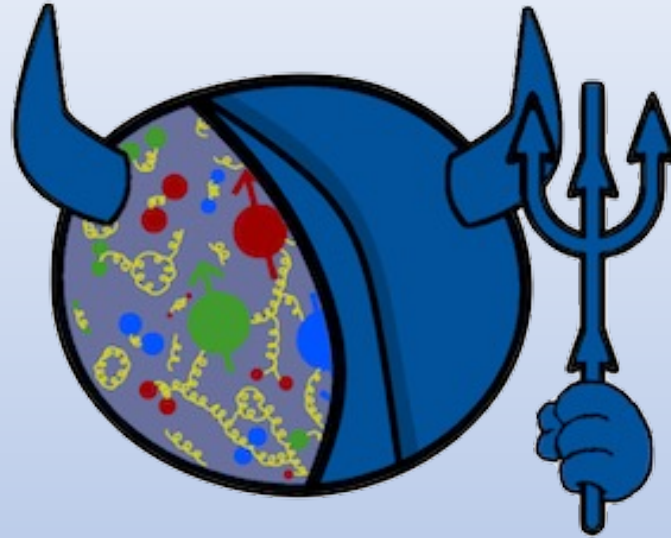


Transverse Spin-Dependent Azimuthal Correlation of Charged Pion Pairs in $p^\uparrow p$ Collisions at $\sqrt{s} = 510$ GeV at STAR



25th International Symposium on Spin Physics (SPIN 2023)
Durham, North Carolina



Navagyan Ghimire
(For the STAR Collaboration)
09/25/2023



Supported in part by

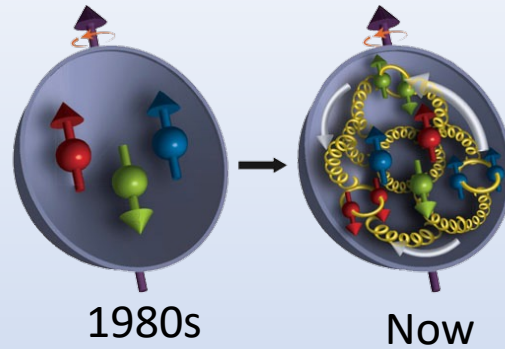


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Motivation

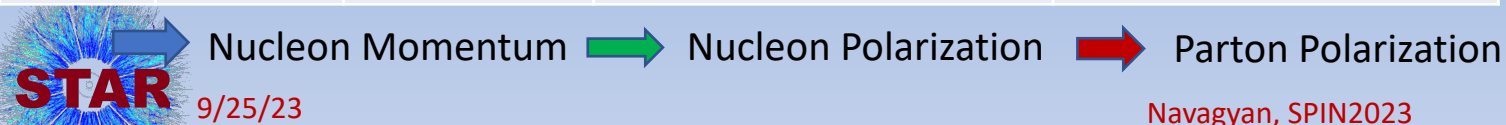
- Proton spin structure:



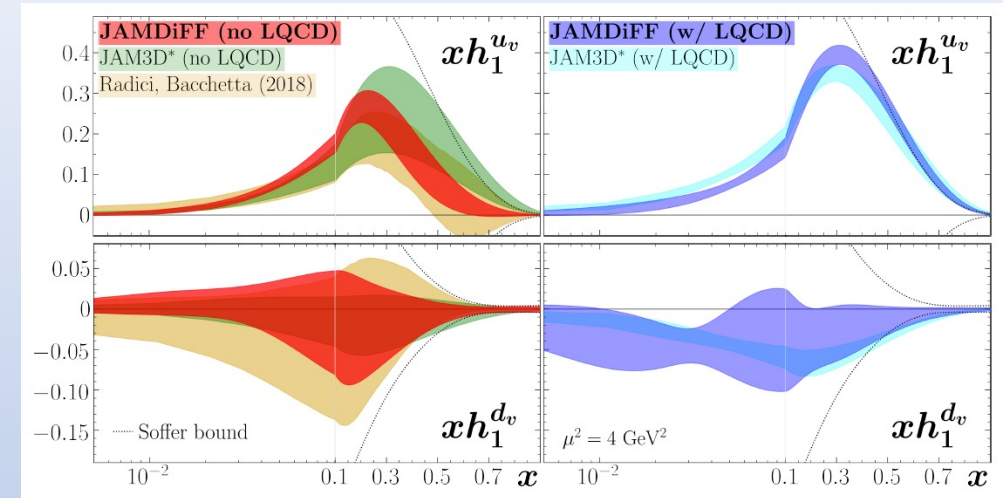
- Parton Distribution Functions (PDFs):

At leading twist three collinear PDFs, integrated over parton transverse momenta, k_T

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U			
	L			
	T			



Transversity PDF



C. Cocuzza et. al., arXiv:2306.12998 [hep-ph]

- Less known from experiments than $f_1(x)$ and $g_1(x)$
- Chiral-odd quantity
- Extraction requires coupling to another chiral-odd distribution, such as Collins or Interference Fragmentation Functions (FFs)
- For estimating tensor charge (g_T), a precise determination of transversity is necessary

$$g_T = \int_0^1 dx [h_1^q(x) - h_1^{\bar{q}}(x)]$$

Transversity ($h_1(x)$) in $p^\uparrow p$ Collisions

- Interference Fragmentation Function(H_1^{\pm}) channel :

$$p \uparrow + p \rightarrow h^+ h^- + X$$

- Collinear framework preserved
- No jet reconstruction required
- Better access to d-quark than SIDIS

