ATLAS Higgs and Supersymmetry Physics Prospects at the High-Luminosity LHC

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On behalf of the ATLAS Collaboration
EPS 2017
Outline

• The **High Luminosity**-LHC program

• **ATLAS Phase II Upgrade** program

• **Higgs** analysis prospect:
  - Higgs boson coupling
  - Higgs boson self-coupling
  - Higgs boson rare decays
  - VBF Higgs boson production

• **Supersymmetry** (SUSY) analysis prospect:
  - Stop pair direct production
  - Stau pair direct production
  - Chargino and neutralino direct production

• Conclusion
High Luminosity LHC (2024-2037)

Physics targets: precision measurements/rare decays/Beyond SM

**LHC / HL-LHC Plan**

http://hilumilhc.web.cern.ch/about/hl-lhc-project

<table>
<thead>
<tr>
<th>HL-LHC mode</th>
<th>Peak Luminosity (cm(^{-2}) s(^{-1}))</th>
<th>Mean number of interactions per bunch-crossing (&lt;\mu_{PU}&gt;)</th>
<th>Integrated luminosity (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5\times10^{34}</td>
<td>140</td>
<td>3000</td>
</tr>
<tr>
<td>Ultimate</td>
<td>7.5\times10^{34}</td>
<td>200</td>
<td>4000</td>
</tr>
</tbody>
</table>
ATLAS Phase II Upgrade Program (2024-2026)

- **ATLAS Phase II upgrade:** for performance and degradation/limitation
  -> **maximize the physics performance** and discovery potential of ATLAS
    - increased pile-up
    - higher backgrounds
    - higher trigger rates
  -> **Physics targets:** precision measurements / rare decays / beyond SM

- Longer latency for **Trigger System**
- Upgrade electronics for **Tile Calorimeter**
- **Inner detector** with fully Silicon (strip and pixel) **up to |η| = 4**
- New Inner **Muon** barrel trigger chambers
- Options for: - **forward muon tagger**
  - **timing detectors**
Higgs Couplings

• Extrapolation from Run-1 analysis at $<\mu_{PU}> = 140$ (ATL-PHYS-PUB-2014-016)

**ATLAS Simulation Preliminary**

$\sqrt{s} = 14$ TeV: $\int Ldt = 300$ fb$^{-1}$; $\int Ldt = 3000$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>Signal Strength $\mu = \sigma/\sigma_{SM}$</th>
<th>(\Delta\mu/\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\rightarrow\gamma\gamma$ (comb.)</td>
<td>0.28 - 0.27</td>
<td>0.23</td>
</tr>
<tr>
<td>$H\rightarrow ZZ$ (comb.)</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>$H\rightarrow WW$ (comb.)</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>$H\rightarrow Z\gamma$ (incl.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow b\bar{b}$ (comb.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow \tau\tau$ (VBF-like)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow \mu\mu$ (comb.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Run-1

$\mu_{\gamma\gamma} = 1.17^{+0.28}_{-0.27}$

$(\Delta\mu/\mu \sim 0.23)$

$\mu_{ZZ} = 1.46^{+0.40}_{-0.30}$

$(\Delta\mu/\mu \sim 0.24)$

$\mu_{WW} = 1.18^{+0.42}_{-0.37}$

$(\Delta\mu/\mu \sim 0.33)$

With 3000 fb$^{-1}$:

• $W$, $Z$ couplings to 3%
• **Muon** coupling to 7%
• $t, b, \tau$ couplings to 8-12%
Higgs Self-coupling

- First opportunity to measure Higgs boson trilinear self-coupling
- $\sigma_{NNLO}(HH) \sim 40 \text{ fb} \rightarrow$ combine as many decay channels as possible

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio (%)</th>
<th>$\sigma.\text{Br (fb)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}+b\bar{b}$</td>
<td>33</td>
<td>12.9</td>
</tr>
<tr>
<td>$b\bar{b}+W^+W^-$</td>
<td>25</td>
<td>9.9</td>
</tr>
<tr>
<td>$b\bar{b}+\tau^+\tau^-$</td>
<td>7.4</td>
<td>2.9</td>
</tr>
<tr>
<td>$W^+W^-+\tau^+\tau^-$</td>
<td>5.4</td>
<td>2.1</td>
</tr>
<tr>
<td>$ZZ+b\bar{b}$</td>
<td>3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>$ZZ+W^+W^-$</td>
<td>1.2</td>
<td>0.48</td>
</tr>
<tr>
<td>$b\bar{b}+\gamma\gamma$</td>
<td>0.3</td>
<td>0.12</td>
</tr>
<tr>
<td>$\gamma\gamma+\gamma\gamma$</td>
<td>0.001</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Comparable light jets rejection: with $\langle \mu \rangle = 200$ and Run-2

