Higgs and High Energy Probes: Main couplings
Experimental vision

Andrew Gilbert
on behalf of the ATLAS & CMS Collaborations

Ultimate precision at hadron colliders | 2 December 2019
Introduction

- Precision Higgs coupling measurements are a key pillar of the HL-LHC physics programme
- BSM physics can manifest as percent-level deviations

HL/HE-LHC Physics Workshop:
- Extensive studies of the HL-LHC physics potential based on latest understanding of the upgraded detectors, experimental techniques and theoretical developments
- Higgs WG: ultimate precision for SM Higgs properties, sensitivity to rare channels & indirect NP

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_h$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$\sim -0.4%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3-9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim +1%$</td>
</tr>
</tbody>
</table>

Table 1-8. Generic size of Higgs coupling modifications when the scale of new physics is $M_T\approx 1\text{ TeV}$ and mixing angles satisfy precision electroweak fits. The Decoupling MSSM consists of order $X$, while large Yukawa couplings are required $\Delta M_T\approx 10\%$, which can potentially be significantly reduced with the inclusion of recent data. The error includes factorization/renormalization scale uncertainty and PDF choice, which are added linearly. The scale uncertainty on $\kappa_V$ is $\sim 4\%$, which can potentially be significantly reduced with the inclusion of recent data. The error includes factorization/renormalization scale uncertainty and PDF choice, which are added linearly. The scale uncertainty on $\kappa_V$ is $\sim 4\%$.
Progress with Run 2 data

- Higgs couplings to 3rd generation fermions established
- All main production & decay modes targeted
- Couplings measured with 10-15% precision (w/ partial datasets)

Figure 11: Summary plots for the $k$-framework model in which the ggH and H!gg loops are scaled with effective couplings. The points indicate the best fit values while the thick and thin horizontal bars show the 1s and 2s CL intervals, respectively. In the left figure the constraint $B_{BSM}=0$ is imposed, and both positive and negative values of $k_W$ and $k_Z$ are considered. In the right figure a constraint $|k_W|, |k_Z| \leq 1$ is imposed (same sign of $k_W$ and $k_Z$), while $B_{inv} > 0$ and $B_{undet} > 0$ are free parameters.

- 2nd generation couplings remain challenging...
- ...but sensitivity approaching SM level for $H \rightarrow \mu\mu$
HL-LHC upgrade

- Nominal HL-LHC scenario:
  - \( L = 5 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1} \Rightarrow 300 \, \text{fb}^{-1} / \text{year} \Rightarrow 3000 \, \text{fb}^{-1} \text{ total, } <\text{PU}> = 140 \)

- Ultimate scenario:
  - \( L = 7.5 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1} \Rightarrow 400 \, \text{fb}^{-1} / \text{year} \Rightarrow 4000 \, \text{fb}^{-1} \text{ total, } <\text{PU}> = 200 \)

- HL-LHC is a Higgs factory:
  - 170M Higgs bosons
  - 120k HH pairs (\( \Rightarrow \) Talk by E. Petit this afternoon)
Challenges for the experiments

• 140-200 pileup interactions per bunch crossing
  - Major challenge in terms of irradiation and triggering for the experiments

• Real data event with 136 simultaneous collisions from October 2018:
Detector upgrades

- Comprehensive upgrade programme to prepare for HL-LHC conditions:

  - Trigger / HLT / DAQ
    - Track information at L1
    - HLT output: 7.5 kHz
  - Muon system
    - Extension to $|\eta| = 2.9$
  - CMS
    - Tracking up to $|\eta| = 4$
  - ATLAS
    - Muon system upgrade
      - New chambers & improved trigger
    - New MIP timing detector
      - 30 ps time-of-flight resolution
    - New high-granularity endcap calorimeters
    - Upgraded calor. electronics
    - Trigger / DAQ
      - HLT output: 10 kHz
    - New inner tracker, up to $|\eta| = 4$
    - High granularity timing detector
Physics studies for HL-LHC

- Many measurements will be **systematics limited**, approaches used:
  - **(1) Projection of existing analyses** - based on the Run 2 analysis statistical model
    - Used for the majority of the following results
    - Generally assumes Run 2 performance (efficiencies, resolutions...) maintained
  - **(2) Analysis based on new simulation** - often with fast techniques, e.g. Delphes
Projection scenarios

- Results given under two assumptions
  - S1: Current uncertainties remain unchanged
  - S2: Theoretical uncertainties scaled down by a factor 1/2, experimental uncertainties reduced with integrated luminosity until expected minimum uncertainty reached

