Measurements of $ep \to e'p'\pi^+\pi^-$ cross section with the CLAS detector for $0.4\ \mathrm{GeV}^2 < Q^2 < 1.0\ \mathrm{GeV}^2$ and $1.3\ \mathrm{GeV} < W < 1.825\ \mathrm{GeV}$

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I. INTRODUCTION

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II. EXPERIMENTAL SETUP

The data reported in this paper were taken at JLab Hall B with CEBAF Large Acceptance Spectrometer (CLAS) [1] which consists of six sectors that are operated as independent detectors. Each sector includes Drift Chamber (DC), Čherenkov Counter (CC), Time-Of-Flight system (TOF), and Electromagnetic Calorimeter (EC). The electron beam was provided by Continuous Electron Beam Accelerator Facility (CEBAF). The measurements were part of the "e1e" run period which lasted from November 2002 until January 2003 and included several datasets with different configurations (hydrogen and deuterium targets as well as two different beam energies of 1 GeV and 2.039 GeV).

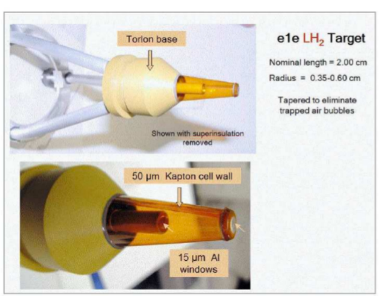

FIG. 1. (colors online) The target cell and support structure used during "e1e" run period.

Experimental configuration for the particular dataset was the following. The torus current was 2250 A and the mini torus current 5995 A. The data were obtained with the 2 cm long liquid hydrogen target located at -0.4 cm along z-axis and a 2.039 GeV polarized electron beam.

The target is specific to the "e1e" experiment and its setup is presented in Fig. 1. It has a conical shape with the diameter varying from 0.4 to 0.6 cm. The reason for the target to be conical originates from the following issue. In some instances cooling system could not extract all the heat generated by the beam and the hydrogen in the target cell could boil. If bubbles stay along the beamline, the real luminosity would deviate from the expected value and the absolute measurement would lack accuracy. The conical shape helps to direct bubbles upwards and into a wider area of the target, thus clearing the beamline. The target cell has entry and exit 15-μm-thick aluminum windows. Beside this, an aluminum foil is located upstream at the distance two cm from the target center. This foil is made exactly the same as the entry/exit windows of the target cell and can serve for both the estimation of the number of events originated in the target windows and the precise determination of the target z position along the beamline.

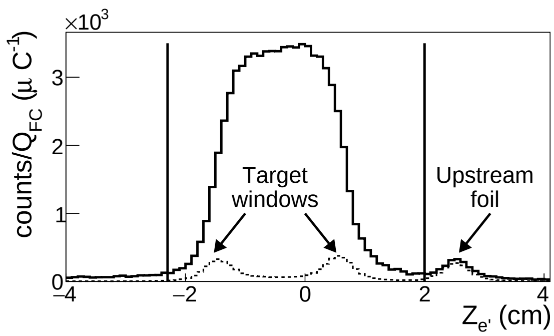

FIG. 2. Distributions of the electron z coordinate at the vertex for full (solid curve) and empty (dashed curve) target runs. Vertical lines show the applied cuts. Both full and empty target distributions are normalized to the corresponding charge accumulated on the Faraday Cup (FC).

The dataset includes either runs with target cell filled out with liquide hydrogen (full target runs) as well as runs with empty target cell (empty target runs). The latter serve to subtract contribution from the non-signal events produced by the scattering of electrons on the target windows. In Fig. 2 distributions of electron coordinate z at the interaction vertex are shown for events from both empty (dashed curve) and full (solid curve) target runs. Both of them are normalized to the corresponded charge accumulated on the Faraday Cup (FC).

The value of the vertex coordinate z was corrected for the effects of beam-offset at the stage of data "cooking". Both distributions in Fig. 2 demonstrate the well-separated peak around $z_{e'} = 2.4$ cm originated from the forward aluminum foil. The distribution of events from the empty target runs also shows two other similar peaks that correspond to the windows of the target cell. In addition to the empty target event subtraction the cut on z coordinate of electron is applied. This cut is shown by two vertical lines in Fig. 2, events outside these lines are excluded from the consideration.

III. EXCLUSIVE REACTION EVENT SELECTION

To identify the reaction $ep \to e'p'\pi^+\pi^-$ the scattered electron and at least two final state hadrons need to be registered, while the four-momentum of the remaning hadron can be restored from the energy-momentum conservation. The first in time particle that gives signals in all four parts of the CLAS detector (DC, CC, TOF, and EC) is chosen as electron candidate for each event. To identify hadrons only signals in DC and TOF are required.

A. Electron identification

To reveal good electrons from the electron candidates electromagnetic calorimeter (EC) and Čerenkov counter (CC) responses need to be analyzed.

According to [2] overall EC resolution, as well as uncertainties in the EC output summing electronics lead to the fluctuation of the EC response near the hardware threshold. Therefore, to select only reliable EC signals the minimal cut on the scattered electron momentum $P_{e'}$ should be applied on the software level. As it is suggested in [2] this cut is chosen to be $P_{e'} > 0.461$ GeV.

Then so-called sampling fraction cut is applied to eliminate in part pion contamination. To develop this cut the fact that electrons and pions have different energy deposition patterns in EC was used. An electron produces an electromagnetic shower, where the deposited energy (E_{tot}) is proportional to its momentum ($P_{e'}$), while a π^- as a minimum ionizing particle loses a constant amount of energy per scintillator (2 MeV/cm) independently of its momentum. Therefore, for electrons the quantity $E_{tot}/P_{e'}$ plotted as a function of $P_{e'}$ should follow the straight line that is parallel to the X-axis and located around the value 1/3 on the Y-axis, since electrons lose 2/3 of their energy in lead sheets (in reality this line has a slight slope).

In Fig. 3 total energy deposited in EC sector one divided by the particle momentum is shown as function of particle momentum for data (top plot) and Monte Carlo (bottom plot). In this figure cut on minimal scattered electron momentum is shown by the vertical line, while two other curves correspond to the sampling fraction cut which was determined via Gaussian fit of different momentum slices of the distribution. The distributions for experimental data and Monte Carlo simulation differ, since the former was plotted for inclusive electrons while the latter for simulated double pion events only. Mean value of the simulated distribution turned out to be slightly below than that of the experimental one due to the inaccuracy in reproduction of electromagnetic showers in the Monte Carlo reconstruction procedure.

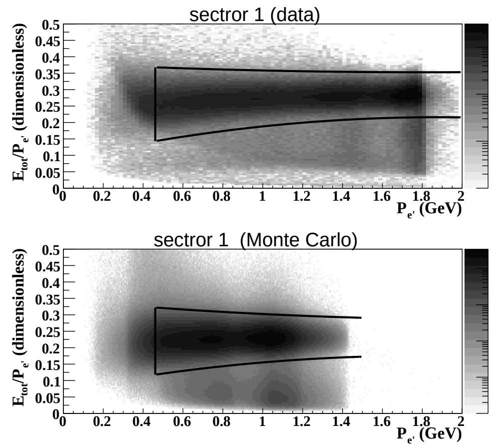

FIG. 3. Sampling fraction distributions for the data (top plot) and Monte Carlo (bottom plot). Both plots correspond to CLAS sector one. Events between the curves are treated as good electron candidates.

