Baryon Resonance Electroproduction at High Momentum Transfer

(Update of TJNAF-CEBAF Experiment 97-101)

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Abstract

This is an update of Hall C experiment 97-101, which is part of a program to study the transition from low Q^2 - low t physics, where *soft* non-perturbative QCD processes characterized by constituent quarks dominate, to the high Q^2 -high t regime where *hard* processes characterized by current quarks correlations are expected to play an increasingly important role, and even to where pQCD becomes important. We will focus on the impact of the new theoretical developments in *Generalized Parton Distributions* (GPD) to this reaction, and the connection of this reaction to other exclusive high t reactions through the GPD formalism. In Hall C experiment 94-014, the excitation of the $\Delta(1232)$ and the $S_{11}(1535)$ resonances were observed via their decay into the π^0 and η respectively at Q^2 near 2.8 and 4 GeV^2/c^2. Experiment 97-101 will extend these measurements to $Q^2 =$ 7.5 GeV^2/c^2, utilizing a 5.75 GeV electron beam energy. The experiment will measure the kinematically complete reactions $p(e, e'p)\pi^0, \eta$. Since at high Q^2 the protons emerge in a narrow cone around the $\vec{q}$ vector, a large fraction of the in-plane and out-of-plane c.m. decay spectrum can be reconstructed using the HMS and SOS spectrometers.

Reaction: $p(e, e'p)\pi^0, \eta$ @ $Q^2 \sim 7.5$ GeV^2/c^2

E_{beam}	I_{max}	Target	beam time	proton detector	electron detector
6 GeV	90 μA	4cm LH_2	25 days	HMS	SOS

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1 Introduction

Experiment 94-014 measured the inelastic nucleon transition amplitudes to the $\Delta(1232)$ and $S_{11}(1535)$ baryon resonances, via the reactions $p(e,e'p)\pi^0$ and $p(e,e'p)\eta$ respectively, in the previously inaccesible momentum transfer range $Q^2 = 2.8$ and 4 GeV^2/c^2. The quality of the data was excellent, enabling us to extract resonance amplitudes in a previously unexplored physical regime with very high statistical precision. The timeliness and widespread interest in the obtained data has resulted in a large number of invited talks and references to these results in international conferences. In the case of the $\Delta(1232)$, the Q^2 dependence of the extracted ratio of the amplitudes E_{1+}/M_{1+} and the M_{1+} amplitudes have unequivocally demonstrated that the reaction mechanism cannot be explained in terms of *perturbative QCD* ($pQCD$) dominance, even though the three momentum transfer wavelength (0.05 fm) is smaller than expected for the validity of the constituent quark model (CQM). Experiment 97-101 will enable us to extend the Q^2 frontier to 7.5 GeV^2/c^2, utilizing an electron beam energy of 5.75 GeV. In the following we will use Q^2 and t interchangably, where t is the squared momentum transfer from the proton to Δ or $S_{11}(1535)$. Taken together with the anticipated high t results from the elastic G_{EP} and wide angle Compton scattering (WACS) in Hall A, the data on the $\Delta(1232)$ and $S_{11}(1535)$ will place tight constraints on quark/parton based models. Within the framework of the newly evolving *generalized (*or *skewed) parton distributions* (GPD's), the body of data will provide information about the transverse momentum and spin distributions of the partons, especially at high $k_\perp$, where parton correlations are expected to be significant.

2 Physics of the Experiment

2.1 The $N \to \Delta$ form factors.

The $\Delta(1232)$ resonance has been one of the most studied objects in nuclear and particle physics. As the lowest lying, relatively isolated object, it continues to evolve as an unparalleled test case of the structure and dynamics of baryons. Likewise, the $S_{11}(1535)$ also is the subject of widespread study, since it is the negative parity partner of the elastic form factor, and is easily isolated experimentally through its strong η decay channel branching ratio.

Much of the original physics motivation behind approved experiment 97-101, for instance a study of the evolution from low-to-high Q^2 physics and a search for definitive signals of the onset of hard perturbative reaction mechanisms, remains important today. However, in the past year there has been a major development in the description of exclusive reactions in the few GeV^2/c^2 momentum transfer range, in terms of GPD's, and its application to high Q^2, high t reactions, which bridges the gap between physics of very low Q^2, low t, and that of the high Q^2, high t region characterized by $pQCD$.

Elastic and transition form factors are specifically favorable for the application of the GPD formalism, in that the photon-parton vertex in the handbag picture (fig. 1) is exactly perturbative above a moderate t, thus isolating the non-pertubative baryon physics expressed in terms of GPD's, graphically represented by the handbag. The fits to elastic nucleon form factors demonstrated that this picture is adequate at $Q^2 > 1$ GeV^2/c^2, about the same Q^2 required for the onset of Bjorken scaling in $p(e,e')X$. The GPD's are intrinsic properties of the baryonic structure. Different aspects can be accessed by different exclusive reactions. In the case of form factor measurements at high t, they are uniquely sensitive to hard parton-parton correlations, and are directly related to the transverse distributions of parton spin and momentum within the baryon.

