Understanding the QCD: from observables to QCD dynamics

- Projections as motivation for future studies
  - Projections for observables (x-sections, multiplicities, asymmetries)
  - Projections for underlying physics objects of interest (GPDs, TMDs,.. guts of QCD)
- Extending the phase space in $P_T$, $Q^2$ and $x$
- Studies of evolution properties
- Future studies of 3D

Summary
QCD: from testing to understanding

**Testing stage:**
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, IMF)

**Understanding stage:**
non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)

Production in SIDIS provides access to correlations inaccessible in simple SIDIS (dihadron fragmentation, correlations of target and current regions, entanglement....)
Projections to motivate the JLab 20+ upgrade

Classify observables, summarize the set of projection from future facilities

1) Identify the flagship measurements that can be done only with 20+ GeV

2) Identify the flagship measurements with 22 GeV that can extend, improve the 11 GeV, helping interpretation, multidimensional bins in extended kinematics

3) Identify the measurements with 22 GeV that can set the bridge between JLab12 and EIC (complementarity)

- Produce sets of event for relevant observables (SIDIS, DVCS, Large x,....) and process them using existing detector reconstruction chains (ex. CLAS12, SoLID, Hall-A/C/D), evaluate count rates, define kinematical coverage and resolutions
  - Identify observables that can provide critical input without detector upgrades
  - Identify critical observables, that require certain detector upgrades

Most importantly: projections teach us what we can do with our JLab12 data, and where we need to combine it with higher energy data
SIDIS kinematical coverage and observables

Studies of azimuthal modulations give access to underlying 3D partonic distributions

QCD predicts only the $Q^2$-dependence of 3D PDFs
What we learned: missing parts of the mosaic

• SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space \((x,Q^2,z,P_T,\phi)\)

• Collinear SIDIS, is just the proper integration, over \(P_T,\phi\)

• SIDIS observations relevant for interpretations of experimental results:
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex. \(x,P_T\)-range)
  2. Understanding of \(P_T\)-dependences of observables in the full range of \(P_T\) dominated by non-perturbative physics is important
  3. Understanding of phase space effects is important (additional correlations)
  4. Understanding the role of vector mesons is important
  5. Understanding of evolution properties and longitudinal photon contributions
  6. Understanding of radiative effects may be important for interpretation
  7. Overlap of modulations (acceptance, RC,…) is important in separation of SFs
  8. Multidimensional measurements with high statistics, critical for separation of different ingredients
• QCD calculations may be more applicable at lower energies when 1)-7) clarified
• Need a realistic chain for MC simulations of SIDIS to produce realistic projections with controlled systematics
Opportunities with 20+ GeV

Significantly wider phase space would allow

- Enhance the range in transverse momentum $P_T$ of hadrons
  - Access to $P_T$-region where the dependence of the $k_T$-dependences of different flavors (valence and sea) and polarization states is most significant

- Enhance the $Q^2$ range
  - Increase significant the range of high $Q^2$, where the theory is supposed to work better, and allow studies of evolution properties

- Enhance the $x$-range
  - Access the the full kinematical range ($x>0.03$) where the non-perturbative sea is expected to be significant
Multiplicities of hadrons in SIDIS

Gaussian Ansatz

\[ f_1^q \otimes D_1^{q \rightarrow h} = x f_1^q(x) D_1^{q \rightarrow h}(z) \frac{e^{-p_{T}^2 / \langle p_{T}^2 \rangle}}{\pi < p_{T}^2 >} \]

TMDs universal, so what is the origin of the differences observed?

COMPASS:1709.07374

JLab: not enough energy to produce large \( P_T \)

HERMES: not enough luminosity to access large \( P_T \)

- What is the origin of the “high” \( P_T \) (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?
For some kinematic regions, at low $z$, the high $P_T$ distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).

If the effect is accounted, the CLAS data follows global fits.
Most critical with JLab20+: access to large $P_T$

List if of possible sources of large non-perturbative $P_T$ in SIDIS

1. Non perturbative sea

2. Wider in $k_T$ u- distributions (need long.pol.target)

3. Wider in $k_T$ d-quark distributions

4. Wider in $P_T$ longitudinal photon contributions ($F_{UU,L}$)

5. Vector meson decay pions (low $P_T$) vs direct pions (high $P_T$)

Large $P_T$-coverage critical for sorting out flavor dependence of $k_T$-distributions of TMDs!!!
Azimuthal distributions in SIDIS (unpolarized)

EMC-1983 (PL,v130,118)

