Transverse Spin Dependent Azimuthal Correlations of Charged hadron(s) in $p^{\uparrow}p$ Collisions at $\sqrt{s}$ = 200 GeV

Babu Pokhrel
(For the STAR collaboration)
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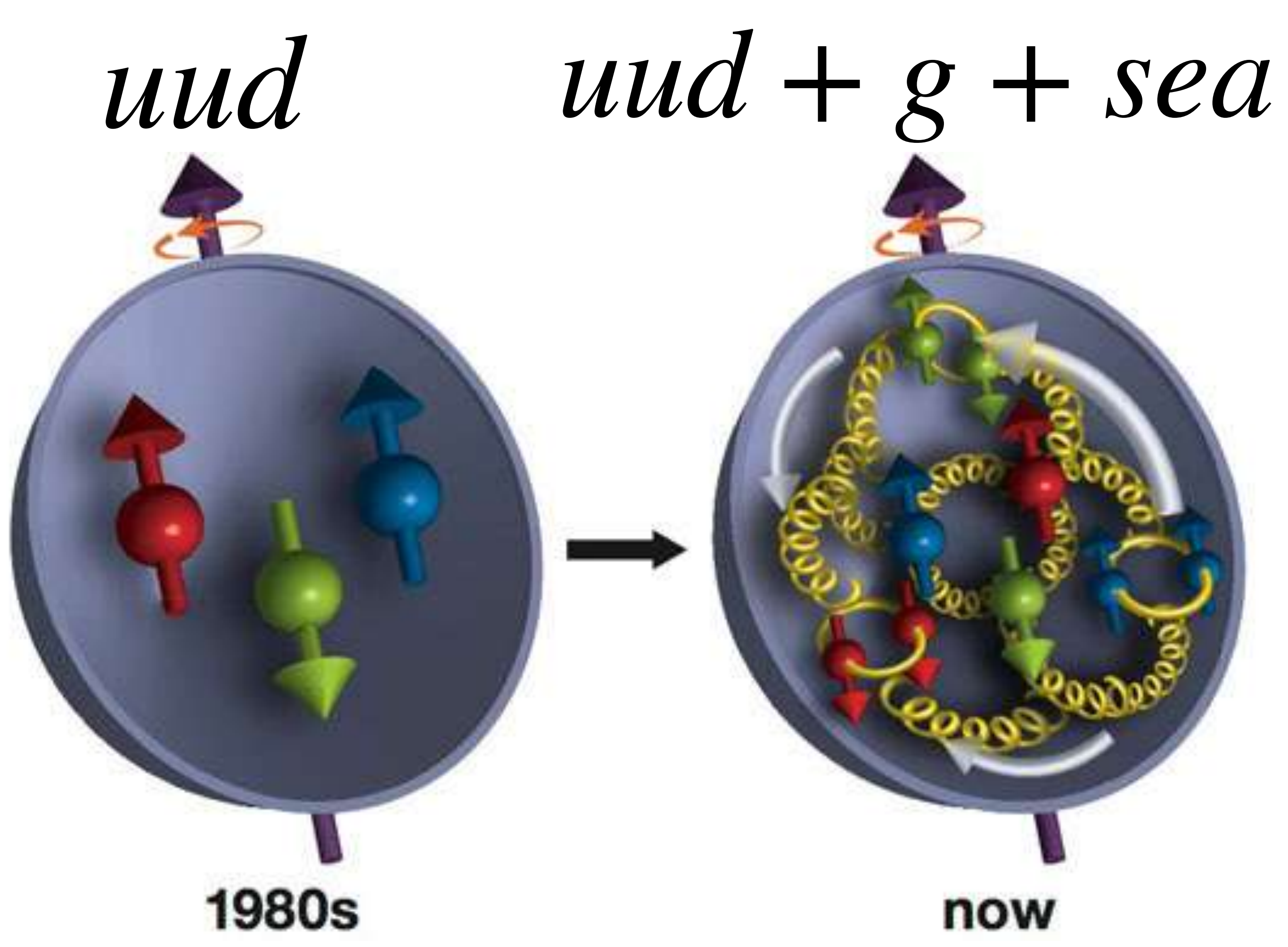
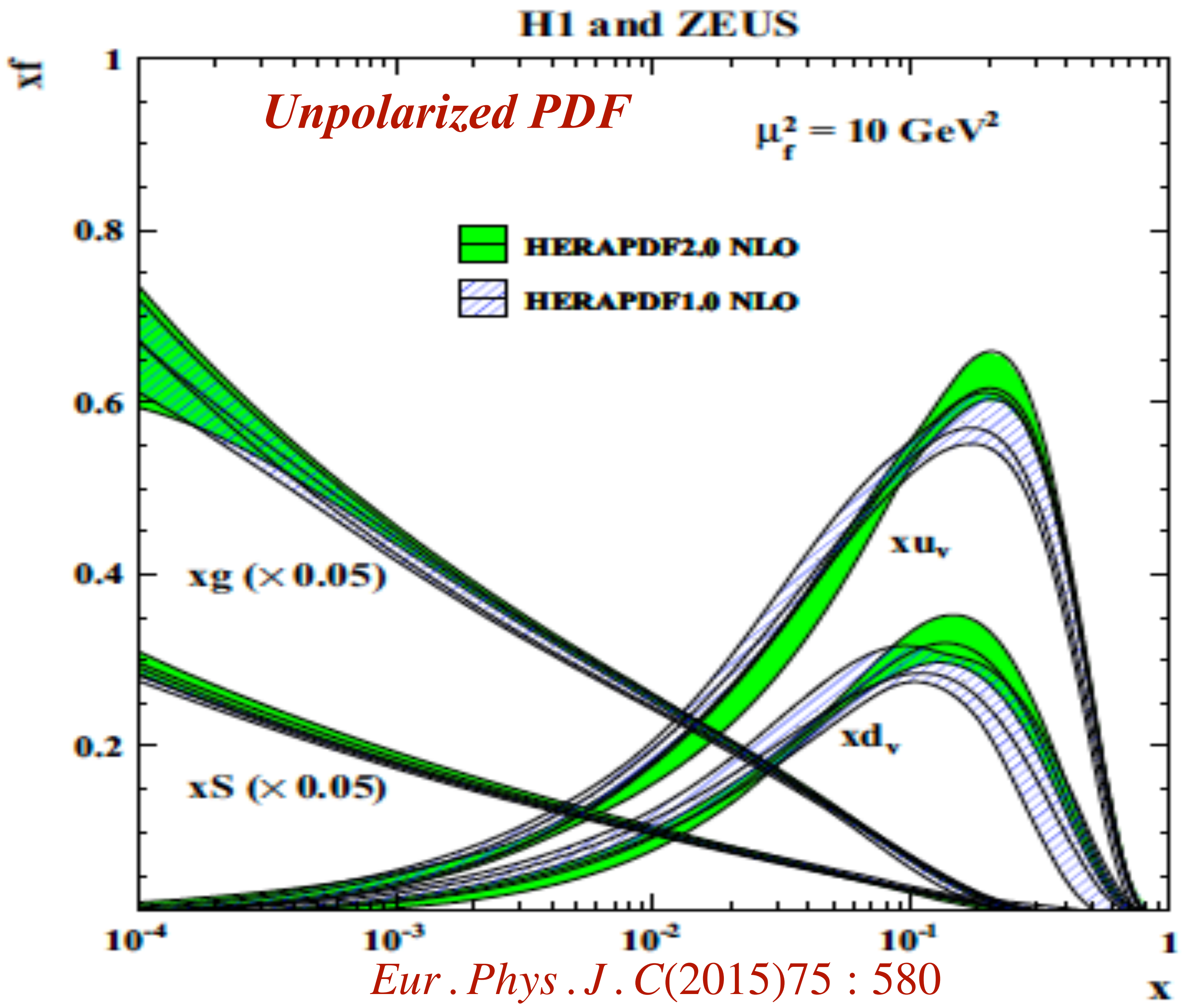
Motivation

Nucleon Structure:

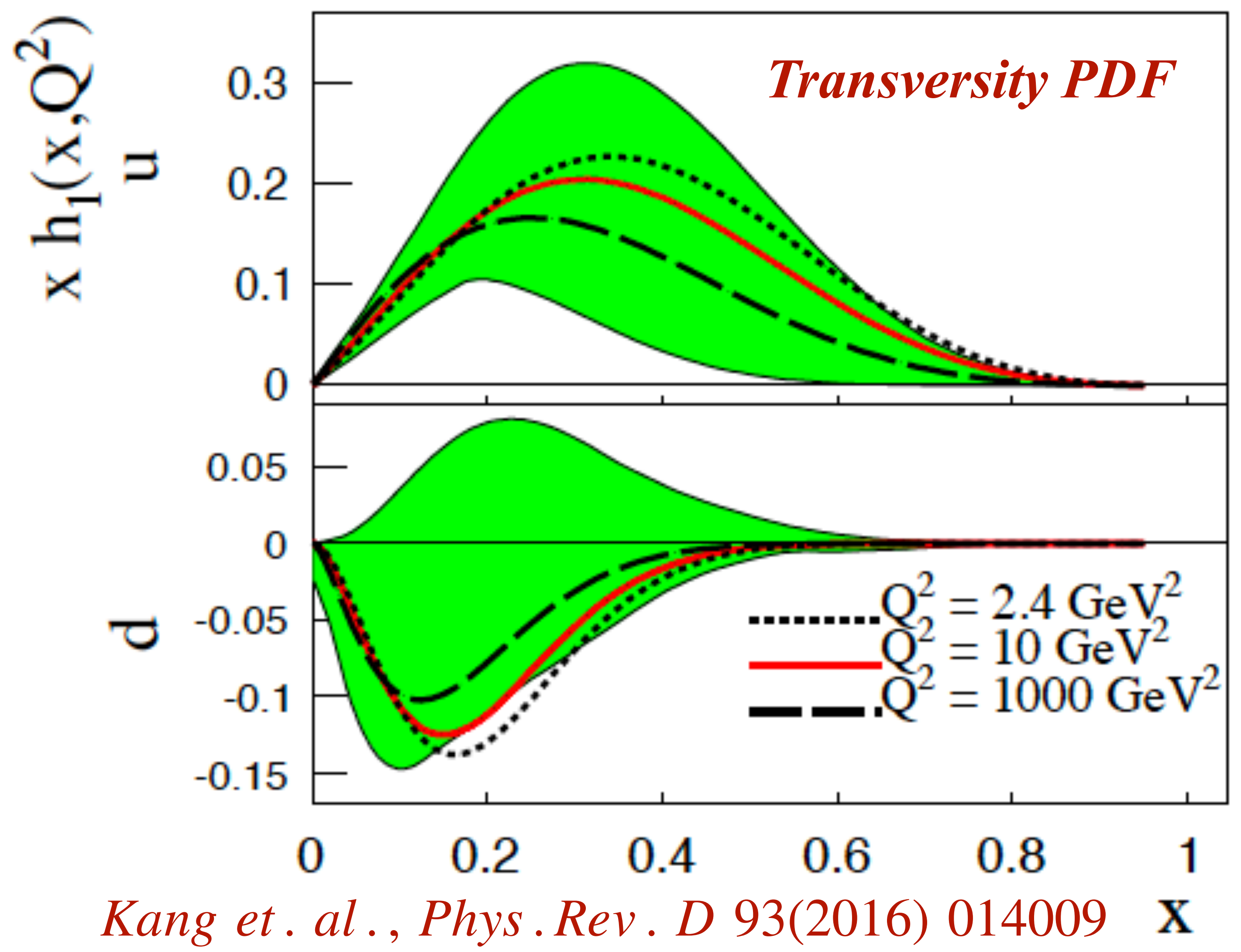




Eur . Phys . J . C(2015)75 : 580

- **At leading twist, three parton distribution functions (PDFs) describe the nucleon structure.**
  - $f_1^q(x) \rightarrow$ **Unpolarized PDF (Well constrained from unpolarized DIS)**
  - $g_1^q(x) \rightarrow$ **Helicity PDF (Well constrained for *q*, but poorly known for $\bar{q}$, g, and q_{sea})**
  - $h_1^q(x) \rightarrow$ **Transversity PDF (less known from experiments)**

- **Transversity describes transversely polarized quark in transversely polarized nucleon, which is chiral-odd.**
- **Due to its chiral-odd nature, its extraction requires coupling to another chiral-odd object, such as Fragmentation Function (FF), in polarized proton-proton (*pp*) collisions.**



Kang et . al ., Phys . Rev . D 93(2016) 014009

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Observable For h_1^q Extraction Coupling with FF

- **FFs can be defined as probability densities for finding color-neutral hadrons inside parton fragments.**
- **In *pp*, the coupling of h_1^q and FF leads to the azimuthal modulation in cross section, resulting in observed asymmetries.**

$$\sim h_1^q \otimes FF$$

Collins FF ($H_{1,q}^{\perp}$) Channel:

$$p^{\uparrow} + p \rightarrow jet + h^{\pm} + X$$

$$\sim h_1^q \otimes H_{1,q}^{\perp}$$

Interference FF ($H_{1,q}^{\sphericalangle}$) Channel:

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

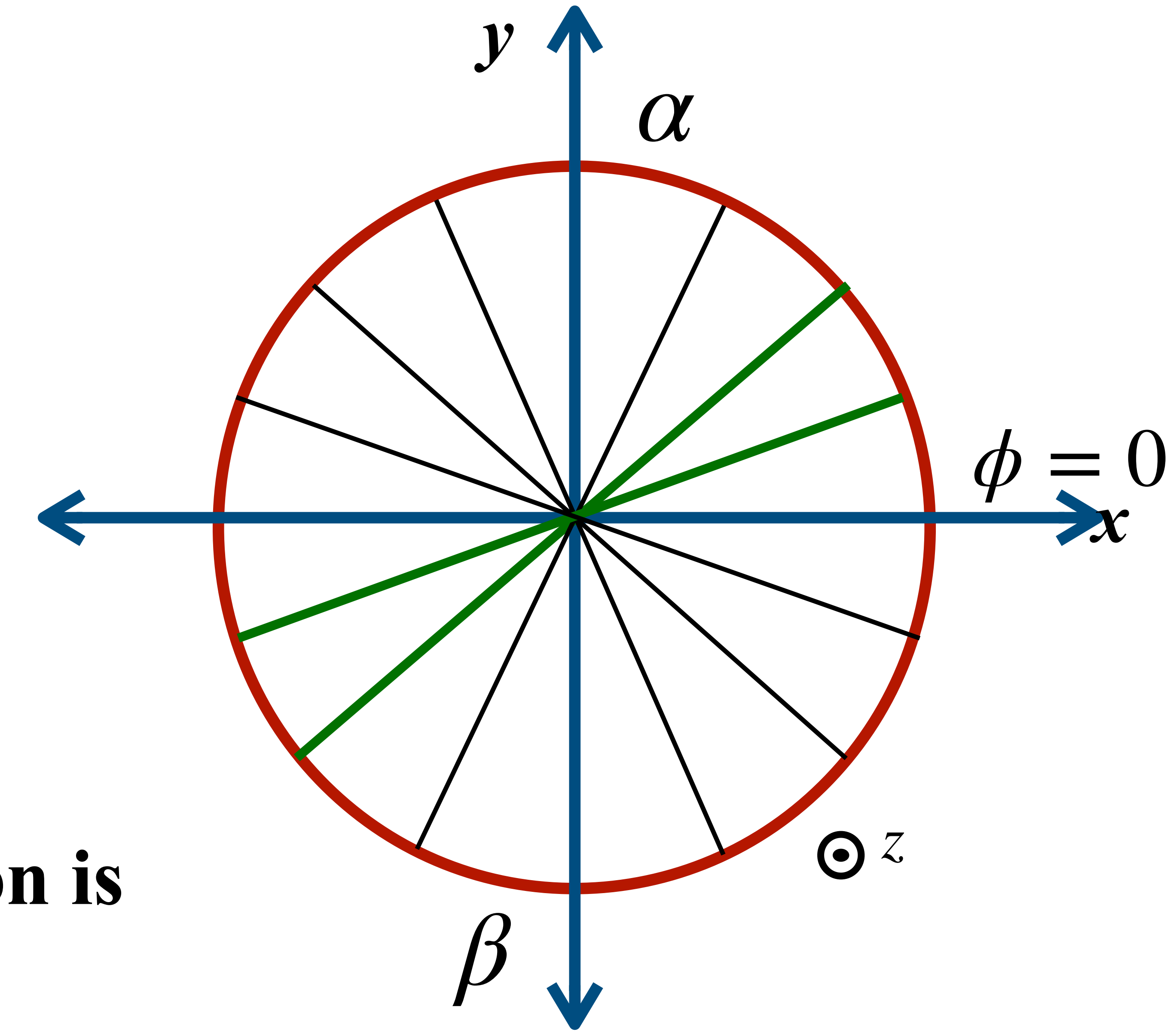
$$\sim h_1^q \otimes H_{1,q}^{\sphericalangle}$$

$$A_{UT}^{sin(\phi)} = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$

- **Experimentally extractable observable.**
- $A_{UT}^{sin(\phi)} \sim h_1^q \otimes FF$

