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Exclusive π^0 production in the backward region

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Abstract

Recently there has been some theoretical research on the extension of GPD's to TDA's. The exclusive π^0 production in the backward region is especially interesting in this respect. In this study we investigated methods to select these kind of events using data obtained at HERMES. Both the Forward Spectrometer and the Recoil Detector were used to apply cuts for event selection. After all cuts had been applied, no signal was found.

Contents

1 Introduction

1.1 The HERMES experiment

The HERMES (HERA measurement of nucleon spin) experiment is one of the four experiments at the HERA collider. It's purpose is to study the spin structure of the proton. Although the data taking stopped in 2007, the data analysis is still ongoing. HERMES was a fixed target experiment, which used only the HERA lepton beam. This 27.6 Gev electron or positron beam was then made to collide with a fixed gas target, which was usually hydrogen. At the start of the data taking in 1995 there was only a detector in the forward direction, called the Forward Spectrometer (see figure 1). In 2006 the Recoil Detector was added (see figure 2a). This made it possible to detect particles in the backward region.

1.1.1 The Forward Spectrometer

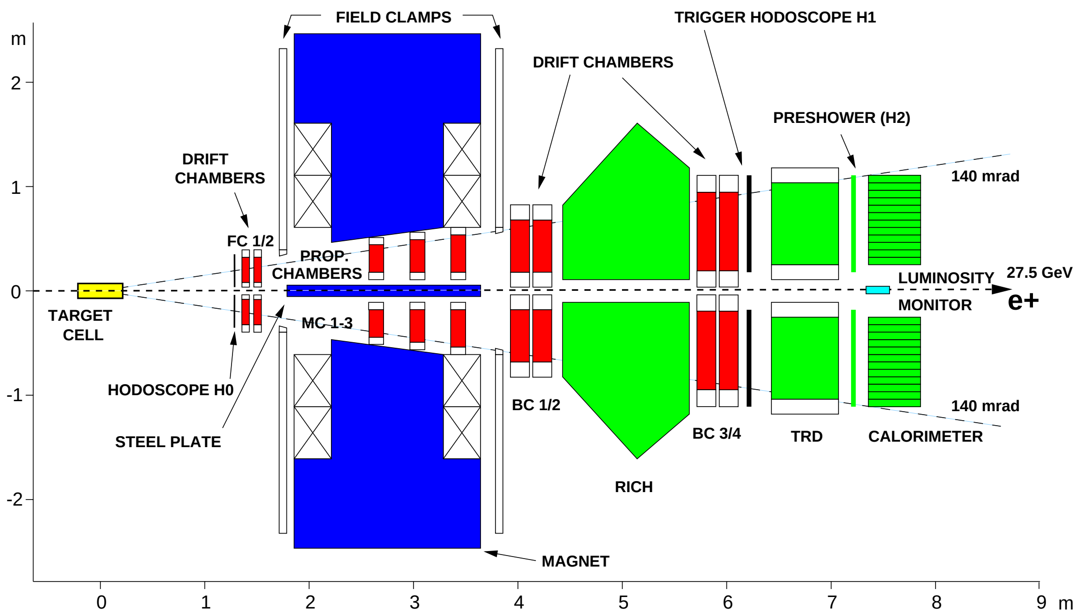


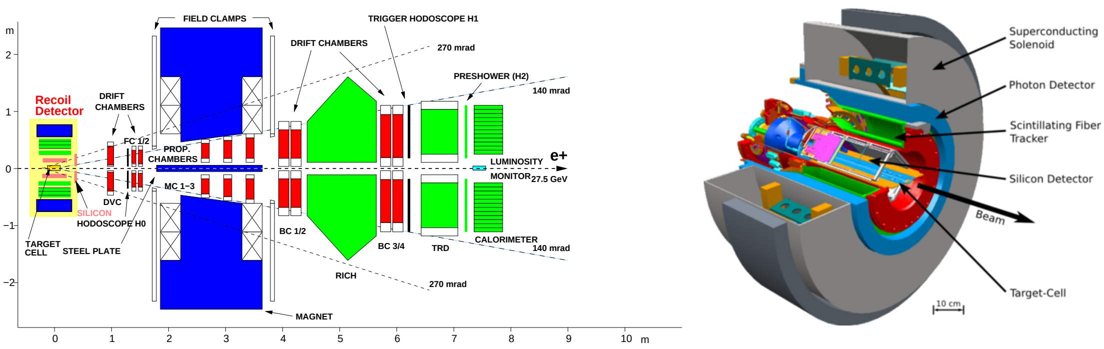
Figure 1: The HERMES Forward Spectrometer

The Forward Spectrometer (FS) consisted of several components. There were numerous tracking chambers (micro-strip gas chambers, drift and proportional chambers), shown in red in figure 1. Particle identification was performed by the structures shown in green: the RICH (Ring Imaging Cherenkov Detector), TRD (Transition Radiation Detector), preshower detector and the lead-glass calorimeter. The parts in blue are bending magnets, allowing momentum determination.