Observables:
- Azimuthal Moments
- Multiplicity

- Quark-gluon correlations are significant in electro production experiments (even if at high energy).
- Large $\cos \phi$ modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.
Attempts to understand $Q^2$-dependence of HT

The ratios of SFs (to $F_{UU}$) are not decreasing with $Q$!!!
The HT observables, don’t look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies

H. Avakian, JLab, July 8
Hadron production in hard scattering

\( x_F \) – fractional momentum in the CM frame

\( x_F > 0 \) (current fragmentation) \( \times \) \( F \)

\( x_F < 0 \) (target fragmentation) \( \times \) \( F \)

Karliner, Kharzeev, Ellis & Kotzinian
Strikman, Weiss & Schweitzer
Anselmino, Barone, Kotzinian

FSI

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles

H. Avakian, JLab, July 8
Spin-azimuthal correlations in hadron pair production are very significant

Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)

Direct pions dominate only at relatively high $P_T$, ($P_T > 0.6-0.7$ GeV)

Contributions to $\pi^+$ in $e'\pi^+\pi^-X$ sample from different channels

Large $M_{\pi\pi}$ pions with $P_T > 0.5$ GeV

 mc

theory
CFR/TFR correlations in 2 hadron production


\[ A_{LU} = -\sqrt{1 - \epsilon^2} \frac{F_{LU}}{F_{UU}} \sin \Delta \phi \]

- Depolarization factor becomes negligible at high energies at large x

The correlation is most significant at large x, where the valence quarks (non-perturbative sea?) most relevant
“Only JLab” measurements (suppressed at EIC)

\[ A_{LL} = \frac{F_{LL}}{F_{UU}} \]

Double spin asymmetries in hadron production CFR and TFR

\[ F_{LU} \sin(\phi_1 - \phi_2) \sin \Delta \phi \]

Beam spin asymmetries in correlations of CFR and TFR

\[ \sin \phi_h F_{LU}^{\sin \phi_h} \]

Beam spin asymmetries in CFR (single and dihadron)

\[ A_{LU}^{\sin \phi_{R \perp}} \]

Examples in slides (10-15)

Exclusive processes in the x>0.1 domain, may most be in this category, due to resolutions and rapidly decreasing x-sections at higher energies
Fixed target experiments are sensitive to all SSAs
- Higher energy opens up the phase space allowing access to, sea and large $Q^2$
- Measurements of beam SSAs (+some others) at large $x$, will be challenging at EIC
Full simulation of CLAS12 at 22 GeV with pol. target

/volatile/cebaf24/sidis/reconstructed/clas12/lpol-target/..

- Studies of evolution of observed double spin asymmetries will be a critical task in validating the QCD predictions $g_1(x,k_T)$-studies CLAS12
- Asymmetries measured with input polarized and unpolarized PDFs, can be used to test the flavor decomposition capabilities
- Kinematical correlations, even for small bins relevant (multidimensional bins critical)
3D PDFs: Common features

CS kernel describes the interaction of out-going parton with the confining potential.
Provides nonperturbative part of evolution for TMDs.

\[ Q^2 \frac{dF(x, b; Q)}{dQ^2} = - \left( \frac{\gamma V(Q)}{2} + D(b, Q) \right) F(x, b; Q) \]

- quark AD perturbative known at N^3LO
- CS kernel nonperturbative
- TMD distribution any tw2 many tw3

nonperturbative \( Q \) and \( x \) can be factorized
\[ F(x, b; Q) = R[D, Q]F(x, b) \]
- \( R \) is known function
- \( D \) can be determined directly from data
  - requires dense coverage in \( p_T \)
  - requires proper adjustments of \( (x, z, Q) \)

The Collins Soper kernel, defining the evolution properties of TMDs related to non-perturbative q-q
Detailed studies of evolution properties of observables in different x-range will be needed.
Unknown “known” $f_1, g_1$ TMDs

Models and lattice predict very significant spin and flavor dependence for TMDs

Large transverse momenta are crucial to access the large $k_T$ of quarks

Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12

Understanding of $k_T$-dependence of $g_1$ will help in modeling of $f_1$
**Impact of limitations from theory**

- Gain with 22 GeV will be more critical with additional kinematical cuts imposed by theory.

\[ 0.25 < x < 0.35 \]
\[ 0.4 < z < 0.6 \]

Dominated by direct \( \pi^+ \)

\[ P_T / z / Q < 0.5 \]

More theory limitation, may convert the observable from major improvement (type 2) to only possible with 20+ GeV (type 1)
Summary

• Measurements of SFs from the azimuthal distributions of final state hadrons in electroproduction, requires high statistics in multidimensional bins (ex. $Q^2$-dep.)

