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CORSO DI LAUREA IN FISICA
TESI DI LAUREA

Study of the kinematic properties of muons / antimuons produced at threshold by a beam of positrons impinging on a fixed target

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1 Introduction

Nowadays two kind of accelerator are in use or have been used, the hadronic (LHC) and the leptonic one (LEP). Those study strong and the weak interactions but they differ in the particle production processes, indeed the hadronic one produce particles by strong interactions instead the leptonic one by electromagnetic or weak interactions. Leptonic accelerators use electrons and positrons as projectiles for many reasons but mainly because these particles are easily produced and elementary. Electrons and positrons are the lightest massive charged particles (0.510 MeV[1]) but because of this fact the synchrotron radiation, that for a charged particle varies inversely to the fourth power of the mass, leads to a large amont of energy loss. So these particles can not reach energy higher than 209 GeV [1].

Physicists in order to verify the existing theories and to reach new borders need energies in the teraelectronvolt range but this goal can not be achieved by using electrons and their anti-particles. A solution could be using hadrons, in particular protons whose mass (938 MeV) is more o less 1840 higher than the electron mass, but there are several problems. First of all protons are not elementary, in fact a proton is composed by quarks and gluons so for this reason backgrounds are higher than in a processes with elementary particles involved, moreover because of the quarks and gluons substructure not all the proton's momentum is available. Another solution would be use muons because they are elementary as the electron even if they are more massive (105 MeV) and the teraelectronvolt range could be reached, but muons decay and their life time in very short ($\sim 2.2 \mu s$).

Muon beams are customarily obtained via K/π decays produced by proton interactions on target but these muons have a continuous spectrum of energy because of the β decay, instead we would like to obtain a muon beam with a well defined momentum range. A novel approach would be to produce low emittance muon beams from electron-positron collisions at a centre-of-mass energy just above the $\mu^+\mu^-$ production threshold, corresponding to a positron beam of about 45 GeV interacting on electrons at rest.

The most important key properties of the muons produced are:

- low muon momentum in the centre of mass frame
- large boost $\gamma \sim 200$.

These characteristic results in the following advantages:

- the final state muons are highly collimated and have very small emittance[2][6];
- the muons have an average laboratory lifetime of about $500 \mu s$.

2 2017 LEMMA test beam

2.1 Beam conditions

Properties of $\mu^+\mu^-$ pairs produced by 45 GeV positron beam can be studied with a suitable test beam. A first test beam was carried out at CERN at the end of July 2017, the experiment lasted a week. The first days were dedicated to the arrangement of the instrumentation according to the Monte Carlo simulations. The following days were spent in the data acquisition which was divided into two parts:

- Calibration runs: positron beams at 18 and 22 GeV without target;
- Data taking runs: high intensity positron beam at 45 GeV impinging on a Beryllium target.

During the data acquisition the SPS could provide up to 4 spills/minute with $5\ 10^6$ positrons/spill. The spill duration was 4.8 s.

The main goals of this test beam were:

- measure the kinematical properties of the produced muons, in particular the emittance
- measure the cross section at threshold and comparison with the theoretical prediction.

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[1] In this thesis will be use the naural units with c=1 , so masses, momenta and energies will be measured in multiples or submultiples of the MeV.

[2] 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). A low-emittance particle beam is a beam where the particles are confined to a small distance and have nearly the same momentum.

In order to achieve these goals it is fundamental to identify particles after the target, reconstruct their tracks and momentum. Obviously during the scattering process muon pairs production is not the only process that take place; in fact the main reactions are shown in Figure 1,2.

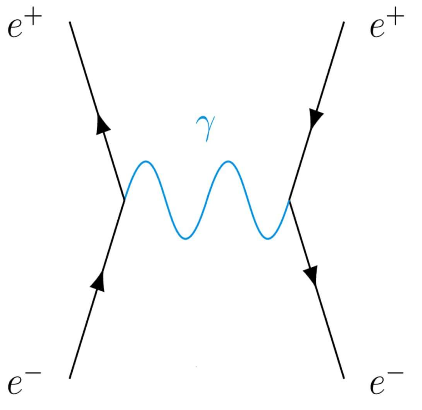

Figure 1: Bhabha production

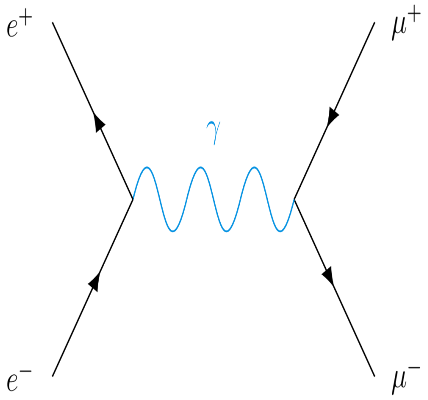

Figure 2: Muons production

The most significant process is the elastic scattering (Bhabha), which represent the principal source of background, so one fundamental point was to reduce as much as possible its contribution. To achieve this aim a iron shield was interposed between the silicon detectors and the muon chamber.

