

Consistent threshold π^0 electro-production at $Q^2 = 0.05, 0.10$, and $0.15 \text{ GeV}^2/c^2$

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Abstract

New, accurate data are presented on the near threshold $p(e, e'p)\pi^0$ reaction in the range of four-momentum transfers between $Q^2=0.05$ and $0.15 \text{ GeV}^2/c^2$. The data were taken with the spectrometer setup of the A1 Collaboration at the Mainz Microtron MAMI. The complete center of mass solid angle was covered up to a center of mass energy of 4 MeV above threshold. These results supersede the previous analysis based on three separate experiments, and are compared with calculations in Heavy Baryon Chiral Perturbation Theory and with phenomenological models.

Keywords: Pion electro-production, Threshold production, Chiral Perturbation Theory

1. Introduction

Threshold electromagnetic pion production is a fundamental process since the pion is a Nambu-Goldstone boson due to the spontaneously broken chiral symmetry of QCD [1]. Calculations at low energies which are good approximations to QCD are carried out by an effective field theory called Chiral Perturbation Theory (ChPT) [2, 3, 4], and are generally in good agreement with experiment. The systematic application of Heavy Baryon Chiral Perturbation Theory (HBChPT) [5, 6] has been generally successful in describing $\pi - N$ scattering and electromagnetic pion production from the nucleon [7].

In recent years there has been a considerable experimental effort to test this theoretical approach. The latest published and most accurate of a series of experiments of photo-pion production experiments which was performed at Mainz [8] was in good agreement with the HBChPT [9]¹. These experimental tests can also be extended to four-momentum transfer $Q^2 > 0$ via pion electro-production. This adds another small scale whose convergence properties are not presently known.

The first threshold neutral pion electro-production experiments were performed at NIKHEF [11, 12] and MAMI [13] at $Q^2 = 0.10 \text{ GeV}^2/c^2 \approx 5m_\pi^2$ and the results were in reasonable agreement with the calculations [14]. A second measurement at $Q^2 = 0.05 \text{ GeV}^2/c^2$ at Mainz [15] indicated a surprisingly rapid Q^2 variation which was not in agreement with the calculations [14]. However, this conclusion was problematic for three

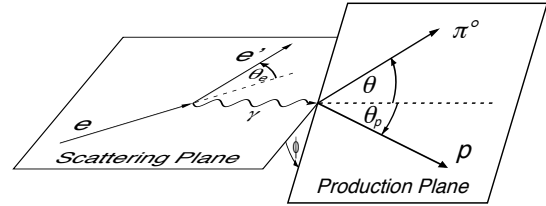


Figure 1: Definition of angles.

reasons. First, the observed variation was based on three independent experiments [8, 13, 15]. Second, the data analysis programs that were used have been subsequently revised. Finally, a subsequent, independent experiment performed at Mainz at $Q^2 = 0.05 \text{ GeV}^2/c^2$ was extended to higher energies above threshold ($\Delta W < 40 \text{ MeV}$ at a center of mass pion production angle of 90°) [16]. This most recent experiment disagreed with the previous values [15] in the near threshold region, and was not in agreement with the calculations based on HBChPT [14]. It was also not in agreement with the phenomenological MAID model [17], but was in generally good agreement with the DMT model which uses a chiral Lagrangian [18, 19].

To resolve the experimental uncertainties of the previous experiments, a new measurement of the variation of the π^0 electroproduction cross section was performed in the near threshold region ($\Delta W \leq 5 \text{ MeV}$) for $Q^2 = 0.05, 0.10, 0.15 \text{ GeV}^2/c^2$. These new results are the subject of this article and will be compared to model [17, 18, 19] and to HBChPT [14] calculations. We point out that since several of the low energy constants of HBChPT have been fitted to the older data with significant experimental errors, these calculations should not be considered

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¹A more recent accurate measurement at Mainz has been performed and is in the final stages of data analysis [10]

as prediction and will have to be re-adjusted to take this into account. For this reason these calculations are not projected to $Q^2 > 0.10 \text{ GeV}^2/c^2$.