• Extending JLab measurements to a wider range in $Q^2$ and $P_T$ with energy upgrade, will be crucial in studies of evolution properties of underlying PDFs, and separation of higher twist contributions, critical for understanding the QCD dynamics

• Better understanding of the process of extraction of final physics quantities (motivating the measurements) can help to optimize the output format of the data (ex, multidimensional binning, providing events…)

• The 3D physics with SIDIS and hard exclusive production processes can provide a set of flagship measurements
  – Measurements superior at JLab24, in the kinematics where non-perturbative effects are relevant, will compete both with JLab12 (exclusive processes) and EIC (SIDIS in perturbative regime)

• The data used in production of projections should be available, to allow reproduction and further improvement of those projections

Development of a procedure for making transparent and reproducible projections will be important for making a strong case for future experiments, and JLab20+ in particular (combined effort with computing+lattice+theory).
Support slides...
Organization of projections: “Process files” txt files

Organizing a common storage process
/volatile/cebabf24/sidis/generated/polarized-minus-22GeV-proton/
   /polarized-plus-22GeV-proton/
   /nitrogen-22gev-proton/
   /carbon-22gev/

   detector data-set
   /reconstructed/clas12/lpol-target/ rgc-pplus/ inbending/gev22/hipo/txt
   /outbending/…
   /rgc-pminus/…

   /proton-target/…
   /deuteron-target/…
   /carbon-target/…
   /nitrogen-target/…

   /hep/…
   /hsg/…

Reconstructed files stored in both reconstruction format (hipo files for clas12) and txt format
Organization of projections: “Process files” txt files

Come up with as general as possible set of variables
1) event info (run#,event#,helicity)
2) 3 momenta of involved particles (momentum, polar angle, azimuthal angle)
3) all relevant variables describing the process (x,Q²,y,W,z,PT,f, all relevant missing and invariant masses, more complex variables x_Feynman, rapidity,...)

/volatile/cebaf24gev/sidis/reconstructed/clas12/lpol-target/rgc-pplus/inbending/gev22/txt/
rgc_pplus_inbending_22GeV_eppi+X.txt
rgc_pplus_inbending_22GeV_epi+X.txt
rgc_pplus_inbending_22GeV_epX.txt

Ex. ep→e’π+X

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<td>5.8741</td>
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</table>

• Process files, even in the text version occupy few Gb
• We can come up with a header (JSON, HepMC,...) so the analysis software will read it without major efforts.
SIDIS kinematical coverage and observables

Higher energies open the phase space for large transverse momenta and $Q^2$, and lower $x$, but move events to lower $y$.

- Wider range in $Q^2$ allows evolution studies of 3D PDFs
  - Higher statistics, better resolutions vs wider range in EIC (complementary)

Crucial to evaluate counts in the fiducial region (resolutions, acceptance, RC, ...)

\[ \sigma \propto F_{UU} + P_b \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin \phi} \sin \phi + P_t \epsilon F_{UL}^{\sin 2\phi} \sin 2\phi + \ldots \]

- Higher energies open the phase space for large transverse momenta and $Q^2$, and lower $x$, but move events to lower $y$.
- Wider range in $Q^2$ allows evolution studies of 3D PDFs
  - Higher statistics, better resolutions vs wider range in EIC (complementary)
From JLab to EIC: complementarity

- Understanding of $Q^2$-dependence of multiplicities crucial for interpretation
- JLab at 24 GeV will provide critical input in evolution studies of TMDs
- Higher $Q^2$-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large $x$
$A_{LU}$: New look at SSAs in $ep \rightarrow e'\pi X$  

S. Diehl

Higher Twist PDFs

<table>
<thead>
<tr>
<th>$N/q$</th>
<th>$U$</th>
<th>$L$</th>
<th>$T$</th>
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<td>$f_1^u$</td>
<td>$g_1^u$</td>
<td>$h_1,\epsilon_L$</td>
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<tr>
<td>$L$</td>
<td>$f_1^d$</td>
<td>$g_1^d$</td>
<td>$h_L,\epsilon_L$</td>
</tr>
<tr>
<td>$T$</td>
<td>$f_1,\bar{f}_1$</td>
<td>$g_1,\bar{g}_1$</td>
<td>$h_T,\epsilon_T,\bar{h}_T,\epsilon_T$</td>
</tr>
</tbody>
</table>

$ep \rightarrow e'\pi^+ n$  

$\pi^+$ from $u$-quark

$A_{LU} \sin \phi$  

$z_{\pi^+}$

$ep \rightarrow e'\pi^0 X$  

$ep \rightarrow e'\pi^{-} X$

$A_{LU} \sin \phi$

$z_{\pi^-}$

Single beam SSA tends to change the sign, when the observable is dominated by the struck $u$-quarks.

