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Corso di Laurea in Fisica

Tesi di Laurea

Design of 2018 LEMMA test beam

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Abstract

In contemporary physics new tools and methods to explore new high energhy physics are investigated. Between them, the study of a muon accelerator is very interesting because it would allow new applications. Particularly, the possibility to obtain a low emittance muon beam starting from a 45 GeV positron beam on target is investigated. To test this possibility, 2 test beam experiments were made at CERN: the first from 26^{th} July 2017 to 2^{nd} August 2017, the second from 15^{th} to 22^{nd} August 2018. The main goal was to verify that muons made by interactions between positrons beam and target had low emittance and could be used in a still object-of-study muon accelerator. Particles coming from interactions were deflected by a magnet and collected by some detectors placed along a "V" shape after magnet; informations from them allowed to identify different particles and their kinematic quantities. The aim of this work is to show the simulation analysis made before 2018 test beam and the first results of data analysis.

Contents

1 Introduction

1.1 Muon collider

In contemporary High Energy Physics more powerful colliders are needed in order to explore and study new physics, which can be eventually found beyond the standard model at higher energies. To achieve this results, new colliders are studied. In this situation, a **muon collider** can be a good candidate thanks to muon characteristics.

- Untill now, muons are elementary particles: thanks to this feature, in a muon beam the full momentum and energy of particels are avaiable. Indeed in modern accelerators the use of protons (or not-elementary particles in general) implies that the momentum of the beam particles is not totally avaiable due to the subsystem interactions;
- Muons are heavier than other (suitable) elementary particles: thanks to this characteristic for example they lose less energy than electrons due to synchrotron radiation when accelerated in a collider: in fact this type of radiation goes as $mass^{-4}$.

These 2 characteristics make the study of a muon collider very interesting to explore new physics. However, there are many obstacles to be discussed, such as muons' very short lifetime in their rest frame of reference, which is about 2.2 μs. An experiment should be able to produce, accelerate them and make them collide in that amount of time not to lose the majority of them.

1.2 Muon production and beam emittance

Other issues affect the production of a muon beam, which must have some specific features that are not easy to achieve. Indeed muons produced by a process must be manipulated to become a beam with low emittance, which then can be used in a collider.

Emittance is a property of a charged particle beam in a particle accelerator. It is a measure for the average spread of particle coordinates in position-and-momentum phase space and has the dimension of length (e.g., meters) or length times angle (meters times radians). As a particle beam propagates along magnets and other beam-manipulating components of an accelerator, the position spread may change, but in a way that does not change the emittance. If the distribution over phase space is represented as a cloud in a plot, emittance is the area of the cloud. A more exact definition handles the fuzzy borders of the cloud and the case of a cloud that does not have an elliptical shape.

A low-emittance particle beam is a beam where the particles are confined to a small distance and have nearly the same momentum. A beam transport system will only allow particles that are close to its design momentum, and of course they have to fit through the beam pipe and magnets that make up the system. In a colliding beam accelerator, keeping the emittance small means that the likelihood of particle interactions will be greater resulting in higher luminosity[6].

The goal to achieve is the production of a muon beam with low emittance. To produce muons there are the following ways:

- Muons can be produced by $K^{\pm}/\pi^{\pm}$ decays: it is the easiest way to produce them, but it involves two processes, $K^{\pm}/\pi^{\pm}$ production and their decay, and the muons resulting have a large emittance so they have to be "cooled" to reduce it: this "cooling" process requests time, during which muons decay due to their short lifetime and the number that arrives to the collider become smaller.
- A novel way to produce muons is e^+/e^- collisions just above $\mu^+\mu^-$ threshold ($2m_\mu = 0.212$ GeV). In this case muons production is rare due to his small cross section (1 μb), about 10^{-5} every e^+e^- annihilation; indeed at this energy main processes are e^+e^- production and scattering. Otherwise, one good characteristic of this process is that resulting muons have low emittance and so the "cooling" process is not necessary[4][5]. Furthermore, muons produced in this way have an high Lorenz boost, with $\gamma \sim 200$: this implies they have about 500μs laboraotry lifetime, that allows to manipulate them for a long time compared with their 2.2μs proper lifetime.

2 LEMMA

2.1 General information

This last way is being studied by LEMMA team (LEMMA stands for Low EMittance Muon Accelerator), which is studying muons production from a positron beam on Berillium target[4][5].

Last year a test beam has been done during the end of July. It was the first one and the team had some noise problems with detectors. Also, they asked 2 weeks for the test beam but they were allowed only 1 week. This year test beam was done during August 15-22.

2.2 Experimental setup

The 2018 final experiment layout is shown in the figure. The layout used in Geant4[1][2] simulations was a bit differrent: it has been modified during data taking. The layout is shown from above. As shown in figure, the coorinate system has the z axis along the beam, the x axis pointing upwards and y axis pointing towards the reader. Berillium target is shown in blue. Silicon detectors are shown in black: two of them, named T1 and T2, are placed upstream the target and are used to measure the direction of the incoming positron beam; two others, named C0 and C1, are placed downstream the target but upstream the magnet and are used to measure the surviving positrons and others charged particles produced by the incoming beam; the other silicon detectors, named C2-C7, are placed downstream the magnet and upstream other detectors and are used to measure the direction of the particles produced by the collision of the beam with the target: all silicons dimensions are written in figure. The dark green rectangle represents the magnet deflecting charged particles coming from the collisions: in 2018 the field was 1.872 T. This value was used to ensure a good separation between 45 GeV positron tracks and positive muon tracks in the [18,26] GeV momentum range, according to the detectors' positions. Positive tracks are deflected to C3-C5-C7 direction, while negative ones are deflected in the C2-C4-C6 direction. Orange rectangles are scintillators. Yellow detectors are calorimeters: positrons are expected to lose most of their energy in them. Light green objects represent Čherenkov detectors: they are used to identify μ^- or e^- tracks. Muon chambers are shown in light blue: they are composed by 2 sections as shown in figure. They were used to identify $\mu^{\pm}$'s tracks. Dark grey rectangels represent iron blocks: they are usefull to stop electrons and positrons before muon chamber, reducing the noise on them.

2.3 Data taking

Scintillators are used to see if there is an interesting event and to send the signal to write the event to a file. Muon chambers are triggerless: they keep looking for events, recording the time in which the events happen. When a trigger is sent, muon chambers write their signal and the time in which it was recorded. Scintillator S1 could identify almost every particle passing through it: it has refresh frequency of 1MHz. The system of scintillators S1-S2-S3 was supposed to identify muons: it had a frequency of 2KHz. During 2018 test beam it was discovered to trigger also with a lot of noise events; its frequency was too high to record data. This sistem of trigger was improved during 2018 test beam with another scintillator, named 63 in the figure, which was placed between the 2 sections of μ^- muon chamber: to insert this new trigger, some calibration runs were made using only mouns to be sure that it worked properly. Using this new system noise events were no more a problem; furthermore, the frequency of trigger became lower and comparable with data recording frequency. Because of that high frequency, data analysis cound not be done runtime: in case of trigger, the event was written onto a file and saved. Later those files could be analyzed offline.