(AML-TDR-025 LHCC-017-055)
Higgs self-coupling

- **HH -> b\bar{b} \gamma\gamma**
  - Cut based analysis, ATLAS upgrade design y performance
  - SR: 9.5 signal, 91 total background

\[ Z_0 : 1.05 \sigma \ (\pm 0.026 \text{ stat only}) \]
\[ -0.8 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 7.7 \ (95\% \text{ C.L.} , \text{ no syst.}) \]

- **HH -> b\bar{b} b\bar{b}**
  - Extrapolation from Run-2 analysis
  - Systematic as in 2016 (tt-bar, multi-jets bckg modeling)
  - Present exclusion limit : \( \mu = \frac{\sigma}{\sigma_{SM}} = 29 \)

<table>
<thead>
<tr>
<th>Jet Threshold [GeV]</th>
<th>Background Systematics</th>
<th>( \sigma/\sigma_{SM} ) 95% Exclusion</th>
<th>( \lambda_{HHH}/\lambda_{SM} ) Lower Limit</th>
<th>( \lambda_{HHH}/\lambda_{SM} ) Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 GeV</td>
<td>Negligible</td>
<td>1.5</td>
<td>0.2</td>
<td>7</td>
</tr>
<tr>
<td>30 GeV</td>
<td>Current</td>
<td>5.2</td>
<td>-3.5</td>
<td>11</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Negligible</td>
<td>2.0</td>
<td>-3.4</td>
<td>12</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Current</td>
<td>11.5</td>
<td>-7.4</td>
<td>14</td>
</tr>
</tbody>
</table>

\[ \text{ttHH}\rightarrow WbWb \ bbbb \]

\[ \text{HH}\rightarrow b\bar{b} \tau^- \tau^+ \]

ALTL-PHYS-PUB-2016-023

\[ \text{HH}\rightarrow b\bar{b} \tau^- \tau^+ \]

ALTL-PHYS-PUB-2015-046

\[ \rightarrow \text{ BACK-UP } \]
Higgs rare decays

• $H \to J/\Psi (\to \mu^+\mu^-) \gamma$ (with $<\mu_{PU}> = 140$, $L = 3000 \text{ fb}^{-1}$)
  - Higgs coupling to $c$-quark. Run-1 detector performances
  - MVA analysis $m_{\mu^+\mu^-\gamma}$ in [115, 135] GeV
  - 3 signal events and 1700 background (with no systematics)

$\text{BR} (H \to J/\Psi (\to \mu\mu) \gamma) = 44^{+19}_{-22} \times 10^{-6}$ (95% C.L.)

$\text{SM: } 2.9 \pm 0.2 \times 10^{-6}$ (Run-1 Limit: $1.5 \times 10^{-3}$)

• $H \to \mu^+\mu^-$ (with $<\mu_{PU}> = 200$, $L = 300/3000 \text{ fb}^{-1}$)
  - Low BR, high $Z/\gamma^*$ background, high mass resolution
  - Based on Run-1 analysis (cut optim.), $m_{\mu^+\mu^-}$ in [110, 160] GeV
  - Total background shape and normalization data-driven
  - ITK-Upgrade -> improve mass resolution by 25% (w.r.t Run-2)

$Z_0$: $2.3\sigma$ (300 fb$^{-1}$) $7.0\sigma$ (3000 fb$^{-1}$)

$\Delta \mu/\mu$: $46\%$ (300 fb$^{-1}$) $21\%$ (3000 fb$^{-1}$)
VBF Higgs production

• Pile-up suppression:
  - $<\mu_{PU}> \sim 200$ 4.8 pu jets/event
  - $R_{PT}$ based on charge vertex fraction
  - Applied to all non b-tagged jets with: $p_T < 100$ GeV and $|\eta| < 3.8$

