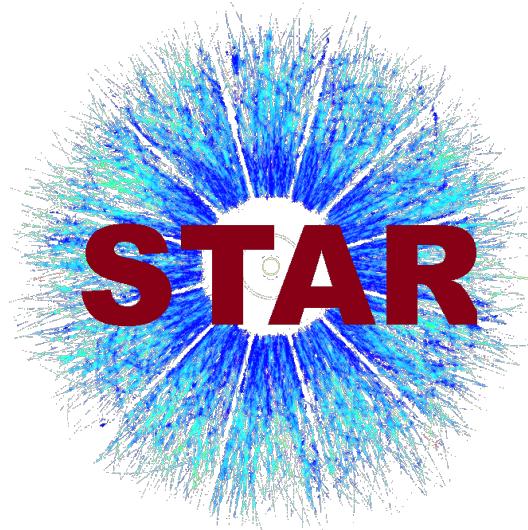


Measurements of Transverse Spin Dependent $\pi^+\pi^-$ Azimuthal Correlation Asymmetry and Unpolarized $\pi^+\pi^-$ Cross-Section in pp Collisions at $\sqrt{s} = 200$ GeV at STAR



Babu Pokhrel
for the STAR Collaboration
Nov. 26 - Dec. 1, 2023



Supported in part by:

Leading Twist Parton Distribution Functions (PDFs)

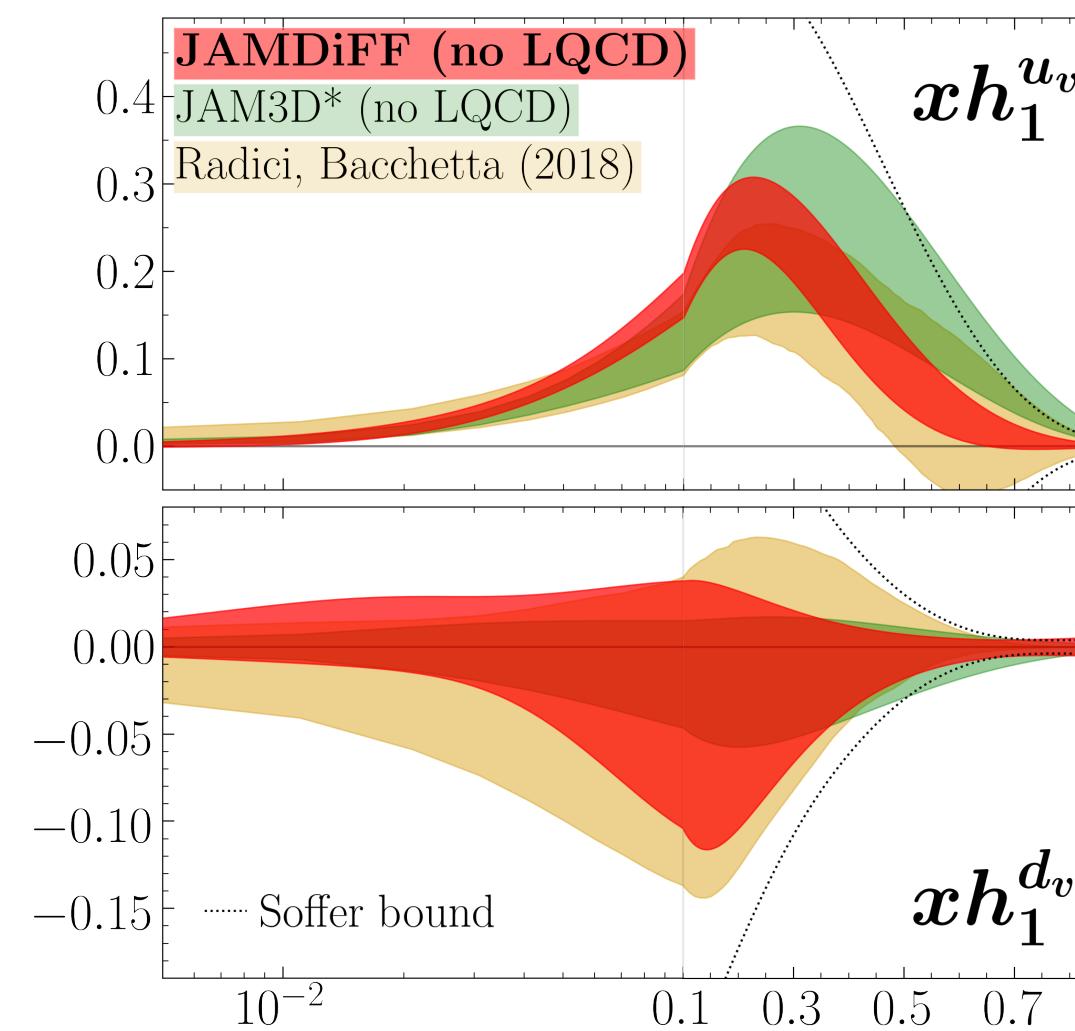
- Nucleon spin structure is described in terms of parton distribution functions (PDFs).

- Three **leading twist collinear PDFs**:

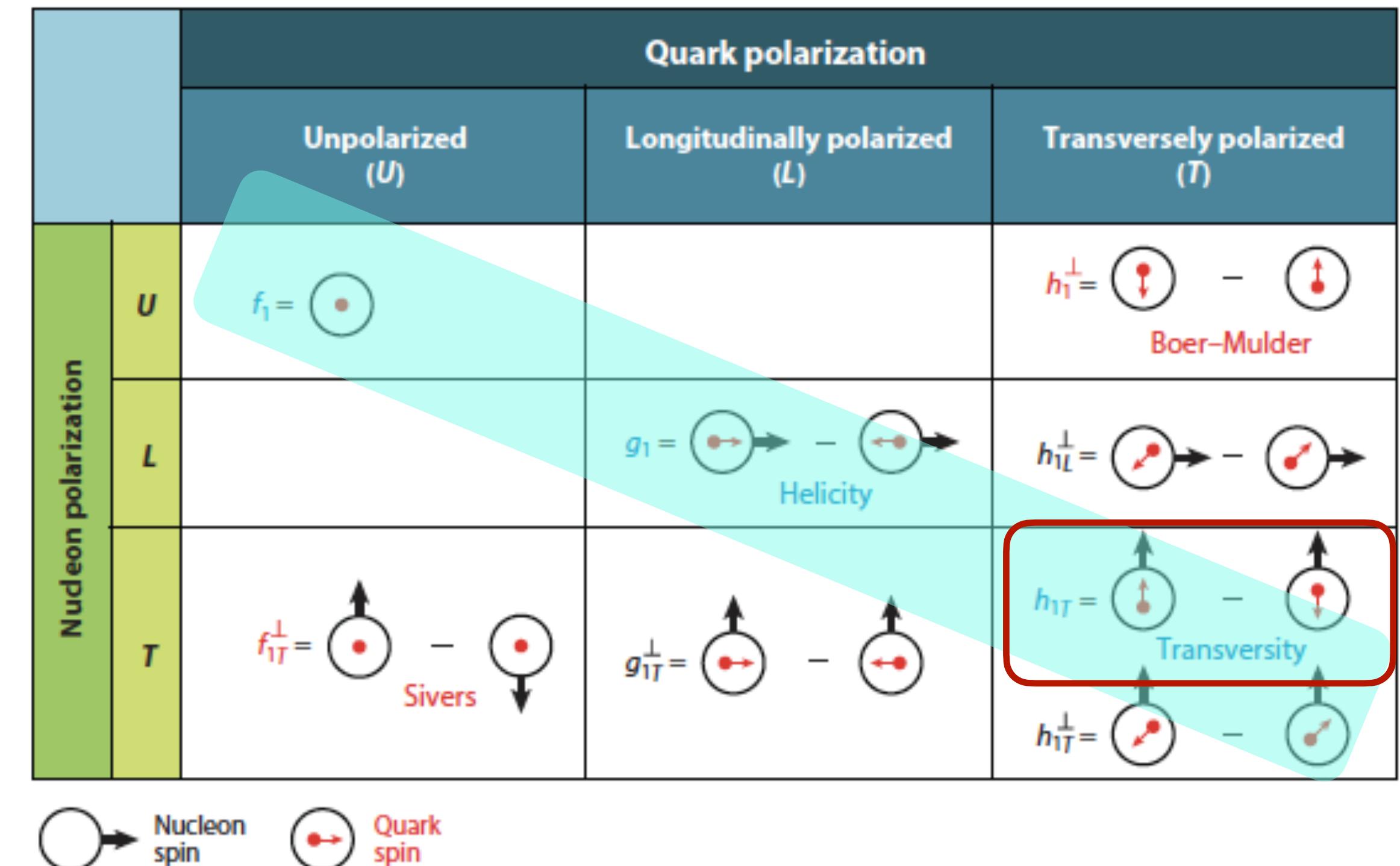
$f_1(x)$ = Unpolarized PDF

$g_1(x)$ = Helicity PDF

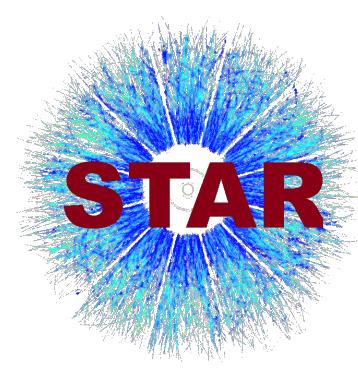
$h_1^q(x)$ = Transversity PDF



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



- $h_1^q(x)$ gives net transverse spin of parton in transversely polarized nucleon.
- $h_1^q(x)$ is chiral-odd, less known from experiments than $f_1(x)$ and $g_1(x)$.
- Its extraction requires coupling to another chiral-odd object, such as Interference Fragmentation Function (IFF) in dihadron (h^+h^-) production channel in polarized proton proton (pp) collisions.



Observables for $h_1^q(x)$ in pp via h^+h^- Channel

h^+h^- channel offers convenient access to observables constraining $h_1^q(x)$ in the collinear framework in polarized pp collisions.

Dihadron Channel: $p^\uparrow + p \rightarrow h^+h^- + X$

Bachetta & Radici
Phys.Rev.D 70 (2004) 094032

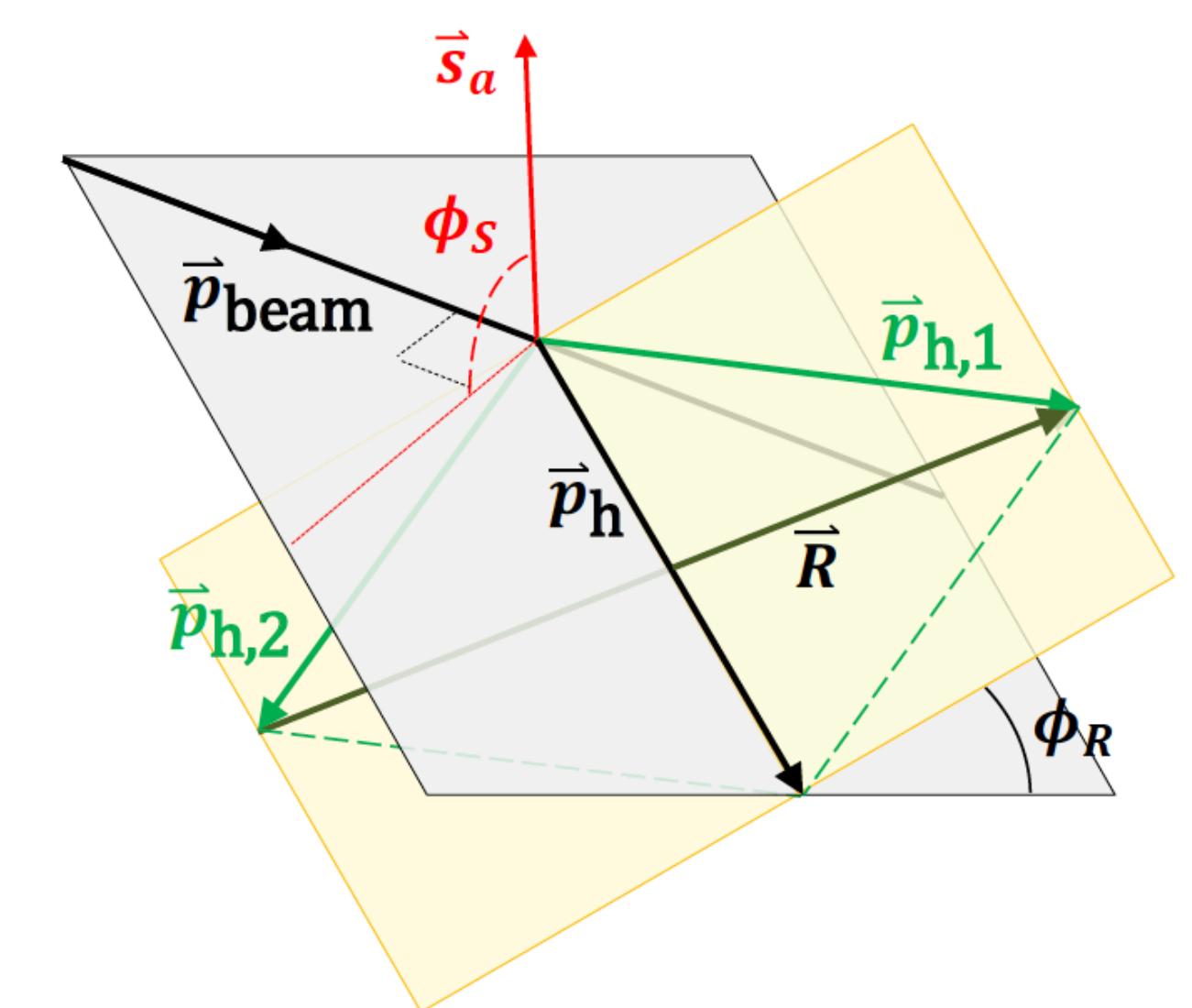
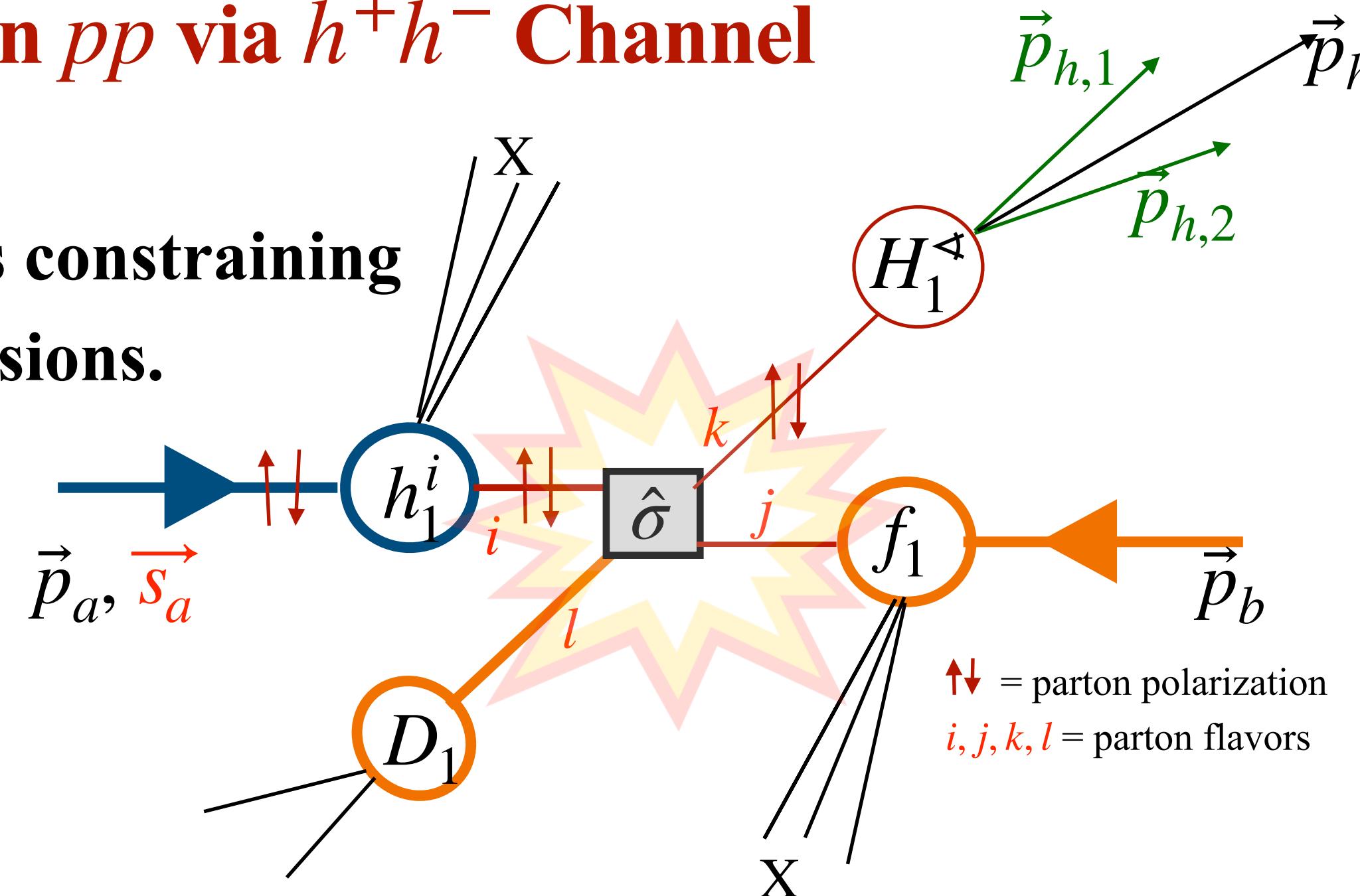
Polarized Cross Section:

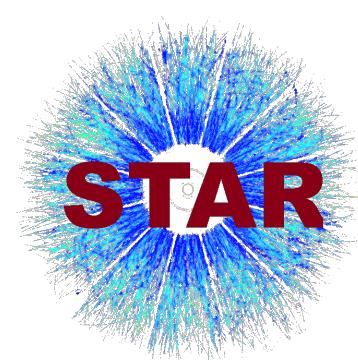
$$d\sigma_{UT}^{p_a^\uparrow p_b \rightarrow (h_1, h_2)X} \propto \sin(\phi_S - \phi_R) \sum_{i,j,k,l} \int dx_a \int dx_b \int dz h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) \frac{d\hat{\sigma}^{i^\uparrow j \rightarrow k^\uparrow l}}{d\hat{t}} H_1^{\leftarrow h_1 h_2 / k}(z, M_h^2)$$

Unpolarized Cross Section:

$$\vec{p}_a^\uparrow \leftrightarrow p_a, h_1^q \leftrightarrow f_1, H_1^{\leftarrow} \leftrightarrow D_1$$

$$d\sigma_{UU}^{p_a p_b \rightarrow (h_1, h_2)X} \propto \sum_{i,j,k,l} \int dx_a \int dx_b \int dz f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) \frac{d\hat{\sigma}^{ij \rightarrow kl}}{d\hat{t}} D_1^{h_1 h_2 / k}(z, M_h^2)$$





Observables for Transversity $h_1^q(x)$ in pp

- **Dihadron Azimuthal Correlation Asymmetry, A_{UT} , in $p^\uparrow + p \rightarrow h^+h^- + X$**

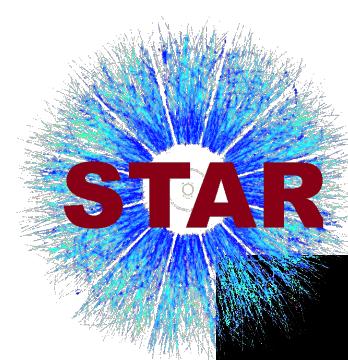
$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\sum_{i,j,k} h_1^{ilp_a}(x_a) f_1^{jl/p_b}(x_b) H_1^{\leftarrow h_1 h_2 / k}(z, M_h^2)}{\sum_{i,j,k} f_1^{ilp_a}(x_a) f_1^{jl/p_b}(x_b) D_1^{h_1 h_2 / k}(z, M_h^2)}$$

- Independent measurement of H_1^\leftarrow is required from e^+e^- experiments.
- $D_1^{h_1 h_2}$ is least known, specifically for gluon fragmentation.

