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The 3D nucleon structure at Jlab 12 and 22

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The superior luminosity of CEBAF, high resolutions of detectors, and ability for multidimensional and multiparticle detection, makes the Jefferson Lab unique in disentangling the genuine intrinsic transverse structure of hadrons encoded in 3D partonic distributions, including Transverse Momentum Distributions (TMDs) and Generalized Parton Distributions (GPDs) in the kinematics dominated by valence quarks. Measurements of multiplicities and asymmetries of multiparticle final states in wide kinematics, including dihadrons and vector mesons, will be crucial for a separation of different structure functions, and different dynamical contributions to specific structure functions, used in phenomenological studies of Semi-Inclusive DIS (SIDIS). Recent studies of exclusive vector measons performed at JLab indicate understanding of the impact of exclusive vector mesons is absolutely critical for interpretation of SIDIS, and will be even more relevant for measurements performed or planed at higher energies. A new analysis framework has been proposed, called "rho-free SIDIS", allowing separation of contributions from exclusive vector mesons from inclusive pion SIDIS. Precision measurements at JLab, including detailed studies of the Q^2 dependences of observables, would also allow testing the impact of several theoretical assumptions used in phenomenological studies of generalized PDFs (GPDs, TMDs) , also providing a mechanism for validation of extraction frameworks, which is critical for proper evaluation of systematic uncertainties.

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1. Introduction

Semi-inclusive deep inelastic scattering (SIDIS), where an electron scatters off a nucleon target at a high enough energy so that it can be described by scattering off a single parton in the target, emerged as a powerful tool for investigating nucleon structure and quark-gluon dynamics. Measurements of the SIDIS cross sections for various hadron production processes and different configurations for initial lepton and target nucleon polarizations provide essential information about the underlying quark distributions and their interactions within the nucleon.

The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations. In the one-photon exchange approximation, SIDIS reactions can be decomposed into contributions from 18 structure functions (SFs) [1] depending on combinations of beam and target polarizations. The SFs contain various convolutions of twist-2 or higher twist PDFs and fragmentation functions that are multiplied by specific kinematic pre-factors [1], each offering unique information about quark-gluon dynamics in the nucleon. In addition to the standard DIS kinematic variables x and Q^2, the SFs responsible for different azimuthal modulations in ϕ_h (azimuthal angle between hadronic and leptonic planes) and ϕ_S (azimuthal angle of the transverse spin), depend also on the fraction of the virtual photon energy carried by the final-state hadron, z, and its transverse momentum with respect to the virtual photon, P_T. The cross section for a longitudinally polarized beam and target can be expressed in a model-independent way by a subset of structure functions [1–4].

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dQ^2\,dz\,dP_T^2\,d\phi_h} = \\
&\frac{\pi\alpha^2}{x^2Q^4}\frac{(2x+\gamma^2)}{(1+\gamma^2)}K(y)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad+S_{\|}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]\Bigg\}. \qquad (1)
\end{aligned}
$$

The subscripts in the structure functions (SFs) $F_{UU,LU,LL...}$, specify the beam (first index) and target (second index) polarization, U, L for the unpolarized and longitudinally polarized case, respectively, the third index indicates the polarization of the virtual photon (T, L), and λ and $S_{||}$ are longitudinal polarizations of the lepton and nucleon and the elasticity $y = Q^2/2MxE_{beam}$. The depolarization factors account for the fraction of the initial electron polarization that is transferred to the virtual photon, and are described by the variables

$$K(y) = 1 - y + y^2/2 + \gamma^2y^2/4, \qquad \varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2y^2}, \qquad \gamma = 2Mx/Q \quad (2)$$

