Towards searching for trapped slepton decays in ATLAS

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Abstract

Charged sleptons with long lifetimes (~days) are cosmologically favoured in supergravity where the gravitino is the lightest supersymmetric particle. When no proton collisions are occurring, cosmic rays are the major background in searches for decays of sleptons trapped in the ATLAS detector. This project develops a method to suppress this background by distinguishing between upward-going and downward-going muons using timing information recorded by ATLAS's monitored drift tubes.

Introduction

Supergravity unites supersymmetry with general relativity to yield a quantum field theory of gravity. If the gravitino is chosen to be the lightest supersymmetric particle (LSP) in the theory, the next-lightest supersymmetric particle (NLSP) is predicted to have a long lifetime of 0.1 – 1000 days. The effects of a long-lived NLSP's decays on the early universe provide both constraints on the theory as well as interesting predictions. Observations of the cosmic microwave background favour a slepton NLSP, particularly the right-handed stau. The gravitino LSP is an ideal superWIMP dark matter candidate, as it inherits the graviton's property of only interacting gravitationally. As the LSP, it is stable, and its abundance could be explained by the decay of heavier supersymmetric particles. Also, an NLSP with a lifetime of about a month could also resolve the Lithium-7 abundance anomaly (Feng, Rajaraman, & Takayama, 2003).

Sleptons produced in the LHC could become trapped in its detectors, the muons from their decays to be later observed. If slepton decays are searched for during periods when the LHC beams are off, the predominant backgrounds are cosmic rays and muons induced by upward-going neutrinos passing through the Earth. With this method, on the order of 10 signal events per year are expected when the LHC is running at full luminosity, which is drowned by the cosmic ray rate of kHz. Observations of upward-going neutrino flux by Super-Kamiokande imply a background muon flux on the order of 100 per year (The Super-Kamiokande Collaboration, 1999). Stau induced muons are a possible background of similar magnitude. The cosmic ray background could be removed by ignoring all downward-going muons. The other backgrounds could be removed by ignoring muons whose origin is not from within the detector (Pinfold & Sibley, 2011).

Therefore, an important first step in searching for trapped slepton decays is to distinguish upward-going from downward-going muons. Looking at only the curvature of a particle's track in a magnetic field, the direction of the particle's momentum is ambiguous since the observed particle could be a particle or the oppositely-charged antiparticle. In looking at the tracks of collision products, the assumption can be made that particles must be travelling away from the interaction point, resolving the direction ambiguity. Cosmic rays, neutrino-induced muons, and trapped slepton decay muons do not originate from the interaction point, so the direction ambiguity must be resolved differently. This project works towards using timing information recorded by the ATLAS detector to determine the direction of observed muons.

The ATLAS Cosmic Ray Trigger

The ATLAS trigger is a combination of hardware and software whose purpose is to select events to record, as current data storage technology can only handle on the order of 100 events per second. During collision runs, the trigger must make decisions quickly in order to scrutinize the incoming data from 400 million bunch crossings per second. The detector is also kept on during periods when the beams are off, so-called cosmic ray runs. In these runs, a modified cosmic ray trigger operates to trigger data acquisition whenever a cosmic ray passes through the detector. As the trigger decides whether or not an event is recorded in the first place, it is important to understand when considering the trapped slepton decay search.

The first level of the trigger is completely implemented in embedded electronics onboard ATLAS. In the muon spectrometer, resistive plate chambers (RPCs) in the barrel and thin gap chambers (TGCs) in the endcaps drive the trigger. The muon-specific first level trigger (before 2011) looks for events where the majority of trigger layers report hits and where these hits have some coincidence in φ and η. These sectors of the detector are then designated regions of interest. In the cosmic ray running, the trigger in the upper half of the detector was delayed by 125 ns, so that only the lower half triggers regions of interest (The ATLAS Collaboration, 2010).

The high level trigger is implemented as software on dedicated server farms. Reconstruction algorithms are attempted on the event, and will trigger if the reconstruction is successful and meets desired criteria. Hits are searched for in the more precise monitored drift tubes (MDTs) using the regions of interest identified by the trigger chambers. In collision running, an attempt is made to fit these hits to a track originating from the interaction point. In the cosmic ray trigger, the usual requirement that tracks originate at the interaction point is relaxed. Also, the reconstruction algorithm is modified for cosmic ray runs to allow hits on opposite sides of the detector to be combined into the same track, whereas they would normally be interpreted as two separate tracks on opposite sides (Snuverink, 2009).

As the LHC increases its energy and luminosity, the trigger requirements will have to become more stringent for collisions; as the cosmic ray trigger shares the same trigger menu as the collision trigger, the cosmic ray trigger will inherit the new requirements. In particular, higher minimum momentum requirements will affect cosmic ray triggering. When a muon hits the middle RPC or TGC layer, a timing signal is sent to the corresponding outer layer. When that muon later hits the outer layer, it can be deemed high momentum if it arrives within a certain period after the timing signal does. Cosmic rays will not activate this trigger in the upper half of the detector: they hit the outer layer before the middle layer. Also, a condition requiring hits to weakly point back to the interaction point will be implemented in the first level trigger (Della Volpe, 2011).

As the trigger currently stands, cosmic rays are triggered upon. Upward-going neutrino induced muons and trapped slepton decay muons should also trigger, as only weak φ and η coincidence is needed. In collision runs, cosmic rays are interpreted as back-to-back muons, but in cosmic ray runs, they appear as unified tracks. However, future trigger menu changes will affect how many cosmic ray muons, neutrino induced muons, and trapped slepton decay muons are triggered. Because they go from the outside of the detector in, cosmic ray muons and neutrino induced muons may not be triggered in the future. As they originate from the inside, trapped slepton decay muons should still trigger. Also, the long lived particles group has implemented triggers for vertices displaced from the interaction point. These triggers have been introduced for the 2011 data, and will be useful, as slepton decays will not come from the interaction point. When looking at the data, it is important to look at the triggers that were in effect during data collection.