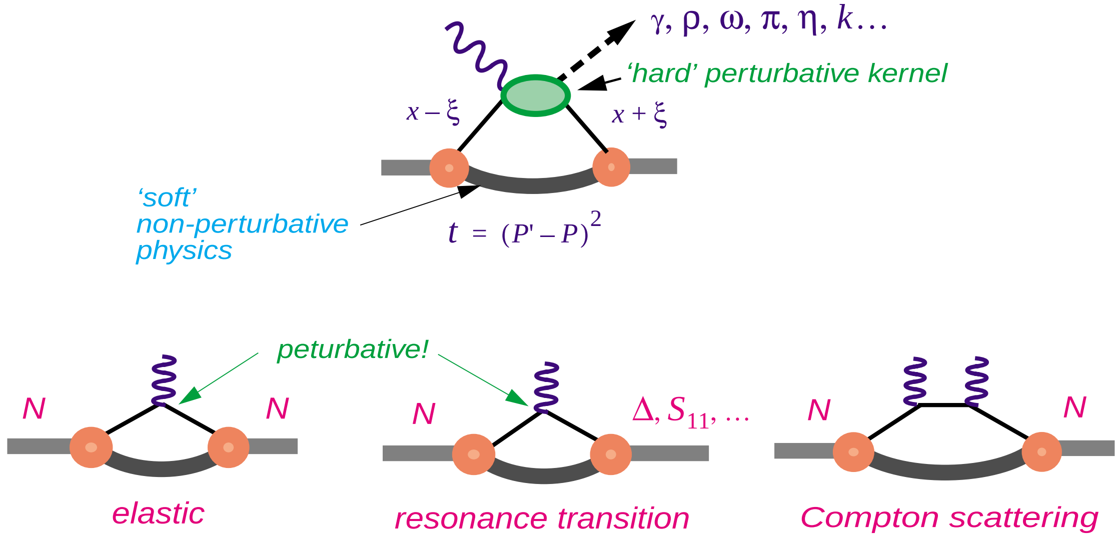


Figure 1: Schematic representation of the GPD approach to exclusive reactions, and their connection with baryon elastic and transition form factors and wide angle Compton scattering.

Form factors are the 0'th moments of the GPD's. For elastic scattering

$$F_1(t) = \int_{-1}^{1} \sum_q H^q(\xi, x, t)dx \quad \text{and} \quad F_2(t) = \int_{-1}^{1} \sum_q E^q(\xi, x, t)dx$$

For the $N \to \Delta$ the relationship is

$$G_M^* = \int_{-1}^{1} \sum_q H_M^q(\xi, x, t)dx \quad G_E^* = \int_{-1}^{1} \sum_q H_E^q(\xi, x, t)dx \quad G_C^* = \int_{-1}^{1} \sum_q H_C^q(\xi, x, t)dx$$

where G_M^*, G_E^* and G_C^* are magnetic, electric and Coulomb transition form factors [1], and H_M^q, H_E^q, and H_C^q are axial (isovector) GPD's, which can be related to elastic GPD's in the large N_C limit through isospin rotations. Similar relationships can obtained for the $N \to S_{11}$ transition.

For Compton scattering the appropriate *form factor-like* quantities [2] are the -1 moments of the GPD's

$$R_1(t) = \int_{-1}^{1} \sum_q \frac{1}{x} H^q(\xi, x, t)dx$$

Thus, the importance of constraining the t and x dependence of the GPD models by the various *form factor-like* amplitudes is manifest.

The $N \to \Delta$ transition is one of the best cases to map the transition from low to high t reaction physics. The measurement of the ratio E_{1+}/M_{1+} remains one of the primary objectives of this experiment, in that it is a sensitive measure of the evolution from soft to hard reaction mechanisms. At low Q^2 in the framework of a constituent quark model (CQM) the $N \rightarrow \Delta$ transition is nearly purely M_{1+} in character, involving a single-quark spin-flip. The color hyperfine interaction adds a very small E_{1+} contribution of a few percent. At $Q^2 = 0$ the most recent data from Mainz [4] and BNL [5] bear this out. A theoretical fit by two of us (Da-97) finds $E_{1+}/M_{1+} = -.029 \pm .0023$ At very high Q^2, according to valence $pQCD$ only helicity conserving amplitudes should contribute, leading to the prediction $E_{1+}/M_{1+} \rightarrow 1$. Figure 2 shows E_{1+}/M_{1+} vs. t, including the measured data from E94-014 as well as the recent low t results.

