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

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STAR

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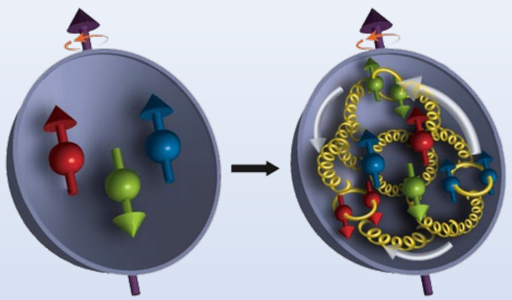
Motivation

- Proton spin structure:



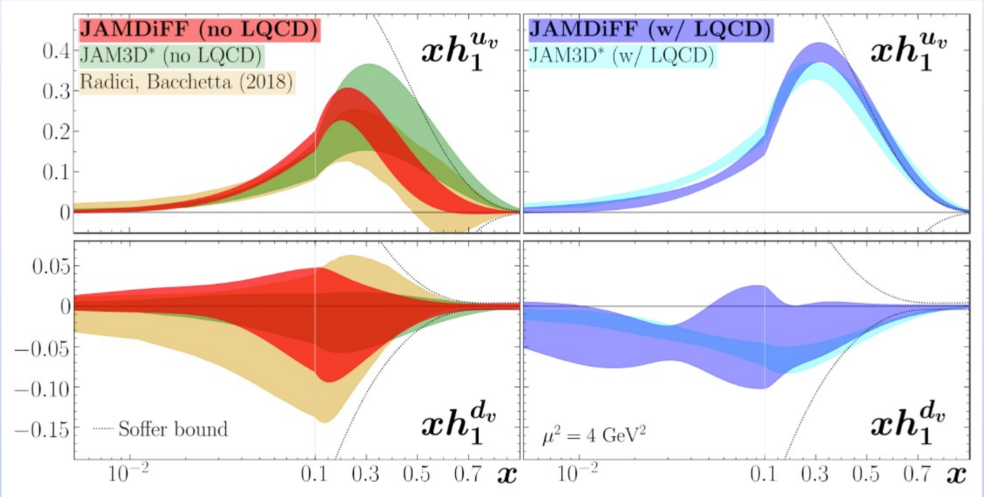
- Parton Distribution Functions (PDFs):

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	$f_1(x)$		
	L		$g_1(x)$ −	
	T			$h_1(x)$ −

Nucleon Momentum | Nucleon Polarization | Parton Polarization

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

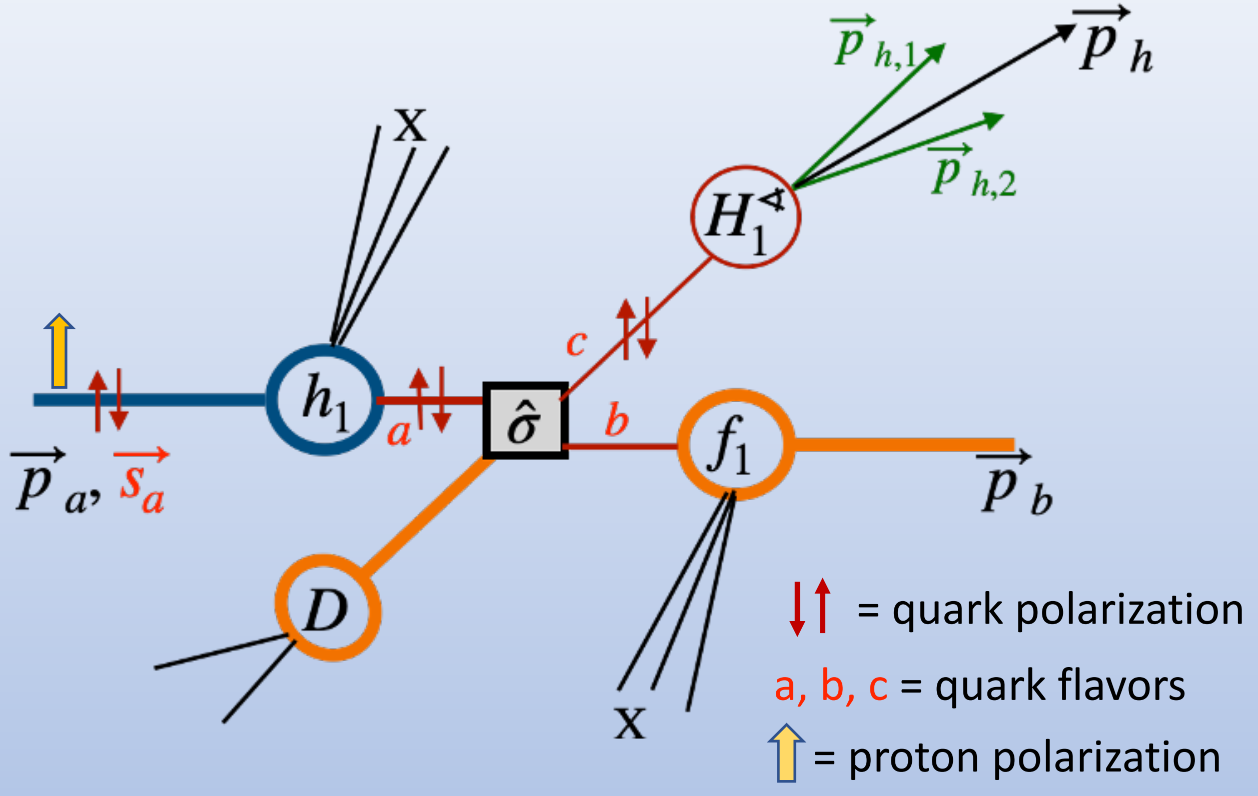
- Interference Fragmentation Function($H_1^{\sphericalangle}$) channel :

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

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

$$d\sigma_{UT} \propto \int dx_a dx_b f_1(x_b) h_1(x_a) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