Monitored Drift Tubes and Timing

While the RPCs drive the trigger in the muon spectrometer barrel, the MDTs are designed to take precise position measurements. They are long aluminum tubes 30 mm in diameter, filled with a mixture of argon, nitrogen, and methane gas, with a 50 micron tungsten-rhenium wire at a potential 3270 V. As a muon passes through the tube, it ionizes a trail of molecules behind it. The ionization electrons then drift towards the central wire, and provide an electrical signal. The perpendicular distance from the wire to the track can be found from the time it takes the first electrons to drift to the wire after the particle hits, using a radius-time relation known for the tubes.

Determining the drift time is thus important in the reconstruction of muon tracks. There is no signal produced when the muon first hits the tube, so the drift time cannot be measured directly by an individual drift tube; instead, it must record the time when the first electrons arrive, relative to the bunch crossing clock. To determine the drift time, an assumption is made about the muons travelling through the tubes: that they originate from a collision (timed to the bunch crossing clock) at the interaction point, and travel at nearly the speed of light. Then for a specific tube in ATLAS, the time of flight for a collision product muon to get from the interaction point to that tube is known (t_{flight}). Propagation ($t_{propagation}$) and electronics (t_0) delays can be found from calibration of the detector, allowing the drift time to be determined (Aben, 2010).

Equation 1

$$t_{measured} = t_{drift} + t_{flight} + t_{propagation} + t_0$$

Because of the fact there are multiple tubes in a MDT chamber, t_0 can be determined by a refit method rather than calibration. All of the delays to the drift time should be about the same for all tubes in the same chamber. Using a set of $t_{measured}$ measurements from the tubes and the known t_{flight} and $t_{propogation}$ for the chamber, the chamber t_0 can be adjusted until the resulting t_{drift} times are consistent with a straight line path through the chamber. This $t_{0,refit}$ should be about the same as the $t_{0,calibration}$ determined by calibration, and the difference is recorded.

Cosmic rays completely violate the timing assumptions made for collision product muons. Unlike collision muons, cosmic rays can be in the center of the detector at arbitrary times, adding a jitter t_{jitter}. Also, they travel downwards through the detector, and so travel from the outer layers to the inner layers in the upper half of the detector, changing t_{flight} in the upper half of the detector. If the approximation is made that cosmic rays pass through the interaction point, the t_{flight} for a cosmic ray in the upper half of the detector is actually the negative of the time of flight expected for a collision muon ($t_{flight,collision}$); a collision muon goes from the interaction point to the tube, a cosmic ray goes from the tube to the interaction point. In the lower half of the detector, a collision muon and cosmic ray would have the same time of flight from the interaction point (Benekos, Coggeshall, & Liss, 2011).

The $t_{0,refit}$ is calculated using the collision muon assumptions on t_{flight}, even during cosmic ray runs. Thus, Equation 1 can be rewritten for the refit procedure.

Equation 2

$$t_{0,refit} = t_{measured} - t_{drift} - t_{propogation} - t_{flight,collision}$$

Substituting the actual t_{flight}, adding the t_{jitter}, and using the $t_{0,calibration}$, Equation 1 can be rewritten for cosmic ray muons.

Equation 3

$$t_{measured} = t_{jitter} + t_{drift} - t_{flight,collision} + t_{propagation} + t_{0,calibration} \text{ (upper half)}$$
$$t_{measured} = t_{jitter} + t_{drift} + t_{flight,collision} + t_{propagation} + t_{0,calibration} \text{ (lower half)}$$

Substituting $t_{measured}$ from Equation 3 into Equation 2 yields an expression for the $t_{0,refit}$ compared to $t_{0,calibration}$.

Equation 4

$$t_{0,refit} = t_{jitter} + t_{0,calibration} - 2t_{flight,collision} \text{ (upper half)}$$
$$t_{0,refit} = t_{jitter} + t_{0,calibration} \text{ (lower half)}$$

The difference between $t_{0,refit}$ and $t_{0,calibration}$ is recorded ($t_{0\ correction}$), so that $t_{0\ correction}$ can be expected to be zero for collision product muons. Thus, cosmic rays can be expected to have a $t_{0\ correction}$ of t_{jitter} in the lower half of the detector, and $t_{jitter} - 2t_{flight,collision}$ in the upper half of the detector. If we also approximate upward-going muons (neutrino induced or slepton decay products) as going through the interaction point and travelling at almost the speed of light, the converse can be expected: $t_{0\ correction}$ being $t_{jitter} - 2t_{flight,collision}$ in the lower half of the detector, and t_{jitter} in the upper half of the detector. These results can be better summarized by comparing the direction of the muon with the direction a collision muon would be going. A muon travelling down through the upper half of the detector or up through the lower half of the detector is travelling outside-in; otherwise, it is travelling inside-out, as a collision muon would. Equation 4 can then be made to apply to all muons.

