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

Peter Vankov, DESY
for the ATLAS Collaboration

Outline

- Motivation for ATLAS Upgrade(s)
- Timeline & Individual Sub-System Upgrades
  - Phase 0 (consolidation)
  - Phase 1
  - Phase 2 (HL-LHC)
- Summary

LHC 2012 pp run, $\sqrt{s}=8$ TeV

- Outstanding LHC performance, 23.3 fb$^{-1}$ delivered,
- Peak luminosity routinely over $7.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Excellent ATLAS performance, 21.7 fb$^{-1}$ recorded
  - ~94% data-taking efficiency
  - dominated by detector dead-time
- Main challenge: higher number of pile-up events ($<\mu>\sim 35$)

More about the ATLAS performance in I. Riu's talk

19.07.2013

Peter Vankov, EPS-HEP 2013, Stockholm
Motivation for ATLAS Upgrade

- European Strategy for Particle Physics:
  
  - "The discovery of the Higgs boson is the start of a major program of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program."
  
  - "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."

  Physics prospects with High-Luminosity LHC at ATLAS:

- Higgs measurements:
  - Higgs couplings (exp. precision 5-30%)
  - Higgs rare processes
    - H→μμ
    - ttH with H→γγ or H→μμ
  - Higgs self-coupling
    - HH→bbγγ, HH→bbττ

- Vector boson scattering
- BSM physics
  - High mass gauge bosons
  - tt resonances
  - SUSY, Extra dimensions
  - Quark and lepton substructure
  - Dark matter candidate, …

More in N. Konstantinidis’s talk

- HL-LHC environment is a great challenge to ATLAS. Upgrades are needed.
Foreseen schedule → as shown by CERN DG ('13)

- **Phase-0**
  - LHC startup, $\sqrt{s} = 900$ GeV
  - $\sqrt{s} = 7\sim 8$ TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
  - Go to design energy, nominal luminosity - Phase-0

- **Phase-1**
  - $\sqrt{s} = 13\sim 14$ TeV, $L = 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
  - Injector and LHC Phase-1 upgrade to ultimate design luminosity

- **Phase-2**
  - HL-LHC Phase-2 upgrade, IR, crab cavities?
  - $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity levelling

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

**Run II**
- ~75-100 fb$^{-1}$

**Run III**
- ~350 fb$^{-1}$

- ~3000 fb$^{-1}$
Upgrades of ATLAS sub-systems are planned in order to maintain or improve the present performance as the instantaneous luminosity increases. The upgrades are devised in three phases, following the LHC upgrade periods. The goal is to optimize the physics reach for each LHC run.

Detector challenges:

- Expected peak luminosity $\rightarrow$ from $1 \times 10^{34}$ to $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - higher particle fluxes, larger event sizes, higher trigger rate
  - improved triggers needed
- Multiple interactions per bunch crossing – "pileup" $\rightarrow$ up to $\mu=\langle 200 \rangle$
  - higher detector occupancy
  - readout limitations
  - increasing reconstruction complexity
- Increasing fluences $\rightarrow$ up to $10^{16}n_{eq}/cm^2$
  - close to beam pipe
  - increased radiation damage
  - increased activation of materials

ATLAS event with 200 pileup
ATLAS Phase-0 Upgrade

- **Phase-0 upgrade** (duration - 18 months, 2013-2014, during the LHC LS1) → Now!
  - Run II (2015): $\sqrt{s}=13-14$ TeV, $L\sim1\times10^{34}$ cm$^{-2}$s$^{-1}$, $<\mu>\sim23$, @ 25 ns, ~100 fb$^{-1}$ expected

- **Detector upgrade**
  - Insertion of an additional, 4$^{th}$ pixel layer (Insertable B-Layer, IBL)
  - New Pixel services (nSQP)
  - Completion of Muon Spectrometer
    - Chambers added to improve acceptance for $1.0<|\eta|<1.3$, the so called Endcap Extension (EE) Muon Chambers

