Standard Model and Higgs Physics at the HL-LHC with ATLAS and CMS

P. Krieger, University of Toronto
(on behalf of the ATLAS & CMS Collaborations)
The High-Luminosity Large Hadron Collider (HL-LHC)

- Upgrade LHC luminosity to permit accumulation of 3 ab$^{-1}$ data sample over a ~10 year run period following LS3 for machine and detector upgrades
- Plan for $\mathcal{L} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with ultimate luminosity of $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

High $\mathcal{L}$ results in higher radiation dose and detector occupancy issues

Detector upgrades needed, with focus on pileup mitigation (PU) strategies
Detector Challenges at High Rate

• Existing detectors were designed for 10 years of running at $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
• Harsher HL-LHC conditions dictate what MUST be replaced:
  – Need to maintain current performance for object reconstruction
  – New detectors can be developed with improved coverage / performance

• Tracking critical to PU mitigation strategies. Both ATLAS & CMS planning for new silicon trackers (with options for coverage out to to (as far as) $|\eta| \approx 4$):
  – Increased granularity for reduced occupancy, reduced material budget
  – Inclusion of tracking information for improved PU rejection in L1 trigger

• Trigger upgrades: up to 1MHz L0/L1, 10kHZ recording
• Muon system: some coverage, trigger improvements expected
• Endcap calorimeters:
  – CMS to replace endcap calorimeter with “HGCAL” (with good timing)
  – ATLAS considering new high-granularity forward calorimeter, as well as a dedicated timing detector in the endcap/forward region.

For details see Sat. morning talks by A. Henriques (ATLAS) and A.Belloni (CMS)
• Full simulations for all channels impractical. Different strategies:
  – Parametrize object-level performance based on full simulations: use parametrizations (efficiencies, fake rates, smearing) for generator-level studies of benchmark channels

Main ATLAS strategy

Extrapolate 8 TeV analyses to higher $\mathcal{L}$ and $\sqrt{s}$ based on assumption that strategies will be developed to allow performance to be maintained at high PU

Main CMS strategy

Quoted CMS results from CMS Note-13-002 [arXiv: 1307.7135] except where noted

Two scenarios for scaling of systematic uncertainties
  • Scenario 1: all systematic uncertainties remain the same
  • Scenario 2: Theoretical uncertainties scaled by $1/2$ and all others scaled by $\mathcal{L}^{-1/2}$

Most available results (ATLAS & CMS) from studies done for $\mu = 140$
The HL-LHC as a Higgs Factory

- Large numbers of Higgs bosons expected at the HL-LHC:
  - All production mechanisms can be investigated

- Expect:
  - Higher precision for quantities measured with 300 fb$^{-1}$
  - Differential cross-sections for all production modes
  - Access to second-generation fermion couplings: $H \rightarrow \mu\mu$
  - Other rare decay modes: e.g. $H \rightarrow Z\gamma$
  - Studies of other Higgs properties (width $\Gamma_H$, CP) as well as vector boson scattering (VBS)
  - $HH$ production, for study of self coupling
Where Things Stand Now

• See talks from Monday afternoon (J.Strandberg, S.Donato + J.Takana for BSM)

H(125): Spin-parity $J^P=0^+$ strongly favoured

• Couplings to both fermions and bosons observed
  – couplings still not precisely measured
  – $ggF$ and VBF production modes seen
  – Associated production modes ($WH, ZH, t\bar{t}H$) investigated; statistics not yet sufficient

• Statistics also too low for detailed studies of CP properties, total width $\Gamma_H$

• Not yet known if there are other Higgs bosons

• Focus here will be on improvements to SM Higgs measurements
• Still “golden”: narrow peak over low background: Access to all production modes.

Performance sensitive to upgrade scenario:
  – Illustrated on next slide for CMS
  – Above ATLAS results do not include improvements from tracker extension (+ 21% acceptance for 4μ)
  – Better than 10% precision expected on ZZ signal strength from both ATLAS and CMS (w. current theory uncertainties)

• Updated results for VBF production (BDT analysis)
This channel an excellent illustration of the need for detector upgrades:

- Other physics studies utilizing $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$
  - Comparison of off-/on-shell couplings sensitive to $\Gamma_H$:
    - Interference between signal and ZZ background
    - Run-1 measurements from both ATLAS and CMS
    - For 3000 fb$^{-1}$ ATLAS projects $\Gamma_H = 4.2 \pm 1.5 \pm 2.1$ MeV
  - Differential cross-sections for all modes
  - CP studies and tests of tensor structure of $HZZ$ coupling have been investigated for HL-LHC, using this channel
$H \rightarrow \gamma\gamma$

