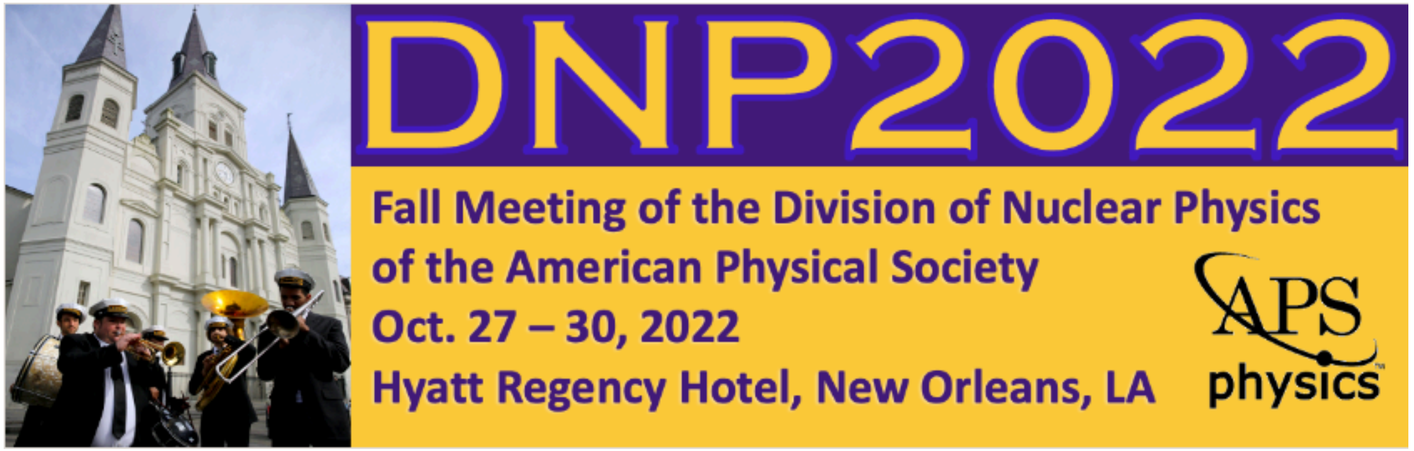
Measurements of Transverse Spin Dependent $\pi^+\pi^-$ Azimuthal Correlation Asymmetry and Unpolarized $\pi^+\pi^-$ Cross Section in *pp* Collisions at $\sqrt{s}$ = 200 GeV at STAR



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10/30/2022

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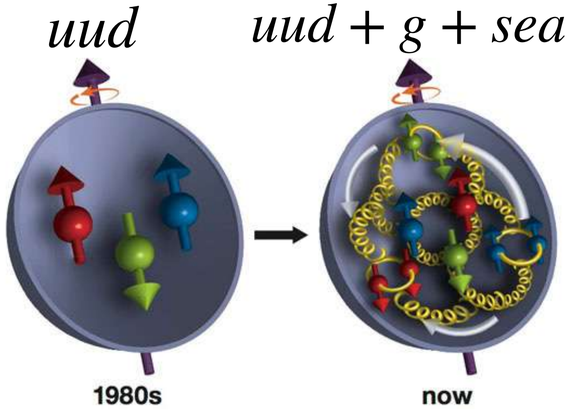
Nucleon Structure and Transversity



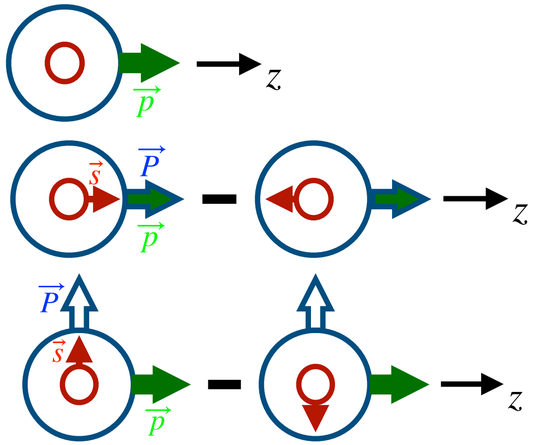
Parton distribution functions (PDFs):

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

Unpolarized: $f(x) \approx$

Helicity: $g(x) \approx$

Transversity: $h_1(x) \approx$



$\vec{P}$ = Nucleon polarization

$\vec{p}$ = Nucleon momentum

$\vec{s}$ = Quark polarization

Transversity, $h_1(x)$:

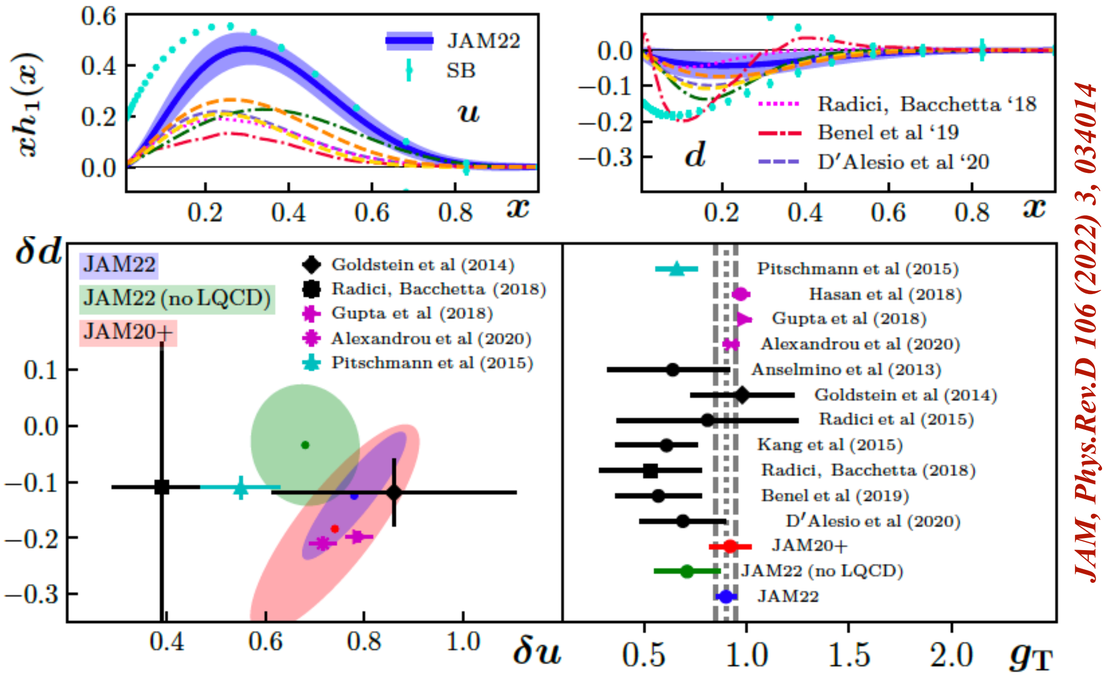
- Chiral-odd quantity, less known from experiments than $f(x)$ and $g(x)$.
- Its extraction requires coupling to another chiral-odd object, such as Interference Fragmentation Function (IFF).

