DESY Summer Students Program 2008:
Exclusive π^+ Production in Deep Inelastic Scattering

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Contents

1 Abstract

In the HERMES Experiment at DESY in Hamburg the scattering of positrons off protons at rest forming a positron, a neutron and a positive charged pion in the final state, can be observed. Until now there were only indirect methods available to supress the background of these exclusive events. In a kind of feasibility study it is investigated, if there is a possibility to exclude the background directly from the detector data, especially by using the data from the in 2006 installed Recoil Detector. Several proposals were examined to reduce the background in a sufficient amount, but none of the proposals looked very promising. Further research is necessary.

2 Introduction

2.1 The HERMES Experiment

2.1.1 Purpose

The **HERA ME**asurement of nucleon **S**pin (HERMES) experiment was designed to study the source of the proton spin. For this reason electrons and positrons with an energy of 27.5 GeV collided on fixed gas targets. Originally, the experiment consisted of a spectrometer in the scattering direction (called the Forward Spectrometer). In 2006, the Recoil Detector was added, surrounding the target, to detect particles at large angles and low energies. See Fig. 2.1 for a schematic.

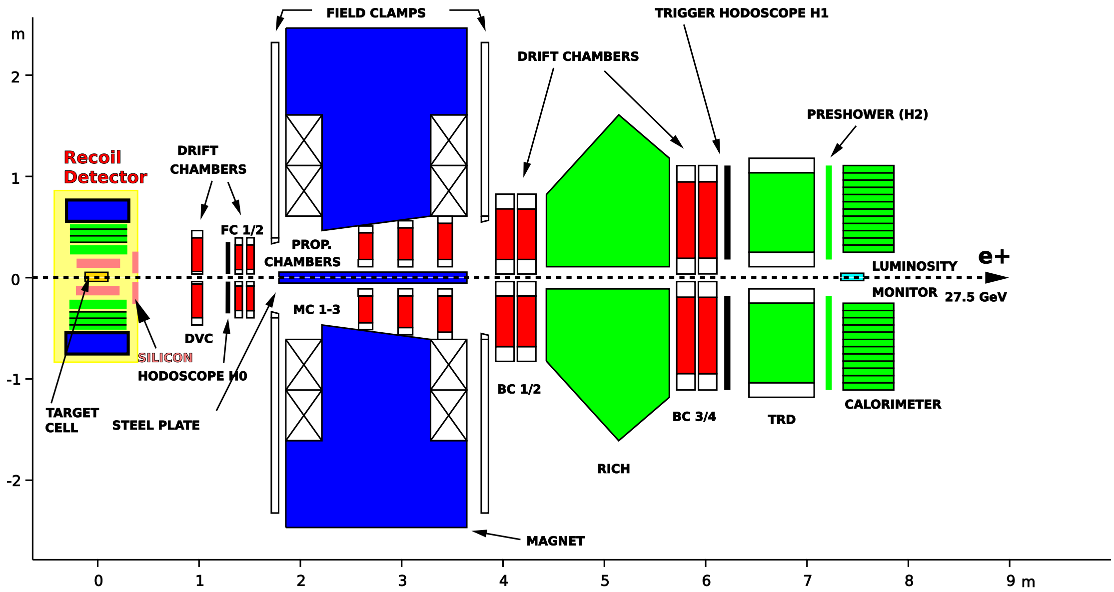

Figure 2.1: Schematic of the HERMES detector.

2.1.2 Forward Spectrometer

The HERMES Spectrometer, shown on the right part of Fig. 2.1, is composed of several detectors. The red colored components are used for particle tracking. These are:

1. Drift Vertex Chambers (DVC): wire chamber

2. Front Chambers (FC 1/2): drift chambers

3. Magnet Chambers (MC 1/3): multiwire proportional chambers for momentum analysis of relatively low energy particles

4. Back Chambers (BC 1-4): drift chambers

The tracking chambers allow for momentum reconstruction.
The green parts in the schematic are used for particle identification:

1. Dual-Radiator Ring Image Čherenkov Counter (RICH): allows separation of pions, kaons and protons

2. Transition Radiation Detector (TRD): distinguishes between electrons and hadrons

3. Preshower: composed of scintillators, discrimination between electrons and hadrons supports particle identification

4. Calorimeter: meassures the energy of the particles

For further information see the Technical Design Report [4].

2.1.3 Recoil Detector

The HERMES Recoil Detector, shown in Fig. 2.2, consists of three active detector components, all in a magnetic field of 1.0 T longitudinal to the beam:

1. a silicon tracker, surrounding the target cell inside the beam vacuum,

2. a scintillating fiber (SciFi) tracker and

3. a photon detector consisting of several scintillator strips, which uses an extra layer of lead, the cryostat and the return yoke of the magnet as shower material.

The silcon detector and the SciFi detector are used to gain momentum information for recoiling particles. Further the main purpose of the SciFi detector is to distinguishes protons from pions, but information from the other detector parts is used for particle identification as well. The photon detector detects neutral pions due to their decay to photons.
For further information see the Technical Design Report [5].