The coordinate system used by HERMES is as follows: the z-axis points along the beam momentum, the y-axis goes vertically upwards and the x-axis is horizontal, pointing towards the outside of the ring. In this way a right-handed Cartesian coordinate system is constructed.

The HERMES spectrometer has a good acceptance and is able to identify leptons (e^+ or e^-) and hadrons (pions, kaons, (anti)protons). [1]

1.1.2 The Recoil Detector



(a) The HERMES Spectrometer

(b) The Recoil Detector

Figure 2: The HERMES Spectrometer as it was in 2006 and 2007

The HERMES Recoil Detector (RD) had three main components (see figure 2b): a Silicon Strip Detector (SSD) surrounding the target cell, a Scintillating Fiber Tracker (SFT) and a Photon Detector (PD). These were mounted in a 1 Tesla superconducting solenoid.

Using the RD, one can study different kinds of events, including DVCS (Deeply Virtual Compton Scattering) and exclusive ρ^0 production.

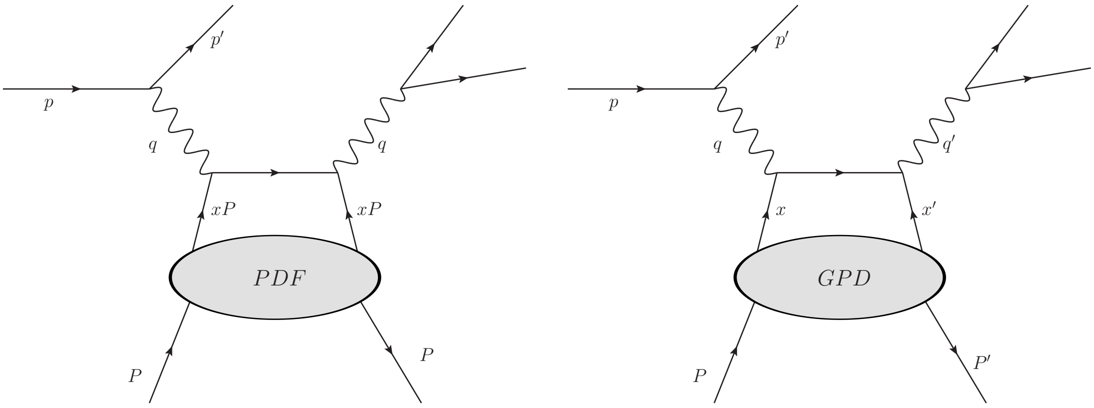
1.2 Exclusive π^0 production

1.2.1 Motivation

The process studied here is the exclusive production of π^0's in the backward region, which can be written in the following way:

$$ep \longrightarrow ep\pi^0$$

In this process the scattered lepton (either e^- or e^+) and the produced proton (p) move in the forward direction, while the pion has a low momentum and moves



(a) PDF's

(b) GPD's

Figure 3: An illustration of PDF's and GPD's

backwards in the center of mass frame. The lepton and proton can be detected by the FS, the two decay photons of the π^0 by the RD, if they are within the acceptance.

In standard Deep Inelastic Scattering (DIS), one looks at PDF's (Parton Distribution Function). These are calculated as an expectation value using the same state for both the initial and final state. In DVCS for example, this concept is then extended to GPD's (Generalized Parton Distribution), where the hadron is in a different state in the initial compared to the final state. One could for instance have a proton in the initial state and a Δ^+ in the final state. An illustration of PDF's and GPD's can be found in figure 3.

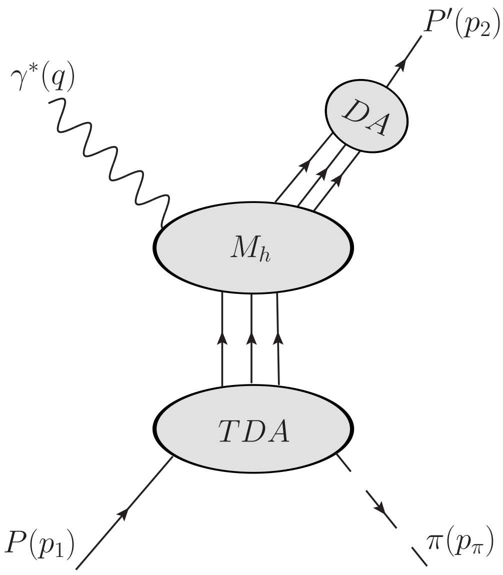


Figure 4: Feynman diagram of the exclusive production of π^0's in the backward region

The exclusive pion production studied here offers an extra extension. This process makes it possible to study the transition of a proton into a pion. In this case one has two different hadrons in the initial and final state: a proton in the initial state and a π^0 as proton remnant in the final state. This is mathematically described by TDA's (Transition Distribution Amplitudes). These TDA's give an indication about how close the structure of the proton resembles the one of a pion. In this respect we can also refer to the meson cloud model. In this model the proton is described as consisting of three valence quarks and a cloud of mesons surrounding it. The π^0 is of special importance since it can be transferred over a large distance.