Nucleon tensor charge

$$g_T = \delta u - \delta d,$$

$$\delta u = \int_0^1 dx(h_1^u(x) - h_1^{\bar{u}}(x)),$$

$$\delta d = \int_0^1 dx(h_1^d(x) - h_1^{\bar{d}}(x))$$



JAM, Phys.Rev.D 106 (2022) 3, 034014

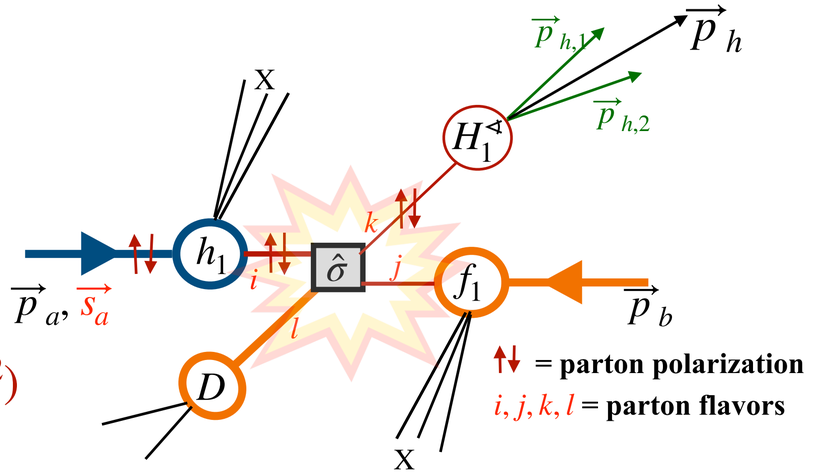
Observables for Transversity $h_1(x)$ in pp

Reaction Channel:

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

Cross Section:

$$d\sigma_{UT}^{p_a^{\uparrow}p_b \rightarrow (h_1,h_2)X} \propto sin(\phi_{S_a} - \phi_R) \sum_{i,j,k,l} \int dx_a \int dx_b \int dz \; h_1^{i/p_a}(x_a)\, f_1^{j/p_b}(x_b) \frac{d\Delta\hat{\sigma}^{ij\rightarrow kl}}{d\hat{t}} \; H_1^{\sphericalangle h_1 h_2/k}(z, M_h^2)$$



Dihadron Correlation Asymmetry:

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z, M_h)}$$

- Spin dependent IFF, needed for the extraction of transversity, h_1^q.
  - Extracted from the e^+e^- data.

- Access to transversity coupled with the spin dependent interference fragmentation function (FF), $H_1^{\sphericalangle h_1 h_2}$.
- No jet reconstruction required.
- Collinearity is preserved.

- Spin averaged FF, needed for the extraction of spin dependent FF, $H_1^{\sphericalangle h_1 h_2}$, and transversity, h_1^q.
- Limited knowlegde from the e^+e^- data.
- pp channel requires the knowledge of $D_1^{h_1 h_2/q}$ and $D_1^{h_1 h_2/g}$, for quark and gluon respectively.

Unpolarized Dihadron Cross Section in pp:

- Channel: $\sigma^{pp\rightarrow h_1 h_2 + X}$
- Much needed measurement, which gives access to the unpolarized gluon FF, $D_1^{h_1 h_2/g}$.

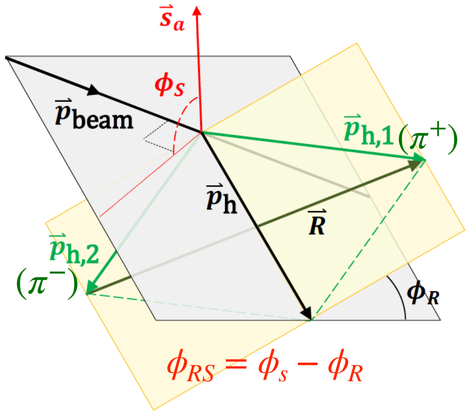
Bacchetta & Radici et al. Phys.Rev.D 70 (2004) 094032