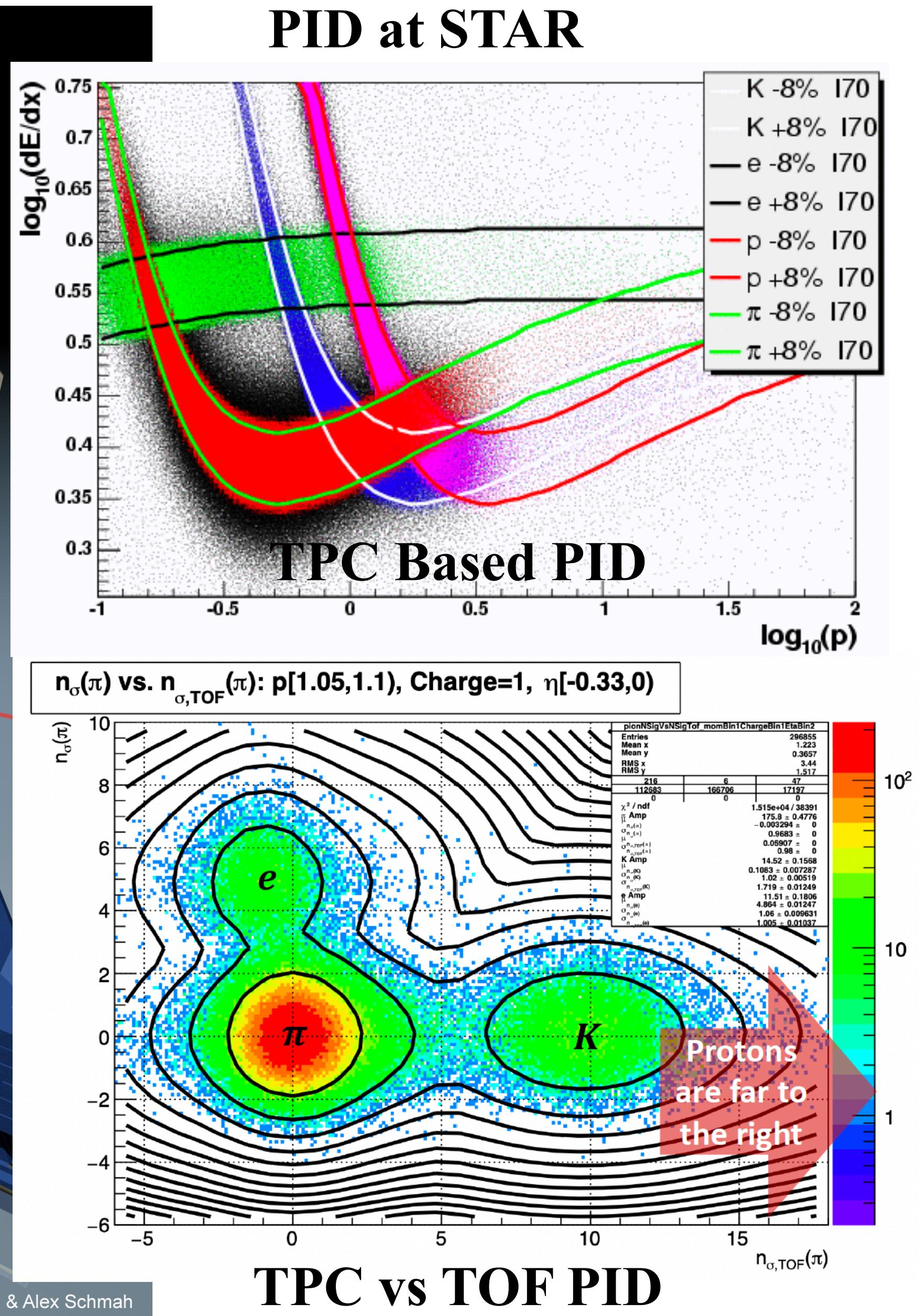
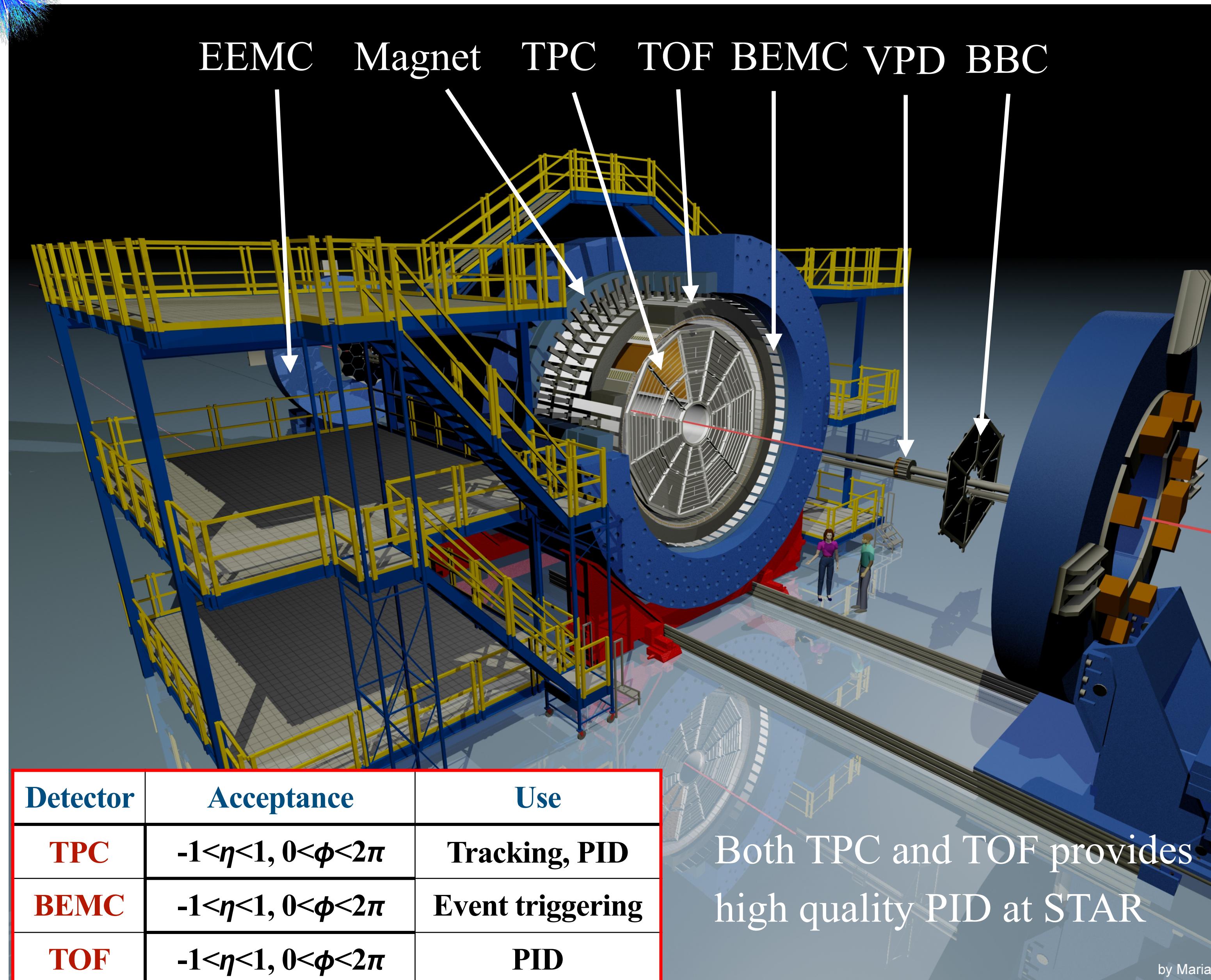
- **Unpolarized Dihadron Cross-Section, $d\sigma_{UU}$, in $p + p \rightarrow h^+h^- + X$**

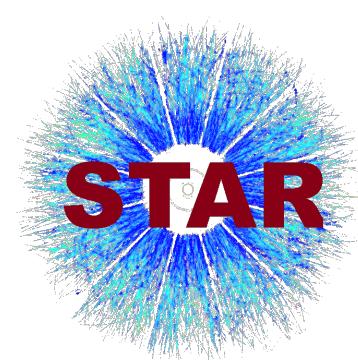
- $d\sigma_{UU}$ is crucial for the $D_1^{h_1 h_2}$, which provides equal access to quarks and gluons.

- $d\sigma_{UU}$ and A_{UT} allows model-independent extraction of $h_1(x)$.



Solenoidal Tracker At RHIC (STAR)





IFF Studies at STAR

Collision	proton-proton						
Polarization	transverse						
Year	2006	2011	2012	2015	2017	2022	2024
\sqrt{s} (GeV)	200	500	200	200	510	508	200
L_{int} (pb^{-1})	~ 1.8	~ 25	~ 22	~ 52	~ 350	~ 400	??
$\langle P_{beam} \rangle$ (%)	~ 60	~ 53	~ 57	~ 57	~ 55	~ 52	??

