The impacts of the muon spoiler background on the ILC detector performance

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September 7, 2016

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Abstract

Report about the summer student project: "The impacts of the muon spoiler background on the ILC detector performance" at DESY in summer 2016. The following pages will include an enfold description of the simulated muon background for the planned "International Linear Collider" and its impacts on the detector performance of the "Silicon Detector".

Contents

1. Introduction

Studies on the muon background of the SiD detector

This report is about my summer student project at DESY from 18. July to the 9. September. During my studies: “The impacts of the muon spoiler background on the ILC detector performance” I was part of the ATLAS group at DESY. In the following pages, I will present my results of the SiD performance studies, with the focus on the muon background. The SiD could be one of the detectors at the planned linear collider ILC. The muon background causes unwanted detector noises for linear high energy colliders and therefore a muon shielding is needed. In my work, I will mainly compare two different shielding scenarios which are discussed in the “Linear Collider Collaboration”. [1]

2. Theory

2.1. The international Linear Collider - ILC

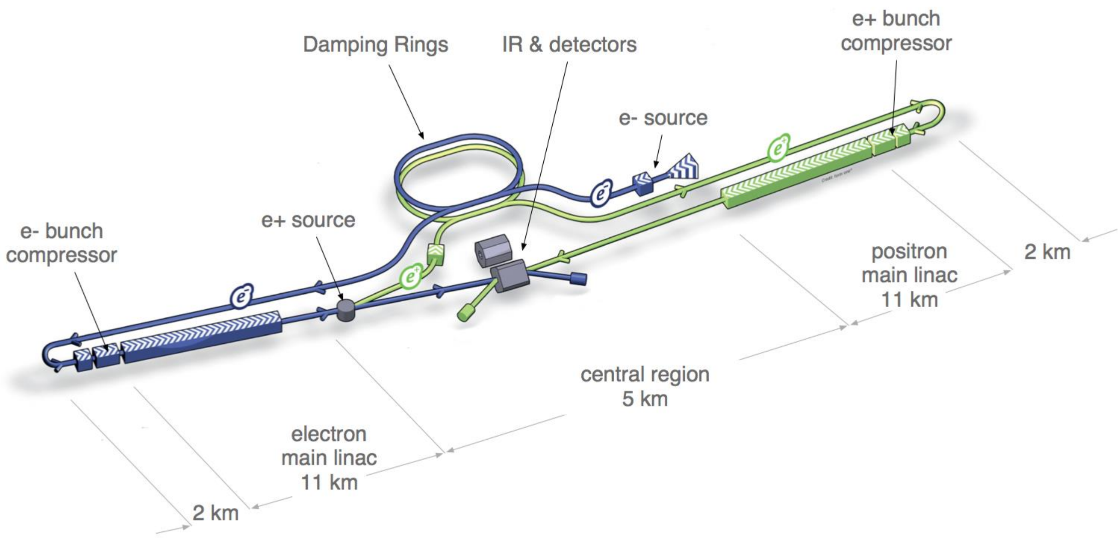


Figure 1: Overview over the planned ILC based on the Technical Design Report

The ILC is a planned linear electron positron collider in japan. The plan is to build this collider in the Kitakami Mountains. In the baseline concept, the ILC would have a length of 31 km with a cavity strength of 30 MV/m. The final focus of the accelerator, which is crucial for the muon background studies can be seen in the central region in Figure 1.

The aim is to reach in a first stage a center of mass energy of 500 GeV. This energy would be high enough to create a precise Higgs factory. Also, the ILC is able to reach higher luminosities due to very small bunch dimensions. On later stages, some upgrades are planned, which can be seen with a direct comparison to the LHC data in Figure 2.

		Baseline 500	Lumi Upgrade	TeV Upgrade	LHC 25ns
E_{CM}	[GeV]	500	500	1000	14 000
n_b		1312	2625	2450	2808
Δt_b	[ns]	554	366	366	25
N		2.0×10^{10}	2.0×10^{10}	1.74×10^{10}	11.5×10^{10}
q_b	[nC]	3.2	3.2	2.7	18.4
σ_x^*	[nm]	474	474	481	16 700
σ_y^*	[nm]	5.9	5.9	2.8	16 700
σ_z	[mm]	0.3	0.3	0.25	0.755
L	[$cm^{-2} s^{-1}$]	1.8×10^{34}	3.6×10^{34}	3.6×10^{34}	1.0×10^{34}

Figure 2: Technical comparison between the ILC baseline concept, ILC upgrades and the present LHC [2]

The big advantage of a linear collider is the very small detector occupancy due to leptonic interactions. This means that the physics events are only caused by electroweak interactions. So you get rid of the hadronic interactions which create a large background in hadron colliders. In Figure 3 the interactions after one bunch crossing at the LHC can be seen. In comparison, there is next to the LHC bunch crossing one physics event at the ILC. The big difference is the mean expectations of events per bunch crossing. For the LHC you expect around 30 - 40 interactions per bunch crossing. At the ILC the expectation is one event per train (1 train = 1312 bunch crossings)! So the background studies for both detectors are completely different. For experiments at linear colliders, the detector is empty at the most time. So at the ILC the detector occupancy is dominated by the beam background and detector noise. Therefore the background analysis, becomes very important. In my summer student project, I focused on one of the beam backgrounds: The muon background.

Because of the usually very clear detector, another big difference is that the SiD has no trigger, only every 1312 bunch crossings the buffer will be read out.

In the middle of the Figure 1 the interaction region (IR) of the ILC can be seen, which would contain in the center the International Large Detector (ILD) and the Silicon Detector (SiD). In my work, I only investigate in the detector response of the SiD, but in principle the results can be used for both detectors. The SiD can be seen in Figure 4.

