Exclusive ρ^0 Production in Deep Inelastic Scattering

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Abstract

This report investigates methods to select events with exclusive ρ production from the HERMES experimental data using an unpolarized hydrogen target. It studies appropriate DIS cuts and event selection cuts and also how to implement these cuts. In this investigation exclusive events are selected using different methods, one of which uses the Recoil Detector information. These methods are then compared and analysed with the results of $M_{\rho} = 0.766 GeV/c^2$ using spectrometer track data only to apply exclusive cuts, $M_{\rho} = 0.764 GeV/c^2$ using the Recoil detector data and $M_{\rho} = 0.768 GeV/c^2$ when using these cuts combined. The combined value is in exact agreement with the invariant mass of the ρ meson.

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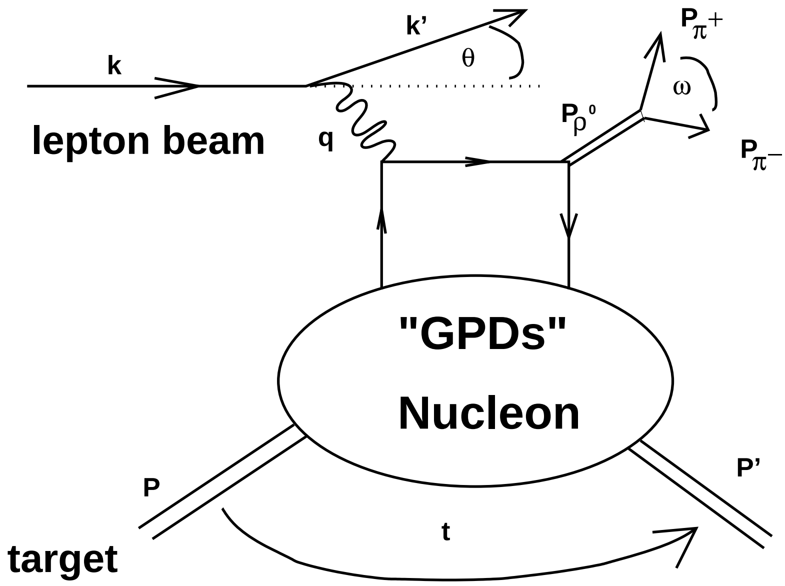

Figure 1.1: A Feynman diagram of exclusive ρ production from Deep Inelastic Scattering of a lepton on a target nucleon.

1 Introduction

1.1 ρ Meson Production

The ρ^0 meson is a hadronic and strongly interacting particle and has a mass of $0.77GeV/c^2$. It has a very short lifetime and decays to a pion pair with a branching rate of 99.9%.[1]

$$\rho^0 \rightarrow \pi^+\pi^-, \tag{1.1}$$

Fig.1.1 is a representation of exclusive ρ meson production of this study. It shows a lepton beam incident on a target nucleon. A lepton from the lepton beam interacts via a virtual photon with a quark from the target nucleon. The lepton is scattered and, as the nucleon recoils, a ρ meson is emitted with then quickly decays into two pions with opposite charge. Four particles emerge from this interaction: The scattered lepton, k', the two hadrons, P_{π^+},P_{π^-}, and the recoiling nucleon, P'. [2] [3]

1.2 The HERMES experiment

HERMES is an experiment at DESY in Hamburg which took data from 1995 to 2007. It stands for HERA MEasurement of Spin and is an experiment for the study of the spin structure of the nucleon. It consists of the HERA lepton beam, with an energy of

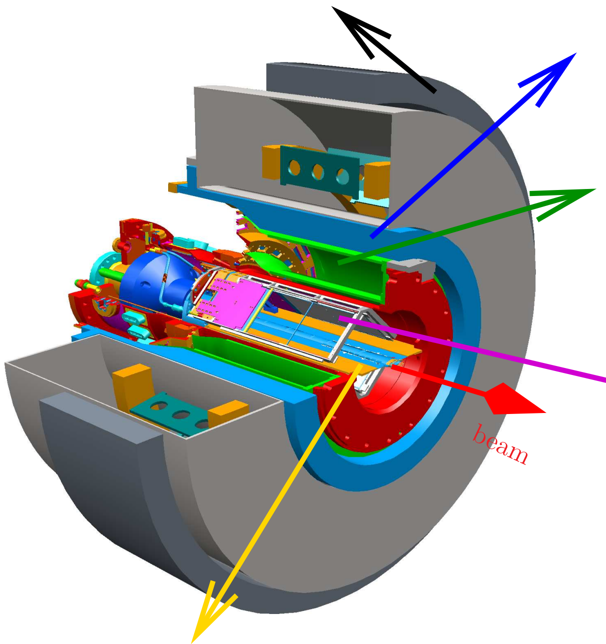

Figure 1.2: An illustration of the HERMES Recoil detector.