- Published IFF A_{UT}

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

STAR, Phys. Rev. Lett. 115 (2015) 242501

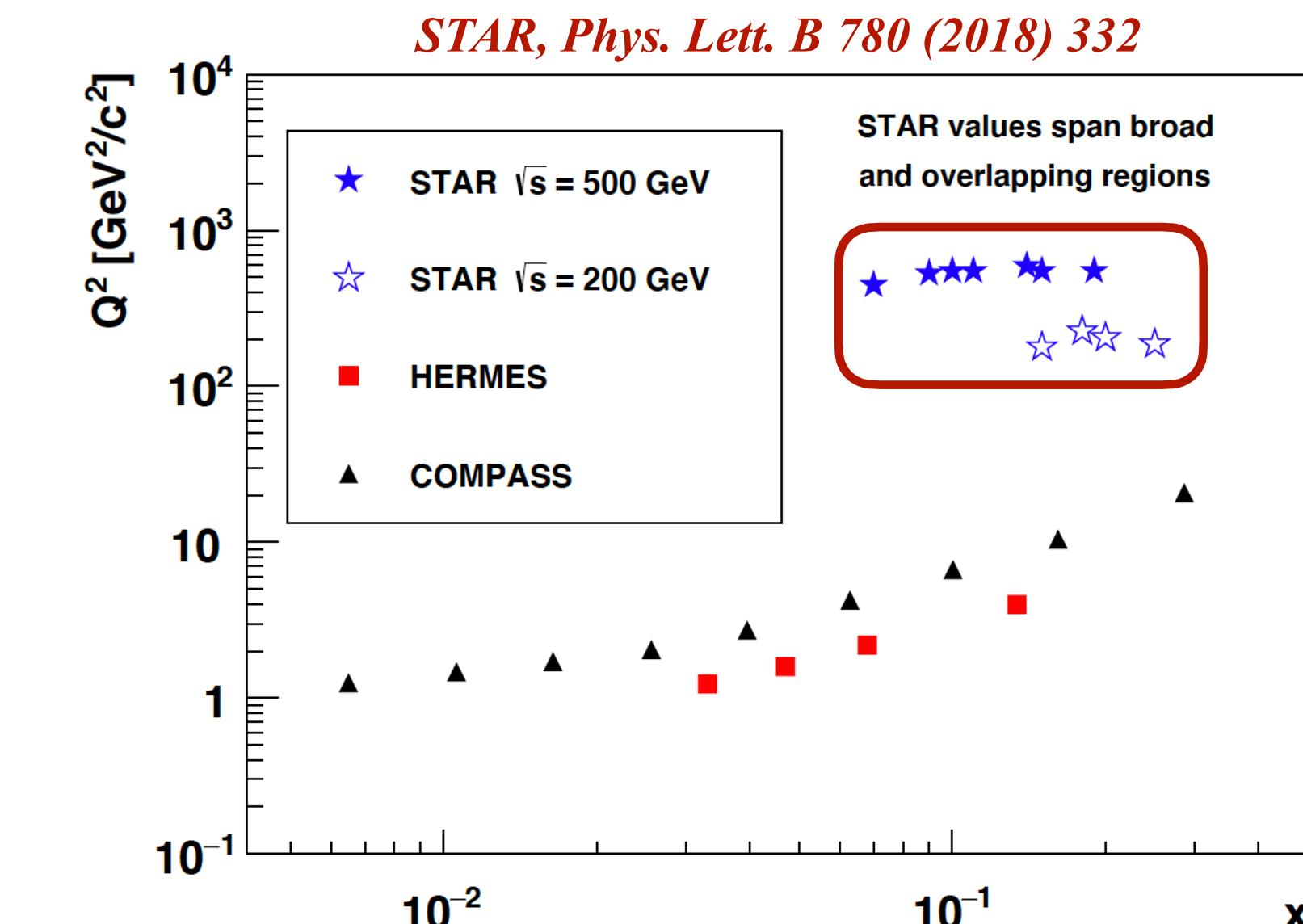
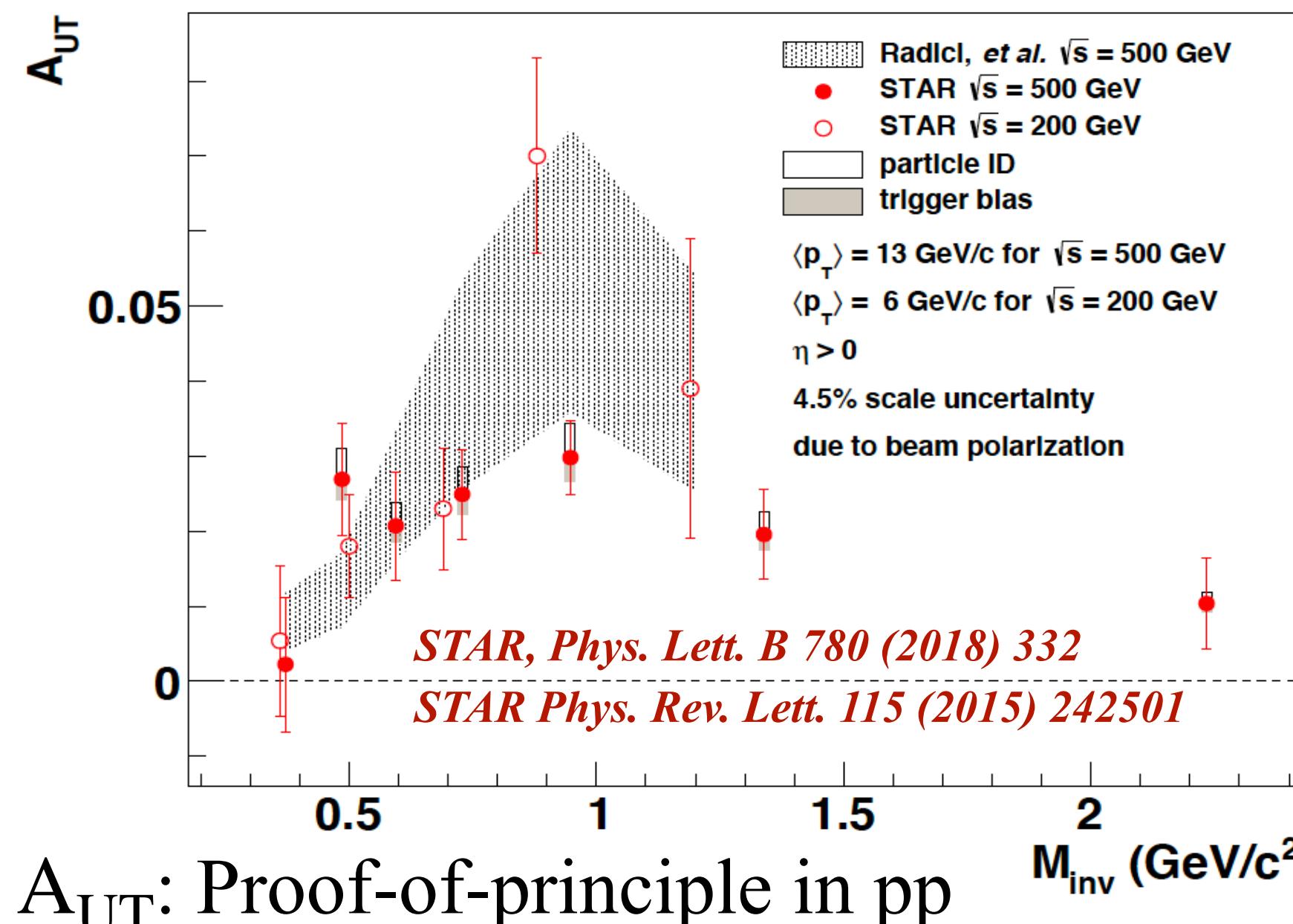
- STAR Preliminaries

