ (subdominant):
  - DY normalization measured in control region, lepton misidentification probability estimated from data
Di-boson and tri-boson production (minor):
  - Estimated via MC simulation
Results

- Fiducial and differential ($p_T^H, N_{jets}$) cross sections
- All production modes are considered
- Nominal prediction form POWHEGv2 at NLO, ggH reweighted to NNLOPS
- Results also compared to MG5@NLO
- Good agreement to SM, highest excess for $N_{jets} \geq 4$ at $1.4\sigma$

- Total fiducial cross section obtained from fit on $p_T^H$
- Good agreement with SM prediction obtained from POWHEGv2

$\sigma_{fid} = 86.5 \pm 9.5$ fb

$\sigma_{SM} = 82.5 \pm 4.2$ fb

$\mu_{fid} = 1.03^{+0.12}_{-0.11} (\pm 0.05\text{(stat.)})^{+0.08}_{-0.07}\text{(theo.)} \pm 0.03\text{(lumi.)} \pm 0.07\text{(exp.)}$
H → ZZ → 4ℓ
The $H \rightarrow ZZ \rightarrow 4\ell$ channel

- Relatively low BR compensated by very well reconstructed final state
- Selected events contain 4 leptons ($e, \mu$), grouped into same-flavor opposite-charge (SFOC) pairs to form $Z$ candidates
- Access to the full kinematics of the Higgs system

Main backgrounds

- Non-resonant $ZZ/Z\gamma$ production (dominant):
  - ATLAS: shape estimated from simulation and normalization measured in $m_H$ sidebands
  - CMS: shape and normalization estimated from simulation
- $Z + jets, t\bar{t}, WZ$ (subdominant):
  - Estimated in dedicated control regions
- Triboson, $tVV$ and $t\bar{t}V$ (minor):
  - Taken from simulation
Results - fiducial cross sections

- Results compared to different MC predictions
- Good compatibility with the SM expectation

Total cross section extrapolated assuming SM acceptance and BRs
Results - differential cross sections

**ATLAS+CMS**

\[ p_T^H, y_H, N_{jets}, p_T^{j1} \]

**ATLAS**

\[ m_{12}, m_{34}, |\cos \theta^*|, \cos \theta_1, \cos \theta_2, \phi, \phi_1 \]

\[ N_{b-jets}, p_T^{j2}, m_{jj} \]

\[ |\Delta \eta_{jj}|, |\Delta \phi_{jj}| \]

\[ p_T^H, m_A, p_T^H, m_{Hjj} \]

- Statistically dominated uncertainties
- Sensitive in the full range of many variables
- Good SM compatibility
Results - double-differential cross sections

- ATLAS also measured a set of double-differential cross sections:

  \[ p_T^H \text{ VS } |y_H|, \quad p_T^H \text{ VS } N_{\text{jets}} \]
  \[ m_{12} \text{ VS } m_{34}, \quad p_T^H \text{ VS } p_T^{H1} \]
  \[ p_T^{Hj} \text{ VS } m_{Hj}, \quad p_T^H \text{ VS } p_T^{j1} \]
  \[ p_T^{j1} \text{ VS } |y_{j1}|, \quad p_T^{j1} \text{ VS } p_T^{j2} \]

- 2D differential cross sections being made possible with Run II data
- Compared to NNLOPS and MG5@NLO-FxFx reweighted to N^3LO
- Jet-related distributions also compared to NNLOJET and RadISH
\[ H \rightarrow \gamma \gamma \]
The H → γγ channel

- Relatively small SM branching ratio (~0.2%) offset by very clean final state
- The full 4-momentum of the diphoton pair is accessible
- Excellent diphoton mass (m_{γγ}) resolution of 1-2%
- Vertex assignment challenging (no tracker info)
  - Use of ML discriminants (BDT for CMS and NN for ATLAS)
- Main backgrounds: SM diphoton production (dominant), γ + jets, dijet (with misidentified jets)