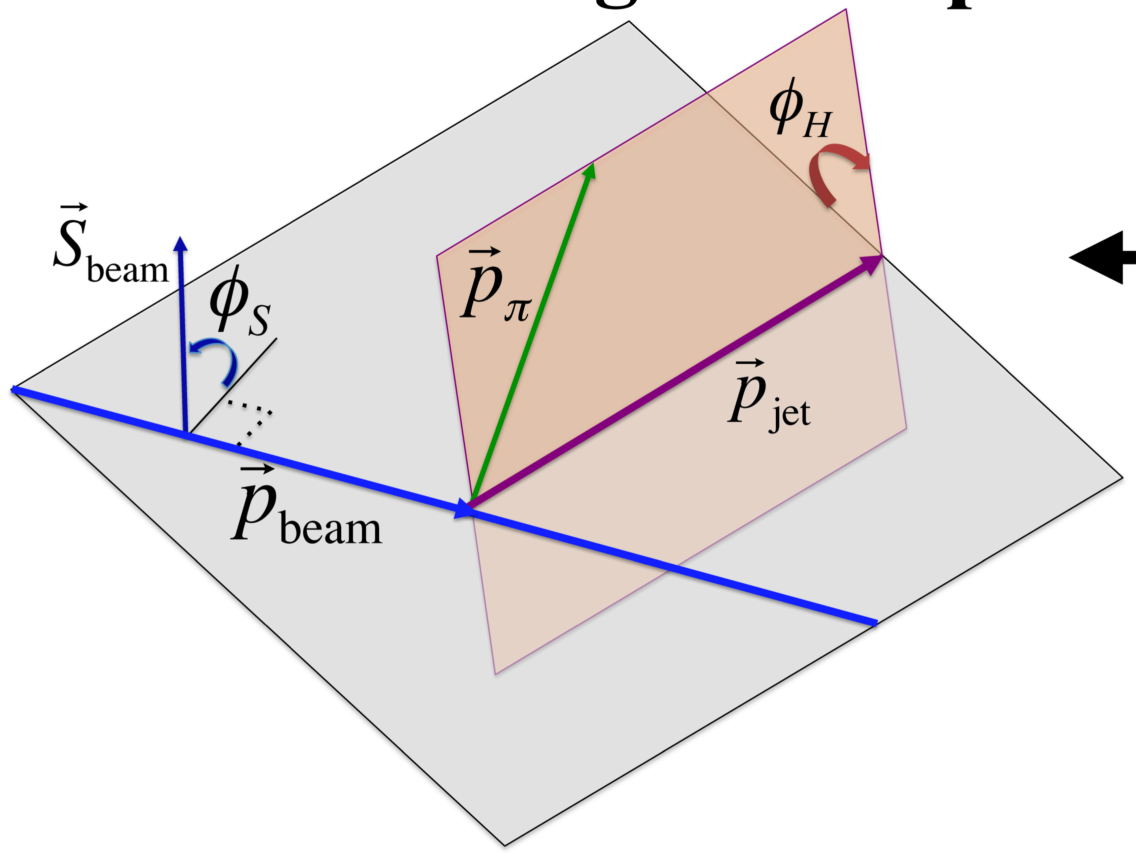
- **In STAR, both beams are polarized.**
- **Single spin asymmetry is achieved by integrating over the polarization of the other beam.**

Cross-Ratio Formalism for Asymmetry Extraction

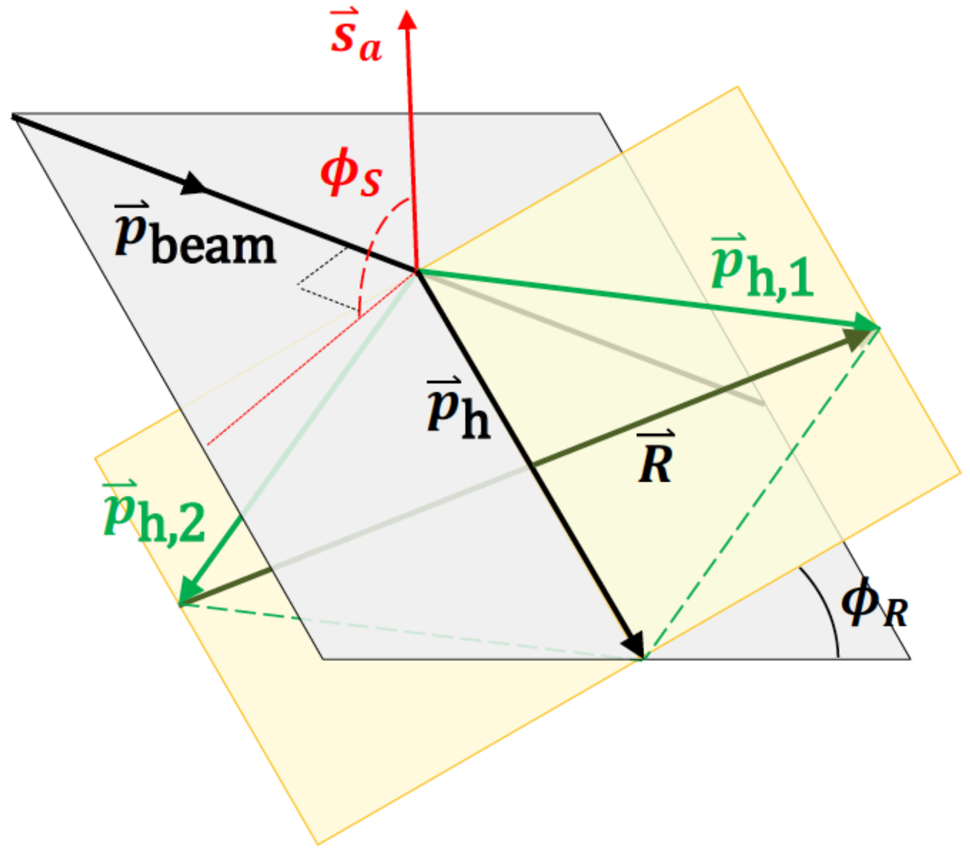


$$A_{UT}sin(\phi) = \frac{1}{P}\frac{\sqrt{N^{\uparrow}_{1,\alpha}N^{\downarrow}_{1,\beta}} - \sqrt{N^{\downarrow}_{1,\alpha}N^{\uparrow}_{1,\beta}}}{\sqrt{N^{\uparrow}_{1,\alpha}N^{\downarrow}_{1,\beta}} + \sqrt{N^{\downarrow}_{1,\alpha}N^{\uparrow}_{1,\beta}}}$$

- $N^{\uparrow(\downarrow)}_{1,\alpha(\beta)} \rightarrow$ **Number of** $h^{+(-)}$ **(*Collins Channel*) or number of** $h^{+}h^{-}$ **(*IFF Channel*) in upper,** α **(lower,** β**), half of detector when beam polarization is** $Up(\uparrow)(Down\ (\downarrow))$**.**
- P **is average beam polarization.**



- **Sivers,** $\phi \rightarrow \phi_s$
- **Collins,** $\phi \rightarrow \phi_s - \phi_H$
- **Collins-Like,** $\phi \rightarrow \phi_s - 2\phi_H$
- **IFF,** $\phi \rightarrow \phi_s - \phi_R$



Azimuthal angle definition for Collins channel

- **In this approach, all the detector acceptance effect and the relative luminosity terms cancel out, reducing the systematic uncertainties.**

Azimuthal angle definition for IFF channel

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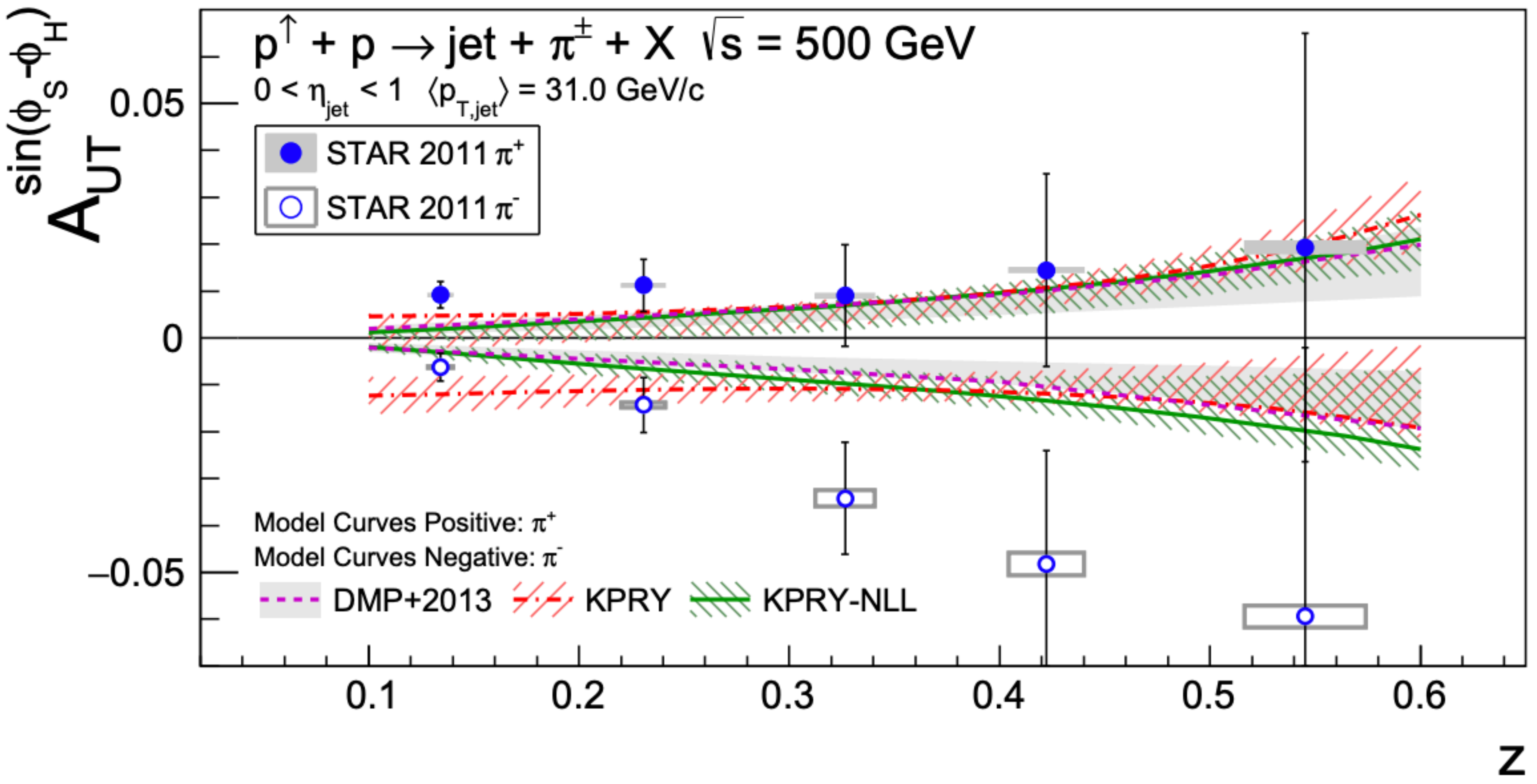
Previous STAR Collins and IFF Asymmetries

