A tool for monitoring the ILD single muon reconstruction performance.

A tool to look at the efficiency of reconstructed tracks in the ILC software framework looking at the dependence of theta and transverse momentum

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Abstract

The international linear detector (ILD) is a proposed detector for the international linear collider (ILC). Currently continual software updates are being made to simulate how particles will interact and behave in this detector. This will help with the analyse of data in the future as well as being vital in the design and building of the detector. It is therefore important to understand the performance of the detector. This tool currently use muons, due to there deep penetrating nature, to look at the theta distribution and transverse momentum of particles within the ILD. The efficiency of the software to reconstruct and identify the particle is then found. This successfully showed 4 areas of low efficiency within the reconstruction software. A soon to be released version of the software (ILCsoft v02-00-02-pre02) was then tested where it was found that there was an improvement of two regions within the detector.

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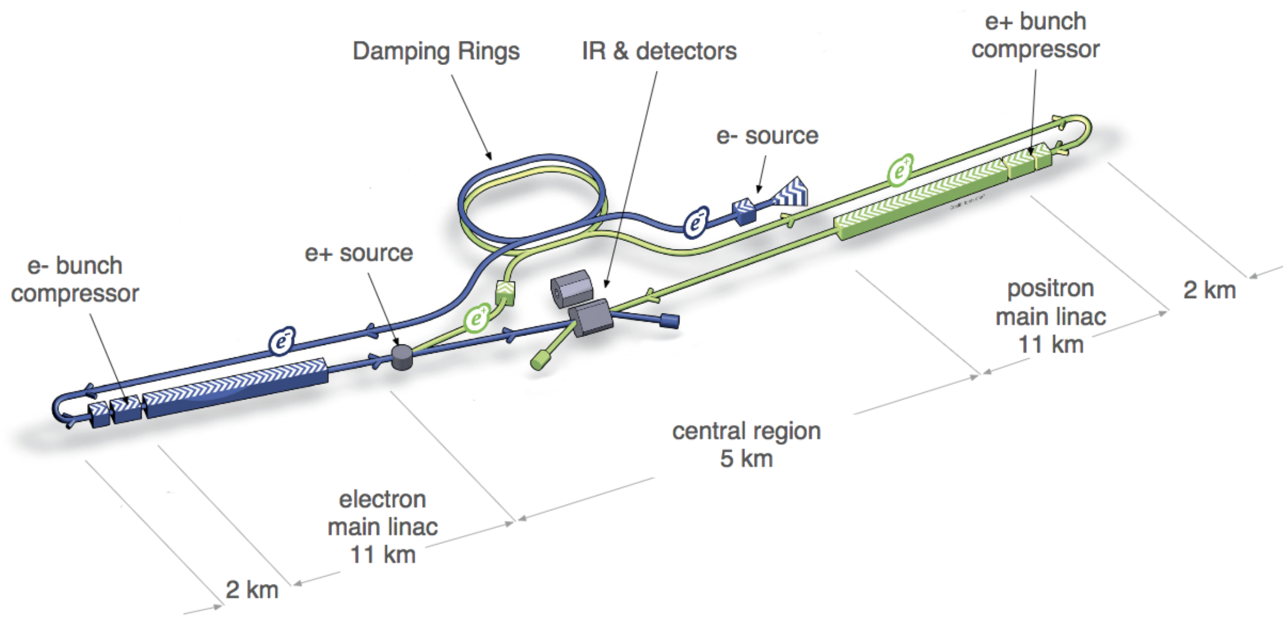


Figure 1: A schematic of the ILC accelerator layout indicating all major elements [1]

The international linear collider (ILC) is a proposed new electron positron collider with an initial centre-of-mass energy of 250GeV with the use of 1.3GHz superconducting radio-frequency[1] accelerating cavities, with plans to reach up to 1TeV in later phases. The schematic of the ILC accelerator can be seen in figure 1. This design results in a luminosity of 250fb^{-} [2] which is need for the ILC ambitious physics programme. Unlike the LHC, electrons and positrons are point like particles making 'cleaner' collisions with better reconstruction capabilities improving the precision of measurements.

Initially at energies up to 160GeV, the ILC will be looking at improving measurements in the electroweak model. This will include improved measurement of asymmetries and coupling of the Z boson by orders of magnitude and the mass of the W boson with MeV precision. At centre-of-mass energies up to 250GeV , precision measurement of the coupling and properties of the 125GeV higgs boson can occur, mainly using the $e^+e^- = hZ$ reaction. [2]

Currently this is the energy limit of the first phase of the ILC. Beyond this energy to around 400GeV, rare higgs reactions occur providing further measurements. The production of top quark also occur which will provide a precise measurement of the mass and cross-sections in addition to providing further constraining measurements of the electroweak asymmetry. Furthermore, coupling of WW bosons will provide a probe into physics beyond the standard model as the coupling grows exponentially in strength. Once 500GeV is reached studies of fermion pair production can probe vector resonance peaks, quark and lepton compositeness and new ferimon interactions. At 1 TeV higgs coupling to top quarks and self coupling can be studied.

The ILC will help with our understanding of physics beyond the standard model. As well as the already mentioned studies, searches for new particles will occur. It is hoped that supersymmetric particles will be found as well as a dark matter particle candidate will appear. Dark matter accounts for about 23% of the matter in the universe. There are many theories as to what dark matter could be from WIMPs to axions. The ILC should reach the required energy to look for supersymmetric WIMPs.

2 Detector - ILD

This ambitious physics programme requires detectors with high precision. As can be seen in figure 1 two detectors are proposed as to, in affect, have two experiments. Unlike circular colliders there is only one interaction point (IP). Therefore, the detectors will lie on tracks so they can be swapped in and out of the beam line.

