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Ralf W. Gothe · Ye Tian

Impact of the γ_νNN* electrocoupling parameters at high photon virtualities and preliminary cross sections off the neutron

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Abstract Meson-photoproduction measurements and their reaction-amplitude analyses can establish more sensitively, and in some cases in an almost model-independent way, nucleon excitations and non-resonant reaction amplitudes. However, to investigate the strong interaction from already explored – where meson-cloud degrees of freedom contribute substantially to the baryon structure – to still unexplored distance scales – where quark degrees of freedom dominate and the transition from dressed to current quarks occurs – we depend on experiments that allow us to measure observables that are probing this evolving non-perturbative QCD regime over its full range. Elastic *and* transition form factors are uniquely suited to trace this evolution by measuring elastic electron scattering *and* exclusive single-meson and double-pion electroproduction cross sections off the nucleon. These exclusive measurements will be extended to higher momentum transfers with the energy-upgraded CEBAF beam at JLab to study the quark degrees of freedom, where their strong interaction is responsible for the ground and excited nucleon state formations. After establishing unprecedented high-precision data, the imminent next challenge is a high-quality analysis to extract these relevant electrocoupling parameters for various resonances that can then be compared to state-of-the-art models and QCD-based calculations.
The vast majority of the available exclusive electroproduction cross sections are off the proton. Hence flavor-dependent analyses of excited light-quark baryons are lacking experimental data off the neutron. The goal is to close this gap by providing exclusive $\gamma_\nu(n) \to p^+\pi^-$ reaction cross section off deuterium and to establish a kinematical final-state-interaction (FSI) correction factor (R) map that can be determined from the data set itself. The "e1e" Jefferson Lab CLAS data set, that is analyzed, includes both a hydrogen and deuterium target run period, which allows a combined analysis of the pion electroproduction off the free proton, the bound proton, and the bound neutron under the same experimental conditions. Hence it will provide the experimentally best possible information on the off-shell and final state interaction effects in deuterium, which must be considered in order to extract the information off the neutron. The cross section analysis of this data set, that is currently underway, will considerably improve our knowledge of the Q^2 evolution of resonance states off bound protons and neutrons.
Recent results presented here and in these proceedings are demonstrating the status and continuous progress of data analyses and their theoretical descriptions, as well as highlighting the experimental and theoretical outlook of what shall and may be achieved in the new era of the 12-GeV upgraded transition form factor program.

Keywords Baryon resonances · Baryon structure · Transition form factors · Meson electroproduction

R.W. Gothe
University of South Carolina, Columbia, SC 29208, USA
Tel.: +1-803-777-9025
Fax: +1-803-777-3065
E-mail: gothe@sc.edu

1 Introduction

Already in the early inclusive high-energy deep inelastic scattering (DIS) experiments at SLAC [1], scaling and quasi-free scattering off still dressed quarks was observed at the then highest beam energies of up to $E = 20\,GeV$ but yet moderate four-momentum transfers of $Q^2 < 2\,(GeV/c)^2$. In these early inclusive measurements, as shown and discussed previously [2], the quasi-free peak becomes visible at high beam energies and high center-of-mass energies W, where the electrons seem to scatter off constituent quarks. Although the absolute strength of quasi-free scattering starts to dominate the elastic and resonance contributions with increasing W and Q^2, it is pushed out so far in W [3] that its relative contribution in the resonance regions becomes even smaller with increasing Q^2. The resonance-to-background ratio further increases due to the decreasing meson-baryon contributions to the baryon structure at increasing Q^2. Both effects are less evident if observed relative to the $\Delta(1232)$ resonance yields, since these drop faster with Q^2 than the resonance contributions in the second and third resonance region [3], where the individual resonance contributions can only be separated in exclusive electroproduction measurements like those carried out with the large-acceptance spectrometer CLAS at Jefferson Lab.

Mapping out the transition from exclusive resonance production to quasi-free scattering over W and Q^2 in detail, lays the experimental foundation to investigate quark-hadron duality [4], scaling [5; 6], the bound-quark structure, confinement, dynamical mass generation, and the structure of baryons [7]. The accepted research proposal E12-09-003 at Jefferson Lab, Nucleon Resonance Studies with CLAS12 [8], will establish this experimental foundation to address in a unique way these most pressing questions in QCD. Properly extracting and interpreting the results from the measured electron scattering data, particularly for transition form factors to high-lying excited nucleon states, might even pose a greater challenge than the measurement itself. A steadily growing collaboration of experimentalists and theorists is working together to enable the measurements, the analysis of the data, and the QCD-based interpretation of the results. The progress in this field presented here and in this proceedings has also been summarized in recent review articles [9; 10] and most comprehensively in, Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction [7].