Collins Asymmetry:

$$p^{\uparrow} + p \rightarrow jet + \pi^{\pm} + X$$

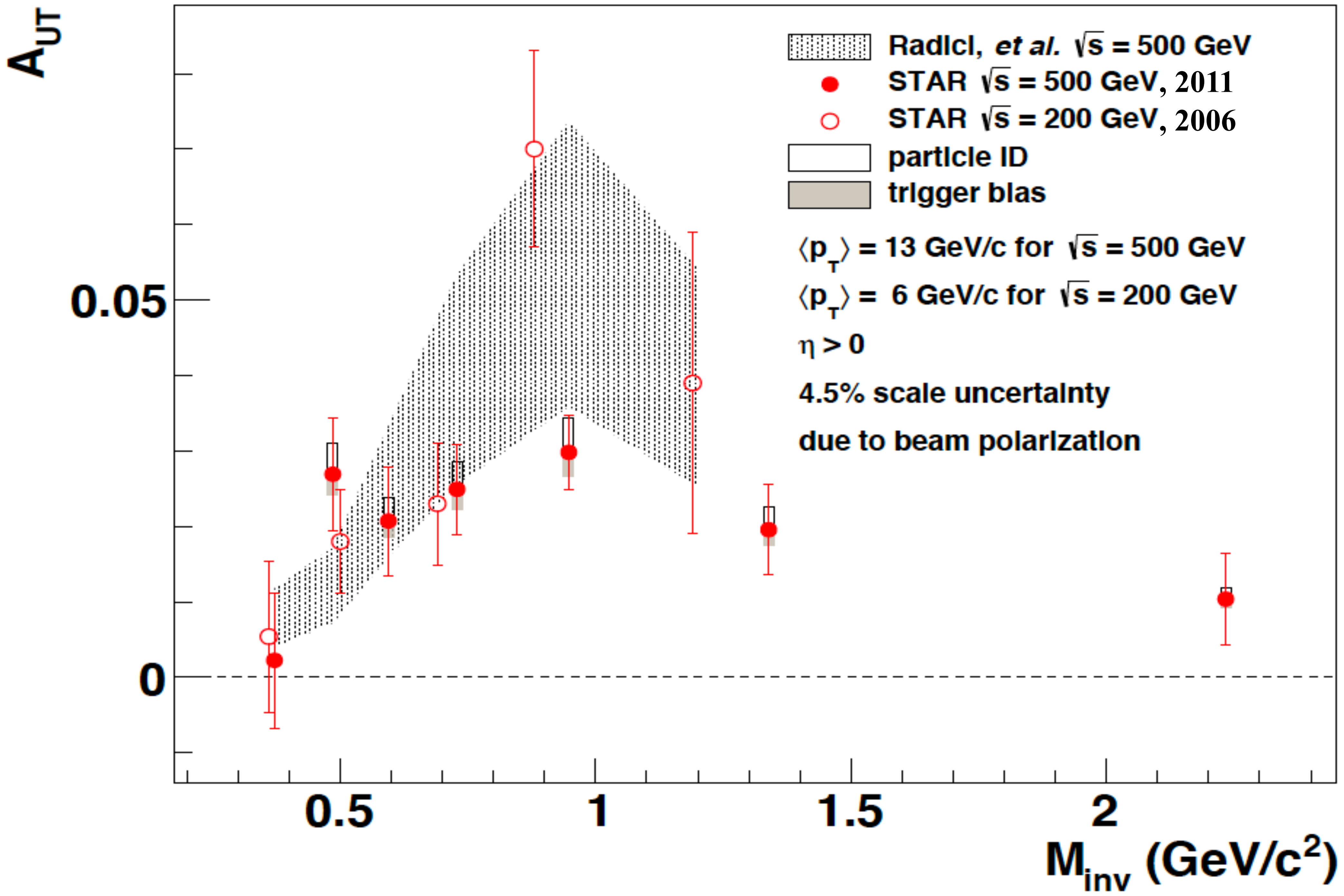
STAR, Phys. Rev. D 97 (2018) 32004



IFF Asymmetry:

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

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

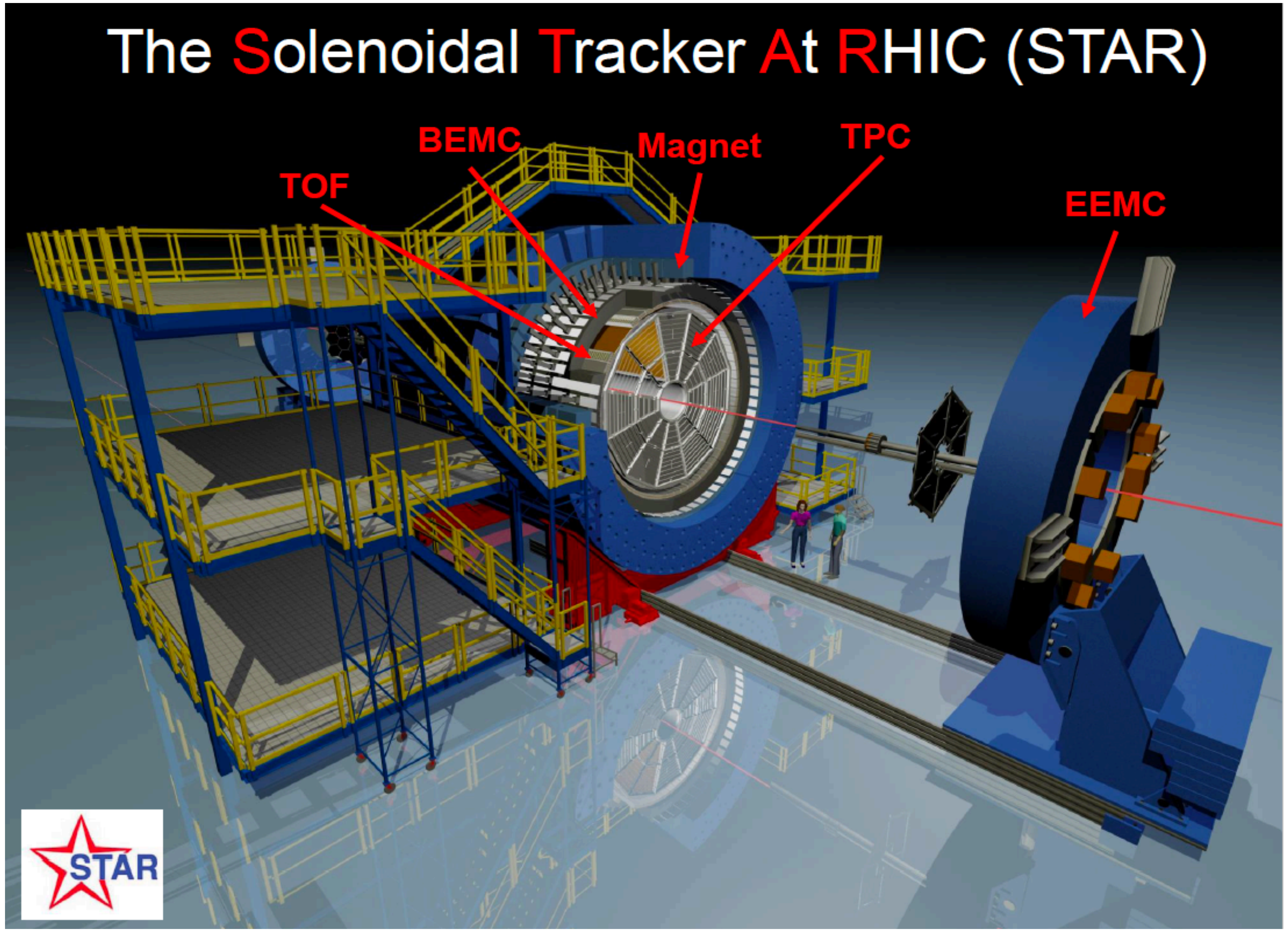


- **Collins asymmetry is positive for π^+ and negative for π^-. IFF asymmetry for $\pi^+\pi^-$-pair is significant with the enhancement at $M_{inv}^{\pi^+\pi^-} \sim M_\rho(\approx 0.775\ GeV/c^2)$.**
- **Although the results are encouraging, statistical error is large due to limited data sample size.**

STAR Experiment at RHIC

Barrel Electromagnetic Calorimeter (BEMC):
- $|\eta| < 1$, $0 < \phi < 2\pi$ coverage.
- Measures energy deposited by electromagnetically charged particles and photons.
- Provides event triggering.

Time of Flight (TOF):
- $|\eta| < 1$, $0 < \phi < 2\pi$ coverage.
- Acts as a stopwatch for each track in an event.
- In conjunction with VPD, TOF helps improve STAR PID capability.



Time Projection Chamber (TPC):
- $|\eta| < 1$, $0 < \phi < 2\pi$ coverage.
- Used for charged particle tracking and momentum reconstruction.
- Measures ionization energy loss (dEdx), useful for particle identification.

Magnet:
- Uniform magnetic field of 0.5 T along z-direction.
- Used for particle momentum reconstruction and charge determination, based on the direction of curvature.

STAR Datasets And Kinematic Coverage

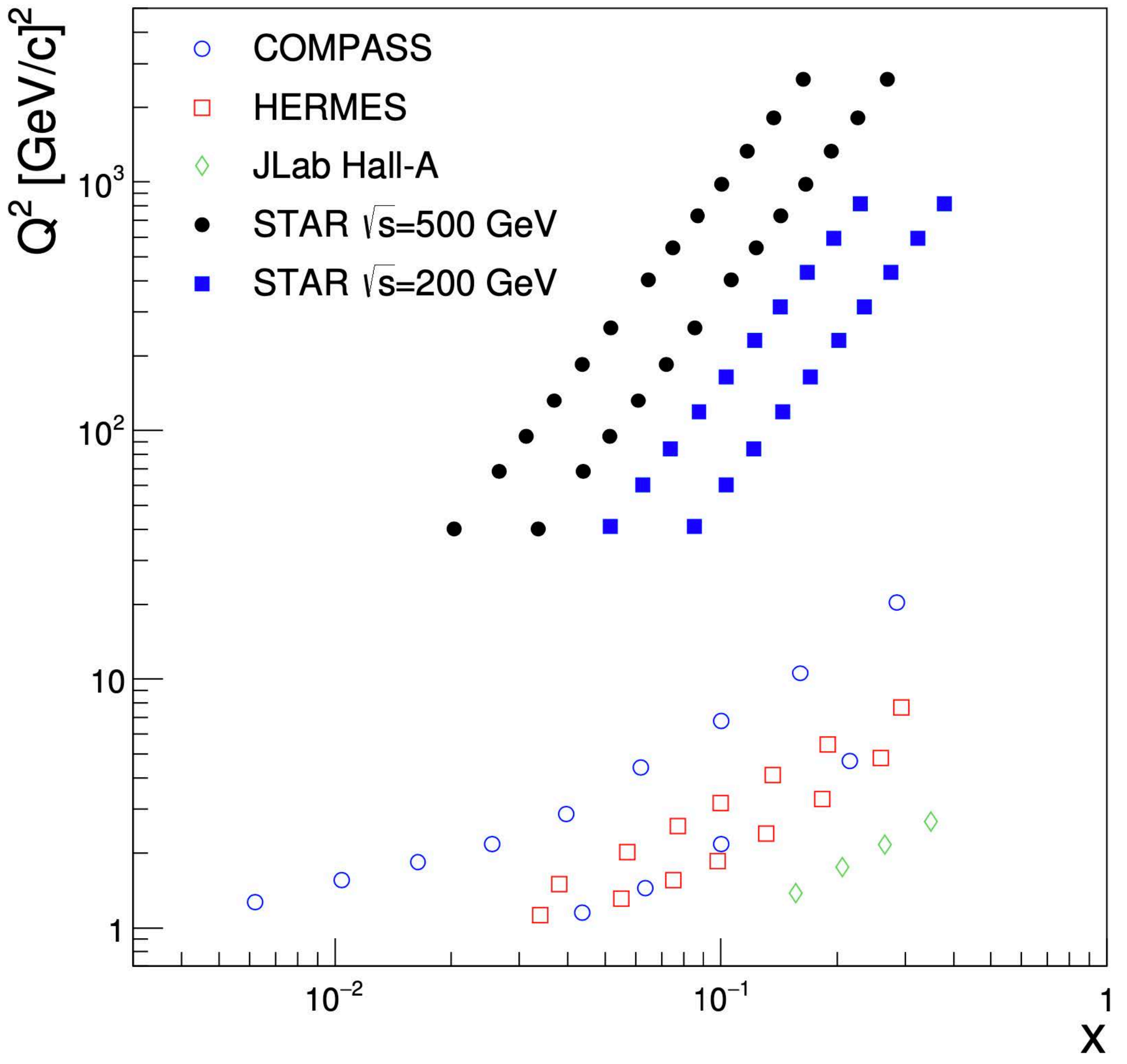
Collision	*pp*			
Year	2006	2011	2012	2015
$\sqrt{s}$ (GeV)	200	500	200	200
L_{int} (pb^{-1})	≈ 1.8	≈ 25	≈ 14	≈ 52
Avg . P_{beam} (%)	≈ 60	≈ 53	≈ 57	≈ 57

2006, 2011 → **Previous Measurements**

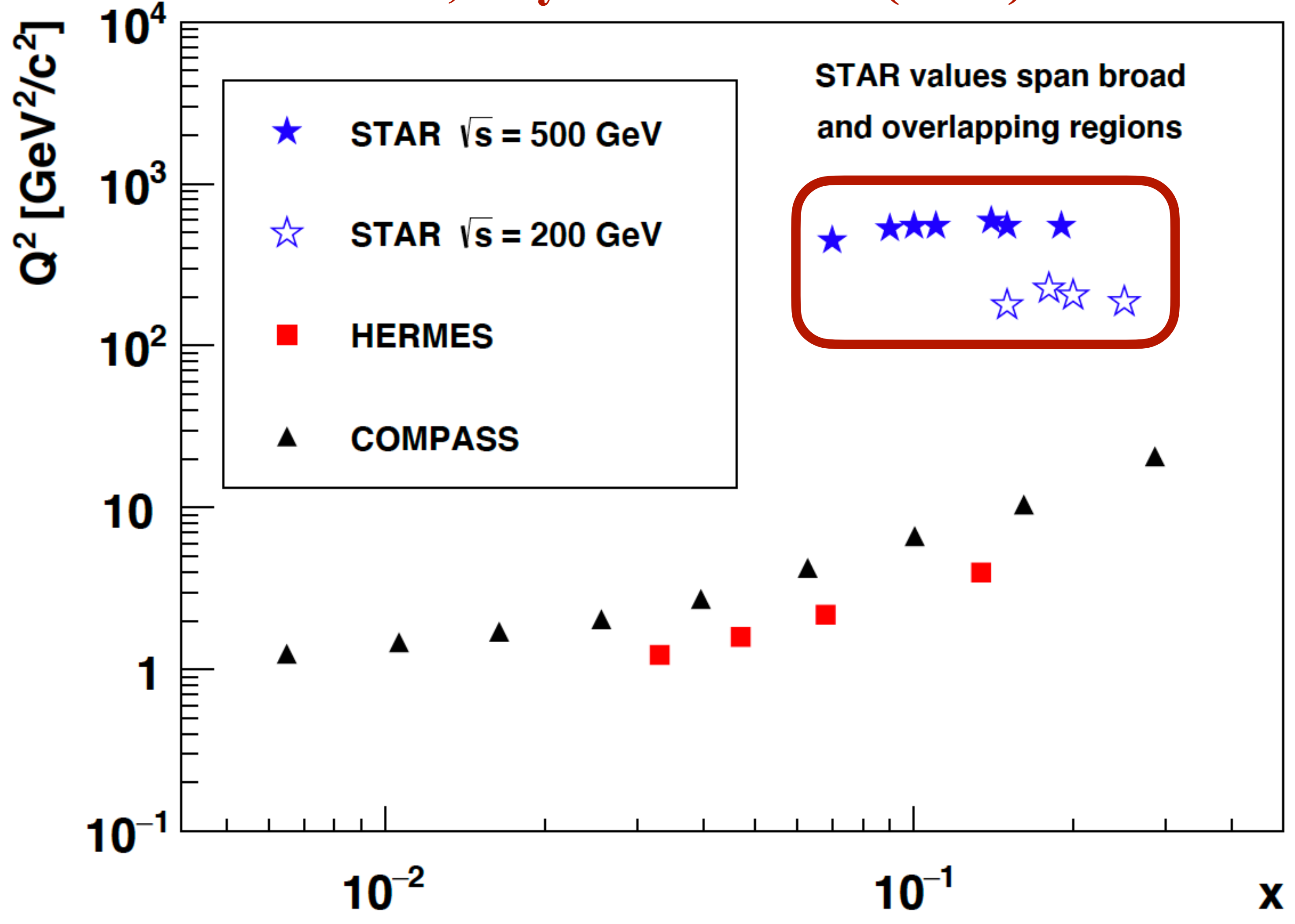
2012, 2015 → **New Measurements**

- **New Collins analysis is based on 2012+2015 datasets and IFF analysis is based on 2015 dataset.**
- **STAR covers a similar range in momentum fractions (*x*) to that of SIDIS experiments with much higher Q^2.**
- **Analysis is performed in mid-pseudorapidity region ($|\eta| < 1$).**
- **Statistical precision is significantly improved with Run 2015 data, in combination with 2012 data.**

