Studies for the ATLAS Tracker Upgrade

Nataliia Zakharchuk
National University Kyiv-Mohyla Academy, Ukraine

DESY ATLAS Group
Supervisor: Peter Vankov

9th September 2011, Hamburg

Abstract

At Phase II, currently scheduled for 2022, the operating luminosity of the Large Hadron Collider (LHC) will be increased significantly. This will imply an upgrade of all ATLAS subsystems. In particular, the Inner Detector (ID) of ATLAS will be fully replaced with a tracker completely made of Silicon, having higher granularity and radiation hardness.

In this document, the results of a simulation study on the tracking performance of the upgraded ID are reported. The impact of the stereo angle between the module sides in the Silicon Strip detector has been analyzed under conditions close to the high luminosity expected in Phase II.

Contents

1 Introduction

The LHC [1] at the European Laboratory for Particle Physics, CERN, in Geneva, Switzerland is currently the world's most powerful particle accelerator. It is designed to collide protons with a center-of-mass energy of $\sqrt{s} = 14$ TeV at a maximum luminosity of the order of 10^{34} cm^{-2}s^{-1}.
ATLAS [2] is a general-purpose, high-energy physics experiment designed to explore the proton-proton collisions at the LHC in a search for new fundamental particles and interactions.
In the next years, an upgrade of the LHC machine is foreseen which will allow up to ten times higher luminosity. Thus, the LHC physics discovery potential will be enlarged considerably.
The higher instantaneous luminosity is a challenge that will require significant changes in the ATLAS experiment too.
The LHC/ATLAS high-luminosity upgrade is expected to proceed in three stages:

- Phase 0 (2013-2014)
  - LHC: expected peak luminosity above $L_{\text{peak}} = 5 \times 10^{33}$ cm^{-2}s^{-1};
  - ATLAS: installing of an insertable B-Layer (IBL) in the Pixel detector; opto-electronics repair for Pixels, infrastructure consolidation.

- Phase I (2017-2018)
  - LHC: upgrade to configuration which can eventually deliver 3×10^{34} cm^{-2}s^{-1};
  - ATLAS: additional SCS layers in the Muon detector; moderate upgrades; improved level-2 triggers.

- Phase II (2022-)
  - LHC: upgrade to enable Super-LHC (SLHC) luminosity of $5 - 10 \times 10^{34}$ cm^{-2}s^{-1};
  - ATLAS: ID will be fully replaced with a tracker completely made of Silicon, having higher granularity and radiation hardness; LAr, new electronics in the tile calorimeter, new forward layers; major upgrades in the Trigger/DAQ systems.

2 Physics Motivations for the LHC Upgrade

It is planned that super-LHC (i.e. the High-Luminosity LHC, or sLHC) will exceed the instantaneous luminosity of the LHC by a factor of 10 and will allow collection of an integrated luminosity of 3000 fb^{-1} in the next 5 years, or by ∼2030 [6].
The main motivation for a sLHC machine to follow the LHC is to explore the physics beyond the Standard Model (SM), while at the same time completing the SM physics started at the LHC. Among the physics issues to be addressed at the sLHC are [12]:

- Precision SM physics, for example anomalous gauge boson couplings WWV (where V=γ,Z)

- Higgs boson physics

  - Rare decay modes
  - Higgs couplings to fermions and bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- New gauge bosons (Z', W')
- Supersymmetry
  - sLHC statistics will be vital for reconstruction of SUSY
  - Properties of SUSY particles (mass, decay BR's, etc.) channels
- Strong electroweak symmetry breaking
- Compositeness (excited quarks and leptons)
- Extra dimensions
  - Black Hole production.

In order to exploit the full potential of sLHC it is important that the performance of the detectors remains at the same level as at the LHC. Major detector upgrades will be needed to fully make use of the factor of ten increase in luminosity [13].

3 ATLAS Inner Detector

The ATLAS Inner Detector [5] consists of three sub-systems: the Pixel detector - silicon pixels, the SemiConductor Tracker (SCT) - silicon strips, and the Transition Radiation Tracker (TRT) - gaseous straw tubes, Fig. 1.

The information of the ID is used for track and vertex reconstruction, pattern recognition and electron identification. All charged particles leave hits in the ID, and therefore high resolution is required to provide precise track information and to resolve the high track density. The acceptance of the inner detector is limited to $|\eta| < 2.5$ due the increasing amount of radiation damage induced in the detector at higher values of $|\eta|$ [5]. Since the inner detector uses a solenoid magnet, in which charged particles are mostly deflected in the XY -plane, the ID is designed to have the highest precision in the transverse plane.

