Prospects for Higgs Boson Measurements at the HL-LHC with CMS

Sylvie Braibant
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on behalf of the CMS Collaboration
To extend the sensitivity for new physics searches → 2023-2025: **LHC major upgrade**

- **LS2 → Run3**
  - \( L = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  - \( \sqrt{s} = 14 \text{ TeV} \)
  - PU = 50

- **LS3 → HL-LHC**
  - \( L = 5 \times 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  - \( \sqrt{s} = 14 \text{ TeV} \)
  - PU = 140 (200)

**HL-LHC or Phase 2**

- **Pile-up [PU]:** average number of proton-proton collisions per bunch crossing

**Run-2 event with 100 vertices**

- **2020-2023:** 300 fb\(^{-1}\) per experiment
- **2025-2035:** ≈3000 fb\(^{-1}\) per experiment
CMS Detector Upgrades

- Performance compromised by **radiation damage** and **increased pile-up**
- Detector upgrades crucial to **maximise physics potential** and **maintain a good object reconstruction** in this harsh environment → increased radiation hardness, increased forward acceptance, higher granularity …

**New Tracker**
- Increased radiation hardness
- Higher granularity
- Increased forward acceptance up to $\eta = 4$
- Reduced material in the tracker volume
- Tracks in hardware trigger (L1)

**Muons**
- In the forward region, improved RPC + new GEM detectors → Increased acceptance up to $\eta \sim 3$
- Front-end electronics upgrade for DT’s and CSC’s

**New Endcap Calorimeter**
- Radiation tolerant
- High granularity (HGCAL)
- Timing information
Over **170 million Higgs** bosons in 3000 fb$^{-1}$

**Unique opportunity** to thoroughly test the Higgs boson properties

- **High precision coupling measurements** - down to a few percents
- **Sensitivity to coupling to 2nd generation** - $H \rightarrow \mu\mu$
- **Di-Higgs production** and **Higgs self-coupling measurement**
  
  *See Luca Cadamuro’s talk “HH production at the HL-LHC with CMS”*
- **Sensitivity to rare decays** involving new physics

Picture of the experimental reach on Higgs boson properties measurements obtained from **projections with 3000 fb$^{-1}$**

**NB:** 3000 fb$^{-1}$ per experiment studied as benchmark although ultimate collider scenario with $\mathcal{L} = 7.5 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$ might provide up to 4000 fb$^{-1}$
Higgs Production Modes and Cross-sections

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>ggF (a)</th>
<th>VBF (b)</th>
<th>VH (c)</th>
<th>ttH (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>54.67</td>
<td>4.45</td>
<td>2.50</td>
<td>0.613</td>
</tr>
</tbody>
</table>

Cross-sections in pb for $M_H = 125$ GeV

Higgs Working Group Report
arXiv:1610.07922v2 Yellow Report 4
What do we measure?

- Traditional **signal strength** modifiers:
  - $\mu_i$ for $i = \text{ggH, VBF, VH, ttH production modes}$
  - $\mu^f$ for $f = \gamma\gamma, ZZ, WW, \tau\tau, bb, \text{etc decay modes}$

- “Reduced” coupling scale factors $y_i$

- Deviations from the Standard Model implemented as **scale factors** ($\kappa$'s) of Higgs couplings relative to their SM values

- $\kappa_i$ scale factors (“**coupling modifiers**”) defined in such a way that the cross-sections $\sigma_i$ and the partial decay widths $\Gamma_i$ associated with the SM particle $i$ scale with $\kappa_i^2$ compared to the SM prediction

\[
\begin{align*}
\mu_i &= \frac{\sigma_i}{\sigma_i^{SM}} \\
\mu^f &= \frac{\sigma^f}{\sigma^{SM}_f} \\
\mu_i^f &= \mu_i \cdot \mu^f \\
y_{V,i} &= \sqrt{\kappa_{V,i}} \frac{g_{V,i}}{2\nu} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{\nu} \\
\left(V,i = W,Z\right) \\
y_{F,i} &= \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{\nu} \\
\left(F,i = \mu, \tau, b, t\right) \\
\kappa_i^2 &= \frac{\sigma_i}{\sigma_i^{SM}} \\
\kappa_i^2 &= \frac{\Gamma_i}{\Gamma_i^{SM}}
\end{align*}
\]
Run-2 Measurements