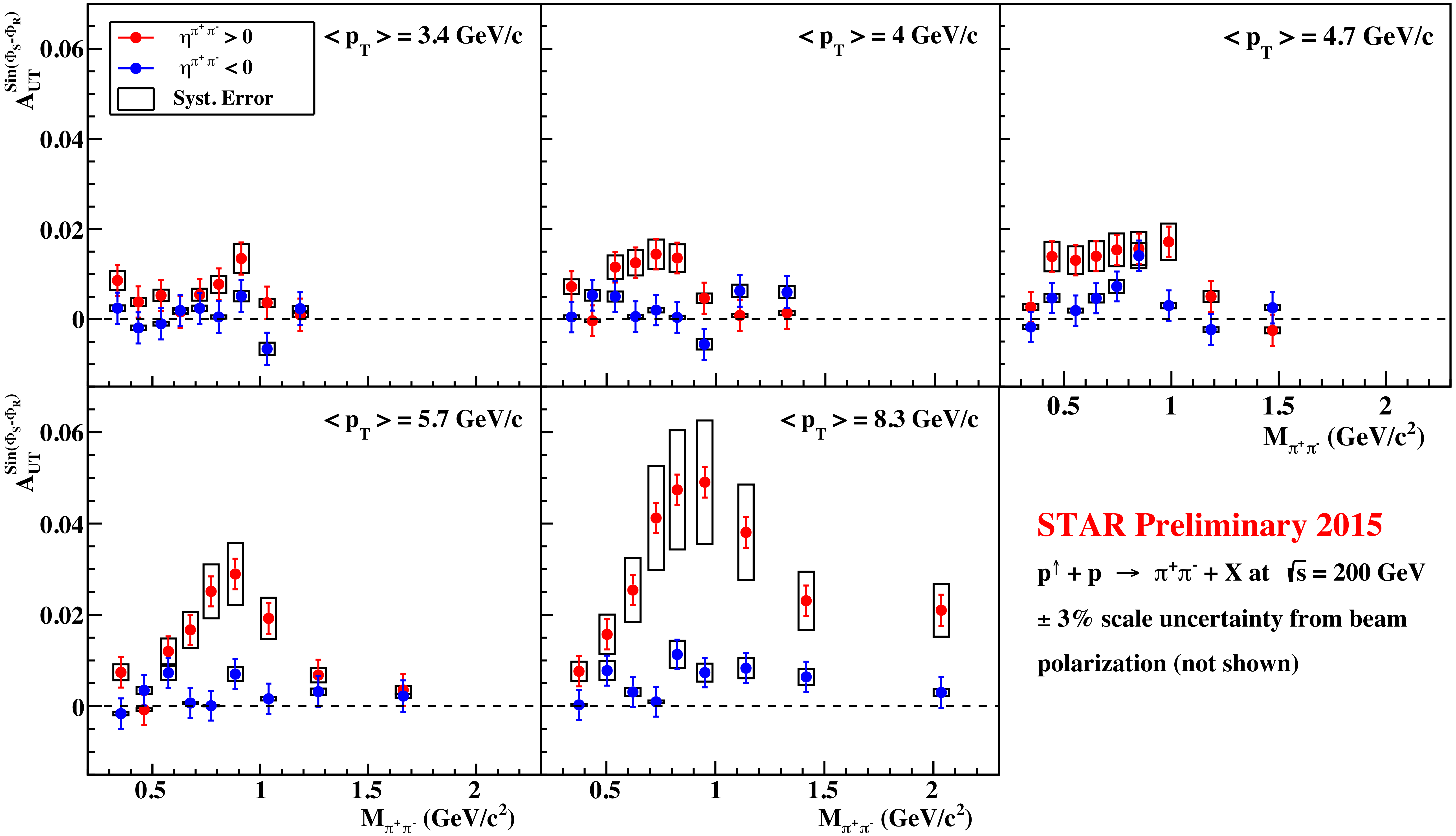
STAR, Phys. Rev. D 97 (2018) 32004



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

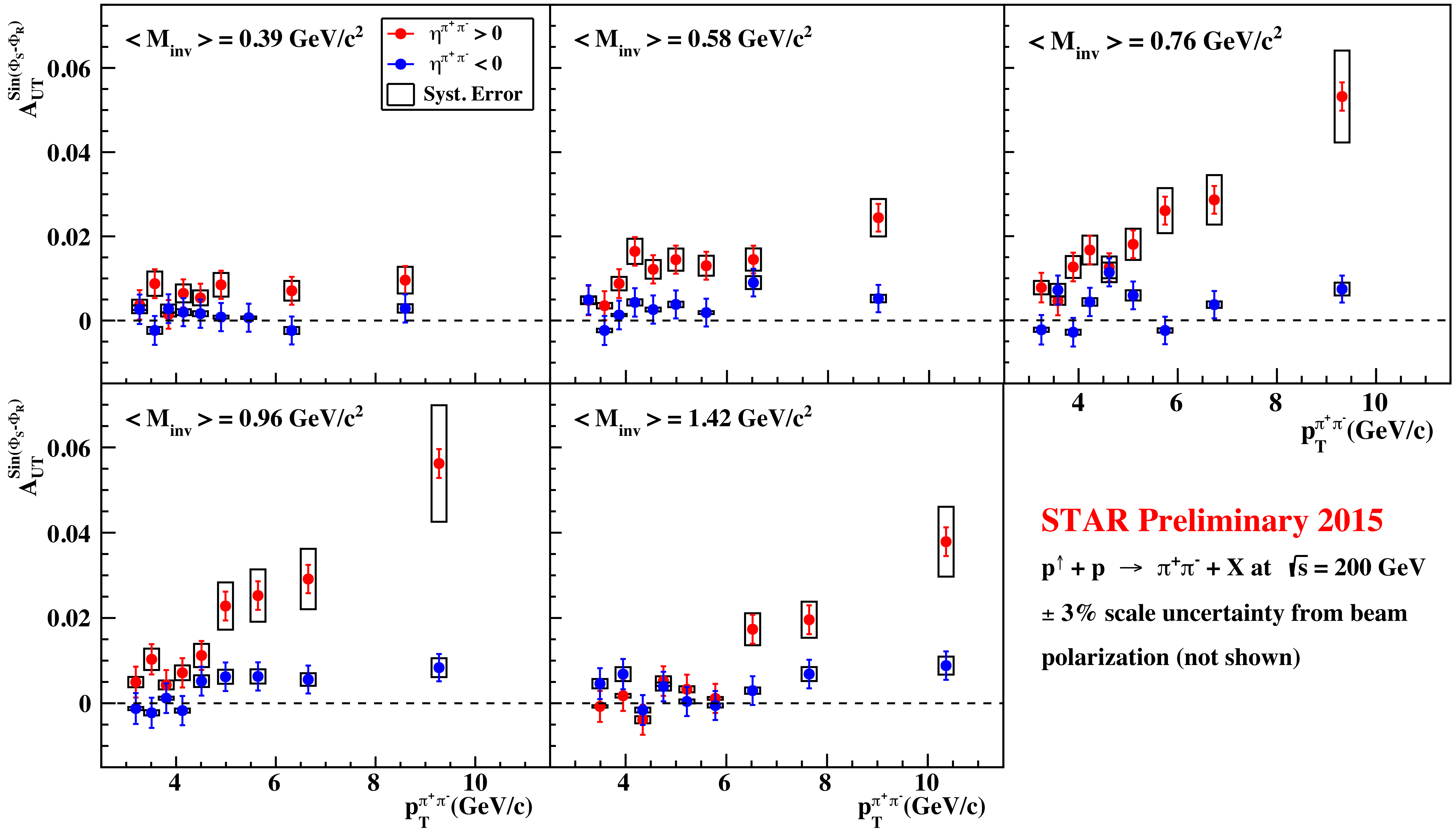


New IFF Preliminary Results from STAR 2015 Data: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$



- $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$ in $\eta^{\pi^+\pi^-} > 0$ and $\eta^{\pi^+\pi^-} < 0$ regions for five $p_T^{\pi^+\pi^-}$ bins. In $\eta^{\pi^+\pi^-} > 0$, enhanced $A_{UT}^{sin(\phi_s-\phi_R)}$ signal at $M_{inv}^{\pi^+\pi^-} \sim 0.8\ GeV/c^2$ (close to $M_\rho \sim 0.775\ GeV/c^2$).
- Small backward asymmetries.
- Systematic uncertainty includes effects related to particle identification (PID) and trigger bias.

New IFF Preliminary Results from STAR 2015 Data: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$



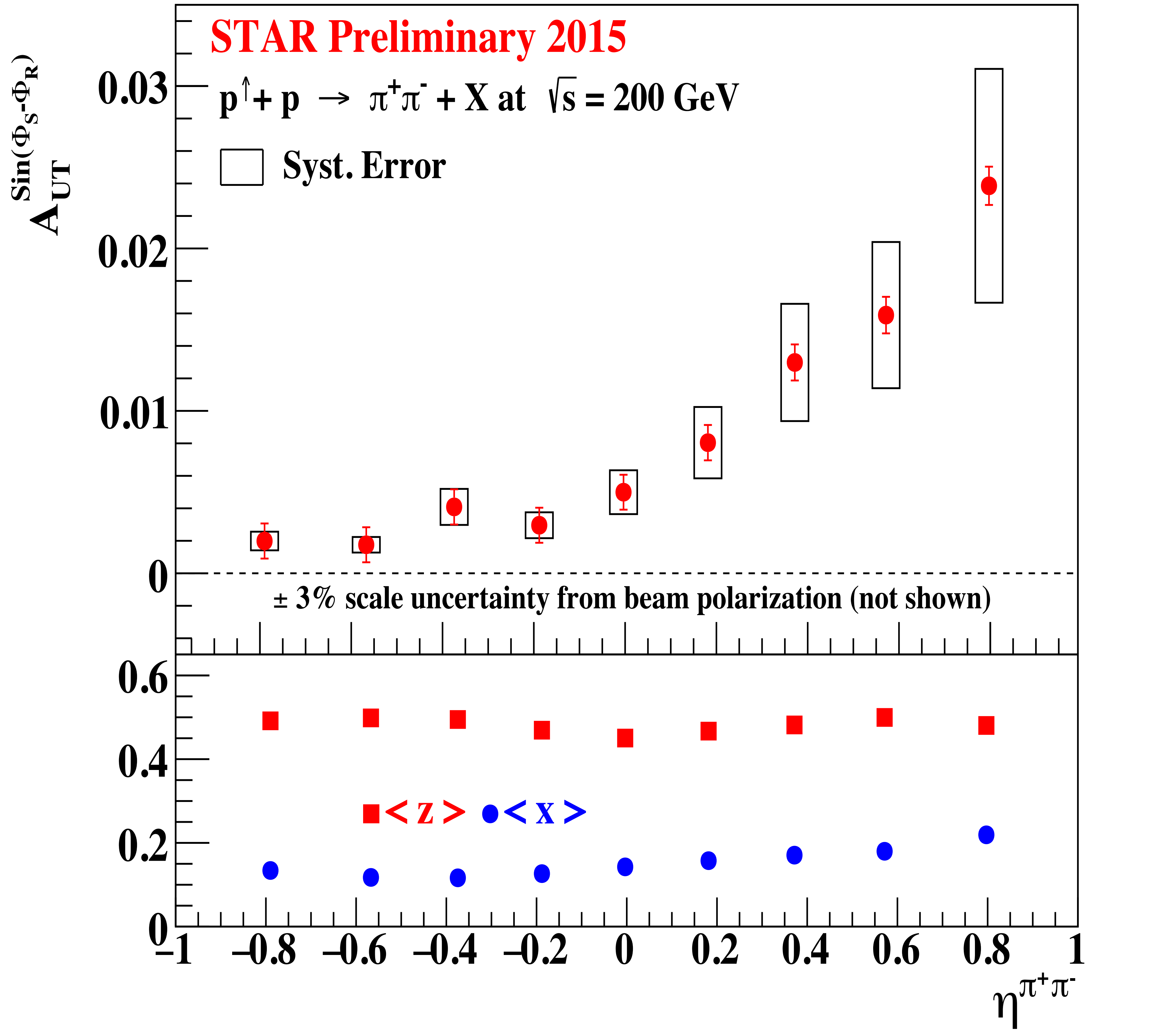
STAR Preliminary 2015

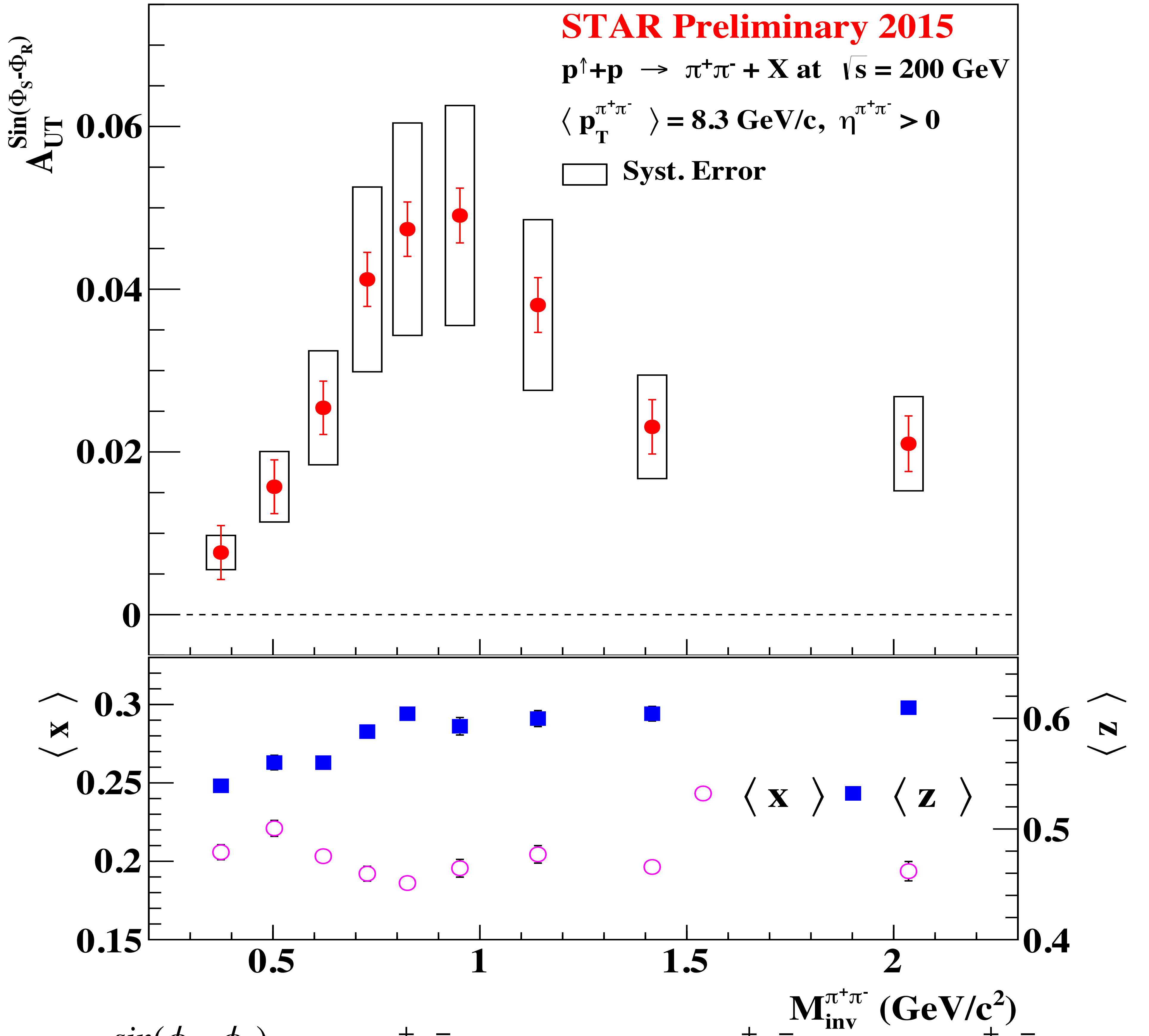
$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

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

- $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$ in $\eta^{\pi^+\pi^-} > 0$ and $\eta^{\pi^+\pi^-} < 0$ regions for five $M_{inv}^{\pi^+\pi^-}$ bins. Large forward asymmetries, which are more prominent when $< M_{inv}^{\pi^+\pi^-} > \sim M_\rho$.
- Small backward asymmetries.
- Systematic uncertainty includes effects related to PID and trigger bias.

