ATLAS Trigger Studies

Lily Asquith
Supervisor: Dr. Nikos Konstantinidis

University College London, 09-06-06

Abstract

This first year transfer report presents an overview of the ATLAS detector at the LHC at CERN, In particular the work being undertaken on the Level 2 Trigger. An investigation into the effect on the Inner Detector efficiency of the size of the region of interest is presented, including first results obtained with a new RoI constructed using information from the muon spectrometer at Level 2.

Contents

List of Tables

List of Figures

1 Introduction

This report covers the work I have done during the first 8 months of my phD studies on the ATLAS detector. One of the most striking features of the ATLAS detector is its size. The detector itself is huge,as is the amount of software needed to cope with the enormous amounts of datawe will have access to. The possibilities of what we might find with ATLAS are massively exciting for all involved. There are thousands of physicists and engineers working on ATLAS, and it has taken over 20 years to get where we are today. The LHC starts taking data next year, in 2007, and within a few years we expect to be able to provide answers to many big questions in particle physics, (and more than likely come up with some more questions as a result.)

We know that there are 6 quarks and 6 leptons and that they share various common characteristics conserved quantities which obey our framework of laws: spin, flavour, colour, abstract descriptive terms which we have developed in order to describe the things we observe on some common ground. We have developed a standard model of particle physics which successfully describes many of the phenomena observed in our world, but we have evidence that this model is not complete, and is perhaps just a first step in our understanding, a rough approximation to the truth.

1.1 The LHC

The Large Hadron Collider is a 27km diameter particle accelerator situated underground at CERN on the Swiss-French border.When the LHC starts data taking in 2007, it will collide beams of protons with a centre of mass energy of $\sqrt{s} = 14$ GeV, the highest energy ever achieved by a collider. For a period of about a year the LHC will be running at Ł= $2x10^{33}cm^{-2}s^{-1}$. This will then be upgraded to the design luminosity of L = $10^{34}cm^{-2}s^{-1}$. There will be bunch crossings every 25 ns, with an expected average of 23 events per crossing. There are four detectors situated at different points along the beam line, ALICE, CMS, LHCb and ATLAS.Figure 1.1 shows the LHC.

2 ATLAS

2.1 Detector Hardware

The ATLAS Detector has a cylindrical geometry with different sub-detectors at increasing radii from the beam pipe. The nominal p-p interaction vertex is situated at the centre of the detector in both the ρ-z and x-y planes, as illustrated in Figure 2. The positional coordinates used in ATLAS are (ϕ, η) rather than (ϕ, θ), where η is the pseudo-rapidity. The pseudo-rapidity is so-named because it is equal to true the rapidity for a particle travelling at the speed of light. The η coordinate is used rather than θ for two reasons:

- Particle production is roughly constant as a function of η
- The difference in rapidity between two particles is Lorentz Invariant under boosts along the beam axis

η is defined in Eq. 1 and the true rapidity y is defined in Eq. 2

$$\eta = -\ln \tan \tfrac{\theta}{2}; \tag{1}$$

$$y = \tfrac{1}{2} \ln \tfrac{E+P_L}{E-P_L}; \tag{2}$$

Where P_L is the component of momentum along the beam line.