2.2 Expermental setup

The experimental setup as reproduced in Geant4 [3] is shown in Fig. 5. The coordinate system used, has the z axis pointing along the incoming positron beam direction, the y axis pointing upwards and the x axis completing a right handed coordinate system. Two silicon tracking devices, 2×2 cm^2 , labeled T1 and T2 in Fig. 5, were placed upstream of the 6 cm long beryllium target. These are used to measure the direction of the incoming positron(s). Downstream of the target but upstream of the magnetic field region, two silicon devices, T3, 2×2 cm^2, and C1, 10×10 cm^2, were measuring the beam positrons surviving the passage trough the target as well as any additional charged particle produced by the incoming beam. A magnet was used in order to produce the deflection corresponding to a 1.26 T magnetic field directed along the y axis acting on a 2 m distance. This value was used to ensure a good separation between 45 GeV positron tracks and positive tracks in the [18,26] GeV momentum range. Negative tracks were deflected towards the silicon devices C3 and C5, both 10×10 cm^2, and the negative x side of a large, about 2 m wide and 1 m height, drift tubes device, a (spare) CMS muon chamber. C3 and C5 where placed in order to have good acceptance in the momentum range [18,26] GeV. Positive tracks in the same momentum range were recorded in the silicon devices C2 and C4, both 10×10 cm^2 . The two sides on which elecrons and positrons were deflected are called branches. Positrons were expected to deposit most of their energy in the Ecal, a lead glass calorimeter. Any eventual leakage was absorbed by the iron shielding placed downstream. Hence only μ^+ tracks were expected to be recorded in the positive x side of the muon chamber. Photons emerging from the target were absorbed in a PbWO4 calorimeter, the γcal. Finally a Cherenkov detector is placed downstream of the negative x side of the muon chamber to differentiate between electron and muon tracks, with acceptance in the [18,26] GeV momentum range. A trigger was provided using a triple coincidence between scintillator pads located upstream of T1 and downstream of C4 and C5, figure 3.

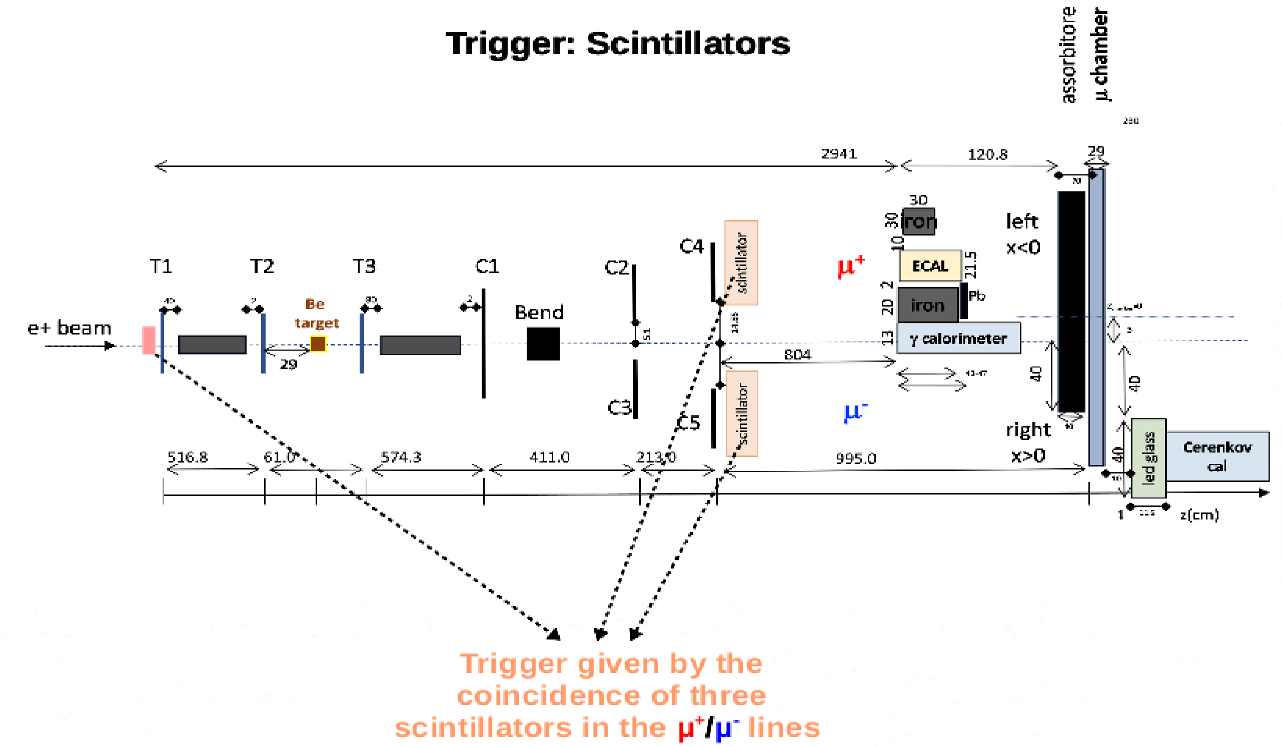

Figure 3: Trigger.

Silicon detectors were providing hits along the x and y axis. The pitch between readout strips was in the range between 5 and 25 μm, depending on the size of the silicon detector, the smaller detectors having also the smaller pitch. The muon chamber was providing 8 hits along the x axis, bending axis, with a 150 μm expected resolution, and 4 along the y axis, with a 200 μm expected resolution.