- **Detector consolidation**
  - New evaporative cooling plant for the Si trackers (Pixel and SCT)
  - New, Al (forward region) and Be (central region) beam pipes
  - Replace all calorimeter Low Voltage Power Supplies
  - Add additional neutron shieldings (e.g. behind the endcap toroid)
  - Upgrade the magnets cryogenics and decouple toroid and solenoid cryogenics
ATLAS Phase-0: IBL

- Core activity of the ATLAS Phase-0 Upgrade: installation of a new, 4th pixel layer b/w the innermost Pixel (B-)layer and the beam pipe – the Insertable B-Layer, IBL
  - Smaller pixels (50x400 μm → 50x250 μm)
  - Technology: planner and 3D Si sensors
  - New readout chip (FE-I4 Pixel Chip in 130nm CMOS, 26880 channels)
- New Be beam pipe with smaller radius is foreseen, r = 29mm → 25 mm

- Compensate for defects in the existing B-layer
- Improves tracking, vertex resolution, secondary vertex finding, b-tagging, $\tau$-reconstruction at high pileup

More in Jens Dopke’s talk
ATLAS Phase-1 Upgrade

- **Phase-1 upgrade** (duration - 14 months, 2017-2018, during the LHC LS2)
- Run III (2018): $\sqrt{s}=14$ TeV, $L\sim 2-3\times 10^{34}$ cm$^{-2}$s$^{-1}$, $<\mu>=55-80$, @ 25 ns
- ~ 300 fb$^{-1}$ expected

- Detector upgrades
  - New Muon **Small Wheels (NSW)** for the forward muon spectrometer
  - Higher precision Level-1 calorimeter trigger (L1Calo)
    - New front-end readout interface for the LAr to exploit finer granularity
  - Fast TracK trigger (FTK) - input for Level-2
  - Topological (multi-object) trigger processors for Level-1
  - Central Trigger Processor (CTP) upgrades

- New project
  - New forward diffractive physics detectors at ± 210 m, **ATLAS Forward Physics (AFP)**

- All upgrades **compatible** with Phase-2

Phase-1 LoI: [https://cds.cern.ch/record/1402470?ln=en](https://cds.cern.ch/record/1402470?ln=en)
Consequences for the current fwd Muons (Small Wheels)

- Substantial degradation of the tracking performance, both in terms of efficiency and resolution for hit rates corresponding to luminosities greater than the design value.
- Rate of L1 muon triggers exceeds available bandwidth unless thresholds raised.

Replace Muon Small Wheels with New Muon Small Wheels with improved tracking and trigger capabilities.

- Composed of gas chambers of higher precision and robustness, assuring:
  - position resolution < 100 μm
  - reduction of fake triggers, 3x reduction of trigger rate for pt(μ)>20 GeV at Level-1, using IP-pointing segment in NSW (σθ~ 1 mrad)
  - higher rate capabilities (up to L~5x10^{34} cm^{-2}s^{-1})

Technology: MicroMegas and sTGCs

See the talks of M. Bianco and Y. Benhammou
ATLAS Phase-1: FTK

有效的触发在高亮度下非常具有挑战性，特别是在需要轨迹重建的触发中。

- **Fast TracK trigger (FTK)** - 一个专用的、硬件基础的轨迹查找器，作为L2的输入。
  - 在ID的硅层（包括IBL）中找到并拟合轨迹（约25 µs），对于通过L1的事件。
  - 处理过程分为两步：
    1. 粗略匹配到10^9预存储的模式（粗糙）。
    2. 在FPGA中进行精确线性拟合。
- 受到CDF硅顶点触发器（SVT）的启发。
- 重大改进用于b- tagging, tau ID, lepton isolation。

**ATLAS Trigger**

- **Level-1 (L1)**: 硬件基础 (~50 kHz)
- **Level-2 (L2)**: 软件基础，全粒度数据 (~5 kHz)
- **Event Filter**: 软件触发 (~500 Hz)