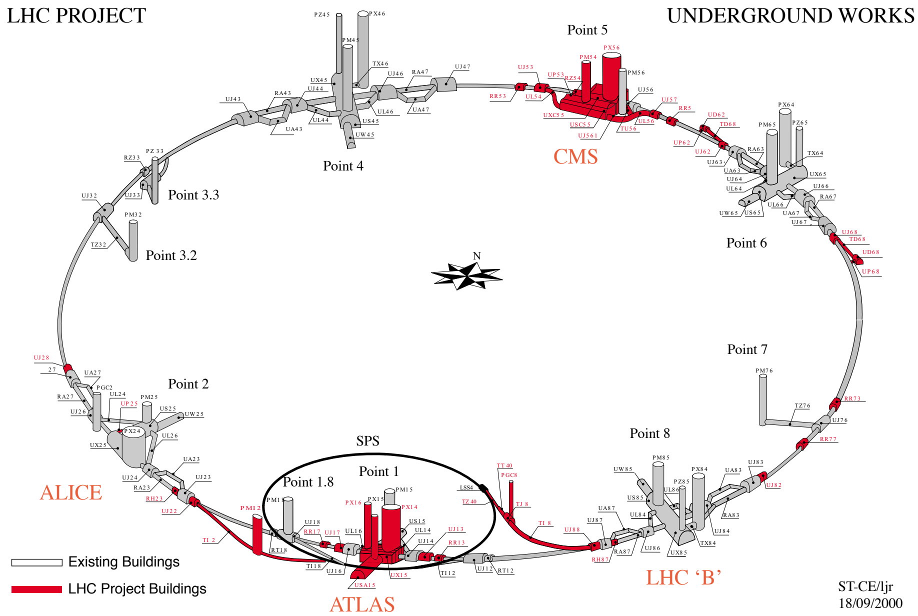

Figure 1: The Large Hadron Collider

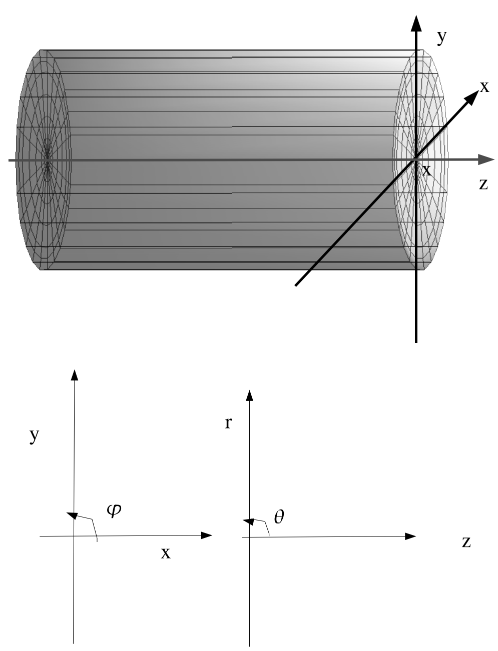

Figure 2: The ATLAS coordinate system

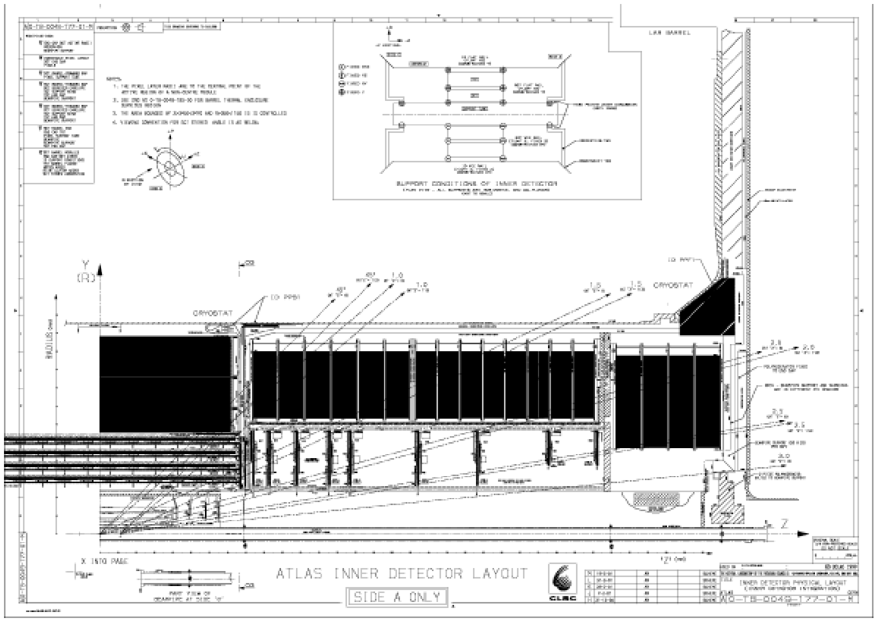

Figure 3: Layout of the Inner Detector

2.1.1 The Inner Detector

The main role of the Inner Detector is to reconstruct the tracks and vertices of interesting physics events with a high degree of accuracy. The Inner Detector consists of three mechanical parts: a barrel section about the beam pipe and centred on the nominal proton-proton interaction vertex, and two endcaps perpendicular to the beam pipe at either end of the barrel, making the total length of the inner detector 700cm. The barrel extends from an inner radius of 5cm to an outer radius of 115cm and 80cm either side of the nominal vertex. It houses three different types of detector at increasing radii from the beam pipe: the pixel, SCT (semi-conductor tracker)and TRT (Transition Radiation Tracker) sub-detectors.

The pixel detector is positioned innermost and comprises three concentric layers at radii 50.5mm,88.5mm and 122.5mm from the beam pipe,and 4 endcap disks on each side. It provides very high precision measurements and is particularly useful for identifying short-lived particles due to its proximity to the interaction vertex.

The SCT is made up of four barrel layers at 300mm, 373mm, 447mm and 520mm from the beam pipe,and 9 endcap wheels on each side. These provide a spatial resolution of 16 μm in (ρ/ϕ) and 580 μm in z. The SCT detectors are double sided- two modules are glued together back to back, with the 'top' layer at a small angle of 40 mrad to the 'bottom' layer. If there is a hit on a strip in the bottom layer and that strip crosses a strip with a hit in the top layer then these hits are classed as a space point.

The TRT uses 4mm diameter straws filled with gas and each with its own sense wire.There are 50k of these in the barrel and a further 320k in the endcaps. The barrel covers radial range from 560mm to 1070mm. The TRT provides an average 36 measurements to be made for every track.

2.1.2 The Central Solenoid

The Central Solenoid is a superconducting magnet providing a field of 2 Tesla in the Inner detector (dropping to 0.5 Tesla at large z). It is maintained at a temperature of 2.5 K. The magnetic filed in the Inner detector causes bending of charged particles in the x-y plane, known