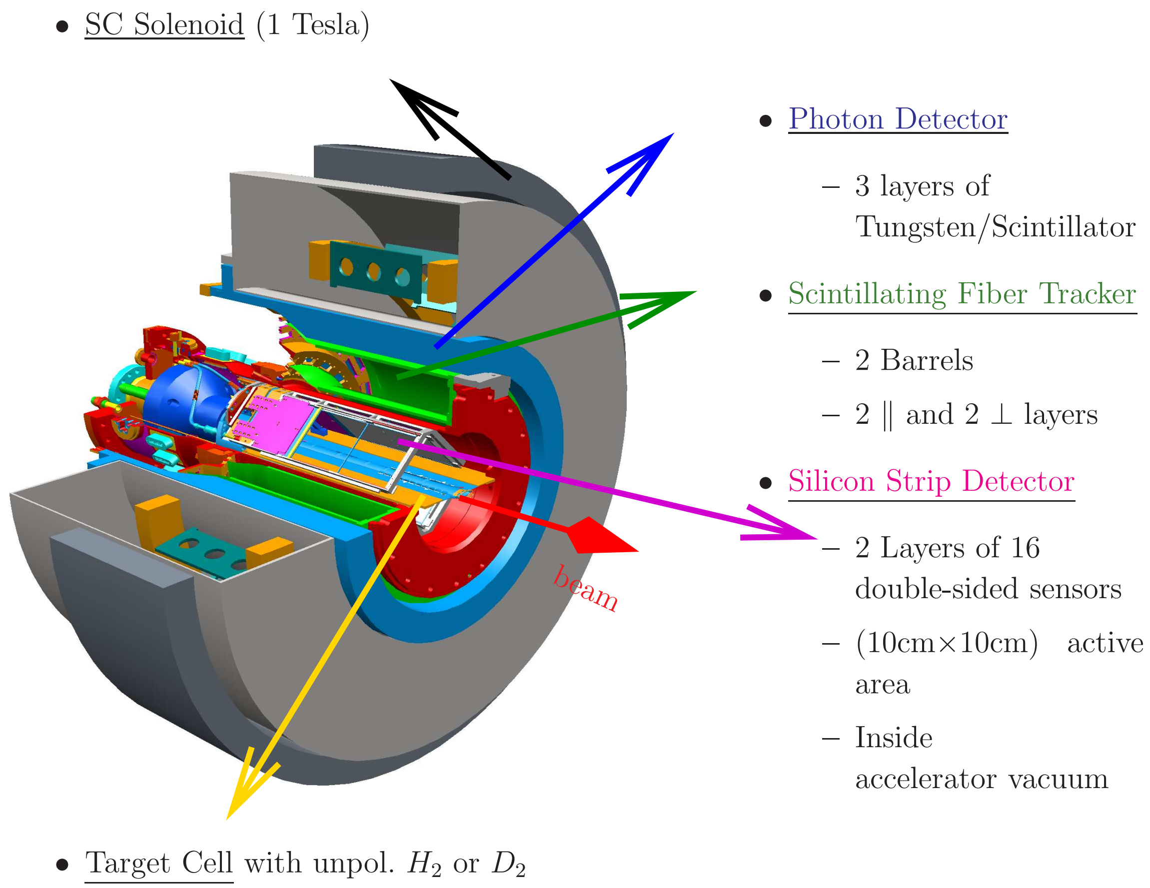

Figure 2.2: Schematic of the HERMES Recoil Detector.

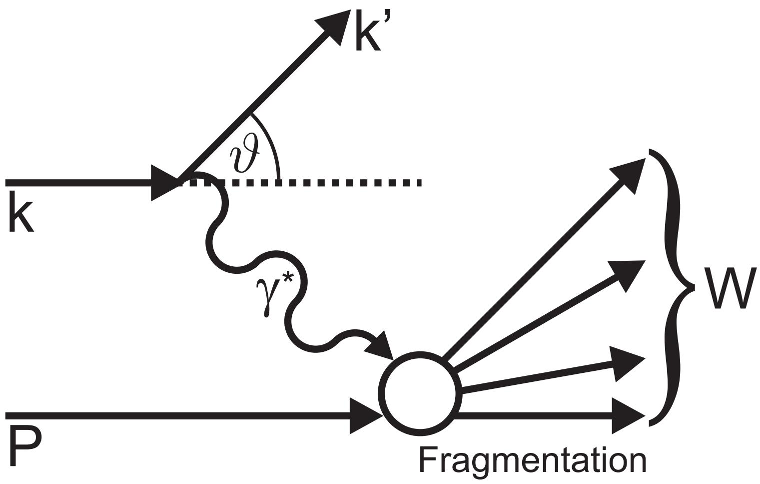

Figure 2.3: Schematic of kinematics of a DIS event.

2.2 Deep Inelasic Scattering (DIS) Events

Scattering of a lepton off a nucleon can kinematically be desribed by the following schematic where $P = \left(M_p, \vec{0}\right)$, $k = \left(E, \vec{k}\right)$ and $k' = \left(E', \vec{k'}\right)$ are the 4-momenta of the proton, the incomming beam lepton and the scattered beam lepton respectively. Further $W = \left(E_p, \vec{p}\right)$ is the sum of the 4-momenta of the proton fragmentations. The 4-momentum transfer from the beam lepton to the proton can be calculated with

$$-Q^2 = q^2 = (k - k')^2 \stackrel{lab}{=} -4EE' \sin^2\left(\frac{\vartheta}{2}\right) \tag{2.1}$$

where ϑ is the scattering angle in the labatory frame. The energy transfer from beam lepton to proton is

$$\nu \stackrel{lab}{=} E - E' \tag{2.2}$$

Further one often uses the fractional energy transfer, calculated

$$y = \frac{E - E'}{E} = \frac{\nu}{E} \tag{2.3}$$

Scattering processes where the invariant mass of the initial state equals the invariant mass of the final state, i. e. $W^2 = M^2$, are referred to as elastic scattering. Whereas they are called inelastic scattering, if $W^2 > M^2$.
With $Q^2 > 1$ GeV^2 the wavelength $\lambda \sim \frac{1}{\sqrt{Q^2}}$ of the virtual photon γ^*, mediating the scattering process, becomes so small, that it is possible to resolve the constituents of the nucleon. In this domain the reaction may be described as scattering off individual quarks in the nucleon which breaks apart and forms a hadronic final state.

3 Exclusive Pion Events

3.1 Exclusive π^+ Production in DIS

Consider exclusive pion production in positron-proton scattering:

$$e^+ + p \rightarrow e^+ + n + \pi^+ \tag{3.1}$$

In HERMES one can only observe the charged final state particle produced in this reaction, i. e. the scattered beam lepton e^+ and the produced positively charged pion π^+, whereas the neutron n is not detectable. For this reason the so called missing mass technique is needed to identify the reaction.

