LIP-STUDENTS-21-35

What are nucleons and pions made of?

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Abstract. This paper presents the study performed in the context of the 2021 summer internship at LIP, Lisbon. Our objective is to study the Drell-Yan process generated in a Monte Carlo simulation of the AMBER experiment. The main physics goal of this experiment is to study the hadrons, specially the pion, parton distribution functions (PDFs). From a simulation file, data is anlysed and saved in a root tree using PHAST (http://ges.home.cern.ch/ges/phast/), then a ROOT macro is used to calculate the geometrical acceptance and also the experimental resolutions, and their dependence in mass and vertex position.

Keywords: Hadron, Drell-Yan, dimuon, AMBER, experimental resolution, geometrical acceptance

1 Introduction

1.1 Hadrons

Hadrons are particles that are composed of quarks and gluons. One of the main objective of the "AMBER experiment" is to study the distribution of the parents momentum carried by the quarks, using the Drell-Yan process. As explained in the next subsection, in this measurement the valence u-quarks contribution dominates throughout our work.

1.2 Parton Distribution Functions and the Drell-Yan Process

The Parton Distribution Function (PDF) gives us the probability density of a quark with a certain relative momentum to that of the hadron. A good way to access these PDF´s is through the Drell-yan process.

The Drell-Yan process occurs when a quark and an antiquark from two different hadrons annihilate each other, first creating a virtual photon, that then decays to a muon and an antimuon pair, also known as a dimuon, as shown in the diagram of 2. The cross section of the process gives us information about the Parton Distribution Functions of both hadrons involved in the process.
In figure 1, we can see the the Z position of the vertex for reconstructed events, which gives a clear illustration of the AMBER's tungsten and carbon target's position and thickness.

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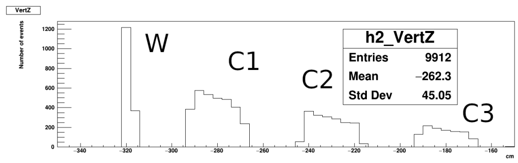
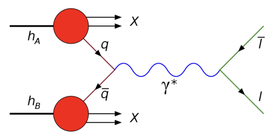


Figure 1. Position of the vertex along the beam line, the labels identify the different targets



$$\sigma^{DY} = \sum_{ab} \int dx_a \int dx_b \underbrace{f_a(x_a, Q^2)}_{\text{PDF}} \underbrace{f_b(x_b, Q^2)}_{\text{PDF}} \hat{\sigma}_{ab \to l\bar{l}}(x_a, x_b, \dots)$$

Figure 2. Drell-Yan process Feynman diagram and expression for the cross section

1.3 AMBER Experiment

The AMBER experiment is being prepared and is expected to start the data taking in 2022 at CERN. It is the successor of COMPASS, an experiment which has been active in the same experimental hall, more than 200 researchers from various countries including Portugal collaborate in COMPASS. The experiment is expected to finish the data taking next year. Its main goal is to study more about hadrons and its properties. In the COMPASS experiment there is a spectrometer about 50m long. For the AMBER measurements this spectrometer will be upgraded, by replacing some of the detectors. A main difference will be in the Drell-Yan targets region, since different materials, target lengths and positions will be used. It is a fixed target experiment, and in opposition to CERN's LHC experiments, this one is at surface level, protected by concrete blocks because of the radiation levels that it emits. There is a 190

GeV pion beam which collides against a 2cm tungsten target and three larger (25cm each) carbon targets. The rest of the spectrometer is composed of detectors, absorbers and magnets. In figure 1, we can see the the vertex Z position for reconstructed events, which gives a clear look of the AMBER's Tungsten and carbon target's position and thickness.

2 Acceptance and resolution

The geometrical acceptance gives the fraction of generated events that were successfully reconstructed. It is defined as:

$$acc = \frac{\text{\# reconstructed events}}{\text{\# generated events}} \tag{1}$$

The resolution in a variable X is defined by:

$$Xres = X(\text{gen}) - X(\text{rec}) \tag{2}$$

that is calculated for each event. The obtained distribution is expected to be centered at 0 (meaning that the reconstruction does not bias the measurement). The width of the distribution is what we usually quote as resolution. A good resolution corresponds to a narrow distribution, meaning that the smearing introduced by the measurement is small.