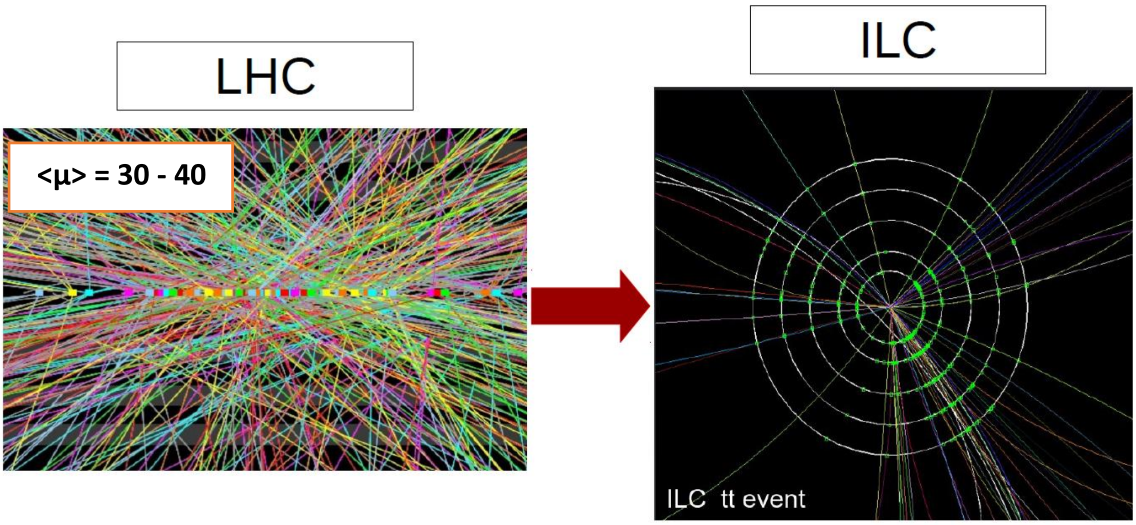


Figure 3: Contrast between a pile up at LHC and on simulated ttbar-event at ILC

2.2. The SiD – Silicon Detector

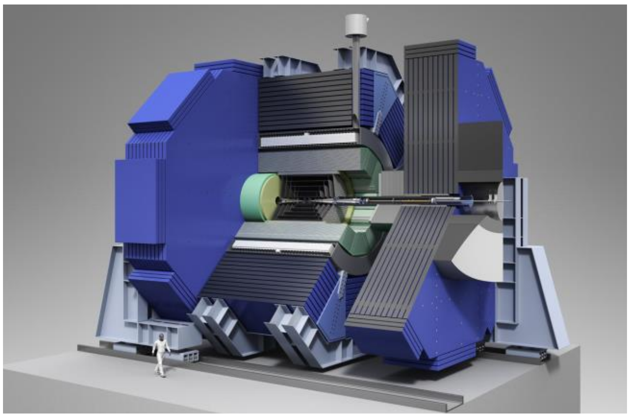


Figure 4: Simulated picture of the SiD - Silicon Detector

The SiD is a compact Silicon Detector and could be one of the detectors operating at the ILC. Nearly all of the detecting cells are semiconducting silicon cells, which are state of the art. The SiD would have a length of 12 m and a height of 14 m. To compensate the small detector dimensions a relatively large solenoid field of 5 T is needed. The SiD is designed in the typical shell style of high energy detectors including from in to out a vertex tracker, a tracker an electromagnetic calorimeter, a hadronic calorimeter and a muon detector. Also a beam- and luminosity calorimeter would be available. The cell size of the subdetector vary between 50 microns (VertexTracker, Tracker) and 3.5 cm (MuonChamber).

To form a closed volume, the subdetector usually consists of a barrel in the middle and endcaps on both sides. The barrel and endcaps then also insist several layers. The number of the layers differs from 50 (LumiCal) to 4 (VertexTracker).

3. The muon background

3.1. Production of muon pairs

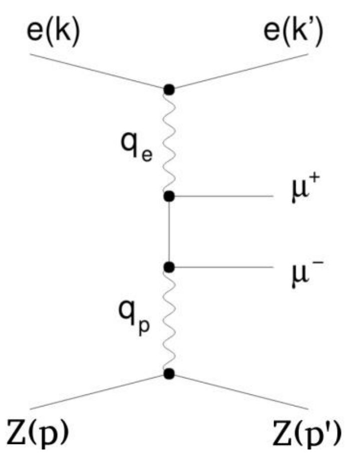


Figure 5: The Bethe-Heitler pair production process

In the International Linear Collider, electrons and positrons are accelerated to 250 GeV. The Beam is separated in bunches, which includes 1312 particles what is called a train. Inside the beam pipe, the electron and positron beam can interact with surrounding matter and create muons. The first order process for this muon creation is the Bethe-Heitler pair production process. (See Figure 5) This leads to nearly parallel traveling muons along the beam line because of the boosted beam frame according to the lab frame. The Bethe-Heitler process is suppressed $\sim\left(\frac{m_e}{m_\mu}\right)^2$ through normal pair production but becomes significant for detector background because of the relatively high particle density per bunch and the larger mean free path of the muons.