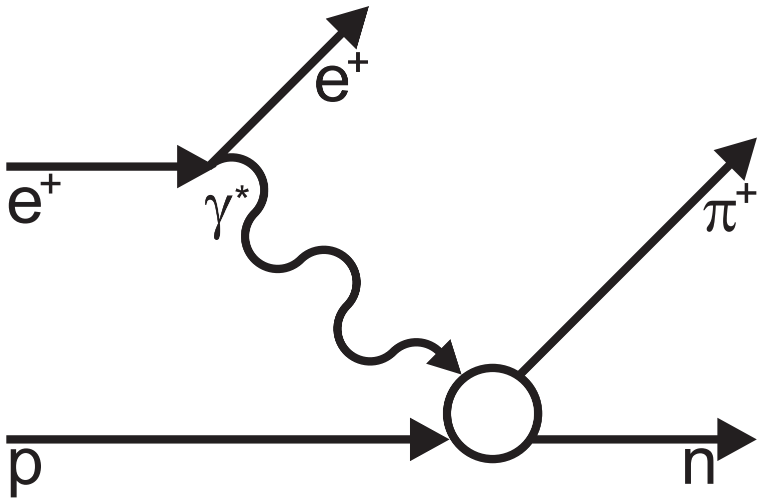

Figure 3.1: Feynman diagram of exclusive pion production in positron-proton scattering

Due to energy and momentum conservation we obtain the equation:

$$P + k = P' + k' + v \tag{3.2}$$

where P, k and k' are the 4-momenta of the proton, the incomming lepton and the scattered beam lepton respectively. Further P' refers to the 4-momentum of the recoiling particle, here a neutron, and v is the momentum of the produced π^+. Introducing the momentum transfer $q = k - k'$ yields to the equation:

$$P' = P + q - v \tag{3.3}$$

After squaring this equation, we end up with:

$$M_n^2 = P'^2 = (P + q - v)^2 \tag{3.4}$$

where M_n is the invariant mass of the neutron.
The 4-momenta P, q and v can be gained from the detector data, so that one can calculate the missing mass $M_x^2 = (P + q - v)^2$ for each event. Due to the missing mass technique, we claim an event to be an exclusive pion event if its missing mass is approximately $M_n^2 = 0.883$ GeV^2. That means, if the event selection is well done and most of the background (all events not of the type described in Eq. 3.1) is suppressed, we should obtain a missing mass plot with a peak centered around M_n^2. The width of this peak corresponds to the resolution of the system. For this reason the missing mass plot is a good tool to check accuracy of the cuts applied for event selection and sometimes the only way to select a certain event category.

3.2 Event Selection

The data sample used for this study was taken in 2007 (07c). The lepton storage ring was filled with positrons and hydrogen gas was used as a fixed target in the storage cell. To select the exclusive pion events (Eq. 3.1) one has to apply several cuts on the data.

3.2.1 Cuts on the Spectrometer Data

The exclusive π^+ production only occurs in deep inelastic scattering (DIS). For this reason we considered only events fulfiling the following DIS cuts:

$$Q^2 > 1 \text{ Gev}^2 \quad , \quad y < 0.85 \quad \text{and} \quad W^2 > 10 \text{ Gev}^2 \tag{3.5}$$

where Q^2 is the 4-momentum transfer from the beam lepton to the target, y the fractional energy transfer of the vitual photon to the target and W^2 the photon-nucleon invariant mass. The threshold for Q^2 assure the breaking up of the proton, by applying the W^2-cut we leave the resonance region of protons, whereas the cut on y suppresses mistakes in the calculation of the fractiona energy transfer due to radiative corrections. We required the scattered beam lepton and the produced pion to be observed in the forward spectrometer because this means low momentum transfer to the target. This regime of low momentum transfer is where we are particularly interested. Since the considered reaction is exclusive, we required just two tracks in the spectrometer (one track referring to the scattered beam lepton and one being the pion track). Further we required no photon observed in the detector. In Addition we applied a cut on the momentum to the produced pion p_π:

$$7 \text{ Gev} < p_\pi < 15 \text{ Gev} \tag{3.6}$$

because that is the range in which the RICH, which is used to identify the particles, works best.

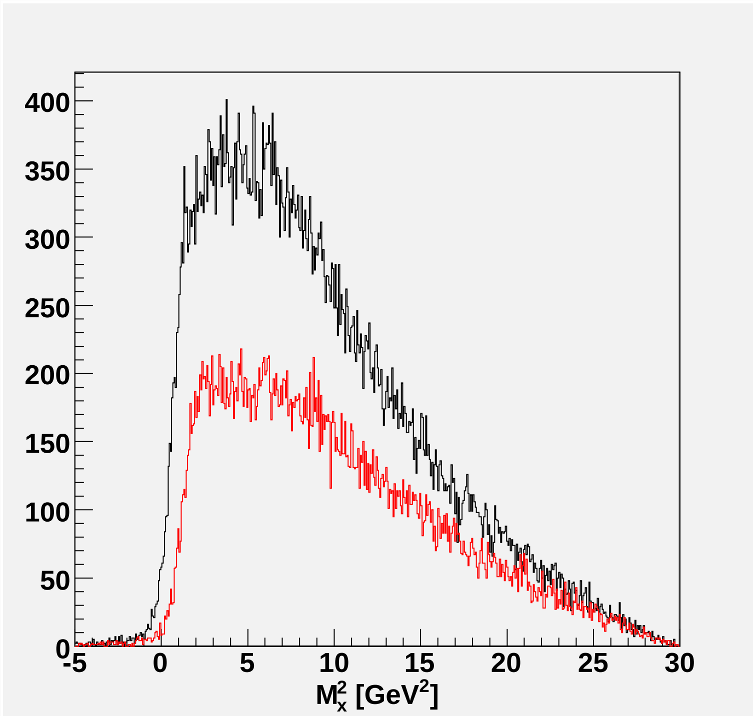

Figure 3.2: Missing mass plot after cuts on the spectrometer data. Black curve: π^+ and red curve: π^-.

