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Precision Measurement of Electroproduction of π^0 Near Threshold: A Test of Chiral QCD Dynamics.

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A high precision measurement of $p(e,e'p)\pi^0$ has been made in Hall-A of Jefferson Laboratory, on a fine grid of Q^2 and ΔW in the range of $0.05 < Q^2 < 0.14\,(GeV/c)^2$ and $0 < \Delta W < 30\,MeV$. Further measurements were also made on a coarser grid up to $Q^2 = 0.50\,(GeV/c)^2$. The experiment has been performed using one of the Hall-A High Resolution Spectrometers (e') and the large acceptance spectrometer BigBite (p), which, close to threshold, has 4π coverage. The asimuthal dependence of the differential cross section has been used to extract structure functions $\sigma_T + \varepsilon\sigma_L, \sigma_{TT}, \sigma_{LT}$ and in addition the beam helicity dependence yields $\sigma_{LT'}$. These results will provide a stringent test of the predictions of Heavy Baryon Chiral Perturbation Theory and also give valuable input to Partial Wave Analyses such as SAID and MAID.

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1. Motivation

Quantum Chromodynamics (QCD) describes hadronic interactions in terms of the underlying dynamics of the quark-gluon degrees of freedom. However it is non-perturbative at the energy and distance scales of hadrons so that descriptions of hadronic structure in fundamental QCD terms remains elusive. Although Lattice QCD has recently made impressive progress in the light-quark sector, quantitative predictions of hadronic structure observables in general remain some way off. Thus Effective Field Theories (EFT), constrained by the fundamental symmetries of QCD, still represent the most direct connection to QCD at low energy. At low energy QCD exhibits approximate chiral symmetry, broken spontaneously as manifested by the existence of Goldstone bosons such as the pion. Nevertheless the interaction between pions and nucleons is constrained by chiral symmetry, allowing expansion about the chiral limit of amplitudes in terms of m_π/M and q/M where m_π is the pion mass, M is the nucleon mass and q is any (small) momentum or mass appearing in the formalism. This approach is known as Heavy Baryon Chiral Perturbation Theory (HBχPT). Since χPT is an effective theory, details of the interaction are masked in any calculation beyond tree level and the effects are absorbed into empirically determined constants: the so called low energy constants (LEC). Once these constants have been determined from particular experimental data it should in principle be possible to predict the amplitudes for different kinematic conditions.

In any χPT expansion one must determine how many powers are necessary to achieve convergence and how many loops beyond tree level must be included. In practice conditions are chosen where the ratios of the expansion are small, which for $\gamma^* + N \rightarrow N + \pi$ corresponds to small squared four-momentum transfer Q^2, at energies just above threshold. In such kinematics the values of the LECs can be fixed and then used to predict higher energy and momentum situations. Thus the range of validity of the χPT approach can be gauged. Although χPT has in general been extremely successful, an apparently serious inconsistency in the description of pion electroproduction has come to light at Mainz. This is in contrast to the successful HBχPT description of photoproduction data [1], which however has presented a less exacting challenge to theory.

Fits to LEC values have been made [2] using the $p(e,e'p)\pi^0$ data at $Q^2 = 0.1\,(GeV/c)^2$ [3] and these were then used to predict S and P-wave amplitudes at $Q^2 = 0.05\,(GeV/c)^2$. In Fig. 1 the amplitudes extracted from measured cross sections [3, 4, 5] are compared to the predictions of HBχPT and the Unitary Isobar model MAID [6]. Note that the extraction of E_{0+} and L_{0+} in [3, 4] used P-wave contributions calculated as in [7]. It is clear that HBχPT (with LECs adjusted to the data of [3]) does not reproduce the measured Q^2 evolution of S-wave multipole strength, which could be due to a number of possibilities including:

- Cross section measurements at very low values of Q^2 and ΔW are technically difficult so that data point(s) may be in error.
- The chiral expansion might require higher order terms (and hence extra LECs).
- The basic formulation of HBχPT may have deficiencies.

Near threshold S-wave amplitudes dominate, but it turns out [8] that the calculation of E_{0+} converges rather slowly in terms of m_π/M so that this is not the most reliable observable for a precision test. In contrast the calculation of the P-wave multipoles converges much more rapidly. However the agreement between P_1 and P_{23}^2 extracted from data and χPT predictions (Fig.1) is also poor. It is also interesting to compare the apparently increasing discrepancy in $d\sigma_{LT}/d\Omega$ as ΔW increases.