To improve the quality of electron candidate selection and π^-/e^- separation a Čerenkov counter is used. It turned out that CC had some inefficient zones and their map could not be reproduced by Monte Carlo. Moreover, as it was shown in [3] there was a contamination in the measured CC spectrum that manifested itself as a so-called single photoelectron peak, which was actually located at a few photoelectrons. The main source of this contamination was found to be the coincidence of accidental PMT noise signal with measured pion track [3].

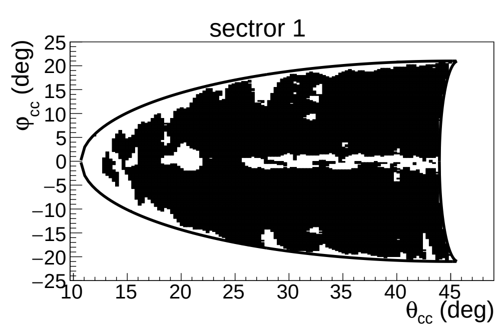

FIG. 4. Zones where CC is efficient enough to accept good electron candidates are shown in black as function of the polar (θ_{cc}) and azimuthal (φ_{cc}) angles in the CC plane for CLAS sector one.

Signals from inefficient zones being depleted of good events have therefore strong relative noise contribution that in turns results in very pronounced single photoelectron peak. This fact was used for geometrical separation of CC regions with reliable detection efficiency from the inefficient areas. In Fig. 4 the distribution of zones with small relative noise contribution are shown in black as a function of polar and azimutal angles defined in the CC plane for CLAS sector one. As it is seen in Fig. 4, there is an inefficient area in the middle of the sector shown in white, that is expected since two CC mirrors are joined there. The curves which are superimosed on the distribution show fiducial cut that is applied in the CC plane. For both experimental data and Monte Carlo simulation only electron candidates originated from black regions within the fiducial cut were analyized.

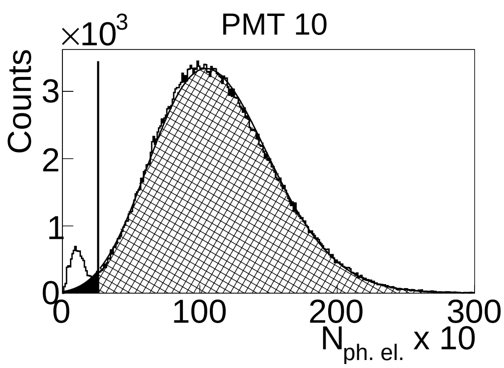

FIG. 5. Number of photoelectrons multiplied by ten for the left side PMT in segment ten of sector one of CC. Black curve shows the fit by function (1). Vertical line shows the applied cut. Regions that are needed to calculate the correction factor are shown in hatch and black.

Although being substentionally reduced after eliminating of signals from inefficient zones, single photoelectron peak is still presented in the experimental CC spectrum as it is shown in Fig. 5 for left PMT in CC segment ten from sector one. This peak in photoelectron distribution is cut out for each PMT in each CC segment individually. The cut position is shown by the vertical line in Fig. 5. Since Monte Carlo does not reproduce photoelectron spectrum well enough, this cut is applied only to the experimental data, and good electrons lost in this way are recovered by the following procedure. The part of the distribution on the right side of the vertical line is fit by the function $y = y(x)$, which is a slightly modified Poisson distribution (1).

$$y = P_1 \left(\frac{P_3^{\frac{x}{P_2}}}{\Gamma\left(\frac{x}{P_2}+1\right)} \right) e^{-P_3}, \tag{1}$$

where P_1, P_2, and P_3 are free fit parameters.

The fitting function is then continued into the region on the left side of the vertical line. In this way the two regions, shown in black and hatch in Fig. 5, are determined. Finally, the correction factors are defined by (2) and applied as a weight for each event which corresponds to the particular PMT.

$$F_{ph.\ el.} = \frac{hatched\ area + black\ area}{hatched\ area} \tag{2}$$

The correction factor $F_{ph.\ el.}$ depends on PMT number and is typically on a level of a few percent.

B. Hadron identification

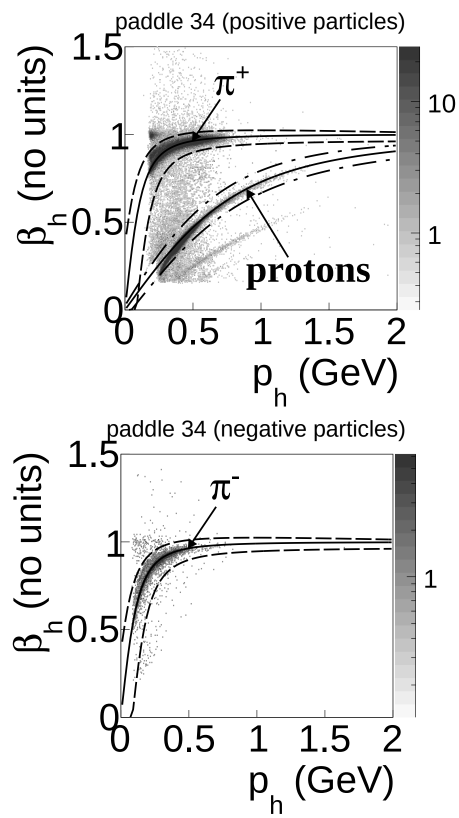

FIG. 6. β_h versus momentum distributions for positively charged hadron candidates (top plot) and negatively charged hadron candidates (bottom plot) for scintillator number 34 in CLAS sector one. Black solid curves correspond to the nominal β_n given by (3). Events between the dashed and dot-dashed curves are selected as π^+ (π^-) and protons, respectively.

The CLAS TOF system provides information, based on which the velocity ($\beta_h = v_h/c$) of the hadron candidate can be determined. The value of the hadron candidate momentum (p_h) is in turn provided by the Drift Chambers. The charged hadron can be identified by the comparison of β_h determined by TOF with β_n given by the following formula (3).

$$\beta_n = \frac{p_h}{\sqrt{p_h^2 + m_h^2}}. \tag{3}$$

In (3) β_n is a so-called nominal value that is calculated using the hadron candidate momentum (p_h) and exact hadron mass assumption m_h.

The experimental event distributions β_h versus p_h were investigated for each TOF paddle in each CLAS sector. An example of these distributions is shown in Fig. 6 for positively charged hadron candidates (top plot) and negatively charged hadron candidates (bottom plot). The example is given for the paddle 34 of the CLAS sector one. In Fig. 6 solid curves are given for β_n calculated according to (3) for the corresponded hadron mass assumptions. The event bands of the pion and proton candidates are clearly seen around the corresponded β_n curves. The dashed curves show the cuts that were used for pions identification, while the dot-dashed curves serve to identify protons.

It was figured out that during the run some TOF paddles worked improperly and therefore their signals were considered to be unreliable and were removed from the consideration either for data and simulation. For all remaining properly worked paddles the hadron identification cuts were chosen to be the same as shown in Fig. 6. They were applied for both experimental and reconstructed Monte Carlo events. It needs to be mentioned that in experimental distributions hadron candidate bands were slightly shifted from the nominal positions for some paddles. To cure that effect a special procedure of correcting the timing information provided by TOF was used.

C. Momentum correction

Due to the slight misalignments in the DC position, small inaccuracies in the description of the torus magnetic field, and other possible reasons the momentum and angle of particles may have some small systematic deviations from the real values. Since the effects are of unknown origin, they cannot be simulated, and therefore a special momentum correction procedure is needed for the experimental data. According to [4] the evidence of the need of such corrections is most directly seen in the dependence of the elastic peak position on the azimutal angle of the scattered electron. It is shown in [4] that the elastic peak position turned out to be shifted from the proton mass value and this shift depends on CLAS sector.