- Also provides a narrow peak, so useful for studies of rare modes:
  - Also gives access to all production modes.
    - Classify signal into events with exactly 0, 1, 2 jets
      - different sensitivities to ggF, VBF
    - Separate analysis for associated production modes
      - Also classify according to number of leptons, $b$-tags
      - $\mathcal{O}(100)$ events reconstructed in VH, $ttH$ modes

- Inclusive signal strength precision: 9%
- For non-ggF modes, signal strength uncertainties at level of 17-28% depending on the production mode
- Estimated significances:

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}H$</th>
<th>WH</th>
<th>ZH</th>
<th>VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>8.2</td>
<td>4.2</td>
<td>3.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

High significance for $t\bar{t}H$

CMS expects 4/8% (inclusive) signal strength precision for Scenario 2/1
Study based on 8 TeV samples:
- Includes emulation of expected performance degradation:
  - $E_T^{\text{miss}}$, $b$-tagging, jet-energy resolution all an issue
- Divide events according to number of jets (0,1,2): study ggF and VBF modes (below)
- Select $e\mu$ / $\mu e$ only, to reduce backgrounds: final selection on transverse mass $m_T$
- VBF analysis updated in 2015 for $\mu=200$, three ATLAS scoping scenarios

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

ATLAS anticipates combined signal strength sensitivity of $\sim 10\%$
CMS projects signal-strength sensitivity of $4/7\%$ in Scenario 2/1
Associated Production: $H \rightarrow b\bar{b}$

- $(W/Z)H$ with leptonic final states can be used to investigate $H \rightarrow b\bar{b}$
  - Leptons needed for triggering
- ATLAS: 18 signal categories according to $p_T^V$, the number jets, $b$-jets, leptons
- Analysis validated by comparison with 8 TeV data

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Stat-only} & \text{Significance} & \text{One-lepton} & \text{Two-lepton} & \text{One+ Two-lepton} \\
\text{\quad \mu}_{\text{Stat}} & \text{error} & 15.4 & 11.3 & 19.1 \\
\hline
\text{Theory-only} & \text{\mu}_{\text{Theory}} & +0.07 - 0.06 & +0.09 - 0.09 & +0.05 - 0.05 \\
\text{\quad error} & & & & \\
\hline
\text{Scenario I} & \text{Significance} & 2.7 & 8.4 & 8.8 \\
\text{\mu}_{\text{w/Theory}} & \text{error} & +0.37 - 0.36 & +0.15 - 0.15 & +0.14 - 0.14 \\
\text{\mu}_{\text{w/Theory}} & \text{error} & +0.36 - 0.36 & +0.14 - 0.12 & +0.12 - 0.12 \\
\hline
\text{Scenario II} & \text{Significance} & 4.7 & & 9.6 \\
\text{\mu}_{\text{w/Theory}} & \text{error} & +0.23 - 0.22 & & +0.13 - 0.13 \\
\text{\mu}_{\text{w/Theory}} & \text{error} & +0.21 - 0.21 & & +0.11 - 0.11 \\
\hline
\end{array}
\]

- Anticipate combined 8.8σ observation and 14% precision on signal strength
- CMS projects precision of 5/8% on the signal strength in Scenario 2/1

ATL-PUB-2014-011
VBF $H \rightarrow \tau\tau$

- VBF for background suppression
- Need effective suppression of PU in forward region and good $E_T^{miss}$ resolution:
  - both are strong motivations for high-$|\eta|$ tracker extension
- ATLAS study extrapolates from Run-1 BDT analysis: $\ell\tau_{had}$ final states, $\mu=140$
  - Also investigate performance improvements from increased tracker acceptance
  - Expect uncertainty on signal strength of about 8% for tracker coverage out to $|\eta|=4.0$

CMS projects 5/8% precision on the signal strength in Scenario 2/1.
Access to second generation fermion couplings via $H \rightarrow \mu\mu$

Good mass resolution: can contribute to precision mass measurement
  - Resolution depends on upgrade scenario (as shown here for CMS):
    - Improvements due to better spatial hit resolution and reduced material

CMS projection for precision on coupling updated to 5% in 2015

ATLAS: expect $\sim20\%$ measurement of signal strength, $7\sigma$ significance
  - ATLAS results do not take advantage of tracker extension to higher $|\eta|$|\eta|
  - ATLAS has also investigated $ttH$, $H \rightarrow \mu\mu$
    - Gives access to product of top, $\mu$ Yukawa couplings
    - Expect 33 signal events over 22 background
Other rare decays

- Other rare decay modes investigated:
  - $H \to Z\gamma$
    - via loops so sensitive to possible heavy new states

ATLAS projects:
- combined ($ee/\mu\mu$) significance of $3.9\sigma$
- Signal strength uncertainty of $\sim 30\%$, dominated by statistics.

