Performance of the ATLAS Tracking and Vertexing in the LHC Run-2 and Beyond

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Introduction

In this talk:

✦ Hardware overview with details on Insertable b-layer and its impact for tracking
✦ Software technicalities: The ATLAS approach, CPU reduction, plans for Run3
✦ Material measurements
✦ Time depending alignment
✦ Tracking performance: standard, inside Jets, heavy ions and large radius tracking.
✦ Vertex performance

ATLAS topics discussed in upcoming/passed talks:

✦ Lossless data compression for the HL-LHC silicon pixel detector readout by Stamatios Piulios (06/03/17, 18:15)

✦ The design and simulated performance of a fast Level 1 track trigger for the ATLAS High Luminosity Upgrade by Mikael Martensson (07/03/2017, 09:00)

✦ Improved AM chip pattern recognition with optimized ternary bit usage by Stefan Schmidt (07/03/2017, 11:30)

✦ Optimal use of charge information for HL-LHC pixel readout by Ben Nachman

✦ Expected Performance of ATLAS Inner Tracking at the High-Luminosity LHC by Nora Pettersson (08/03/17, 9:30)

✦ Identification of Jets Containing b-Hadrons with Recurrent Neural Networks at the ATLAS Experiment by Zihao Jiang (09/03/2017, 10:30)
The Inner Detector (ID)

- Reconstruction of charged particles with $|\eta| < 2.5$:
  - Input for many physics objects:
    - Electrons and muons
    - Jet substructure and jets mass resolution
    - B-tagging
    - Mitigate pileup effects by separating Primary Vertexes
  - New Insertable-B layer (IBL)
    - 6.02 M channels
    - Resolution: 8x40 $\mu$m (pixel size 50x250 $\mu$m)
  - Silicon Pixel detector (Pixel)
    - ~80M channels
    - Resolution: 10x115 $\mu$m (pixel size 50x400 $\mu$m)
  - Semiconductor tracker (SCT)
    - Silicon microstrips
    - 6M channels
    - Resolution: 17x580 $\mu$m
  - Transition Radiation Tracker (TRT)
    - 2mm radius drift tubes + Transition radiation
    - ~350k channels
    - Resolution ~130 $\mu$m
  - 2T axial B-field
ID Upgrades for Run 2

New insertable B-layer (IBL)
- Inner most additional pixel layer (4th) at radius 33 mm from the beam line
- New beampipe
- Preserve tracking with increased luminosity
- Improves vertexing, impact parameter resolution and b-tagging
- 14 staves overlapping in the r-φ plane of length 332 mm with 130nm CMOS modules with 2 technologies:
  - 12 planar and 2 x 4 3D modules

Done during Long Shutdown (2013-2015)

Pixel:
- New services, new optical links, 3% modules recovered.

TRT:
- Gas leaks for the end-caps repaired, new firmware to operate at 100kHz, validity gate, PID optimised

New Diamond Beam monitors (DBM) installed in the Pixel volume
Atlas Inner Detector Tracking

Hit preparation:

- **Pixel and SCT clustering**: finding connected cells (pixels/strips) on module via a connected component analysis
- **TRT Drift Circle creation**
Space point formation:

- Using the local cluster positions and sensor surface form 3D/2D space points
Space point seeding:

- Build triplets of seeds and evaluate their compatibility (To 4th layer or to Beam Spot)
- Road building for combinatorial Kalman filter
Atlas Inner Detector Tracking

✦ Track finding and ambiguity solving
  ✦ Resolve detector elements in a given road and start track candidate search based on space point seeds
  ✦ Precise least square fit with full geometry of the track candidates
  ✦ Tracks are ranked by an ambiguity solving

✦ Ambiguity solving
  ✦ Favour tracks with good fit quality and large number of hits
  ✦ Penalise tracks with holes or shared hits
  ✦ Tracks with highest score survive

Track parameters:

\[ t = (d_0, z_0, \eta, \phi, q/p) \]
Atlas Inner Detector Tracking

- Extend to the TRT
  - Progressive finder in a given road
  - Refit extended track
  - Use ambiguity to keep new or old track

Up to here this is the inside to outside tracking

ATLAS also performs outside to inside tracking:

- Hough transform in the TRT for pattern recognition with remaining hits
- Back-extrapolation to SCT and Pixel, only using unused hits
- Full global Chi2 fit
- This is only performed in regions of interest: EM Calorimeter clusters (conversions)
Some more details about SW