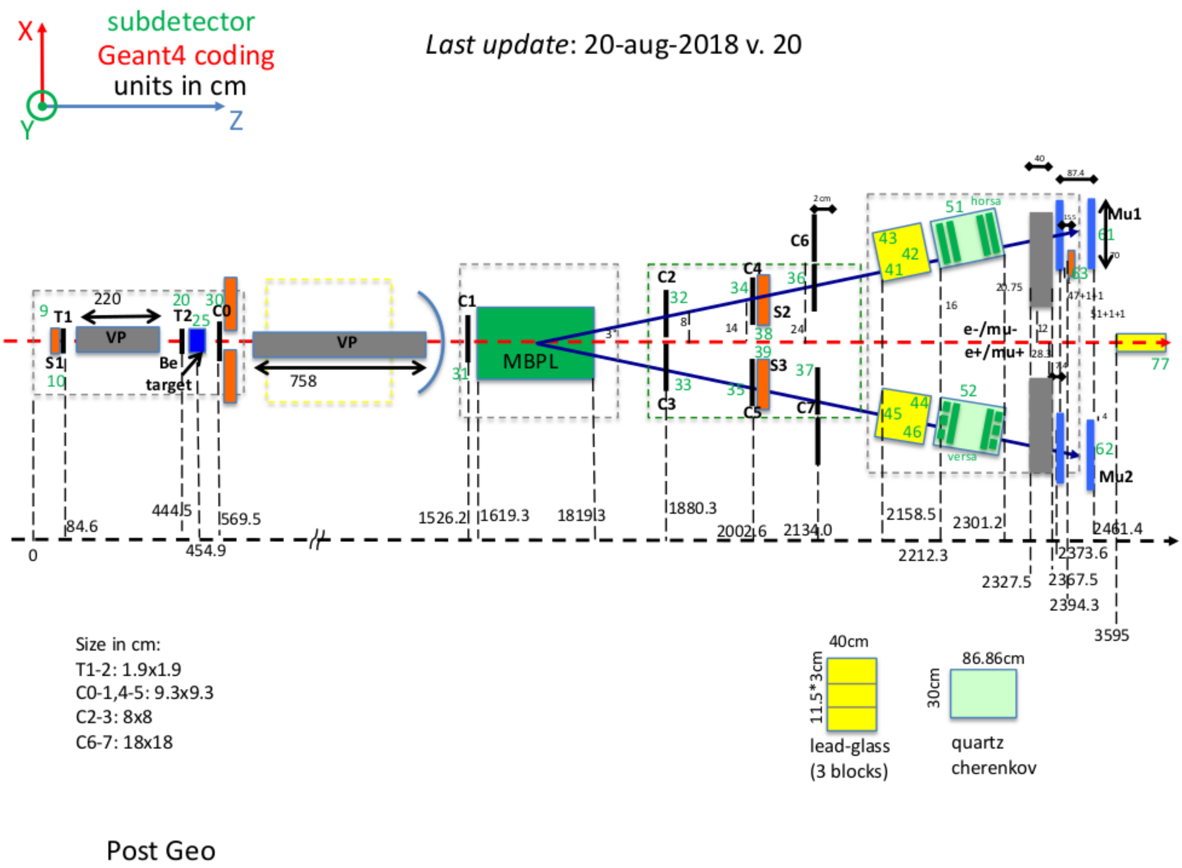

Figure 1: This figure shows the final experimental setup used in 2018 test beam. The section after the magnet is smaller than the section before the magnet.

3 Simulations analisys

Simulations were done and were analyzed to check for a large geometrical acceptance, if not the setup could be modified properly.

The simulation files were root[3] files which could be opened and manipulated with root. They were of different types:

- positron files: in these files there was a positron beam of 45 GeV colliding with the target; analyzing these files one could esteem the proportion between noise and signal and can see if detectors were too noisy.
- signal files: in these files there were only muons. They were produced by the generator "BabaYaga": vertices of the $\mu^{\pm}$ pairs were generated in target volume, which in the simulations was filled with berillium. They had uniform distribution along all the axis in a volume of 2cm·2cm·6cm. Their momenta were generated from 18 GeV to 26 GeV (the range expected was calculated from experimental characteristics) with uniform distribution. In this case the signal could be analyzed alone: for example one could look for the good positioning of detectors or other characteristic of the signal.
- Bhabha files: Bhabha is a technical term used to denote the $e^{+}e^{-}$ scattering. The $e^{\pm}$ pairs were generated by "BhabhaYaga"[7] in the same way as muons. These files were useful to see how $e^{\pm}$ scattering worked (they were not used in this work analysis).

3.1 Signal distribution

The first step analyzing simulations was to test some detectors' positions. For this reason a root macro was built (a list of comands to be executed by root); it analyzed signal files plotting histograms of x position of the muons on silicon detectors. In plots there were also 2 vertical lines to show detectors' limits (silicon detectors C31-C37 have a 10cm width in x direction): then they have been placed so that their centre corresponded to the centre of the signal.

The plot in figures n. 2, 3 and 4 shows x positions compared with subdetectors as written just above in a simulation made after 2018 test beam; these new simulations were made to simulate the effective esperiment: in fact, during the test beam, setup was a bit changed respect to first simulations' one.

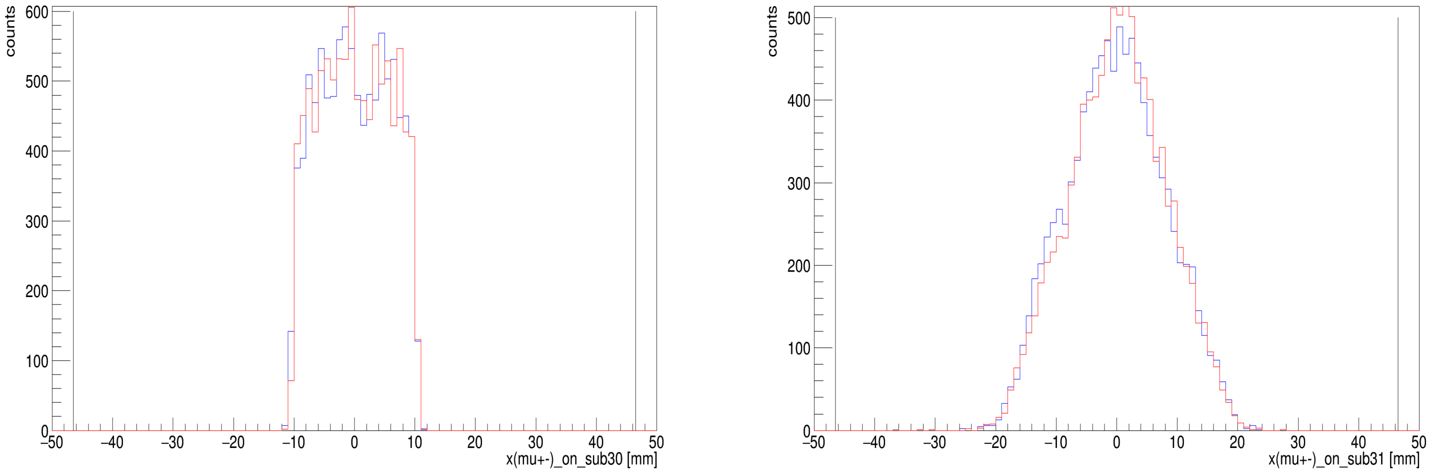

Figure 2: Figure shows x position of μ^+ (red) and μ^- (blue) on subdetector 30 (left plot) and subdetector 31 (right plot).

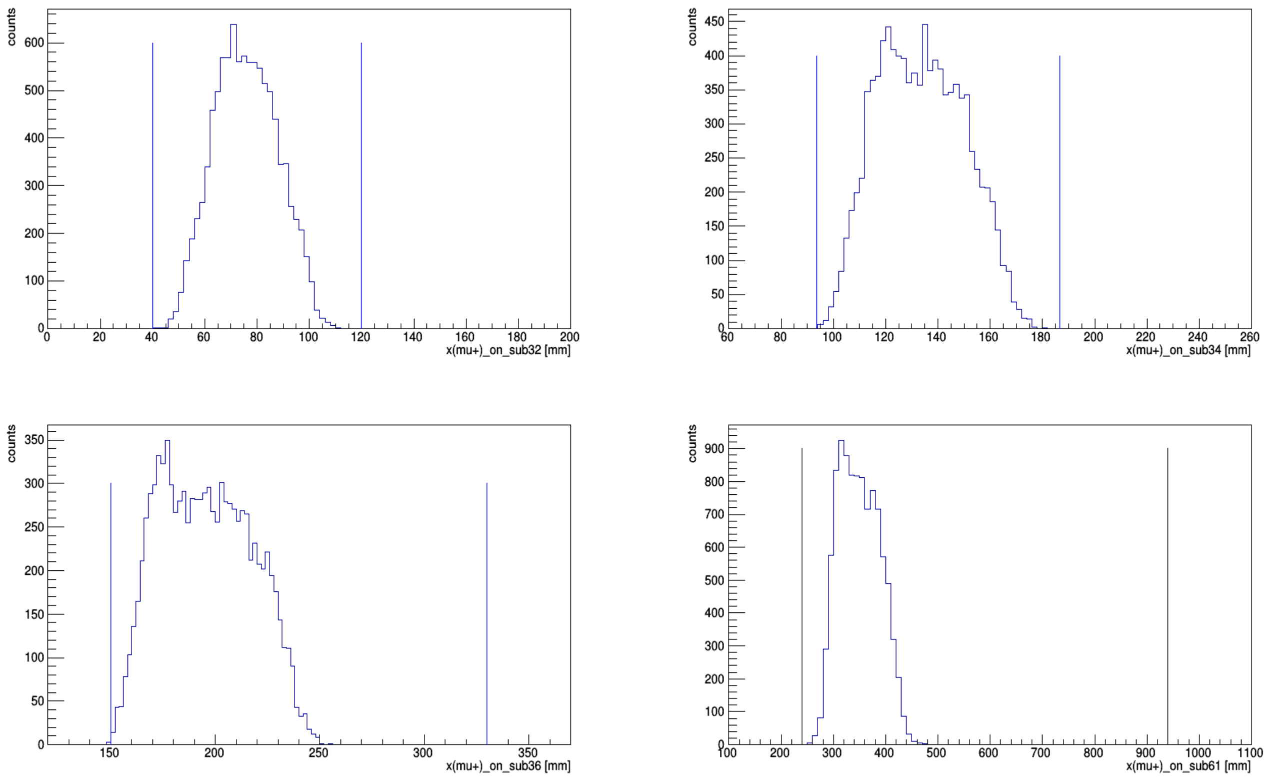

Figure 3: Plots show the positions of μ^- compared with the positions of detectors (silicon detectors, as subdetector 32, 34, 36) and muon chambers (subdetector 61).