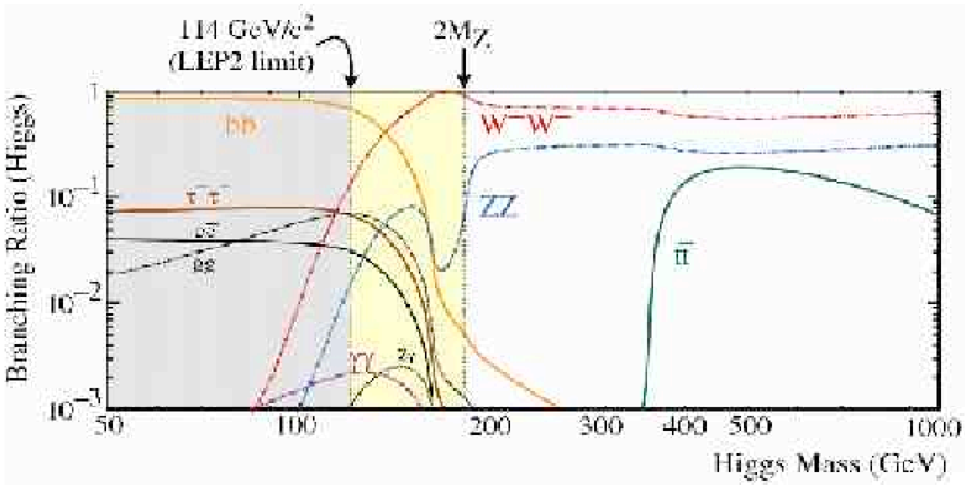

Figure 4: Branching ratios for Higgs decays as a function of M_H

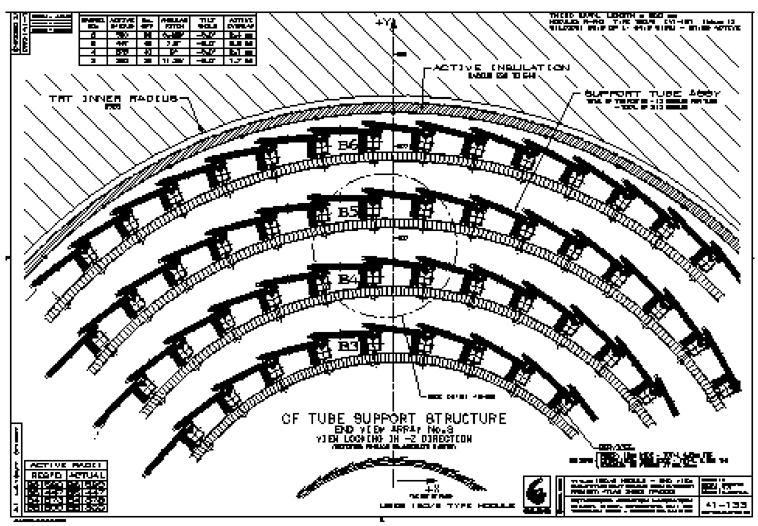

Figure 5: The four layers of the semiconductor tracker

as the bending plane,with a radius of curvature given by Eq. 4. The curvature is linearly proportional to P_t in a uniform magnetic field, thus high P_t tracks will be straighter. Tracks in the (ρ/z) projection are not effected by the solenoidal field and remain straight.

2.1.3 The Calorimeters

ATLAS has a tile calorimeter for hadrons and a liquid Argon calorimeter for e^-/e^+ and γ 's. The electromagnetic (liquid argon) calorimeter is composed of layers of lead inter spaced with liquid argon. At the entrance to the calorimeter is a presampler made up of a single layer of argon to measure the energy lost in the Inner Detector, the solenoid and the cryostat wall. There are then three samplers at increasing radii, the third of which will only be reached by very high energy e^- 's. The tile calorimeter is made up of a steel matrix with tile inserts made of scintillators and read out by λ shifting fibres to photomultiplier tubes. The total energy deposited by hadrons is measured here.

2.1.4 The Toroid

The Toroidal magnet system has a barrel section and two endcap sections each comprising 8 superconducting coils.The field strength varies with ϕ but is roughly 4 Tesla in both the barrel and endcaps. The magnetic field produced by the Toroid bends charged particles in the muon spectrometer in the (ρ/z) plane. There is no further bending in the ϕ projection.

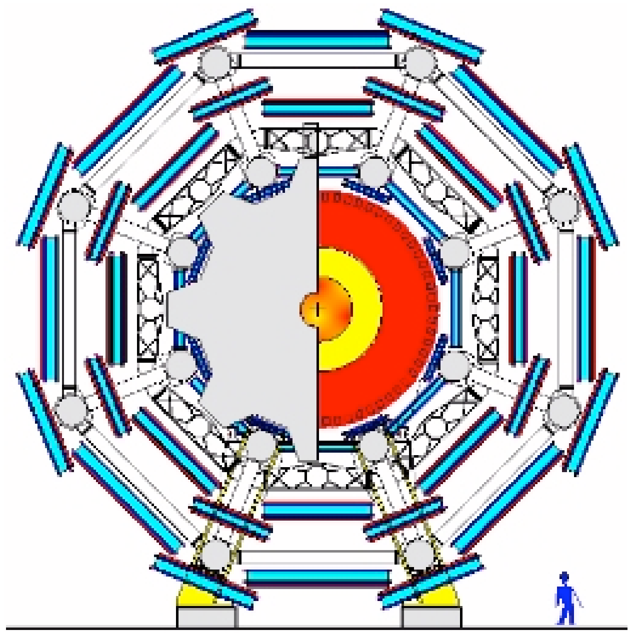

Figure 6: The muon spectrometer

2.1.5 The Muon Spectrometer

The muon spectrometer is situated outside the calorimeters and provides triggering and measurements on μ's with Pt from a few GeV (eg muons produced in Beauty decays)up to TeV(possible new heavy gauge bosons).It is called the muon spectrometer because the only detectable particles capable of getting this far through the detector are μ's: all other hadrons and leptons will have decayed or been absorbed in the calorimeters. The muon spectrometer will be used

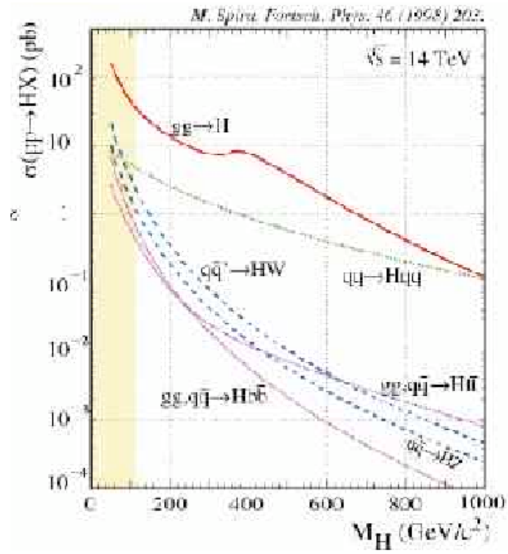

Figure 7: Higgs production cross-sections

for (amongst other things) triggering on and measuring muons produced in Higgs decays via ZZ* and WW*, corresponding to muon's with Pt in the range 5-50 GeV. Just as with the Inner Detector, the muon spectrometer has three mechanical sections: the barrel region and two endcaps. There are four different types of detector within the muon spectrometer, two each for the barrel and endcaps. Two types of detector are required because the muon chambers are used both for triggering at level 1, which requires a rough description of what is going on very quickly, and in the HLT where there is a bit more time to play with but the information needs to be more detailed in order to allow tracking.

The barrel detectors are the Resistive Plate Chambers (Fast and coarse-grained) and the Monitored Drift Tubes (not so fast and finer grained). These are positioned at three measurement stations at increasing radii from the beam pipe.The first station contains only an MDT chamber, the second station contains an MDT chamber sandwiched between two RPCs, and the third station contains an RPC followed by an MDT chamber.