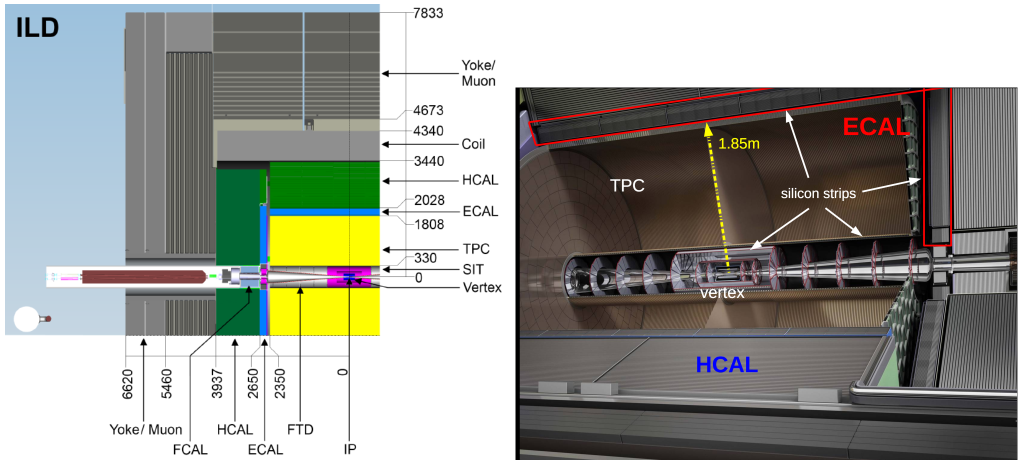


Figure 2: A quadrant view of the ILD detector in the yz plane. The individual layers of the detector can be seen all measurements are in mm.[3][4]

The international large detector (ILD) is one of these detectors. The ILD combines excellent tracking and finely-grained calorimetry systems. This gives ILD the ability to reconstruct the energy of individual particles, known as the Particle Flow approach. ILD has been developed for high precision event reconstruction, as needed by the science program at the ILC. As can be seen in figure 2, the ILD is a multilayer detector, which is typical of detectors built for accelerator based experiments.

The main parts of the detector are [5]:

- **Vertex detector**: The Vertex detector (VTX) is the inner most layer of the detector as can be seen in 2. The VTX allows for high performance flavour tagging using reconstructed vertices. It also is important in track reconstruction of low momentum particles which don't reach the main trackers as well as shallow angle produced particles. It is made of 6 cylindrical layers and can cover $|\cos\theta| \leqslant 0.97$.

- **Inner silicon trackers**: surrounding the VTX before the time projection chamber (TPC) are a layer of silicon detectors. This improves tracking in the transition from the VTX to the TPC. It also improves the momentum resolution and reconstruction of low momentum as well as long lived stable particles. Silicon trackers are also in the forward tracking region. These detectors are positioned in the innermost section of the tracking region comprised of several disks.

- **Time projection chamber**: The large volume Time projection chamber (TPC) will produce 220 points of reference per track. It is a unique selling point of the ILC providing excellent 3-dimensional point resolution for minimal material requirements. It provides dE/dx particle identification methods.

- **External silicon tracker**: Between the TPC and electrocalorimeter (ECAL) is another set of silicon detectors providing a similar job to the last silicon trackers.

- **Electrocalorimeters (ECAL)**: The ECAL is the first of the calorimeter system and is designed to make measurements of tracks energy and identify photons. Consisting of tungsten absorber plates interwoven with layers of silicon detectors provide fine segmentation readout. The Particle flow approach requires unprecedented granularity in all the calorimeters, with energy leackage minimised. [6]

- **Hardrocalorimeters (HCAL)**: The HCAL is planned to be a sampling calorimeter with steel absorber plates and scintillator cells with fine granularity and multi-bit analogue readout. This is designed to deal with the bulk of hadronic showers. THe HCAL has been optimised to measure neutral hadrons and provide he topological resolution power need to for shower separation.

- **Calorimeters**: Three other calorimeters are planed for the very forward region of the ILD close to the IP. LumiCal will provide precise measurements of the luminosity while BeamCal will provide a fast estimate of the luminosity. LHCAL with provide measurements of neutral hadrons at very small angles.

- **Superconducting coil**: All these will sit inside a superconducting coil creating an axial magnetic field of 3.5T.

- **Muon detector** A iron yoke is instrumented with scintillator strips. As well as acting as a return yoke for the magnetic flux it will serve as a muon filter and detector. Due to the clean environment of a electron-postrion collider the muon detector can be much more simple when compared to hardon colliders. This allows event linking between tracks in the inner detector to the muon detector. It will also be important as a tail catcher to handle any leakage from the calorimeters.

2.1 Finding theta and transverse momentum

For mcparticle and PFOs finding theta of a particles angle in the detector can be found using the momentum vector in both collections and can be seen in equation 1.

$$\theta = \frac{p_z}{|p|} \tag{1}$$

where, p=(p_x, p_y, p_z).

For the Marlin tracker this becomes a slightly more complicated affair. No information is known about the particle. There are 5 parameters that characterise the tracks. These are [7]:

- ϕ_0, Azimuthal angle of track tangent (momentum of particle) at the point of closet approach to the reference point (typically (0, 0, 0)) in the xy-plane.
- Ω, track curvature $|\Omega| = R^{-1}$
- d_0, impact parameter in the xy-plane
- $\tan\lambda$, slope of $\frac{dz}{ds}$ here s is the arc length of the xy plane
- z_0, z-coordinate of the point of closest approach

$\tan\lambda$ is directly related to the polar angle theta and the momentum vector such that,

$$\tan\lambda = \frac{p_z}{\sqrt{p_x^2 + p_y^2}} = \cot\theta.[7] \tag{2}$$

From this theta is found to be,

$$\theta = \frac{\tan\lambda}{\sqrt{1 + \tan\lambda^2}}. \tag{3}$$

Similarly, the transverse momentum with respect to the beam line can be found to be,

$$p_T = a\left|\frac{B_z}{\Omega}\right|.[7] \tag{4}$$

For a transverse momentum in GeV/c, B_z must be in tesla, Ω is in mm^{-1} and a=c$\times 10^{-12}$.

3 ILCSoft and Selection

3.1 Aim

The aim of the project is to create a tool for looking at the efficiency of reconstructed muon tracks.

3.2 ILCSoft

Using ILCsoft software under the Marlin and DD4hep framework, simulations were ran on ILD_l5_o1_v02 detector model with most using the v02-00-01 ILCsoft other then a test case for the next version update v02-00-02-pre02 prerelese. From theses simulations I am interested in 4 collections.