$27.6 GeV/c$, incident on a fixed target of pure gases (unpolarised hydrogen or deuterium in 2006/2007). HERMES began in 1995 using a forward spectrometer only to study exclusive ρ production, Fig. 1.1. Of the four emerging particles from this interaction only three can be detected using the forward spectrometer. These three are the lepton and the pion pair from ρ decay. The target proton recoils and therefore is not detected in the forward spectrometer. Method 1 of this investigation is the determination of the mass of the ρ meson using only this forward spectrometer data [2], [3].

1.2.1 The HERMES Recoil Detector

The Recoil detector was built to detect the recoiling particles and select the events with a recoiling target nucleon and no othere recoiling particle, the exclusive events. It was in use from 2006 onwards. It consists of a Photon Detector, a Scintilating Fiber Detector and a Silicon Detector and it is situated around the target gas to detect the recoiling particles. In this investigation the Recoil track data is used in method 2 for detecting exclusive ρ events. [2], [4].

2 Detecting Rho Events

2.1 Standard Cuts

The data used was taken in 2007 using an unpolarised hydrogen target (07c "hrc" production). Fig. 1.1 shows that for an exclusive ρ event, there are four emerging particles, the lepton from the beam, two hadrons from ρ decay and the recoiling target nucleon. Therefore the first cut on the data is at event level and reduces the data to events that have exactly the right number of detected particles emerging from them. When only using the forward spectrometer the right number of tracks for ρ events is three as the recoiling target nucleon is not detected by the spectrometer but by the Recoil detector. These three track spectrometer events (lepton, $\pi^+\pi^-$) are taken as ρ event candidates. [2]

2.1.1 Particle Identification

Firstly, each spectrometer track of an event is taken in turn and the type of particle that created the track is determined as either a hadron or a lepton. This is done using PID (Particle IDentification). PID at HERMES applies a Bayesian algorithm to seperate the hadrons (heavy) and leptons (lighter) with a high accuracy. The most common types are defined as [5],

$$PID2 = PID_{cal} + PID_{pre} \tag{2.1}$$

$$PID5 = PID_{trd} = \sum_{i=1}^{6} PID_{trd,i}, \tag{2.2}$$

where PID2 is a combination of information from the calorimeter and the preshower and PID5 information from the TRD.

For this investigation the $PID2 + PID5$ value was found for each track. If this value was less than 0 then the particle is found to be a hadron. If the value is larger than 1 then the particle is found to be a lepton. Applying these cuts on each track in the candidate event it is simple to select events that have 1 lepton track and two hadron tracks only in the forward spectrometer.

2.1.2 DIS cuts

The second cut is to exclude non-DIS events, as ρ production only occurs from deep inelastic interactions. This cut is achieved by studying three kinematic values of the scattered lepton beam, Q^2, W^2 and y, which can be easily calculated from the track data.[2]

Q^2 is the negative, squared four-momentum transfer of the lepton and is calculated as in Eq. 2.3. W^2 is the square mass of the final hadronic state and is found in Eq. 2.4 and Eq. 2.5 shows y which is the fractional energy of the virtual photon.

$$Q^2 = -q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right), \tag{2.3}$$

$$W^2 = (P+q)^2 = M^2 + 2Mv - Q^2 \tag{2.4}$$

$$y = \frac{P.q}{P.k} = \frac{v}{E}, \tag{2.5}$$

The cuts on these values that select Deep Inelastic Scattering events are shown below.[6]

$$Q^2 > (1GeV/c)^2, \tag{2.6}$$

$$W^2 > (4GeV/c)^2, \tag{2.7}$$

$$y < 0.85. \tag{2.8}$$

2.2 Invariant Mass of the two Hadrons

With these cuts applied the remaining events are now DIS events and have one lepton and two hadron tracks in the forward spectrometer. These tracks contain information about the particles such as momentum, P, and scattering angles, θ and ϕ. Therefore using the relativistic energy-momentum equation,

$E^2 = P^2 + m^2$,

where m is the rest mass of the particle, we can calculate the energy of the emerging particle and also using,

$$\cos(\omega) = \sin(\theta_1)\cos(\phi_1)\sin(\theta_2)\cos(\phi_2) + \sin(\theta_1)\sin(\phi_1)\sin(\theta_2)\sin(\phi_1) + \cos(\theta_1)\cos(\theta_2) \tag{2.9}$$

we can find ω whis is shown in Fig. 1.1 and is the angle between the two emerging hadrons. To use these equations, the rest mass of the particle must be known. With the cuts applied on my data there are two possible interactions left to consider.