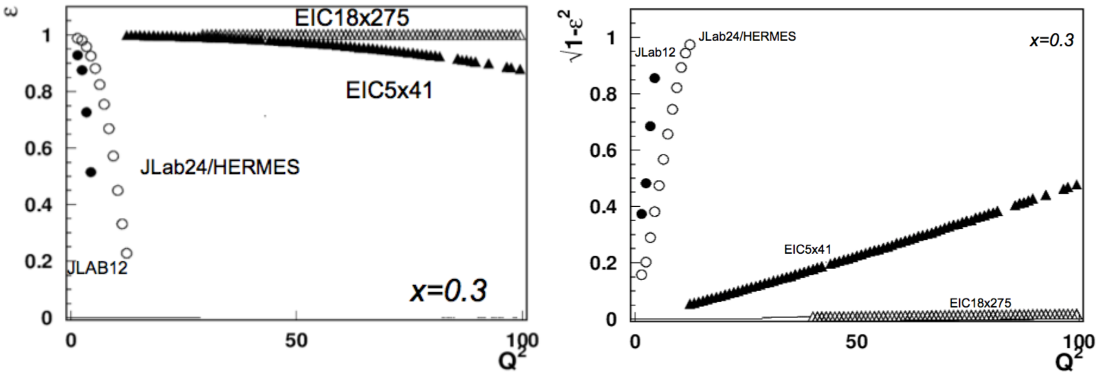

Figure 1: The ratio of fluxes of longitudinal to transverse photons, ϵ, as a function of Q^2 for different experiments (left) and variation of the kinematic term $\sqrt{1-\epsilon^2}$ (right) vs Q^2 in a small bin in x ($0.3 < x < 0.32$), z $0.45 < x < 0.55$ and P_T $0.45 < P_T < 0.55$.

SIDIS cross sections, hadron multiplicities, polarization-independent, and spin-dependent azimuthal asymmetries are multidifferential in nature. Therefore, a multidimensional analysis is mandatory to unravel the intricate dependencies of the kinematical variables x, Q^2, P_T, z. From an experimental point of view, the SIDIS, with detection of e' and hadrons in the final state, is always multidimensional. That means, for providing an input for "collinear" SIDIS studies, the experimentalists have to properly measure the cross section in the multidimensional phase space of $x, Q^2, z, P_T, \phi, \phi_S$ + lepton and nucleon helicity states, and only after proper corrections over the acceptance, integrate them to 1D or 2D distributions where the collinear physics can be applied. In addition, comparing results obtained by different SIDIS experiments for vrious single-dimensional kinematic dependencies of cross sections or asymmetries while integrating over other dimensions of non-equal phase-space contours, may result in significant discrepancies.

High-statistics data that accurately cover the full relevant kinematics will be also critical for the separation of contributions from different production mechanisms into observables that define the given SF of interest. The possible impact on DIS from diffractive DIS (DDIS) processes has been recently discussed by Stan Brodsky et al. [5] suggesting that the quark and gluon parton distributions intrinsic to the hadron structure will be misidentified, unless one excludes the DDIS events. The total fraction of DDIS was estimated to be $\sim 10\%$ of DIS [6]. The complexity of the SIDIS reaction poses significant experimental challenges in isolating each SF from cross sections / asymmetries, since SFs have intricate kinematic dependencies, such as x, Q^2, z and P_T. In particular, measuring each of these SFs requires the full ϕ dependence of the reaction and, in some cases, the ϵ dependence, which defines the relative cross-section contributions from longitudinal (σ_L) and transverse photons (σ_T). Separation of these contributions will be important for future phenomenological studies, in particular, for large hadronic transverse momenta, where theory is heavily based on the assumptions for dominance of the transverse photon contributions.

