Recent Transverse Spin Measurements in pp Collisions with STAR

Carl Gagliardi
Texas A&M University
for the STAR Collaboration

Outline

• Introduction
• Recent (and near future) measurements
• STAR Forward Upgrade plans
Complementarity of DIS and p+p

- **Deep-inelastic scattering** primarily probes via:
  - Electromagnetic interactions
    - Couple to charge\(^2\)
    - Insensitive to color
  - Weak interactions
    - Couple to weak charge (~flavor)
    - Insensitive to color
  - Only accesses gluons through higher-order effects

- **pp collisions** primarily probe via:
  - Strong interactions
    - Couple to color charge
    - Direct leading-order sensitivity to gluons
    - Insensitive to flavor

- Need both for a consistent and complete picture
- **Combine DIS and p+p** to explore universality and separate interaction-dependent phenomena from intrinsic properties
A well-proven method

The key role of hadronic collision data to determine the unpolarized PDFs of the proton has long been exploited

RHIC provides equally critical data to determine polarized PDFs

- Have provided essential constraints on gluon and anti-quark polarizations
- Now also providing critical insights in transverse spin phenomena

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RHIC: the Relativistic Heavy Ion Collider

- Search for and study the Quark-Gluon Plasma
- Explore the partonic structure of the proton
- Determine the partonic structure of nuclei
Recent Transverse Spin Measurements with **STAR**

- **RHIC**: the world’s first (and only!) polarized hadron collider
  - Spin varies from rf bucket to rf bucket (9.38 MHz)
  - Spin pattern changes from fill to fill
  - Spin rotators provide choice of spin orientation
  - Billions of spin reversals during a fill with little depolarization
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance
Excellent particle identification

The Solenoidal Tracker At RHIC
Recent transverse spin measurements
Why TMDs?

- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  - Tomography of the nucleon!
- Access to transverse momenta at non-perturbative scales
  - Probe at the confinement scale
- Exhibit correlations arising from spin-orbit effects
- Close connection to Twist-3 quark-gluon-quark correlations

$x f_1(x, k_T, S_T)$
Initial state: TMDs and Twist-3

Requires 2 scales:
- Hard scale $Q^2$
- Soft scale $p_T$

SIDIS, Drell-Yan, W/Z, ...

Access the full transverse momentum dynamics $k_T$

Single hard scale: $p_T$

Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

Access the average transverse momentum $<k_T>$

\[-\int d^2k_\perp \frac{k_\perp^2}{M} f_{1T} q(x, k_\perp^2)|_{SIDIS} = T_{q,F}(x, x)\]
Separating initial- from final-state effects

Sivers or twist-3 mechanisms:

- Signatures:
  - $A_N$ for jets or direct photons
  - $A_N$ for $W^{+/−}$, $Z^0$, Drell-Yan
  - $A_N$ for heavy flavor (gluon)
- Sivers NOT universal
  - Sign change from SIDIS to $W$, $Z$, and Drell-Yan

Collins or novel FF mechanisms:

- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - $A_N$ for pions $\rightarrow$ novel FF
- Collins predicted to be universal

Sensitive to proton spin – partron transverse motion correlations
Color interactions in QCD

Controlled non-universality of the Sivers function

\[ \text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{Drell-Yan}} \text{ or } \text{Sivers}_{W} \text{ or } \text{Sivers}_{Z} \]

\( A_N \) for direct photon has related sign change in Twist-3

Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

Can explore all of these observables in 510 GeV pp collisions at RHIC
STAR performed an exploratory measurement of $A_N$ for W production with a small data set recorded in 2011
- W kinematics fully reconstructed

- Favors sign change if evolution effects are modest
  - TMD evolution is non-perturbative at low $k_T$ – no absolute theory predictions
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- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable $x$ but very different $Q^2$
    - $W$ and $Z$ $A_N$ at 510 GeV
    - Drell-Yan at 510 GeV

2017 RHIC run, data currently under analysis
Propose a return to 510 GeV in 2021:
Go beyond testing the sign
Are the magnitudes really equal in SIDIS and pp collisions?
- Access similar observables at comparable $x$ but very different $Q^2$
  - $W$ and $Z$ $A_N$ at 510 GeV
  - Drell-Yan at 510 GeV