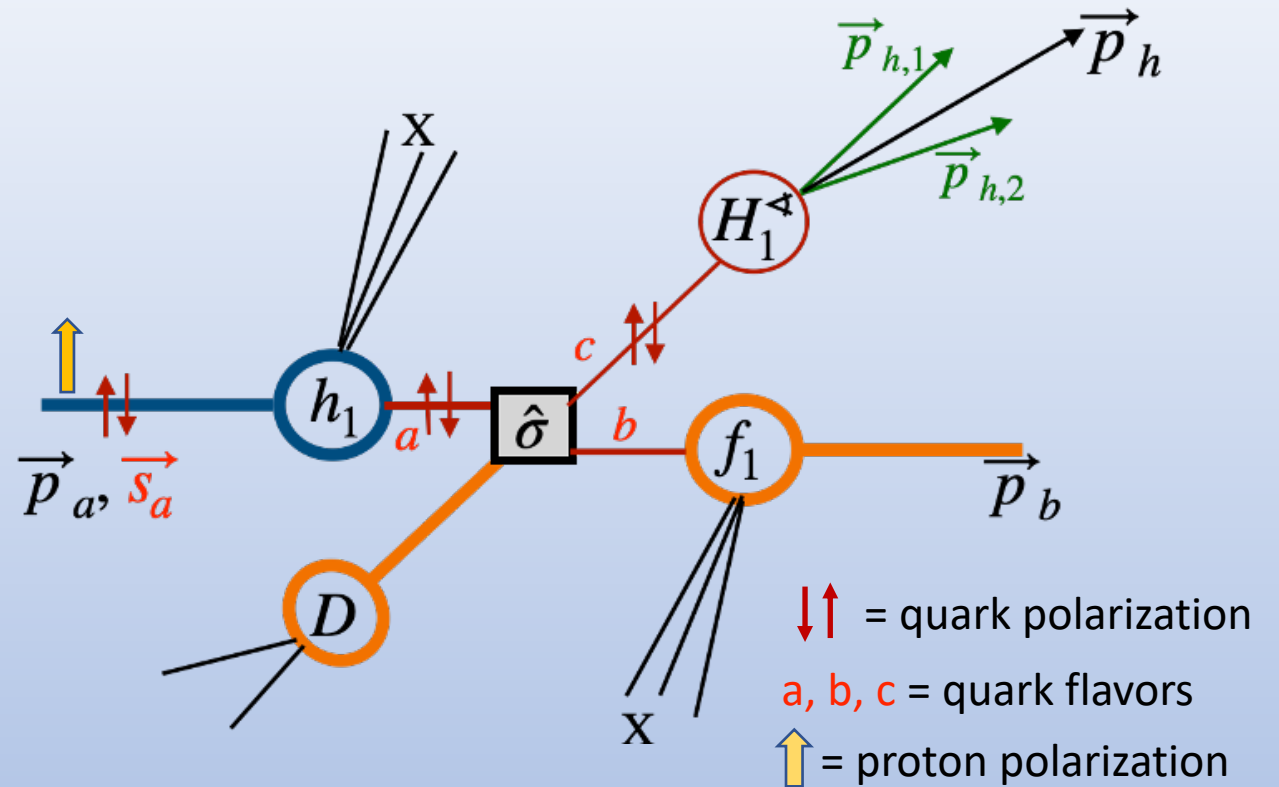
$$d\sigma_{UT} \propto \int dx_a dx_b f_1(x_b) \underbrace{h_1(x_a)}_{\text{A. Bacchetta and M. Radici}} \underbrace{\frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sharp}(z, M)}_{\text{Bacchetta et al.}}$$

A. Bacchetta and M. Radici
Phys. Rev. D 70 (2004) 094032

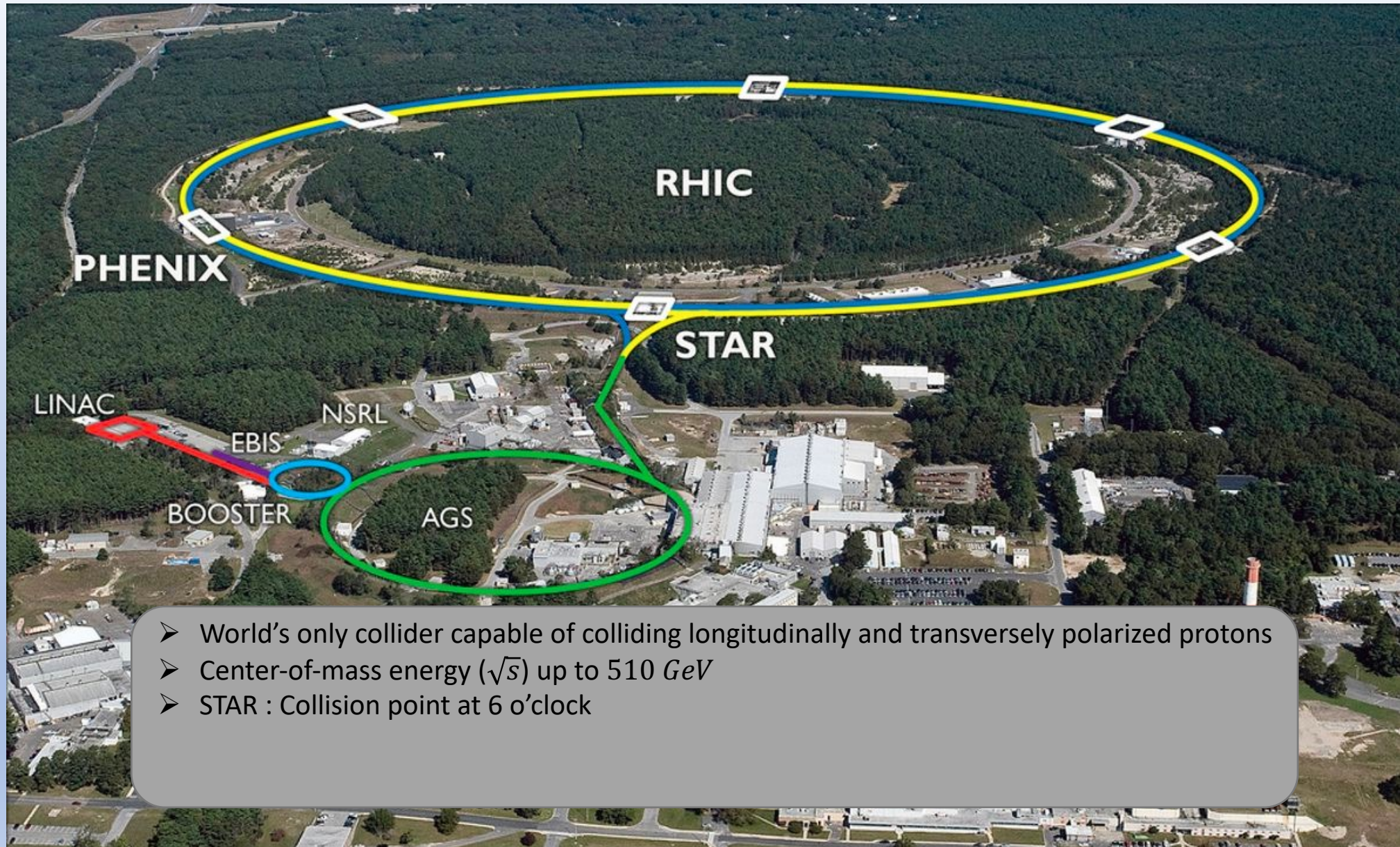
- Di-hadron correlation asymmetry

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{h_1(x)H_1^\sharp(z, M)}{f_1(x)D_1(z, M)}$$

- Independent measurement of H_1^\star is required from e^+e^- experiments (e.g. BELLE)
- D_1 is least known, specifically for gluon fragmentation
(New constrain from STAR at $\sqrt{s}=200$ GeV, Refer to B. Pokhrel's talk 09/25, SPIN2023)



Relativistic Heavy Ion Collider(RHIC)



- World's only collider capable of colliding longitudinally and transversely polarized protons
- Center-of-mass energy (\sqrt{s}) up to 510 GeV
- STAR : Collision point at 6 o'clock