- mcparticle: This is the collection containing information about the true information of a particle within the ILD. This can be used later when finding the efficiency as we expect the reconstructed tracks to contain the same information as the mcparticle class.
- Marlin Track (track): This collection only contains information about what area of the detector has been hit and makes a fit accordingly. It does not contain any information about the particle other then where there was a hit.
- Reconstructed Particle class (PFOs): This collection takes the tracking information and calaorimeter information then determines information about the particles from it. The result is that it should contain the same information as the mcparticle class but this is only determined by the information provide by the detector and not from knowledge of the particle simulation. The ILD needs good reconstruction efficiency to provide accurate results.
- LCRelation: is a class that allows the user to find out the single weighted relationship between a LCObjects anf the truth information. This will allow later for the truth information to be shared between the different collections.

3.3 Cuts

A number of cuts have to be made as to insure only events from a single muon are used to find the efficiency as well as to help with the fitting. The type of cuts made are very important to the accuracy of my efficiency plots.

For the mcparticle class the following cuts were made:

- The particle must have charge
- They must be stable in the generator. This means that the particle didn't decay or was from some other physical event when first created resulting in a different momentum.
- It doesn't decay. This means that the particle doesn't decay inside the tracker and produce new particles.
- Is less then 10mm from the vertex to stop smearing
- Is a muon.

For the Marlin tracks this is a more difficult task as there is no information about the state of the particle. The only cuts made are to compare reconstruction by using the difference of the transverse momentum and theta as seen in equation 5 and 6.

$$\Delta p_t = p_t^{trk} - p_t^{mc} \tag{5}$$

$$\Delta\theta = \theta_{trk} - \theta_{mc} \tag{6}$$

Defining that $\Delta p_t = \pm 0.15 GeV$ and $\Delta\theta = \pm 0.1°$ for the marlin track case.

For the reconstruction class cuts on type can be made:

- It must be charged
- $\Delta p_t = \pm 0.2 GeV$
- $\Delta\theta = \pm 0.1°$
- is a muon.

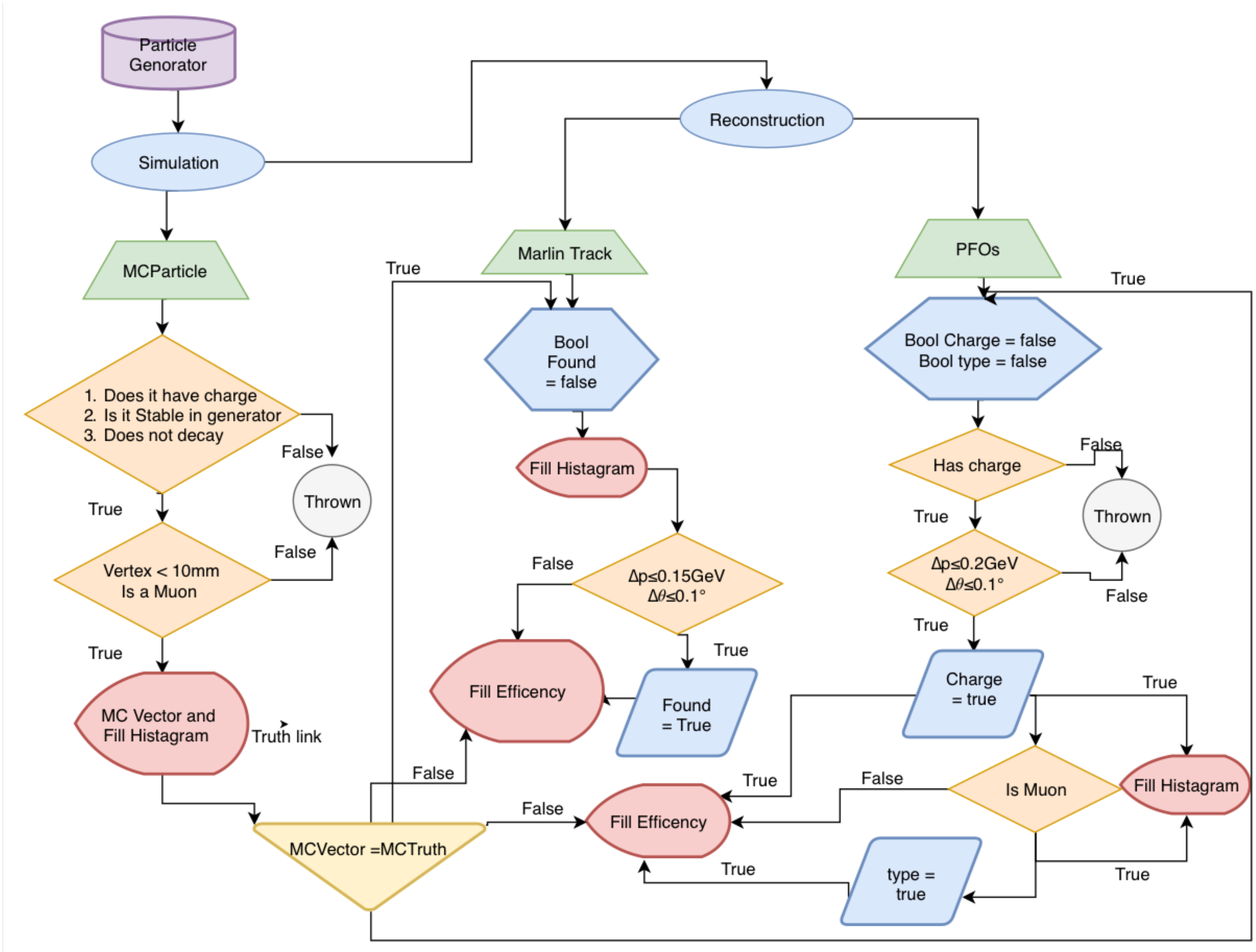


Figure 3: This flow digram shows the selection logic of the programme. The blue represents the input of a boolen, green represents the collection, orange means a cut, red is an output and yellow represents a mcparticle truth.

3.4 Selection

Applying cuts isn't enough to find the efficiency. As can be seen in figure 3, this flow diagram shows the logic applied to determine the efficiency. The cuts are made on the mcparticle collection if any are false the event is thrown, if true, a vector is created containing the particles truth link and also fills a histogram of theta distribution.