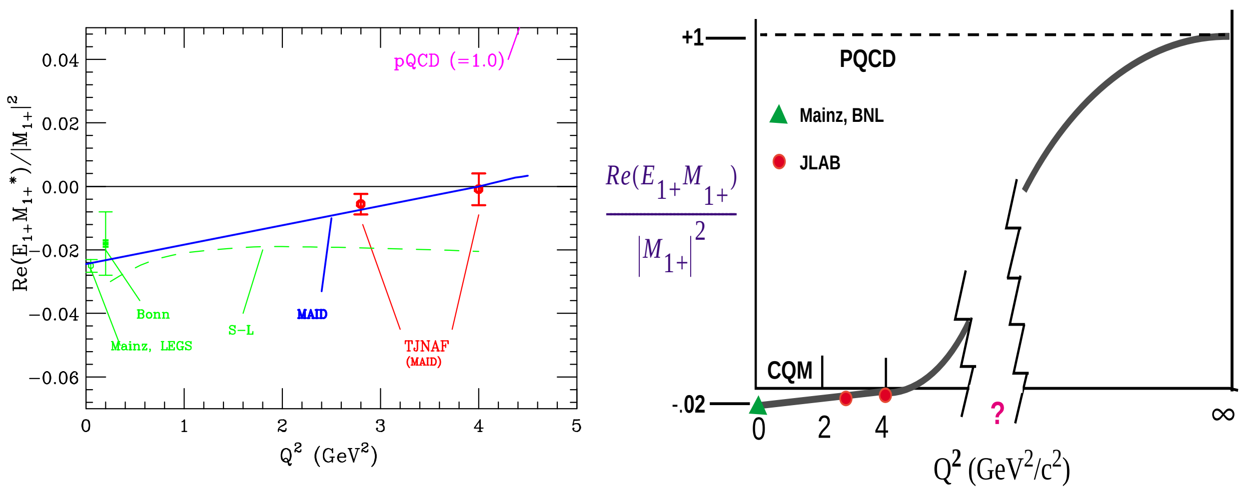


Figure 2: Left figure; the result of the $ReE^*_{1+}M_{1+}/|M_{1+}|^2$ measurement of E94-014. The data represent the most recent MAID [3] fit to E94-014 plus the the world's lower Q^2 data in a self-consistent way. Also shown are the results of measurements at Q^2=0 from Mainz [4] and LEGS [5]. Right; the expected evolution of $ReE^*_{1+}M_{1+}/|M_{1+}|^2$ from $t = 0$ to assymptotically high t. The question mark (?) indicates our uncertainty where in t the increase in $ReE^*_{1+}M_{1+}/|M_{1+}|^2$ will occur.

Clearly, the data are in rough agreement with the CQM expectations, and do not exhibit the increase expected in the eventual evolution to $pQCD$. This is difficult to understand, since the data at 4 GeV^2/c^2 involve a three-momentum transfer wavelength $\lambda \sim 1/p \sim 0.05$fm, presumably at the limit of, or smaller than the size of dressed constituent quarks with which the virtual photons interact. In this region of t the small E_{1+} amplitude is a very sensitive constraint on GPD's since it involves delicate cancellations of larger amplitudes.

Experiment 94-014 showed us that at least up to a t of 4 GeV^2/c^2 the reaction mechanism is dominated by soft physics. The magnetic form factor G^*_M actually falls faster with Q^2 ($\equiv t$) than the dipole form factor G_D. Figure 3 exhibits the current status of the $N \rightarrow \Delta$ magnetic form factor G^*_M divided by the dipole form $3/(1+t/0.71)^2$.

For elastic scattering, ref. [2] and ref. [7] utilize the following model for the soft GPD:

$$H^q \sim f^q(x) e^{\bar{x}t/4x\lambda^2}$$

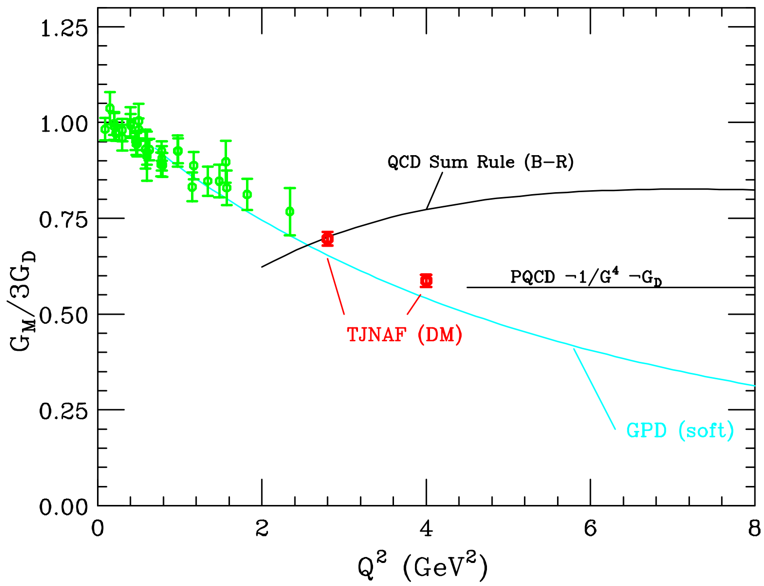


Figure 3: The magnetic form factor G_M^* divided by the dipole $G_D = 3/(1+t/0.71)^2$ as a function of momentum transfer $t \sim Q^2$. The data at $Q^2 = 2.8$ and 4 GeV^2/c^2 are the results of E94-014. The lower Q^2 data are a compillation of older data by [6]. The curve labelled GPD is the result using a GPD model discussed in the text. The $\sqrt{\langle k_\perp^2 \rangle} \sim 180$ MeV/ is smaller that that obtained for the elastic $F_1(t)$ (~ 250) MeV/c, implying the $\Delta(1232)$ is a physically softer object than a proton, or more likely the x dependence of the Δ is different from that of the proton. This result of the simple model employed should not be taken too literally, but it does show that we have a lot to learn about the interplay between the $k_\perp$ and longitudinal x. The horizontal curve is what one expects from $pQCD$ scaling.

where $f^q(x)$ is the usual longitudinal parton density obained from inclusive DIS, and λ is a parameter related to $\sqrt{\langle k_\perp^2 \rangle}$.

With this simple model the t dependence of the elastic G_{MP} and G_{EP} can be reasonably and consistently fit up to $t \sim 5$ with $\langle k_\perp \rangle \sim 250$ MeV/c. For larger t the calculated G_M becomes progressively smaller than the data, presumably due to the onset of higher $k_\perp$ correlations. Figure 3 shows a fit to the $N \rightarrow\ \Delta\ G_M^*$ using the GPD model of refs. [2, 7] with a Gaussian $k_\perp$ distribution. The $\langle k_\perp^2 \rangle \sim 180$ MeV^2/c^2 implies either the distribution of the $\Delta(1232)$ is softer than that for the proton, and/or the x dependence of the GPD for the $N \rightarrow \Delta\ G_M^*$ must be different from that for G_M for elastic scattering. If one parameterizes the hard processes by a power law falloff the model GPD could be expressed as

$$H^q = f^q(x)\{e^{\bar{x}t/4x\lambda^2} + \sum_n c_n \frac{(\alpha_s/\pi)^{2n}}{t^{2n}}\} \equiv H^q_{soft} + H^q_{hard}$$

Since $G^*_{M(soft)}$ for the Δ is decreasing with t faster than $G_{MP(soft)}$ for elastic scattering, the contribution of $G^*_{M(hard)}$ may be observable at a lower, more accessible t than for the elastic form factor. This would manifest itself in a leveling off of the G_M^*/G_D vs t.

Finally, for completeness, we show in figure 4 the results for the ratio S_{1+}/M_{1+}, which were measured in E94-014.

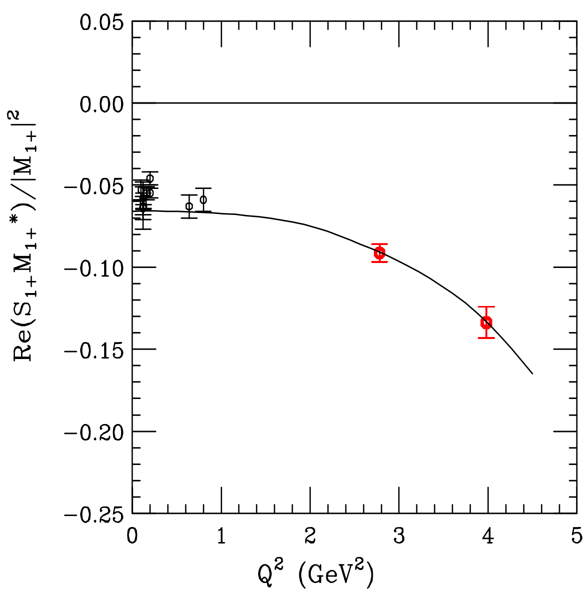


Figure 4: The result of S_{1+}/M_{1+} measurement of E94-014 at $Q^2 = 2.8$ and 4 GeV^2/c^2. At the lower Q^2 are recent data from Bates and Bonn. All data are the results of MAID [3] fits to the compiled recent world data. Fits using *dynamic models* [3, 10] yield somewhat different results.

