Vertex Detector Performance for CLICdet, FCCee & FCChh

CERN - EP LCD

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Introduction

The Large Hadron Collider (LHC) is currently the most powerful particle collider in the world. It successfully discovered the Higgs boson, one of its initial design goals and it has a major programme ahead of it to measure the Higgs' properties with high precision [2].
However hadron colliders are inherently a difficult environment to make precision measurements in because hadrons, protons in the case of LHC, are not elementary particles. They are instead a composite of quarks and gluons. Gluon-gluon interactions will dominate at the LHC energies. This means that the initial state of the hard scattering and its centre of mass energy are not well defined. The remnants of the protons contribute to underlying events. This combined with pile up leads to a very complex final state. A very clean experimental setup for precision measurement are electron-positron collisions because the initial conditions for the hard scattering are well known because electrons and positrons are elementary particles.
CERN is currently pursuing studies two future e^+e^- colliders, the Compact Linear Collider (CLIC) and the Future Circular Collider electron positron (FCCee) which will collide particles at up to 3 TeV and 400 GeV. The detectors in both of these colliders will require excellent vertex detectors and trackers to find secondary vertices for flavour tagging and to reconstruct the momenta of high energy tracks.
These machines represent the precision frontier and CLIC will to some extent be able to push the energy frontier. However a hadron machine is needed to really extend the centre of mass energy beyond what the LHC is capable of.
For this the FCChh is being planned, which is designed to collide protons at $\sqrt{s} =$ 100 TeV. There will be far more pile-up in the detector for this collider and objects will be boosted which means the detector will have to have an extended coverage in η compared to CLIC and FCCee.

Vertex Detector Performance

Transverse Impact Parameter Resolution

The performance of a vertex detector can be described by the resolution of the transverse impact parameter $\sigma(d_0)$. The transverse impact parameter d_0 is defined as the distance of closest approach between a track and the interaction point (IP) in the plane transverse to the beam. This can be used for flavour tagging because "long" lived particles such as b-hadrons will have a significant d_0 compared to lighter hadrons which decay almost instantaneously. The resolution can parametrised using eq. 1.

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3(\theta))} \tag{1}$$

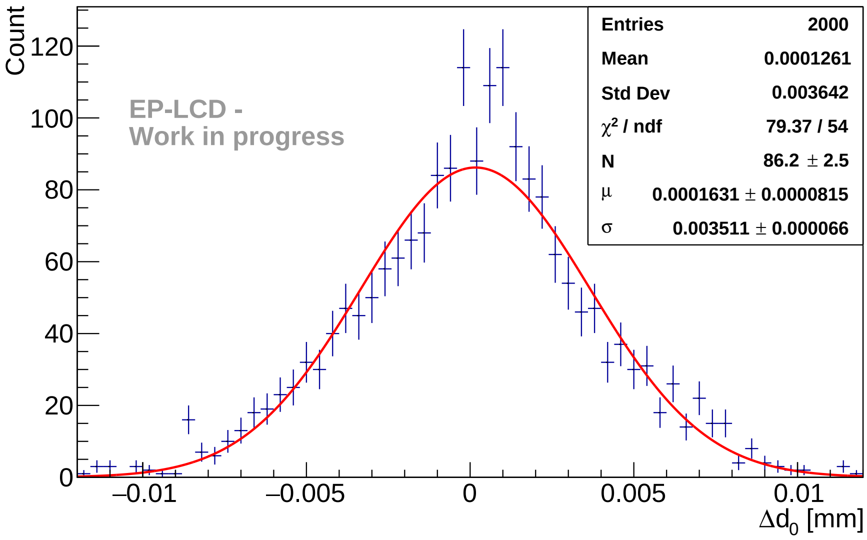
Here a accounts for the point resolution of the detector and b is related to multiple scattering so it depends on the material budget of the detector.

