The Halls B and C semi-inclusive deep inelastic scattering program towards the transverse momentum dependence of valence quarks

Rolf Ent
Jefferson Lab
12 GeV Upgrade Project

Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.

Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6....

Project Scope (~92% complete):
- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~97%
- Upgrades to Experimental Halls B & C - ~80%
12 GeV Scientific Capabilities

Hall B – understanding nucleon structure via generalized parton distributions

Hall D – exploring origin of confinement by studying exotic mesons

Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)

Hall C – precision determination of valence quark properties in nucleons/nuclei
12 GeV Upgrade: Halls B and C

Hall C
- HB & Q1 @JLab
  (MSU/FRIB & SMI, UK)
- Dipole
  (Sigma Phi, France)
- Pre-shower & shower counters and detector stands installed

Hall B
- Torus
  5 of 6 coils @JLab
  (FNAL)
- SVT
  @JLab
- HTCC
  @JLab
What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?

Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?

Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?

What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?

Can we discover evidence for physics beyond the standard model of particle physics?
New Paradigm for Nucleon Structure

- **TMDs**
  - Confined motion in a nucleon (semi-inclusive DIS)

- **GPDs**
  - Spatial imaging (exclusive DIS)

- **Requires**
  - High luminosity
  - Polarized beams and targets

**Major new capability with JLab12**
Features of partonic 3D non-perturbative distributions

\[ f^\alpha(x, k_T^2; Q^2) \]

Ex. TMD PDF for a given combination of parton and nucleon spins

Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum and space distributions

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- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

quark polarization

transversity pretzelosity

U Sivers

L helicity

T worm-gear

worm-gear

Sivers
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects

  - Sivers angle, effect in distribution function: \((\phi_h-\phi_s)\)
    Or other combinations: Pretzelosity: \((3\phi_h-\phi_s)\)
  - Collins angle, effect in fragmentation function: \((\phi_h+\phi_s)\)
  - Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)

Naturally, two scales:
- High Q: localized probe to “see” quarks and gluons
- Low \(P_T\): sensitive to confining scale to “see” their confined motion
+ Theory input: TMD QCD factorization
  TMD QCD evolution
CLAS12 – Ring Imaging Cherenkov

- Two (of six) sectors: INFN-led project with funds from INFN, JLab/DOE, Chile
- ID of kaons vs $\pi$ and $p$ with momentum 3-8 GeV/c with a $\pi/K$ rejection factor 1:500

Aerogel tests underway in Ferrara (Italy)

Optical test of the spherical mirror prototype at the CMA (Tucson-USA)

Electronic panel prototype (LNF/Italy)

Universal FPGA BOARD (JLab)

3 x ASIC BOARD (INFN) matching the
Good performance with cosmic ray tests with tray of n=1.03 Aerogel with “wrong way” muons.
(In spectrometer, particles will pass through Aerogel before the diffusion box. In cosmic tests, Aerogel on bottom.)

Essentially ready for installation in SHMS. Trays with n = 1.011, 1.015, 1.02, 1.03 available (inner tray only for n = 1.011). Some from Matsushita (ex-MIT/BLAST), some from Japanese Fine Ceramics Center.
validate basic reaction mechanism of SIDIS at JLab energies

and then

spin and flavor dependence of quark transverse momentum distributions
SIDIS – Flavor Decomposition

**Solution:** Detect a final state hadron in addition to scattered electron

→ Can ‘tag’ the flavor of the struck quark by measuring the hadrons produced: ‘flavor tagging’

\[ M_x^2 = W'^2 \sim M^2 + Q^2 \left( \frac{1}{x} - 1 \right) (1 - z) \]

\[
\frac{1}{\sigma_{(e,e')} \int dz} \frac{d\sigma}{dz} (ep \rightarrow hX) = \sum_q e^2_q f_q(x) D^h_q(z) \\
= \sum_q e^2_q(x)f_q(x) \sum_q e^2_q(x) D^h_q(z)
\]

\[ f_q(x) : \text{parton distribution function} \]

\[ D^h_q(z) : \text{fragmentation function} \]

**DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks:**

\[ \sum e^2_q(q + \bar{q}) \]