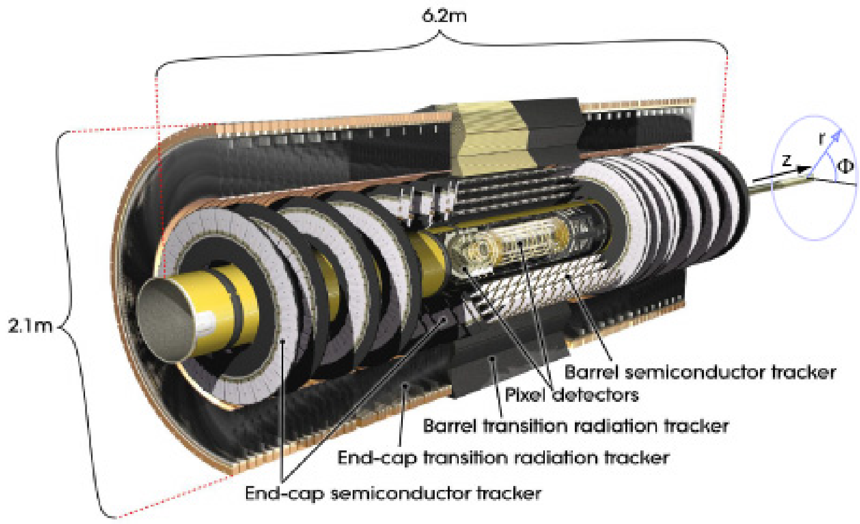


Figure 1: ATLAS Inner Detector.

4 Semi-Conductor Tracker

The Semi-Conductor Tracker (SCT) is the middle component of the inner detector. It is similar in concept and function to the Pixel Detector but with long, narrow strips rather than small pixels, making coverage of a larger area practical. SCT is the most critical part of the inner detector for basic tracking in the plane perpendicular to the beam, since it measures particles over a much larger area than the Pixel Detector, with more sampled points and roughly equal (albeit one dimensional) accuracy.
Each SCT end-cap module is composed of two silicon strip sensors and electronics to read-out the signals on the strips. The main components of the module are indicated in Fig. 2. Each module consists of two silicon sensor surfaces, that are glued back to-back onto a spine with a relative stereo angle of 40 mrad. The spine gives mechanical support to the module and connects the back planes of the sensors to the bias voltage. The aluminum strips on the silicon sensors are wire-bonded to the ABCD read-out chips, that are supported by the front-end electronics hybrid. Two washers made out of glass fiber with a aluminum precision inserts, are glued onto the spine and determine the precision of the mounting position of the sensors on the discs. The alignment software can determine the sensor position with a precision of the order of 1 μm, which reduces the need for very precise placement of the modules [9].
The design of SCT modules is optimized within the constraints for radiation hardness, high-rate capability, low mass and redundancy options.

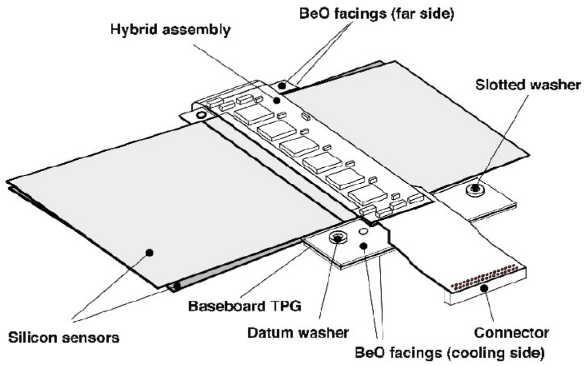


Figure 2: An SCT module and its components.

5 Detector Requirements for Upgrade of ATLAS

The reliability of the upgraded ATLAS detector has to be very high. The detector elements and electronics should be sufficiently radiation hard and have to be able to run for long periods at the increased luminosity of 10^{35} $cm^{-2}s^{-1}$, without a necessity of replacement of components on an yearly basis.
The plans for an upgrade of the ATLAS Inner Detector include a complete replacement of the entire ID with a new system fully built of silicon detectors. This is implied since the TRT at large radius will have prohibitively large occupancy, and the SCT and Pixel systems at smaller radii will have reduced performance because of radiation damage to the sensors and front-end electronics.
It is expected that the upgraded ID tracker (denoted throughout this report by ITk) will have about 200 m^2 of semiconductor detectors. Because of the increased particle fluence, the search for radiation-hard sensors is of highest priority, coupled with an optimization of the detector layout with respect to the radius, and increased granularity, which might require increased multiplexing.
A major constraint on the tracker is the existing ATLAS detector, implying a maximum radius of about 1 m and a 2 T magnetic field, and the limiting existing gaps for services. The outer silicon layers require more services than the TRT they are replacing, which means that for ATLAS the space available seems to preclude an increase in services due to granularity, implying that the multiplexing must be improved drastically [14].
The main detector requirements for ITk are listed below:

- Several space points with adequate precision in both rϕ and z to limit ambiguities;
- Very precise r-space points over significant range of radii;
- Limited material;
- Precise space point near IP;

In conclusion, building a successful and optimal design of the ATLAS at sLHC, requires a detailed simulation of the harsh, sLHC radiation environment and its impact with the detector. The good pattern reconstruction, good tracking efficiency, low fake-rate and minimal detector occupancy are amongst the essential quantities to be monitored.