Simulation & Track Fitting

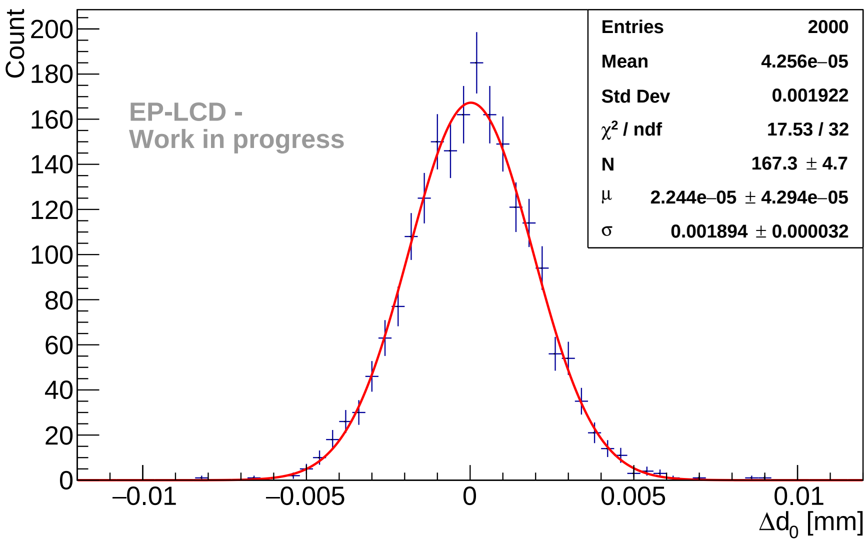
$\sigma(d_0)$ is studied using a μ^- beam which is simulated using a Geant4 particle gun. These muons are fired at different polar angles θ with a uniform distribution in $\phi = 0$

to 2π. This is repeated at $p = 1$ GeV, $p = 10$ GeV and $p = 100$ GeV to examine the second term of eq. 1.

The hits of the simulated particles are digitised by smearing them according to the resolution of the detector layer a specific hit is in. The hits of an event are parsed to a *truth* tracking algorithm which fits the track of a Monte Carlo particle by only using the hits it created. So no pattern recognition is needed in the algorithm. The results of the fit gives one observables such as the momentum of the particle and d_0. $\sigma(d_0)$ for a specific energy and angle is found by fitting the distribution $\Delta(d_0) = d_{0,reco} - d_{0,true}$ with a Gaussian, where the width of the Gaussian is the d_0 resolution. An example of this can be seen in fig. 2.



(a) $\Delta(d_0)$ for CLICdet with the original truth tracking.



(b) $\Delta(d_0)$ for CLICdet with the new truth tracking.

Figure 2: Examples of $\Delta(d_0)$ for CLICdet with μ^- at $p = 100$ GeV μ^- with $\theta = 85°$

Fig. 2a shows the $\sigma(d_0)$ for tracks reconstructed with the original version of the truth

tracking and fig. 2b shows the $\sigma(d_0)$ for particles reconstructed with an improved version of truth tracking which was developed during the project.
The old fit was done in two stages. First a prefit was performed using the first, middle and last hits associated with a track. This was combined with the magnetic field in the detector and the direction of the particle to make a helix. The parameters from this helix was used to initialise the actual track fit. These starting parameters specifically the reference point of the track resulted in a poor fit. The new track fit uses all the hits for the prefit and then refits the track using parameters from the first fit.

CLICdet

A conceptual design report was released in 2012 with two different detector designs. The CLIC_SiD featured an all silicon tracker while the CLIC_ILD had a silicon vertex detector and a time projection chamber for tracking [3]. The lessons learned from the CDR studies have resulted in a single detector design, the CLICdet [1].

