ATLAS Detector Upgrade Prospects

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Outline

★ Introduction

★ Detector upgrades
  - Trigger and data acquisition system
  - Muon detector
  - Tracking
  - Calorimeter

★ Physics prospects
  - Physics performance of physics objects
  - Higgs measurements
  - Standard Model studies
  - Beyond Standard Model searches

★ Conclusions and Outlook
LHC has had a successful Run2 so far, with good operation and many physics results published with the newly recorded data by all experiments (ATLAS results in particular were presented by S. Smirnov in the previous talk).

In order to maximize the physics output of this unique facility, major upgrades of the machine and of the detectors are planned to start after Run2 to increase the nominal luminosity by up to a factor of 7.5, aiming to deliver 3000 fb$^{-1}$.

The aim of the detector upgrades is to achieve a similar or better performance than with the current design, even in the presence of high pileup rates.
During LS2, the upgrade of several detector systems is foreseen and it will function as a foundation for the HL-LHC upgrades: the upgrades of the calorimeter trigger system and of the associated LAr trigger electronics, the New Small Wheel (NSW) and the Fast TracKer trigger (FTK).

Many studies and possible detector designs were published for the HL-LHC upgrade, the most recent being the Scoping Document (LHCC-G-166) and the notes for this year's workshop of the European Committee for Future Accelerators (ECFA)

The proposals for each subdetector's design are analysed and the impact on the physics potential is assessed through detailed studies using parametrizations of the expected detector performance.

The main changes foreseen for the detector upgrade are: new all-silicon tracker, new muon trigger chambers, complete upgrade of readout electronics, higher trigger rate and readout capabilities

The upgraded detector should be able to give a similar or better performance to the one of the current detector setup, in conditions of very high pileup rates (from ~24 in Run 2 to ~200 in HL-LHC)
Trigger and Data Acquisition System

☆ The current ATLAS detector electronics was designed to buffer data for a maximal latency of \(2.5 \, \mu s\) and cope with Level-1 trigger rates up to \(100 \, \text{kHz}\).

☆ For Phase-II Upgrade, **Level-0 trigger** will be introduced to accommodate latencies less than \(6 \, \mu s\) and rates up to \(1 \, \text{MHz}\), with the L1 rates going up to \(400 \, \text{kHz}\).

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**Detector electronics** (ITk, Tile, LAr, MS)

- **L0** (6/10 \(\mu s\))
  - (1 MHz)
- **L1** (30/60 \(\mu s\))
  - (400 kHz)
- **L1 Accept/Region of Interest**

☆ **L0 trigger** will have two components: L0 Muon Triggers and L0 Calorimeter Triggers.

☆ **L0 Muon Triggers** will have an efficiency in the barrel region of 92%-96% and the local polar angle \(\beta\) can be used to reduce the trigger rate by up to 50% with minimal losses in efficiency.

☆ **L0 calorimeter triggers** will reuse the system installed as part of the Phase-I ATLAS upgrade and will be adapted for the Phase-II ATLAS upgrade.

☆ **L0 calorimeter triggers** will be based on feature extractor processors with very fine granularity covering the areas \(|\eta| < 2.5\) for electrons, photons and taus, \(|\eta| < 4.9\) for jets and allowing an entire event to be processed in a single module.
Trigger and Data Acquisition System

**L1Track** will use hits from ITk strips and pixels to find tracks within Regions of Interest (RoI) which are seeded by L0 triggers – $p_T$ of the tracks used for the templates will be restricted to $p_T > 4$ GeV.

**L1Track** has the largest impact on electron identification and on pileup rejection for multi-object events.

**L1Global** is a time-multiplexed trigger system receiving input from the LAr and Tile Calorimeters, from L0 and from L1Track, with the calorimeter data being transmitted to it with a latency of 1-2 μs after the L0 decision.

The central trigger processors (CTP), **L0 CTP** and **L1 CTP**, will ensure that L1Track and L1Global do not overflow.