6 ITk Utopia Layout

The benchmark ITk layout, oftenly denoted *Utopia*, is shown in Fig. 3 and is composed of silicon pixels and silicon strips detectors. In the barrel region it consists of 4 pixel and 5 Si-strip layers. The length of the pixels varies from 250 μm in the two inmost layers to 400 μm in the two outer layers. Similarly, there are two sizes of Si-strips: 2.5 cm (short strips) in the three intermediate layers and 10 cm (long strips) in the two outer layers. In the end-cap part Utopia is built of 6 pixel and 5 Si-strip discs (for each of the two end-caps).
Alike SCT, the basic unit of the Utopia Si-strip detector is the module, which is made of two sensors tilted relatively to each other at a stereo angle of 40 mrad.

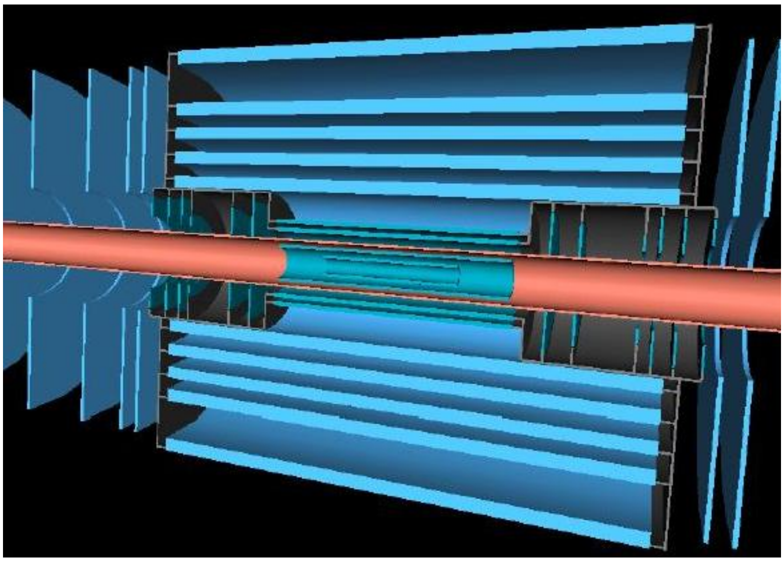


Figure 3: Utopia layout.

The ITk sensors are designed with smaller feature sizes 65 nm plan or new 3D-technologies and smaller feature sizes more tolerant to permanent errors, but more sensitive to transient errors; improved services expected less material, less power dissipation, better cooling, better power supplies (serial power or DC-DC).

The goal of the Utopia project is to study different ITk layouts, keeping the overall Utopia architecture and varying basic parameters such as pixel/strip size, barrel/endcap radii, stereo-angle, etc.

At this moment of the ITk R&D process, it is of particular importance, to evaluate the Utopia tracking performance as a function of the stereo-angle in the Si-strip detector. This is the focus of the present report and will be discussed in what follows.

7 Simulation description and Analysis

7.1 Athena framework

The ATLAS software for reconstruction and simulation is implemented in the Athena [?] framework. The software is designed to reconstruct the data taken by ATLAS. At the same time it is also capable of performing a full simulation of the proton-proton collisions and their detector response.
The simulation and reconstruction with Athena follow the steps:

1. Event generation;
2. Detector simulation;
3. Detector response (digitization);
4. Reconstruction (tracking).

7.2 Pileup events simulation

Pile-up occurs when the readout of a particle detector includes information from more than one primary, beam-particle interaction - these multiple interactions are said to be "piling-up".
At the design luminosity of 10^{34} cm^{-2}s^{-1} LHC beams will produce an average of 23 interactions each time they cross.
It has to be mentioned that the ATLAS detector is sensitive to tracks from more than one bunch crossing.
Depending on the chosen bunch-space time (BX), it is expected that in the sLHC will happen $\sim$ 100 (BX=25 ns) or $\sim$ 200 (BX=50 ns) events per bunch-crossing at the sLHC nominal luminosity of 5×10^{34} cm^{-2}s^{-1}. It is clear that performing a track reconstruction in such an environment is very challenging and requires improved tracking algorithms in addition to the detector upgrade.
In Athena framework, a special pileup tool allows the user to choose the number of minimum-bias events between either fixed number or number randomly pulled form a poissonian distribution with a specified mean. In our studies we used the second option.

7.3 Reconstruction and analysis criteria

The track reconstruction in the Utopia-ITk uses the measurements of the pixel and Si-strip detectors.
The tracking performance of a given Utopia layout is usually quantified by quoting the *tracking efficiency*, the *fake-rate* and the resolution of the *track-perigee parameters*.
In our analysis, the tracks used to define the above quantities were subject of the selection procedure described below:

- the candidate track has to be with $P_t > 1$ GeV;
- the transverse impact parameter, d_0, and the longitudinal impact parameter, z_0, of the candidate track have to satisfy: $d_0 < 1$ mm, $z_0 < 150$ mm;
- the candidate track has to be reconstructed with at least 9 hits;
- the truth, MC candidate must have a barcode different from zero and less than 100000. This enforces that the particle was not generated by Geant;
- to calculate the tracking efficiency we require that the reconstructed track matches a truth particle with a probability greater than 0.5;

7.4 Track parametrization

For completeness, here, we shortly describe the tracks parametrization in ATLAS.
As shown in Fig 4, a track in ATLAS is parametrized at the point of closest approach with the global Z-axis using five perigee parameters [9].

