Transverse Spin Dependent Azimuthal Correlations of $\pi^+\pi^-$ pair in $p^\uparrow p$ Collisions at $\sqrt{s}$ = 200 GeV at STAR

Overview:

- Motivation
- Transversity in *pp*
- Cross-Ratio Formalism
- STAR Experiment at RHIC and Datasets
- IFF Results
- Summary

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STAR

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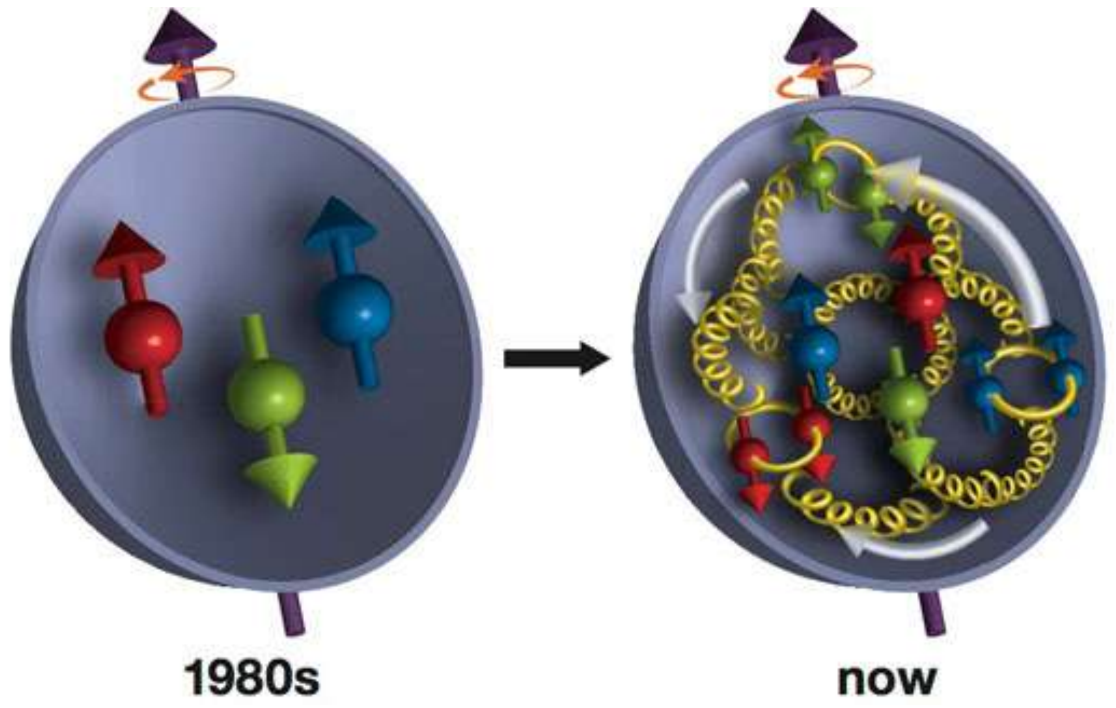
Motivation

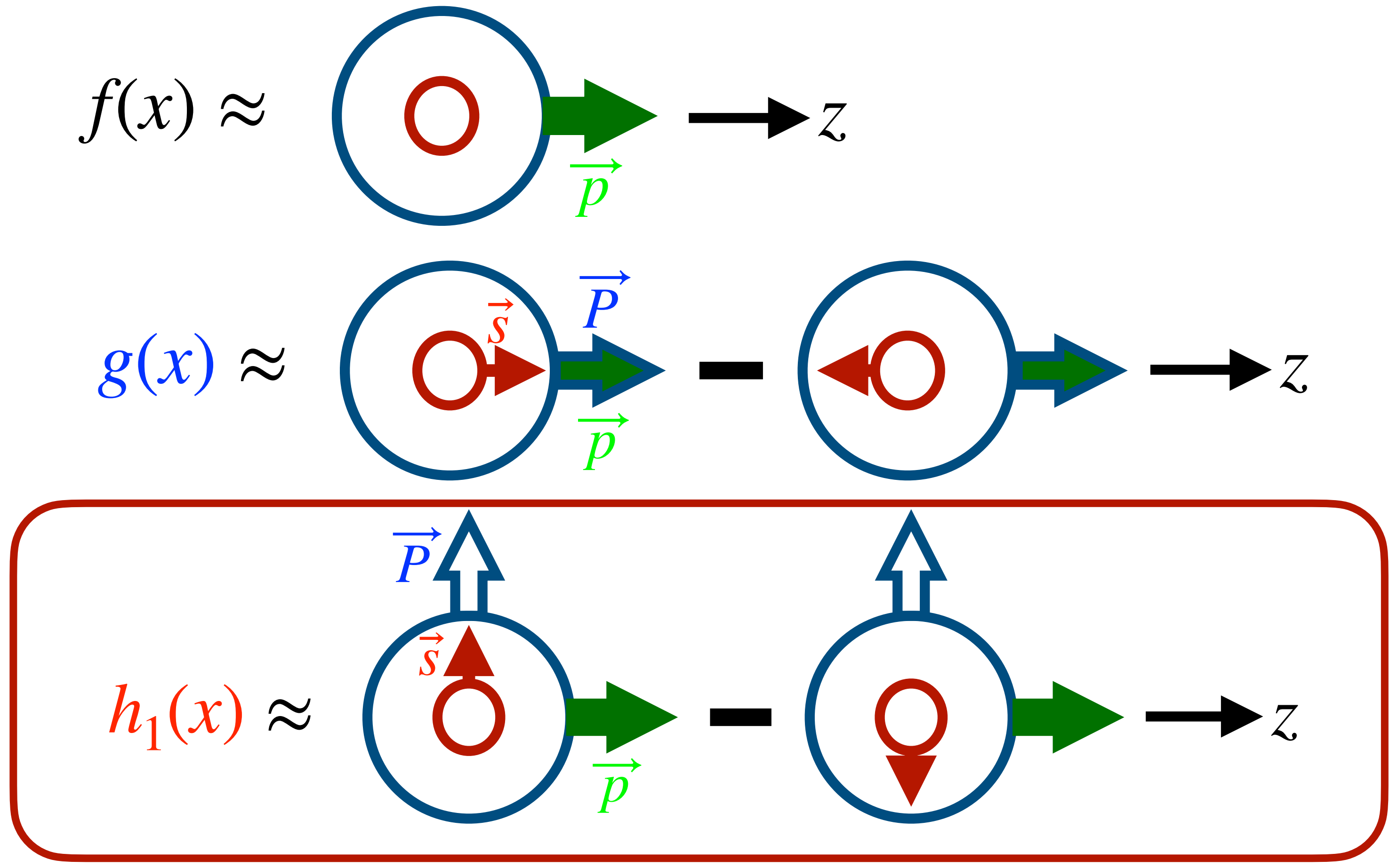
Nucleon Structure:

uud $\quad$ $uud + g + sea$



Leading order parton distribution functions (PDFs):

$$f(x) \otimes g(x) \otimes h_1(x)$$



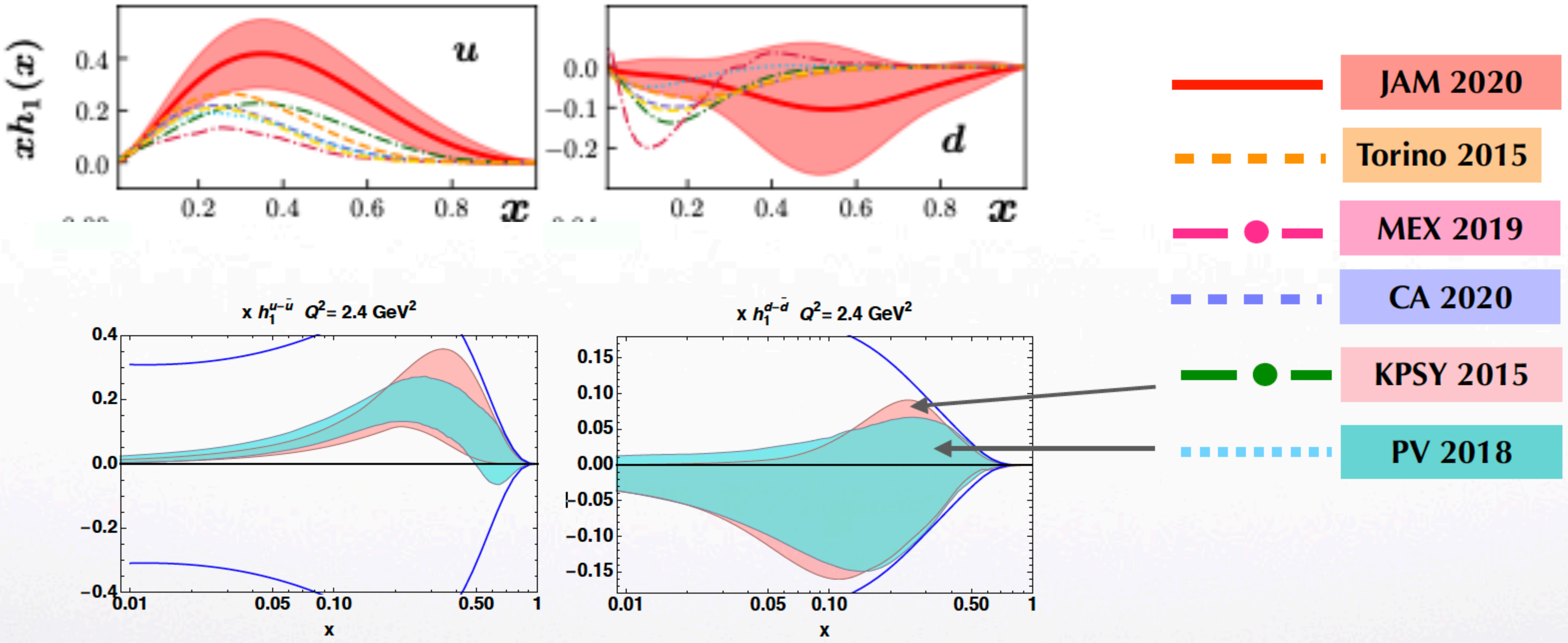
$\vec{P}$ = Nucleon polarization

$\vec{p}$ = Nucleon momentum

$\vec{s}$ = Quark polarization

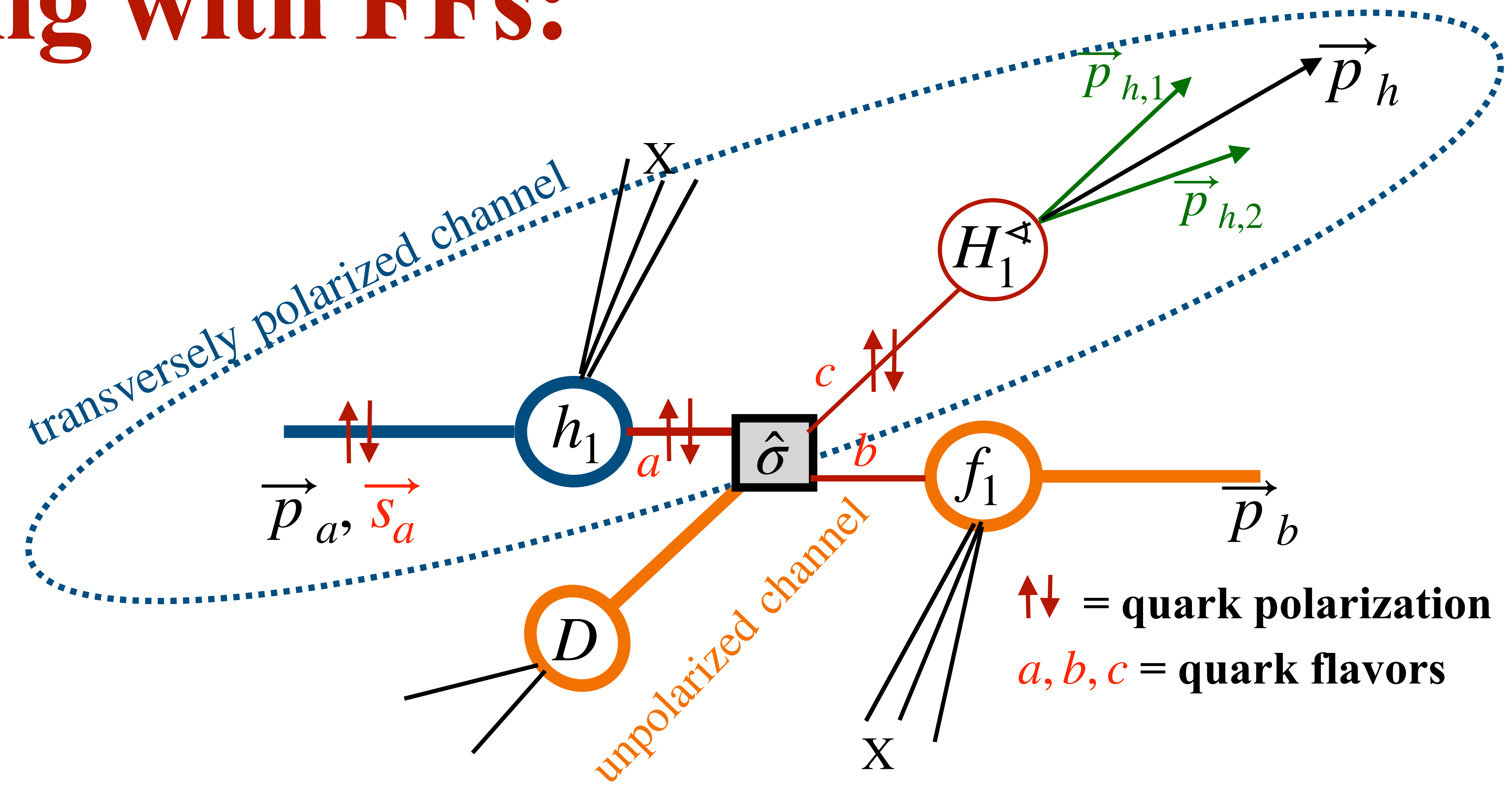
Transversity, $h_1(x)$:

- **Chiral-odd quantity, independent measurement is difficult.**
- **Less known from experiments.**
- **Its extraction requires coupling to another chiral-odd object, such as Fragmentation Function (FF).**



M. Radici, Cracow School of Theoretical Physics, 2021

Transversity ($h_1(x)$) in $p^{\uparrow}p$ Collision, Coupling with FFs:



Interference Fragmentation Function (IFF) Channel:

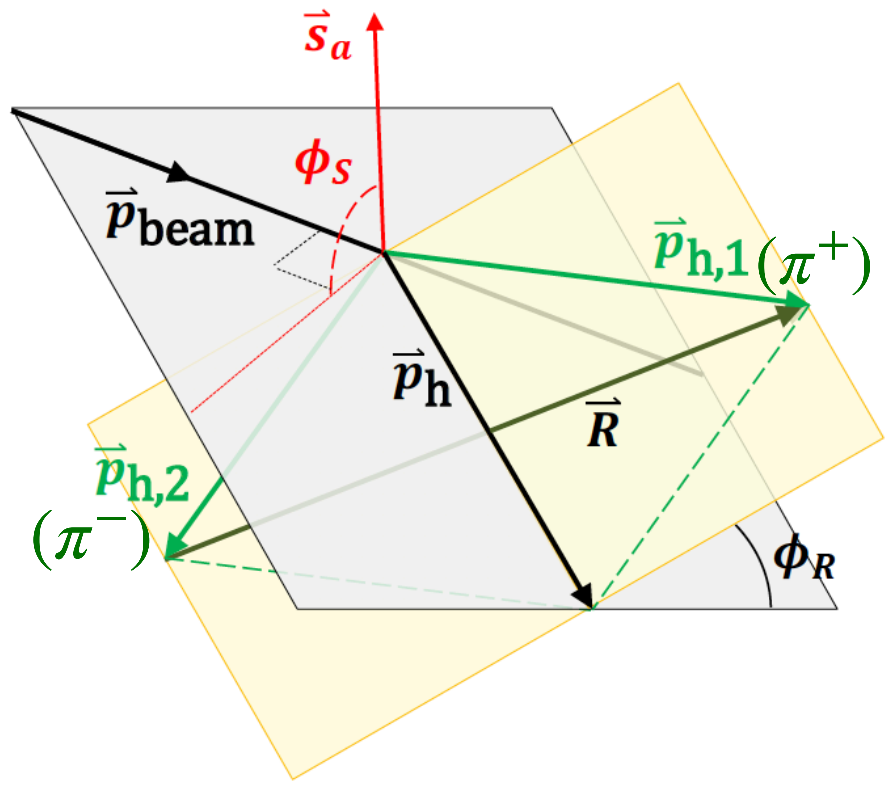
$$p^{\uparrow} + p \rightarrow h^{+}h^{-} + X$$

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

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto h_1 H_1^{\sphericalangle} \qquad z = \frac{E^{h^+h^-}}{E^{parton}}$$

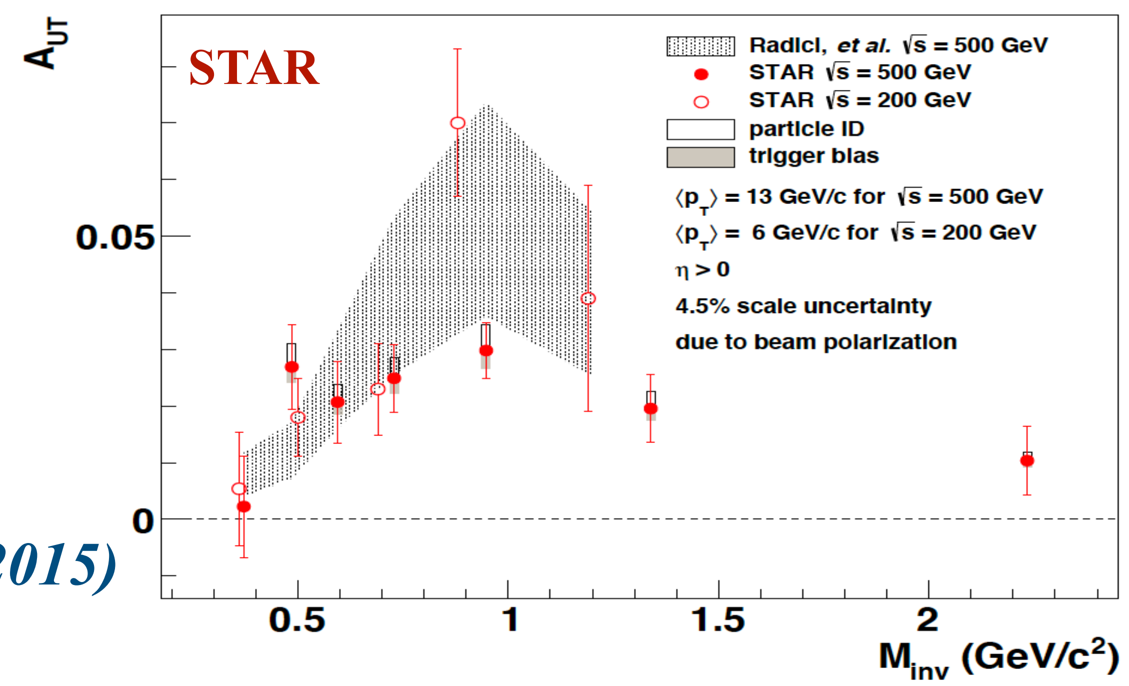
Azimuthal angle definitions for IFF channel:

- ϕ_s = angle between quark spin vector, $\vec{s}_a$, and scattering plane (spanned by $\vec{p}_{beam}$ and $\vec{p}_h$)
- ϕ_R = angle between scattering plane and di-hadron plane (spanned by $\vec{p}_{h,1}$ and $\vec{p}_{h,2}$)



STAR publications:

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



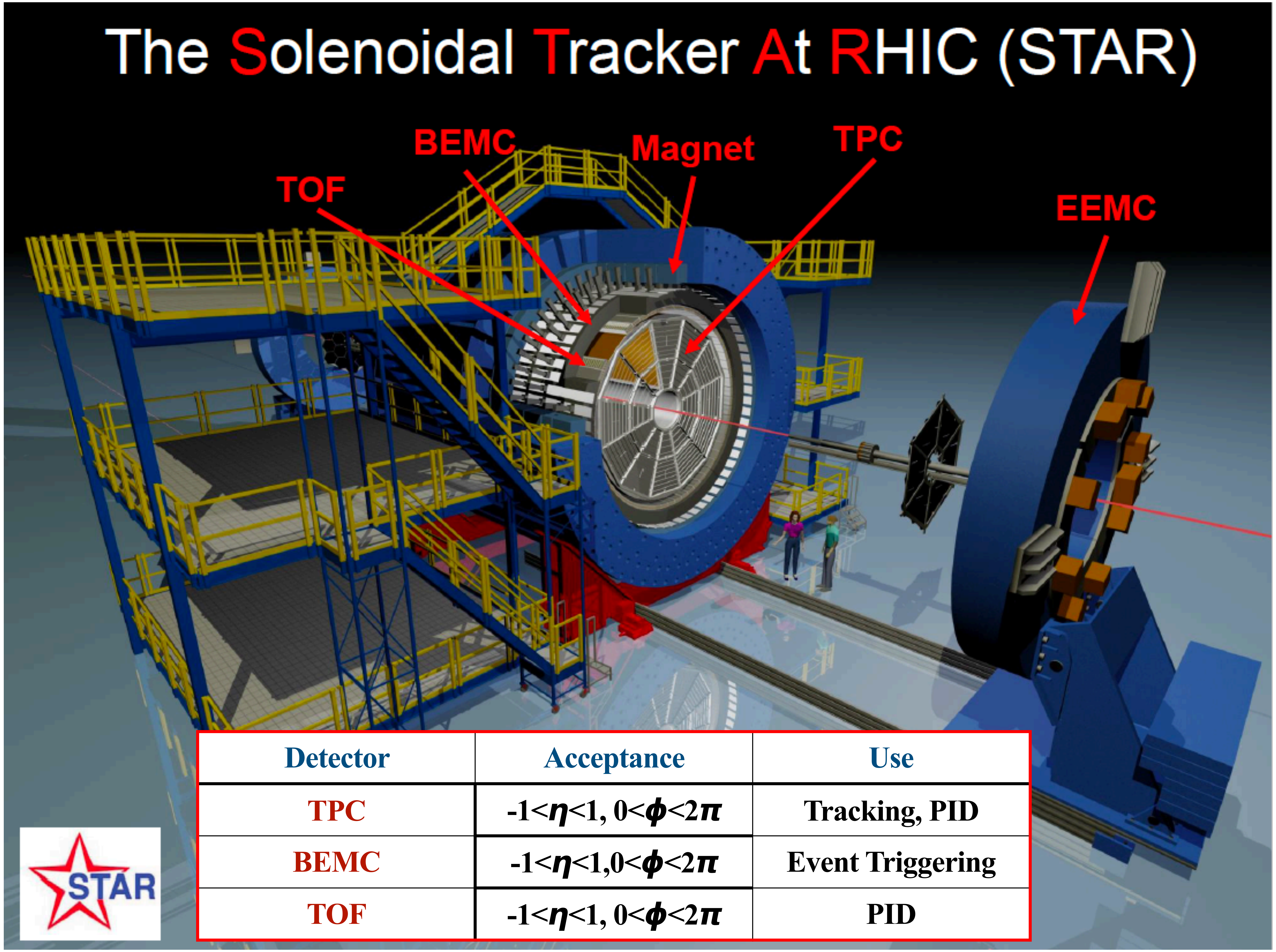
Experimental extraction of A_{UT} using Cross-Ratio Method:

$$A_{UT} sin(\phi_S - \phi_R) = \frac{1}{P} \frac{\sqrt{N_{1,\alpha}^{\uparrow} N_{1,\beta}^{\downarrow}} - \sqrt{N_{1,\alpha}^{\downarrow} N_{1,\beta}^{\uparrow}}}{\sqrt{N_{1,\alpha}^{\uparrow} N_{1,\beta}^{\downarrow}} + \sqrt{N_{1,\alpha}^{\downarrow} N_{1,\beta}^{\uparrow}}}$$

- $N_{1,\alpha(\beta)}^{\uparrow(\downarrow)}$ → Number of $\pi^+\pi^-$ in upper, α (lower, β), half of detector when spin direction is $Up(\uparrow)(Down\ (\downarrow))$
- P is average beam polarization.

