Prospects on SM and Higgs Physics at the HL-LHC

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on behalf of the ATLAS and CMS Collaborations

Istituto Nazionale Fisica Nucleare

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Index

• Higgs results at LHC with Run1 data
• High Energy Physics in the new era: *What Next?*
• Prospects with LHC and the luminosity upgrade, HL-LHC
  • Higgs Coupling Combination
• Summary
Higgs boson mass

- Combined mass through simultaneous fit to $H \to 4l$ and $H \to \gamma\gamma$ datasets
- Scale accuracy at the level of 0.1%! ← spectrometer & calorimeter calibration important

<table>
<thead>
<tr>
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<th>ATLAS</th>
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</tr>
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<tbody>
<tr>
<td>$H \to 4l$</td>
<td>124.51 ± 0.52 ± 0.06</td>
<td>125.6 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>125.98 ± 0.42 ± 0.28</td>
<td>124.70 ± 0.31 ± 0.15</td>
</tr>
<tr>
<td>Combination</td>
<td>125.36 ± 0.37 ± 0.18</td>
<td>125.09 ± 0.21 (stat) ± 0.11(scale) ± 0.02 (other) ± 0.01 (theory)</td>
</tr>
</tbody>
</table>

Uncertainty dominated by statistics, it will improve with more data from Run2
Higgs boson mass

- Combined mass through simultaneous fit to $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ datasets
- Scale accuracy at the level of 0.1%! $\Leftarrow$ spectrometer & calorimeter calibration important

- $m_H$ was the only fundamental parameter missing to completely set the SM structure
- We just entered a new era: precision tests are now needed in order to “discover” possible deviations from SM

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<td>$125.02^{+0.26}<em>{-0.27}^{+0.14}</em>{-0.15}$</td>
</tr>
<tr>
<td>ATLAS + CMS</td>
<td>$125.09 \pm 0.21$ (stat) $\pm 0.11$ (scale) $\pm 0.02$ (other) $\pm 0.01$ (theory)</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty dominated by statistics, it will improve with more data from Run2
Signal strength combination: decays

Assume SM values for ratios between different production cross sections

- Results are fully consistent with SM predictions

\[
\begin{align*}
\mu(\text{ATLAS}) &= 1.20 ^{+0.15}_{-0.14} \\
\mu(\text{CMS}) &= 0.98 ^{+0.14}_{-0.13} \\
\mu(\text{Comb.}) &= 1.09 ^{+0.11}_{-0.10}
\end{align*}
\]

See also talk from M. Pieri, this conference
**$k$-framework:**

determination of coupling deviations

Write rates in terms of $k_i$ parameters

- **Production:** $\sigma_i \sim k_i^2 \sigma_i^{SM}$
- **Decay:** $\Gamma_i \sim k_i^2 \Gamma_i^{SM}$
- **Total Width:** $\Gamma_H = \Sigma_i k_i^2 \Gamma_i^{SM}$

**Assumptions:**

- **Only one Higgs boson**
- **Only scalar modifications of the coupling strength:** kinematics as in SM
- $J^P = 0^+$

The index $i$ is related to each individual elementary particle

Example:

$$\frac{\sigma \cdot B (gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{SM}(gg \rightarrow H) \cdot B_{SM}(H \rightarrow \gamma\gamma)} = \frac{k_g^2 \cdot k_\gamma^2}{k_H^2}$$

Total width not measured at LHC (upper limits can be derived from off-shell production studies)

Interference in $H \rightarrow \gamma\gamma$, $gg \rightarrow H$, ...

$- \kappa_\gamma^2 = |1.28 \kappa_w - 0.28 k_i|^2$

See also talk from W. Verkerke and M. Pieri, this conference
Absolute coupling deviations

- Absolute coupling determination needs some theory assumption, for example assume no BSM Higgs boson decay, and no BSM particles in the $gg \rightarrow H$, $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loops

- All results compatible between ATLAS and CMS, and with SM

Overview of best-fit values of parameters for the combined measurements with the assumption of the absence of BSM particles in the loops and $BR_{BSM} = 0$. 
What’s Next

• The discovery of the 125 GeV Higgs boson opens a new era in Particle Physics

• Current data indicate consistency of the 125 GeV new particle with the Higgs boson predicted by SM