Equation 5

$$t_{0\ correction} = t_{0,refit} - t_{0,calibration}$$
$$t_{0\ correction} = t_{jitter} - 2t_{flight,collision} \text{ (outside-in)}$$
$$t_{0\ correction} = t_{jitter} \text{ (inside-out)}$$

t_{jitter} presents a problem for differentiating muons based on direction, as it will be different for every muon. However, since a single muon will pass through multiple MDT chambers in the same half of the detector, it will have multiple $t_{0\ correction}$ values which share the same t_{jitter}. These $t_{0\ correction}$ values from different chambers will depend on the $t_{flight,collision}$ from the interaction point to that specific chamber. By using multiple $t_{0\ correction}$ values, the effect of t_{jitter} can be removed, as described later in this report, allowing outside-in and inside-out travel to be differentiated.

Software and Datasets

CERNVM 2.3.0 with the ATLAS and Grid software distributions was used as the development environment for this project. C++ packages were compiled against Athena 16.6.3.7 to analyze event summary data files (ESDs) and produce ROOT files. Ganga 5.6.9 was used to run these programs on CERN's Grid. Using the PyROOT wrapper, Python 2.6.5 with ROOT 5.28 libraries was used to analyze the outputted ROOT files to give final results.

2010 ATLAS data is considered in this project, as the first full year of LHC operation. Looking only at one year ensures that the trigger menus and reconstruction algorithms are the same across the data. Data taken during physics runs are designated part of the data10_7TeV project; data taken during cosmic ray runs are designated part of the data10_cos project. ATLAS Run Query yields that all of the data10_cos combined represents just less than 25 days of data collection.

The different triggers in the trigger menu send events to different streams of data files. The physics_CosmicMuons stream will be of primary interest in both data10_7TeV and data10_cos data, being triggered by the cosmic ray trigger. The event summary data contains the full output of reconstruction, and so identifies muon tracks and includes the timing information associated with them. The output from different reconstruction methods is included; StacoMuonCollection is considered here, which uses MuonBoy to do reconstruction in the muon spectrometer.

Looking at some data10_7TeV physics_CosmicMuons data, the reconstructed muons can be seen to be prevalent in both the top (φ positive) and bottom (φ negative) of the detector. This distribution is indicative of the fact that a cosmic ray during a collision run will get interpreted as two back-to-back reconstruction muons, as explained in the trigger section. There is an excess of top half muon tracks – perhaps these cosmic rays were not energetic enough to be detected in the bottom half.

Similarly, one can consider the φ distribution of reconstructed muons in the data10_cos physics_CosmicMuons data. Because of the modified reconstruction in cosmic ray running, cosmic rays are reconstructed as downward going muons, and φ negative dominates. However, there are still some muons reconstructed with φ positive – these muons may not have triggered the bottom half, and so were reconstructed in the top half. If some cosmic muons are indeed leaving tracks in the top half of the detector, but not the bottom half, the cause of this inefficiency will be important to understand.

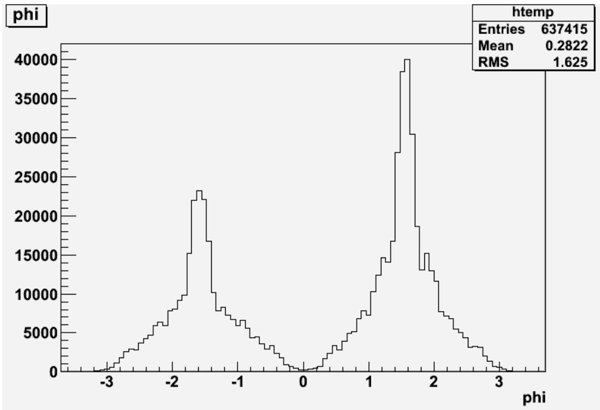


Figure 1. φ distribution of reconstructed muons in the cosmic ray stream, physics run 160472

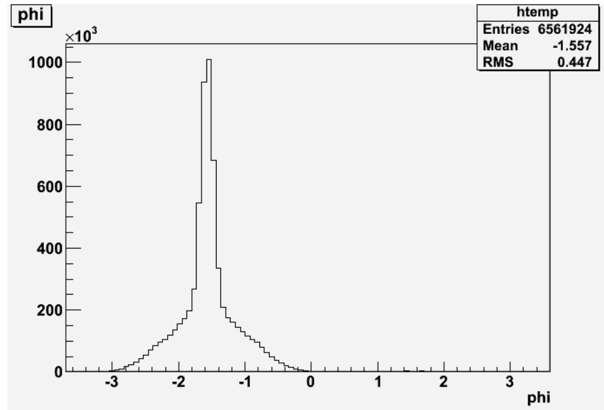


Figure 2. φ distribution of reconstructed muons in the cosmic ray stream, cosmic ray run 159934

$t_{0\ correction}$ Difference Method

Taking Equation 5 and considering the difference in $t_{0\ correction}$ between the outer and inner MDT layers of the same half of the detector ($\Delta t_{0\ correction}$) yields Equation 6.

Equation 6

$$\Delta t_{0\ correction} = t_{0\ correction,outer} - t_{0\ correction,inner}$$
$$\Delta t_{0\ correction} = 2\left(t_{flight,collision,inner} - t_{flight,collision,outer}\right)\ \text{(outside-in)}$$
$$\Delta t_{0\ correction} = 0\ \ \text{(inside-out)}$$

Outside-in travel can then be distinguished from inside-out travel on the basis of $\Delta t_{0\ correction}$. The outer MDT layer is at about a 10 m radius from the beam, and the inner MDT layer at about 5 m. Then, the $\Delta t_{0\ correction}$ for outside-in travel can be expected to be about 33 ns. The t_0 refit procedure is deemed to have a precision of 6 ns, so outside-in and inside-out muons should be differentiable.