A more theoretical background regarding exclusive pion production can be found in [2]. We can just mention here that the interaction can be factorized in three parts: the TDA, the hard scattering matrix element M_h and the distribution amplitude (DA) for the proton. This is illustrated in figure 4.

1.2.2 Kinematics of DIS events

Deep Inelastic Scattering is usually described by several kinematic variables. An illustration of these variables can be found in figure 5.

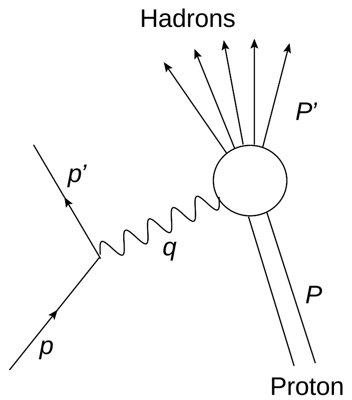


Figure 5: Diagram of a DIS event

In this figure p, p', q, P and P' are the four-momenta of respectively the incoming beam lepton, the scattered lepton, the virtual photon, the target proton and the final hadronic state.

The four-momentum transfer q^2 from the beam lepton to the target proton can be calculated in the following way:

$$-Q^2 = q^2 = (p - p')^2 \approx \frac{-4EE'}{c^2} \sin^2 \frac{\theta}{2}$$

with E, E' and θ the energy of the incoming and scattered lepton and the scattering angle between them. Q^2 is used instead of q^2 in order to work with positive quantities.

Other kinematic variables that are commonly used are the energy transfer ν from beam lepton to target proton, the fractional energy transfer y, the invariant mass W of the final state hadrons and the Bjorken scaling variable x. These variables can be expressed in the following way, with M the rest mass of the proton:

$$\nu = \frac{Pq}{M} \overset{lab}{=} E - E'$$

$$y = \frac{\nu}{E}$$

$$\begin{aligned} W^2c^2 &= P'^2 = (P + q)^2 \\ &= M^2c^2 + 2Pq + q^2 = M^2c^2 + 2M\nu - Q^2 \end{aligned}$$

$$x = \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu}$$

x is a measure of the inelasticity of the process. If $x = 1$ the process is elastic and $W = M$. If on the other hand $0 \leq x < 1$ the process is called inelastic and $W > M$.

2 Event Selection

In order to investigate the π^0 production, we make different cuts on the selected events. The events used in this analysis come from the production 2007c2 and are all events with an unpolarized proton target and a positron beam. The applied cuts will be explained in the following sections. After all cuts have been made and the scattered lepton and proton have been identified, the missing mass can be calculated. When the missing mass spectrum is plotted in a histogram, a peak near the π^0 mass should be visible.

2.1 Missing Mass method

In general, the missing mass MM of an event is given by

$$MM^2 = (\sum P_i - \sum P_f)^2$$

where P_i is the four-momentum of a particle in the initial state and P_f is the four-momentum of a detected particle in the final state. In the case of π^0 production we get the following:

$$MM^2 = (p + P - p' - P')^2$$

where p, P, p' and P' are the four-momenta of respectively the incoming beam lepton, the target proton, the scattered lepton and the produced proton.

These four-momenta can be calculated using the information stored in the track tables.

2.2 Particle Identification (PID)

Particle identification is performed by using the responses (measured energy deposits) of the different PID detectors. Let R be the responses of all the PID detectors for one track and p the momentum of a particle. We can then construct two probability distributions: $P^l(p, R)$ for the probability distribution that a lepton of momentum p caused a response R and $P^h(p,R)$ the same distribution, but for a hadron. The PID for a certain track is then calculated as follows:

$$\text{PID} = \log_{10} \frac{P^l(p,R)}{P^h(p,R)}$$

A positive value means that the track was probably an lepton and a negative value that it was most likely a hadron. The separation of the different kind of hadrons is done by the RICH detector, see below.

