

MENU 2026

The 17th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon



Supported by



Probing Nucleon Structure and QCD Dynamics with STAR

- STAR Cold QCD Recent Highlights

Xiaoxuan Chu, BNL

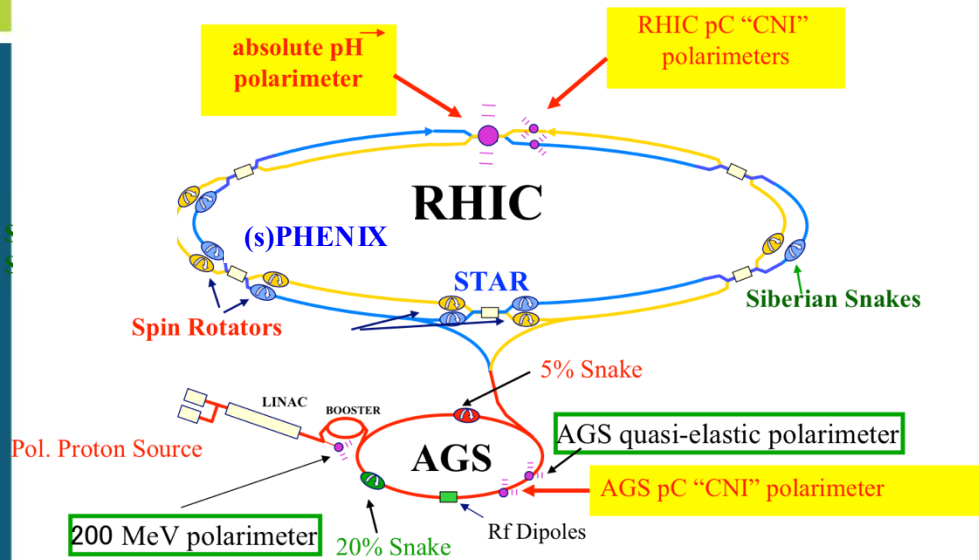
MENU2026, Stony Brook University, Oct 19-23rd 2026

Date: 10/22/2026



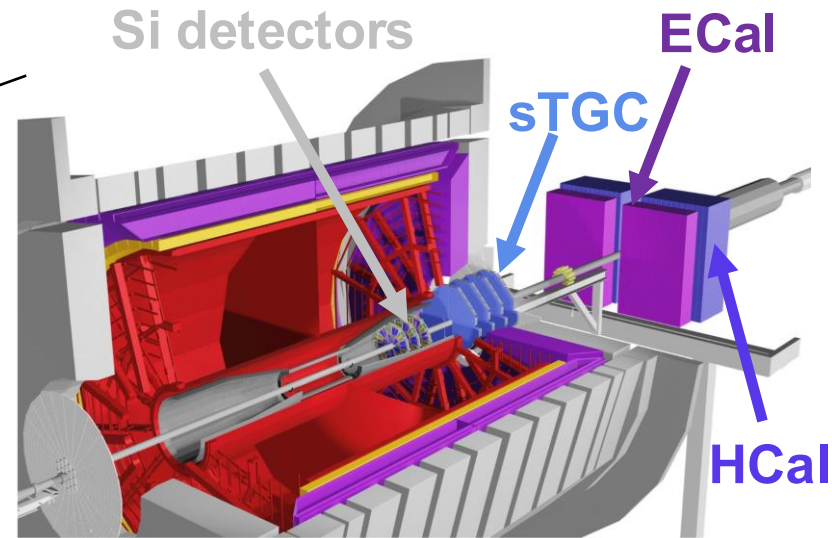
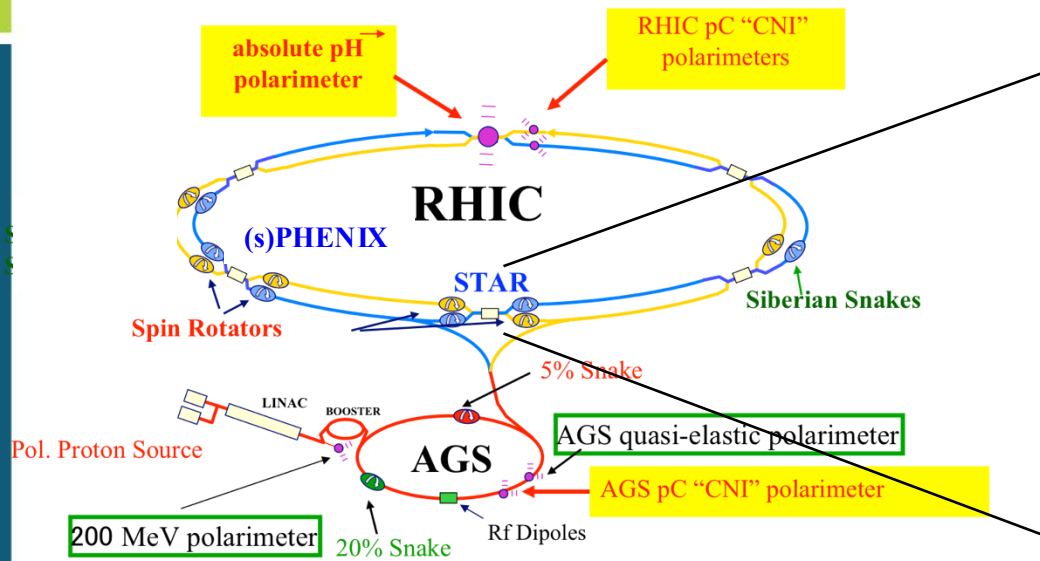
@BrookhavenLab

Relativistic Heavy Ion Collider



- RHIC: first and only (**longitudinally and transversely**) polarized pp collider, also capable of colliding pA with polarized proton beam and AA

STAR Experiment at RHIC



STAR, Forward Upgrade ($2.5 < \eta < 4$)

- RHIC: first and only (**longitudinally and transversely**) polarized *pp* collider, also capable of colliding *pA* with polarized proton beam and *AA*
- STAR: has been collecting data with its **forward-upgraded detectors** since 2021 (RHIC Run22) and concluded its data-taking in Jan. 2026

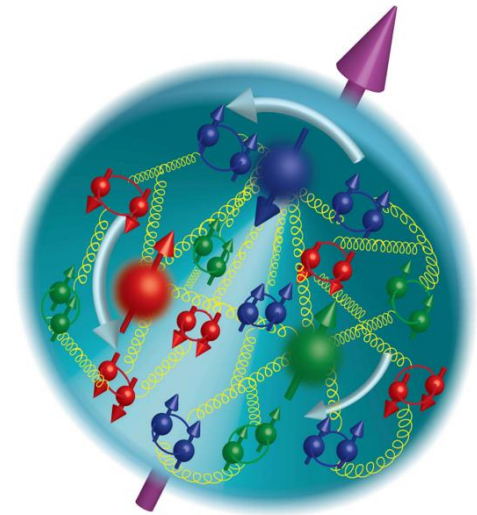
STAR Cold QCD Recent Highlights

1. Decomposition of **proton spin**:

- (anti)quark and gluon helicity

Long. polarized pp

EIC White Paper



Inner building blocks of a proton, quarks and gluons, and their possible orbital motion, contribute to proton spin.

$$S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

STAR Cold QCD Recent Highlights

1. Decomposition of **proton spin**:

- (anti)quark and gluon helicity

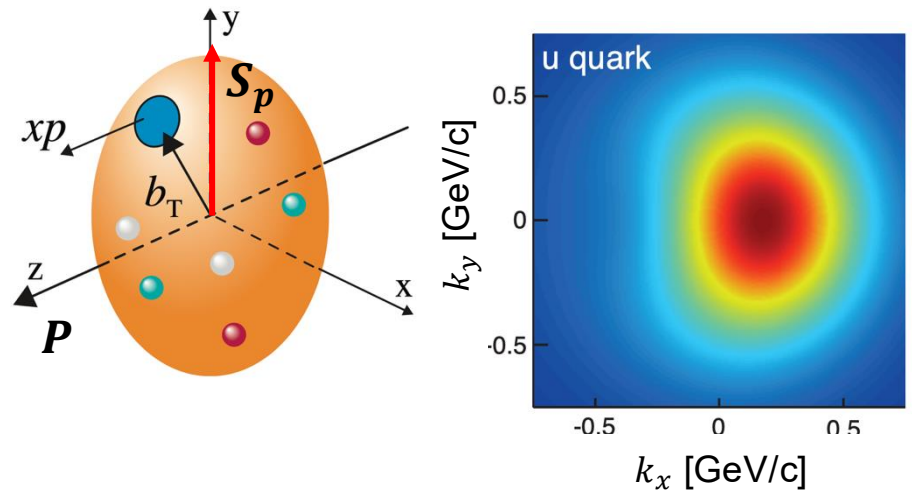
Long. polarized pp

EIC White Paper

2. **Multidimensional landscape** in coordinate and momentum space of nucleons and nuclei:

- initial and final state TMD*
- di-hadron interference FFs

Tran. polarized pp and pA



3-dimensional image of the structure of a proton: $k_\perp$ is the transverse momentum of a parton

*Transverse momentum dependent parton distribution function (TMD): $f(x, k_\perp, Q^2)$

STAR Cold QCD Recent Highlights

1. Decomposition of **proton spin**:

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Long. polarized pp

2. **Multidimensional landscape** in coordinate and momentum space of nucleons and nuclei:

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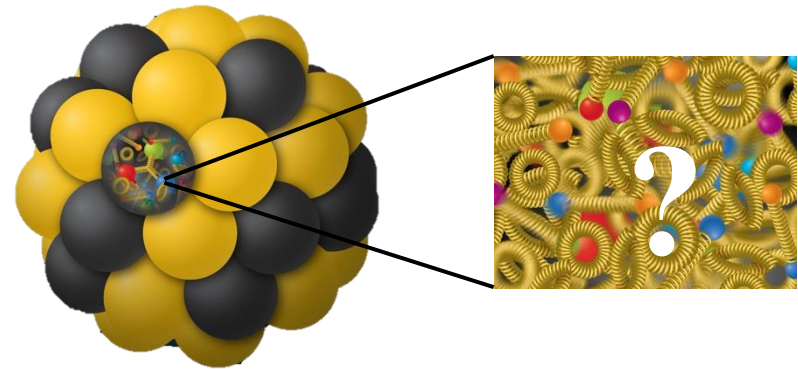
Tran. polarized pp and pA