2.2 The $N \to S_{11}(1535)$ form factors.

The $S_{11}(1535)$ is the lowest mass state with a $J^\pi = 1/2^-$ with isospin $T = 1/2$, and therefore among the easiest to get in lattice, $pQCD$ sum rules, and CQM and other sophisticated models. The $p \to S_{11}$ transition is purely helicity conserving. In the valence $pQCD$ limit, sum rules find the structure to be similar to the proton's [8], Since the reaction is purely helicity conserving, a leveling of $Q^3 A_{1/2}$ should be a good test case for any evidence of a transition from the the dominance of soft to hard processes. We are currently in the process of modeling the GPD for the helicity conserving form factor $F_1^*(S_{11})$ to compare with that of the proton.

A unique feature of the $S_{11}(1535)$ is that it is strongly excited, and the only excited state with a large η decay branching ratio ($\sim$ 50%), so that experimentally it is easily isolated via that channel. The $S_{11}(1535)$ form factor remains very large at all measured Q^2.

Figure 5 shows the $Q^3 A^p_{1/2}$ for the $S_{11}(1535)$, which is predicted by $pQCD$ to assymptotically approach a constant at high Q^2. As has been pointed out elsewhere [9], such scaling might be due to non-perturbative contributions. While there is no *strong* scaling evident in the figure, our data indicate that $Q^3 A^p_{1/2}$ may be approaching a constant value by $Q^2 \sim 5$ (GeV/c)^2.

3 Analysis of Experiment 94-014

Experiment 94-014 measured the reactions $p(e, e'p)\pi^0$ from the $\Delta(1232)$ at $Q^2 = 2.8$ and 4 GeV^2/c^2, and $p(e, e'p)\eta^0$ from the $S_{11}(1535)$ at $Q^2 = 2.4$ and 3.6 GeV^2/c^2, with electron energies 3.2 and 4.0 GeV respectively. The experiment utilized about 200 hrs of beam at a current of

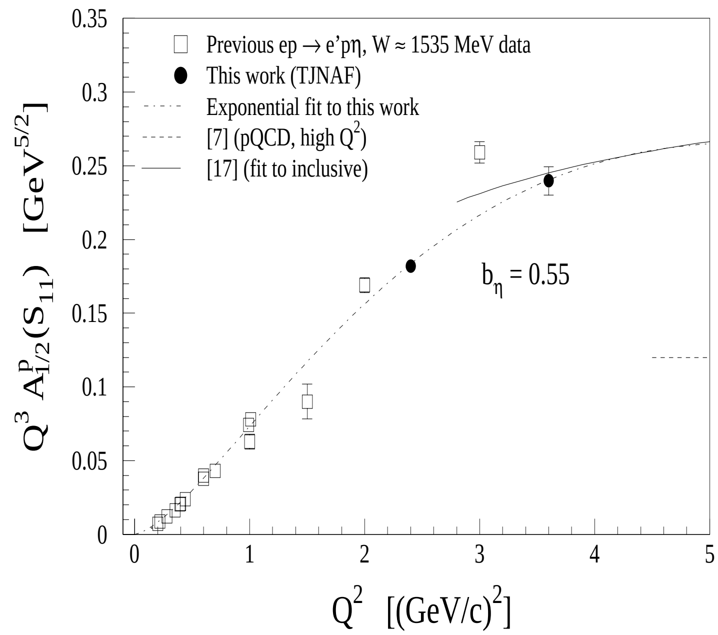


Figure 5: $Q^3A^p_{1/2}(Q^2)$ for the $S_{11}(1535)$ The various curves and the earlier data are discussed in ref. [11].

about 100 μA, producing about 50,000 events each for the Δ and S_{11} at each Q^2 setting. For each beam energy the electrons were detected by the SOS spectrometer, which was fixed in angle and momentum to cover the entire W range from elastic through about 1600 MeV. Protons were detected by the HMS spectrometer. At high momentum transfer the protons emerge in a rather narrow cone around $\vec{q}$ corresponding to 4π in the c.m., as shown in fig. 6

At 4 GeV about 5 angular and 5 momentum settings of the HMS were sufficient to cover a large part of 4π with 50% overlap between adjacent settings. Since the experiment was kinematically complete, the identification of π^0's and η's was accomplished by missing mass reconstruction on an event by event basis, as were the kinematic variables Q^2, W, and the resonance c.m. decay angles θ_{cm}. This is shown in fig. 7 for one run as an example.

The reconstructed c.m. decay angles are typically about $\delta\phi \sim 3°$ and $\delta(cos\theta) \sim .04$. For the Δ the 2 pion background is totally eliminated, whereas for the S_{11} only a small multipion background remains. "As an example of the overall quality of our data, fig. 8 shows a subset of our $\theta_{c.m.}$ distributions at $Q^2 \sim 2.8$ GeV^2/c^2 for several intervals of W and ϕ.

Global fits to the data have been carried out by several groups, most recently MAID(2000) [3], shown in figure 2, and Collaborators Davidson and Mukhopadhyay, using a fully unitarized effective Lagrangian approach to extract G^*_M (i.e. $|M_{1+}|$, $Re(E^*_{1+}M_{1+})/|M_{1+}|^2$, and $Re(S^*_{1+}M_{1+})/|M_{1+}|^2$).