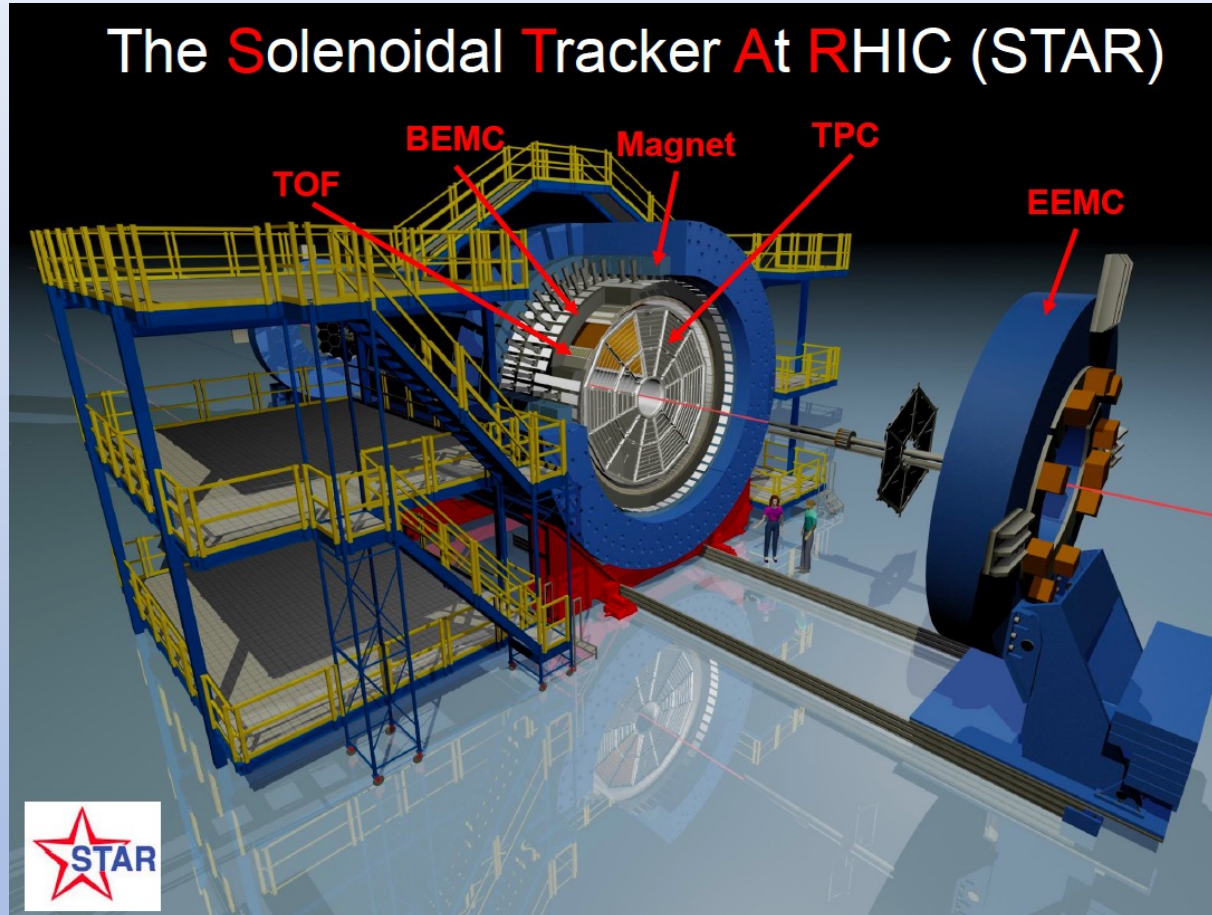
Solenoidal Tracker At RHIC (STAR)

Magnet :

- Uniform magnetic field of 0.5 T

Barrel Electromagnetic Calorimeter(BEMC) :

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Event triggering



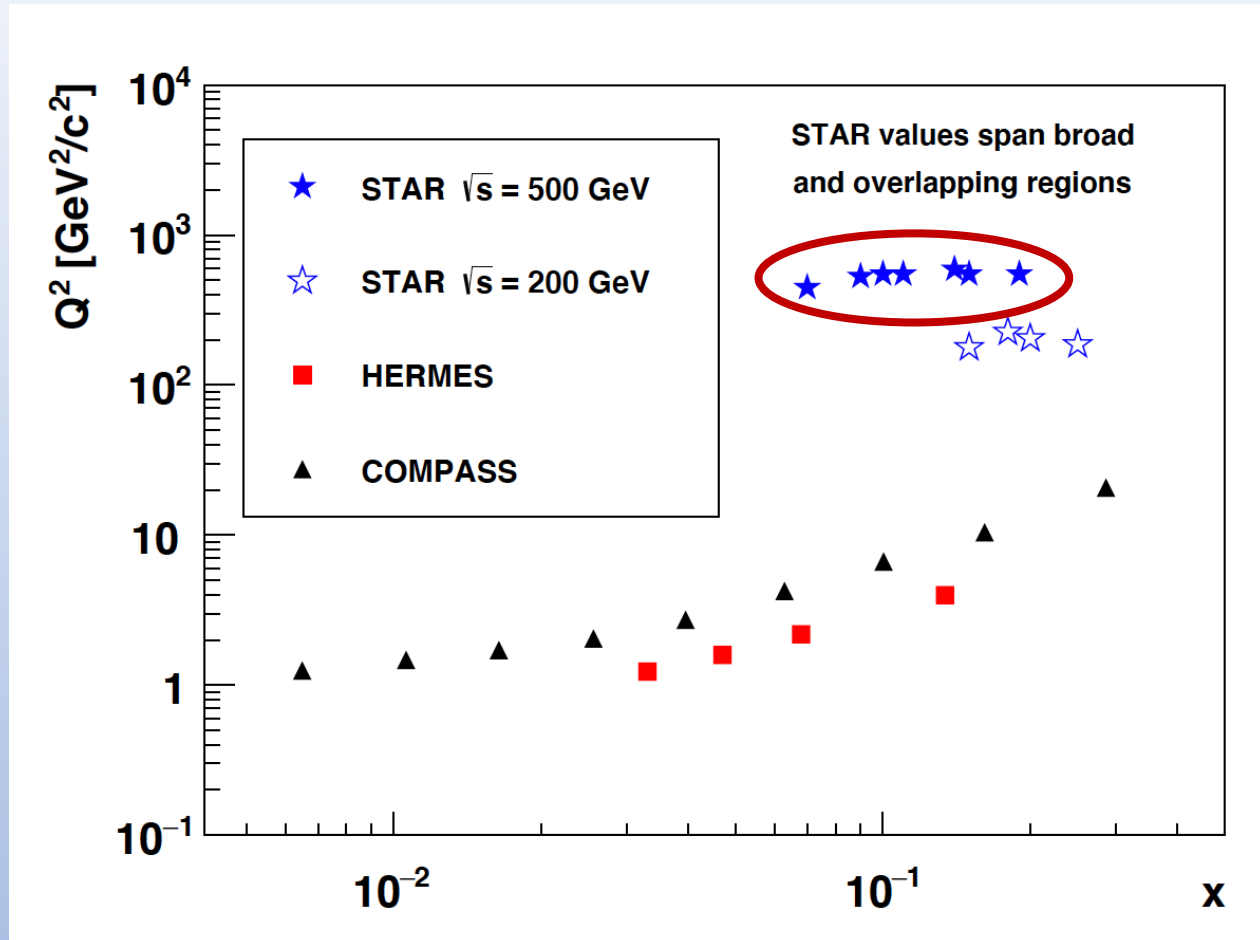
Time Projection Chamber(TPC) :

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Charge determination and particle momentum reconstruction
- PID via measuring ionization energy loss

Time Of Flight(TOF) :

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Stopwatch for particles
- Helps to improve PID

STAR Kinematics



- STAR covers much higher Q^2 than HERMES and COMPASS.
- Results from $p^\uparrow p$ at 510 GeV will provide valuable information about evolution and allow to access lower x compared to 200 GeV.