**Target-Mass corrections at large z**

\[ \ln(1-z) \text{ corrections at large } z \]

- Leading-Order (LO) QCD
- after integration over \( p_T \) and \( \phi \)
- NLO: gluon radiation mixes \( x \) and \( z \) dependences

\[ Z = E_h / \nu \]
General formalism for \((e,e'h)\) coincidence reaction w. polarized beam:

\[
\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h,t}} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right\}
\]

\[
\sqrt{2\varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} + \lambda_e \sqrt{2\varepsilon(1 + \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}
\]

\((\Psi = \text{azimuthal angle of } e' \text{ around the electron beam axis w.r.t. an arbitrary fixed direction})\)

If beam is \textit{unpolarized}, and the \((e,e'h)\) measurements are fully integrated over \(\phi\), only the \(F_{UU,T}\) and \(F_{UU,L}\) responses, or the usual transverse \((\sigma_T)\) and longitudinal \((\sigma_L)\) cross section pieces, survive.
\[ R = \frac{\sigma_L}{\sigma_T} \text{ in DIS} \]

- \( R_{\text{DIS}} \) is in the naïve parton model related to the parton’s transverse momentum: \( R = \frac{4(M^2x^2 + \langle k_T^2 \rangle)}{(Q^2 + 2\langle k_T^2 \rangle)}. \)

- \( R_{\text{DIS}} \rightarrow 0 \) at \( Q^2 \rightarrow \infty \) is a consequence of scattering from free spin-\( \frac{1}{2} \) constituents

- Of course, beyond this, at finite \( Q^2 \), \( R_{\text{DIS}} \) sensitive to gluon and higher-twist effects

- No distinction made up to now between diffractive and non-diffractive contributions in \( R_{\text{DIS}} \)

- \( R_{\text{DIS}}^H = R_{\text{DIS}}^D \), to very good approximation (experimentally)
  - from formal point of view they should not be identical!
  
  \( u \) not equal to \( d \) at large \( x \) + evolution in \( Q^2 \),
  
  \( H = \text{spin-}1/2 \) and \( D = \text{spin-1, at low } Q^2 \)
R = \sigma_L/\sigma_T \text{ in } (e,e'\pi) \text{ SIDIS}

Knowledge on R = \sigma_L/\sigma_T in SIDIS is essentially non-existing!

- If integrated over z (and p_T, \phi, hadrons), R_{SIDIS} = R_{DIS}
- R_{SIDIS} = R_{DIS} test of dominance of quark fragmentation
- R_{SIDIS} may vary with z
- At large z, there are known contributions from exclusive and diffractive channels: e.g., pions from \Delta and \rho \rightarrow \pi^+\pi^-
- R_{SIDIS} may vary with transverse momentum p_T
- Is R_{SIDIS}^{\pi^+} = R_{SIDIS}^{\pi^-} ? Is R_{SIDIS}^{H} = R_{SIDIS}^{D} ?
- Is R_{SIDIS}^{K^+} = R_{SIDIS}^{\pi^+} ? Is R_{SIDIS}^{K^+} = R_{SIDIS}^{K^-} ?

E12-06-104 measures kaons too! (with ~20% of pion statistics)

\[ \sigma = \sum_q e_q^2 f(x) \otimes D(z) \]

quark

\[ \pi \]

“\text{A skeleton in our closet}”
Only existing data: Cornell 70’s data (H and D, $\pi^+$ and $\pi^-$)

Conclusion: “data consistent with both $R = 0$ and $R = R_{\text{DIS}}$”

Some hint of large $R$ at large $z$ in Cornell data?
So what about $R = \sigma_L/\sigma_T$ for pion electroproduction?

“Semi-inclusive DIS”

Here, $R_{\text{SIDIS}} \rightarrow R_{\text{DIS}}$ disappears with $Q^2$

“Deep exclusive scattering” is the $z \rightarrow 1$ limit of this “semi-inclusive DIS” process

Here, $R = \sigma_L/\sigma_T \sim Q^2$ (at fixed $x$)

Not including a comparable systematic uncertainty: $\sim 1.6\%$

Have no idea at all how $R$ will behave at large $p_T$

Planned scans in $z$ at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV$^2$ ($x = 0.4$) should settle the behavior of $\sigma_L/\sigma_T$ for large $z$.