3. Collinear PDFs, FFs and Λ spin, and their nuclear modification:

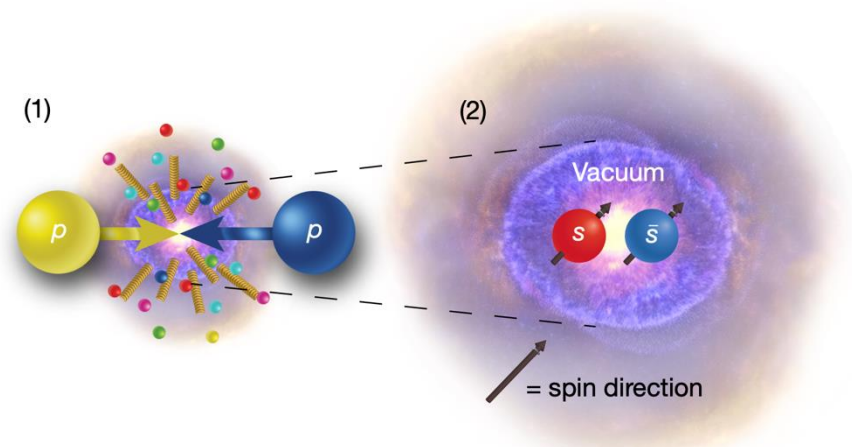
- gluon distribution at low- x
- nuclear modified FFs
- origin of Λ spin

Unpolarized pp and pA

Courtesy: BNL



Small x gluon dynamics



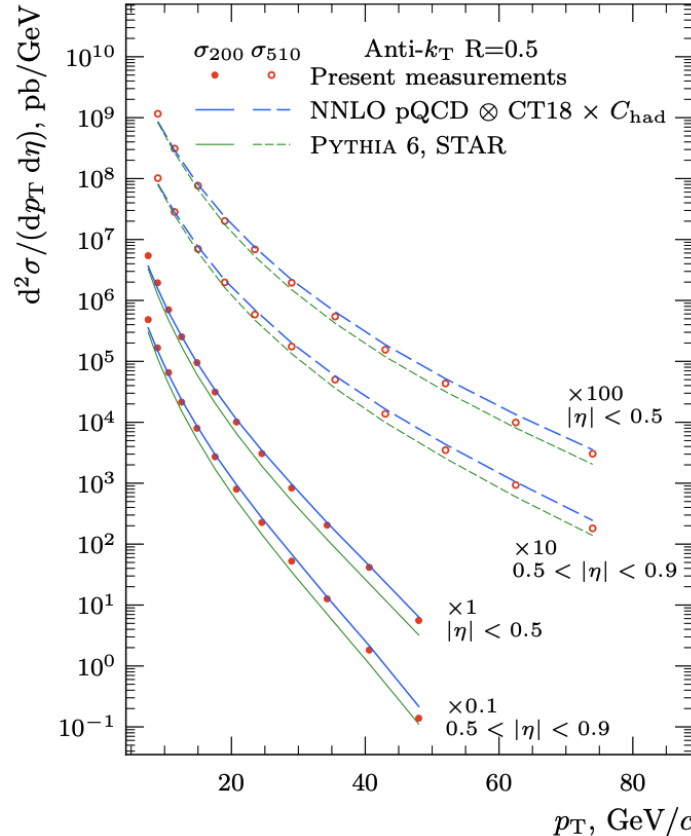
STAR, Nature 650, 65-71 (2026)

Part I: Collinear PDF and TMD Physics in pp

Only the recent *pp* runs listed

Year	$\sqrt{s}$ (GeV)	Polarization	Sampled L (pb^{-1})
2015	200	Transverse	53
2015	200	Longitudinal	53
2017	510	Transverse	350
2022	508	Transverse	452
2024	200	Transverse	164

Inclusive Jet Cross Section



Measurement

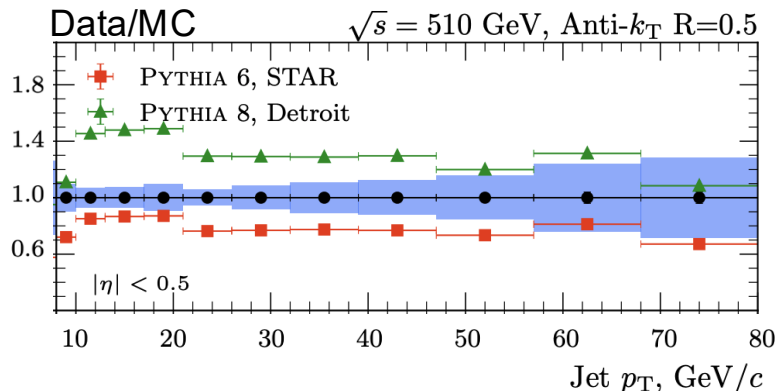
- Double-differential jet cross section in p_T and η from 200 and 510 GeV pp
- Anti- k_T algo., $R = 0.5$, two η bins: $|\eta| < 0.5$ and $0.5 < |\eta| < 0.9$
- Off-axis cone method for U.E. correction

Comparison to NNLO pQCD

- + NNLOJet+FastNLO with 4 PDF sets + hadronization
- HERAPDF2.0: best agreement overall
- CT18, MSHT20, NNPDF4.0: predict $\sim 20\text{-}30\%$ lower at low p_T

Key Conclusions

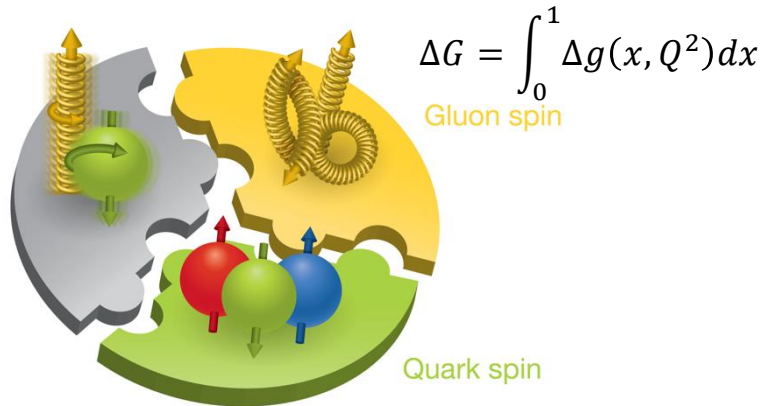
- ✓ First double-differential measurement at RHIC
- ✓ Discriminates between PDF sets at medium x
- ✓ Opens path to precision QCD at RHIC energies



Proton Spin - Helicity Measurement

Proton Spin:

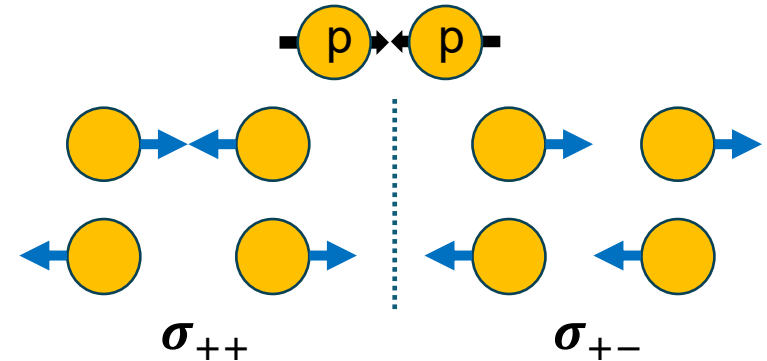
$$S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$



Description of A_{LL} measurement:

Proton beam spin direction

Proton beam momentum direction



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a_{LL} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D} \xrightarrow{\text{Global fit}} \Delta f(x, Q^2)$$

Measurements at RHIC using **longitudinally polarized pp data to extract:**

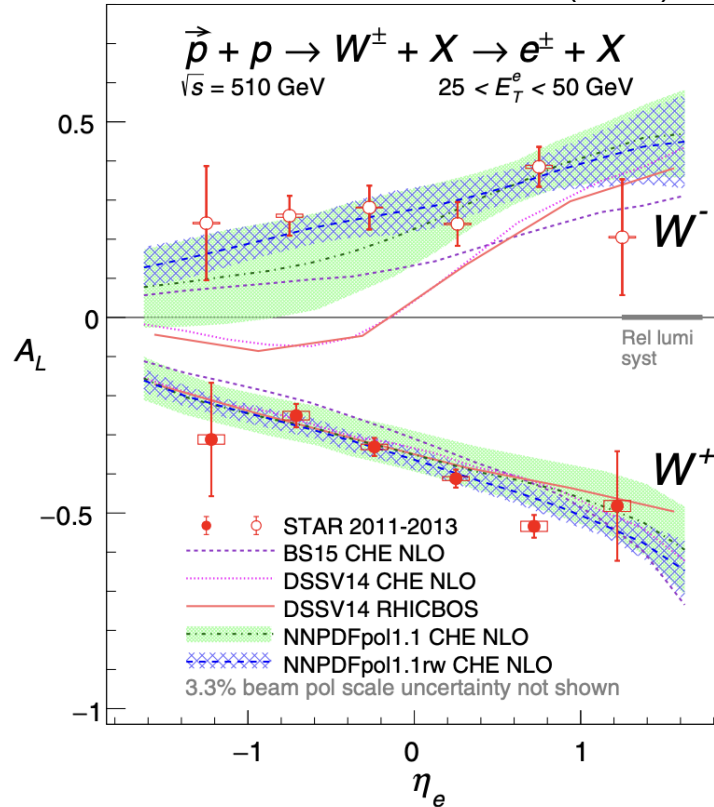
- $\Delta \bar{u}$ and $\Delta \bar{d}$: $\vec{p} + p \rightarrow W + X, W^{+/-} \rightarrow$ natural flavor separation
- Δg : jet/hadron/direct γ , A_{LL} or $A_L \propto \Delta f$, sensitive to Δg at RHIC energy