3.2.2 Traditional Background Subtraction

Due to conservation of charge there is no exclusive reaction of a positron and a proton with a positron and a negative charged pion in the final state. Since π^+ and π^- have a similar quark content, they should physically act almost identically. Therefore, one can expect the background in the exclusive pion production to be similar to the production of negative charged pions.

The plots in Fig. 3.3 are similar to plots obtained in a HERMES Release Report [1]. But one cannot see a real peak centered around M_n^2, yet. Too many background events are still taken into account.
The π^- yield obtained in the experiment is lower than the π^+ yield. In order to achieve a better background suppressing, one has to scale up the π^- yield so that it is approximately equal to the number of background events in the exlusive pion production. To determine the scaling factor we plot the ratio of the number of π^+ events and of π^- events within a specific range of missing mass values. Doing so, we

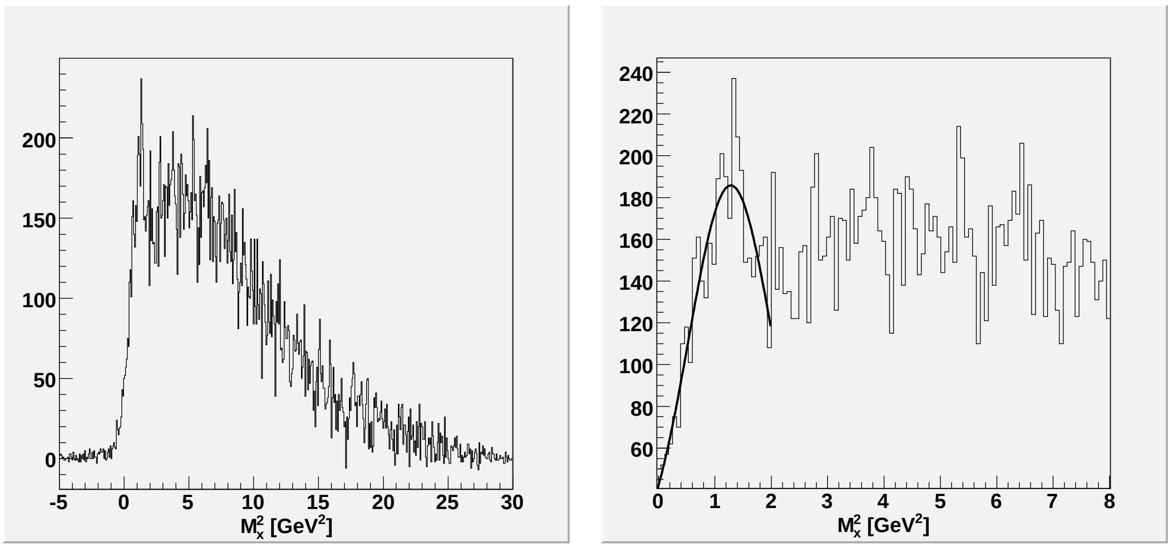

Figure 3.3: Left: After substracting the π^- yield from the pi^+ yield one can guess a peak in the missing mass plot approximately around the squared invariant mass of the neutron. Right: Magnification of this slight peak.

can find an almost flat area in the range 2.9 GeV^2 $< M_x^2 <$ 5.4 GeV^2. Fiting this region with a constant function we obtain a scaling factor of 1.88 ± 0.49.

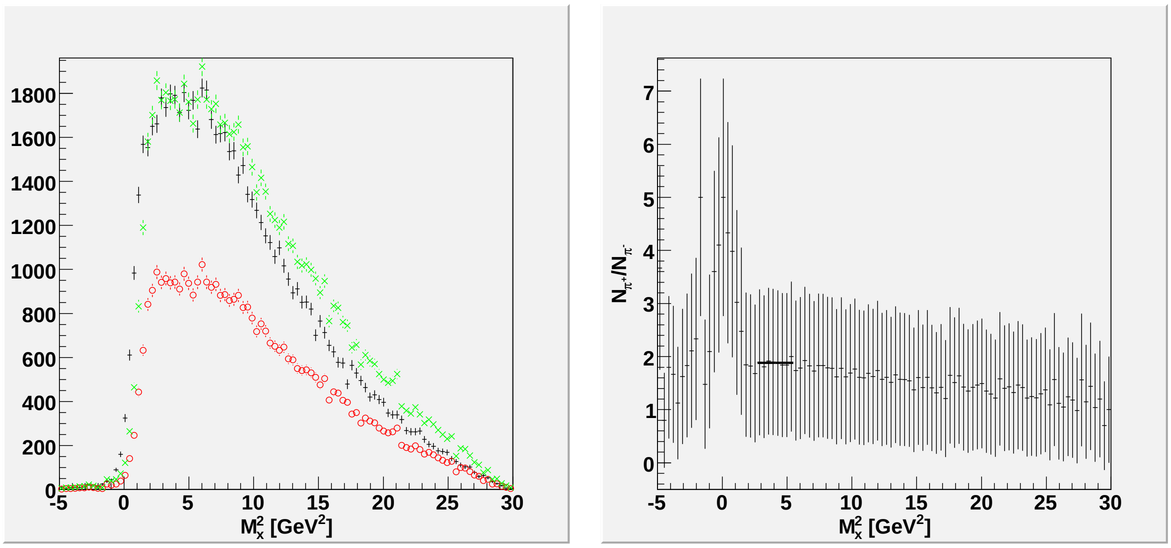

Figure 3.4: Left: Missing mass plot of π^+ (black) and π^- (red) events. The green curve shows the missing mass distribution of the π^- events scaled by a factor of 1.88. Right: Ratio of the number of π^+ events and of π^- events within a specific range of missing mass values. In the range 2.9 GeV^2 $< M_x^2 <$ 5.4 GeV^2 the flat area was fit with a constant function in order to estimate the scaling factor.