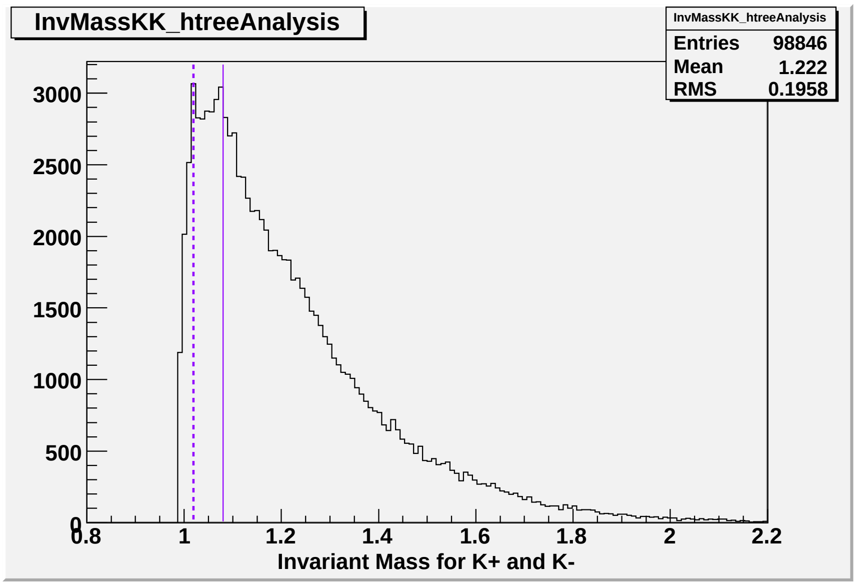

Figure 2.1: This is a histogram of the invariant mass of the ρ candidate events under the assumption that they were all ϕ production/K pair detection. I.e. using the rest mass of Kaons for m ($0.49368GeV/c^2$). The dashed vertical line indicates m_ϕ at $1.019GeV/c^2$ and the full line indicates the ϕ event exclusion cut.

- ρ production/π pair detection

$$\rho \to \pi^+\pi^- \tag{2.10}$$

$m_\rho = 0.768GeV/c^2$

- ϕ production/K pair detection

$$\phi \to K^+K^- \tag{2.11}$$

$m_\phi = 1.019GeV/c^2$

Eq. 2.10 and Eq. 2.11 show the main decay channels of the two types of events. To distinguish the ρ events from the ϕ the invariant mass is calculated for both of the two possibilities using Eq.2.12 and the distributions are shown in Fig.2.1 and Fig.2.2. [2]

$$M_{mm} = \sqrt{2m_{mm}^2 + 2(E_1E_2 - |P_1P_2|\cos(w))}, \qquad m \in \{\pi, K\} \tag{2.12}$$

2.3 Exclusion of Exclusive ϕ Meson Production Events

Fig.2.1 shows the distribution of the invariant mass of two kaons, therefore assuming all interactions produce ϕ mesons. The graph is mainly background apart from a peak

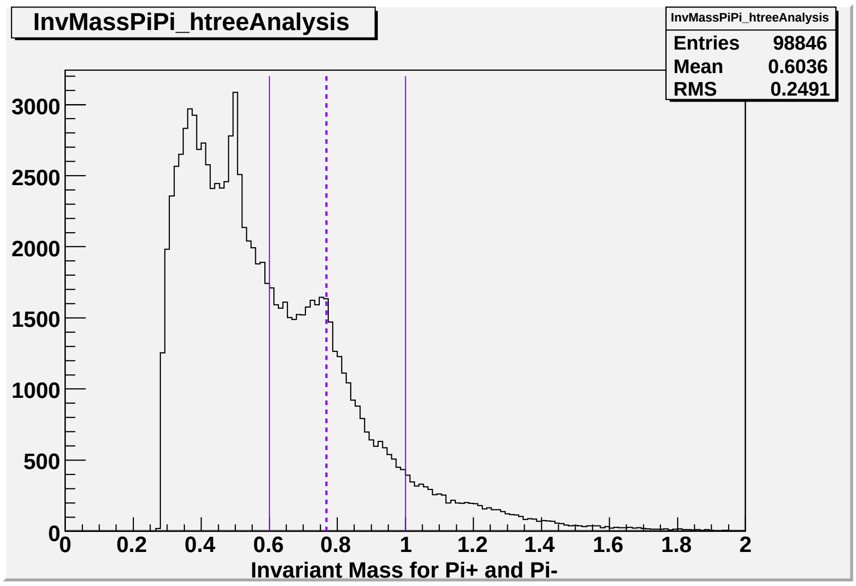

Figure 2.2: This histogram shows the invariant mass of the candidate events under the assumption that they were all ρ production/π pair detection interactions. I.e. the rest mass of Pions was used for m $(0.13957GeV/c^2)$

on the background spectrum at about $1.02GeV/c^2$. This corresponds to the detection of kaons for some events, so to exclude these events we need to apply a cut to the data which excludes the peak but keeps the majority of the events. The cut applied is $M_{KK} > 1.08GeV/c^2$ and is shown in Fig.2.1 as the full line. [2]