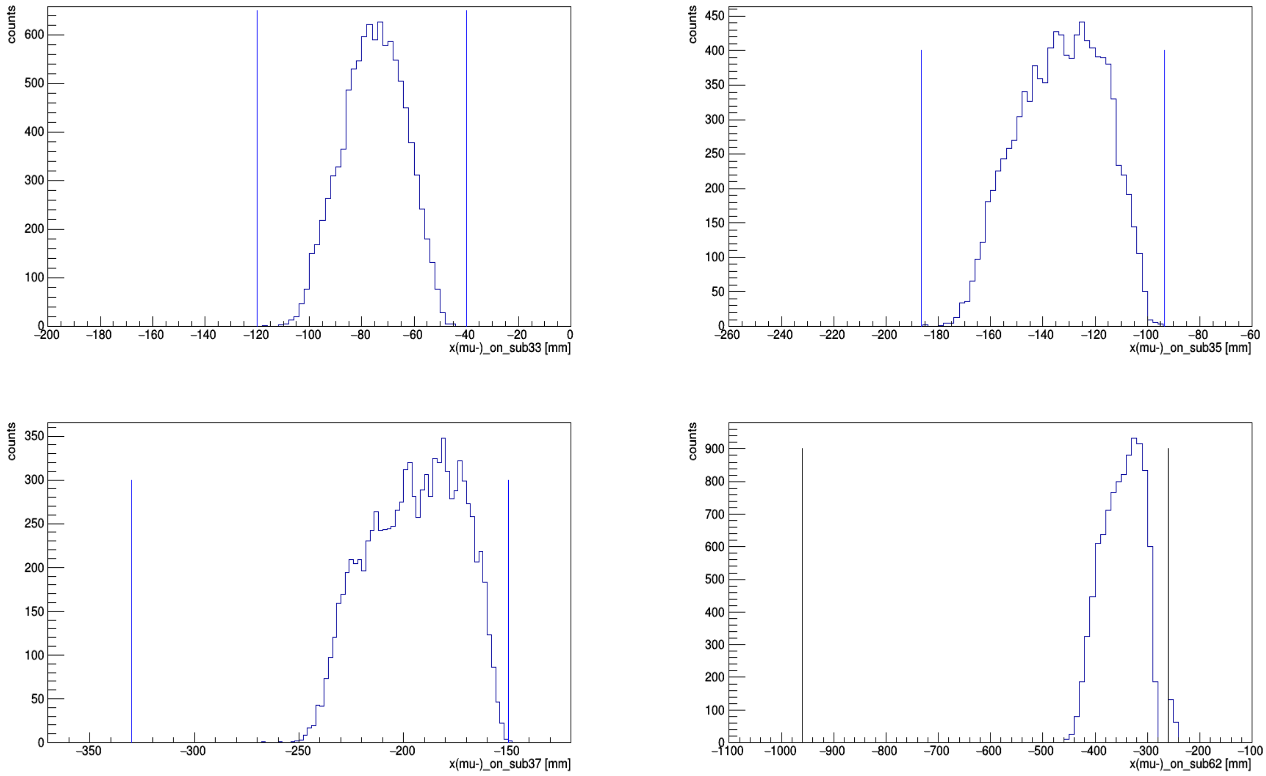

Figure 4: Plots show the positions of μ^+ compared with the positions of silicon detectors (subdetectors 33, 35, 37) and muon chambers (subdetector 62).

To check if the hits of $\mu^+\mu^-$ pairs on subdetector n. 30 were expected to be too close, their difference was plotted and compared with the width of a silicon strip, represented by 2 vertical lines of 242μm width. It shows that the majority of $\mu^+\mu^-$ pairs were detected as 2 different particles.

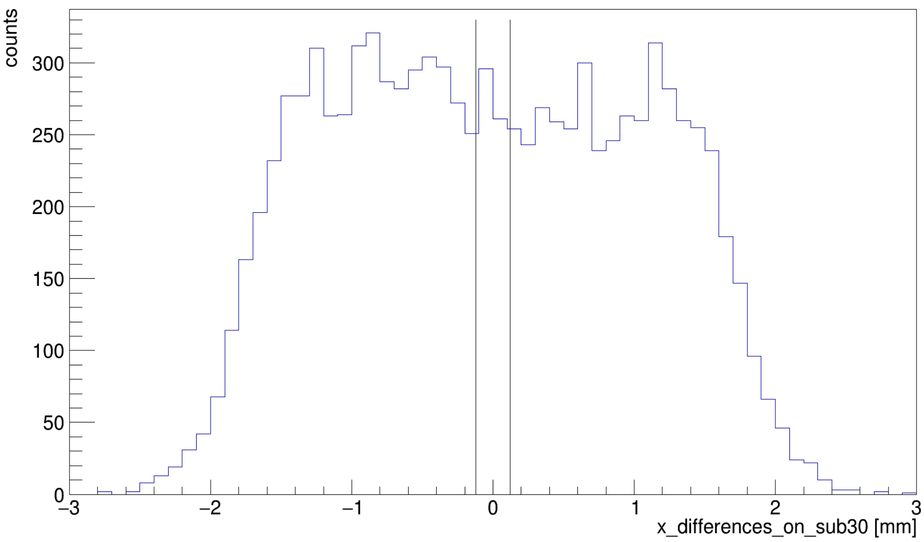

Figure 5: Figure shows the differences between the x position of μ^+ and that of μ^- on subdetector 30.

3.2 Background studies

Second step was to analyze backgrounds to better know if there were problems with it and if they could be solved with some setup modifies: for example, noise could simply be too much, or maybe it could overlap signal regions. As told before, background was made of electrons and positrons: electrons were produced by electromagnetic showers due to positron interactions with the target, while positrons were both produced by electromagnetic showers and by scattered positrons in the starting beam. For this reason, to study background positrons file were analyzed. Another root macro analyzed a 10000 positrons beam drawing histograms of the normalized flux of different particles on muon chambers:

- electrons;
- positrons;
- photons (which are produced in electromagnetic showers);
- all remaining particles (together in the same histogram).

It must be said simulations background were different from experimental background, starting from number of positrons. During test beam experiment there are 4 spills of positrons every minute; every spill has about $5 \cdot 10^6$ positrons. It implies there are on average $3.33 \cdot 10^5$ positrons/second. Analyzed file had 10000 positrons: in this case normalized flux on muon chambers was obtained by multiplying the number of hits on every bin by a factor $3.33*10^1$ and dividing for bin area; in that macro, bin area was $2 \times 2\ \mathrm{cm}^2 = 4\ \mathrm{cm}^2 = 0.0004\ \mathrm{m}^2$.

Results showed that both histograms of photons and other particles were negligible, so they are not shown here.

First simulation was done with a symmetric setup. Analyzing histograms one could notice that there was a lot of noise on μ^+'s muon chamber: it was due to positrons interaction with lead glass calorimeter in the μ^- branch, as shown in left image of figure 6. To fix this situation, the iron block standing before μ^+ chamber was moved inner (according to experimental space and possibilities of realization). New simulation was done, and the results was very good: noise was significantly decreased. Therefore asymmetric setup was chosen to be better.

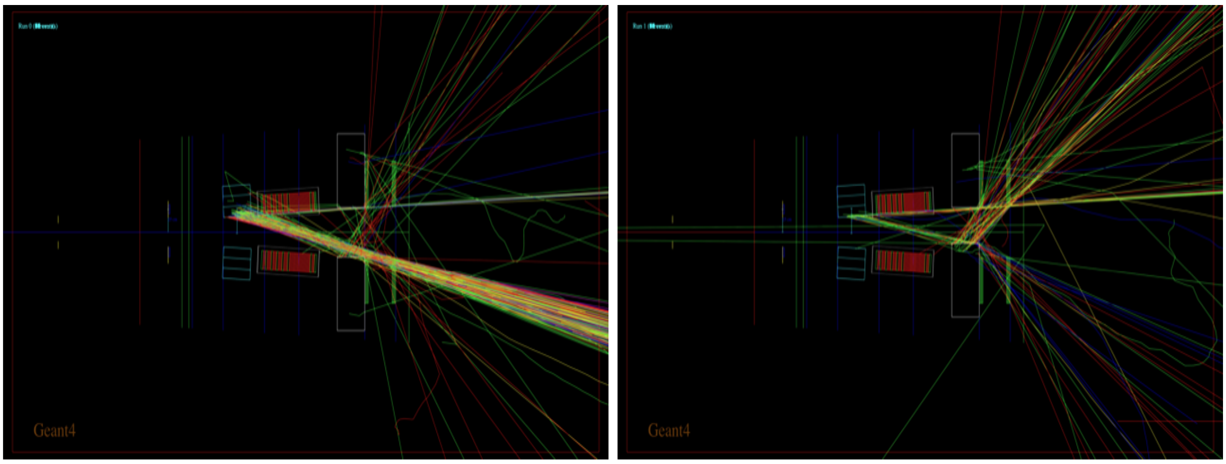

Figure 6: Figure on the left shows the scheme of experimental setup and positron scattering in symmetric conditions. Figure on the right shows the same beam, but in asymmetric conditions.