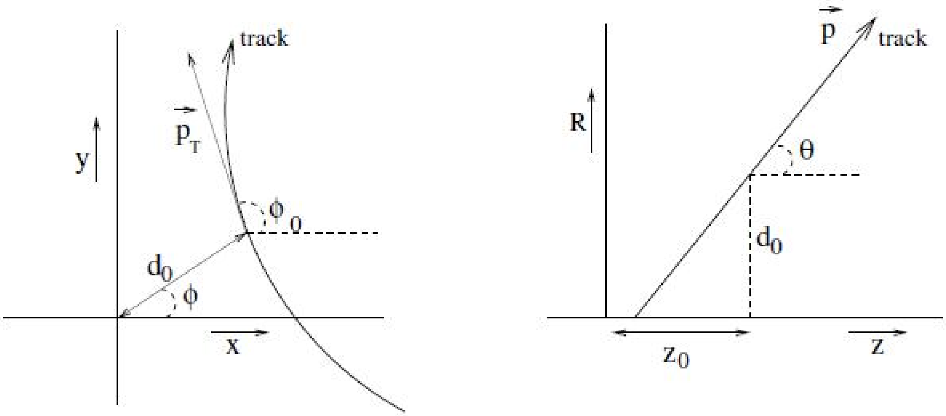


Figure 4: Illustration of the perigee parameters of a track in the transverse plane (left) and RZ-plane (right), as defined in the global ATLAS tracking frame.

- $\frac{q}{p}$: the charge of the particle divided by the momentum;
- d_0: the signed distance to the z-axis. The sign of d_0 is positive, when $\phi - \phi_0 = (\pi/2)\text{mod}(2\pi)$, where ϕ denotes the angle to the perigee position in the x-y plane, as shown in Fig. 4;
- z_0: the z-coordinate of the track at the point of closest approach to the global Z-axis;
- ϕ_0: the angle with the x-axis in the X-Y plane at the perigee point;
- θ_0:the angle with the z-axis in the R-Z plane.

8 Results

We have examined the performance of the standard ITk-Utopia layout in comparison to Utopia layouts with changed values of the stereo-angle in the Si-strip detector. Layouts with stereo-angle of 0 mrad and 20 mrad have been studied in addition to the nominal Utopia layout with stereo-angle of 40 mrad.

8.1 Data sets

- The Data-sets used are listed below:

  –Single electrons and muons of 5GeV and 50 GeV for 10000 events;

  –Single electrons of 5GeV +50 pileup;
- Atlas Software Release: 16.4.2.1 (SLHC);

8.2 Event displays (Utopia)

Event displays produced after the completion of the full simulation cycle (i.e., simulation, digitization and reconstruction) are presented in Fig. 5. Left figure shows a single muon of 50 GeV, and the right figure illustrates an event with 50 pile-ups on the top of a "signal" electron of 5 GeV. Both displays reflect the standard ITk-Utopia layout.

8.3 Results for single particles (no pile-up)

First, we present the obtained results for the tracking efficiency as a function of the pseudorapidity, $|\eta|$, for single particles.
Figure 6 shows the track-reconstruction efficiency for single muons and single electrons with a transverse momentum of 50 GeV. The efficiency of the muon reconstruction is almost 100% throughout the barrel and endcap. It has also been checked that the muon

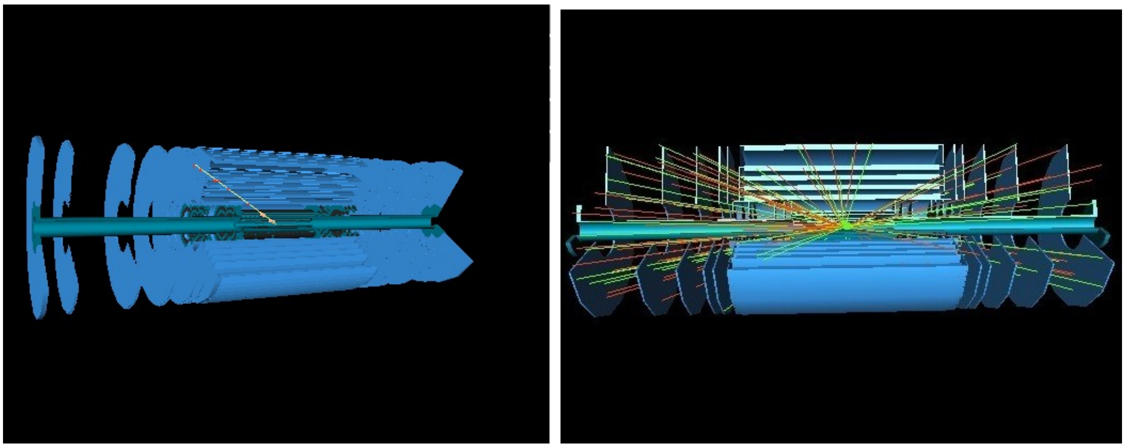


Figure 5: Event displays for single particle (muon) (left) and pile-up of 50 (right).