---

![Graphs showing efficiency, resolution, and muon p_T resolution](image-url)

*Muons*  
1.00 < p_T < 1.25 GeV
ATLAS Phase-2 (HL-LHC) Upgrade

- **Phase-2 upgrade** (duration ~ 18 months, 2022-2023, during the LHC LS3)
  - HL-LHC (~2023): $\sqrt{s}=14$ TeV, $L=5\times10^{34}$ cm$^{-2}$s$^{-1}$ (leveled), up to $L=7\times10^{34}$ cm$^{-2}$s$^{-1}$
  - $<\mu>=140$ (leveled), up to $<\mu>=200$

- Detector upgrades
  - All new Inner Detector → Inner Tracker (ITk)
  - Trigger upgrades
    - TDAQ upgrade
  - Implementation of L1 Track Trigger

- Calorimeter upgrades
  - New LAr, Tile and HEC readouts
  - Possible upgrade of FCal

- Muon system upgrades
  - Muon Barrel and Large Wheel trigger electronics
  - Possible upgrades of TGCs in Inner Big Wheels

- Software & Computing

Phase-2 LoI: [https://cds.cern.ch/record/1502664?ln=en](https://cds.cern.ch/record/1502664?ln=en)
Adding tracking information at Level-1 (L1)
- Move part of High Level Trigger (HLT) reconstruction into L1
- Goal: keep thresholds on pT of triggering leptons and L1 trigger rated low

Options considered:
- Region of Interest (RoI) based approach with L0 seeding necessary
- Standalone approach (subset of layers, layout important)
- Challenge: squeeze into existing latency

**ATLAS – ROI trigger**
Improve calo and muon trigger granularity (already in Phase 1)
→ New Level 0 trigger within 5 μs uses calorimeter and muon system to reduce the rate from 40 MHz to ≈ 500 kHz and define RoIs
→ Level1 extracts tracking for just RoIs from detector front-ends
Current Inner Detector (ID) - designed to operate for 10 years at $L=1\times10^{34}\, \text{cm}^{-2}\text{s}^{-1}$ with $<\mu>=23$, @25ns, $L_1=100\, \text{kHz}$

Limiting factors at HL-LHC
- Bandwidth saturation (Pixels, SCT)
- Increased occupancies (TRT, SCT)
- Radiation damage (Pixels (SCT) designed for 400 (700) fb$^{-1}$)

New Inner Tracker for HL-LHC (ITk)
- All-silicon tracker, no TRT
- Higher granularity
- Improved material budget
- Baseline: Layers of Si pixels and micro-strips

Baseline ITk Layout

Pixels (638M channels)
- 4 barrel layers + 6 fwd disks
- inner 2 layers replaceable: $25\, \mu\text{m} \times 150\, \mu\text{m}$
- outer Pixel: $50\, \mu\text{m} \times 150\, \mu\text{m}$
- sensors bump bonded to readout chip using 65nm CMOS

Strips (74M channels)
- 5 barrel layers + 7 fwd disks
- stub layer for overlap region
- 2 Si sensors at 40mrad

all silicon tracker, 14 hits
- robust tracking @ $<\mu>=140$ for $\eta<2.5$
<μ> = 23

Num. Hits vs η

Efficiency

100 GeV

Occupancy

<μ> = 140

b-tagging: ITk with <μ> = 140 better than ATLAS+IBL with <μ> = 0

Efficiency

5 GeV

X₀ vs η
LoI proposal: 7 disks per Si-strip end-cap
- Many different sensor sizes
- Strip length 8.1mm to 58.3mm
- 32 “petals” per disk
- 6 rings of sensors/radial strips

“Petalet” program underway
- Double-sided, six-sensor prototype
- Explore many options
- Prototypes sensors & hybrids available
- First modules produced successfully

Petalet

Castellated disks

Turbo fan arrangement
Alternative layouts being considered which include either a further pixel layer or inclined pixel sensor possibly attached to the same barrels.

