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Backward Angle (u-Channel) Exclusive and Semi-Inclusive DIS Processes at JLab 12 GeV and Future EIC

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The exclusive backward-angle (u-Channel) meson electroproduction from Jefferson Lab electron-proton fixed-target scattering experiments in the Deep Inelastic Scattering (DIS) hints at a new domain of applicability of QCD factorization in a unique kinematics regime, where the Mandelstam variable $t \rightarrow t_{\text{max}}$. The interest in studying nucleon structure through the backward meson production observables has grown significantly. In a recent development, the Semi-Inclusive DIS (SIDIS) process in the u-Channel kinematics (observables involved the baryon number exchange between the target and ejected particle) was linked to the existence of a baryon junction that was predicted by the local gauge invariance of the baryon wave function. It is suggested that this structure could carry the baryon number. In this presentation, we provide an overview of the upcoming exclusive and the SIDIS measurements, the underlying theory, and the expected results from the JLab 12 Hall C GeV program with future remarks.

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1. Introduction

Probing the nucleon structure through exclusive and semi-inclusive Deep Inelastic Scattering (SIDIS) using a virtual photon (γ^*) probe has been a key objective of the hadron physics community in the past decades. In the proceedings, we focus on one specific type of interaction, known as the u-Channel (backward) interaction, where the Mandelstam variable $|u| \ll |t|$. Here, u is the squared momentum transfer between a produced meson M and the target N is $|u| = |(p_M - p_N)^2|$; t is the squared momentum transfer for the target before and after the interaction $|t| = |(p'_N - p_N)^2|$. The non-intuitive nature of such an interaction is revealed in the following example: a virtual photon (γ^*) probe is induced by the accelerated electron and interacts with a fixed proton target. The coiling nucleon absorbs most of the momentum transfer from the probe and travels forward. In the case of deep exclusive meson production case, a meson is produced and remains close to the target, nearly at rest; Whereas, for the SIDIS case, multiple final state hadrons could be produced. As one can see from Fig. 2, for these processes to occur, the baryon number must be exchanged between the target and recoiled/ejected leading proton (high momentum). Therefore, this type of reaction is referred to as a "knocking a proton out of a proton" process and offers access to unique information about the parton distribution for the nucleon wave function. Terminologically, the u-Channel meson production is equivalent to the t-Channel baryon (proton) production in the ep collision setup.

2. A colinear factorization scheme in u-Channel kinematics regime

The baryon-to-meson Transition Distributions Amplitudes (TDAs) [1–3] are the backward-angle analog of Generalized Distribution Amplitudes [4, 5]. TDAs describe the underlying physics mechanism of how the target proton transitions into a meson during the final state. One fundamental difference between GPDs and TDAs is that the TDAs require three parton exchanges between πN TDA and Colinear Factorization (CF) in backward angle kinematics: $-t \to -t_{max}$, $-u \to -u_{min}$, $t > Q^2$ and $W > 2$ GeV. The interaction diagrams of GPDs and TDAs are represented in Fig. 1.

The TDA colinear factorization has made two specific qualitative predictions regarding backward meson electroproduction, which can be verified experimentally [3, 6–8]:

- The characteristic $1/Q^{10}$-scaling behavior of the transverse cross section for fixed x, following the quark counting rules.
- The dominance of the transverse polarization of the virtual photon results in the suppression of the σ_L cross section by a least $1/Q^2$: $\sigma_L/\sigma_T < 1/Q^2$, or $\sigma_T \gg \sigma_L$.

These predictions were separately validated by the exclusive backward π^+ electroproduction from CLAS [9] and the L/T separated ω cross-section from Hall C [10], respectively. Both results were from JLab 6 GeV era.