3 The ATLAS Trigger

The challenge of the ATLAS Trigger is to reduce the 40MHz bunch crossings at the LHC by a factor 200,000 to a rate of 200Hz, which is the maximum feasible rate that can be dealt with by the offline computers.[6] The Trigger has to be able to cope with data from 10^8 readout channels from various parts of the detector, providing 1.3 petabytes ($1.3 * 10^{15}$ bytes) per year of raw data.To put this into context, the estimated total amount of storage space held by the search engine Google is about 5 petabytes [1].

The Trigger must be able to implement this massive reduction in data while maintaining the ability to identify and keep any rare and interesting physics processes that ATLAS was designed to detect. The first step in doing this is to use a hardware trigger, known as the Level 1 Trigger, which must reduce the amount of events to be processed to a rate of 75kHz. It has just 2.5 μs to do this (there are bunch crossings every 25 ns and the maximum amount of events that can be stored in the pipelines is 100). The Level 1 Trigger looks in the Calorimeters and the Muon Spectrometer for Regions of Interest using the fast Trigger chambers in these sub-detectors. These Trigger chambers are fast because they provide only coarse grained information. These regions of interest are classified at this level as having a predefined number of coincidence hits within one of the sub-detectors and passing a certain Pt threshold. The Pt threshold is of importance here because it reduces the likelihood of triggering on pile-up events, which are generally of low Pt.

The size of the RoI constructed at level 1 depends on the event type and is limited by the granularity of the Trigger chambers. The Calorimeters have a granularity(in $(\Delta\eta, \Delta\phi)$) of (0.1,0.1), for cluster trigger and (0.2,0.2) to (0.6,0.6) for jets and about 0.2,0.2 for the muon chambers[2].

This is about 200 mrad in ϕ and 260 mrad in θ, which is 6% of the detector volume. There are usually a few RoI per event, so the volume of data labelled as interesting at this point is reduced dramatically[3].

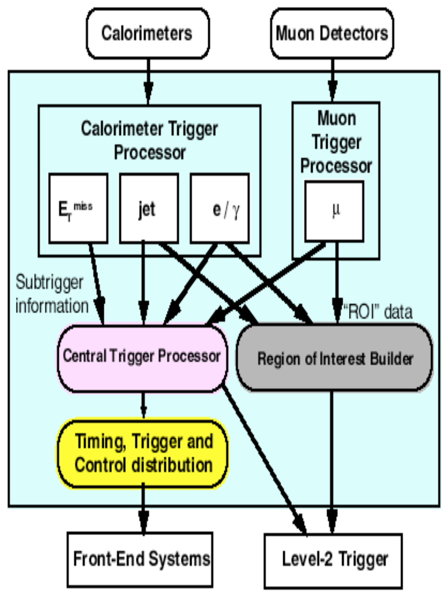

Figure 8: The Level 1 Trigger

3.1 Trigger Software

The software used in the High Level Trigger is known as the event selection software. There are four major components to the event selection software:

- HLT algorithms, executed in a sequence defined by the..
- HLT Steering, which decides which sequence to run depending on the type of RoI
- HLT Data Manager, which provides access to the data
- HLT raw Event Data Model

There are Trigger Menus for Level 1 and for the HLT. Figure 10 shows an example of a Level 1 menu.

The Trigger Menu for the HLT is more complex. It determines which algorithms should be called, and in which order (the **sequence;**), and states which **signatures;** must be satisfied in order for the sequence to continue. For example,Level 1 may satisfy a signature for Mu6, meaning that there is an event which fits the description of a μ with $P_T \geq 6$GeV. The HLT may then have an algorithm sequence of (for example):

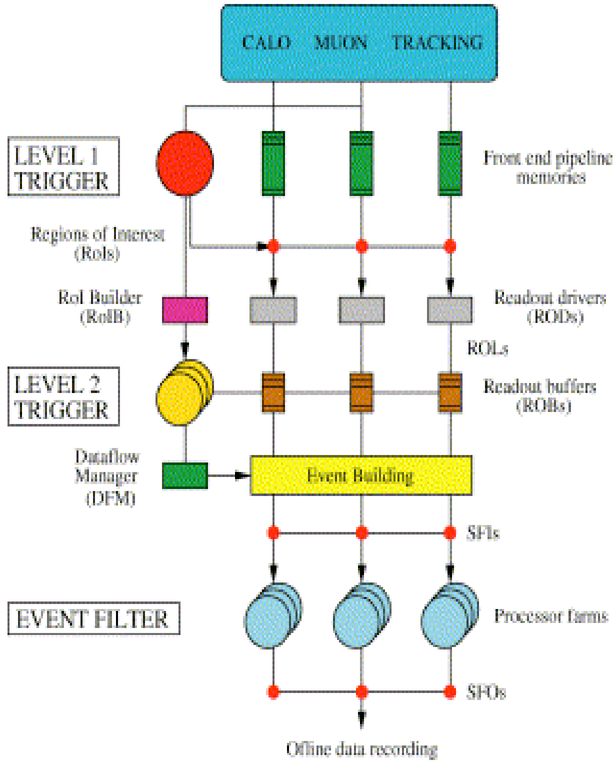

Figure 9: Schematic of the ATLAS Trigger and DAQ system

LVL1 Menu	$2 \times 10^{33} cm^{-2} s^{-1}$
MU20	0.8
2MU6	0.2
EM25i	12.0
2EM15i	4.0
J200	0.2
3J90	0.2
4J65	0.2
J60+xE60	0.4
TAU25+xE30	2.0
MU10+EM15i	0.1
Others	5.0
Total rate (kHz)	**~ 25**

Figure 10: An example of a Level 1 Trigger menu

*muon spectrometer algorithm
  * confirm μ in spectrometer
    * satisfy signature μ candidate

Inner detector algorithm
  *confirm μ in inner detector
    *satisfy signature μ
  *confirm $P_t \geq$ 10GeV
    *satisfy signature μ10
  *confirm μ is isolated
    *satisfy signature μ 10i

If at any point in the sequence a signature is satisfied, then execution is discontinued. The HLT sequence can be configured to look for more than one signature, such as an e^- or μ for example, and if either signature is satisfied the sequence is continued accordingly.