Thus it was clear that an independent high precision measurement was vital to achieve a better understanding of the S and P-wave components of the cross section. Experiment E04-007 was run in 2008 in Hall-A of Jefferson Lab. It measured differential cross sections on a fine grid of Q^2 and ΔW in the range $0.05 < Q^2 < 0.14\,(GeV/c)^2$ and $0 < \Delta W < 30\,MeV$. It also extended the kinematic reach up to 0.50 $(GeV/c)^2$ to examine systematic deviations outside of the range of validity of HBχPT and to facilitate comparison with partial wave analyses such as MAID [6] and SAID [9]. In addition the beam helicity asymmetry was measured, which provides access to the imaginary parts of the S-wave amplitudes.

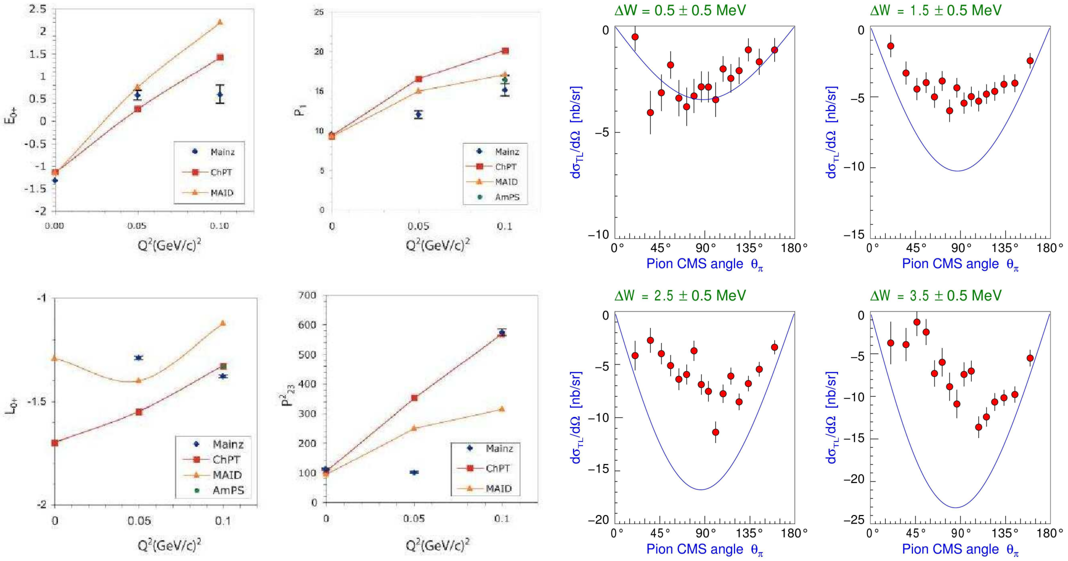

Figure 1: Left Q^2 dependence S and P-wave multipoles. Data points: Mainz $0.05\,(GeV/c)^2$ [5], Mainz $0.1\,(GeV/c)^2$ [3], AmPs [4]. Model Predictions: ChPT[2], MAID [6]. The P-wave combination $P_{23}^2 = (P_2^2 + P_3^2)/2$. **Right** $d\sigma_{LT}/d\Omega$ at $Q^2 = 0.05$. Data points [5], full curve χPT [2].

2. Experiment

The $p(e,e'p)\pi^0$ reaction has been measured in Hall-A of Jefferson Laboratory using the left High Resolution Spectrometer (HRS) to detect the scattered electron and the large acceptance spectrometer BigBite to detect the proton. The former gives precise determination of the excitation energy and momentum transfer, while the latter permits a large fraction of the forward emitted (along $\vec{q}$) protons to be detected simultaneously. The π^0 is not detected, but the reaction channel is identified via a missing mass analysis of $p(e,e'p)$.

BigBite, with a solid angle of ~ 90 msr and a momentum range of 200 - 900 MeV/c, has proved an extremely versatile addition to the Hall-A experimental tool kit. For the present experiment it was equipped with two, six-plane multi-wire drift chambers (MWDC) and two plastic-scintillator trigger planes (3 and 30 mm thick), which provide proton identification by $\delta E - E$ and also by time of flight. In low Q^2, low ΔW kinematics the recoiling proton has low momentum, so that the