• $H \rightarrow WW^* \rightarrow ev\mu\nu$
  - ATLAS performances: Run-1 ($e/\mu$)
  - Jets and $E_T^{Miss}$ from expected upgrade performance
  - Experimental systematic (no theo. syst. on signal)

• $H \rightarrow ZZ^* \rightarrow 4l$
  - 2 jets( $m(jj) > 130$ GeV)
  - Main background ggF (separated via BDT) and qqZZ
  - Systematic only from signal QCD scale

<table>
<thead>
<tr>
<th>Tracking coverage</th>
<th>$E_{H \rightarrow WW^*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
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<tr>
<td>$</td>
<td>\eta</td>
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<tr>
<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

stat | stat+syst
--- | ---
$Z_0$: 11.1 | 7.7
$\Delta\mu$: 0.144 | 0.170
Supersymmetry Searches at HL-LHC

• Supersymmetry (SUSY) is one possible extension of the SM:
  - predicts bosonic/fermionic partner for existing fermion/bosons
  -> lightest SUSY particle is stable (if R-parity conservation) -> DM candidate
  -> Cancel out quadratic divergences in the Higgs mass corrections
  -> Can accommodate the gauge coupling unification

• Focus on HL-LHC benchmark studies:
  - 14 TeV, $<\mu_{PU}> = 200$, total integrated luminosity of 3000 fb$^{-1}$
  - smearing function for upgraded ATLAS detector simulation
  - truth level particle corrected for detector effects
  - assume 30% systematic on background
Stop pair direct production

- Cut based analysis, top decaying leptonically
- Small mass splitting among stop and neutralino
  -> ISR jets to boost the stop-system
- Final state with 2b-jets, isolated leptons and $E_T^{\text{Miss}}$
- Profile-likelihood-ratio test statistics for expected exclusions
- Run-1 exclusion: $[m_t, 191] \times [230, 380]$ GeV

Discovery up to 480 GeV

Exclusion up to 700 GeV

\[ \Delta M(\tilde{t}, \tilde{\chi}_1^0) = 173 \text{ GeV} \]
Stau pair direct production

- Extend the ATLAS exclusion scenario of combined \( \tilde{\tau}_L \tilde{\tau}_L \) and \( \tilde{\tau}_R \tilde{\tau}_R \) production with \( \tilde{\chi}_1^0 \) massless.
- Cut based analysis: tau decaying hadronically, large \( E_T^{\text{miss}} \), low jet activity.
- Main background: W+jets and tt-bar.

5σ discovery sensitivity (\( \tilde{\chi}_1^0 \) massless):

- **100-500** GeV in \( \tilde{\tau} \)-mass for \( (\tilde{\tau}_L \tilde{\tau}_L \text{ and } \tilde{\tau}_R \tilde{\tau}_R) \) combined production.
- **120-430** GeV for pure \( \tilde{\tau}_L \tilde{\tau}_L \).

Exclusion limit (\( \tilde{\chi}_1^0 \) massless):

- **700** GeV in \( \tilde{\tau} \)-mass for \( (\tilde{\tau}_L \tilde{\tau}_L \text{ and } \tilde{\tau}_R \tilde{\tau}_R) \) combined production.
- **650** GeV for pure \( \tilde{\tau}_L \tilde{\tau}_L \).
- **540** GeV for pure \( \tilde{\tau}_R \tilde{\tau}_R \) (Run-1: 109 GeV).

For stau mass of 200 GeV:

\[ \sigma(\tilde{\tau}_L \tilde{\tau}_L) \sim 0.02 \text{ pb} \quad \sigma(\tilde{\tau}_R \tilde{\tau}_R) \sim 0.01 \text{ pb} \]
Direct chargino and neutralino production

• Extend the present ATLAS sensitivity to electro-weakinos mass range $O(100 \text{ GeV})$

• Simplified model:
  - $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$ are wino-like and with equal mass
  - sleptons and sneutrino with high mass, SM Higgs

• Cut based and MVA analysis

• Main background: tt-bar

5σ discovery sensitivity:

— 950 GeV in mass $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$ for $m(\tilde{\chi}_1^0) = 0$

Exclusion limit:

---- 1310 GeV in mass $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$ for $m(\tilde{\chi}_1^0) = 0$

$\sigma^{NLO}(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \sim 0.005 \text{ pb (at 500 GeV)}$

$\sigma_{\text{bkg}} = 30\%$

$<\mu_{\text{PU}}> = 140$
Conclusions

• HL-LHC will represent a **challenging environment** for ATLAS:
  -> $<\mu_{PU}> = 200$, large backgrounds, high radiation dose

• **Higgs and SUSY physics** program will **benefit greatly** from HL-LHC data and ATLAS Phase II Upgrade
  -> Can explore the $HH$ production mechanism
  -> Precise measurements of Higgs couplings
  -> Can extend the present sensitivities to heavy SUSY particles greatly

• The current expected ATLAS **precisions** at HL-LHC are still **preliminary**
  -> Better analysis techniques, better data-driven methods for background
  -> Theoretical uncertainties expected to decrease with time
BACK UP
# Summary of Higgs results at HL-LHC

<table>
<thead>
<tr>
<th>Channels</th>
<th>Result</th>
<th>HH final State</th>
<th>Significance Coupling limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $H \rightarrow WW^*$</td>
<td>$\Delta \mu/\mu \approx 14$ to $20%$</td>
<td>$HH \rightarrow b\bar{b} \gamma\gamma$ (stat)</td>
<td>$1.05 \sigma$ $-0.8 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 7.7$</td>
</tr>
<tr>
<td>VBF $H \rightarrow ZZ^*$</td>
<td>$\Delta \mu/\mu \approx 15$ to $18%$</td>
<td>$HH \rightarrow b\bar{b} \tau^+\tau^-$ (stat+syst)</td>
<td>$0.6 \sigma$ $-4.0 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12.0$</td>
</tr>
<tr>
<td>$ttH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \approx 17$ to $20%$</td>
<td>$HH \rightarrow b\bar{b} b\bar{b}$ (stat+syst)</td>
<td>-- $-3.5 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 11.0$</td>
</tr>
<tr>
<td>$VH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \sim 25$ to $35%$</td>
<td>$ttHH, HH \rightarrow b\bar{b} b\bar{b}$</td>
<td>$0.35 \sigma$ --</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\Delta \mu/\mu \sim 30%$</td>
<td>$H \rightarrow ZZ^* \rightarrow 4l$ (m(4l) &gt; 220 GeV)</td>
<td>$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat.+syst.)</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>$\Delta \mu/\mu \sim 15%$</td>
<td>$\mu\rightarrow e\tau\nu$</td>
<td>Run-1: $\Gamma_H &lt; 22.7$ MeV</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi \gamma$</td>
<td>$BR &lt; 44 \times 10^{-6}$ @ 95% C.L.</td>
<td></td>
<td>ATL-PHYS-PUB-2015-024</td>
</tr>
</tbody>
</table>
Higgs self-coupling: 3000 fb$^{-1}$

- $t\bar{t}HH\rightarrow WbWb\ b\bar{b}b\bar{b}$ with $<\mu_{PU}> = 200$
  - $\sigma(t\bar{t}HH) \sim 1$ fb
  - Cut based analysis, Final State: $HH\rightarrow b\bar{b}b\bar{b}\ t\bar{t}\rightarrow b\bar{b}l\nu q\bar{q}$
  - Signal Region ($\geq 5$ b jets): 25 signal, 7100 background (dominated by c-jets mis-tagged as b-jets)
    
    *Significance: $\sim 0.35\ \sigma$ (no systematics)*
    
    -> small contribution

- $HH\rightarrow b\bar{b}\ \tau^\pm\ \tau^+$ with $<\mu_{PU}> = 140$
  - Different triggers/cuts for $\tau_{\text{had}}\tau_{\text{had}}$ resp. $\tau_{\text{had}}\tau_{\text{lep}}$ channels
  - Constraint on $m(b\bar{b})$ and $m(\tau\tau)$
  - Systematic: 2% lumi., 3% for major bckg (Z+jets, tt-bar)
  - Combined channels yields: Signal: 48 Bckg.: 7810
    
    *Significance: $\sim 0.60\ \sigma$ (with syst.)*
    
    -4 $< \lambda_{HHH}/\lambda_{SM} < 12$ (95% C.L. with syst)
• Two approaches to study the HL-LHC physics performance with ATLAS