The nucleon resonance (N^*) studies are crucial to our understanding of the structure and interaction of hadrons, and are poised to push the development of quark models and QCD-based calculations forward. In the perturbative regime at large Q^2, QCD describes the strong interaction successfully based on current quarks and gauge gluons as the fundamental degree of freedom, however when Q^2 drops into the non-perturbative regime, a transition to completely different degrees of freedom, the dressed quarks and gluons as well as the mesons and baryons, happens. This transition is neither experimentally mapped out nor theoretically understood from first principles. Therefore a sufficiently complete electroexcitation data base has to be established to pin down the distance-dependent baryon structure and to aid the development of a QCD-based strong interaction theory. On the experimental side, most of the low-lying excited states of the proton have already been studied in the low-Q^2 range, but there is still very little data available on the neutron excitations [11]. Because of the inherent difficulty in obtaining a free neutron target, a deuterium target is the next best alternative to investigate the isospin-dependent structure of the nucleon and its excited states.

2 Hadronic structure analysis

The general analogy to the hydrogen atom – which is the simplest atom bound by electromagnetic fields of well-known dynamics – that the ground state can be unambiguously described by the spectrum of its excited states, does not hold for the nucleon – which is the lightest three-quark system bound by strong fields – since the evolution of the strong interaction from small to large distance scales is not known. Hence even the spectrum of *all* excited states is by itself not sufficient to pin down the baryonic structure, but it is the best possible approach to disentangle the individual interfering resonance and background amplitudes in an almost model-independent way by so-called complete experiments. Here in the simplest case of pseudo-scalar meson photoproduction, the cross section can be decomposed into four gauge- and Lorentz-invariant complex amplitudes. In a combination of unpolarized, beam-, target-, and recoil-polarization experiments, a total of up to 16 observables can be measured with a large solid angle detector, where only eight (or seven, taking into account an overall undetermined phase) are linearly independent. With the caveat that most baryon resonances, except the lowest lying ones, decay dominantly into vector-meson or multi-meson channels, complete experiments in single pseudo-scalar meson photoproduction and corresponding partial wave analyses will allow for the highest quality extraction of resonance parameters under minimal model assumptions. New complete sets of observables [12; 13] that exploit the high analyzing power of some hyperon decays led to several new or PDG-upgraded [14] excited states seen in the recently updated Bonn-Gatchina coupled-channel analysis [15].

Beyond baryon spectroscopy at the real photon point $Q^2 = 0\,(GeV/c)^2$, electron scattering experiments are essential to investigate the strong interaction and thereby the internal hadronic structure at various distance scales by tuning the four-momentum transfer from $Q^2 \approx 0\,(GeV/c)^2$, where the meson cloud contributes significantly to the baryon structure, over intermediate Q^2, where the three constituent-quark core starts to dominate, to Q^2 up to $12\,(GeV/c)^2$, attainable after the $12\,GeV$ upgrade at JLab [8], see Fig. 3, where the constituent quark gets more and more undressed towards the bare current quark [16; 17].