CMS (36 fb\(^{-1}\))
- \(p_T^{H}, |y_{H}|, N_{jets}, |\cos \theta^*|, p_T^{j_1}, p_T^{j_2}, |y_{j_1}|, |y_{j_2}|, |\Delta \phi_{H,j_1}|, |\Delta y_{H,j_2}|, |\Delta \phi_{jj}|, |\Delta \phi_{H,jj}|, m_{jj}, |\Delta \eta_{jj}|, z\)

ATLAS (139 fb\(^{-1}\))
- \(p_T^{H}, |y_{H}|, N_{jets}, p_T^{j_1}, m_{jj}, \Delta \phi_{jj}\)

Combinations with H → ZZ and H → bb, see talk by Haider Abidi
Results

**CMS (36 fb⁻¹)**

\[
\sigma_{fid} = 84 \pm 11 \text{(stat.)} \pm 7 \text{(syst.) fb}
\]

\[
\sigma_{SM} = 73 \pm 4 \text{ fb}
\]

**ATLAS (139 fb⁻¹)**

\[
\sigma_{fid} = 65.2 \pm 4.5 \text{(stat.)} \pm 5.6 \text{(syst.) fb}
\]

\[
\sigma_{SM} = 63.6 \pm 3.3 \text{ fb}
\]

- Good agreement with SM predictions
- ATLAS: default prediction from POWHEG@NNLOPS, compared with NNLOJET and others
- CMS: default prediction from MG5@NLO+FxFx reweighted to NNLOPS, compared to POWHEGv2
I have presented the most recent fiducial and differential measurements in the Higgs sector from the ATLAS and CMS collaborations.

- Wide range of production modes, decay channels and observables - first $H \rightarrow \tau\tau$ differential result!
- Results are unfolded to particle level, allowing direct comparison with theory.
- Most measurements still statistically dominated, looking forward to Run III of the LHC and beyond!
- More Run II results still to come, stay tuned!

Thank you very much for your attention.
Backup
Recent Higgs Results from CMS with the Full LHC Run 2 Dataset

**CMS (36 fb⁻¹)**

\[ H \rightarrow \gamma\gamma + H \rightarrow ZZ + H \rightarrow b\bar{b} \]

**ATLAS (139 fb⁻¹)**

\[ H \rightarrow \gamma\gamma + H \rightarrow ZZ \]

- Measurements must be extrapolated from the fiducial volume to the full phase space
- Done assuming SM acceptances
- Good agreement with predictions
Fiducial volume definitions - $H \rightarrow \tau\tau$

**CMS**

- **$e\tau_h (\mu\tau_h)$:**
  - Electron (muon) $p_T > 25\,(20)$ GeV and $|\eta| < 2.1$
  - Visible $\tau_h$ $p_T > 30$ GeV and $|\eta| < 2.3$
  - $m(e/\mu, p_T^{miss}) < 50$ GeV

- **$\tau_h\tau_h$:**
  - Visible $\tau_h$ $p_T > 40$ GeV and $|\eta| < 2.1$
  - At least one jet with $p_T > 30$ GeV

- **$e\mu$:**
  - Leading (subleading) lepton $p_T > 24\,(15)$ GeV
  - Lepton $|\eta| < 2.4$
  - $m_T(e\mu, p_T^{miss}) < 60$ GeV

Momenta of photons radiated within $\Delta R = 0.1$ of a lepton are added to the lepton’s momentum.
Migration matrices - $H \rightarrow bb$

| $p_T^H$ [GeV] | $|\eta_H|$ | SRL | SRS | SRL/SRS |
|---------------|-------------|-----|-----|---------|
| > 450         | > 450       | -   | -   | < 2     |
| > 1000        | -           | -   | -   | < 2     |
| 450–650,      | 300–450,    | -   | -   | < 2     |
| > 650         | 450–650,    | -   | -   | < 2     |
| > 650         | > 650       | -   | -   | < 2     |