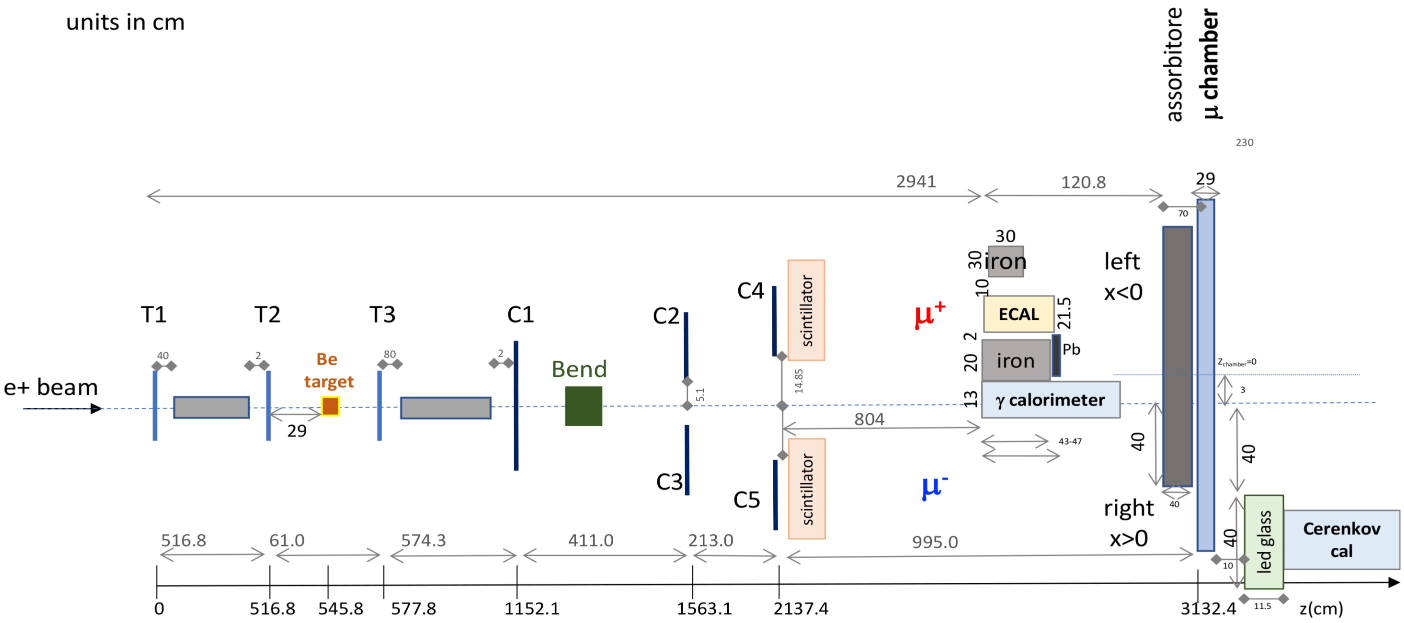

Figure 4: experiment set up.

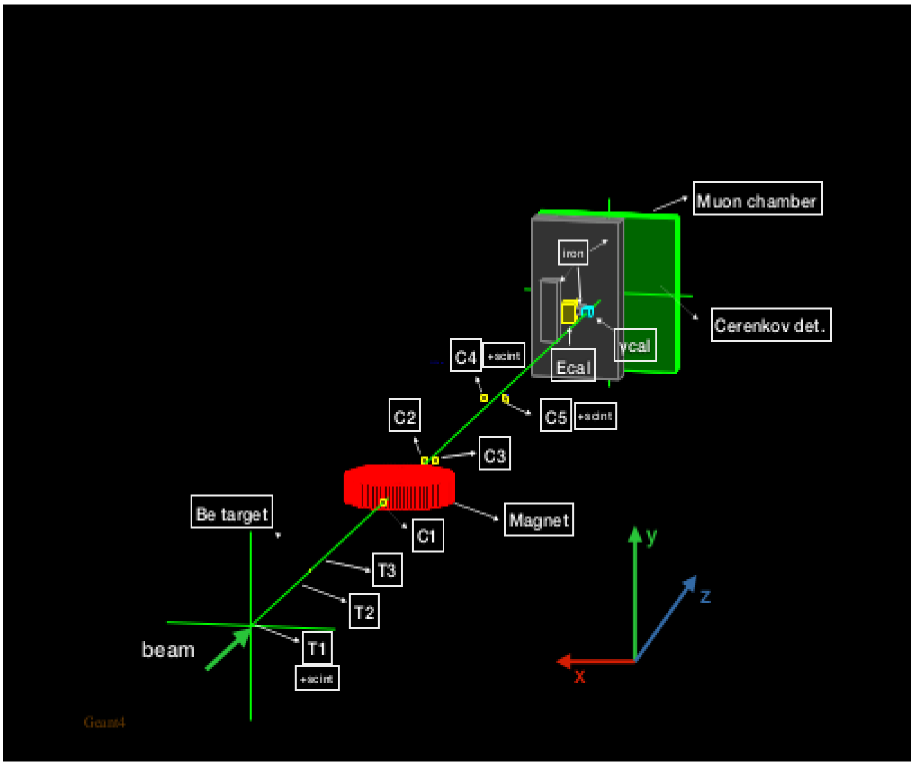

Figure 5: Geant4 implementation.

3 Data Analysis

All the data analysis present in the following sections was done using root[2], simulated event were processed with the same reconstruction software as used for the data.