2. Formalism

In the one photon exchange approximation, the electro-production cross section of pseudo-scalar mesons can be written as (see e.g. [20])

$$\begin{aligned} \frac{d^5\sigma(\theta, \phi)}{dE_e d^2\Omega_e d^2\Omega} &= \Gamma(\sigma_T(\theta) + \epsilon \sigma_L(\theta) \\ &+ \epsilon \sigma_{TT}(\theta) \cos 2\phi \\ &+ \sqrt{2\epsilon(1+\epsilon)} \sigma_{LT}(\theta) \cos \phi), \end{aligned} \quad (1)$$

with the virtual photon flux

$$\Gamma = \frac{\alpha}{2\pi^2} \frac{E'}{E} \frac{k_\gamma}{(-q^2)} \frac{1}{1-\epsilon} \quad (2)$$

and the transverse photon polarization

$$\epsilon = \left(1 - \frac{2(\omega^2 - q^2)}{q^2} \tan^2 \frac{\theta_e}{2}\right)^{-1}. \quad (3)$$

The energy of the initial and scattered electron in the laboratory frame is given by E and E' , the photon equivalent energy is defined as $k_\gamma = (W^2 - m_p^2)/(2m_p)$. The photon four-momentum transfer is $q^2 = -Q^2 = \omega^2 - \vec{q}^2$, with the photon laboratory energy and momentum ω and \vec{q} . Figure 1 shows the definition of the pion production angles θ and ϕ , which are given in the proton-photon center of mass system (CMS) in the following. In addition, the cross sections also depend on the center of mass energy W (or $\Delta W = W - m_{\pi^0} - m_p$).

Without variation of the photon polarization ϵ , $\sigma_T(\theta)$ and $\sigma_L(\theta)$ cannot be separated and only the unseparated cross section

$$\sigma_0(\theta) = \sigma_T(\theta) + \epsilon \sigma_L(\theta) \quad (4)$$

can be extracted.

3. Experiment

The experiment was performed at the spectrometer setup of the A1 collaboration at MAMI (see Ref. [21] for a detailed description of the setup). The MAMI accelerator delivered an unpolarized electron beam with an energy of 855 MeV and a beam current of up to $9 \mu\text{A}$ to an oblong liquid Hydrogen target cell with a width of 1 cm and a length of 5 cm. The beam was rastered across the target cell to avoid local boiling of the liquid hydrogen. A luminosity of $L = 1.2 \cdot 10^{37} \text{ s}^{-1} \text{ cm}^{-2}$ was achieved.

The scattered electron was detected by Spectrometer B with an angular acceptance of 5.6 msr and a momentum acceptance of $\Delta p/p = 15\%$. The recoil proton was detected by Spectrometer A with an angular acceptance of 21 msr and a momentum acceptance of $\Delta p/p = 20\%$. Three different setups were chosen corresponding to three values of the four-momentum transfer Q^2 , table 1 summarizes the kinematic setups. Due to the

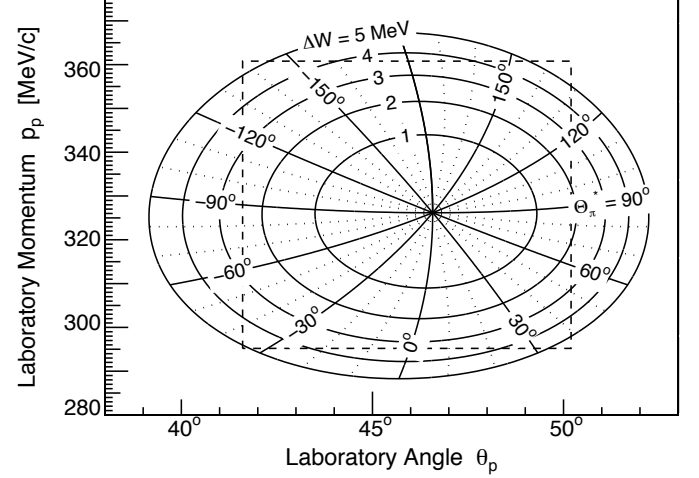


Figure 2: Acceptance of the proton for $Q^2 = 0.10 \text{ GeV}^2/c^2$. Lines of constant center of mass energy ΔW and constant center of mass production angle θ_π are drawn. The dashed line shows the acceptance of spectrometer A (including energy loss corrections).