- **No jet reconstruction required.**
- **Collinearity is preserved.**

STAR Experiment



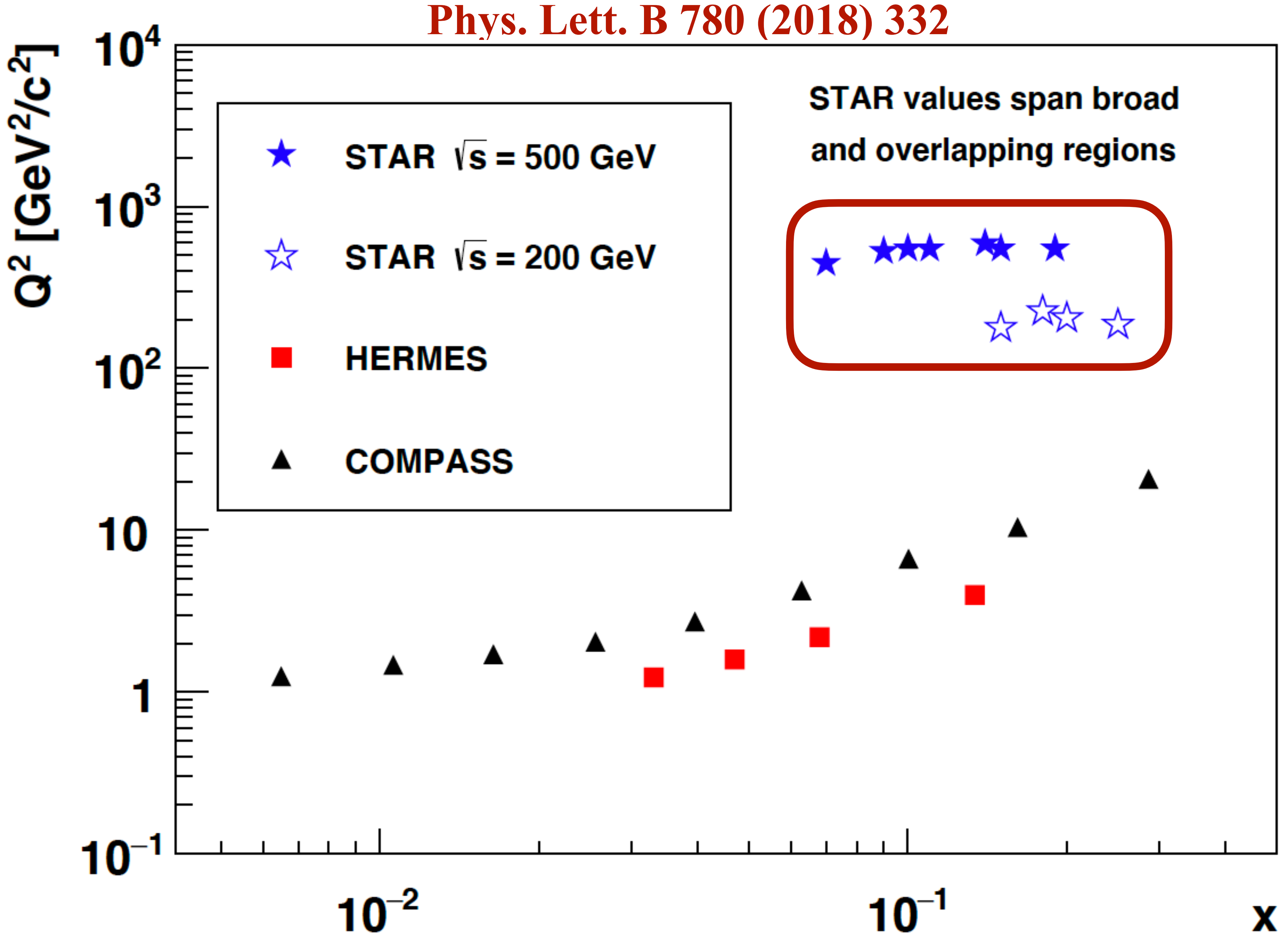
Detector	Acceptance	Use
TPC	$-1<\eta<1$, $0<\phi<2\pi$	Tracking, PID
BEMC	$-1<\eta<1$,$0<\phi<2\pi$	Event Triggering
TOF	$-1<\eta<1$, $0<\phi<2\pi$	PID

STAR Polarized Proton-Proton Dataset

Collision	*proton-proton*			
Polarization	transverse			
Year	2006	2011	2015	2017
$\sqrt{s}$ (GeV)	200	500	200	510
L_{int} (pb^{-1})	~ 1.8	~ 25	~ 48	~ 350
$< P_{beam} >$ (%)	~ 60	~ 53	~ 57	~58