In case of exclusive processes, the longitudinal photon contributions are leading-twist, while in case of semi-inclusive hadron production, the leading-twist contributions will come from transverse photons. Moreover, separation of contributions becomes increasingly difficult in the valence region at high energies, where $\epsilon \longrightarrow 1$, and in addition certain SFs, such as helicity-dependent SFs sensitive to longitudinal spin-dependent TMDs, are suppressed due to kinematic factors. For a given x and Q^2 the contribution from longitudinal photon increases (see Fig. 1) at higher energies (ex. at EIC 5 times bigger at $Q^2 \sim 10$, $x \sim 0.3$ than at JLab), indicating that understanding of longitudinal photons will be critical for already collected and all planned future experiments involving SIDIS. Several experiments have already been approved to measure the most precise ratios of longitudinal to transverse cross sections $R = \sigma_L/\sigma_T$ [7–9] at JLab. A possible contribution to the SIDIS spin-dependent and even spin-independent observables from longitudinal photons can come from exclusive diffractive processes. These contributions were widely accepted to be one of the main challenges in the description of the SIDIS data, in particular at relatively low transverse momenta of hadrons accessible in polarized experiments ($P_T < 0.6$ GeV) [10]. Recent studies in JLab indicate that exclusive rho contributions, which are not included in the current formalism of 3D studies, can indeed dramatically change single- and most importantly even double-spin asymmetries for charged pions. For proper comparison with the theory, the data should be cleaned up from exclusive VMs, in particular ρ^0 contributions. Precision measurements of single and dihadron SIDIS, also allow for detailed studies of the Q^2 dependences of observables, providing important tests of the impact of several theoretical assumptions used in the phenomenology of TMDs. Proper account of evolution [11] will be critical for these studies, providing an important tool for the validation of the extraction frameworks, allowing the proper evaluation of systematic uncertainties. Additionally, the detection of multiparticle final states and the study of multiplicities and asymmetries of dihadrons and vector mesons will offer crucial insights into the source of single-spin asymmetries and the dynamics of the polarized quark hadronization process.

2. Separating exclusive rho contributions in inclusive charged pion production in SIDIS

Production of correlated hadron pairs plays an increasingly important role in the interpretation of pion electroproduction data in general, and the hadronization process of quarks in particular. More significant, than originally anticipated, fraction of pions coming from correlated di-hadrons, indicated by recent measurements at JLab, and supported by various realistic models describing the hadronization process, may have a significant impact on various aspects of data analysis, including the modeling, composition, and interpretation of semi-inclusive DIS data, as well as calculations of radiative corrections (RC). Since the contributions of the diffractive VMs, rho, in particular, will be much higher for charged pion inclusive DIS case, the impact of those will certainly be even more dramatic.

Procedures to account for exclusive rho production in inclusive pion production in SIDIS ($eN \to e'hX$) were traditionally based on measurements of Spin Density Matrix Elements (SDMEs) describing the spin transfer from the virtual photon to the vector meson, and implementation of those SDMEs in some kind of Monte Carlo generators (e.g. HEPGEN [12]). A proper normalization of SIDIS and exclusive contributions under the missing mass of the 2 pion sample [13–16], with subtraction of MC simulated contributions from actual data [17] is, in principle, expected to exclude the the VM contributions. That kind of procedure, however, heavily relies on the validity of SDMEs, and for proper measurements require detailed studies in the multidimensional phase space for all kinds of single- and double spin asymmetries. The missing mass resolutions, providing limits on