Sea Quark Helicity: $\Delta\bar{d}, \Delta\bar{u}$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

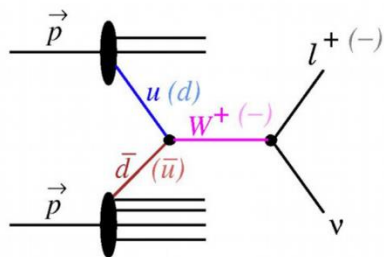
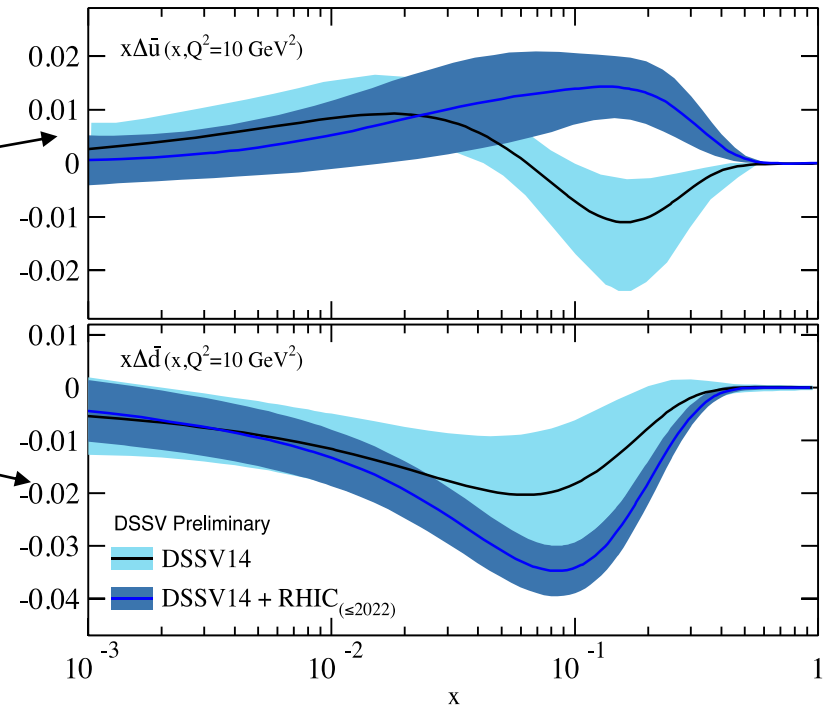
STAR, PRD 99, 051102 (2019)

arXiv:2302.00605



$x\Delta\bar{u}$

$x\Delta\bar{d}$



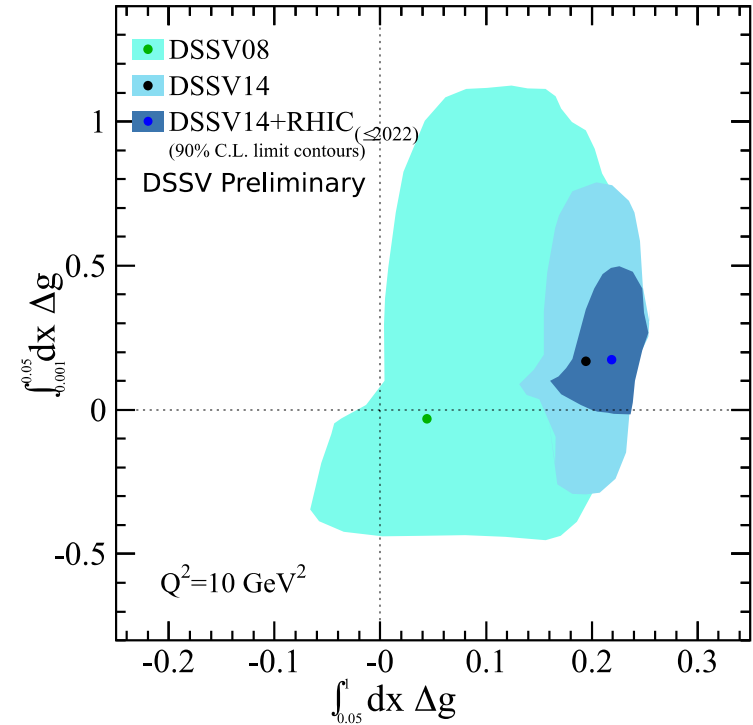
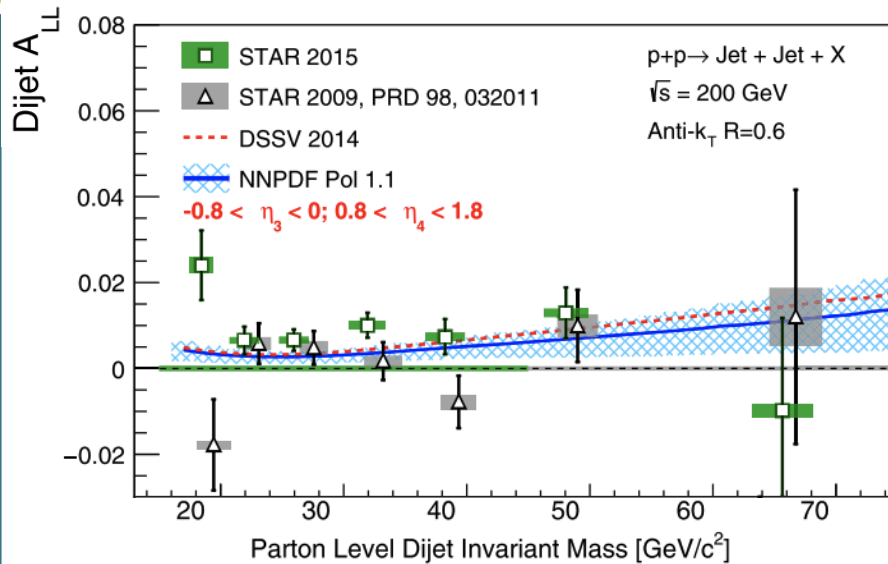
- Measured single-spin asymmetry of $W^{+(-)} \propto \Delta\bar{d}(\Delta\bar{u})$
- For the first time, we can conclude an asymmetry between $\bar{u}$ and $\bar{d}$ polarization: $\Delta\bar{u} > \Delta\bar{d}$ with **STAR 2013 $W^{+/-}$ data**, opposite to the spin-averaged quark-sea distributions

Gluon Helicity

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

STAR, PRD 112, 012003 (2025)

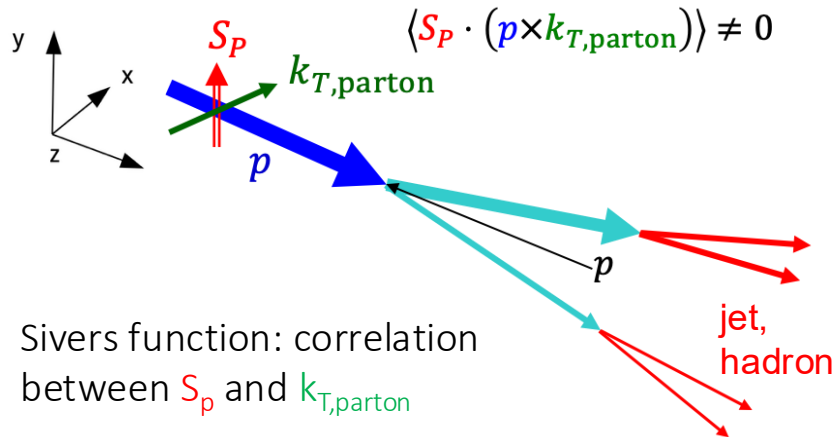
arXiv:2302.00605



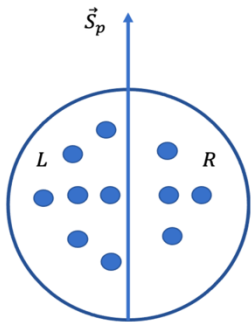
- STAR recent dijet A_{LL} : consistent with earlier measurements and further constrain $\Delta g(x)$ for $x > 0.05$
- Impact of ΔG from RHIC data: [RHIC concluded the data taking with longitudinally polarized protons in 2015](#); the data provide the most precise insights in ΔG : 8- σ positive gluon spin ΔG for $x > 0.05$

Sivers Effect

Initial state TMD: Sivers



How to measure:



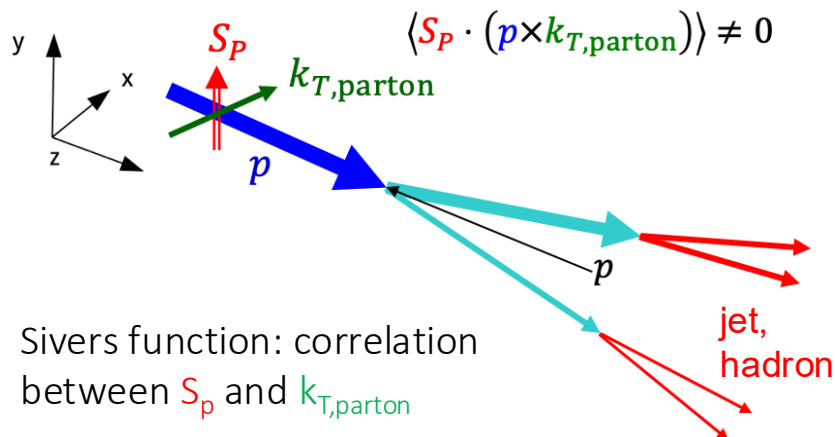
A_N : left-right asymmetry of final state

$$A_N \cdot \cos(\phi) =$$

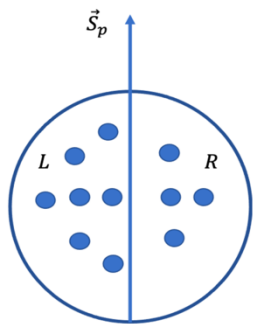
$$\frac{1}{\langle P \rangle} \cdot \frac{\sqrt{N_{\uparrow}(\phi)N_{\downarrow}(\phi + \pi)} - \sqrt{N_{\uparrow}(\phi + \pi)N_{\downarrow}(\phi)}}{\sqrt{N_{\uparrow}(\phi)N_{\downarrow}(\phi + \pi)} + \sqrt{N_{\uparrow}(\phi + \pi)N_{\downarrow}(\phi)}}$$