3. Upcoming exclusive π^0 production experiment at JLab 12 GeV

Similar to the 6 GeV era Hall C measurements [10], additional u-channel meson electroproduction data were fortuitously acquired during the KaonLT and PionLT experiment at Jefferson Lab

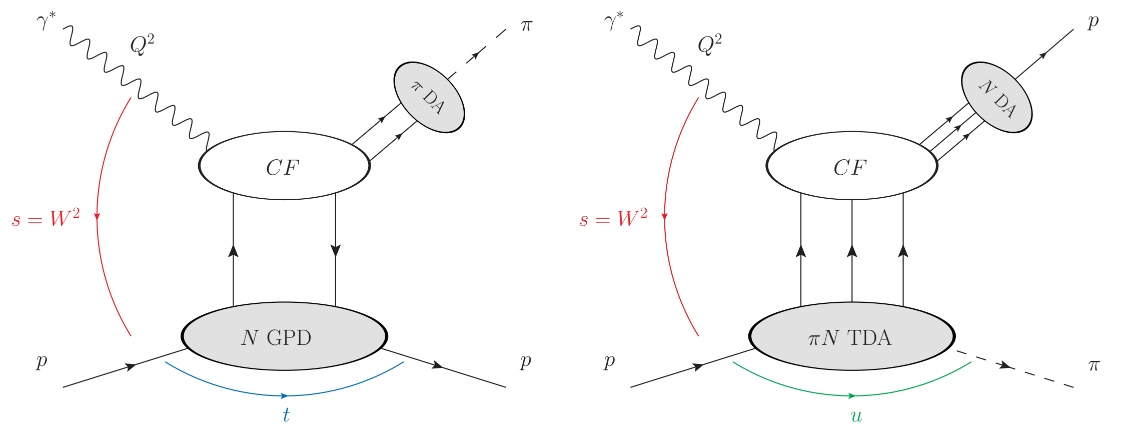

Figure 1: Left: t-Channel π^0 electroproduction interaction ($\gamma^* p \to p\pi^0$) diagram under the (forward-angle) GPD collinear factorization regime (large Q^2, large s, fixed x_B, fixed $t \sim t_{min}$). N GPD is the quark nucleon GPD. π DA stands for the vector meson distribution amplitude. The CF corresponds to the calculable hard process amplitude. Right: shows the (backward-angle) TDA collinear factorization regime (large Q^2, large s, fixed x_B, $u \sim u_{min}$) for $\gamma^* p \to p\pi^0$. The πN TDA is the transition distribution amplitude from a nucleon to a vector meson.

(JLab) Hall C (E12-09-011 [11] and E12-19-006 [12]). The primary purpose for the acquisition of these data was the study of the K^+ and π^+ electromagnetic form factor, but the detector apparatus allowed $^1\text{H}(e, e'p)X$ data to be acquired in parallel. Data were taken well above the resonance region ($2.32 < W < 3.02$ GeV), at selected settings between $Q^2 = 0.5$ and 5.50 GeV^2. For each Q^2-W setting, data were taken at two beam energies, corresponding to $\Delta\epsilon \sim 0.25$ (ϵ: longitudinal to transverse virtual photon ratio), so that L/T/LT/TT separations could be performed. The ep missing mass spectral from the data suggested the existence of η, ω, ρ, η' peak. The L/T-separated cross-section of these mesons could provide further validation to the TDA model.

The approved JLab E12-20-007 [13] is the first dedicated u-Channel physics experiment and is an important step towards the objectives of studying TDAs. The measurement aims to probe the $^1\text{H}(e, e'p)\pi^0$ exclusive electroproduction reaction over the $2 < Q^2 < 6.25$ GeV^2 kinematic range, at fixed $W = 3.1$ GeV ($s = 10$ GeV^2) and $-u_{\text{min}}$. The experiment will utilize the 11 GeV electron beam on an unpolarized liquid hydrogen target (LH$_2$), in combination with the high precision High Momentum Spectrometer (HMS) and super High Momentum Spectrometer (SHMS) available in Hall C. The key observable involves the detection of the scattered electrons in coincidence with energetic recoiled protons, and resolving the exclusive π^0 events using the missing mass reconstruction technique [14]. The separated cross sections, σ_T, σ_L, and the $\sigma_\text{T}/\sigma_\text{L}$ ratio at 2-5 GeV^2 will directly challenge the two predictions of the TDA model, $\sigma_\text{T} = 1/Q^{10}$ and $\sigma_\text{T} \gg \sigma_\text{L}$, in u-Channel kinematics. This will be an important step forward in validating and providing constraints to a backward factorization scheme and establishing its applicable kinematics range.