The significance of the named above effect depends on beam energy. It was found that in this dataset with the beam energy 2.039 GeV the small shift ($\sim$ 3 MeV) in elastic peak position took place, while the study [4] demonstrated that in case of 5.754 GeV beam energy this shift reached 20 MeV. Moreover, the study [4] also showed that this effect became discernible only if the particle momentum was sufficiently high (e.g. for pions the correction was needed only if their momentum was higher than 2 GeV). Thus, the small beam energy and the fact that in double pion kinematics hadrons carry only a small portion of the total momentum allow to come to the conclusion that for the presented data the correction is needed only for electrons, while deviation in hadron momenta can be neglected.

The electron momentum corrections used in this analysis had been developed according to [4] for each CLAS sector individually and included electron momentum magnitude correction as well as electron polar angle correction. Although the corrections had been established using elastic events, they were applied for all electron candidates in the dataset. The influence of these corrections on the elastic peak position is shown in Fig. 7. As it is seen from Fig. 7 the corrections bring the position of the elastic peak closer to the proton mass for all six CLAS sectors.

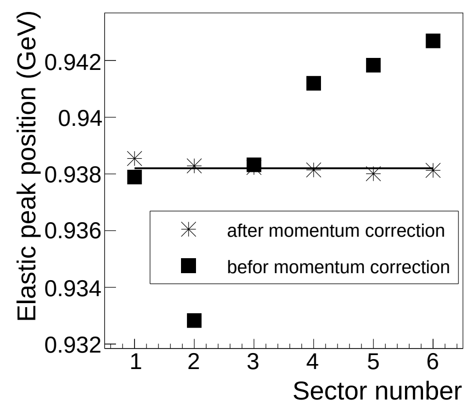

FIG. 7. Elastic peak position for six CLAS sectors before (squares) and after (stars) electron momentum correction. Horizontal line shows the proton mass.

Although the named above effects do not lead to the substential distortions of the hadron momenta, hadrons lose part of their energy due to the interaction with detector and target media, hence their measured momentum appears to be lower than the ones the hadrons actually had right after the interaction. Simulation of the CLAS detector correctly propagates hadrons through the media and therefore the effect of the hadron energy loss being included into the efficiency do not impact the extracted cross section value. However in order to avoid shifts in distributions of some kinematical quantities (e.g. missing masses) from their expected values the energy loss correction was applied to the proton momentum magnitude (both experimental and reconstructed Monte Carlo), since the low-energetic protons are mostly affected by this effect.

D. Other cuts

1. Fiducial cuts

An active detection solid angle of the CLAS detector was smaller than 4π [1]. This happened because the areas covered by the torus field coils were not equipped with any detection system thus forming gaps in the azimutal angle coverage. In addition to that the detection area was also limited in polar angle from 8^o up to 45^o for electrons and up to 140^o for other charged particles. Moreover, the edges of the detection area do not provide a safe region for particle registration, being affected by rescattering from the coils, field distortions, and similar effects. Therefore it is now a common practice to consider only those particles that were registered in “safe” areas inside specific fiducial cuts, i.e. cuts on the kinematic variables (momentum and angles) of each particle. These cuts are applied for both real events and Monte Carlo reconstructed events.

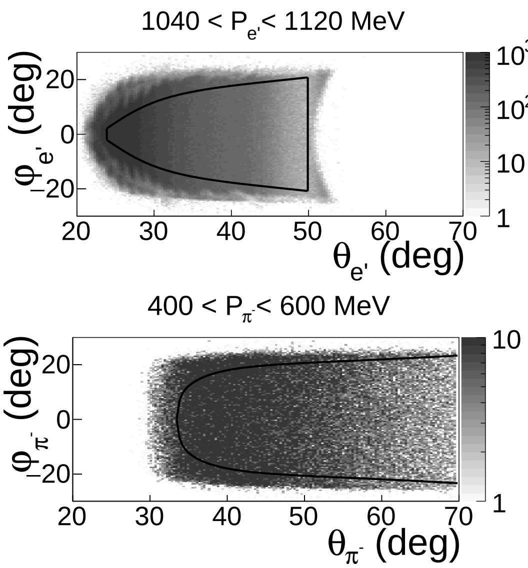

FIG. 8. Fiducial cuts for negatively charged particles. Top plot shows φ versus θ destribution for electrons, while bottom plot corresponds to that for π^-. Both distributions are given for CLAS sector one and corresponding range over momentum specified in the plots. Solid black curves stand for the applied fiducial cuts.

The “e1e” run period had the normal direction of the torus magnetic field that forces negatively charged particles to be inbending. For that type of particles sector independent, symmetrical, and momentum dependent cuts are applied. Fig. 8 shows the number of registered electrons (top plot) and π^- (bottom plot) as a function of angles φ and θ for CLAS sector one and one slice over corresponded particle momentum. The angles φ and θ are taken at the interaction vertex. Solid black curves correspond to the applied fiducial cuts. These cuts isolate the regions with relatively stable yield of events along azimutal angle.

For positively charged particles, which were outbending in “e1e” run period, momentum independent and slightly asymmetrical fiducial cuts are the best choice. These cuts were established in the same way as for negatively charged particles, i.e. by selecting the areas with relatively stable event yield along the φ angle. In Fig. 9 these cuts shown by black curves are superimposed on φ versus θ event distributions for protons (top plot) and π^+ (bottom plot). All angles are given at the interaction vertex.

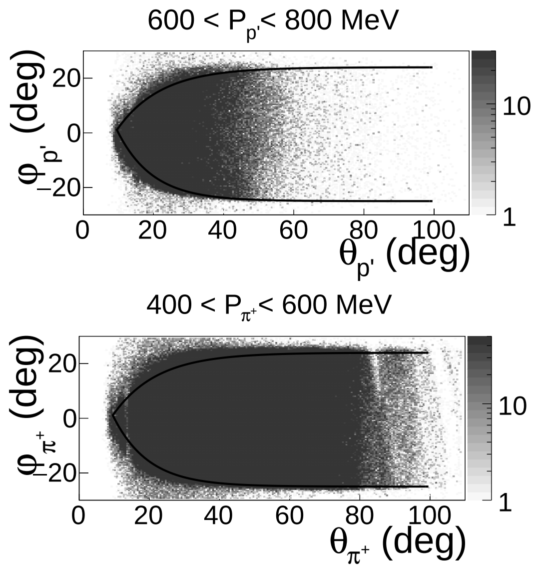

FIG. 9. Fiducial cuts for positively charged particles. Top plot shows φ versus θ destribution for protons, while bottom plot corresponds to that for π^+. Both distributions are given for CLAS sector one and corresponding range over momentum specified in the plots. Solid black curves stand for the applied fiducial cuts.

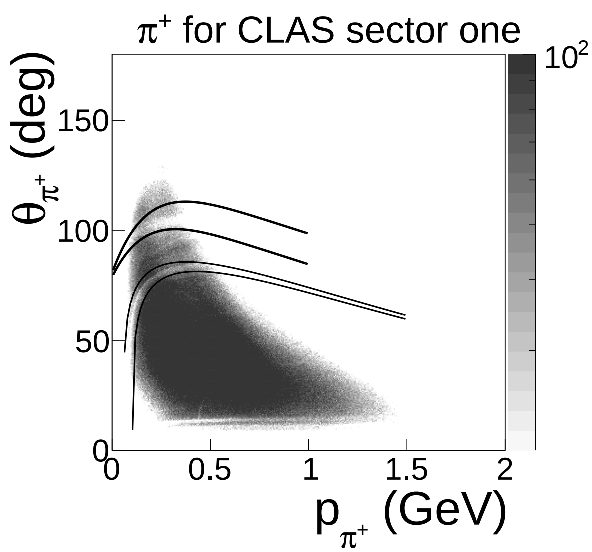

FIG. 10. θ versus momentum distribution for π^+ in CLAS sector one. The angle θ is taken at the point of interaction. Black curves show the applied fiducial cuts.