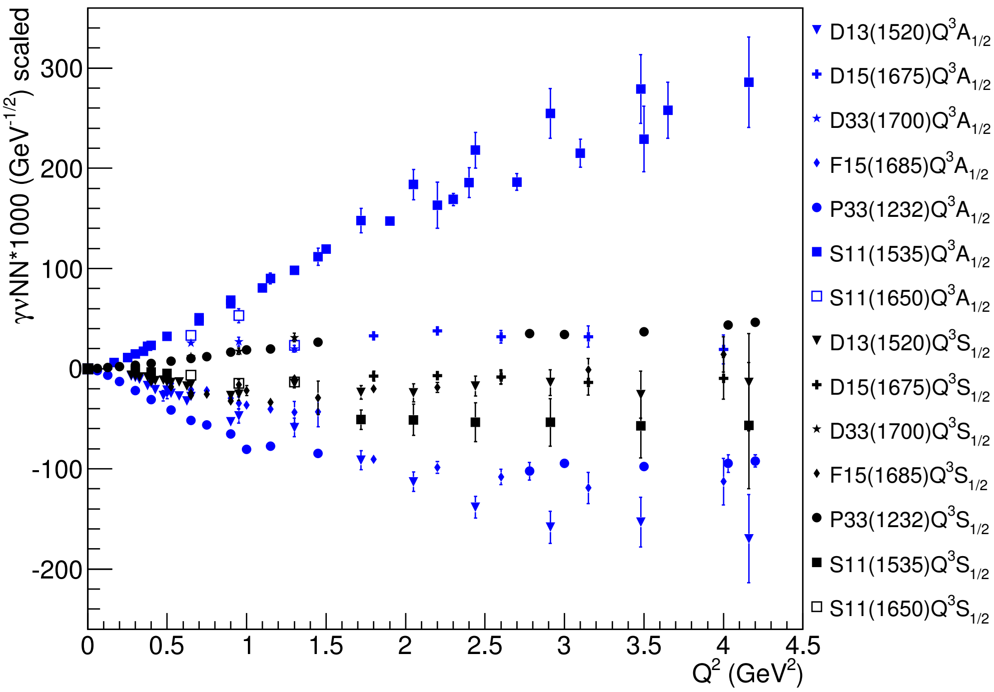

Fig. 1 (Color online) The Q^2 dependence of the γ_νNN* helicity amplitudes $A_{1/2}$ and $S_{1/2}$ off the proton that have been extracted from CLAS data [18; 19; 9] is shown. These helicity conserving amplitudes for resonances with masses up to $1700\,MeV$ are scaled by Q^3 as predicted for baryons with three effective constituents only.

Although originally derived in the high Q^2 limit [6], constituent counting rules describe in more general terms how the transition form factors and the corresponding helicity amplitudes scale with Q^2, dependent on the number of effective constituents [5]. The available CLAS results for $Q^2 < 4.5\,(GeV/c)^2$ [18; 19; 9] may already indicate, particularly for the helicity conserving transition amplitudes $A_{1/2}$ and $S_{1/2}$, the onset of the predicted scaling with $1/Q^3$ for effective three-quark systems, as shown in Fig. 1. Whether this constituent counting rule scaling truly sets in at such low momentum transfers, will be one of the first results based on the experimental data gathered in the first run period with the 12-GeV upgraded CLAS detector (CLAS12) in Hall B [8]. If verified at higher Q^2, this further indicates that in these cases the meson-baryon contributions become negligible in comparison to those of the three constituent-quark core, which coincides with the Argonne-Osaka dynamical coupled channel calculation [7; 20].

Along the same line of reasoning perturbative QCD (pQCD) predicts in the high-Q^2 limit, by neglecting higher twist contributions, that helicity is conserved. The fact that this predicted behavior seems to set in already at much lower Q^2 values than expected [18; 19; 9] challenges our current understanding of baryons even further. For $N(1520)D_{13}$ the helicity conserving amplitude $A_{1/2}$ starts to dominate the helicity non-conserving amplitude $A_{3/2}$ at $Q^2 \approx 0.5\,(GeV/c)^2$, see Fig. 2, as typically documented by the zero crossing of the corresponding helicity asymmetry $A_{hel} = (A^2_{1/2} - A^2_{3/2})/(A^2_{1/2} + A^2_{3/2})$. The $N(1675)D_{15}$ and $N(1680)F_{15}$ resonances show a similar behavior with zero crossings below $Q^2 \approx 1\,(GeV/c)^2$, see Fig. 2, whereas the $\Delta(1232)P_{33}$ helicity asymmetry stays negative with no indication of an upcoming zero crossing; and even more surprising are the results for the $N(1720)P_{13}$ $A_{1/2}$ amplitude, which decreases so rapidly with Q^2 that the helicity asymmetry shows an inverted behavior with a zero crossing from positive to negative around $Q^2 \approx 0.5\,(GeV/c)^2$. Figure 2 also illustrates the statistical limitations of the currently available data, because the helicity asymmetry is due to the difference of large numbers more error sensitive than the helicity amplitudes themselves, and higher statistics and thus higher accuracy would be desirable.