At small $P_T$ the counts are dominated by VMs coming fro $u$-quarks.
The SSA, clearly changing the sign, may be used to define separation of TFR and CFR regions

More baryons in the TFR, mesons in the CFR
Evolution in TFR

Fatiha’s talk at CPHI-2022


Accounting for correlation between $Q^2$ and $P_T$
Multidimensional measurements

Beam SSAs as a tool to access the longitudinally polarized quarks

Low $P_T$ dominated by VM decays from $u$-quarks

$\pi^-$ has sensitivity to polarized $d$-quarks, but require multidimensional measurements
Projects for involved processes

Steps for making transparent, reproducible projections, to convince ourselves, first, before trying to convince others

- Define the cross sections for a given process
  - Collect realistic sets of Structure Functions (to be stored on common disk space)
  - Test with existing data (HERMES/CLAS/….)
  - Test with available full event generators (PYTHIA,…)
- Generate events of interest base on x-section defined by SFs
- Reconstruct particles in a given framework (CLAS12/SoLID/Hall-A/C/D) with actual resolutions and phase space (to be stored on common disk space)
- Make projections of extraction of relevant objects from the reconstructed data sets, with a well documented set of assumptions

Ex. of SIDIS with single hadron production for polarized targets

\[
\frac{d\sigma}{dx dQ^2 dz dP_{hT}^2 d\phi_h d\phi_l d\phi_s} = \sum_{l=1}^{L} SF_l
\]
Making projections: extraction procedure

Extraction procedure should have clear definition of systematics

- The role of multidimensional measurements should be well defined, accounted in the extraction
  - The same parameterization used in production of data and extraction of TMDs will have practically unconstrained systematics
  - Using statistical errors from simulation to evaluate the errors on a given TMDs can produce absolutely unrealistic projections, in particular in boundaries.
Making projections: data set

Pseudo data set (counts)

Some prediction (parameterization?)

Extraction procedure

Projection for measurements

Data set

Full statistics

Fiducial volume

Full cuts \( (E_{\text{min}}, y_{\text{min}}, y_{\text{max}}, \ldots) \) may reduce the sample from \( \sim 50\% \) to 1-2%

Quality

- Cross sections + geometrical cuts
- Generated events (real phase space)
- Reconstructed after GEANT (ideal)
- GEANT simulation + resolutions+ID
- Generate the physics and detector backgrounds
- Generated full x-section + radiative effects
- Reconstructed with realistic detector (trigger, tracking, efficiencies, resolutions, particle ID, ….)
Contributions for 3D structure studies: Sivers

$y > 0.05, 100$ days (corrected for EIC official lumi)

- Measurements of $Q^2$-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region

Pavia grids

$\times = 0.3$
$z = 0.7$
$P_T = 0.3$
B2B correlations with long. Pol. Target

<table>
<thead>
<tr>
<th>Niq</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( \hat{u}_1 )</td>
<td>( \hat{i}_{1L} )</td>
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<td>( \hat{u}_{1L} )</td>
<td>( \hat{i}_{1L} )</td>
<td>( \hat{i}_{1L} )</td>
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<tr>
<td>T</td>
<td>( \hat{u}_{1T} )</td>
<td>( \hat{i}_{1T} )</td>
<td>( \hat{i}_{1T} )</td>
</tr>
</tbody>
</table>

A. Kotzinian, arXiv:1107.2292

\[
\sigma_{UU} = F_0 \hat{u} \cdot D_1
\]

\[
\sigma_{UL} = -\frac{P_{T1} P_{T2}}{m_2 m_N} F_{k1} \hat{u}_{1L} \cdot D_1 \sin(\phi_1 - \phi_2)
\]

No depolarization, like Sivers!