2.4 ρ Mass Window

Fig. 2.2 shows the invariant mass spectrum for $\pi^+\pi^-$. The dotted line indicates m_ρ at $0.768GeV/c^2$. There is an obvious peak here from ρ events which lies on a background curve that was produced by other interactions that we are not interested in. Therefore the region of interest for ρ events is $0.6 < M_{\pi\pi} < 1GeV/c^2$, and is shown by the full lines in Fig.2.2. [2]

3 Rho events from Spectrometer Data only: Method 1

Method 1 selects exclusive ρ events only using the event infomation from the forward spectrometer. This can be done by studying the missing mass from the events as if they were exclusive ρ events. Fig.1.1 illustrates how the missing energy for a ρ event is the energy of the recoiling target proton.

3.1 Missing Energy, ΔE

Using the candidate events, as selected above, it is now possible to calculate the missing energy, ΔE. This is the difference between the incoming energy and the out going detected energy in the spectrometer. Fig.1.1 illustrates how the missing energy for a ρ event is just the energy of the recoiling proton. Therefore the missing energy was calculated with the rest mass of a proton subtracted, Eq. 3.1, so ΔE should be zero for an exclusive ρ event. To begin, the missing mass,M_x^2, must be calculated, Eq. 3.1, from the squared four momentum given to the recoling target nucleon. This is determined from the spectrometer information about the candidate events. Then, using M_x^2 the missing energy ΔE can be found for each candidate event($M_p = 0.938GeV/c^2$). [2]

$$M_x^2 = (P + q - P_\rho)^2 \tag{3.1}$$

$$\Delta E = (M_x^2 - M_p^2)/2M_p \tag{3.2}$$

Fig. 3.1 shows the missing energy.The figure includes a cut on the $M_{K^+K^-}$ distribution to exclude ϕ meson contributions and also a window cut on the invariant mass $M_{\pi^+\pi^-}$ to select the ρ region. The peak around zero indicates the exclusive region and the interactions of interest. The magenta histogram represents ΔE after a t-cut is applied in the next chapter. The solid purple lines represent the ΔE cut of $-1 < \Delta E < 0.6GeV$. This is an important exclusive cut as it selects the exclusive events, the proton does not fragment, from the semi-inclusive events, when the proton does fragment.

3.2 Transfered Squared Momentum to Target Nucleon, t'

Fig. 1.1 shows exclusive ρ-meson production in DIS when the recoiling proton does not fragment into other particles. To ensure that the candidate events contain this feature a cut can be applied to the amount of squared momentum transfered, $-t'$, to the nucleon during the interaction. $-t' = t_0 - t$ where t_0 is the maximum value of t permitted by this kinematics and, in this case, can be neglected as it is sufficiently small. Therefore t' is equal to t. Earlier analysis of HERMES data has shown that if $t > 0.4GeV/c^2$ the proton will have sufficient energy to break up into other particles. This is then called a semi-inclusive event and may create tracks in the forward spectrometer which interfers with the event track data.[2] Fig. 3.2 shows the t-values for the ρ-candidate events before the ΔE exclusive cut and after. It illustrates the effectivness of the ΔE cut. Before, the majority of the candidate events are semi-inclusive whereas after the

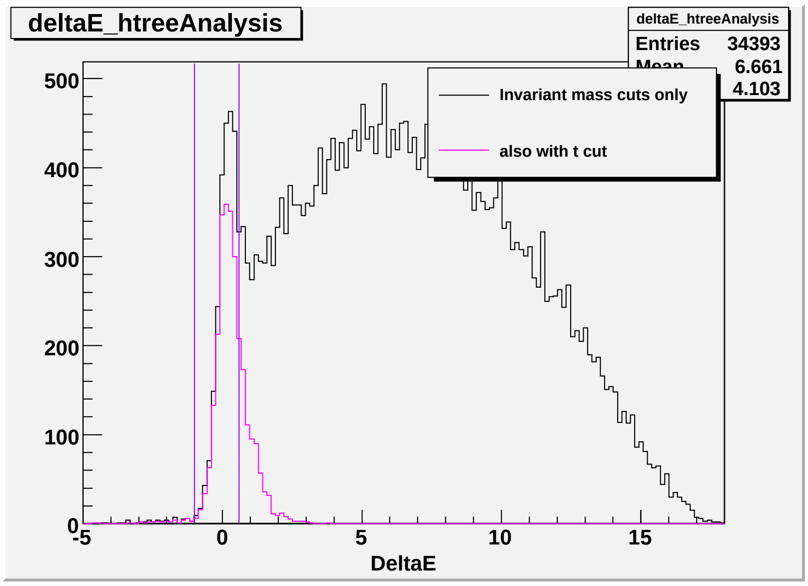

Figure 3.1: This histogram shows for all ρ-candidate events the difference, ΔE, between the missing mass in the events and the actual mass of a proton at rest.

majority are exclusive. The t-cut of $-t' < 0.4\,(GeV/c)^2$ further selects only exclusive events.