• **Direct searches** of new particles and new phenomena at the 13-14 TeV LHC are of paramount importance; in particular searches for partners of this newly discovered particle is mandatory

• **Precision Higgs boson and SM measurements are also essential** to verify the properties of this new object and to probe for possible effects from New Physics (**approach complementary to direct searches**)}
What’s Next – an example

arXiv:1206.3560v3
Rick S. Gupta\textsuperscript{a,b,c}, Heidi Rzehak\textsuperscript{a*}, James D. Wells\textsuperscript{a,b}

<table>
<thead>
<tr>
<th></th>
<th>$\Delta hVV$</th>
<th>$\Delta htt$</th>
<th>$\Delta hbb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>8%</td>
<td>tens of %</td>
<td>tens of %</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>&lt; 1%</td>
<td>3%</td>
<td>10%\textsuperscript{a}, 100%\textsuperscript{b}</td>
</tr>
<tr>
<td>LHC Run1 experiment</td>
<td>~15%</td>
<td>~40%</td>
<td>~30%</td>
</tr>
<tr>
<td>LHC 14 TeV 300 fb\textsuperscript{-1} (1 exp.)</td>
<td>~6%</td>
<td>~15%</td>
<td>~12%</td>
</tr>
</tbody>
</table>

Quite a few BSM implementations show coupling deviations in the range from few to several \%.

- 14 TeV & 300 fb\textsuperscript{-1} projections based on what we learnt from early 2011 analyses
  - Since then more channels have been included in the 125 GeV Higgs boson data analyses
LHC and HL-LHC timeline

- 2015 $\sqrt{s} = 13$ TeV – 10 fb$^{-1}$
- 2015-2018 $\sqrt{s} = 13$-14 TeV – 100 fb$^{-1}$
- 2021-2023 $\sqrt{s} = 14$ TeV – 300 fb$^{-1}$
- mid 2025-203? $\sqrt{s} = 14$ TeV – 3000 fb$^{-1}$

HL-LHC instantaneous (levelled) luminosity: $5.0 \text{ (7.5?)} \times 10^{34}$ cm$^{-2}$ s$^{-1}$

see Sergio Bertolucci’s talk
ATLAS and CMS upgrades

• Present ATLAS and CMS detectors have been designed for a event pileup level $<\mu> \sim 23$ pp interactions / bunch-crossing
  – And continue to do an excellent job with 35
  – But cannot handle (an average of) 140-200 events of pileup

• See talks on detector upgrade of ATLAS and CMS for the high-luminosity LHC, HL-LHC by:
  – Lucia Silvestris (CMS)
  – Anadi Canepa (ATLAS)
125 GeV Higgs sector milestones

- Observe the Higgs in $\tau\tau$ and $bb$ decay modes in ATLAS and CMS independently
- Observe the Higgs boson in VBF and VH in ATLAS and CMS independently
- Study Higgs boson differential cross sections
- Observe the Higgs boson in $ttH \rightarrow$ crucial to investigate the top quark Yukawa coupling
- Search for rare Higgs boson decays: in primis $H \rightarrow \mu\mu$
- Higgs coupling precision measurements
- HH production
- Search for CP mixing in the Higgs sector

**Direct Search** for partners of the 125 GeV Higgs boson
Projection methodology

- **ATLAS:**
  - Efficiency and resolution functions are applied to physics objects
  - Performance of the new detector will not be worse than the current detector at Run I conditions

- **CMS:**
  - Scale signal and background yields of current analyses
  - Two scenarios for systematic uncertainties
    - Scenario 1: Systematic uncertainties remain the same
    - Scenario 2: Theoretical uncertainties scaled by $\frac{1}{2}$, other systematic uncertainties scaled by $\frac{1}{\sqrt{L}}$
Full simulation object studies

- Parametrization of object performance in the HL-LHC pile-up environment using full MC samples simulated in the upgraded ATLAS detector
- Some examples here:
  - ATLAS $E_T^{\text{miss}}$ resolution with parametrization overlayed
  - ATLAS $b$-tag fake rate for 70% efficiency compared with rate assumed for ES studies
    - ITK brings enhanced tracking
    - Mistag below 0.5% (2%) for $\langle \mu \rangle = 140$ (200) and $p_T = 100$ GeV

More recent studies available since fall 2014:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LargeEtaECFA2014
Higgs Coupling studies