The data from the detector will be transferred to the readout system, Front-End Link Interface eXchange (**FELIX**), then to a network which will pass it to the event filter and to the monitoring and calibration processors.

The ATLAS event size is expected to increase from the current 1.5 MB to approximately 5 MB, leading to a trigger rate a factor of 4 larger than today.

The expected recording rate will be **5-10 kHz**, leading to output rates of **1-2.2 kHz** each for electrons with $p_T > 22$ GeV and for muons with $p_T > 20$ GeV.
Muon Spectrometer (MS)

- 44m
- 25m

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Semiconductor tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
Muon Spectrometer

☆ **Phase-I upgrade:** the detectors of the inner layer in $1.3 < |\eta| < 2.7$ will be replaced by an additional layer of **Resistive Plate Chambers (RPC)**, small-strip **Thin Gap Chambers (sTGC)** and **MicroMegas (MM)** detectors.

☆ **Phase-II upgrade:** replacement of the whole readout electronics in order to be able to cope with the larger rates expected.

☆ **Current Monitored Drift Tubes (MDT)** chambers can safely operate in most of the MS during the HL-LHC period.

- *exception:* the higher rates in the end-cap inner layer (EI), which will be addressed by the installation of the **New Small Wheel (NSW)**

- new small MDTs will replace some of the current ones to make space for the additional RPCs

☆ **A new type of TGC** will be installed in the EI to improve the accuracy of the muon track $\theta$ angle measurement, during Phase-I.
Introduction  Detector Upgrades  Physics Prospects  Conclusions

Muon Spectrometer

Upgrades foreseen for LS2

Upgrades foreseen for LS3

Unchanged
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Muon Spectrometer

- A new layer of RPC will be added to improve the performance of the inner barrel stations of the MS - the efficiency of the barrel triggers will be ~95%
- A muon tagger for the high $\eta$ region will be added to extend the inner tracker capabilities
- New paths and methods are studied to reduce the trigger rates and improve the reconstruction of the tracks
- The current power supplies will also be replaced during Phase-II, to cope with the large radiation doses foreseen

Rate study for single muon trigger with 20 GeV threshold based on Run 1 data, 8 TeV, 25 ns bunch spacing
Introduction   Detector Upgrades   Physics Prospects   Conclusions

Tracker

25m

44m

Muon chambers

Toroid magnets

Solenoid magnet

Transition radiation tracker

Semiconductor tracker

Pixel detector

LAr electromagnetic calorimeters

LAr hadronic end-cap and forward calorimeters

Tile calorimeters
The **Internal Tracker (ITk)** for the Phase-II Upgrade will be an all-silicon tracker.

The eta coverage up to $|\eta| = 4.0$ is under study.

ITk will have two components: **Pixel** and **Strip**.

Two designs studied for the Pixel detector: **Extended** and **Inclined**.

The **Pixel** barrel design is divided into an insertable 2-layer inner barrel, surrounded by a fixed outer barrel.

- the insertable part is necessary in order to ensure high performance for the entire 3000 $\text{fb}^{-1}$, as it may necessitate replacement due to radiation damage.
The *Strip* detector of the ITk is situated just outside the Pixel detector

- It consists of four double-sided barrels and six strip discs in each of the two forward regions

- For a mean pileup of 200 and at the smallest radius of the pixel detector, each of the front-end readout chips will be producing data at a rate of ~5 Gb/s.

  - R&D is in progress for solutions for cables and configurations for such large data transmission volumes and rates

- Due to the large increase in the number of both strip (from 4,088 to 20,000) and pixel modules (from 1,744 to 10,000), the powering scheme needs to be changed with respect to the current Inner Detector's

  - groups of modules will share the same low voltage and high voltage supplies
Calorimeters

The Liquid Argon (LAr) calorimeter, the Scintillating Tile hadronic barrel detectors (TileCal) and the Hadronic End-cap Calorimeter (HEC) maintain their required performance under HL-LHC conditions and will not be replaced.