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

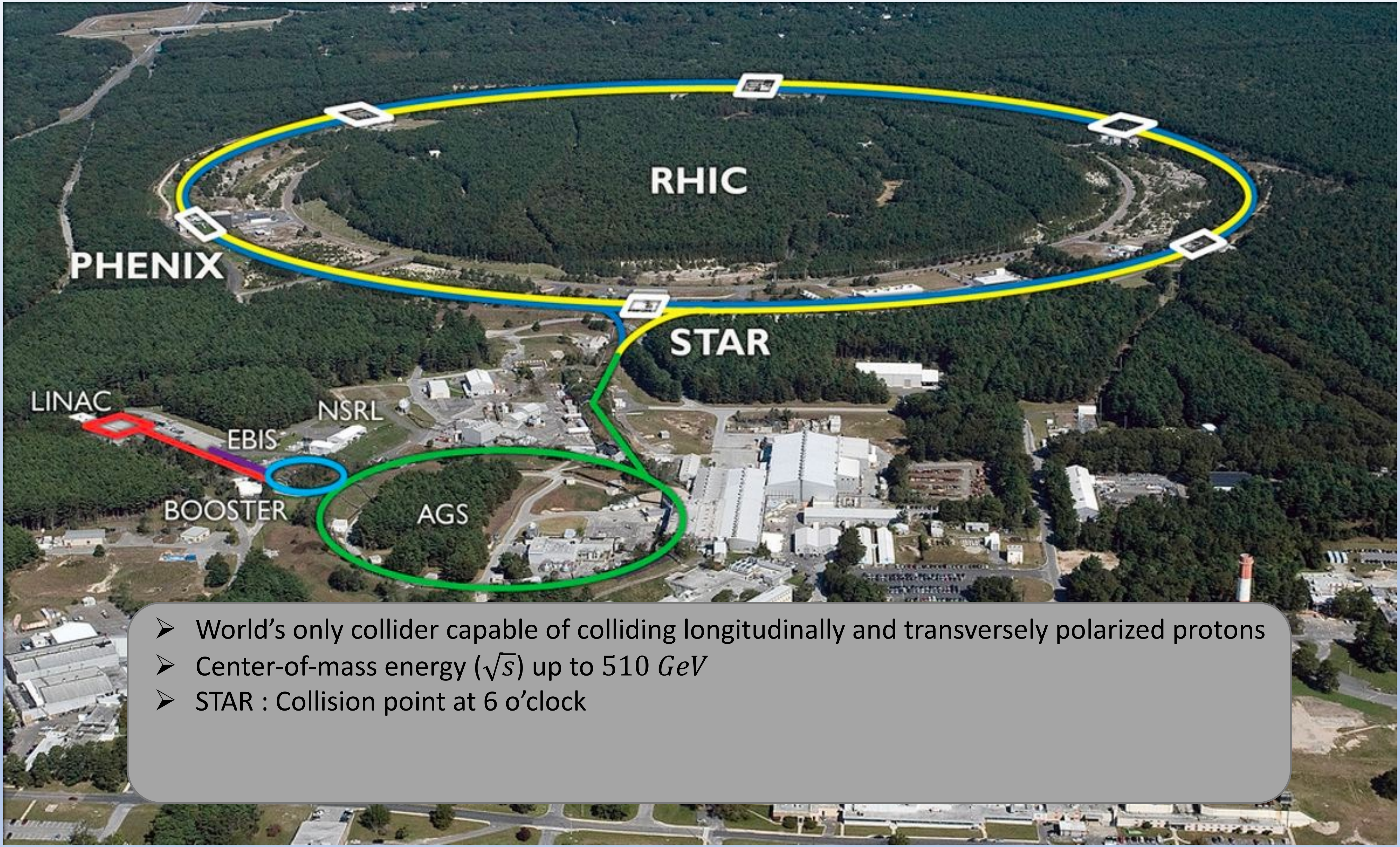


- Di-hadron correlation asymmetry

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

- Independent measurement of $H_1^{\sphericalangle}$ 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)