<table>
<thead>
<tr>
<th>Production and decay modes considered in the projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg→H / inclusive</td>
</tr>
<tr>
<td>VBF</td>
</tr>
<tr>
<td>VH</td>
</tr>
<tr>
<td>ttH</td>
</tr>
</tbody>
</table>
H → ZZ* → 4l

- Very high signal purity
- Separate into all 5 production modes
- WH, ZH use lepton tags

**ttH only possible at HL-LHC**

**ATLAS Simulation Preliminary**

\[ \int L = 3000 fb^{-1}, \sqrt{s} = 14 \text{ TeV} \]

**CMS Simulation**

\[ \int L = 3000 fb^{-1}, \sqrt{s} = 14 \text{ TeV} \]

<table>
<thead>
<tr>
<th>ATLAS Selected signal event rates</th>
<th>ttH</th>
<th>ZH</th>
<th>WH</th>
<th>VBF</th>
<th>ggH</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000fb^{-1}</td>
<td>35</td>
<td>5.7</td>
<td>67</td>
<td>97</td>
<td>3800</td>
</tr>
</tbody>
</table>

**ATL-PHYS-PUB-2013-014**  

**CMS [CERN-LHCC-2015-010]**
Experimental uncertainty on ttH signal strength: $\sim 12\%$

- Sensitive to top in both production and decay
- Yields top Yukawa coupling
Rare decays

$H \rightarrow \mu\mu$

CMS [CERN-LHCC-2015-010]

- Allows direct study of coupling to two different leptons
- Test lepton flavour-violation carefully
- Signal significance, ATLAS:
  - CMS: revised projection, expect 5% on coupling measurement at HL-LHC

$H \rightarrow Z\gamma$

ATL-PHYS-PUB-2014-006

- In Standard Model, this decay proceeds entirely via loops predominantly involving heavy charged particles
- Sensitive to possible new physics
- Observation of the SM decay is possible at HL-LHC

<table>
<thead>
<tr>
<th>$L$ [fb$^{-1}$]</th>
<th>300</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal significance</td>
<td>$2.3\sigma$</td>
<td>$7.0\sigma$</td>
</tr>
<tr>
<td>$\Delta\mu/\mu$</td>
<td>46%</td>
<td>21%</td>
</tr>
</tbody>
</table>

$m_{ll\gamma}-m_{ll}$ of signal and background after the full event selection and parameterized lepton and photon reconstruction
## Precision on signal strength

<table>
<thead>
<tr>
<th>channel</th>
<th>Prec. (%) 100 fb(^{-1})</th>
<th>Prec. (%) 300 fb(^{-1})</th>
<th>Prec. (%) 3000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH H→γγ</td>
<td>~65</td>
<td>38</td>
<td>17</td>
</tr>
<tr>
<td>ttH H→ZZ*→4l</td>
<td>~85</td>
<td>49</td>
<td>20</td>
</tr>
<tr>
<td>VBF H→γγ</td>
<td>~80</td>
<td>47</td>
<td>22</td>
</tr>
<tr>
<td>VBF H→ZZ*→4l</td>
<td>~60</td>
<td>36</td>
<td>21</td>
</tr>
<tr>
<td>H→μμ</td>
<td>~70</td>
<td>39</td>
<td>16</td>
</tr>
<tr>
<td>H→ττ</td>
<td>~18</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>H→bb</td>
<td>~20</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>H→γγ</td>
<td>~15</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>H→4l</td>
<td>~15</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>H→4l</td>
<td>~15</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>

ATLAS: experimental & theory uncertainties; only exp. uncertainty
CMS: current exp. & theory uncertainties; exp. uncertainty \(\propto 1/\sqrt{L}\) and ½ theory unc.

ATLAS assumed luminosity uncertainty: 3%
Higgs Couplings

- VH->bb included in ATLAS, updates for H->Z\gamma, VH/ttH->\gamma\gamma (*)
- No BSM Higgs decay modes assumed
  - Comparable numbers for \kappa_W, \kappa_Z, \kappa_t, and \kappa_\gamma between the two experiments
  - Couplings can be determined with 2-10% precision at 3000fb^{-1} (for CMS Scenario 2)