4 Proposed Experiment

In light of the success of E94-014, and evolving physics interest, in 1997 the PAC awarded 25 days beam time (E97-101) to extend the Q^2 data to 7.5 GeV^2/c^2 utilizing an electron beam energy

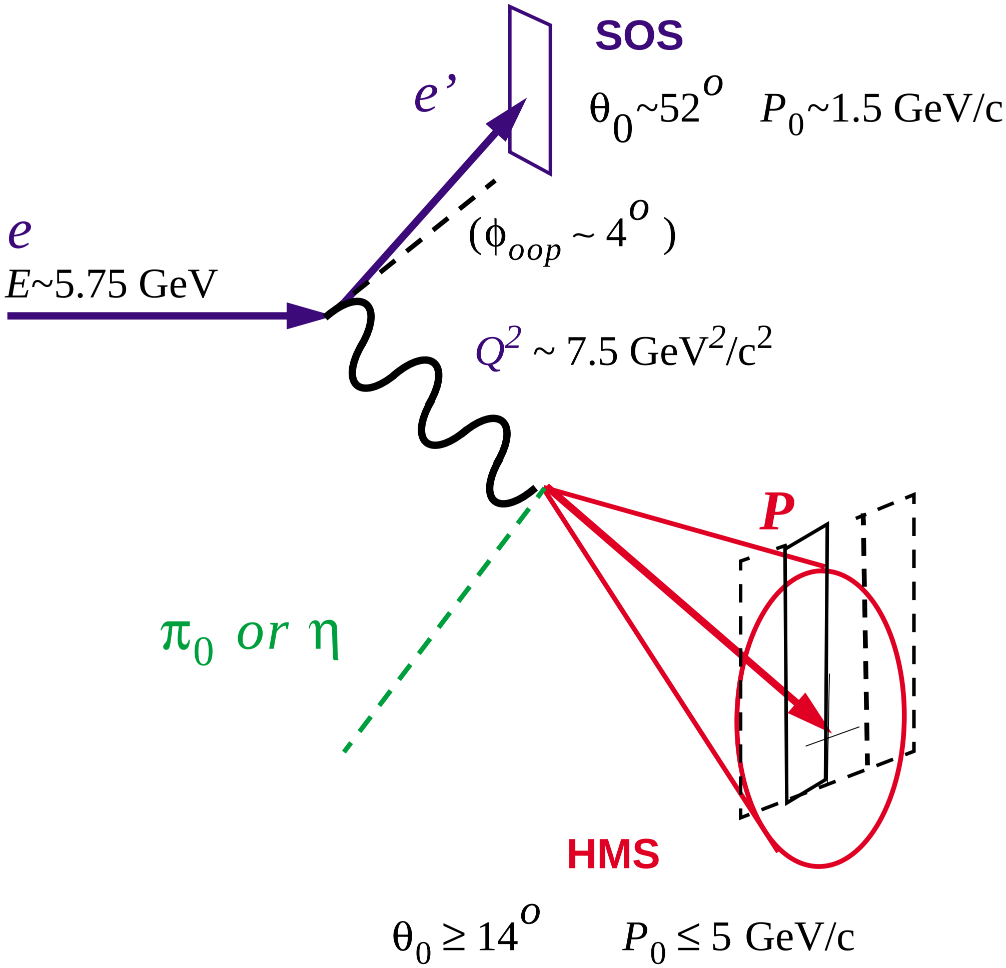


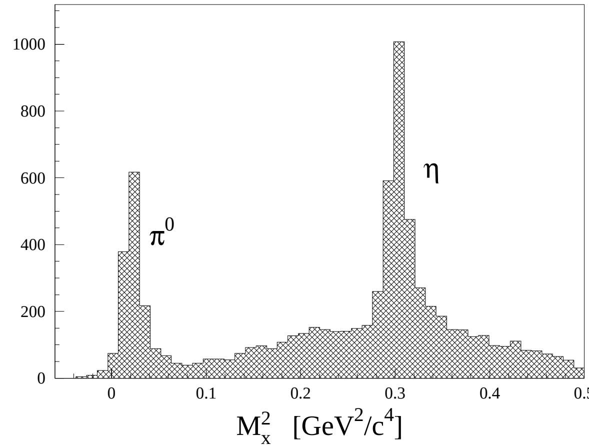
Figure 6: The kinematics of the experiment E94-014 for the reactions $p(e, e'p)\pi^0, \eta$.

of 5.75 GeV. Since that time there has further evolved a major new framework (GPD's) which theoretically unifies the present experiment to an entire program of high t physics including elastic and transition form factors and wide angle Compton scattering. Taken together we expect that they will yield a new frontier of information about transverse space and spin correlations of partons. The experiment will measure the reactions $p(e, e'p)\pi^0$ from the $\Delta(1232)$, and $p(e, e'p)\eta$ from the $S_{11}(1535)$.