@ $\sqrt{s} = 200$ GeV

- STAR IFF Preliminary

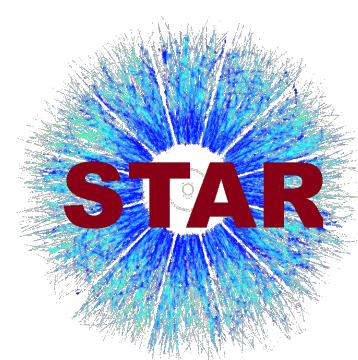
@ $\sqrt{s} = 510$ GeV

- Planned IFF and Cross Section Measurements



A_{UT} : Proof-of-principle in pp

STAR Kinematic Coverage

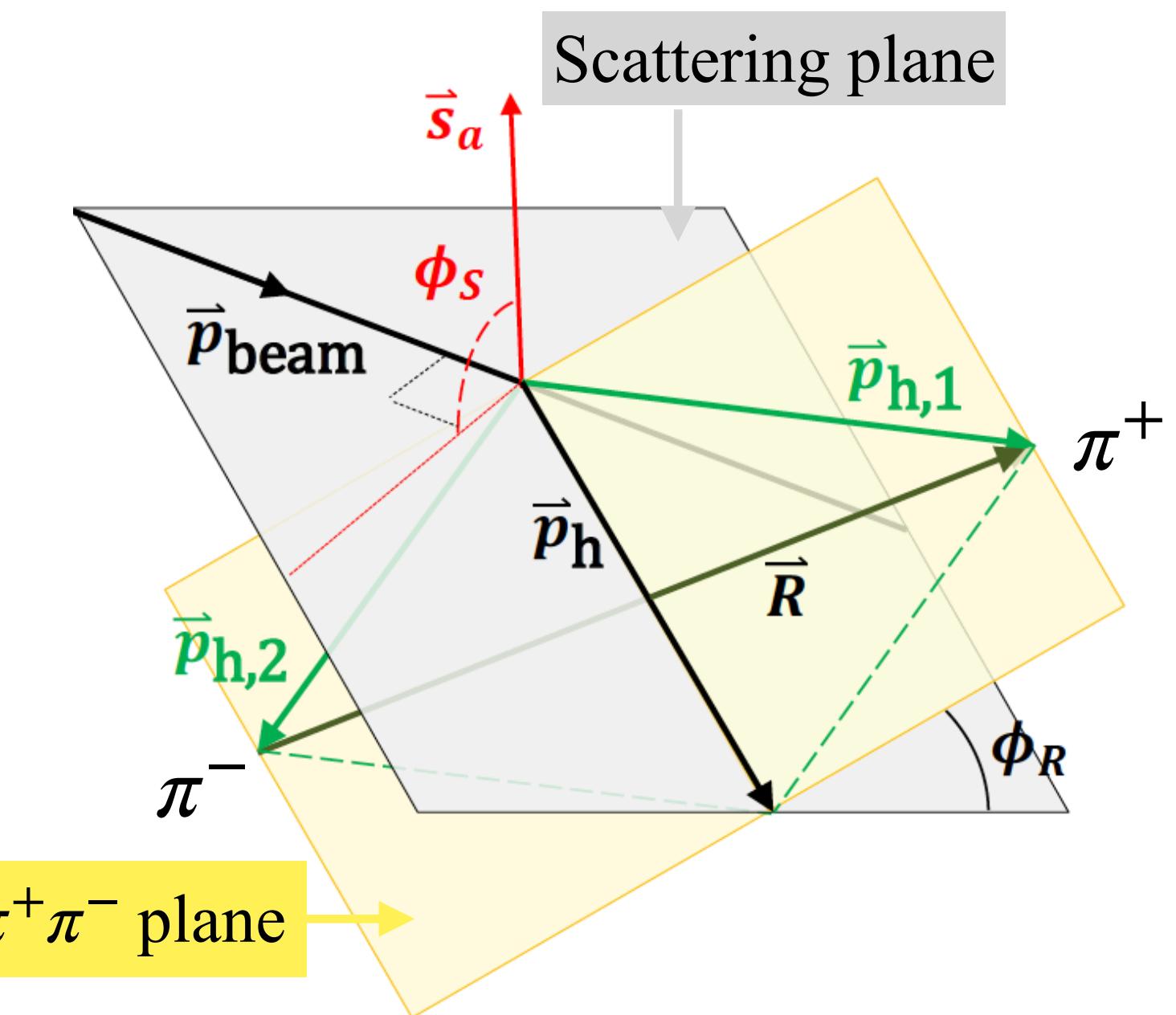


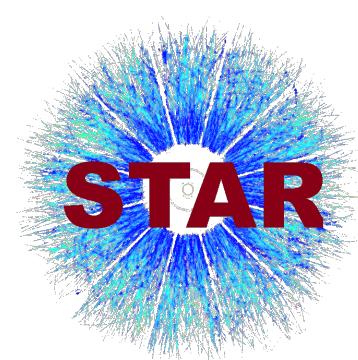
STAR Run 2015 $\pi^+\pi^-$ Asymmetry Analysis

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

$\pi^+\pi^-$ Formation and Azimuthal Angles

- Polarized parton fragments to $\pi^+\pi^-$.
- Two crucial vectors: $\vec{p}_h = \vec{p}_{h_1} + \vec{p}_{h_2}$, $\vec{R} = \frac{1}{2}(\vec{p}_{h_1} - \vec{p}_{h_2})$
- Access to the quark polarization $\sim \vec{S} \cdot \vec{R} \times \vec{p}_h$.
- Pion identification by measuring the ionization energy loss (dE/dx) with $p_T^\pi > 1.5 \text{ GeV}/c$ and $|\eta| < 1$.
- Oppositely charged pion pairs, $\pi^+\pi^-$.
- Direction of \vec{R} points from π^- to π^+ (or the other way); otherwise A_{UT} gets diluted.
- $\pi^+\pi^-$ Azimuthal angle, $\phi_{RS} = \phi_S - \phi_R$





STAR Run 2015 $\pi^+\pi^-$ Asymmetry Analysis

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

- $A_{UT}^{\sin(\phi_{RS})}$ extracted as a function of $M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$, and $\eta^{\pi^+\pi^-}$.

Cross-ratio formula:

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

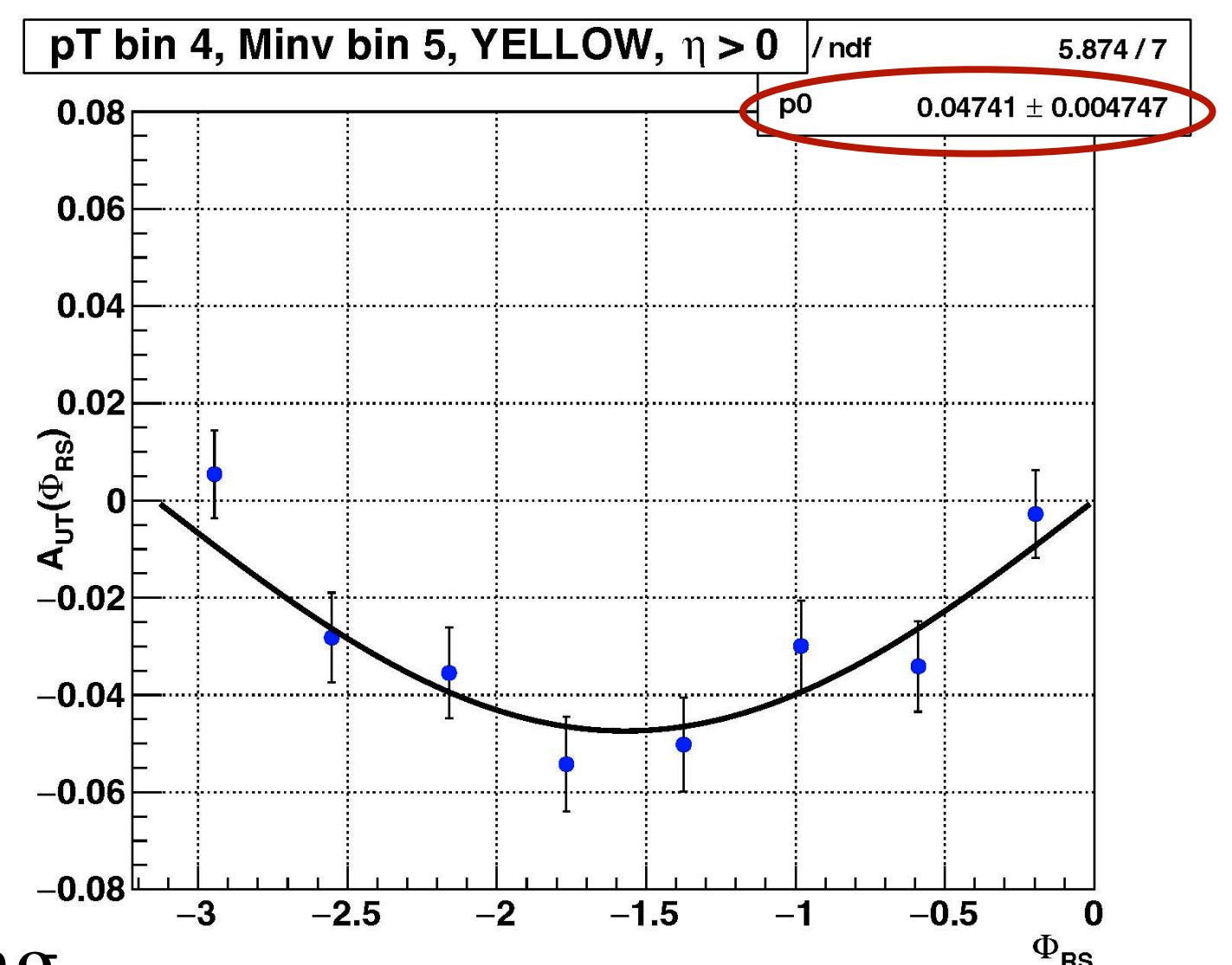
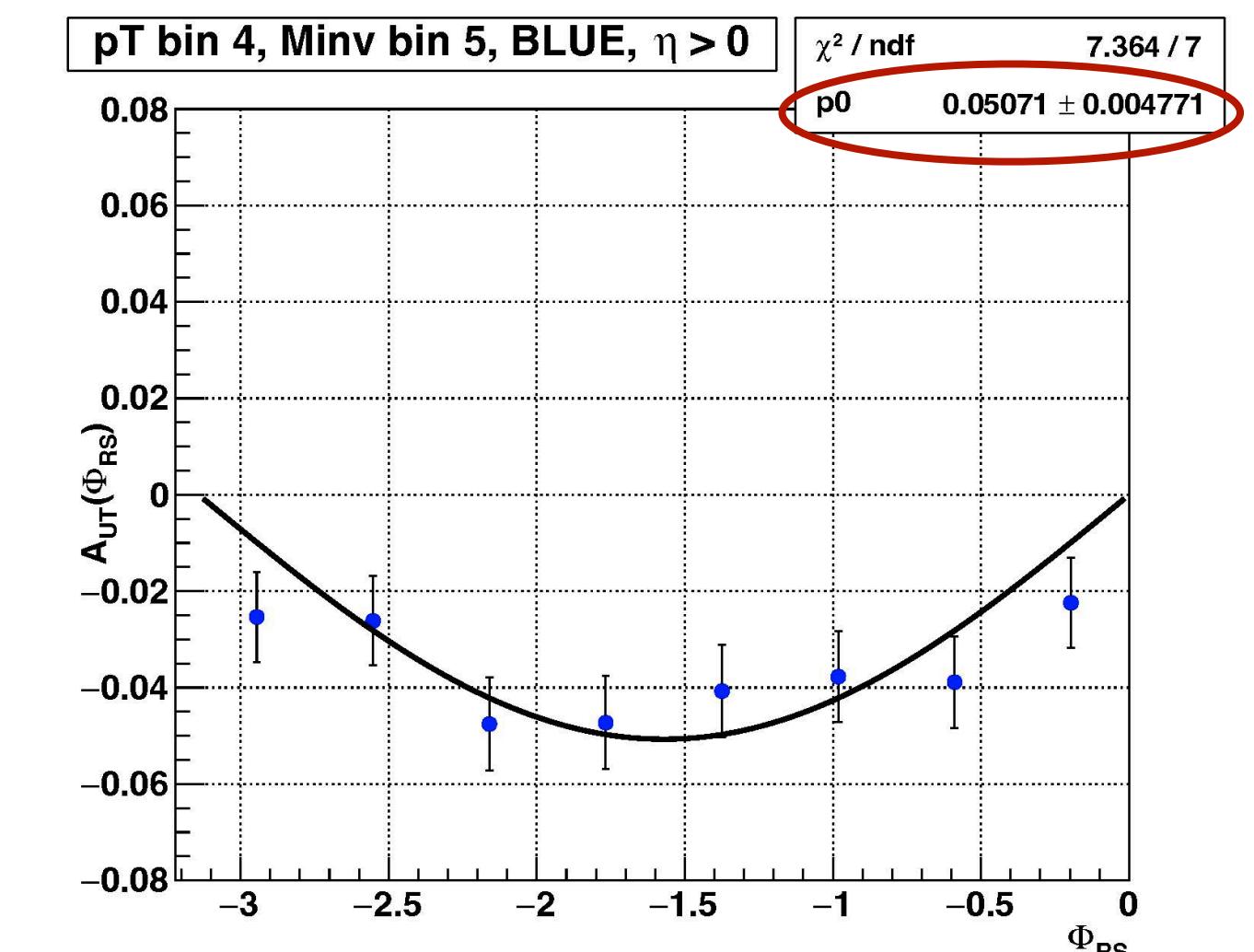
- Free from relative luminosity terms (cancels out in symmetric detector system!)

- Amplitude of the fit in $[-\pi, 0]$ gives the A_{UT} .

- A_{UT} extracted for both* beams separately. Final A_{UT} is the weighted average of both.

*Both beams (Blue and Yellow) are polarized at STAR.