3.3 Results using Method 1

With the inclusion of the invariant mass and the exclusive ΔE and t cuts on the data the invariant mass for ρ production, $M_{\pi^+\pi^-}$, is shown again in Fig. 3.3. A fit of a non-relativistic Breit-Wigner function which is described in Eq. 3.3 has been applied to the data.[2]

$$\frac{dN}{dM_{2\pi}} = \frac{1}{4}\frac{\Gamma_\rho}{(M_\rho - M_{2\pi})^2 + \Gamma_\rho^2} \tag{3.3}$$

The mean of this fit gives a calculation of M_ρ using the spectrometer data. In this analysis $M_\rho = 0.766 GeV/c^2$ which corresponds with the value found in the Particle Data Group Booklet (PDG) of $M_\rho = 0.768 GeV/c^2$. [1]

3.4 Cut Effectivness

The red histogram in Fig.3.4 shows $M_{\pi\pi}$ of the events after track selection and DIS cuts have been applied. The blue histogram also includes the ϕ meson exclusion cut on M_{KK} and the green histogram includes all the previous cuts and the exclusive ΔE

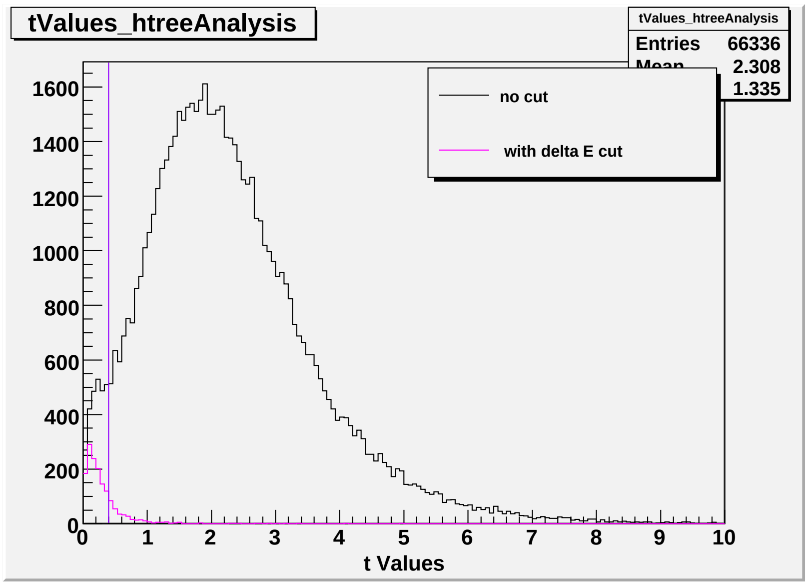

Figure 3.2: This histogram shows the spread of t-values before the cut on t (indicated by the purple line) is applied.

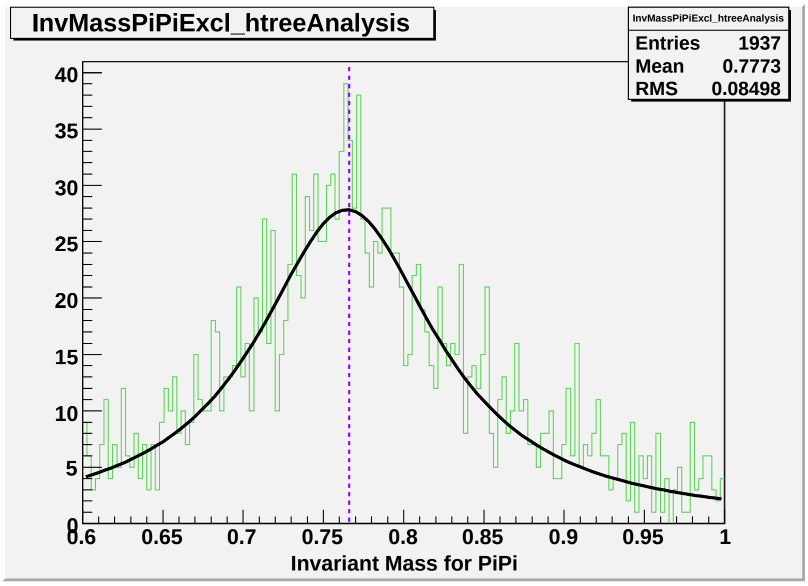

Figure 3.3: Invariant mass of $\pi^+\pi^-/\rho$-system after all exclusive cuts(see text) are applied.