A new High Granularity Timing Detector (HGTD) is an option considered to be added in front of the LAr end-caps to allow a mitigation of pileup effects in the forward and end-cap regions.

The readout electronics of the LAr and the TileCal need to be exchanged due to limited radiation tolerance and the necessary upgrade in the trigger chain.

During Phase-I upgrade additional electronics will be installed to ensure finer granularity signals for the L1 calorimeter trigger, and the paths will then be used in the new trigger scheme of Phase-II upgrade.
Physics Objects Performance: Introduction

The main areas of interest in the physics programme of the HL-LHC are:
→ Higgs boson measurements of its properties, production and decay modes
→ Standard Model precision measurements and the study of rare processes
→ searches for phenomena beyond Standard Model

The performance of the upgraded detector is assessed using events generated at 14 TeV from several Standard Model processes, including $Z \rightarrow ll$, $t\bar{t}$bar and vector boson fusion production of the Higgs boson $H \rightarrow \gamma \gamma$.

Minimum-bias pileup events are overlaid on the hard scatter events of interest, this information being used to reconstruct the physics objects.

The response of the detector is simulated by
→ smearing $p_T$ and energy of the reconstructed physics objects using smearing functions
→ applying reconstruction efficiencies for the objects

Trigger response is also emulated by applying trigger efficiency functions.
Physics Objects Performance: Tracking

The large $\eta$ extension of the tracker has a significant impact on the identification of physics objects and on pileup mitigation.

- most visible contributions are in the area of jets and missing $E_T$ performance.

The latest tracking performance study used ttbar and minimum bias samples.

- very good tracking efficiency across full acceptance
- non-primary and fake tracks are under control
- excellent impact parameter resolution
  - $d_0$: $<30$ μm in $|\eta|<3.5$ and $<50$ μm in $|\eta|<4$ for $p_T = 10$ GeV muons
  - $z_0$: $<300$ μm in $|\eta|<3.5$ and $<450$ μm in $|\eta|<4$ for $p_T = 10$ GeV muons
- excellent $p_T$ resolution

Although the performance of the 'Inclined' layout is usually shown as representative, no conclusion was yet reached about the choice of layout.
Physics Objects Performance: Tracking

ATLAS Simulation Preliminary

Efficiency

Region $p_T > 1$ GeV, $<\mu> = 200$

$\sqrt{s} = 14$ TeV

$N_{\text{rec}}/N_{\text{true}}$

Region $p_T > 1$ GeV, $<\mu> = 200$

$\sqrt{s} = 14$ TeV

ATLAS Preliminary Simulation

Single muons, $\mu = 0$

$\sigma(d_0) [\mu m]$

$\sigma(z_0) [\mu m]$

$\sigma(d_0) [\mu m]$

$\sigma(z_0) [\mu m]$
The performance of primary vertex finding is studied using samples of $t\bar{t}$, $Z \rightarrow \mu\mu$ and $H \rightarrow \gamma\gamma$ events with $\mu = 200$

The vertexing performance does not depend strongly on the layout, but on the process

→ exception: the identification efficiency

→ good overall vertexing performance
Physics Objects Performance: Electrons

- Re-optimized electron identification in the context of a different detector configuration
- Main backgrounds: photon conversions and jet-fakes
  - charge misidentification rate from $Z \rightarrow ee$: *(0.026±0.013)%*
  - identification efficiency is estimated to be around 70% (compared to 85% in Run2)

- Pileup affecting only the resolution of low $p_T$ electrons
- The forward electron performance still needs to be optimised for the new detector
Physics Objects Performance: Photons

☆ Photon identification studied using calorimeter-based variables only

☆ Cutting $E_T < 6$ GeV in a radius of 0.2 around the photon leads to a good isolation and to an efficiency of over 95%

☆ The mean combined efficiency is around 70%

☆ Average combined fake rates of $7 \times 10^{-5}$ and $8 \times 10^{-4}$ for the pileup and hard scatter jets, respectively
Upgrades of the MS are not expected to change significantly the reconstruction performance but improvements are foreseen in the resolution for combined (ITk+MS) muons and in the large $\eta$ region.