- Common treatment for ATLAS & CMS:

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Run 2 uncertainty</th>
<th>Projection minimum uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>0.5–2%</td>
<td>0.25–1%</td>
</tr>
<tr>
<td>Hadronic tau ID</td>
<td></td>
<td>6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Absolute</td>
<td>0.5%</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>0.1–3%</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>Pileup</td>
<td>0–2%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td>Method and sample</td>
<td></td>
<td>0.5–5%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet flavour</td>
<td></td>
<td>1.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td>Time stability</td>
<td></td>
<td>0.2%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet energy res.</td>
<td></td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td>MET scale</td>
<td></td>
<td>Varies with analysis selection</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td>b-Tagging</td>
<td>b-/c-jets (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>b-/c-jets (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td></td>
<td>2.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Example: \texttt{ttH(→bb)}

- Important channel for \textbf{top Yukawa} coupling, but challenging:
  - Good b-jet energy resolution required
  - High jet & b-jet multiplicity $\Rightarrow$ categorisation improves S/B
  - Main systematics from modelling of \texttt{tt+HF} with simulation

\textbf{ATLAS impacts @ 3000 fb}^{-1}

- \texttt{tt+HF} cross section uncertainties expected to reduce by factor 2-3

10-20\% precision on $\sigma(\texttt{ttH→bb})$ achievable in each experiment
Example: $H \rightarrow \mu\mu$

- Search for narrow peak on smoothly falling $Z/\gamma^* \rightarrow \mu\mu$ background
- Measurement sensitive to di-muon mass resolution
- ATLAS upgraded Inner Tracker improves resolution by 15-30%
- CMS upgraded tracker expected to give 40% improvement

### Table: Higgs boson production cross section measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>S1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+15%</td>
</tr>
<tr>
<td>Statistical uncert.</td>
<td>+12%</td>
</tr>
<tr>
<td>Experimental uncert.</td>
<td>+3%</td>
</tr>
<tr>
<td>Theory uncer.</td>
<td>+8%</td>
</tr>
</tbody>
</table>

### Table: CMS extrapolation

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>S1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>13%</td>
</tr>
<tr>
<td>Statistical uncert.</td>
<td>9%</td>
</tr>
<tr>
<td>Experimental uncert.</td>
<td>8%</td>
</tr>
<tr>
<td>Theory uncer.</td>
<td>5%</td>
</tr>
</tbody>
</table>

Reduction from 1.1% to 0.65% for muons in the barrel region
Combination: production & decay rates

- ATLAS+CMS combination assumes experimental uncertainties uncorrelated, theory uncertainties 100% correlated

![Graph showing relative uncertainty for ATLAS and CMS with different processes and uncertainties](image)

- NB: in these projections the inclusive SM theory uncertainties are not included
  - "Theory" = signal acceptance + all background theory

2/12/19

A. Gilbert (NWU)
Higgs couplings

- Coupling modifier projections in the $\kappa$-framework
- $ggH$ and $H\rightarrow\gamma\gamma$ loops treated with effective modifiers $\kappa_g$ and $\kappa_{\gamma}$

$$k_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad k_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

$$\Rightarrow \sigma_i \cdot BR^f = \frac{\sigma_i(\kappa) \cdot \Gamma^f(\kappa)}{\Gamma_H^{SM}}$$

where $$\Gamma_H^{SM} = 1 - (BR_{\text{undet.}} + BR_{\text{inv.}})$$

$BR_{\text{undet}} = BR_{\text{inv}} = 0$ here

Expected uncertainties reduced with additional data and improved calibrations
Higgs couplings

- CMS + ATLAS combination: most couplings measured with 2-4% precision for scenario 2
- NB: unlike $\sigma$ and BR projections the inclusive signal uncertainties are included here and tend to dominate
- Impact of some uncertainties can be reduced by measuring ratios of couplings: $\lambda_{xy} = \kappa_x / \kappa_y$ where uncertainties cancel (see backup)

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{\gamma}$</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\kappa_{W}$</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>$\kappa_{Z}$</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>$\kappa_{g}$</td>
<td>2.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$\kappa_{t}$</td>
<td>3.4</td>
<td>0.9</td>
</tr>
<tr>
<td>$\kappa_{b}$</td>
<td>3.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$\kappa_{\tau}$</td>
<td>1.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$\kappa_{\mu}$</td>
<td>4.3</td>
<td>3.8</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>9.8</td>
<td>7.2</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$ per experiment
Charm Yukawa coupling