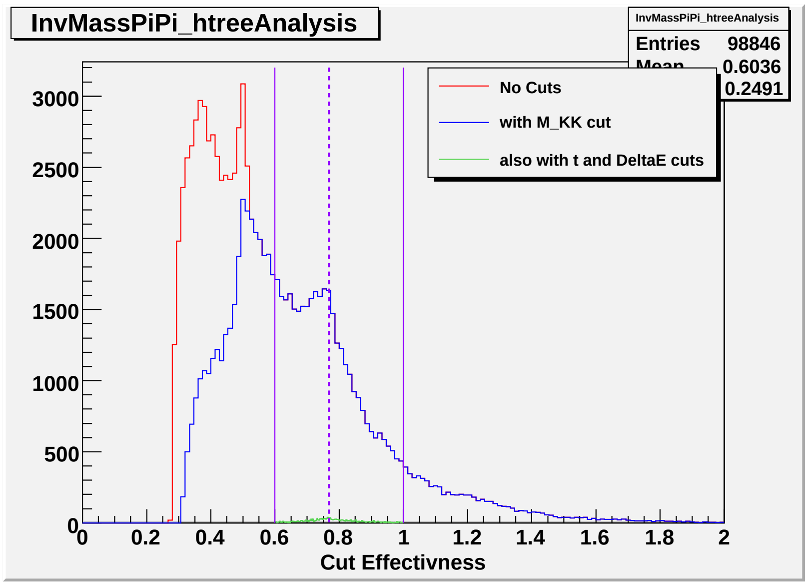

Figure 3.4: This histogram shows the invariant mass of the two pions for candidate events under the assumption that they were all ρ production/π pair detection interactions. I.e. the rest mass of pion was used for m(0.13957GeV).

and t cuts within the $0.6GeV/c^2 < M_{\pi^+\pi^-} < 1GeV/c^2$ window. This illustrates how the invariant mass cuts exclude particular events from the data and how exclusive cuts reduce the background curve from the data.

4 Rho Events from the Spectrometer and the Recoil Detector: Method 2

The first method of detecting exclusive ρ events is the classical method. However, when also using the Recoil detector the track data of the recoiling particles is known. Method 2 applies the same standard data cuts as in method 1, the track selection, lepton DIS and invariant mass cuts. However, instead of the exclusive ΔE and t cuts on the forward spectrometer data, the Recoil data is analysed.

4.1 Detecting the Recoiling Proton

In parallel to the forward spectrometer data selection the Recoil data can also be analysed. The aim is to select events with only one recoiling proton as this is a feature of exclusive ρ events, Fig. 1.1. Each candidate event is considered in turn and to begin only tracks with positive momentum are selected. Then the track with the highest momentum is taken as the recoiling proton track.

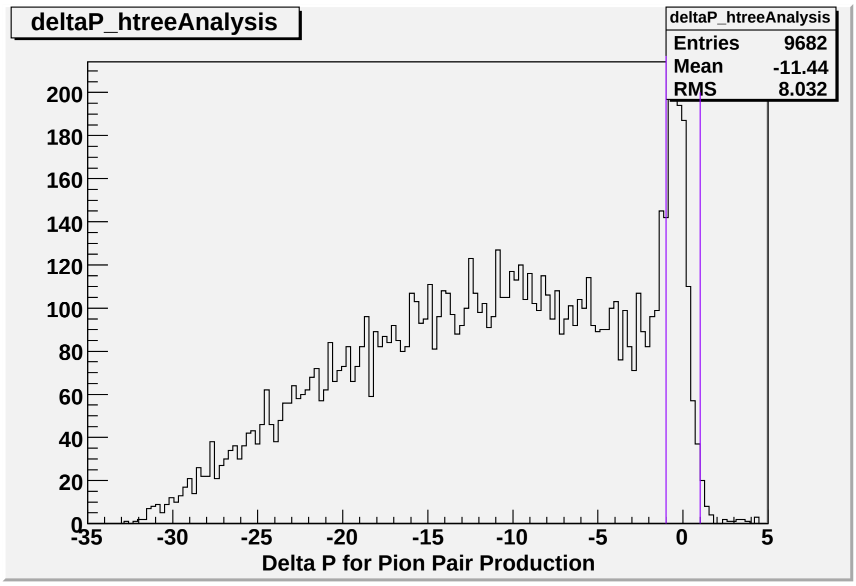

Figure 4.1: Comparison of expected recoil momentum and detected recoil momentum. The solid purple lines indicate the cut of $-1 < \Delta P < 1GeV/c^2$.

4.2 ΔP

ΔP is the comparison between the detected proton momentum from Recoil Detector data and the missing momentum calculated from the forward spectrometer data. Fig. 4.1 is the histogram for ΔP and shows the exclusive ρ events as a peak around 0 as in these events the missing momentum is roughly equal to the momentum for the detected recoiling proton. Therefore an exclusive cut on ΔP of $-1 < \Delta P < 1GeV/c^2$ can be used.

$$\Delta P = P^{exp.} - P^{recoil} \tag{4.1}$$

4.3 ΔP cut: Results

Using the ΔP cut on the data as the exclusive cut, the invariant mass of the two detected hadrons, the pion pair, can be plotted, see Fig. 4.2. As with method 1, a Breit-Wigner function which is described in Eq. 3.3 has been applied to the data. The resulting mean from this fit gives a value of M_ρ=0.764GeV/c^2. This result agrees with the actual value but is less accurate than the result when using Method 1.