<table>
<thead>
<tr>
<th></th>
<th>\kappa_\gamma</th>
<th>\kappa_W</th>
<th>\kappa_Z</th>
<th>\kappa_g</th>
<th>\kappa_b</th>
<th>\kappa_t</th>
<th>\kappa_\tau</th>
<th>\kappa_{Z\gamma}</th>
<th>\kappa_\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>300fb^{-1}</td>
<td>ATLAS</td>
<td>[9,9]</td>
<td>[9,9]</td>
<td>[8,8]</td>
<td>[11,14]</td>
<td>[22,23]</td>
<td>[20,22]</td>
<td>[13,14]</td>
<td>[24,24]</td>
</tr>
<tr>
<td>300fb^{-1}</td>
<td>CMS</td>
<td>[5,7]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[6,8]</td>
<td>[10,13]</td>
<td>[14,15]</td>
<td>[6,8]</td>
<td>[41,41]</td>
</tr>
<tr>
<td>3000fb^{-1}</td>
<td>ATLAS</td>
<td>[4,5]</td>
<td>[4,5]</td>
<td>[4,4]</td>
<td>[5,9]</td>
<td>[10,12]</td>
<td>[8,11]</td>
<td>[9,10]</td>
<td>[14,14]</td>
</tr>
<tr>
<td>3000fb^{-1}</td>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[4,7]</td>
<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
</tr>
</tbody>
</table>

- ATLAS: [no theory uncert., full theory uncert.]
- CMS: [Scenario 2, Scenario1]

(*) ATLAS documents:
ATL-PHYS-PUB-2014-011
ATL-PHYS-PUB-2014-006
ATL-PHYS-PUB-2014-012
ATL-PHYS-PUB-2014-016

Coupling fit with $L=300$ and $3000$ fb$^{-1}$

Measurement accuracy per experiment!

<table>
<thead>
<tr>
<th>Coupling modifier</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{W,Z}, k_{\gamma}$</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>$k_{b}$</td>
<td>12%</td>
<td>5%</td>
</tr>
<tr>
<td>$k_{t}$</td>
<td>15%</td>
<td>7%</td>
</tr>
<tr>
<td>$k_{\tau}$</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>$k_{\mu}$</td>
<td>22%</td>
<td>7%</td>
</tr>
</tbody>
</table>

based on the results here available

Higgs Couplings

**Most generic model:** remove the assumption on the total width

- Only ratios of the coupling scale factors can be determined at LHC
- Use given process as a reference

- Total Higgs boson width can be probed at LHC studying the comparison of on-shell and off-shell Higgs boson production
- Recent study by ATLAS indicates that, under a number of assumptions, the (SM) Higgs boson width can be estimated with a systematic uncertainty of \(~2\) MeV:

\[
\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\text{ MeV (stat+sys)}.\]
Higgs Couplings

**ATLAS** Simulation Preliminary

\( s = 14 \text{ TeV}; \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>( \kappa_{gZ} )</th>
<th>( \lambda_{WZ} )</th>
<th>( \lambda_{tg} )</th>
<th>( \lambda_{bZ} )</th>
<th>( \lambda_{tZ} )</th>
<th>( \lambda_{\mu Z} )</th>
<th>( \lambda_{gZ} )</th>
<th>( \lambda_{\gamma Z} )</th>
<th>( \lambda_{(Z\gamma)Z} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS [Scenario2, Scenario1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L (\text{fb}^{-1}) )</td>
<td>( \kappa_{g} \cdot \kappa_{Z} / \kappa_{H} )</td>
<td>( \kappa_{\gamma} / \kappa_{Z} )</td>
<td>( \kappa_{W} / \kappa_{Z} )</td>
<td>( \kappa_{b} / \kappa_{Z} )</td>
<td>( \kappa_{t} / \kappa_{Z} )</td>
<td>( \kappa_{\mu} / \kappa_{Z} )</td>
<td>( \kappa_{Z} / \kappa_{g} )</td>
<td>( \kappa_{Z} / \kappa_{\gamma} )</td>
</tr>
<tr>
<td>300</td>
<td>[4,6]</td>
<td>[5,8]</td>
<td>[4,7]</td>
<td>[8,11]</td>
<td>[6,9]</td>
<td>[13,14]</td>
<td>[22,23]</td>
<td>[40,42]</td>
</tr>
<tr>
<td>3000</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,3]</td>
<td>[3,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[6,8]</td>
<td>[7,8]</td>
</tr>
</tbody>
</table>

- **2-3% accuracy on a few coupling constants at HL-LHC**
- **Reduced theoretical uncertainties needed**
For renormalisation and factorisation scales equal to half the Higgs mass, the N^{3}\text{LO} corrections are of the order of +2.2%. The total scale variation at N^{3}\text{LO} is 3%, reducing the uncertainty due to missing higher order QCD corrections by a factor of three.