Table 1: Kinematic setups. The beam energy was $E = 855 \text{ MeV}$ for all three setups.

Photon		Proton (A)		Electron (B)	
Q^2	ϵ	θ_p	p_p	θ_e	E'
(GeV ² /c ²)			(MeV/c)		(MeV)
0.05	0.932	45.7°	235.8	16.8°	683.5
0.10	0.882	45.9°	320.0	24.4°	652.9
0.15	0.829	45.5°	387.9	30.6°	630.0

relativistic boost of the center of mass system, nearly the complete solid angle fits within the acceptance of spectrometer A in a single setup. Figure 2 shows the acceptance in the laboratory system with lines of constant CMS energy and constant CMS angle for the intermediate value of the four-momentum transfer $Q^2 = 0.10 \text{ GeV}^2/c^2$. As can be seen, complete acceptance can be reached up to nearly $\Delta W = 4 \text{ MeV}$.

At the focal plane of the spectrometers, vertical drift chambers were used for the position and angular reconstruction of the particle trajectories. Two layers of scintillators were used for trigger purpose and coincidence time measurement. In addition, threshold gas Čerenkov detectors were used to verify that there are no sizable contributions of pions in the electron or proton arm. However, they were not used in the final analysis to reduce systematic errors due to the determination of the inhomogeneous efficiency of these detectors. Both spectrometers reach a momentum resolution (FWHM) of $\delta p/p < 10^{-4}$ and an angular resolution of better than 0.2 mrad.

Figure 3 shows the distribution of the coincidence time $|t_{A \wedge B}|$ between spectrometer A and B after correction for the path length of $\approx 12 \text{ m}$ in each spectrometer. A clear coincidence peak with a width of 1.1 ns FWHM is visible. In addition, a background of random coincidences of a few percent is visible. In the analysis, a cut of $|t_{A \wedge B}| < 2 \text{ ns}$ was used as true coincidences, while cuts on the side bands of $-30 \text{ ns} < t_{A \wedge B} < -5 \text{ ns}$ and $5 \text{ ns} < t_{A \wedge B} < 45 \text{ ns}$ were used to determine the contribution

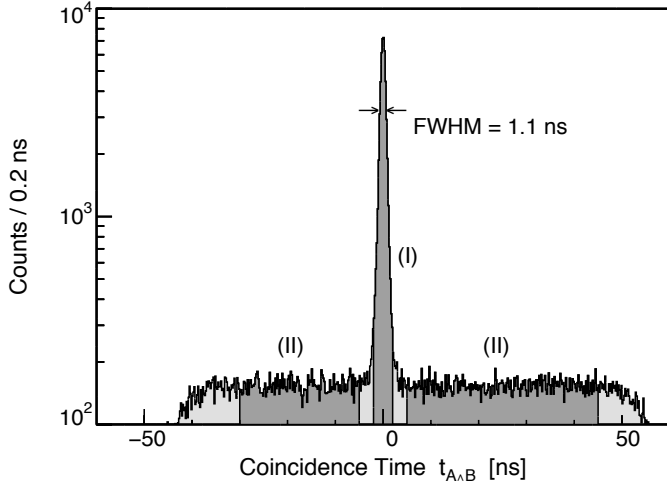


Figure 3: Coincidence time distribution (logarithmic scale). Region (I) was used as true coincidences, while region (II) was used for the estimation of the background contribution by random coincidences.

