Prospects on Higgs Physics at the HL-LHC for ATLAS

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
CERN, 30 October 2017 - 1 November 2017

Marianna Testa,
on behalf of the ATLAS Collaboration
Introduction

- Higgs boson studies are a major component of HL-LHC physics program

- High luminosity of HL-LHC needed to achieve:
  - High precision $O(1-10\%)$ measurements of coupling across broad kinematics
    - can reveal new particles in loops or non-fundamental nature of Higgs
  - Sensitivity to coupling to 2nd generation ($H \rightarrow \mu \mu$)
  - Exploration of Higgs potential ($HH$ production)
  - Sensitivity to rare decays involving new physics
HL-LHC environment

- Design for peak leveled luminosity of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  
  $\rightarrow$ average pileup of $\sim 200$ collisions/crossing

- Aim for integrated luminosity of $3000 \text{ fb}^{-1}$, x 10 data by end Run3  
  $\rightarrow$ 170M of Higgs boson, 120k of Di-Higgs

- Good object reconstruction (b-tagging, jet/E_{T}^{miss}, leptons) in harsh environment is crucial to maximize physics potential  
  - Essential to mitigate effects from pileup  
  $\rightarrow$ Upgrade of ATLAS detector

Need to consider for prospect Higgs analysis at HL-LHC:  
Higher $\sqrt{s}$, higher pile-up, upgraded detectors
Analysis strategy

**Smearing function**
- Smear generator level particle @ 14 TeV using parametrized performance of upgraded detectors from full simulation at $\langle \mu \rangle = 140,200$
- Pile-up jets are overlaid

**Extrapolation from Run1/2**
- Same analysis strategy as Run2/Run1
- Correct for higher $\sqrt{s} = 14$ TeV
- Correct for different object performance between Run2 and HL-LHC
- Scale yield of signal and background to 3000 fb$^{-1}$

- Can quantify impact of upgraded detector ✓
- Can quantify impact from pile-up jets ✓
- Large MC statistics required ❌
- Difficult to address mismodeling ❌

- Analysis is optimized (BDT,..) ✓
- QCD background from data ✓
- Tricky to evaluate impact of upgraded detectors and pile-up effects ❌

**Systematic uncertainties:**
- *Hard to predict how these will evolve with luminosity/time*
- Theoretical unc: same as Run 1/Run 2 analysis, reduced by 1/2 vs absent
- Experimental unc: scaled wrt current analyses in Run 1/Run 2 or current Run2
Higgs Signal Strength at HL-LHC

Run 1 analysis strategy with expected performance at $<\mu>=140$

- 4-5% for main channels, 10~20% on rare modes
- Do not include improved detector designs or improvements in analysis techniques
- Impact of theoretical uncertainty (shadow band) not negligible for several channels
  - but already reduced a lot since then (see SL 8) → update really needed
Higgs Signal Strength at Run2

**H \rightarrow ZZ^{*} \rightarrow 4l**

Run2 36.1 fb$^{-1}$

\[
\mu = 1.28^{+0.18}_{-0.17} \text{ (stat.)} + 0.08 \text{ (exp.)} + 0.08 \text{ (th.)} = 1.28^{+0.21}_{-0.19}.
\]

HL-LHC: $\Delta \mu / \mu = [0.09, 0.04]$(all unc., no theory unc.)

**H \rightarrow \gamma \gamma**

Run2 36.1 fb$^{-1}$

\[
\mu = 0.99^{+0.14}_{-0.14} = 0.99^{+0.12}_{-0.11} \text{ (stat.)} + 0.06 \text{ (exp.)} + 0.06 \text{ (theory)}
\]

Significant reduction of theory uncertainty from Run1 NNLO $\rightarrow$ Run2 N3LO

At HL-LHC: $\Delta \mu / \mu = [0.09, 0.04]$(all unc., no theory unc.)