During Long Shut Down 1:

✦ Mayor campaign to clean and SPEED UP the code: 4x
✦ Use of EIGEN + code optimisation
✦ Simplified data model
✦ Pattern recognition fine tuned
✦ Tracking in dense environments

Upcoming Challenge:

✦ ID tracking should be fully thread safe for LHC run 3

A-Common-Tracking-SW (ACTS):

✦ Ambitious plan to externalise tracking code from ATLAS, so can be used by other groups/experiments as FCC: https://gitlab.cern.ch/acts/a-common-tracking-sw/

✦ Tracking geometry description which can be constructed from TGeo, DD4Hep or gdml input
✦ Simple and efficient event data model
✦ Performant and highly flexible algorithms for track propagation and fitting
✦ Basic seed finding algorithms
✦ Plenty of details in a dedicated talk: 09/03/17, 12:00

Q1/2017:
Now release 0.4 coming, with:
- TrackingGeometry building for ID like detectors
- Material mapping from Geant4 for the TrackingGeometry
- Extrapolation, Geometry digitization, Fitting (Kalman filter)

Q2/2017:
- Try to release the first release 1.0-beta around summer with the full demonstrator without pattern recognition
- Thread-friendly

Q3/2017 - Q4/2017
- First wrapping with ATLAS: make a fork of ATLAS and exchange everything after pattern recognition with ACTS
- In parallel, port the pattern recognition, but that will not be there before the end of the year
Measuring the ID material

Beam pipe material known to 1% precision

- **SCT extension Efficiency:**
  Material between SCT and Pixel

- **Photon conversions**
  Sensitive to radiation lengths

- **Hadronic interactions**
  Sensitive to interaction lengths
  Very good position resolution

Updated Geometry for Run2:

- Initial underestimation of IBL material

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**Hadronic Interactions**

*ATLAS Preliminary*

- Initial underestimation of IBL material

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**Photon Conversions**

*ATLAS Preliminary*

- Initial underestimation of IBL material
**ATLAS Preliminary**

Data $\sqrt{s} = 13$ TeV (2015) $|\eta_{SV}| < 2.4$

- Beam pipe material known to 1% precision
- SCT extension efficiency sensitive to radiation lengths
- Photon conversions sensitive to interaction lengths
- Hadronic interactions sensitive to interaction lengths
- Very good position resolution
- Updated geometry for Run2: Initial underestimation of IBL material

**Graphical Content**

- Vertex Y [mm]
- Vertex X [mm]

**ATL-PHYS-PUB-2015-050**
Inner Detector Alignment

Track based algorithm

✦ Using track Chi2 to estimate alignment parameters (t) with r (residual) and covariance matrix (V):

\[ \chi^2 = \sum_{tracks} r^T(t, a) V^{-1} r(t, a) \]

Detector stable on long time scales (no if power cut, magnet ramp, cooling issues..)

Run-by-run and within run alignment:

✦ IBL mechanical instability with temperature
✦ Vertical movement of pixel within fill
✦ Alignment determine movement of detector volumes / staves automatically:
  ✦ Every 20 minutes during first hour of the fill
  ✦ Every 100 minutes after
  ✦ Alignment updated within 24h after the run is over
MC and data for IBL, Pixel, SCT and TRT in great agreement.

After alignment, very good detector resolution, very close to MC expectations.
In busy environment, large probability to have 2 or more very close charged particles

**Neural network** to identify clusters *shared* by more than 1 particle, split them and estimate the position and error of each one:

- Uses cluster charge, shape, correlation with previous layer and incidence angle
- **Improves**: b-tagging, $\tau$ reconstruction, jet-mass reconstruction, etc..

Performance validated in data by independent 2 methods:

- Geometrical extrapolation and using the overlap region in phi
- Energy loss ($dE/dx$) in the pixel:

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ATL-PHYS-PUB-2015-044

ATL-PHYS-PUB-2016-007
Tracking in Dense Environments (TIDE)

Tracking inside jets is fundamental for:
- $b$-tagging
- $\tau$ reconstruction
- High precision jet mass measurement (used for analysis as BSM searches)

Large efficiency increase with ATLAS tracking in dense environments (TIDE)

TIDE is used as default for whole Run 2 and future:

ATL-PHYS-PUB-2015-006/
Impact parameter resolution

- The impact parameter resolution has been unfolded to remove the contribution from the vertex resolution.
  