3 Experimental procedure

We analysed the reconstructed output of a Monte-Carlo simulation of the Drell-Yan process in the conditions of the AMBER experiment. There were 9992 Monte Carlo events generated, but there were a lower number of events that were reconstructed with data from the detectors. When the real time filter (the so-called dimuon trigger) detects a possible Drell-Yan event, the information regarding that event is stored. These Monte-Carlo events were reconstructed as we would see them in the real AMBER experiment.

3.1 Selection of the Drell-Yan Events

The stored information of each event includes both generated (Monte Carlo truth) and reconstructed characteristics. A c++ program called a "User Event" was developed using the analysis software of AMBER, PHAST (http://ges.home.cern.ch/ges/phast/), in order to analyse the Monte Carlo sample.

We started to make a user event for individual particles where, by using the C++ classes already developed in the PHAST library, we saved the information in trees and histograms of the number particles, tracks and vertices per event, both generated and reconstructed. We have then made a loop over the particles, filtering the ones that had a particle ID (in accordance to the table of GEANT3 particles that associates a positive integer number to each particle and -1 to unknown particles) of 5 and 6 corresponding to the muons and anti-muons, saving their characteristics, the charge, the ID and other properties like the momentum and the mass to further analyse. As we can see in figure (PID), there are 5000 muons and anti-muons in a total of 9992 events, but figure (n muons per event) shows us that only around 3000 events have at least 2 muons. So we will need to filter the number of muons per event and combine the possible correct muon pairs.

After this, we made a second and more important user event where we search for a muon and and anti-muon reconstructed in the same event in order to obtain possible Drell-Yan pairs. We made a selection comparing the common vertexes between each possible pair and their respective $chi2/ndf$ so as to only save the pair that has the lowest $chi2/ndf$ per event. Then, now for the saved pairs, we stored the same properties we had saved for the individual particles and again organized this information in trees and histograms to analyse and calculate the geometrical acceptances and resolutions.

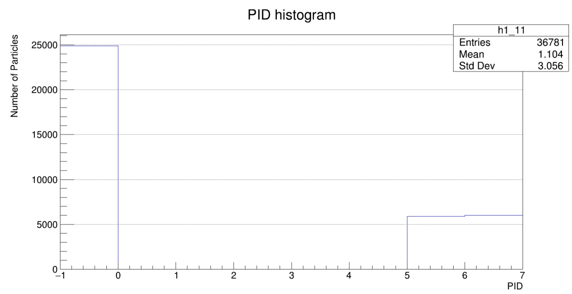


Figure 3. Reconstructed Z position of the vertices of muon pairs

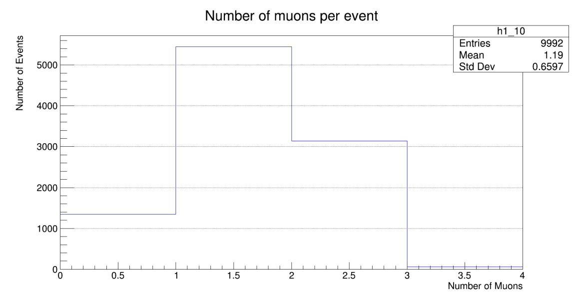


Figure 4. Number of reconstructed muons per event

3.2 Computation of the geometrical acceptance and the experimental resolution

A C++ Root (https://root.cern/) Macro file was created to calculate the geometrical acceptance and the experimental resolution.

To calculate the geometrical acceptance as a function of the Z position of the vertices, we imported the information contained in the ROOT file created with PHAST and created 4 acceptance histograms, one per target cell. A cut in the Z position of the vertex was made for each one of the targets and the generated and reconstructed events were saved, then the histograms with the reconstructed information were divided by the histograms with the generated events. In figure djghsdg we can observe the acceptance's histograms for each one of the targets.

For the resolution, 8 histograms were created, containing the mass and vertex Z position resolution for each of the target cells. For each targets' resolution, we calculated the difference between the reconstructed information and the generated information (truth), per event. The events considered as possible Drell-Yan dimuons, were filtered by our analysis code. Table 3.2 lists the selection criteria.