2017 RHIC run, data currently under analysis
$A_N$ for direct photon

- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

Not a replacement for $A_N(W, Z, DY)$, but an important complementary piece of the puzzle
$A_N$ for direct photon

- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

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Projected sensitivities

Expected to return to 200 GeV in 2023:

- Reduce 200 GeV uncertainties by ~3
- Precision measurement of Twist-3 evolution

important complementary piece of the puzzle
Transversity

- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Before STAR, only observed in SIDIS combined with $e^+e^-$
- Much less data than for helicity
- Several recent global analyses including:
  - Collins effect input:
    - PRD 93, 014009
    - PRD 92, 114023
  - IFF input:
    - arXiv:1802.05212
  - All show large uncertainties

\[ \delta q(x) \quad \Delta_T q(x) \]

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First transversity signals in hadronic collisions

- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Complementary results that obey different evolution equations
STAR measurements provide the first observations of transversity at very high scales
- One to two orders of magnitude higher than COMPASS measurements
STAR IFF and global analysis

- **STAR** IFF measurements in 200 and 500 GeV pp collisions are well described by recent IFF calculations.
- Radici and Bacchetta have performed a global analysis including the **STAR** IFF results from 200 GeV pp collisions (PRL 115, 242501)
  - **STAR** data significantly reduce the uncertainty for $h_1^{u\text{-val}}$
  - $g \rightarrow \pi^+ \pi^-$ FF dominates the uncertainty for $h_1^{d\text{-val}}$
π⁻⁺ azimuthal distribution in jets

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 1711, 068
- TMD evolution effects appear to be small

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Additional azimuthal modulations

- **Inclusive jet $A_N$**
  - Sensitive to the gluon Sivers function via the Twist-3 relationship

- **“Collins-like” effect**
  - World’s first ever limit on linearly polarized gluons in a polarized proton

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Projected uncertainties for upcoming results

- Final Collins results from 200 GeV collisions will be coming soon
- Recorded > 10 times as much data at 510 GeV in 2017 as in 2011
  - Precision data at fixed $x$, different $\sqrt{s}$ ideal to constrain TMD evolution
  - Much tighter limits (or first observation?) for Collins-like effect
- Also have data for a first look at the Collins effect in p+Au collisions
What about orbital angular momentum?

• Generalized parton distributions (GPDs), measured via exclusive reactions, provide access to $L_q$ and $L_g$
• Exclusive $J/\psi$ production in ultra-peripheral collisions with transversely polarized p+p and p+Au provides access to the GPD $E_g$
  – The GPD $E$ is responsible for orbital angular momentum
  – Access to $E_g$ before EIC
    • Set the scale to inform EIC detector and experiment planning
• Data from the 2015 and 2017 RHIC runs are under analysis
STAR Forward Upgrade plans

For a more detailed discussion, see:
E.-C. Aschenauer, WG6-WG7 Joint Session, 14:00-14:30 today
Planned forward upgrade for the 2020’s

- Si disks + small Thin Gap Chambers for tracking
- Compact electromagnetic and hadronic calorimeters
- Transverse spin phenomena:
  - Precision TMDs through jets at forward rapidity
  - Precision $A_N$(Drell-Yan) to complete the Sivers measurements
Sivers and Collins coverage at RHIC

- Kinematics of RHIC
  - Dramatic extension in \((x, Q^2)\) reach before EIC
  - \(W\) production probes the highest \(Q^2\) over a wide \(x\) range
  - Precision tests of universality when EIC data become available
Future precision with the Forward Upgrade

- Measurements of the Collins effect in forward jets will sample transversity at high scales over a very wide $x$ range
- Will also much higher precision Drell-Yan and direct photon $A_N$ measurements
Drell-Yan $R_{pA}$ at 200 GeV

- Similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the $Q^2$ lever arm at low $x$ relative to future EIC data

Projected impact on sea quark nPDFs
Conclusions

• The **STAR** transverse spin program has made a number of striking observations

• **STAR** has a huge body of additional spin data under analysis

• The **STAR** Forward Upgrade will provide a bright future for **STAR** in the coming decade

• **STAR** is a key component of the RHIC Cold QCD program: an essential bridge between the physics of RHIC and the physics of the future Electron Ion Collider