See Nick Wardle’s talk - “Measurements of the Higgs boson mass, production and decay rates and constraints on its couplings at CMS”

Signal strengths
\[ \mu_i^f = \mu_i \cdot \mu_f^f \]

Fit results in the \( \kappa \)-framework model with \( BR_{BSM} = 0 \)

Measurements with 2016 data at \( \sqrt{s} = 13 \) TeV corresponding to an integrated luminosity of 35.9 fb\(^{-1}\)

Start to exploit **new production-decay models**, e.g. VH and ttH with \( H \rightarrow \tau\tau \) decay channel
\[ \mu = 1.17 \pm 0.06 \text{ (stat.)} + 0.06 \text{ (theory)} + 0.06 \text{ (syst.)} \]

**Uncertainties** now reaching 10-20% level for most parameters
Existing Projections on Signal Strengths

Projections based on 2016 data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 12.9 fb$^{-1}$ for 3000 fb$^{-1}$ (ECFA16)

- Two projection scenarios that include higher PU and detector upgrades effects
  - **S1+**: all systematic uncertainties constant
  - **S2+**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a lower limit based on estimates of achievable accuracy with upgraded detector)

- Since then reduction in theory uncertainties (e.g. $N^3$LO ggF prediction) and improvement in analysis techniques

- Statistics is crucial in $t\bar{t}H(\rightarrow \gamma\gamma, ZZ \rightarrow 4\ell)$ channels

- HL-LHC can bring uncertainty on $t\bar{t}H$ down to 10% level
Existing Projections per Decay Mode

- Projections scenarios (Snowmass report of 2013) - unchanged detector performance (no upgrade considered)
  - **S1**: systematic uncertainties constant
  - **S2**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity

Projected uncertainties per decay mode based on 5.1 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV and up to 19.6 fb\(^{-1}\) at \(\sqrt{s} = 8\) TeV

### Signal strengths

- \(H \rightarrow \gamma \gamma\)
- \(H \rightarrow WW\)
- \(H \rightarrow ZZ\)
- \(H \rightarrow bb\)
- \(H \rightarrow \tau \tau\) 

Expected uncertainties on Higgs boson signal strength

- 3000 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV Scenario 1
- 3000 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV Scenario 2

### Couplings

- \(K_\gamma\)
- \(K_W\)
- \(K_Z\)
- \(K_g\)
- \(K_b\)
- \(K_t\)
- \(K_\tau\)

Expected uncertainties on Higgs boson couplings

- 3000 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV Scenario 1
- 3000 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV Scenario 2

### Existing Projections

- [5-8]\% [S2,S1]
- [2-5]\% [S2,S1]
- About 20 000 ggF $\rightarrow$ H$\rightarrow$ ZZ$^*$ $\rightarrow$ 4$\ell$ + another $\sim$1550 VBF expected
- Upgraded detectors bring significant improvements
- Signal acceptance and mass resolution fairly immune to pile-up conditions

H $\rightarrow$ ZZ$^*$

**m$_{4\mu}$**

**$\sigma$(m$_{4\mu}$)**

- CMS Phase-2 Simulation: 3000 fb$^1$, 14 TeV, 200 PU
- CMS Stage-2 Simulation: 14 TeV, 200 PU

$\eta$ of the most forward muon
VBF $H \rightarrow \tau \tau$ and $H \rightarrow \gamma \gamma$

- **VBF** is of particular interest → higher signal purity compared to dominant ggF production mechanism
- CMS High granularity and precision timing capabilities of the High-Granularity Calorimeter (HGCAL) → improvement in pile-up suppression, isolation, jet shape observables and missing energy → improved reconstruction and identification of forward jets in VBF production

(1M) $H \rightarrow \tau \tau$ events → sensitivity to the Yukawa couplings between H and tau leptons

- Excellent mass resolution required to obtain reasonable separation of the H and Z peaks

![](image1.png)

$\sigma(1M) H \rightarrow \tau \tau$ events → sensitivity to the Yukawa couplings between H and tau leptons

- Excellent mass resolution required to obtain reasonable separation of the H and Z peaks

$H \rightarrow \gamma \gamma$: Analysis performed using a multivariate discriminator (BDT)

- Discriminating power between ggF and VBF comparable to Run-2 despite the increase in amount of pile-up
AT HL-LHC, rare decays become accessible - $\text{BR}(H\rightarrow\mu\mu)=0.022$