efficiency is stable and remains constantly close to 100% irrespectively of the muons momentum. However, this is not the case for the electrons. The reason is the greater sensitivity of the electrons to the traversed material. As a result, the electron efficiency curves as a function of $|\eta|$ actually reflect the material budget in the ITk in the forward direction. We can see also, in Fig.11, that the electron efficiency gets lower at lower transverse momentum, for instance 5 GeV, due to the fact that at lower P_t the electrons are even more sensitive to material.

The average efficiency for the layouts with different stereo-angles is listed in the Tab. 1. It can be seen that there is no significant difference in the efficiencies between the layouts with stereo-angles of 0 mrad and 40 mrad. The same is valid for d_0, z_0 and P_t resolutions, as demonstrated in Fig. 7, Fig. 8 and Fig. 9.

The tracking performance for a layout with a stereo-angle of 20 mrad also shows no significant deviations, see Fig. 12 and Fig 13.

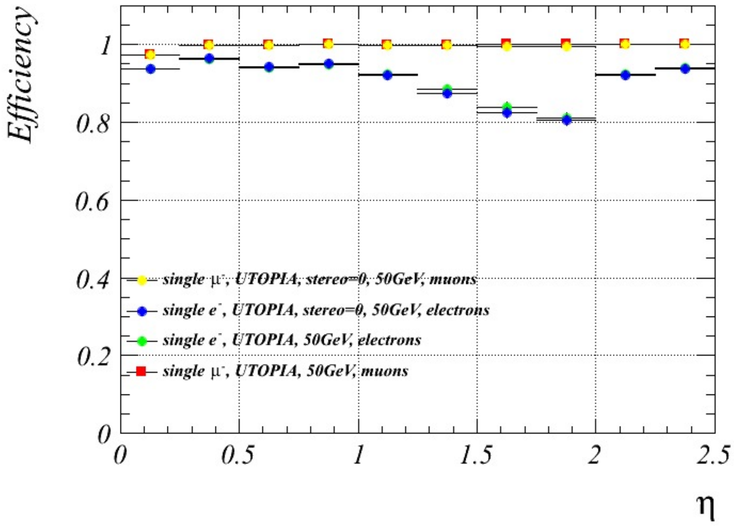


Figure 6: Efficiency for 50 GeV electrons and 50 GeV muons as function of rapidity.

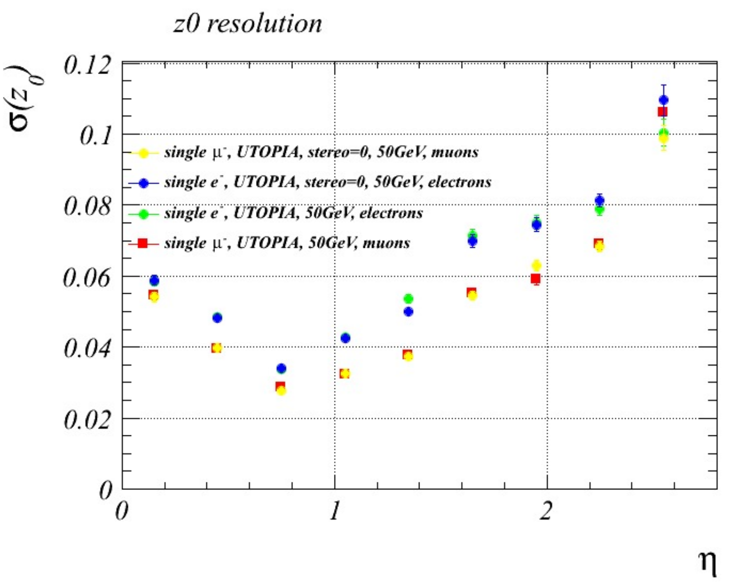


Figure 7: z0 resolution for 50 GeV electrons and 50 GeV muons function of rapidity