2.2.1 PID3+5

There are different PID parameters, depending on the number of detectors used in the calculation. PID3 uses the preshower (H2), the calorimeter (Calo) and the Cherenkov (Cher). It can be expressed in the following way:

$$\text{PID3} = \log_{10} \frac{P^l_{\text{H2}}(p,R) P^l_{\text{Calo}}(p,R) P^l_{\text{Cher}}(p,R)}{P^h_{\text{H2}}(p,R) P^h_{\text{Calo}}(p,R) P^h_{\text{Cher}}(p,R)}$$

PID4 also adds the TRD. PID5 uses only the TRD, but uses a more sophisticated calculation of the TRD probabilities than PID4. Therefore, it is common to use PID3+5 as the standard PID parameter. Due to the logarithmic character PID3+5 is just an alternative version of PID4.

2.2.2 RICH PID

Using the RICH detector, one can distinguish between pions, kaons and protons. However, the RICH can't perform lepton-hadron separation, for this the other PID detectors still have to be used. There are different ways in which the RICH PID can be performed, such as DRT (Direct Ray Tracing) and EVT (Event Level DRT algorithm). In the end a decision is made: the hypothesis with the highest probability gives us the particle identity (or IdType). The RQP (RICH Quality Parameter) is a measure of the confidence of this decision.

2.3 Finding the DIS lepton

The first step to selecting the appropriate events is finding the scattered lepton and requiring that the event is a DIS event. To do this we loop over all tracks and stop when we have found the scattered lepton.

A track needs to fulfill certain requirements in order to be a candidate for the DIS lepton. One set has to do with the detector. The track needs to be a long track, meaning that it cannot be bent too much by the magnet since it needs to stay within the acceptance of the detector. Also, the vertex position needs to be situated inside the target cell and the tracked clusters in the calorimeter need to be in range. We also apply cuts to avoid the field clamps of the magnet.

To make sure that the track is a lepton, we calculate PID3+5 (see section 2.2.1) and require that it is larger than one. In order to be in the DIS regime we apply the following cuts: $W^2 > 4$ Gev^2, $Q^2 > 1$ Gev^2 and $y < 0.85$. At this point we also calculate the four-momentum of the scattered lepton.

2.4 Finding the produced proton

Now that we have found the scattered lepton track, we also require that there are only two tracks and no trackless clusters (or photons) in the FS. Then we loop over all tracks again and demand that there is a proton track. To do this we again impose the detector cuts and in addition we demand that PID3+5 is smaller than zero and that the RICH IdType (see section 2.2.2) is that of a proton.

We can then calculate the four-momentum of the proton. Together with the four-momentum of the scattered lepton and the fixed initial state (27.6 Gev lepton beam and target proton at rest), we can calculate the square of the missing mass (MM^2) and save it in a histogram. Due to detector resolution we can also get small negative values for MM^2. The π^0-peak is expected to be centered around 0 Gev^2.

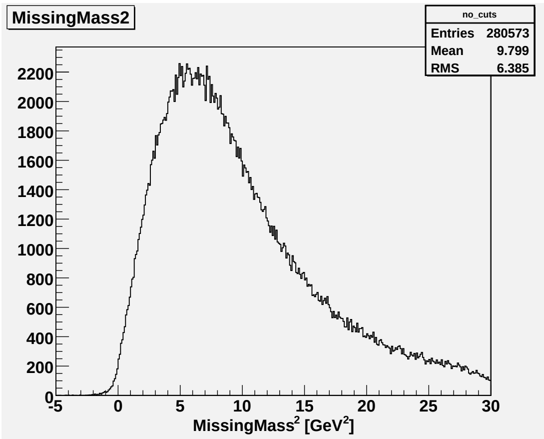
The missing mass spectrum obtained after these cuts is shown in figure 6a. As can be seen from this figure, no peak is observed near 0 Gev^2. We can only see semi-inclusive background. To try and improve this, we will now impose some additional cuts.

2.5 Additional cuts using the Forward Spectrometer

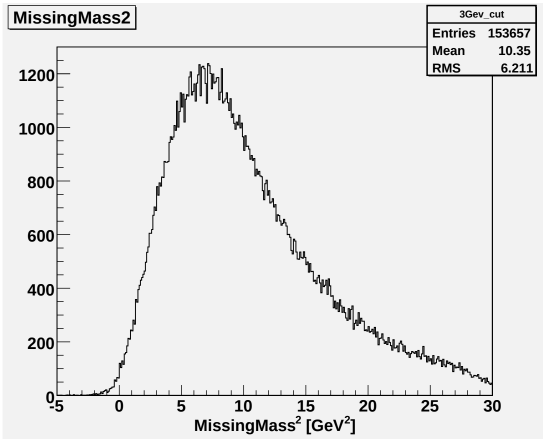
The first thing one can try, is to make a momentum cut on the produced proton. This provides better RICH PID. We tried a 3 Gev and a 4 Gev momentum cut (see figures 6b and 6c). This reduced the number of entries by a factor of two, respectively three. There was, however, still no evidence of a peak.