**Alpine pixels**
- Uses the same stave for barrel and endcap modules
- No barrel-endcap transition region
- Less services material
- Simplified mechanical support
- Large reduction in sensor area

**Conical pixels**
- Uses bent staves on outer barrel pixels
- Improves hermeticity and material in transition region

**Very Forward pixels**
- Extends tracking to $|\eta| \sim 4$

**Optimize Si-strip barrels**
- Reconfigure layers in the strip detector
ATLAS collaboration has devised a detailed, 3-phase program to reflect the changes in the LHC conditions towards the HL-LHC, characterized by high track multiplicity and extreme fluences, with intention to:

- maintain/improve the present detector performance, ensuring optimal physics acceptance as the instantaneous luminosity increases

The foreseen, major ATLAS upgrades include:

- **Phase-0** (2013/2014 LHC shutdown)
  - Installation of a new, 4th pixel layer (IBL)
- **Phase-1** (2016/2017 LHC shutdown)
  - Installation of a New Muon Small Wheels
  - Fast Track Trigger
- **Phase-2** or HL-LHC (2022/23 LHC shutdown):
  - Inner Detector challenged by high radiation & occupancy
  - Build completely new all-silicon ID (pixel and strips)
  - Introducing L1 Track Trigger
  - Prepare the detector for HL-LHC and 8-10 more years
  - Further detector R&D is in progress
LHC: p-p collider

- Center of mass energy $\sqrt{s} = 7$ TeV
- $\sqrt{s} = 8$ TeV @ 2012
- $\sqrt{s} = 13-14$ TeV after 2013-2014
- Multi-purpose experiments: ATLAS and CMS
Higgs Prospects @ HL-LHC

- Higgs 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 at 5-15% level

- Higgs self-coupling in SM becomes accessible only at HL-LHC luminosity

- Self-interaction is a fundamental property of the SM Higgs
- Higgs pair production includes destructive interference between the two diagrams
- ATLAS HH→bbγγ yields ~2σ significance with 3000 fb⁻¹ (preliminary)
- Combining with HH→bbττ, + CMS, it is believed that it is possible to reach a 30% or 40% precision on λ
Rare Higgs Processes @ HL-LHC

- \( H \rightarrow \mu\mu \)
  - ATLAS expect \( >6\sigma \) significance with 3000 fb\(^{-1}\)

- \( ttH \) - allows precise measurement of top-Yukawa coupling
  - \( ttH, H \rightarrow \gamma\gamma \)
    - \( >100 \) signal events @ 3000 fb\(^{-1}\)
    - S/B \~\~20\%
  - \( ttH, H \rightarrow \mu\mu \)
    - Only \~30\ signal events but S/B\~1 with 3000 fb\(^{-1}\)

\( ttH, H \rightarrow \gamma\gamma \), 1-lepton final state
Allow bunches to meet “head on” even though the beams have a crossing angle
2 different sensor technologies:
- double chip (DC) modules with 2 FE-I4 and 1 planar n-in-n sensor tile
- single chip (SC) modules with 1 FE-I4 and 1 n-in-p 3D sensor tile

### Planar sensor vs 3D sensors

<table>
<thead>
<tr>
<th>Planar sensor</th>
<th>3D sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 μm thickness</td>
<td>230 μm thickness</td>
</tr>
<tr>
<td>inactive edge &lt;250 μm (minimize gaps in η, no overlap)</td>
<td>inactive edge 200 μm</td>
</tr>
<tr>
<td>low Q generated after irradiation → low threshold operation and high HV</td>
<td>low depletion voltage (&lt;180V) even after high doses</td>
</tr>
<tr>
<td>cheaper and easier to fabricate</td>
<td>electrode orientation suitable for highly inclined tracks</td>
</tr>
</tbody>
</table>