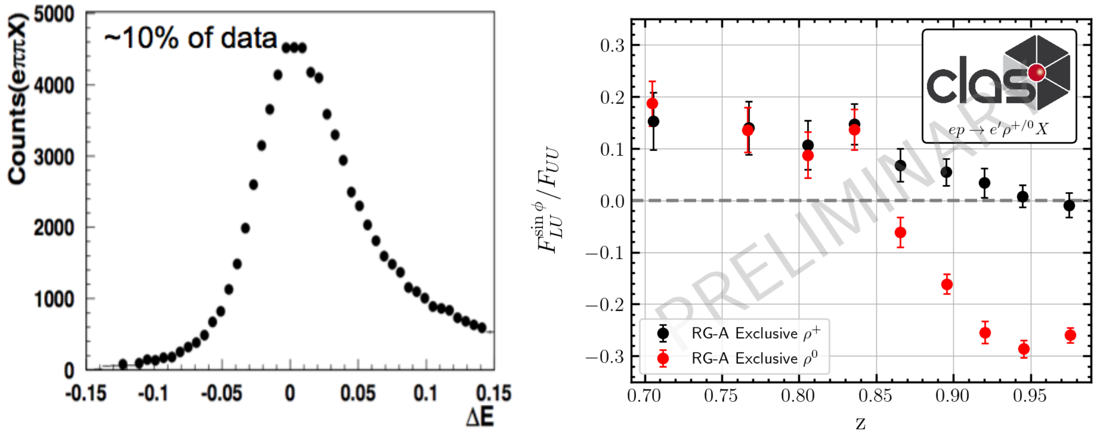

Figure 2: The Missing energy for $eN \longrightarrow e'p\pi\pi X$ system calculated using the missing mass of $eN \rightarrow e'\pi\pi X$ ($\Delta E = (M_X^2 - M^2)/2M$ (left) and the beam spin asymmetry (F_{LU}/F_{UU}) of the events (left) and dependence of inclusive pion beam SSAs for exclusive ρ^0 and ρ^+ as a function of the fraction of the energy of the virtual photon carried by VMs 2 bins in P_T of pions plotted versus the missing mass of the epX for the same x, Q^2, z bins.

missing energy of the system at high energy experiments ($\sim$ 0.6 and 2 GeV, for HERMES and COMPASS, respectively) and poor statistics, impose limitations on extraction and validation of kinematic dependences of SDMEs, critical for proper subtraction of diffractive contribuions in the multidimensional phase space. An example of the missing energy measured by CLAS12 for exclusive $ep \longrightarrow e'p\rho^0 X$, is shown in Figure 2. High resolution of the CLAS12 allows clean separation of exclusive di-hadrons in general, and exclusive rhos, in particular. Clean separation of exclusive rho, appeared to be critical for proper measurements of SSAs of exclusive rhos. In the exclusive limit, both the ρ^0 and ρ^+ asymmetries were measured to be very significant (Fig. 2). The asymmetry values for ρ^0 and ρ^+ plotted as a function of the fraction of the energy of the virtual photon carried by VMs ($z_\rho = E_\rho/\nu$) are consistent with each other for the values of z below 0.85, and are also consistent with the beam SSAs measured for exclusive π^+ and π^0 [18], indicating that all contributions in that particular kinematics come from polarized u quarks.

Available statistics in high-energy polarized experiments prevent direct studies of the impact of decay pions in the multidimensional space on different SIDIS observables, making the subtraction procedure MC-dependent. The measured SSAs for exclusive rhos, typically integrated in wide bins, were also found to be mostly consistent with 0, both at HERMES and COMPASS. Measurements of single- and double-spin asymmetries of exclusive rhos at JLab, however, indicate that the effects indeed can be dramatic, and the behavior of observables for decay pions can change completely the kinematic dependences of the overall SIDIS sample. An example of the missing energy measured by CLAS12 for exclusive $ep \longrightarrow e'p\rho^0 X$. The significant SSA for exclusive ρ^0 for very large z, corresponding to a small momentum transfer t ($z = 1 + tx_B/Q^2$) with negative sign, may indicate dominant contributions of diffractive ρ^0 contributions with negative polarization of the gluons. We will consider exclusive ρ^0 "diffractive" in kinematics where their beam SSA is dramatically different from exclusive ρ^+ beam SSAs. The higher x, the higher the minimum t, t_{min},

