ATLAS physics prospect at the HL-LHC

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4-15 July 2016

Chania, Greece
Outline

1. Higgs Sector and SM Physics
   - Higgs couplings, rare Higgs decay, VBS, HH

2. Supersymmetry
   - Electroweak channels

3. Exotics
   - Dark matter, EFT
**HL-LHC: 3000 fb⁻¹ at a center-of-mass energy equal to 14 TeV**

\[
<\mu_{PU}> \approx 140 \quad \Rightarrow \quad 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}
\]

\[
<\mu_{PU}> \approx 200 \quad \Rightarrow \quad 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}
\]

multiple interaction in the same bunch crossing
Detector upgrade

- Planned system upgrades to cope with the increase of luminosity
  - Radiation damage on some subsystems of the present detector
  - Replacement of the Inner Detector (ITK)
  - Trigger redesign
  - Muon upgrade: increase coverage, trigger improvement
  - Considering new high-granularity forward calorimeter + timing detector

- Guide line: achieve same or better performances as in Run 1

- Pile-up mitigation essential element for the design
  - Tracking information in L1 trigger
  - Tracking coverage up to $|\eta| \approx 4$
    - Reference scenario: $|\eta| < 4.0$
    - Middle scenario: $|\eta| < 3.2$
    - Low scenario: $|\eta| < 2.7$
Complete understanding of the challenges of operation at $\langle \mu_{PU} \rangle \sim 140-200$

- The performance of physics objects has been studied with full simulation MC events in the pile up conditions of HL-LHC
- Results have been parametrized with **smearing functions**
- MC samples with generator level information have been processed applying these smearing functions

Unless specified, the analysis presented are made with $\langle \mu_{PU} \rangle = 140$
Higgs Sector and SM Physics

What's Next?
Mass: $125.09 \pm 0.21\text{(stat.)} \pm 0.11\text{(syst.)} \text{ GeV}$

Signal strength $\mu$: $1.09^{+0.11}_{-0.10}$

$J^P$ consistent with $0^+$

Precision measurement Higgs couplings need more statistics

Rare decays

Precision tests are needed in order to confirm that the Higgs mechanism is the responsible of the EWKSB and discover possible deviations from SM theory
### Production and decay mode considered in the study:

<table>
<thead>
<tr>
<th>Production Mode</th>
<th>$H \rightarrow \gamma \gamma$</th>
<th>$H \rightarrow ZZ$</th>
<th>$H \rightarrow WW$</th>
<th>$H \rightarrow \tau \tau$</th>
<th>$H \rightarrow bb$</th>
<th>$H \rightarrow Z \gamma$</th>
<th>$H \rightarrow \mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>$VBF$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>$VH$</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$ttH$</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

→ $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4l$ Higgs decays from $ttH$ production mode, particularly important for probing top-quark Yukawa coupling

→ $H \rightarrow \mu \mu$ second generation charged lepton coupling
High purity signal

Analysis presented here do not account for tracker extension
- preliminary study: main improvement comes from the trigger upgrade

<table>
<thead>
<tr>
<th>Production modes</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>3800</td>
</tr>
<tr>
<td>VBF</td>
<td>97</td>
</tr>
<tr>
<td>WH</td>
<td>67</td>
</tr>
<tr>
<td>ttH</td>
<td>35</td>
</tr>
<tr>
<td>ZH</td>
<td>5.7</td>
</tr>
</tbody>
</table>
• Framework to look for deviations from the SM: disentangle deviations in production and decay with explicit modeling of Higgs width

• Introduce one scalar factor $k$ per SM particle with ‘observable’ Higgs coupling

• Assumptions:
  - Only one Higgs
  - Width of the Higgs boson is narrow

$$\frac{\sigma_i \cdot \Gamma_{ff}}{\Gamma_H}$$

rate for a given channel

production x-sec via initial state $i$

decay width into final state $ff$

Higgs total width
• Framework to look for deviations from the SM: disentangle deviations in production and decay with explicit modeling of Higgs width

• Introduce one scalar factor $k$ per SM particle with ‘observable’ Higgs coupling