**FE-I4 chip** (16.8x20 mm²)
336x80 pixels (50μm x 250 μm)

75% planar, 25% 3D sensors (@ large η)
robust tracking in case of failures in the current pixel system
- from $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ b-tagging efficiency will start to degrade
- improves impact parameter resolution, vertexing, $\tau$-reconstruction at high pile-up

occupancy B layer (current innermost layer)

Light jet rejection

IBL

ATLAS

IP3D+SV1

Number of pileup interactions

Rejection at 60% b tagging efficiency

Double-hit Inefficiency
Busy/Waiting Inefficiency
Late Copying
Total Inefficiency

$1 \times 10^{34}$

$2 \times 10^{34}$
- nSQP will replace current Pixel services
  - opto-boards on the panels will be replaced with e-boards connected to new opto-boards outside the Pixel detector volume (easier access for optical link replacement)
- Also: repair of Pixel RO channels, redundant links, faster
- Diamond Beam Monitor attached to nSQP
  - uses diamond detectors produced for IBL trials
  - will provide very fast monitoring of beam in high rate environment
Endcap Extension (EE) Muon Chambers

- New shielding at 7m
- Gap between forward calorimeter and shielding disk
- Endcap Extension (EE) Muon Chambers
  - Finish installation of the EE muon chambers staged in 2003 + additional muon chambers in the feet (with new electronics) and elevators region
  - Addresses low efficiency in the region $1.0 < |\eta| < 1.3$

beam interaction hits (w and w/o shielding)
Precision chambers combine small-strip TGCs and MicroMegas technologies for robustness to Phase-II luminosities

- **sTGC** (small-strip Thin Gap Chambers): reduced cathode resistivity of 100kΩ/square → *rate capability has been increased* substantially up to 30kHz/cm²

- **MicroMegas** (MM)
  - MM consists of a planar drift electrode, a gas gap of a few mm thickness, acting as ionization and drift region, and a thin metallic mesh at ~100 μm distance from the read-out electrode, creating the gas amplification region
Diffractive Physics
- ATLAS Forward Proton (AFP) detectors
  - Tag and measure scattered protons at ± 210m
- Hardware
  - Radiation-hard edgeless 3D silicon developed in IBL context
  - 10ps timing Cerenkov detector for association with high pT primary vertex
  - Probe hard diffractive physics and central exclusive production of heavy particles

<table>
<thead>
<tr>
<th>Acceptance</th>
<th>Tagged proton momentum loss $\xi$</th>
<th>$0.02 &lt; \xi &lt; 0.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical di-photon mass acceptance</td>
<td>$300 &lt; \sqrt{(\xi_1 \xi_2)} &lt; 1200$ (GeV)</td>
</tr>
<tr>
<td>Si Tracker</td>
<td>Spatial Resolution</td>
<td>~ 15 µm</td>
</tr>
<tr>
<td></td>
<td>Angular Resolution</td>
<td>~ 1 µrad</td>
</tr>
<tr>
<td></td>
<td>Reconstructed Mass Resolution</td>
<td>~ 5 GeV</td>
</tr>
<tr>
<td>QUARTIC</td>
<td>Time resolution</td>
<td>&lt; 10 ps</td>
</tr>
</tbody>
</table>
Calorimeters

- EM and Hadronic Calorimeters require no upgrade
- full upgrade of FE and BE electronics for both Lar EM and Tile Hadronic:
  - radiation effects and expected flux will deteriorate their performance
- Hadronic EndCap calorimeter cold electronics designed for 1000 fb⁻¹
  - assuming safety factors → possible replacement

- Current Forward Calorimeter (3.2<|η|<4.9) not designed for L>10^{34} cm⁻²s⁻¹
  - space charge effects cause significant signal deterioration

**Option 0**
detector unchanged

**Option 1**
complete replacement of FCAL
smaller LAr gaps (to reduce ion build up /HV drop)
+ better cooling (to avoid overheating)

**Option 2**
installation small calorimeter in front of current Fcal: Mini-Fcal
→ reduce energy and ionization @ FCal