From [2] follows that the π^0 production under study is expected to take place at low absolute values of the Mandelstam variable t. This variable can be expressed as follows:

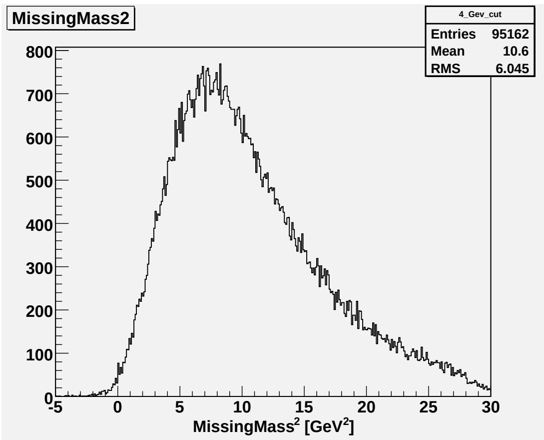
$$t = (P' - q)^2$$



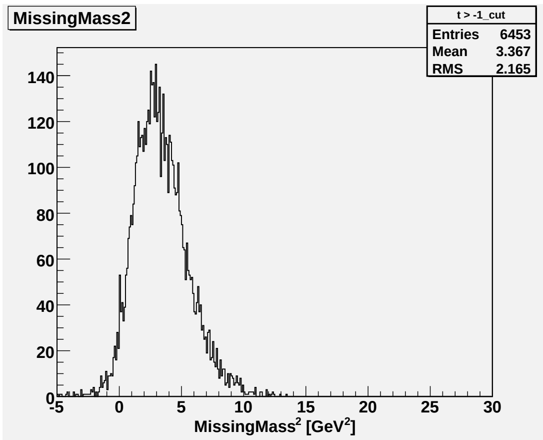
(a) No extra cuts applied



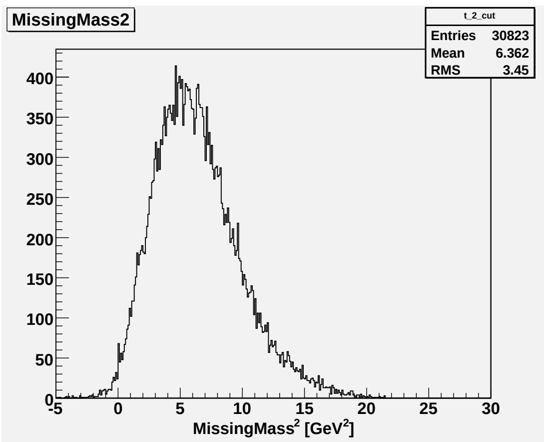
(b) 3 Gev momentum cut



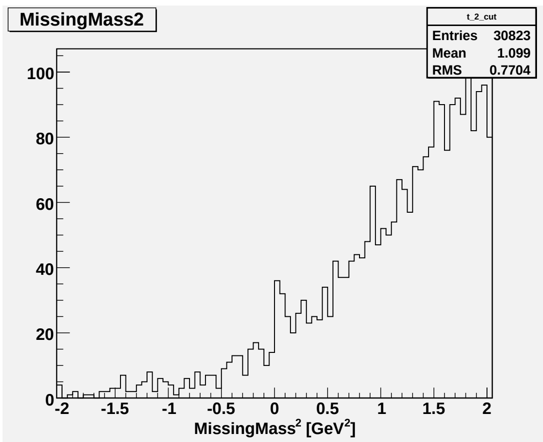
(c) 4 Gev momentum cut



(d) $t > -1$



(e) $t > -2$



(f) $t > -2$

Figure 6: Cuts using only the Forward Spectrometer

where P' is the four-momentum of the final state proton and q the four-momentum of the virtual photon. The t-distribution for the events that passed the 4 Gev momentum cut on the proton is shown in figure 7.