• Assumptions:
  - Only one Higgs
  - Width of the Higgs boson is narrow

\[
(\sigma \cdot BR)(i \to H \to f f) = \frac{\sigma_i \cdot \Gamma_{ff}}{\Gamma_H}
\]

production x-sec via initial state $i$

rate for a given channel

decay width into final state $ff$

Higgs total width

absolute

ratios
Assumption on the total width allows **absolute** coupling scale factors to be extracted

- No BSM Higgs decay modes assumed

\[
\begin{align*}
\Gamma_i &\sim k_i^2 \Gamma_i^{SM} \\
\sigma_i &\sim k_i^2 \sigma_i^{SM} \\
\Gamma_H &= \sum_i k_i^2 \Gamma_i^{SM}
\end{align*}
\]

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

Combined fit to determine the Higgs boson scale factors

<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_\tau)</th>
<th>(\kappa_{Z\gamma})</th>
<th>(\kappa_{\mu\mu})</th>
</tr>
</thead>
<tbody>
<tr>
<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>
<td>[7, 8]</td>
</tr>
</tbody>
</table>

At HL-LHC, couplings can be determined with ATLAS with 4-14% precision.
**Higgs coupling ratio**

Most generic model:

- **No assumption on the total width:** only coupling ratios can be measured

\[
\lambda_{XY} = \kappa_X / \kappa_Y
\]

- Systematic uncertainties partly cancel in ratios

- **2~3% precision reachable in some channel if syst. unc. controlled**

- **HL-LHC yields a factor 2~3 improvement in coupling ratio determination**
Study of the potential improvement due to extend tracking:

- **Reference scenario**: $|\eta| < 4.0$
- **Middle scenario**: $|\eta| < 3.2$
- **Low scenario**: $|\eta| < 2.7$

![Distinctive - two high energetic jets in the final state](image.png)

<table>
<thead>
<tr>
<th>Scoping scenario</th>
<th>VBF + 2j events</th>
<th>ggF + 2j events</th>
<th>$qqZZ + 2j$ events</th>
<th>$Z_0$</th>
<th>$\Delta \mu/\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>192 (168)</td>
<td>287 (140)</td>
<td>39 (16)</td>
<td>10.2</td>
<td>0.152</td>
</tr>
<tr>
<td>Middle</td>
<td>218 (167)</td>
<td>454 (155)</td>
<td>69 (15)</td>
<td>9.5</td>
<td>0.157</td>
</tr>
<tr>
<td>Low</td>
<td>259 (159)</td>
<td>803 (182)</td>
<td>124 (21)</td>
<td>8.6</td>
<td>0.165</td>
</tr>
</tbody>
</table>

Improvement in both discrimination between VBF and ggF (MVA) and in pile up rejection thanks to tracking extension

- Expected significance $Z_0$ reduced by 4% (14%) from Reference to Middle (Low) scenario
- Rel. uncertainty on the signal strength increases by 3% (9%) from Reference to Middle (Low) scenario
One of the strongest points of the HL-LHC physics program:

- **Direct study of the coupling to second generation leptons**
- **Test lepton non-universality in the Higgs boson sector**
- **~20% accuracy in signal strength measurement**
- **$7\sigma$ significance expectation**
- **Can improve with tracker extension - not yet studied**
Higgs trilinear self-coupling $\lambda_{HHH}$ probe

Several BSM processes expect much larger rate than the SM predictions

SM = destructive interference

<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>

Results can be improved by combining as many other channels as possible

NNLO $\sigma^{\text{SM}} = 40.8$ fb
Higgs pair production

**H → bb, H → γγ**

- Expected significance: 1.3σ
- Exclusion regions

\[ \frac{\lambda_{HHHH}}{\lambda_{HHHH}^{SM}} \leq -1.3 \text{ or } \geq 8.7 \]

**H → bb, H → ττ**

- Expected significance: 0.6σ
- Exclusion regions

\[ \frac{\lambda_{HHHH}}{\lambda_{HHHH}^{SM}} \leq -4 \text{ or } \geq 12 \]
Supersymmetry
Still one of the most attractive framework

Stop, sbottom, gluino and higgsinos are light in natural models

EWK production benefits from the high luminosity

All the upgrade analyses presented here assume:

- R-parity conserving
- Simplified model (next slide)

May dominate the SUSY production at LHC if the masses of the gluinos and squarks are large
- Small number of sparticles, assumed BR - usually 100%
- Described by masses and cross sections
- Simple and broad approach for designing SUSY searches