STAR $\pi^+\pi^-$ Azimuthal Correlation Asymmetry

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

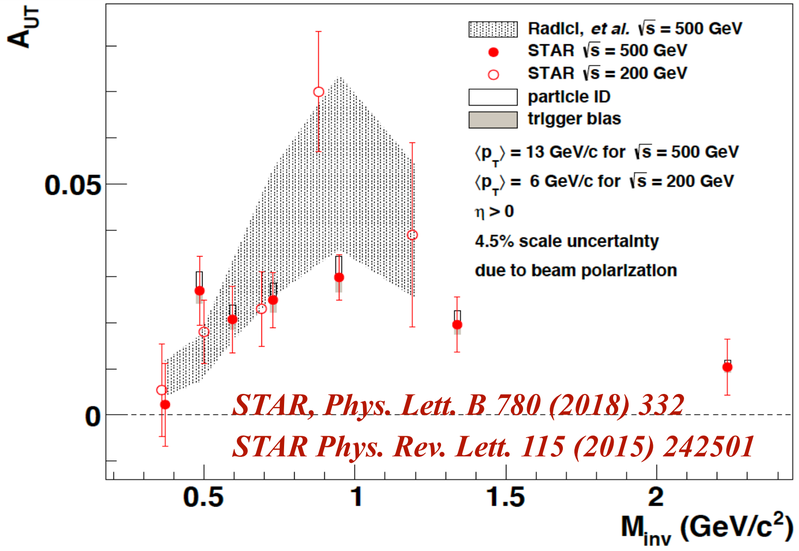
Cross-Ratio Method

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

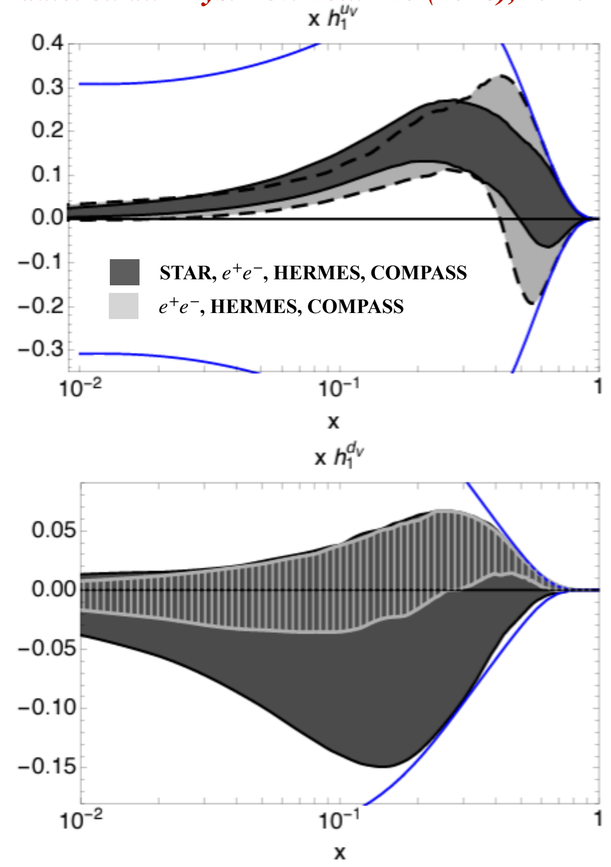


- $N^{\uparrow(\downarrow)} \rightarrow$ Number of $\pi^+\pi^-$ in respective ϕ_{RS} bin when the polarization is Up($\uparrow$) (Down ($\downarrow$)).
- P is average beam polarization.

- STAR observed significant $\pi^+\pi^-$ correlation asymmetry, A_{UT}, using 200 GeV and 500 GeV $p^{\uparrow}p$ datasets.
- $A_{UT} \propto h_1 H_1^{\sphericalangle h_1 h_2}$
- A_{UT} enhanced around ρ-mass region.