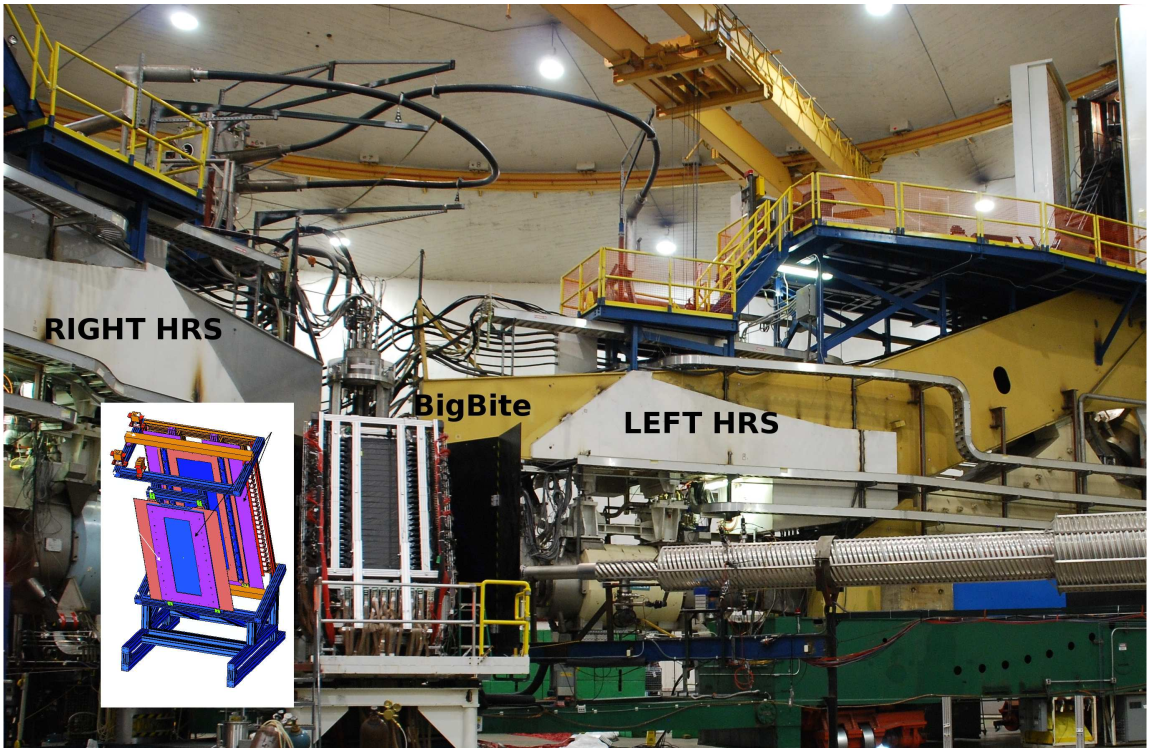

Figure 2: The Hall-A setup for $p(e,e'p)\pi^0$. Showing the left HRS, exit beam line, BigBite and the right HRS. A 3D rendering of the BigBite detector stack is displayed in the insert

amount of material in the path of the proton must be minimised to maintain clean detection and accurate track reconstruction. A thin-walled liquid hydrogen target and scattering chamber were specially constructed for this experiment and the air gaps in the detector stack were filled with helium bags. As BigBite is a simple, open dipole the detector stack has a direct view of the target and counting rates are high. Experience in track reconstruction from fast-counting drift chambers gained from a prior Hall-A BigBite experiment [10] proved invaluable to the present project and luminosities of $\sim 10^{37}$ Hz/cm^2 were achieved.

2.1 Kinematics

The experiment was run with a longitudinally polarised electron beam ($P_e > 80\%$) so that the five-fold differential cross section for $\vec{\gamma}^* + p \rightarrow p + \pi^0$ (Fig.3) may be written

$$\frac{d\sigma(\theta,\phi)}{dE_e d\Omega_e d\Omega} = \Gamma\{\sigma_T(\theta) + \varepsilon_L\sigma_L(\theta) + \varepsilon\sigma_{TT}(\theta)\cos 2\phi + \sqrt{2\varepsilon_L(1+\varepsilon)}\sigma_{LT}(\theta)\cos\phi$$
$$+h\sqrt{2\varepsilon(1-\varepsilon)}\sigma_{LT'}(\theta)\sin\phi\}$$

where Γ is the γ^* flux, θ,ϕ specify the direction of π^0 emission with respect to $\vec{q}$ (Fig.3), ε is the transverse polarisation of the γ^* and h $(=\pm 1)$ is the electron beam helicity. The longitudinal polarisation $\varepsilon_L = \varepsilon Q^2/\omega^2$, where ω is the γ^* energy. Decomposition of the ϕ dependence of the unpolarised cross section yields $\sigma_T + \varepsilon_L\sigma_L, \sigma_{TT}, \sigma_{LT}$. A beam helicity asymmetry may also be defined

$$A_{LT'}(\theta) = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}\sigma_{LT'}(\theta)}{\sigma_T(\theta) + \varepsilon\sigma_L(\theta) - \varepsilon\sigma_{TT}(\theta)}$$

where $\sigma_{+/-}$ are the cross sections for $h = +/-$. Close to threshold, amplitudes with $l > 1$ are negligible and the angular coefficients of the two-fold differential cross sections (structure functions) $\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT}$ can be related to the two S-wave and five P-wave multipoles. The structure function $\sigma_{LT'} \propto \Im(E^*_{0+}P_5 + L_{0+}P^*_2)$, accesses $\Im(L_{0+})$ primarily since $|P_2| \gg |P_5|$ and relates to the unitary cusp in the ΔW dependence of $\Re(E_{0+})$, observed when the $n\pi^+$ channel opens.