Table 1. Criteria for event selection.

Variable	Cut
PID	=5 or =6
Dimuon mass	4.0 < m < 9.0 (GeV)
Zfirst	<300 (cm)
Zlast	>1500 (cm)
Trigger Mask	=4 or =256
$\sqrt{(X_{vertex}) + (Y_{vertex})}$	<2 (cm)
Tungsten position	-319.5 < Z < -317.5 (cm)
Carbon 1 position	-292 < Z < -268 (cm)
Carbon 2 position	-242 < Z < -210 (cm)
Carbon 3 position	-193 < Z < -168 (cm)

Muon PID: the particle is required to have PID 5 or 6. This flag is set for any particle that crosses more than 30 radiation lengths of material in between the first and the last measured points of its trajectory.
4 < M < 9 GeV/c2 : the mass of the dimuon pair is required to be in the high mass range, where other physics contributions to the spectrum can be neglected;
ZFirst<300 cm : the first measured point of the particle in the spectrometer should be before the first bending dipole magnet, in order to guarantee good precision in momentum;
ZLast>1500 cm: the last measured point of the particle in the spectrometer should be after the first muon filter, an iron wall of 60 cm thickness, to guarantee good particle identification;
Trigger mask with bits 2 or 8 fired: these trigger correspond to either one muon at large angle and another at small angle (bit 2, LAS-Outer trigger), or the both muons emitted at large angles (bit 8, LAS-LAS trigger).
Radial cut: as the target cells are 2 cm in radius, the vertices are also required to be within this limit in the transverse plane.

4 Results and Conclusions

In figures 10,11,12 and 13 we observe a mass resolution between 180 and 276 MeV. Plotting the dimuon invariant mass distribution (figure 15) and comparing to the real data distribution, as measured by the COMPASS experiment, we see that our histogram of the dimuon mass is in accordance to the data as we can see that the frequency decreases exponentially as we increase the dimuon mass linearly. Improving the mass resolution would allow to decrease the lower mass limit (presently at 4 GeV) and therefore, increasing significantly the number of events selected for the Drell-Yan physics analysis..
In figure 14, we can observe a constant acceptance value, fluctuating around 10% for each one of the targets, although it is also observable that this value increases for targets closer to the detector region. It is clear from this study that, in order to evaluate accurately the acceptance as function of mass or as a function of Z position of vertices, one needs a MC sample with much larger statistics.
The resolutions' histograms, both for dimuon mass and Vertex Z position, can be interpreted as a sum of Gaussian centered around the origin with a standard deviation value equal to the target's resolution and a better resolution means a lower value. However we can observe a systematic shift to the left in the resolution histogram for the Vertex Z position. This likely caused by the low number of entries in the histograms.
One expects that the Z resolution value decreases the closer we get to the detectors. As for the mass resolution, the lighter the target material is, the better the resolution is expected to be.
The distance between the targets is already optimised to increase the acceptance and the resolution so it is not possible to move the targets much closer to the detector region, due to the presence of the hadron absorber. Nevertheless, it might be possible to still optimize the setup, for example by modifying the absorber, and/or by adding addition tracking detectors close to the target region.