$\rightarrow$ Extrapolation of $\Delta \mu / \mu$ from Run2 to HL-LHC lumi gives stat. precision better by factor $\sim 2$ compared to latest prospect analysis (assuming exp syst. scales with $\sqrt{L}$)

$\rightarrow$ ZZ, $\gamma \gamma$ dominated by syst. uncertainty at HL-LHC
Higgs Signal Strength at Run2

VH, $H \rightarrow bb$

$$\mu = 1.20^{+0.24}_{-0.23} \text{(stat.)}^{+0.34}_{-0.28} \text{(syst.)}.$$  

Leading systematic uncertainty is signal modelling
Dominated by PS-UE-HAD effects
At HL-LHC: $\Delta \mu / \mu = [0.14, 0.12]$
(all unc., no theory unc.)

$t\bar{t}H$
Significance $= 4.2(3.8)\sigma$ obs (exp)
Evidence for $t\bar{t}H$ production.

$$\mu = 1.17 \pm 0.19 \text{ (stat.)}^{+0.27}_{-0.23} \text{ (syst.)}.$$  

Main systematics
• $t\bar{t}H$ signal modelling and cross section (QCD scale)
• $ttb$ bkg modelling systematics in $t\bar{t}H(bb)$
At HL-LHC: $t\bar{t}H \rightarrow \gamma\gamma(Z\gamma) \quad \Delta \mu / \mu = [0.17(0.20), 0.12(0.16)]$
Higgs Couplings I

- Leading order tree level motivated framework

- Signal cross section scaled

\[ \frac{\sigma \cdot B (gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \]

- \( \kappa_x \) determined from a combined fit to \( VV, \gamma\gamma, bb, \tau\tau, \mu\mu, Z\gamma \) channels

- Use Parametrization of expected performance at \( \langle \mu \rangle = 140 \)

- Assumption
  - Single resonance of mass 125 GeV Zero width approximation
  - Tensor structure of Lagrangian assumed to be the same of SM
  - Effective couplings for loop induced processes: \( H \to \gamma\gamma, H \to Z\gamma, \) and \( gg \to H \)

\( \Delta \kappa / \kappa = [\text{no theory uncert.}, \text{full theory uncert.}] \) Model allowing contributions from new physics in loop

<table>
<thead>
<tr>
<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 t )</th>
<th>( \kappa Z\gamma )</th>
<th>( \kappa \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 fb(^{-1})</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>3000 fb(^{-1})</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>
</tbody>
</table>

Couplings can be determined with 4-12% precision at 3000 fb\(^{-1}\)

Reduced theoretical uncertainties needed (already improvement since 2014)
Impact of theoretical uncertainties

- Theoretical uncertainties limit the precision of several coupling scale factor $k_x$ and ratios $\lambda_{xy} = k_x/k_y$ measurements.

- Size of each source of theory uncertainty to give a contribution to coupling measurement < 30% of total experimental uncertainty.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Status 2014 [10-12]</th>
<th>Deduced size of uncertainty to increase total uncertainty by ≤10% for 300 fb$^{-1}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td></td>
<td>$\kappa_{gZ}$ $\lambda_{gZ}$ $\lambda_{\gamma Z}$ $\kappa_{\gamma Z}$ $\lambda_{\gamma Z}$ $\lambda_{qZ}$ $\lambda_{lZ}$ $\lambda_{tg}$</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>8</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td>7</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$p_T$ shape and 0j $\rightarrow 1j$ mig.</td>
<td>10-20</td>
<td>-</td>
<td>3.5-7</td>
</tr>
<tr>
<td>1j $\rightarrow 2j$ mig.</td>
<td>13-28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1j $\rightarrow$ VBF 2j mig.</td>
<td>18-58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBF 2j $\rightarrow$ VBF 3j mig.</td>
<td>12-38</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBF PDF</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
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<tr>
<td>PDF</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td>8</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

“-”: theoretical uncertainty already small

Recent progress in theory (G. Salam talk at ECFA16):
- Example of gluon fusion process: calculation at N3LO (NNLO) in Yellow Report4(3)
  - $\Delta$ From QCD scale: (-7.4, -7.9) % $\rightarrow$ 3.9%
  - $\Delta$ From (PDF + $\alpha_s$): (+7.1, -6.0) % $\rightarrow$ 3.2%
New Physics in Higgs Couplings