3.2. Muon shielding

To reduce the muon background at the SiD two different concepts were proposed:

The Spoiler Scenario
In the spoiler scenario three so-called "Donut Spoiler" should be installed. The spoilers are magnetized and would have a radius of 70 cm by a length of 5 m. Due to their magnetization, the spoilers are able to curve the muon tracks and stop low energetic muons. [3]

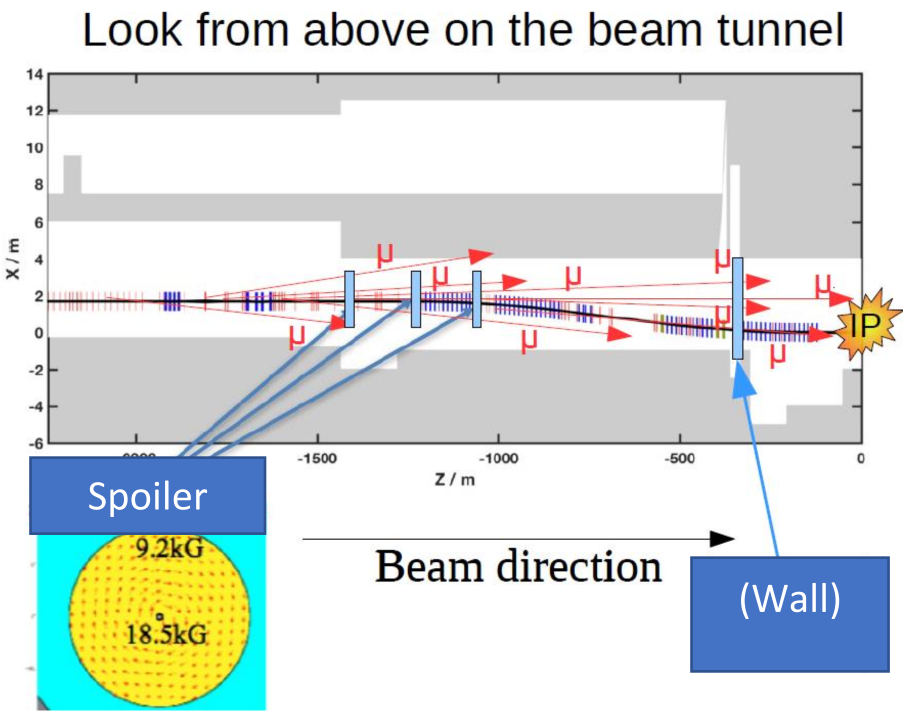


Figure 6: Prospects to shield the muons: Scenario A: 3 Spoilers || Scenario B: 3 Spoilers + Wall

As you can see on the magnetic field lines marked in the spoiler in Figure 6 above, the positively charged muons will be defocused by the spoiler, while the negatively charged muons will be focused. But the negatively charged muons will later be defocused in the quadrupole magnets.

The Spoiler + Wall scenario
In this scenario also three donut spoilers should be installed, but also a magnetized 5 m thick wall out of copper would be added.

The wall could provide the last step of muon shielding with a distance of around 400 m to the interaction point. Only the material costs of such a big copper wall (dimensions: 3.32 m x 5 m x 5 m) would be in the order of 3 million euros. Besides the high costs of such a wall security issues exists, because the wall nearly fills the complete tunnel. These problems make the first scenario the favorite one. [1]

3.3. MUCARLO

Because of the non-reality of the ILC at this time, the data which is used in this analysis has to be simulated. This simulation was done by the Monte Carlo based software MUCARLO. This software is developed at the Stanford Linear Accelerator Center (SLAC) by L. Keller who produced the given MUCARLO data. [5] The Monte Carlo generator picks randomly initial values for physical parameters which follow different distributions and then simulate the interactions with the spoiler (and the wall). The Monte Carlo method which is based on random numbers allows a good description of particle phenomena in the statistic limit. Afterwards, the simulated MUONCARLO data, of the mostly parallel to the beam traveling muons, is used to simulate the detector interactions with SLIC, a software based on GEANT4 (Geometry And Tracking), which also uses Monte Carlo Methods. The resulting detector response and the Monte Carlo data is the base of the following analysis.

For both scenarios, the simulated files provide data out of 5 trains for the positron beam and 5 trains for the electron beam. This data collection makes it possible to study if the muons out of the electron or positron beam interacting same. Furthermore, the full beam data out of the electron beam and the positron beam can be discussed.

4. Analysis

Muon interaction inside the SiD

If a muon penetrates through the detector, it deposits energy in the silicon cells, which causes an unwanted noise and could fake particle tracks. The background of muons created by an electron train and interacting with the SiD can be seen in the edited Event Display of WIRED4[1] in Figure 7. The linear tracks of the muons moving parallel to the beam line and the dedicated hits can be clearly seen. The design of the planned readout architecture for the SiD provides only a capacity for a maximum of 8 hits per train and cell. This mean that if during one train, one cell gets more than 8 hits it would be blind. Therefore the muon background has to be examined on this event types.