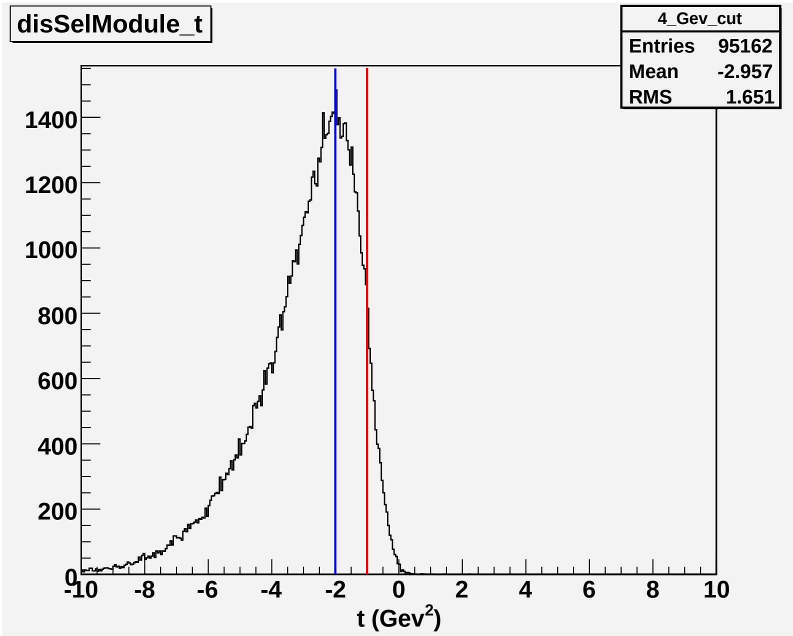


Figure 7: t-distribution after 4 Gev momentum cut

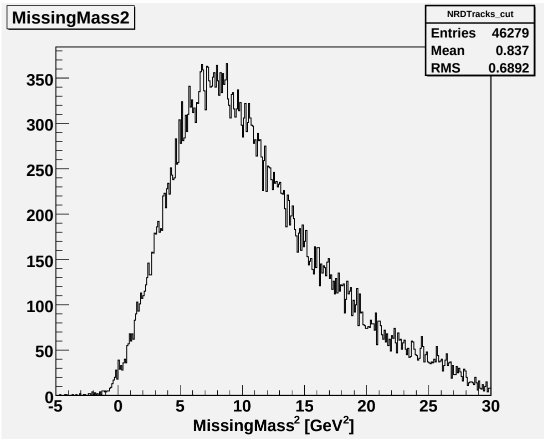
We can now try different t-cuts. $t > -1$ Gev^2 and $t > -2$ Gev^2 are shown in figures 6d and 6e. We observe that this cuts away a lot of events. From these plots we could conclude that there is a hint of a peak in the desired region. When we look closer however (see figure 6f), we see that there is not enough statistics to make any definite conclusions.

We can thus conclude that when using only the Forward Spectrometer, we cannot distinguish the exclusive π^0 production from the semi-inclusive background.

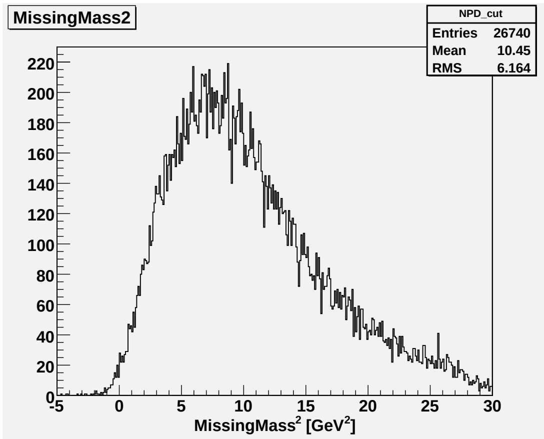
2.6 Additional cuts using the Recoil Detector

Since using only the FS did not give good results, the next step was to include the RD. In order to have more entries we first dropped the t-cut. The first recoil cut we made was demanding that there were no tracks of charged particles in the recoil detector. The corresponding missing mass spectrum is shown in figure 8a. This, however, did not yield any good result. There was still no visible peak.

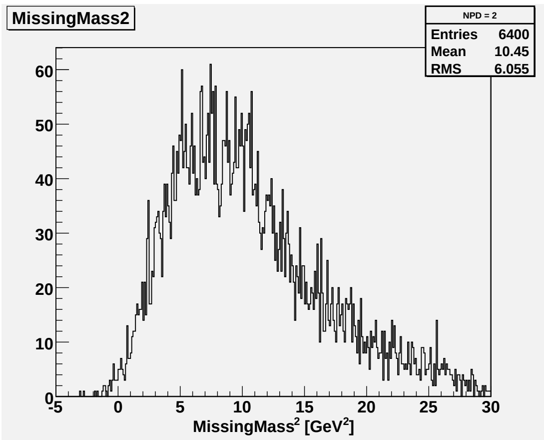
In a second attempt we also included information about the number of hits in the photon detector. We tried requiring at least one hit and tried also with exactly two hits. Unfortunately this also did not help (see figure 8b and 8c).