With this factor the π^- yield is scaled up and subtracted from the π^+ yield. This results in a missing mass plot with a peak centered approximately at M_n^2. Fiting this peak with a gaussian, one finds:

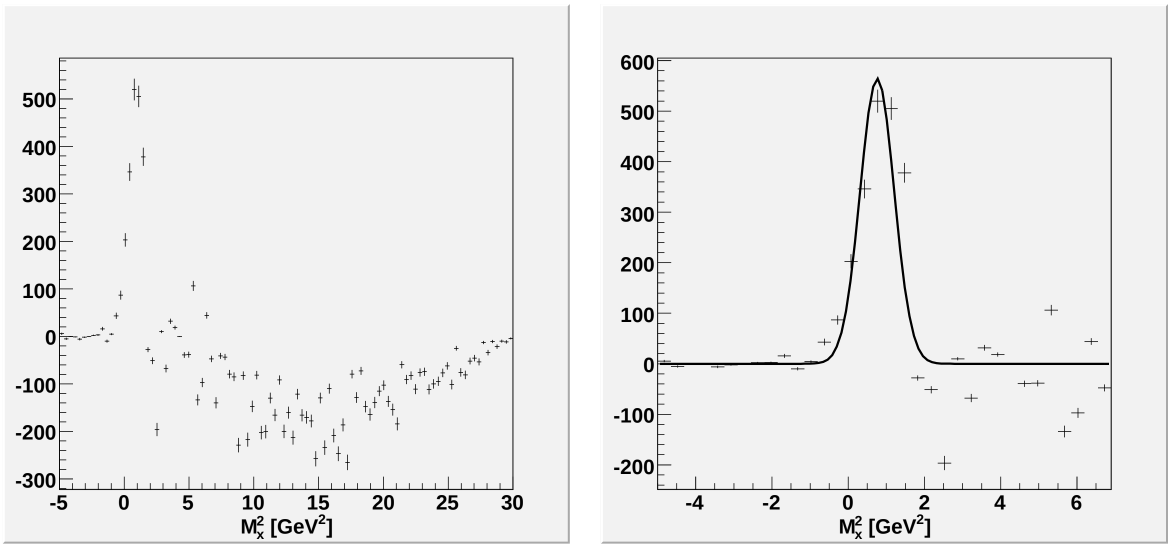

Figure 3.5: Left: Substracting the scaled π^- yield from the π^+ yield leads to a peak in the missing mass plot approximately around the squared invariant mass of the neutron. Right: Fitting this peak with a gausian yields: $M_x^2 = 0.760 \pm 0.016$ and $\sigma_{M_x^2} = 0.447 \pm 0.010$.

We tryed to find a more direct way to get rid of the background by using also information from the Recoil Detector.

3.2.3 Cuts on the Recoil Data

We can identify background events via a track in the recoil detector. All tracks with one spacepoint in the outer silicon, one spacepoint in the inner silicon and at least one spacepoint in the SciFi were assumed to belong to background events, since we were looking for exclusive π^+ events.

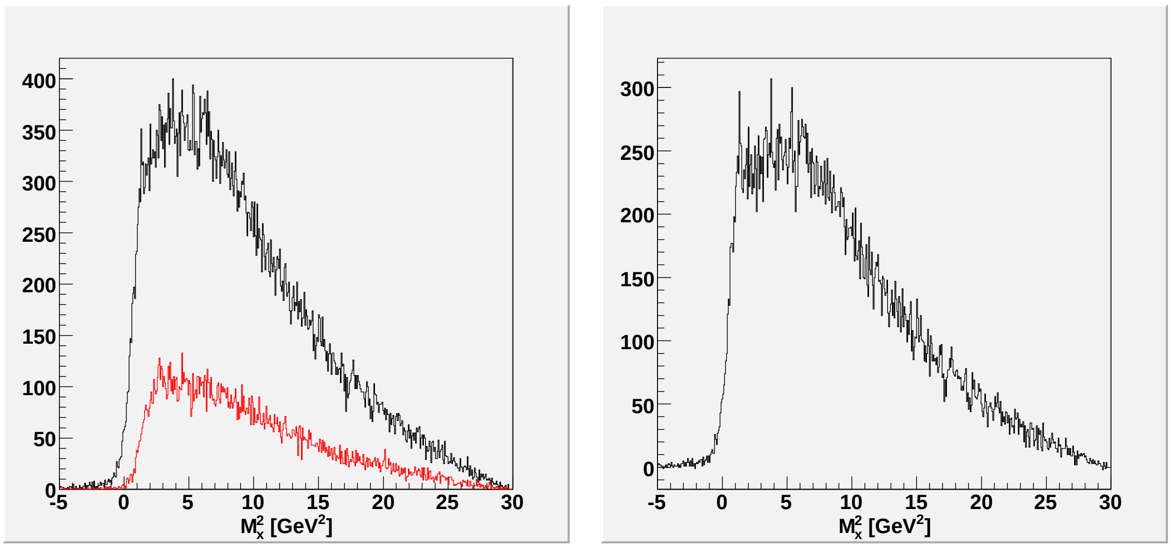

Figure 3.6: Left: Missing mass plot after cuts on the spectrometer data (black) and background events identyfied with the recoil detector (red). Right: Background events substracted from missing mass plot of π^+.

In Fig. **??** one might guess a small peak arround M_n^2 after the substraction of background events observed with the recoil detector, but the result is not satisfying at all. Too many background events are not in the acceptance of the recoil detector as one can see from the low number of identified background events for a high missing mass. For a missing mass value > 5 GeV^2 all events are background.
Since the recoil detector is not able to exclude more background events, we had to look for further cuts on the spectrometer data.

3.2.4 Exclude events by expected ϑ-angle

Since we can reconstruct the 4-momenta of the scattered beam lepton and the produced pion, one can calculate the 4-momentum of the missing mass according to Eq. 3.3. The hope was that there is a correlation between the angle ϑ expected from the 4-momentum of the missing mass and the angle ϑ of the background tracks in the recoil detector, so that one could exclude background events with tracks that are not in the acceptance of the recoil detector. We saw a correlation in the angle φ, but unfortunately not in the angle ϑ as one can see from Fig. 3.7.