Use VV, $\gamma\gamma$, bb, $\tau\tau$, $\mu\mu$, $Z\gamma$ channels

**Minimal composite model:**
- Pseudo-Nambu-Goldstone boson instead of elementary particle
- Rescale the rates as functions of the modified couplings $\kappa = \kappa_V = \kappa_f = \sqrt{1 - \xi}$ or $\kappa_V = \sqrt{1 - \xi}$ and $\kappa_f = 1 - 2\xi / \sqrt{1 - \xi}$

**2HDM models:**
- Second Higgs doublet present in many BSM models
- Existence of 5 observable Higgs bosons
- Fit parameter: $\kappa_V, \kappa_u, \kappa_d$ couplings

**Higgs portal to Dark Matter:**
- Fit parameters: $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, \text{BR}_{\text{inv}}$
- No assumption on total width
- $\text{BR}_{\text{inv}} < 0.13 (0.09 \text{ w/o the. unc.})$
- Run2: $\text{BR}_{\text{inv}} < 67\% (39\%) \text{ obs. (exp)}$
Searches for additional Higgs states

Two-Higgs-doublet models in many BSM models
  - Existence of 5 observable Higgs bosons:
    - $A \rightarrow Zh$ decay dominant at $m_Z+m_h < m_A < 2m_{top}$
    - Relevant at low $\tan\beta$
    - Consider $Z h \rightarrow llbb$ decay
    - 30 % syst. unc. assumed
  - $H,A \rightarrow \mu\mu$ relevant at high $\tan\beta$
    - For masses $m_{H,A}> 500$ GeV large improvement in HL-LHC
    - Only stat. uncertainty

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- Heavy $H \rightarrow ZZ \rightarrow 4l$
  - Extrapolation from Run1 analysis
  - at HL-LHC $\times 10 - 150$ better wrt SM Higgs boson production
Rare Higgs Boson decays

\( H \rightarrow J/\psi(\mu\mu) \gamma \)
- probe \( c \)-quark couplings
- SM expectation: \( \text{BR}(H \rightarrow J/\psi \gamma) = (2.9 \pm 0.2) \times 10^{-6} \)
- ATLAS Run 1 limit: \( \text{BR}(H \rightarrow J/\psi \gamma) = 1.5 \times 10^{-3} \)
- Extrapolation from Run1 results and correct for performances at \( <\mu> = 140 \)
- Using multivariate analysis, events in \( m(\mu+\mu-\gamma) \subseteq 115-135 \text{ GeV} \): \( \sim 3 \) signal, \( 1700 \) background
- \( \text{BR} (H \rightarrow J/\psi \gamma) < (44^{+19}_{-22} \times 10^{-6}) @ 95\% \text{ CL} \)

\( H \rightarrow \Phi\gamma/\rho\gamma \) to probe \( light \)-quark couplings
Run2: \( \text{B} (H \rightarrow \phi\gamma) < 4.8 \times 10^{-4} \), exp SM \( (2.31 \pm 0.11) \times 10^{-6} \)
- \( \text{B} (H \rightarrow \rho\gamma) < 8.8 \times 10^{-4} \), exp SM \( (1.68 \pm 0.08) \times 10^{-5} \)

\( H \rightarrow \mu\mu \): low BR with very large irreducible from \( Z/\gamma \)
- parametrization of exp. performances at \( <\mu>=200 \)
- Upgraded layout improves the di-muon invariant mass resolution by 25%
- Run2: \( \sigma \times \text{BR} / (\sigma \times \text{BR})_{SM} < 3.0(3.1) \), obs.(exp)
- HL-LHC (Run3 300 fb\(^{-1}\)): significance \( =7.0(2.3) \sigma \)
\( \Gamma_H \) from off-shell couplings

Off-shell production to indirectly constrain the Higgs boson width \( \Gamma_H \)

