TOWARDS TRANSVERSE MOMENTUM DEPENDENCE IN DISTRIBUTIONS AND FRAGMENTATION

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Outline

• New 3D Paradigm for Nucleon Structure

• Semi-Inclusive Deep Inelastic Scattering and TMDs

• Transverse Momentum Dependence: 3D Distributions
  o validate basic reaction mechanism of SIDIS at “our” energies
  o spin and flavor dependence of quark transverse momentum distributions

• Transverse Momentum Dependence: 3D Fragmentation
  o The emergence of hadrons
    ▪ Lessons from the 70’s
    ▪ To disembroil the Lund string
  o Towards a QM description of the final state
    ▪ Balancing the transverse momentum – candles of space-time
    ▪ The Collins Function – candle of $D_{SB}$
    ▪ Balancing the spin
    ▪ Creating polarization from nothing

• Summary
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
JLab: 21st Century Science Questions

• 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?
**12 GeV (GPD/TMD) Scientific Capabilities**

**Hall B** – understanding nucleon structure via generalized parton distributions

**Hall A** – polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)

**Hall C** – precision determination of valence quark properties in nucleons/nuclei

- TMDs and GPDs comprehensive study
- SIDIS/DES cross-section factorization tests
- Ultimate TMD statistical precision in valence region
<table>
<thead>
<tr>
<th>Topic</th>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall D</th>
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**1D-3D nucleon structure science in Hall B (CLAS12 + ancillary equipment), Hall C (HMS, SHMS, NPS) and Hall A (SBS + SoLID)**
## 12 GeV Approved Experiments by PAC Days

<table>
<thead>
<tr>
<th>Topic</th>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall D</th>
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<td>644</td>
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1D-3D nucleon structure = half of approved 12-GeV science program
Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction ($x_{Bj}$) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- Deep Exclusive Scattering (DES) cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) $x$ at a transverse location $b$.

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($k_T$) of a parton and transverse momentum ($p_T$) created during the [parton $\rightarrow$ hadron] fragmentation process.
Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

\[ W_{\Gamma}(r, k) = \frac{1}{2M_N} \int \frac{d^3q}{(2\pi)^3} e^{-i\mathbf{q} \cdot \mathbf{r}} \left\langle \frac{q}{2} \left| \hat{\mathcal{W}}_{\Gamma}(0, k) \right| - \frac{q}{2} \right\rangle , \]

\[ W_{\Gamma}(r, k) = \int \frac{dk^-}{(2\pi)^2} W_{\Gamma}(r, k) \]

Integrate over transverse \textit{momentum} space

Polarized DVCS directly probes GPDs

Sensitivity to GPD

Generalized Parton Distributions (GPD) \( H, \tilde{H}, E, \tilde{E} \)

3D nucleon imaging in transverse coordinate and longitudinal momentum space

DVMP is required for flavor separation
Transverse Momentum Structure of Nucleon – TMDs

\[ W_\Gamma(r, k) = \frac{1}{2M_N} \int \frac{d^3q}{(2\pi)^3} e^{-i\mathbf{q} \cdot \mathbf{r}} \left\langle \frac{q}{2} \left| \hat{\mathcal{N}}_\Gamma(0, k) \right| - \frac{q}{2} \right\rangle \]

\[ W_\Gamma(r, k) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(r, k) \]

Integrate over \textit{spatial} dimensions

3D imaging of the nucleon in momentum space

Transverse Momentum-dependent Distributions (TMD)

JLab has planned a complete SIDIS program with \( \pi/K \) to access quark TMDs

\[
\begin{array}{|c|c|c|c|}
\hline
N & q & U & L & T \\
\hline
U & f_1 & f_{1T} & h_{1T} \\
L & g_1 & g_{1T} & h_{1L} \\
T & h_1 & h_{1L} & h_{1T} \\
\hline
\end{array}
\]

Quark spin polarization
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’