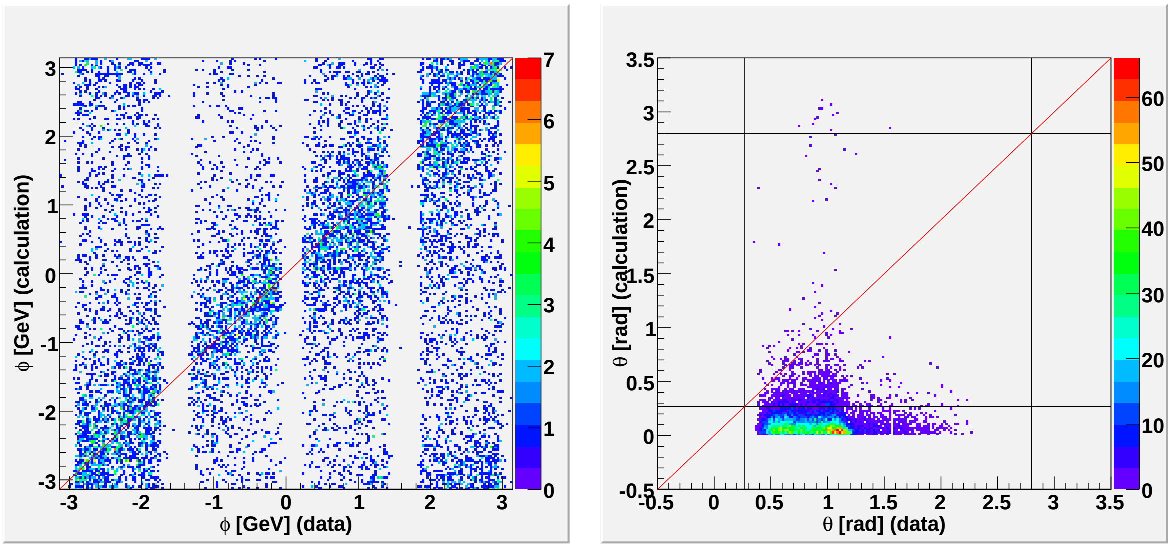

Figure 3.7: Left: This plot shows the measured φ-angle from the recoil data versus the expected angle φ from the spectrometer calulation. One can find a correlation between both. Right: This plot shows the measured ϑ-angle from the recoil data versus the expected angle ϑ from the spectrometer calulation. The black lines indicate the acceptance of recoil detector. One determines a strong deviation between expected and measured values.

What are the reasons for this deviation? First off all, the background tracks can be anywhere and only their sum equals the momentum of the missing mass. So from the plots it seems obvious that the tracks of the background events are widely spread and deviate very much from the momentum of the missing mass. One has also to take into account the uncertainty in momentum resolution in the main spectrometer. Assuming a constant relative uncertainty for the spectrometer, the absolute value of the uncertainty gets pretty large for high momenta. This results in a quite large uncertainty in ϑ of the missing mass track.
Since one cannot foresee the ϑ-angle of the background tracks, this method to find undetectable background events seems not to be applicable.

3.2.5 Exclude undetectable background events by spectrometer data

Another idea was to look for differences in the spectrometer data, for background events that leave tracks in the recoil detector and those ones that are fully out of the acceptance of the recoil detector. For this reason Monte Carlo (MC) data that simulated background events where used. The files:

`/mcdata06/DATA/RICH_SYSTEMATI_STUDIES/PYTHIA/RESULTS_P06_Q2cut_RAD_MSTP18_3_2004C_MSEL2_STD/pythia_p_rad_1.smdst.gz`

...

`/mcdata06/DATA/RICH_SYSTEMATIC_STUDIES/PYTHIA/RESULTS_P06_Q2cut_RAD_MSTP18_3_2004C_MSEL2_STD/pythia_p_rad_200.smdst.gz`

were used for this purpose. They were generated with PHYTHIA.

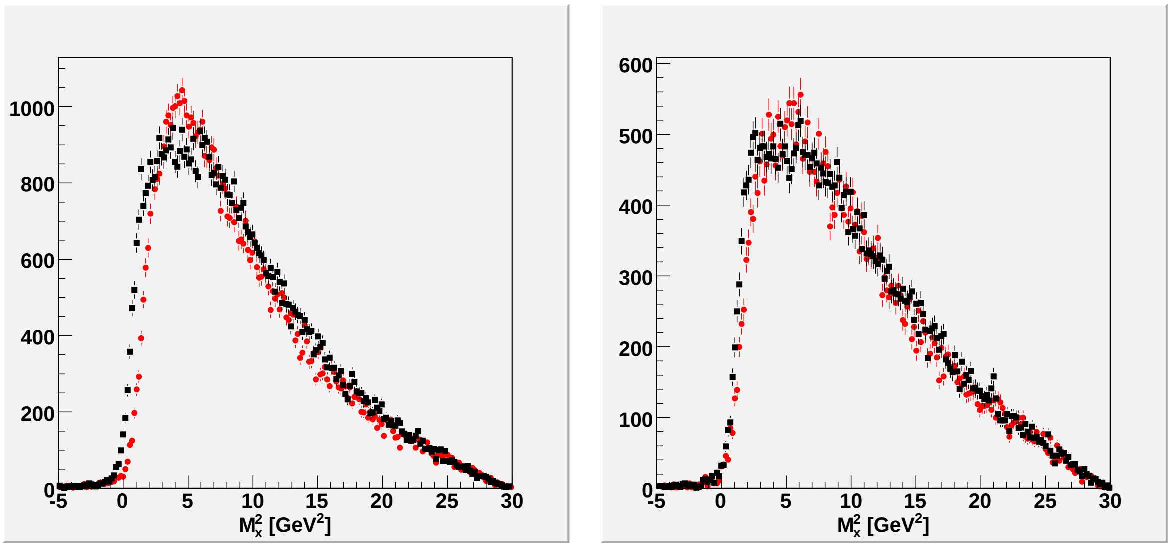

Figure 3.8: Left: Missing mass plot of π^+ events, measured data (black) and MC data (red). Right: Missing mass plot of π^- events, measured data (black) and MC data (red).

