Higgs measurements at the HL-LHC with CMS

A. de Wit

on behalf of the CMS collaboration
Outline

• Introduction
  • Higgs physics
  • HL-LHC
• SM Higgs boson measurements at the HL-LHC
  • H→γγ
  • H→ZZ
  • Non-resonant HH
• BSM Higgs boson searches at the HL-LHC
  • Resonant HH
  • A/H→ττ
  • VBF H→invisible
• Summary and outlook
Introduction

- 5 years since the discovery of the Higgs boson, what do we know?

**Run 1**: good precision on mass and couplings

**Run 2**: re-discovery of the Higgs boson and fiducial/differential cross-sections

**Parameter value**

\[
\begin{align*}
\text{mm} &= 125.02 \pm 0.51 \ (\pm 0.43 \pm 0.27) \ \text{GeV} \\
\text{CMS} H \rightarrow \gamma \gamma & \quad 124.70 \pm 0.34 \ (\pm 0.31 \pm 0.15) \ \text{GeV} \\
\text{ATLAS} H \rightarrow ZZ \rightarrow 4l & \quad 125.15 \pm 0.40 \ (\pm 0.37 \pm 0.15) \ \text{GeV} \\
\text{ATLAS} H \rightarrow ZZ \rightarrow 4l & \quad 125.59 \pm 0.45 \ (\pm 0.42 \pm 0.17) \ \text{GeV} \\
\text{ATLAS} + \text{CMS} \gamma \gamma & \quad 125.07 \pm 0.29 \ (\pm 0.25 \pm 0.14) \ \text{GeV} \\
\text{ATLAS} + \text{CMS} \gamma \gamma & \quad 125.15 \pm 0.40 \ (\pm 0.37 \pm 0.15) \ \text{GeV} \\
\text{ATLAS} + \text{CMS} \gamma \gamma & \quad 125.09 \pm 0.24 \ (\pm 0.21 \pm 0.11) \ \text{GeV} \\
\end{align*}
\]

**CMS Preliminary**

35.9 fb^{-1} (13TeV)

**ATLAS+CMS PRL 114(2015) 191803**

**ATLAS+CMS JHEP 08 (2016) 045**

**CMS-PAS-HIG-17-015**

**Run 1LHC**

**Total**

- Total Stat. Syst.

- CMS

- ATLAS

**Parameter value**

\[
\begin{align*}
\text{13} & \quad \text{35.9 fb}^{-1} \ (13\text{TeV}) \\
\end{align*}
\]

**Run 1LHC**

**Total**

- Total Stat. Syst.

- CMS

- ATLAS
Introduction

- The Higgs sector looks standard-model like... but is it?
- At the HL-LHC, expect $L=3000$ fb$^{-1}$
  - Precision measurements
  - Access to Higgs self coupling
  - Find BSM physics?
- High luminosity→high PU: Upgrades to various parts of the detector to function in this challenging environment

Tracker: coverage up to $|\eta|<4$, increased granularity, L1 triggering capabilities

Calorimeter endcaps: highly granular calorimeter, 3D shower imaging

Barrel calorimeter: Upgrades to electronics, ECAL noise reduction, HCAL scintillators

Muon endcaps: additional systems covering $1.5<|\eta|<2.4$, increased muon system coverage up to $|\eta|<3$

Trigger: Track-trigger at L1, higher rates
Extrapolation strategy

- Extrapolations of analyses at 13 TeV on 2015 dataset (2.3-2.7 fb\(^{-1}\)) or early 2016 dataset (12.9 fb\(^{-1}\))
- Several extrapolation scenarios considered:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Uncertainties change</th>
<th>high-PU effects modelled</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>no</td>
<td>no</td>
<td>systematic uncertainties constant</td>
</tr>
<tr>
<td>S1+</td>
<td>no</td>
<td>yes</td>
<td>systematic uncertainties constant, analysis-dependent modifications for high PU</td>
</tr>
<tr>
<td>S2</td>
<td>yes</td>
<td>no</td>
<td>theoretical uncertainties halved, experimental uncertainties scaled down by (\sqrt{L}) until a lower limit is reached</td>
</tr>
<tr>
<td>S2+</td>
<td>yes</td>
<td>yes</td>
<td>theoretical uncertainties halved, experimental uncertainties scaled down by (\sqrt{L}) until a lower limit is reached, analysis-dependent modifications for high PU</td>
</tr>
<tr>
<td>Stat. Only.</td>
<td>yes</td>
<td>no</td>
<td>only statistical uncertainties considered</td>
</tr>
</tbody>
</table>
SM Higgs boson measurements
\[ H \rightarrow \gamma \gamma \]