A_{UT} at STAR

- A non-zero A_{UT} signal has been observed against different kinematic observables ($\eta_{pair}, p_{T,pair}, M_{inv}$) of the pion pairs ($\pi^+\pi^-$) in final state.

Including STAR
2006 results

M. Radici and A. Bacchetta
Phys. Rev. Lett. 120 (2018) 192001

A_{UT} with $p^\uparrow p$ at STAR				
Year	2006	2011	2015	2017
\sqrt{s} (GeV)	200	500	200	510
$L_{int}(pb^{-1})$	~ 1.8	~ 25	~ 52	~ 350

↓

Published

- STAR, Phys. Rev. Lett. 115, 242501 (2015)
- STAR, Phys. Lett. B 780 (2018) 332

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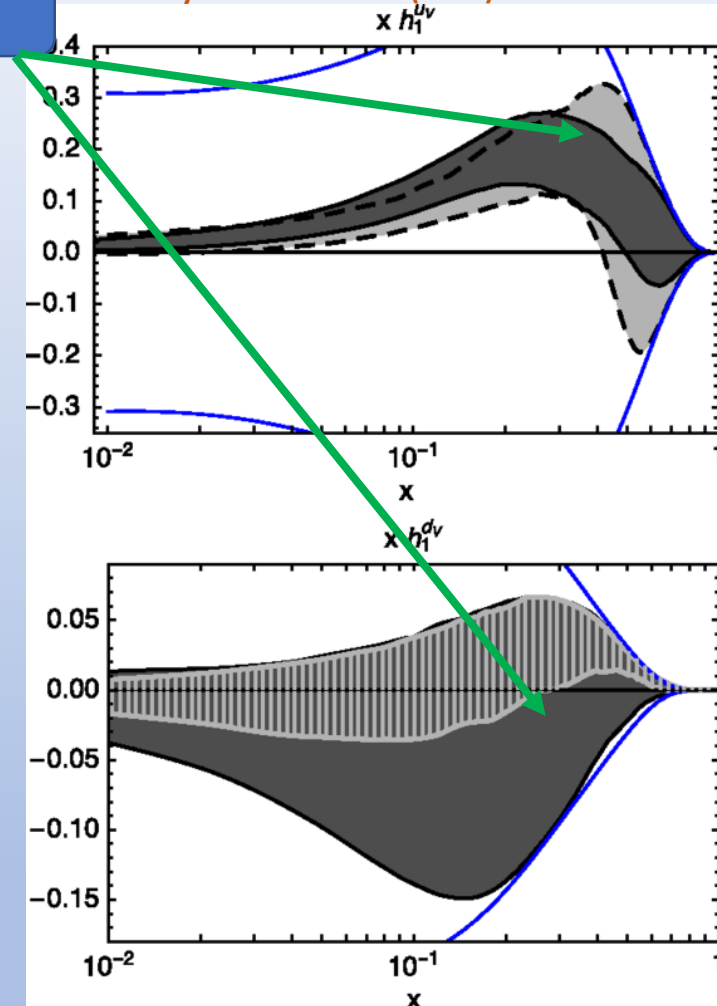
STAR Preliminary

Refer to B. Pokhrel's Talk
09/25, SPIN2023

↓

This analysis

- STAR completed taking another large pp dataset at 508 GeV ($L_{int}(pb^{-1}) \sim 400$) in 2022 and is planning to take another pp 200 GeV dataset in 2024.



STAR results play a crucial role in constraining the global fit of transversity.

Analysis details for A_{UT} measurement

- A_{UT} is measured using a transversely polarized beam colliding with another unpolarized beam (integrating over all spin states).

- Two hadrons in final state allow to relate spin with di-hadron momentum.

$$\vec{s}_a \cdot (\vec{R} \times \vec{p}_h)$$

- Two oppositely charged pions ($\pi^+\pi^-$) in the final state are paired.
- Direction of \vec{R} should point from π^- to π^+ (or the other way) through out the analysis.

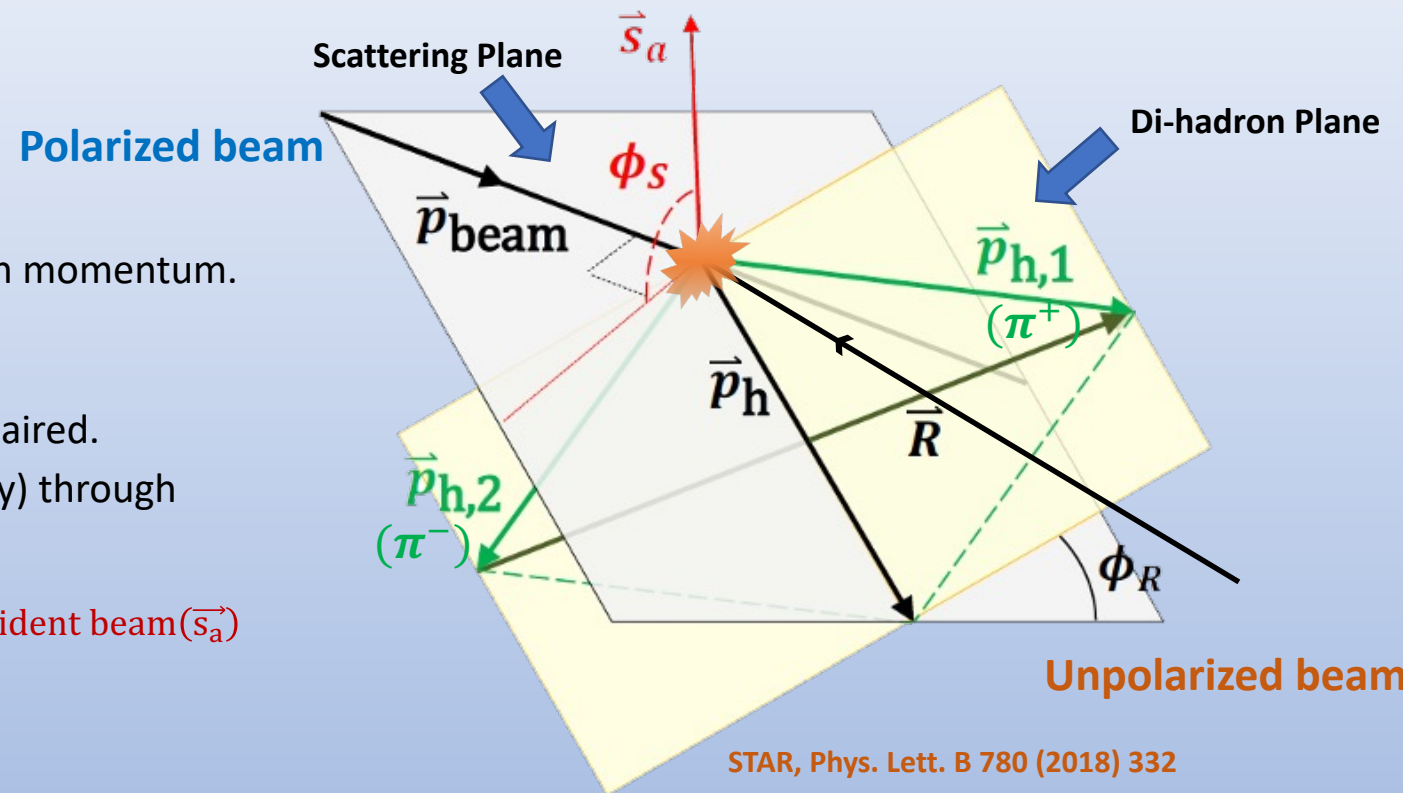
ϕ_s = Angle between scattering plane and polarization of incident beam (\vec{s}_a)