- New IBL
  
- Material reduction in the pixel boundaries

Impact parameter sensitive to material description at low pT

Improved discrimination between primary and secondaries: Important for MB analyses.

- The impact parameter resolution has been unfolded to remove the contribution from the vertex resolution.
Tracking efficiency in pp

Very good tracking efficiency:

- at large instantaneous luminosity: increase of fakes mitigated by tighter track selection
- Track efficiency measure in MC and systematics applied to fit to data
- Large uncertainty is material budget
**Tracking performance in Heavy Ions**

- Insight of performance at very large occupancy
- Data overlay samples: simulated hard-scattering pp collisions embedded into real Pb+Pb events.
- Efficiency defined as a fraction of generated primary particles that are matched to reconstructed tracks with respect to all generated primary particles.

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**ATLAS Simulation Preliminary**

- **Pb+Pb, |s_{NN}| = 5.02 TeV**
- **η**

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**ATLAS Simulation Preliminary**

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**ATLAS Simulation Preliminary**

- **Pb+Pb, |s_{NN}| = 5.02 TeV**
- **η**
The large radius tracking is performed as a second pass after the standard tracking using unused hits to improve the signal track reconstruction efficiency at large impact radii.

The reconstructed tracks are required to fulfil the following quality criteria: \( p_T > 1 \text{ GeV}, \ |\eta| < 2.5, \ \text{hit quality requirements}, \ |d_0| < 300 \text{ mm}, \ |z_0| < 1,500 \text{ mm}. \) The efficiency is calculated for truth particles fulfilling the same \( \eta \) and \( p_T \) requirements.

![Efficiency vs. R for ATLAS Preliminary Simulation](chart1.png)

![Efficiency vs. R for ATLAS Preliminary Simulation](chart2.png)
The standard vertex fitter used in ATLAS is a kalman filter with an iterative annealing procedure.

- Due to the large number of tracks, it is very optimised to keep CPU time low.

Up to 140 tracks per vertex:
Vertex efficiency vs mu

Relationship between the number of reconstructed vertices and the average number of interactions per crossing

- Beam induced background extracted.
- Vertexes are merged when they are closer than vertex resolution causing a non-linearity in mu.
Vertex resolution

- Estimated by Data/MC studies (minimum bias events), differences due to:
  - Description of the sub-detector hit errors
  - Multiple scattering, ionization energy losses
  - Residual misalignment

![Graphs showing vertex resolution vs. number of tracks for different studies.](image-url)
Summary

- ATLAS Inner Tracking has an outstanding performance even operating over its design specifications
  - ID detectors did a huge work to operate at very high rates
- IBL is operating smoothly, giving an improved performance with respect to Run 1
- Time dependent alignment allows to correct for detector changes within runs
- Tracking in dense environments improved the reconstruction at large mu and inside jets
- Ready to collect data for the remaining part of Run 2 and algorithms improvements expected for Run 3
- Preparing our tracking for Run 3: Multithread safe and new ideas WELCOME!
The ATLAS Experiment

✦ LHC General purpose experiment:
  ✦ Inner tracking
  ✦ Electromagnetic and hadronic calorimeter
  ✦ Muon system
  ✦ Forward detectors

✦ Wide range of physics:
  ✦ Proton-proton collisions at 0.9, 7, 13 and hopefully 14 TeV
  ✦ Lead-Lead and proton lead
The Insertable b-layer (IBL)
Imaging inspired vertexing

Alternative vertex finding algorithm inspired in medical imaging

- 3D binned histogram with linearised helical trajectories. Histogram content in each traversed bin is incremented by the path length of the track in that bin
- The track image is transformed into frequency space using the FFTW3
- A filter is multiplied with the frequency space histogram. The filtered frequency space image is then back transformed to position space,
- The resulting image is then passed to a separate clustering
- Linear in CPU with luminosity. While combinatorial vertexing is quadratic.

ATL-PHYS-PUB-2015-008
Overall vertex fitter is very insensitive to the presence of outlying tracks—this helps the performance of the hard-scatter primary vertex against infiltration from pile up tracks.

The efficiency for Hard Scatter vertex reconstruction is near 100% for all pile-up studied. At \( \mu = 40 \), 8% of Zmumu primary vertices have Highest level of pile-up contamination\( \rightarrow \) transverse resolution worsened by \( \sim 20\% \), longitudinal resolution worsened by factor of 5. (Transverse resolution is aided by beam spot constraint)