As in 94-014 the scattered electrons will be detected by SOS in coincidence with recoil protons detected by HMS. The SOS central momentum and angle will be fixed throughout the experiment for each run interval, while the HMS momentum and angle will be varied to cover the resonance decay cone and outgoing proton momentum range. The proposed kinematic settings are listed in Table 1.

The Hall C nominal point to point spectrometer optics tunes will be used for both SOS and HMS. The Hall C data acquisition system and standard trigger setup are adequate for this experiment's needs.

Figure 7: Missing mass squared m^2 vs. W for the reaction $p(e, e'p)$ obtained in experiment 94-014. This corresponds to one kinematic setting in θ_0^{HMS} and P_0^{HMS}. The π^0 and η reconstructions are clearly visible in the projection on the m^2 axis on the right, as is the multipion continuum. A projection on W with a cut on the missing masses of the π^0 and η shows the clean separation of the $\Delta(1232)$ and the $S_{11}(1535)$ by means of π^0 and η production respectively.



The increase in Q^2 from 4 to 7.5 GeV^2/c^2 results in a successively narrower decay cone of the resonance, which makes the total number of settings smaller, and yields greater acceptance at larger out-of-plane center of mass angles. Acceptances as a function of $cos(\theta_{cm})$ for different out-of-plane center of mass angles ϕ_{cm} at intervals of W near the $\Delta(1232)$ are shown in fig. 9

The price one has to pay for increasing the Q^2 is the degradation of the center of mass angular and energy resolutions and the resolutions of the reconstructed missing mass, all by more than 30 %, which makes it more difficult to apply missing mass cuts to separate the radiative elastic process from the pion production in case of the $\Delta(1232)$ and to suppress the multipion background under the eta peak in case of the $S_{11}(1535)$. However, there are additional techniques which we have learned since E94-014 was run. Also there has been progress in the careful modelling of the radiative and multipion backgrounds. Since the SOS angular resolution is the biggest contributor to the reconstruction resolutions in E94-014, for the $Q^2 = 7.5$ GeV^2/c^2 run we will consider decreasing the quadrupole field and thereby improve angular resolution at the expense of some acceptance.

Using a current of 100 μA incident on the Hall C 4 cm liquid hydrogen target we expect to collect about 25,000 events for each resonance simultaneousely in 25 days of running. The SOS momentum and angle will be fixed at $P_0 = 1.6$ GeV/c, and $\theta_0 = 53°$. Table 1 shows the proposed HMS angular and momentum settings. The expected ratio of true to accidental rates is on the order of a few percent per beam bunch for the settings at the smallest angle and momentum, and is much smaller for the rest of the settings.

Electrons (SOS)				Protons (HMS)			
Q^2	E_{beam}	E'_0	θ'_0	P_{max}	P_{min}	θ_Q	$P-\theta$ settings
7.5 GeV^2/c^2	5.75 GeV	1.6 GeV	53°	5.1 GeV/c	3.1 GeV/c	14°	10

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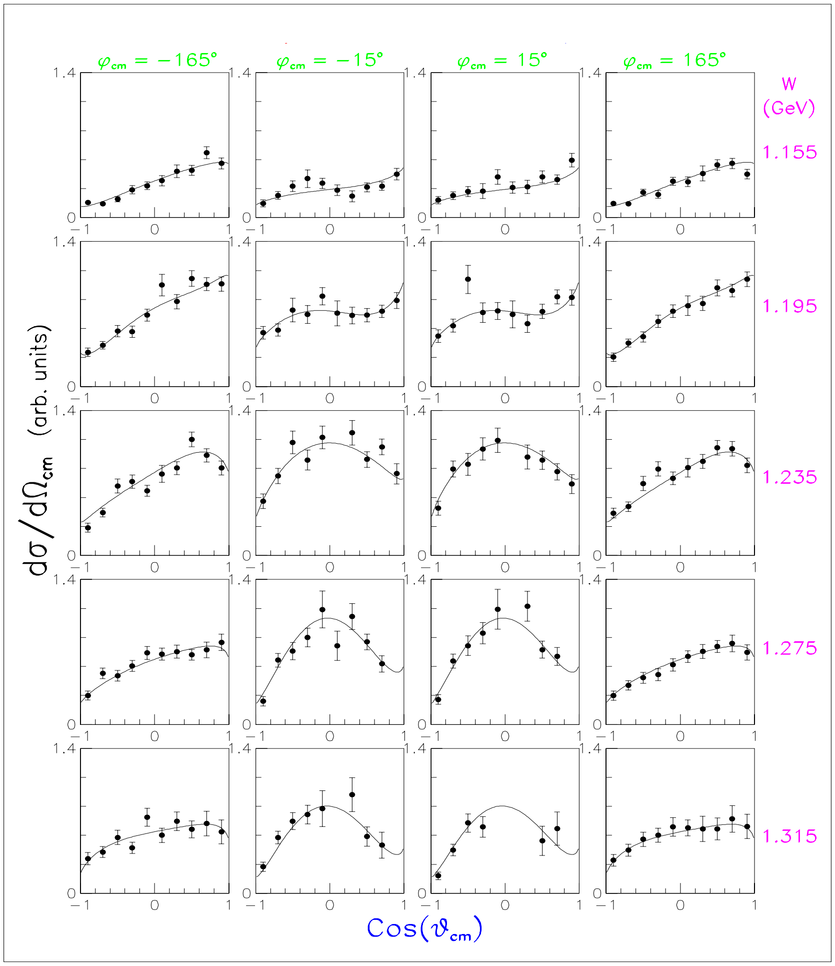

