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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Motivation

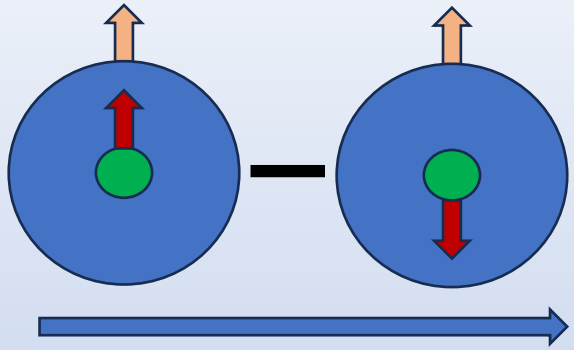
- Parton Distribution Functions (PDFs) :
  At leading twist three collinear PDFs describes the spin structure of nucleon

Quark Polarization

Nucleon Polarization

	Unpolarized	Longitudinal	Transverse
Unpolarized	$f_1(x)$		
Longitudinal		$g_1(x)$	
Transverse			$h_1(x)$

$h_1(x) =$

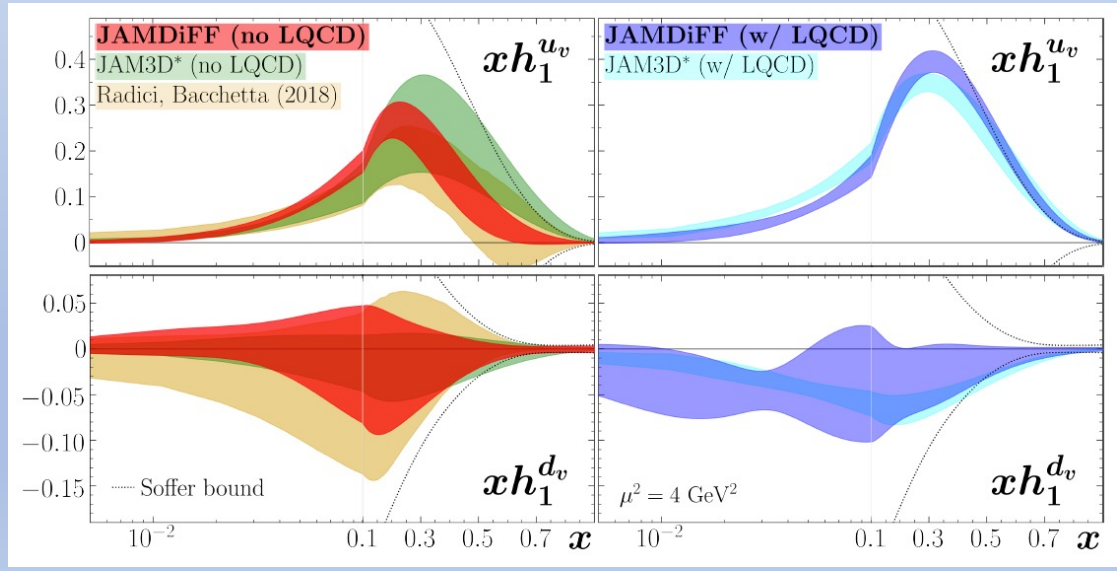


Proton momentum

= Proton polarization = Quark polarization

Transversity PDF

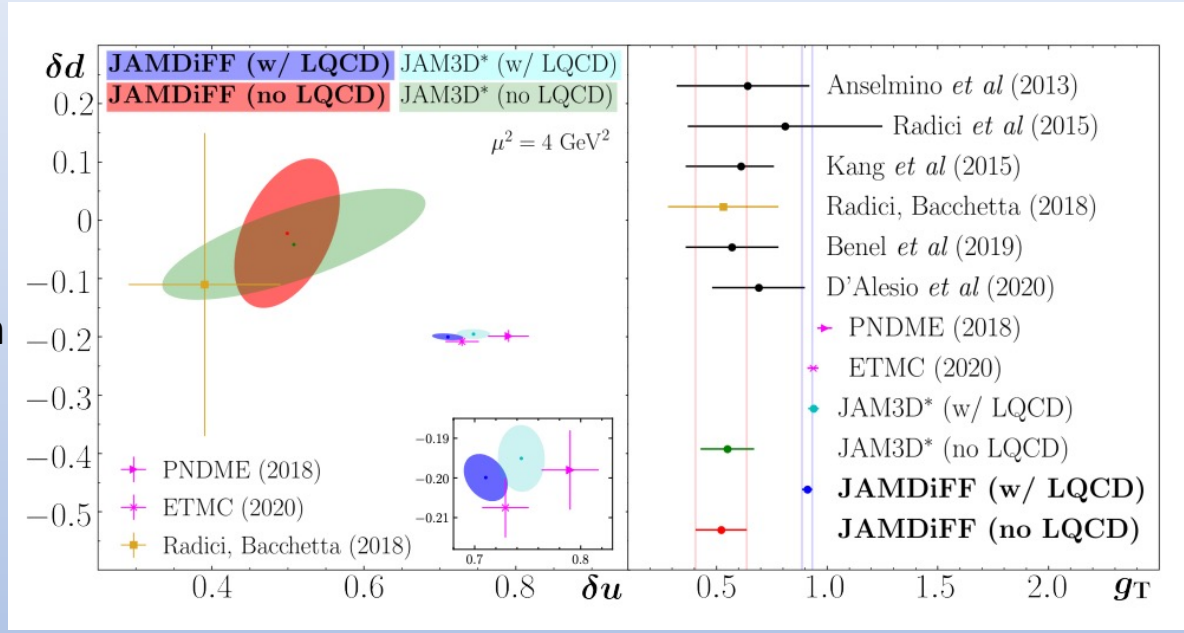
- $h_1(x)$ describes the transversely polarized quarks inside transversely polarized nucleon
- Less known from experiments than $f_1(x)$ and $g_1(x)$
- Chiral-odd quantity
- Extraction requires coupling to another chiral-odd distribution, such as Collins or Interference Fragmentation Functions (FFs)



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

Significance and Applications of Transversity

- Essential input for beyond the Standard Model Calculation, such as neutron electric dipole moment and nuclear beta decay, through the determination of quark tensor charge(δq) and iso-vector tensor charge(g_T)
  - $\boldsymbol{\delta q = \int_0^1 dx\, h_1^{q_v}(x)\,;\, h_1^{q_v}(x) \equiv h_1^q - h_1^{\bar{q}}}$ valance quark distribution
  - $\boldsymbol{g_T = \delta u - \delta d}$
  - One of the few observables involving transverse polarization where experiments can be compared with lattice QCD.
- Quark orbital angular momentum is directly related to difference between helicity and transversity.
- To test the universality of the mechanism generating azimuthal correlations across SIDIS, e^+e^-, lattice QCD, and $p^\uparrow p$ collisions.