3.1 Calibration Runs

In a calibration run a beam of particles is produced with the required energy. This is very useful to set up the apparatus. Two runs of positrons without the beryllium target were acquired, with a momentum of 18 GeV and 22 GeV (figure 6). From the plots below we could see how the momentum is spred around the appropriate value, actually the mean value of these distibution is a little bit under the expected value.

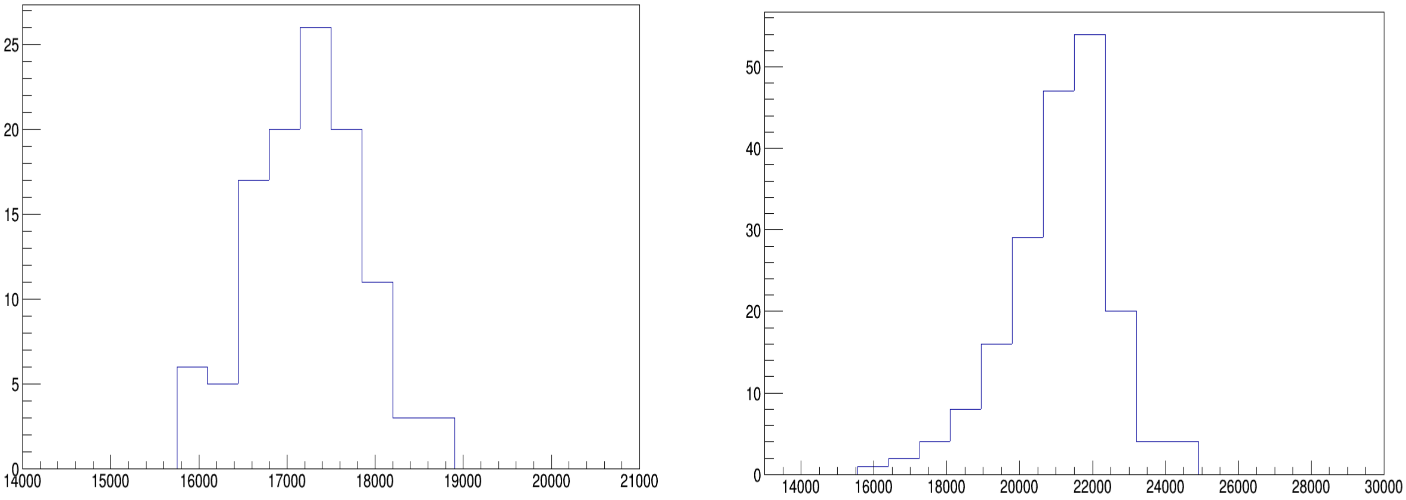

Figure 6: The figure on the left shows the momentum distribution of the 18 Gev beam, the figure on the right show the momuntum distribution of the 22 Gev beam.

First of all these runs were used to align all the detectors necessary for the tracking. These runs were also used to estimate the probability that one positron could pass the iron thickness located in front of the muon chamber, in other words the probability that one signal coming from the muon chamber was a fake signal. This probability was compatible with zero. Moreover from these runs we could find out the resolution [3] of the apparatus that is around 0.03-0.04 (figure 7).

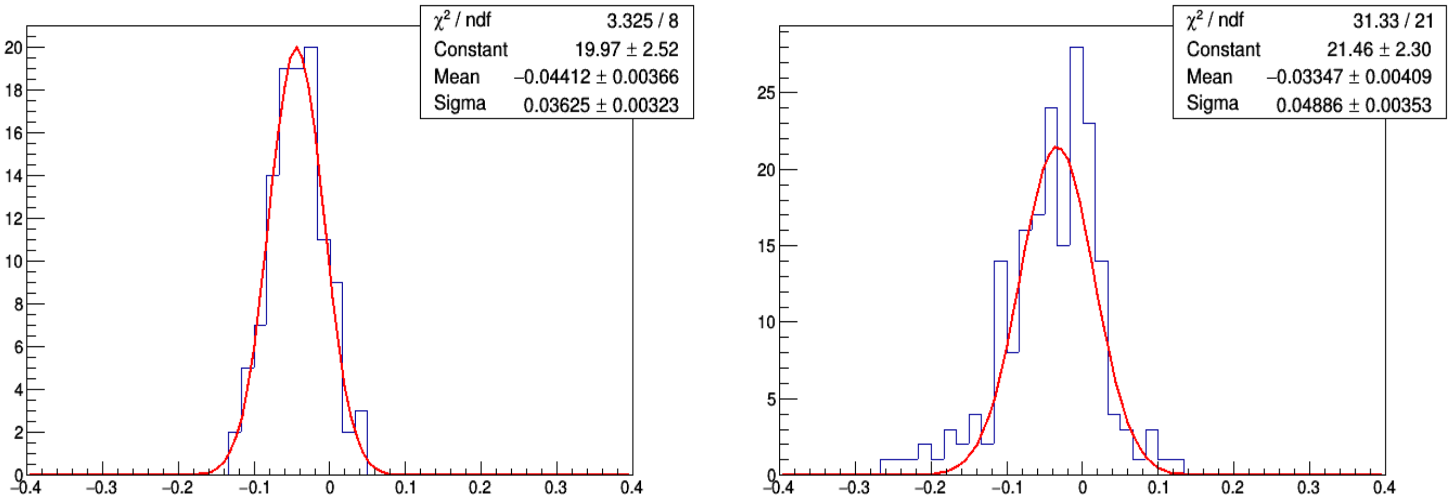

Figure 7: The figure on the left shows the resolution of the 18 GeV beam, the figure on the right show the resolution of the 22 GeV beam.