Planned data cover range $Q^2 = 1.5 - 5.0$ GeV$^2$, with data for both H and D at $Q^2 = 2$ GeV$^2$.

Planned data cover range in $P_T$ up to $\sim 1$ GeV. The coverage in $\phi$ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV.
Goal: Measure the basic SIDIS cross sections of $\pi^+$, $\pi^-$, $\pi^0$ (and $K^+$) production off the proton (and deuteron), including a map of the $P_T$ dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate a flavor decomposition and the $k_T$ dependence of (unpolarized) up and down quarks.

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Why need for (e,e’$\pi$) cross sections?

PAC37 Report: “the cross sections are such basic tests of the understanding of SIDIS at 11 GeV kinematics that they will play a critical role in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate $P_T$ and $\phi$-dependence for small $P_T$.”

Basic precision cross section measurements:
- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain TMD evolution
  - Questions on target-mass corrections and $\ln(1-z)$ re-summations require precision large-z data

\[ \sigma = \sum_q e^2_q f(x) \otimes D(z) \]
General formalism for \((e,e'h)\) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

\[
\frac{d\sigma}{dxdy\psi dzd\phi_h dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \right\}
\]

\[
\sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} + \lambda_e \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \}
\]

\(\psi\) = azimuthal angle of \(e'\) around the electron beam axis w.r.t. an arbitrary fixed direction)

If beam is unpolarized, and the \((e,e'h)\) measurements are fully integrated over \(\phi\), only the \(F_{UU,T}\) and \(F_{UU,L}\) responses, or the usual transverse \((\sigma_T)\) and longitudinal \((\sigma_L)\) cross section pieces, survive.

**Unpolarized \(k_T\)-dependent SIDIS:** \(F_{UU}^{\cos \phi}\) and \(F_{UU}^{\cos(2\phi)}\), in framework of Anselmino et al. described in terms of convolution of quark distributions \(f\) and (one or more) fragmentation functions \(D\), each with own characteristic (Gaussian) width. Transverse momentum widths of quarks with different flavor (and polarization) can be different.

Final transverse momentum of the detected pion \(P_t\) arises from convolution of the struck quark transverse momentum \(k_t\) with the transverse momentum generated during the fragmentation \(p_t\).

\[P_t = p_t + z k_t + O(k_t^2/Q^2)\]
Probing the flavor-dependence of $k_T$-distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of the $k_T$ dependence of quark flavor distribution.

Higher probability to find more sea & d-quarks at large $k_T$.

Measurements of hadronic multiplicities provide a crucial input for studies of $k_T$ dependence of spin independent distributions.

HERMES, PRD 87 (2013) 074029
COMPASS, EPJC 73 (2013) 2531

P.Schweitzer et al. arXiv:1210.1267

COMPASS Preliminary
$h^+$ from D

$0.30 < z < 0.6$
$\langle x \rangle = 0.054$
$\langle Q^2 \rangle = 4.57$

Hall C SIDIS Program (typ. $x/Q^2 \sim$ constant)

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in $(x,z,P_T)$
Overlap with E12-09-017 & E12-09-002
Parasitic with E12-13-010

E00-108 (6 GeV)

11 GeV phase space

11 GeV phase space

Charged pions:
E12-06-104
L/T scan in $(z,P_T)$
No scan in $Q^2$ at fixed $x$: $R_{DIS}(Q^2)$ known

- E12-09-017
  Scan in $(x,z,P_T)$
  + scan in $Q^2$
  at fixed $x$

- E12-09-002
  + scans in $z$
Hall C Projected Results – Kaons

\[ x, Q^2, E, z = 0.3 \ 3.0 \ 11.0 \ 0.4 \]

\[ \text{sig (a.u.)} \]

\[ \text{Pt (GeV)} \]

I

II

III

IV

V

VI

\[ d(K^+) \]

\[ d(K^-) \]

\[ p(K^+) \]

\[ p(K^-) \]
Charge symmetry (CS) is an approximate symmetry in the nuclear world, respected to better than 1%: $M_p \approx M_n$, energy levels in mirror nuclei (after Coulomb corrections), …

At the quark level CS implies $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$. This is widely assumed but never thoroughly checked by experiment!