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

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

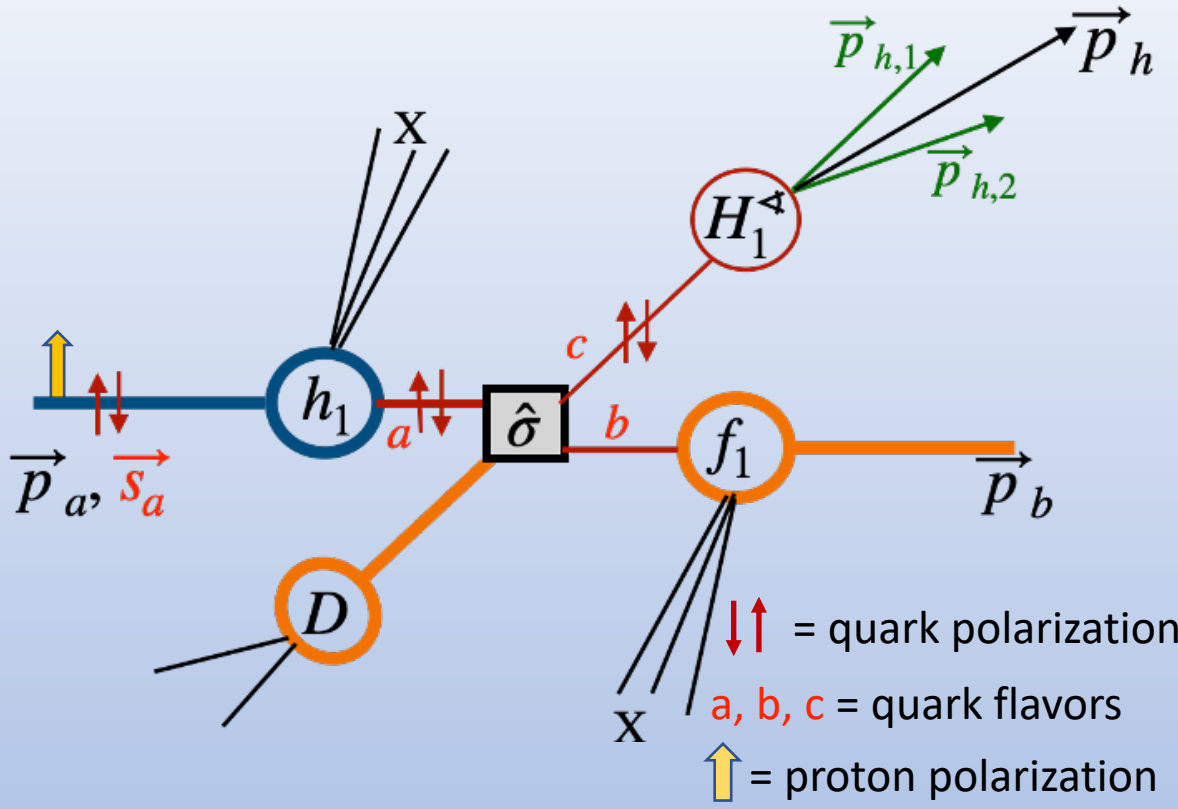
- Interference Fragmentation Function($H_1^{\sphericalangle}$) channel :