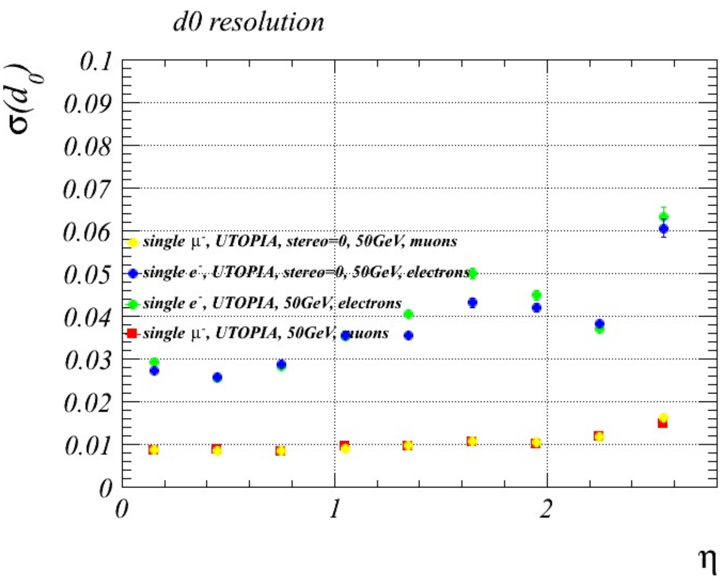


Figure 8: d0 resolution for 50 GeV electrons and 50 GeV muons function of rapidity

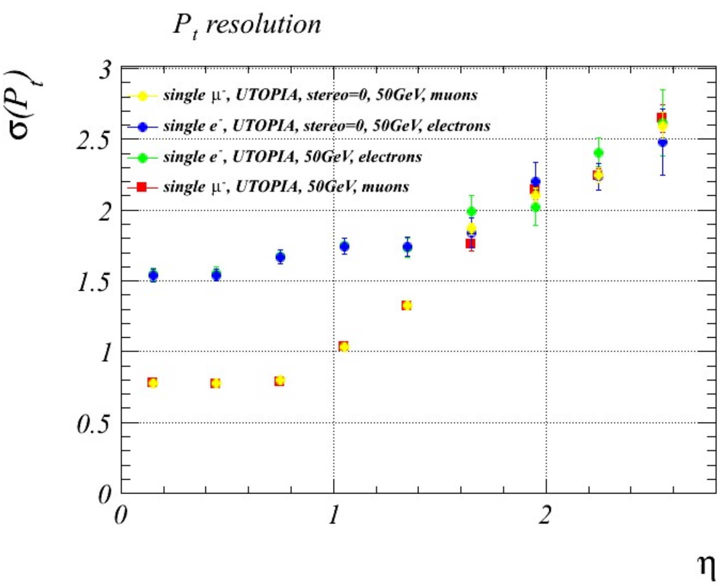


Figure 9: P_t resolution for 50 GeV electrons and 50 GeV muons function of rapidity

Table 1: Average efficiency for single particles (50 GeV)

Particle	40 mrad	0 mrad
muon	0.925	0.926
electron	0.841	0.844

8.4 Results for pile-up of 50

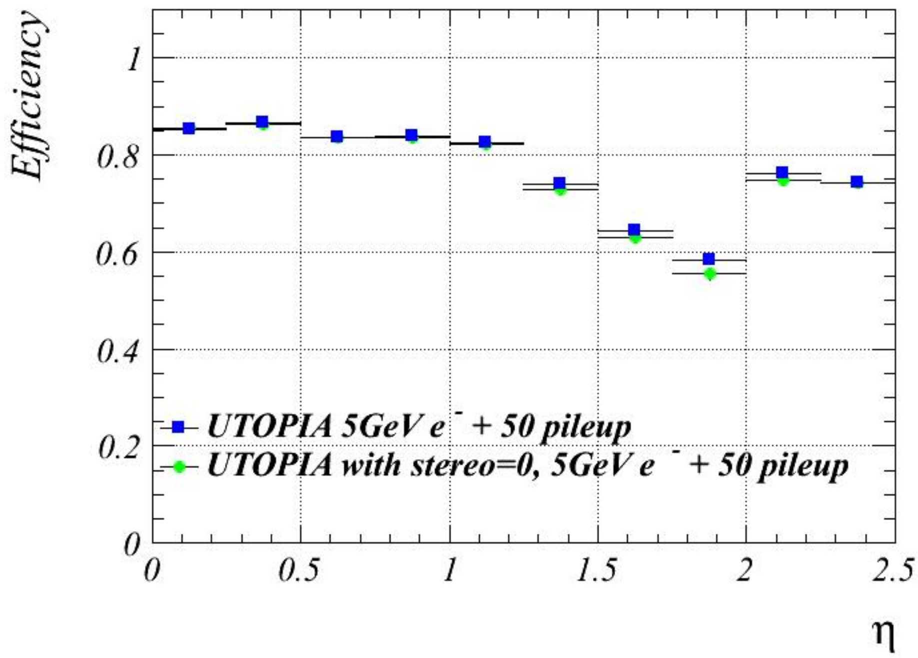
The results for pile-up of 50, presented in Fig. 10, show that the efficiency, more or less, stays the same. However, a significant difference in the levels of fake-rate is observed. The fake-rate increase for the layout with stereo-angle of 0 mrad is almost 100%. The average efficiency and maximum fake-rate for the layouts with different stereo-angles are listed in Tab. 2 and Tab. 3.
Because of limited CPU resources and time for work, the results shown here are for pile-up of 50 only. In the next steps we will try to perform simulations with the more realistic sLHC scenario of pile-up of 200. It will be interposing to see what will be the levels of efficiency and fake-rate at this pile-up.