SRL(S): leading (subleading) jet tagged

ATLAS Simulation Preliminary

<table>
<thead>
<tr>
<th></th>
<th>SRL1</th>
<th>SRL2</th>
<th>SRS0</th>
<th>SRS1</th>
<th>SRS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^H &gt; 650$</td>
<td>10</td>
<td>8</td>
<td>26</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>$300 &lt; p_T^H &lt; 450$</td>
<td>13</td>
<td>4</td>
<td>47</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>$450 &lt; p_T^H &lt; 650$</td>
<td>75</td>
<td>14</td>
<td>27</td>
<td>73</td>
<td>8</td>
</tr>
<tr>
<td>$p_T^H &gt; 650$</td>
<td>3</td>
<td>74</td>
<td>74</td>
<td>9</td>
<td>83</td>
</tr>
</tbody>
</table>

CMS Simulation

<table>
<thead>
<tr>
<th>$p_T^H$ (GeV)</th>
<th>0.1</th>
<th>0.5</th>
<th>0.9</th>
<th>3.3</th>
<th>7.2</th>
<th>3.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Folding matrix $M_{ij}$ (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450–500</td>
<td>3.5</td>
<td>2.7</td>
<td>2.0</td>
<td>1.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>500–550</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550–600</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600–675</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>675–800</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800–1200</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GEN

RECO
### Fiducial volume definitions - $H \rightarrow WW$

<table>
<thead>
<tr>
<th>Observable</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton origin</td>
<td>Direct decay of $H \rightarrow W^+ W^-$</td>
</tr>
<tr>
<td>Lepton flavors; lepton charge</td>
<td>$e \mu$ (not from $\tau$ decay); opposite</td>
</tr>
<tr>
<td>Leading lepton $p_T$</td>
<td>$p_T^{l_1} &gt; 25 \text{ GeV}$</td>
</tr>
<tr>
<td>Trailing lepton $p_T$</td>
<td>$p_T^{l_2} &gt; 13 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Dilepton mass</td>
<td>$m_{ll} &gt; 12 \text{ GeV}$</td>
</tr>
<tr>
<td>$p_T$ of the dilepton system</td>
<td>$p_T^{ll} &gt; 30 \text{ GeV}$</td>
</tr>
<tr>
<td>Transverse mass using trailing lepton</td>
<td>$m_T^{l_2} &gt; 30 \text{ GeV}$</td>
</tr>
<tr>
<td>Higgs boson transverse mass</td>
<td>$m_T^H &gt; 60 \text{ GeV}$</td>
</tr>
</tbody>
</table>

Moments of photons radiated within $\Delta R = 0.1$ of a lepton are added to the lepton’s momentum.
### Correlation matrices - H → WW

#### Regularized

<table>
<thead>
<tr>
<th>$p_{T}^H$ (GeV)</th>
<th>0-20</th>
<th>20-45</th>
<th>45-80</th>
<th>80-120</th>
<th>120-200</th>
<th>&gt; 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>0.034</td>
<td>0.010</td>
<td>0.039</td>
<td>0.020</td>
<td>-0.083</td>
<td></td>
</tr>
<tr>
<td>20-45</td>
<td>0.052</td>
<td>0.040</td>
<td>0.101</td>
<td>0.176</td>
<td>-0.197</td>
<td></td>
</tr>
<tr>
<td>45-80</td>
<td>0.034</td>
<td>0.122</td>
<td>-0.265</td>
<td>-0.393</td>
<td>0.114</td>
<td></td>
</tr>
<tr>
<td>80-120</td>
<td>0.305</td>
<td>-0.372</td>
<td>-0.483</td>
<td>0.270</td>
<td>-0.019</td>
<td></td>
</tr>
<tr>
<td>120-200</td>
<td>-0.556</td>
<td>-0.551</td>
<td>0.283</td>
<td>-0.076</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>&gt; 200</td>
<td>0.653</td>
<td>0.457</td>
<td>-0.130</td>
<td>0.130</td>
<td>0.008</td>
<td></td>
</tr>
</tbody>
</table>

