Higgs and precision: Coupling Measurements and Systematic Uncertainties

Ed Scott, on behalf of the CMS Collaboration

HE and HL-LHC workshop, CERN, 20th June 2018
We have entered the era of precision Higgs physics: now need to consider carefully how we measure the couplings and how we might be limited by systematic uncertainties as we move to high luminosity

1. Latest measurements of couplings and existing projections

2. Impact of systematics on current results

3. Evolution of systematics with increased luminosity

4. Considerations for 2018 YR
What do we measure?

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$

or $$\kappa_j^2 = \frac{\Gamma_j}{\Gamma_{SM}^j}$$

- Traditional signal strength modifiers $$\mu_i$$, for $$i = \text{ggH, VBF, ttH etc production modes}$$, or $$\mu^i$$ for $$i = \gamma\gamma, ZZ, \tau\tau$$ etc decay modes
- LO-motivated $$\kappa$$ framework that modifies Higgs’ couplings to SM particles
  - applies for both production and decay
  - additional effective coupling modifiers, $$\kappa_g$$ and $$\kappa_\gamma$$, describe the loop processes for ggH production and $$\gamma\gamma$$ decay respectively
  - BSM contributions can cause deviations here at O(few%) level

Introduced here and in YR3
What do we measure?

- Results can then be re-interpreted with new theories
- Kinematic regions isolate BSM effects
- And provide coherent framework for combination of channels & experiments

**Simplified Template Cross-section (STXS) framework** aims to minimise measurements’ dependence on theory
Coupling measurements

\[ \mu = 1.17^{+0.10}_{-0.10} \]

\[ = 1.17^{+0.06}_{-0.06} \text{ (stat.) } +0.06^{-0.05} \text{ (sig. th.) } +0.06^{-0.06} \text{ (other sys.)} \]
### Production process

<table>
<thead>
<tr>
<th></th>
<th>ggH</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H → bb</strong></td>
<td>2.51</td>
<td>1.73</td>
<td>0.99</td>
<td>0.91</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>+2.44</td>
<td>+0.70</td>
<td>+0.48</td>
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<tr>
<td></td>
<td>−0.21</td>
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<td>(+2.06)</td>
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<td>(−0.51)</td>
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<td>(−0.24)</td>
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<tr>
<td><strong>H → ττ</strong></td>
<td>1.05</td>
<td>1.12</td>
<td>0.96</td>
<td>1.60</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>+0.53</td>
<td>+0.45</td>
<td>+1.81</td>
<td>+0.66</td>
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<tr>
<td></td>
<td>−0.47</td>
<td>−0.43</td>
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<tr>
<td></td>
<td>(+0.01)</td>
<td>(+0.37)</td>
<td>(+1.37)</td>
<td>(+0.38)</td>
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<tr>
<td></td>
<td>−0.23</td>
<td>(−0.35)</td>
<td>−0.81</td>
<td>−0.39</td>
<td>−0.45</td>
</tr>
<tr>
<td><strong>H → WW</strong></td>
<td>1.35</td>
<td>3.91</td>
<td>0.96</td>
<td>1.60</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>+0.20</td>
<td>+2.26</td>
<td>+1.81</td>
<td>+1.67</td>
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<td></td>
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<td>−1.37</td>
<td>−0.53</td>
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<tr>
<td></td>
<td>(+0.10)</td>
<td>(+1.89)</td>
<td>(+1.74)</td>
<td>(+1.61)</td>
<td>(+0.38)</td>
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<td></td>
<td>−0.10</td>
<td>−1.72</td>
<td>−1.44</td>
<td>−1.35</td>
<td>(+0.38)</td>
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<tr>
<td><strong>H → ZZ</strong></td>
<td>1.22</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.14</td>
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<tr>
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<td>+0.24</td>
<td>+2.32</td>
<td>+4.26</td>
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<td></td>
<td>(+0.22)</td>
<td>(+1.00)</td>
<td>(+4.19)</td>
<td>(+1.48)</td>
<td>(+0.81)</td>
</tr>
<tr>
<td></td>
<td>−0.26</td>
<td>−0.76</td>
<td>−0.00</td>
<td>−0.00</td>
<td>−0.00</td>
</tr>
<tr>
<td><strong>H → γγ</strong></td>
<td>1.15</td>
<td>3.71</td>
<td>0.00</td>
<td>2.14</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>+0.21</td>
<td>+1.49</td>
<td>+1.13</td>
<td>+1.87</td>
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<td></td>
<td>−0.18</td>
<td>−1.35</td>
<td>+0.00</td>
<td>−0.74</td>
<td>−0.81</td>
</tr>
<tr>
<td></td>
<td>(+0.17)</td>
<td>(+0.49)</td>
<td>−0.00</td>
<td>−0.72</td>
<td>−0.31</td>
</tr>
<tr>
<td></td>
<td>−0.14</td>
<td>(−0.42)</td>
<td>−0.00</td>
<td>−0.14</td>
<td>−0.62</td>
</tr>
</tbody>
</table>