- BR(H→cc) ~ 2.9%, but suffers from large background

- Direct searches from ATLAS & CMS:
  - ATLAS: $\mu_{ZH(cc)} < 110 \times SM$ @ 95% CL
  - CMS: $\mu_{VH(cc)} < 70 \times SM$ @ 95% CL

- Projection of ATLAS result to 3000 fb$^{-1}$ gives expected limit: $\mu_{ZH(cc)} < 6.3 \times SM$ @ 95% (stat. only)
  - Systematics expected to increase limit by 36%

- Will benefit from future improvement in c-tagging techniques

- VH(bb/cc) also studied in LHCb, projection [*] gives $\mu_{cc}$ limit of ~ 50 x SM, but with detector upgrades can reach 5-10 x SM level

[*] LHCb-CONF-2016-006


CMS-PAS-HIG-18-031
A note of caution

- These projections are predictions of future improvement to measurements we have already made, but new measurements will go beyond this

- Current projections are not the final word on HL-LHC physics reach

- For example, in going from inclusive $\sigma \times \text{BR}$ measurement to simplified template cross sections can use distributions to constrain EFT coefficients
Differential cross sections

- Projection of $H \rightarrow \gamma\gamma + H \rightarrow ZZ \rightarrow 4l$ differential cross section for $p_T(H)$

**CMS Projection**

3000 fb$^{-1}$ (13 TeV)

- $\Delta \sigma(p_T^H > 600) / 250$
- $\Delta \sigma(p_T^H > 200) / 120$
- $\Delta \sigma(p_T^H > 600) / 250$

**ATLAS Preliminary**

Projection from Run 2 data

$\sqrt{s}=14$ TeV, 3000 fb$^{-1}$

$H \rightarrow \gamma\gamma + H \rightarrow ZZ \rightarrow 4l$

- HL-LHC No Sys

**Expected precision of ~10% for $p_T(H) > 350$ GeV, statistically limited**

**Njet precision of 5-10%, systematically limited**
Differential cross sections

- Parameterise differential cross section in terms of coupling modifiers - low $p_T(H)$ region gives access to $K_c$

CMS Projection 3000 fb$^{-1}$ (13 TeV)

w/ YR18 syst. uncert. (S2)

$\Delta \sigma (p_T^H > 600) / 250$

$\Delta \sigma (p_T^H > 200) / 120$

$\Delta \sigma (p_T^H > 600) / 250$

Combination

$H \rightarrow bb$

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ$

aMC@NLO, NNLOPS

$\alpha_{SM}$ from CYRM-2017-002

Ratio to prediction

$\Delta \alpha (p_T^H) / \alpha_{SM}$

$\alpha_{SM}$ from CYRM-2017-002

Coupling-dependent BRs
(assumes no $B_{inv}$, resolved loops)

Floating BRs
(i.e. constraint from "shape" only)
Prospects for light quark couplings

- **Exclusive decays** to $\gamma$+meson include contributions from light quark Yukawa couplings.

- **Interpretation of Higgs width constraint** (from direct measurement or via off-shell).

- **Interpretation of kinematic distributions**

- **Direct search** for $H \rightarrow cc$

- **Global fit** of all Higgs couplings (assuming no other BSM decays)
Higgs width & mass

- Indirect constraint from $H \rightarrow ZZ$ off-shell & direct constraint using $gg \rightarrow \gamma\gamma$ interference

- **Higgs mass**: ultimate precision will depend strongly on the calibration of muons, electrons & photons, but 10-20 MeV considered possible
  - cf. CMS+ATLAS Run 1: $m_H = 125.09 \pm 0.21\text{(stat.)} \pm 0.11\text{(syst.) GeV}$
Invisible decays

- Current 95% observed (expected) upper limits on $B_{\text{inv}}$:
  - 26% (17%) - ATLAS combination of direct $H \to \text{inv}$ channels in Run 1 + Run 2
  - 22% (17%) - CMS combination of direct $H \to \text{inv}$ channels + all visible channels in Run 2

- In both experiments sensitivity dominated by the VBF channel

- Delphes-based study of CMS sensitivity in HL-LHC

- Optimal selections: $m_{jj} > 2500 \text{ GeV}$, $E_T^{\text{miss}} > 190 \text{ GeV} \Rightarrow B_{\text{inv}} < 3.8\%$ @ 95% CL