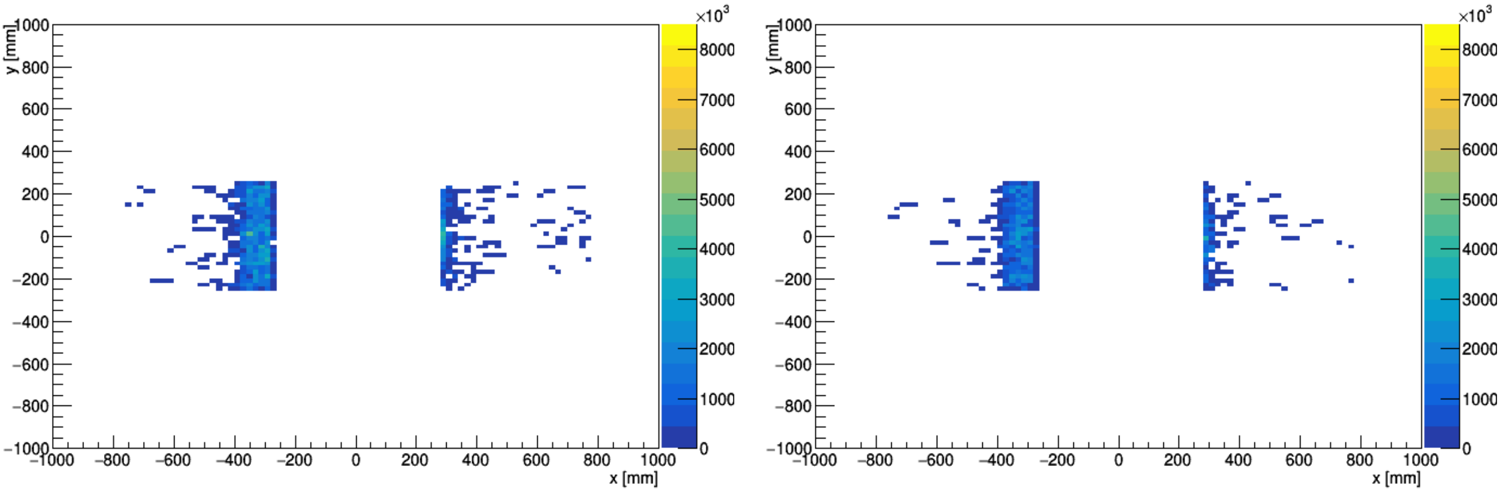

Figure 7: Flux of the electron hits (on the left) and the positron hits (on the right) in the case of symmetric setup.

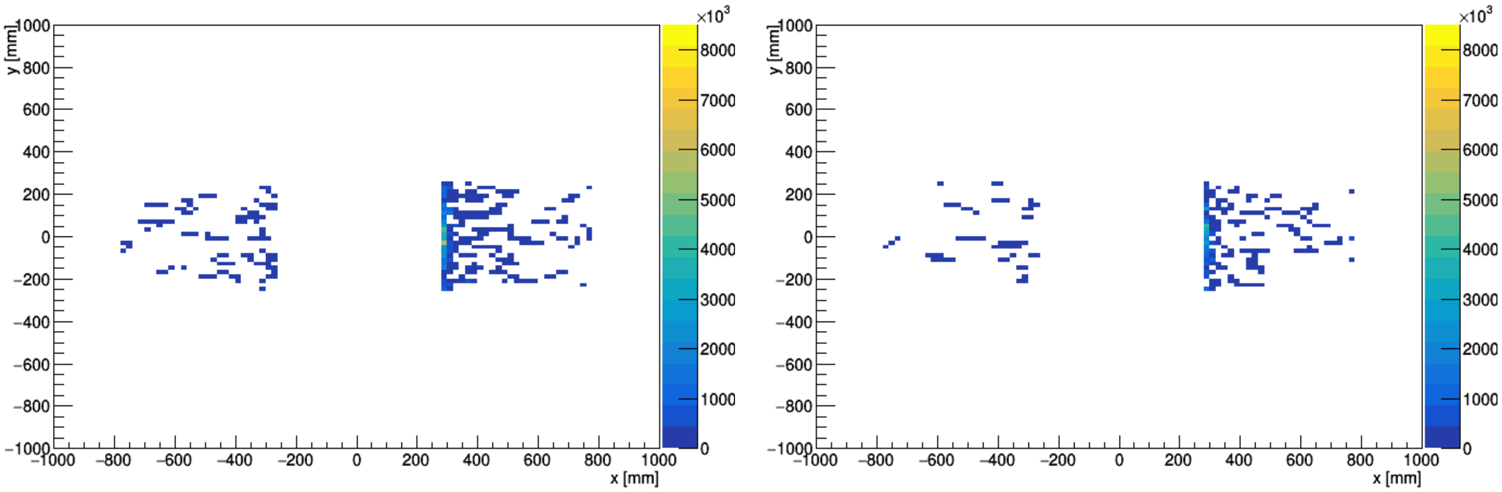

Figure 8: Flux of the electron hits (on the left) and the positron hits (on the right) in the case of asymmetric setup.

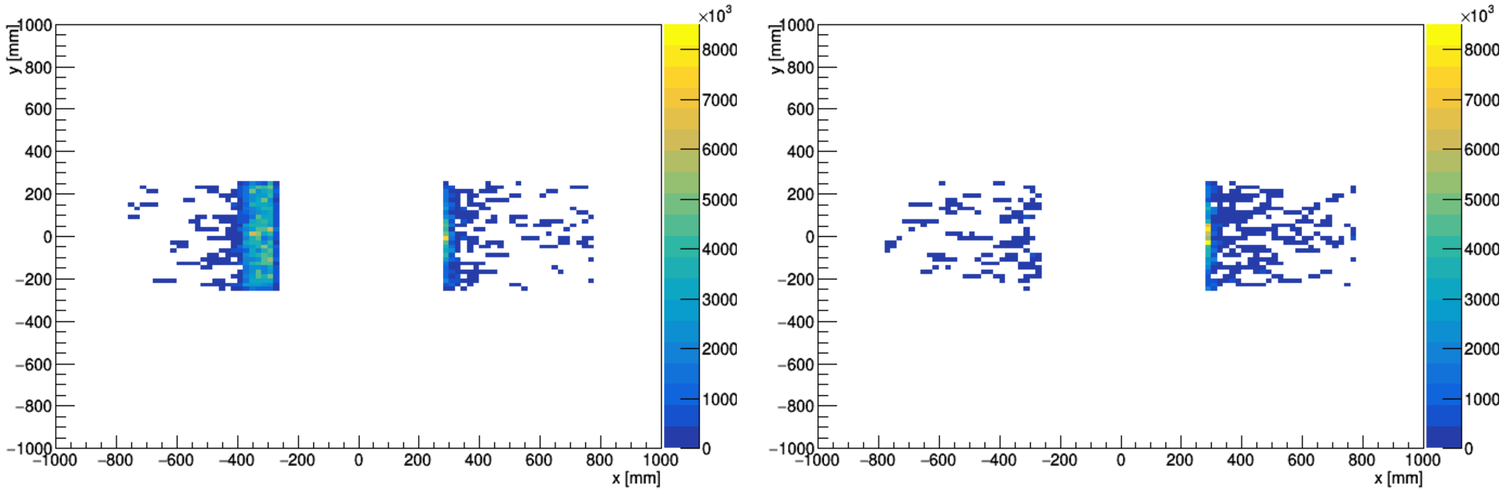

Figure 9: Total flux on in symmetric setup (on the left) and in asymmetric setup (on the right) (in those simulations there were no γ nor other particles produced by electromagnetic showers).

3.3 Momentum recostruction

Final step of simulations analysis were trying to build some experimental-like files starting from simlu-ations. Those files were build using the reconstruction algorithm: analyzing simulation file it tries to identify $\mu^{\pm}$ tracks and to calculate their momentum. Since these files were built from simulation files we could compare results from the algorythm with "Monte Carlo truth" to see if reconstructed results were significant. First part was to analyze $e^{\pm}$ momenta. Results are show in figure 10. Here one can see that $e^{\pm}$ momenta on muon chambers are very low compared with expected $\mu^{\pm}$ momenta on same detectors, which is in the range of 18-26 GeV.