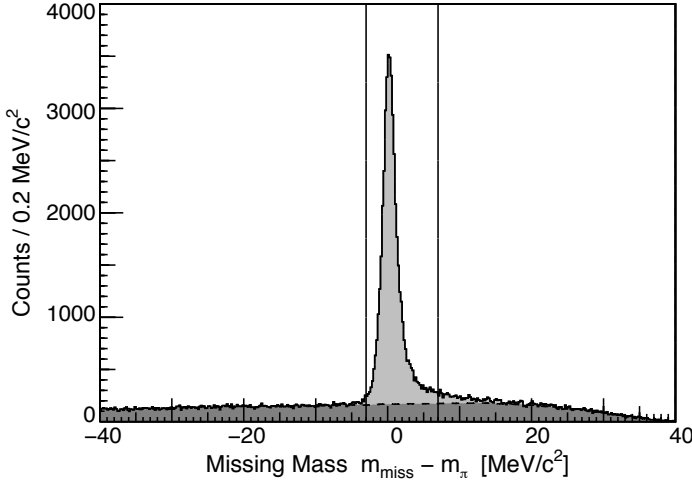


Figure 4: Missing mass distribution (for setup $Q^2 = 0.15 \text{ GeV}^2/c^2$). The light shaded area was used as pion production yield after subtraction of the background (dark shaded area) by random coincidences. The vertical lines show the additional cut in missing mass.

of random coincidences.

The single pion production process was identified by the missing mass of the pion via the four-momentum balance

$$m_{\text{miss}}^2 = (e_{\text{in}} + p_{\text{in}} - e_{\text{out}} - p_{\text{out}})^2.$$

Figure 4 shows the missing mass distribution of one setup with all events below the timing peak (light shaded area) and the events of the side band, scaled by the width of the timing window (dark shaded area). After subtraction of the random coincidences, a background free missing mass peak remains. A cut $-3 \text{ MeV}/c^2 < m_{\text{miss}} - m_{\pi} < 7 \text{ MeV}/c^2$ was used for the identified production events.

The resulting background subtracted events were histogrammed with $\Delta W = 1 \text{ MeV}$ energy bins and eight bins each in the CMS angles $\cos \theta$ and ϕ . These bins were compared to a detailed simulation of the experiment, including the dead-time corrected luminosity and the cross section of the MAID model

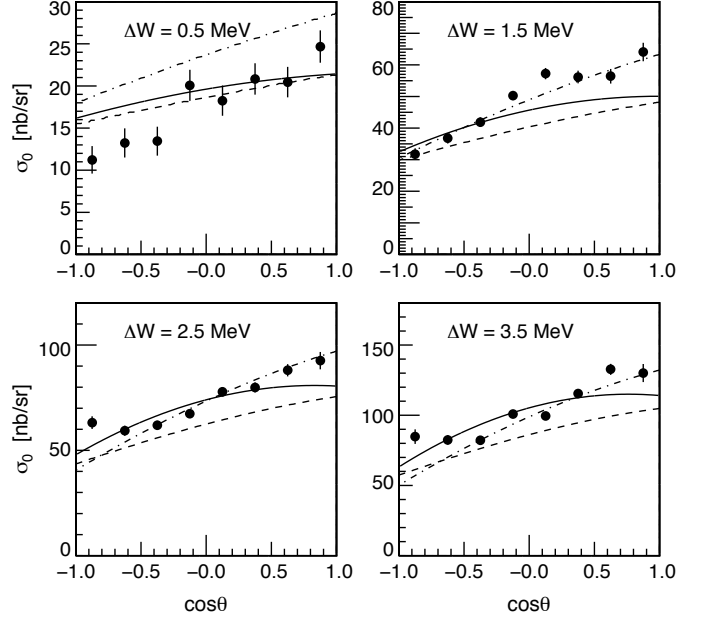


Figure 5: Cross section σ_0 for $Q^2 = 0.05 \text{ GeV}^2/c^2$. Only statistical errors are shown. The solid line is the prediction in HBChPT [14], the dashed line is the MAID model [17], and the dashed-dotted line is the DMT model [19].

[17] as generator input. All resolution and line-shape effects, as well as standard radiative corrections [22] were included.

To take the small variation of the cross section within each bin into account, their relative variations were estimated using models. This minimized the effects of non-uniform distribution within the bins and the extracted cross sections can be accurately compared directly to theoretical calculations at the central value of each bin.

