Physics prospects for high-luminosity LHC with ATLAS

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on behalf of the ATLAS collaboration
HL-LHC goals

Peak luminosity 5-7x10^{34} \text{cm}^{-2}\text{s}^{-1}

1.4x10^{34} \text{ in 2016}

L = 3000 fb^{-1}

Compared to the initial LHC goal 300 fb^{-1}

\sqrt{s} \rightarrow 14 \text{ TeV}

Currently we are at 13 TeV

• 3000 fb^{-1} is the target integrated luminosity
• 5x 10^{34} \rightarrow 140 \text{ Pil}e-up is the nominal peak luminosity
• 7x 10^{34} > 200 \text{ Pil}e-up is the ultimate peak luminosity (>LS 4)

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Currently we are at 13 TeV
HL-LHC implications

• x10 integrated luminosity : $1/\sqrt{n}$ stat uncertainties $\rightarrow \sim 1/3$
  • Exp. systematics may also go as $1/\sqrt{n}$
  • Theory uncertainties affect in various ways

• Higher precision measurements
• Access to rare processes (low cross-section x Br, low efficiency, ..)
• Access to higher mass objects not yet seen :
  • Lower cross-section -- small PDF for large parton collision energy
Higgs program at HL-LHC

Measurements include

- Higgs couplings
- Higgs self coupling
- Rare Higgs decays, incl. BSM
- Heavy Higgs searches

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \text{ TeV} \)
Projected accuracy of Higgs production rate measurements

Based on Run1 analysis

\( \mu = 140 \)

Additional contribution from theory uncertainty

HL-LHC

Higgs at HL-LHC

ATLAS Simulation Preliminary

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

- \( H \rightarrow \gamma \gamma \) (comb.)
- \( H \rightarrow ZZ \) (comb.)
- \( H \rightarrow WW \) (comb.)
- \( H \rightarrow Z\gamma \) (incl.)
- \( H \rightarrow b\bar{b} \) (comb.)
- \( H \rightarrow \tau\tau \) (VBF-like)
- \( H \rightarrow \mu\mu \) (comb.)

\[ 0, 0.2, 0.4 \]

\( \Delta \mu / \mu \)
Couplings relative to the SM values

\~5\% for W, Z
\~7\% for \( \mu \)
\~10\% for t, b, \( \tau \)
Higgs at HL-LHC

Higgs self-coupling

Measurement of Higgs pair production

\begin{align*}
\sigma(pp \to HH) &= \frac{1}{(4\pi)^2} (4\lambda_{HHH}^2 - 3\lambda_{HHH}^4)
\end{align*}

SM \sim 40 \text{ fb}
HH $\rightarrow$ bb $\gamma\gamma$ analysis

ATL-PHYS-PUB-2014-019

-1.3 < $\lambda/\lambda_{SM}$ < 8.7 95%CL
Look more decay modes: $\gamma\gamma bb$ (Br=0.3%), $\tau\tau bb$ (7%), $bbbb$ (33%), ....

bb bb analysis: large background from multijets, top, ...

ATL-PHYS-PUB-2016-024
Higgs contribution unitarises the cross-section

Look for same sign lepton pairs as the $W^+W^+$ scattering signal

$$2 \text{ Jets } + W^+W^+ \rightarrow 2 \text{ jets } + \ell^+\ell^+$$

8 TeV results

**ATLAS**
20.3 fb$^{-1}$, $\sqrt{s} = 8$ TeV

SM Prediction (NLO, POWHEG-BOX, CT11)

- $e^+e^+$: 0.4 ± 1.1 ± 0.4 fb
- $e^+\mu^+$: 1.5 ± 0.7 ± 0.3 fb
- $\mu^+\mu^+$: 1.9 ± 0.9 ± 0.2 fb
- Combined: 1.5 ± 0.5 ± 0.2 fb

**Measured cross-sections**

- $e^+e^*$
- $e^+\mu^+$
- $\mu^+\mu^*$
- Combined

Tracking and muon ID to $|\eta|=4.0$

Good pile-up rejection for forward jets.

3$^{rd}$ lepton veto.

Same tracking acceptance as now

**CERN-EP-2016-167**
Search for $t \rightarrow Zq$ and $t \rightarrow Hq$ in $tt$ events

- $t \rightarrow Zq \rightarrow llq$
- $t \rightarrow Wb \rightarrow l\nu b$
  
  3 leptons + b jet

- $t \rightarrow Hq \rightarrow bbq$
- $t \rightarrow Wb \rightarrow l\nu b$
  
  3 b jets, 1 lepton

$B(t \rightarrow Zq) < 2.4 - 5.8 \times 10^{-5}$ (FCNC modelling) at 95% CL

$B(t \rightarrow Hq) < 0.55 - 1.2 \times 10^{-4}$ (flavour of q) at 95% CL

ATL-PHYS-PUB-2016-019
Stop pair production

\[ p \rightarrow t \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

\[ 2 \text{ leptons} + 2 \text{ b-jets} + \text{MET} + \text{ISR jet} \]

\[ m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 173 \text{ GeV} \]

Cross-section limit vs \( m_t \)

\[ > 5\sigma \text{ sensitivity} \]

\[ \text{ATL-PHYS-PUB-2016-022} \]

17.12.2016

Tatsuo Kawamoto

~200 GeV gain on \( m_t \) reach
Recent ATLAS HL-LHC studies include:

<table>
<thead>
<tr>
<th>Process</th>
<th>Report Number</th>
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</thead>
<tbody>
<tr>
<td>$HH \rightarrow \tau\tau + bb$</td>
<td>ATL-PHYS-PUB-2015-046</td>
</tr>
<tr>
<td>$tt , HH$</td>
<td>ATL-PHYS-PUB-2016-023</td>
</tr>
<tr>
<td>$VBF , H \rightarrow WW$</td>
<td>ATL-PHYS-PUB-2016-018</td>
</tr>
<tr>
<td>Direct stau production</td>
<td>ATL-PHYS-PUB-2016-021</td>
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<tr>
<td>Dijet resonance</td>
<td>ATL-PHYS-PUB-2015-004</td>
</tr>
<tr>
<td>Off-shell H couplings with 4-leptons</td>
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</table>
The Challenge of Pile-up

Ø Instantaneous luminosity of 5 (7) to an average pile-up of 140 (200)

Simulated pile-up in ATLAS detector

Run 1
Pile-up = 23

Need to maintain the low lumi performance or even improve

HL-LHC
Pile-up = 230
ATLAS upgrade

Higher rate, longer latency Trigger

New all silicon Inner tracker

New front-end electronics

After and in front of Endcap calo.: Forward muon tagger
High granularity timing detector

New inner endcap Muon chamber
New inner barrel muon trigger chamber
Trigger + DAQ

Very simplified illustration

Now

Muon Calo

μ e, γ, jets, MET, τ,…

Level-1
Hardware processors

Muon Calo

μ e, γ, jets, MET, τ,…

Level-0
Hardware processors

100 kHz
Latency 2.5 μs

1 MHz
Latency 10 μs

Data readout

Event Filter
Computer farm

FTK:
High speed
Track rec. processor

Data reading

Level-1
Hardware processors

400 kHz

Data readout

Level-0 only scheme
Also considered

Higher trigger rate
Higher data recording rate/volume
Better selectivity

HL-HLC upgrade
1 of the proposed schemes

Data recording
Tracking

Inner tracker will be completely replaced with new all silicon tracker (ITk)

- Higher granularity
- Extended coverage to high $\eta$ (2.5 $\rightarrow$ 4.0)
- Increased radiation hardness
- Reduced material

One of the proposed layouts (inclined pixel)

```
ATLAS Simulation Internal
Inclined
```

Tracking efficiency

```
ATLAS Simulation Preliminary
$\sqrt{s} = 14$ TeV
```

Pile up jet rejection by requiring tracks from PV

```
ATLAS Simulation
$p_T > 30$ GeV, $\mu = 200$, $\varepsilon_{PU} = 2\%$
```

- No Track Conf
- Reference
- Middle
- Low
LAr and Tile detectors will remain

- Upgrade all readout and trigger electronics
- Possible addition of new high granularity precision timing detector in front of endcap calo
LAr electronics

- Phase-1 (LS2) : upgrade of Level-1 trigger electronics
  - x10 increase of granularity $\rightarrow$ e/γ, jet separation $\rightarrow$ maintain E threshold

- Phase-2 : upgrade of readout electronics
  - Digitize and send data to backend at 40 MHz
  - High bandwidth optical links
Muon spectrometer

- Upgrades for tracking and trigger performance
- New electronics to make compatible with the new Trigger+DAQ of higher rate
New small wheels

New inner endcap muon station

- Installed in 2019-2020 (LS2) in preparation for $L = 2-3 \times 10^{34} \text{ cm}^2\text{s}^{-1}$ (Phase-1 upgrade)
- Precision tracking (existing MDTs will not work at high luminosity)
- Trigger improvement
  - Reduction of fake muon trigger
  - Sharpening of $p_T$ threshold combined with other phase-2 muon upgrade

Combination of precision wire chambers (sTGC) and Micromegas
New inner barrel trigger chamber

• Rate limitation of existing RPSs.
• Risk of ageing, possibly need to reduce gas gain, i.e. efficiency.
• With 4 layers available → higher redundancy, acceptance and efficiency
• Acceptance increase at the cost of low $p_T$ resolution → MDT trigger

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Use of MDT for L0 trigger

- MDTs are everywhere
- Replacement of FE electronics with all new FE
- Confirmation of $p_T$ by RPC trigger
Conclusions

- Many physics opportunities become possible with HL-LHC
  - including many topics not touched in this talk
- HL-LHC is a very challenging environment
- Major detector upgrades being planned
  - TDRs in next 1-2 years
- Big challenges are also for computing
- Upgraded detectors will perform as good as the current detector at highest pile-up environment and will do even better in some areas
- Analyses will also improve for better sensitivity
Backup
Triggering multi jets with low $p_T$ threshold would be difficult at High luminosity: pile up

Higher threshold
⇒ equivalent to lower L

e.g. 30 GeV (current) ⇒ 75 GeV:

3000 fb$^{-1}$ ⇒ ~1000 fb$^{-1}$

• Trigger challenge
• Analysis improvements
• Reduction of systematics
Physics projection to HL-LHC

Detector performance: two ways, depending on analysis, as appropriate

- Generator level particles smeared with parametrised detector performance
  - Parametrisation based on full HL-LHC detector simulation
  - Pile-up effects considered for either 140 or 200 pp collisions per crossing

- Extrapolation of Run-1, Run-2 analysis
  - Scaling of numbers of signal and background events
  - Assuming the same event selection, analyses
  - Assuming the same detector performance

Systematics

- Experimental systematics
  - Not easy to forecast: best estimate/guess for luminosity evolution
- Theory systematics
  - Quote results with and without theory uncertainties.
ATLAS upgrade

Calorimeters

Muon spectrometer

Inner tracker
Where we are now (2016)

- The Higgs boson has been discovered in 2012 at LHC
- Study of the nature of the particle

Where we are now (2016)

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Where we are now (2016)

Signals of new physics searched for

Testing the SM processes

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<th>$W^+W^-$</th>
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*Only a selection of the available SM limits to new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

1 Small radius (large radius) jets are denoted by the letter $j_1$.