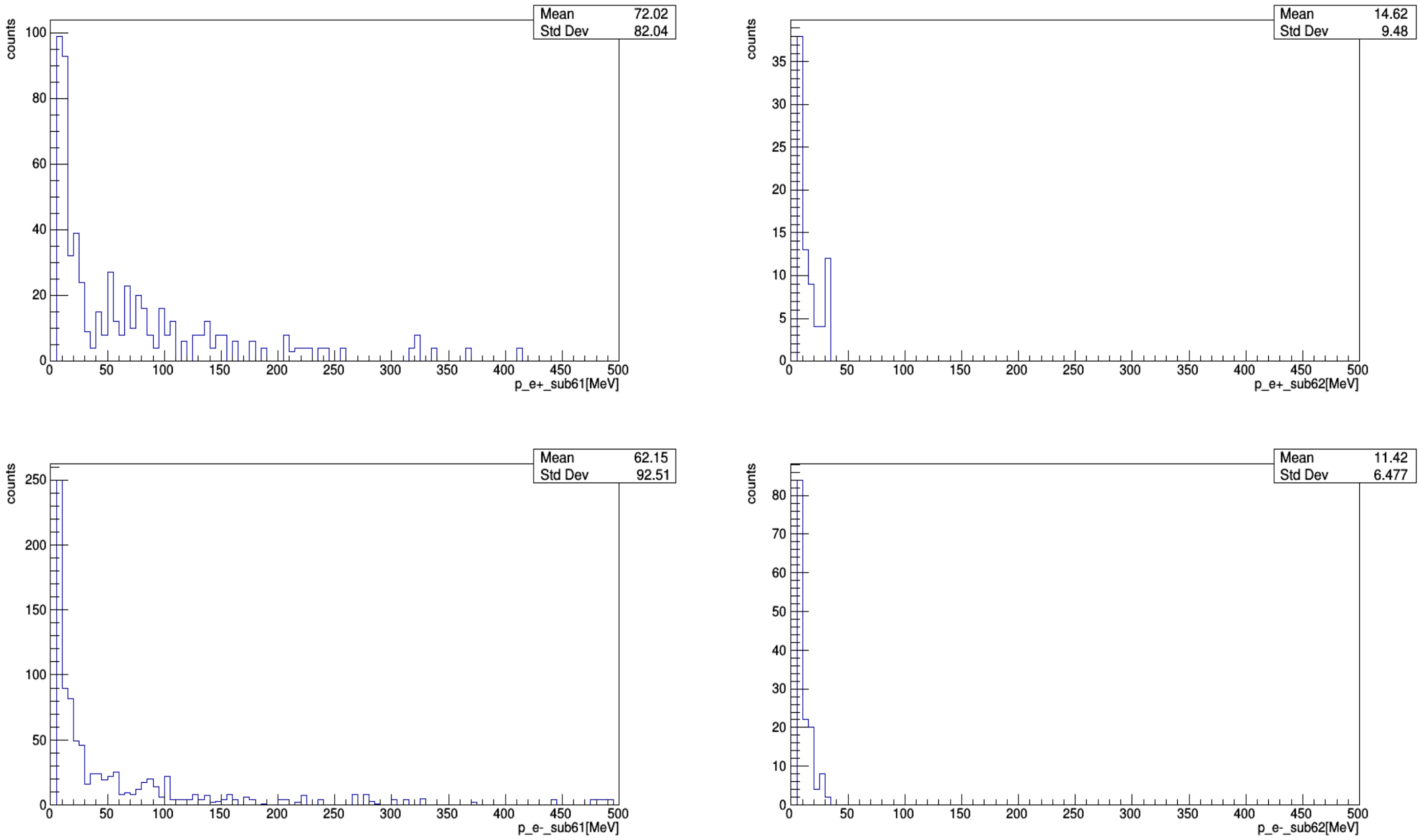

Figure 10: This figure shows the momentum of positrons, upper plots, and electrons, lower plots, on muon chambers. The x<0 muon chamber is subdet62 while x>0 muon chamber is subdet61.

Second part was to compare Monte Carlo $\mu^{\pm}$ momenta with reconstructed ones to see if the algorithm results had a significant or negligible difference. Results are shown in figure 11. To make a more significant research, macro compared the quantities $\frac{p_{reco}-p_{gen}}{p_{gen}}$ to see if the difference exceeded 3% of generated momenta: this value is the precision expected on the momenta esteems made from experiment. As it is shown in figure 12 the difference between the 2 values of momenta does not go beyond 2%, and has an average of about 4‰(fit with gaussian). These results imply that the algorithm can be used to reconstruct $\mu^{\pm}$ momenta starting from experimental files having good accuracy.

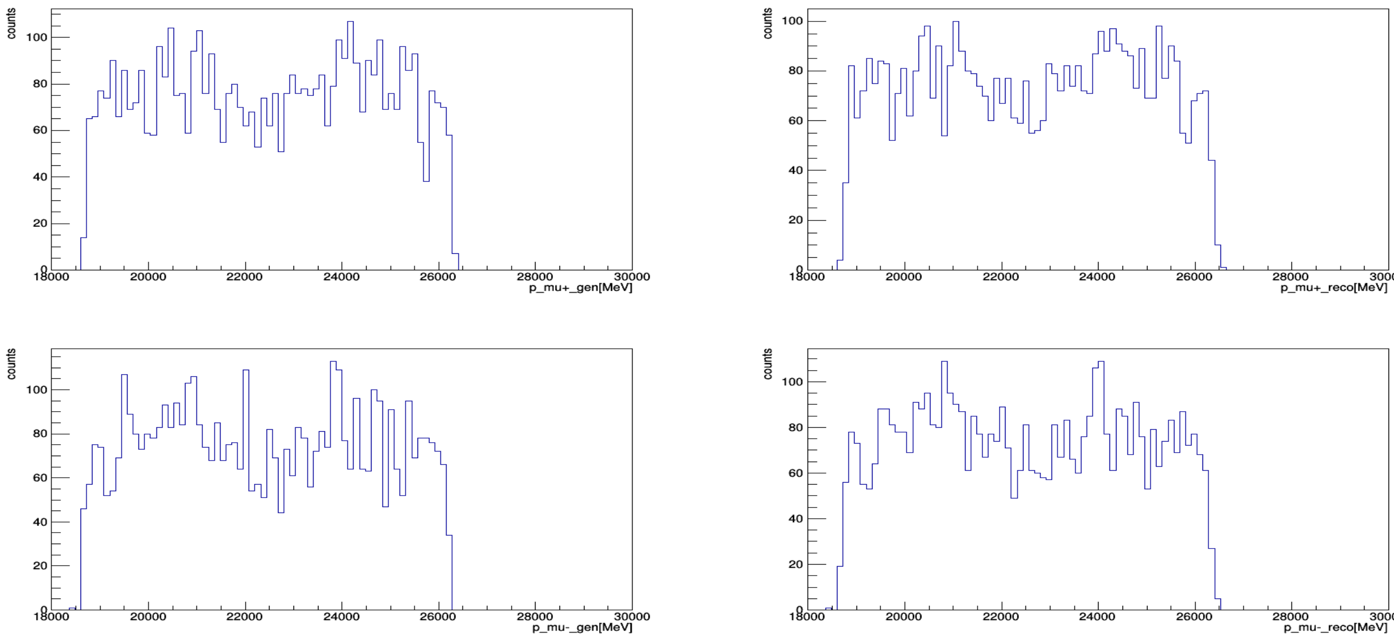

Figure 11: Figures show the μ^+, upper plots, and μ^- momenta, lower plots. Generated quantities are on the left, reconstructed ones on the right.