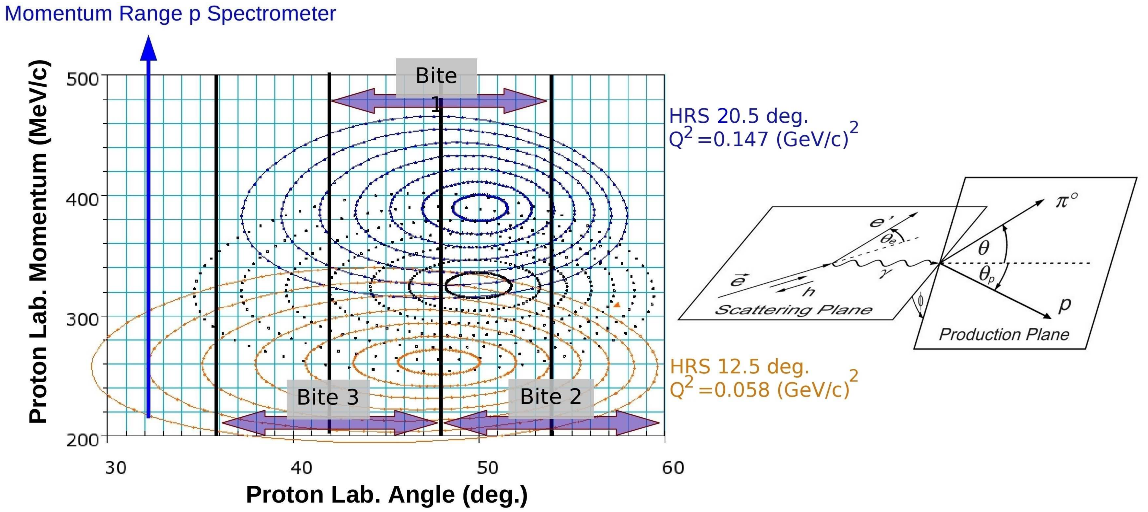

Figure 3: Left: the acceptance of BigBite for recoiling protons. The ellipses denote paths of constant ΔW, starting at 0.5 MeV and increasing in ~1-MeV wide steps. Right: the kinematic variables of $\gamma^* + p \rightarrow p + \pi^0$.

A summary of the kinematic settings employed in the 2008 experiment is given in Table.1. In addition to production runs there were numerous runs to calibrate the optics of the spectrometers, the absolute energy scale, detection efficiency, and rate effects.

2.2 Preliminary Analysis and Status

Since experiment E04-007 was proposed, the Mainz A1 collaboration has remeasured the $p(e,e'p)\pi^0$ differential cross section at $Q^2 = 0.05,\ 0.10,\ 0.15\,(GeV/c)^2$, as reported at Chiral Dynamics 09 [11]. Their new determination of the Q^2 dependence of σ_{tot} is less steep than previous measurements [3, 5], more in keeping with HBχPT at low Q^2 (bearing in mind that the LEC were fitted to the data of [3]) and in good agreement with the Mainz Meson Exchange Dynamical Model [12]. This emphasises the absolute need to have a complete understanding of systematic effects, which for the detected proton become maximum as Q^2 and $\Delta W \rightarrow 0$, before disclosing cross sections. The difficulty of low-Q^2 measurements is illustrated in Fig.4 where the π^0 missing mass peak becomes progressively less well defined as Q^2 is reduced.