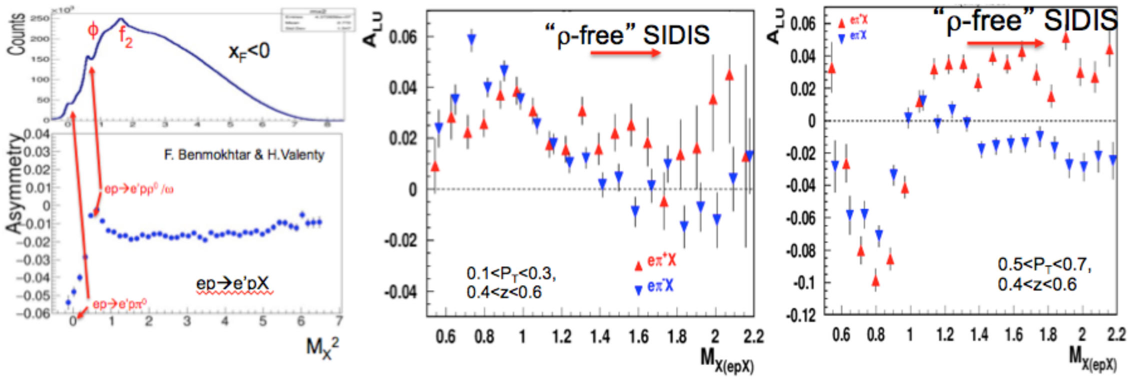

Figure 3: The Missing mass of the epX events (left) and dependence of inclusive pion beam SSAs for 2 bins in P_T of pions plotted versus the missing mass of the epX for the same x, Q^2, z bins.

accessible kinematics, suppressing diffractive contributions in the valence region of large x, leading to suppression at relatively large Q^2, also correlated kinematically with large x.

In general, SIDIS measurements can be divided into 3 classes:

1) Standard SIDIS ($eN \to e'hX$, h=p,K,..) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space

2) Standard SIDIS ($eN \to e'\pi X$) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space, with subtracted in multi-D bins for exclusive ρ^0 contributions ("rho-subtracted SIDIS")

3) SIDIS subsamples ($eN \to e'p\pi X$, $eN \to e'\pi\pi X$) within the full accessible kinematics, allowing clear eliminiation of the exclusive ρ^0 contributions using cuts on missing masses of epX or $e\pi\pi X$ ("rho-free SIDIS").

The meathods, called "rho-free SIDIS", will require detection of an additional hadron and elimination of the subsample of rho-decay pions using cuts on missing mass of the system. That may include detection of an additional nucleon in the target fragmentation region (TFR), or possibly an additional hadron in the current fragmentation region (CFR). In case of the proton detected in CFR, the missing mass of the $e'pX$ system could be used to cut above the ρ^0 mass. The dependence of inclusive pion beam SSA, plotted versus the missing mass of $e'pX$ shows a very strong dependence, with similar very large values for π^+ and π^- when the missing mass crosses the value of the rho (Fig. 3). In case of an additional pion, the missing mass of the $e'\pi^+\pi^-X$ system may be used to cut above the proton mass. The "rho-free" method certainly introduces some bias, which is, however, much easier to quantify than evaluation of the systematics due to unaccounted impact of rho decay pions. Data sets with additional hadron detected can be analised in two configurations, with and without a cut on the missing mass of the system eliminating completely the rho. With that, we get six version of measurements of inclusive pion observables, including 1) regular $e'\pi X$ within the detector acceptance, which includes the exclusive rho contributions 2) $e'\pi X$ with contributions of rho, subtracted in multidimensional bins 3) $e'\pi X$ with an additional proton detected in CFR, but no cuts imposed on the missing mass, 4) the same as 3) but with an additional cut on the missing mass of the proton 5) $e'\pi X$ with an additional pion detected without addition cuts on the sample, 6) the