Figure 8: Center of mass angular distribution for π^0 production at the delta resonance, for selected kinematic intervals of W and out of plane angles ϕ at Q^2= 2.8 GeV^2/c^2, obtained in experiment 94-014. The curves represent a global fit in terms of multipoles, up to p waves, and assuming M_{1+} dominance.

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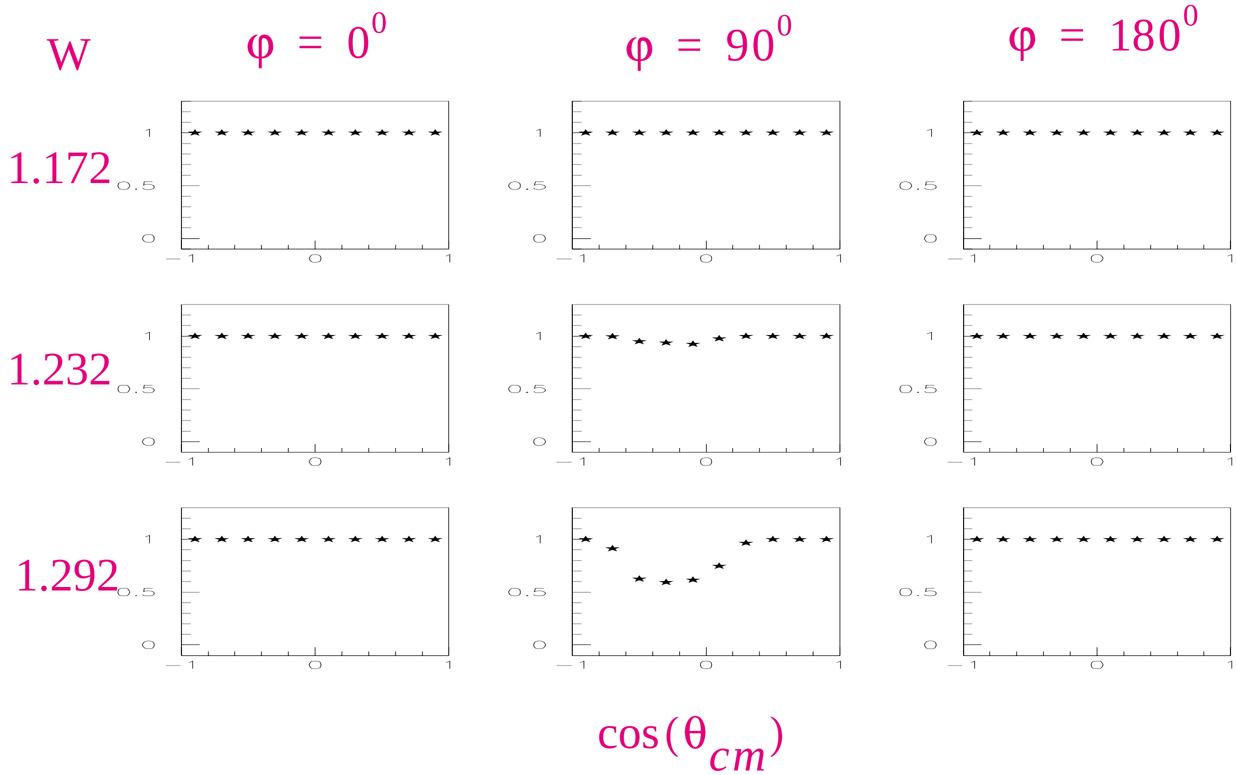

Figure 9: The calculated acceptance function for the reaction $p(e, e'p)\pi^0$ at three values of out of plane angle $\phi = 0°, 90°$, and $180°$ at three values of W for $Q^2 = 5$ and 7.5 $\mathrm{GeV}^2/\mathrm{c}^2$ respectively.

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