However the procedure to transfer the scale variations to theory uncertainty on the cross section is not firmly established (why considering a factor 2 and $\frac{1}{2}$, for example?)
Interpretation for BSM Higgs sector

- Use expected accuracy in the couplings $k_i$ of the 125 GeV Higgs boson
- Same decays as in the SM are assumed (b-associated production included as a correction)

$h(125)$ is the light scalar of the 2HDM
Direct BSM Higgs searches:

**example H→ZZ→4l**

- The 4l final state has small cross section but is clean and well reconstructed.
- A heavy SM-like Higgs boson decaying to 4l occurs in several extensions of the scalar sector (2HDM, EWK singlet).
- Limits improve by a factor ~3 with 3000 fb⁻¹ wrt 300 fb⁻¹.
- Similar sensitivity for ATLAS and CMS (~0.01-0.1 fb).
HH production and self-coupling

\[ V_H = \mu^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda (\Phi^\dagger \Phi)^2; \quad \lambda = \frac{M_H^2}{v^2} \text{ and } \mu^2 = -\frac{1}{2}M_H^2 \]

• In the Standard Model, the shape of the Higgs potential is fully determined by the mass of the Higgs boson, now known.

• This is not the case in several BSM implementations \( \rightarrow \) experimental verification is essential, e.g. measuring HH production

• One of the exciting prospects of HL-LHC
  – Cross section at \( \sqrt{s}=14 \) TeV is 40.2 fb [NNLO]
  – Challenging measurement: small signals and large backgrounds
  – Preliminary studies performed by ATLAS and CMS are available
  – Examples: \( HH \rightarrow bb\gamma\gamma, bb\tau\tau, bbWW, + \) many others
Double Higgs production

CMS [CERN-LHCC-2015-010]

- Final states investigated: $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$
- CMS estimated accuracy on $HH \rightarrow bb\gamma\gamma$ production: 67%
- CMS Combination of $HH \rightarrow bb\tau\tau$ and $HH \rightarrow bb\gamma\gamma$ yields a significance of 1.9 standard deviations; measurement accuracy: 54%

ATLAS $HH \rightarrow bb\gamma\gamma$ significance: 1.3 standard deviations

<table>
<thead>
<tr>
<th>process</th>
<th>Expected events in 3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM $HH \rightarrow bb\gamma\gamma$</td>
<td>$8.4 \pm 0.1$</td>
</tr>
<tr>
<td>$bb\gamma\gamma$</td>
<td>$9.7 \pm 1.5$</td>
</tr>
<tr>
<td>$cc\gamma\gamma, bbj\gamma, bbjj, jj\gamma$</td>
<td>$24.1 \pm 2.2$</td>
</tr>
<tr>
<td>top background</td>
<td>$3.4 \pm 2.2$</td>
</tr>
<tr>
<td>$ttH(\gamma\gamma)$</td>
<td>$6.1 \pm 0.5$</td>
</tr>
<tr>
<td>$Z(bb)H(\gamma\gamma)$</td>
<td>$2.7 \pm 0.1$</td>
</tr>
<tr>
<td>$bbH(\gamma\gamma)$</td>
<td>$1.2 \pm 0.1$</td>
</tr>
<tr>
<td>Total background</td>
<td>$47.1 \pm 3.5$</td>
</tr>
<tr>
<td>S/\sqrt{B} (barrel+endcap)</td>
<td>1.2</td>
</tr>
<tr>
<td>S/\sqrt{B} (split barrel and endcap)</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Probing EWK symmetry breaking: QGC

• In the SM it is the Higgs particle which is responsible for avoiding unitarity violation in the VV cross section at increasing scattering energy.