A preliminary study [15] has confirmed the feasibility of studying $e + p \to e' + p' + \pi^0$ over the range $6.25 < Q^2 < 10.0$ GeV^2. Furthermore, other studies [16, 17], also demonstrated the overall feasibility of detecting DVCS, π^0, ρ and ω in the wider u-Channel kinematics. The EIC offers a unique opportunity to provide a definitive test of TDA predictions beyond JLab 12 GeV

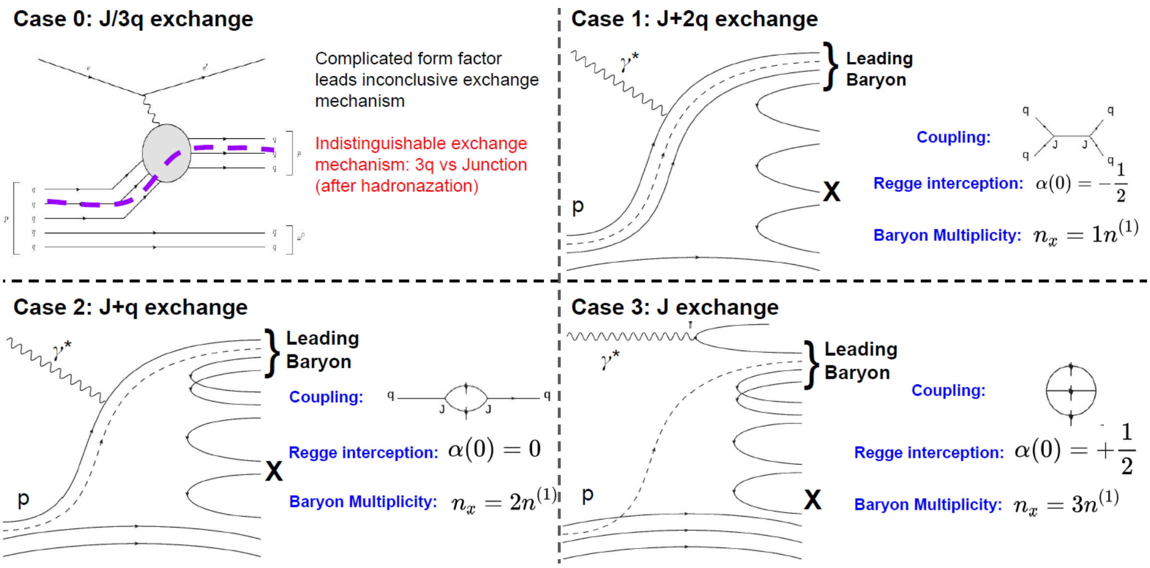

Figure 2: Top-left: exclusive u-Channel meson production diagram where the exchanged particle consists of three quark and (or) baryon junction (purple dashed line); Top-right, bottom-left and bottom-right show semi-inclusive processes in which the baryon junction mediates the forward baryon production, either 2,1 or 0 valence quarks are exchanged with the baryon junction, respectively; the final-state mesons X are produced as a result of 1, 2, or 3-string fragmentation, respectively. Solid lines represent quarks, and dashed lines represent the junction.

kinematics. Backward π^0 production will be studied by the $\overline{\text{P}}$ANDA experiment at FAIR [18, 19]. This experimental channel can be accessed through observables including $\overline{p} + p \longrightarrow \gamma^* + \pi^0$ and $\overline{p} + p \longrightarrow J/\psi + \pi^0$. Note that this backward π^0 production involves the same TDAs as in the electroproduction case. They will serve as very strong tests of the universality of TDAs in different processes [18, 19].

4. Semi-Inclusive DIS Observable and Baryon Junction

In the early 70s, it was argued that local gauge invariance of the baryon wave function would lead to the emergence of a baryon junction, which corresponds to the three (or N, in SU(N) gauge theory) string operators [20].