Sivers Effect in Charge-Tagged Dijets

Initial state TMD: Sivers



How to measure:

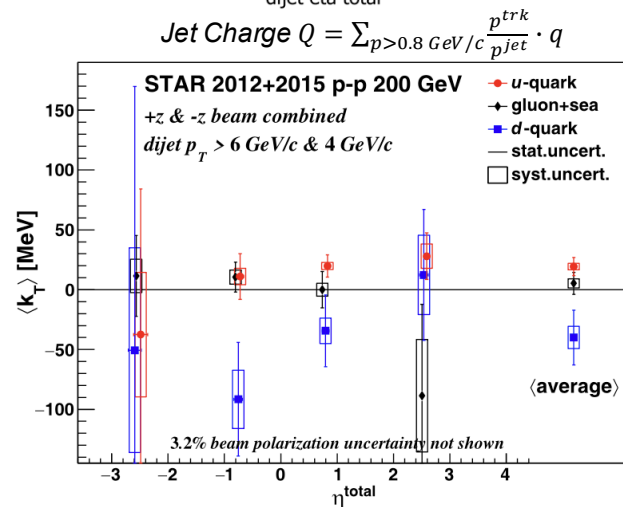
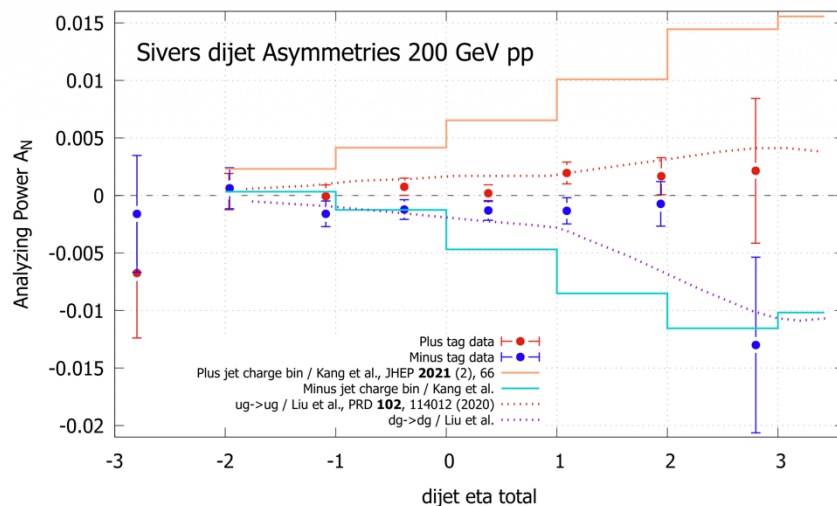


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$$A_N \cdot \cos(\phi) =$$

$$\frac{1}{\langle P \rangle} \cdot \frac{\sqrt{N_{\uparrow}(\phi)N_{\downarrow}(\phi + \pi)} - \sqrt{N_{\uparrow}(\phi + \pi)N_{\downarrow}(\phi)}}{\sqrt{N_{\uparrow}(\phi)N_{\downarrow}(\phi + \pi)} + \sqrt{N_{\uparrow}(\phi + \pi)N_{\downarrow}(\phi)}}$$

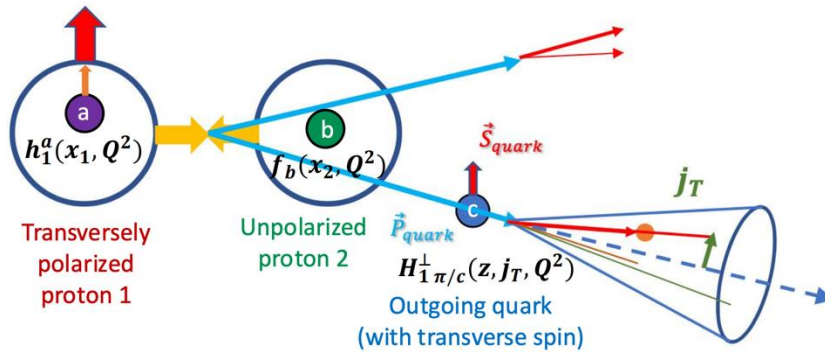
STAR, PRD 114, L011504 (2026)



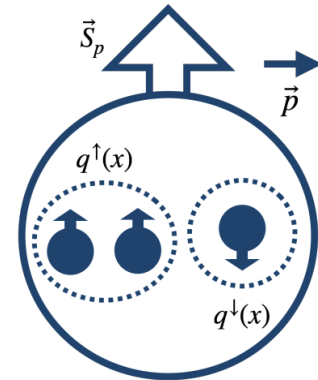
- 3.1σ separation between $\langle k_T^u \rangle$ and $\langle k_T^d \rangle$
- First evidence for nonzero Sivers effect in pp, consistent with SIDIS

Collins Effect

Final state: Collins FF



Transversity

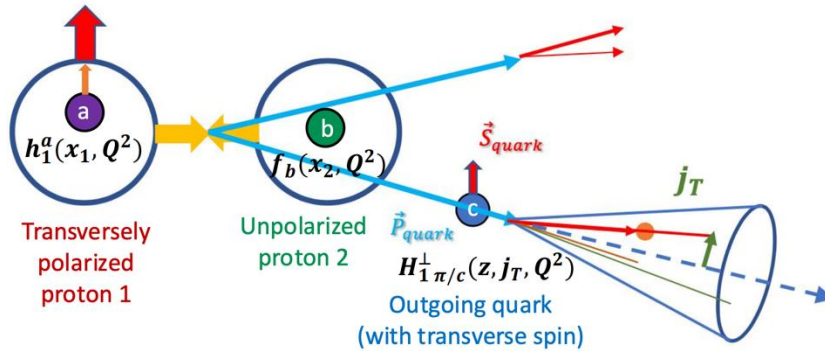


Diagrams by Ting Lin and Zilong Chang

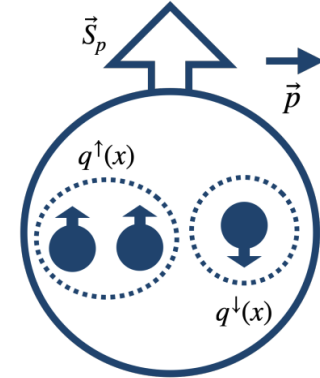
Collins Effect with EEC

STAR, PRL 137, 111902 (2026)

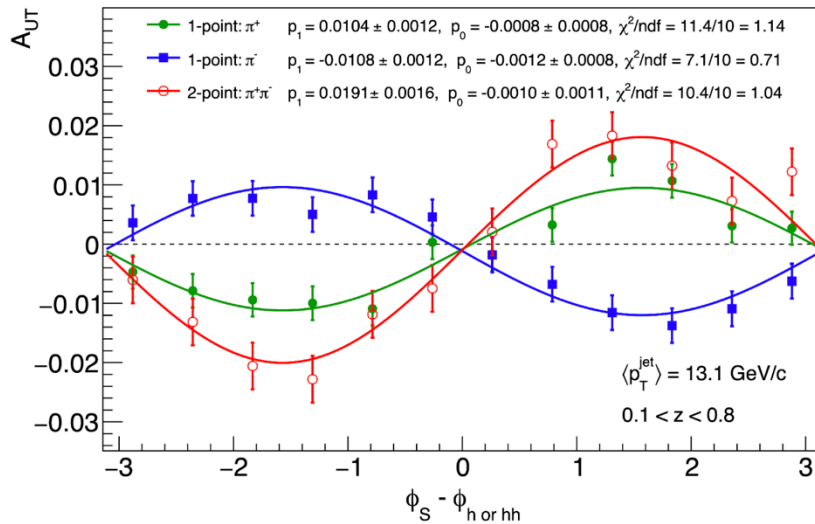
Final state: Collins FF



Transversity



Diagrams by Ting Lin and Zilong Chang



$$\Sigma_{\text{EC}}(\theta_h, \phi_h) = \frac{d \left(\sum_{\text{jet}} \sum_{i \in \text{jet}} z_{h,i} \right)}{d\theta_h d\phi_h}$$

$$\Sigma_{\text{EEC}}(\theta_{hh}, \phi_{hh}) = \frac{d \left(\sum_{\text{jet}} \sum_{i,j \in \text{jet}} z_{h,i} z_{h,j} \right)}{d\theta_{hh} d\phi_{hh}}$$

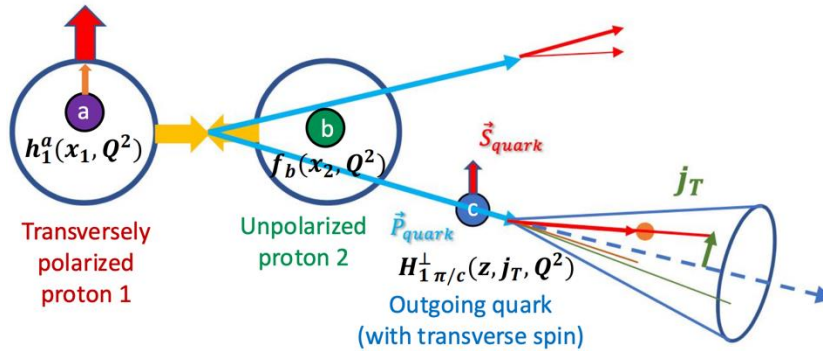
$$A_{UT}^{\sin(\phi_S - \phi_h)} \cdot \sin(\phi_S - \phi_h) = \frac{1}{\langle P \rangle} \cdot \frac{\sqrt{\Sigma_{EC}^\uparrow \Sigma_{EC}^\downarrow, \pi} - \sqrt{\Sigma_{EC}^\downarrow \Sigma_{EC}^\uparrow, \pi}}{\sqrt{\Sigma_{EC}^\uparrow \Sigma_{EC}^\downarrow, \pi} + \sqrt{\Sigma_{EC}^\downarrow \Sigma_{EC}^\uparrow, \pi}}$$