- **Most model-independent fit**: one parameter per production × decay mode
- Remarkably, some of these already highly impacted by systematics
- And this is for just one year of Run 2 data, with one experiment

[1] Higgs: couplings and systematics

HL-LHC workshop, 20.06.18

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**Remarkably, some of these already highly impacted by systematics**

**Most model-independent fit:** one parameter per production × decay mode

**And this is for just one year of Run 2 data, with one experiment**
- Perform **resolved** (left) and **unresolved** (right) fits in $\kappa$ framework
- Uncertainties now reaching 10-20% level for most parameters
### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_t$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\tau$</th>
<th>$\kappa_\mu$</th>
</tr>
</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>
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<tr>
<td>Uncertainty</td>
<td>$-0.17$</td>
<td>$+0.11$</td>
<td>$+0.09$</td>
<td>$-0.04$</td>
<td>$-0.01$</td>
<td>$-0.10$</td>
</tr>
<tr>
<td>Stat.</td>
<td>$-0.13$</td>
<td>$+0.11$</td>
<td>$+0.07$</td>
<td>$+0.05$</td>
<td>$-0.22$</td>
<td>$-0.10$</td>
</tr>
<tr>
<td>Syst.</td>
<td>$+0.08$</td>
<td>$+0.09$</td>
<td>$+0.07$</td>
<td>$-0.06$</td>
<td>$+0.09$</td>
<td>$+0.06$</td>
</tr>
</tbody>
</table>

With the exception of $\kappa_b$ and $\kappa_\mu$, all of these are on the point of becoming systematics limited:

- theoretical and experimental contributions both important here
- and approximately equal in size

We have now reached observation in difficult analyses like $ttH$ and $H\rightarrow\tau\tau$: systematics is these searches are substantial

Important to reduce them as much as possible in order to realise full HL-LHC physics potential

[1]
Existing projections

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>300 fb(^{-1})</th>
<th>3000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling parameter</td>
<td>7-parameter fit</td>
<td></td>
</tr>
<tr>
<td>(\kappa_\gamma)</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
</tr>
<tr>
<td>(\kappa_g)</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
</tr>
<tr>
<td>(\kappa_W)</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
</tr>
<tr>
<td>(\kappa_Z)</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
</tr>
<tr>
<td>(\kappa_u = \kappa_t)</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
</tr>
<tr>
<td>(\kappa_d = \kappa_b)</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
</tr>
<tr>
<td>(\kappa_\ell = \kappa_\tau)</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
</tr>
<tr>
<td>(\Gamma_H)</td>
<td>12 – 15%</td>
<td>5 – 8%</td>
</tr>
</tbody>
</table>

- Projections made in Snowmass report of 2013
- Both per-decay \(\mu\) and \(\kappa\) framework fits included
- Range in predictions come from different assumptions on systematic uncertainties
- No consideration of changes due to PU or upgrades
- Expect major improvements over these extrapolations

[2] additional parameters (see text)

<table>
<thead>
<tr>
<th></th>
<th>300 fb(^{-1})</th>
<th>3000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\kappa_Z \gamma)</td>
<td>41 – 41%</td>
<td>10 – 12%</td>
</tr>
<tr>
<td>(\kappa_\mu)</td>
<td>23 – 23%</td>
<td>8 – 8%</td>
</tr>
<tr>
<td>BR(_{BSM})</td>
<td>&lt; 14 – 18%</td>
<td>&lt; 7 – 11%</td>
</tr>
</tbody>
</table>