ϕ_R = Angle between scattering plane and dihadron plane

$$\vec{p}_h = \vec{p}_{h_1} + \vec{p}_{h_2}$$

$$\vec{R} = \vec{p}_{h_1} - \vec{p}_{h_2}$$

$$\phi_{RS} = \phi_R - \phi_s$$

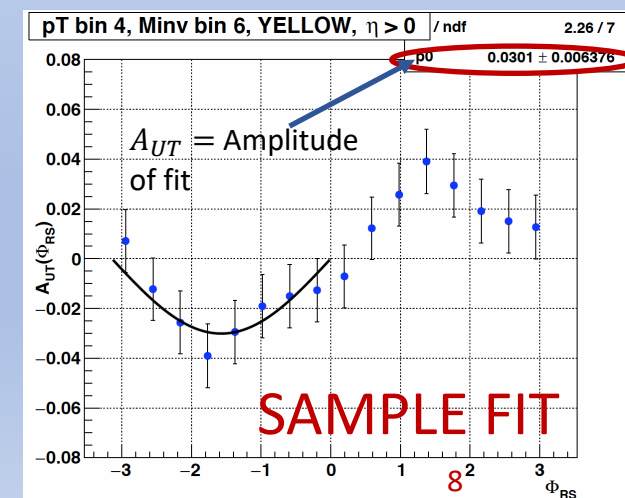
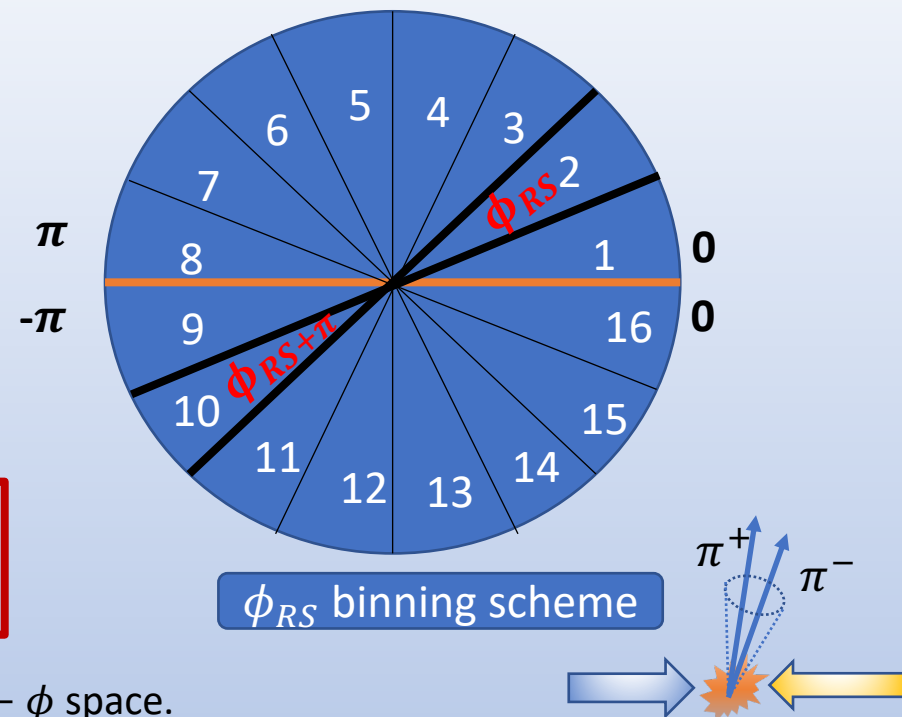


Analysis details for A_{UT} measurement

- For a symmetric detector like STAR (in azimuthal space),
 - A_{UT} can be extracted from cross-ratio formula for different kinematic variables ($M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$, $\eta^{\pi^+\pi^-}$).
 - Free from effects related to detector efficiencies and spin-dependent luminosities.

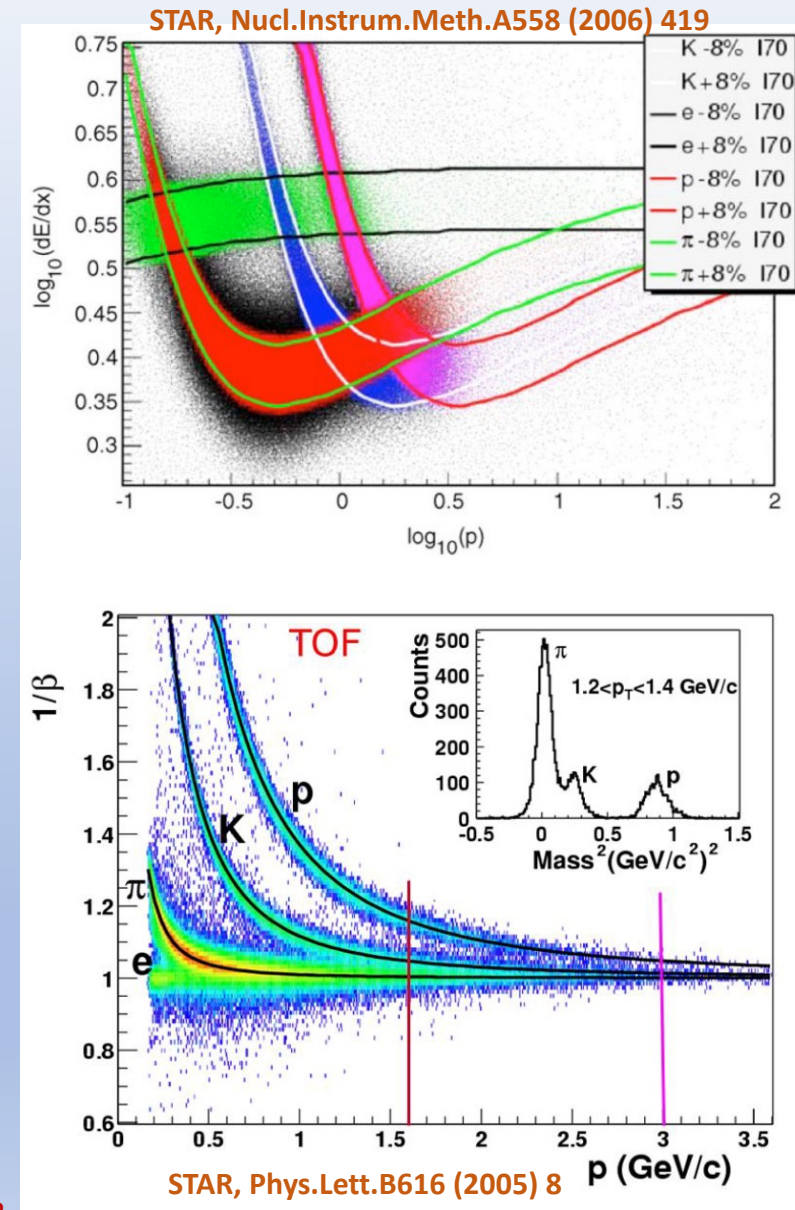
$$A_{UT} \cdot \sin(\phi_{RS}) = \frac{1}{P} \cdot \frac{\sqrt{N \uparrow(\phi_{RS}) N \downarrow(\phi_{RS} + \pi)} - \sqrt{N \downarrow(\phi_{RS}) N \uparrow(\phi_{RS} + \pi)}}{\sqrt{N \uparrow(\phi_{RS}) N \downarrow(\phi_{RS} + \pi)} + \sqrt{N \downarrow(\phi_{RS}) N \uparrow(\phi_{RS} + \pi)}}$$