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

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

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

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

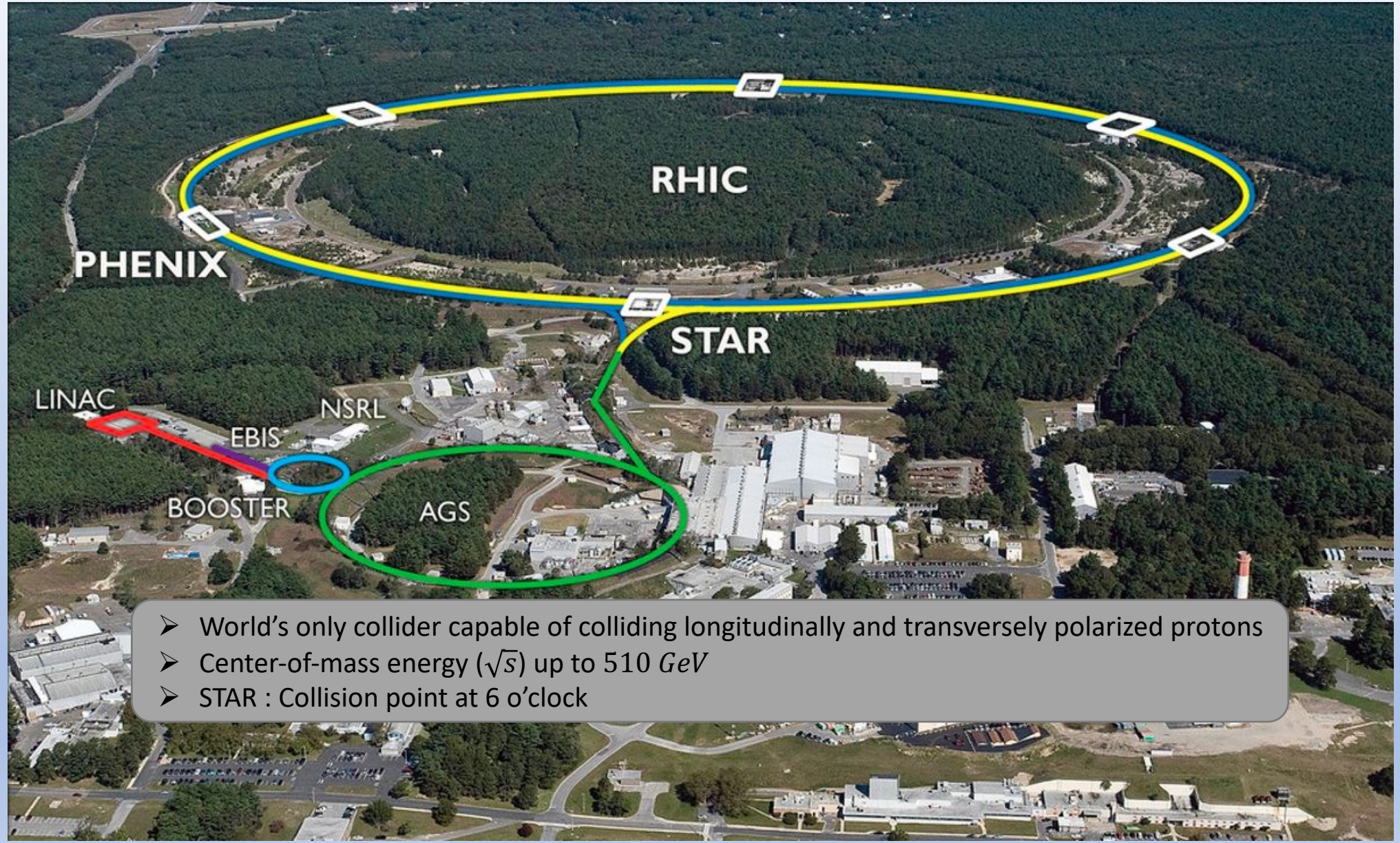


- Di-hadron correlation asymmetry

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

- 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 11/29, DNP/JPS HAW23)

Relativistic Heavy Ion Collider(RHIC)

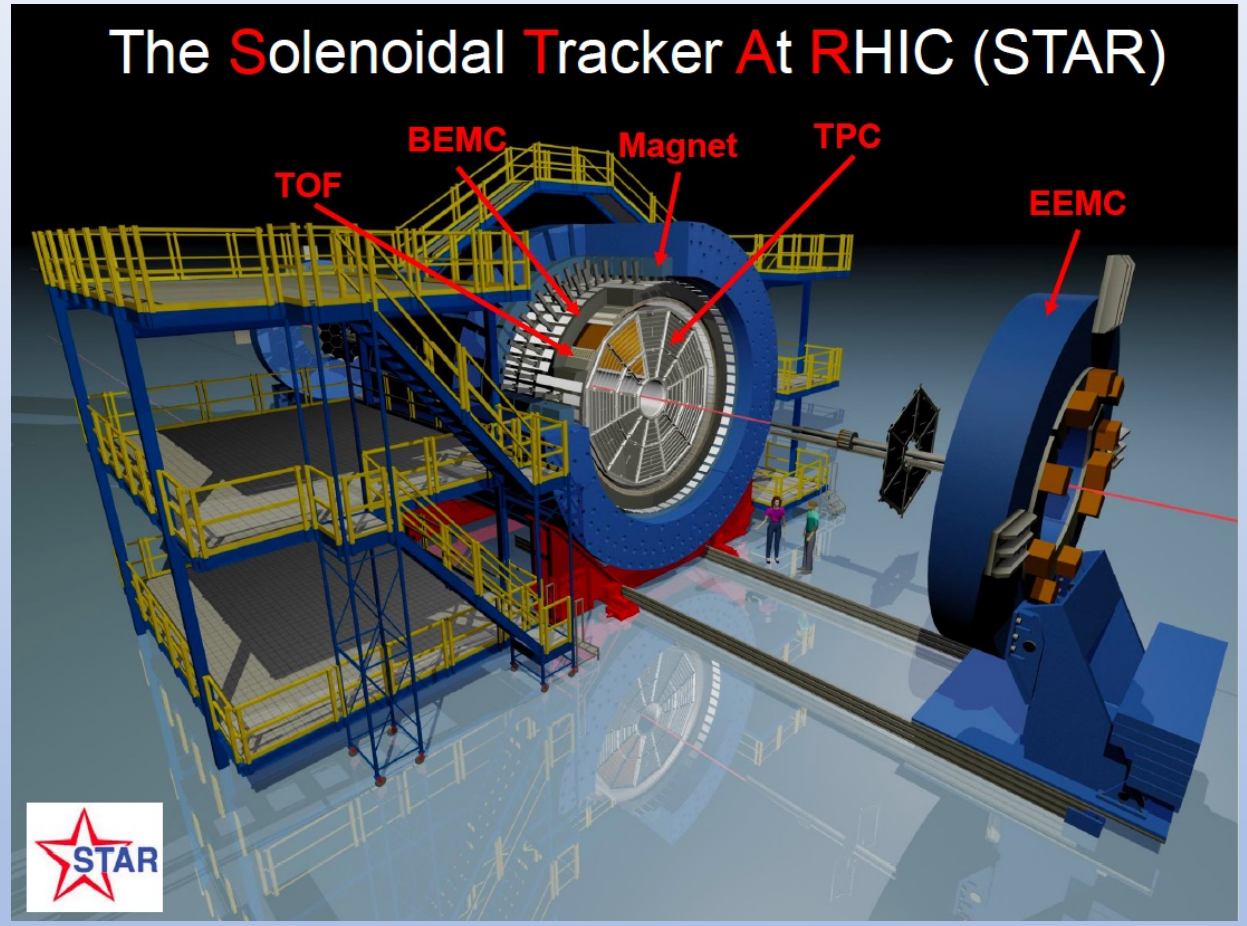


- World's only collider capable of colliding longitudinally and transversely polarized protons
- Center-of-mass energy ($\sqrt{s}$) up to $510\ GeV$
- STAR : Collision point at 6 o'clock

Solenoidal Tracker At RHIC (STAR)

Magnet :

- Uniform magnetic field of 0.5 T



Time Projection Chamber(TPC) :

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

Barrel Electromagnetic Calorimeter(BEMC) :

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

Time Of Flight(TOF) :

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

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.