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

\[ \frac{1}{\sigma_{(e,e')} \ dz} \frac{d\sigma}{d\gamma} (ep \to hX) = \sum_q e_q^2 f_q(x) D_q^h(z) \]

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

\[ D_q^h(z) \text{ : fragmentation function} \]

- Leading-Order (LO) QCD
- after integration over \( p_T \) and \( \phi \)
- NLO: gluon radiation mixes \( x \) and \( z \) dependences
- Target-Mass corrections at large \( z \)
- \( \ln(1-z) \) corrections at large \( z \)
Need precision over range in $Q^2 @$ fixed $x$

\[ \langle Q^2 \rangle (\text{GeV}^2) \]

\begin{align*}
\frac{d\sigma(ep \rightarrow e' hX)}{dx dy dz dP_{h\perp}} & \propto \sum_q e_q^2 C[q(x,k_T)D^h_q(z,p_T)]
\end{align*}

Still many complications:
- Description valid? At what energies?
- TMD evolution
- Target-Mass effects
- ln(1-\(z\)) resummation

Symbols and rectangles indicate the kinematics of approved Hall C experiments within the available phase space.
12 GeV SIDIS/TMD Scientific Capabilities

- **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
validate basic reaction mechanism of SIDIS at “our” 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

... but, keep in mind overall goal of 3D nucleon structure...
General formalism for \((e,e'h)\) coincidence reaction w. polarized beam:

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

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

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

If beam is \textbf{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 = σ_L/σ_T in SIDIS (ep → e'π^+/−X)

Knowledge on R = σ_L/σ_T in SIDIS is essentially non-existing!

“Semi-inclusive DIS”

quark \[ \sum e_q^2 q(x) D_q^p(z) \]

Here, \( R_{\text{SIDIS}} \to R_{\text{DIS}} \) disappears with \( Q^2 \)

“Deep exclusive scattering” is the \( z \to 1 \) limit of this “semi-inclusive DIS” process

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

Only existing data: Cornell 70’s data (H and D, π^+ and π^-)

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

Some hint of large \( R \) at large \( z \) in Cornell data?
Longitudinal Cross Section: $R = \sigma_L/\sigma_T$ in SIDIS

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

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

Only existing SIDIS data:
Cornell 70’s (H and D, $\pi^+$ and $\pi^-$)

- Knowledge on $R_{\text{SIDIS}}$ is non-existing
- $R_{\text{SIDIS}}$ may (will!) vary with $z$, and with $p_T$
  (JLab E12-06-104 will scan versus $p_T$ too)

- Knowledge on $R_{\text{SIDIS}}$ needed for any TMD-related asymmetry

- Even if one can relate $R_{\text{SIDIS}}$ to a flavor-dependent average transverse momentum in a naïve parton model
  (W. Melnitchouk et al, in progress), $R_{\text{SIDIS}}$ can not easily be integrated in a global TMD analysis as it is
  sensitive to gluon and HT effects.
General formalism for \((e,e'h)\) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

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

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

If beam is \textbf{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.

\textbf{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 \textbf{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 \(p_t\). \(P_t = p_t + z k_t + O(k_t^2/Q^2)\)
TMDs and 3D FFs

Functions surviving on integration over Transverse Momentum

Distribution Functions
\[ f^a(x, k_T^2; Q^2) \]

- \( f_1 \)
- \( g_1 \)
- \( h_1 \)
- \( f_{1T} \)
- \( h_{1T} \)
- \( h_{1L} \)

Transversity

- Sivers
- Boer-Mulders
- Pretzelosity

Fragmentation Functions
\[ D^a_h(z, p_t^2; Q^2) \]

- \( D_1 \)
- \( G_1 \)
- \( H_1 \)
- \( D_{1T} \)
- \( H_{1T} \)
- \( H_{1L} \)

Polarizing FF

- Collins

The others are sensitive to intrinsic \( k_T \) in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects

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

- **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: \( (\phi_h+\phi_s) \)
  
  Pay attention to this one!

- Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)
**Features of 3D Distributions/TMDs**

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

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

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

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

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

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical $z$ range 0.3-0.65

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

- **6 GeV phase space**
- **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**

- **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 $z$
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.

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

(*) 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**

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain $Q^2$ dependence & TMD evolution
  - Questions on target-mass corrections and $\ln(1-z)$ re-summations require precision large-z data
Hall C Projected Results – Kaons
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 \textit{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 \((e,e'\pi^0)\) 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 advantages:
- Can verify: \(\sigma^{\pi^0}(x,z) = \frac{1}{2} (\sigma^{\pi^+}(x,z) + \sigma^{\pi^{-}}(x,z))\)
- 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.

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)*
- **E12-17-008** – Polarization Observables in Wide-Angle Compton Scattering at large s, t and u (Cond. Approved)
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

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
CLAS12 is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.

CLAS12 lacks the precision of Hall C for basic cross section measurements, but does boast a (very) good coverage in \((p_T, \phi)\) relevant to access the general TMD observables.
Towards the 3D Structure of the Proton

- CLAS12 is expected to measure all the TMD observables accessible with a polarized beam, with a longitudinally polarized target, and (hopefully) a transversely polarized target.

TMDs from unpolarised SIDIS data $\rightarrow p_T$ dependence of $f_1$, azimuthal asymmetries

$$
\frac{d\sigma}{dx dy dz d\phi_h dP_{h,t}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} + \lambda_e \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
$$

and Boer-Mulders

$$
F_{UU}^{\cos 2\varphi} \propto h_1^\perp H_1^\perp + [f_1 D_1 + \ldots] / Q^2
$$
SIDIS $\pi/K$ on unpolarized protons/deuterons

$$\frac{d\sigma}{dx_B dy d\psi dz dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2 (1-\epsilon)} \left(1 + \frac{\gamma^2}{2 x_B}\right) \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2 \epsilon (1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_{e} \sqrt{2 \epsilon (1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\};$$

Kaons

(CLAS12) (Hall C, Kinematics II, $z = 0.4$ bin only)
Towards the 3D Structure of the Proton

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

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

\[F_{UU}^{\cos 2\phi} \propto h_1^\perp H_1^\perp + [f_1 D_1 + \ldots]/Q^2\]

CLAS12 E12-06-112 projections

CLAS12 E12-09-008 projections

Vanish like $1/p_T$ (Yuan)
Overview of SoLID - Solenoidal Large Intensity Device

• SoLID is unique in that it provides equipment that combines
  - The capability to handle high luminosity ($10^{37-39}$)
  - A large acceptance detector with full $\phi$ coverage
→ This allows a full exploitation of the JLab 12 GeV Upgrade

• SoLID Science Program:
  - Unprecedented precision in three-dimensional imaging of the nucleon in momentum space in the valence quark region.
  - A search for new physics in the 10-20 TeV region, complementary to the reach at LHC, for example uniquely improving sensitivity to a lepto-phobic $Z'$ of 100-200 GeV.
  - Allowing access to a completely unexplored kinematic region near the threshold of $J/\psi$ production, allowing access to the QCD conformal anomaly without competition for its precision

• There is wide interest in SoLID science as evidenced by:
  - More than 250 collaborators over 50 institutions and 13 countries
  - Already quite significant international contributions and potential further commitments, particularly from China
  - strong theoretical support
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
Momentum Tomography with TMDs

Sivers function for d-quarks extracted from model simulations with a transverse polarized $^3$He target.