- Two oppositely charged pions in the final state are paired if they are close (<0.7) in $\eta - \phi$ space.
- The angle ϕ_{RS} modulates the A_{UT} by $\sin(\phi_{RS})$.
- ϕ_{RS} is divided into 16 bins of uniform bin-width in the range $[-\pi, +\pi]$ and $N \uparrow (\downarrow)$ in each ϕ_{RS} bin is counted.
- For each kinematic bin, the cross-ratio is calculated for each ϕ_{RS} and fitted with a sinusoidal function.
- The amplitude of this sin fit gives the A_{UT} .
- A_{UT} is extracted for Blue and Yellow beams separately and the final result is weighted average.



Particle Identification (PID) at STAR

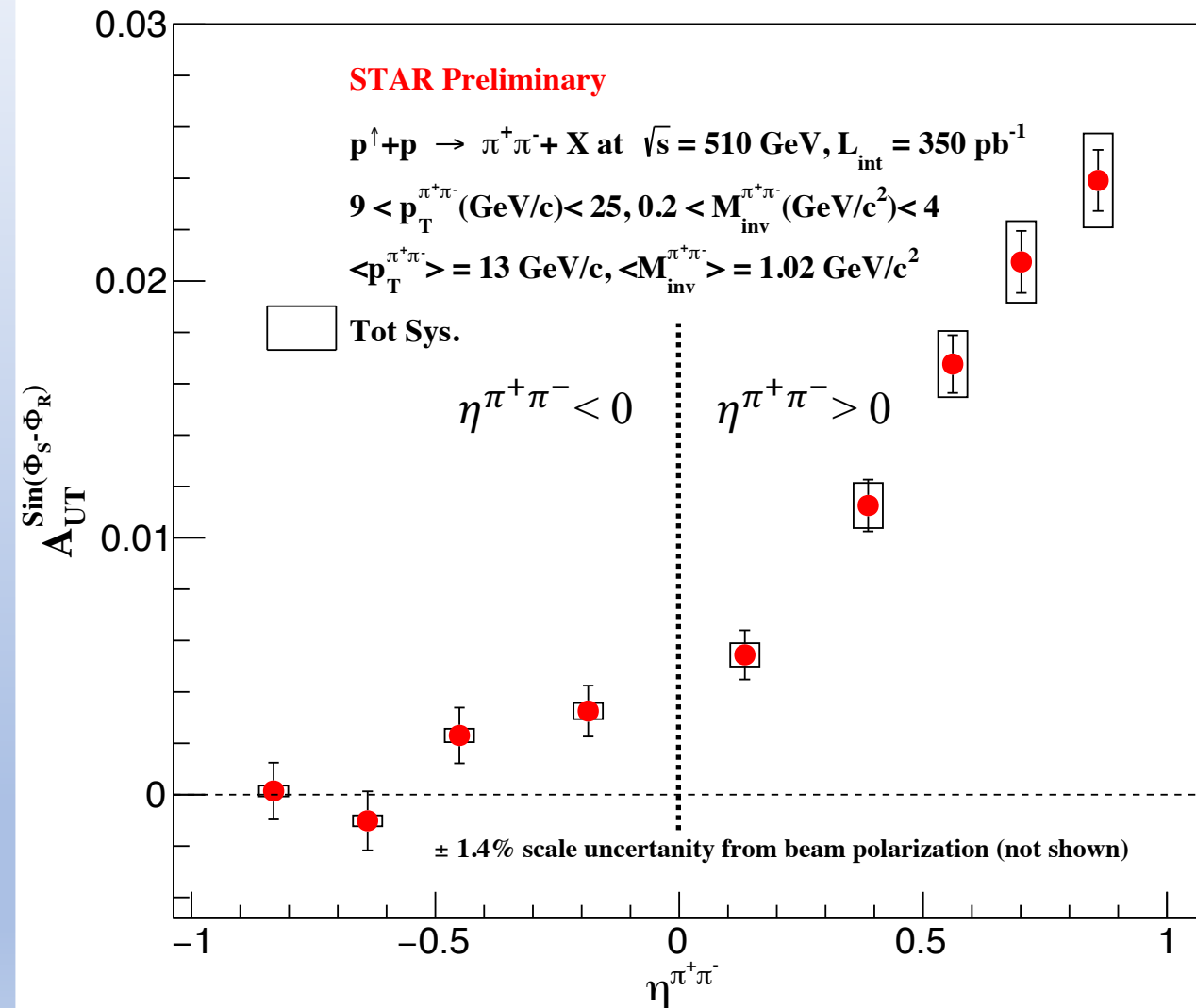
- At STAR PID is done by measuring average specific ionization energy loss $\left\langle \frac{dE}{dx} \right\rangle$ in TPC.
- When the $\frac{dE}{dx}$ vs p bands for two different particle types are close together or cross, TOF is extremely useful for PID.
 - TOF detector is capable of separating proton from kaon and pion for momenta up to 3 GeV/c.



