ATLAS Upgrades Towards the High Luminosity LHC:
Extending the Discovery Potential

Diane Cinca, University of Glasgow
on behalf of the ATLAS collaboration

DIS 2014 - Warsaw
Before data-taking, expected in-time pileup (PU) was 23 (25ns BS (bunch spacing), design luminosity).

In 2012, average PU was regularly over 30 (50ns BS)

**Inner Detector:**
- High reconstruction efficiency
- Vertex reconstruction performing well

**e/γ performances:**
- Electron energy response and photon conversion reconstruction show excellent stability versus increasing pileup.

**Jet/\text{E}_\text{T}^{\text{Miss}} performances:**
- \text{E}_\text{T}^{\text{Miss}} reconstruction is performing well
- Stable resolution performances

**Particle Identification:**
- Identification efficiency is robust against pileup

**DAQ and trigger:**
- Developed algorithms are robust against pileup
- 21.7 fb$^{-1}$ recorded by ATLAS (94% DAQ efficiency)
Motivation for an upgrade

“Europe’s top priority should be exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.”

* Higgs boson precision measurements:
  * Expected uncertainties on signal strength reduced by a factor of 2-3 with HL-LHC.
  * Ratio of partial widths to measure ratios of couplings and probe New Physics.
  * SM Higgs rare decays and processes, e.g. $H \rightarrow \mu\mu$, and $ttH$ can be measured.

* Higgs self-coupling in SM accessible only at HL-LHC.

* Probing New Physics:
  * SUSY and other New Physics beyond SM.
  * Enhancements in vector boson scattering amplitudes.
  * Rare processes, e.g. FCNC decays from top accessible to $10^{-5}$.  

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The challenge

- Higher instantaneous luminosity means that more protons will collide in one event:
  - Pileup could reach up to 200 collisions per event.
  - Increased occupancy and saturation of available data transmission bandwidth.
  - Triggers rates cannot increase in line with luminosity so greater selectivity required to preserve efficiency.

- Higher integrated luminosity means higher total particle flux through detector:
  - Increased radiation damage (especially in inner layers).
  - Increased activation of the materials.

- The goal is to achieve the same (or better) performances (resolution, ...) at HL-LHC as at LHC, despite the large increase of event rate.
LHC roadmap

LHC startup, $\sqrt{s} = 900$ GeV

$\sqrt{s} = 7+8$ TeV, $L \sim 6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 50ns

Go to design energy, nominal luminosity - Phase 0

$\sqrt{s} = 13-14$ TeV, $L \sim 1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

Now!

Injector + LHC Phase I upgrade to ultimate design luminosity

$\sqrt{s} = 14$ TeV, $L \sim 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

HL-LHC Phase II upgrade: Interaction Region, crab cavities?

$\sqrt{s} = 14$ TeV, $L \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, luminosity levelling

Run 1

$\sim 25 \text{ fb}^{-1}$

Run 2

$\sim 75-100 \text{ fb}^{-1}$

Run 3

$\sim 350 \text{ fb}^{-1}$

$\sim 3000 \text{ fb}^{-1}$

From LHCC Open meeting, 03.12.2013

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LHC roadmap

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2012
$\sqrt{s} = 13$–14 TeV, $L \sim 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$, bunch spacing 25ns

2013
LS1

2014
Injector + LHC Phase I upgrade to ultimate design luminosity

2015
Run 1
$\sim 25$ fb$^{-1}$

2016
Run 2
$\sim 75$–100 fb$^{-1}$

2017
Run 3
$\sim 350$ fb$^{-1}$

2018
LS2

2019
2020
2021
2022
2023
LS3

2024
HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2025
$\sqrt{s} = 14$ TeV, $L \sim 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, luminosity levelling

2026
...

2035?