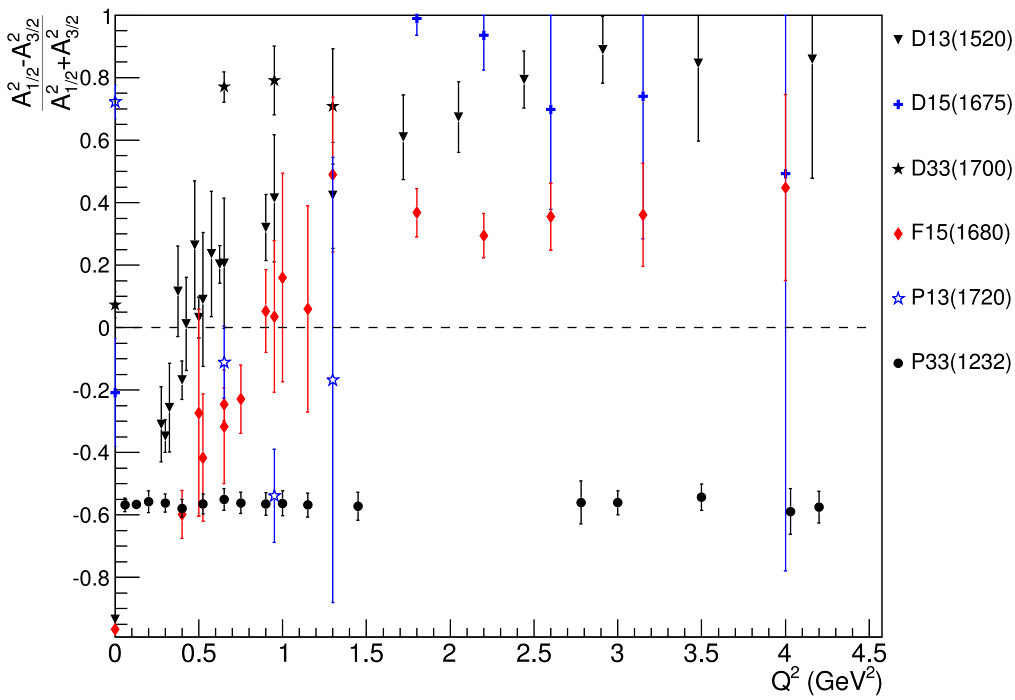

Fig. 2 (Color online) The Q^2 dependence of the helicity amplitude asymmetries off the proton that have been extracted from CLAS data [18; 19; 9] is shown for resonances with masses up to 1720 MeV.

This essentially different behavior of transition form factors to various excited states with different quantum numbers underlines that it is necessary but not sufficient to extend the measurements of the elastic form factors to higher momentum transfers. To comprehend the strong interaction at intermediate distance scales, where dressed quarks degrees of freedom are responsible for the formation and diverse behavior of baryons in distinctively different quantum states, the Q^2 evolution of transition form factors to multiple resonance states up to $12\,(GeV/c)^2$ is absolutely crucial [7; 8]. Figure 3 shows two examples of projected results for the $A_{1/2}$ helicity amplitudes of the p to $P_{11}(1440)$ and $D_{13}(1520)$ transitions. Attempts to extract N to N^* transition form factors in vector-meson electroproduction and off the neutron in deuterium are currently pursued to further complement the data base.

3 Preliminary results off the neutron

In order to extract from electron scattering off deuterium the exclusive $\gamma_\nu(n) \to p^+\pi^-$ reaction cross section, the FSI corrections and the off-shell effects need to be studied thoroughly. The kinematical