- Using \( H \rightarrow ZZ^* \rightarrow 4l \) final state with \( m(4l) > 220 \) GeV
- Use Run1 results with correction to \( \sqrt{s} = 14 \) TeV
- Assume same detector performances at HL-LHC
- Use \( m(4l) \) shape and matrix element to discriminate between signal and background

- Signal strength \( \mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50} \)
- \( \Gamma_H = 4.2^{+1.5}_{-2.1} \) MeV (stat+sys)
- Run 1 limit: \( \Gamma_H < 22.7 \) MeV
- Large theory uncertainties, \( \sim 30\% \)
  - dominated by LO-NNLO k-factor uncertainty for \( pp \rightarrow H^* \rightarrow ZZ \) and \( gg \rightarrow H^* \rightarrow ZZ \)
  - Unc. on bkg/signal k-factor ratio expected to be reduced at HL-LHC \( \rightarrow \sim 10\% \)
  - same treatment as in Run1 analysis
Amplitude describing the interaction of a spin-0 particle and and two spin-one gauge bosons

\[ A(X_{J=0} \rightarrow VV) = v^{-1} \left( g_1 m_v^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu \nu}^{(1)} f^{(2), \mu \nu} + g_3 f_{\mu \nu}^{(1), \mu \nu} f_{\mu \alpha}^{(2)} \frac{q_\alpha q_\nu}{\Lambda^2} + g_4 f_{\mu \nu}^{(1)} \tilde{f}_{(2), \mu \nu} \right) \]

- **Coupling** \( g_1(g_2) \) describe the tree-level (loop-induced) interaction of a CP even scalar
- **Coupling** \( g_4 \) describes the interactions of a CP odd scalar
- **Coupling** \( g_3 \) can be absorbed into \( g_2 \)
- SM prediction, CP-conserving tree-level interaction: \( g_1 > 0 \) and \( g_{2,3,4} = 0 \).

**Parametrization:**

\[ f_{g_i} = \frac{|g_i|^2 \sigma_i}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4} ; \quad \phi_{g_i} = \arg \left( \frac{g_i}{g_1} \right) . \]

\( f_{g_4} < 0.037 \) and \( f_{g_2} < 0.12 \)

at 95\% CL for 3000 fb\(^{-1}\)

Sensitive test of the tensor structure of the \( H \rightarrow ZZ^* \) couplings at the high luminosity LHC.
VBF $H \rightarrow WW \rightarrow ev\,\mu\nu$

- **Impact of recent layout of upgraded detector**
- jets, b-tagging from expected performances at $<\mu>=200$
- e/\mu efficiency from Run-1 detector

- Impact of acceptance of the new Inner tracker
  - pileup jet mitigation in the fwd region
  - b-jets veto (ttbar) in the fwd region

- precision on the visible cross-section measurement for these different scenario

<table>
<thead>
<tr>
<th>Tracker acceptance</th>
<th>Expected precision</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>\eta</td>
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<td>$</td>
<td>\eta</td>
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<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

No theoretical uncertainties on VBF and ggF Higgs-boson production
- Impact of recent layout of upgraded detector
- Use parametrization of expected performances at $<\mu> = 200$
- The acceptance of the new Inner Tracker up to $|\eta|<4.0$ enables better separation between ggF and VBF kinematic distributions $\Rightarrow$ smaller $\Delta\mu/\mu$

<table>
<thead>
<tr>
<th>Tracker acceptance</th>
<th>VBF + jets</th>
<th>ggF+2j</th>
<th>qqZZ+2j</th>
<th>$Z_0$</th>
<th>$\Delta\mu/\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;4.0$</td>
<td>192</td>
<td>287</td>
<td>39</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;3.2$</td>
<td>218</td>
<td>454</td>
<td>69</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;2.7$</td>
<td>259</td>
<td>803</td>
<td>124</td>
</tr>
</tbody>
</table>

Last column: QCD scale variation systematic uncertainty: ( included, not included )
Accurate measurement of Higgs boson $p_T$ distribution

- probes perturbative QCD calculations
- information about (new) particles contributing to the gluon fusion loop

$$\sigma_{i,fid} = \sigma_i \times A_i \times BR = \frac{N_{i,\text{fit}}}{\mathcal{L} \times C_i}, \quad C_i = \frac{N_{i,\text{reco}}}{N_{i,\text{part}}}.$$ 