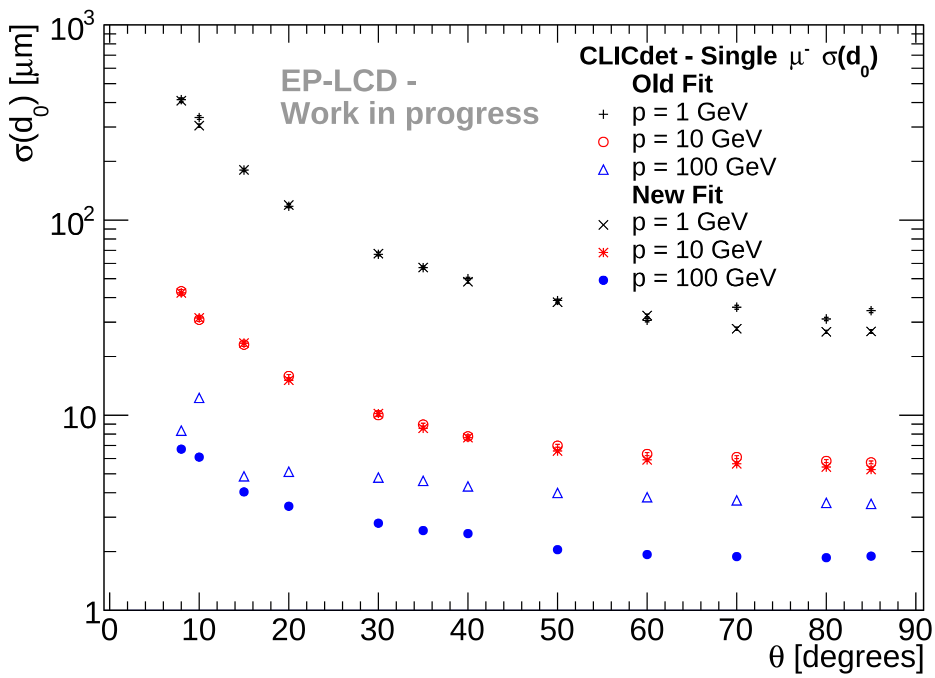


Figure 3: $\sigma(d_0)$ as a function of θ for CLICdet detector model for single μ^- at $p = 1, 10, 100$ GeV. Tracks are fitted with the old and new truth tracking.

Fig. 3 shows the $\sigma(d_0)$ as a function of θ for muons at $p = 1, 10, 100$ GeV comparing the original and improved truth tracking. Here we can see a large discrepancy between the old and the new fitting method for muons at $p = 100$ GeV.
The dependence of the $\sigma(d_0)$ on material budget and the method on which it was derived was also tested for the old truth tracking. To test the dependence of the material budget was studied by recalculating $\sigma(d_0)$ with thinner support structures to see if it improved the resolution. The result from this study can be seen in fig. 4. 1
Different methods for calculating the $\sigma(d_0)$ from the $\Delta(d_0)$ distributions were also tested. We can see from the χ^2/n_{dof} in figure 2a that it is not compatible with a Gaussian fit.