Some additional inefficient areas not related to the CLAS geometrical acceptance were revealed in this dataset. These areas are typicaly caused by drift chamber and time-of-flight system inefficiencies (dead wires or PMTs). To exclude them from the consederation additional fiducial cuts on θ versus momentum distributions were applied, where θ was taken at the point of interaction. These cuts are individual for each CLAS sector. An eaxample of the cut for π^+ in CLAS sector one is shown by black curves in Fig. 10.

2. *Quality check cut*

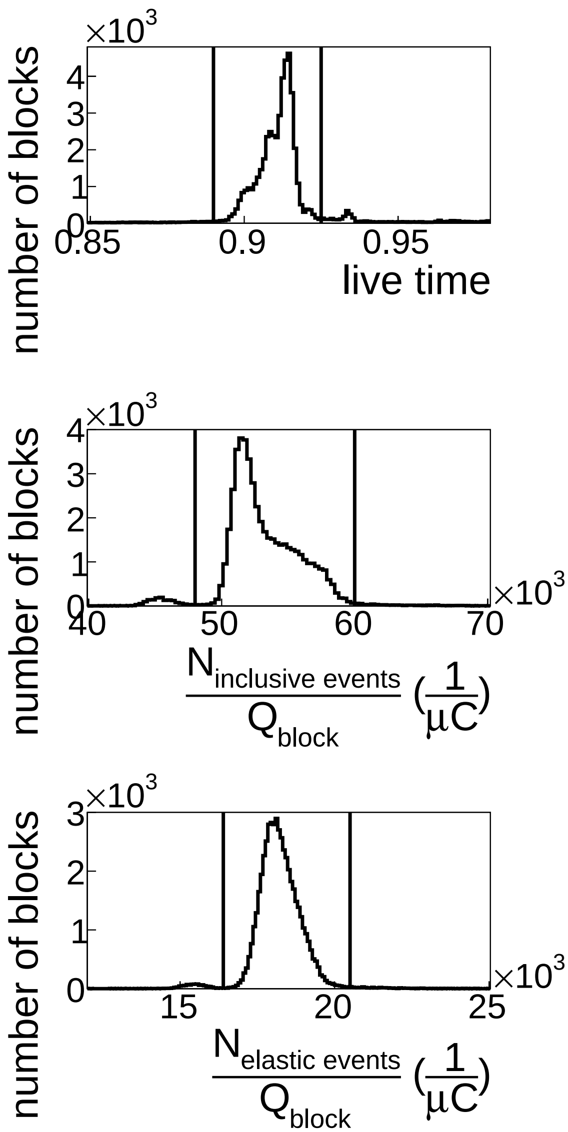

FIG. 11. Quality check plots. The number of blocks as functions of DAQ live time (top plot), and yields of elastic (middle plot) and inclusive events (bottom plot) normalized to FC charge are shown. The vertical black lines stand for the applied cuts.

During the quite long experimental run the variations of the experimental conditions, like the target density deviation or improper operation of some parts of the detector, can lead to fluctuations in event yields. Only parts of the run with relatively stable event rates should be considered. Therefore cuts on DAQ live time and number of events per Faraday cup (FC) charge need to be established.

FC charge updated with a given frequency, hence the whole run time could be divided into so-called blocks. Each block corresponded to the portion of time between two FC charge readouts. The block number ranged from one to the certain maximum number over the run time.

DAQ live time is the portion of time within the block during which the DAQ was able to accumulate events. A significant deviation of the live time from the average value indicates event rate alteration.

In Fig. 11 the number of blocks is shown as functions of DAQ live time and yields of elastic and inclusive events normalized to FC charge (from top to bottom). The blocks between the vertical black lines in Fig. 11 were taken into the consideration.

3. *Exclusivity cut*

For picking out the reaction $ep \to e'p'\pi^+\pi^-$ it is sufficient to register at least two final hadrons along with the scattered electron. The four-momentum of the remaining unregistered hadron can be restored using the energy-momentum conservation (so-called "the missing mass technique"). Thus one can distinguish between four so-called "topologies" depending on the specific combination of registered final hadrons.

1. $ep \to e'p'\pi^+X$
2. $ep \to e'p'\pi^-X$
3. $ep \to e'\pi^+\pi^-X$
4. $ep \to e'p\pi^+\pi^-X$

Due to the experimental conditions the topology with π^- missing contains about 70% of total statistics, leaving each topology that requires π^- registration to acquire only about 10% of that. This uneven distribution of the statistics between the topologies originates from the fact that CLAS does not cover the polar angle range $0^\circ < \theta_{lab} < 8^\circ$ [1]. The presence of this forward acceptance hole does not affect much the registration of the positive particles (p and π^+), since their trajectories are bent by the magnetic field away from the hole, whereas the negative particles (e and π^-) are inbending that means that their trajectories are bent in the forward direction. Electrons being very light and rapid undergo small track curvature and therefore the presence of the forward hole leads for them only to the constraint on the minimal achivable Q^2. However, for the negative pions the situation is dramatic: being heavier and slower they are bent dominantly into the forward detector hole and, therefore, most of them can not be registered. This leads to the fact that the π^- missing topology contains the dominant part of the statistics.

The topologies are defined in a way they do not overlap. For example the topology $ep \to e'p'\pi^+X$ requires the presence of e', p' and π^+ candidates and absence of π^- candidates, avoiding in this way double counting. In most of the CLAS papers on double pion electroproduction [5–7] only topologies one and four are used. However here all four topologies are used in combination. This approach allows not only to slightly increase the statistics (about 20%) but also to populate with events broader part of the reaction phase-space, since the topologies have non-identical kinematical coverage.

For the case when one of the final hadrons is not registered, the missing mass M_X for the reaction $ep \to e'h_1h_2X$ is determined by

$$M_X^2 = (P_e + P_p - P_{e'} - P_{h_1} - P_{h_2})^2, \qquad (4)$$

where P_{h_1} and P_{h_2} are the four-momenta of the registered final hadrons, P_e and P_p - four-momenta of initial electron and proton, and $P_{e'}$ - four-momentum of the scattered electron.

While for the topology four, the missing mass M_X for the reaction $ep \to e'p'\pi^+\pi^-X$ is given by

$$M_X^2 = (P_e + P_p - P_{e'} - P_{\pi^+} - P_{\pi^-} - P_{p'})^2, \qquad (5)$$

where P_e, P_p, $P_{e'}$, P_{π^+}, P_{π^-}, and $P_{p'}$ are the four-momenta of the initial and final particles.

Distributions of the missing mass squared for various topologies are shown in Fig. 12 for $1.675 < W < 1.7$ GeV in comparison with Monte Carlo. Stars show the experimental data, while curves stand for the simulation. The plots in Fig. 12 stand for the topologies one to four from top to bottom. The arrows show the applied exclusivity cuts. Each distribution in Fig. 12 is normalized to the corresponded integral.