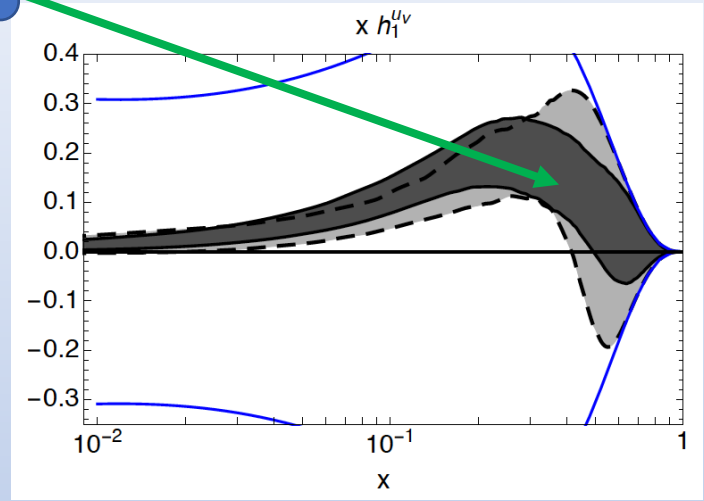
A_{UT} with $p^{\uparrow}p$ at STAR				
Year	2006	2011	2015	2017
$\sqrt{s}$ (GeV)	200	500	200	510
$L_{int}(pb^{-1})$	~1.8	~25	~52	~350
	Published		STAR Preliminary	This analysis

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

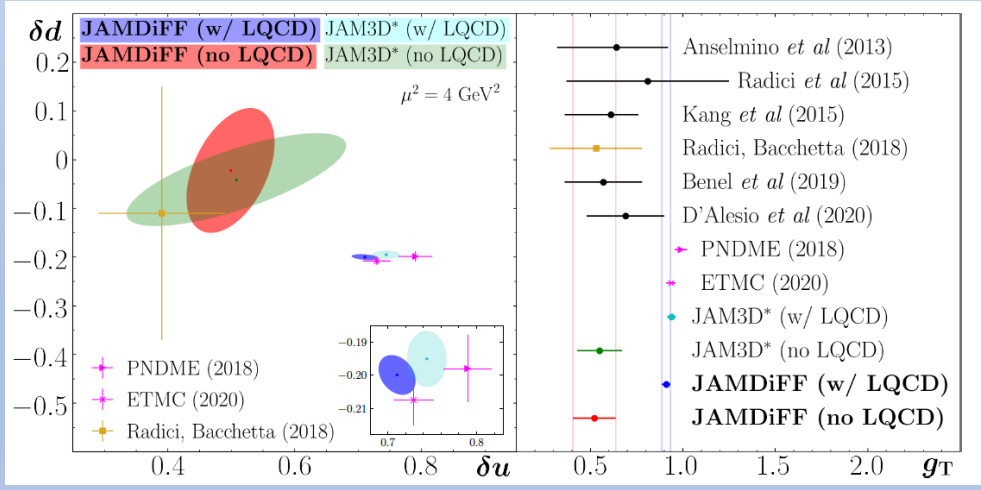
Refer to B. Pokhrel's Talk
11/29, DNP/JPS HAW23

Including STAR 2006 results

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



- STAR results play a crucial role in constraining the global fit of transversity.
  - First extraction of $h_1(x)$ from global analysis of ep and pp data using STAR 2006 A_{UT} result.
  - JAM collaboration incorporated both STAR 2006 and 2011 A_{UT} result for their global analysis to extract $h_1(x)$ and g_T in their recent 2023 paper.
- STAR completed taking another large pp dataset at 508 GeV ($L_{int}(pb^{-1})$~400) in 2022 and is planning to take another pp 200 GeV dataset in 2024.



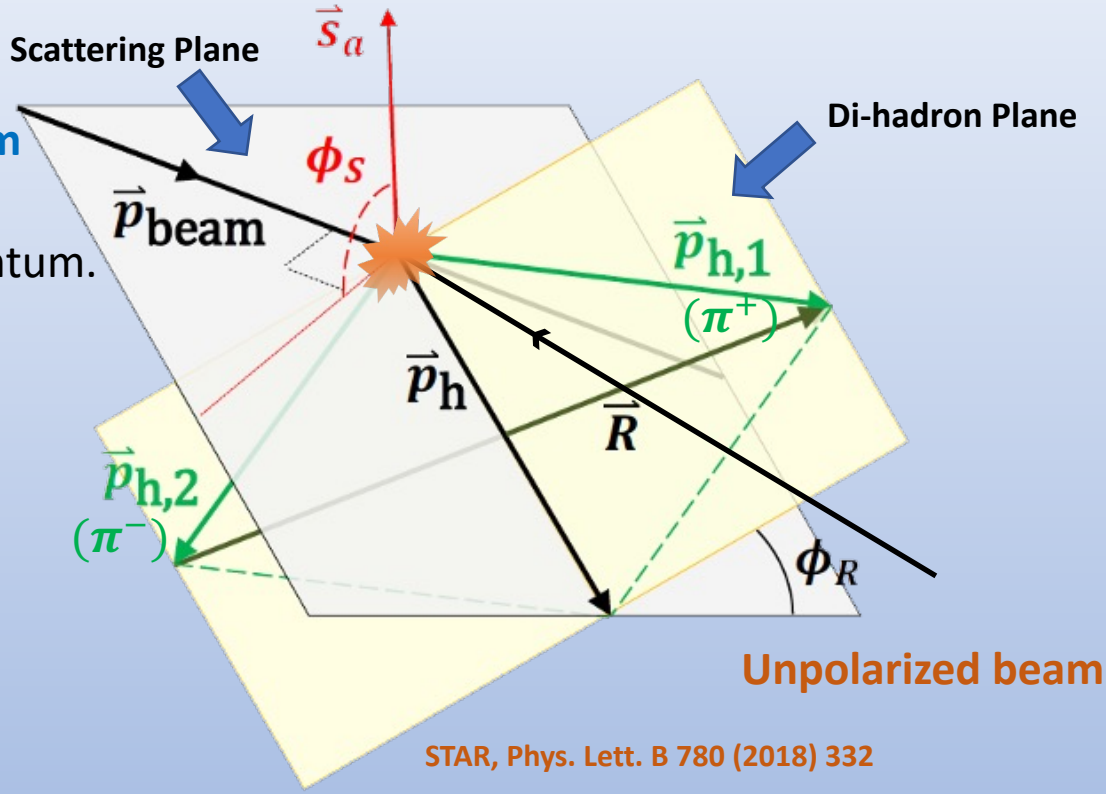
C. Cocuzza et. al., arXiv:2306.12998 [hep-ph]