By comparing the MC data with the measured data, one can see, that the MC data describe the background events very good. The deviation in the missing mass plot of π^+ for low missing mass values is due to the exclusive π^+ events, which do not occur in the MC data.

We plotted the momentum vs. the angle ϑ for both the scattered beam leptons and the positive charged pions in the spectrometer for background events simulated with MC. We distinguished between events that could be detected from the recoil detector, because there would be at least one track in the acceptance of the detector and events that would be invisible for the recoil detector.

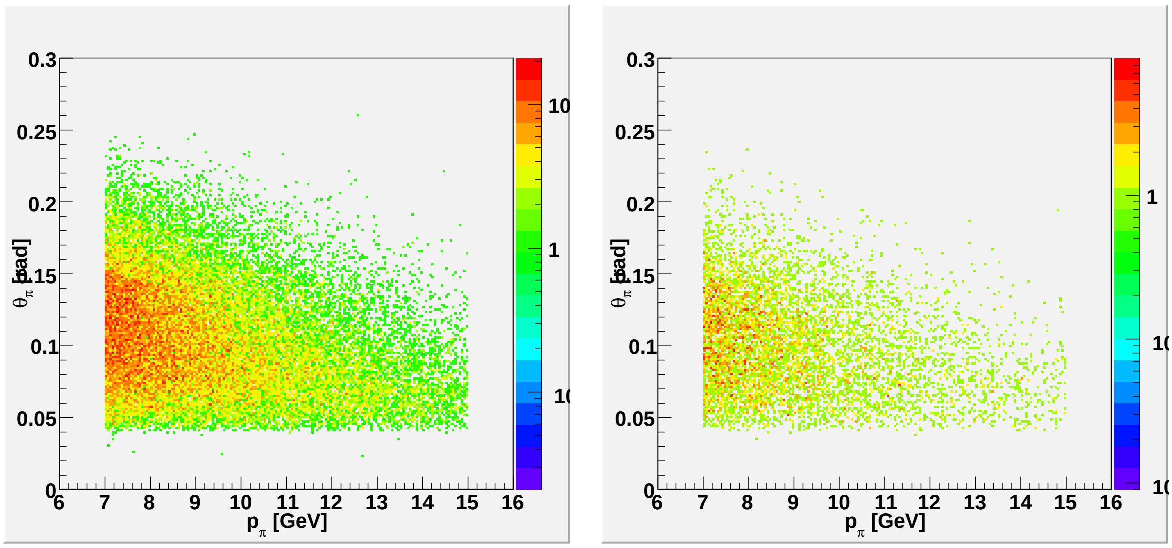

Figure 3.9: Left: Momentum p_π vs. ϑ_π of the pion when no track of this MC background event would be seen by the recoil detector. Right: Momentum p_π vs. ϑ_π of the pion when at least one track of this MC background event would be seen by the recoil detector.

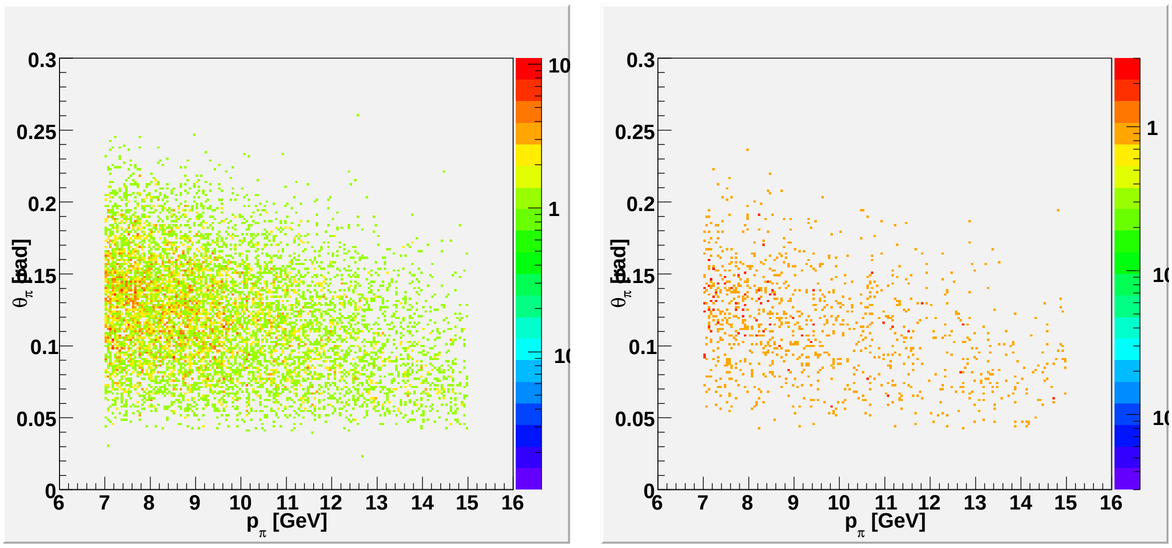

Figure 3.10: The same plots as shown in Fig. 3.9, but with a cut of $M_x^2 < 4$ GeV^2.