CMS projects:
- Signal strength uncertainty of $20/24\%$ in Scenario 2/1.

- $H \to (J/\psi)\gamma$ (would give access to 2nd generation quarks)

Only limits anticipated

<table>
<thead>
<tr>
<th>Expected $\sigma \times \mathcal{B}$ limit at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \to H) \times \mathcal{B}(H \to J/\psi\gamma)$ [fb]</td>
</tr>
<tr>
<td>$300 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>10.4$^{+2.9}_{-4.5}$</td>
</tr>
<tr>
<td>$3000 \text{ fb}^{-1}$</td>
</tr>
</tbody>
</table>

ATL-PHYS-PUB-2015-043
Signal Strengths & Couplings

- Couplings extracted from simultaneous fit to signal strength measurements. For coupling ratios:
  - No assumptions about total width
  - Cancellation of some experimental & systematic uncertainties
  - Couplings vs. mass: current uncertainties can be reduced to the few-% level with 3000 fb⁻¹

Assuming the SM

ATL-PHYS-PUB-2014-016

For CMS see

arXiv:1307.7135
HH Production

- Di-Higgs (HH) production relevant to investigations of Higgs trilinear coupling $\lambda_{HHH}$. Dominant production (~90%) via ggF.

- Destructive interference: $\lambda_{HHH} = \lambda_{SM}^{HHH}$ yields near-minimal cross-section
  - minimum is at $\lambda_{HHH} / \lambda_{SM}^{HHH} = 2.44$
  - $\lambda_{HHH} = 0$ increases cross-section by ~ factor of 2

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
<th>Total Yield (3000 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b} + b\bar{b}$</td>
<td>33%</td>
<td>$4.1 \times 10^4$</td>
</tr>
<tr>
<td>$b\bar{b} + W^+W^-$</td>
<td>25%</td>
<td>$3.1 \times 10^4$</td>
</tr>
<tr>
<td>$b\bar{b} + \tau^+\tau^-$</td>
<td>7.4%</td>
<td>$9.0 \times 10^3$</td>
</tr>
<tr>
<td>$W^+W^- + \tau^+\tau^-$</td>
<td>5.4%</td>
<td>$6.6 \times 10^3$</td>
</tr>
<tr>
<td>$ZZ + b\bar{b}$</td>
<td>3.1%</td>
<td>$3.8 \times 10^3$</td>
</tr>
<tr>
<td>$ZZ + W^+W^-$</td>
<td>1.2%</td>
<td>$1.4 \times 10^3$</td>
</tr>
<tr>
<td>$\gamma\gamma + b\bar{b}$</td>
<td>0.3%</td>
<td>$3.3 \times 10^2$</td>
</tr>
<tr>
<td>$\gamma\gamma + \gamma\gamma$</td>
<td>0.0010%</td>
<td>1</td>
</tr>
</tbody>
</table>

Studied in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states by both ATLAS & CMS.

CMS has additionally studied $b\bar{b}(WW \rightarrow l\nu l\nu)$

ATLAS has studied RS $G_{KK}^+ \rightarrow hh$. 

P.Krieger, Toronto  
LCHP 2016, Lund, Sweden, June17, 2016
Di-Higgs Production in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ Final States

- $m_{\gamma\gamma}$ distribution narrow, while $m_{bb}$ is broad: 2D fit (CMS) or cut & count (ATLAS)

\[ \lambda_{HHH}/\lambda_{HHH}^{SM} \leq -1.3 \text{ or } \geq 8.7 \]

Expected significances:

**ATLAS**: 1.3σ  
**CMS**: 1.6σ

ATLAS projects exclusion regions for non-SM trilinear coupling:

- CMS: $\tau_+ \tau_- \mu$  
- ATLAS: $\tau_+ \tau_- \mu$, $\tau_+ \tau_- \ell$, $\tau_+ \tau_- \ell$, $\ell = e, \mu$

**ATLAS**: 0.6σ  
**CMS**: 0.9σ

ATLAS projects exclusion regions for non-SM trilinear coupling:

\[ \lambda_{HHH}/\lambda_{HHH}^{SM} \leq -1.4 \text{ or } \geq 12 \]
Vector Boson Scattering (VBS)