3.1.1 IdScan

IdScan is a fast tracking algorithm for the inner detector, designed to be used for level 2 triggering.The goal of IdScan is to sort the interesting physics events from the pile-up in under 10ms.It receives the central (η, ϕ) position of the RoI(currently obtained from the level 1 Calorimeter and/or muon spectrometer trigger algorithms via the Trigger Element). The size of this RoI is (0.4 x 0.4) when obtained from level 1. IdScan gets positional information on hits in the pixel and SCT detectors from the Transient Event Store via the Region Selector. The first step in deciding which hits correspond to possibly interesting physics events is to determine the z vertex position of the interaction. This is done with the ZFinder. ZFinder is described in detail elsewhere (ref) but the basic principle is as follows: The RoI is divided into thin slices in ϕ , taking account of the fact that interesting physics events will usually have higher transverse momentum than pile-up, and therefore will be almost straight in ϕ. Pairs of hits belonging to the same ϕ bin but with different radial positions are then used to make a linear extrapolation back to the beam pipe. This is done for all pairs in the ϕ bin, and the most popular z vertex position obtained from all the extrapolations is the one defined as the ZFinder vertex for the track in question.This z vertex position is then used to make a cone in (η, ϕ). The Hit Filter searches through this new region and counts how many different radial layers contain hits for each bin in (η, ϕ) space. Of the seven radial layers in the Inner detector, the Hit Filter rejects all of those hits belonging to a bin with hits in less than 5 layers. The remaining hits are called groups.The next step is to combine accepted triplets of hits with the group cleaner.Each triplet constitutes a potential track. The transverse momentum and ϕ at the vertex of these potential tracks are calculated. Quality cuts are then made, and a track candidate is accepted if it has at least 4 hits. The track candidates produced are then fitted.

3.1.2 muFast

muFast is a level 2 feature extraction algorithm for the muon spectrometer.It receives RoI and Pt threshold information from level 1. muFast processes the data from the level 1 RoI in three steps. First it uses the RPC trigger data to construct 'muon roads' in the MDT chambers in which to look for clusters of hits. To do this it performs a level 1 emulation to find the RPC hits, and then finds the level 1 muon trajectory by drawing a straight line through two points in the r-z plane and a circle + its tangent line in the (ρ/ϕ) plane(the bending projection).The width of the muon road is defined such that it collects 96 % of muon hits. Next the distances between the centre of the tube which contains a hit and the muon trajectory is calculated, and all hits outside the road are thrown away. A contiguity algorithm is then implemented, which

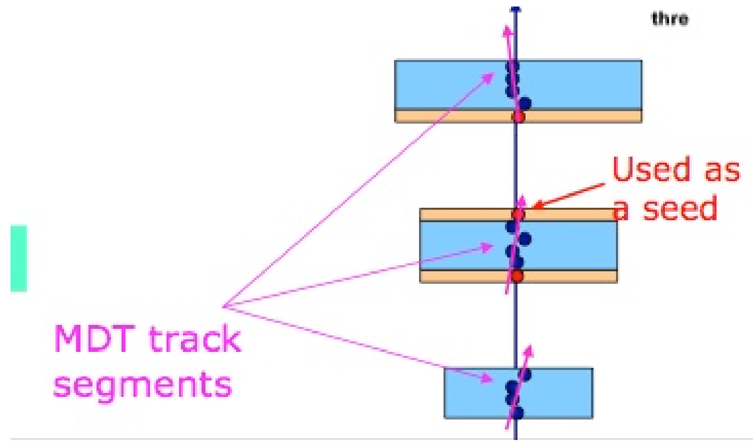

Figure 11: MDT track segments

calculates the mean position of the cluster of hits and the deviation from the mean of the drift tubes containing hits. The tube with the greatest deviation from the mean is thrown away and the process starts again, until there is just one drift tube in each layer. The second step is to perform a track fit. Straight line fits are made in each of the MDT chambers separately. If there are 4 out of 6 (or 8 for the inner station) hit drift tubes in a chamber then a track segment is made. The point where the track segment crosses the centre of the chamber is then defined as the superpoint.There must be at least 2 superpoints in an event for acceptance. The final step uses the superpoints from the different stations to calculate the Pt from the bending of the track. This is done using three hit positions in (ρ,z) and then using the inverse linear relationship between the sagitta and the Pt shown in Eq. 3

$$\frac{1}{s_m} = a_0 \cdot P_t + a_1; \tag{3}$$

Where a_0 is related to the magnetic field in the spectrometer and a_1 is related to the energy loss in the calorimeter.

3.1.3 muComb

muComb is a Level 2 hypothesis algorithm that is run in sequence after muFast and IdScan. It uses the track parameters reconstructed by IdScan to extrapolate up to the muon spectrometer, correcting for the energy loss and multiple scattering within the calorimeters. It uses this information to match muFast tracks with IdScan tracks, which is particularly useful for rejecting fake muons and secondary muons from π and κ decays.

4 Optimisation of The Inner Detector Region Of Interest

4.1 Background and Motivation

The size of the region of Interest passed from muFast to IdScan in the Level 2 Trigger is important. A smaller RoI will reduce the amount of pile-up hits included in the pattern recognition stage of tracking, which in turn reduces the amount of combinatorics which must be considered. Therefore the amount of time taken for a decision to be reached is reduced and the statistical possibility of misidentification is also decreased. In brief this means that an optimally sized RoI leads to improved Inner Detector efficiency.

The RoI passed to LVL2 from LVL1 is (0.2,0.2) in $(\Delta\eta, \Delta\phi)$. LVL2 uses full granularity detector information, and can therefore reduce the size of the RoI fairly significantly. In the

Muon system the LVL1 Trigger is given by the Resistive Plate Chambers, of which there are 3, each with two layers. Hits found in the first measurement station are extrapolated back along a straight line in (ρ, z) through the z_0 position of the beam line (the approximate, assumed interaction point. The true z vertex of the interaction can be ±168 mm from z_0).

This new RoI information (currently just (η_0, ϕ_0) is passed to IdScan in the form of a TrigRoIDescriptor, which is created at the end of the muFast algorithm.