• It is important to confirm this effect experimentally. Other mechanisms for enhancing/reducing vector boson scattering at high energy are possible, even after the existence of the SM-like Higgs boson is established.
  – Early analyses for HL-LHC made by ATLAS: ATLAS-PHYS-PUB-2012-005

• Recent studies by CMS on *Vector Boson Scattering and Quartic Gauge Coupling Studies in WZ Production at 14 TeV* [CMS-PAS-FTR-13-006]
Probing EWK symmetry breaking: QGC

- EFT approach:
- EFT for modelling aQGCs (no new physics (yet) at the LHC)
- Operator: \( L_{T1} = (f_{T1}/\Lambda^4) \text{Tr}[\hat{W}_{\alpha\nu} \hat{W}_{\mu\beta}] \text{Tr}[\hat{W}_{\mu\beta} \hat{W}_{\alpha\nu}], \)
  - involves direct interaction of the gauge boson fields via a field strength tensor operator

Sensitivities for SM EWK scattering discovery and aQGC. The integrated luminosities for SM EWK discovery at 3\(\sigma\) and 5\(\sigma\) are reported while aQGC prospects for discovery are given in terms of the \(L_{T1}\) operator coupling constant.

For 3000 fb\(^{-1}\) the expected sensitivity to aQGC at 3\(\sigma\) is \(f_{T1}/\Lambda^4 = 0.45\text{ TeV}^{-4}\), and at 5\(\sigma\) is \(f_{T1}/\Lambda^4 = 0.55\text{ TeV}^{-4}\) using a proposed CMS Phase-2 detector configuration without extended acceptance.

Anomalous couplings studies also by ATLAS: ATL-PHYS-PUB-2013-006
Probing EWK symmetry breaking: QGC

- ATLAS also studied aQGCs from ZZjj, WWjj, WZjj (all VBS) and Zγγ for 300 fb\(^{-1}\) and 3000 fb\(^{-1}\), at HL-LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>300 fb(^{-1}) 5σ</th>
<th>3000 fb(^{-1}) 5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_φW/Λ^2)</td>
<td>6</td>
<td>ZZ</td>
<td>34 TeV(^{-2})</td>
<td>16 TeV(^{-2})</td>
</tr>
<tr>
<td>(f_{S0}/Λ^4)</td>
<td>8</td>
<td>(W^±W^±)</td>
<td>10 TeV(^{-4})</td>
<td>4.5 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T1}/Λ^4)</td>
<td>8</td>
<td>WZ</td>
<td>1.3 TeV(^{-4})</td>
<td>0.6 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T8}/Λ^4)</td>
<td>8</td>
<td>Zγγ</td>
<td>0.9 TeV(^{-4})</td>
<td>0.4 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T9}/Λ^4)</td>
<td>8</td>
<td>Zγγ</td>
<td>2.0 TeV(^{-4})</td>
<td>0.7 TeV(^{-4})</td>
</tr>
</tbody>
</table>

- The higher integrated luminosity increases the discovery potential for the operators’s coefficients here studied by more than a factor of two to three, from 2.0 TeV\(^{-4}\) to 0.7 TeV\(^{-4}\)
Conclusions

• A Higgs boson SM-like discovered in 2012. Its mass is $125.09 \pm 0.24$ GeV.

• Standard Model: from “model” to “theory” status

• A data sample of 300 fb$^{-1}$ at the LHC will allow to exclude strong deviations of the Higgs-like particle recently discovered from the Higgs boson predicted by Standard Model

• A complete investigation on the physics properties of this new boson will require the search for rare decay final states, selfcoupling processes, CP violation effects, as well as the reduction of experimental (and theoretical) uncertainties. High-Luminosity LHC with L=3000 fb$^{-1}$ can provide the required statistics with an accuracy on the Higgs couplings in the range of 1-4%;

• HL-LHC extends the searches of LHC of BSM physics, and offers the required data to study the properties of new particles if found at the LHC
Outlook

- **LHC Run2-100 fb⁻¹:**
  - Observation of $H \rightarrow bb$;
  - Evidence for $ttH$;
  - Differential cross sections

- **LHC Run2+3 300 fb⁻¹:**
  - Probably observation of $ttH$;
  - Evidence $H \rightarrow \mu\mu$;
  - Precision measurement of Higgs couplings at the level of 10 %

- **HL-LHC 3000 fb⁻¹:**
  - Observation $ttH$;
  - Observation of (SM) $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$;
  - Precision measurement of Higgs couplings at the level of few %;
  - Evidence for $HH$ production
backup
Signal strength combination: decays