In QCD charge symmetry violation (CSV) originates from EM interactions (small at high energies) and $\delta m = m_d - m_u$.

Naively, CSV $\sim (m_d - m_u)/<M>$, where $<M> \sim 0.5 - 1$ GeV from the strong Hamiltonian → one expects an $\sim 1\%$ effect.

Experiment aims, assuming a thorough understanding of the SIDIS reaction mechanism is validated, to extract CSV info from the charged-pion yield ratio on a D target.
Hall C SIDIS Program – basic (e,e’π) cross sections

(Hall C’s basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C’s role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible convolution in terms of quark distribution and fragmentation functions, at JLab-12 GeV must be well validated to substantiate the SIDIS science output. Many questions remain at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2).

Why need for (e,e’π^0) beyond (e,e’π^+/-)?

(e,e’π^0) experimental advantages:
- ☺ no diffractive ρ contributions
- ☺ no exclusive pole contributions
- ☺ reduced resonance contributions
- ☺ proportional to average D

Further advantages:
- Can verify: \( \sigma^{π^0}(x,z) = \frac{1}{2} (\sigma^{π^+}(x,z) + \sigma^{π^−}(x,z)) \)
- Confirms understanding of flavor decomposition & of \( k_T \) dependence
The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles ($\gamma$ and $\pi^0$). The NPS will be remotely rotatable off the SHMS platform.

**NPS angle range:** 5.5 – 30 degrees

**NPS angle range:** 25 – 60 degrees

The large interest for such a device can be exemplified by the PAC-approved science program:

- **E12-13-007** – Measurement of Semi-inclusive $\pi^0$ production as Validation of Factorization
- **E12-13-010** – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

(E12-13-007 & E12-13-010 runs as one run group – first run group in Hall C)

- **E12-14-003** – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
- **E12-14-005** – Wide Angle Exclusive Photoproduction of $\pi^0$ Mesons (runs as run group with E12-14-003)
- **E12-14-006** – Initial State Helicity Correlation in Wide-Angle Compton Scattering
E12-09-017: $P_T$ coverage

Can do meaningful $\pi^+/-$ measurements at low $p_T$ (down to 0.05 GeV) due to excellent momentum and angle resolutions!

- Excellent $\phi$ coverage up to $P_T = 0.2$ GeV
- Sufficient up to $P_T = 0.4$ GeV → coverage at $\phi = 0, \pi$
- Limited up to $P_T = 0.5$ GeV → use $f(\phi)$ from CLAS12

E12-13-007: $P_T$ coverage

Basic $\pi^0$ SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent $\phi$ coverage up to $P_T = 0.3$ GeV
- Good up to $P_T = 0.4$ GeV
- Limited up to $P_T = 0.5$ GeV → use $f(\phi)$ from CLAS12
spin and flavor dependence of quark transverse momentum distributions

Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less u-quarks at large $k_T, b_T$)
CLAS12: $K_T$ Helicity Dependence

- Higher probability to find a quark anti-aligned with proton spin at large $k_T$
- Important to have $q^+$ and $q^-$ $k_T$-dependent distribution separately
- $q^-$ sensitive to orbital motion:
  $$q_L^{-1} \sim (1 - x)^5 \log^2(1 - x)$$

- Double spin asymmetries from CLAS@JLab consistent with wider $k_T$ distributions for $f_1$ than for $g_1$
- Wider range in $P_T$ from CLAS12 is crucial!