This Measurement

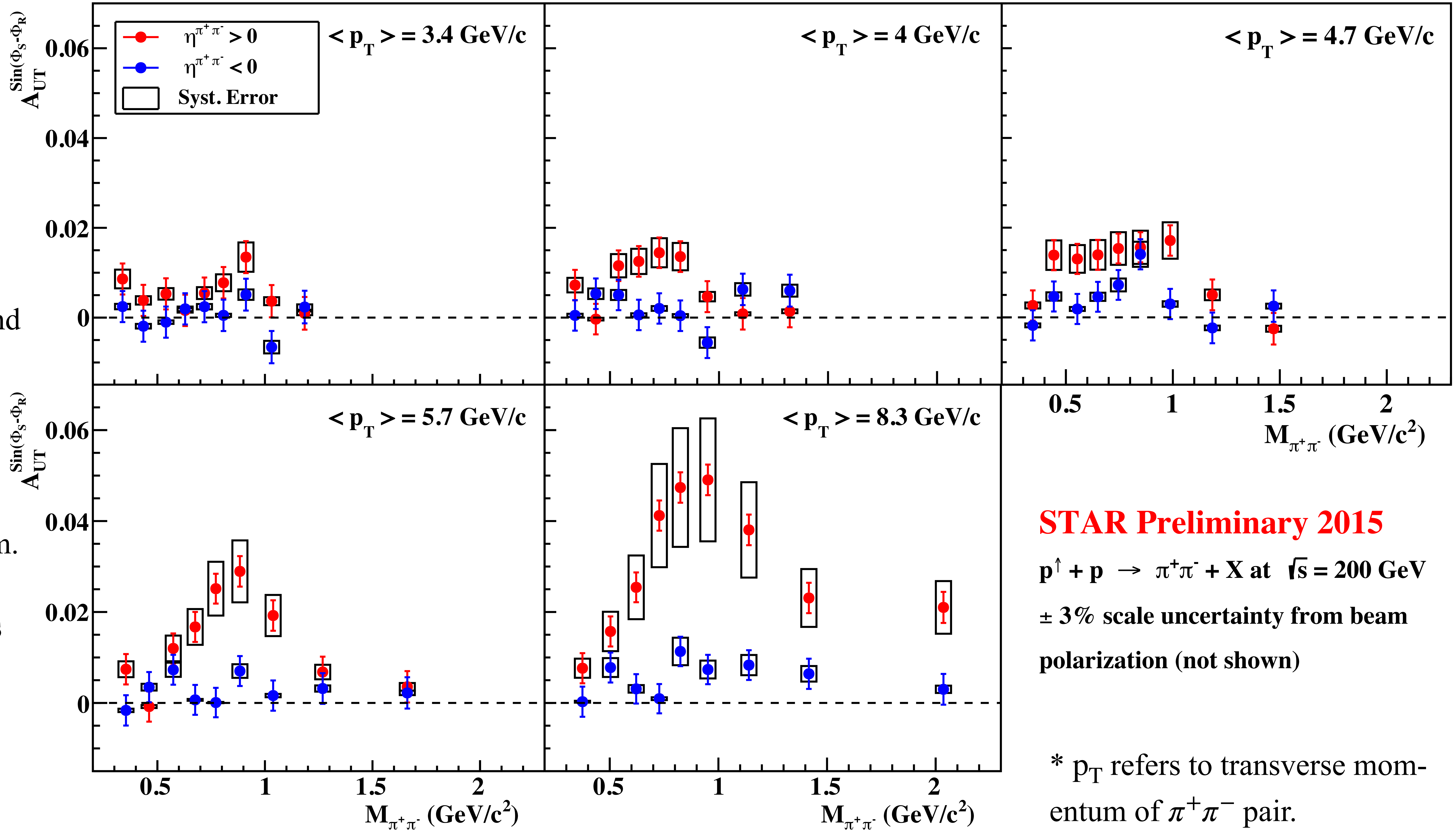
Phys. Lett. B 780 (2018) 332



- STAR Kinematic Coverage:
  - Covers much higher in Q^2 than HERMES and COMPASS.
  - Intermediate *x* coverage, valence quark region.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$

- $A_{UT}^{\sin(\phi_s-\phi_R)}$ **vs** $M_{inv}^{\pi^+\pi^-}$ **in different** p_T **and** $\eta^{\pi^+\pi^-}$ **bins .**
  - Signal grows stronger at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Resonance peak around $M_{inv}^{\pi^+\pi^-} \sim 0.8$ GeV/c$^2 \sim M_\rho$.
  - Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from unpolarized beam.
- **Systematic uncertainty includes effects related to PID and trigger bias.**



STAR Preliminary 2015

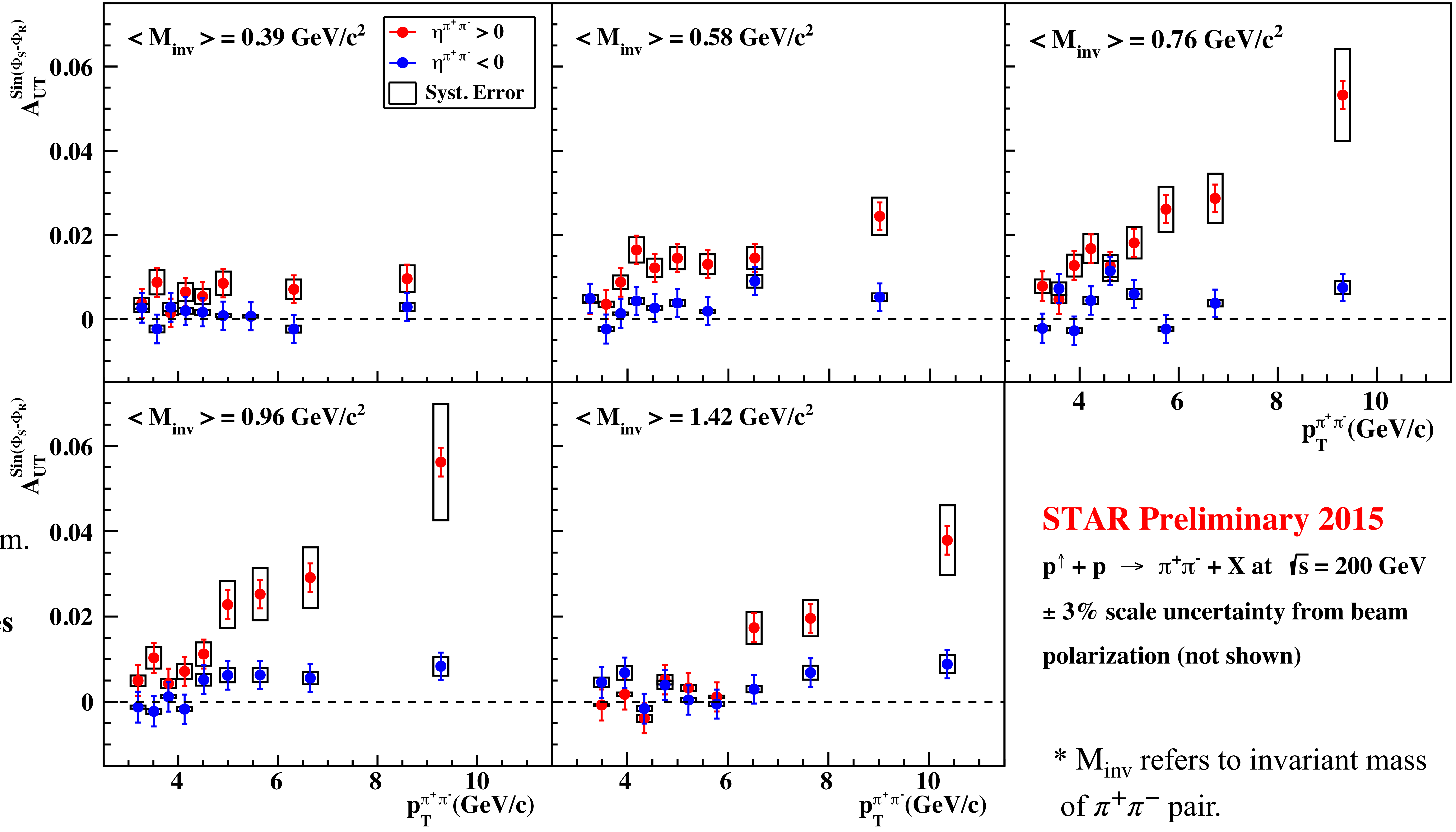
$p^\uparrow + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