Use of smearing functions:
- Study detector performances for phys. objects (e, mu, ..) with full MC simulations
- Apply ‘smearing functions’ to truth distributions for analysis, overlay PU jets

Extrapolation of Run-1/Run-2 results
- similar detector performance and analysis approach as Run-1/Run-2
- Scale signal and background level to higher luminosity, c.o.m. energy

• Systematics (will have ~x10 more higgs at HL-LHC than at the end of Run-2)
  - Theoretical: from Run1/Run2
  - Experimental: scaled to best guess for ATLAS upgraded detector at HL-LHC
• For combined average efficiency of 70% for isolated photons:
  - Rejection factor of ~4000 for hard-scattered jets
  - Rejection factor of ~14000 for pile-up jets
• For an electron identification efficiency of 69%, a jet rejection factor of about 4000 is obtained. Also, an electron charge mis-identification of about 0.26% has been evaluated for the first time.

• For 70% b-jet efficiency (with MV1 tagger):
  - light jet rejection of ~380 with <mu> = 200 (best optimized Run-2 b-tagger has 380 at 70% eff.)

• Muon with Pt < 200 GeV greatly benefit from Itk momentum resolution
  - $B_s^0$ mass resolution in the $B_s^0 \rightarrow \mu^+ \mu^-$ will improve by a factor of about 1.65 (1.5) in the barrel (end-cap) region.

6/30/17
Pile-up suppression

• Typical jet selections require $p_T (\text{jet}) > 30 \text{ GeV}, |\eta(\text{jet})| < 3.8$

• With $<\mu_{PU}> = 200$ expected 4.8 pileup jets with $p_T > 30 \text{ GeV}, |\eta|<3.8$ per event

• Pile-up suppression with a parametrized track-confirmation requirement

• Applied to all non $b$-tagged jets with $p_T < 100 \text{ GeV}$ and $|\eta|<3.8$

Analyses typically use factor 50 rejection

-~0.2 pile-up jet per event

-~ 85-70 % efficiency on hard-scatter jets
Figure 4.38: Signal resolution for $H \to \mu\mu$ signal events, the Run 2 resolution is compared to the HL-LHC with pile-up conditions corresponding to $\langle \mu \rangle = 200$. 

$H \to \mu\mu$ decay channel with the largest branching ratio (33.3%) is $H \to b\bar{b}b\bar{b}$. Predictions for this channel have been made, extrapolating from the ATLAS Run 2 analysis [43], to estimate the sensitivity to Higgs-boson pair production with the full HL-LHC dataset of 3000 fb$^{-1}$. This extrapolation assumes similar detector performance to Run 2 for jet reconstruction and $b$-jet identification; as such it gives a pessimistic estimate of the sensitivity.
ATLAS Running Conditions

High particle density

High integrated radiation dose

Detector requirements to maximize benefits from high int. luminosity:
- Replace detector not sustaining integrated radiation dose
- Minimize pile-up effect (high granularity, fast timing)
- Higher trigger acceptance and event rate
- Improve or maintain current detector performances
Figure 4: Regions of the \((\cos(\beta - \alpha), \tan \beta)\) plane of four types of 2HDMs expected to be excluded by fits to the measured rates of Higgs boson production and decays. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours where \(-2 \ln \Lambda = 6.0\), corresponding approximately to 95% CL (2\(\sigma\)), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the expected exclusions.
Analysis Techniques

ATLAS HL-LHC studies have to consider:
- upgraded ATLAS detector + trigger systems
- collision energy, $\sqrt{s} = 14$ TeV
- high pile-up, $<\mu_{PU}>$, of 140 or 200

- We use generator-level $\sqrt{s} = 14$ TeV Monte Carlo samples
- Overlay with jets from dedicated pile-up library
  - pile-up library contains fully simulated pile-up jets with $<\mu_{PU}> = 140$ or 200
- Reconstruct electron, muons, jets, photons and missing-$E_T$ from generator+overlay information

- To simulate the response of the detector:
  - smear $p_T$ and energy of reconstructed physics objects using *smearing functions*
  - apply reconstruction efficiencies for electrons, muons and jets