For each bin in θ and ΔW a fit of the form

$$A + B \cos \phi + \cos 2\phi$$

was performed to extract σ_0 and σ_{LT} (see eqn. 1 for cross section structure). Since σ_{TT} is small compared to the error bar, it cannot be extracted from the data and the MAID model value was used as a constraint for the fit.

4. Systematic Errors

Since consistency was the problem of the previously existing data sets, special care was taken to minimize and control the systematic errors.

The detection efficiency of a modern high resolution spectrometer is above 95%, thus the efficiency corrections are small and introduce only systematic errors below the percent level. The beam current was measured with a fluxgate magnetometer (Förster probe) in the acceleration path of the last microtron stage, i.e. as the current sum of 90 staggered turns. By this enhancement of the sensitivity, the current was measured on the 1% level. The effective target length introduced the largest error to the overall normalization of the cross section by roughly 3%. In addition to monitoring all these parameters, the normalization was calibrated for each setup by an additional measurement

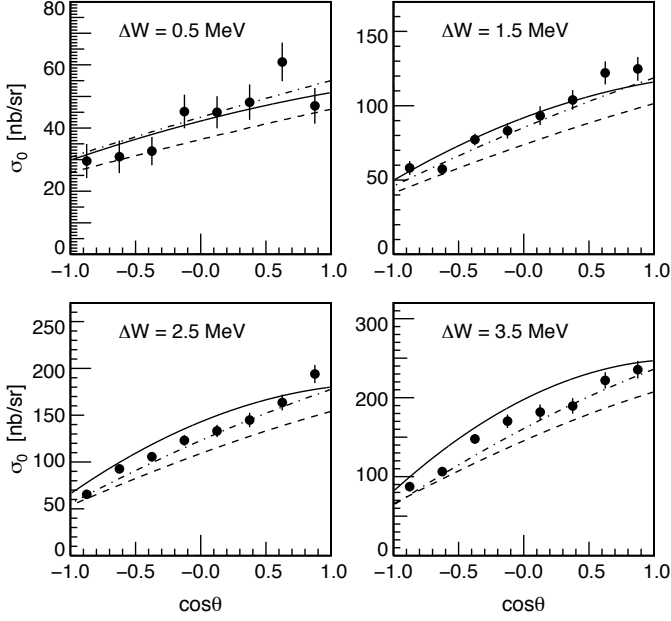


Figure 6: Cross section σ_0 for $Q^2 = 0.10 \text{ GeV}^2/c^2$ (as Fig. 5).

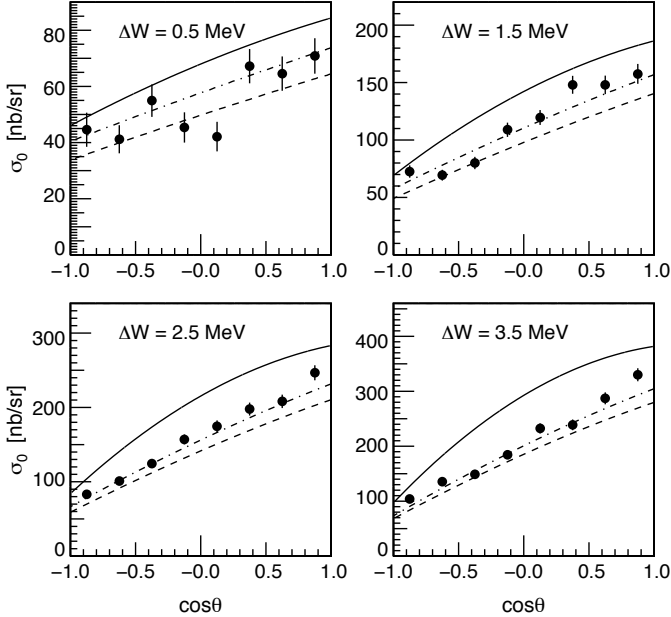


Figure 7: Cross section σ_0 for $Q^2 = 0.15 \text{ GeV}^2/c^2$ (Notation as in Fig. 5).