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[3] The resolution was obtained from the relative difference between the reconstructed and the beam particle of the calibration run.

3.2 Runs with target

An event is a set of hits collected in a small fraction of time. The informations collected by the detectors in this small time interval are then saved but during the saving process all the additional information coming from the detectors is lost. During this first teast beam the acquisition's frequency was about 1 MHz. Almost 620K events have been collected. The first step necessary before using the events collected is the convertion of the hits to global coordinate frame. This was done comparing the calibration runs with the simulation. Before starting the data analysis it was crucial to decide which condition was necessary to reconstruct a particle's track and how to identify a pair of muons. For both the branches to reconstruct a track we required at least a hit on one of the two detectors upstream and downstream of the magnet plus a track on the muon chamber. Since the positrons couldn't pass throught the iron shielding a hit on the muon chamber on the μ^+ side would prove for sure that a pair was produced.

The magnetic field was set up in order to reveal only particles with a momentum that was approximately between 18 and 26 GeV. Nonetheless hits on detectors were plentiful because the cross section of the process $e^+e^- \to \mu^+\mu^-$ is very low if compared with the elastic scattering so just a small fraction of the particles produced were actually muons. For each event we calculated all the possible tracks between the hits of the two detectors located after the magnet and this operation was done for both the branches, but in this way there were also a large amount of fake tracks due to combinatorial processes. In order to select only good tracks it was necessary to find also a track in the muon chamber but this operation was quite complicated because the muon chamber was very noisy[4] and therefore generated a great amount of fake tracks. Once we had reconstructed the track downstream of the magnet we proceeded looking for compatibles tracks in the detectors upstream. After that the track was fully refitted so we could reconstruct the momentum of these particles looking at the deflection in the magnetic field.

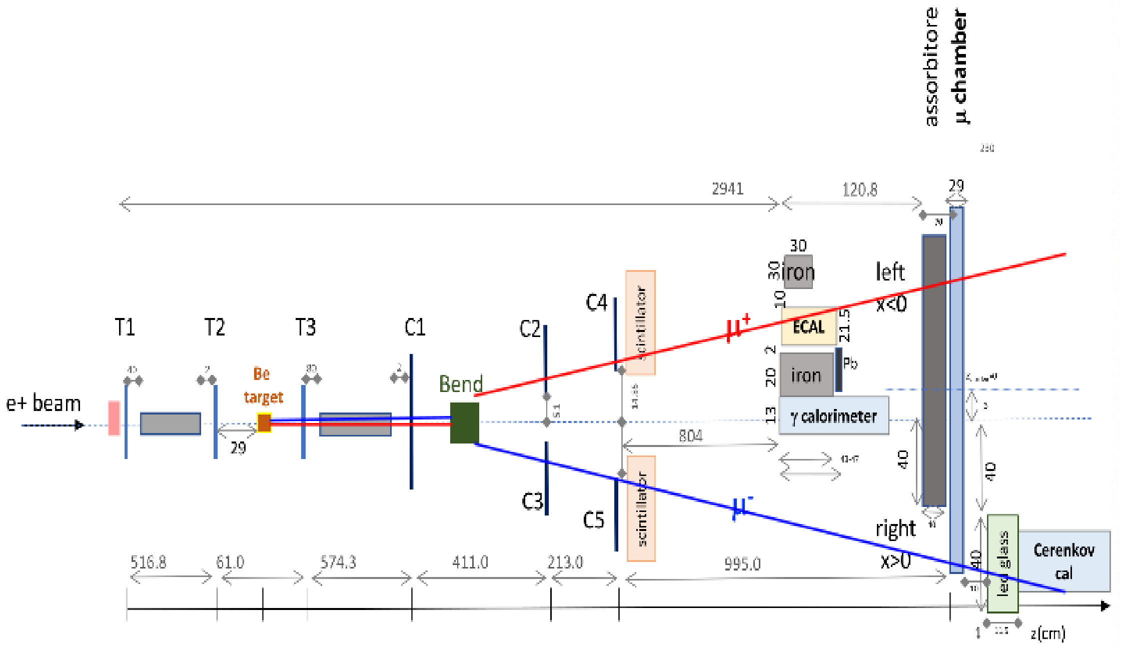

Figure 8: signal event topology .

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[4] Part of the "noise" was likely due to an electronic problem and part to spurious hits, hence an improper shielding issue.