- First experimental measurement of one- and two-point EECs within jets in $p^\uparrow p$ collisions

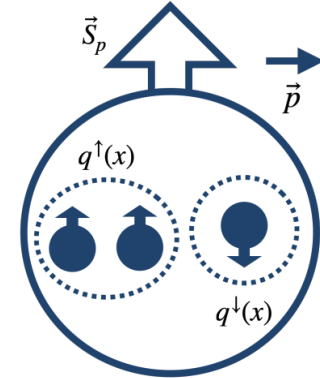
Collins Effect with EEC

STAR, PRL 137, 111902 (2026)

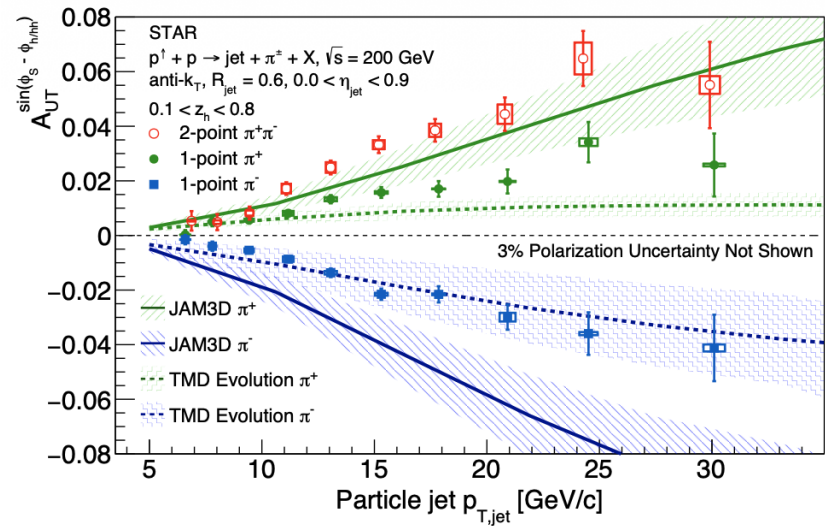
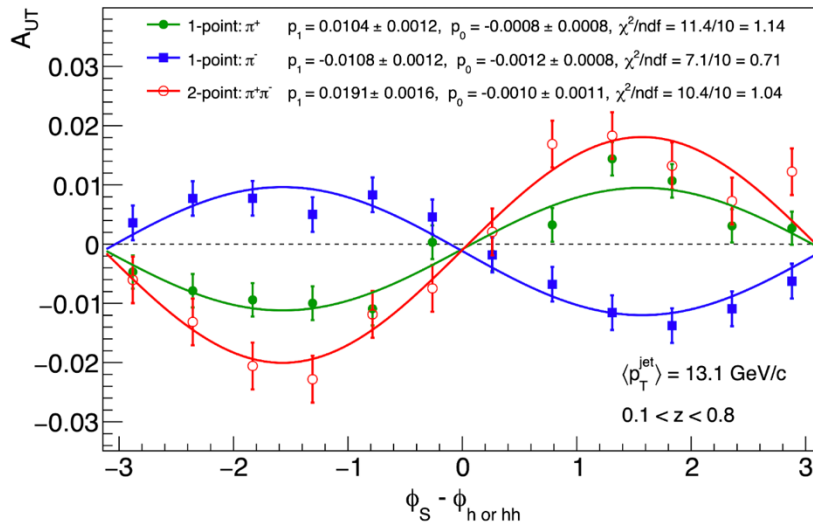
Final state: Collins FF



Transversity



Diagrams by Ting Lin and Zilong Chang



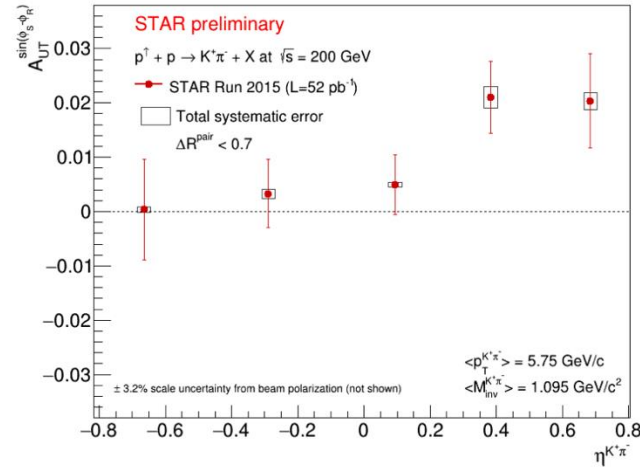
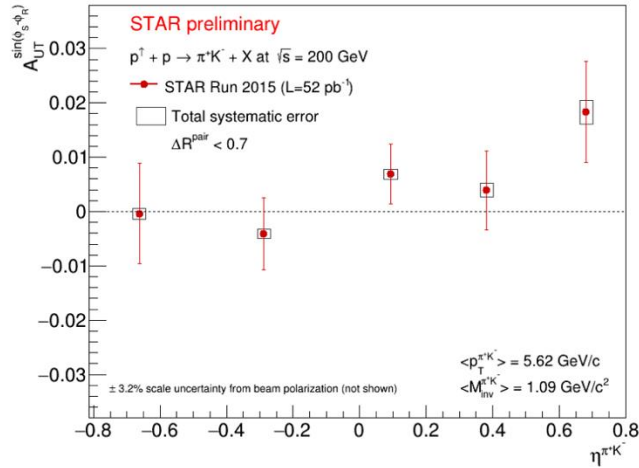
- First experimental measurement of one- and two-point EECs within jets in $p^\uparrow p$ collisions
- Spin-dep. asymmetries of π^+ , π^- in jets $\rightarrow$ sensitive to H.O. Mellin moments of spin-dep. FFs

Di-hadron Asymmetry

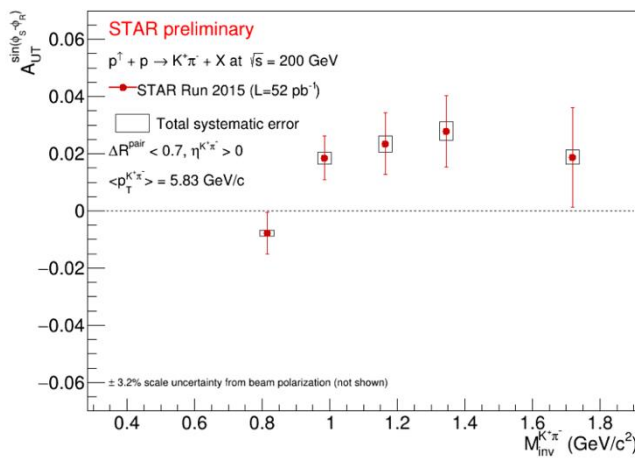
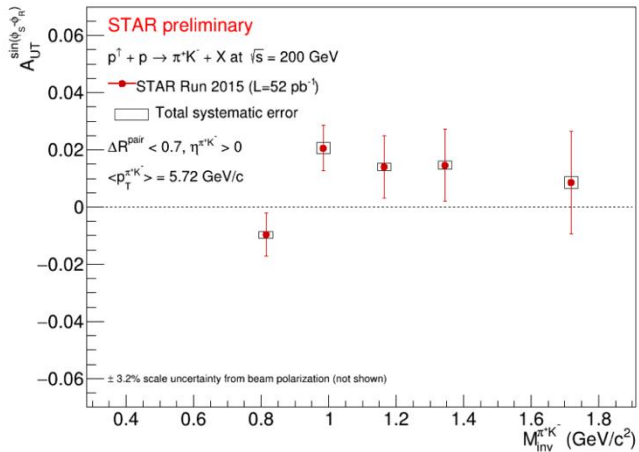
See Surrow's talk, 4:40pm this afternoon

$\pi^+ K^-$

$K^+ \pi^-$



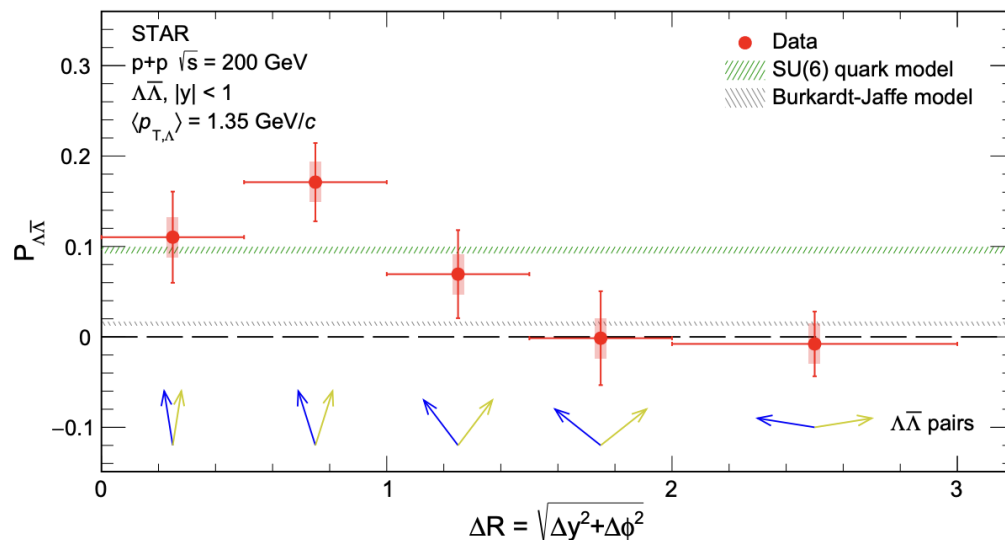
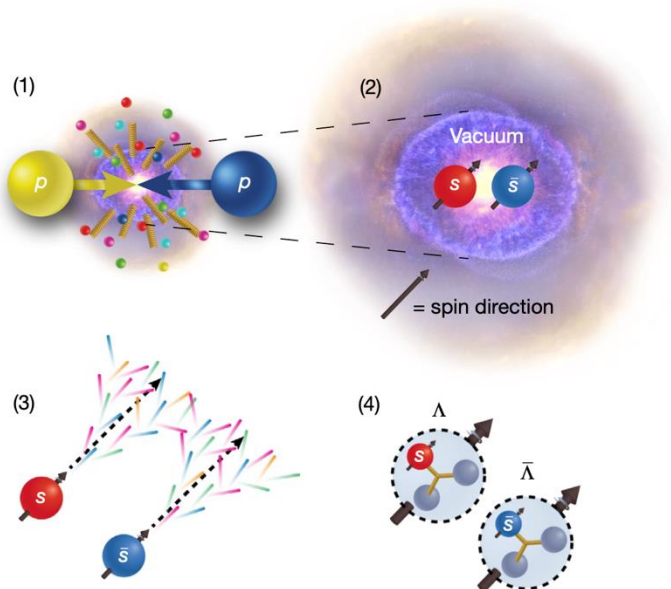
Asymmetry vs η