New studies of the muon performance are available, using the full ITk simulation instead of the parametrised resolution.
Physics Objects Performance: Jets

- For 2% pile up survival probability we have ~75%, 80% and 85% efficiency for the hard scatter jets, depending on the η region.

- Different algorithms investigated for pileup mitigation at cluster level.

- Large impact of the pileup on jet reconstruction.

\[\text{JETM-2016-012}\]
Tracking extension improves the $E_T^{\text{miss}}$ resolution

→ Applying $R_{pT} > 0.1$ to all jets improves the $E_T^{\text{miss}}$ resolution significantly

$$R_{pT} = \sum_{i \in PV0} \frac{P_{T}^{\text{track,}i}}{P_{T}^{\text{jet}}}$$
Physics Objects Performance: Flavour Tagging

- b-tagging studied using a ttbar sample with at least one semileptonic top decay
- Jet $p_T > 20$ GeV, $|\eta| < 2.7$
- b-jet defined as jets matched to b-quark from top quark decay only (i.e. hard scattered b-quark)
- The performance is estimated to be similar to the one of the Inner Detector in Run2 conditions
- Considering a working point of 70% average b-tagging efficiency, the mistag rate is 0.1-1%, c-jet efficiency 10-25% and b-jet efficiency 40-80%
ATLAS presented comprehensive results for Higgs bosons couplings at HL-LHC at the ECFA workshop in 2014.
The subsequent studies concentrated on the impact of various detector designs on the precision Higgs boson measurements and on the study of the rare Higgs boson processes.
# Higgs Production and Rare Processes

<table>
<thead>
<tr>
<th>Channel</th>
<th>Result</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to J/\Psi \gamma$</td>
<td>$\text{BR} &lt; 44 \times 10^{-6} \ @ 95% \ CL$ (pileup 140)</td>
<td>ATL-PHYS-PUB-2015-043</td>
</tr>
<tr>
<td>off shell $H \to ZZ \to 4l$</td>
<td>$\Delta \mu/\mu \approx 50%$ (pileup 140)</td>
<td>ATL-PHYS-PUB-2015-024</td>
</tr>
<tr>
<td>VBF $H \to W^+ W^-$</td>
<td>$\Delta \mu/\mu \approx 14$ to $20%$ (pileup 140 and 200)</td>
<td>ATL-PHYS-PUB-2016-018</td>
</tr>
<tr>
<td>VBF $H \to ZZ \to 4l$</td>
<td>$\Delta \mu/\mu \approx 15$ to $18%$ (pileup 140 and 200)</td>
<td>ATL-PHYS-PUB-2016-008</td>
</tr>
<tr>
<td>$HH\to b\ b\ \tau\ \tau$</td>
<td>$0.6 \sigma$ (pileup 140)</td>
<td>ATL-PHYS-PUB-2015-046</td>
</tr>
<tr>
<td>$HH\to bbbb$</td>
<td>$0.4 \sigma$ (pileup 200)</td>
<td>ATL-PHYS-PUB-2016-024</td>
</tr>
<tr>
<td>$ttHH, HH\to bbbb$</td>
<td>$0.35 \sigma$ (pileup 200)</td>
<td>ATL-PHYS-PUB-2016-023</td>
</tr>
</tbody>
</table>
Higgs Production and Rare Processes: HH → bbbb

Estimates of the sensitivity for 3000 fb$^{-1}$ are based on the extrapolation of the results obtained using the 2016 dataset of 10.1 fb$^{-1}$ proton-proton collision events at 13 TeV