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2015
HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2016
$\sqrt{s} = 14$ TeV, $L \sim 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, luminosity levelling

Run 1
~25 fb$^{-1}$

Run 2
~75-100 fb$^{-1}$

Run 3
~350 fb$^{-1}$

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Ongoing: Phase 0

* Long Shutdown 1: duration 18 months

* **LHC upgrades:**
  * Run 2 (2015-2018): $\sqrt{s}=13-14$ TeV, $L=1.10^{34}$ cm$^{-2}$s$^{-1}$, $<\mu>=27$, @ 25ns (start at 50ns), $-75-100$ fb$^{-1}$ expected
  * Consolidation of superconducting circuits
  * Replace/repair superconducting splices for 13 TeV energy and nominal peak luminosity

* **ATLAS upgrades:**
  * Insertion of an additional 4th pixel layer: Insertable B-Layer (IBL), Diamond Beam Monitor (DBM)
  * Completion of Muon Spectrometer Chambers added to improve acceptance for $1.0 <|\eta|< 1.3$ (Endcap Extension (EE) Muon Chambers)
  * New Pixel Service Quarter Panels (nSQP)
  * Usage of outer most layer of Tile Calorimeter for L1 Muon trigger

* **ATLAS consolidation:**
  * New Al/Be beam pipe
  * New evaporative Inner Detector cooling plant
  * New Low Voltage Power Supplies for the calorimeters
  * Power network, magnet cryogenics, services
Phase 0: Insertable B Layer (IBL)

* Physics motivations:
  * From $L = 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ b-tagging efficiency will start to degrade.
  * Robust tracking in case of failures in the current pixel system.
  * Improves impact parameter resolution, vertexing, $\tau$-reconstruction at high pileup.
  * Replace beam pipe.

* Insertable B-Layer (IBL)
  Additional pixel layer as innermost tracking layer
  * Important ingredient for low mass, rad-hard construction: 2 cm x 2 cm FE-I4 Pixel Chip, 130 nm CMOS process.
  * Sensors: planar pixel sensors and 3D.
  * Installation of IBL in the pixel detector, in the pit: May 2014.
  * Will stay until Phase-II (~7 years).

- Reduced material budget: 0.015 $X_0$
- Coverage: $z = 60 \text{cm}, |\eta| < 2.5$
- Sensors @33mm (now@50.5mm) => smaller beam pipe (29 -> 25mm)
- 14 staves with phi overlap
- No eta overlap due to clearance => minimize modules edge
Phase 0: Muon chambers

* Endcap Extension (EE) Muon Chambers
  * Installation of the chambers to address low efficiency in the region $1.0 < |\eta| < 1.3$
  * Need to bring Muon Small Wheel (9m diameter) on the surface out of the way of the IBL
  * New shielding at 7m: gap between forward calorimeter and shielding disk
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- **2018**: Injector + LHC Phase I upgrade to ultimate design luminosity
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- **2023**: HL-LHC Phase II upgrade: Interaction Region, crab cavities?
- **2035?**: $\sqrt{s} = 14$ TeV, $L \sim 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, luminosity levelling

From LHCC Open meeting, 03.12.2013
ATLAS upgrades - Phase 1

  * Run 3 (2020-2022): $\sqrt{s}=14$ TeV, $L=3.10^{34}$ cm$^{-2}$s$^{-1}$, $<\mu>-50-80$, @ 25 ns, $-300$ fb$^{-1}$ expected
  * Consolidation of injection chain, collimators

* **ATLAS upgrades:**
  * Fast Track Trigger at “Level 1.5”
  * Higher granularity and precision in L1 Trigger for calorimeter
  * New Small Wheels for the forward muon spectrometer
  * Topological (multi-object) L1 Trigger processors
  * Central Trigger Processor (CTP) upgrades
  * ATLAS Forward Physics (AFP), proton det. at ±210 m

Phase-I Upgrades should be forward compatible with Phase-II

In 2013, 4 TDRs for Phase-I construction projects were prepared within ATLAS, approved by CB and endorsed at the LHCC meeting (December 2013)
**Fast track trigger**

* Motivation: Track information at the start of Level 2.