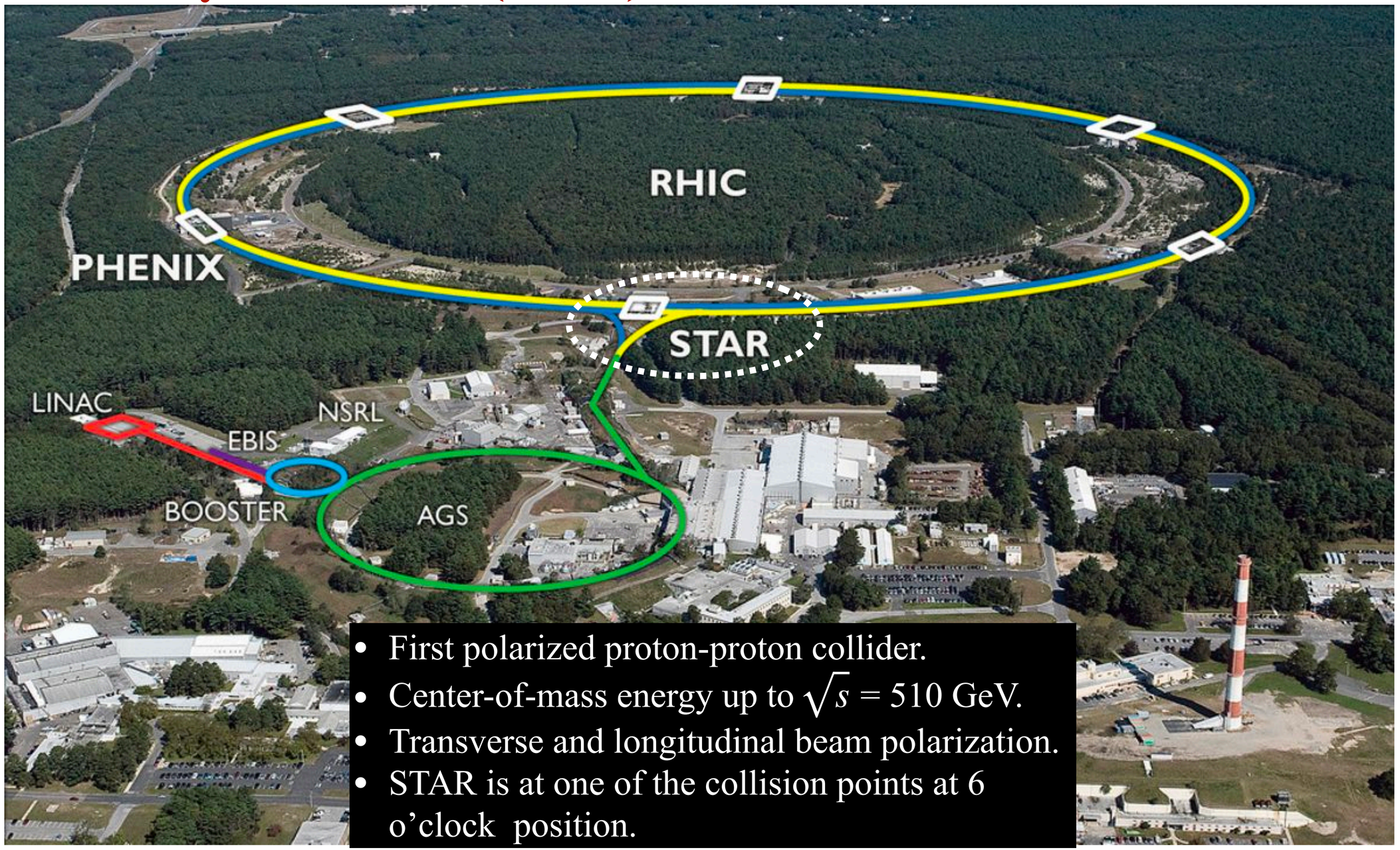


Radici et. al. Phys. Rev. Lett. 120 (2018), 19 192001



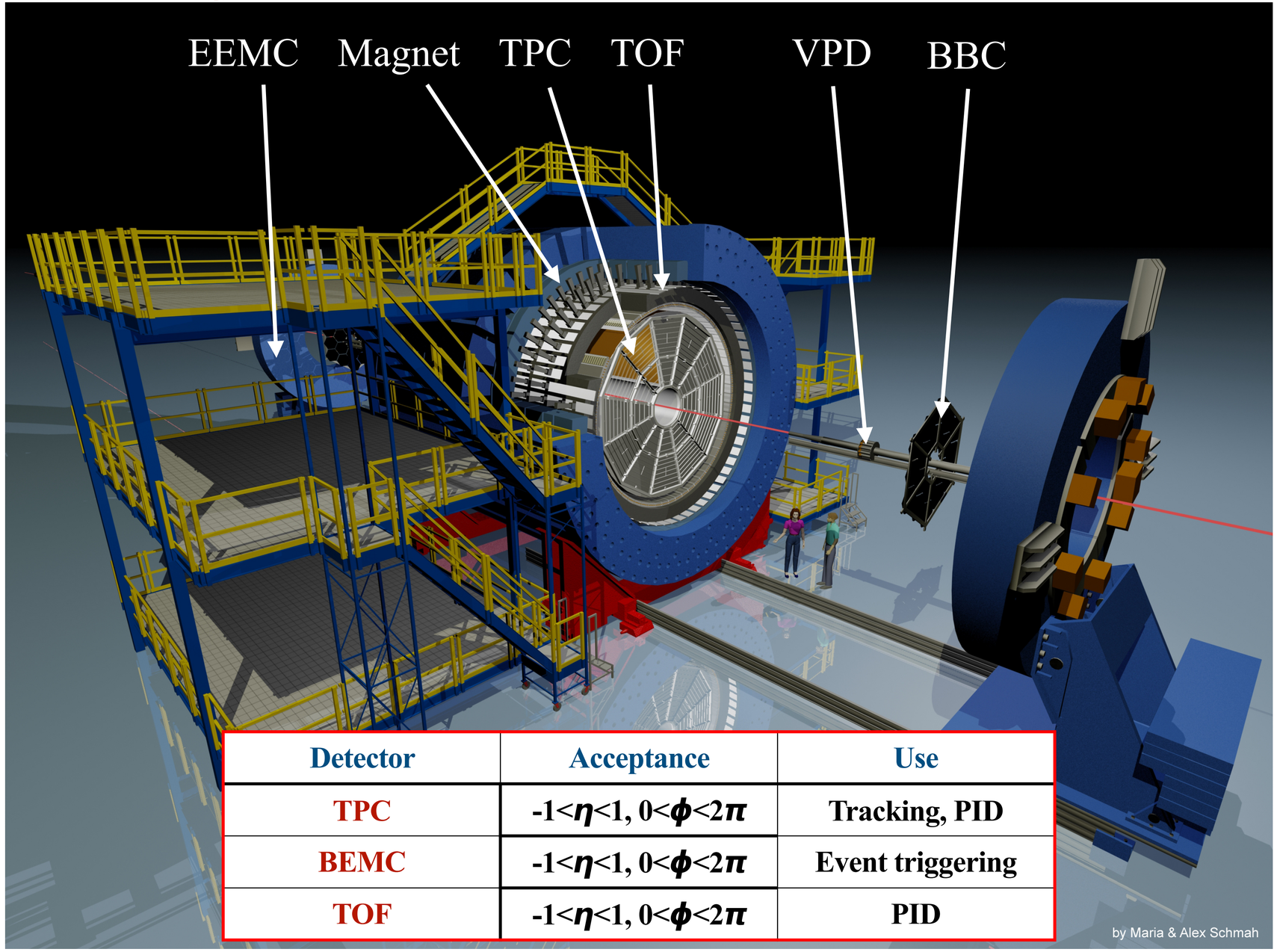
Significant impact on h_1^q from the STAR data at $\sqrt{s} = 200$ GeV

Relativistic Heavy Ion Collider (RHIC)



- First polarized proton-proton collider.
- Center-of-mass energy up to $\sqrt{s}$ = 510 GeV.
- Transverse and longitudinal beam polarization.
- STAR is at one of the collision points at 6 o'clock position.

