2025 RHIC/AGS ANNUAL USERS' MEETING

#### RHIC 25: A quarter century of discovery May 20-23, 2025



#### Brookhaven National Laboratory

Register here: https://www.bnl.gov/rhicagsaum/

#### An Overview of STAR Spin Physics Program: From RHIC to EIC

for the **STAR** collaboration

#### 2025 RHIC/AGS Annual Users' Meeting

May 20-23, 2025

#### ePIC/EIC Workshop

May 20, 2025

Supported in part by:



Office of Science

### **RHIC and STAR**

Relativistic Heavy Ion Collider (RHIC)



#### Solenoidal Tracker At RHIC (STAR)



- RHIC continues to serve as world's first and only polarized pp collider
- Facilitates hadron collisions with various hadron species and collision energies
- At RHIC, protons can be polarized either Longitudinally or Transversely w.r.t proton momentum
- Recent STAR Forward Upgrade extending the kinematic reach





### **Electron Ion Collider**

Electron-Ion Collider (EIC)



One of the primary objectives of the ...

Electron Ion Collider: The Next QCD Frontier Understanding the glue that binds us all

Is to understand...

Spin and Three-Dimensional Structure of the Nucleon

#### And the questions we would like to answer include...

- What is the dynamical origin of sea quarks and gluons inside the proton?
- How does the proton spin originate at the microscopic level?
- How does confinement manifest itself in the structure of hadrons?

# Unique capabilities of STAR/RHIC provide ideal tests of EIC physics, not readily available elsewhere!



### **Electron Ion Collider**

#### Electron-Ion Collider (EIC)



- Highly polarized eA collider with a wide range of ion species and collision energy
- High luminosity (~2 orders of magnitude of HERA)



### **Electron Ion Collider**



Access to  $\sim 10^2$  lower values of x and a wider coverage of  $Q^2$  at EIC  $\rightarrow$  Most powerful tool for, e.g., Spin Physics Programs



### **STAR Spin Program**

Jaffe-Manohar Spin Decomposition



#### • Longitudinal Spin Program

- DIS data suggests  ${\sim}30\%$  valence quark helicity contribution
- STAR provides large acceptance tracking/calorimetry and excellent particle identification
- → Access to both **quarks** and **gluon** helicity via measurements of *W*, hadrons, and jets

$$Helicity = \bigcirc - \bigcirc +$$



## **STAR Spin Program**



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- Transverse Spin Program

\*Transverse Momentum Dependent

- Origin of large forward  $A_N \rightarrow \text{TMD}$  Formalism
- Initial vs Final state effects
- 3D Tomography of the proton
- Transverse spin contribution: Transversity



2025 DUIC (ACS Appuel Hears' Masting

Transversity =

#### **Longitudinal Spin Programs at STAR**





8

## **Longitudinal Spin Physics**





**Longitudinally-polarized** pp collisions at STAR allow measurements of...

- Asymmetrically produced hadronic objects
  - Inclusive-jet and dijet
  - Sensitivity to the size and functional form of gluon helicity Δg(x)
- Asymmetrically produced **EW** objects
  - $W^{\pm}$  boson, naturally provides flavor separation
  - Probes the sea (anti-)quark helicity  $\Delta \bar{u} / \Delta \bar{d}$  and its functional form



## Measurements of Jet-/Dijet- $A_{LL}$



- STAR jet/dijet  $A_{LL} \rightarrow$  probe of gluon helicity distribution in its *x*-dependent form
- STAR data favor positive gluon helicity
- Limited statistical precision for lower values of x (< 0.05)





TAR

## Measurements of W-A<sub>L</sub>



- Impact of STAR/RHIC data in global fit favoring  $\Delta \overline{u} > \Delta \overline{d}$
- Also provides constraints for **non-pQCD models** of SU(2)  $\overline{u}/\overline{d}$  asymmetry
- Only *loosely constrained* with currently-available RHIC + SIDIS data