- Use parametrization of expected performance
- Assume Run2 systematic uncertainties dominated by
  - lepton efficiency and resolution 3%
  - unfolding method 3-4%
  - $qqZZ$ modelling 2-5%

- Optimistic scenario: experimental uncertainties of Run2 reduced by $\times 2$

- Theory unc. $\sim$ experimental unc. at HL-LHC
**H → γγ differential cross section**

- Run2 strategy with correction due to expected performances and pile-up effects
- Systematics uncertainties from Run2 = 6.8% dominated by
  - background modelling 3.7%
  - theoretical modelling 4.2%
  - both expected to be reduced for HL-LHC

- **Optimistic(pessimistic) scenario** for photon energy resolution
  - Constant term = 0.7% (1% barrel-1.4% endcap)
  - pileup noise = value from full simulation at <μ>=75(200)

- **Optimistic(pessimistic) scenario** for pile-up jets faking photons:
  - same as Run2 (scaled by 200 / μevt )
  - Constant term = 0.7% (1% barrel-1.4% endcap)
  - pileup noise = value from full simulation at <μ>=75(200)
Higgs self-couplings: $HH \rightarrow bb\gamma\gamma$

- Very promising channel thanks to narrow mass peak of $H\rightarrow\gamma\gamma$ but low BR = 0.3%
- Use parametrization of expected performances of upgrade detector at $\langle\mu\rangle=200$
- Photon ID and b-tagging critical
- Main background:
  - non resonant $bb\gamma\gamma$ and $bbj\gamma$
  - single H background production

**Result**
- $S/VB$ significance $\sim 1.05$ (only stat.)
- $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$ at 95 CL
  - No systematic uncertainty
- Run2 (3.2 fb$^{-1}$): $\sigma < 3.9$ (5.4) pb obs.(exp)
  $\sigma_{SM} = 37.9$ fb @13 TeV
Higgs self-couplings: HH → 4 b

- Higher BR 33% but large QCD background
- Need excellent b-tagging
- Extrapolation and systematic uncertainties from Run2 (10fb⁻¹)
  - Assume the current performance in jet reconstruction and b-tagging

- High sensitivity to jet trigger threshold:
  - Trigger system upgrade critical

- -3.5 < \( \lambda_{HHH}/\lambda_{SM} \) < 11 @ 95% CL
  - Largest systematics from b-tagging and ttbar background modeling
  - Improvements expected with increased luminosity

<table>
<thead>
<tr>
<th></th>
<th>( p_T^{\text{jet}} &gt; 75 \text{ GeV, Full unc} )</th>
<th>( p_T^{\text{jet}} &gt; 75 \text{ GeV, stat only} )</th>
<th>( p_T^{\text{jet}} &gt; 30 \text{ GeV, Full unc} )</th>
<th>( p_T^{\text{jet}} &gt; 30 \text{ GeV, Stat only} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{HHH}/\lambda_{SM} )</td>
<td>[-7.4, 14]</td>
<td>[-3.4, 12]</td>
<td>[-3.5, 11]</td>
<td>[0.2, 7]</td>
</tr>
<tr>
<td>( \sigma/\sigma_{SM} \text{ excluded} )</td>
<td>11.5</td>
<td>2.0</td>
<td>5.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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**HH → bb ττ and λ_{HHH}**

- **BR HH → bbττ = 7.3%**
- had-had, lep-had tau final states
- Use parametrization of expected performances of upgrade detector at < μ >=140
- Main systematic uncertainty: background modeling uncertainty (Run 1)

- Combined significance (no syst. error): 0.6 σ
- σ/σ_{SM} < 4.3 @ 95% C.L
- -4 < λ_{HHH}/λ_{SM} < 12 @ 95% C.L. (reco. efficiency dependence on λ_{HHH} neglected)