* Dedicated, hardware-based track finder (based on CDF Silicon Vertex Triggering development)
  - Runs after the first level trigger on duplicated Si-detector read-out links
    Provides tracking input for the level-2 trigger for the full event
    * not feasible with software tracking at L2
    * Finds and fits tracks (~25 μs) in the ID silicon layers at an “offline precision”

* Processing performed in two steps:

**Diagram:**
- Hit pattern matching to pre-stored patterns (coarse)
- Subsequent linear fitting in FPGAs (precise)
**Motivation: maintain high efficiency for Level-1 triggering on low $P_T$ objects (electrons-photons)**

- The current Level 1 EM calorimeter trigger uses:
  - $E_T$ thresholds based on $\eta \times \phi = 0.1 \times 0.1$ trigger towers
  - No fine-grained EM sampling info available at L1 trigger to compute shower shapes

- LAr calorimeter Upgrade: changes on the front-end electronics to exploit finer granularity:
  - Computation of lateral and longitudinal shower shapes
  - Improve granularity of trigger for better discrimination between electrons and jets
  - Requires new trigger electronics located in replacement trigger daughter boards for the Front End boards.
New trigger readout architecture for LAr, forward and backward compatibility:

- On-detector: New layer sum and digitizer boards (LTDB)
- Off-detector: Digital Processing System (DPS) and Feature Extractor in L1Calo.

Better shower-shape discrimination:

- lower EM threshold by ~ 7 GeV at the same rate

In addition significantly improved resolution

- lower EM threshold by another few GeV at same rate
Consequences of luminosity rising beyond design values for forward muon wheels:
* Degradation of the tracking performance (efficiency / resolution)
* L1 muon trigger bandwidth exceeded unless thresholds are raised

Replace Muon Small Wheels with New Muon Small Wheels:
* Improved tracking and trigger capabilities
* Position resolution < 100 μm
* IP-pointing segment with $\sigma_0 \sim 1$ mrad
* Meets Phase-II requirements:
  * compatible with $\langle \mu \rangle = 200$, up to $L \sim 10^{34}$ cm$^{-2}$ s$^{-1}$
* Technology: MicroMegas and strip Thin Gap Chambers (sTGC)
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2020?

2021
From LHCC Open meeting, 03.12.2013
## Goals for HL-LHC

### Physics

| Study EWSB Mechanism          | Precision meas's of Higgs couplings (5-30%), Higgs self-coupling |
| Probe for signatures of New Physics | SUSY, Extra Dimensions, .... |
| Measure rare decay modes      | Higgs, B, top, .... |

### Detector Requirements

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<td>$H \rightarrow \tau\tau$</td>
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- Improved trigger inputs and algorithms and increased detector coverage
- New detector technologies required
ATLAS upgrades - HL-LHC

* **LHC (after LS3: duration - 30 months, 2023-2025)**
  * prepare for luminosity levelling
  * peak luminosity $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (levelled), considered up to $7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ ($<\mu>=200$) for safety, $\sim 3000 \text{ fb}^{-1}$ @ 14 TeV

* **ATLAS upgrades:**
  * All new Tracking Detector
  * Level-1 track trigger
  * Calorimeter electronics upgrades
  * Upgrade muon trigger system
  * Possible changes to the forward calorimeters
Inner TracKer (ITK)

Current Inner Detector - designed to operate for 10 years at $L=1.10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with $\langle \mu \rangle = 27$, $\sigma_{25\text{ns}}$, $L_1=100 \text{ kHz}$

* Limiting factors at HL-LHC ($L=5.10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $\langle \mu \rangle = 140$, $3000 \text{ fb}^{-1}$):
  * Bandwidth saturation (Pixels, SCT)
  * Increased occupancies (TRT, SCT) – up to 100% in TRT
  * Radiation damage (Pixels, SCT designed for 400 (700) fb$^{-1}$)