± 3% scale uncertainty from beam polarization (not shown)

* p_T refers to transverse momentum of $\pi^+\pi^-$ pair.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$

- $A_{UT}^{\sin(\phi_s-\phi_R)}$ **vs** $p_T^{\pi^+\pi^-}$ **in different** M_{inv} **and** $\eta^{\pi^+\pi^-}$ **bins.**
  - Large asymmetry signal at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Stronger signal when $< M_{inv} > \sim M_\rho$.
  - Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from unpolarized beam.
- **Systematic uncertainty includes effects related to PID and trigger bias.**



STAR Preliminary 2015

$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

± 3% scale uncertainty from beam polarization (not shown)

* M_{inv} refers to invariant mass of $\pi^+\pi^-$ pair.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $\eta^{\pi^+\pi^-}$

Top Panel:

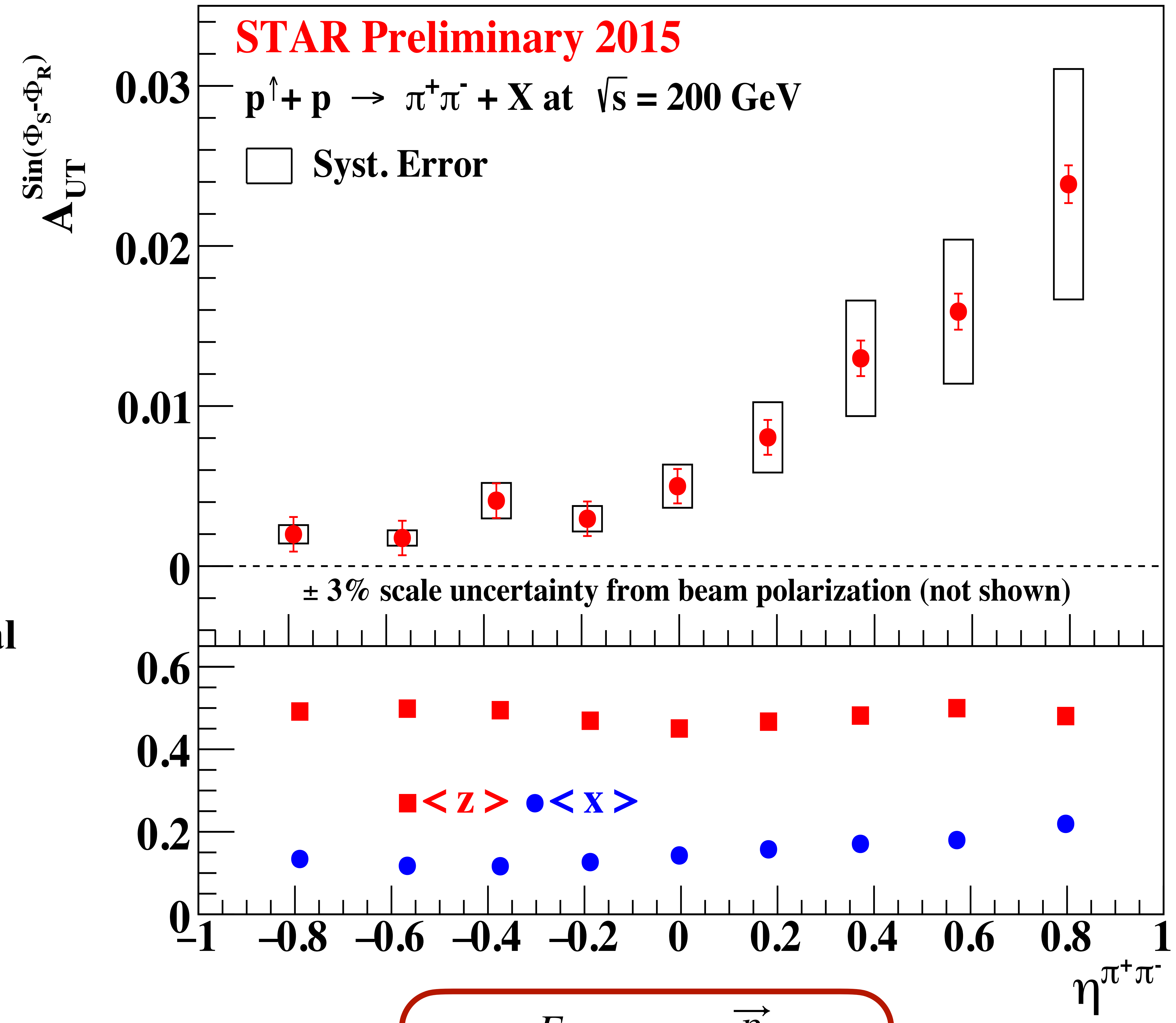
- A_{UT} as a function of $\eta^{\pi^+\pi^-}$ with $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$ integrated.

Bottom Panel:

- x, fractional momentum of proton carried by quark, and z, fractional energy of struck quark carried by $\pi^+\pi^-$, as a function of $\eta^{\pi^+\pi^-}$.
- x and z are estimated from simulation.