- Projection of analysis on 12.9 fb\(^{-1}\) to 300(0) fb\(^{-1}\)
- 2 scenarios considered for projection:
  - **S1**: all systematic uncertainties kept constant
  - **S2**: theoretical uncertainties scaled down by 1/2, experimental uncertainties scaled down by $\sqrt{L}$ until a lower limit is reached
- At 3000 fb\(^{-1}\), modifications for high PU included:
  - Reduction of vertex identification efficiency and photon identification efficiency

<table>
<thead>
<tr>
<th>CMS Projection (13 TeV)</th>
<th>3000 fb(^{-1}) (13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$\mu_\gamma$</strong></td>
<td>$\pm 0.01$ (stat.) $\pm 0.08$ (exp.) $\pm 0.06$ (theo.)</td>
</tr>
<tr>
<td><strong>$\mu_\gamma$</strong></td>
<td>$\pm 0.01$ (stat.) $\pm 0.02$ (exp.) $\pm 0.03$ (theo.)</td>
</tr>
<tr>
<td><strong>$\mu_\gamma$</strong></td>
<td>$\pm 0.01$ (stat.) $\pm 0.02$ (exp.) $\pm 0.03$ (theo.)</td>
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<td>$\pm 0.01$ (stat.) $\pm 0.02$ (exp.) $\pm 0.03$ (theo.)</td>
</tr>
</tbody>
</table>

Projection to 3000 fb\(^{-1}\) of uncertainty on the signal strength measurement:
experimental and theoretical uncertainties limit the precision.

Projection to 300 and 3000 fb\(^{-1}\) of uncertainty in fiducial cross-section measurement:
at 3000 fb\(^{-1}\) measurement again limited by size of experimental uncertainties.
**H → ZZ**

- Projection from 12.9 fb⁻¹ to 300(0) fb⁻¹
- Same two scenarios as for H → γγ
- High-PU effects taken into account at 3000 fb⁻¹
- Effects on lepton efficiency/misidentification rates

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**CMS Projection**

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ* → 4l</td>
<td>± 0.02 (stat.) ± 0.04 (exp.) ± 0.07 (theo.)</td>
</tr>
<tr>
<td>μ^ZZ</td>
<td>± 0.02 (stat.) ± 0.03 (exp.) ± 0.03 (theo.)</td>
</tr>
</tbody>
</table>

Projection to 3000 fb⁻¹ of uncertainty in differential cross-section measurement: relative uncertainty 4-10%
Non-resonant HH

- **Access to the Higgs self-coupling via Higgs boson pair production**
  - Destructive interference $\sigma(pp \rightarrow HH) = 33.4$ fb
  - Projections of 4 non-resonant HH final states, 2.3-2.7 fb$^{-1}$ projected to 3000 fb$^{-1}$
  - Scenario with systematic uncertainties scaled down + a scenario without systematic uncertainties (stat. only)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Median expected limits in $\mu_r$</th>
<th>Z-value</th>
<th>Uncertainty as fraction of $\mu_r = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow HH \rightarrow \gamma\gamma bb$ (S2+)</td>
<td>1.44</td>
<td>1.37</td>
<td>1.43</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow \tau\tau bb$</td>
<td>5.2</td>
<td>3.9</td>
<td>0.39</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow VV bb$</td>
<td>4.8</td>
<td>4.6</td>
<td>0.45</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow bbbb$</td>
<td>7.0</td>
<td>2.9</td>
<td>0.39</td>
</tr>
</tbody>
</table>

**Expected upper limits on $\sigma_{HH}/\sigma_{HHSM}$ projected to 3000 fb$^{-1}$**
Analysis has not yet been performed with Run-2 data

Instead, study based on simulation using Delphes to model the upgraded detector performance