In Ref. [21], it describes the emergence of the baryon junction in high-energy pp collisions. The baryon contribution can be separated from the valence quarks, and the final-state baryon always emerges around the junction. The implication is that the baryon number is associated with the junction, and is not fractionally carried by the quarks. In a high-energy inelastic proton-proton collision configuration, the valence quarks carry a high fraction of the proton's momentum and are hard to stop. However, the baryon junctions are made of gluons, carry much smaller momentum, and can thus be stopped in the mid-rapidity region of the collision. When this happens, the strings connecting the junction to the valence quarks break producing a large number of quark-antiquark pairs, but the final-state baryon is always produced around the junction. It is important to note that it is uncorrelated in flavor with the original baryon, even though it carries the original junction. The energy dependence of baryon stopping (predicted by Ref. [21]) was observed at RHIC and

LHC [22–24]. A recent result from the STAR Collaboration suggested a clear difference between the stopping of electric charge and baryon number in collisions of RuRu and ZrZr isobars [23], which suggests the presence of the baryon junction.

In a recent paper [25], the possibility of probing the baryon junction using the fixed target ep scattering experiment at JLab was explored. Under this interaction picture, one relies on direct coupling between the induced virtual photon probe (γ^*), and the baryon junction inside of the target proton. Since the baryon junction has a smaller size and is more "point-like", it is expected to recoil forward and bring 0, 1, or 2 valence quarks and form a leading (fast) final state hadron after the interaction with high z, where

$$z = \frac{E_{\text{proton}}}{E_{\gamma^*}}.$$

Hence, the leading baryon production is produced in the u-Channel kinematics.

Applying the Regge phenomenological description, the manifestation of the baryon junction via the exchange mechanism could yield the following cases (demonstrated in Fig. 2):

Case 0 u-Channel exclusive electroproduction, with three quarks and baryon junction exchange.

Case 1 u-Channel SIDIS electroproduction, with one quark and baryon junction exchange: $M_2^J = (q\bar{q}J\bar{J})$, with an interception of $\alpha_2^J \simeq 0$

Case 2 u-Channel SIDIS electroproduction with two quarks and baryon junction exchange: $M_4^J = (qq\overline{qq}J\bar{J})$ with an interception of $\alpha_4^J \simeq -1/2$.

Case 3 u-Channel SIDIS electroproduction, with only baryon junction exchange: $M_0^J = (J\bar{J})$ with an interception of $\alpha_0^J \simeq 1/2$.

Among all cases, one comment signature is the presence of a leading baryon (high momentum) in the final state, it can be detected along with the scattered electron in coincidence mode.

It is also worth noting that, in the exclusive u-Channel production (Case 0), one has to exchange the entire baryon and, therefore cannot separate the flow of valence quarks from the flow of baryon number, which is the signature of the presence of the baryon junction (in high energy interactions). The SIDIS ep fix-target scattering measurement is the prime observable (underlined by Cases 2, 3, and 4) to search for the existence of the baryon junction.

In a recently completed SIDIS experiment at Jefferson Lab (JLab) Hall C: E12-09-017, whose primary observable is to measure the SIDIS cross-section for the π and K electroproduction (using the standard unpolarized ep fix-target configuration), fortuitously, collected the u-Channel SIDIS proton data (ep coincidence, where proton gains high momentum). This unexpected reaction accounts for 30% of the experimental data set [26, 27]. It can be expected that the proton SIDIS differential cross-section as a function of rapidity (y^*, with respect to the virtual photon momentum) will be extracted or support a phenomenological study to separate different cases of producing the junction-quark combination described above and in Fig. 2.

5. Concluding remarks and future outlook

The initiations of a systematic research program of the u-Channel Exclusive and Semi-Inclusive DIS measurement at JLab 12 GeV, provide unique access to the nucleon wavefunction that was previously unknown. The results from these measurements are anticipated by the theory community and are expected provide significant insight to further research in this under-explored kinematic region. These studies can be carried naturally into the Electron-Ion Collider (EIC) thanks to its innovative and comprehensive far-forward detection and tagging capability. Top on the author's wishlist, the community will soon initiate the single-spin asymmetry (SSA) and the double-spin asymmetry (DSA) studies in the u-Channel kinematics, which could unveil the hidden spin structure of the $q\bar{q}$-qqq system. The existing result from the pioneering work at CLAS12 [28], has indicated a sign flip in the extracted $\sigma_{\rm LT}$ cross-section in the $-t$, which initiated a transition mechanism that is currently not well understood.

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