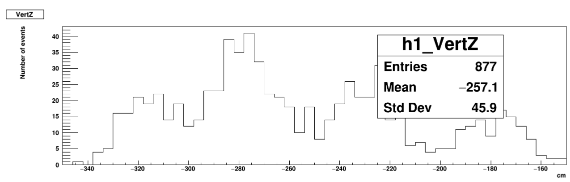


Figure 5. Reconstructed Z position of the vertices of muon pairs

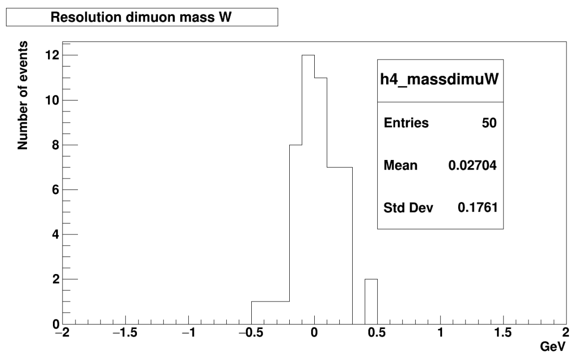


Figure 6. Resolution dimuon mass - tungsten target

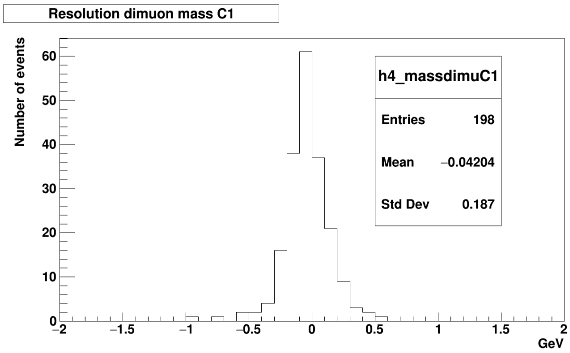


Figure 7. Resolution dimuon mass - 1st carbon target

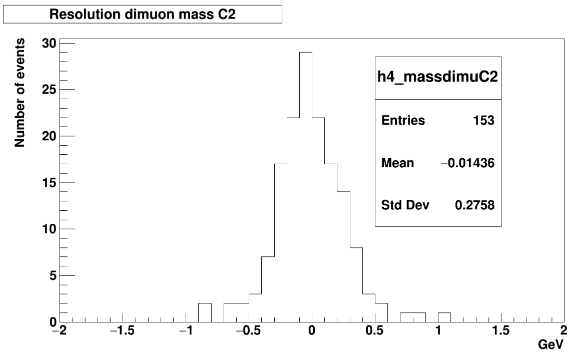


Figure 8. Resolution dimuon mass - 2nd carbon target

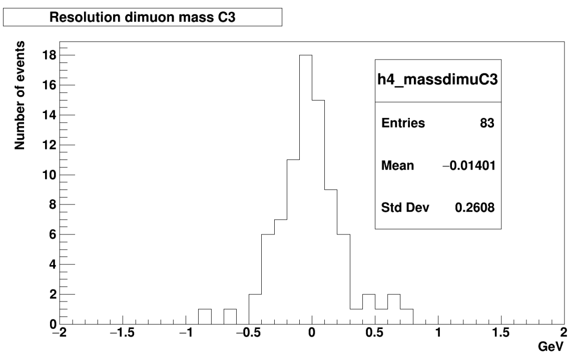


Figure 9. Resolution dimuon mass - 3rd carbon target

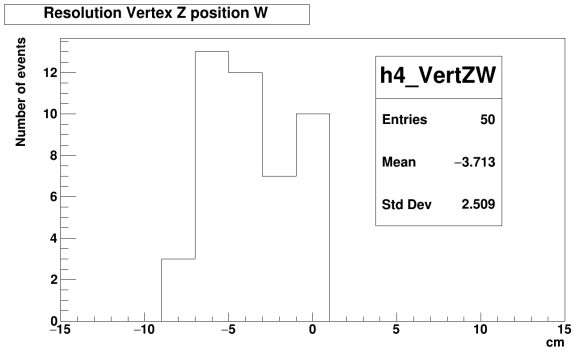


Figure 10. Resolution Vertex Z position - tungsten target

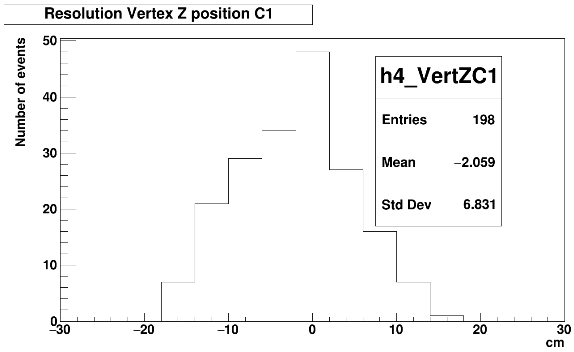


Figure 11. Resolution Vertex Z position - 1st carbon target