* Biggest changes compared to current tracker:
  * pixels system extends out to larger radii
  * more pixel hits in forward direction to improve tracking
  * smaller pixels and short inner strips to increase granularity
  * outer active radius slightly larger to improve momentum resolution
  * Remove Transition Radiation Tracker (TRT) as occupancy is too high during HL-LHC
  * Install new all-silicon tracker with pixels and strips
  * Granularity increases by a factor 4
L1 track trigger

* Adding tracking information at Level-1 (L1)
  * Move part of the “offline” High Level Trigger (HLT) reconstruction into the early stage of trigger
  * Goal: keep thresholds on pT of triggering leptons and L1 trigger rates low

* Triggering sequence
  * L0 trigger (Calo/Muon) reduces rate within ~6 μs to ≥ 500 kHz and defines RoIs
  * L1 track trigger extracts tracking info inside RoIs from detector FEs

* Challenge
  * Finish processing within the latency constraints

* Requires changes to detector FE electronics feeding trigger system
The ATLAS collaboration developed a detailed program to reflect the changes in the LHC conditions towards the HL-LHC, characterised by high track multiplicity and extreme fluences.

We aim at:

- maintaining/improving the present detector performance.
- ensuring optimal physics acceptance as the instantaneous luminosity increases.

The major ATLAS upgrades include:

**Phase 0**
- New Inner Pixel Layer
- Detector consolidation

**Phase 1**
- Improve L1 trigger capabilities to cope with higher rates
- Improve Muon system with nMSW

**Phase 2**
- Prepare for 200 pileup events
- Replace Inner Tracker
- New L0/L1 trigger scheme
- Upgrade muon/calorimeter electronics

An exciting new chapter is beginning!
ATLAS Forward Physics (AFP)

* Tag and measure scattered protons at +/- 210m
  * Link to system triggered in central ATLAS
  * Radiation-hard edgeless 3D silicon developed in IBL context
  * 10ps timing detector for association with high pT primary vertex
  * Probe hard diffractive physics and central exclusive production of heavy systems/particles
**New LHC schedule beyond LS1**

- **LS2**  
  Starting in 2018 (July)  
  18 months + 3 months BC (BC: Beam Commissioning)

- **LS3**  
  Starting in 2023  
  30 months + 3 BC

- **Injectors:** in 2024  
  13 months + 3 BC
Higgs rare process/Decay projections

Signals only accessible with 3000 fb⁻¹ with errors limited by statistics

**ttH production with H → γγ**
- Direct access to Higgs-top coupling.
- Today’s sensitivity (30 fb⁻¹): 6xSM cross-section
- With 3000 fb⁻¹: expect 200 signal events > 5σ
- Higgs-top coupling can be measured to about 10%

**H → μμ**
- Gives direct access to Higgs couplings to fermions of the second generation.
- Today: 8xSM cross section
- With 3000 fb⁻¹ expect 17000 signal events and 7 σ significance
- Higgs-muon coupling can be measured to about 10%
**Vector Boson Scattering**

- Not yet observed - test of Higgs role in cancelling VBS divergence in SM can be measured to 30% (10%) with 300 (3000) fb⁻¹
- If new physics exists: sensitivity to anomalous triple or quartic couplings increases by factor of ~ 2 between 300 and 3000 fb⁻¹
In Phase-I, $ZH \rightarrow vvbb$ with 160 GeV $E_T^{\text{miss}}$ trigger (XE40) would exceed total L1 rate due to pile-up jets faking missing energy.

- Increasing threshold rapidly costs signal efficiency.
- Combination with inclusive jet trigger brings rate down to ~10 kHz (still too high).
- L1Topo: cut on azimuthal distance between jet and $E_T^{\text{miss}}$ ($\Delta \phi > 1$) reduces rate by ~45% with negligible loss in signal efficiency.
- Radial distance ($\Delta R$) cut could be used to further reduce rate.