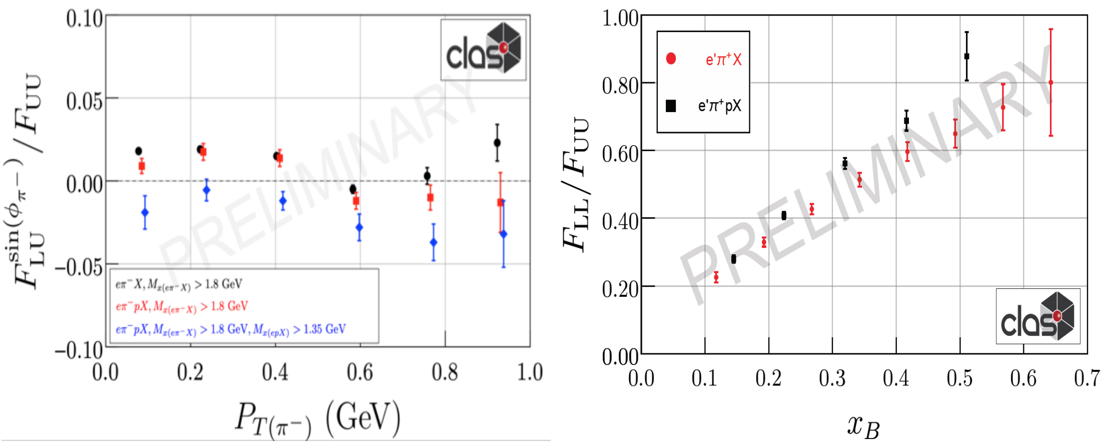

Figure 4: The beam SSA measurements for inclusive π^- ($ep \to e'\pi^- X$) for three subsamples. The right panel shows the double spin asymmetry for inclusive π^+ ($ep \to e'\pi^+ X$) for standard SIDIS (red circles) and "rho free" SIDIS (black squares) using a cut on the missing mass of the epX above 1.35 GeV to suppress contributions from exclusive VMs.

same as 5) but with an additional cut applied on the missing mass of the two muon system above the nucleon mass.

All six samples will have different biases, with respect to the existing theory, and the kinematics they agree with each other can be considered properly cleaned up from diffractive rho contributions. Measurements indicate that the bias introduced in the $e'\pi X$ by the rho contributions is the biggest with options 1) 3) and 5) giving roughly the same values for single and double spin asymmetries (minor biases from additional proton or pion), while the elimination of the rho using either 2) "rho subtracted SIDIS" or 4) or 6) "rho free SIDIS" makes a big difference with original observables with no cuts on rho contributions. Proper account of the contributions from rho can dramatically change the phenomenology of the $e\pi X$ studies. In fact, as shown in Fig. 4 (left panel), the beam SSA for the "rho-free SIDIS" sample can have an opposite sign to the standard "contaminated" SIDIS.

The $e'\pi^+\pi^- X$ (2 pions in the CFR) are in any case part of the regular SIDIS, and can probably, with some effort, be used to evaluate the bias introduced by the integration over the second pion phase space. The $e'p\pi X$ is a new process, which is currently under study, involving fracture function formalism, and most recently the "semi-exclusive" formalism, assuming the TFR baryon is exclusive [19]. Since most of the TFR protons are indeed exclusive in TFR, this formalism looks very attractive for accessing GPDs/GTMDs on the target side and TMD FFs on the CFR side.

Since the inclusive pion samples are more dominated by decay products from corresponding vector mesons (VMs), the understanding of the VM contributions will be critical for interpretation of the kinematic dependence of multiplicities, and most importantly, SSAs of pions and kaons. Large differences in the SSAs of the pions and kaons measured by HERMES [20] and COMPASS [21] Collaborations can come to a significant extent from different fractions of pions and kaons from the corresponding VM decays. The asymmetries from decay pions may lead to significant dilution of the measured asymmetry for the inclusive pions, indicating that a direct comparison of polarized fragmentation functions with models accounting for spin-orbit correlations in hadronization will require separation of direct-pion contributions.

In general, the measured SSAs [22] clearly demonstrate a dependence on the invariant mass of the pion pair, indicating significant correlation effects in hadron production in the CFR. Measurements of correlations between hadrons in target and current fragmentation regions [23], on the other hand, open new possibilities to quantify the relationship between the spin and transverse momenta of quarks in the nucleon and provide a new avenue for studies of the complex nucleonic structure in terms of quark and gluon degrees of freedom.