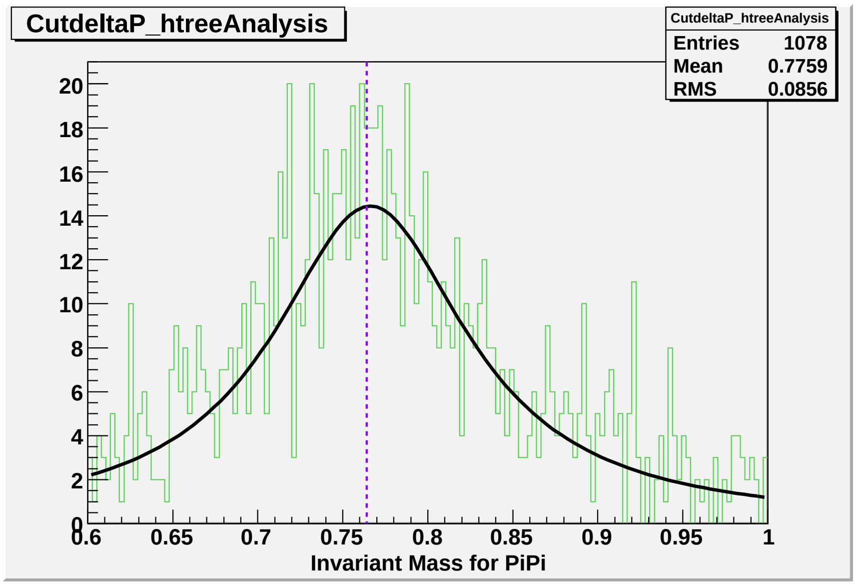

Figure 4.2: Invariant Mass of detected π-pair after data selection and ΔP cut using Recoil Detector information. Also the data has been fitted with a Breit-Wigner curve to give a value of M_ρ=0.764GeV/c^2.

4.4 ΔP_t

Where ΔP is a comparison of the momentum, ΔP_t compares the transverse momentum of the calcuated and detected recoiling proton data and is given in the two Equations 4.2 and 4.3.

$$P_t = \sqrt{P_x^2 + P_y^2} \tag{4.2}$$

$$\Delta P_t = P_t^{exp.} - P_t^{recoil} \tag{4.3}$$

The histogram of ΔP_t for the data is shown in Fig. as a peak around 0. As ΔP_t for the exclusive events will be the closest to zero a cut of $-0.5 < \Delta P_t < 0.5GeV/c^2$ can be applied to ΔP_t.

4.5 ΔP_t cut: Results

As before but now using the ΔP_t cut on the data as the exclusive cut, the invariant mass of $\pi^+\pi^-$ can be plotted, Fig. 4.4. However when applying a Breit-Wigner function

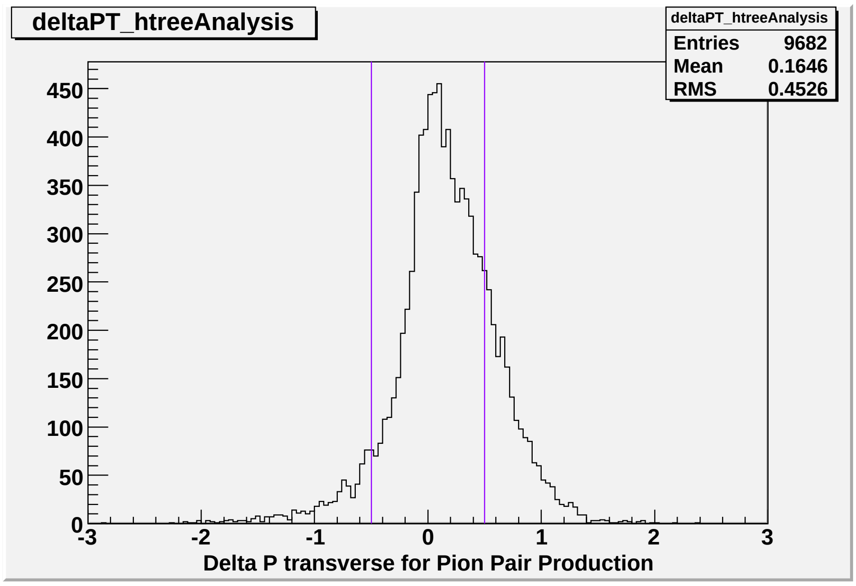

Figure 4.3: ΔP_t with the purple lines representing the exclusive cut of $-0.5 < \Delta P_t < 0.5 GeV/c^2$.

which is described in Eq. 3.3 to the data, $M_\rho = 0.716 GeV/c^2$. This suggests that a cut on ΔP_t alone is not sufficiant as an exclusive cut. This is also seen in the shape of $M_{\pi\pi}$ in Fig. 4.4.