→ Probe coupling to 2nd generation of fermions (only possible at HL-LHC)

Upgraded tracker allows to reach a mass resolution better than 1%

→ Width of Gaussian fit to di-muon mass 65% lower than the Run-1 version

Prospects for coupling measurement

→ 5% uncertainty@3000fb$^{-1}$
Higgs Differential Cross-Section

Higgs $p_T$ bin uncertainty:

- **Run-2** (35.9 fb$^{-1}$) combination: **25-30%**
  
  *See Vittorio Tavolaro’s talk “Fiducial inclusive and differential Higgs boson cross sections at CMS”*

- **Projections:** 4-9%

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**Projections**

Based for $H \rightarrow ZZ^*$ on 12.9 fb$^{-1}$ 2016 data at $\sqrt{s} = 13$ TeV and for 3000 fb$^{-1}$
Higgs Charge-Parity Measurement

SM leading tree-level contributions

\[ A(HVV) \sim \left[ a_{1}^{VV} + \kappa_{1}^{VV} q_{1}^{2} + \kappa_{2}^{VV} q_{2}^{2} \right] \left( \Lambda_{1}^{VV} \right)^{2} \]

- \( H \to ZZ \to 4\ell \) gives sensitive test of charge-parity
- Expect to have significant improvement (x 50 or more) in expected limits from new experimental techniques introduced in Run-2
- Improvement from Run-1 to Run-2 in the 68% CL expected limit by nearly an order of magnitude comes from utilising VH and VBF production information (Phys.Lett. B775 (2017) 1)

Fraction of events for a_i operator

**Projections** for \( H \to ZZ^* \to 4\ell \) based on 5.1 fb^{-1} at \( \sqrt{s} = 7 \) TeV and up to 19.6 fb^{-1} at \( \sqrt{s} = 8 \) TeV for 300 fb^{-1} and 3000 fb^{-1}

\( m_{H} = 125 \) GeV
Summary and Plans

- **HL-LHC**: first Higgs factory
- Higgs studies are central to the HL-LHC program
- Impact of new upgraded detectors under HL-LHC pile-up condition → Potential to reach the **percentage level in precision** on the Higgs coupling modifiers, signal strengths and differential cross-sections

- **On-going update of projections** from Run-2 results to be published in the **CERN Yellow Report** by the end of the year
Backup
Precision measurement in the (B)SM Higgs sector
- Couplings, cross-sections, differential distributions
- Rare & Exotic decays

BSM Higgs searches (extra scalars, BSM Higgs resonances, anomalous couplings)
- Di-Higgs Production → Higgs self coupling

Precision SM physics with High Luminosity
- Electroweak Physics (VBF and VBS, Triboson production, Forward EW physics)
- Strong Interactions (Photons and Jets, PDFs, Forward QCD physics)
- Top physics (Cross section, properties, couplings, mass, FCNC)

More exotic models become accessible thanks to the detectors upgrades at HL-LHC
- Supersymmetry
- Dark Matter Searches
- Long Lived Particles, HSCP
- Heavy Resonances, VLQ

Flavor: Can we solve the puzzle of flavor with HL-LHC data?
- Flavour Anomalies, CKM, Spectroscopy, …
CMS Experiment and Detector Upgrades

**New Tracker**
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta < 4$

**Barrel ECAL**
- Replace FE electronics
- Cool detector/APDs

**Barrel HCAL**
- Replace HPD by SiPM
- Replace inner layers scint. tiles?

**Trigger/DAQ**
- L1 (hardware) with tracks and rate up $\sim 750$ kHz
- L1 Latency 12.5 $\mu$s
- HLT output rate 7.5 kHz
- New DAQ hardware

**Other R&D**
- Fast-timing for in-time pileup suppression

**Muons**
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate muon-tagging up to $\eta \sim 3$
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

**New Endcap Calorimeter**
- Radiation tolerant
- High granularity (HGCAL)

**New all Al beam pipe with smaller cone angle and cyl. central pipe**

**Proposal for a Timing layer**
- Timing resolution $\sim 10$ ps
- Space resolution $\sim 10$'s of $\mu$m
Series of detector upgrades needed to recover the detector performance compromised by radiation damage (especially in the endcaps) and increased pile-up.

CMS detector upgrades are crucial to maximise physics potential in this harsh environment.