STAR Detector at RHIC



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 Proton-Proton Collisions Dataset

Collision	proton-proton				
Polarization	transverse				
Year	2006	2011	2012	2015	2017
$\sqrt{s}$ (GeV)	200	500	200	200	510
L_{int} (pb^{-1})	~ 1.8	~ 25	~ 22	~ 52	~ 350
$< P_{beam} >$ (%)	~ 60	~ 53	~ 57	~ 57	~58

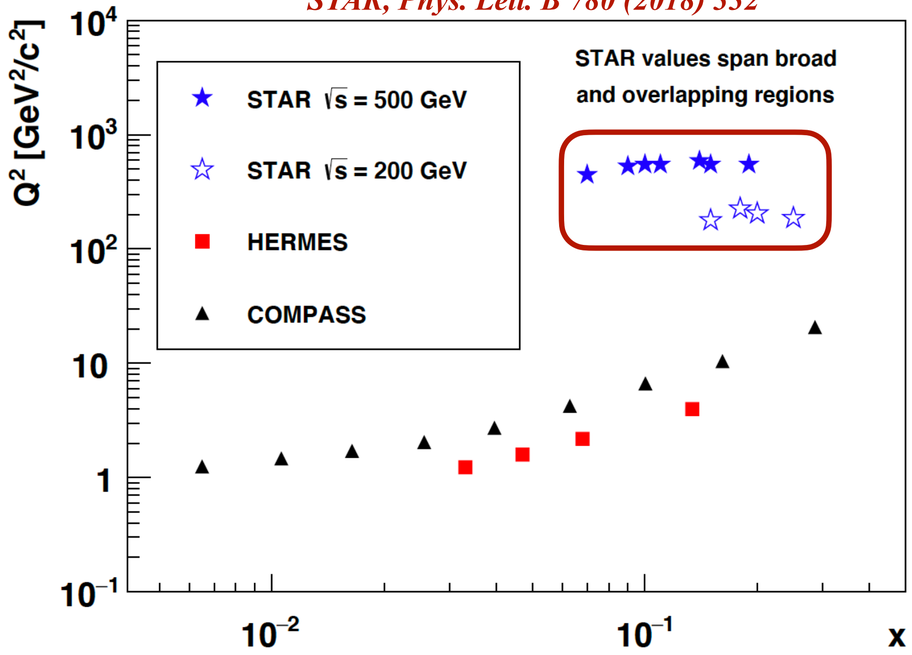
Published IFF A_{UT}
STAR, Phys. Lett. B 780 (2018) 332
STAR, Phys. Rev. Lett. 115 (2015) 242501

Ongoing dihadron cross-section measurement

IFF A_{UT} preliminary results released

Ongoing IFF A_{UT} analysis

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



STAR Kinematic Coverage:

- Covers much higher Q^2 than HERMES and COMPASS.
- Intermediate x coverage, valence quark region.

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

Top Panel:

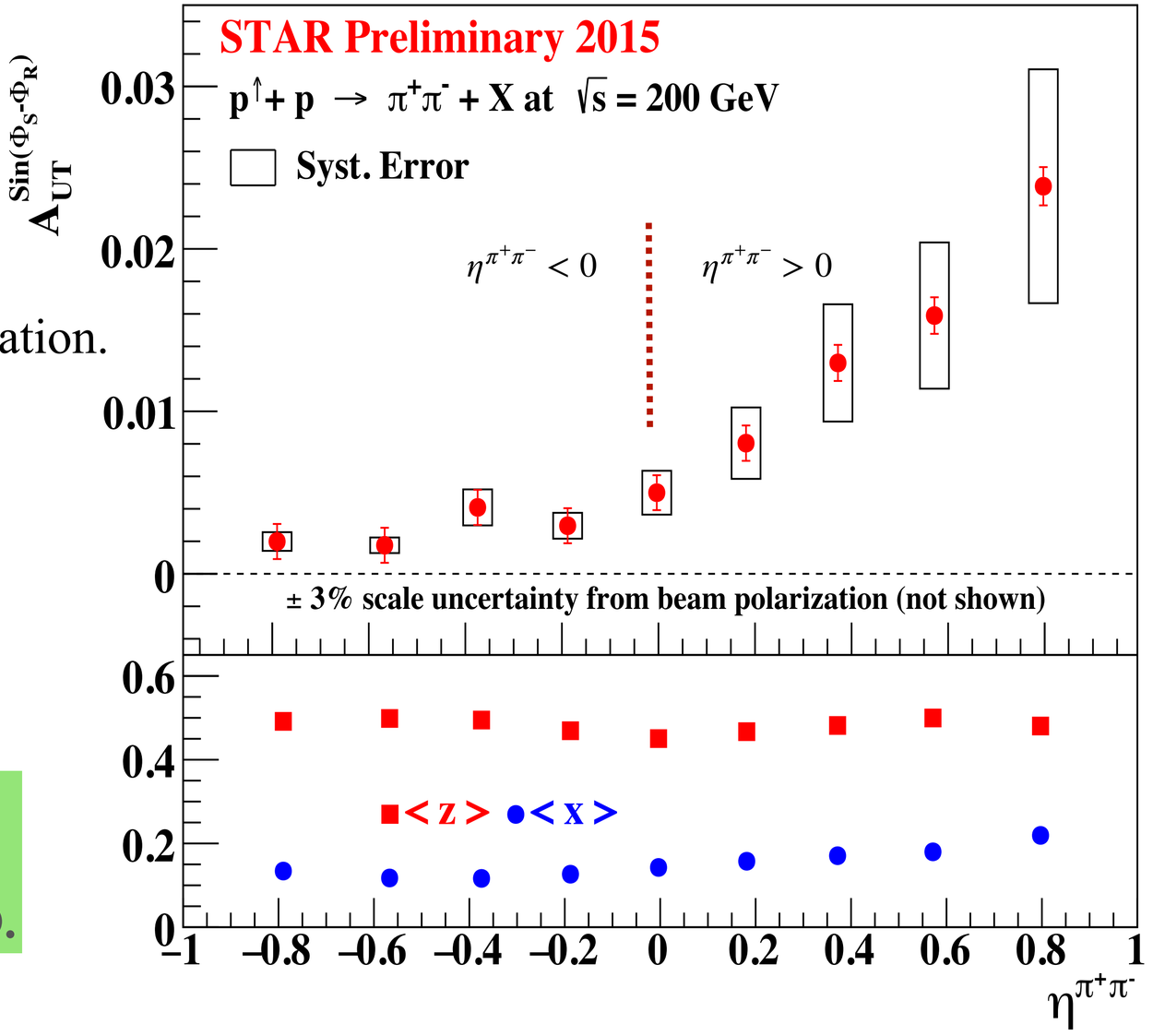
- A_{UT} as a function of $\eta^{\pi^+\pi^-}$ with $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$ integrated.