<table>
<thead>
<tr>
<th>trigger</th>
<th>Signal events</th>
<th>Bkg events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{lep}) (\tau_{had})</td>
<td>Single e or mu (p_{T}&gt;25) GeV</td>
<td>20</td>
</tr>
<tr>
<td>(\tau_{had}) (\tau_{had})</td>
<td>Di-(\tau): (p_{T}^{vis}&gt;40) GeV</td>
<td>19</td>
</tr>
</tbody>
</table>
Conclusions

A lot of progress in the prospect of Higgs analysis in last 5 years:
• Benefit from new detectors has been addressed
• Impact of performances of reconstruction under HL-LHC pile-up condition addressed
  • more will come with TDR next year

• Take into account improvements in Run2 analysis for more realistic sensitivity studies

• Need to update some prospect analysis (for ex. Higgs couplings) with current theoretical uncertainties
Backup
\[ \sigma(t\bar{t} \, H) \sim 1 \, \text{fb} \]

- Use \( HH \rightarrow b\bar{b} \, b\bar{b} \) final state and semi-leptonic final state of \( t\bar{t} \).
- single lepton trigger requirement (e, \( \mu \))
- 6 \( b \)-jets, 2 light jets, e/\( \mu \) and missing-\( E_T \)

- For \( \geq 5 \) \( b \)-tags: 25 signal events, 7100 background
- background is dominated by \( c \)-jets mistagged as \( b \)-jets from \( W \rightarrow cs \)
- significance of \( t\bar{t}HH \) production (no syst. error): \( 0.35 \, \sigma \)
- With systematic uncertainties, the SM \( t\bar{t} \, HH \) production found to give small contribution to HH production.
Higgs Couplings: mass dependence

- Higgs boson couplings versus the SM particle masses
- Define ‘reduced’ coupling parameters

\[
y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2 v}} = \sqrt{\kappa_{V,i} \frac{m_{V,i}}{v}}
\]

\[
y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v}
\]

- Use results from fit with 6 parameters

[no theory uncert., full theory uncert.]

<table>
<thead>
<tr>
<th></th>
<th>κW</th>
<th>κZ</th>
<th>κb</th>
<th>κt</th>
<th>κτ</th>
<th>κμ</th>
</tr>
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<td>[9,10]</td>
<td>[7,7]</td>
</tr>
</tbody>
</table>
HH and $\lambda_{HHH}$

Higgs production crucial for the measurement of Higgs \textit{self- coupling}

Last piece missing in the Standard Mode

$$\mathcal{L} = -\frac{1}{2}m_h^2h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4,$$

SM: $\lambda_3 = \lambda_4 = 1$;

Strong dependence near $\lambda \sim 1$

High sensitivity to deviations from SM

Very challenging measurement:

- Prospective at HL-LHC still not clear
- Room to \textit{impact} for optimal trigger and reconstruction and detector design

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
<th>Total Yield (3000 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb + bb$</td>
<td>33%</td>
<td>40,000</td>
</tr>
<tr>
<td>$b\bar{b} + W^+W^-$</td>
<td>25%</td>
<td>31,000</td>
</tr>
<tr>
<td>$b\bar{b} + \tau^+\tau^-$</td>
<td>7.3%</td>
<td>8,900</td>
</tr>
<tr>
<td>$ZZ + b\bar{b}$</td>
<td>3.1%</td>
<td>3,800</td>
</tr>
<tr>
<td>$W^+W^- + \tau^+\tau^-$</td>
<td>2.7%</td>
<td>3,300</td>
</tr>
<tr>
<td>$ZZ + W^+W^-$</td>
<td>1.1%</td>
<td>1,300</td>
</tr>
<tr>
<td>$\gamma\gamma + b\bar{b}$</td>
<td>0.26%</td>
<td>320</td>
</tr>
<tr>
<td>$\gamma\gamma + \gamma\gamma$</td>
<td>0.0010%</td>
<td>1.2</td>
</tr>
</tbody>
</table>
• Remove the assumption on the total width
• Only ratios of the coupling scale factors can be determined at LHC
• Some uncertainties cancel in the ratio
• But Reduced theoretical uncertainties needed