- Sensitive to EWSB mechanism:
  - In SM, $\sigma(V_L V_L \to V_L V_L)$ unitarized by the Higgs boson
  - Strong and EW-only contributions:
    - Same sign $VV$ best channel: cross-section not dominated by strong component
    - $W^\pm W^\pm + 2$ jets $\to \ell^\pm \ell^\pm + E_T^{\text{miss}} + jj$: Signal selection based on $m_{jj}$ and $|\Delta \eta_{jj}|$
    - Evidence for EW production from Run-1 (ATLAS: 30% uncertainty on $\sigma_{EW}$)
- Prospects for HL-LHC: ATLAS (WW), CMS (WW,WZ)
  - Sensitive to performance improvements from increased tracker acceptance:
    - Increased lepton acceptance, PU suppression
    - For WW, expect $\sim5\%$ measurement of $\sigma_{EW}$ from each experiment

Sensitivity to models in which Higgs only partially responsibly for unitarizing $\sigma(V_L V_L \to V_L V_L)$
Precision SM Measurements: $B_s^0 / B^0 \to \mu^+\mu^-$

- Decay $B_s^0 / B^0 \to \mu^+\mu^-$ highly suppressed in SM
  - CMS measured $Br(B_s^0 \to \mu^+\mu^-) = 3.0 \pm^{+1.0}_{-0.9} \times 10^{-9}$ consistent with SM prediction
  - Branching ratio for $B^0 \to \mu^+\mu^-$ predicted to be lower by a factor of 30
  - CMS+LHCb combined results:
    \[
    Br(B_s^0 \to \mu^+\mu^-) = 2.8 \pm^{+0.7}_{-0.6} \times 10^{-9} \quad (6.2\sigma)
    \]
    \[
    Br(B^0 \to \mu^+\mu^-) = 3.9 \pm^{+1.6}_{-1.4} \times 10^{-10} \quad (3.2\sigma)
    \]
  - $Br(B_s^0 \to \mu^+\mu^-)$ will be precisely measured at the HL-LHC
  - $Br(B^0 \to \mu^+\mu^-)$ should be well measured with expected significance of 6.9σ

ATLAS measures lower values:
arXiv:1604.04263
Top Quark: Mass, Rare Decays

- Searches for FCNC via $t \rightarrow Zq$ : SM predicts $BR(t \rightarrow Zq) \approx \mathcal{O}(10^{-14})$
  - Can be $\mathcal{O}(10^{-4})$ in some BSM models:
    - Current CMS limit $5 \times 10^{-4}$ (9 $\times$ $10^{-4}$ expected)
    - CMS Projects 95% CL limit for 3000 fb$^{-1}$: $1 \times 10^{-4}$

- Top quark mass determination: CMS has investigated expected precision on the top quark mass for a number of techniques. Expect $\sim$ 200 MeV precision for 3000 fb$^{-1}$ (with standard methods)

<table>
<thead>
<tr>
<th>Center-of-mass energy</th>
<th>Current 7 TeV</th>
<th>13 TeV</th>
<th>Future 14 TeV</th>
<th>14 TeV</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Integrated luminosity</td>
<td>5 fb$^{-1}$</td>
<td>30 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
<td>3000 fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Fit calibration</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>MC statistics</td>
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<tr>
<td>b-JES</td>
<td>0.61</td>
<td>0.27</td>
<td>0.09</td>
<td>0.03</td>
<td>3D fit</td>
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<tr>
<td>Residual JES</td>
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<td>0.28</td>
<td>0.2</td>
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<td>differential</td>
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<tr>
<td>Lepton energy scale</td>
<td>0.02</td>
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<td>0.02</td>
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<td>unchanged</td>
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<td>Missing transverse momentum</td>
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<td>0.06</td>
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<td>Jet energy resolution</td>
<td>0.23</td>
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<td>0.2</td>
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<td>b tagging</td>
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<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>factor 2 (data)</td>
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<td>Pileup</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
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<td>Non-tt background</td>
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<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>factor 2 (S/B)</td>
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<tr>
<td>Parton distribution functions</td>
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<td>0.04</td>
<td>0.04</td>
<td>factor 2 (PDF fits)</td>
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<tr>
<td>Renormalization and factorization scales</td>
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<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
<td>full NLO + differential</td>
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<td>ME-P5 matching threshold</td>
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<td>0.09</td>
<td>0.09</td>
<td>0.06</td>
<td>full NLO + differential</td>
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<tr>
<td>Total</td>
<td>1.07</td>
<td>0.62</td>
<td>0.44</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• Detector design, physics & performance studies well advanced and continuing:

  ![Diagram showing timeline from European Strategy 2012 to Detector Scoping 2015]

• Preparations in progress for ECFA HL-LHC 2016 (3-6 Oct, Aix-Les-Bains):
  – Performance updates planned (reference upgrade detectors + options)
• Many existing performance studies not optimized for higher energy and $\mathcal{L}$
• Most are also not fully optimized to take advantage of detector upgrade features
• Detector design and associated performance studies will continue to evolve