The Fig. 12 demonstrates a good agreement between the experemental and Monte Carlo distributions, since the simulation included both radiative effects and a background from other exclusive channels. The former were taken into account according to inclusive approach [8]. The main source of the exclusive background was found to be the reaction $ep \to e'p'\pi^+\pi^-\pi^0$. The events for that reaction were combined with the double-pion events considering the ratio of three-pion/double-pion cross sections taken from [9]. The simulation of double-pion events was carried out based on the JM05 version of double-pion production model [10–12], while for the 3π events a phase space distribution was assumed.

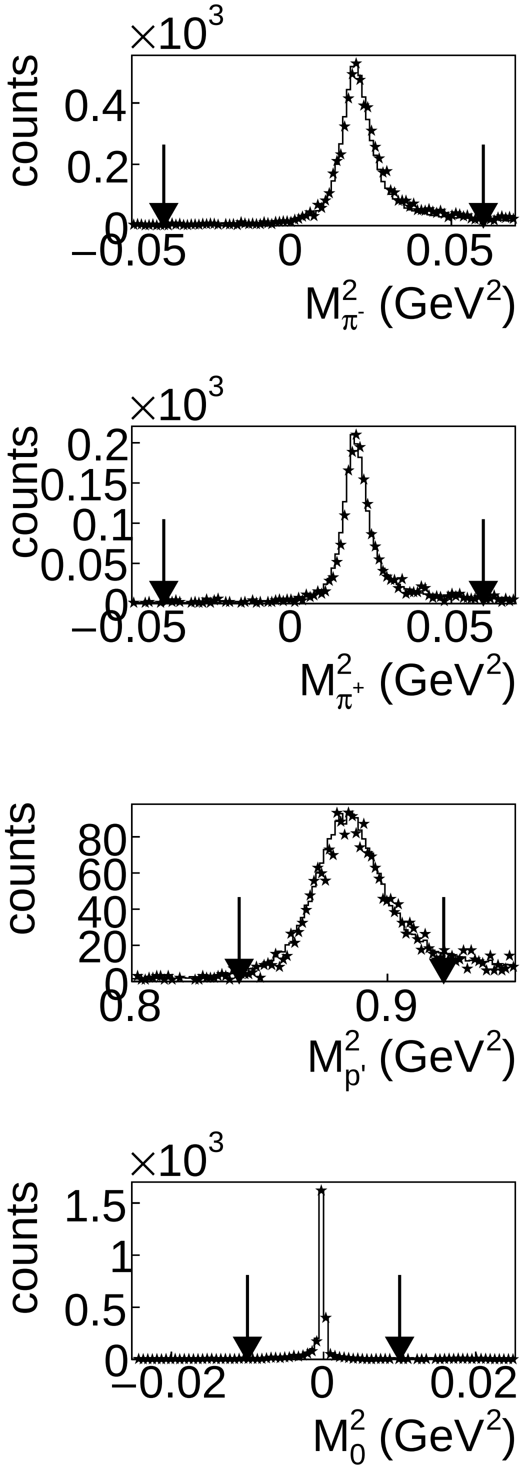

FIG. 12. Missing mass squared distributions for various topologies for $1.675 < W < 1.7$ GeV in comparison with Monte Carlo. Stars show the experimental data, while curves stand for the simulation. The plots stand for the topologies one to four from top to bottom. The arrows show the applied exclusivity cuts. Each distribution is normalized to the corresponded integral.

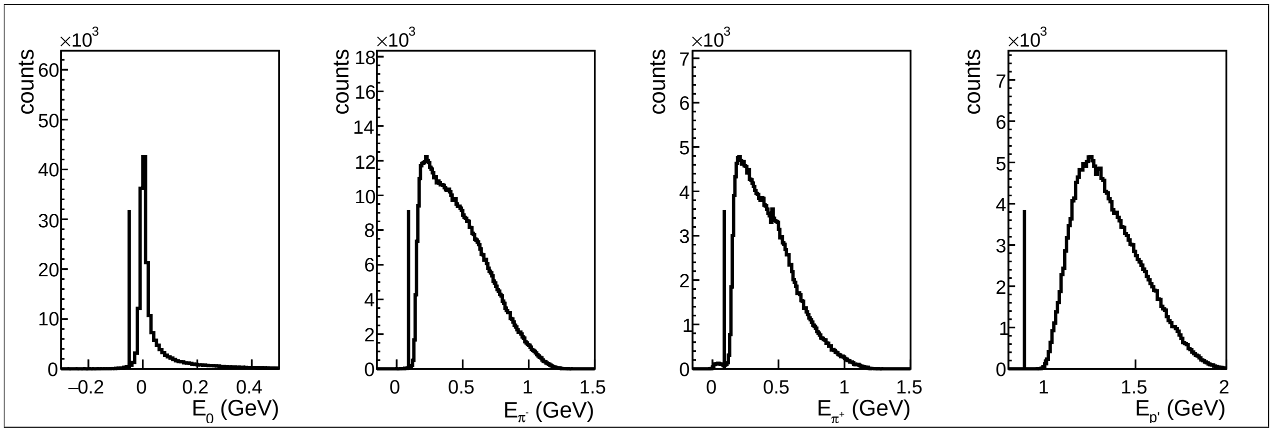

FIG. 13. Missing energy distributions for various topologies. Left plot corresponds to the topology where all final hadrons are registered and other plots correspond to the topologies with missing π^-, π^+, or proton, respectively. Vertecal lines show the applied cut. All events on the right side of the lines are selected as good for analysis.

IV. CROSS SECTION CALCULATION

A. Kinematical variables

Once the described above selection of the double-pion events is carried out, the four-momenta of the final hadrons are known (either registered or calculated as missing) and defined in the lab frame that corresponds to the system, where the target proton is at rest and the axis orientation is the following: z_{lab} – along the beam, y_{lab} – up, and x_{lab} – along $[\vec{y}_{lab} \times \vec{z}_{lab}]$.

The cross sections are obtained in the single-photon exchange approximation in the center of mass frame of the *virtual photon – initial proton* system (c.m.s.). The c.m.s. is uniquely defined as the system, where the initial proton and the vitrual photon move towards each other with the axis z_{cms} along the photon and the net momentum equal to zero. The axis x_{cms} is situated in the elctron scattering plane, while y_{cms} is along $[\vec{z}_{lab} \times \vec{x}_{lab}]$.

To transform lab system to the c.m.s. two rotations and one boost should be perfomed [13]. The first rotation situates the axis x in the electron scattering plane. The second one alignes the axis z with the virtual photon direction. Then the boost along z is performed.

To calculate the kinematical variables that describe the final hadron state the four-momenta of the final hadrons in the c.m.s. must be used. The three-body final state is unambiguously determined by five kinematical variables. Beside that the variables W and Q^2 are needed to describe the initial state.

There are many ways to choose the five variables for the final hadron state description. Here the following generalized set of variables is used [13, 14].

- invariant mass of the first pair of the hadrons $M_{h_1h_2}$;
- invariant mass of the second pair of the hadrons $M_{h_2h_3}$;
- the first hadron solid angle $\Omega = (\theta_{h_1}, \varphi_{h_1})$;
- the angle α_{h_1} between two planes: one of them is defined by the three-momenta of the virtual photon (or initial proton) and the first final hadron, the second plane is defined by the three-momenta of all final hadrons (see Appendix VI).