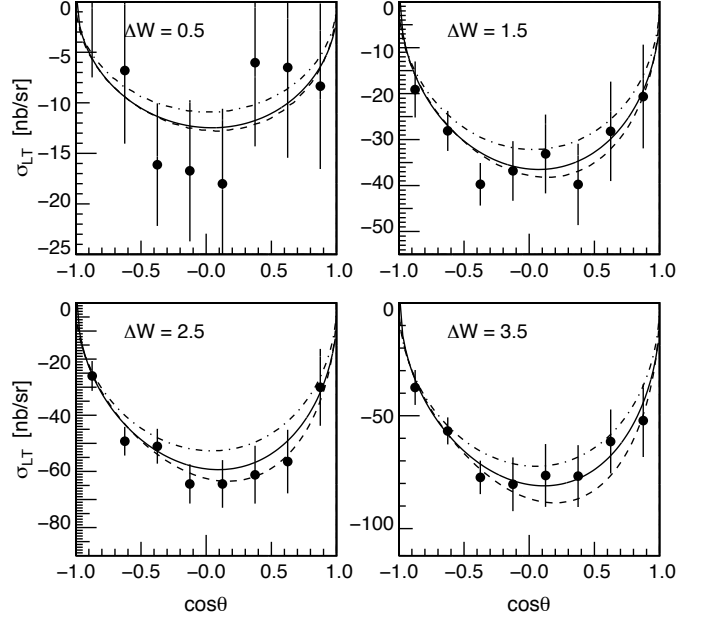


Figure 8: Interference cross section σ_{LT} for $Q^2 = 0.10 \text{ GeV}^2/c^2$ (Notation as in Fig. 5).

of the elastic scattering from the proton using a standard form factor parametrization [23]. These calibration measurements agreed within 2% with the calculations.

A major source of systematic errors for threshold measurements is introduced by the calibration of the momentum measurement of the electron detection. In the chosen setups, a calibration error of 0.1% can cause a cross section error of up to 14% in the lowest bin by shifting events below the production threshold. Therefore the momentum detection of the electron arm was calibrated in situ by a measurement of the electron momentum in the elastic peak. Since the momentum in the elastic peak is determined only by the scattering angle, the absolute momentum could be calibrated to $\pm 50 \text{ keV}$ central value. This corresponds to a systematic error of 5% on the normalization in the lowest bin. An uncertainty of the incident beam energy had not to be considered, since a deviation of this energy would affect the elastic line of the calibration measurement by the same amount, resulting in no additional uncertainty in the cross section determination and only a negligible error in the reconstruction of the four-momentum transfer.

The detection of the electron angle and the momentum and angle of the proton was calibrated by considering the recoil proton with a narrow cut on $\Delta W = 2 \text{ MeV}$. As can be seen in Fig. 2, these events form a ring in the acceptance of spectrometer A (after correction for different electron scattering angles) and all misalignments would show up as a shift of this ring.

The estimated systematic errors add up to 10% for the lowest bin, 5% for $\Delta W = 1.5 \text{ MeV}$, and 3% for the two highest bins.

5. Results and Discussion

Figures 5, 6, and 7 show the cross section $\sigma_0(\theta)$ for the first four energy bins above the threshold. For comparison, three cal-