To calculate $\Delta t_{0\ correction}$, hits are needed in an inner MDT chamber as well as an outer one. A program was written to carry out this calculation. For reconstruction muons with positive φ, at least one chamber $t_{0\ correction}$ is required in each of the inner and outer MDT layers, with only the upper half of the detector considered. For reconstruction muons with negative φ, only the lower half of the detector is considered.

Cosmic Ray Run, Cosmic Ray Stream

The physics_CosmicMuons stream of the data10_cos.00159934 dataset was analyzed. For reconstruction muons with positive φ, $\Delta t_{0\ correction}$ is centered at 25 ns, with an RMS of 29 ns. The $\Delta t_{0\ correction}$ is less than the expected 33 ns for outside-in travel, and the spread overlaps the 0 ns expected for inside-out travel, so any upward-going muons cannot be distinguished from the cosmic rays. For reconstruction muons with negative φ, $\Delta t_{0\ correction}$ is centered at -11 ns, with an RMS of 15 ns. The peak for $\Delta t_{0\ correction}$ is not at the expected 0 ns. Interestingly, the difference between the $\Delta t_{0\ correction}$ in the upper and lower half is 36 ns, which is much closer to 33 ns than 25 ns is.

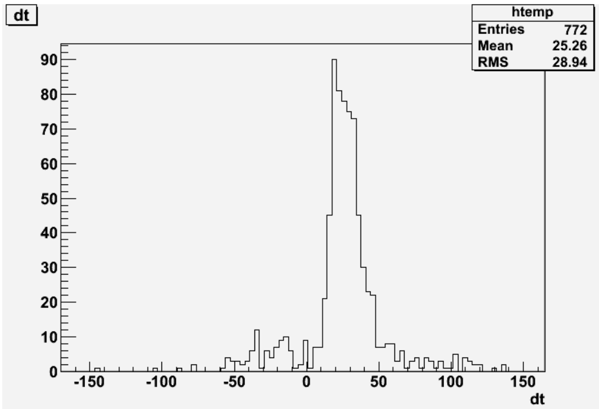


Figure 3. Δt_0 correction of reconstruction muons of positive φ in the cosmic ray steam, cosmic ray run 159934

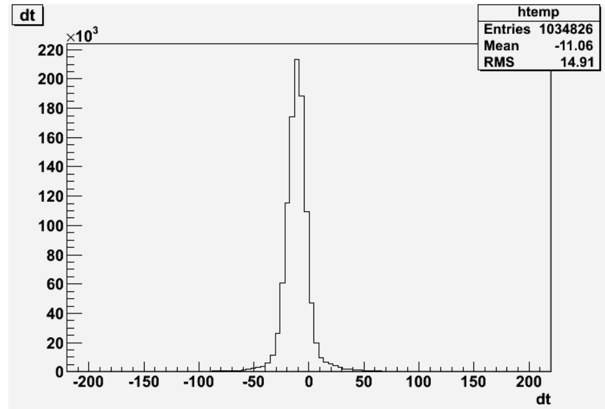


Figure 4. Δt_0 correction of reconstruction muons of negative φ in the cosmic ray steam, cosmic ray run 159934

To confirm that run 159934 was not just erroneous, runs 159831, 151219, and 152344 were also analyzed with the same procedure. Similar results for the $\Delta t_{0\ correction}$ peaks and spreads were obtained. However, given the size of the datasets, the differences in $\Delta t_{0\ correction}$ of a few ns seem to be significant. The cause of these differences between runs is unknown.

Physics Run, Cosmic Ray Stream

The physics_CosmicMuons stream of the data10_7TeV. 00160472 dataset was also analyzed for comparison. For reconstruction muons with positive φ, $\Delta t_{0\ correction}$ is centered at -38 ns, with an RMS of 17 ns. The $\Delta t_{0\ correction}$ is of the opposite sign of the $\Delta t_{0\ correction}$ in the cosmic run – there must be a difference in how the timing information is recorded. For reconstruction muons with negative φ, $\Delta t_{0\ correction}$ is centered at -2 ns, with an RMS of 18 ns. The peak for $\Delta t_{0\ correction}$ is not quite at the expected 0 ns, but is better than the cosmic run's -11 ns. Again, the difference between the $\Delta t_{0\ correction}$ in the upper and lower half is 36 ns.

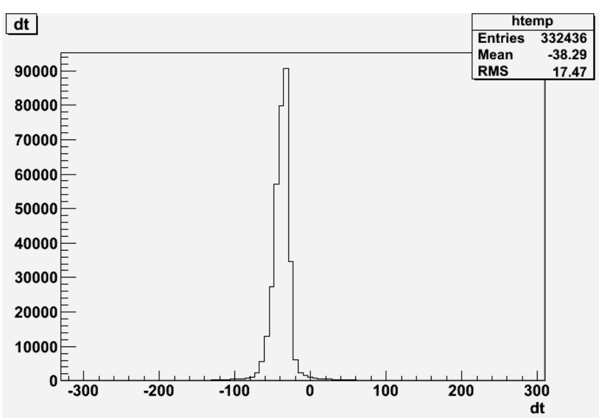


Figure 5. Δt_0 correction of reconstruction muons of positive φ in the cosmic ray steam, physics run 160472