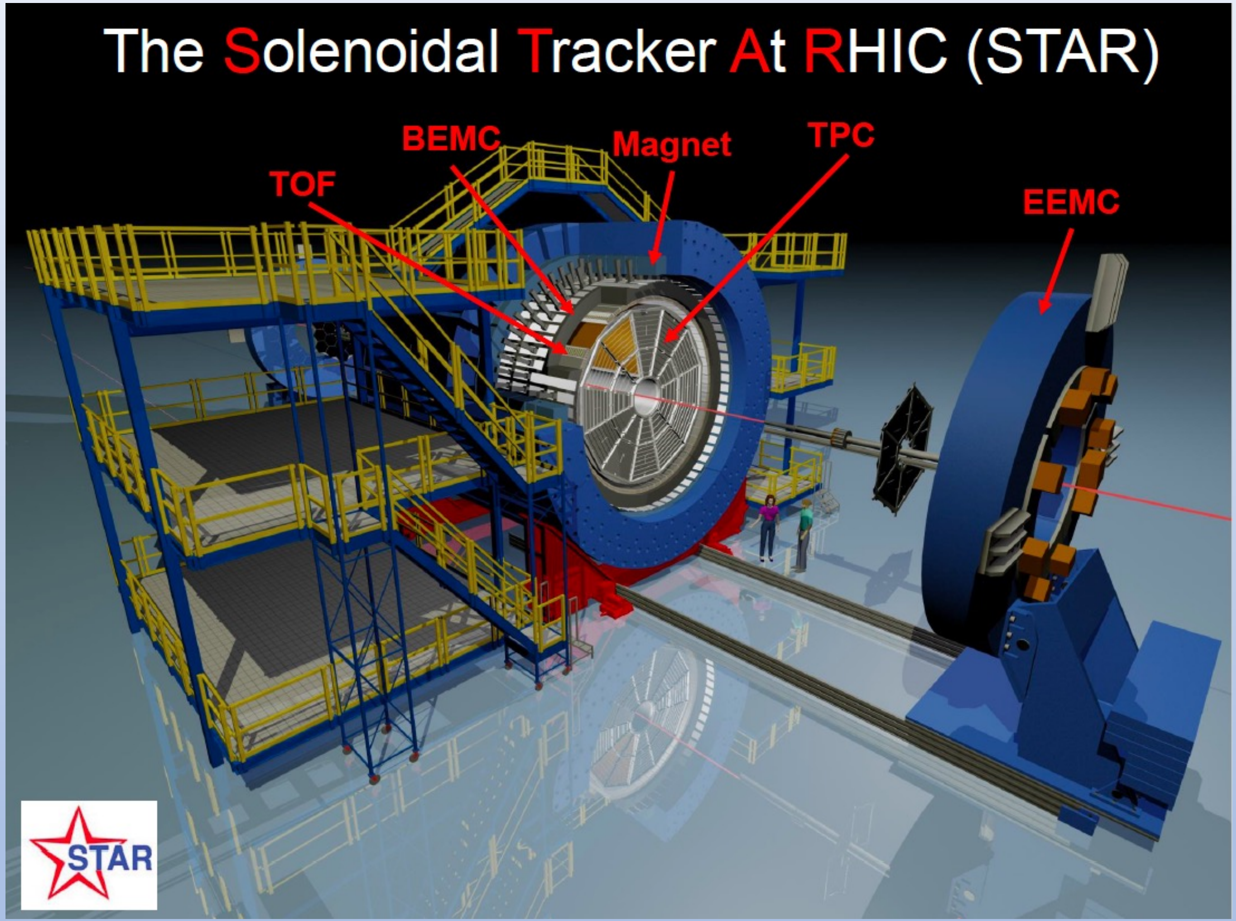


- World’s only collider capable of colliding longitudinally and transversely polarized protons
- Center-of-mass energy ($\sqrt{s}$) up to $510\ GeV$
- STAR : Collision point at 6 o’clock

Solenoidal Tracker At RHIC (STAR)

Magnet :
- Uniform magnetic field of 0.5 T

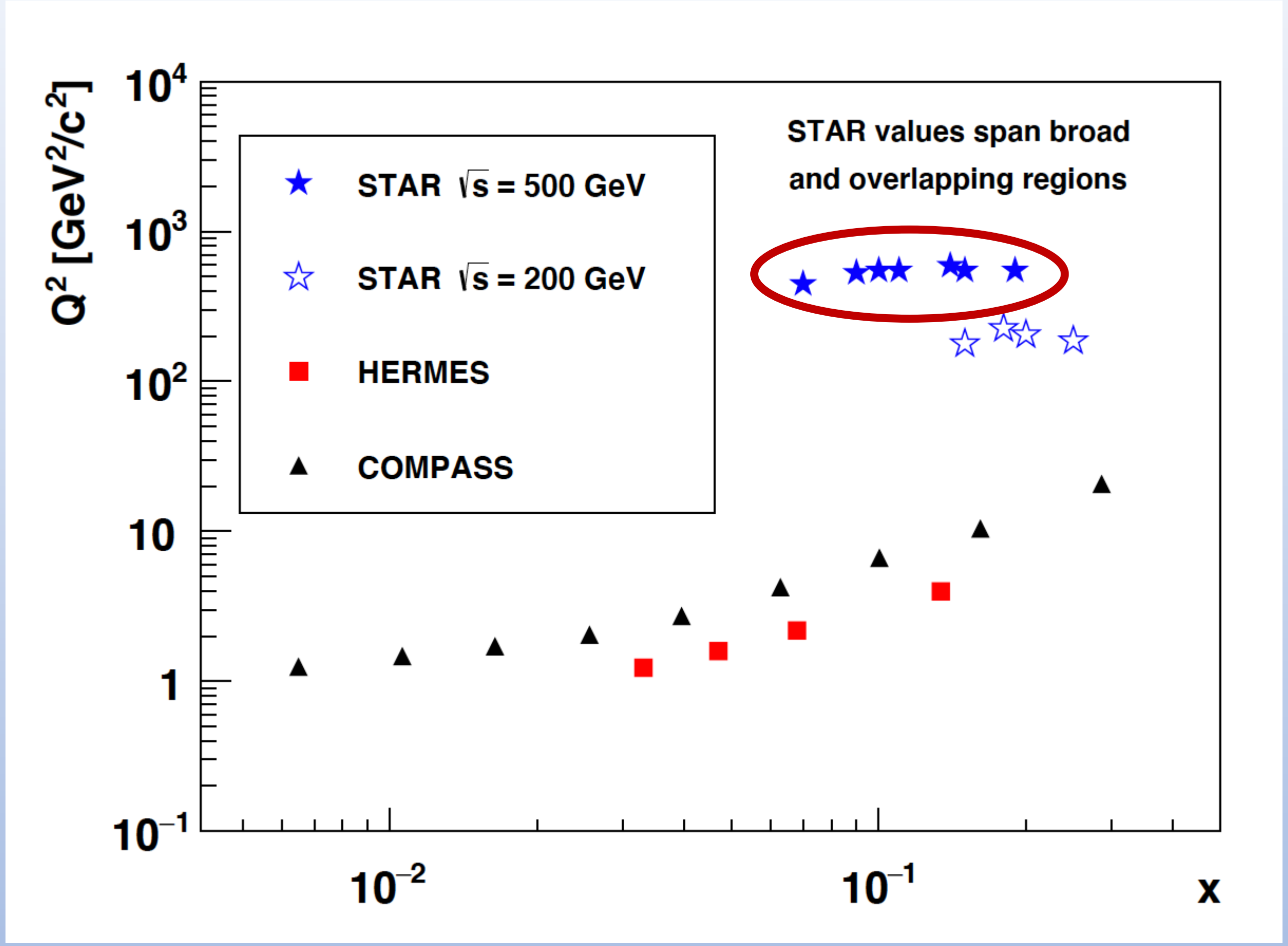
Barrel Electromagnetic Calorimeter(BEMC) :
- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Event triggering



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.