The cross sections were obtained in three sets of variables depending on various assignments for the first, second, and third final hadrons:

1. ***first* $-\, p'$, *second* $-\, \pi^+$, *third* $-\, \pi^-$**:
   $M_{p'\pi^+}$, $M_{\pi^+\pi^-}$, $\theta_{p'}$, $\varphi_{p'}$, $\alpha_{p'}$ (or $\alpha_{(p,p')(\pi^+,\pi^-)}$);
2. ***first* $-\, \pi^-$, *second* $-\, \pi^+$, *third* $-\, p'$**:
   $M_{\pi^-\pi^+}$, $M_{\pi^+p'}$, θ_{π^-}, φ_{π^-}, α_{π^-} (or $\alpha_{(p\pi^-)(p'\pi^+)}$) and
3. ***first* $-\, \pi^+$, *second* $-\, \pi^-$, *third* $-\, p'$**:
   $M_{\pi^+\pi^-}$, $M_{\pi^-p'}$, θ_{π^+}, φ_{π^+}, α_{π^+} (or $\alpha_{(p\pi^+)(p'\pi^-)}$).

B. Binning and kinematical coverage

The kinematical coverage in the initial state variables is shown by the Q^2 versus W distribution in Fig. 14. The color code of the distribution represents the number of exclusive double-pion events left after the cuts and corrections described above. The white boundary limits the kinematical area, where the double-pion cross sections were extracted. The black grid demonstates the chosen binning in the initial state variables.

The binning in the final hadron variables is listed in Tab. I. It is chosen to maintain the resonable statistical uncertanties in all W and Q^2 bins. The binning choice also takes into account the fact that the cross section decreases as W goes to the double-pion production threshold at ≈ 1.22 GeV.

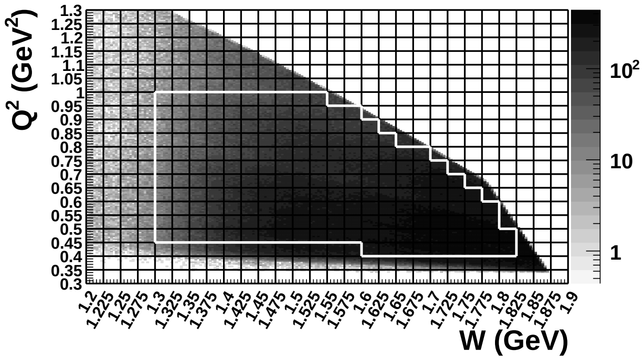

FIG. 14. Q^2 versus W distribution populated with selected double-pion events. The cross section is calculated in 2D cells within the white boundaries.

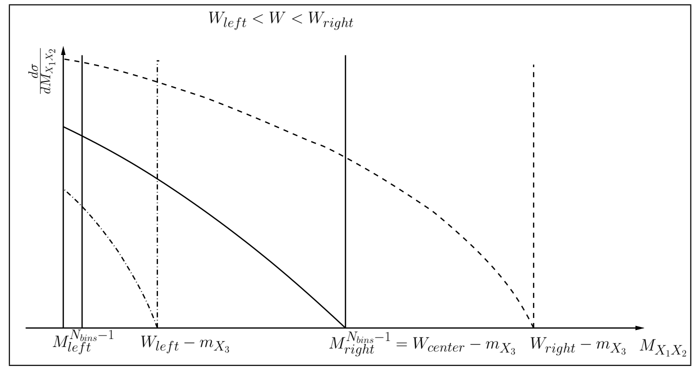

FIG. 15. Schematic representation of the cross sections in the next to last bin in the invariant mass ($M_{X_1X_2}$) for various W. Dot-dashed and dashed vertical lines show maximal invariant mass values that can be reached with W_{left} and W_{right}, respectively, while vertical black lines show the boundaries of the next to last bin in the invariant mass.

It also needs to be mentioned that the right boundary of the invariant mass distributions depends on the value of W, while the left does not (see Eq. 6).

$$\begin{aligned} M_{left} &= m_{h_1} + m_{h_2} \\ M_{right} &= W - m_{h_3}, \end{aligned} \tag{6}$$

where M_{left} and M_{right} are the left and right boundaries of the invariant mass distribution. m_{h_1}, m_{h_2}, and m_{h_3} are the masses of final hadrons. The value of W is taken in the center of the corresponding W bin.

It leads to the fact that invariant mass distributions are broader at high W and hence a more detailed binning in that area is necessary (see Tab. I).

Variable / W range	Number of bins in invariant mass M	Number of bins in polar angle θ	Number of bins in azimuthal angle φ	Number of bins in angle between two planes α
1.3 - 1.35 GeV	8	6	5	5
1.35 - 1.4 GeV	10	8	5	6
1.4 - 1.45 GeV	12	10	5	8
> 1.45 GeV	12	10	8	8

TABLE I: Number of bins for the given final hadron variables.

Since M_{right} is calculated using the value of W in the center of the corresponding W bin some events are located beyond the boundaries determined by Eq. 6. Therefore the binning in invariant mass needs special attention. Firstly the bin width is determined as:

$$width = \frac{M_{right} - M_{left}}{N_{bins} - 1}, \tag{7}$$

where N_{bins} is the number of bins.

Then the invariant mass distributions are obtained with the number of bins N_{bins} and the left boundary of the first bin is set to M_{left}. That makes the last bin to be situated completely out of the boundaries given by Eq. 6. Although the cross section obtained in this bin is very small, it is kept in analysis since its content contributes to all other cross sections obtained by integration over the corresponding invariant mass. After the binning corrections this effect is assumed to be taken into account and this last bin in invariant masses is neglected.

It needs to be mentioned that the next to last bin in each invariant mass also needs special attention. Since the cross sections are obtained in W bin, the right boundaries of the invariant mass distributions vary for different events within this bin. In Fig. 15 the distribution of the invariant mass of the two final hadrons X_1 and X_2 is schematically illustrated for the bin in W from W_{left} to W_{right}. The green and red vertical dashed lines show maximal invariant mass values that can be reached with W_{left} and W_{right}, respectively, while the vertical black dashed lines show the boundaries of the next to last bin in the invariant mass. As it is seen in Fig. 15 events in this bin with W between W_{left} and $M_{right}^{N_{bins}-1} = W_{center} - m_{X_3}$ are distributed in the range in $M_{X_1X_2}$, which is less than invariant mass bin width defined by Eq. 7.

Correction for this effect is made using the new double pion event generator [15]. For that purpose for each invariant mass two one-dimensional distributions are generated in each W bin. The first one mimics the data distribution, for which all events in the next to last bin are divided by the same bin width defined by Eq. 7. For the second one events with W between W_{center} and W_{right} are divided by the same bin width defined by Eq. 7, while events with W between W_{left} and W_{center} are divided by the bin width that is individual for each event and equal to $W - m_{X_3} - M_{left}^{N_{bins}-1}$. The correction factor, by which obtained single-differential cross sections in the next to last bin should be multiplied, is defined as the ratio of the second distribution over the first one. This factor typically varies from 5% to 10%.

Q2 vs W plot + table with binning. Mass border points corrections.

C. Cross section formula

So electron scattering cross section for double-pion electroproduction should be seven-differential: five variables for the final hadrons plus W and Q^2 that are determined by the scattered electron kinematics. Such seven-differential cross sections may be written as $\frac{d^7\sigma}{dW dQ^2 d^5\tau}$, where $d^5\tau$ is five-dimensional phase space differential.