This truth information from the vector is then feed back into the track and PFOs. In a similar fashion the cuts are made and then the efficiency is filled depending on if the particle is seen in both mcparticles and the tracking information. The same logic is applied to the PFOs with a distinction that a cut is made on charge and then efficiency is found and a second cut is made on type to be a muon and then efficiency is found again separately.

The most important part of this logic is this truth link vector. If the difference between the true tracks and the reconstructed tracks is not the same, then there is a lack of performance within the software to reconstruct the tracks and determine the properties of the particle. By finding out where in the detector these lower performance areas are it can be possible to find the cause and try to improve the code.

4 Results

4.1 20GeV Gun

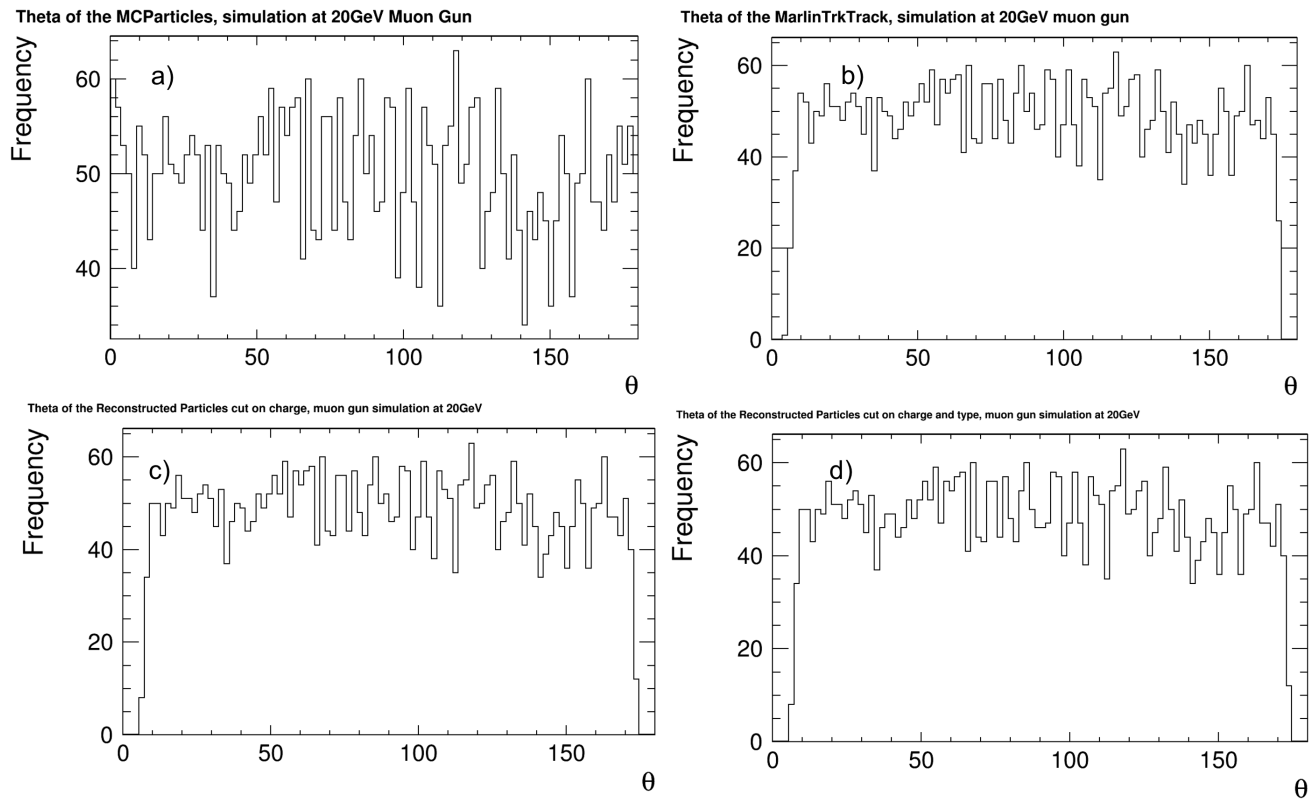


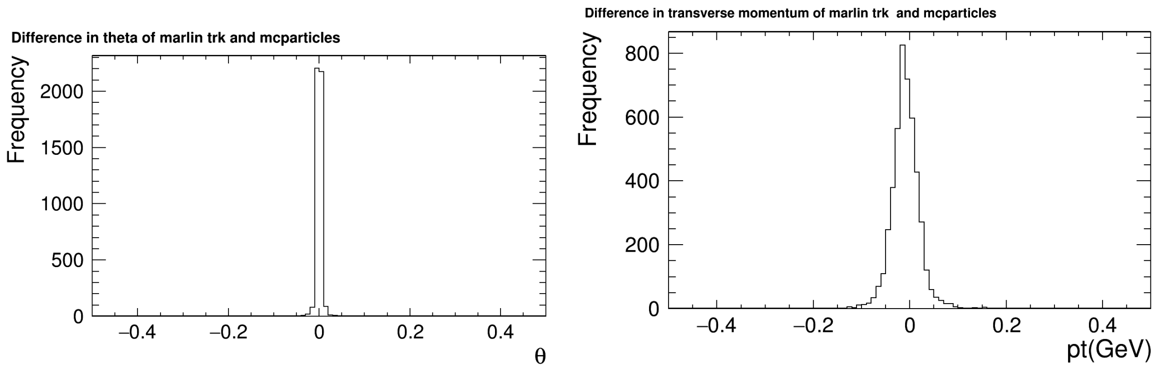
Figure 4: Theta distribution of a 20GeV muon gun simulation. a) The theta distribution of MCparticles. b) The theta distribution of marlin tracks. c) The theta distribution of PFO's with cut on charge only. d) The theta distribution of PFO's with cut on charge and is a muon.

The first simulation ran was a simple 20GeV muon gun with theta randomly assigned for 5000 events. Figure 4, the theta distribution can be seen. Looking at the graph for mcparticles we can see that there are muons within the beam pipe (0-3° and 178-180°). This is due to the fact, as descried earlier (3.2) , this class knows the information about the particle, irrespective of the detector. Meaning, despite the lack of detector within the beam pipe, this class knows that the muon is there. This becomes clear when compared to the other 3 histograms where there are no muons seen at these angles. On close inspection it can be seen that the first few degrees after the beam pipe the number of muons is less then the general average. The rest of the histogram follows the trend that is expected. As theta was set randomly you would expect to see a almost equal amount of muons in each bin. There are a few bins in a) that have relatively few muons this is likely from a relatively small number of events and the fact a bin is only 1.8° big.