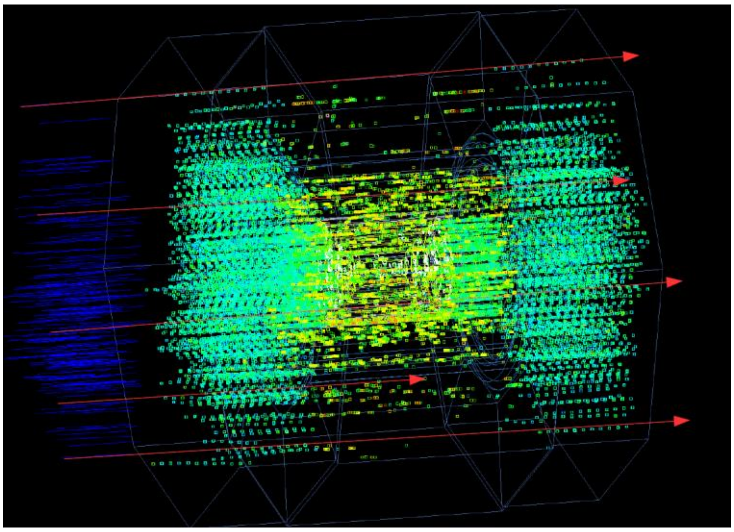
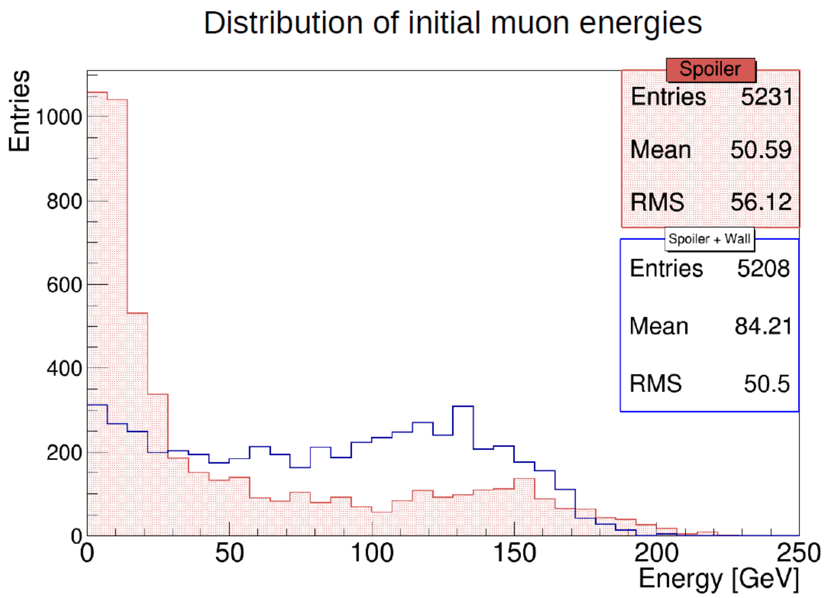


Figure 7: Edited Event Display of muon background created due to a simulated electron train.

[1] WIRED4 – Is a flexible and extendable experiment-independent event display developed and maintained by the FreeHEP team at SLAC. [7]

4.1. Energy Distribution of the incoming muons

Out of the MUCARLO simulation, the energy distribution of the muons can be studied. So the following presented data shows the energy distribution of the muons in a distance of 10 m away from the interaction point. So this muons already penetrated through the 3 spoilers or the 3 spoilers and the wall.



Both energy distributions show a cut off at high energies. This cut off exist because of the maximum beam energy of 250 GeV per beam. The shape of both distributions look similar at high energies, only the cut off for the spoiler and wall scenario is a little bit shifted to the left. The distribution differs at most for low energies. For the spoiler scenario in the first bins a lot of muons can be found, whereas in the second scenario much less low energetic muons can be observed. This difference exists because of inelastic interactions of the muons with the shell electrons of the wall. So low energetic muons will be stopped by the wall and higher energetic muons will lose energy due to the stopping power of the wall which leads to a shifting of the distribution to the left. The different height of the bump between 100 and 150 GeV is due to the not complete simulation file because the files for giving a final statement on absolute numbers are missing. With this files, the curves should be at higher energies rather similar.

4.2. Multiple cell-hit studies

To analyze if the buffer limit from 8 hits per cell is reached, multiple cell hits have to be studied. The output of the SLIC simulation provides cell information's that can be translated in to two 32 bit codes and for every inner subdetector hit in one 32 bit code. The first bit code, called HIT-ID0, is divided into several segments, but the size and meanings of these segments change for every subdetector. One of the segments always identifies the layer and can later be used to calculate the hits per layers. The second bit code, named HIT-ID1 is divided in two halves. The right half gives the cell number in x orientation and the left half the cell number of the y orientation. By merging both ids a unique cell id can be created. If in one simulated train the same Cell Hit ID is created more than ones, a multiple cell hit was found.

4.3. Occupancy Plots

After summing over all layers and over the data of 5 trains an occupancy plot can be created. To simulate the detector occupancy of the SiD due to the complete muon background, the simulated data of the electrons and positrons can be merged to a full beam. (Muons penetrate in the SiD from both sides) The results for one of the muon endcaps averaged over 5 trains can be seen in Figure 8.