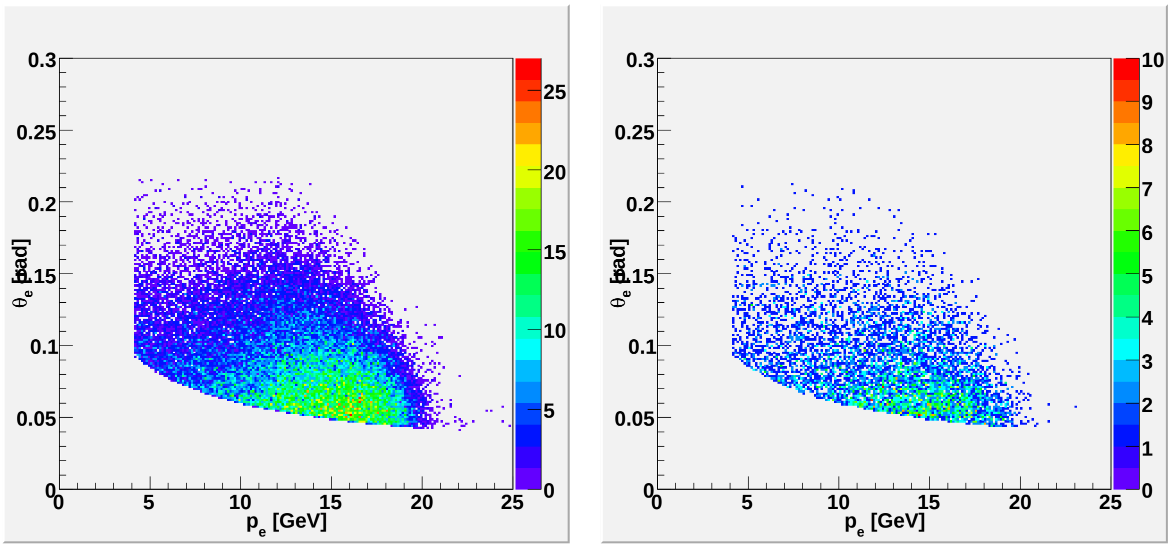

Figure 3.11: Left: Momentum p_e vs. ϑ_e of the scattered beam lepton when no track of this MC background event would be seen by the recoil detector. Right: Momentum p_e vs. ϑ_e of the scattered beam lepton when at least one track of this MC background event would be seen by the recoil detector.

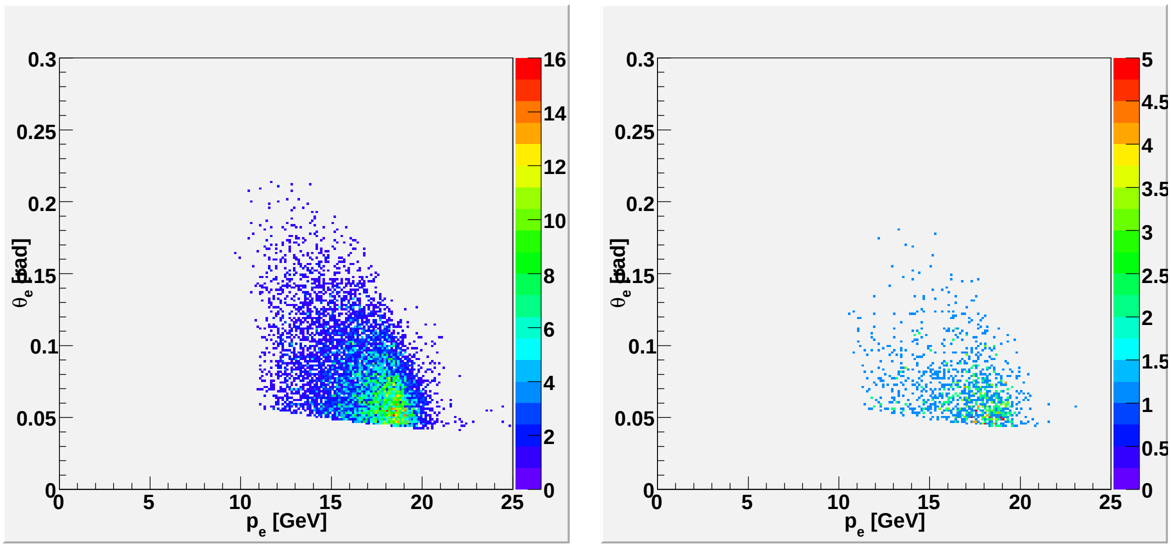

Figure 3.12: The same plots as shown in Fig. 3.11, but with a cut of $M_x^2 < 4$ GeV^2.

Unfortunately in all cases the plots where we expect a track in the recoil detector look quite similar to the plots where no track is in the acceptance of the recoil detector, except from lower statistics. Only 15.6 % of the background events could be detected by the recoil detector due to the acceptance in ϑ. This is consistent with the low number of background events detected in the measured data (See Fig. 3.6). We can conclude that the idea to exclude background events which leave no track in the recoil detector from the spectrometer data does not look very promising.

4 Discussion

The recoil detector was not designed to study the exclusive pion production

$$e^+ + p \to e^+ + n + \pi^+$$

but it would be nice if it could also be used for this purpose. Unfortunately the acceptance of the HERMES Recoil Detector is too small to find a sufficient number of background events in this reaction. This can indirectly be seen from the missing mass plots in Fig. 3.6, because the number of background events could not be sufficiently reduced with the cuts on the recoil data so that the expected peak in the missing mass plot is not very pronounced. From the MC simulations one can see directly that only 15.6% of the background events would leave at least one track in the Recoil Detector. That means, only 15.6% of the background events can clearly be identifyed as background with the data from the Recoil Detector. This amount is too small for a proper event selection.

Furthermore we have not yet found a promesing criteria to apply on the spectrometer data for a better seperation of exclusive pion events and background.

For this reasons there is at the moment no better method available to select exclusive pion events, than the traditional one applied in Sec. 3.2.2 or the subtraction of background events from a MC simulation, which was used in the thesis [2].

Up to now only recoil long tracks (at least three spacepoints) have been used. Maybe there could be some improvement if one looks at short tracks or just at tracks in the inner silicon.

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[4] HERMES Collaboration Technical Design Report. 93-015

[5] The HERMES Recoil Detector. Technical Design Report. 02-003