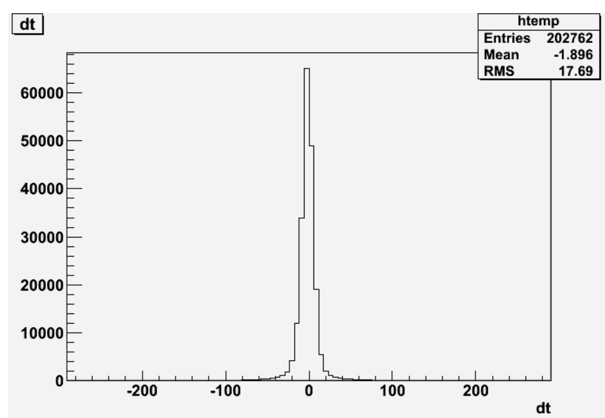


Figure 6. Δt_0 correction of reconstruction muons of negative φ in the cosmic ray steam, physics run 160472

An attempt was made to tighten the peaks in $\Delta t_{0\ correction}$ in the data10_7TeV.00160472 dataset using cuts. Only events with two back-to-back muons (defined as $\Delta\varphi \in [3.1, \pi]$) were considered, being almost certainly cosmic rays. In the upper half, the RMS decreased from 17 ns to 15 ns; in the lower half, the RMS decreases from 18 ns to 16 ns. Bad reconstruction is not to blame for most of the spread in $\Delta t_{0\ correction}$.

Physics Run, Physics Muon Stream

For comparison to the physics_CosmicMuons stream, the same analysis was done on the physics_Muons stream of the data10_7TeV.00160472 dataset. The φ distribution of these muons is fairly even and only reflects the structure of the detector, as is expected of collision product muons. For reconstruction muons with positive φ, $\Delta t_{0\ correction}$ is centered at -4 ns, with an RMS of 21 ns; for reconstruction muons with negative φ, $\Delta t_{0\ correction}$ is centered at -3 ns, with an RMS of 21 ns. The peak values are close to the expected 0 ns for collision muons' inside-out travel, but still significantly different. Perhaps there is some difference between runs that causes individual runs to not have peak $\Delta t_{0\ correction}$ values of exactly zero.

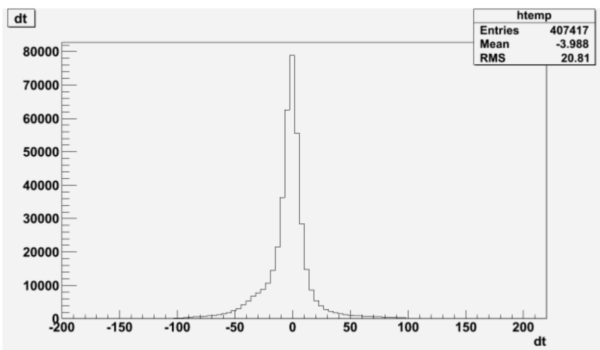


Figure 7. Δt_0 correction of reconstruction muons of positive φ in the physics muon steam, physics run 160472

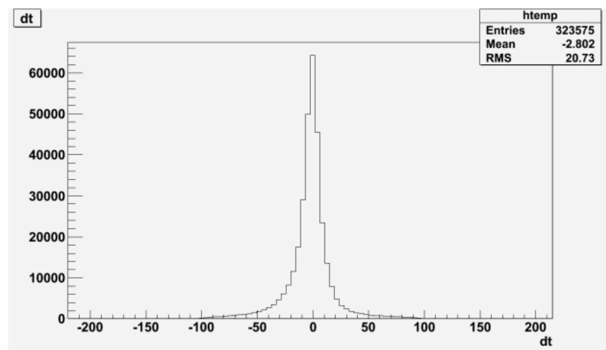


Figure 8. Δt_0 correction of reconstruction muons of positive φ in the physics muon steam, physics run 160472

$t_{0\ correction}$ Linear Least-Squares Fitting Method

With this method, $t_{0\ correction}$ is regarded as a function of $t_{flight,collision}$ at different chambers, and thus of the radial distance r of the chamber from the beam line.

Equation 7

$$t_{0\ correction} = t_{jitter} - \frac{2}{c} r \text{ (outside-in)}$$
$$t_{0\ correction} = t_{jitter} \text{ (inside-out)}$$

The $t_{0\ correction}$ from outside-in travel has a linear dependence on r, while inside-out travel should have a constant $t_{0\ correction}$. This method uses the $t_{0\ correction}$ from all three MDT layers, instead of just the inner layer and outer layer. An r can be assigned to each layer in one half of the detector (5, 7.5, and 10 m). The $t_{0\ correction}$ values on these r fitted to a straight line $t_{0\ correction} = a + br$ using the method of least squares, with the goodness of fit reflected in the coefficient of codetermination of the fit R^2. a

(being t_{jitter} in all cases) should be evenly distributed around a range of 25 ns, the frequency of the bunch crossing clock. b is expected to be 6.671 $\frac{ns}{m}$ for outside-in travel and 0 for inside-out travel.

In an attempt to clean the data, only events with hits (from any muon in the event) in all three layers in both the upper and lower halves of the detector are considered. Analysis is now done on an event-by-event basis, since data10_cos physics_CosmicMuons events typically have one reconstruction muon, but data10_7TeV physics_CosmicMuons events have two. A least squares fit is then done for each the top and bottom half of the detector.

Cosmic Ray Run, Cosmic Ray Stream

The physics_CosmicMuons stream of the data10_cos.00159934 dataset was analyzed. Far from being evenly spread, a in the lower half of the detector was peaked at -1 ns with an RMS 2 ns, with long tails to the tens of nanoseconds. A similar distribution holds for the upper half of the detector. Interesting, when a cut requiring a good fit is imposed ($R^2 > 0.99$), the distributions tighten considerably: mean of -0.2 ns and RMS of 0.4 ns in the lower half, mean of -0.05 ns and RMS of 0.3 ns in the upper half. There must be some connection between how well the $t_{0\ correction}$ fits a straight line and the t_{jitter}. It seems only muons with t_{jitter} close to zero can be measured well.