Measurements of the $P_T$-dependence of $A_{LL}$ ($\propto g_1/f_1$) provide access to transverse momentum distributions of quarks anti-aligned with the proton spin.
A$_1$ $P_T$-dependence in SIDIS

\[ A_1(\pi) \propto \frac{\sum q e_q^2 g_1^q(x) D_1^{q\rightarrow\pi}(z)}{\sum q e_q^2 f_1^q(x) D_1^{q\rightarrow\pi}(z)} \cdot e^{-z^2 P_T^2 (\mu_0^2 - \mu_2^2) / (\mu_0^2 + z^2 \mu_2^2)} \]

- $A_{LL}(\pi)$ sensitive to difference in $k_T$ distributions for $f_1$ and $g_1$
- Wide range in $P_T$ allows studies of transition from TMD to perturbative approach

**Perturbative limit calculations available for $g_1^q(x, k_T)$, $f_1(x, k_T)$**

\[ f_1^q(x, k_T) = f_1(x) \frac{1}{\pi \mu_0^2} \exp\left(-\frac{k_T^2}{\mu_0^2}\right) \]
\[ g_1^q(x, k_T) = g_1(x) \frac{1}{\pi \mu_2^2} \exp\left(-\frac{k_T^2}{\mu_2^2}\right) \]
\[ D_1^q(z, P_T) = D_1(z) \frac{1}{\pi \mu_D^2} \exp\left(-\frac{P_T^2}{\mu_D^2}\right) \]

$\mu_0^2 = 0.25\text{GeV}^2$
$\mu_D^2 = 0.2\text{GeV}^2$

M.Anselmino et al
hep-ph/0608048

Transversity with CLAS12

Large $x$ important to constrain the tensor charge

High Impact Exp. From PAC41 (C12-11-111 + C12-12-009)

- HD-transversely polarized target and CLAS12

CLAS12 projected results

$2\langle \sin(\theta + \phi) \rangle_{\text{UT}}$

\begin{align*}
\text{N/q} & & \text{U} & & \text{L} & & \text{T} \\
\text{U} & & f_1 & & h_1^+ & & h_{1L}^+ \\
\text{L} & & g_1 & & h_{1T}^+ & & h_{1T}^- \\
\text{T} & & f_{1T}^+ & & g_{1T}^+ & & h_1 \\
\end{align*}
Accessing transversity in dihadron production

Measurements with polarized protons

\[ A_{UT}(\phi_R, \theta) = \frac{1}{fP_t} \frac{(N^+ - N^-)}{(N^+ + N^-)} \]

Measurements with polarized neutrons

Di-hadron (Chiral-odd interference fragmentation function)

\[ \frac{H_{1,sp}^{q,u}(z, M_{h_i})[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)} \]

\[ \frac{H_{1,sp}^{q,u}(z, M_{h_i}) (4h_1^d(x) - h_1^u(x))}{D_1^u(4f_1^d(x) + f_1^u(x))} \]
Measurements of fracture functions opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular.

\[ A_{TFR}^{LUL} = \hbar S || \frac{y \left( 1 - \frac{y}{2} \right) \sum a e_a^2 \Delta M^L}{\left( 1 - y + \frac{y^2}{2} \right) \sum a e_a^2 M} \]

...
Together stronger: SIDIS Studies with 12 GeV

- **CLAS12 in Hall B**
  General survey, medium lumi

- **SHMS, HMS, NPS in Hall C**
  L-T studies, precise $\pi^+/$$\pi^-$/\(\pi^0\) ratios

- **SBS in Hall A**
  High x, High \(Q^2\), 2-3D

- **SOLID in Hall A**
  High lumi and acceptance – 4D
The Incomplete Nucleon: Spin Puzzle

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \]

- \( \Delta \Sigma \sim 0.25 \) (world DIS)
- \( \Delta G \sim 0.2? \) (RHIC+DIS)
- \( L_q? \)

Longitudinal momentum fraction \( x \) and transverse momentum images

Longitudinal momentum fraction \( x \) and transverse spatial images

Up quark Sivers Function

\( -x f_{1T}(x, k_T) \)

12 GeV projections: valence quarks well mapped
validate basic reaction mechanism of SIDIS at JLab energies
and then
spin and flavor dependence of quark transverse momentum distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different $k_T$ dependences of quark flavor distributions
3D Mapping of the Nucleon

TMDs: Longitudinal momentum fraction $x$ and transverse momentum $k$

Transverse Momentum Imaging

$W(x, k_{\perp}, r_{\perp})$

GPDs: Longitudinal momentum fraction $x$ at transverse location $b$

Transverse Spatial Imaging

Parton Distribution Functions

Form Factors

DIS2015 Conference @ SMU, April 27-May 2 2015
Hard Exclusive Processes $\rightarrow$ GPDs