Conditions:
- Centre-of-mass energy 14 TeV, 200 PU, integrated luminosity 3000 fb$^{-1}$
- Only the dominant $t\bar{t}$ background considered as background process

**Expected upper limit on $\sigma_{HH}/\sigma_{HHS_{SM}}$**
as a function of the relative uncertainty on the background:
median expected limit
3.5xSM for 0% uncertainty
10.5xSM for 5% uncertainty

\[
\text{CMS Simulation preliminary}
\]
BSM Higgs boson searches
Resonant HH→4b

- Heavy resonance X decaying to pair of 125 GeV Higgs bosons
- Access to models with warped extra dimensions, SUSY
- Projection of analysis on 2.3 fb$^{-1}$ to 3000 fb$^{-1}$
  - 2 scenarios used:
    - Statistical uncertainty only
    - Systematic uncertainties scaled down with $\sqrt{L}$, theoretical uncertainties halved

3 mass points: 300 GeV, 700 GeV, 1 TeV

<table>
<thead>
<tr>
<th>$m_X$ (TeV)</th>
<th>Median expected limits on $\sigma$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>46</td>
</tr>
<tr>
<td>0.7</td>
<td>7.3</td>
</tr>
<tr>
<td>1.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Limits indicated on the reference analysis results in red
MSSM $\phi \rightarrow \tau \tau$

- Projection of search on 2.3 fb$^{-1}$ to 300 and 3000 fb$^{-1}$
- Three scenarios considered:
  - Systematic uncertainties unchanged (scenario 1)
  - Experimental uncertainties scaled down with $\sqrt{L}$, theoretical by factor 1/2 (scenario 2)
  - Statistical uncertainties only (stat. only)
- Analysis considers two heavy Higgs boson production modes (gluon fusion, b-associated production)
  - Interpretation in MSSM $m_h^{mod+}$ benchmark scenario

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Pink shaded area: expected exclusion from reference analysis
Grey bands: pm 1/2$\sigma$ expected (reference analysis)
Blue lines: projection to 300 fb$^{-1}$
Red lines: projection to 3000 fb$^{-1}$

Even at 3000 fb$^{-1}$, analysis remains statistically limited at high mass
VBF H → invisible

- Projecting search for invisibly decaying Higgs boson produced via vector boson fusion using 2.3 fb$^{-1}$
- Scenarios considered:
  - Unchanged systematic uncertainties
  - Exp uncertainties scaled down by $\sqrt{L}$ until lower bound is reached, theoretical uncertainties scaled by 1/2
  - Uncertainties scaled down by $\sqrt{L}$ (No lower bound), theoretical uncertainties scaled by 1/2

With unchanged systematic uncertainties, upper limit on BR(H → inv) plateaus around 300 fb$^{-1}$, scaling systematic uncertainties by $\sqrt{L}$ allows upper limit of BR(H → inv)=5% at 3000 fb$^{-1}$
Summary and outlook

• Projections to 300(0) fb^{-1} of analyses using Run-2 data and studies based on simulation of upgraded detector shown
  • Expected precision of property measurements
  • Access to HH production
  • Physics reach in BSM scenarios

• Next steps: studies of analysis improvements with upgrades to specific subsystems
  • TDRs for subsystems to be submitted throughout the remainder of 2017
    • Higgs analysis studies to feature in all of these TDRs
      → Increasingly clear picture of the prospects for Higgs physics at the HL-LHC
Backup
Projected analyses

- $H \rightarrow \gamma\gamma$: CMS-PAS-HIG-16-020
- $H \rightarrow ZZ \rightarrow 4l$: CMS-PAS-HIG-16-033
- $HH \rightarrow bby\gamma\gamma$: CMS-PAS-HIG-16-032
- $HH \rightarrow bbbbb$ (non resonant): CMS-PAS-HIG-16-026
- $HH \rightarrow bbbbb$ (resonant): CMS-PAS-HIG-16-006
- $HH \rightarrow bb\tau\tau$: CMS-PAS-HIG-16-012
- $HH \rightarrow bbWW \rightarrow bblvlv$: CMS-PAS-HIG-16-024
- MSSM $H \rightarrow \tau\tau$: CMS-PAS-HIG-16-006
- VBF $H \rightarrow inv$: CMS-PAS-HIG-16-016