This more precise RoI information makes it possible to define a smaller RoI,the half-width of which is defined as 3σ of the (η/ϕ) resolutions obtained from muFast. The ϕ resolution is dependent on the P_t of the μ : (lower P_t = more bending)and is equal to the maximum bending angle in the $(r - \phi)$ plane of the Inner detector, as illustrated in Figure 12 and Eq. 4

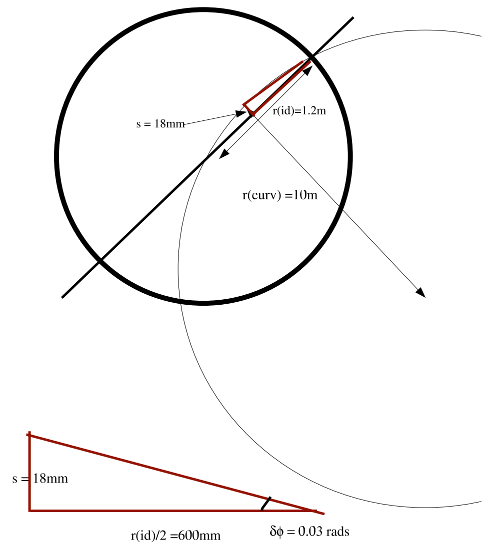

Figure 12: The sagitta measurement

$$P_t(eV) = c(ms^-1) \cdot B(T) \cdot R_curv(m); \tag{4}$$

.

4.2 Preparatory work

To investigate the effect on the Inner Detector efficiency of the RoI size a comparison was made using the Level RoI position but with different sizes. The results obtained for RoI sizes of $(\Delta\eta, \Delta\phi)$ =(0.1,0.1), (0.2,0.2) and (0.3,0.3) are shown in Figure 13.The mean and σ of the z resolution plots are summarised in Table 1

It can be seen from these results that constructing an RoI of size smaller than (0.2,0.2) would mean losing a large amount of information: of the data. 43% of (0.1,0.1) sized RoIs have **no tracks reconstructed;** within them, compared to 14% with RoI size (0.2,0.2).This is due to coarse granularity of the Level 1 Trigger.

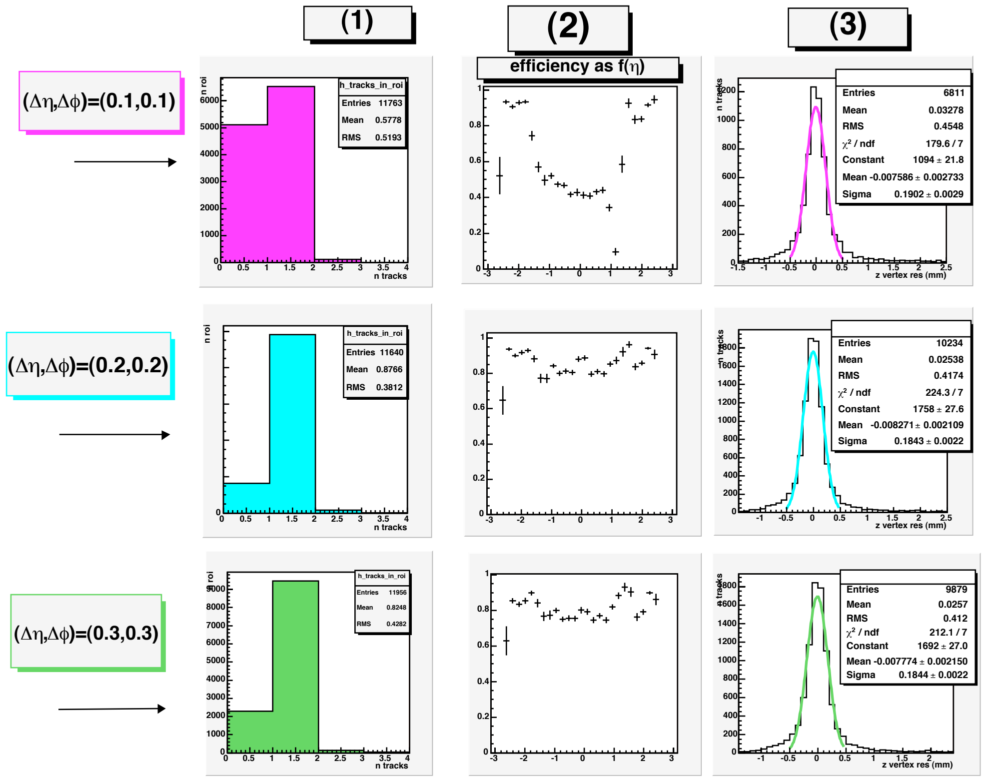

Figure 13: Histograms showing for different sizes of RoI: (1)the number of tracks per RoI, (2)the efficiency for reconstructing η within 0.6 of true η for 30 bins in η, and (3)the resolution Ztrue -Ztrack for the Inner Detector

Size of RoI	Z resolution:mean (mm)	Z σ(mm)
(0.1,0.1)	0.03278	0.1902
(0.2,0.2)	-0.00827	0.1843
(0.3, 0.3)	-0.007774	0.1844