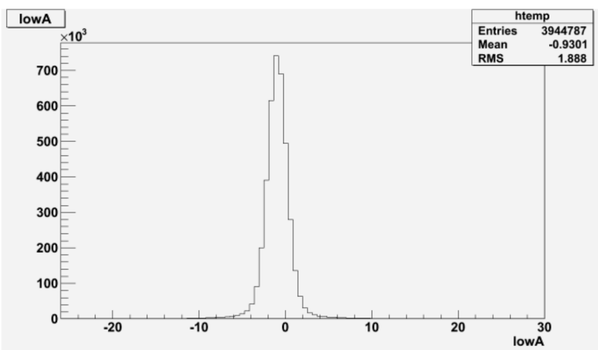


Figure 9. a distribution in the lower half of the detector for events in the cosmic ray stream, cosmic ray run 159934

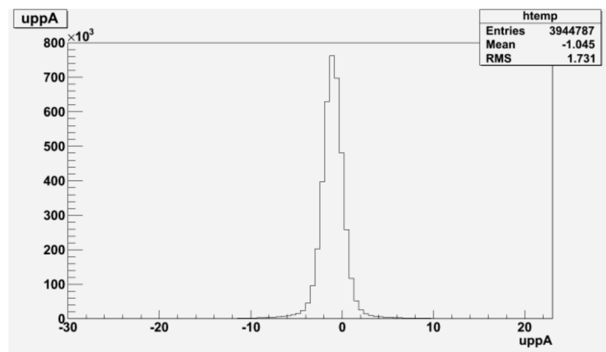


Figure 10. a distribution in the upper half of the detector for events in the cosmic ray stream, cosmic ray run 159934

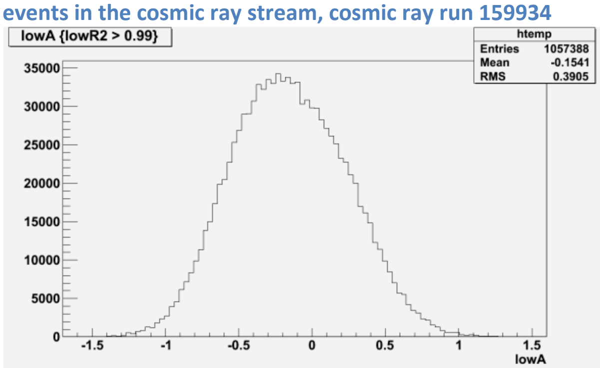


Figure 11. a distribution in the lower half of the detector for events in the cosmic ray stream, cosmic ray run 159934, after goodness of fit cut

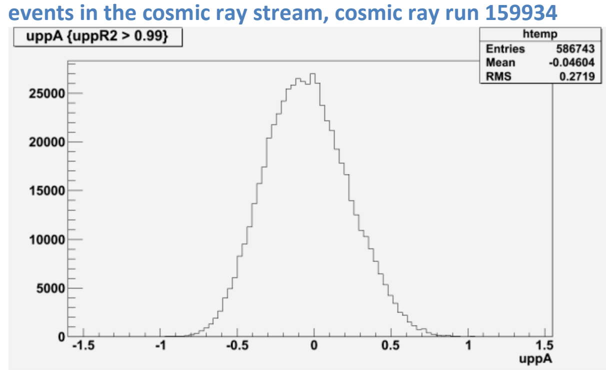


Figure 12. a distribution in the upper half of the detector for events in the cosmic ray stream, cosmic ray run 159934, after goodness of fit cut

In the lower half of the detector, b was peaked at -4.5 $\frac{ns}{m}$ with an RMS of 1.9 $\frac{ns}{m}$, far from the expected zero for cosmic rays. In the upper half of the detector, b was peaked at 1.6 $\frac{ns}{m}$ with an RMS of 1.7 $\frac{ns}{m}$, far from the expected $6.671\,\frac{ns}{m}$. Strangely, when the good fit condition is imposed in the upper half, the distribution of b changes drastically to have a mean of $3.0\,\frac{ns}{m}$ and RMS of $1.5\,\frac{ns}{m}$. Again, something is different about the tracks with good fits. These b values are much different than what is predicted – there might be additional considerations about $t_{0\ correction}$ to take into account before this method is usable.

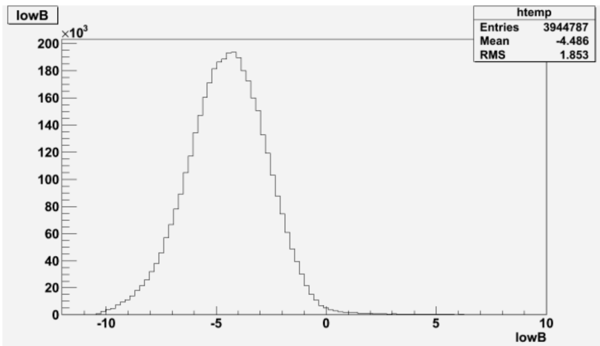


Figure 13. b distribution in the lower half of the detector for events in the cosmic ray stream, cosmic ray run 159934

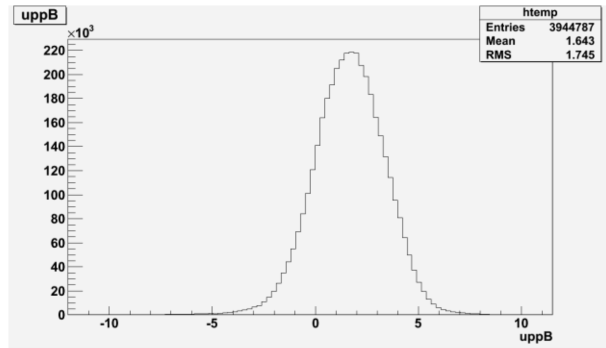


Figure 14. b distribution in the upper half of the detector for events in the cosmic ray stream, cosmic ray run 159934