12 GeV ~ Valence Quark Region ($x > 0.1$)

d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $k_x$. A non-zero $\delta k_x$ value requires a non-zero orbital angular momentum.
spin and flavor dependence of quark transverse momentum distributions

Distributions of PDFs may (will) 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:
  \[ q_{L=1}^- \sim (1 - x)^5 \log^2 (1 - x) \]
  
  H. Avakian et al. PRL 99 (2007) 082001

- 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.
$A_1(\pi) \propto \frac{\sum q e_q^2 g_1^q(x) D_1^{q\rightarrow\pi}(z)}{\sum q e_q^2 f_1^q(x) D_1^{q\rightarrow\pi}(z)} e^{-z^2 P_T^2 (\mu_0^2 + z^2 \mu_0^2)(\mu_D^2 + z^2 \mu_D^2)}$

M. Anselmino et al
hep-ph/0608048

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

Perturbative limit calculations available for:
\[ g_1^q(x, k_T), f_1(x, k_T) \]


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

\[
\frac{d\sigma(ep \rightarrow e' hX)}{dx dy dz dP_{h\perp}} \propto \sum_q e_q^2 C[q(x, k_T)D_q^h(z, p_T)]
\]

Different \(Q^2\) for same \(x\) range

Complementary experiments

Adapted from Marco Contalbrigo
TMDs from SIDIS Analysis framework

- Differential input (SIDIS):

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<th>bin#</th>
<th>x</th>
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M. Aghasyan et al arXiv:1409.0487 (JHEP)

Need a TMD extraction framework to define the input data info needed
- Define all the data from other experiments which may be needed (data preservation)

Need to combine precision experiments with more limited acceptance to broad-survey experiments with excellent acceptance
TMDs and 3D FFs

Functions surviving on integration over Transverse Momentum

The others are sensitive to intrinsic $k_T$ in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197
**3D Fragmentation**

$D_h^a(z, p_t^2; Q^2)$

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 $p_t$.

Ex. $p_t$-dependent FF for a given combination of parton and hadron species

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

$$f^a(x, k_T^2; Q^2)$$

$$D_a^h(z, p_t^2; Q^2)$$

Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence.

Unpolarized

Spin-Spin Correlations

Spin-Momentum Correlations

Polarizing FF

Collins
In Steven Weinberg’s seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a “first frame” when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the emergence of hadrons from quarks and gluons.
The emergence of hadrons – mass from massless gluons and nearly-massless quarks

Basis on Parton Model Intuition:
- Localization in space-time & momentum
- Lorentz contraction, time dilation, causality
- Sharp separation of scales (…)
- Ideas about string-like hadronization

Issues: no direct connection with field theory
Sharp separation of scales?
Final state evolution in space-time??

History/timeline
- Late 60s/early 70s: Parton Model
- QCD ~ 1974
- Factorization ~ 1980
- ~2008 Transverse spin physics provokes new definition of pdfs (TMDs) - Back to need for separation of scales
Successful predictions at High E

Z production at the LHC

\[ \sqrt{s} = 7 \text{ TeV}; \int L \, dt = 4.7 \text{ fb}^{-1} \]

- **Data uncertainty**
- **ResBos-GNW (PDF + sca. unc.)**
- **ResBos-GNW (PDF unc.)**
- **ResBos-BLNY**

\[ p_T^Z \text{ [GeV]} \]
To Disembroil the Lund String

• Excellent description of high-energy transverse momentum spectra → Lund model must do something right…

• Started from best quantum mechanical insight of the time (Schwinger)

• Incorporates acquisition of mass and transverse momentum

\[ \mathcal{P} \propto e^{-\frac{\pi m_q^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_{\perp}^2}{\kappa}} \]

• The transverse momentum acquired in the LUND string model a la Schwinger is about what we see from the (early stage) TMD analyses.

• Is there reciprocity between TMDs and fragmentation?

What does the Lund Model know that we don’t know?
There have been important conceptual advances (\ldots) to recent times. One important area needing much further advance:

How do we properly and accurately understand the space-time evolution from a state simply described in terms of a few partons of large relative rapidity to a measurable state of many hadrons?