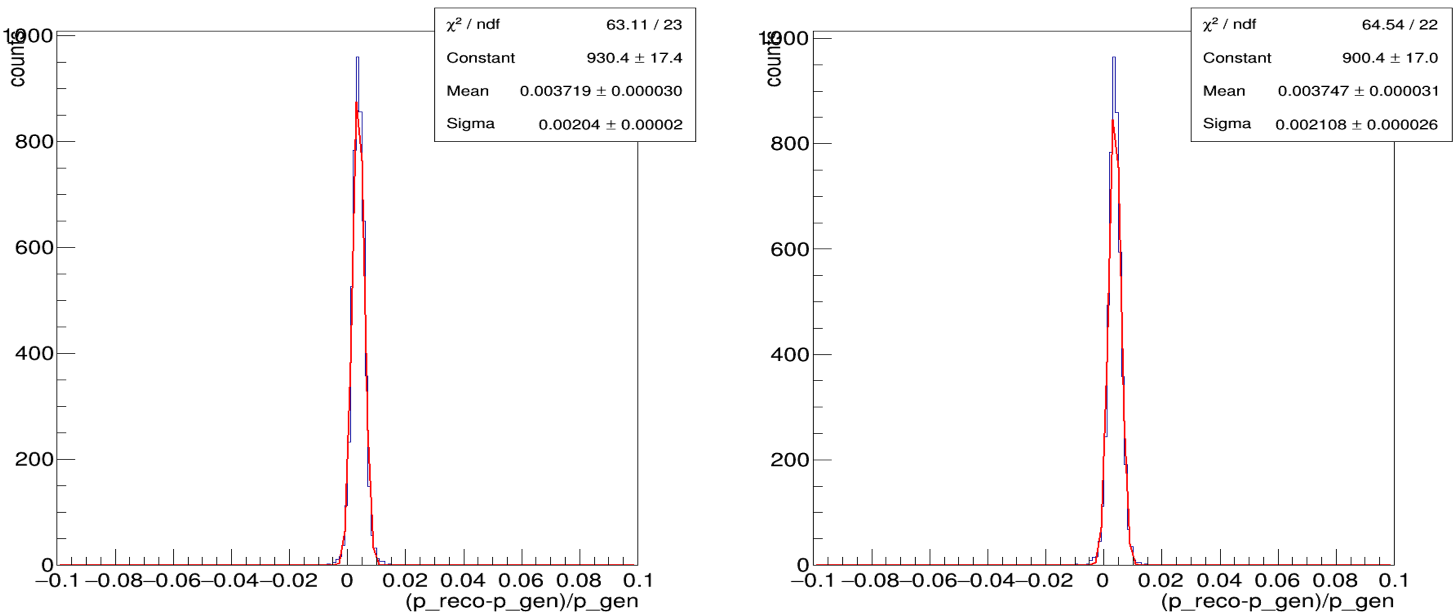

Figure 12: Histograms show of the difference between generated and recostructed momentum divided by the generated one for μ^+, left plot, and for μ^-, right plot, and their gaussian fit parameters.

Other things that can be done to see if the algorithm worked properly were to verify the bias on esteems and check if the sums of the momenta of a pair $\mu^+\mu^-$ was similar to that of the incoming positrons beam, which was 45 GeV. Those tests were done plotting quantities shown in following figures. Figure 13 shows that the plot of $\Delta p/p_{gen}$ does not depend on p_{gen}, while figure 14 shows that the sum of reconstructed momenta is about 45 GeV, which is that expected.

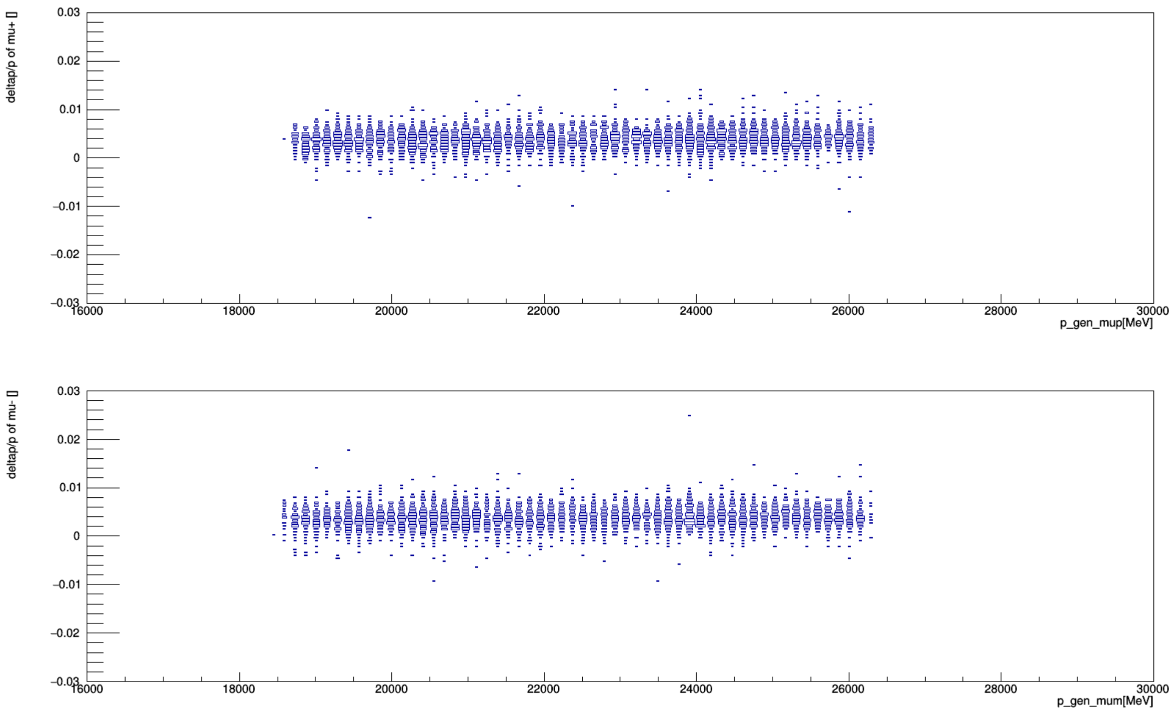

Figure 13: These plots show the quantities $\Delta p/p_{gen}$ vs p_{gen} for μ^+ (upper plot) and μ^- (lower plot).

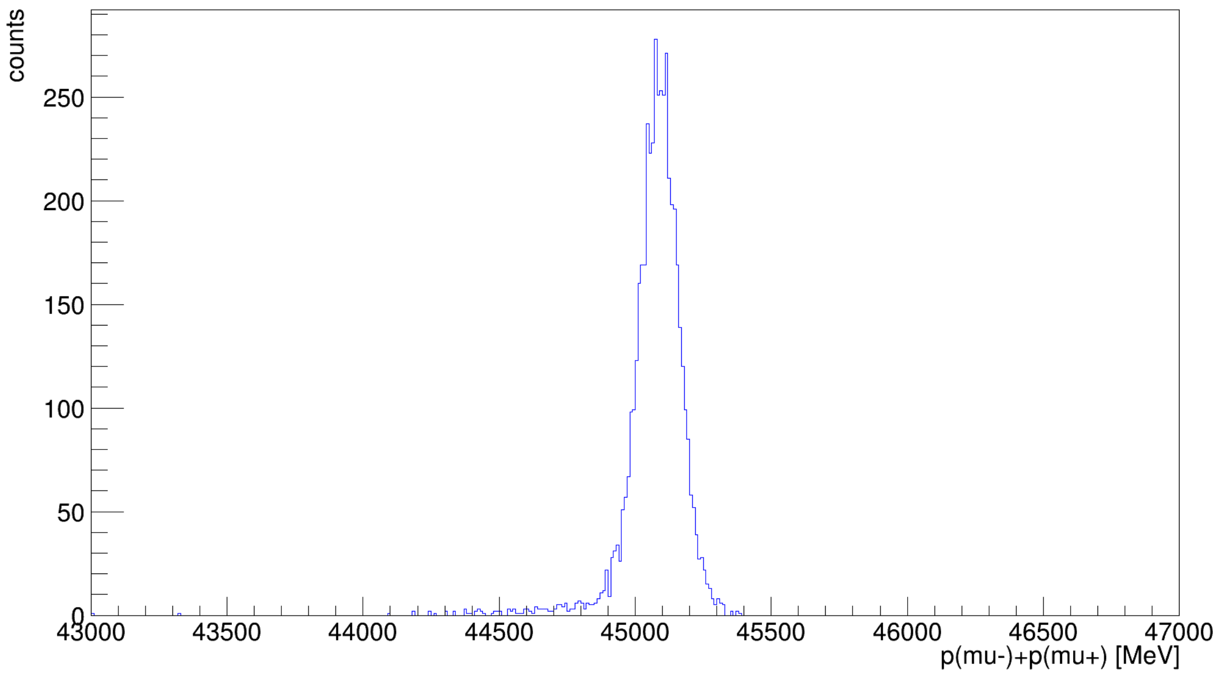

Figure 14: Figure shows the sum of μ+ and μ- momenta reconstructed by Pattern Recognition.

4 First results from 2018 test beam

After 2018 test beam, first results files were done. Some event displays are shown in figures 15-18: they show data acquired with trigger signal respectively 0, 1, 2, 1228. These show that data taking went well. Subdetectors 33, 35, 37 seem to be noisy: better analysis and studies will be done offline.