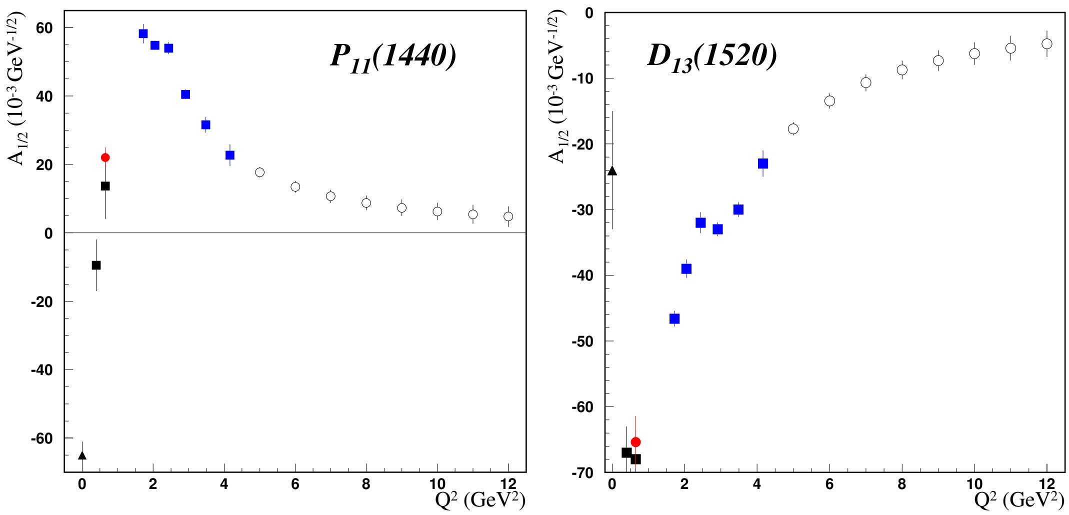

Fig. 3 (Color online) Available (filled symbols) [18] and projected CLAS12 [8] (open symbols) $A_{1/2}$ electrocouplings of the $P_{11}(1440)$ (left) and the $D_{13}(1520)$ (right) excited states.

FSI correction factor can be extracted directly from the measured data by using

$$R_{FSI} = \frac{\left(\frac{d\sigma^{quasi-free}}{d\Omega^*_{\pi^-}}\right)}{\left(\frac{d\sigma^{full}}{d\Omega^*_{\pi^-}}\right)}, \tag{1}$$

where the exclusive quasi-free process can be isolated by applying two cuts, one on the missing mass square of the spectator proton (m_s^2) and one on the magnitude of its missing momentum ($|\mathbf{P_s}|$), whereas the exclusive full process is obtained by only cutting on the missing mass square of the spectator proton. The comparison of the measured spectator momentum distribution (black line) with the generated proton momentum distribution from the Bonn potential [21] that has been smeared according to the

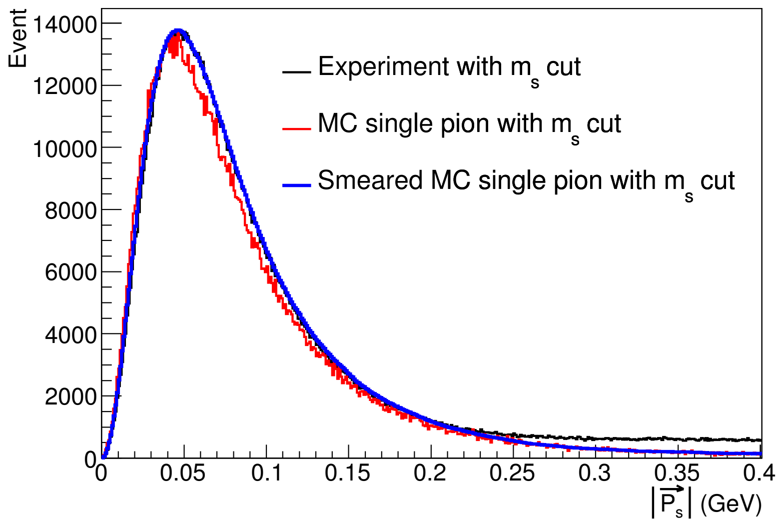

Fig. 4 (Color online) The black line represents the missing momentum distribution of the unmeasured proton from data. The Monte-Carlo simulated proton momentum distribution (red line) is based on the Bonn potential [21] and has been smeared according to the detector resolution (blue line).

detector resolution (blue line) for $|\mathbf{P_s}| < 200\,MeV$, seen in Fig. 4, reveals that the quasi-free process is absolutely dominant in this kinematic region, while for $|\mathbf{P_s}| > 300\,MeV$ the final state interactions start to dominate the process. This shows that the quasi-free process can be successfully isolated by cutting on $|\mathbf{P_s}|$ at $200\,MeV$. Preliminary results on the kinematical FSI correction factor R_{FSI} as a function of the pion polar angle (θ^*_π) in the Center of Mass frame (COM) indicate that the kinematical FSI corrections are largest at small angles, θ^*_π, with respect to the virtual photon direction.