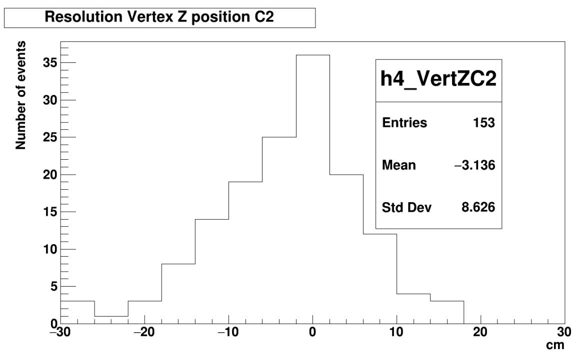


Figure 12. Resolution Vertex Z position - 2nd carbon target

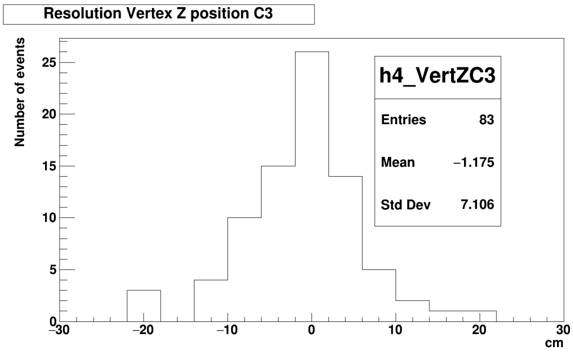


Figure 13. Resolution Vertex Z position - 3rd carbon target

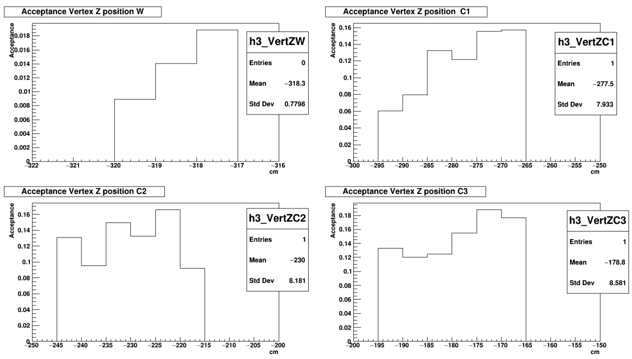


Figure 14. Acceptances vertex Z position

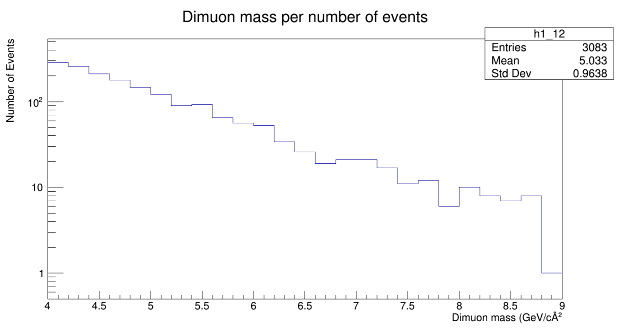


Figure 15. Reconstructed Monte Carlo dimuon mass spectrum.

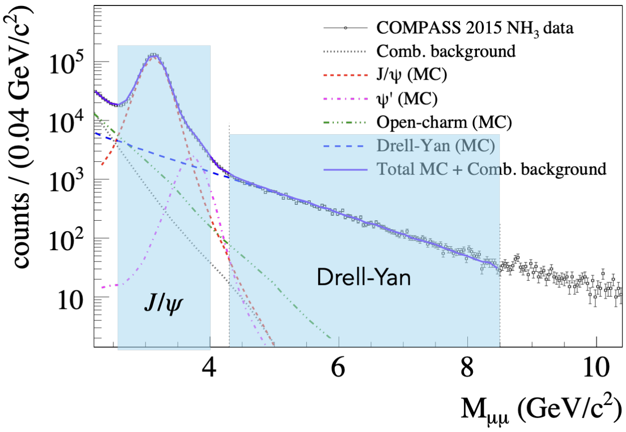


Figure 16. Radial cut: as the target cells are 2 cm in radius, the vertices are also required to be within this limit in the transverse plane.

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References

Márcia Quaresma, The internal structure of the particles