Currently the data analysis has not reached a stage where absolute cross sections can be computed with reliable estimates of the systematic uncertainties. The experimental run itself was a

	E_e (GeV)	θ_{BB} (deg.)	θ_{HRS} (deg.)	$\langle Q^2 \rangle$ $(\mathrm{GeV/c})^2$	IBC (C)		E_e (GeV)	θ_{BB} (deg.)	θ_{HRS} (deg.)	$\langle Q^2 \rangle$ $(\mathrm{GeV/c})^2$	IBC (C)
A	1.19	54.0	20.5	0.15	0.36	I	1.19	43.6	20.5	0.15	0.31
B	1.19	54.0	16.5	0.10	0.31	J	1.19	43.6	16.5	0.10	0.36
C	1.19	54.0	14.5	0.08	0.42	K	1.19	43.6	14.5	0.08	0.45
D	1.19	54.0	12.5	0.06	0.23	L	1.19	43.6	12.5	0.06	0.22
E	1.19	48.0	12.5	0.06	0.38	M	1.19	50.3	27.2	0.21	0.02
F	1.19	48.0	14.5	0.08	0.55	N	2.32	54.0	13.2	0.25	0.22
G	1.19	48.0	16.5	0.10	0.68	O	2.32	54.0	15.8	0.35	0.31
H	1.19	48.0	20.5	0.15	0.56	P	2.32	54.0	18.2	0.45	0.34

Table 1: E04-007 Kinematic settings for production running, where E_e is the electron beam energy, θ_{BB} is the BigBite central lab. angle for proton detection, θ_{HRS} is the central Left HRS angle for scattered electron detection and IBC is the integrated beam charge.

complete success and the amount of data recorded exceeded the original expectations of the proposal in terms of the $A_{LT'}$ observable, the detailed mapping, the extended Q^2 range and the ΔW range of the differential cross sections. The expected range and precision of the data is displayed in Fig.5 and clearly the finely-spaced coverage of the present experiment is superior to previous work.

We look forward to providing data which will produce high precision values for the S and P-wave amplitudes. These will offer an especially exacting test of HBχPT and potentially provide a data set for improved LEC fits. A systematic understanding of how theory relates to these amplitudes in various kinematics will deepen our understanding of HBχPT and hence of QCD in the non-perturbative regime.

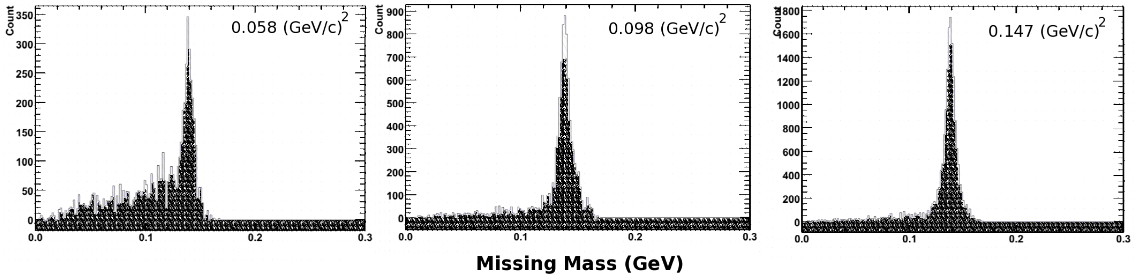

Figure 4: Reconstructed π^0 missing mass in GeV for Q^2 values of 0.058, 0.098 and 0.147 $(\mathrm{GeV/c})^2$.

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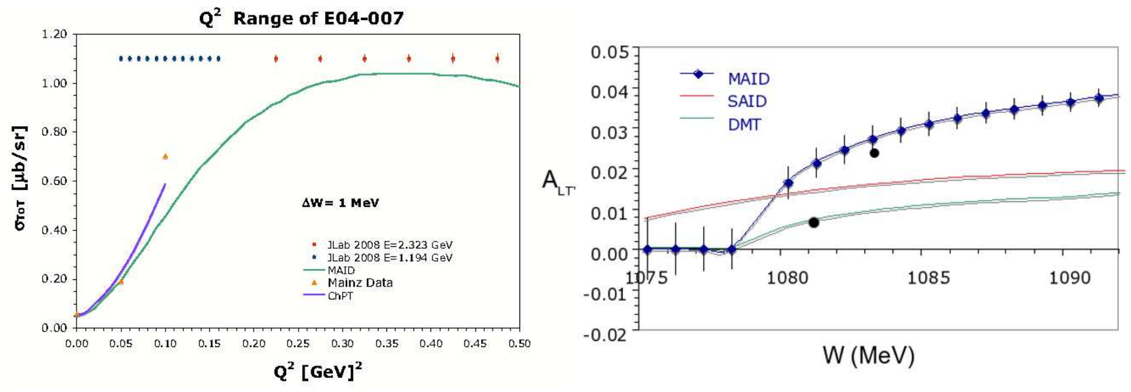

Figure 5: Left: the expected precision (error bars on the line of points at the top of the plot) and Q^2 coverage of σ_{tot} for the present (JLab 2008) data. Right: the expected $A_{LT'}$ precision (error bars on the MAID points) and coverage in W for the present data.

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