3. The impact of ρ^0s on studies of the helicity distributions

One of the most important questions about the 3D structure of the nucleon is the transverse momentum dependence of the distribution and fragmentation TMDs and the flavor and spin dependence of these shapes. The frequently used assumption of factorization of dependencies x and (or z and p_T) [24] can be significantly violated (see Fig. 10 of [25]). The multiplicity of charged pion and kaon mesons has been measured by HERMES using the electron beam scattering off hydrogen and deuterium targets [26]. The multiplicities of charged hadrons produced in deep inelastic muon scattering off a ^{6}LiD target have been measured in COMPASS [27]. These high-statistics data samples have been used in phenomenological analyzes [24, 25, 28] to extract information on the flavor dependence of the unpolarized TMD distribution and fragmentation functions. Restricting the ranges of the available data to $Q^2 > 1.69$ (GeV$/c)^2$, $z < 0.7$ and 0.2 GeV$/c < P_T < 0.9$ GeV$/c$, the authors of [24] obtained a reasonable description of the experimental data within a Gaussian assumption for TMDs with flavour independent and constant widths, $\langle k_T \rangle$ and $\langle p_T \rangle$. However, indications have been reported that favored fragmentation functions into pions have smaller average transverse momentum width than unfavoured functions and fragmentation functions into kaons [28], consistent with predictions based on the NJL-jet model [29].

Collinear PDFs have flavor dependence, therefore, it is not unexpected that the transverse momentum dependence may also be different for the different flavours [28]. Model calculations of the transverse momentum dependence of TMDs [30–33] and lattice QCD results [34, 35] suggest that the dependence of the widths of TMDs on the quark polarization and flavor may be significant. Measurements of the P_T-dependence in double-spin asymmetries (DSAs) in charged-pion electroproduction, conducted for the first time across different x-bins, have revealed interesting insights. These measurements suggest the existence of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin [36, 37], consistent with findings from LQCD simulations [35]. The double spin longitudinal asymmetries, providing access to SF F_{LL} and underlying helicity TMD $g_1(x, k_T)$ due to its ϵ-dependent prefactor (see Eq.1) in the valence region, are significantly suppressed at higher energies. Indeed, as shown in Fig. 1, with $\epsilon \to 1$ the kinematic prefactor is rapidly decreasing with energy, making the JLab a unique place to study helicity TMDs in the valence region. Fig. 4 shows the measurements of longitudinal target double spin asymmetries (F_{LL}/F_{UU}) for the standard SIDIS and the "rho free" SIDIS, indicating the impact of the diffractive rhos can change the double spin asymmetries in certain kinematics from ~ 10-20%. The impact of the diffractive rho can be very significant for double spin asymmetry, and that can change dramatically extractions of helicity distributions performed in last 30 years.

To achieve a detailed understanding of the contributions to measured cross sections and asymmetries in SIDIS with controlled systematics, it is necessary to consider all the kinematical variables involved (x, Q^2, z, P_T and ϕ). JLab is the only facility capable of separating different structure functions involved in polarized SIDIS, including longitudinal photon contributions in general and diffractive vector mesons, in particular. These studies will be critical for the proper interpretation of existing SIDIS data, and even more importantly for future measurements at JLab [38] and EIC [39]. By performing precision multidimensional measurements of single and dihadron SIDIS with an upgraded CEBAF accelerator, and by studying the Q^2 dependences of observables, we can test the impact of several theoretical assumptions used in TMD phenomenology. This will also provide validation of the extraction frameworks, which is critical for the proper evaluation of systematic uncertainties. Additionally, the detection of multiparticle final states and the study of multiplicities and asymmetries of dihadrons and vector mesons will offer crucial insights into the source of single-spin asymmetries and the dynamics of the polarized quark hadronization process.

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