After proper particle identification, fiducial cuts, and the exclusive quasi-free event selection, the cross section for the quasi-free $\gamma_\nu(n) \to p^+\pi^-$ reaction with unpolarized electron beam and unpolarized deuteron target is given by

$$\frac{d^4\sigma}{dW\,dQ^2 d\Omega^*_{\pi^-}} = \Gamma_\upsilon \frac{d\sigma}{d\Omega^*_{\pi^-}}, \tag{2}$$

where Γ_υ is the virtual photon flux defined by Eq. (3), in which ϵ denotes the transverse polarization of the virtual photon, $\nu = E_{beam} - E_{scattered\ electron}$ the energy transfer, and θ_e the scattering angle of electron in the LAB frame with respect to the incoming electron direction.

$$\Gamma_\upsilon = \frac{\alpha}{4\pi}\frac{1}{E^2_{beam}M^2_n}\frac{W(W^2 - M^2_n)}{(1-\epsilon)Q^2},\ \epsilon = (1 + 2(1 + \frac{\nu^2}{Q^2})\,tan^2\frac{\theta_e}{2})^{-1} \tag{3}$$

Finally, the quasi-free differential pion electroproduction cross section, that is corrected for FSI and off-shell effects, is given by

$$\frac{d\sigma}{d\Omega^*_{\pi^-}} = \frac{1}{\Gamma_\upsilon}\frac{1}{R_{FSI}}\frac{d^4\sigma}{dW\,dQ^2 d\Omega^*_{\pi^-}}. \tag{4}$$

Figure 5 shows the $\phi^*_{\pi^-}$ dependent differential cross section in the Δ resonance region as a typical subset of the available data. The preliminary cross sections are compared to two physics models MAID2000 [22] and SAID [23].

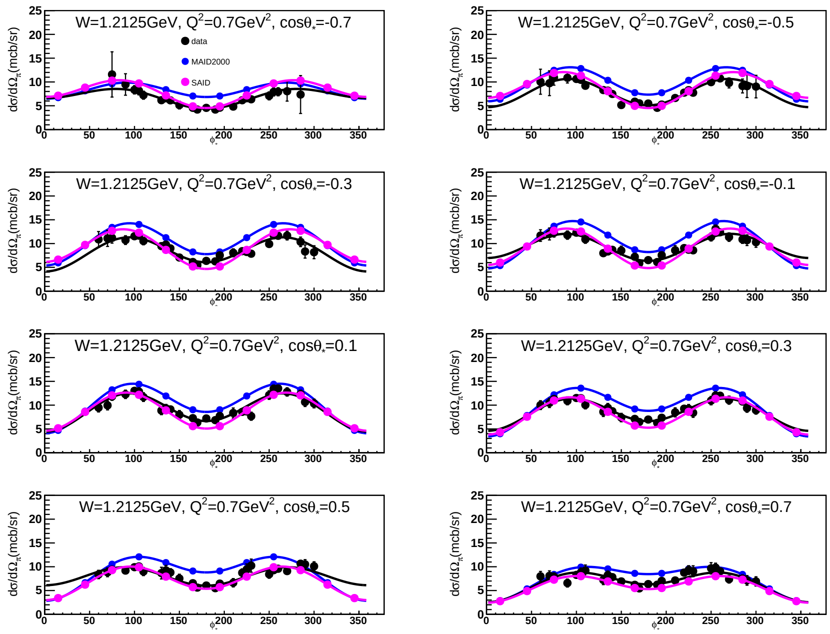

Fig. 5 (Color online) A typical example of preliminary $\phi^*_{\pi^-}$ dependent cross sections in the $P_{33}(1232)$ resonance region for different $cos\theta^*_{\pi^-}$ bins at $Q^2 = 0.7\,GeV$ and $W = 1.2125\,GeV$ in comparison with MAID2000 (blue line) and SAID (purple line) predictions. Black line is the fit to the extracted differential cross sections.

The hadronic cross section $\frac{d\sigma}{d\Omega^*_{\pi^-}}$ is fit in terms of $cos\phi^*_{\pi^-}$ (Eq. (5)) to extract the underlying structure functions. The fit function has three fit parameters a, b, and c, which correspond to the structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT}, and σ_{TL}, respectively,

$$\frac{d\sigma}{d\Omega^*_{\pi^-}} = a + b\cos 2\phi^*_{\pi^-} + c\cos\phi^*_{\pi^-},\ a = \sigma_T + \epsilon\sigma_L,\ b = \epsilon\sigma_{TT},\ c = \sqrt{2\epsilon(1+\epsilon)}\sigma_{TL}. \quad (5)$$

An example of a typical structure function separation as a function of $cos\theta^*_{\pi^-}$ for $Q^2 = 0.5\,GeV$, $0.7\,GeV$, and $0.9\,GeV$ at $W = 1.212\,GeV$ is shown in Fig. 6 in comparison to the SAID [23] and MAID2000 [22] models. In order to gain some insight on the dominant partial wave contribution in this particular Δ-resonance energy bin, a Legendre polynomial expansion of the structure functions up to $l = 2$ has been performed, see Fig. 6.