To show that the cuts made using the difference between theta and between transverse momentum are allowed you can look at figure 5. As can be seen in theses plots most muons lie within these ranges. This means we can remove any muons outside of this range without it affecting the efficiency plots.

In figure 6, the first efficiency plots for marlin tracks can be seen. The efficiency in the beam pipe is zero (figure 6a) which is what would be expected as there is no detectors in this region so no reconstruction can occur. There are no areas where there is a dramatic drop in efficiency. This is good as it would imply that the software can find tracks that match that of the true physics event.

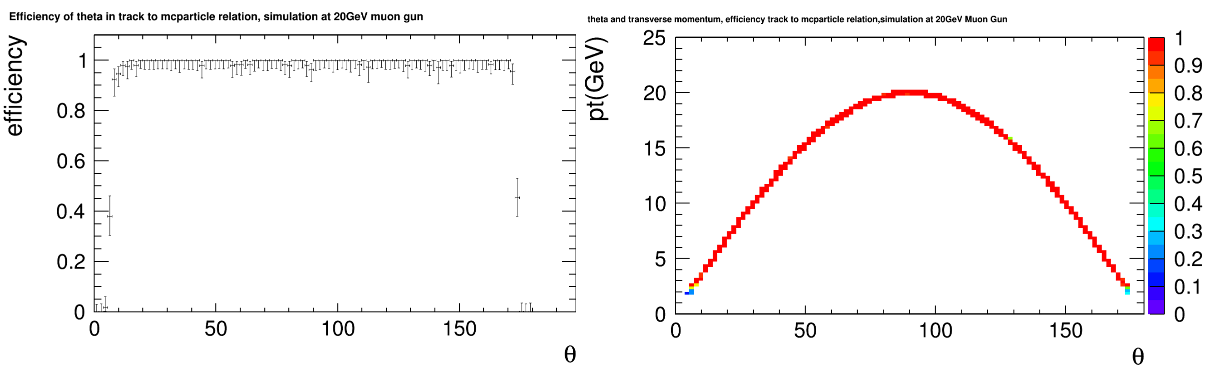
Now looking at the reconstruction case (figure 7 and 8) we start to see points of low efficiency. This is clearest in figure 8 where there are 4 distinct spots of low efficiency. In plot 8a there are three points of low efficiency at 45°, 90° and 143° there is also region of lower efficiency around 125°. The lower efficiency



(a) The difference in theta

(b) Difference in transverse momentum

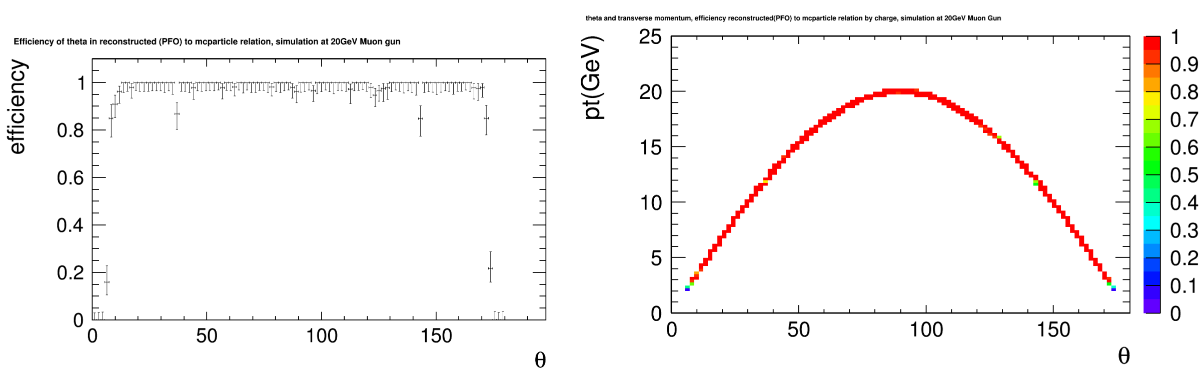
Figure 5: The difference of theta and transverse momentum for marlin tracks as defined by equation 5 and 6.



(a) The efficiency of theta.

(b) 2D efficiency of theta and transverse momentum

Figure 6: Efficiency of the marlin tracks in comparison to mcparticles of a 20GeV gun.

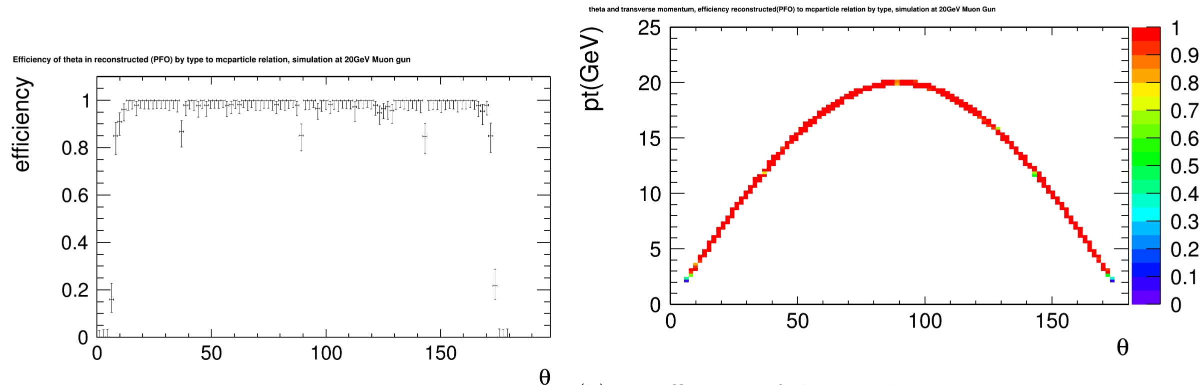


(a) The efficiency of theta with charge but doesn't have to be muon.