**Goal 1: Transverse Imaging of Nucleon**

Fourier transform of $t$-dependence

The proton’s transverse profile as function of the impact parameter $b$

Distortions induced by spin direction

**Goal 2: Orbital Angular Momentum**

Ji’s Sum Rule for $J^q = \frac{1}{2} \Delta \Sigma + L^q$

$J^q = \frac{1}{2} \int_{-1}^{1} x dx [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]$

CLAS12 with help from Halls A & C

GPD H and E  
GPD E only

DIS2015 Conference @ SMU, April 27-May 2 2015
A surprise of transverse-spin experiments

- Access orbital motion of quarks
  - contribution to the proton’s spin
- Observables: Azimuthal asymmetries due to correlations of spin q/n and transverse momentum of quarks

Illustration of the possible correlation between the internal motion of an up quark and the direction in which a positively-charged pion (ud) flies off.

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Boer-Mulders

Sivers

worm-gear

transversity pretzelosity
Correlations in quark distributions

Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less $u$-quarks at large $k_T,b_T$)

\[ g_1^q = \Delta q = (q^+ - q^-)/2 \]

\[ \langle x \rangle \approx 0.3 \]
**TMD Program in Hall A with SoLID & SBS**

(match large acceptance devices at high luminosity to anticipated polarized $^3\text{He}$ target performance)

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**SoLID & SBS: Complementary Kinematics**

- **SOILID projections**
- **Extractions from existing data**
- **LQCD**
- **DSE**
- **Models**

---

SoLID projection extraction by A. Prokudin using **only** statistical errors and based on:

- a set of data with a limited range of $x$ values
- the assumption of a negligible contribution from sea quarks
- assumption on $Q^2$ evolution
- model dependent assumptions on the shape of underlying TMD distributions
As long as we do not quantitatively understand the extraction of a basic and known quantity like $d_v/u_v$ (at intermediate $x$) from SIDIS data, we should question the SIDIS analysis, and leave no stone unturned to reach final quantitative understanding.
Hall C SIDIS Program – basic \((e,e^{'\pi})\) cross sections

(Hall C’s basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C’s role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy \((x,z)\) factorization, or possible convolution in terms of quark distribution and fragmentation functions, at JLab-12 GeV must be well validated to substantiate the SIDIS science output. Many questions at intermediate-large \(z\) (~0.2-1) and low-intermediate \(Q^2\) (~2-10 GeV\(^2\)) remain.

Why need for \((e,e^{'\pi^0})\) beyond \((e,e^{'\pi^+/-})\)?

\((e,e^{'\pi^0})\) experimental advantages:
- no diffractive \(\rho\) contributions
- no exclusive pole contributions
- reduced resonance contributions
- proportional to average \(D\)

Further non-trivial contributions to \((e,e^{'\pi^+})\) Cross Sections:

Radiation contributions, including from exclusive
Hall C goals: Measure the basic SIDIS cross sections of $\pi^+$, $\pi^-$, $\pi^0$ production off the proton, including a map of the $P_T$ dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate (*) flavor decomposition and the $k_T$ dependence of (unpolarized) up and down quarks.

Transverse momentum widths of quarks with different flavor (and polarization) can be different.

Advantages of $(e,e'\pi^0)$ beyond $(e,e'\pi^+/-)$:
- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions.
- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2} (\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/$k_T$ dependence.

Linked to framework of Transverse Momentum Dependent Parton Distributions:
- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation.
- Need to constrain TMD evolution w. precision data.
- Questions on target-mass corrections and $\ln(1-z)$ resummations require precision large-$z$ data.

Requires SHMS and new ~25 msr Neutral-Particle Spectrometer.

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Hall C SIDIS Program – basic $(e,e'\pi)$ cross sections

PAC: “the cross sections are such basic tests of the understanding of SIDIS at 11 GeV kinematics that they will play a critical role in establishing the entire SIDIS program of studying the partonic structure of the nucleon.”