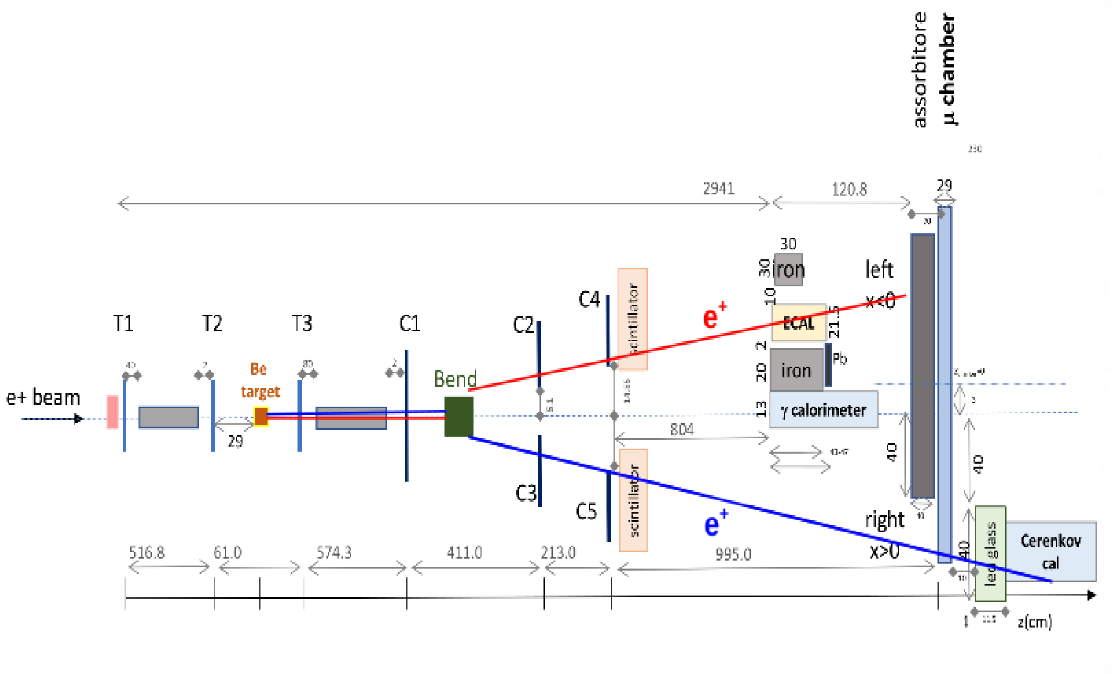

Figure 9: bhabha event topology.

The analysis provided 27 couples of particles which were the candidates muon pairs. In order to understand if these particles were from the $e^+e^- \to \mu^+\mu^-$ process we analyzed some fundamental properties. First of all were plotted the hits of these particles in the detectors downstream of the magnet and compared the resulting distribution with the Monte Carlo. In figure 10 we could see how the data are distributed according to the Monte Carlo simulation of the signal.

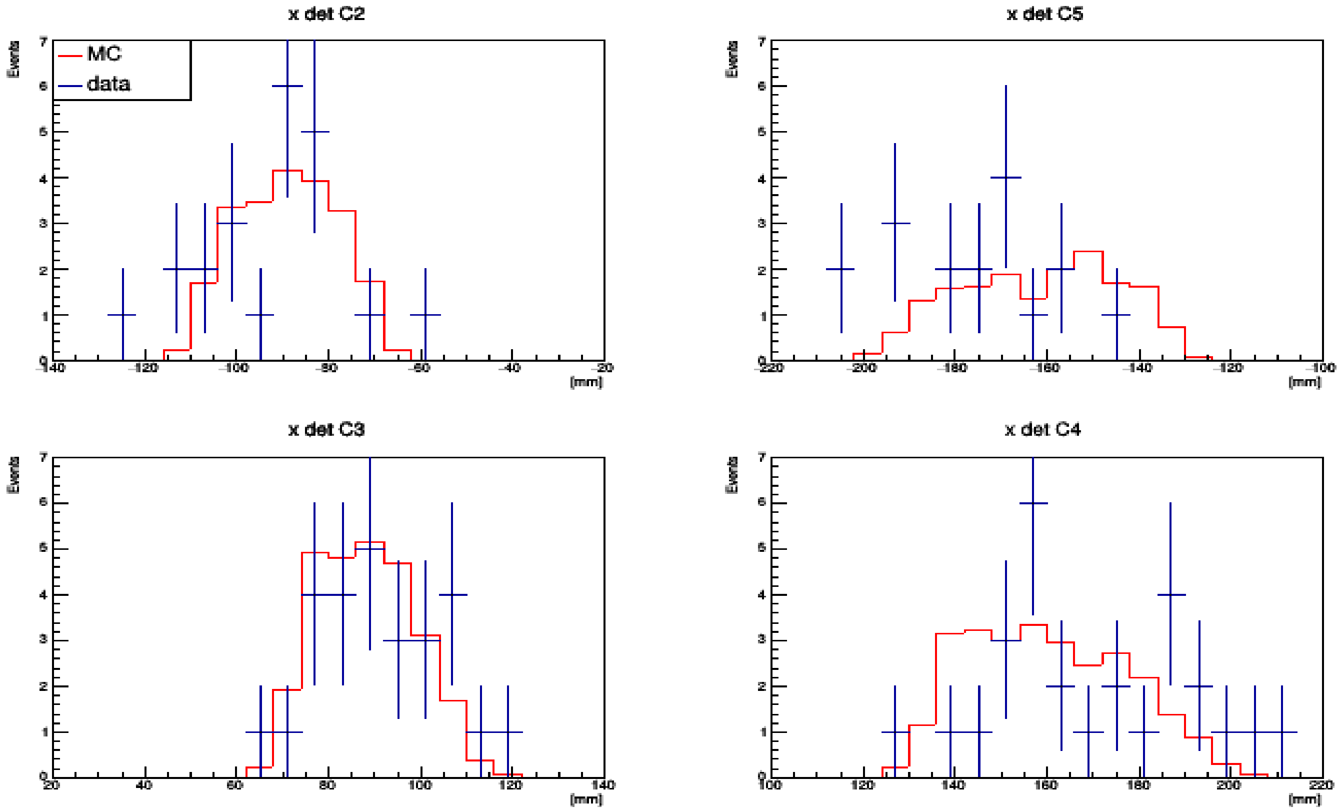

Figure 10: hit's position on the silicion detector downstream the magnet .