- Target SSA can be measured in the full \( Q^2 \) range, combining different facilities
- Advantages: Higher Lumi for JLab, less suppression at high \( Q^2 \) for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

CL AS12 proposals
NH3/ND3
  - E12-09-009
  - E12-07-107
  - E12-09-007A

\( ^3 \text{He} \)
  - C12-20-002

\( ^7 \text{LiD} \)
  - E12-14-001
Relevance of RC in studies of complex azimuthal modulations

In the presence of QED radiation, the q direction is not fixed

Overlap of modulations from RC (Sivers → Collins)

\[
\sigma_{XY}^{h}(x, z, P_T) \rightarrow \sigma_{XY}^{B,h}(x, z, P_T) \times R(x, z, P_T, \phi_h) + \sigma_{XY}^{R,h}(\ldots).
\]

\[
R(x, z, P_T, \phi) = f_{XY}(x, z, P_T) \times (1 + a_{XY} \times \cos \phi + \ldots)
\]
From JLab to EIC: complementarity

The ratio of radiative cross ($\sigma_{RC}$) section to Born ($\sigma_B$) in SIDIS

$\sigma_{RC}/\sigma_B$ vs $Q^2$

Cross section at low $Q^2$ suppressed at higher CM energies

- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.
- Most sensitive to RC will be all kind of azimuthal modulations sensitive to cosines

T. Liu et al

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Gaussian $F_{UU} (\phi_h=0)$
MC simulations: Why LUND works?

- A single-hadron MC with the SIDIS cross-section where widths of $k_T$-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- Accessible phase space properly accounted
- The correlations between hadrons, as well as target and current fragments accounted
- ….

To understand the measurements we should be able to simulate, at least the basic features we are trying to study ($P_T$ and $Q^2$-dependences in particular).

The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!
SIDIS ehhX: CLAS12 data vs MC

CLAS12 dihadron production $ep \rightarrow ehhX$

CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters "default" is in a good agreement with CLAS12 measurements for all relevant distributions
SIDIS ehhX: CLAS12 data vs MC

CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters "default" is in a good agreement with CLAS12 measurements for all relevant distributions.
b2b SSAs

\[ A_{LU}^{\sin(\phi_1 - \phi_2)} \propto \frac{C[w_5 \hat{i}_{1h} D_1]}{C[\hat{u}_1 D_1]} \]

\[ w_5 = \frac{(k_{\perp} \cdot P_{2\perp})(P_{1\perp} \cdot P_{2\perp}) - (k_{\perp} \cdot P_{1\perp})P_{2\perp}^2}{(P_{1\perp} \cdot P_{2\perp})^2 - P_{1\perp}^2 P_{2\perp}^2} \]

CLAS12 Preliminary

3 independent methods used

0.25 < x < 0.35

No significant \( Q^2 \)-dependence observed for b2b \( A_{LU} \)

First indication in large x SIDIS of a LT observable

H. Avakian, JLab, July 8
Sensitivity of d-quark structure to $^3$He: Simulation

Statistics for 30 days
Bin:

\[ \langle x \rangle = 0.425 \]
\[ \langle Q^2 \rangle = 5.0 \]
\[ \langle z \rangle = 0.44. \]

Using:
LO GRV for PDF $x,Q^2$
LO DSS for $D_1(z,Q^2)$

\[ <p_T^2> = 0.16 \]
\[ <k_T^2> u = 0.3 \]
\[ <k_T^2> \Delta u = 0.33 \]
\[ <k_T^2> \Delta d = 0.22 \]
\[ <k_T^2> \Delta d = 0.25 \]

Note: for proton $\pi^+$ (triangle up) $\pi^-$ (triangle down) $A_{LL}$s have the same sign for proton and opposite signs for neutron

\[
F_{LL}^N = x \sum_q e_q^2 g_1^q(x,Q^2) D^q(z,Q^2) P_{\Delta q}
\]

\[
f_1^{q/N}(x,k_T) = f_1^{q/N}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle_q}}{\pi \langle k_T^2 \rangle_q},
\]

\[
g_1^{q/N}(x,k_T) = g_1^{q/N}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle_{\Delta q}}}{\pi \langle k_T^2 \rangle_{\Delta q}},
\]
We all contributed....
Polarized quark structure from proton and $^3$He

The $k_T$-dependent width of polarized d-quarks has significantly smaller uncertainty from neutron data due to order of magnitude large and canceling contributions in proton (input values for $u \rightarrow 0.22$, $d \rightarrow 0.25$)

- unpolarized widths for $u$ and $d$ known within 10%
- $\Delta d / \Delta u$ at large $x$ known within 20%
- 1sigma spread of ALLs

\[
P_{\Delta d} = - \frac{p_T^2}{\pi \left( \langle k_T^2 \rangle \Delta d z^2 + \langle p_T^2 \rangle \right)} \left. \right| e^{\langle k_T^2 \rangle \Delta d z^2 + \langle p_T^2 \rangle} \]

\[
P_{\Delta u} = - \frac{p_T^2}{\pi \left( \langle k_T^2 \rangle \Delta u z^2 + \langle p_T^2 \rangle \right)} \left. \right| e^{\langle k_T^2 \rangle \Delta u z^2 + \langle p_T^2 \rangle} \]