Table 1: The mean and σ for resolution Ztrue -Ztrack

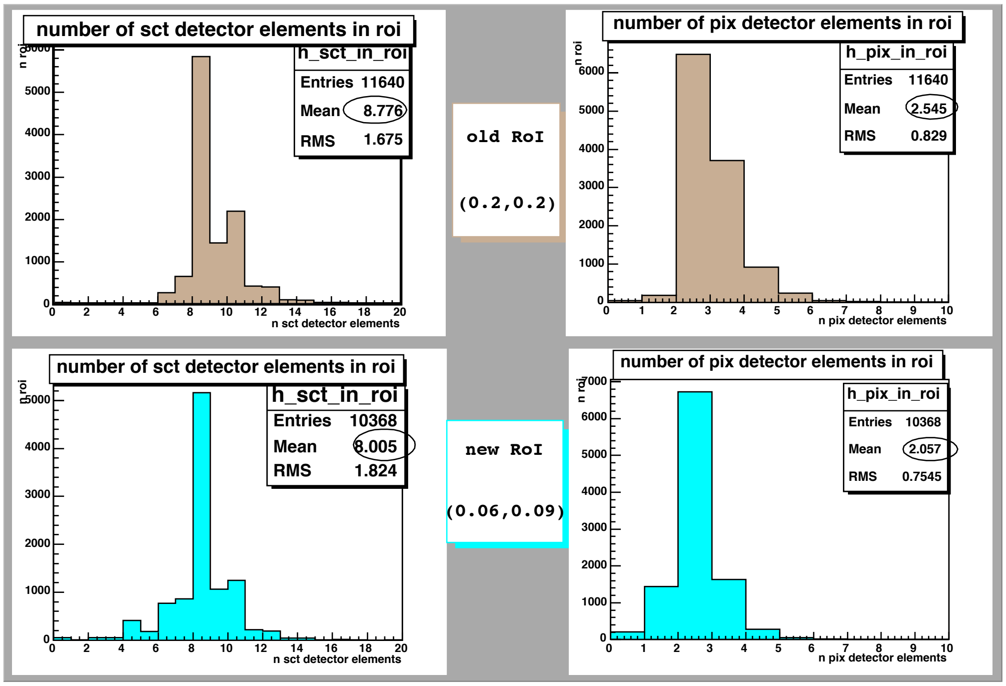

Figure 14: Histograms showing the number of SCT and pixel detector elements in an RoI for (top) the old RoI, with η_0 and ϕ_0 passed from Level 1 with an RoI size of (0.2,0.2) and (bottom)for the new RoI, with η_0 and ϕ_0 passed to IdScan from μFast via the TrigRoIDescriptor with an RoI size of (0.06,0.09)

4.3 Study with new RoI Descriptor

As discussed in scetion 4.1 of this report, Reducing the size of the RoI is expected to improve the subsequent efficiency. An optimally sized RoI will provide the advantage of reducing the number of **Detector Elements** in the RoI, thus shortening the amount of time needed to process an event and reducing the probability of error due to background hits.Detector elements which are wholly or partially within a region of interest are processed for each event. A Detector Element is the object where the geometrical info of the readout elements is obtained. For pixels this is the silicon sensor in a pix module. For SCT it is one side of the module. Figure 14 shows the reduction in the number of detector elements in an RoI when using the new TrigRoIDescriptor for 6 GeV μ's.

The η and ϕ resolutions are shown in Figure 15 for both the old and new RoIs, again for 6 GeV μ's. The resolutions obtained are very similar, with the new RoI descriptor having the slight advantage. Note that the number of reconstructed tracks in the new RoI is 4124, compared with 10234 in the old RoI. This suggests a large amount of data is being lost by implementing the new RoI descriptor.

Figure 16 shows the dramatic **decrease;** in efficiency when using the new TrigRoIDescriptor (bottom right) compared to the Level 1 RoI information (top right) This is due to the fact that only about 40% of generated muons are reconstructed at all in the new RoI, compare with 88% in the old RoI. This is almost certainly due to the method by which the muFast algorithm provides the TrigRoIDescriptor with the η_0 value at the vertex. This is simply passed in as the η of the track at the centre of the first measuremennt station in the muon spectrometer, without taking into account the effect of energy loss and multiple scattering in the calorimeters. The deflection a muon experiences traversing the calorimeters and solenoid is given by Eq. 5

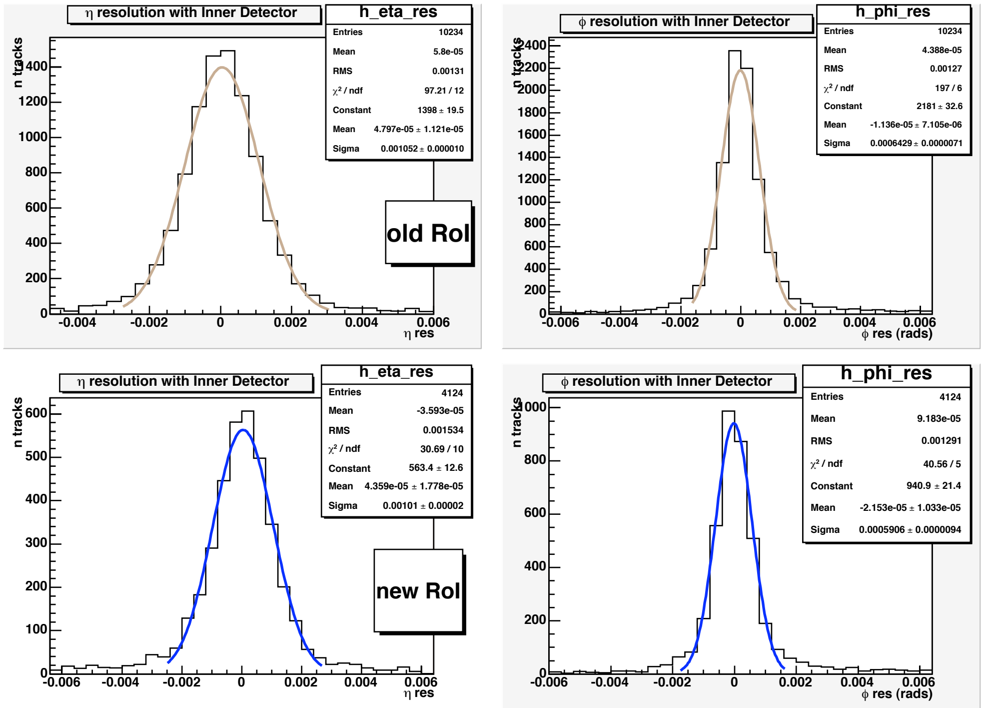

Figure 15: Histograms showing the η and ϕ resolutions (truth-reconstructed) obtained when using the Level 1 η_0 and ϕ_0 ((top) and the new TrigRoIDescriptor η_0 and ϕ_0 (bottom)