Asymmetry vs M_{inv}

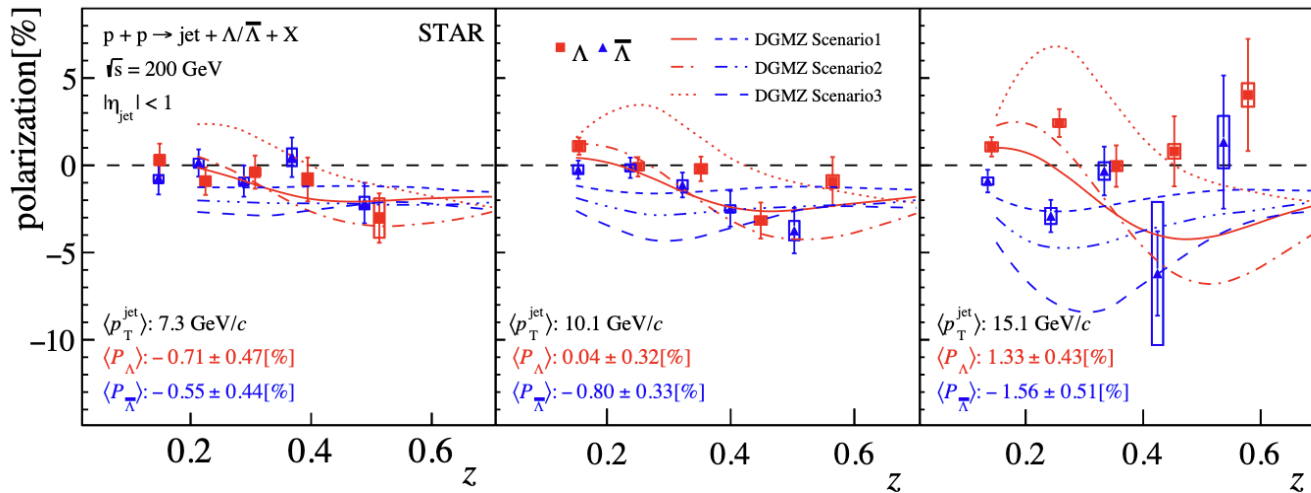
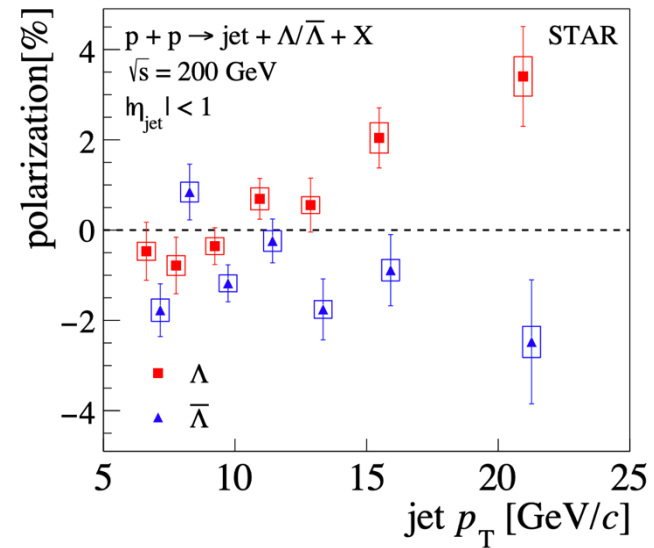
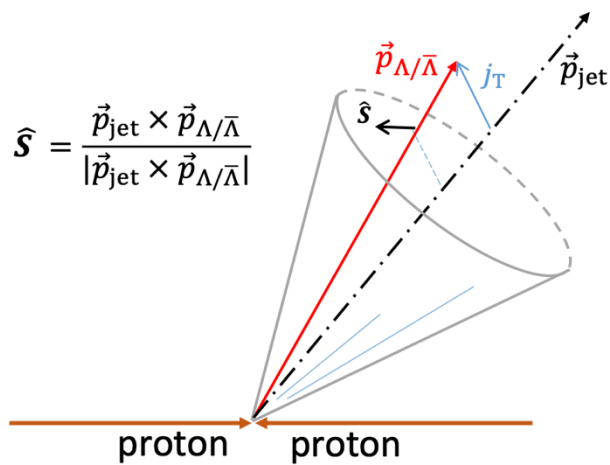
- Mixed pairs: Small positive slopes, implying a weak forward η dependence and a weak M_{inv} dependence
- $K^+ K^-$: Asymmetry values fluctuate around zero, but offers constraint on s quark transversity

Λ Spin Correlation



- STAR observes **4.4 σ evidence** for transverse spin correlations in short-range $\Lambda\bar{\Lambda}$ pairs - first observation of QCD spin entanglement surviving hadronization
- Long-range pairs consistent with zero - **quantum decoherence** over large rapidity gaps constrains the decoherence scale in hadronization

Λ Transverse Polarization in Jet



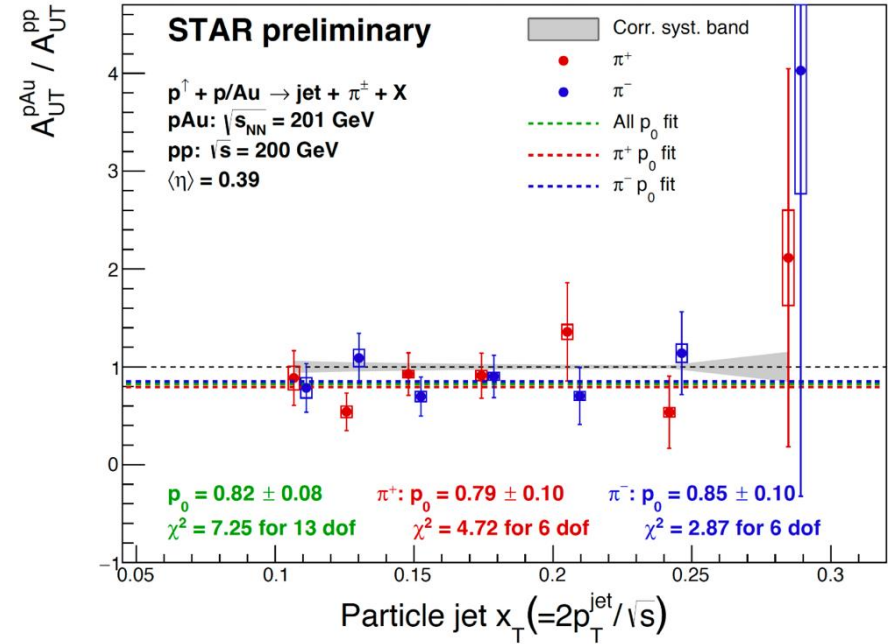
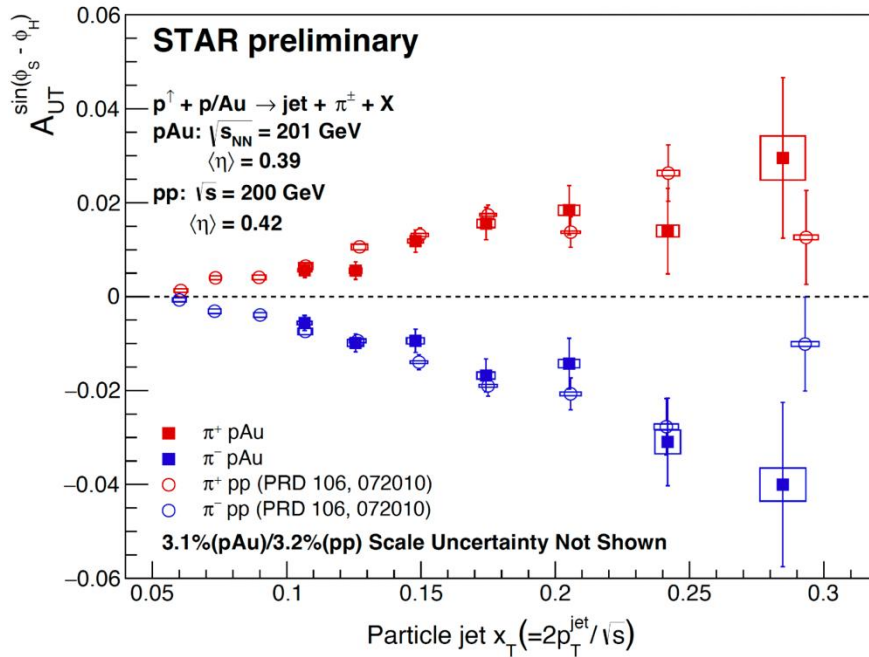
First STAR constraints on gluon PFF: $\Lambda/\bar{\Lambda}$ polarization in jets shows p_T -dependent sign change, disfavoring all DGMZ scenarios - complementary to $\Lambda\bar{\Lambda}$ spin correlations in probing hadronization spin dynamics