Bottom Panel:

- Mean x and z as a function of $\eta^{\pi^+\pi^-}$ from simulation.
- $|\eta^{\pi^+\pi^-}|<1$, with respect to the polarized beam.
- **$0.1 < \langle x \rangle < 0.22$, $\langle z \rangle \sim 0.46$**

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

- Systematic uncertainty includes effects related to PID and trigger bias.
- **Dominant systematic uncertainty from the PID.**

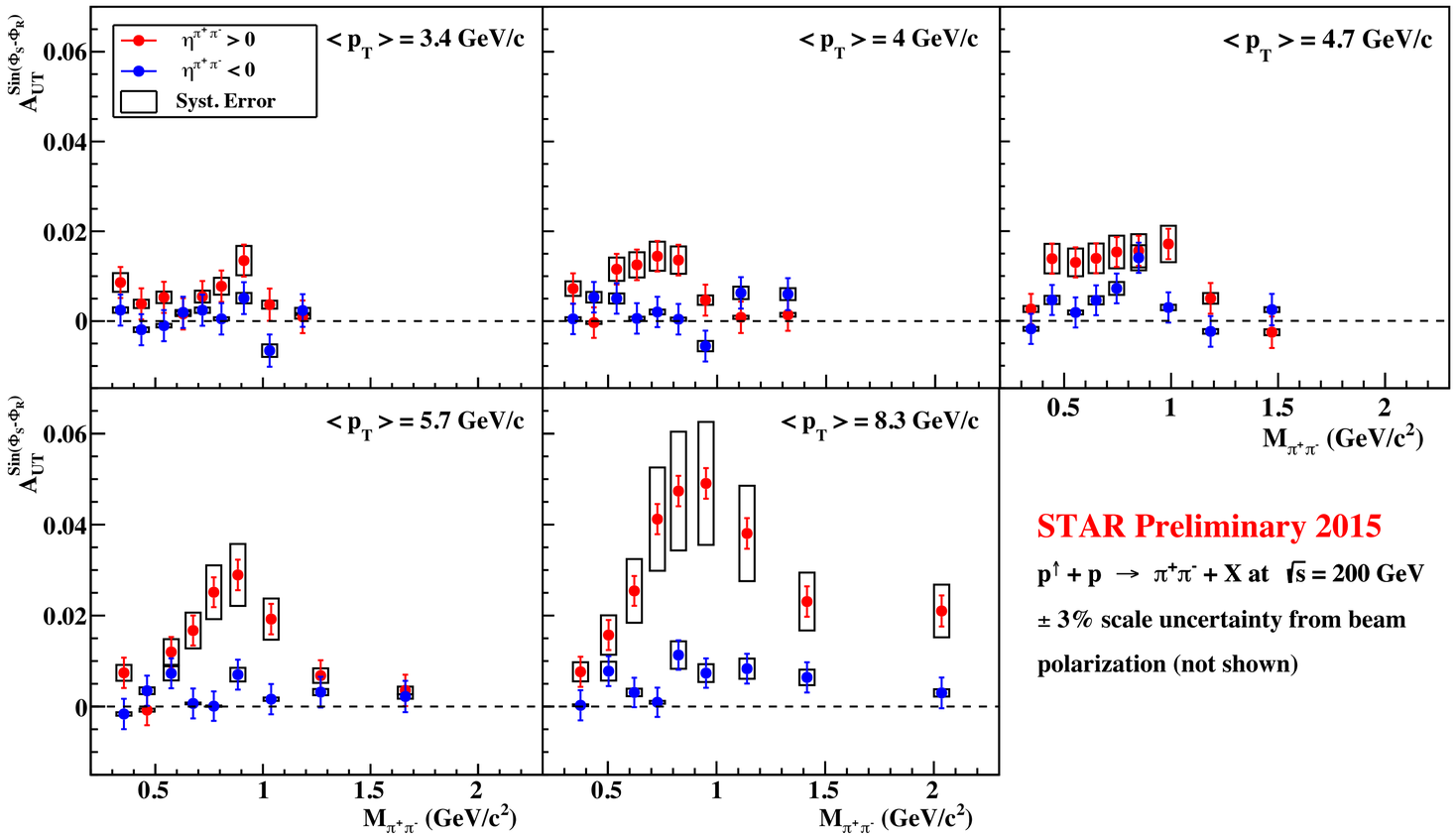


STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$

- $A_{UT}^{\sin(\phi_s-\phi_R)}$ **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 $M_{inv}^{\pi^+\pi^-} \sim 0.8\ GeV/c^2 \sim M_\rho$.