Example: exploit characteristic location of pile-up jets wrt $E_T^{\text{miss}}$ vector.
Higgs self-coupling measurement

- In order to determine the parameters of the SM completely, a measurement of the Higgs self-coupling is essential
  - Higgs potential and the EWSB mechanism
  - Measurement of double Higgs production
  - Destructive interference between diagrams with triple Higgs coupling and other diagrams

<table>
<thead>
<tr>
<th>$\sigma_{HH}$ (fb)</th>
<th>$\lambda$</th>
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<tbody>
<tr>
<td>71</td>
<td>$\lambda = 0$</td>
</tr>
<tr>
<td>34</td>
<td>$\lambda = \lambda_{SM}$</td>
</tr>
<tr>
<td>16</td>
<td>$\lambda = 2 \cdot \lambda_{SM}$</td>
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Double Higgs production yields

Event yields of various channels

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<th>Decay channel</th>
<th>Branching ratio (%)</th>
<th>Yield with 3 ab⁻¹</th>
</tr>
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<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>33.4</td>
<td>34,000</td>
</tr>
<tr>
<td>$b\bar{b}W^+W^-$</td>
<td>25.0</td>
<td>25,500</td>
</tr>
<tr>
<td>$b\bar{b}\tau\tau$</td>
<td>7.36</td>
<td>7,500</td>
</tr>
<tr>
<td>$W^+W^-W^+W^-$</td>
<td>4.66</td>
<td>4,750</td>
</tr>
<tr>
<td>$b\bar{b}ZZ$</td>
<td>3.09</td>
<td>3,150</td>
</tr>
<tr>
<td>$ZZW^+W^-$</td>
<td>1.15</td>
<td>1,170</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>0.26</td>
<td>265</td>
</tr>
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- Very challenging due to low yield and contributions from irreducible backgrounds ($t\bar{t}H, ZH$, etc.)
- **Ongoing studies suggest some sensitivity to constrain the triple Higgs coupling**
- Also, several phenomenological papers suggest this possibility
**Muon Trigger: Tile coincidence**

- Main source of fake triggers are low-momentum protons emanating from endcap toroid and shielding
- \(1.0 < |\eta| < 1.3\) region of Big Wheel TGC not covered by the NSW
- Use hadronic TileCal extended barrel (D-layer) for trigger coincidence
- Energy resolution smeared by electronics noise in Level-1 read-out path lowers efficiency above 500 MeV
- Tile Muon coincidence reduces rate by 82% at that threshold
**Trigger system architecture**

- New design for Phase II
  - 2-level system, Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Make use of improvements made in Phase 1 (NSW, L1Calo) in L0
  - Introduce precision muon and inner tracking information in L1
    - Better muon pT resolution
    - Track matching for electrons,…
  - Requires changes to detector FE electronics feeding trigger system

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**Level-0**
Rate ~ 500 kHz, Lat. ~6 µs
Muon + Calo

**Level-1**
Rate ~200 kHz, Lat. ~20 µs
Muon + Calo + Tracks

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FTK technique is candidate for L1Track trigger

Will also have new timing/control links and LHC interface system
ATLAS Silicon Strip tracker

* Outer tracker is a silicon strip detector with n-in-p sensors:
  * 5 barrel layers, 7 discs EC, “stubs”

* Double-sided layers with axial strip orientation and rotated by 40mrad on other side (z-coordinate)
  * Short (23.8 mm) and long strips (47.8 mm) with 74.5 μm pitch in barrel
  * End-Cap with radial strips of different pitch (6 different module designs)

* Silicon Modules directly bonded to a cooled carbon fibre plate.

* A sandwich construction for high structural rigidity with low mass.

* Services integrated into plate including power control and data transmission.