A_{UT} Results

A_{UT} as a function of $\eta^{\pi^+\pi^-}$

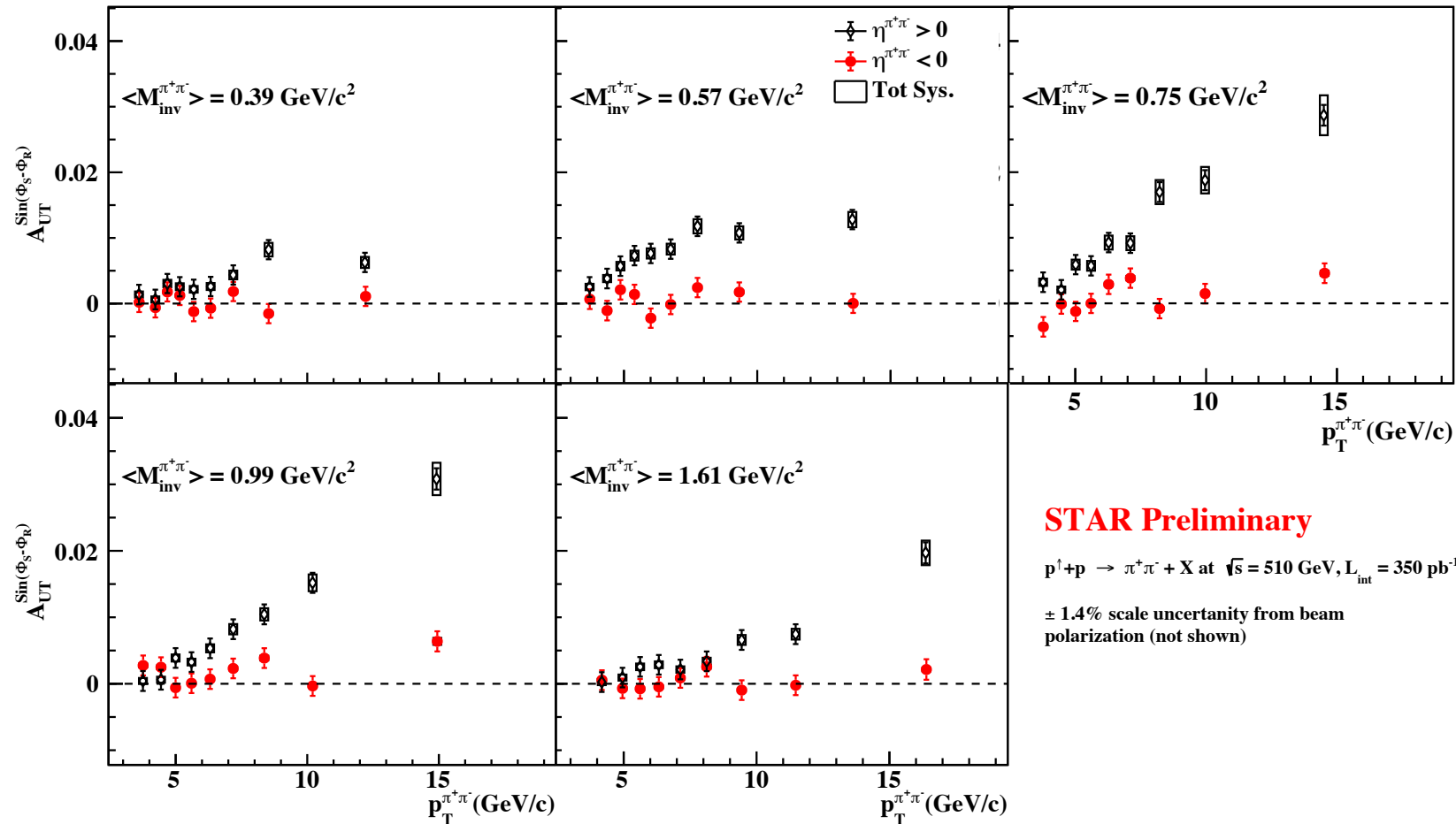
- A_{UT} increases with $\eta^{\pi^+\pi^-}$
- Forward direction ($\eta^{\pi^+\pi^-} > 0$) probes higher x , valence region, where $h_1^q(x)$ is sizable, hence A_{UT} is large.
- Backward direction ($\eta^{\pi^+\pi^-} < 0$) probes lower x resulting lower A_{UT} signal.
- Systematic uncertainties arising from the impurity of the sample and trigger biasing effect against quark-jets have been investigated.



A_{UT} Results

A_{UT} as a function of $p_T^{\pi^+\pi^-}$ in different $M_{inv}^{\pi^+\pi^-}$ bins

- Strong $p_T^{\pi^+\pi^-}$ dependence of A_{UT} has been found in the +ve $\eta^{\pi^+\pi^-}$ direction in all $M_{inv}^{\pi^+\pi^-}$ bins.
- Stronger rise in A_{UT} signal around ρ meson mass ($\sim 0.8 \text{ GeV}/c^2$) region.
- Signal is stronger in forward ($\eta^{\pi^+\pi^-} > 0$) direction and small in backward ($\eta^{\pi^+\pi^-} < 0$) direction.



STAR Preliminary

$p^\dagger + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 510 \text{ GeV}$, $L_{int} = 350 \text{ pb}^{-1}$

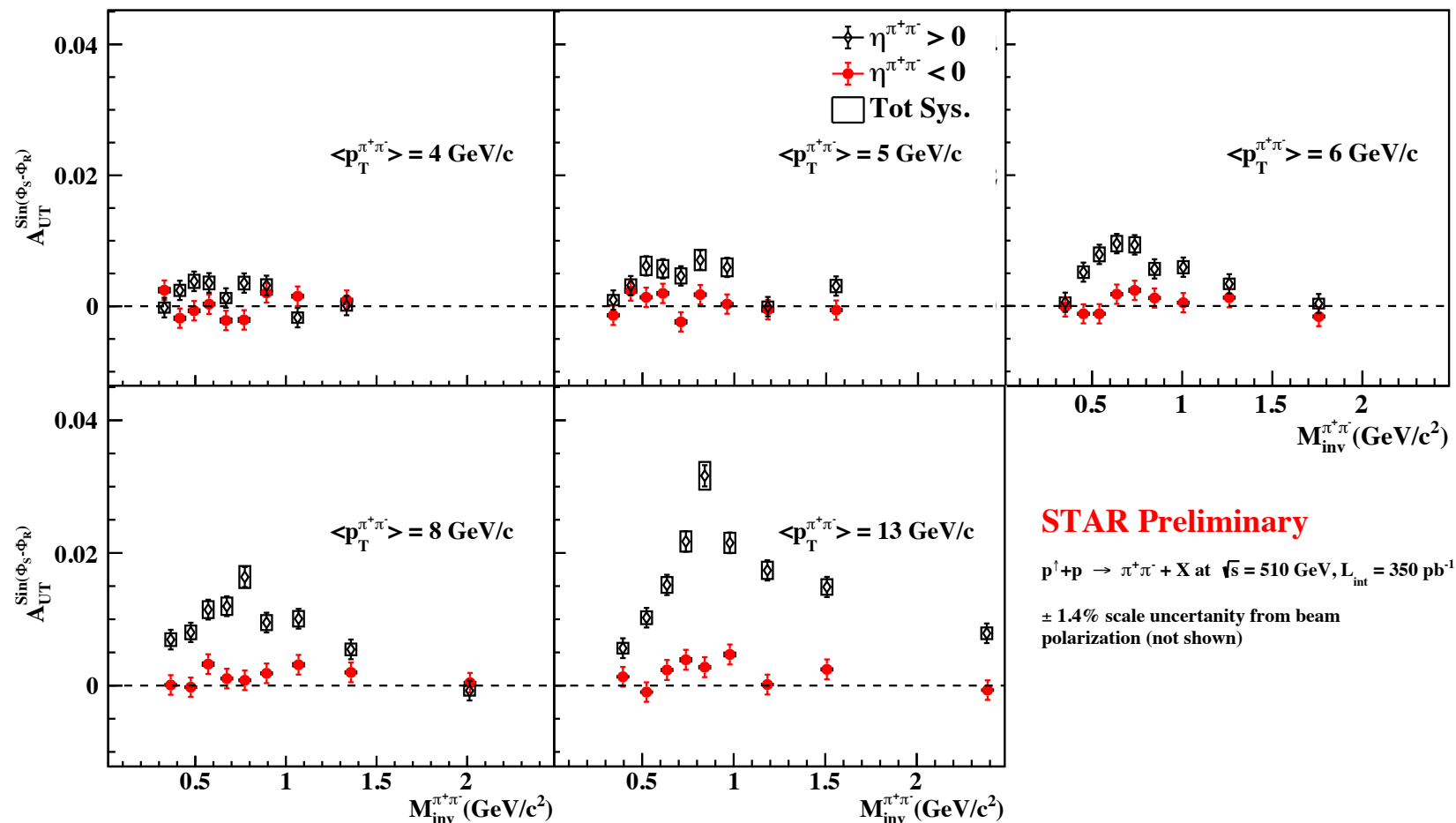
$\pm 1.4\%$ scale uncertainty from beam polarization (not shown)