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

2006, 2011 → **Published**
- STAR, Phys. Rev. Lett. 115, 242501 (2015)
- STAR, Phys. Lett. B 780 (2018) 332

2015 → **STAR Preliminary**

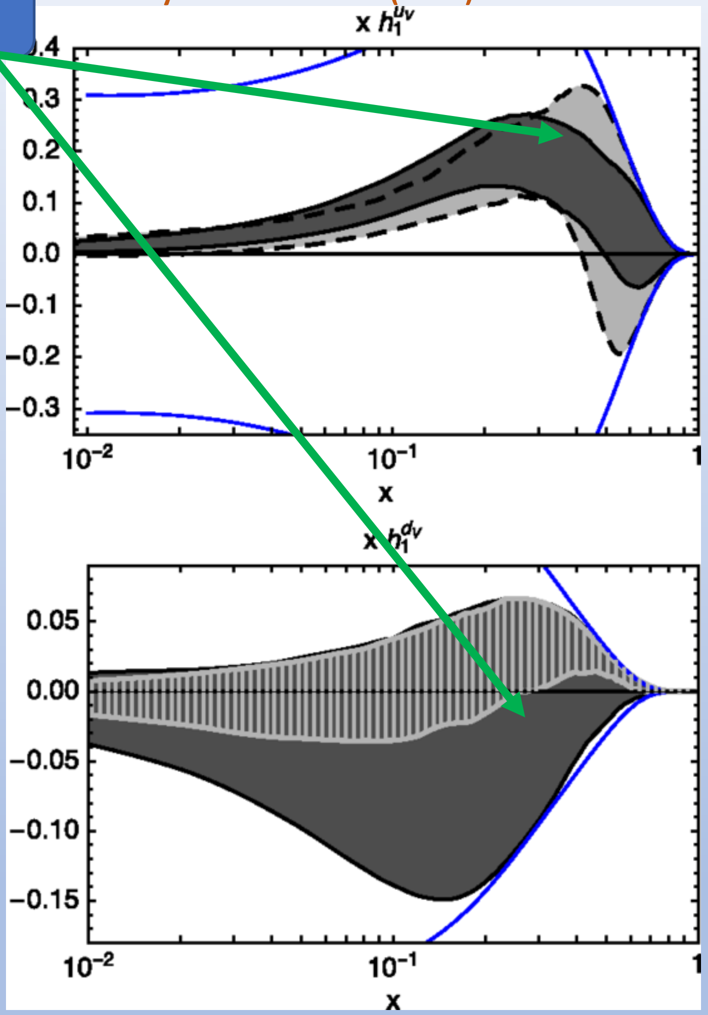
Refer to B. Pokhrel's Talk 09/25, SPIN2023

2017 → **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.

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

Including STAR 2006 results



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

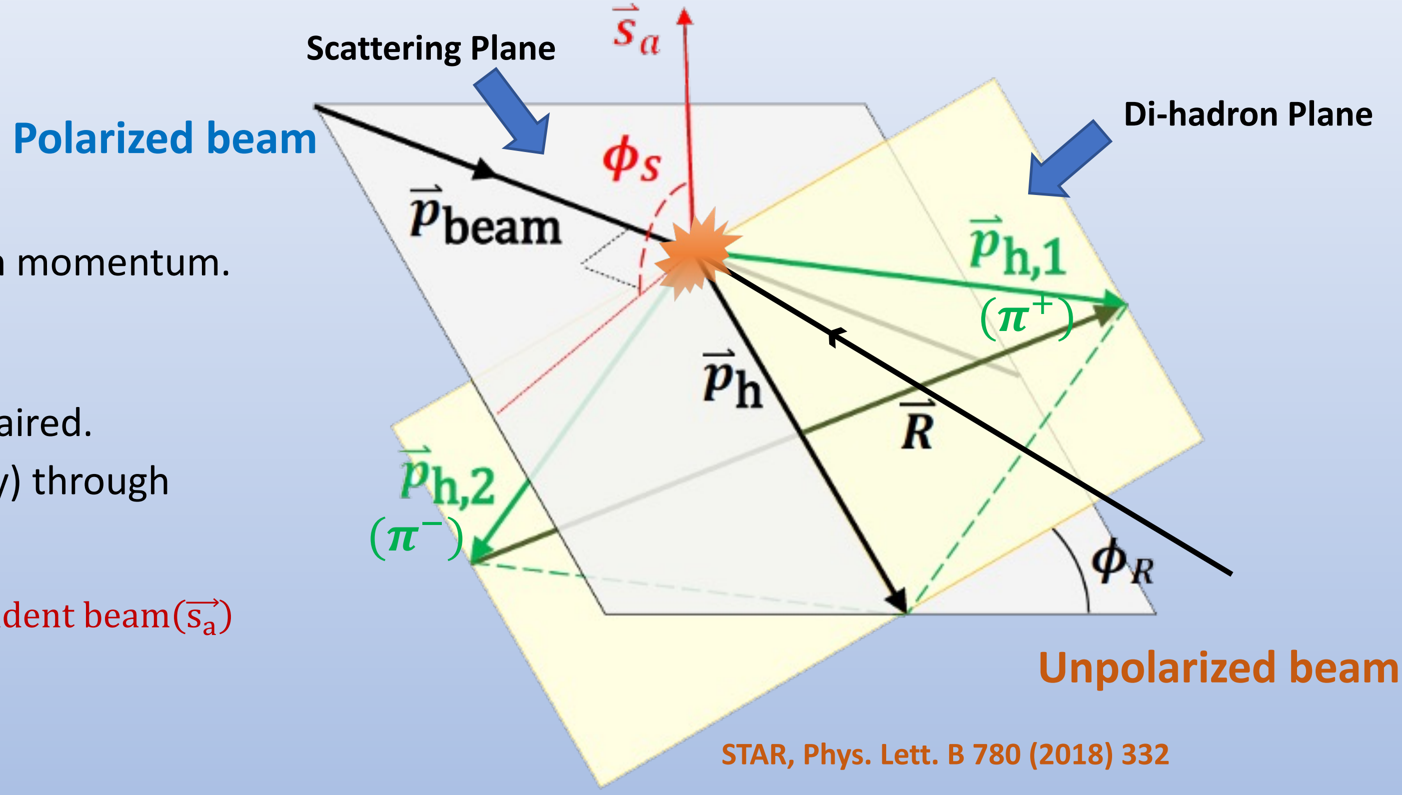
Analysis details for A_{UT} measurement

- 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 away) through out the analysis.