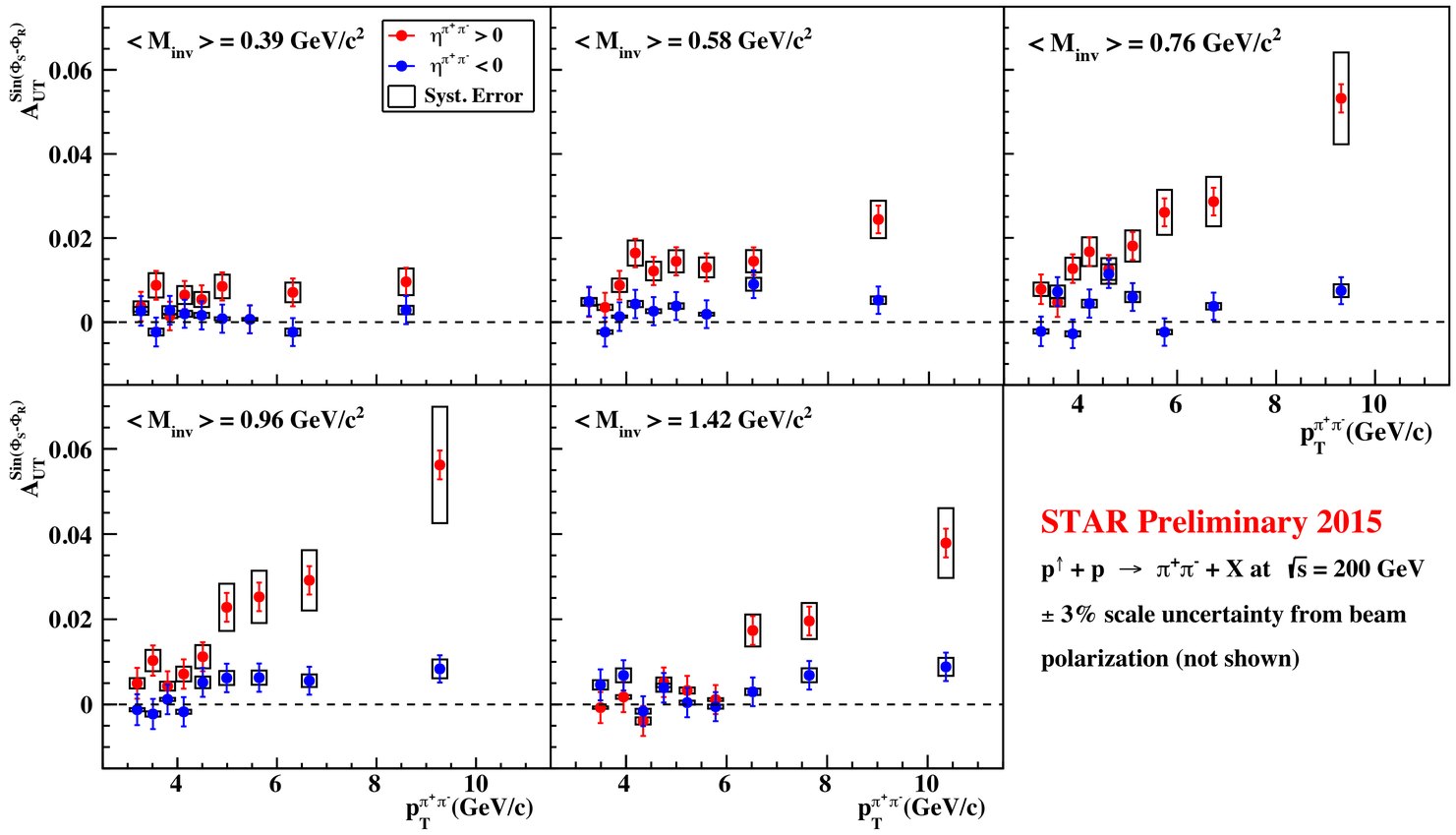
- Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from polarized beam.



* p_T refers to transverse momentum of $\pi^+\pi^-$ pair relative to the beam direction.

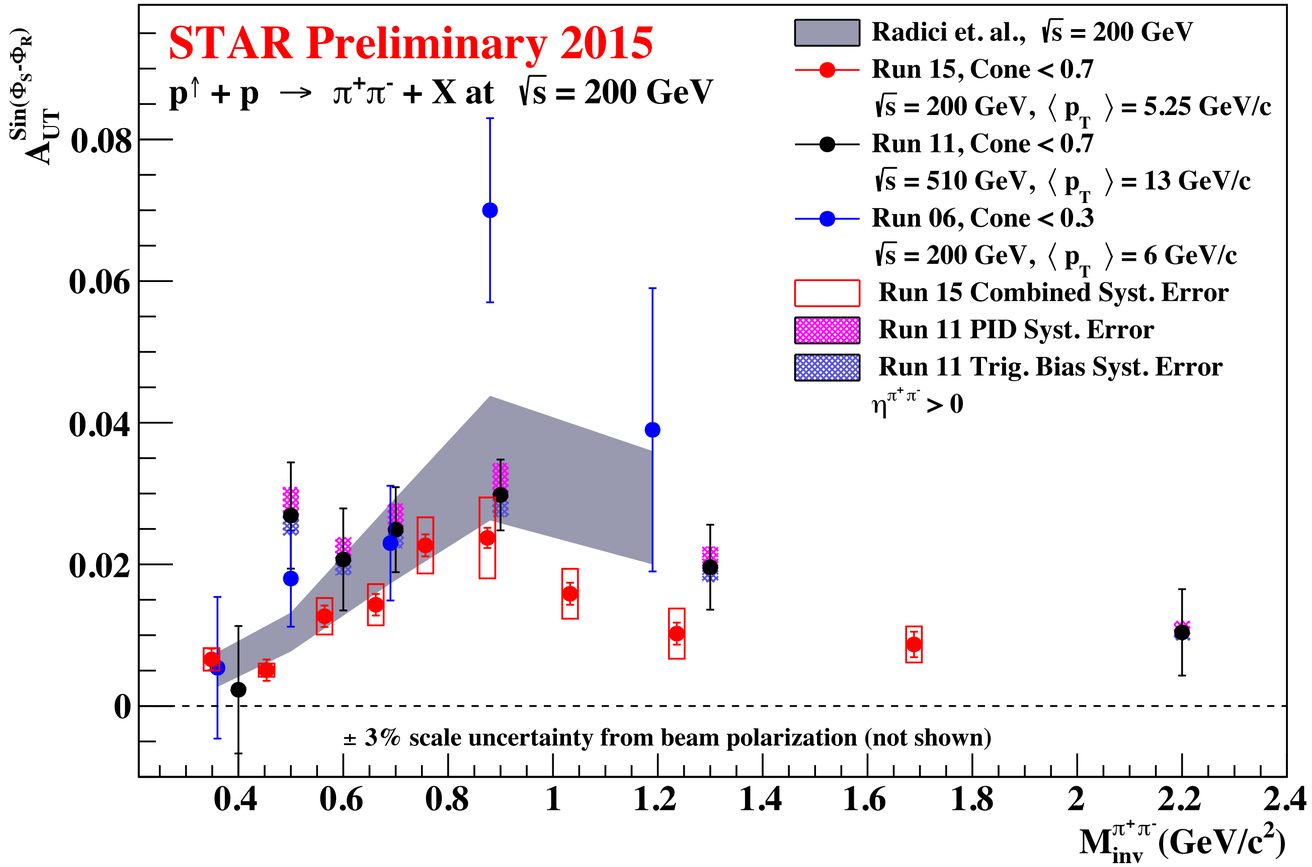
STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$