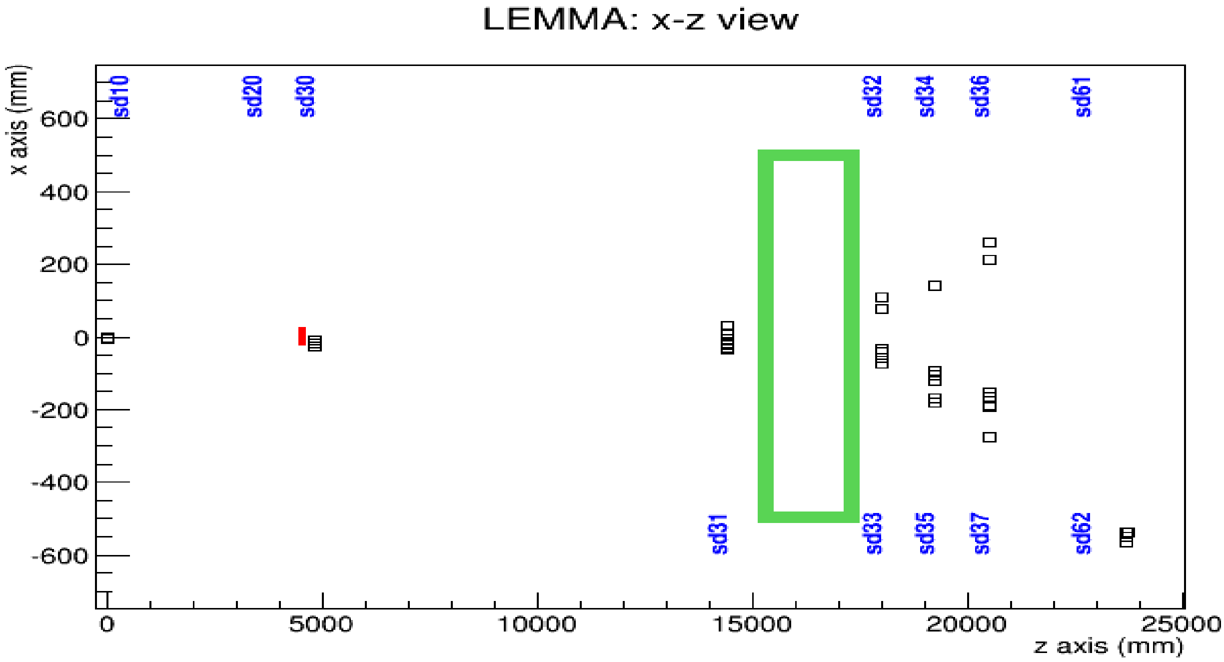

Figure 15: Figure shows event display of event n.0 of 2018 tet beam.

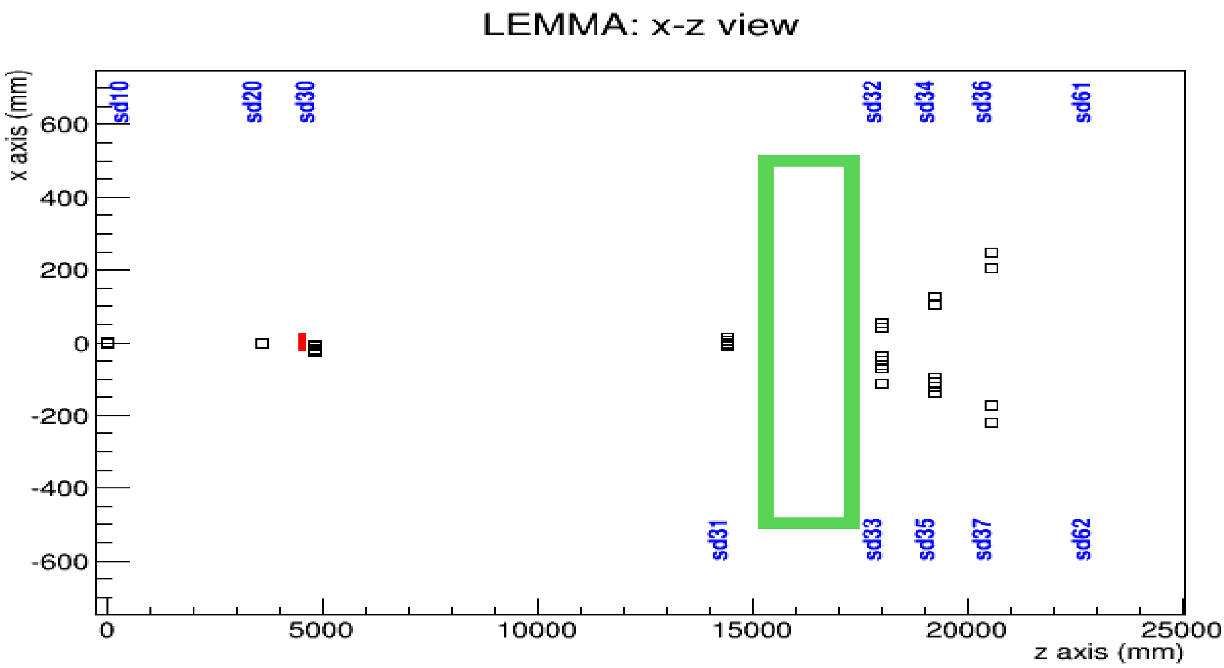

Figure 16: Figure shows event display of event n.1 of 2018 tet beam.

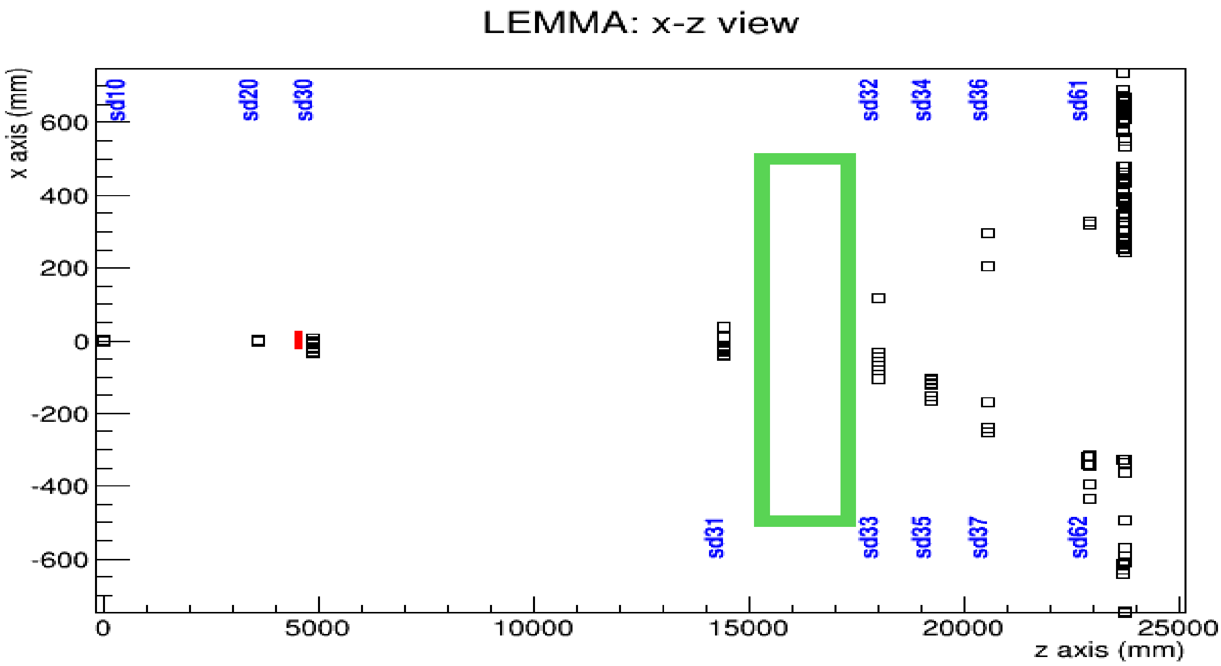

Figure 17: Figure shows event display of event n.2 of 2018 tet beam.