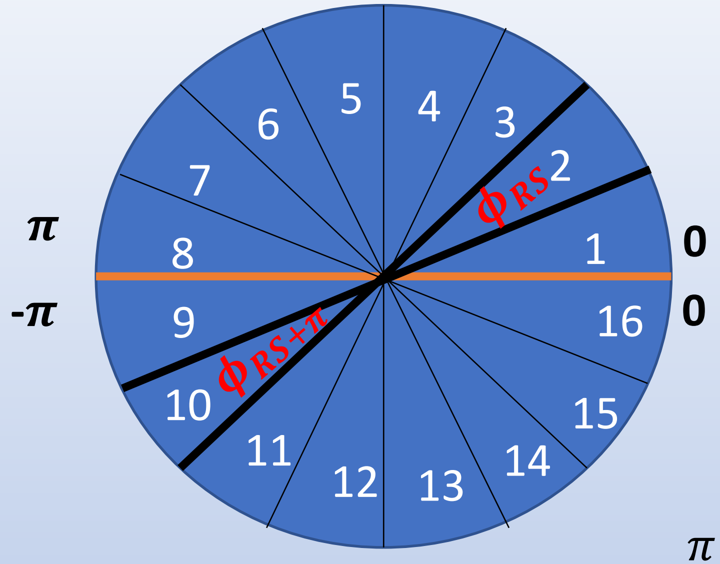
ϕ_s = Angle between scattering plane and polarization of incident beam($\vec{s_a}$)
ϕ_R = Angle between scattering plane and dihadron plane
$\vec{p}_h = \vec{p}_{h_1} + \vec{p}_{h_2}$
$\vec{R} = \vec{p}_{h_1} - \vec{p}_{h_2}$
$\phi_{RS} = \phi_R - \phi_s$



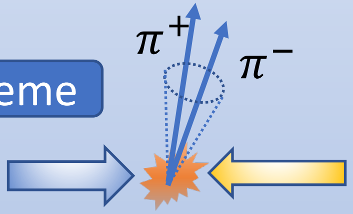
STAR, Phys. Lett. B 780 (2018) 332

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.

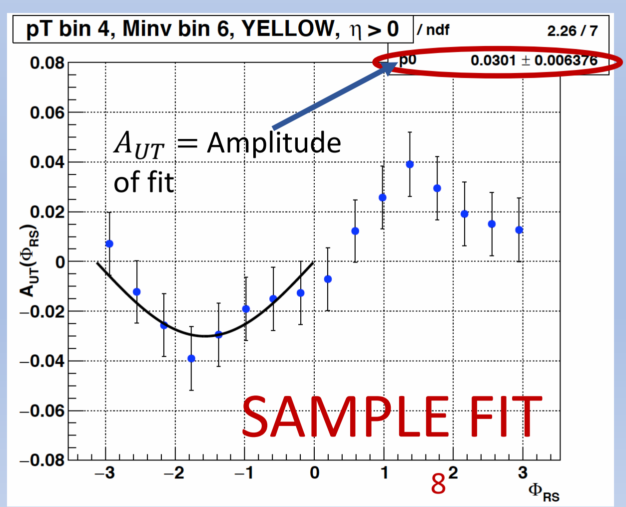


ϕ_{RS} binning scheme



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

- 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.