- Scenario 1: All systematics remain constant with luminosity
- Scenario 2: Experimental nuisances scale with \(\sqrt{L}\), theory uncertainties halved
Existing projections

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<td>3 – 5%</td>
</tr>
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<td>2 – 5%</td>
</tr>
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<td>2 – 4%</td>
</tr>
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<td>7 – 10%</td>
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Projections made in Snowmass report of 2013

Both per-decay $\mu$ and $\kappa$ framework fits included

Range in predictions come from different assumptions on systematic uncertainties

No consideration of changes due to PU or upgrades

Expect major improvements over these extrapolations

$\int L dt$

<table>
<thead>
<tr>
<th>(fb$^{-1}$)</th>
<th>$\gamma\gamma$</th>
<th>$WW^*$</th>
<th>$ZZ^*$</th>
<th>$b\bar{b}$</th>
<th>$\tau\tau$</th>
<th>$\mu\mu$</th>
<th>$Z\gamma$</th>
<th>$BR_{inv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>6 – 12%</td>
<td>6 – 11%</td>
<td>7 – 11%</td>
<td>11 – 14%</td>
<td>8 – 14%</td>
<td>40 – 42%</td>
<td>62 – 62%</td>
<td>&lt; 17 – 28%</td>
</tr>
<tr>
<td>3000</td>
<td>4 – 8%</td>
<td>4 – 7%</td>
<td>4 – 7%</td>
<td>5 – 7%</td>
<td>5 – 8%</td>
<td>14 – 20%</td>
<td>20 – 24%</td>
<td>&lt; 6 – 17%</td>
</tr>
</tbody>
</table>
Existing projections

- Scenario 1: All systematics remain constant with luminosity
- Scenario 2: Experimental nuisances scale with $\sqrt{L}$, theory uncertainties halved

Extrapolation based on 12.9fb$^{-1}$ 2016 data; all but $\mu_{ttH}$ syst-limited at 300fb$^{-1}$

Progress already made since then
- reduction in theory uncertainties (e.g. $N^3LO$ ggH prediction)
- and improvement in analysis techniques (c.f. ttH analyses)

CMS plans to produce an update based on 2016 grand combination
Existing projections

- Scenario 1+: All systematics remain constant with luminosity + some detector upgrade effects included
- Scenario 2+: Experimental nuisances scale with $\sqrt{L}$, theory uncertainties halved + some detector upgrade effects included

- Extrapolation based on 12.9 fb$^{-1}$ 2016 data; all but $\mu_{ttH}$ syst-limited at 300 fb$^{-1}$
- Progress already made since then
  - reduction in theory uncertainties (e.g. N$^3$LO ggH prediction)
  - and improvement in analysis techniques (c.f. ttH analyses)
- CMS plans to produce an update based on 2016 grand combination
Existing projections

- Also performed projections for ZZ - this is the only channel where systematics may remain be negligible for all processes except ggH
- Not necessarily the case however: analysis improvements can change this
• Use $H \rightarrow \gamma \gamma$ as an example since they produced this informative table

• Current dominant uncertainties for overall $\mu$:
  - uncertainty on photon identification BDT
  - overall theory uncertainties (due to QCD scale variations, primarily on ggH)
Latest results: $H \rightarrow \gamma\gamma$

- Use $H \rightarrow \gamma\gamma$ as an example since they produced this informative table.
- Current dominant uncertainties for overall $\mu$:
  - uncertainty on **photon identification BDT**
  - **overall theory uncertainties** (due to QCD scale variations, primarily on ggH)
Photon identification

- Plot shows the data vs MC agreement of the photon identification BDT output
- Inputs are shower shape and isolation variables
- Some scope for reduction before Run 2
- Legacy results - somewhat conservatively assigned at present
- However substantial long-term improvements requires detailed studies of the detector response

- Are improvements really feasible at HL-LHC, even with upgraded detector?
- Also to consider:
  - change in strategy, e.g. harder cuts on ID score
  - improved MC modelling
• Use $H \rightarrow \gamma \gamma$ as an example since they produced this informative table.