Every point in the grid is a different signal model where the mass of the sparticles change.
The current searches have yielded sensitivity in few hundreds GeV mass range: their reach at HL-LHC is expected to significantly extend beyond these limits.
- DM produced in association with a jet $\rightarrow E_T^{\text{miss}} + \text{jet}$
- Physics described as a **point coupling** in Effective Field Theory (EFT) if the mass $M_{\text{med}}$ of the quark-DM interaction mediator is much larger than the typical momentum transfer
  
  - Allow comparison with direct measurement experiments
  - Strength of point couple determined by
    \[ M^* = M_{\text{med}} / \sqrt{g_{\text{SM}} g_{\text{DM}}} \]
  - Validity of EFT in discussion
    \[ Q_{tr} < M_{\text{med}} \]
    
    **Typical scale of interaction**
The discovery of the Higgs boson opens a new era in the LHC physics within and beyond the Standard Model.

Precision tests requiring high luminosity are needed in order to discover possible deviations from the Standard Model theory.

HL-LHC allows to measure Higgs coupling to a few percent precision and rare processes.

If new physics is found at the LHC, ATLAS at HL-LHC can measure its properties. If not, it will significantly increase the discovery reach in many signatures with small production cross sections.
• Sensitivity studies are carried out with 14 TeV Monte Carlo samples and by applying detector response corrections to generator level particles.

• Three detector layouts (Reference, Middle and Low) which correspond to three costing scenario and differs in both acceptance and performances.

• Discovery reach critically relies on the performance of the lepton trigger, lepton reconstruction, b-jet identification and missing transverse momentum reconstruction.
Unique window into the nature of the EWKSB

- VBS amplitude unitarized by the Higgs boson
- Many physics scenarios predict enhancement

WW-ewk offers clear signature of two same-sign leptons with two forward jets

- Final state comparable to QCD-induced processes
- Tracker extension increases the precision of the measurement

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$Z_{\sigma_B}$</th>
<th>$\Delta\sigma/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference scenario</td>
<td>11.3 ± 0.6</td>
<td>5.9%</td>
</tr>
<tr>
<td>Middle scenario</td>
<td>6.06 ± 0.3</td>
<td>11%</td>
</tr>
<tr>
<td>Low scenario</td>
<td>5.02 ± 0.2</td>
<td>13%</td>
</tr>
</tbody>
</table>
Many extensions of the SM predict new resonances

**Benchmark models**

- **Extradimension**: Kaluza Klein (KK) gluons decaying to a pair of top-antitop
  - $Z' \rightarrow e^+e^-$, $Z' \rightarrow \mu^+\mu^-$ offer clear signatures

- **Top color**: $Z'$ bosons decaying to top-antitop pairs

<table>
<thead>
<tr>
<th>model</th>
<th>mass reach [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{KK}$</td>
<td>6.7 (5.6)</td>
</tr>
<tr>
<td>$Z'_{\text{topcolor}}$</td>
<td>5.5 (3.2)</td>
</tr>
</tbody>
</table>

1lep  
2lep
Flavour changing neutral current (FCNC) — sign of new physics

- GIM suppression relaxed → coupling larger than SM (QS, FC-2HDM, MSSM)

SM \[ \text{BR}(t \to cH) = 3 \times 10^{-15} \]

BSM \[ \text{BR}(t \to cH) \sim 10^{-5} - 10^{-3} \]

Expected limit

\[ \text{BR}(t \to cH) = 1.5 \times 10^{-4} \]
ITK layouts

- Higgs sector and SM Physics
- Supersymmetry
- Exotic and FCNC

ATLAS ITk Simulation

- Extended 3.2
- Extended 4.0
- Inclined 4.0
- Fully Inclined 4.0

6-14 July 2016  ICNFP2016, Chania, Greece  stefania stucci, BNL
Efficiency to tag a jet of flavor $q$ as $b$-jet:

$$\varepsilon_q = \frac{\text{Number of jets of real flavor } q \text{ tagged as } b}{\text{Number of jets of real flavor } q}$$

$\varepsilon_{udsc}$ = mistagging rate

$r_{udsc} = 1/\varepsilon_{udsc}$ : light jet rejection