**Selection**: at least 4 b-tagged jets with $p_T > 30$ GeV and $|\eta| < 2.5$

**Reach**: In the absence of any signal and without (with) systematics, cross-sections 1.5 times (5.2 times) greater than the SM prediction are excluded at the 95% confidence level

Higher $p_T$ thresholds investigated – positive impact on the reach
Higgs Production and Rare Processes: ttHH production

Study using 14 GeV simulated events, with ttbar decaying semileptonically and HH → bbbb
- important for measuring the HHH coupling

Selection: cut-based, at least 7 jets with $p_T > 30$ GeV and $|\eta| < 4.0$, with at least 5 or 6 b-tagged jets among them, exactly 1 electron or muon

Results: statistical significance of the ttHH production will not exceed 0.35 $\sigma$
SM studies will be able to reach unprecedented precision

Studies published so far for HL-LHC
→ $W^\pm W^\pm$ and $WZ$ scattering
→ Flavour changing neutral currents (FCNC) analyses

$W^\pm Vjj \rightarrow l^\pm + \text{hadrons} + \text{tag jets} + E_T^{\text{miss}}$

$V (W,Z)$ decaying hadronically and reconstructed as 2 jets or 1 large-R jet

Interpret as limit on anomalous quartic gauge couplings

Benefits from the tracker extension in the forward region

<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>$11.3 \pm 0.6$</td>
<td>5.9%</td>
</tr>
<tr>
<td>Middle scenario</td>
<td>$6.06 \pm 0.3$</td>
<td>11%</td>
</tr>
<tr>
<td>Low scenario</td>
<td>$5.02 \pm 0.2$</td>
<td>13%</td>
</tr>
</tbody>
</table>
Standard Model: Top Measurements

**FCNC analyses:** top quark → Zq trilepton
top quark → Hq

★ **Selection (tZq):** three leptons, one OSSF in Z-mass window
≥1 b-jet, ≥1 non-b-jet
★ Sensitivity increases by a factor of 2 to 6 (depending on channel and scenario)

★ **Selection (tHq):** several topologies with different numbers of b-jets and non-b-jets
★ Sensitivity increases by a factor of 20

![ATLAS Simulation](image1)

![ATLAS Simulation](image2)
**Beyond Standard Model Searches**

New result for ECFA 2016: **compressed top squark pair production** \( (\Delta(m_{\tilde{t} - m_{N1}}) \approx m_{\text{top}}) \)

**Selection:** 2 central leptons (electrons, muons) having \( p_T > 25 \text{ GeV} \), at least 2 central b-jets with \( R=0.4 \) and \( p_T > 30 \text{ GeV} \)

**Reach:** discovery potential up to top squark masses of 480 GeV and exclusion potential for top squark masses of 700 GeV for 3000 fb\(^{-1}\)

<table>
<thead>
<tr>
<th>SR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Standard Model</td>
<td>13.8 ± 6.5</td>
</tr>
<tr>
<td>( \tilde{t})</td>
<td>11.4 ± 5.1</td>
</tr>
<tr>
<td>( \tilde{t}\tilde{t} + Z)</td>
<td>2.4 ± 1.5</td>
</tr>
<tr>
<td>Others</td>
<td>0.0±1.8</td>
</tr>
</tbody>
</table>

\( \tilde{t}_1 \tilde{t}_1 \) \( m(\tilde{t}_1, \chi_1^0) \) = (350, 177) GeV
\( \tilde{t}_1 \tilde{t}_1 \) \( m(\tilde{t}_1, \chi_1^0) \) = (700, 527) GeV

\[ m_{\tilde{t}_1} - m_{\chi_1} = 173 \text{ GeV} \]

**ATLAS Preliminary Simulation**
\( \sqrt{s}=14 \text{ TeV} , \ L = 3000 \text{ fb}^{-1} , \ \mu=200 \)

**Expected production**
- \( \tilde{t}\tilde{t} \) production
- \( m_{\tilde{t}_1} = 300 \text{ GeV} \), \( m_{\tilde{t}_2} = 700 \text{ GeV} \)