Table 2: Average efficiency for pileup of 50

Stereo angle	Average efficiency
40 mrad	0.706
0 mrad	0,700

Table 3: Fake rate for pileup of 50

Stereo angle	Max. fake rate
40 mrad	0.35×10^3
0 mrad	0.75×10^3



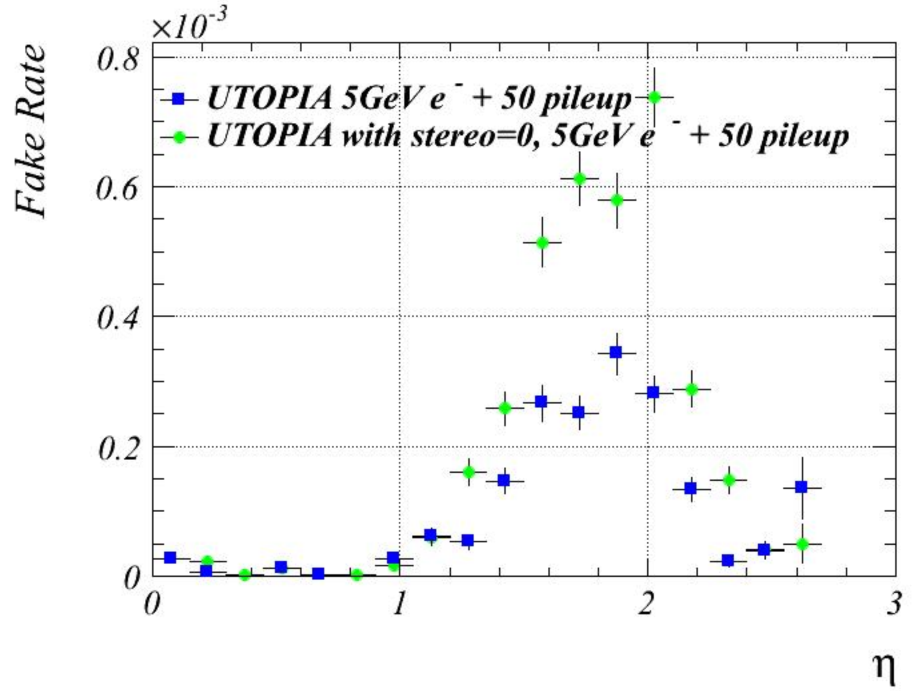


Figure 10: Efficiency for 50 pileup as function of rapidity and fake rate for 50 pileup

9 Summary

Attaining or exceeding the ultimate LHC performance will be even more challenging. Further accelerator physics studies in view of a luminosity upgrade, e.g., by optimizing machine operation near the beam-beam limit, will be directly applicable also to reach nominal machine performance, e.g., with fewer bunches of higher intensity. Upgrades in beam intensity are a viable option for a staged increase of the LHC luminosity.
ATLAS ITk Upgrade is an active and important area of research. The tracker of ATLAS must be replaced for LHC upgrade with an all-silicon tracker. A number of possible ITk geometries are proposed and are under study. The benchmark layout is the so-called UTOPIA scenario, including Si-Strip modules with 40 mrad stereo angle b/w the module sides. In my project, I have studied the tracking performance with different values of the stereo angle for single particles and pile-up events (efficiency, fake-rate, d0, z0 and P_t resolutions).The results obtained showed that in the high particle multiplicity environment of SLHC, the presence of stereo angle of 40mrad could decrease significantly the reconstruction fake-rate and were obtained by using 50 pileup/BC. The impact on the tracking efficiency could be much stronger when move to the expected levels of 200 pileup-s/BC .Also I have studied the ATLAS Software framework and the steps to simulate and reconstruct (simulation, digitization, reconstruction).