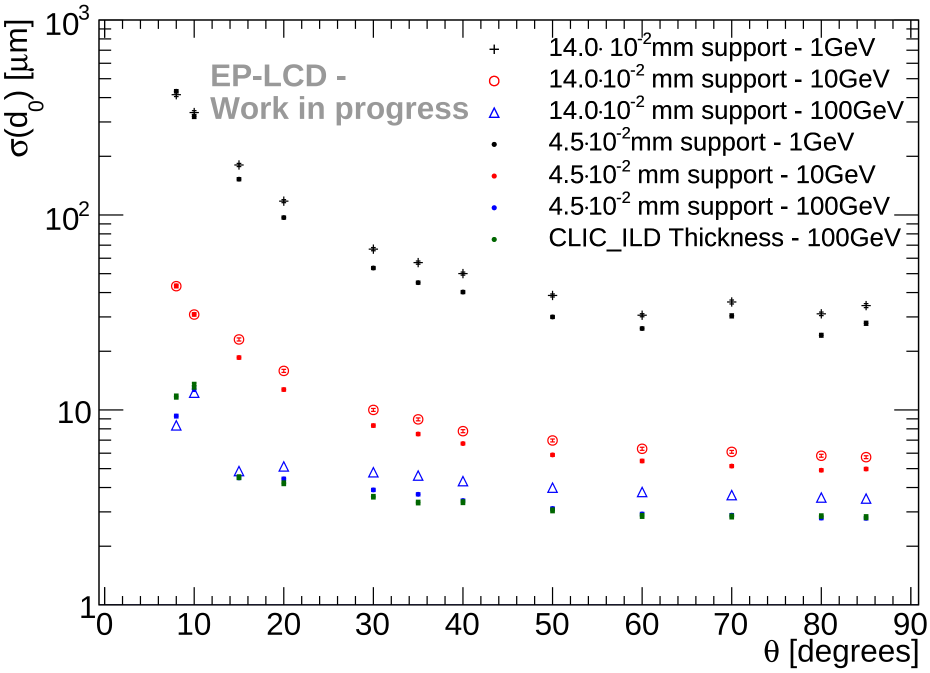


Figure 4: $\sigma(d_0)$ as a function of θ for CLICdet detector model with varying support structure thickness for single μ^- at $p = 1, 10, 100$ GeV. Tracks are fitted with the old truth tracking.

Therefore a double Gaussian fit and the RMS_{90}, which is defined as the root mean square of part of the distribution which contains 90% of the events, was used to see if the bad resolution of the old truth tracking was because the distributions were not Gaussian. The smallest σ of the double Gaussian fit was used as the $\sigma(d_0)$,
This can be seen in fig. 5. These methods were only done on tracks with $p = 100$GeV because lower momentum tracks were consistent with a Gaussian fit. The RMS_{90} improves the resolution as it ignores the tails of the $\Delta(d_0)$. Uncertainty of $\sigma(d_0)$ from the double Gaussian fit is too large to tell if it improves the resolution. This fit requires more than 2000 mu^- pr. angle in θ.

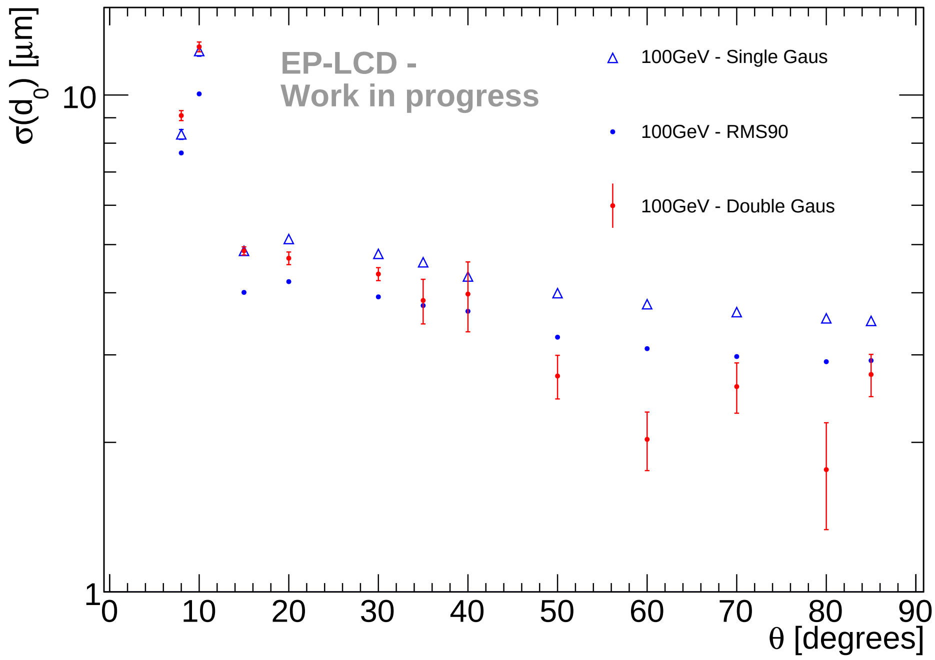


Figure 5: $\sigma(d_0)$, found using a single Gaussian fit, RMS_{90} and double Gaussian fit for single μ^- at $p = 100$ GeV as a function of θ for CLICdet detector mode. Tracks are fitted with the old truth tracking.