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.
- Ensure the direction of $\vec{R}$ is consistently oriented from π^- to π^+(or vice versa) throughout the analysis.



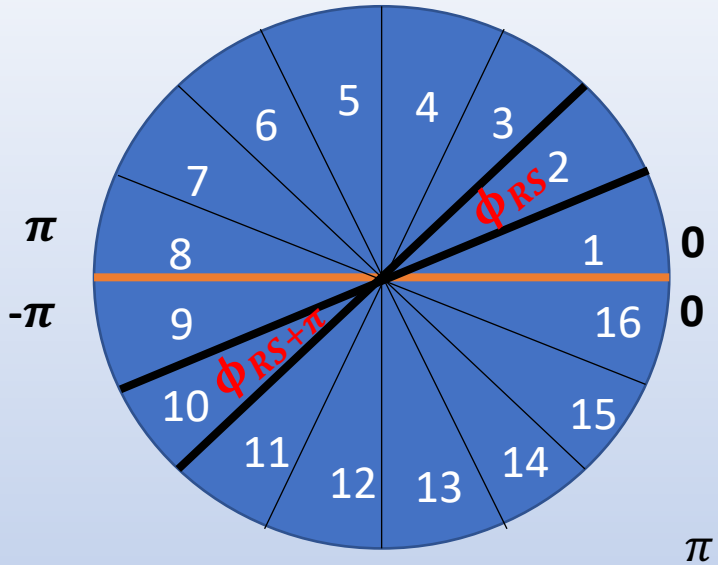
STAR, Phys. Lett. B 780 (2018) 332

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

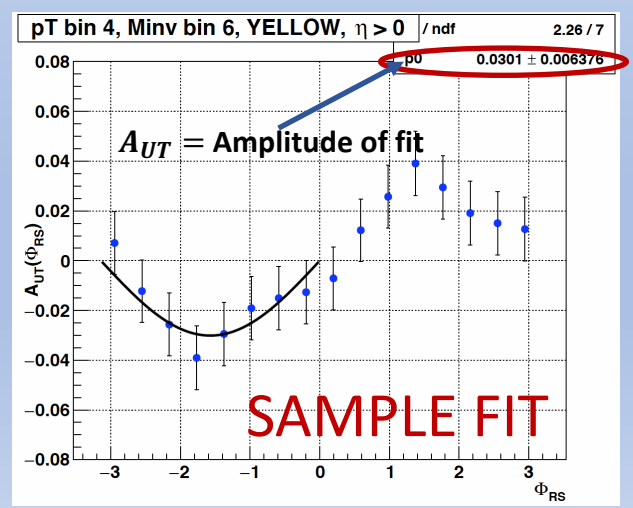
- For a symmetric detector like STAR (in azimuthal space),
  - A_{UT} can be extracted from cross-ratio formula for different kinematic variables ($M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$, $\eta^{\pi^+\pi^-}$).
  - Free from effects related to detector efficiencies and spin-dependent luminosities.

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



ϕ_{RS} binning scheme

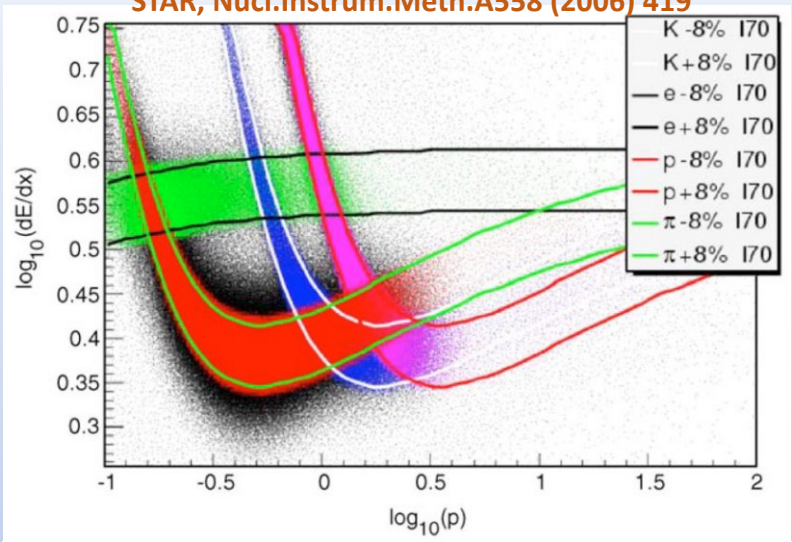
- Two oppositely charged pions in the final state are paired if they are close (<0.7) in $\eta - \phi$ space.
- The angle ϕ_{RS} modulates the A_{UT} by $sin(\phi_{RS})$.
- ϕ_{RS} is divided into 16 bins of uniform bin-width in the range $[-\pi, +\pi]$ and $N\uparrow(\downarrow)$ in each ϕ_{RS} bin is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