#### Unregularized

<table>
<thead>
<tr>
<th>$N_{pt}$</th>
<th>0-1</th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>≥ 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>0.038</td>
<td>0.152</td>
<td>0.023</td>
<td>0.059</td>
<td></td>
</tr>
<tr>
<td>20-45</td>
<td>-0.199</td>
<td>0.153</td>
<td>0.029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45-80</td>
<td>-0.378</td>
<td>0.191</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80-120</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120-200</td>
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</tr>
</tbody>
</table>

**Correlations among the unfolded signal strength modifiers**
# Fiducial volume definitions - \( H \rightarrow ZZ \)

## ATLAS

**Leptons and jets**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

**Lepton selection and pairing**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton kinematics</td>
<td>( p_T &gt; 20, 15, 10 \text{ GeV} )</td>
</tr>
<tr>
<td>Leading pair ( (m_{12}) )</td>
<td>SFOC lepton pair with smallest (</td>
</tr>
<tr>
<td>Subleading pair ( (m_{34}) )</td>
<td>Remaining SFOC lepton pair with smallest (</td>
</tr>
</tbody>
</table>

**Event selection (at most one quadruplet per event)**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass requirements</td>
<td>( 50 \text{ GeV} &lt; m_{Z_2} &lt; 106 \text{ GeV} ) and ( 12 \text{ GeV} &lt; m_{Z_1} &lt; 115 \text{ GeV} )</td>
</tr>
<tr>
<td>Lepton separation</td>
<td>( \Delta R(\ell_1, \ell_2) &gt; 0.1 )</td>
</tr>
<tr>
<td>Lepton/Jet separation</td>
<td>( \Delta R(\ell, \text{jet}) &gt; 0.1 )</td>
</tr>
<tr>
<td>( J/\psi ) veto</td>
<td>( m(\ell_1, \ell_2) &gt; 5 \text{ GeV} ) for all SFOC lepton pairs</td>
</tr>
<tr>
<td>Mass window</td>
<td>( 105 \text{ GeV} &lt; m_{4\ell} &lt; 160 \text{ GeV} )</td>
</tr>
</tbody>
</table>

If extra lepton with \( p_T > 12 \text{ GeV} \), Quadruplet with largest matrix element value

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## CMS

**Lepton kinematics and isolation**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading lepton ( p_T )</td>
<td>( p_T &gt; 20 \text{ GeV} )</td>
</tr>
<tr>
<td>Next-to-leading 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(5) \text{ GeV} )</td>
</tr>
<tr>
<td>Pseudorapidity of electrons (muons)</td>
<td>(</td>
</tr>
<tr>
<td>Sum of scalar ( p_T ) of all stable particles within ( \Delta R &lt; 0.3 ) from lepton</td>
<td>( &lt; 0.35p_T )</td>
</tr>
</tbody>
</table>

**Event topology**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above</td>
<td></td>
</tr>
<tr>
<td>Inv. mass of the ( Z_1 ) candidate</td>
<td>( 40 &lt; m_{Z_1} &lt; 120 \text{ GeV} )</td>
</tr>
<tr>
<td>Inv. 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>Inv. mass of any opposite sign lepton pair</td>
<td>( m_{\ell^+\ell^-} &gt; 4 \text{ GeV} )</td>
</tr>
<tr>
<td>Inv. mass of the selected four leptons</td>
<td>( 105 &lt; m_{4\ell} &lt; 140 \text{ GeV} )</td>
</tr>
</tbody>
</table>
Correlation matrices - $H \rightarrow ZZ$
The sum on $p_T^i$ is extended to all charged particles within $\Delta R = 0.2$ of the photon.