D. Radiative correction

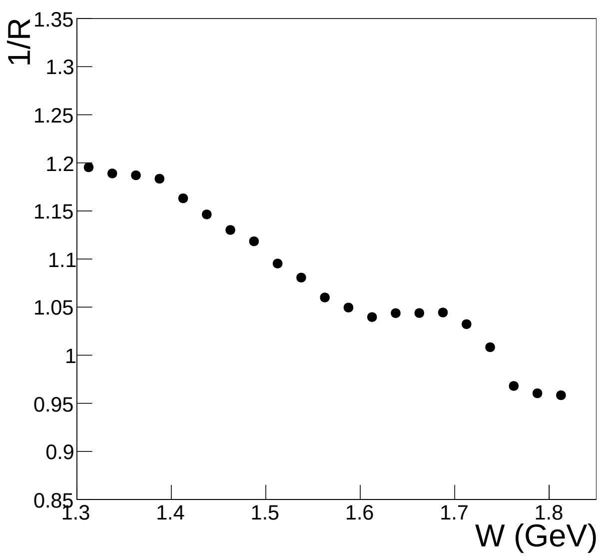

FIG. 16. One over radiative correction factor (see formula **??**) as function of W averaged over all Q^2 bins.

E. Efficiency evaluation

The simulation is carried out with the JM05 version of double-pion production model [10–12].

Include how empty cells were filled out + combinations of various topologies. 1D plots with comparison of the cross section with and without empty cells filled out. Describe efficiency error cut.

F. Systematic errors

Discription + ref to the plots from Section "Comparison with the model".

V. COMPARISON WITH THE MODEL

1D plot for one Q2 & W bin + int plots with sys errors.

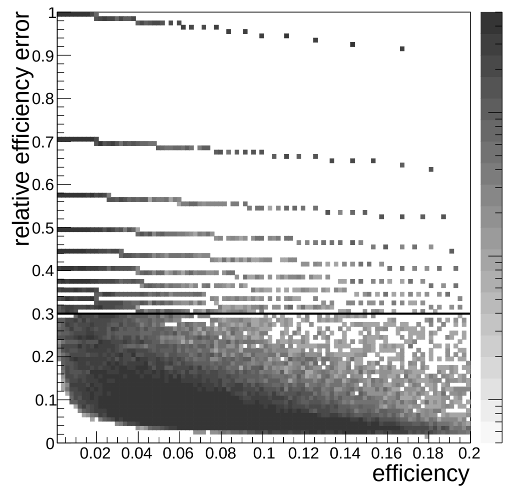

FIG. 17. Relative efficiency error versus efficiency for one particular bin in W and Q^2 (W = 1.6375 GeV, Q^2 = 0.525 GeV^2). Color code shows the number of five-dimensional cells.

VI. CONCLUSIONS

Comparison with previously avaliable data.

ACKNOWLEDGMENTS

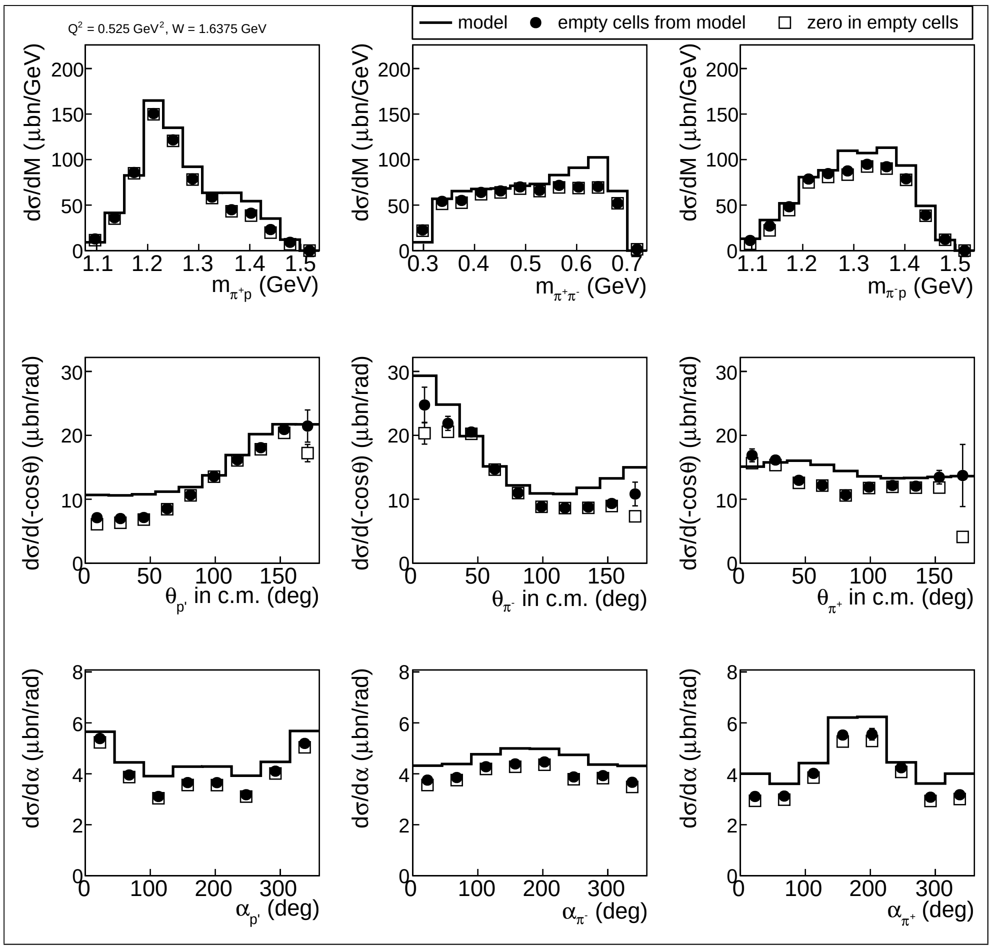

FIG. 18. Triangles are for the cross sections with unfilled empty cells and the circles are for the cross sections with filled empty cells. Curves show the cross sections that are used for the purpose of filling empty cells. All distributions are given for one particular bin in W and Q^2 ($W = 1.6375$ GeV, $Q^2 = 0.525$ GeV^2).