(b) 2D efficiency of theta and transverse momentum with charge

Figure 7: Efficiency of the reconstructed tracks in comparison to mcparticles at a 20GeV gun.

at 90° is due to the cathode which is at 90° around the TPC (refer to section 2). The issue at 45° and 143° is due to a steeping issue in the TPC calculation of track position at the transition point. 125° is an interesting point as it is not symmetric. The reason for this is not clear. It could be due to cuts made within



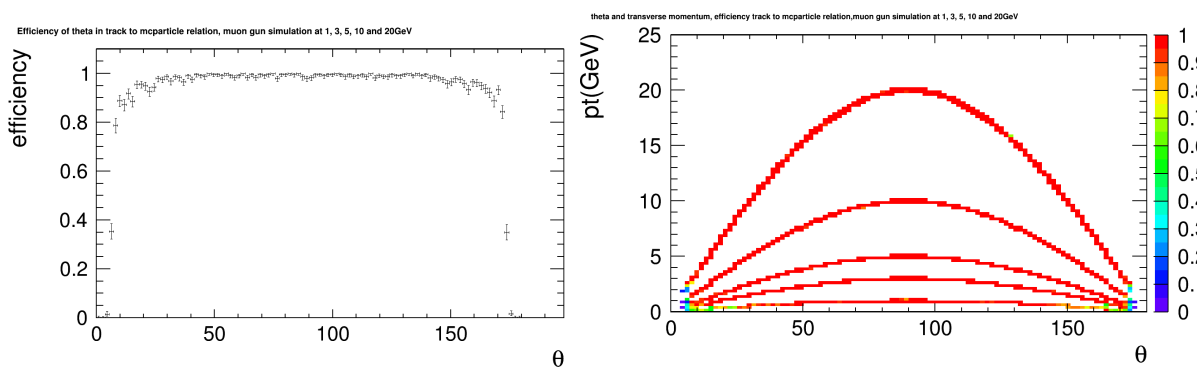
(a) The efficiency of theta with charge and is a muon.

(b) 2D efficiency of theta and transverse momentum with charge and is a muon

Figure 8: Efficiency of the reconstructed tracks in comparison to mcparcticles at a 20GeV gun.

the reconstruction software itself. Further investigation is required. We can see comparing 7 and 8 that there isn't a huge different between charge and muon plots this would suggest that there is good particle identification occurring.

4.2 1, 3, 5, 10 and 20 GeV Gun



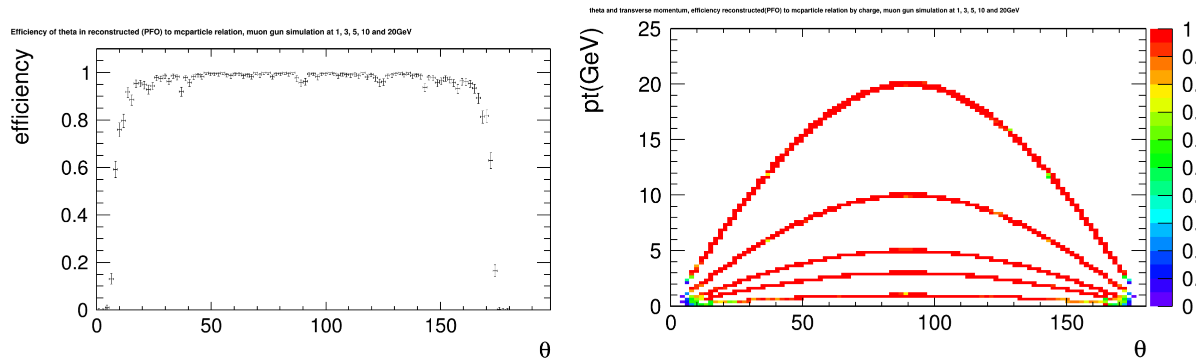
(a) The efficiency of theta.

(b) 2D efficiency of theta and transverse momentum

Figure 9: Efficiency of the marlin tracks in comparison to mcparcticles at a 1, 3, 5, 10 and 20GeV gun.

The same simulation is made at 1, 3, 5 and 10 GeV and combined to see how the efficiency changes at lower momentum. The efficiency in the track (figure 9) remains similar to that seen before. The error bars have decreased as the number of event has increased by a factor of 4.

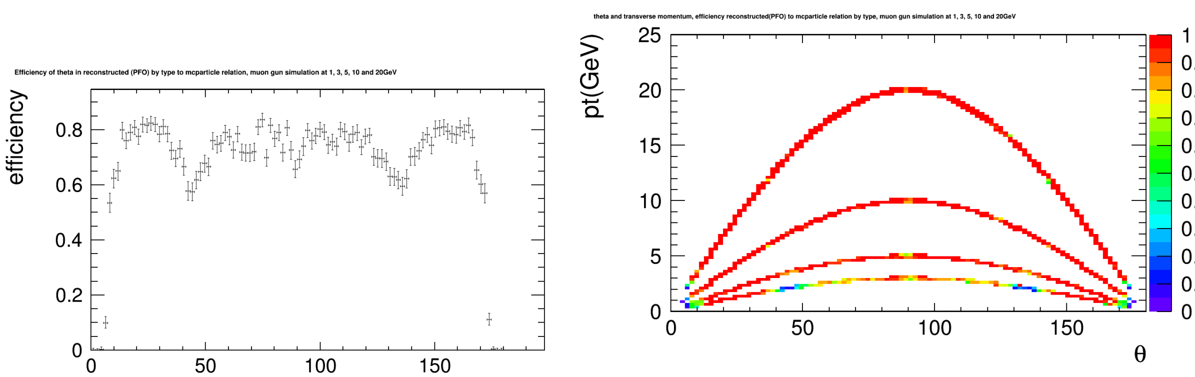
We see a similar plot for the reconstructed tracks with a cut just on charge. Interestingly the story is very different when it is included that it must be a muon. In figure 11 there is a stark difference to the plot seen in figure 8. This m type shape has minimum at the 3 points seen earlier but the blur at 125° is lost. Implying that there is low accuracy in correct particle identification. Looking at 11b it can be seen that the bottom peak (corresponding to 3GeV events) has extremely low efficiency. Meaning that the cause of this miss identification is a result of low momentum muons. The cause of this is low momentum muon helixing inside the tracker. This means they do not enter the calorimeter so part of the reconstruction information is lost. The result is that the reconstruction can not identify the particle. Inside ILCsoft this issue has been addressed and there is tool designed to identify low momentum muons. Due to time constraints the implementation of theses was not achieved but if implemented a similar result to that seen in 10 should be found.