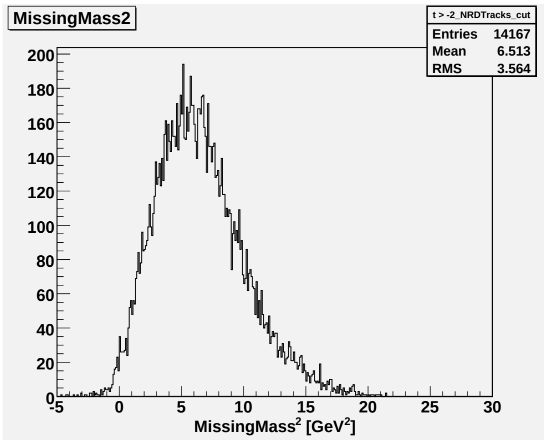
(a) NRDTracks = 0



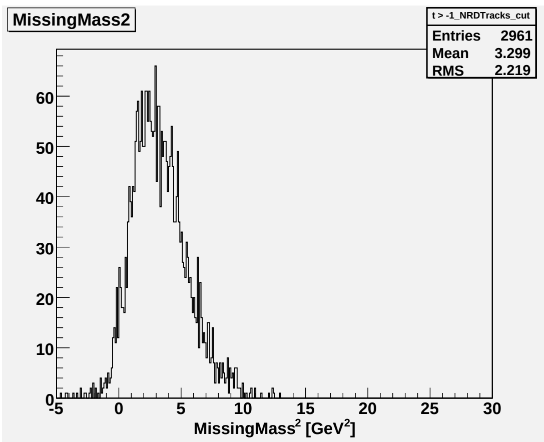
(b) NPD > 0



(c) NPD = 2



(d) t > −2, NRDTracks = 0



(e) t > −1, NRDTracks = 0

Figure 8: Cuts using Recoil Detector

Finally we also combined the t-cut with the cut on the number of RD-tracks. This is illustrated in figures 8d and 8e. After these cuts we had hardly any statistics left and could still not see any peak around the π^0 mass.

In conclusion: including the Recoil Detector did not offer any improvement.

3 Monte Carlo comparison

As a final part of the project, we did a Monte Carlo (MC) comparison to see how well the background is described by the models included in the pythia simulation. The exclusive π^0 production is not included in this simulation. We made some adjustments to the code in order to make it possible to run over MC data. This included removing references to the RD and PID. Particles were identified by using for every track the associated MCTrack, where the original MC input is stored. We identified positrons by demanding that the Lund type was -11 and for protons the Lund type had to be 2212.

The first thing we did, was to compare MC runs and normal runs without any additional cuts. In order to do this we normalized both histograms to unity and plotted them on the same canvas (see figure 9). The MC histogram is shown in red. From this figure we can see that our data is rather well described by the Monte Carlo simulation.

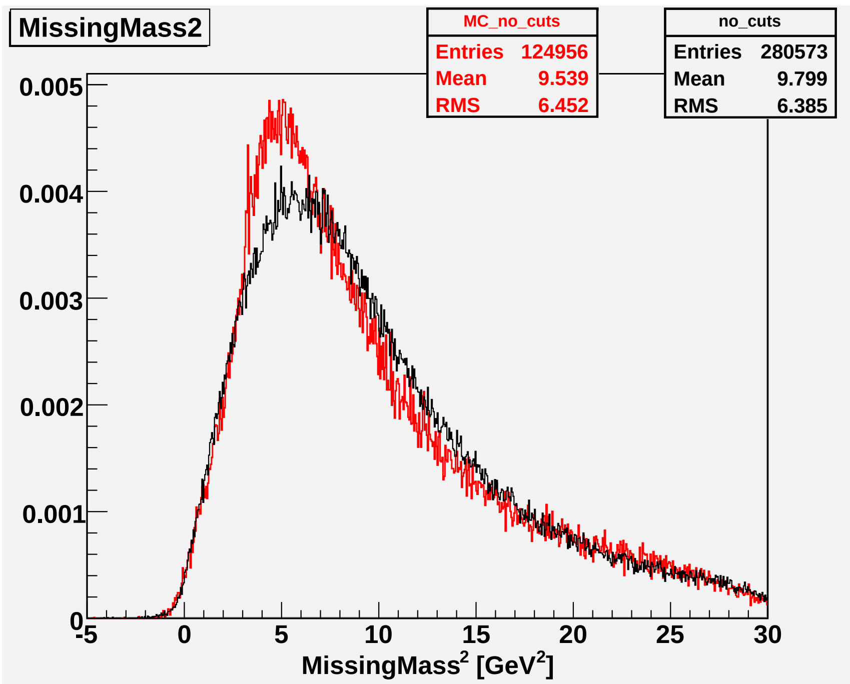


Figure 9: Monte Carlo comparison without additional cuts

We can now also impose the 4 Gev momentum cut and the $t < -2$ cut and compare with the non-MC runs. The plots are shown in figures 10 and 11. From these figures we can see that the MC simulation has a narrower spectrum. This can be explained by the fact that not all processes are included in the simulation, especially not the exclusive ones we are sensitive to.