- Will provide a wider angular coverage, timing detectors, more granular calorimeters
  - Maintain a good object reconstruction (leptons, photons, b-tagging, jets and missing $E_T$)
  - Pile-up mitigation is a critical element of detector designs.

Technical proposal

- Tracker TDR
- Muon TDR
- Barrel Calo TDR
- Endcap Calo TDR
Over 170 million Higgs bosons in 3000 fb$^{-1}$
Over 1 million for each of the main production mechanisms, spread over many decay modes:
- about 400k $H \to \gamma\gamma$
- about 20k $H \to ZZ \to \ell\ell\ell\ell$
- about 38k $H \to \mu\mu$
- about 800 VBF $H \to \tau\tau$
- about ~17k $H \to Z\gamma$

$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

<table>
<thead>
<tr>
<th>Cross section (pb)</th>
<th>$ggF$</th>
<th>VBF</th>
<th>VH</th>
<th>$ttH$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>49.9</td>
<td>4.18</td>
<td>2.38</td>
<td>0.611</td>
<td>57.1</td>
</tr>
</tbody>
</table>

| $H \to \gamma\gamma$ | 344,310 | 28,842 | 16,422 | 4,216 | 393,790 |
| $H \to ZZ^* \to 4\ell$ | 17,847  | 1,495  | 851   | 219   | 20,412  |
| $H \to WW^* \to \ell\nu\ell\nu$ | 1,501,647 | 125,789 | 71,622 | 18,387 | 1,717,445 |
| $H \to \tau\tau$ | 9,461,040 | 792,528 | 451,214 | 115,846 | 10,820,662 |
| $H \to bb$ | 86,376,900 | 7,235,580 | 4,119,780 | 1,057,641 | 98,789,901 |
| $H \to \mu\mu$ | 32,934  | 2,759  | 1,570  | 403   | 37,667  |
| $H \to Z\gamma \to \ell\ell\gamma$ | 15,090  | 1,264  | 720   | 185   | 17,258  |
| $H \to all$ | 149,700,000 | 12,540,000 | 7,140,000 | 1,833,000 | 171,213,000 |

$\sigma$ from Yellow Report 3
Strategy for projections

- Several scenarios assumptions made on how systematic and theoretical uncertainties will evolve and how detector upgrades will perform to compensate degradations due to high pile-up.
- Several assumptions made for the estimates of systematic uncertainties at HL-LHC:
  - Pessimistic scenario [S1(+)]: Unchanged from current data analyses
    - Assume detector upgrades roughly compensate for the pile-up increase
  - Optimistic: Scaled down by $1/\sqrt{L}$
    - More data provides allows for a better control of the systematics uncertainties
- Projection Methods:
  - From Runs 1-2 at 7-13 TeV, extrapolate event yields and potentially systematic uncertainties using $\sqrt{s}$ and $1/\sqrt{L}$
  - In 14 TeV MC, smear truth particles with resolutions expected with upgraded detectors in the Phase 2 collision conditions (200 pile-up interactions per BX)
Several assumptions made for the estimates of systematic uncertainties at HL-LHC:

- **S1**: systematic uncertainties constant, unchanged detector performance (no upgrade considered)
- **S1+**: includes higher PU and detector upgrades effects
- **S2**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a lower limit based on estimates of achievable accuracy with upgraded detector)
- **S2+**: S2 +includes higher PU and detector upgrades effects
Run-1 Measurements

- Good agreement with SM expectation → SM-like Higgs boson
- No deviation with respect to SM expectation

\[ \text{arXiv:1606.02266v2} \quad \text{JHEP 08 (2016) 045} \]

- need to probe small deviations to narrow down New Physics
- need higher precision measurements on signal strengths and couplings
Run-2 Signal Strength Measurements

Summary plot of the fit to the production-decay signal strengths products

\[ \mu_i^f = \mu_i \cdot \mu^f \]

with 2016 data at \( \sqrt{s} = 13 \) TeV, corresponding to an integrated luminosity of 35.9 fb\(^{-1}\)

Start to exploit new production-decay models, e.g. VH and ttH with \( H \to \tau\tau \) decay channel

\[ \mu = 1.17^{+0.06}_{-0.06} \ (\text{stat.})^{+0.06}_{-0.05} \ (\text{theory})^{+0.06}_{-0.06} \ (\text{syst.}) \]
Parameters of the \( \kappa \)-framework model with 2016 data at \( \sqrt{s} = 13 \) TeV, corresponding to an integrated luminosity of 35.9 fb\(^{-1}\)