(a) The efficiency of theta with charge but doesn't have to be a muon.

(b) 2D efficiency of theta and transverse momentum with charge

Figure 10: Efficiency of charged reconstructed tracks in comparison to mcparcticles at a 1, 3, 5, 10 and 20GeV gun.

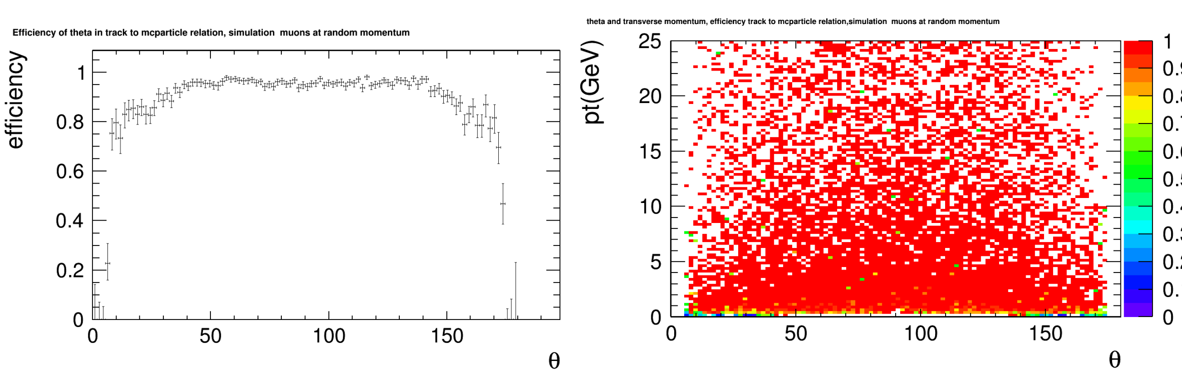


(a) The efficiency of theta has charge and is a muon.

(b) 2D efficiency of theta and transverse momentum has charge and is a muon

Figure 11: Efficiency of reconstructed muon tracks in comparison to mcparcticles at a 1, 3, 5, 10 and 20GeV gun.

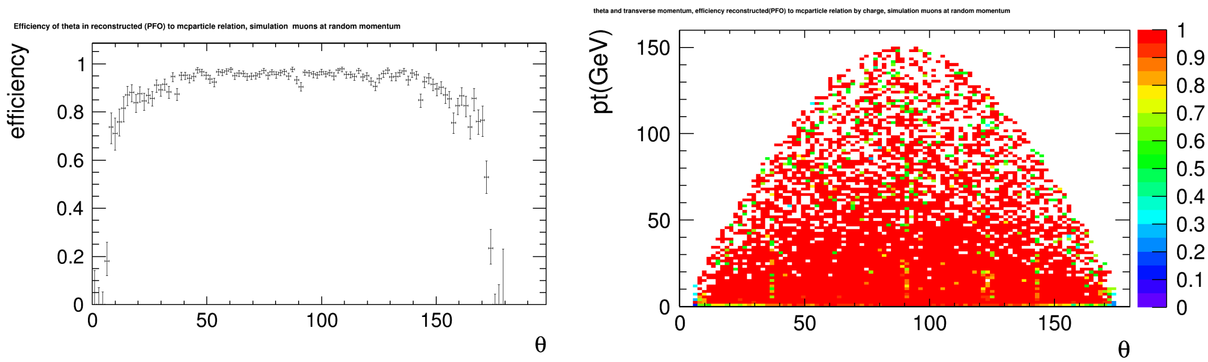
4.3 Random momentum



(a) The efficiency of theta.

(b) 2D efficiency of theta and transverse momentum

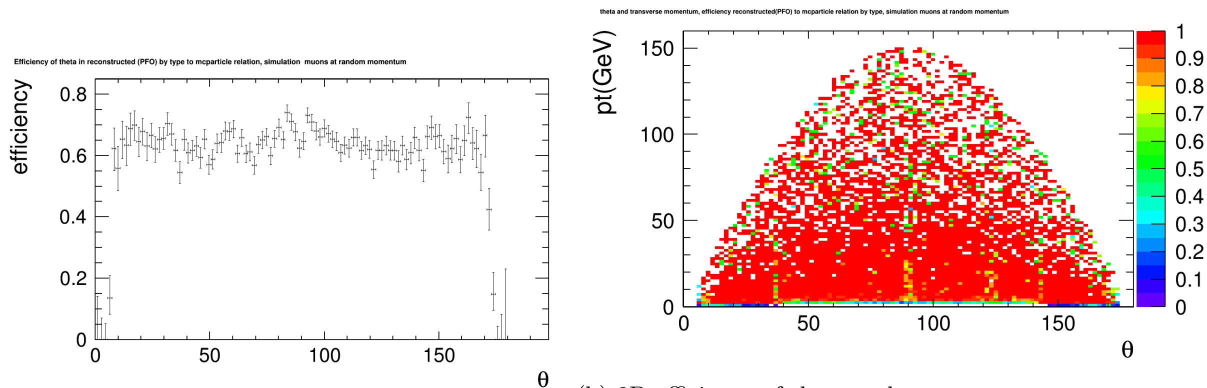
Figure 12: Efficiency of the marlin tracks in comparison to mcparcticles at a random momentum up to 150GeV.



(a) The efficiency of theta with charge but doesn't have to be a muon.

(b) 2D efficiency of theta and transverse momentum with charge

Figure 13: Efficiency of the reconstructed tracks in comparison to mcparcticles at random momentum up to 150GeV.



(a) The efficiency of theta with charge and is a muon.

(b) 2D efficiency of theta and transverse momentum with charge and is a muon

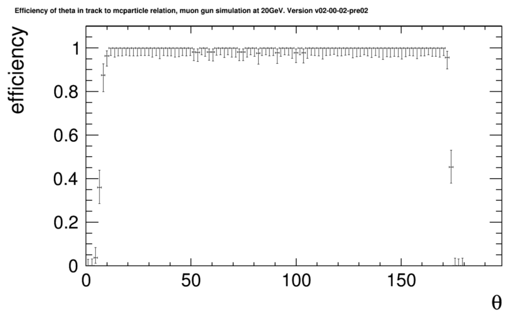
Figure 14: Efficiency of the reconstructed tracks in comparison to mcparcticles at random momentum up to 150GeV.