FCCee

The FCCee detector model is very similar to the CLICdet. There are some differences though. Linear colliders have to maximise luminosity because they cannot reuse the beam. The beam has to be focused far more because of this which leads to beam related backgrounds such as incoherent pairs and $\gamma\gamma \rightarrow$ hadrons. This limits the innermost radius of the vertex detector [1]. The design of the interaction region in FCCee is fairly different and the vertex detector can be closer to the beampipe without experiencing the same occupancy as in CLIC. This leads to the improved performance seen in figure 6 where $\sigma(d_0)$ as a function of θ for μ^- at $p = 1, 10, 100$ GeV is shown. The tracks are reconstructed using the improved truth tracking.

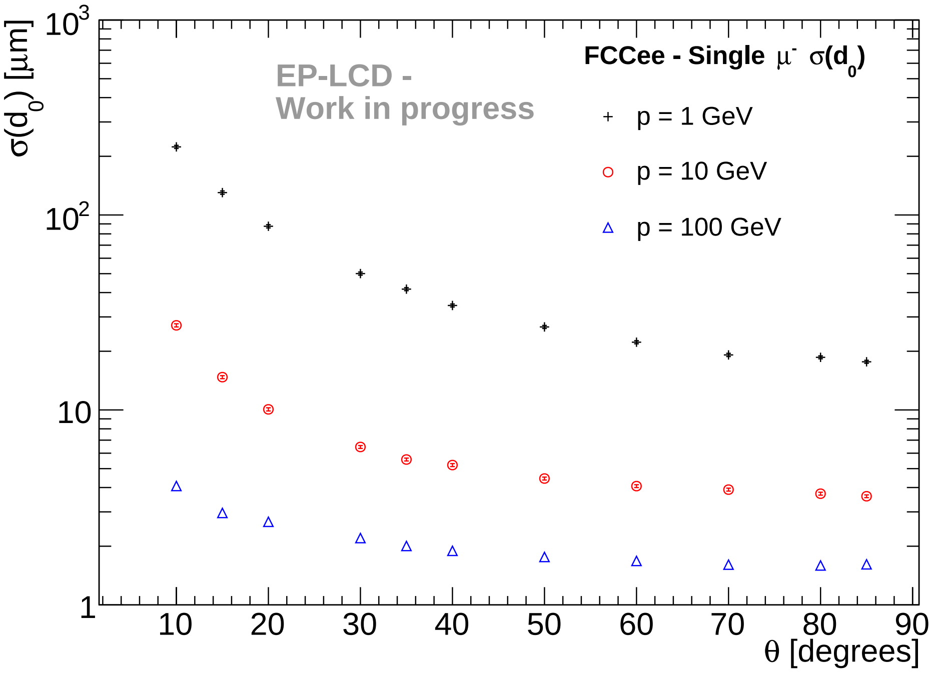


Figure 6: $\sigma(d_0)$ as a function of θ for FCCee detector model for single μ^- at $p = 1, 10, 100$ GeV. Tracks are fitted with the new truth tracking.

FCChh

The FCChh detector model is fairly different from CLICdet and FCCee. This is because it has to capture very boosted events. To do this it has two very forward endcaps to extend its coverage. The simulation of the detector model is not as comprehensive as CLICdet yet and the version simulated for this study only contained the tracker.
This meant that some approximation have been made to make the use of CLIC reconstruction software with the FCChh detector model possible. All surfaces of the detector model have to have a local coordinate system which has to be defined as it is in CLICdet for the tracking to work. Hits have to be collected, digitised and parsed to the reconstruction.
The digitisation process for these events do not accurately represent the resolution in the FCChh detector. The endcaps of this detector have diminishing resolution as a function of r where r is the distance from the beam. This is not the case for CLIC where the resolution in the detector diminishes layer by layer as you move away in z from the IP. This meant the digitisation processor was not able to accurately smear the hits in the FCChh detector.
Another issue was that CLIC and FCCee are committed to using Particle Flow Algorithms (PFAs) which use information from the tracker to improve measurements in the calorimeter. This means that a track is required to be extrapolated to the beginning of the calorimeter. This is not possible for FCChh since the detector model does not contain a calorimeter yet. But this is easily fixed by allowing otherwise correctly fitted tracks to be accepted even if they are not extrapolated to the calorimeter. The $\sigma(d_0)$ can be seen in figure 7. Note that the $\sigma(d_0)$ is a function of the pseudorapidity, η, because we are dealing with a hadron collider.
There were several problems with the reconstruction for low energy and/or forward

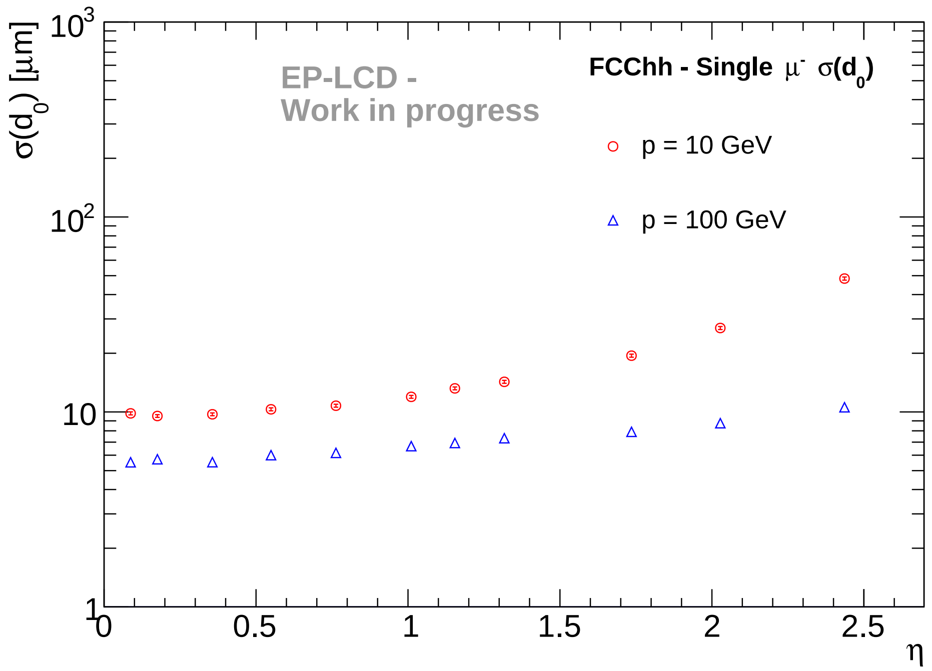


Figure 7: $\sigma(d_0)$ as a function of θ for FCChh detector model for single μ^- at $p = 10, 100$ GeV. Tracks are fitted with the new truth tracking.

tracks. The track fit failed to fit tracks at $p = 1$ GeV. These tracks have too small momentum to escape the tracker and loop inside it which can be problematic for the truth tracking. The reconstruction simply crashed for events with $\eta > 2.5$, however the detector should be able to cover events out to $\eta \approx 6$. $\Delta(d_0)$ for events between $\eta = 1.5$ and $\eta = 2.5$ were biased in that the distribution was not centred around 0. These problems could stem from the software, which is designed for CLIC or be related the FCChh detector model. Events with $0 < \eta < 1.5$ behaved normally. These events are characterised by only having hits in the barrel which might explain why they do not have any bias.

Conclusion

In this project the performance of the vertex detectors for the future colliders CLIC, FCCee, and FCChh were quantified by calculating the resolution of the transverse impact parameter, $\sigma(d_0)$.
This was done by fitting the distribution $\Delta(d_0) = d_{0,reco} - d_{0,true}$ where the σ of the Gaussian function is equal to the resolution. This revealed problems with the track fitting algorithm which was subsequently improved.
The improvements made it possible to easily find $\sigma(d_0)$ for CLICdet and the FCCee detector models using CLIC reconstruction software.
The FCChh detector, which is designed for proton and not electron collisions, was adapted alongside specific parts of the reconstruction software to be compatible which gave some preliminary results for the $\sigma(d_0)$, however there still problems for events with large η and small energies.

References

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