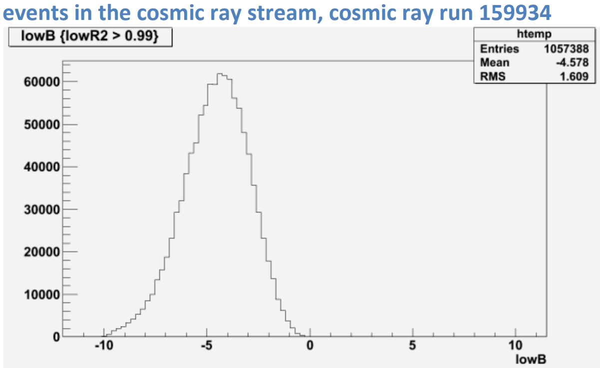


Figure 15. b distribution in the lower half of the detector for events in the cosmic ray stream, cosmic ray run 159934, after goodness of fit cut

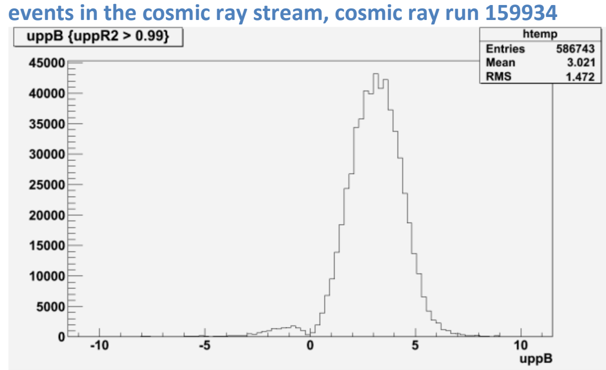


Figure 16. b distribution in the upper half of the detector for events in the cosmic ray stream, cosmic ray run 159934, after goodness of fit cut

Physics Run, Cosmic Ray Stream

The physics_CosmicMuons stream of the data10_7TeV. 00160472 dataset was also analyzed. Again, a is not evenly spread in either half of the detector: both distributions have peaks at 2 ns, and RMS of about 2 ns. When the goodness of fit cut is applied, both distributions narrow to a peak at 0.2 ns and RMS of 0.5 ns; but the shapes look drastically different. These results reinforce that there is some strong connection of goodness of fit with a.

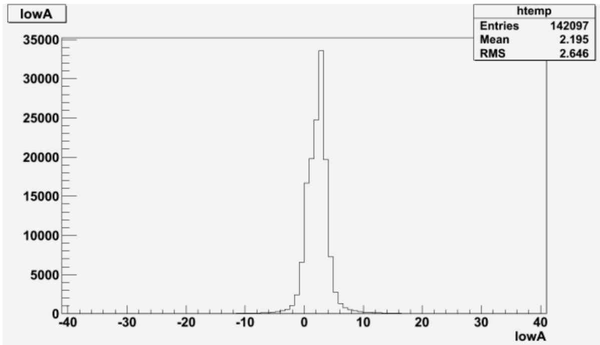


Figure 17. a **distribution in the lower half of the detector for events in the cosmic ray stream, physics run 160472**

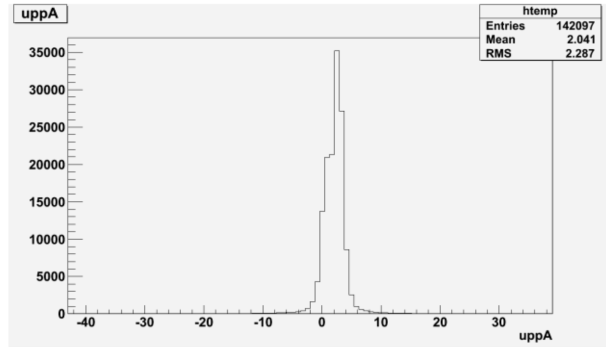


Figure 138. a **distribution in the upper half of the detector for events in the cosmic ray stream, physics run 160472**

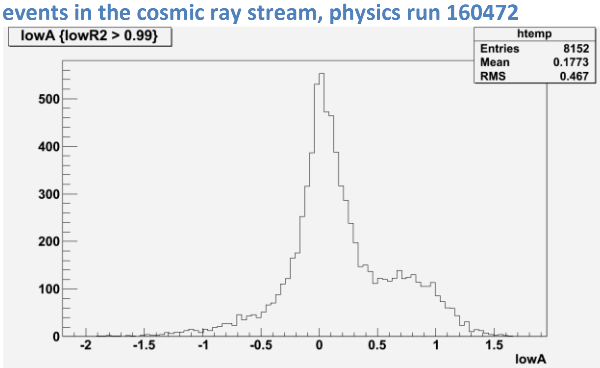


Figure 19. a **distribution in the lower half of the detector for events in the cosmic ray stream, physics run 160472, after goodness of fit cut**