From the track reconstruction we calculated the momentum and the angles of these muons. Data and Monte Carlo are compared in figure 11.

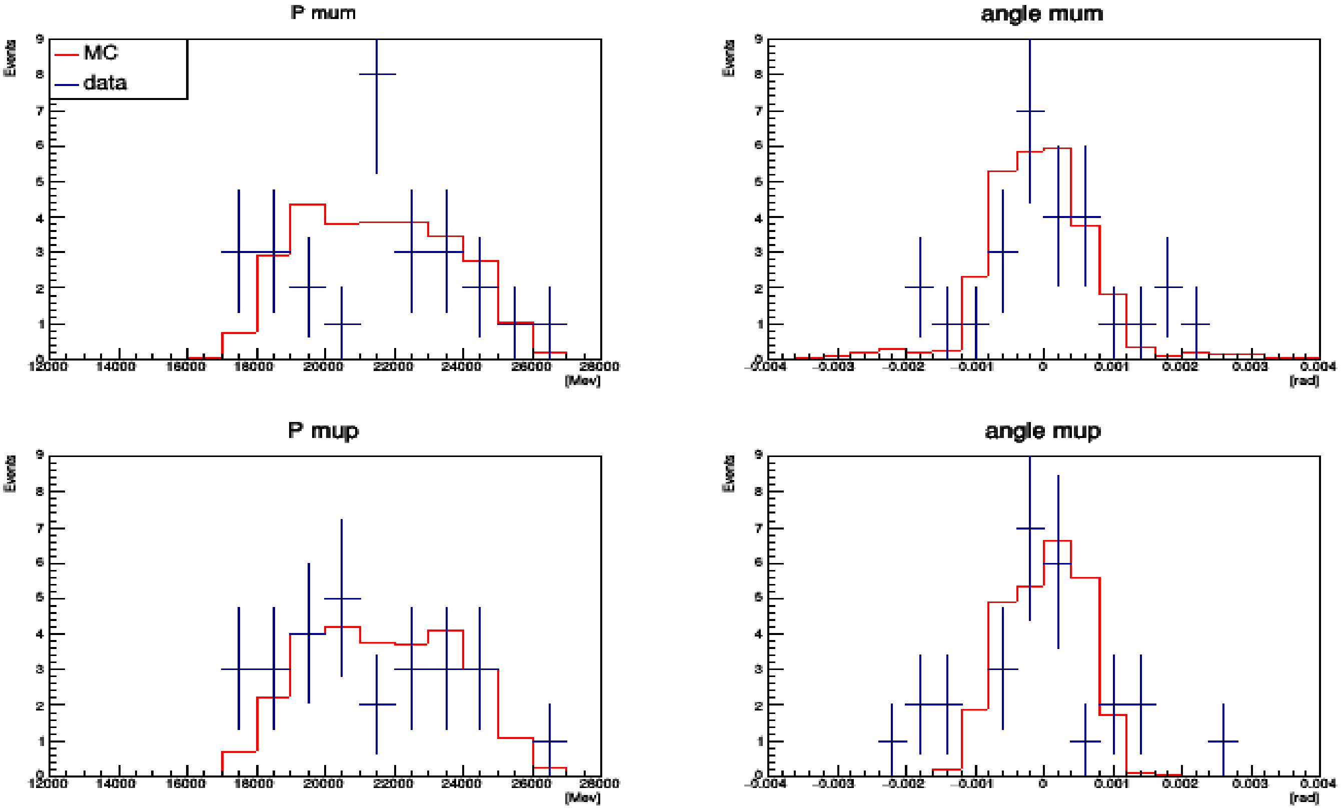

Figure 11: Momentum and angles of the muon pairs.

The next step was the computation of the energy of each particle using the relativistic formula $E = \sqrt{P^2 + M^2}$ and finally the total energy of the pair obtained by the sum of the two energies. We calculated the angle between the momenta of the tracks that was necessary to calculate the invariant mass using the formula: $S = \sqrt{(E_{\mu+} + E_{\mu-})^2 - (P^2_{\mu+} + P^2_{\mu-} + 2P_{\mu+}P_{\mu-}cos\theta)}$ where θ, the angle in 3D, is approximated by the angle in the bending plane.