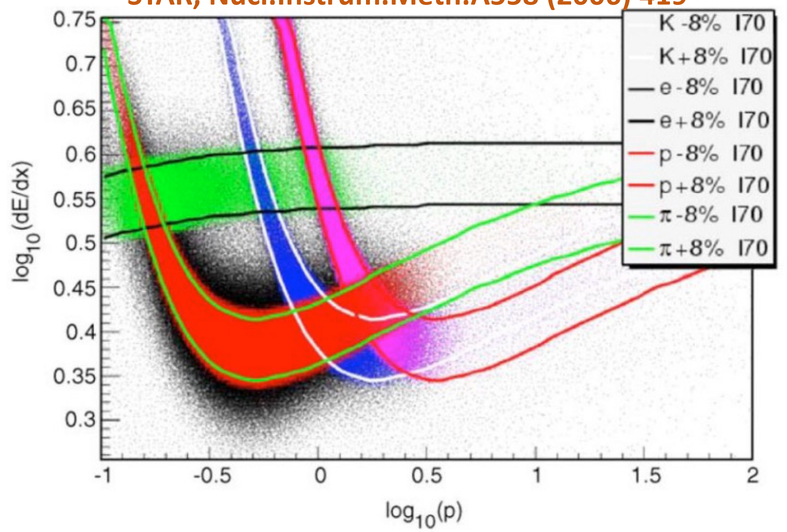


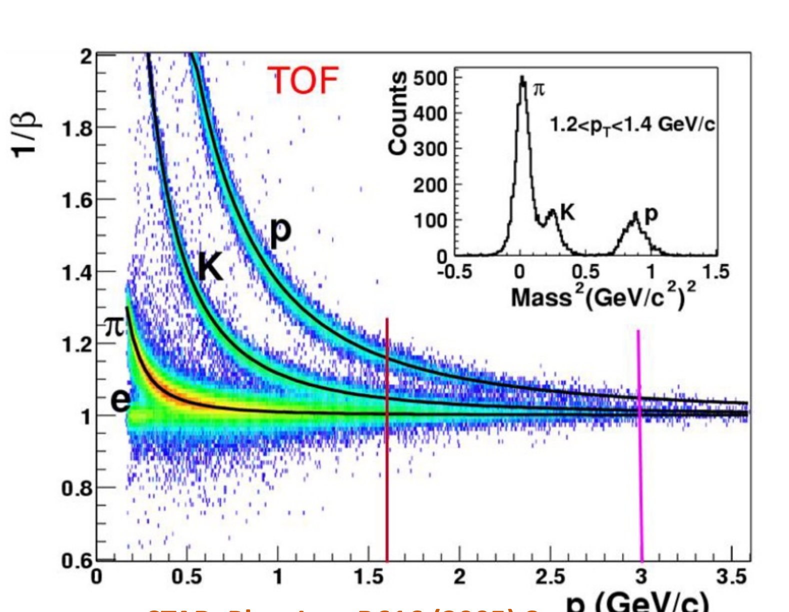
Particle Identification (PID) at STAR

- 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.

STAR, Nucl.Instrum.Meth.A558 (2006) 419





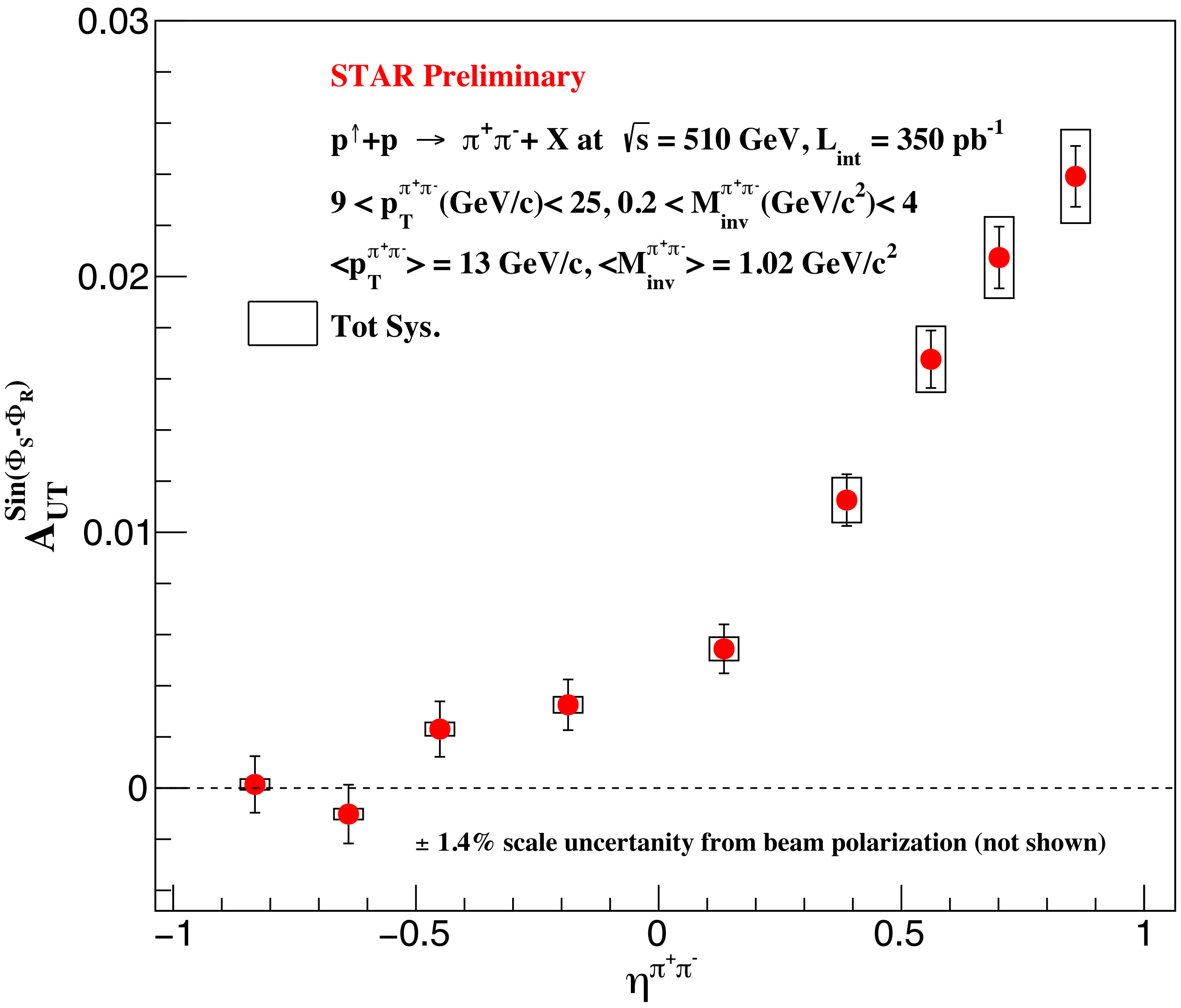
STAR, Phys.Lett.B616 (2005) 8

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.