- **$\eta^{\pi^+\pi^-} > 0$ → higher x quarks → large asymmetry signal**
- **$\eta^{\pi^+\pi^-} < 0$ → low x quarks → small asymmetry signal**

- **Systematic uncertainty includes effects related to PID and trigger bias.**



$$z \rightarrow \frac{E_{\pi^+\pi^-}}{E_{quark}}, \; x = \frac{\vec{p}_{quark}}{\vec{p}_{proton}}$$

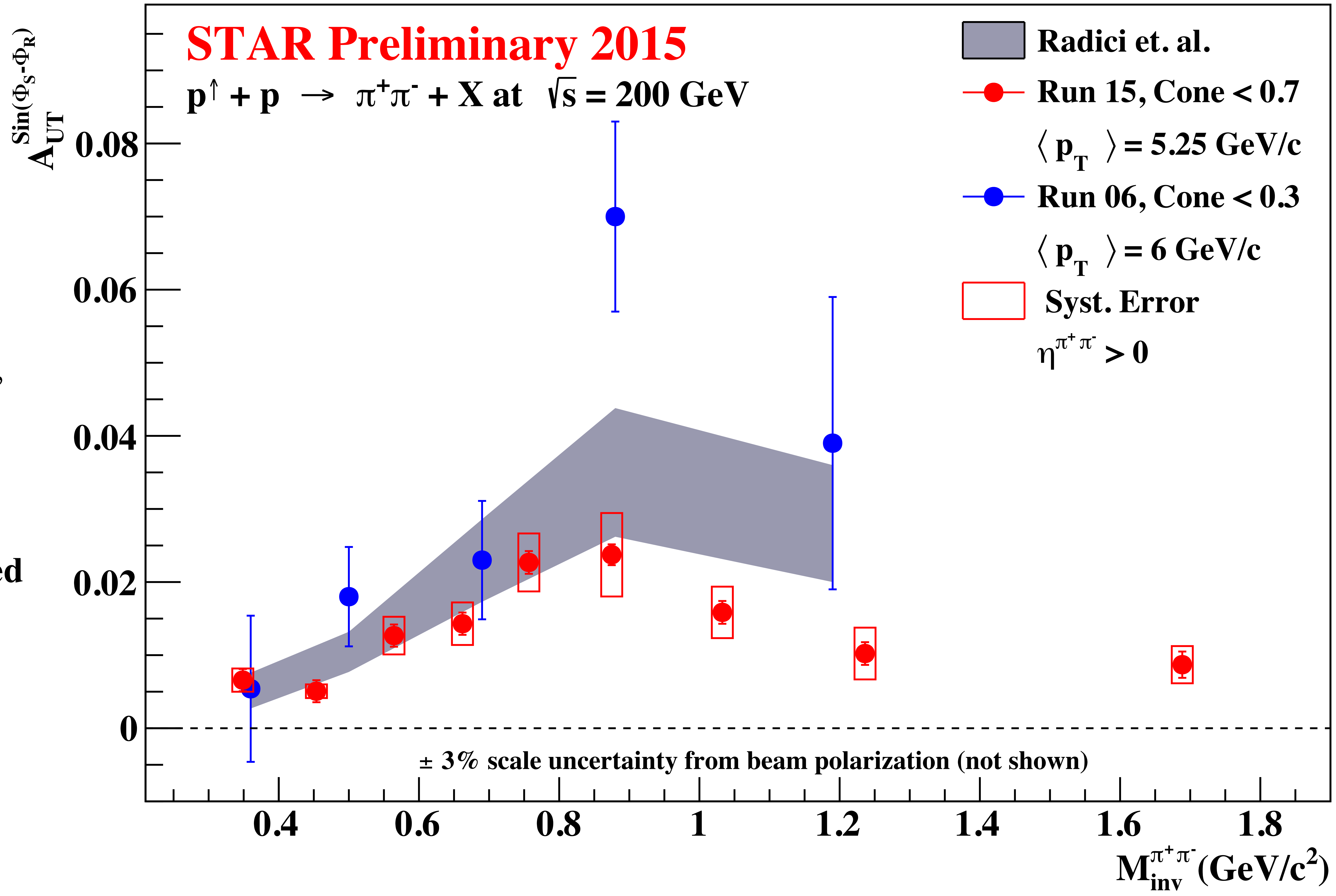
STAR Preliminary: $A_{UT}^{sin(\phi_s - \phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$ integrated

$A_{UT}^{\sin(\phi_s - \phi_R)}$ **vs** $M_{inv}^{\pi^+\pi^-}$ **integrated over** $p_T^{\pi^+\pi^-}$

in $\eta^{\pi^+\pi^-} > 0$**:**

- Asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$, consistent with the previous measurement with improved precision and the theory.

- **Systematic uncertainty includes effects related to PID and trigger bias.**



Summary

- **$\pi^+\pi^-$ azimuthal correlation asymmetries, sensitive to the transversity, have been measured.**
  - In $M_{inv}^{\pi^+\pi^-}$ bins, large forward asymmetries with a prominent peak at $M_{inv}^{\pi^+\pi^-} \sim M_\rho$, consistent with the theory.
  - In $p_T^{\pi^+\pi^-}$ bins, asymmetry increases linearly at higher $p_T^{\pi^+\pi^-}$. Asymmetry signal is more prominent when $M_{inv}^{\pi^+\pi^-} \sim M_\rho$.
  - In $\eta^{\pi^+\pi^-}$ bins, integrated over $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$, asymmetry signal increases linearly in $\eta^{\pi^+\pi^-} > 0$ region, where **quarks with larger *x*** can be probed. Lower asymmetry signal in $\eta^{\pi^+\pi^-} < 0$ is due to ***low x quarks*** coming from unpolarized beam.
- The **statistical precision** of the new 2015 results is **significantly improved** compared to the previous STAR measurements.
- Further improvements in PID systematic uncertainties expected with improved PID method based on TOF ***(In progress***).
- These results can be used to test the universality between SIDIS, e^+e^-, and $p^\uparrow p$. In addition, these high precision results can be used to further constrain the global fits, especially at high x (> 0.1) regions.
- Ongoing IFF analysis using the 2017 dataset at $\sqrt{s} = 510$ GeV ($L_{int} \sim 350\ pb^{-1}$). ***(Follow next talk from Navagyan Ghimire)***
- **Planned unpolarized di-hadron cross-section measurement, combined with these high precision asymmetry results, will help to constrain transversity.**