Decent extraction for $u$-quarks

Extractions of TMDs (both $\Delta d$ and $\Delta u$) can be performed within model assumptions
CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator

- Kinematic distributions, $z, x_F, P_T$-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24
CLAS12 data preservation

https://clasweb.jlab.org/wiki/index.php/Hall-B_Task_Forces_2020#Data_Preservation

Layers of data abstraction hierarchy

Reconstructed data
Relevant train(pass1):
  • id: 4
  • forward: 11:X+:X:-Xn
  • RGA electron: Q2>1 && W>2
  & & p>2 && vz>-25 && vz<20
  • RGB electron: Q2>0.95, W>1.95
  & & p>2 && vz>-25 && vz<20

Recons. Software
Pass1 DSTs

Raw data (production)

Data selection software, java/C++
1) SSA set (1st publications)
2) Multiplicity set (Giovanni, Orlando, ...)
3) x-section set (Nick)

Process file
ep→e′pπ+X
Analysis software

Process file
ep→e′π+X
Analysis software

Process file
ep→e′π+π−X
Analysis software

• Publication plots from analysis note and corresponding publication
Projections from 1D to 4D

Projected error on Sivers?

Projections should contain the size of the effect and the counts for a given interval of time.

For SIDIS the x-section is defined by $F_{UU}$, for Sivers effect $F_{UT}/F_{UU}$.

$Q^2 = x \cdot y \cdot s$

“affinity” → how well theory works

(H. Avakian, JLab, July 8)

Non-perturbative contributions

Non-perturbative sea ("tornado"/$^3P_0$) in nucleon is a key to understand the nucleon structure $\bar{d} > \bar{u}$

- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate ($x>0.02$)
- Large transverse momenta of hadrons most relevant for understanding the non-perturbative QCD dynamics

- Predictions from dynamical model of chiral symmetry breaking [Schweitzer, Strikman, Weiss JHEP 1301 (2013) 163]
  - $k_T$ (sea) >> $k_T$ (valence)
  - short-range correlations between partons (small-size q-qbar pairs)
  - may be directly observable in $P_T$-dependence of hadrons in SIDIS

Understanding of the evolution of transverse momentum dependence most critical in validation of the theory
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of $x$ close to the valence region.

FO vs data for $q_T \gtrsim Q$

\[ F_{XY}^{h}(x, z, P_T, Q^2) \propto \sum H^q \times f^q(x, k_T, ..) \otimes D^{q\rightarrow h}(z, p_T, ..) + Y(Q^2, P_T) + \mathcal{O}(M/Q) \]

\[ \int d^2 k_T d^2 \vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T) \]

quark transverse momentum

The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of $x$ close to the valence region.
Quark distributions at large $k_T$

Higher probability to find a hadron at large $P_T$ in nuclei

$k_T$-distributions may be wider in nuclei?

$P_T = p_{\perp} + z k_T$
Relative fluxes: e- vs pi-

Relative fraction of pi- increases for a fixed energy
For a constant y (y<0.75 used) they are consistent
Relative fluxes: e- vs pi-

Contamination at low energies will be ~50% higher (electrons <2 GeV may not be much useful anyway)
Without clear understanding of systematics from separation of different modulations, and impact of model assumptions/approximations used in their production, this projections suppressed development of proper extraction frameworks with controlled systematics for years.
**TMDs sensitivity to transversity: large x**

- JLab measurements with transversely polarized targets will provide crucial input at large x
- Complementarity of JLab and EIC at large x should be carefully examined for better coordination (theory+experiment)
- Systematics from parameterizations, providing “sensitivity” to kinematical regions not covered by data should be carefully evaluated
A procedure for realistic and reproducible projections for non-perturbative objects of interest (3D PDFs, FFs, FrF, …) from the multidimensional experimental observables with controlled systematics could be used by all interested.
TMD extractions, parameterizations, grids

Important note from theorists: parametrizations should be used in the kinematics they are applicable. Validations mostly done for given Fragmentation Functions, by variations of experimental data within errors (TMD extraction talks).