- Theoretical uncertainty on $W/Z$ ratio important now (~12.5%), but less so with larger control regions in $\geq 300 \text{ fb}^{-1}$

- Sensitivity not impacted too much if $E_T^{\text{miss}}$ resolution degrades in high pileup
Summary

• HL-LHC will dramatically expand the physics reach for Higgs physics:
  - 2-4% precision on Higgs couplings
  - Access to 2nd generation Yukawa couplings, with direct & indirect approaches for probing the charm Yukawa
  - Limit on $B_{\text{inv}} < 2.5\%$ @ 95% CL, combining CMS+ATLAS

• Many inclusive measurements will be systematically limited ⇒ important work ahead on both theory and experimental sides

• Prospects for HE-LHC Higgs couplings not directly studied by the experiments, but see studies by the Higgs@Future colliders group
Backup
The leading-order Lagrangian is already an EFT, leading potentially to symmetry breaking (EWSB). Therefore, included as a scalar singlet, with couplings unrelated to the ones of the Goldstone bosons of electroweak symmetry breaking (EWSB).

The main difference between both EFTs concerns the Higgs field. In the EWChL, the Higgs boson, and symmetries of the SM. These are the same requirements adopted in the construction of the SMEFT.

This Lagrangian, taken in isolation, leads to a theory with a parametrically low cutoff: it has therefore superficially it might seem to be equivalent. In particular, the Standard Model is consistently recovered to be thought as part of a bigger EFT: the EWChL [197]. This is a bottom-up EFT, constructed with the particle content of the SM, and the unitary gauge, are [185]. The filled coloured box corresponds to the statistical and experimental systematic uncertainties (left) and CMS extrapolations. For each measurement, the total uncertainty is indicated by an error bar, with the hatched grey area representing the additional contribution to the total uncertainty due to theoretical systematic uncertainties. (right) Summary plot showing the total expected uncertainty on the ratios of coupling modifier parameters for the combination of ATLAS and CMS data. The expectation is indicated by a blue, green, and red line respectively.

### Expected Relative Uncertainty

- **$\kappa_{gZ}$**: 2% (ATLAS), 4% (CMS)
- **$\lambda_{Zg}$**: 2.6% (ATLAS), 1.2% (CMS)
- **$\lambda_{tg}$**: 3.4% (ATLAS), 0.9% (CMS)
- **$\lambda_{WZ}$**: 1.5% (ATLAS), 0.7% (CMS)
- **$\lambda_{γZ}$**: 1.5% (ATLAS), 0.7% (CMS)
- **$\lambda_{tZ}$**: 1.8% (ATLAS), 0.9% (CMS)
- **$\lambda_{bZ}$**: 3.1% (ATLAS), 1.3% (CMS)
- **$\lambda_{μZ}$**: 4.2% (ATLAS), 3.8% (CMS)
- **$\lambda_{(Z\gamma)Z}$**: 9.8% (ATLAS), 7.2% (CMS)

### Uncertainty [%]

- **Total**
  - ATLAS: 1.8, 0.6, 0.7, 1.5
  - CMS: 2.6, 1.2, 0.9, 2.1
- **Statistical**
  - ATLAS: 2.6, 1.2, 0.9, 2.1
  - CMS: 3.4, 0.9, 1.2, 3.0
- **Experimental**
  - ATLAS: 1.5, 0.7, 0.8, 1.1
  - CMS: 1.5, 0.7, 1.0, 0.8
- **Theory**
  - ATLAS: 1.8, 0.9, 1.0, 1.2
  - CMS: 3.1, 1.3, 1.3, 2.6
- **Total**
  - ATLAS: 4.2, 3.8, 1.0, 1.5
  - CMS: 9.8, 7.2, 1.8, 6.3

### HL-LHC Projection

- **$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$ per experiment**

**Fig. 31**: (left) Summary plot showing the total expected uncertainty on the ratios of coupling modifier parameters for ATLAS (blue) and CMS (red). (right) Summary plot showing the total expected uncertainty on the ratios of coupling modifier parameters for the combination of ATLAS and CMS data. The expectation is indicated by a blue, green, and red line respectively.
Table 2: The expected uncertainties [30] and S2 (with YR18 systematic uncertainties). The total uncertainty is decomposed into four components: statistical (Stat), signal theory (SigTh), background theory (BkgTh) and experimental (Exp). The production and decay rate signal strengths and coupling modifiers for S2 (with YR18 systematic uncertainties) at 300 fb⁻¹ (left) and 3000 fb⁻¹ (13 TeV) (right).