New IFF Preliminary Results from STAR 2015 Data



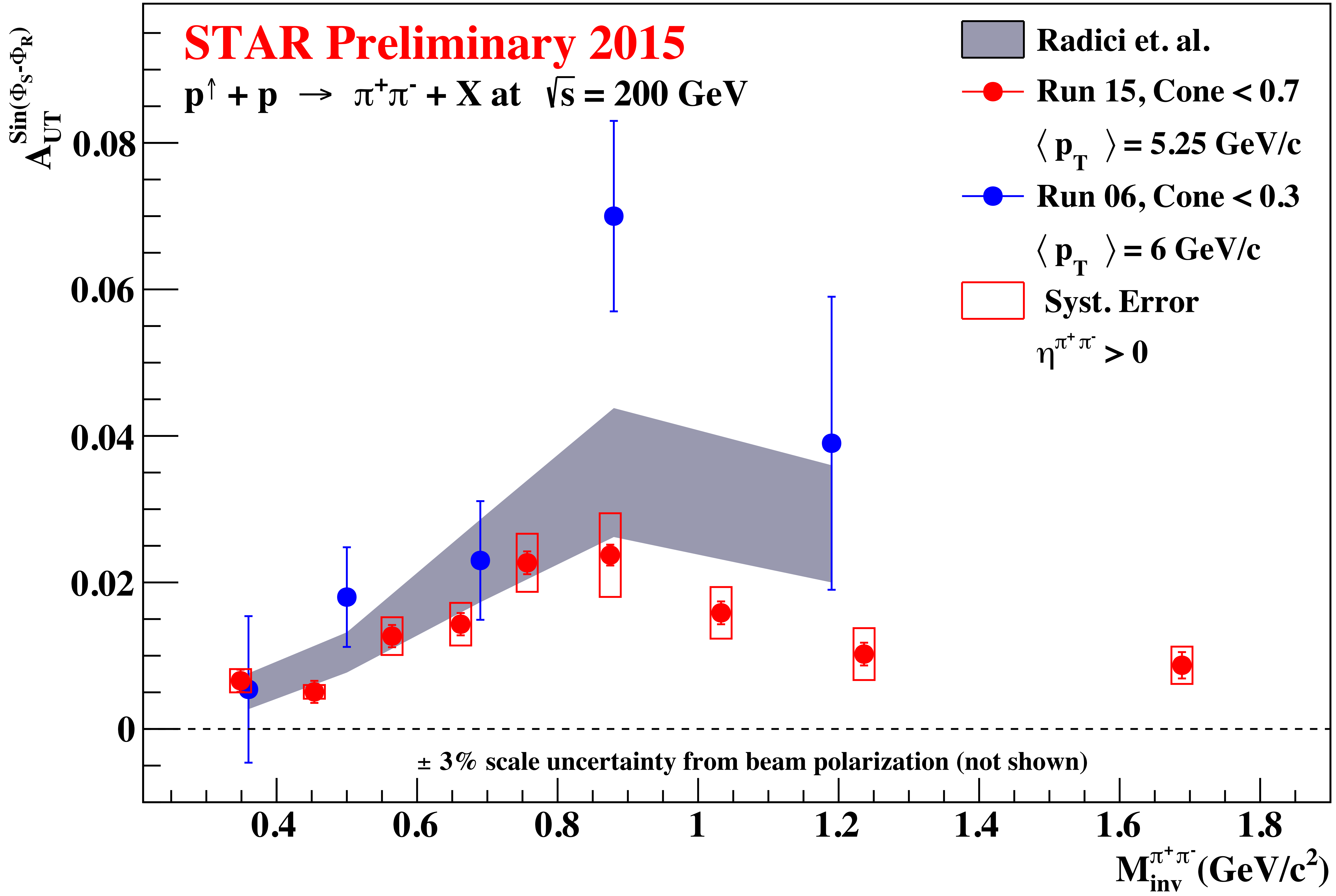


- $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $\eta^{\pi^+\pi^-}$, integrated over $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$ (*top panel*). <x> and <z> in corresponding $\eta^{\pi^+\pi^-}$ bins from simulation (*bottom panel*).
- Higher $A_{UT}^{sin(\phi_s-\phi_R)}$ in $\eta^{\pi^+\pi^-} > 0$, which corresponds to higher x region.
- $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$ for highest $p_T^{\pi^+\pi^-}$ bin in $\eta^{\pi^+\pi^-} > 0$ region (*top panel*). <x> and <z> in corresponding $M_{inv}^{\pi^+\pi^-}$ bins from simulation (*bottom panel*).

$$z \rightarrow \frac{E_{pair}}{E_{quark}}$$

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

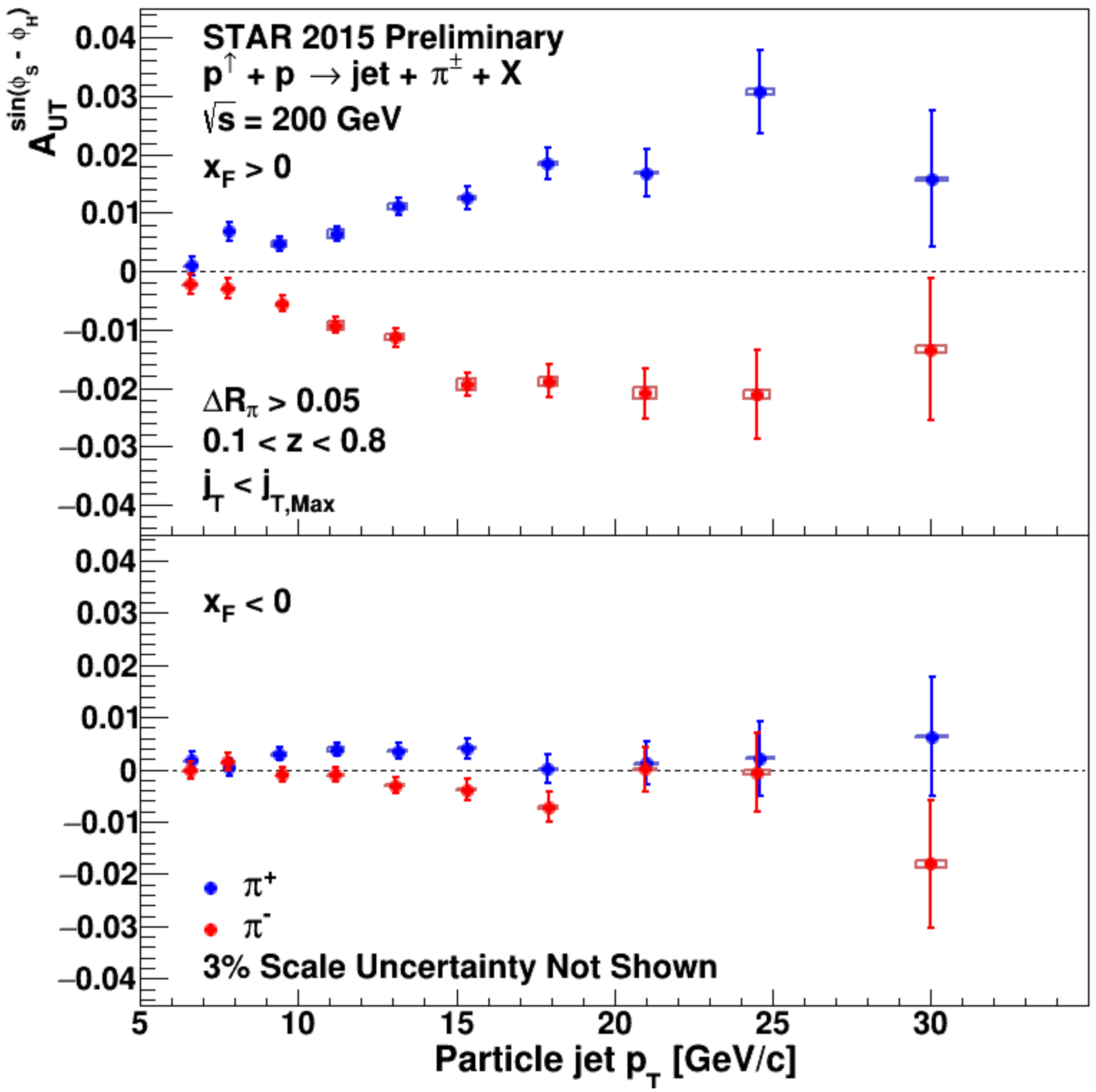
STAR IFF Results at √s = 200 GeV :



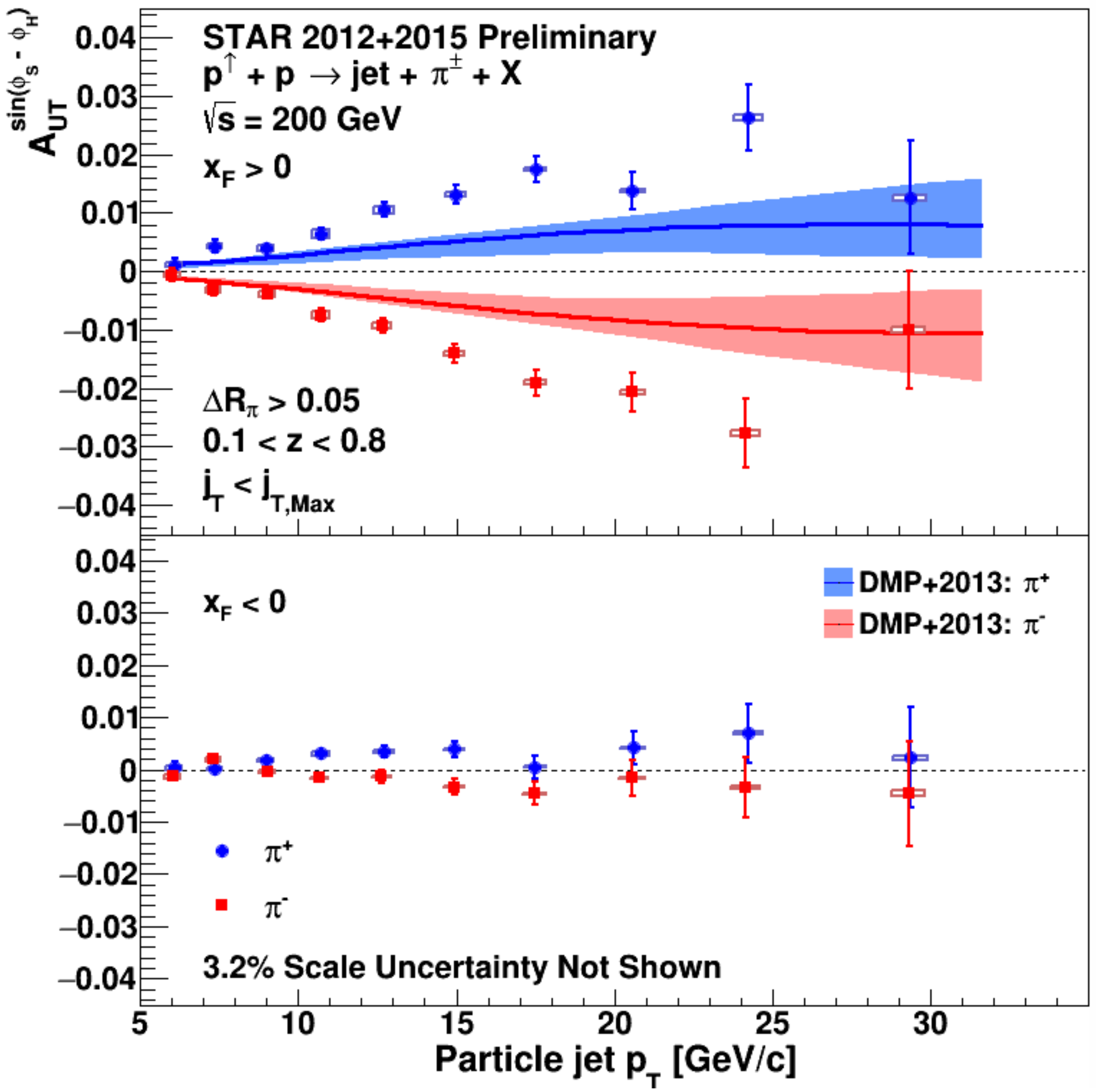
- STAR $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$ integrated over $p_T^{\pi^+\pi^-}$ in $\eta^{\pi^+\pi^-}$> 0 region, compared with the model calculation.
- Enhancement around $M_{inv}^{\pi^+\pi^-} \sim M_\rho$ can be observed, which is consistent with the theory prediction.
- Large improvement in the statistical precision in 2015 result than that of 2006.
- Systematic uncertainty includes effects related to PID and trigger bias.

New Collins Results from STAR 2012+15 Data

- Significant non-zero Collins asymmetries are observed with statistical precision better than previous STAR measurement.
- Collins asymmetry is positive for π^+ and negative for π^-.