- To emulate triggers: apply trigger efficiency functions

- Smearing and efficiency functions determined from fully-simulated samples using ATLAS HL-LHC detector and high pile-up
  - Functions are dependent on $p_T$ and $\eta$

- Most analysis presented use single lepton or di-lepton triggers ($e$, $\mu$)
  - di-$\tau$ triggers and 4-jet triggers used for particular analyses

- Parametrised $b$-tagging (based on ATLAS Run 1 MV1 tagger) is performed on reconstructed jets

- This approach to ATLAS HL-LHC prospects studies has been validated on a limited number of physics studies comparing full simulation and the generator-level+smearing technique
Measure off-shell production of $H \rightarrow ZZ^* \rightarrow 4\ell$ with $m(4\ell) > 220$ GeV

Use $m(4\ell)$ shape and matrix element to discriminate between signal and background

$\begin{align*}
\Rightarrow & \text{stat. uncertainties only: } \mu_{\text{off-shell}} = 1.00^{+0.23}_{-0.27} \\
\Rightarrow & \text{stat.+syst. uncertainties: } \mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}
\end{align*}$

- Off-shell production used to constrain the Higgs boson width $\Gamma_H$

- For $\Gamma = \Gamma_{\text{SM}}$ combining with on-shell measurement, (assuming off-shell measurement dominates):

  $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)

- Run 1 limit: $\Gamma_H < 22.7$ MeV at 95% CL ($WW, ZZ$)
Higgs coupling K-Framework

- Assuming $\Gamma_H$ is sum of SM widths, calculate uncertainties on Higgs boson couplings.
- Deviations from the SM are quantified using $\kappa$ multiplier, in SM $\kappa_i = 1$, e.g.:

$$\left(\sigma \cdot \text{BR}(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}\right)$$

- Assume universal modifications to Higgs couplings to fermions ($\kappa_F$) and vector bosons ($\kappa_V$)

<table>
<thead>
<tr>
<th>Model</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCHM4</td>
<td>620 GeV</td>
<td>810 GeV</td>
</tr>
<tr>
<td>MCHM5</td>
<td>780 GeV</td>
<td>950 GeV</td>
</tr>
<tr>
<td>MCHM4*</td>
<td>710 GeV</td>
<td>980 GeV</td>
</tr>
<tr>
<td>MCHM5*</td>
<td>1.0 TeV</td>
<td>1.2 TeV</td>
</tr>
</tbody>
</table>

Table 2: Expected 95% CL lower limit on the Higgs boson compositeness scale with 300 and 3000 fb$^{-1}$ at $\sqrt{s} = 14$ TeV in the MCHM4 and MCHM5 models, each shown with and without the inclusion of theoretical uncertainties in the coupling measurements.
ATLAS HL-LHC Analysis Strategy

- Detector **performance** of different physics objects (e, μ, γ,...) with MC (Full Sim.)
- Parametrization to provide ‘smeared truth’ simulation to benchmark analysis
- Jets from **pile-up events** are overlaid on the hard-scatter events
- **Signals** from interactions in previous bunch crossings are added (calorimeter response)

**Extrapolation** of Run-1/Run-2 results
- **similar** detector performance and analysis approach as Run-1/Run-2
- **Scale** signal and background level to higher luminosity, c.o.m. energy

- **Systematics** (will have ~x10 more higgs at HL-LHC than at the end of Run-2)
  - **Theoretical**: from Run1/Run2
  - **Experimental**: scaled to best guess for ATLAS upgraded detector at HL-LHC

- **Pile-up suppression** (~factor 50) track-confirmation requirement (~0.2 p.u. jets/event)
Run-1

$\mu = 1.17^{+0.28}_{-0.27}$

$(\Delta \mu / \mu \sim 0.23)$

$\mu = 1.46^{+0.40}_{-0.30}$

$(\Delta \mu / \mu \sim 0.24)$

$\mu = 1.18^{+0.42}_{-0.37}$

$(\Delta \mu / \mu \sim 0.33)$

With 3000 fb$^{-1}$:

- $W, Z$ couplings to 3%
- **Muon** coupling to 7%
- $t, b, \tau$ couplings to 8-12%

Extrapolation from

- Run-1 analysis at $<\mu_{PU}> = 140$
- (ATL-PHYS-PUB-2014-016)