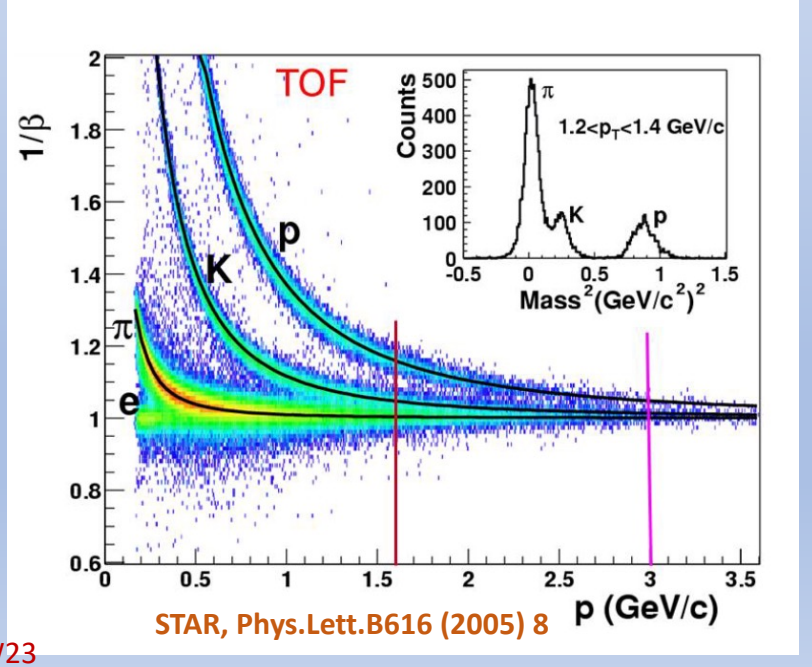


Particle Identification (PID) at STAR

- 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



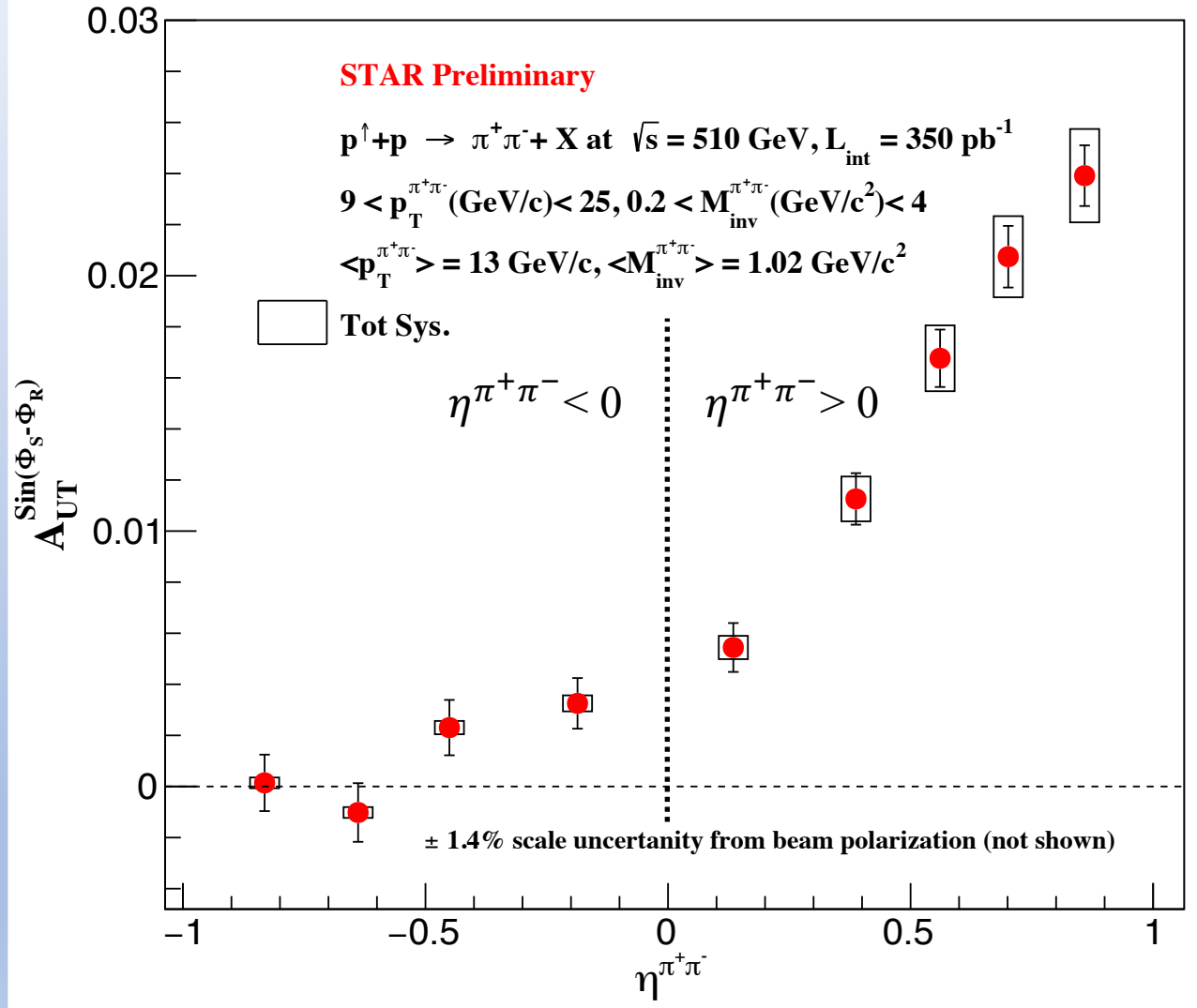


STAR, Phys.Lett.B616 (2005) 8

A_{UT} Results

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

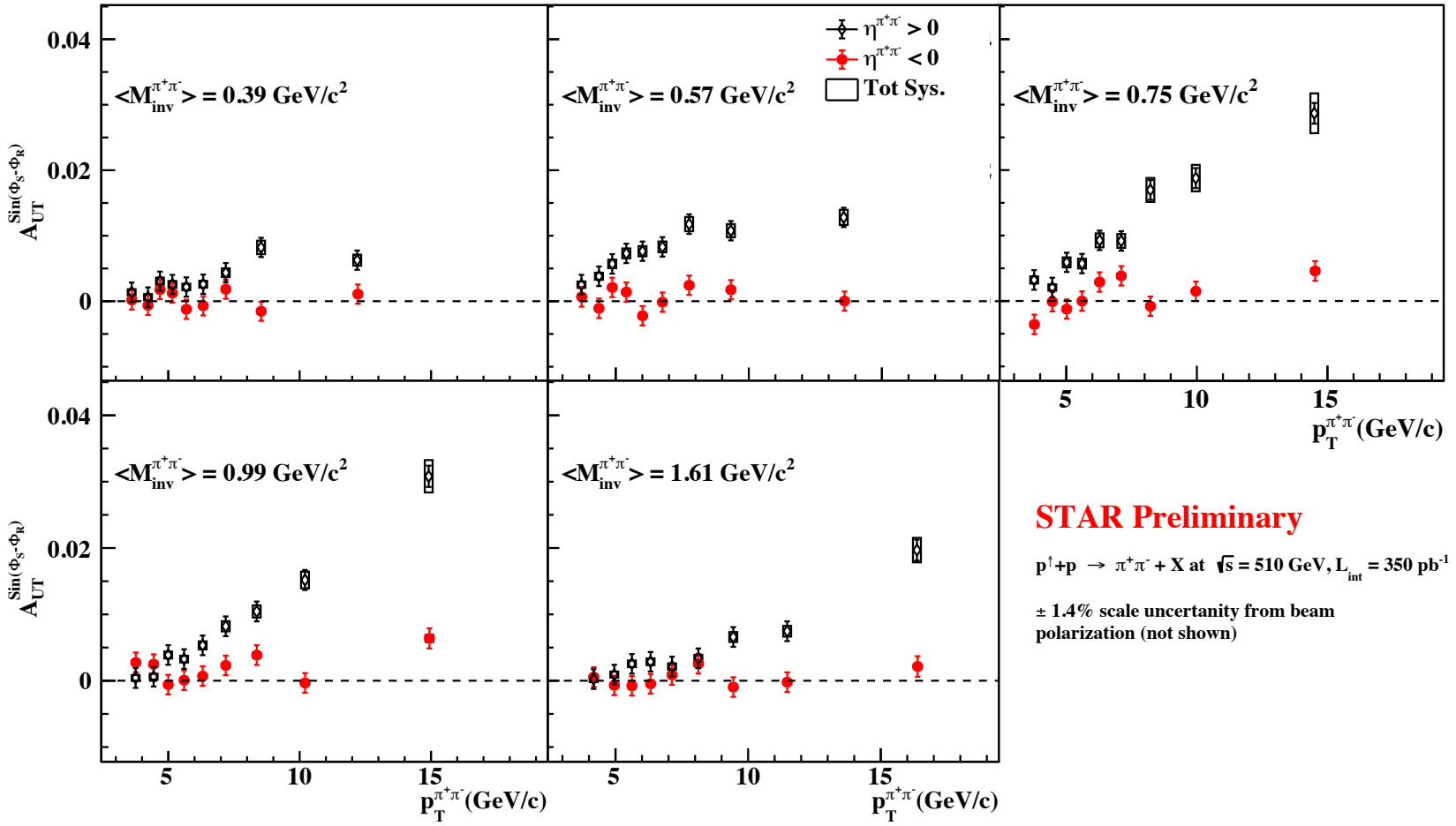
- A_{UT} increases with $\eta^{\pi^+\pi^-}$
  - Forward direction ($\eta^{\pi^+\pi^-} > 0$) probes higher x, valence region, where $h_1^q(x)$ is sizable, hence A_{UT} is large.