• Current dominant uncertainties for overall $\mu$:
  • uncertainty on photon identification BDT
  • overall theory uncertainties (due to QCD scale variations, primarily on ggH)
Jet energy corrections

- Difficult to model jets, especially in the forward region
- Long and arduous process to get the final uncertainties
- Requires the data, and repeated full reconstruction → difficult to project accurately, and can’t do the work ahead of time
- CMS paper on 8 TeV JES and JER came just two years ago → understanding of Run 1 jets significantly better than Run 2
- Large impact on VBF analyses → already affecting precision
• Where background estimates are currently limited by control region statistics we expect an improvement that scales with luminosity
  - this is taken into account in projected fits

• However for uncertainties on extrapolation from control regions to signal regions - this is where theoretical uncertainties will play a big role
  - what matters is the background prediction under the most sensitive bins defined by classifier (BDT, NN etc)
  - So the experiment and theory communities will have to work together in the next few years to refine the modelling

• We assume that in the future we will have efficient ways of generating sufficient MC events such that we can neglect the statistical uncertainties
Latest results: \(H \rightarrow \gamma \gamma\)

- Theory uncertainties:
  - QCD scale uncertainty on ggH overall yield is largest, \(~5\%\)
  - ggH bin migrations: \(p_T\) and nJets
  - QCD scale for other processes
  - branching fraction
  - pdf and \(\alpha_s\)
- These affect all channels: importance varies, e.g. the ttH scale for \(H \rightarrow bb\)

- Is there any way for us to measure these? Perhaps to some extent, e.g. by using differential measurements for \(p_T\) migrations
- If not, then we depend on theory improvements
- Requirements evolve as what we measure changes; become more differential
• Is there any way for us to measure these? Perhaps to some extent, e.g. by using differential measurements for $p_T$ migrations
• If not, then we depend on theory improvements
• Requirements evolve as what we measure changes; become more differential
CMS plans to perform an extrapolation of the grand combination results released this year, using both S1 (systematics unchanged) and S2 (experimental systematics scaled with lumi down to achievable “floor”)
  - floors for S2 still under consideration, and will be synchronised with ATLAS

Currently plan to include two models: $\kappa$ framework and per-decay $\mu$

**Theorists: please let us know** if you want other models, as soon as possible!
  - the same goes for kinematic distributions etc.

Usual caveats apply:
  - effects of detector upgrade not fully incorporated - only $\mu\mu$ and $\gamma\gamma$ altered
  - impossible to account for analysis improvements

Other individual results will be made for specific analyses
  - using either full simulation or Delphes to account for upgrade conditions
Higgs: couplings and systematics

H → μμ improvement

Example: H → μμ sensitivity is greatly improved by tracker upgrade

Lower material budget and better spatial resolution
→ width of Gaussian fit to di-muon mass 65% lower than the Run 1 version

Improvement in mass resolution has large impact on overall sensitivity:
reduce the expected uncertainty on cross-section by approximately 40%
Another thing that can affect the projections is constraints of nuisances

- these can be unrealistically strong constraints, e.g. on luminosity
- or genuine, indicating that the measurement is providing an in-situ constraint, e.g. b-tagging efficiency

There are a couple of ways to deal with this:

- source splitting: many analyses use a single nuisance to cover all effects of e.g. jet energy corrections. Splitting into the physical sources can prevent, or at least delay, constraints due to high statistics
- can also check the impact of an uncertainty ignoring the constraints imposed by the fit: this would potentially confirm that its constraint doesn’t affect the final measurement

In some particular cases, we will try to provide the evolution of an uncertainty as a function of luminosity
Summary

**Precision Higgs measurements are becoming systematics-limited**

- both theoretical and experimental nuisances have an impact
- these will only become more important as we increase integrated luminosity

**Understanding and improving these systematics is key for HL-LHC**

- achieving the best possible sensitivity will involve lots of work understanding these uncertainties and thinking of ways in which they can be reduced
- in the mean-time, need to handle them with care when extrapolating
- plenty of room for optimism: recent developments have already greatly improved our baseline scenario even relative to predictions made in 2016

Lots of interesting work to be done!
Thank you