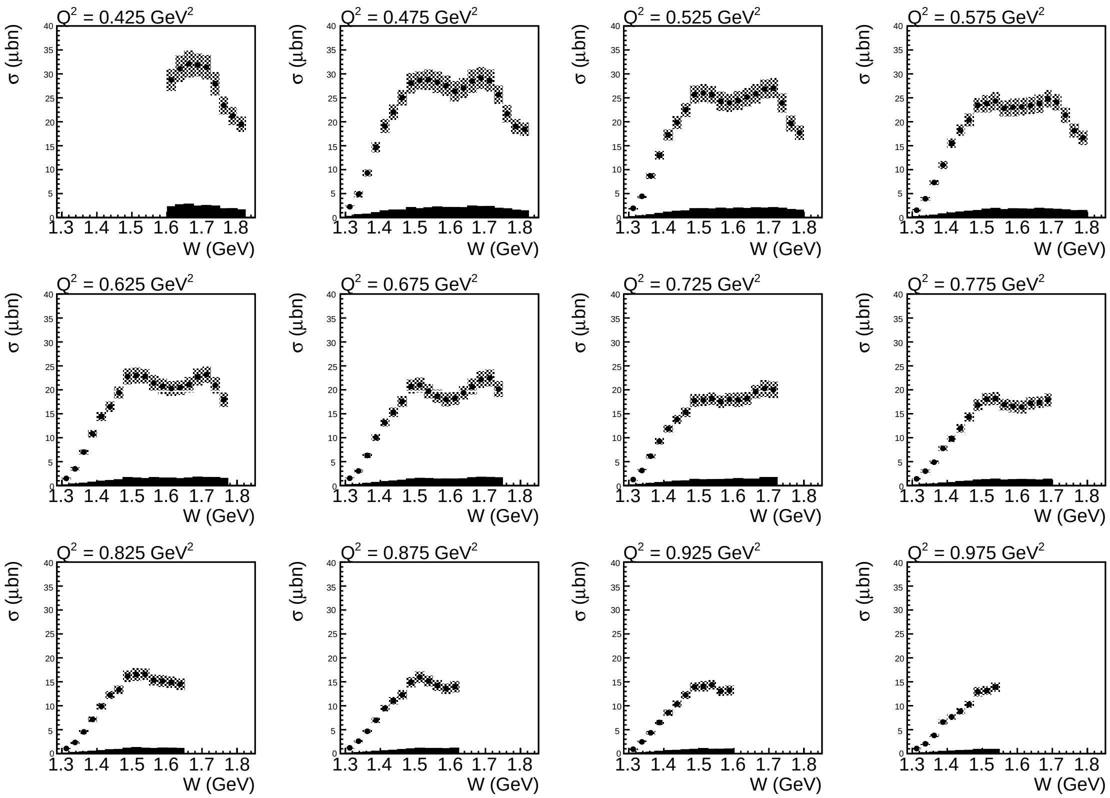

FIG. 19. Systematical errors of the integrated cross sections. The plots show W dependencies of the integrated cross section in various bins in Q^2. The systematical uncertanties are shown as the black bands at the bottom of each plot. The total cross section uncertainty (both statistical and systematical ones summed up in quadrature) is shown by the hatched black areas.

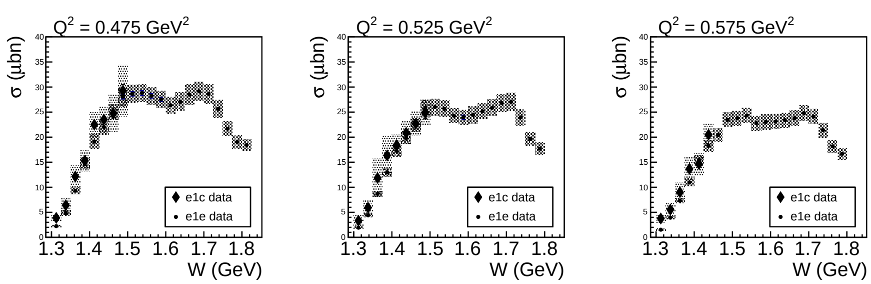

FIG. 20. W dependencies of the obtained in this analysis cross sections (e1e dataset) in comparison with the cross sections from [7] (e1c dataset) for three bins in Q^2. Hatched areas correspond to the total uncertainties (sistematical and statistical).

APPENDIX A: THE DEFINITION OF THE ANGLE α

The calculation of the angle α_{π^-} from the second set of hadron variables mentioned in Sec. IV A is given below. The angles $\alpha_{p'}$ and α_{π^+} from two other sets are calculated analogously [13].

The angle α_{π^-} is the angle between two planes A and B (see Fig. 21). The plane A is defined by the initial proton and π^-, while the plane B is defined by the momenta of all final hadrons. Note that the three-momenta of π^+, π^-, p' are in the same plane, since in c.m.s. their total three-momentum has to be equal to zero.

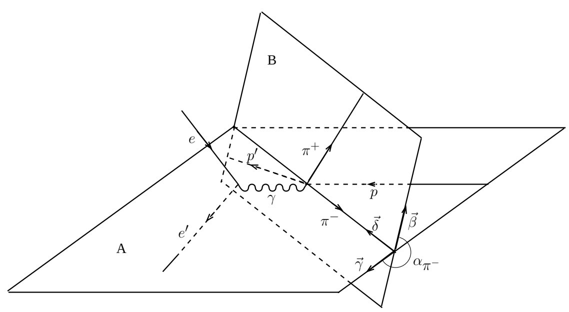

FIG. 21. Definition of the angle α_{π^-} between two planes: the plane B is defined by the three-momenta of all final hadrons, while the plane A defined by the three-momenta of π^- and initial proton. The definitions of auxiliary vectors $\vec{\beta}$, $\vec{\gamma}$, $\vec{\delta}$ are given in the text.

To calculate the angle α_{π^-} firstly two auxiliary vectors $\vec{\gamma}$ and $\vec{\beta}$ should be determined. The vector $\vec{\gamma}$ is the unit vector perpendicular to the three-momentum $\vec{P}_{\pi^-}$, directed toward the vector $(-\vec{n}_z)$ and situated in the plane A. $\vec{n}_z$ is the unit vector directed along z-axis. The vector $\vec{\beta}$ is the unit vector perpendicular to the three-momentum of π^-, directed toward the three-momentum of π^+ and situated in the plane B. Then the angle between two planes α_{π^-} is

$$\alpha_{\pi^-} = acos(\vec{\gamma} \cdot \vec{\beta}), \tag{8}$$

where *acos* is a function that runs between zero and π, while the angle α_{π^-} may vary between zero and 2π. To determine the α angle in the range between π and 2π the relative direction between the π^- three-momentum and the vector product $\vec{\delta} = [\vec{\gamma} \times \vec{\beta}]$ of the auxiliary vectors $\vec{\gamma}$ and $\vec{\beta}$ should be taken into account. If the vector $\vec{\delta}$ is colinear to the three-momentum of π^-, the angle α_{π^-} is determined by (8), and in a case of anti-collinearity by

$$\alpha_{\pi^-} = 2\pi - acos(\vec{\gamma} \cdot \vec{\beta}). \tag{9}$$

The defined above vector $\vec{\gamma}$ can be expressed as

$$\begin{gathered} \vec{\gamma} = a_\alpha(-\vec{n}_z) + b_\alpha \vec{n}_{P_{\pi^-}} \quad \text{with} \\ a_\alpha = \sqrt{\frac{1}{1-(\vec{n}_{P_{\pi^-}} \cdot (-\vec{n}_z))^2}} \quad \text{and} \\ b_\alpha = -(\vec{n}_{P_{\pi^-}} \cdot (-\vec{n}_z)) a_\alpha \ , \end{gathered} \tag{10}$$

where $\vec{n}_{P_{\pi^-}}$ is the unit vector directed along the three-momentum of π^- (see Fig. 21).

Taking the scalar products $(\vec{\gamma} \cdot \vec{n}_{P_{\pi^-}})$ and $(\vec{\gamma} \cdot \vec{\gamma})$, it is straightforward to verify, that $\vec{\gamma}$ is the unit vector perpendicular to the three-momentum of π^-.

The vector $\vec{\beta}$ can be obtained as

$$\begin{gathered} \vec{\beta} = a_\beta \vec{n}_{P_{\pi^+}} + b_\beta \vec{n}_{P_{\pi^-}} \quad \text{with} \\ a_\beta = \sqrt{\frac{1}{1-(\vec{n}_{P_{\pi^+}} \cdot \vec{n}_{P_{\pi^-}})^2}} \quad \text{and} \\ b_\beta = -(\vec{n}_{P_{\pi^+}} \cdot \vec{n}_{P_{\pi^-}}) a_\beta \ , \end{gathered} \tag{11}$$

where $\vec{n}_{P_{\pi^+}}$ is the unit vector directed along the three-momentum of π^+.

Again taking the scalar products $(\vec{\beta} \cdot \vec{n}_{P_{\pi^-}})$ and $(\vec{\beta} \cdot \vec{\beta})$, it is straightforward to see, that $\vec{\beta}$ is the unit vector perpendicular to the three-momentum of π^-.

Further detailed information about kinematic of the reactions with three-particle final states can be found here [14].

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