Uncertainties now reaching 10-20% level for most parameters

Fit results in the \( \kappa \)-framework model with BR\(_{\text{BSM}} = 0\)

Fit results in the \( \kappa \)-framework model in which the ggH and H \( \rightarrow \gamma\gamma \) loops are scaled with effective couplings
### Run-2 Signal Strength Measurements

- Best-fit values and $1\sigma$ uncertainties for the parameters of the model with one signal strength parameter for each production and decay mode combination.
- Remarkably, some of these already highly impacted by systematics.
- And this is for just one year of Run-2 data, with one experiment.

\[ \mu'_i = \mu_i \cdot \mu' \]

<table>
<thead>
<tr>
<th>Production process</th>
<th>ggH</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>Uncertainty</td>
<td>Best fit</td>
<td>Uncertainty</td>
<td>Best fit</td>
</tr>
<tr>
<td>H → bb</td>
<td>2.51</td>
<td>+2.44/-2.01</td>
<td>+1.96/-1.86</td>
<td>+1.46/-0.89</td>
<td>-0.59/-0.33</td>
</tr>
<tr>
<td>H → ττ</td>
<td>1.05</td>
<td>+0.53/-0.47</td>
<td>+0.25/-0.23</td>
<td>+0.47/-0.34</td>
<td>1.12</td>
</tr>
<tr>
<td>H → WW</td>
<td>1.35</td>
<td>+0.20/-0.17</td>
<td>+0.12/-0.10</td>
<td>+0.17/-0.12</td>
<td>0.28</td>
</tr>
<tr>
<td>H → ZZ</td>
<td>1.22</td>
<td>+0.24/-0.19</td>
<td>+0.20/-0.10</td>
<td>+0.12/-0.10</td>
<td>-0.09</td>
</tr>
<tr>
<td>H → γγ</td>
<td>1.15</td>
<td>+0.21/-0.18</td>
<td>+0.17/-0.13</td>
<td>+0.10/-0.09</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Sylvie Braibant  
Higgs Prospects at HL-LHC with CMS  
07/07/2018
### Run-2 Signal Strengths

\[ \mu_i' = \mu_i \cdot \mu' \]

<table>
<thead>
<tr>
<th>Production process</th>
<th>ggH</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → bb</td>
<td>2.51 ± 0.9 0.4 - 0.4 0.3 0.8</td>
<td>0.91 ± 0.45 0.24 0.38</td>
<td>0.91 ± 0.45 0.24 0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → ττ</td>
<td>1.05 ± 0.5 0.2 - 0.3 0.4 0.8</td>
<td>0.22 ± 0.8 0.7 0.5 0.6 0.7</td>
<td>0.22 ± 0.8 0.7 0.5 0.6 0.7</td>
<td></td>
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</tr>
<tr>
<td>H → WW</td>
<td>1.35 ± 0.7 0.3 - 0.5 0.4 0.8</td>
<td>1.60 ± 0.6 0.5 0.4 0.5 0.6 0.7</td>
<td>1.60 ± 0.6 0.5 0.4 0.5 0.6 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → ZZ</td>
<td>1.22 ± 0.5 0.3 - 0.4 0.5 0.8</td>
<td>0.00 ± 0.0 0.0 0.0 0.0 0.0</td>
<td>0.00 ± 0.0 0.0 0.0 0.0 0.0</td>
<td></td>
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</tr>
<tr>
<td>H → γγ</td>
<td>1.15 ± 0.3 0.2 - 0.4 0.3 0.8</td>
<td>3.71 ± 1.4 1.5 1.3 1.3 1.5</td>
<td>0.00 ± 0.1 1.1 1.1 1.1 1.1</td>
<td>2.14 ± 0.8 0.8 0.8 0.8 0.8</td>
<td></td>
</tr>
</tbody>
</table>
Run-2 $\kappa$ Model Couplings Modifiers

- Best-fit values and $1\sigma$ uncertainties for the $\kappa$ model parameters in which the loop processes are resolved