\rightarrow Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.
Connecting the NP and HEP Descriptions

LDRD Scope: Map the non-perturbative description of hadronization in the Pythia MCEG to the correlation functions of TMD factorization.

(Diefenthaler, Collins, Joosten, Lönnblad, Melnitchouk, Prestel, Rogers, Sato, Sjöstrand)

Hadronization / fragmentation:
- How do partonic degrees of freedom transform into the experimentally observed hadrons?

Pythia MCEG
- deal with the theory of final state hadronization in high-energy collisions.

QCD factorization theorems
- first principle QCD calculations of specific cross sections
- non-perturbative physics is contained in universal correlation functions

It is critical for the two to be combined if QCD studies of non-perturbative structure are to proceed.
Fragmentation Process

- Colored object
- Nearly massless object
- Asymptotically free object

- Colorless objects
- Massive objects
- Confined objects

Color to colorless
→ loss of color? No, color of first parton always was balanced by another leg.

Characteristics of fragmentation process must be influenced by
- Dynamical Chiral Symmetry Breaking
- Confinement
Color neutralization – it’s a correlated 3D problem

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 $p_t$.

Can we learn more on how hadrons emerge from color charge by correlating one hadron with the residual system, and track where it’s momentum and spin originate?

Mass of hadrons = $E/c^2$
Towards a QM Description of the Final State

Balancing the transverse momentum – candles of space-time

\[ D_a^h(z, p_t^2; Q^2) \]

From 1D to 3D fragmentation:
- Many more variables, Many more angles
- Multi-dimensional data
- Fine binnings

First step is always unpolarized cross sections \(\rightarrow\) JLab/12 GeV (but limited in kinematics)
Hadronization – parton propagation in matter

\[ \Delta p_T^2 = p_T^2(A) - p_T^2(2H) \]

“p_T Broadening”

Multiple gluon scattering making transverse momentum beyond the Lund string-breaking mechanism

Comprehensive studies possible:
- wide range of energy \( \nu = 10-1000 \text{ GeV} \)
- wide range of \( Q^2 \): evolution
- Hadronization of charm, bottom
- High luminosity for 3D and correlations

EIC: Understand the conversion of color charge to hadrons through fragmentation and breakup
Towards a QM Description of the Final State

The Collins Function – candle of $D_{\chi}\text{SB}$

Recall the origin of the Collins function as motivated by forward $\pi$ spin asymmetry. Requirements for non-zero effect:

1) Interference – helicity must be heavily broken. Can’t be by small current quark mass as $\sim m_q/Q$. Chiral symmetry breaking (in dynamical situation) can do it.
2) Transverse momentum correlations.

\[ \delta q(x) \sim \text{(in transverse basis)} \]
Towards a QM Description of the Final State

The Collins Function – candle of $D_{\chi}SB$

EIC: Map the Collins function over the regions of rapidity?
Towards a QM Description of the Final State

Balancing the Spin

Feynman-x dependence of $\Lambda$ Polarization in hadronic collisions

Proton beams
PRD91, 032004 (2015)
What happens with spin degrees of freedom over the regions of rapidity? Naively one would assume spin diffuses with a few quark-gluon scatterings. Or not …???
Creating Polarization from Nothing – the prototype example

$\Lambda^c$ Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)
Towards a QM Description of the Final State

Creating Polarization from Nothing – some recent TMD examples

Di-hadron interference fragmentation function

- Pion pair hadronizes from same quark
- correlation with quark transverse spin
- chiral-odd

Transverse single-spin asymmetry in dihadron production, 200 GeV p+p
STAR, PRL 115, 242501 (2015)

COMPASS, PLB736, 124 (2014)

- Clear nonzero asymmetry
- Pseudorapidity dependence
- Sensitive to transversity x IFF
Boer-Mulders effect can create polarization due to spin-orbit correlations. Since spin in fragmentation process likely dilutes fast, maybe perhaps more a 12-GeV experiment.

\[ e + p \rightarrow e' + \bar{p} + X \text{ (few mesons only…)} \]

There could be measurable polarization of the proton in the final state in a fully unpolarized SIDIS process! → looking into possible JLab 12-GeV proposal.
Summary

- Overall goal of Jefferson Lab SIDIS Program (in $x > 0.1$ region):
  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

- The final hadron following the SIDIS process accumulates a momentum transverse to the beam direction by a convolution of the transverse momentum of the struck quark and the transverse momentum of the additional antiquark. This turns the understanding of fragmentation into a correlated 3D problem.

- Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

- Characteristics of fragmentation process must be influenced by
  - Dynamical Chiral Symmetry Breaking
  - Confinement

We should isolate experimental signatures that are most likely to give insight
Twist-2 3D Distribution Functions

Unpolarized

Spin-spin correlations

Spin-momentum correlations

$\psi_1$ =

$h_1 \uparrow$

Sivers

Boer-Mulders

$f_1 \uparrow$

$h_{1L} \uparrow$

$h_{1T} \uparrow$

$g_1 \uparrow$

$g_{1T} \uparrow$

$Q^2$

$f^a(x, k_T^2; Q^2)$
Twist-2 3D Fragmentation Functions

$D^h_a(z, p_t^2; Q^2)$

Unpolarized

Spin-spin correlations

Spin-momentum correlations

Polarizing FF

Collins
JLab Tentative Timeline

- Up to FY17: 12-GeV Upgrade Project ongoing
- FY16: ongoing program in
  - Hall A: Deeply-Virtual Compton Scattering & Proton Magnetic Form Factor
  - Hall B < 6 GeV science: Heavy Photon Search & Proton Radius Experiment
- Hall C: Beam line/dump test
- Hall D: GlueX engineering run
- FY17: completion of Halls C and B equipment upgrades official (DOE) start of 12 GeV science operations
- FY18: start of 4-Hall science operations (typical lifetime of facility science program ~ 15 years)

After few years:
- Precision Spatial and Momentum Imaging of Hadrons (note: flexibility as 12 GeV operations compatible with EIC operations)
- Somewhere beyond 2025: EIC construction complete
Hall C SIDIS Program – basic \((e,e'\pi)\) cross sections

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 \(Q^2\) dependence & TMD evolution
  - Questions on target-mass corrections and \(\ln(1-z)\) re-summations require precision large-\(z\) data

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

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 \((P_T \sim \Lambda < 0.5 \text{ GeV})\), 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!)
The Emergence of Hadrons

The emergence of hadrons – mass from massless gluons and nearly-massless quarks

Wikipedia – Emergence is a field of study, defined as:
In philosophy, systems theory, science, and art, emergence is conceived as a process whereby larger entities, patterns, and regularities arise through interactions among smaller or simpler entities that themselves do not exhibit such properties.

Sounds a bit like the larger baryons and mesons resulting through interactions from the smaller and simpler quarks and gluons, with different properties.
To Disembroil the Lund String

mcplots.cern.ch

Lund model must do something right...
To Disembroil the Lund String

The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism (à la Schwinger)

\[ \mathcal{P} \propto e^{-\frac{\pi m_q^2}{\kappa}} = e^{-\frac{\pi m^2}{\kappa}} e^{-\frac{\pi p_t^2}{\kappa}} \]

Gives a natural supression of heavy quarks

\[ d\bar{d} : u\bar{u} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11} \]
Towards a QM Description of the Final State

Creating Polarization from Nothing

Lambda polarization maintained in the (light to medium-heavy) nuclear medium, as observed in semi-inclusive DIS.

HERMES, PRD90, 072007 (2014)
TMDs and SIDIS – General Formalism

General formalism for \((e,e'h)\) coincidence reaction w. polarized beam:

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

\(\psi\) = 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.

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

\[
P_T = p_t + z k_t + O(k_t^2/Q^2)
\]

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 \(p_t\).