Figure 17 shows that in the back extrapolation to the Inner Detector from the muon spectrometer there is a (constant) sizable shift in z_0 of approximately 80mm.

$$d = \frac{Q \cdot FieldIntegral}{P_t - P_t^0}; \qquad (5)$$

Where Q is charge, and P_{t^0} is the the energy lost. MonteCarlo estimates give P_{t^0} as a constant value of around 1.5 GeV.[5]

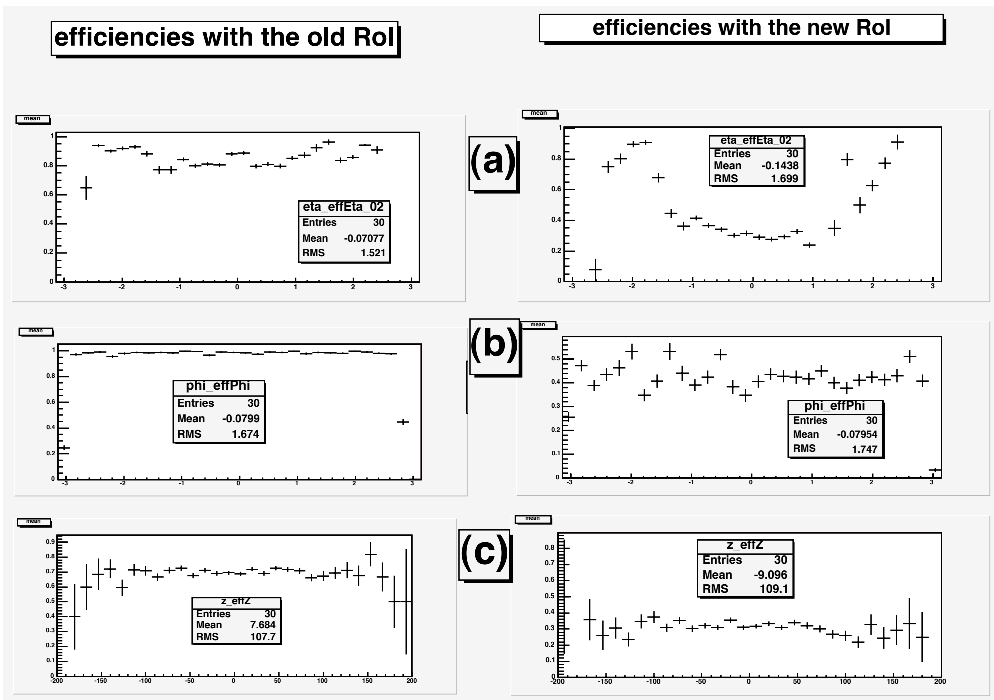

Figure 16: Histograms showing the Inner detector's efficiency at reconstructing (a)the z vertex to within 0.5mm as a function of the true z vertex, (b) the η at the vertex to within 0.2 mrad as a function of true η, (c) the ϕ at the vertex to with 0.02 mrad as a function of true ϕ.

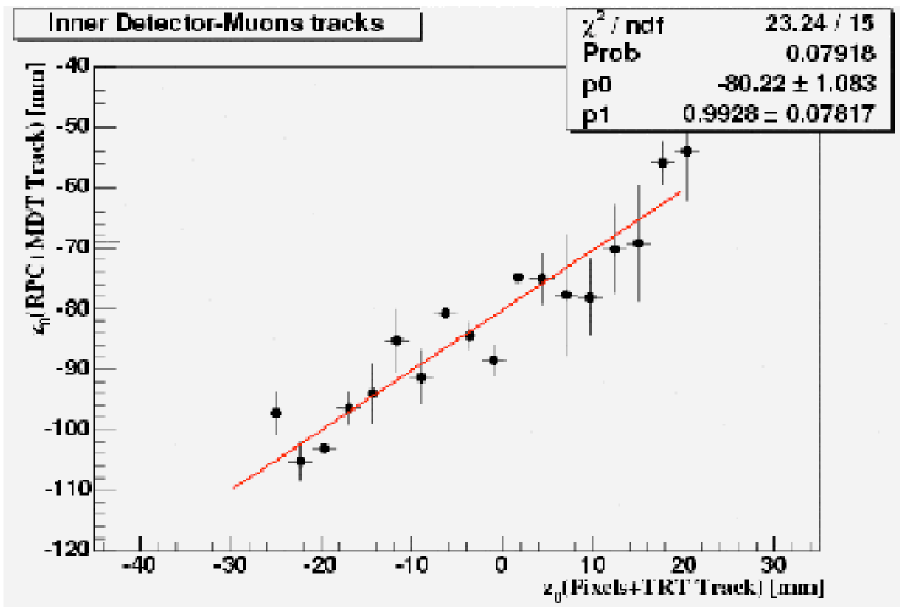

Figure 17: A plot showing the relationship between the z vertex positions obtained from tracking with μFast and IdScan [4]

5 Future Plans

I'm going to be continuing with this work for the next few months. There are improvements that can be made on the new RoI descriptor. If a correction for energy loss/scattering is implemented in muFast in a similar way to muComb except for being outside-in rather than inside-out, then a more accurate η position will be passed to IdScan, improving the efficiency. Also the TrigRoIDescriptor can contain all of the track parameters z_0, d_0 (the point at which the track is at its closest approach to the beam pipe), and $\frac{1}{P_t}$ calculated in muFast. It is believed that an accurate extrapolation back to the z vertex could give a good improvement in the efficiency of IdScan.

References

[1] "http://www.techworld.com"

[2] " ATLAS Level-1 Calorimeter Trigger Algorithms, ATL-DAQ-2004-011"

[3] "A new implementation of the region of interest strategy for the atlas Level 2 Trigger", "The ATLAS HLT group"

[4] "S Rosati, status and preliminary results of the muon test beam in H8", "www.wlap.org/file-archive/2004/20041006-umwlap002-13-rosati.ppt "

[5] "http://www.nikhef.nl/pub/experiments/atlaswiki/index.php/ChapterIII"

[6] "Architecture of the Atlas HLT event selection software. " "The ATLAS HLT group"