- Assume SM values for ratios between different production cross sections

**ATLAS**

- $m_H = 125.36$ GeV

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mu$ (ATLAS)</th>
<th>$\mu$ (CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$1.17^{+0.28}_{-0.26}$</td>
<td>$1.18 \pm 0.15$</td>
</tr>
<tr>
<td>$H \to ZZ^*$</td>
<td>$1.46^{+0.40}_{-0.34}$</td>
<td>$1.00 \pm 0.14$</td>
</tr>
<tr>
<td>$H \to WW^*$</td>
<td>$1.18^{+0.24}_{-0.21}$</td>
<td>$0.83 \pm 0.21$</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$1.44^{+0.42}_{-0.37}$</td>
<td>$0.91 \pm 0.28$</td>
</tr>
<tr>
<td>$H \to b\bar{b}$</td>
<td>$0.63^{+0.39}_{-0.37}$</td>
<td>$0.84 \pm 0.44$</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>$-0.7^{+3.7}_{-3.7}$</td>
<td>$1.12 \pm 0.24$</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>$2.7^{+4.6}_{-4.5}$</td>
<td>$1.12 \pm 0.24$</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.18^{+0.15}_{-0.14}$</td>
<td>$1.00 \pm 0.14$</td>
</tr>
</tbody>
</table>

**CMS**

- $m_H = 125$ GeV

- $p_{SM} = 0.96$

- $\mu(\text{ATLAS}) = 1.18^{+0.15}_{-0.14}$
- $\mu(\text{CMS}) = 1.00 \pm 0.14$

- Results are fully consistent with SM predictions

See also talk from M. Pieri, this conference
Absolute couplings

- Absolute coupling determination needs some theory assumption, for example assume no BSM Higgs boson decay, and no BSM particles in the $gg \rightarrow H$, $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loops

- All results compatible between ATLAS and CMS, and with SM

Coupling fit (when performing the scan for one parameter, the other parameters in the model are profiled)
Future projects allow precision in the sub-percent range

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
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<th>CLIC</th>
<th>TLEP (4 IPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>FCC-ee (4 IPs) (4 IPs)</td>
</tr>
<tr>
<td>∫ L dt (fb⁻¹)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
<td>– /5.5/ &lt;5.5%</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\kappa_\rho$</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>0.67%</td>
<td>3.6/0.79/0.56%</td>
<td>0.79%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
<td>0.39%</td>
<td>0.21%</td>
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<tr>
<td>$\kappa_Z$</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
<td>0.49/0.33/0.24%</td>
<td>0.05%</td>
</tr>
<tr>
<td>$\kappa_\ell$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
<td>1.3%</td>
<td>0.72%</td>
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<td>10 – 13%</td>
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<td>0.4%</td>
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</tr>
<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
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<td>0.9%</td>
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Table 11: Expected precisions on the Higgs coupling scaling factors from a constrained 7-parameter fit assuming no non-SM production or decay modes, and $\kappa_i \equiv g_{hii}/g_{hii}^{(SM)}$. The fit assumes generation universality [34].

HH study requires >1 TeV e+e- collider or FCC-hh
Future projects allow precision in the sub-percent range but need to wait for LHC data at 13-14 TeV before discussing the best solution for future colliders after LHC.

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The SM @ LHC

- We have a good understanding/assessment of the Standard Model process at LHC
- Crucial for precision measurement, assessment of the 125 GeV Higgs boson, and New Physics searches
Fit results for ratios of reduced coupling scaled factors to the photon coupling, $y_{V,i} / \sqrt{\kappa_\gamma}$ for weak bosons and $y_{F,i} / \kappa_\gamma$ for fermions, as a function of the mass of particle $i$, assuming $300/\text{fb}$ and $3000/\text{fb}$ at 14 TeV and a SM Higgs boson with a mass of 125 GeV.
The SM @ LHC

We have a good understanding/assessment of the Standard Model process at LHC.

Crucial for precision measurement, assessment of the 125 GeV Higgs boson, and New Physics searches.
The distribution of the four-lepton invariant mass, $m_{4\ell}$. The signal expectation shown is for a mass hypothesis of $m_H = 125$ GeV.
$H \rightarrow \gamma\gamma$

**Background + Signal fit**

Sum of the $m_{\gamma\gamma}$ distribution from the 7 and 8 TeV datasets, together with the data binned.

**Best-fit signal strength**, $\mu^*$