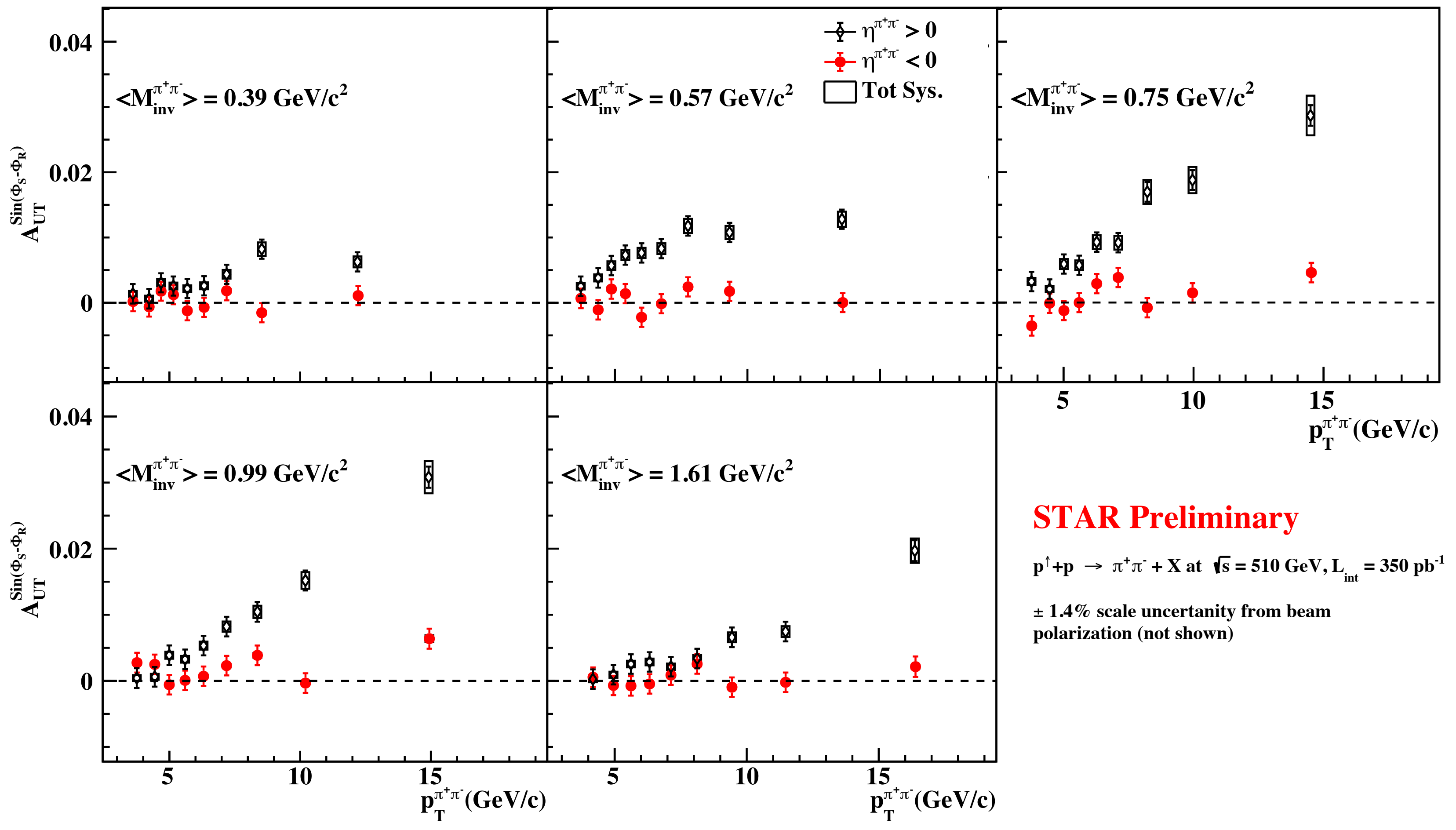
- Systematic uncertainties arising from the impurity of the sample and trigger biasing effect against quark-jets have been investigated.



A_{UT} Results

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

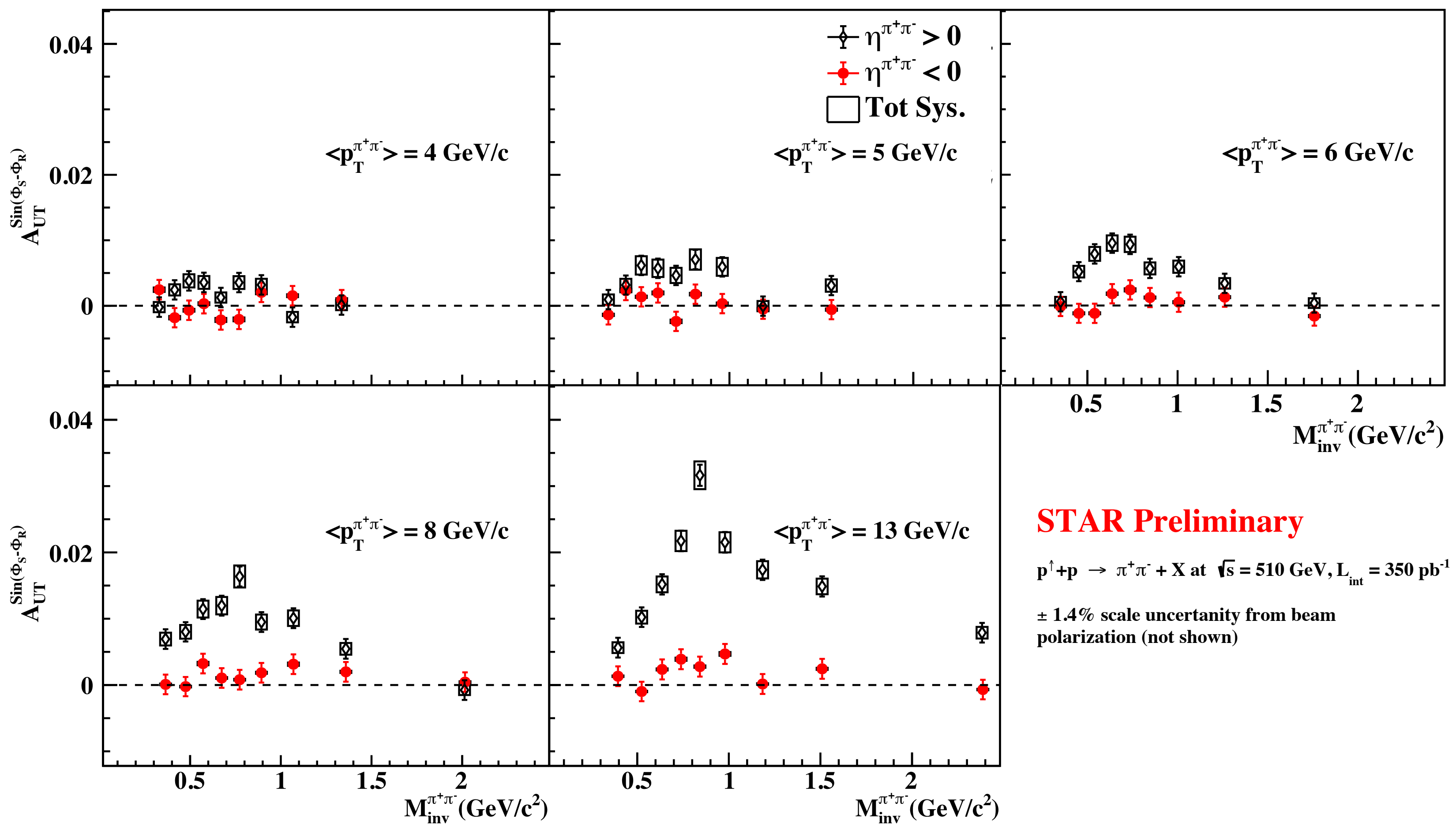
- Strong $p_T^{\pi^+\pi^-}$ dependence of A_{UT} has been found in the +ve $\eta^{\pi^+\pi^-}$ direction in all $M_{inv}^{\pi^+\pi^-}$ bins.
- Stronger rise in A_{UT} signal around ρ meson mass (~0.8 GeV/c^2) region.
- Signal is stronger in forward $(\eta^{\pi^+\pi^-} > 0)$ direction and small in backward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