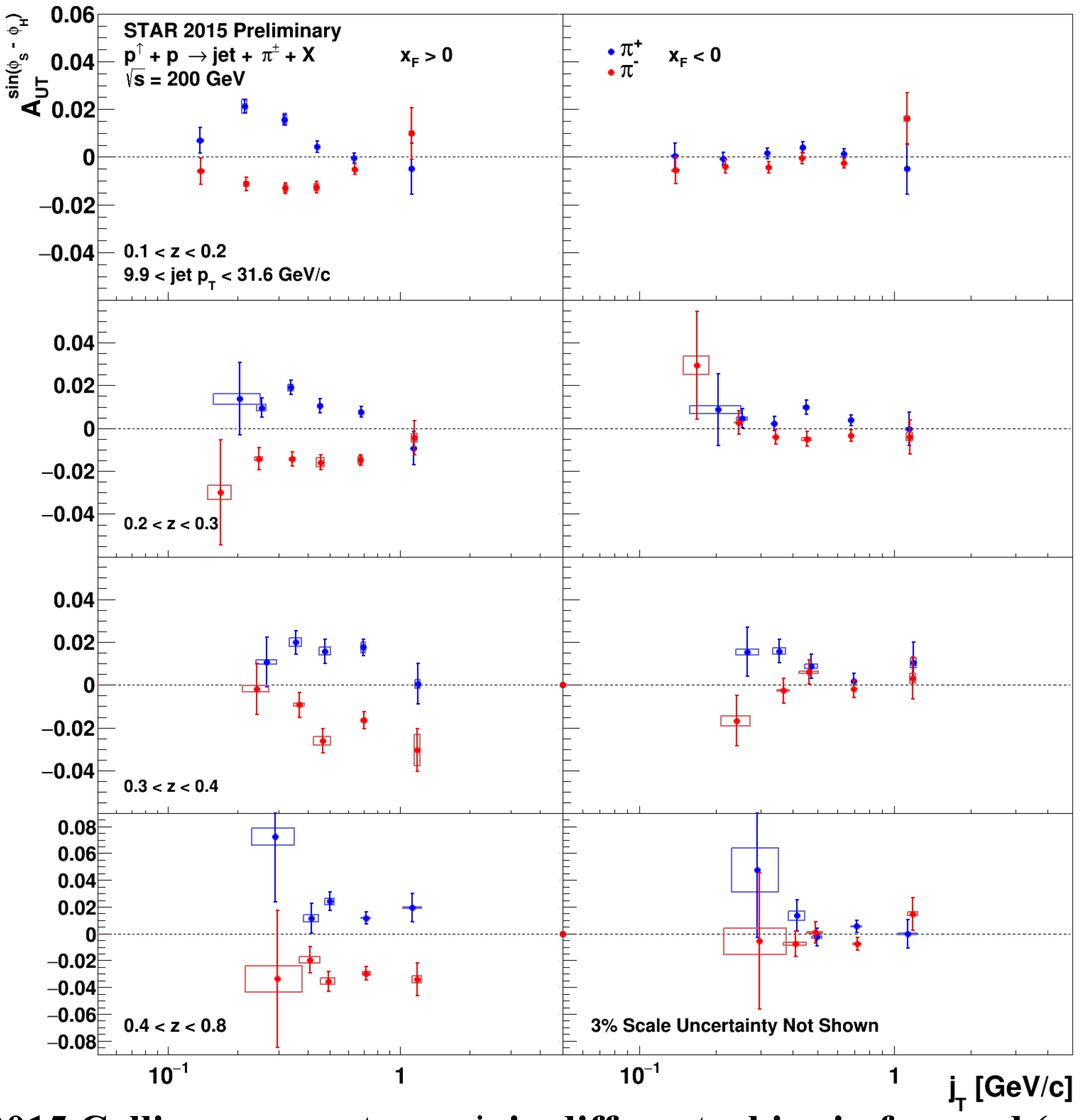
2015 Collins asymmetry vs particle jet p_T for $\pi^\pm$ in $x_F > 0$ (top) and $x_F < 0$ (bottom).

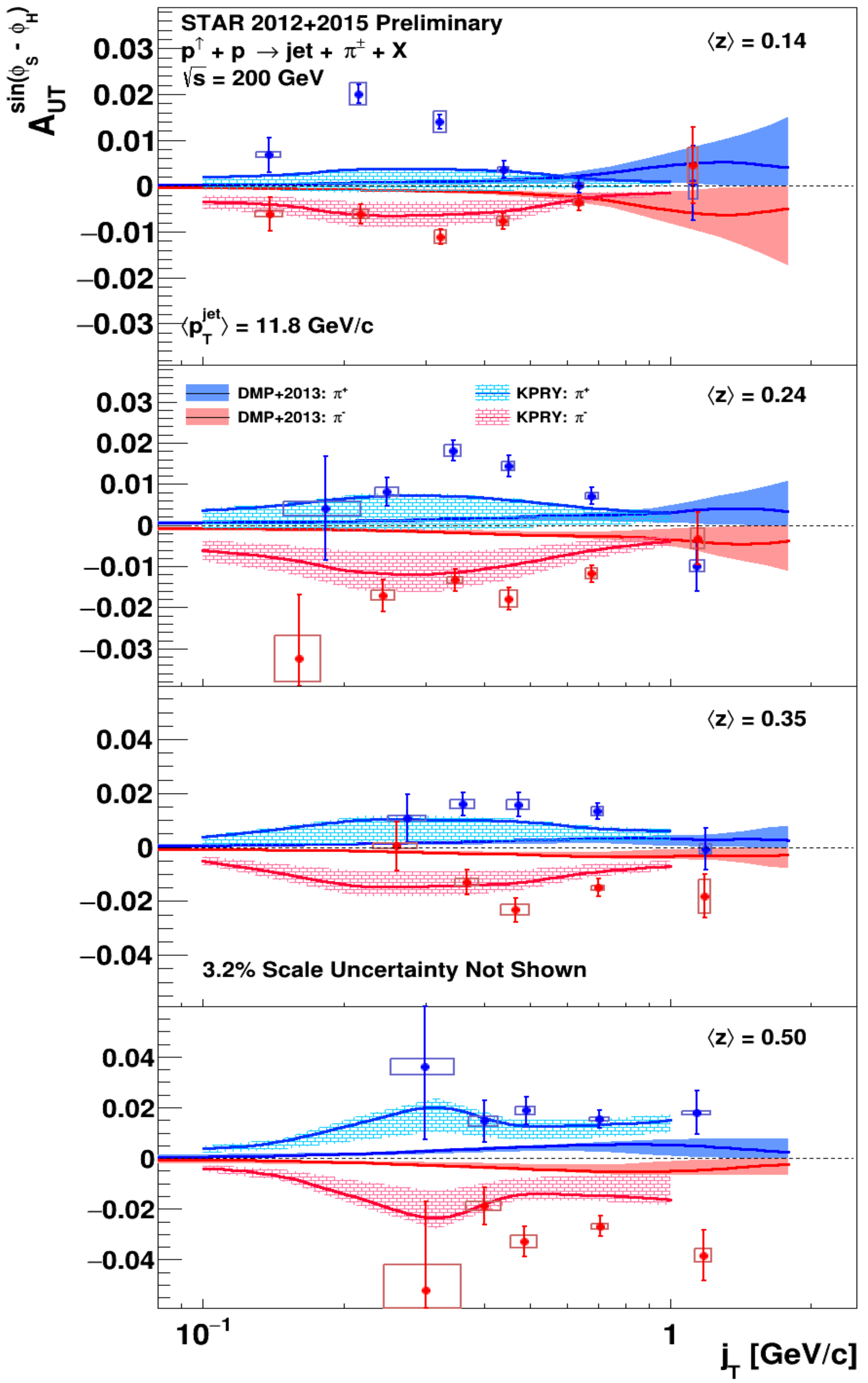


2012+2015 Collins asymmetry vs particle jet p_T for $\pi^\pm$ in $x_F > 0$ (top) and $x_F < 0$ (bottom).

- $j_T \to$ ***pion momentum transverse to the jet axis.***
- $z \to \frac{p_\pi}{p_{jet}}$

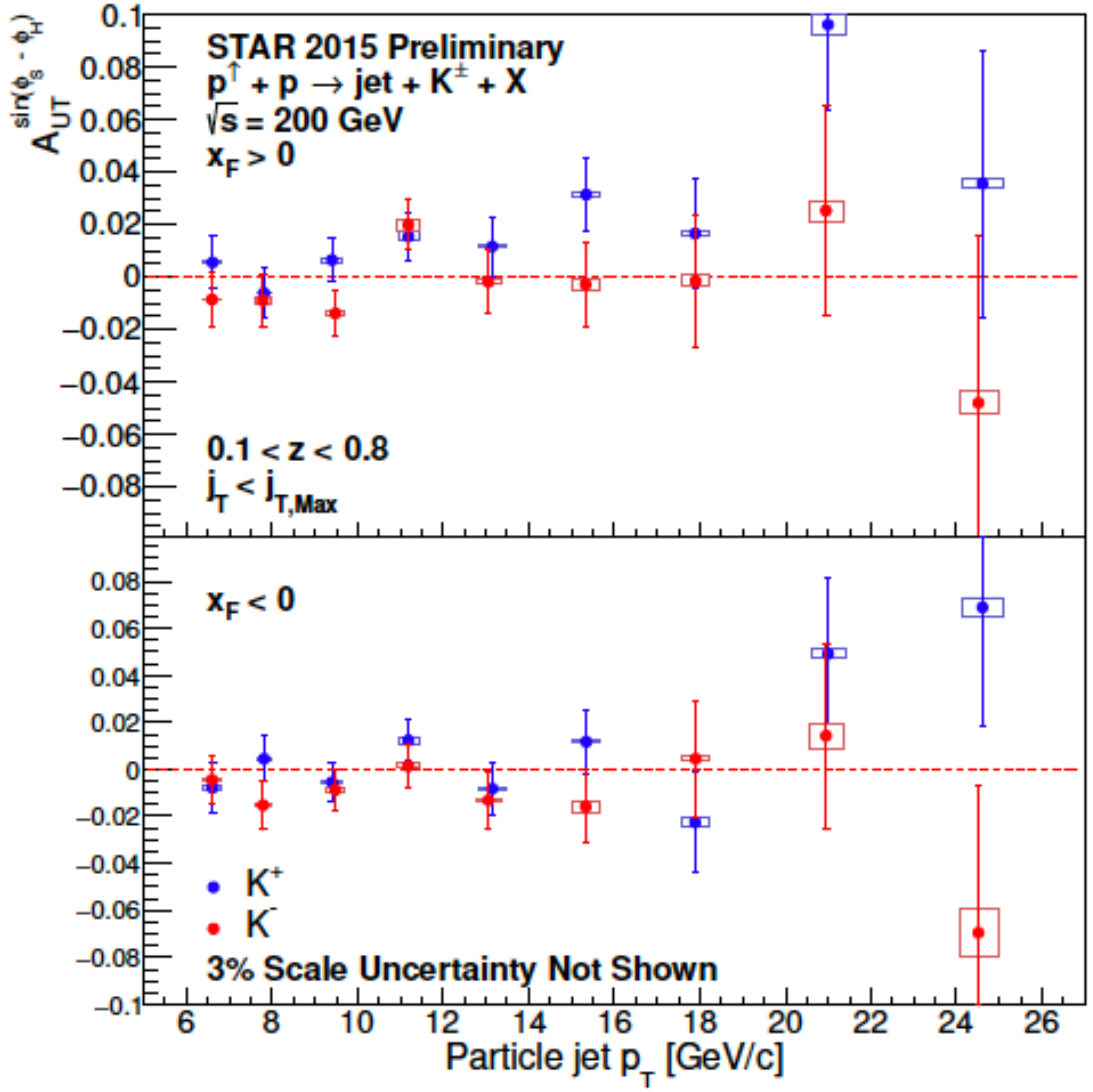
New Collins Results from STAR 2012+2015 Data

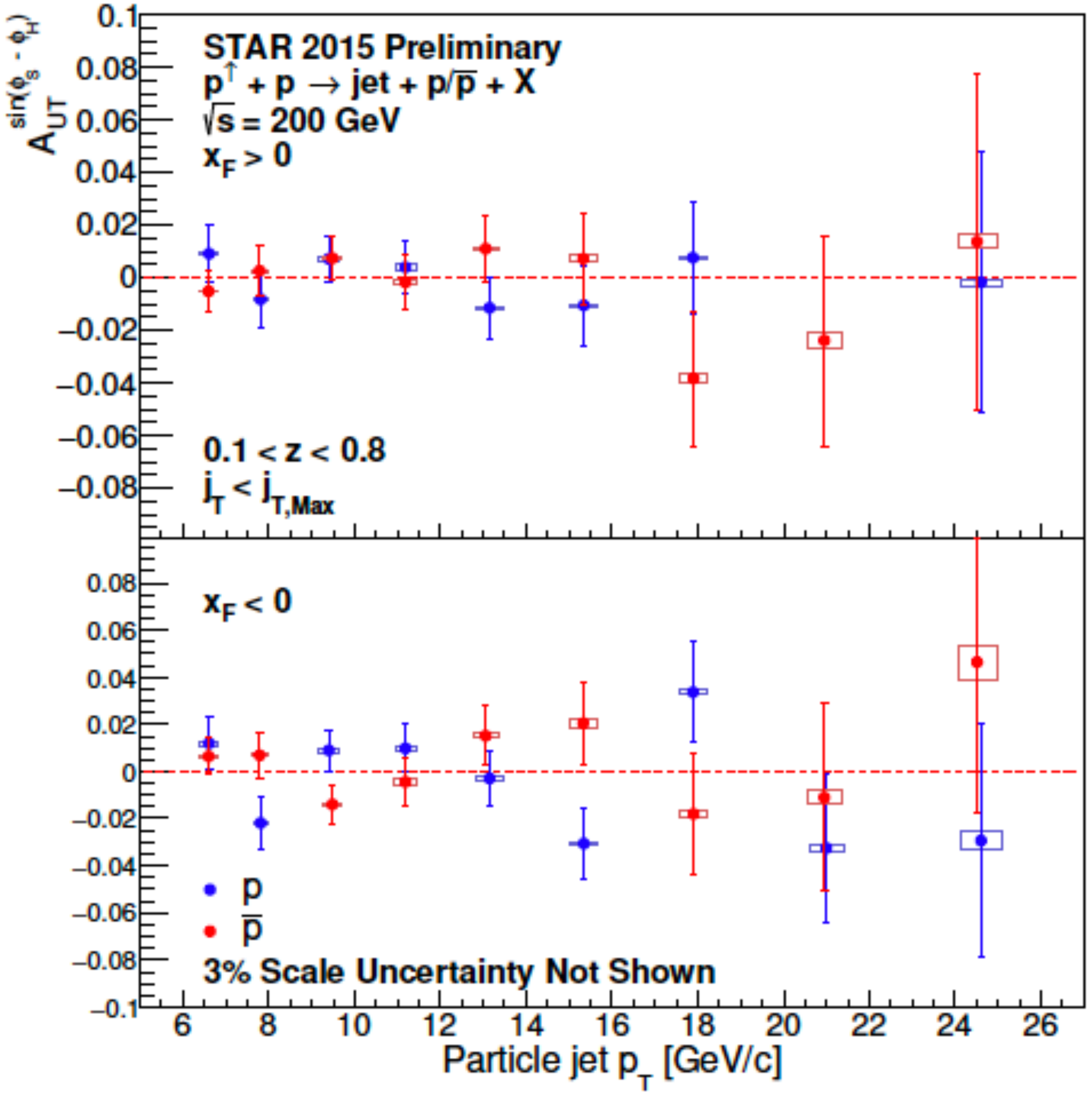




- **2015 Collins asymmetry vs j_T in different z-bins in forward ($x_F > 0$) (*left panel*) and backward ($x_F < 0$) jet scattering direction (*right panel*).**
- **2012+2015 Collins asymmetry vs j_T for $\pi^{\pm}$ in different z-bins in forward ($x_F > 0$) jet direction.**

New Collins Results for $K^{\pm}$ and $p(\bar{p})$ from STAR 2015 Data





- K^+ Collins asymmetries positive for forward jets, consistent within the currently large statistical uncertainties with the π^+ asymmetries.
- Collins asymmetries for $p(\bar{p})$ are consistent with zero, within statistical precision.
- Sivers and Collins-like asymmetries are also extracted, which are consistent with zero (See backup slide 17).