  - Backward direction ($\eta^{\pi^+\pi^-} < 0$) probes lower x resulting lower A_{UT} signal.
- Systematic uncertainties arising 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

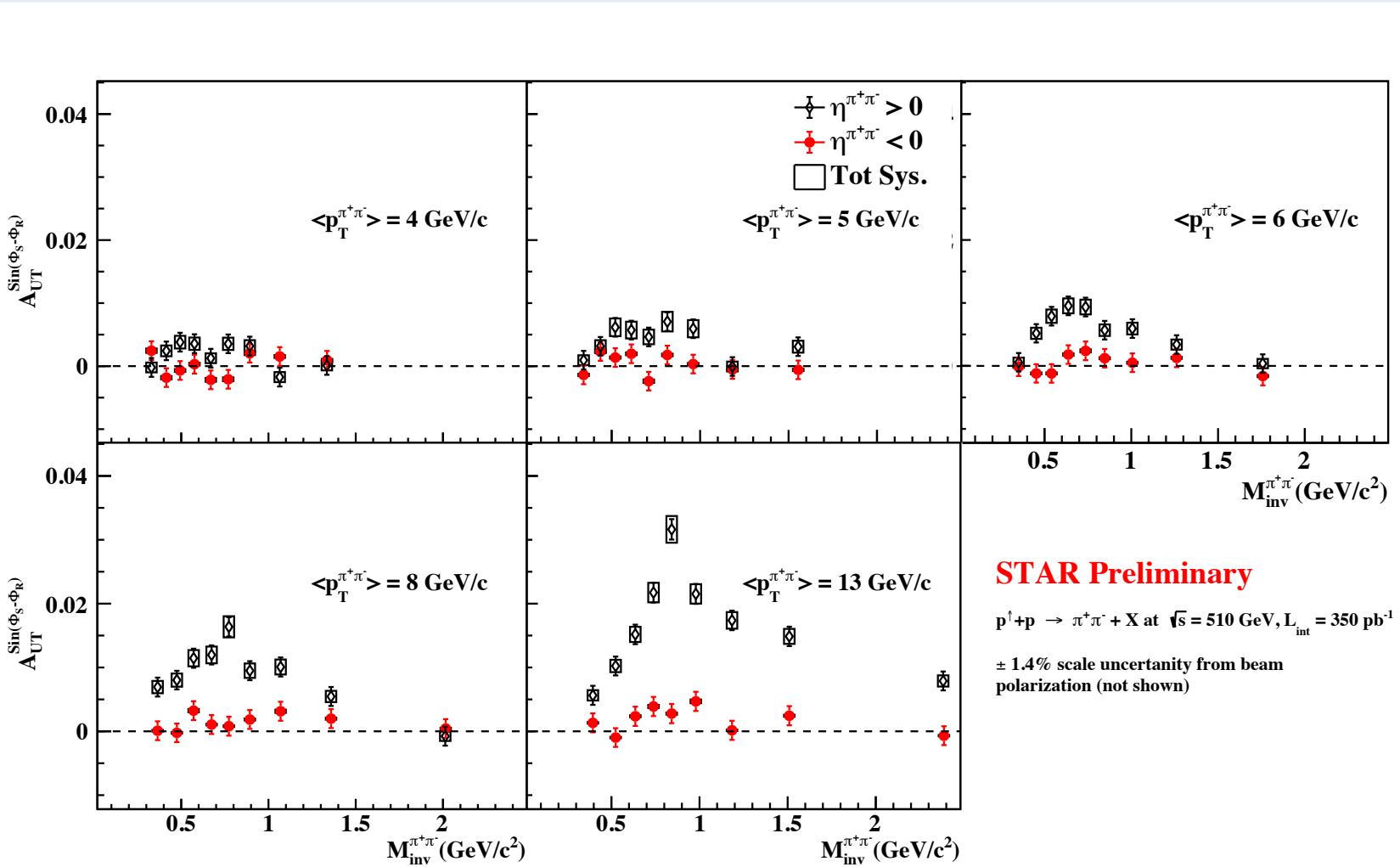
- Strong $p_T^{\pi^+\pi^-}$ dependence of A_{UT} has been found in the forward $\eta^{\pi^+\pi^-}$ direction in all $M_{inv}^{\pi^+\pi^-}$ bins.
- Stronger rise in A_{UT} signal around ρ meson mass (~0.8 GeV/c^2) region.
- Signal is stronger in forward $(\eta^{\pi^+\pi^-} > 0)$ direction and small in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