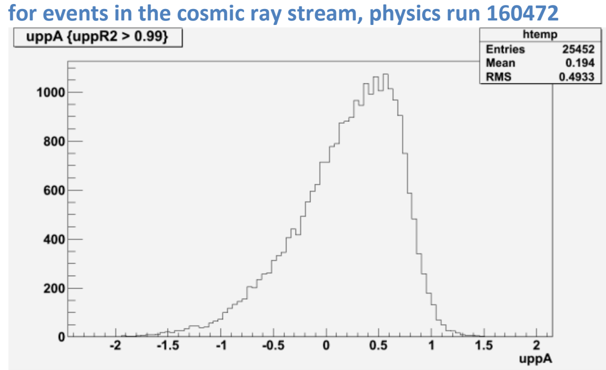
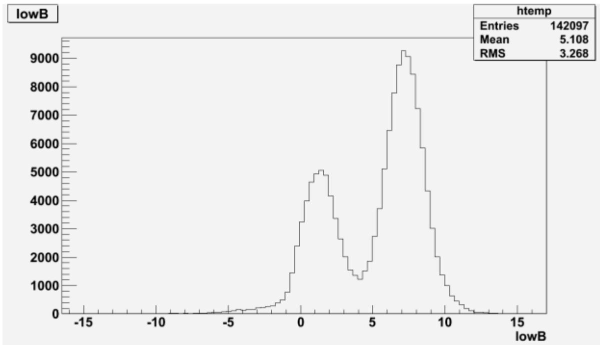


Figure 20. a **distribution in the upper half of the detector for events in the cosmic ray stream, physics run 160472, after goodness of fit cut**

In the lower half of the detector, b has a double humped distribution with peaks at around 1 $\frac{ns}{m}$ and 7 $\frac{ns}{m}$. Recall that the expected b for a cosmic ray muon in the lower half of the detector is zero. If a goodness of fit cut is placed on both the lower half and upper half fit, the distribution is single peaked at 0.8 $\frac{ns}{m}$ with an RMS of 2 $\frac{ns}{m}$. In the upper half of the detector, b has a double humped distribution with peaks at around -6 $\frac{ns}{m}$ and 0 $\frac{ns}{m}$. When a goodness of fit cut is enforced, the distribution is only single peaked at -6 $\frac{ns}{m}$ with RMS 2 $\frac{ns}{m}$. The remaining peak values after the cuts are close to what is expected for a cosmic ray muon, but the spread is still quite large. The cause of these double peaks is unknown; interestingly, the peaks that disappear (7 $\frac{ns}{m}$ in the lower half, 0 $\frac{ns}{m}$ in the upper half) are consistent with an upward going muon.



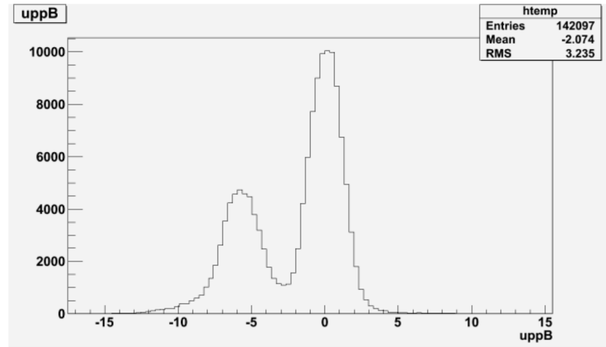
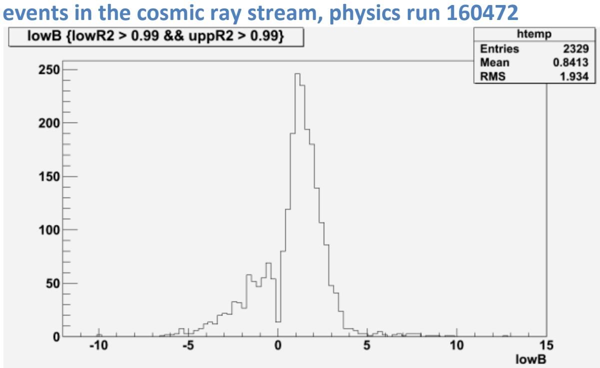


Figure 21. b distribution in the lower half of the detector for events in the cosmic ray stream, physics run 160472

Figure 22. b distribution in the upper half of the detector for events in the cosmic ray stream, physics run 160472



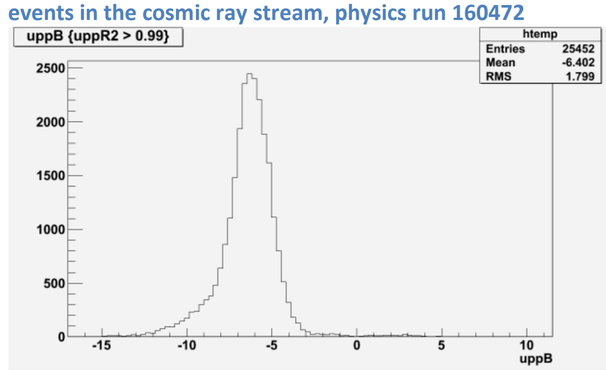


Figure 23. b distribution in the lower half of the detector for events in the cosmic ray stream, physics run 160472, after goodness of fit cuts on both halves

Figure 24. b distribution in the upper half of the detector for events in the cosmic ray stream, physics run 160472, after goodness of fit cut

Conclusion

More research is needed before timing information can be used to distinguish upward-going muons from downward-going muons in ATLAS's cosmic ray runs. Two methods of analyzing the t_0 timings have been developed using an incomplete knowledge of t_0; finding more information on how to interpret t_0 will make these methods useful for analysis. As the ATLAS trigger menu changes, the trapped slepton analysis will be greatly affected, as the muon decays neither originate from the interaction point nor align with the bunch crossing clock. These methods could also be used to study study other upward-going particles, such as neutrino-induced muons and staus.

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