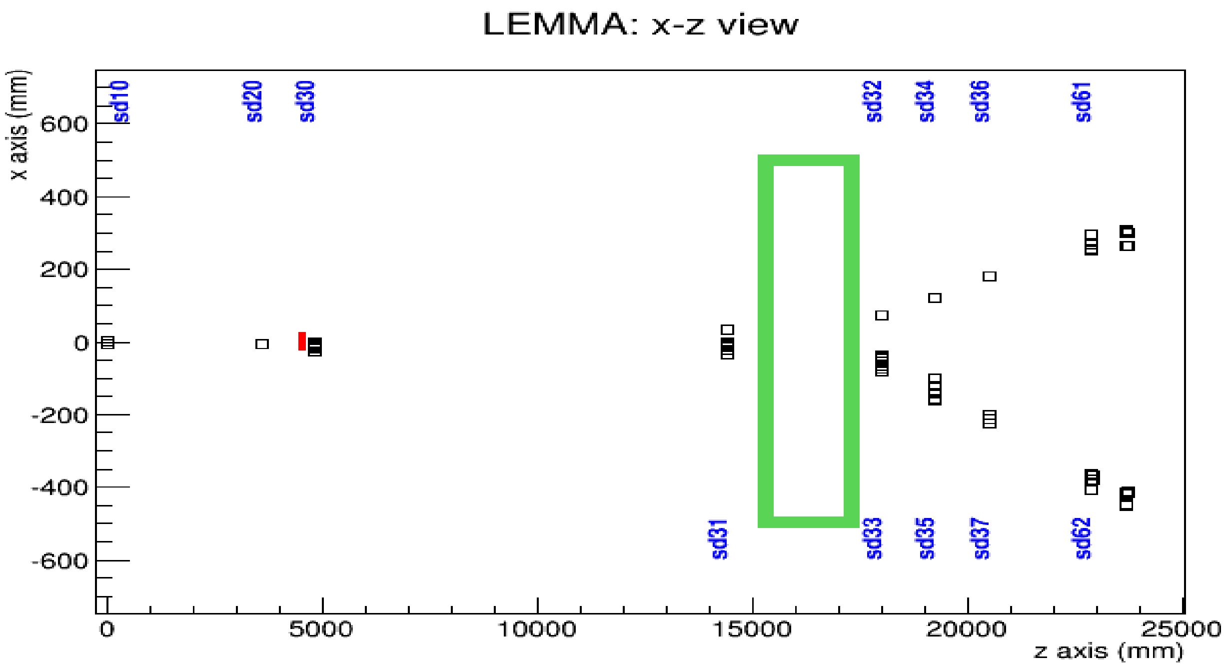

Figure 18: Figure shows event display of event n.1228 of 2018 tet beam.

To see if data acquisition matched with that expected, new simulations were run because of some small changes in experimental setup were made during test beam. Following figure shows histogram of x experimental hits (both signal and noise mixed, taken from many events) on chambers compared with x $\mu^{\pm}$ signal obtained from simulations. These results show that muon chamber are expected to be in a good signal range though in those regions there is a peak of noise that overlap signal. This figure also shows that the μ^{+} muon chamber is not positioned well: in the region between -300mm and -250mm there would be signal while figure shows it is empty.

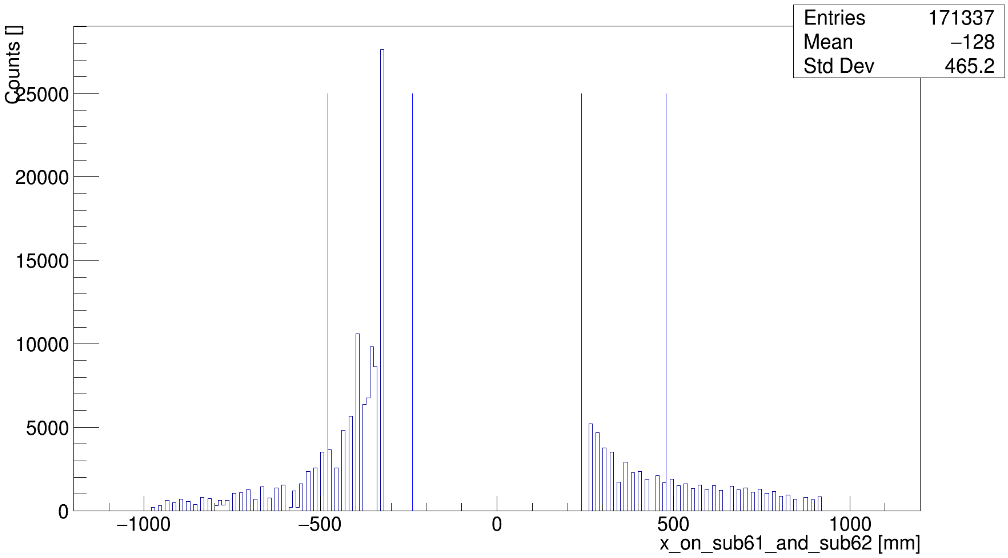

Figure 19: Figure shows x positions of signals on muon chambers compared with muon signals, represented by vertical blue lines, obtained from simulations after test beam.

The following figures show event displays on muon chambers of 2 events that satisfy the algorithm reconstruction conditions: it asks at least 3 hits on 3 different layers in at least 3 muon chambers' sections. For these events, minimun χ^2 fits of the hits in a same section are made, building a corresponding segment. Then, to obtain muon tracks, hits of segments in a same muon chamber are fit together again. The first dispaly is a candidate for signal event. It has 2 tracks with hits in all section of the chambers; furthermore the hits are in the corresponding position as expected in simulation analysis, as shown in figures 3 and 4. The second display shows an event that is not a signal event though it has been selected by the algorithm. There are many hits on chambers, also in positions where they are not ecpected to be. There are many tracks and not only 2 as in figure 20. This may be caused by a small electromagnetic shower or some noise. These examples want to show that the algorithm works well though it needs some improvements: for example maximum and minimum angle can be fixed, so the lines can not reach the angles shown in the second figure and the analysis can be improved.

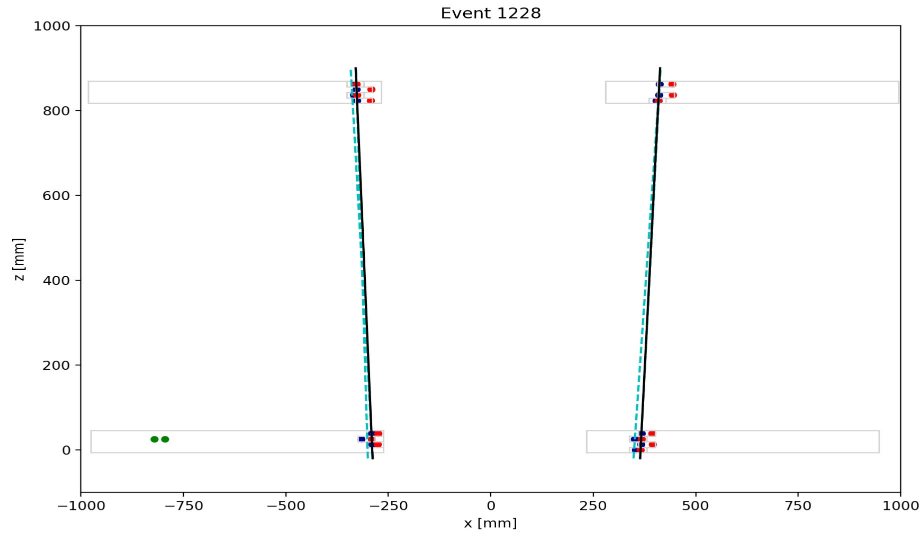

Figure 20: Figure shows reconstructed tracks on muon chambers for the event n. 1228. This is a zoom of event display shown in figure 17.

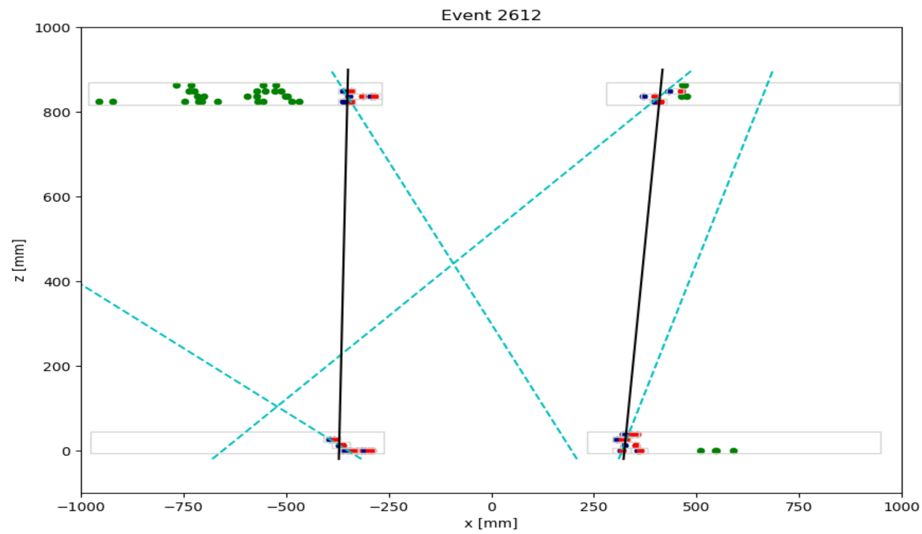

Figure 21: Figure shows reconstructed tracks on muon chambers for the event n. 2612.

5 Conclusions

Thanks to simulation analysis 2018 LEMMA test beam obtained good results. In the near future data file have to be analyzed better to see if muons produced are enough and have the expected characteristics. Giving a first glace to data it seems that there are a lot of $\mu^{\pm}$ good events compared with the 2017 test beam, where only 27 muon pair candidates could be identified. Furthermore noise did not give problems: signal events are often clean. The reconstruction algorithm need some small improvements, but the main goal could be considered achieved: the production and analysis of muons in this experiment can now proceed without big problems and results could lead to deeper studies on this new muon injection scheme.

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