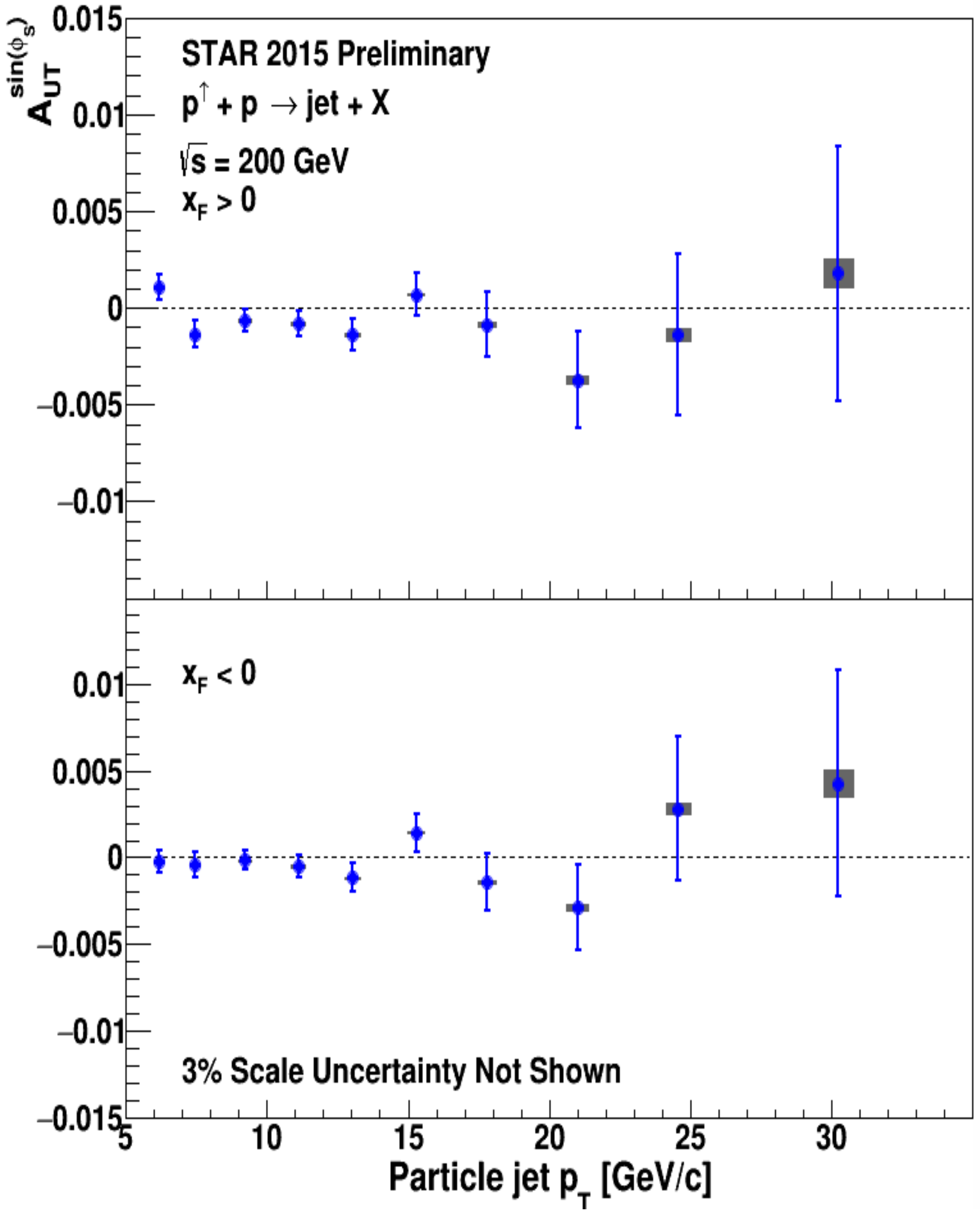
Summary

- Single spin asymmetries, sensitive to the transversity, have been measured.
- **IFF asymmetries from the STAR 2015 dataset:**
  - Azimuthal correlation of $\pi^+\pi^-$, sensitive to transversity and IFF.
  - Large forward asymmetries with a prominent peak at $M_{inv}^{\pi^+\pi^-} \sim M_\rho$, consistent with the theory.
  - Large systematic uncertainty. A major contribution from PID, estimated by conservative approach.
  - PID systematic uncertainty will be significantly reduced by implementing StartLessTOF and improving the background estimation.
- **Collins asymmetries from the STAR 2012+2015 datasets:**
  - azimuthal correlation of $\pi^\pm$, $K^\pm$, and $p(\bar{p})$, sensitive to the transversity and Collins FF.
  - Large $\pi^\pm$ asymmetries in $x_F > 0$ region, consistent with the previous measurement.
  - Zero kaon and proton asymmetries, within statistical precision.
- The statistical precision of the new 2015 results is significantly improved compared to the previous STAR measurements.
- Ongoing IFF and Collins analyses using the 2017 dataset at √s = 510 GeV ($L_{int} \sim 350\ pb^{-1}$).
- Planned unpolarized di-hadron cross-section measurement, with these high precision asymmetry results, will help to constrain transversity.

Back Up

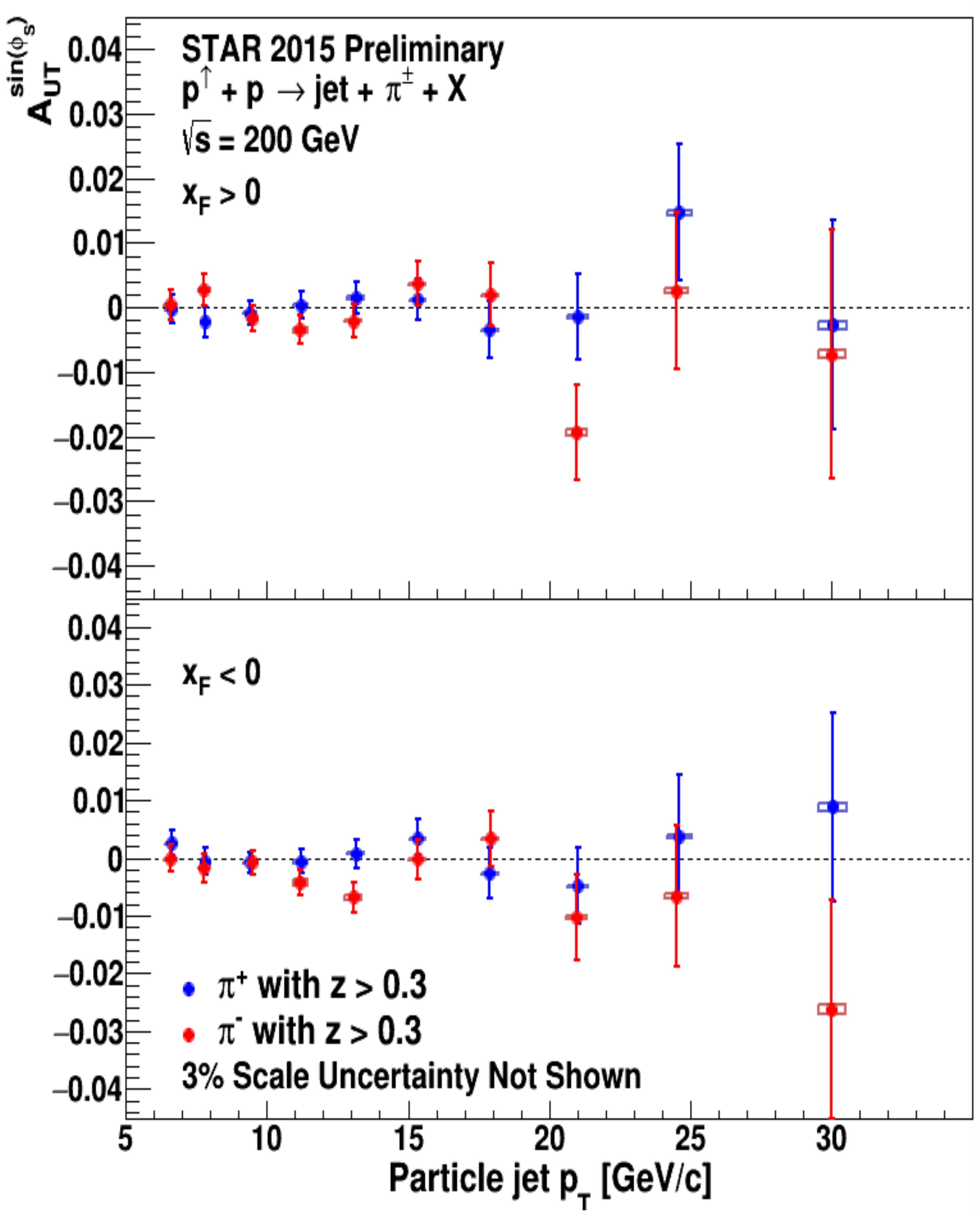
New Sivers and Collins-Like Results from STAR 2015 Data

Sivers (*jet*)



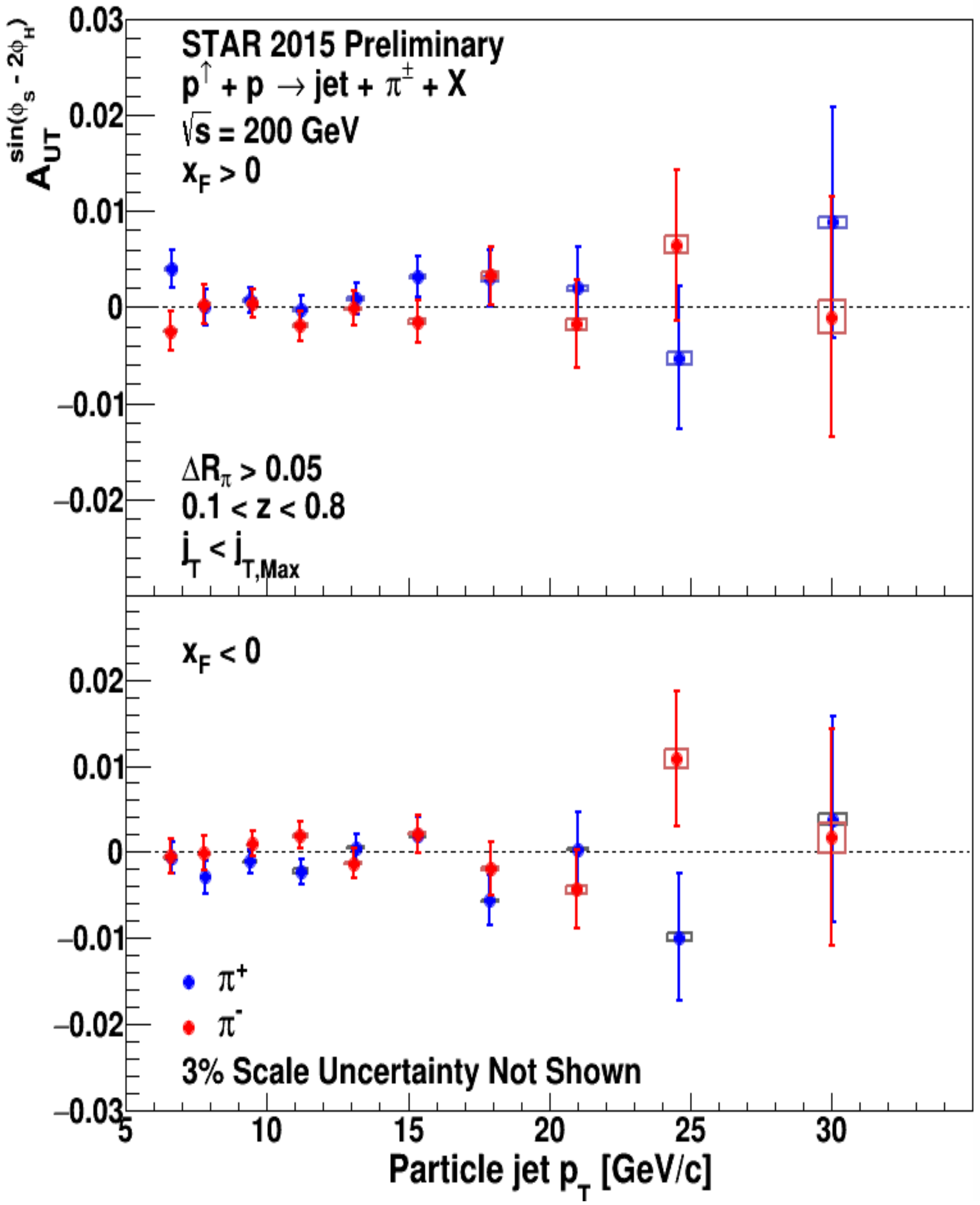
- Inclusive jet asymmetry, sensitive to the gluon Sivers effect.

Sivers ($jet + \pi^{\pm}$)



- Jets with high-*z* pions, to enhance sensitivity to the *u*- and *d-quark* Sivers effects.

Collins-Like ($jet + \pi^{\pm}$)



- Sensitive to the linearly polarized gluons in a polarized proton.