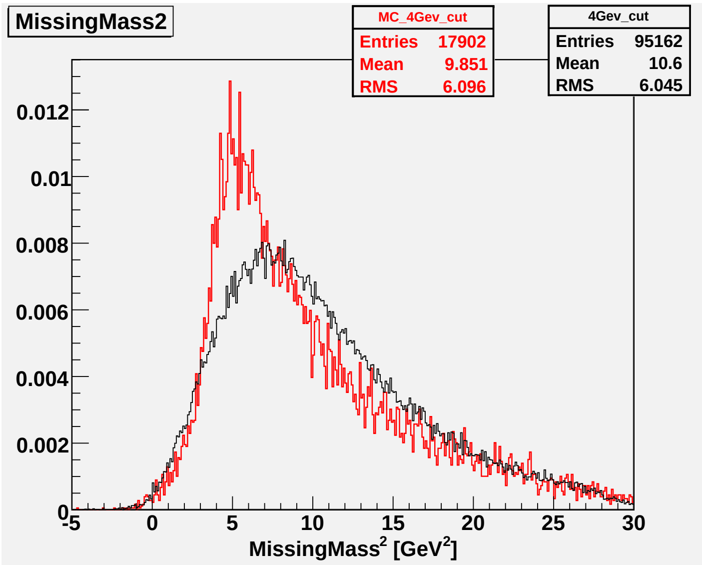


Figure 10: Monte Carlo comparison with 4 Gev momentum cut on proton

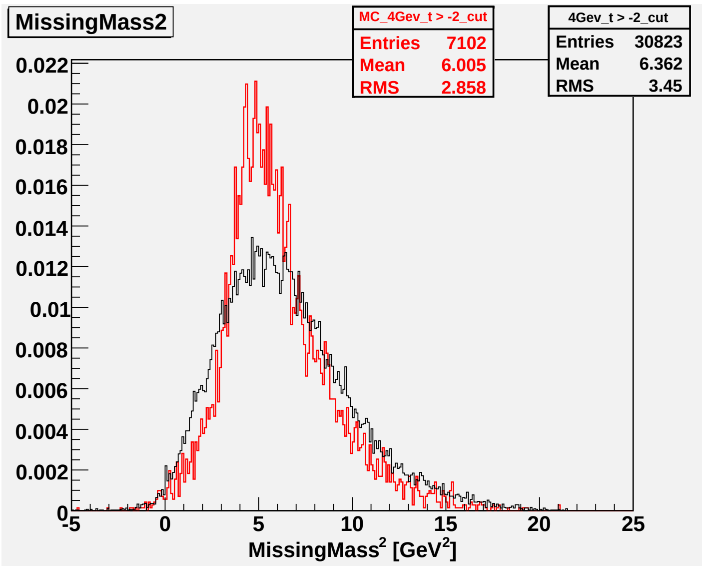
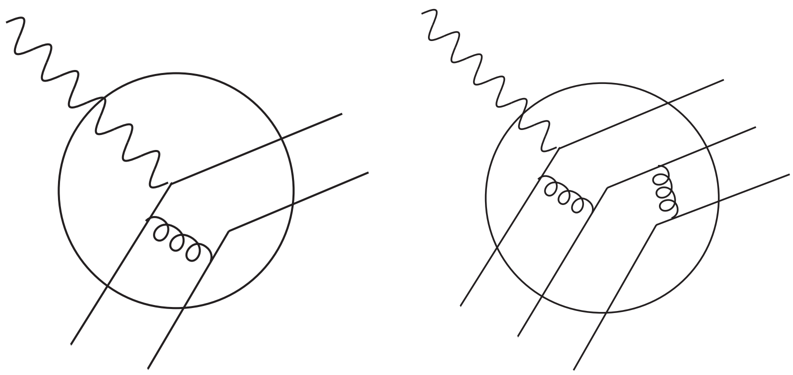


Figure 11: Monte Carlo comparison with 4 Gev momentum cut on proton and $t > -2$ cut

4 Conclusion

We did not find any signal for exclusive π^0 production in the backward region. A possible explanation for this can be found in the hard scattering matrix element (see figure 12). For the π^0 production in the backward region, we have coherent scattering on three quarks (figure 12b). In the case of π^0 production in the forward region, there is only coherent scattering on two quarks (figure 12a), which is less suppressed. Also, from theoretical considerations (see [2]), it follows that the cross section for the π^0 production in the backward region falls off with $\frac{1}{Q^6}$. The resolution and acceptance of the detector also has to be taken into account. All of this combined may explain why the signal could not be detected.

There are still some more options that can be explored in the future. For instance, one could make a less strict cut on Q^2 or demand that there were no hits in the Recoil Detector (and not just no reconstructed tracks).



(a) M_h Pion (b) M_h Proton

Figure 12: Hard scattering matrix element M_h

Acknowledgements

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