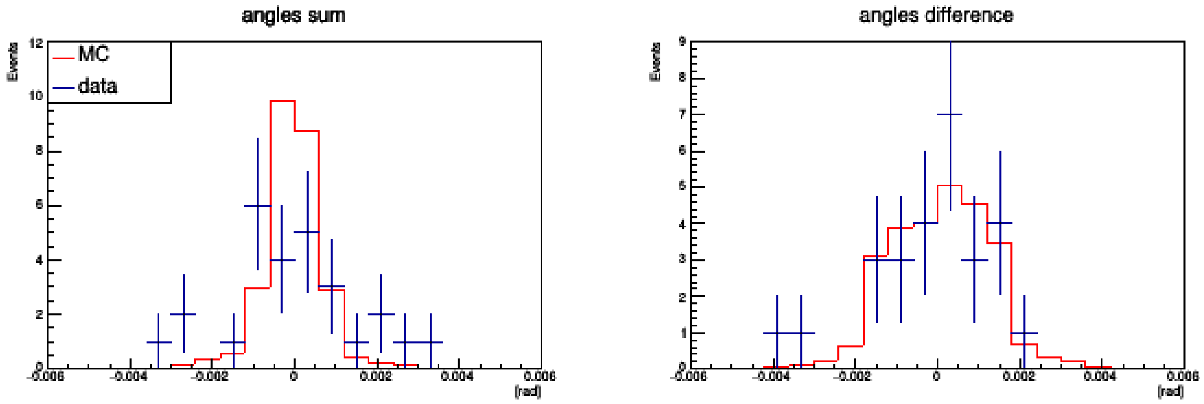

Figure 12: Sum and difference of the angles between the traks of the muons before the magnet.

The invariant mass is expected to be around 210 MeV, twice the mass of the muon, because the positron beam has a momentum of 45 GeV which corresponds to the threshold for the pair production process. This can be seen from:

$$S^2 = (E_{e+} + E_{e-})^2 - (P_{e+} + P_{e-})^2 = (2M_\mu)^2 \tag{1}$$

$$(\sqrt{M_{e+}^2 + P_{e+}^2} + M_{e-})^2 - (P_{e+})^2 = 4(M_\mu)^2 \tag{2}$$

$$2M_e\sqrt{M_e^2 + P_e^2} + 2M_e^2 = 4(M_\mu)^2 \tag{3}$$

$$P_e = \sqrt{\frac{(2M_{u\mu}^2 - M_e^2)^2}{M_e^2} - M_e^2} \sim 45 \ \ GeV \tag{4}$$

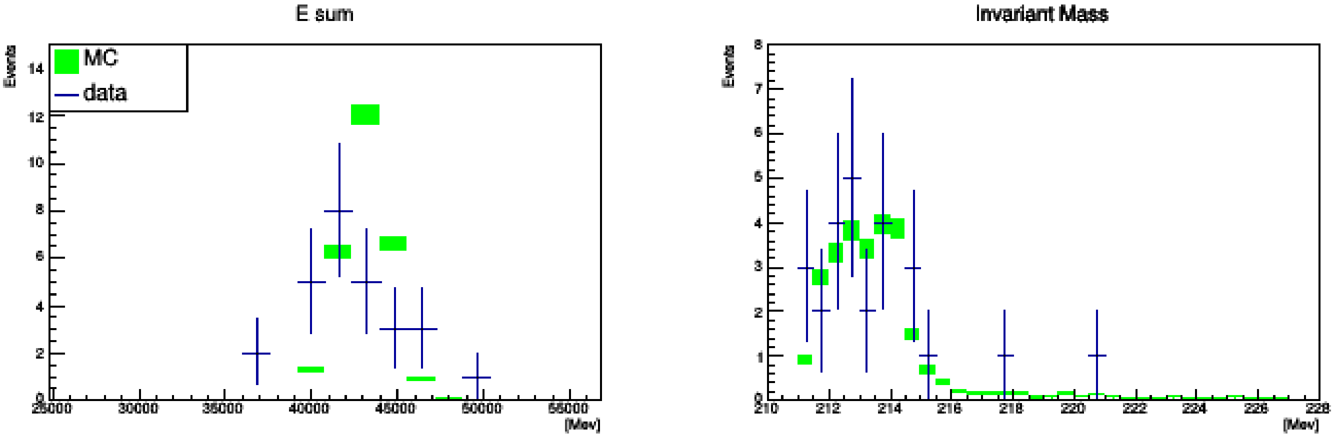

Figure 13: total energy and invariant mass of the couples.

From the plots in figure 12 we see how the invariant mass of the 27 couples of particles is around the expected value and also that the total energy of the pairs are around 45 GeV. Moreover these results are also consistent with the Monte Carlo truth. Fot both distributions the Monte Carlo resolution has been smeared in order to match the resolutions measured in the calibration runs. As only two calibration points are available, at 18 and 22 GeV, the green boxes correspond to the difference observed when using the calibration parameters obtained from the 18 and 22 GeV runs.

4 Conclusions

The analysis of the 2017 test beam data identified 27 pairs of muons and their kinematical properties were consistent with the Monte Carlo simulation of the process $\mathrm{e}^+e^- \to \mu^+\mu^-$, obviously in the 620K events that were collected the pairs of muons were for sure much more than what we found due to instrumentation problems. Because the pairs found are not so many we couldn't estimate the cross section of the process $\sigma(e^+e^- \to \mu^+\mu^-)$ and the emittance of the muons produced. Anyway with this first test beam we were able to demonstrate that is possible to record pairs of muons from the electron-positron collisions and measure their kinematical properties. In order to be able to identify more pairs of muons the 2018 test beam set up has been improved. Detectors alignment will be done with particular care and the muon chamber which didn't work as expected will be replaced by two new smaller chambers. So the main aims of the 2018 test beam are:

1. estimate the cross section of pair production at threshold;
2. estimate the emittance of the muon pairs produced.

The measurement of these quantities will show if a muon accelerator based on this injection scheme is realistic or not.

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