How to validate the TMD parameterization in 3D (discussion session):

• Compare kinematic dependences with new data (ex. $P_T, Q^2$-dependences)
• Compare kinematical dependences with direct calculations and lattice
• Compare kinematical dependences with other extractions
• Compare kinematical dependences with QCD inspired model predictions
• Common sense & intuition about non-perturbative kinematics

Use MC validation: generate pions with probabilities from extracted SFs for a given experiment, including the RC and compare multiplicities and SSAs with a given experiment (accounting phase space limitations & correlations between variables)

$$F^h_{XY}(x, z, P_T, Q^2) \propto \sum H^q \times f^q(x, k_T, ..) \otimes D^{g \rightarrow h}(z, p_T, ..) + Y(Q^2, P_T) + \mathcal{O}(M/Q)$$
Coverage and binning

\[ Q^2 = \ln \left( \frac{Q^2_{\text{max}}}{Q^2_{\text{min}}} \right) / N_q \]
\[ \Delta x = \ln \left( \frac{x_{\text{max}}}{x_{\text{min}}} \right) / N_x \]
\[ \Delta Q^2 = \ln \left( \frac{Q^2_{\text{max}}}{Q^2_{\text{min}}} \right) / N_q \]
\[ Q^2_i = Q^2_{\text{min}} e^{i \Delta Q^2} \]
\[ x_i = x_{\text{min}} e^{i \Delta x} \]
\[ \Delta z = \frac{z_{\text{max}} - z_{\text{min}}}{2N_z} \]
\[ \Delta P_T = \frac{(P_{T_{\text{max}}} - P_{T_{\text{min}}})}{2N_P} \]
\[ z_i = z_{\text{min}} + (2i + 1) \Delta z \]
\[ P_{Ti} = P_{T_{\text{min}}} + (2i + 1) \Delta P_T \]

Grids for N+1 values from i=0,N

- \( N_x = 200 \)
- \( N_q = 200 \)
- \( N_z = 20 \)
- \( N_P = 40 \)

- \( x_{\text{min}} / x_{\text{max}} = 0.02 / 0.98 \)
- \( Q^2_{\text{min}} / Q^2_{\text{max}} = 1.0 / 40 \)
- \( z_{\text{min}} / z_{\text{max}} = 0.05 / 0.95 \)
- \( P_{T_{\text{min}}} / P_{T_{\text{max}}} = 0.0 / 2.0 \)
From JLa12 to JLab24 Larger $Q^2$ at large $P_T$

$H. Avakian, JLab, July 8$

- JLab12
- Cleaner pion sample
- JLab24

$P_T/(zQ)<1$

$P_T/(zQ)<0.5$

$P_T/(zQ)<0.25$

$\frac{f^q(x, k_T)}{D^{q\rightarrow h}_1(z, p_T)}$

Events in the same time interval in CLAS12 acceptance

JLab24 will significantly increase the the $Q^2$ range, allowing detailed separation of higher twist SFs, needed for understanding the QCD
Relative fluxes: $e^-$ vs $\pi^-$

Contamination at low energies will be ~50% higher (electrons $<2$ GeV may not be much useful anyway)
Relative fluxes: e- vs pi-

Relative fraction of pi- increases for a fixed energy
For a constant $y$ ($y<0.75$ used) they are consistent
Current theory limitations (q$_T$/Q)

The q$_T$=P$_T$/z theory “trustworthy” cut:
1) Suppresses moderate Q$^2$ and large P$_T$ (sensitive to k$_T$), where all kind of azimuthal modulations are most significant
2) Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations
3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P$_T$ samples, including ones from HERMES COMPASS, and even EIC.

Details available from https://indico.jlab.org/event/439/JLab/HERMES/COMPASS/EIC talks
Gluon polarization at large x

Photon gluon fusion (PGF) process
direct measurements of the unpolarized
 gluon structure function $G(x_G)$.
• charm production
• production of jets with high
  transverse momentum $P_T$.

Background processes

Depending on required kinematical cuts
can be type 1) or type 2) observable

- Can be studied in electroproduction and quasi-real electroproduction at sufficiently high $P_T$ reflect the high $P_T$ of the quark and antiquark produced in the PGF process.
Complementarity between JLab and EIC

Multiplicities, evolution of unpolarized SFs

Sivers and Collins SSAs (Transverse target)

Longitudinally polarized Target spin asymmetries in correlations of CFR and TFR (single and dihadron)

Observables with no $\varepsilon$-dependence or not suppressed at low $y$ provide complementarity set

$x=0.3$
Hadron production in hard scattering in SIDIS

\( x_F \) – fractional momentum in the CM frame

- \( x_F < 0 \) (target fragmentation)
- \( x_F > 0 \) (current fragmentation)

Different non-perturbative objects may be involved in description, depending on kinematical conditions, introducing different dependence on \( Q^2 \)

H. Avakian, JLab, July 8
Resolutions in x

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Bins ~4sigma
Resolutions in $Q^2$