Part II: Nuclear QCD in p+Au Collisions

pA runs

Year	$\sqrt{s_{NN}}$ (GeV)	<i>p</i> polarization	Sampled L (nb^{-1})
2015	200 <i>pAu</i>	Transverse	0.42
2015	200 <i>pAl</i>	Transverse	1.1

Collins Asymmetry for pA vs pp



- First STAR measurement of Collins asymmetry in polarized pAu , showing the same charge-sign pattern and x_T dependence as pp , consistent with TMD factorization holding in a nuclear environment
- A possible $\sim 18\%$ average suppression from pAu to pp at the $\sim 2\sigma$ level hints at cold nuclear matter effects, motivating dedicated theory calculations

Nuclear Modification R_{pA}

Middle rapidity hadron-in-jet R_{pA}

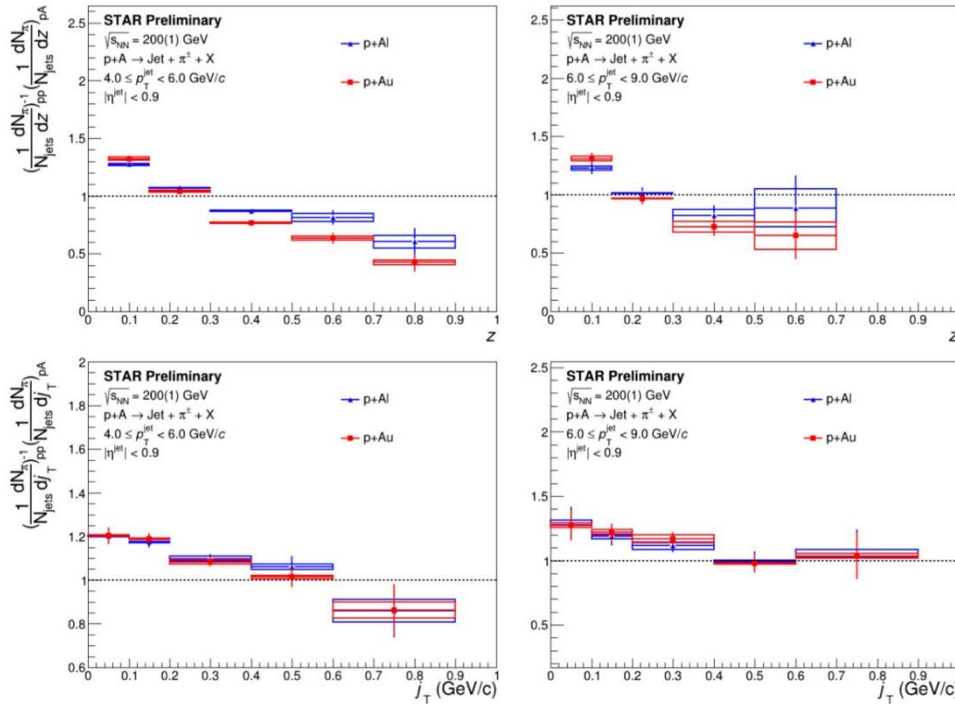
$$D_h(z, j_T) = \frac{1}{N_{jets}} \frac{dN_h}{dz dj_T}$$

$$R_h^{pA}(z, j_T) = \frac{D_h^{pA}(z, j_T)}{D_h^{pp}(z, j_T)}$$

$p_T^{\text{jet}}:$

[4.0 , 6.0] GeV/c

[6.0 , 9.0] GeV/c



- Measurement of nuclear modification of identified hadrons in jets - enhancement at low z and suppression at high z , stronger in pAu than pAl , probing nuclear fragmentation

Nuclear Modification R_{pA}

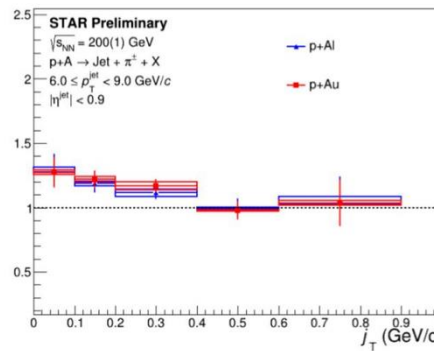
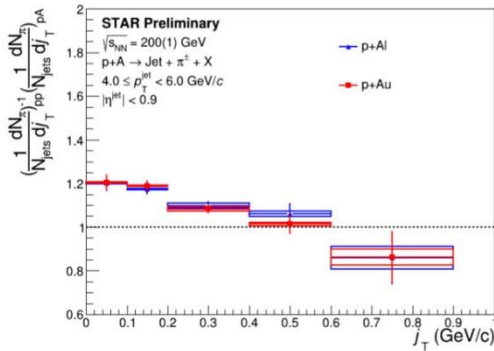
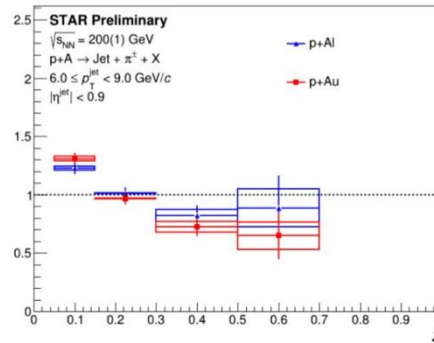
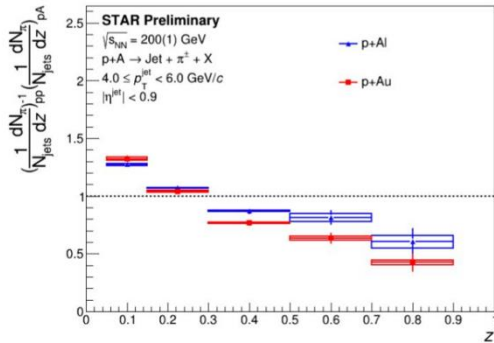
Middle rapidity hadron-in-jet R_{pA}

$$D_h(z, j_T) = \frac{1}{N_{jets}} \frac{dN_h}{dz dj_T}$$

$$R_h^{pA}(z, j_T) = \frac{D_h^{pA}(z, j_T)}{D_h^{pp}(z, j_T)}$$

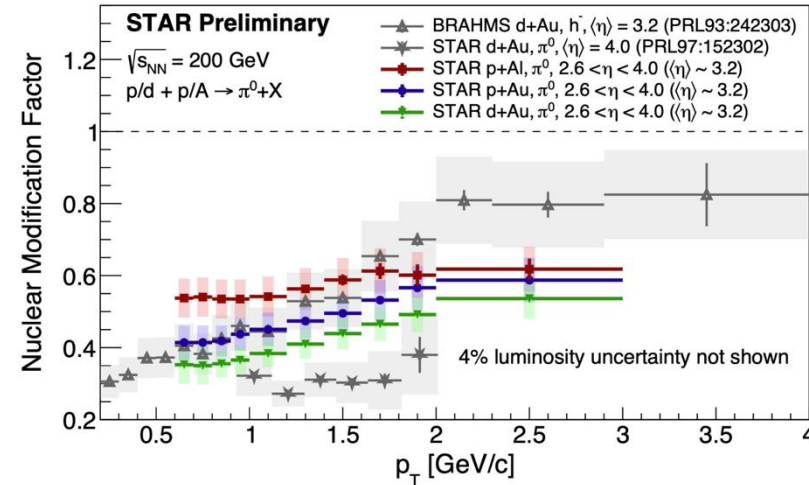
$p_T^{\text{jet}}: [4.0, 6.0] \text{ GeV/c}$

$[6.0, 9.0] \text{ GeV/c}$



Forward rapidity π^0 R_{pA}

$$R_{aA}(p_T, \eta) = \frac{1}{\alpha A} \cdot \frac{L_{pp}}{L_{aA}} \cdot \frac{d^2 N_{aA}^{\pi^0}}{dp_T d\eta} / \frac{d^2 N_{pp}^{\pi^0}}{dp_T d\eta}$$



- Measurement of nuclear modification of identified hadrons in jets - enhancement at low z and suppression at high z , stronger in pAu than pAl , probing nuclear fragmentation
- Forward π^0 shows A-dependent suppression at small x ($R_{pAl} > R_{pAu}$), stronger than BRAHMS $dAu(h^-)$, constraining nPDF evolution, gluon saturation, and nFF at RHIC

Summary

Collinear PDF & TMD in pp:

- ✓ Inclusive jets: NNLO pQCD agreement, PDF discrimination
- ✓ Helicity measurements: ΔG 8- σ positive for $x > 0.05$; $\Delta\bar{u} > \Delta\bar{d}$
- ✓ Collins in jets: TMD factorization in pp validated
- ✓ Energy-Energy Correlators: new transversity probe multidimensional nucleon structure
- ✓ Dihadron (with K) IFF: access to strange quark transversity h_1^s
- ✓ $\Lambda/\bar{\Lambda}$ in jets: first gluon PFF constraints at RHIC; Spin correlations: evidence for spin entanglement and QCD confinement probe

Summary

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Nuclear QCD in $p+A$

- ✓ Forward π^0 R_{pA} : larger suppression at small x with heavier nuclei, CGC signatures?
- ✓ Hadron nFF in jets: nuclear fragmentation enhancement at low z but suppression at large z
- ✓ Collins in pAu consistent with pp : TMD universality holds

Summary and Outlook

Collinear PDF & TMD in pp:

- ✓ Inclusive jets: NNLO pQCD agreement, PDF discrimination
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Nuclear QCD in p+A

- ✓ Forward $\pi^0 R_{pA}$: larger suppression at small x with heavier nuclei, CGC signatures?
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STAR Cold QCD Program Outlook:

Year	$\sqrt{s}$ (GeV)	Polarization	Sampled L (pb^{-1})
2022	508	Transverse	452
2024	200	Transverse	164

Rich legacy ahead: unanalyzed datasets will sharpen Collins, Sivers, IFF, and PFF constraints
- essential pp/pA baselines for the EIC.