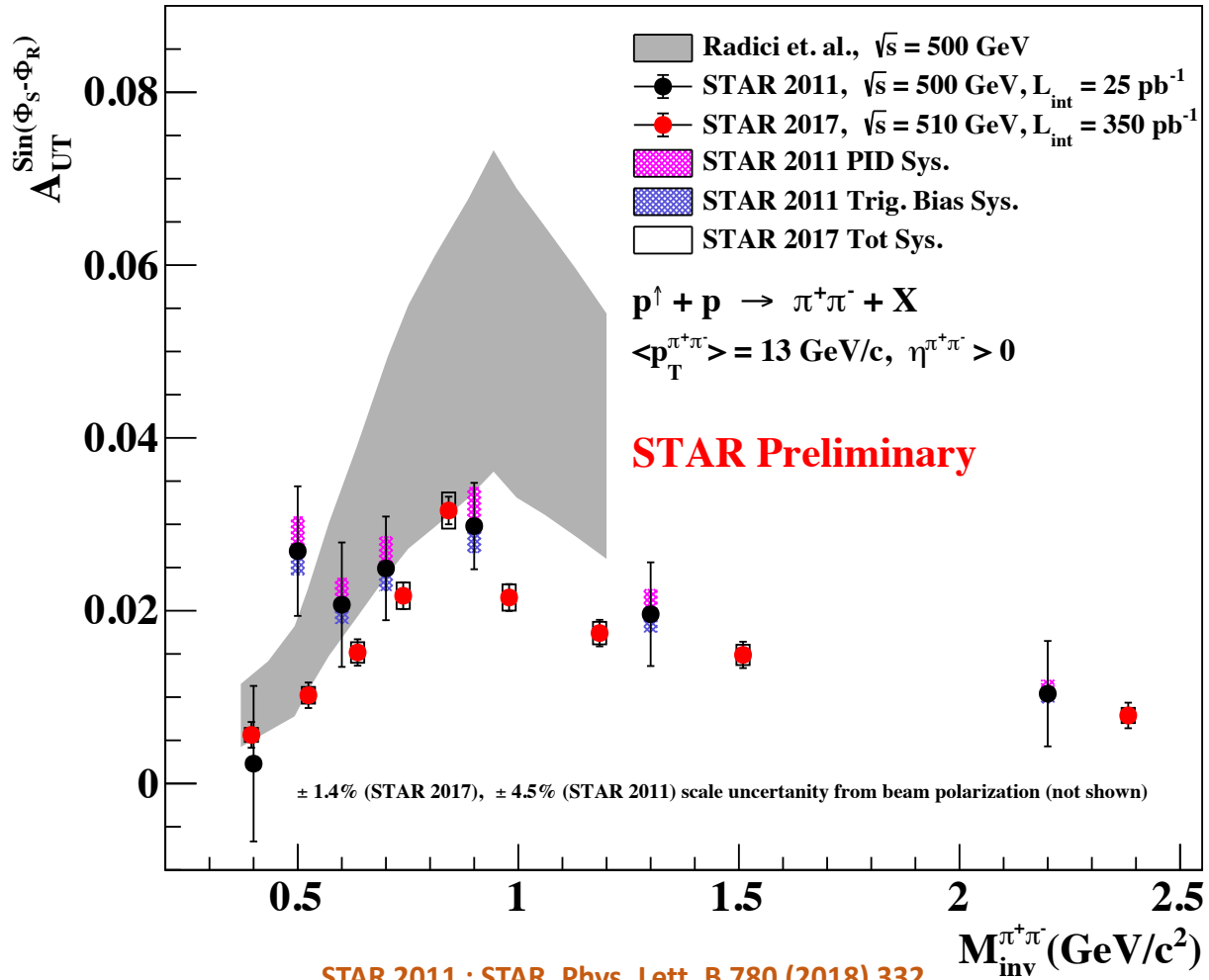


A_{UT} Results

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 helps to extract transversity, tensor charge and test the universality of the mechanism which produces azimuthal correlations across 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.