- 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 polarized beam.



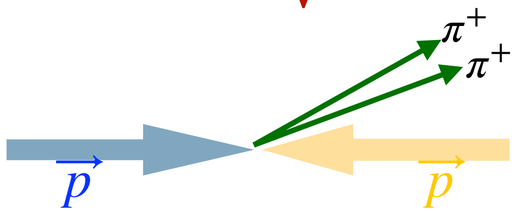
STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$ Integrated

- STAR measurements agree within uncertainties.
- Statistical precision is significantly improved in the new result.
- Asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$, consistent with the previous measurement.
- Theory overshoots the new measurement starting around and beyond the resonance peak.



Unpolarized Dihadron Cross Section Measurement: Status

$$p + p \rightarrow h^+h^- + X \text{ at } \sqrt{s} = 200 \text{ GeV from run 2012.}$$

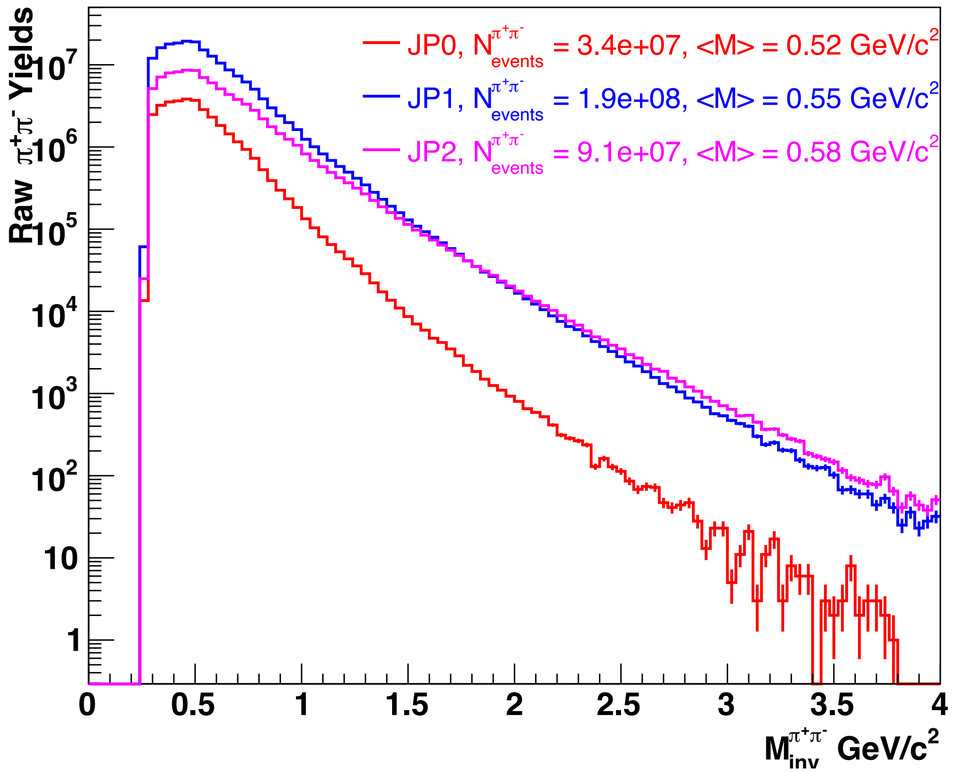


Polarization integrated ≈ Unpolarized

- Lower trigger threshold, better than 2015 dataset for cross-section measurement.

- Inclusive $\pi^+\pi^-$ **differential cross section**:
  - As a **function of invariant mass, $M_{inv}^{\pi^+\pi^-}$, in $|\eta|<1$** .
  - Much needed for the $D_1^{h_1h_2}$ extraction.
  - Access to $D_1^{h_1h_2/g}$.

- Analysis is in progress.



Summary

- **$\pi^+\pi^-$ azimuthal correlation asymmetries, sensitive to the transversity, have been measured at STAR.**
  - The **statistical precision** of the new 2015 results is **significantly improved** compared to the previous STAR measurements.
  - Expect to significantly improve the systematic uncertainty from the PID using Time-of-Flight detector.

- Ongoing IFF analysis using the 2017 dataset at $\sqrt{s}$ = 510 GeV ($L_{int} \sim 350\ pb^{-1}$, ~ 14 times larger than 2011 dataset) probes even **lower *x (> 0.05)*** region.

- Unpolarized $\pi^+\pi^-$ cross section measurement is in progress.
  - Differential **cross section** as a **function of $M_{inv}^{\pi^+\pi^-}$ in $|\eta|<1$**.

- These results can be used to **test the universality** between SIDIS, e^+e^-, and pp, and **further constrain the global fits of transversity**, specially at high x (> 0.05) region.