The RHIC Cold QCD Plan for 2024 to 2028 Completing the RHIC Science Mission

Authors for the RHIC SPIN Collaboration*

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⁴Texas A&M University, College Station, Texas 77843

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⁶Temple University, Philadelphia, Pennsylvania, 19122

⁷RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198

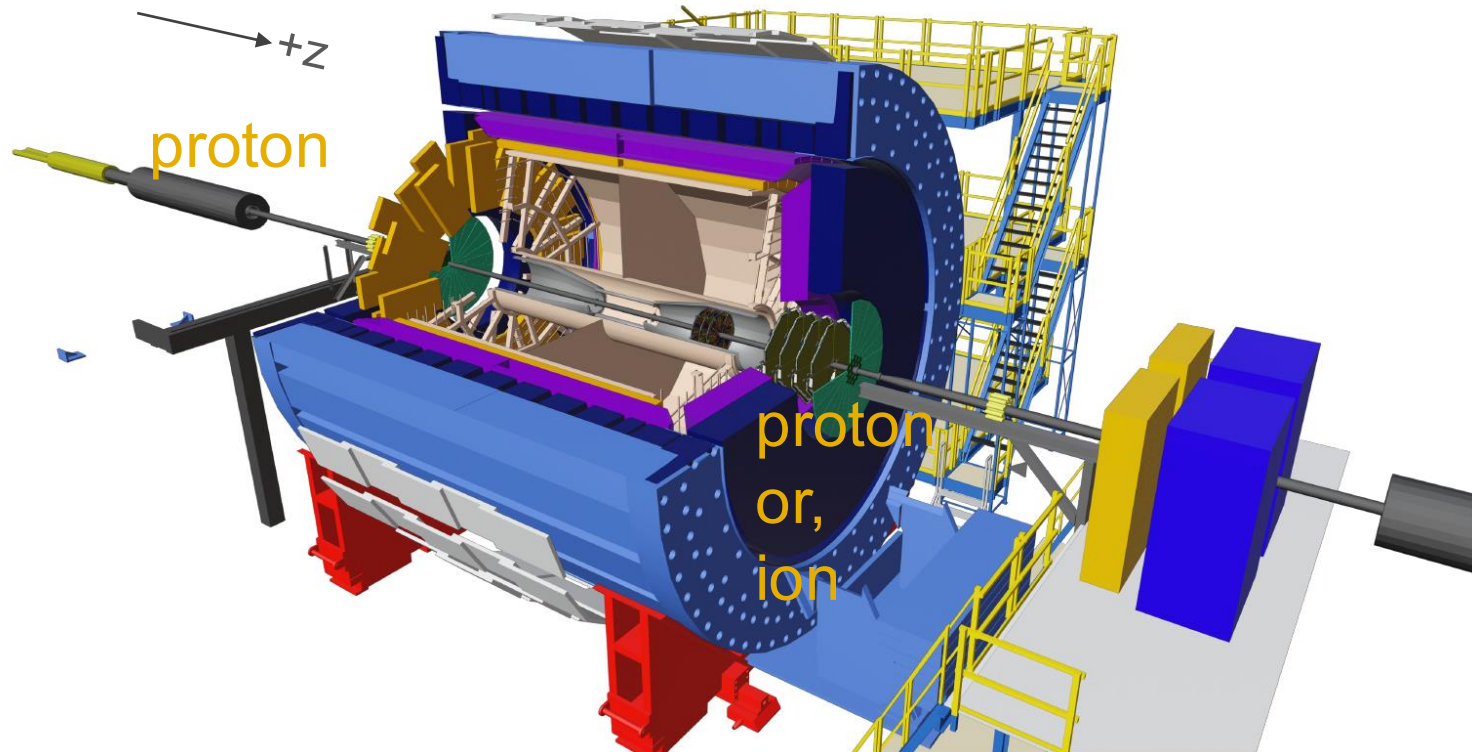
⁸University of Illinois Urbana-Champaign, Urbana 61801

⁹Indiana University, Bloomington, Indiana 47408



Back up

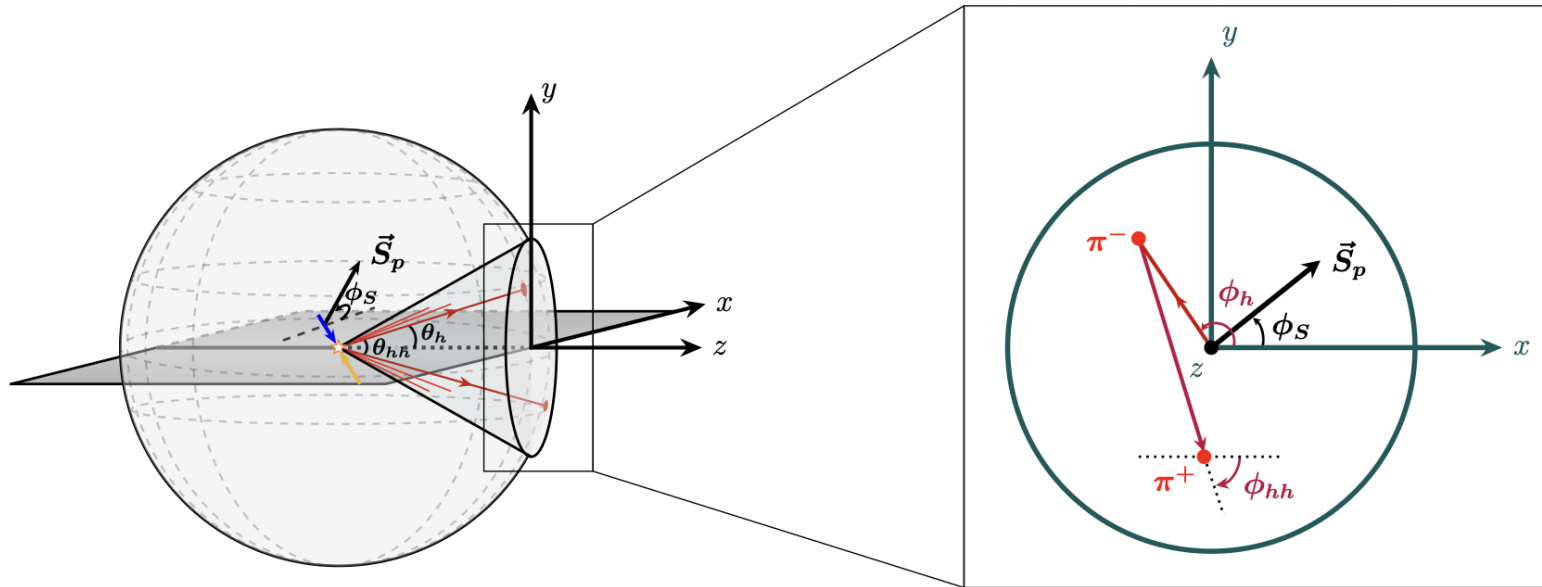
STAR at RHIC



Key STAR Subsystems

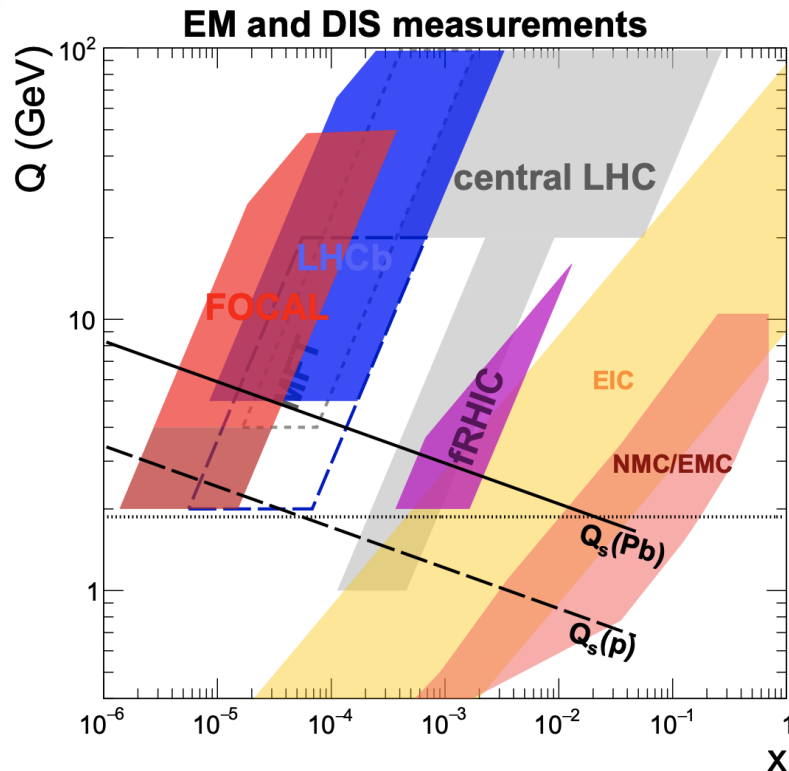
- TPC: charged tracks, $|\eta| < 1.3$
- BEMC/EEMC: electromagnetic calorimetry, $|\eta| < 1$ & $1.09 < \eta < 2$
- TOF: particle ID ($\pi/K/p$ separation)
- FMS: forward photon/ π^0 , $2.6 < \eta < 4.0$

EEC: angular definition



- ϕ_S : azimuthal angle of the proton's S_p around the jet axis
- ϕ_h : azimuthal angle of the hadron around the jet axis
- ϕ_{hh} : azimuthal angle of the h^- to h^+ pair vector around the jet axis

RHIC and EIC, Connection



Test universality at various collision energies → complete phase space, full evolution:

- **RHIC serves as intermediate energy colliders, accessing low and intermediate Q^2** , share a similar phase space with forward production at the EIC
- **LHC data can probe wider region** gaining from high collision energies

Test universality by different probes:

