TMDs from RHIC to EIC

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Not covered:
inclusive hadron $A_N$
IFF $\rightarrow$ Anselm
Why p+p to access TMDs

Complementarity:
QCD has two concepts, which lay its foundation: factorization and universality

→ To test these concepts and separate interaction dependent phenomena from intrinsic nuclear properties different complementary probes are critical

Probes: high precision data from ep, pp, e+e-

Gluons:
One of the driving motivations behind an EIC is the study of gluons. Strong interactions access gluons directly (qg & gg) and are well suited for studying TMD observables like Gluon Fragmentation Functions and Gluon Linear Polarization.

DIS: $F_L$, tag PGF (di-jets, heavy flavor)

Evolution:
TMD evolution is an area of active theoretical research!

→ Proton colliders routinely access higher $Q^2$ and $p_t$ than fixed target experiments (as well as some running scenarios for an EIC).

→ Provides insights into the size of observables we want to measure at an EIC.

Hadron collider data critical to fully realize the scientific promise of the EIC and lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
TMDs at RHIC

Till today TMDs came only from fixed target data $\Rightarrow$ high $x$ @ low $Q^2$

need to establish concept at high $Q^2$ and wide range in $x$

polarised pp at RHIC

RHIC unique kinematics: from low to high $x$ at high $Q^2$

only way to access gluon TMDs before an EIC
The objectives for TMDs

- Constrain TMDs over a wide x and Q^2 range (valence, sea-quarks & gluons)
  - need 2 scale processes (DY, W, Z^0, Di-jet, h^± in jet)
  - different ∫s → different p_t at the same x_t → evolution
  - Test non-universality of TMDs ↔ SIDIS

- observables as transversity can be accessed also in collinear observables (IFF)
  - test of TMD factorization & universality

- observables purely sensitive (1-scale (π^0/γ/jet)) to the TWIST-3 formalism
  - different ∫s → evolution

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<th>Final State</th>
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<td>A_N for W^+/-, Z^0, DY</td>
<td>A_U^π^+/π^0 azimuthal distribution in jets</td>
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<td>[ -\int d^2 k_{\perp} \frac{k_{\perp}^2}{M} f_{1T}^q(x,k_{\perp}^2) \mid_{SIDIS} = T_{q,F}(x,x) ]</td>
<td>A_N for π^+/π^0 and π^0</td>
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<td>[ \hat{H}(z) = z^2 \int d^2 k_{\perp} \frac{k_{\perp}^2}{2M_h^2} H^+<em>1(z,z^2,k</em>{\perp}^2) ]</td>
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**A Golden Observable: “Hadrons in Jet”**

**Observable: Hadron distribution inside jet**

- Study a hadron distribution inside a fully reconstructed jet

\[ F(z, p_t) = \frac{d\sigma^h}{dydp_tdz} / \frac{d\sigma}{dydp_t} \]

\[ f(z, p_t, j_t) = \frac{d\sigma^h}{dydp_tdzdj_t} / \frac{d\sigma}{dydp_t} \]

\[ z = \frac{p_t^h}{p_t^{jet}} \]

- The 1st observable is collinear, while the 2nd observable is a TMD

**Cross section for hadrons in jet**

- High sensitivity to Gluon FF
- Unique to pp

**Nuclear dependence of FFs**

- Seems to follow the feature of p+Pb at LHC
- Will see how energy loss picture will compare

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**Graphical Representations**

- Cross section for hadrons in jet
- Nuclear dependence of FFs
**Jets to access Transversity x Collins**

**Kinematics for hadrons in a jet:**

jets: anti-$k_t$ with $R=0.5$

PRD97 (2018), 032004
First Collins effect measurements in pp collisions are reasonably described by two recent calculations that convolute the transversity distribution from SIDIS with the Collins FF from $e^+e^-$ collisions

- Tests the predicted universality of the Collins FF
  - Kang et al, JHEP 11, 068 (2017)
- TMD evolution effects appear to be small
Collins effect vs $j_T$ in separate $z$-bins

- 500 GeV pp results hinted the $A_{UT}$ peak shifts to higher $j_T$ as $z$ increases
  - 2017 data factor 14 more statistics

- New preliminary 200 GeV pp results provide confirming evidence
What Do We Know about Gluon TMDs
Collective flow signatures seen even in the smallest systems and at the lowest RHIC energies.

TMD formalism in DIS predicts a distribution for linearly polarized gluons in an unpolarized target. This is reflected in \( \cos(2\phi) \) asymmetries in dijet production.

Study azimuthal anisotropy as a function of the rapidity dis-balance of the jets.

\[ xG_{ww}^{ij} = \frac{1}{2} \delta^{ij} xG^{(1)} - \frac{1}{2} \left( \delta^{ij} - \frac{2k^i k^j}{k^2} \right) xh^{(1)} \]
Heavy flavor asymmetries most sensitive to Twist-3 counterpart of Gluon Sivers and tri-gluon correlator,

no final state effects expected due to heavy quark mass

Both contributions poorly known

Model calculations from: Koike et al.

Phys. Rev. D84 (2011) 014026
- Surprising nonzero $J/\psi$ $A_N$ seen in pAu collisions while pp Asymmetries are mostly consistent with zero
- Nonzero effect only visible at the lowest available $P_t$
- Diffractive effects as cause not very likely due to coincidence with hard collision trigger
- pAl data is being analyzed
"Twist-3 Sivers" through Inclusive Jets

No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s} = 500$ GeV & 200 GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s} = 200$ GeV
Shaded bands represent maximal predictions from D’Alesio, Murgia, and Pisano, arXiv:1707.00914 utilizing Kretzer and DSS FF

New preliminary results from 200 GeV pp collisions will provide much stronger limits
Sensitivity to Gluon “TMDs”

**pp:**
- Improved results from 2015!
- Consistent with 0 to 3~$10^{-4}$ precision level at low $p_T$
- constrain of gluon Sivers effect
  - Anselmino et al, PRD 74 (2006), 094011
  - D’Alesio et al, JHEP 1509 (2015), 119

**pA:**
- high precision test of nuclear effects
2017

to

What Will Come

2025
**RUN-17: A goldmine for TMDs@STAR**

Collected:

350 pb$^{-1}$ → 14 times Run-11 for $-1 < \eta < 1.8$ → $A_N$ $W^+/-$ & $Z^0$, Collins, ……

**Will provide data to constrain**

→ TMD evolution,
→ sea-quark Sivers fct
→ through rapidity distribution → neg. $\eta$
→ test of Sivers fct. non-universality

→ $Z^0$ very clean channel no corrections
At 500 GeV in 2017:

Transversity $\times$ Collins

$p^+ p(Au) \rightarrow \text{jet} + \pm + X$

Sivers function through TWIST-3:

$\sin(\theta^*)$

To have high precision data at different $\sqrt{s}$

$\rightarrow$ constrain TMD evolution

$\rightarrow$ fixed $x$ and $Q^2 \rightarrow p_T$ different

linearly polarised gluons

$\rightarrow$ could be an explanation for the ridge seen in pp and pA
**Fragmentation Functions in pp and pA**

**Observable:** hadron in jet

→ pp best way to measure gluon PDFs → direct access through qg and gg scattering

\[ p+p: \quad \pi^+ \quad \pi^- \]

**Fragmentation functions in p+A/p+p at \(|\eta| < 0.4\)**

only at RHIC: measure nuclear effects for polarized FF → nCollins

\[ s_{p+p}, \quad = 200 \text{ GeV (STAR proj. stat. 2012+2015)} \]

\[ s_{p+Au}, \quad = 200 \text{ GeV (proj. stat. 2023)} \]
GPD $E_g$ and Wigner Functions

UPC:

- World wide only access to GPD $E$ for gluons → $J/\Psi$ production in $p^\uparrow Au /p^\uparrow p$ UPC

$$A_{UT}(\tau,t) \sim \frac{\sqrt{t_0} t}{m_p} \frac{\text{Im}(E \ H)}{|H|} = \frac{M_{J/\Psi}^2}{s}$$

Statistics:
- 2017 $p^\uparrow + p$ 400 pb$^{-1}$ → 1k $J/\Psi$s
- $\delta A_{UT} /-0.2$ in 3 $t$-bins
- Run-15 $pA$: ~300 $J/\Psi$

Expect 8000 diffractive di-jets in UPC in 700 pb$^{-1}$ in 2021
**Objective:**
unique program addressing several fundamental questions in QCD

➔ essential to
- the mission of the RHIC physics program in cold and hot QCD
- fully realize the scientific promise of the EIC
  ➢ lay the groundwork for the EIC, both scientifically and by refining exp. requirements
  ➢ Test EIC detector technologies under real conditions, i.e. SiPMs

**Scientific goals:**

**p+p:**
3-dim. characterization of the proton in momentum and spatial coordinates

**p+A**
Nature of initial state and hadronization in nuclear collisions
Onset and $A$-dependence of saturation

**A+A**
Longitudinal medium characterization
Precision flow measurements via long range correlations

**Upgrade includes:**
Forward Calorimeter System: EM and Hadronic
Forward Tracking System: Si + sTGCs
500 GeV: access high x (0.05 - 0.5) at high $Q^2$ (10 - 100 GeV$^2$)

very strong constrain for tensor charge $\delta q^a = \int_0^1 [\delta q^a(x) - \delta q^a(x)] dx$
L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, and Zhong-Bao Yin

Accessing gluon Sivers at EIC

Photon-gluon fusion (PGF)

Leading order DIS (LODIS)

QCD Compton (QCDC)

- Tag signal process PGF
- Vector sum of $p_{T1}$ and $p_{T2}$ reconstruct the gluon $k_T$ in $\gamma^*p$ c.m.s frame.
- Design kinematic cuts to suppress the quark contributions.

**Back-to-back limit:**

$$P_T' = \frac{|P_T^{h1} - P_T^{h2}|}{2}$$

$$k_T' = \frac{|P_T^{h1} + P_T^{h2}|}{2}$$

$$k_T' << P_T'$$

**Final state observables**

1. Open charm
2. Charged hadron pair
3. Dijet pair
Event weighting method

PYTHIA event generator

Beam energy

Photon-gluon fusion

Leading order DIS

QCD compton

Partonic flavor, kinematic info

Weighting events in a final state observable

$A_{UT} = R_g \frac{\sum_i N_g w_i}{N_g} + R_q \frac{\sum_i N_q w_i}{N_q}$

SSA in final state observable

Sivers weight event-by-event (signal, background)

$w = \frac{\Delta^N f_{a/p}^\perp(x, k_{\perp}, Q^2)}{2f_{a/p}(x, k_{\perp}, Q^2)}$. 
Inputs to the model calculation

\[ \Delta^N f_{a/p}(x, k_\perp) = 2N_a(x) f_{a/p}(x, k_\perp) h(k_\perp) \]

\[ w = \frac{\Delta^N f_{a/p}(x, k_\perp, Q^2)}{2f_{a/p}(x, k_\perp, Q^2)} \]

\[ A_{UT} = R_g \frac{\Sigma_i N_g w_i}{N_g} + R_q \frac{\Sigma_i N_q w_i}{N_q} \]

**Quark Sivers:** u and d quarks
JHEP 04(2017) Anselmino et. al.

**Gluon Sivers:**
u, d + Kretzer FF (SIDIS1)

**Positivity bound ansatz:**
\[ f_{1T}^{1g} = -\frac{2\sigma M_p}{k_\perp^2 + \sigma^2} f_g(x, k_\perp), \quad \sigma = 0.8 \]
Unpolarized Data from H1:
Ep: 27.6 GeV x 920 GeV
5<Q^2<10, 0.0005<x_{Bj}<0.002
p_{T*}, \eta^* defined in gamma-hadron center of mass frame

Polarized Data (Sivers) from COMPASS
160 GeV \mu beam on fixed target
0.1<y<0.9, Q^2>1, W>5

The MC reproduces a wide range of data over a wide range of kinematics extremely well
Dilution of parton level asymmetry

Fragmentation momenta smearing and resonance decay contribution accounts for the parton to hadron level asymmetry dilution at COMPASS energy.

Full simulation

PARJ(21)=0

PARJ(21)=0, MSTJ(21)=0

Turn off frag $p_T$

Turn off decay of resonances
Branching ratio: 3.9%

$D^0(c\bar{u}) \rightarrow \pi^+(ud)K^-(s\bar{u})$

$\bar{D}^0(\bar{c}u) \rightarrow \pi^-(\bar{ud})K^+(u\bar{s})$

- Acceptance for PID is assumed to be $|\eta|<3.5$
- Decay products from D mesons are mostly less than 10 GeV in mid-rapidity.
- Decay products $p_T>0.2$ GeV.
Assumptions on $D^0$ reconstruction:
- $D\to K + \pi$ (3.9%)
- Acceptance: $|\eta|^{\pi/K}<3.5$
- $p_T^{\pi/K}>0.2$ GeV, $p_T^{D}>0.7$ GeV, $z^D>0.1$
- $\int L dt = 10$ fb$^{-1}$

- Sensitive to gluon kinematics
- $D^0$-pair statistically challenging
- 10% positivity can be distinguished in single $D^0$ probe
**Assumptions on h-Pair reconstruction:**

Pairs of $\pi, K, p$

Acceptance: $|\eta|^{h_1 h_2} < 4.5$

$p_T > 1.4$ GeV, $z_h > 0.1$

Back-to-Back limit: $k_T' < 0.7 p_T'$

$\int L dt = 10$ fb$^{-1}$

- Gluon initiated process account for a large fraction of events at small $x_B$
- Parton asymmetry dilution larger than open charm
- Statistically more favored than open charm, resolve 5% positivity bound gluon Sivers size
Single out the asymmetry amplitude

\[ A_{UT}^{\sin(\phi_{kS})} = \frac{\int d\phi_{kS}(d\sigma^\uparrow - d\sigma^\downarrow) \sin(\phi_{kS})}{\int d\phi_{kS}(d\sigma^\uparrow + d\sigma^\downarrow)} \]

- Asymmetry size dependence on \( x_B, Q^2 \) can be identified with 5% positivity bound.
- No significant \( Q^2 \) trend as missing TMD evolution.
- \( x_B \) sensitive to the \( x \) dependence of input Sivers function.
Assumptions on di-jet reconstruction:

Anti-\(k_T\), R=1

jet constituents:
\(p_T > 250\) MeV, \(\pi/K/p/\gamma\), \(|\eta|<4.5\)
\(p_{T,jet1}>4.5\) GeV, \(p_{T,jet2}>4\) GeV

\(\int L dt = 10\) fb\(^{-1}\)

- Gluon initiated process dominant at small \(x_B\)
- Stronger correlation between final state observable to parton level kinematics
- Resolution down to 5% positivity bound gluon Sivers size
- Strong correlation of jet momentum to its mother parton
- Direct handle on parton kinematics put stronger constraint such as $x_{\text{parton}}$
- Large statistics allow to explore SSA in multidimensional analysis.

$$x_{\text{parton}}^{\text{rec}} = \frac{p_T^{\text{jet1}} e^{-\eta^{\text{jet1}}} + p_T^{\text{jet2}} e^{-\eta^{\text{jet2}}}}{W}.$$
Hadron fragmentation momentum smearing and resonance decay are important.

Other smearing effects in dijet processes $\rightarrow$ parton radiation.
Unique RHIC forward and midrapidity pp/pA/AA program addressing several fundamental questions in QCD

Hadron-Hadron collider data are crucial to test all aspects of TMDs

Gluon TMDs at EIC good example that it is critical to confront ideas with measurement reality
**Initial State: TMDs vs. Twist-3**

**TMD**

- Requires: \( q >> Q_T = \Lambda_{QCD} \)
- \( Q >> p_T \)

**Twist-3**

- Requires: \( q, Q_T >> \Lambda_{QCD} \)
- \( p_T \sim q \)

 Efremov, Teryaev; Qiu, Sterman or Twist-3 FF

**Intermediate**

\( Q_T/p_T \) \( \ll \) \( \Lambda_{QCD} \)

\( \Lambda_{QCD} \)

- **Requires 2 scales** \( Q^2 \) and \( p_t \)
- **2 scale observables in pp/pA**
- **DY, W/Z-production**
- **Provides access to full transverse momentum dynamics** \( k_T \)

**Intermediate**

\( Q_T/p_T \) \( \ll \) \( \Lambda_{QCD} \)

- Need only 1 scale \( Q^2 \) or \( p_t \)
- But should be of reasonable size
- framework for pp observables \( A_N(\pi^0/\gamma/jet) \)
- Provides access to average transverse momentum \( \langle k_T \rangle \)

\[ -\int d^2k \frac{k^2}{M} f_{Tq}(x,k^2) \big|_{SIDIS} T_{q,F}(x,x) \]
$D^0$ as charm quark proxy

$D$ meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.
Charged hadron vs kaon spectrum

Charged hadron

Charged Kaon
D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.
Assumptions on h-Pair reconstruction:
Pairs of $\pi,K,p$
Acceptance: $|\eta|^{h1h2}<4.5$
$p_T>1.4$ GeV, $z_h>0.1$
Back-to-Back limit: $k_T'<0.7p_T$
$\int Ldt = 10$ fb$^{-1}$

Hadron pair distribution

Large $z$ prefers forward rapidity

Acceptance for all charge
- Gluon Sivers function and other TMDs is an ingredient of complete 3D imaging of nucleon.
- It can be uniquely accessible and constrained in a wide kinematic range at EIC.
- Dihadron and dijet methods are more statistically favored compared to the open charm production.
- Different probes are complementary to each other at EIC.