Bins ~5sigma
Observation of SSAs in $ep \rightarrow e' \pi^+ \pi^- X$


$H_1^{\perp} = \frac{d\sigma_{LU}}{dz} \propto \lambda e \sin(\phi_{R_{\perp}}) \left( x e(x) H_1^{\perp}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\perp}(z, M_h) \right)$

Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons (low x)
First extractions support: quark gluon correlations may be very significant
PDF $e$ describes the force on the transversely polarized quark after scattering, factorization and evolution studies by Vladimirov et al (in preparation)

$A_{LU}$ vs $x$

$e^P(x)$ at 90% CL


A. Courtoy et al. (ArXiv:2203.14975)
At large $x$ fixed target experiments are sensitive to all Structure Functions.
For EIC, observables surviving the $\varepsilon \rightarrow 1$ limit (F$_{UU}$, F$_{UL}$, Transversely pol. F$_{UT}$)
From CLAS12 to CLAS24: Trento and focused workshops

https://indico.ectstar.eu/event/126/

Key speakers/physics items

1) Jianwei Qiu (QCD)
2) Jen-Chieh Peng (non-perturbative sea)
3) Pasquale Dinezza (the LHC fixed target experiments, large x)
4) Simonetta Liuti (GPDs)
5) Marco Battaglieri, Alessandro Pilloni (spectroscopy)
6) Moskov Amaryan/Goldstein (charm)
7) Lubomir Penchev (Hall-D physics/detectors)
8) Ralf Gothe (Hall-B physics/detectors)
9) Jiang-Ping Chen (Hall-A/C physics/detectors)
10) Eric Voutie (positron beam)
11) Carlos Munoz Camacho (exclusive processes)
12) Gunar Schnell/Marco Contalbrigo (HERMES)
13) Moretti/Parsamyan (COMPASS)
14) Signori/Vladimirov/Yuan (TMDs)
15) Yong Zhao/Martha Constantinou (Lattice studies)
16) Misak Sargsian (Medium effects/theory)
17) Lamiaa el Fassi (Medium effects/experiment)
18) Barbara Pasquini (GTMDs)
19) Anselm Vossen (Complementarity with EIC)

Physics Items

a) Measurements of evolution of 3D partonic distribution and fragmentation functions
b) Correlated hadrons and their impact on hadronization
c) Studies of 3D PDFs using combination of the Lattice QCD with the phenomenology and QCD based modeling needed for interpretation of the experimental data, and development of new observables.
d) Advances in the exploration of the structure of excited nucleon states

e) In-medium modifications of fundamental QCD processes
f) Studies of light meson structure
g) Charm production near the threshold
h) Spectroscopy at the intensity frontier
i) Large x physics
j) Electroweak Physics at 24~GeV

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Set of dedicated workshops/meeting to develop projections

H. Avakian, JLab, July 8
Observation of SSAs in $ep \rightarrow e'\pi^+\pi^-X$

Rodini & Vladimirov, arXiv:2204.03856

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Table 1. Quark TMD distributions of twist-three sorted with respect to polarization properties of both the operator (columns) and the hadron (rows). The labels U, H, and T are for the unpolarized, longitudinal and transverse polarizations. The subscript $J$ differentiates different angular momentum for the transversely-polarized case. The bullet $\bullet$ stands for the $\otimes, \ominus$ labels.
Proton structure from 1D to 3D

For real data description understanding the dynamics and related interactions and correlations (Higher Twists) will be important.

• FAMOUS QUOTE OF YURI DOKSHITZER
  • “FOLKS, WE NEED TO STOP “TESTING” QCD AND START UNDERSTANDING IT”, ICHEP 1998, VANCOUVER, BC, CONFERENCE SUMMARY TALK

spherical horse in vacuum

real life

fast moving hadron

Universality of PDFs
Evolution properties
QCD tested confirmed!!!
Nucleon structure, TMDs and SSAs

- Large effects observed at relatively large $x$, relatively large $P_T$ and relatively low $Q^2$
- Theoretical framework works better, and is “trustworthy” at higher $Q^2$ and lower $P_T$
- TMD Fragmentation functions poorly known and understood, systematics not controlled well
- Higher twist SSAs are significant, indicating strong quark-gluon correlations, issues theory has, may become a key to resolve the problems
- Real experiments have “phase space limitations” due to finite energies, introducing correlations between kinematical variables
- Impact of radiative corrections with full account of azimuthal moments in the polarized $x$-sections still in development

The main goal of SIDIS measurements is the study of non-perturbative QCD, through spin-orbit correlations, where they are significant enough to be measurable. Understanding of the limitations of the current TMD framework with all its assumptions and approximations, is important for predictions, and projections for future experiments.
Make Great with 24 GeV