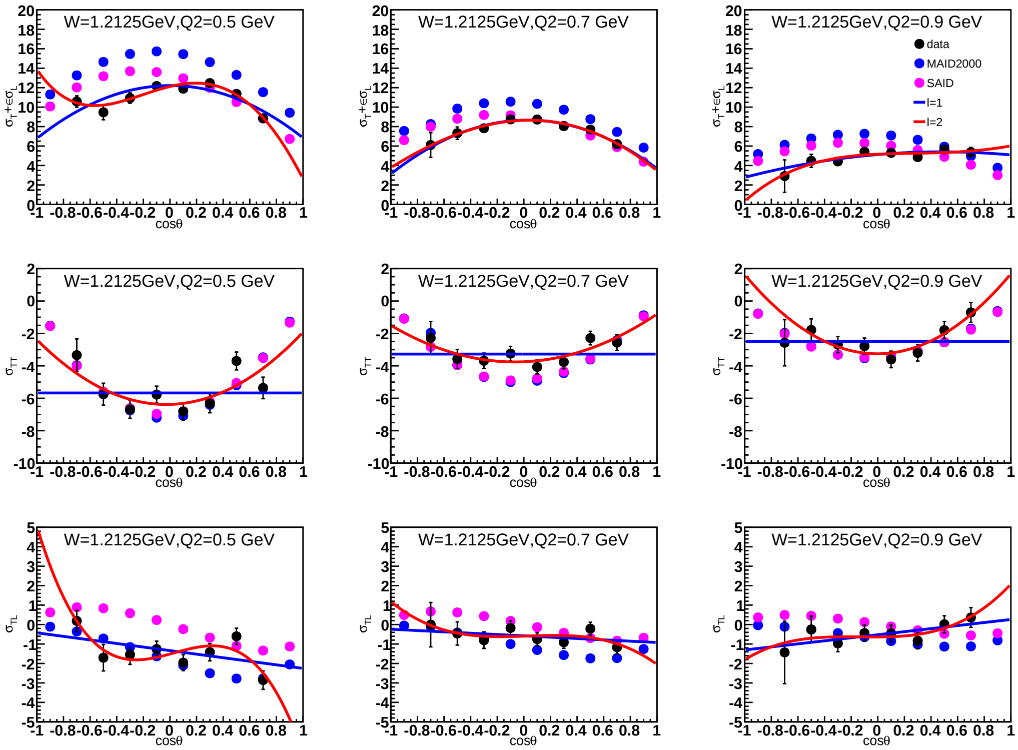

Fig. 6 (Color online) Preliminary $\sigma_T + \epsilon\sigma_L$, σ_{TT}, and σ_{TL} results (top, middle, and bottom row) in the $P_{33}(1232)$ resonance region for different $Q^2 = 0.5\,GeV$, $0.7\,GeV$, and $0.9\,GeV$ (left, middle, and right column) are shown as black points and compared with the MAID2000 (blue points) and SAID predictions (purple points). The blue and red lines are Legendre polynomial fits to the black points for $l = 1$ and $l = 2$, respectively.

4 Summary

All visible matter that surrounds us is made of atoms, which are made of electrons and nuclei; the latter are made of nucleons, which are finally made of quarks and gluons. Contrary to the more publicized discussions, the Higgs, or also frequently called the God Particle, is not responsible for the generation of all mass. It is already known that 98% of all visible mass is non-perturbatively generated by strong fields. Establishing an experimental and theoretical program that provides access to

- the flavor-dependent dynamics of the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and their confinement in baryons,
- the dependence of the light quark mass on the momentum transfer and thereby how the constituent quark mass arises from dynamical chiral-symmetry breaking, and
- the behavior of the universal QCD β-function in the infrared regime,

is indeed most challenging on all levels, but recent progress and future commitments [7] bring a solution of these most fundamental remaining QCD problems into reach. Single- and double-polarization experiments are essential to establish the baryon spectrum, branching ratios, and a detailed separation of individual resonance and background contributions. Elastic and particularly transition form factors are on the other hand needed to uniquely track non-perturbative QCD from long to short distance scales.

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