**Expected limits**
- \( 95\% \text{ CL} \)
- \( 95\% \text{ CL} \) with 300 fb\(^{-1}\)

**ATL-PHYS-PUB-2016-022**
Beyond Standard Model Searches

New result for ECFA 2016: search for direct stau production

Selection: 2 hadronically decaying central taus with $p_T > 20$ GeV, centrally produced electrons and muons with $p_T > 10$ GeV, jets with R=0.4 and $p_T > 50$ GeV

Reach: - discovery potential between 100 and 500 GeV stau mass (depending on the model)
- exclusion potential: 540-700 GeV stau mass (depending on the model)

<table>
<thead>
<tr>
<th>SM process</th>
<th>Event yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>$1.91 \pm 0.19$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.97 \pm 0.23$</td>
</tr>
<tr>
<td>Z+jets</td>
<td>$0.009 \pm 0.009$</td>
</tr>
<tr>
<td>diboson</td>
<td>$0.03 \pm 0.02$</td>
</tr>
<tr>
<td>SM total</td>
<td>$2.9 \pm 0.3$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$, $\mu = 200$

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

$\tilde{\tau}, \tilde{\chi}_1^0, \tilde{\chi}_2^0$
Beyond Standard Model Searches

New result for ECFA 2016: dijet resonance searches

**Benchmark models**: - excited u and d quarks  
- quantum black holes (QBH)

**Selection**: two leading jets within the rapidity interval $|y| < 2.8$, $p_T$(next-to-leading jet) > 50 GeV, $0.5|y_1-y_2| < 0.6$, $m_{jj} \geq 1.5$ TeV

**Reach**: - exclusion potential: excited quarks with masses up to 8 TeV and QBH with masses up to 10 TeV
- discovery potential: already from the first 100 pb$^{-1}$ of data for excited quarks with masses of 4 TeV and QBH with masses up to 8.2 TeV
Updated detector designs and performance studies are published for ECFA 2016

Technical design reports are expected for most of the detector subsystems in 2016-2017

Pileup mitigation is one of the largest concerns for HL-LHC runs and many new or alternative strategies and designs are being studied to address it

The performance of the physics objects is expected to improve due to the extension of the tracker in the large $\eta$ region, new trigger strategy, new and updated electronics for most of the detector subsystems

Good progress is recorded in the Higgs physics studies, with many results published since ECFA 2014, concentrating mostly on rare processes

FCNC studies become more attractive with the higher statistics available

Beyond Standard Model searches will benefit from the upgrade to extend discovery and exclusion potential
BACKUP
Data Acquisition Scheme Layout

[Diagram showing the layout of data acquisition components with labels such as ITK, Tile, LAr, L0 Trig, L1 Trig, Barrel RPC, Barrel MDT, Endcap TGC, Endcap MDT, NSW, Readout, EFPUs, FTK++, SFO, and connections with GBT/Custom and Commodity.]
In the Scoping Document there are three possible detector configurations discussed: Reference, Middle and Low.

Each of them is constrained by a specific budget and are designed such that the physics performance is maximized in conditions of very high pile-up rates.

While the studies made for this year's ECFA workshop assumed a configuration similar to the Reference scenario, no definitive decision is yet reached for the final design of the detector for the HL-LHC runs.

<table>
<thead>
<tr>
<th>System</th>
<th>Reference</th>
<th>Middle</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter trigger (e/γ)</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 4.0$</td>
</tr>
<tr>
<td>Pixel detector</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 4.0$</td>
</tr>
<tr>
<td>Very forward muon tagger</td>
<td>$2.6 &lt;</td>
<td>\eta</td>
<td>&lt; 4.0$</td>
</tr>
</tbody>
</table>