A_{UT} Results

A_{UT} as a function of $M_{inv}^{\pi^+\pi^-}$ in different $p_T^{\pi^+\pi^-}$ bins

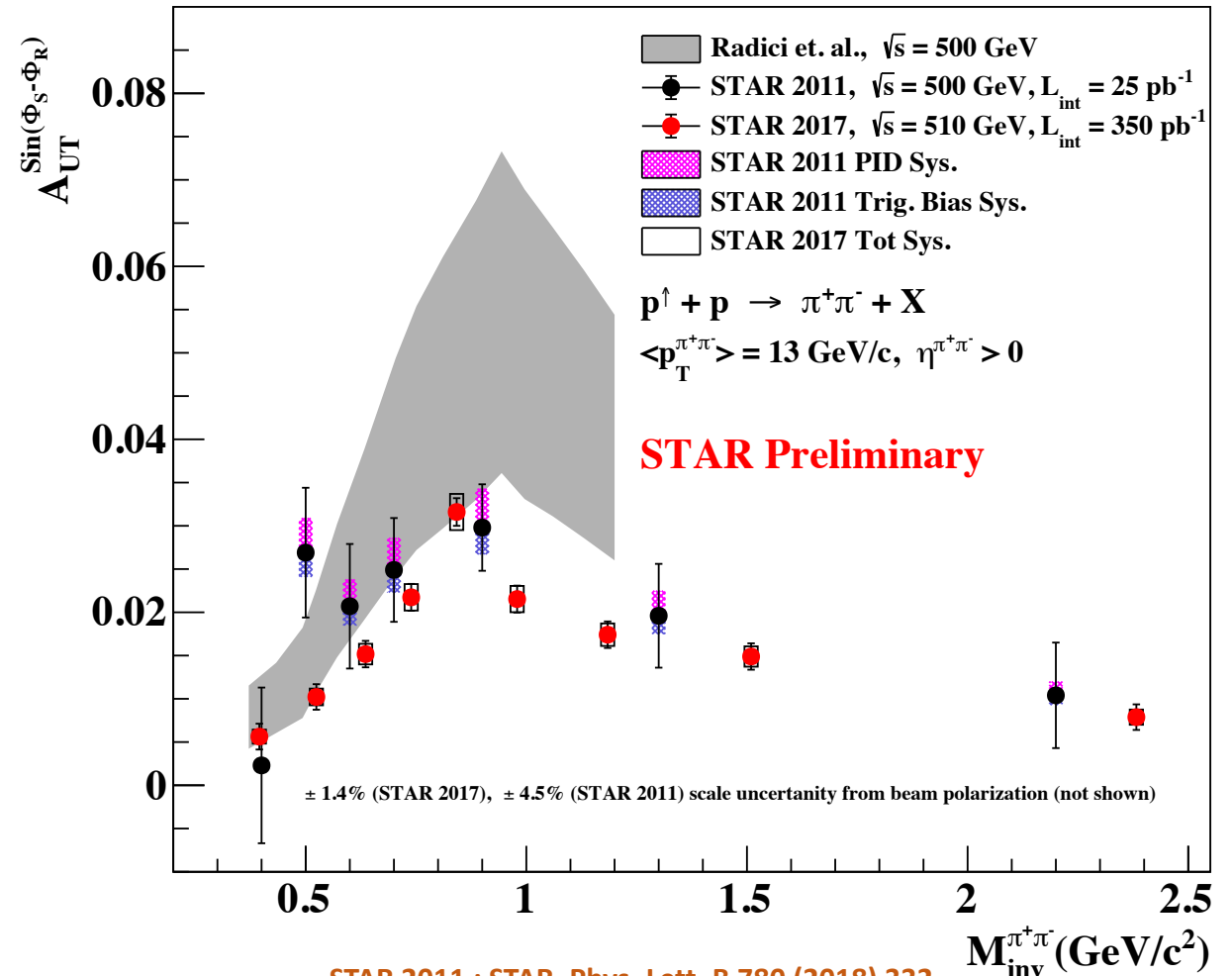
- Strong $M_{inv}^{\pi^+\pi^-}$ dependence of A_{UT} has been found in the +ve $\eta^{\pi^+\pi^-}$ direction in all $p_T^{\pi^+\pi^-}$ bins.
- The enhancement of A_{UT} signal around the ρ meson mass ($\sim 0.8 \text{ GeV}/c^2$) is due to the interference between the different $\pi^+\pi^-$ production channel.
- Signal is stronger in forward ($\eta^{\pi^+\pi^-} > 0$) direction and small in backward ($\eta^{\pi^+\pi^-} < 0$) direction.



A_{UT} Results

A_{UT} as a function of $M_{inv}^{\pi^+\pi^-}$ for highest $p_T^{\pi^+\pi^-}$ bin and $\eta^{\pi^+\pi^-} > 0$

- STAR's latest measurement of A_{UT} from 2017 dataset exhibits a notably higher level of precision.
 - Statistical and systematic precision is significantly improved by the new result.
- A_{UT} from STAR 2017 dataset is consistent with previous STAR 2011 measurement and theory prediction from SIDIS, e^+e^- data.



STAR 2011 : STAR, Phys. Lett. B 780 (2018) 332

Summary and Outlook

- Di-hadron correlation asymmetry A_{UT} of final state pion pairs, as functions of various kinematic observables (η, p_T, M_{inv}), is expected to be sensitive to transversity.
- New STAR 2017 IFF A_{UT} measurement has higher level of precision and is consistent with previous STAR 2011 measurement.
- Results of this analysis will help to probe transversity at much higher Q^2 than SIDIS and test the universality of the mechanism which produces azimuthal correlations amongst SIDIS, e^+e^- , and $p^\uparrow p$ collisions.
- Planning for precision measurement of IFF asymmetries for pions/Kaon from 2017+2022 dataset.
- Planning for unpolarized di-hadron cross-section measurement at 500 GeV, which could reduce uncertainties in transversity extraction.