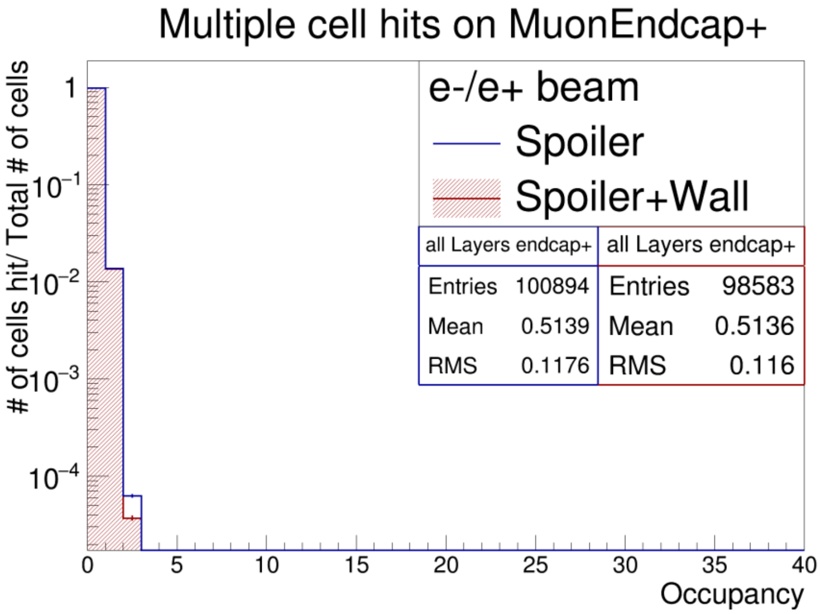


Figure 8: Occupancy plot for one of the MuonEndcaps

On the y-axis of such plot the ratio of numbers of cells hit over the total number of cells can be found, while on the x-axis the occupancy can be found. In the first bin, the fraction of cells which get no hits is represented, whereas the second bin shows the fraction of cells that were hit exactly one time. So every bin atop the 9th represents amounts of blind silicon cells, which are not able to observe physics events. In the spoiler scenario in one train $7 \cdot 10^{-5}$ of all cells were hit exactly two times in average. The first difference between both scenarios can be seen, because for the Spoiler + Wall scenario only an amount $4 \cdot 10^{-5}$ of all endcap cells was hit exactly two times. For both scenarios approximately an amount of 1.5 % of all cells were hit exactly one time in both scenarios. In both scenarios, more than 98 % of the muon endcap cells get no energy deposit from the muon background. So for the muon endcap the background disturbs the detector operation only slightly even if one endcap gets around 20000 hits per train.

The tracker shows a completely different behavior. Due to the small cell size of the silicon cells in the Tracker (50 microns x 50 microns) the amount of cells which got hits are many orders of magnitude smaller. For the spoiler scenario, a total cell amount of 10^{-7} gets exactly one hit. By adding a wall the amount would change by a factor around 3 to $3 \cdot 10^{-8}$. This difference can be observed in every bin that provides high statistics and therefore a small statistical uncertainty. Furthermore, it can be seen that for the tracker the occupancy becomes much higher. Some cells inside the tracker get more than 30 hits. But with respect to the big error bars, the rarity of this event can be clarified. To explain so many tracker hits, one has to consider the produced secondary particles. Inside dense material the inelastic scattering of the muons becomes very important, because the number of produced particles due to bremsstrahlung, photo effect and spallation becomes large. Indeed they get only a small energy amount of the mother particle, they are still able to interact with the detector and deposit energy in the silicon cells.

The high occupancy of the tracker leads to blind silicon cells. The buffer of the cell would be full of background noises, so this cell would not be able to store any energy deposit of due to particles out of a physics event. The largest difference between both scenarios can be observed in the tracker. So in the spoiler scenario only all $\sim 10^8$ hits caused by a muon, one particular cell would be blind. This makes for a first analysis the existence of a wall avoidable because the tracker can also achieve a good track reconstruction if only 6/8 hits would be available. But to make a final statement more statistic is needed especially to compare the absolute numbers of both scenarios. At the moment the simulations are not able to consider a different amount of incoming muons for both scenarios. So only the shape can be compared because for the spoiler scenario the number of incoming muons is expected to be higher.

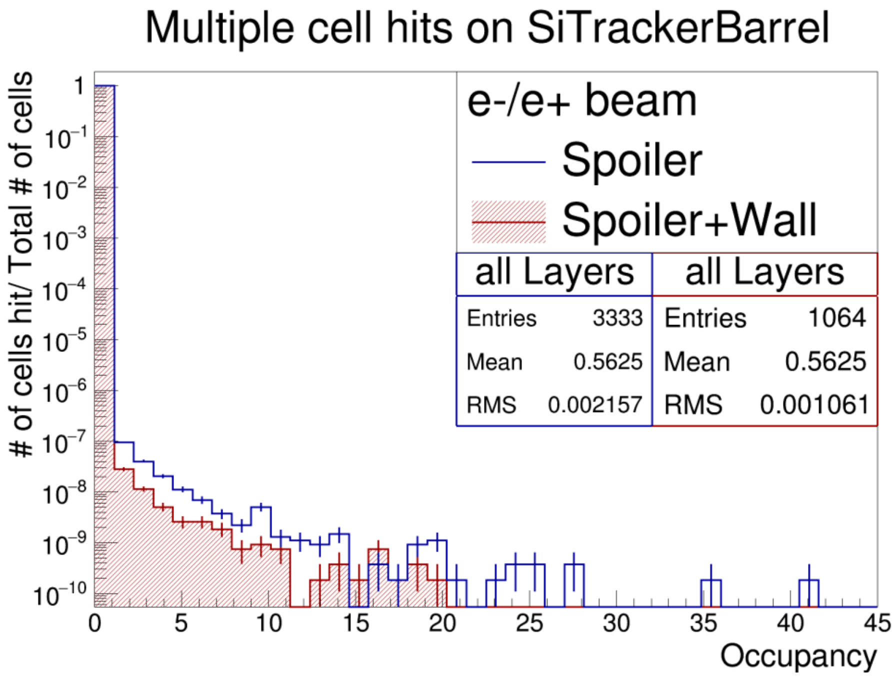


Figure 9: Occupancy plot of the SiTrackerBarrel

4.4. Averaged number of hits

The average number of hits per subdetector per colliding train (electron train plus positron train) can be seen in Figure 10.The most hits can be measured in the muon detector. For the VertexTracker at least hits can be measured. For the other subdetectors, the number of hits does not vary much.

To understand this effect one has to look at the spatial distribution of the incoming muons. In Figure 11 the spatial distribution of the muon background in the x-y plane of the muon endcaps can be seen. The distribution is squared and has the shape of the beam tunnel. With a look on the effective areas of the subdetectors, the impact can be understood as a geometry effect. (For further explanation see appendix: Figure 15)

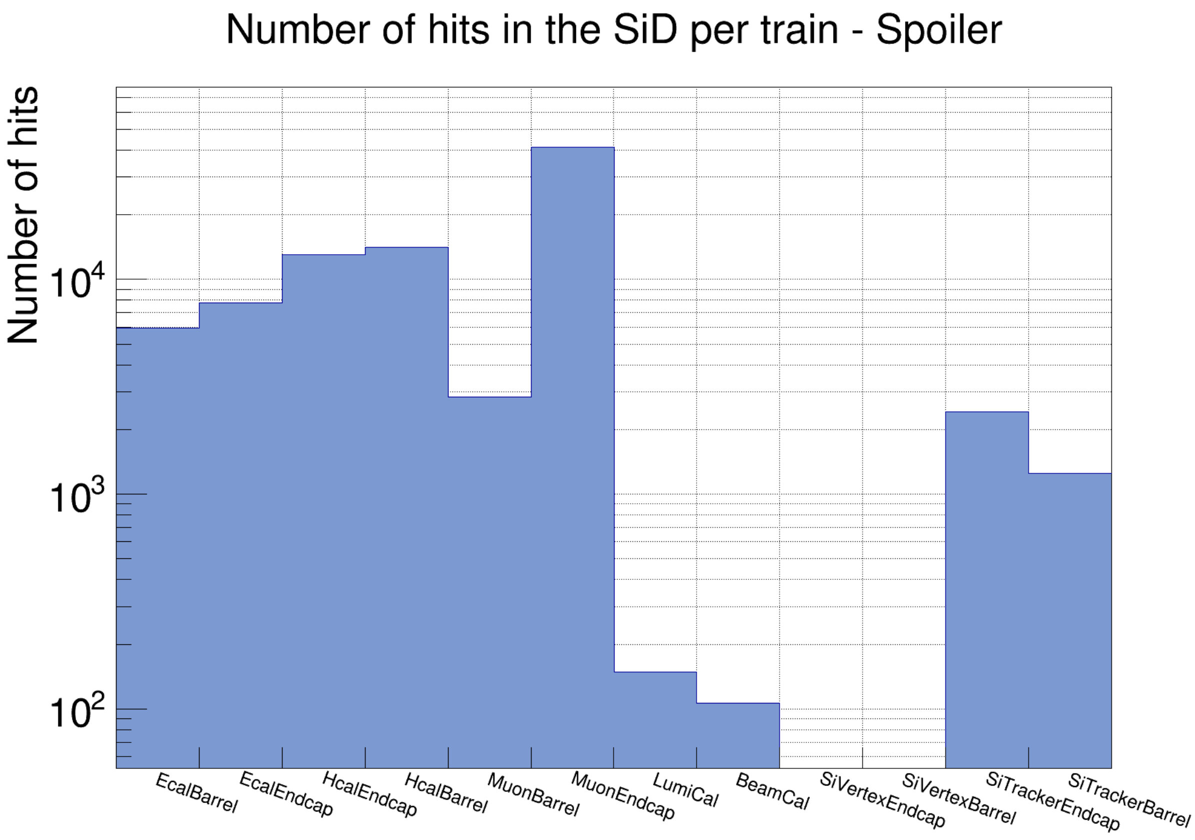


Figure 10: Comparison of the number of hits per train between the subdetectors

The muon detector is the largest subdetector, and so the muon endcaps get the most hits. The muon barrel gets not that many hits, because the effective area of the barrel for muons traveling along the beam axis is rather small. The vertex detector is the smallest subdetector and therefore gets at least hits. The detector sizes are roughly illustrated in the appendix: “Figure 15: Profile of the SiD - displayed the different subdetector sizes” and correlates with the number of hits per subdetector.

Besides the geometry effect, the high number of hits in the HcalBarrel and the EcalBarrel can be observed. These bumps are created due to secondary particles. The muons interact via inelastic scattering with the detector material, this leads to mostly electrons positrons and photons, which can cause cell hits. But concerning their small kinetic energy they are not able to reach the MuonBarrel and causing hits there. So the MuonBarrel gets only a few hits.

4.5. Spatial distribution of the muon backgrounds

The spatial distribution of the muon background of both scenarios can be compared and show a large difference. The shape of both distributions seems to be very different, but it should be a square distribution for both scenarios because of the tunnel dimension. The impression of a hexagonal shape of the Spoiler + Wall scenario arises by reason of the detector structure which is a hexagon. So some muons do not reach the muon endcaps because of their large curved track. The optical disagreement is determined by the disparate spreading of the distributions, which can be numbered with their standard deviation.

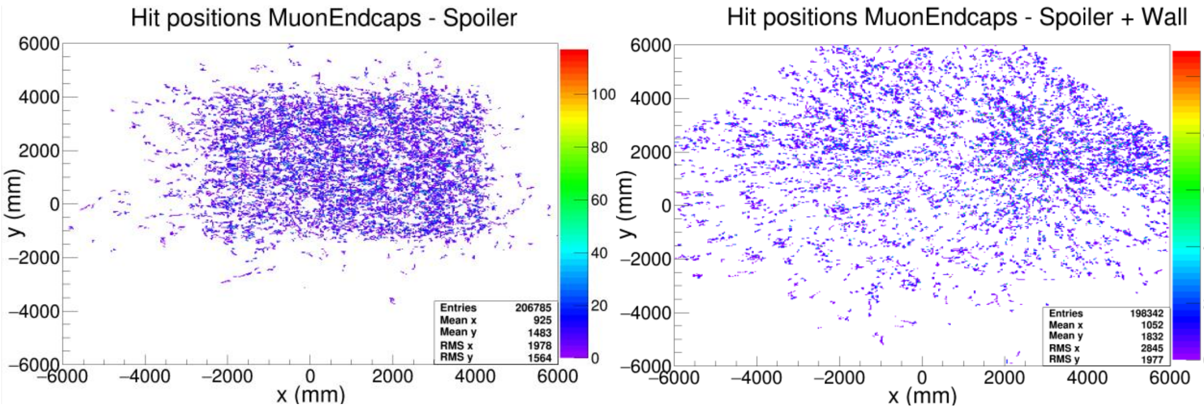


Figure 11: Comparison of the spatial muon background contribution from the Spoiler and the Spoiler+Wall scenario

Besides the bigger spreading of the spatial distribution of the Spoiler + Wall scenario, a shifting of the distribution can be observed. In the center of the coordinate system the beam pipe is placed, which can be noticed by the clean spot. Because both distributions are shifted upwards and to the right, this cannot be a statistical phenomenon and has to be systematic.

The shifting of the distributions can be explained by two effects. The shifting to the right is caused by the curved beam pipe in the final focus of the ILC. The muons are not bent by the magnets and travel straight on. This leads to a shifting to the right in the coordinate system of the detector. (See Figure 12)

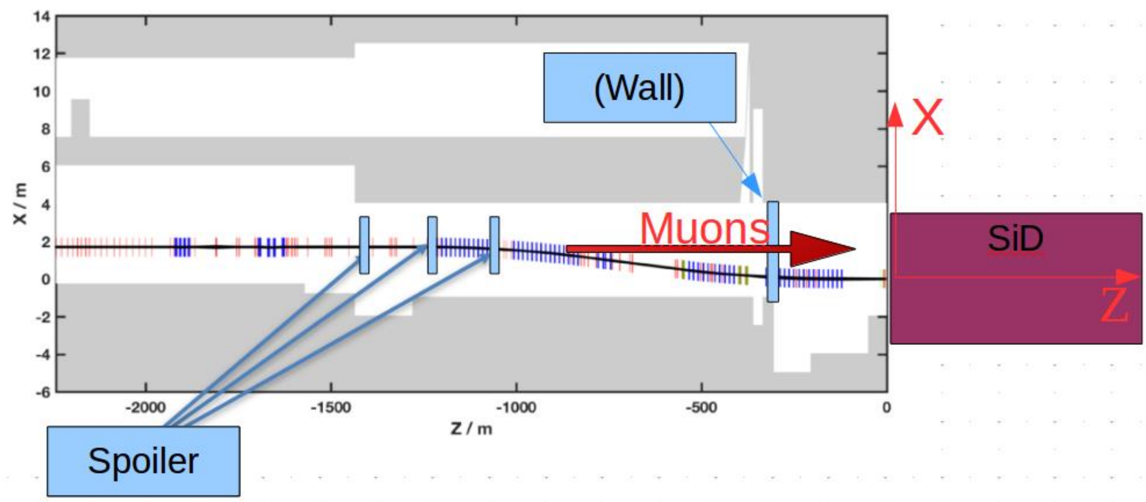


Figure 12: The curved beam pipe in the final focus, cause the shifting to the right

The upward shift of the spatial distributions can be explained by the high tunnel ceiling and the small distance between the beam pipe and the ground.

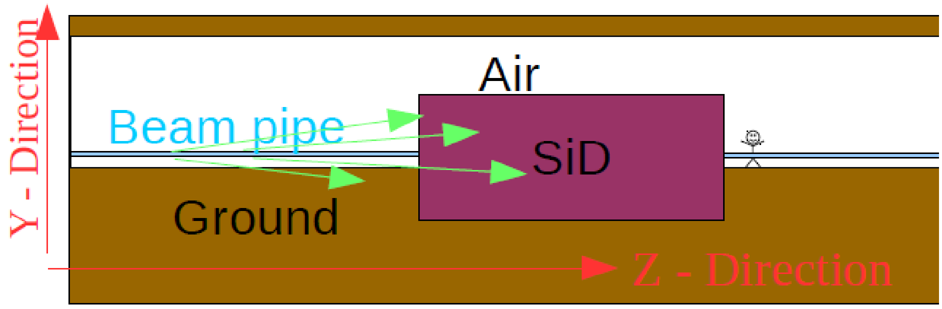


Figure 13: The ground shields the muons, so the spatial muon distribution is shifted upwards

So some muons are not able to reach the SiD because they get stopped in the ground whereas the air is not able to stop the muons because of the low air density. Because of this imbalance, the distribution is shifted upwards.

The different spreading of the spatial distribution occurs concerning the different initial momentums of the muons. Due to multiple scattering in the copper wall and the magnetization, the muon tracks are more curved. This leads to a wider distribution of the initial horizontal and vertical angles.

Conclusion

During the summer student program, I investigated in the muon background which is produced at high energy linear colliders. I focused on the detector performance of the SiD and found differences between the spoiler scenario and the spoiler and wall scenario. Especially by looking on the detector occupancy a shielding factor of 3-5 between both scenarios can be found. But because of missing simulation files, a final statement cannot be made at the moment. The programs to analyze the files are ready for operating, so the analysis can be done easily when the new files are ready. Beside the occupancy studies, I found that the muon background causes different effects on the different subdetectors due to their construction and size.

Also, I found differences in the spatial muon background distributions of both scenarios and could ascribe several aspects to the detector and the possible shielding design.

For an outlook, the high energy part of the muon background could be used to align the tracker, by using muons which travel in straight lines through the detector.

Acknowledgement

I want to thank my family for giving me encouragement during my studies. Especially I want to thank my supervisors Anne Schütz and Dr. Marcel Stanitzki for their kindly support and for seven memorable weeks working on my project at DESY. Furthermore, I want to thank Prof. Erdmann, Dr. Gast and the summer student organizer team for making this great experience possible.

Appendix

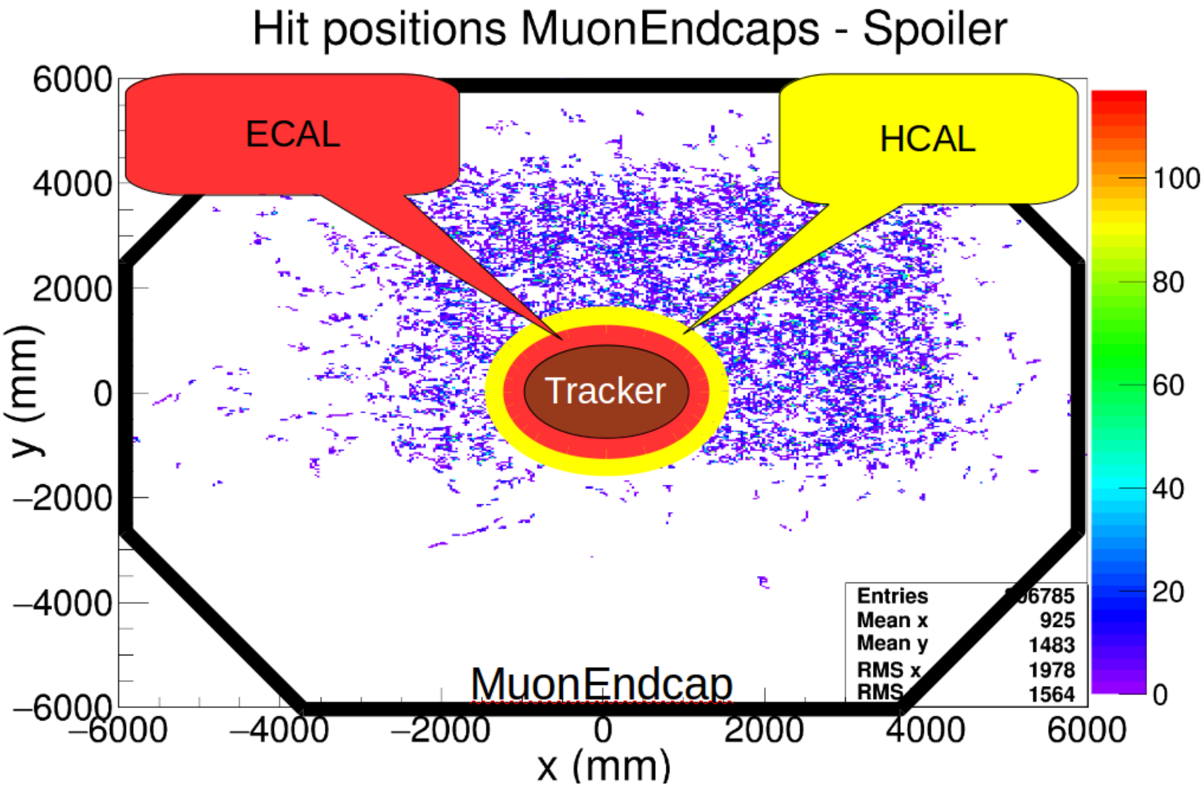


Figure 14: Spatial contribution of the muons with overlayed effective are of the subdetectors

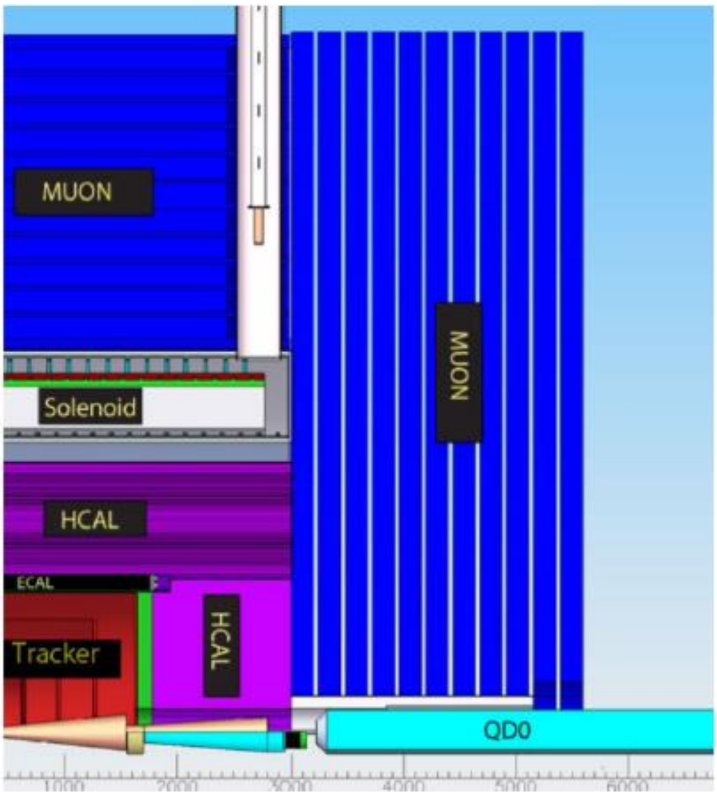


Figure 15: Profile of the SiD - displayed the different subdetector sizes

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