It has been shown that low momentum muons lower the efficiency of the reconstructed tracks to identify a particle. It is now required to find out what happens to high energy muons. This simulation sets both angle and momentum randomly up to 150GeV. Looking at the tracking information (figure 12) we see another similar plot. It should be noted that the efficiency decrease in these end caps when a range of momentum's is considered and this is very clear when looking at these random momentum cases.

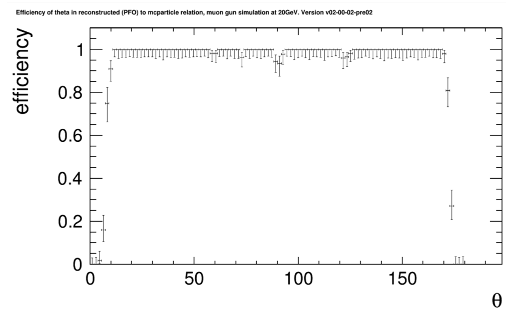
Again we see this difference between the case with only charge (13) and muon identification (15). Looking in at the 2D efficiency both case do show that there are these 4 points with lower efficiency. Figure 14b shows clearly that the points of lower efficiency are present at all momentum but at lower momentum, 5Gev and below, the efficiency is significantly worse. It can also be seen that there is no muon case below 2.4±0.2GeV, which now gives an upper limit that requires improvement in the tools function to use the more specialised muon functions to identify the particle.

4.4 ILCSoft Version v02-00-02-pre02

As has been seen over a few case there is an issue at 45°, 90°, 125° and 143°. The aim of this tool is to test the reconstruction capabilities. A newer version of ILCsoft is set to be realised (v02-00-02-pre02) which is meant to have tackled the issues seen at 45° and 143°. Looking at 15a we see there hasn't been a decrease in performance in marlin track efficiency. 15b shows promisingly that 45° and 143° have improved and looking at figure 16 we see this is a case even when muons are identified. This is excellent as it shows both that the

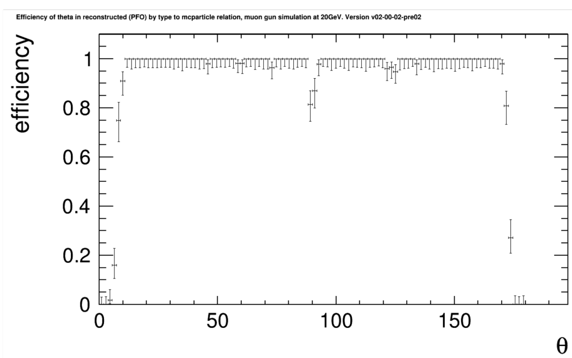


(a) Efficiency of theta of the marlin tracks in comparison to mcparcticles at 20GeV for the new ILCsoft version.

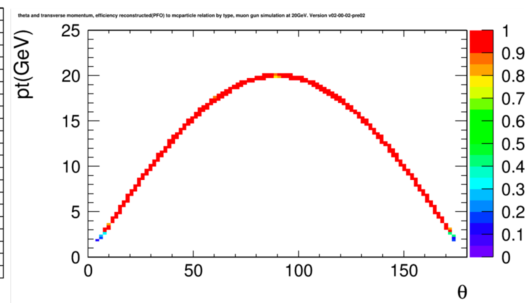


(b) Efficiency of theta of the reconstructed tracks in comparison to mcparcticles at 20GeV for the new ILCsoft version.

Figure 15



(a) The efficiency of theta with charge and is a muon.



(b) 2D efficiency of theta and transverse momentum with charge and is a muon

Figure 16: Efficiency of the reconstructed tracks in comparison to mcparcticles at 20GeV for the new ILCsoft version

new software has successfully improved the reconstruction efficiency and the programme I have developed will provide a powerful tool in monitoring the efficiency of the reconstruction of particles inside the ILD.

The issue in with the cathode currently can't be improved as it is a physical object within the detector. Worryingly, in figure 16a there is now two points of low efficiency around 90° while all previous plots have only one point. This does not imply that this new ILCsoft has made this area worse and is more likely do to the single 5000 run simulation and with more statistics this would improve. It could also be the case that the binning has changed and 90° now lies in the middle of two separate bins. This is very unlikely however as the binning has not been changed.

4.4.1 Muons and Antimuons

There low efficiency still at 125°. Charge was set to be positive and negative. On investigation while writing this report a small line in the simulation code was found that set the charge to -1. A new simulation was made for positive muons. It was found that this had no impact on the results the two points of low energy were both 90° and 125°. This means this did not affect my work or the ability of the programme to find the efficiency.

5 Conclusion

I have been able to make a tool that will measure the efficiency of muons in both marlin tracks and reconstructed tracks. ILC is and exciting project and the ILD is an ambitious detector optimised for reconstructions performance. It is therefore essential for the reconstruction software should be optimised as efficiently as possible.

Looking at the simple 20GeV muon gun simulation, 4 areas of low efficiency were found within the detector at 45°, 90°, 125°and 143°. Below 2.4GeV it was seen that these low momentum muons are not recognised as muons. This lead to very low efficiency's when included into results. At high momentum it was seen that there was consistently low efficiency at these energies. Comparing version v02-00-01 to v02-00-02-pre02 of ILCsoft should that the latest version of the ILCsoftware was improved upon and the problems at 45° and 143° have been resolved. Although little can be done to improve efficiency at 90° as the cathode is there, 125° shows an area that require further investigation. It interestingly is not symmetric which would suggest that it has nothing to do with charge. It is a previous unknown problem within the reconstruction but does provide evidence as to the usefulness of this tool.

To improve the efficiency programme further looking at tools within the reconstruction class to correctly identify muons will greatly improve the accuracy of the efficiency code. It could also be easily adapted to find the efficiency of other particles, however, it might not handle decays and multiparticle simulations well. Further investigation is required.

6 Acknowledgements

I would like to give Dr Shaojun Lu a huge thank you. Without his patience knowledge and wisdom this report would not have been possible. DESY summer school has been an amazing experience and I'm more excited now then ever to begin my career in HEP.

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