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_t$</th>
<th>$\kappa_b$</th>
<th>$\kappa_t$</th>
<th>$\kappa_H$</th>
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</thead>
<tbody>
<tr>
<td>Best fit value</td>
<td>1.09</td>
<td>0.99</td>
<td>1.11</td>
<td>1.10</td>
<td>1.01</td>
<td>0.82</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>+0.12</td>
<td>+0.08</td>
<td>+0.09</td>
<td>+0.07</td>
<td>+0.11</td>
<td>+0.12</td>
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<tr>
<td>Stat.</td>
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<td>-0.04</td>
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<td>-0.11</td>
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<td>(+0.08)</td>
<td>(+0.06)</td>
<td>(+0.11)</td>
<td>(+0.09)</td>
<td>(+0.06)</td>
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<tr>
<td>Best fit value</td>
<td>0.11</td>
<td>+0.33</td>
<td>-0.24</td>
<td>+0.24</td>
<td>+0.16</td>
<td>+0.16</td>
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<tr>
<td>Uncertainty</td>
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<td>+0.09</td>
<td>-0.08</td>
<td>+0.09</td>
<td>+0.06</td>
<td>+0.06</td>
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<tr>
<td>Stat.</td>
<td>-0.11</td>
<td>-0.07</td>
<td>-0.08</td>
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</tr>
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<td>Syst.</td>
<td>(+0.11)</td>
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<td>(+0.06)</td>
<td>(+0.11)</td>
<td>(+0.08)</td>
<td>(+0.06)</td>
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<td>Best fit value</td>
<td>-1.10</td>
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<td>-1.10</td>
<td>-1.10</td>
<td>-1.10</td>
<td>-1.10</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>+0.16</td>
<td>+0.11</td>
<td>+0.12</td>
<td>+0.12</td>
<td>+0.12</td>
<td>+0.12</td>
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<tr>
<td>Stat.</td>
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<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
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</tr>
<tr>
<td>Syst.</td>
<td>(+0.11)</td>
<td>(+0.07)</td>
<td>(+0.06)</td>
<td>(+0.11)</td>
<td>(+0.08)</td>
<td>(+0.06)</td>
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<tr>
<td>Best fit value</td>
<td>1.01</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
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<td>0.82</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>+0.14</td>
<td>+0.49</td>
<td>+0.49</td>
<td>+0.49</td>
<td>+0.49</td>
<td>+0.49</td>
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<td>-0.16</td>
<td>-0.82</td>
<td>-0.82</td>
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<td>-0.82</td>
</tr>
<tr>
<td>Syst.</td>
<td>(+0.15)</td>
<td>(+0.44)</td>
<td>(+0.44)</td>
<td>(+0.44)</td>
<td>(+0.44)</td>
<td>(+0.44)</td>
</tr>
</tbody>
</table>
With an increasing number of pile-up events, the di-photon mass resolution is mostly driven by photon energy and vertexing resolutions.

CMS: The di-Photon mass is shown for a pile-up of 200 and for different radiation ageing scenarios of the barrel calorimeter.
VBF production mode is of particular interest → higher signal purity compared to dominant ggF production mechanism

$\mathcal{O}(1M) H \rightarrow \tau\tau$ events produced → sensitivity to the Yukawa couplings between the Higgs boson and the tau leptons

→ Excellent mass resolution required to obtain reasonable separation of the H and Z peaks

Mass resolution at HL-LHC almost the same as in Run-2

Visible di-$\tau$ mass in the fully hadronic channel after requiring a large opening angle in $\eta$ between the two jets $\Delta\eta(\text{jet1, jet2}) > 4.5$
CMS High granularity and precision timing capabilities of the High-Granularity Calorimeter (HGCAL)
→ improvement in pile-up suppression, isolation, jet shape observables and missing energy
→ improved reconstruction and identification of forward jets in VBF production

- Analysis performed using a multivariate discriminator (BDT)
- **Discriminating power** between ggH and VBF comparable to Run-2 despite the increase in amount of pile-up
Differential cross sections provide an interesting portal to a number of physical observables.

- The shape can be tested vs SM expectation: Small variation of the couplings can lead to significant shape distortions.

- Higgs transverse momentum $p_T$: Sensitivity to modifications of effective Higgs Yukawa couplings at low $p_T$ and to finite top mass effects at high $p_T$.

- Jet multiplicity and first jet $p_T$ → New physics in the loop, sensitivity at high $p_T$.

- Higgs Rapidity $|\eta|$: Theory distribution mostly determined by the gluon PDF - possible test.