Jae D. Nam



11

## Investigations of Strange Helicity ( $\Delta s$ )



- Measurements of  $\Lambda D_{LL} \rightarrow \text{Probe of } \Delta s$  and final-state effects from *Polarized FF* (PFF)
- Tests hypotheses on the origin of  $\Lambda$  polarization
- Measurements of  $z (\equiv p_{\Lambda} \cdot p_j / p_j^2)$  dependence directly probes PFF



## **Expected Impact from EIC**



 $\rightarrow$  Precision measurements of  $g_1$  with a large kinematic coverage



13

#### **Transverse Spin Programs at STAR**





## **Transverse Spin Physics**



RHIC Spin Col., arXiv:1602.03922



• Transverse Momentum Dependent (TMD) frameworks proposes...

$$A_{N} = A_{UT}^{Sivers} sin(\phi_{s}) + A_{UT}^{Collins} sin(\phi_{s} - \phi_{H}) + \cdots$$

- Sivers Mechanism  $\rightarrow S_p \cdot (p \times k_{T,q})$ 
  - Interplay of **initial-state** nucleon spin and parton  $k_{T,q}$
  - Sensitive to Sivers TMD PDF
- Collins Mechanism
  - $\rightarrow S_q \cdot (p \times k_{T,h})$ 
    - Interplay of **final-state** quark spin and hadron  $k_{T,h}$
    - Sensitive to transversity via Collins FF



Sensitive to

transversitv

15

## Measurements of $A_N$ with Jets



- Inclusive jet  $A_N$  consistent with 0, unlike in SIDIS  $\rightarrow$  pQCD suggests **cancellations** of u and d quarks at **initial** and **final** states
- First hint of non-zero Sivers effect in dijet in pp collisions when charge-separated:

$$2\langle k_T^u \rangle \approx \langle k_T^d \rangle, \ \langle k_T^{g+\text{sea}} \rangle \approx 0$$

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#### **Investigations of Sivers Effect with Drell-Yan**



### **Investigations of Collins Effect**



- Hadron-jet correlation measurements at STAR
  - A more direct probe of **Transversity** than SIDIS: <u>Collinear</u> (pp,  $h_1(x)$ ) vs. <u>TMD</u> (SIDIS,  $h_1(x, k_T)$ )
- Measurements of z and  $j_T$  probes both transversity and Collins FF, pioneering investigations of Collins effect
- Two energy modes (200 vs 500 GeV) and hadron species (pp vs. pA)
  → Tests of evolution, universality, factorization breaking



### Measurements of Di-Hadron $A_N$



## **Expected Impact from EIC**

#### **Expected EIC Impact on Collins**



- Opportunities at EIC
  - Access to much lower values of x compared to currently available data
  - Tests of the Non-Universal nature of Sivers effect
  - *Evolution* and *Factorization-Breaking* of Collins → Constraints on Tensor Charge
- 2025 RHIC/AGS Annual Users' Meeting May 20-23, 2025



**Expected EIC Impact on Sivers** 



#### Summary

#### Spin Physics at RHIC

- Decisive constraints of the size and shape of  $\Delta g$  for x > 0.05 via jet/dijet  $A_{LL}$
- First extraction of  $\Delta \bar{d}$  and  $\Delta \bar{u}$  via W- $A_L$
- Identification of cancellation effects of *Sivers* mechanism in *pp* collisions
- Extraction of Sivers functions with DY
- Pioneering investigations of *Collins* mechanism via *hadron-jet* correlations
- Extraction of *collinear* transversity, *Collins* FF, *Interference* FF, *di-hadron* FF

#### Spin Physics at EIC

- Precision measurements at extreme kinematic reach with inclusive DIS
- Excellent PID allows SIDIS measurements providing stringent constraints & complementarity
- Tests of *Non-Universality* of Sivers mechanism (*DY vs. SIDIS*)
- Direct access to *x*-dependent form of Sivers
- Tests of *Universality* of Collins mechanism
- Extraction of TMD transversity

#### ... and much more I failed to highlight today



21