- **Asymmetries sensitive to the Sivers and Collins-like effects are consistently small.**

Supplemental Information For Slide 3 and 4

- **Collins Channel:**

$$p^{\uparrow} + p \rightarrow jet + h^{\pm} + X$$

- **Collins effect involves coupling of $h_1^q(x)$ and Collins FF leading to azimuthal modulation of charged hadrons within jets.**

$$A_{UT}^{sin(\phi)} = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$

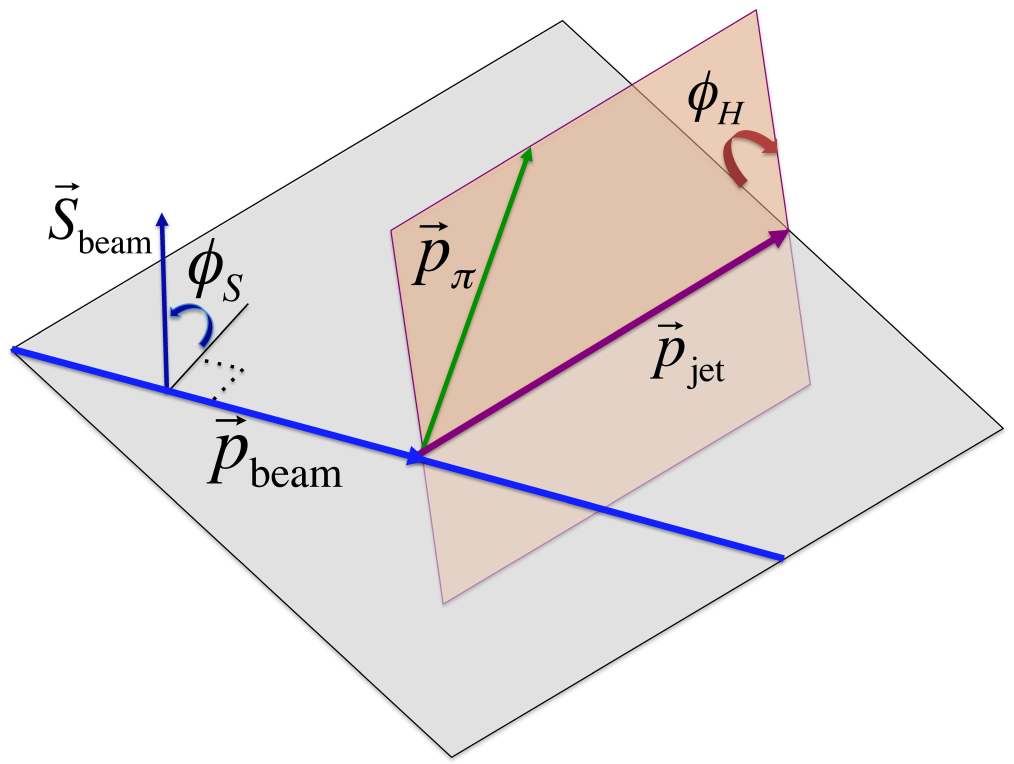
$$d\sigma^{\uparrow}(\phi_s, \phi_H) - d\sigma^{\downarrow}(\phi_s, \phi_H)$$

$$\sim d\Delta\sigma_0 sin(\phi_s) \quad \leftarrow \text{Sivers}$$

$$\text{Collins} \rightarrow + d\Delta\sigma_1^- sin(\phi_s - \phi_H) + d\Delta\sigma_1^+ sin(\phi_s + \phi_H)$$

$$\text{Collins-Like} \rightarrow + d\Delta\sigma_2^- sin(\phi_s - 2\phi_H) + d\Delta\sigma_2^+ sin(\phi_s + 2\phi_H)$$

Azimuthal angle definition for Collins channel



- **Interference Fragmentation Function (IFF) Channel:**

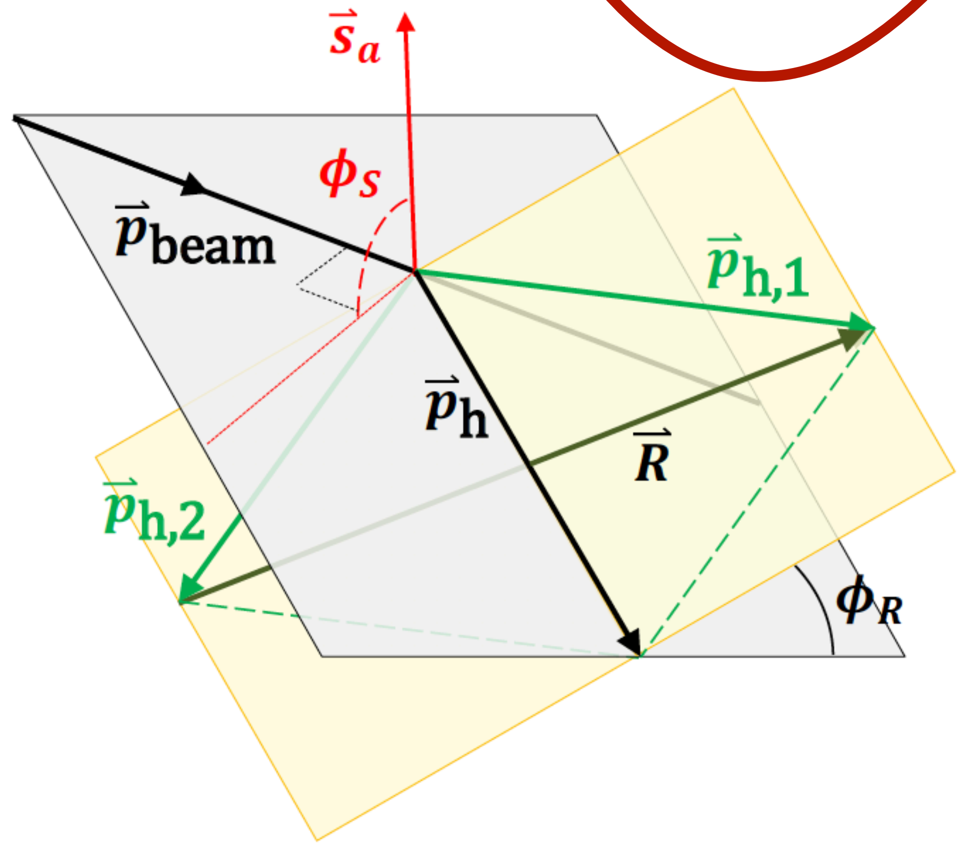
$$p^{\uparrow} + p \rightarrow h^+ h^- + X$$

- **$h_1^q(x)$ couples with IFF leading to azimuthal modulation of oppositely charged hadron-pairs.**
- **No jet reconstruction required.**
- **Collinearity is preserved.**

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto h_1^q \otimes H_1^{\sphericalangle}$$

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

Azimuthal angle definition for IFF channel



- **Though the both beams are polarized, single spin asymmetry is achieved by integrating over the polarization of the one beam.**

Jet Reconstruction And Selection Criteria For Collins Effect

Jet Reconstruction:

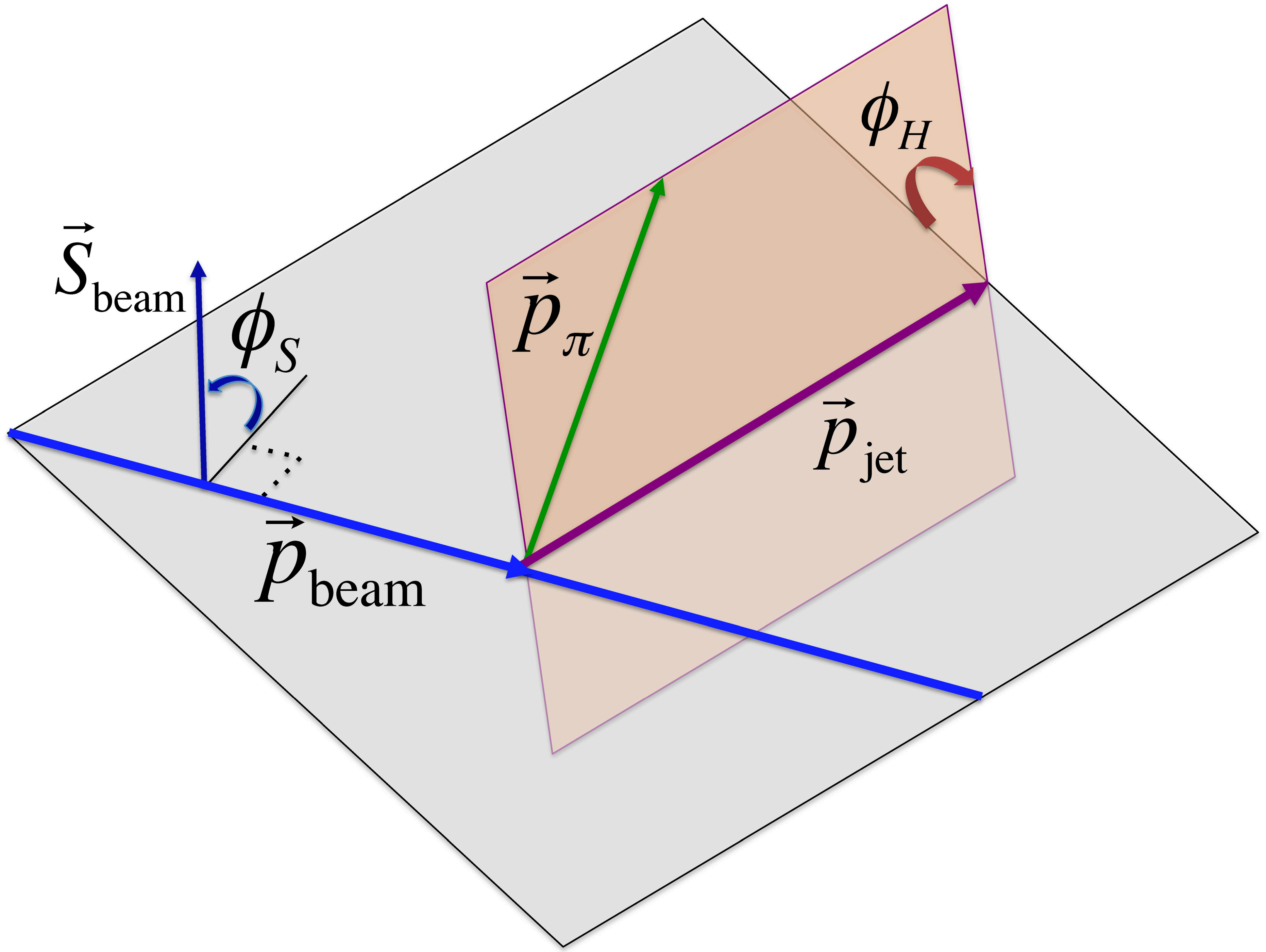
- **anti-K_T Algorithm**
- **Radius = 0.6**

Jet level cuts:

- **$|z_{vertex}|$ < 60 cm , Vertex Ranking > 1e6**
- $p_T^{jet} > 6\ GeV/c$
- $R_T^{jet} < 0.95$
- **Jet** $-0.9 < \eta < 0.9$ **and Jet** $-0.8 < \eta_{detector} < 0.9$
- **No jet has track** $p_T > 20\ GeV/c$
- **Jet track p_T sum > 0.5**

Hadron level cuts:

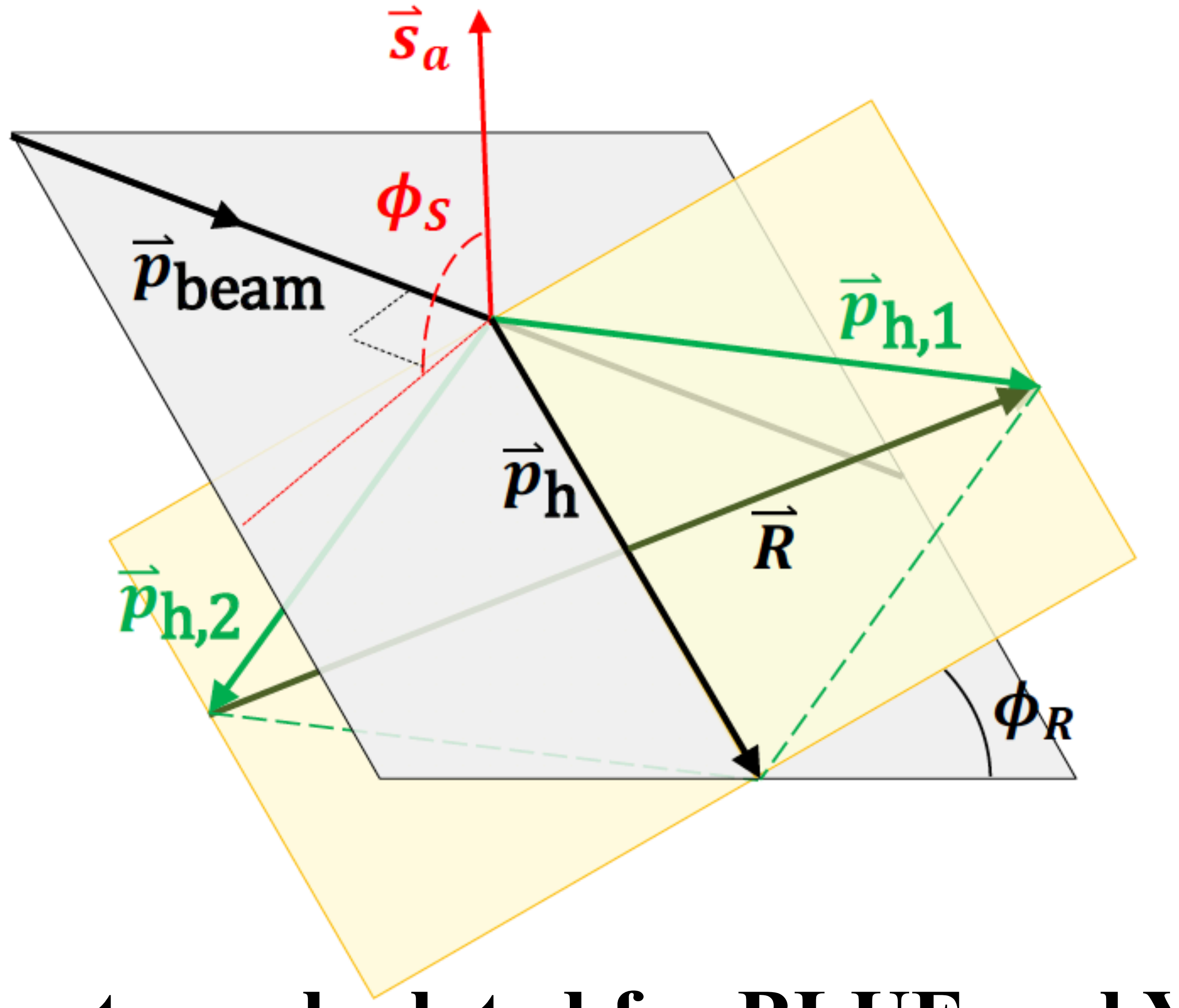
- **hadron z > 0.1**
- **ΔR between jet and hadron > 0.05**



Pion-Pair Formation And Selection Cuts For IFF Channel

- **No jet reconstruction required.**
- **All possible charged pion-pair ($\pi^+\pi^-$) is formed in every events as shown in the diagram below.**
- **$\pi^+\pi^-$ separation in eta-phi space (cone) < 0.7**
- **$\vec{R}$ always points to π^+ (the other way is also equally valid). Otherwise, random ϕ_R direction leads to diluted asymmetry.**

- **Track and pair level cuts are on the table.**



Event and track Selection Cuts	
Z-Vertex	< |60| cm
Triggers	JP1, JP2
Spin Configuration	51,53,83,85
Vertex Ranking	>1e6
Tracks	Primary
Track Dca	< 1 cm
Track p_T	>1.5 GeV
Track nHitsFit	>15
nSigmaPion	$-1<n\sigma_\pi<2$
Track Eta	$-1<\eta<1$
Cone ($\pi^+\pi^-$)	< 0.7
M_{inv} ($\pi^+\pi^-$)	$0.20 < M_{inv} < 4$ (GeV/c^2)
p_T-Pair($\pi^+\pi^-$)	$2.50 < p_T < 15.0$ (GeV/c)
η-Pair($\pi^+\pi^-$)	$-1 < \eta < 1$

- **Asymmetry calculated for BLUE and YELLOW beam separately. The Final asymmetry is the average of both.**