10 Plots for single particles with 20 mrad, 5 GeV

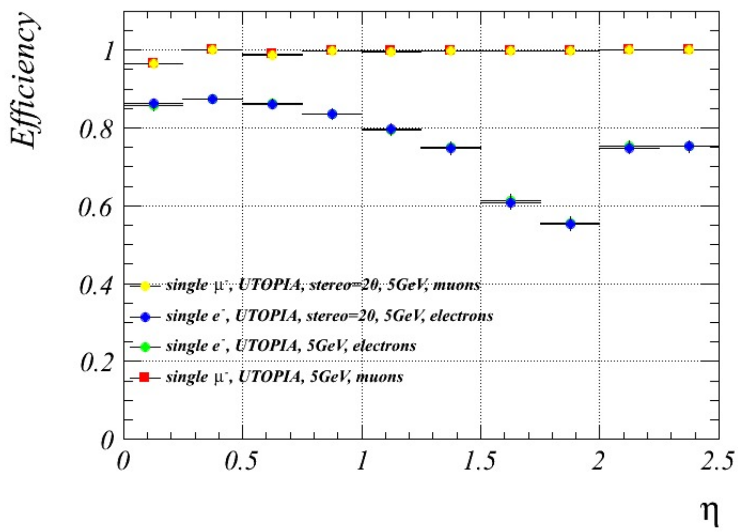


Figure 11: Efficiency 5GeV single particles as function of rapidity

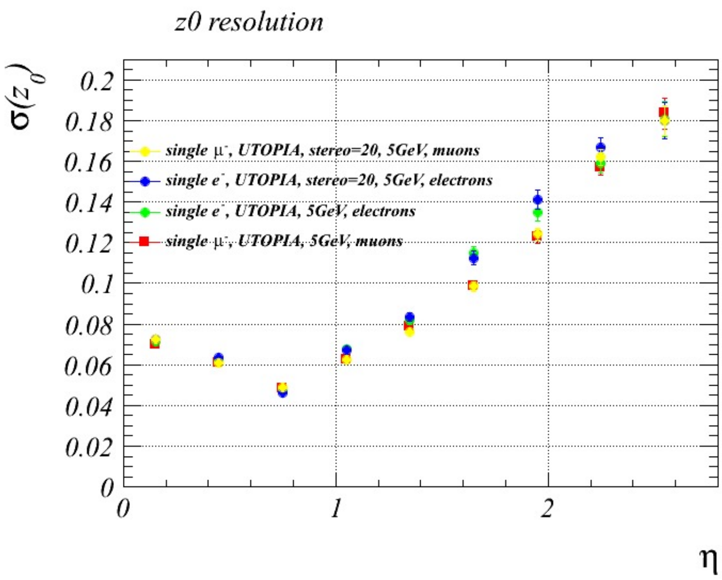


Figure 12: z0 resolution for 5 GeV electrons and 5 GeV muons function of rapidity

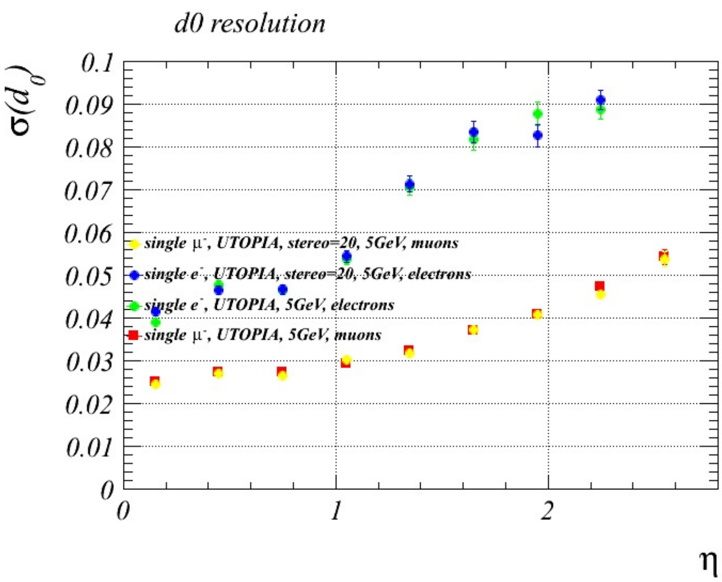


Figure 13: d0 resolution for 5 GeV electrons and 5 GeV muons function of rapidity

References

[1] L. Evans and P. Bryant, *LHC Machine*, J. Instr. 3 (2008) S08001.

[2] G. Aad, *et al.*, *The ATLAS Experiment at the CERN Large Hadron Collider*, J. Instr. 3 (2008) S08003.

[3] The ATLAS Collaboration, *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics*, arXiv:0901.0512v4 (2009).

[4] ATLAS Collaboration, *ATLAS Inner Detector Technical Design Report*, Volume 2, ATLAS TDR 5, CERN/LHCC/97-17, ISBN 92-9083-103-0.

[5] ATLAS Collaboration, *Inner Detector Technical Design Report vol. I & II*, CERN/LHCC/97-16 & CERN/LHCC/97-17 (1997).

[6] P. Allport, *ATLAS tracking at the super-LHC*, Nucl. Instrum. Meth. A579 (2007) 592-594.

[7] A. Abdesselam, *et al.*, *The Barrel Modules of the ATLAS Semiconductor Tracker*. Nucl. Instrum. Meth. A568 (2006), 642.

[8] A. Abdesselam, *et al.*, *The ATLAS semiconductor tracker endcap module*. Nucl. Instrum. Meth. A575 (2007), 353.

[9] M. Limper, *Track and vertex reconstruction in the ATLAS inner detector.*, Ph.D thesis, 2009

[10] G.Duckeck et. al.*ATLAS computing: Technical Design Report*, CERN public note.

[11] Luehring, *Athena Pile-up Requirements*

[12] G.Azuelos et al., *Physics in ATLAS at a Possible Upgraded LHC*, ATL-COM-PHYS-2000-030, March 2001.

[13] Virdee, *Presentation to the Scientic Policy Committee*, September 2001.

[14] Hartmut F.-W.Sadrozinski, *Tracking Detectors for the sLHC, the LHC Upgrade.*