A_{UT} Results

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

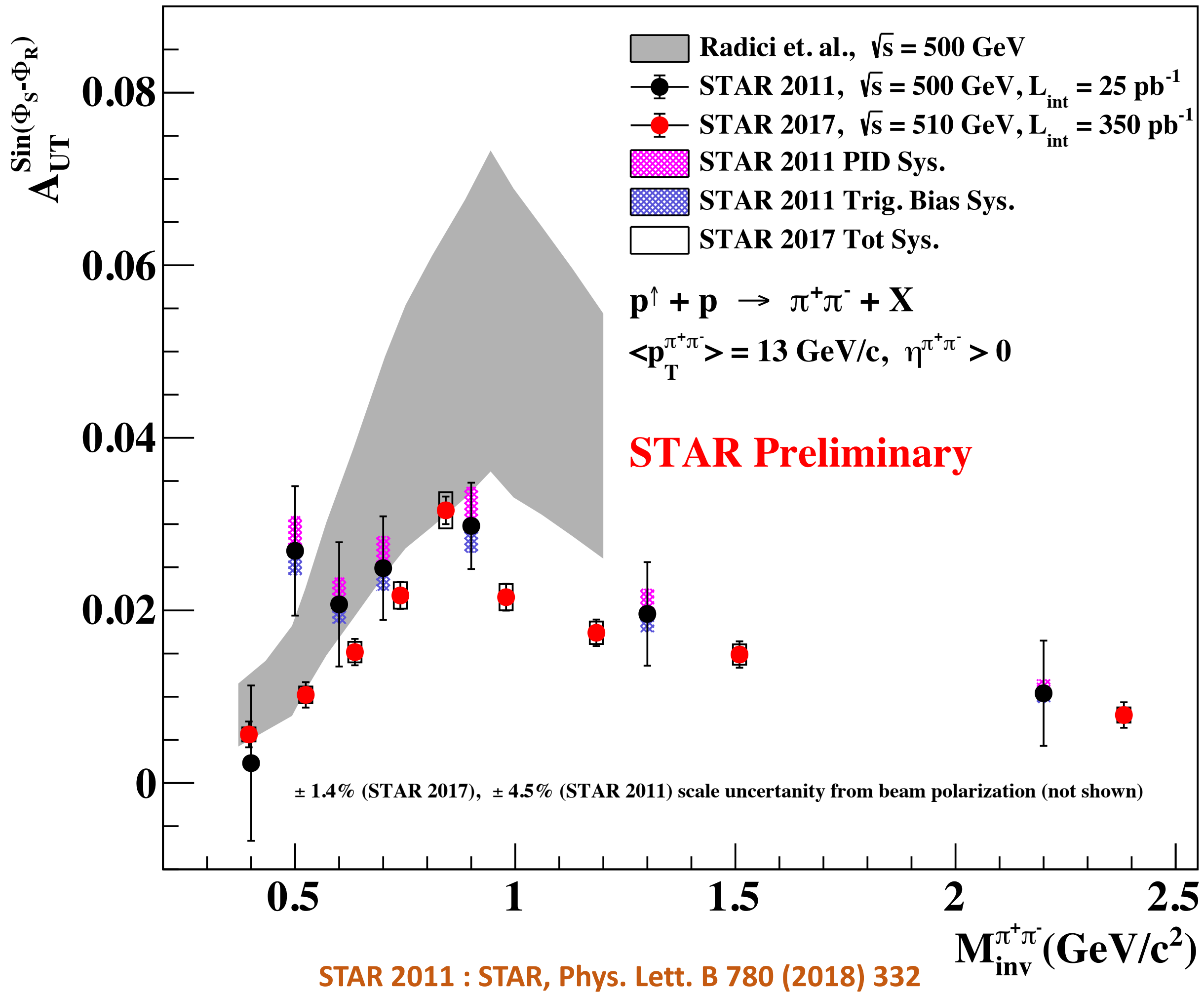
- Strong $M_{inv}^{\pi^+\pi^-}$ dependence of A_{UT} has been found in the +ve $\eta^{\pi^+\pi^-}$ direction in all $p_T^{\pi^+\pi^-}$ bins.
- The enhancement of A_{UT} signal around the ρ meson mass (~0.8 GeV/c^2) is due to the interference between the different $\pi^+\pi^-$ production channel.
- Signal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