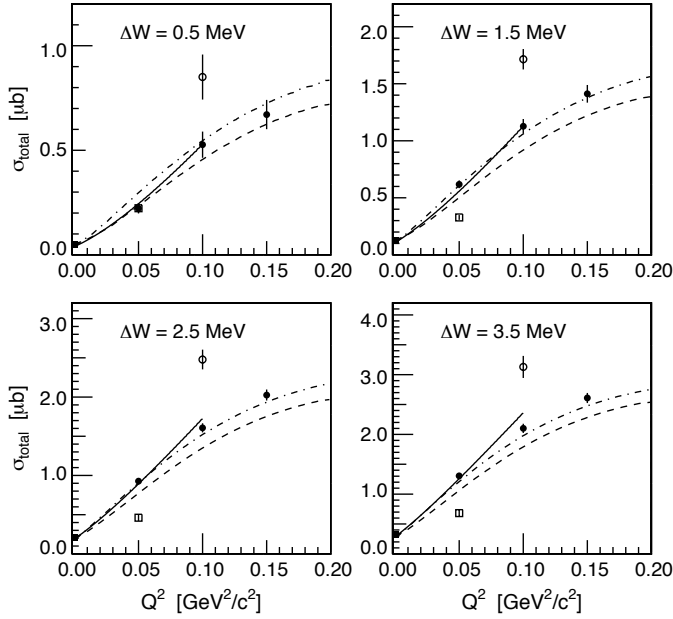


Figure 9: Total cross section σ_{total} versus Q^2 , calculated from a fit of the form $\sigma_0(\theta) = A + B \cos \theta + C \cos^2 \theta \Rightarrow \sigma_{\text{total}} = 4\pi(A + C/3)$. The error bars are the quadratic sum of the statistical error and the systematic error. The solid line is the prediction in HBChPT [14], the dashed line is the MAID model [17], and the dashed-dotted line is the DMT model [19]. The lines are calculated with constant $E_{\text{beam}} = 855$ MeV, *i.e.* variable photon polarization ϵ . In addition the data points from Refs. [8] (photon point), [15] (open box), and [13] (open circle) are drawn.

calculations are included. The dashed line shows the phenomenological isobar model MAID [17]. This model fits basically all existing photo- and electro-production data and is therefore dominated in the threshold region by the amount of existing photo-production data. The overall good agreement of the data with this model can be interpreted as consistency with the world data set. Even better agreement with the data is shown by the dynamical model DMT [19], which is compared to the MAID model expected to be superior in the threshold region since it is based on a chiral Lagrangian.

For completeness, the calculation in Heavy Baryon Chiral Dynamics of Ref. [14] is included. This curve has to be interpreted with care, since the calculation was fitted to the data of Refs. [13, 12], which show serious consistency problems. These consistency problems are illustrated in Fig. 9, which shows the total cross section of this measurement in combination with the photon point [8] and previous electroproduction data points at $Q^2 = 0.05 \text{ GeV}^2/c^2$ (Ref. [15]) and $Q^2 = 0.10 \text{ GeV}^2/c^2$ (Ref. [13], consistent with Ref. [12]). The latter was included in the fit of HBChPT and causes probably the unnatural slope of this calculation. This is the reason that the results of this calculation are not shown for $Q^2 > 0.10 \text{ GeV}^2/c^2$ in Fig. 9. A refit of the empirical low energy constants with this new data set is needed before any conclusions about its accuracy can be made.

Figure 8 shows σ_{LT} for the intermediate Q^2 value (figures of the other two settings and all data as table are available in the online version of this article). Within the error bar, all three

calculations are consistent with the extracted interference cross section.

In summary, the data sets of Refs. [12, 13, 15] seem to have normalization problems beyond the size of the quoted systematic errors. A reanalysis of part of this data at $Q^2 = 0.05 \text{ GeV}^2/c^2$ did not reveal any obvious mistakes, however, the extensive additional calibration measurements of the new data set were not done at that time. As discussed above, *e.g.* a plausible small calibration error in the electron momentum can cause already large normalization errors in the resulting cross section, which was underestimated at that time. We recommend to use the new data for future fits of the total cross section and to use the old data sets only with a free normalization parameter. The old data sets included a full Rosenbluth separation and an extraction of σ_{TT} and σ_{LT} . The relative size of these cross sections might not be affected by an overall normalization problem. The data of Ref. [16] with emphasis on higher energies are consistent with the new measurement.

6. Summary

In this letter a new consistent data set on neutral pion electro-production in the threshold region is presented. The long standing problem of the normalization of the existing threshold data sets has been clarified. The new data are described best by the dynamical model DMT [19]. However, with a refit of the low energy constants in HBChPT [14], this theory will probably also be able to describe the data, although the Q^2 range of validity remains still an open question.

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