5 Conclusion

This report has shown two possible methods of selecting exclusive ρ production events from HERMES data. The first method uses data from the forward spectrometer only and the second method explores ways of using the data from the Recoil Detector as well. The first method gives a better result for M_ρ of $0.766 GeV/c^2$ although there is scope for improvement on method 2. To conclude, Fig. 5.1 shows the invariant mass of the two hadrons with all the mentioned cuts in methods 1 and 2 combined. Again, a Breit-Wigner function which is described in Eq. 3.3 has been applied to the data with $M_\rho = 0.768 GeV/c^2$. This final plot of $M_{\pi\pi}$ gives the most accurate result of the investigation for the ρ meson mass as it is in exact agreement with the value found in the Particle Data Group Booklet(PDG) of $M_\rho = 0.768 GeV/c^2$.[1]

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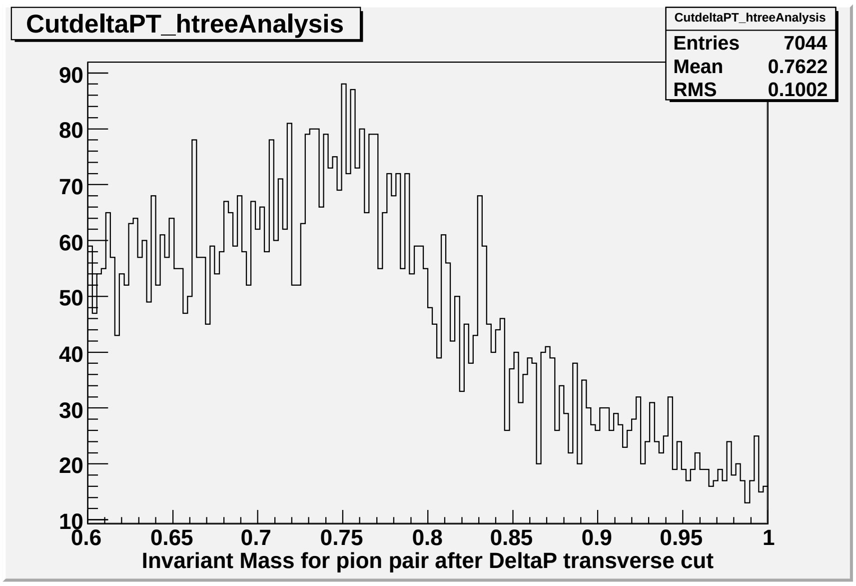

Figure 4.4: Invariant Mass of detected π-pair after data selection and ΔP_t cut using Recoil Detector information.

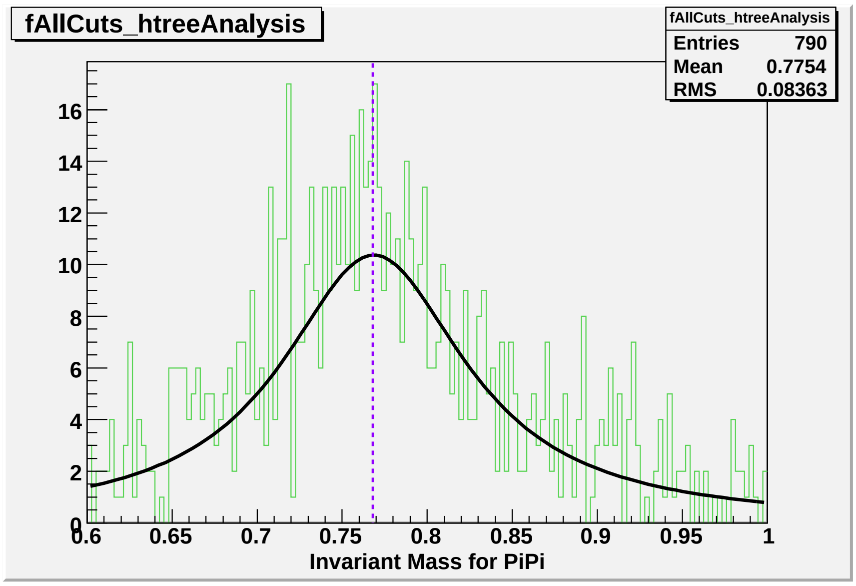

Figure 5.1: Invariant Mass of detected π-pair after all previous cuts are applied. Also the data has been fitted with a Breit-Wigner curve to give a value of M_ρ=0.768GeV/c^2.

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