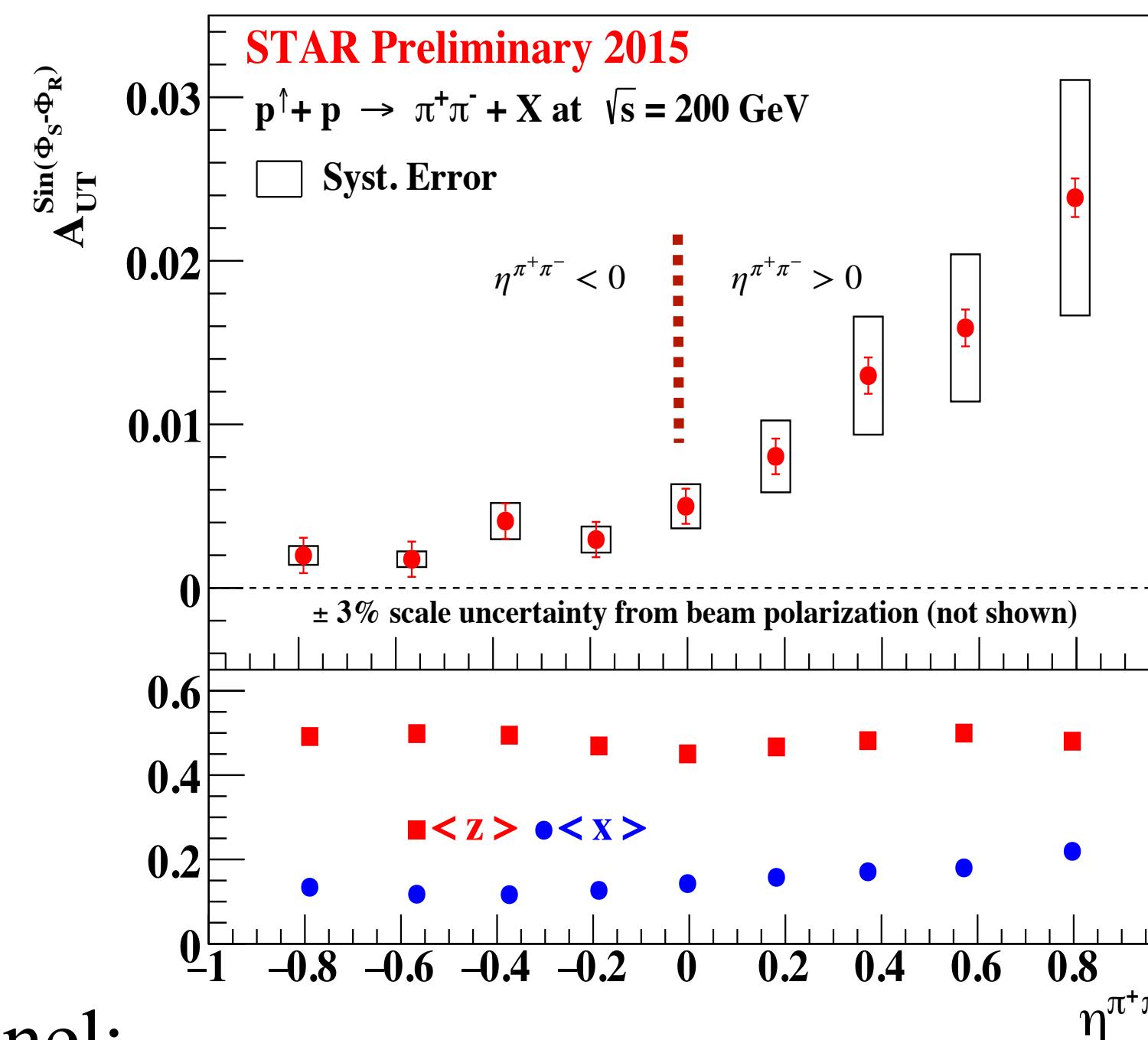
Each beam can be treated as polarized independently while analyzing.



STAR Run 2015 $\pi^+\pi^-$ Asymmetry Analysis

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

STAR Run 06, Phys. Lett. B 780 (2018) 332

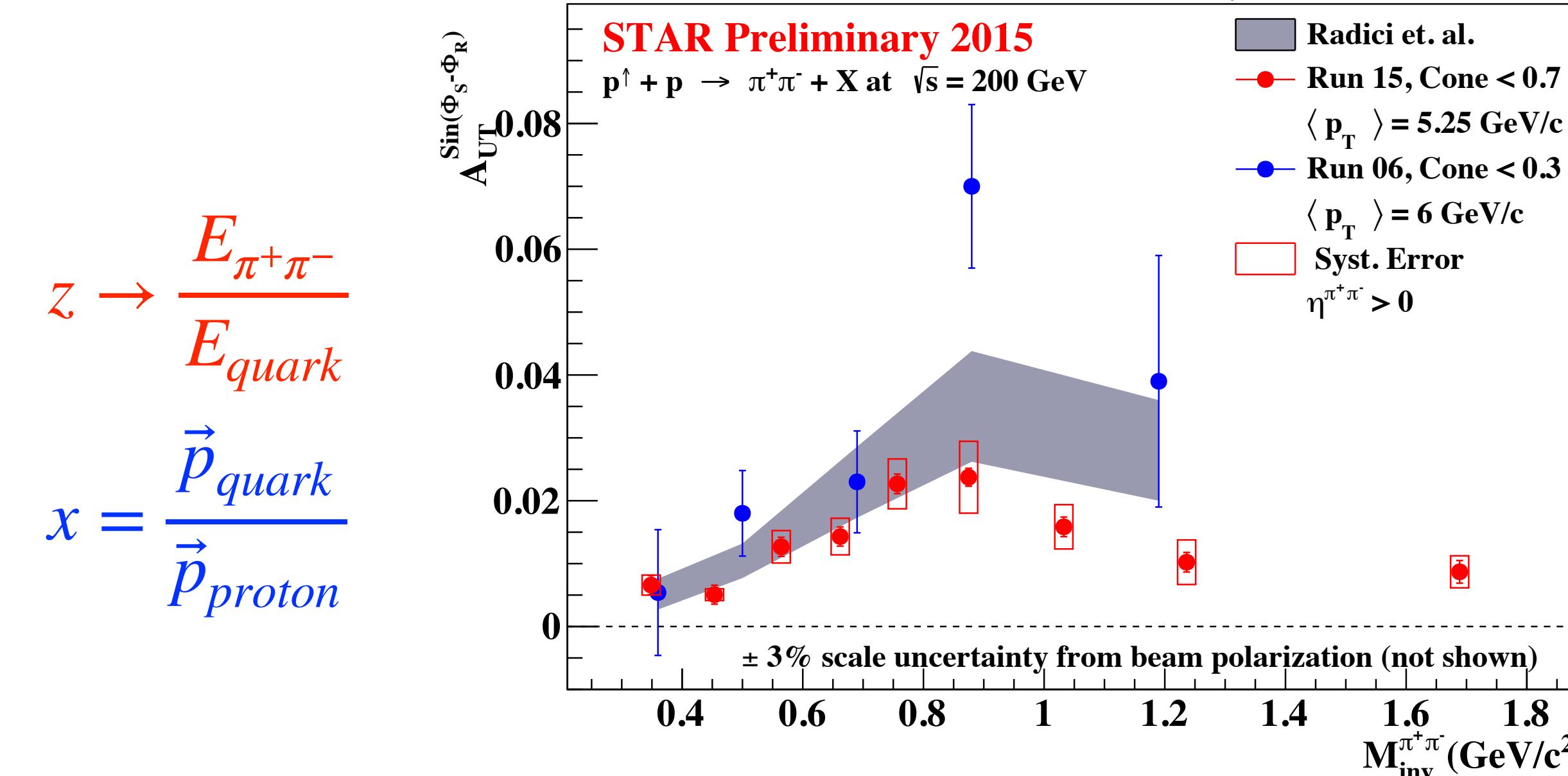


Top Panel:

- A_{UT} increases with the $\eta^{\pi^+\pi^-}$.
- Sizable $h_1^q(x)$ is expected in the $\eta > 0$ region.

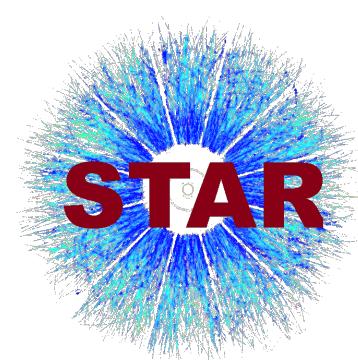
Bottom Panel:

- Mean x and z from simulation.
- $0.1 < \langle x \rangle < 0.22$, $\langle z \rangle \sim 0.46$



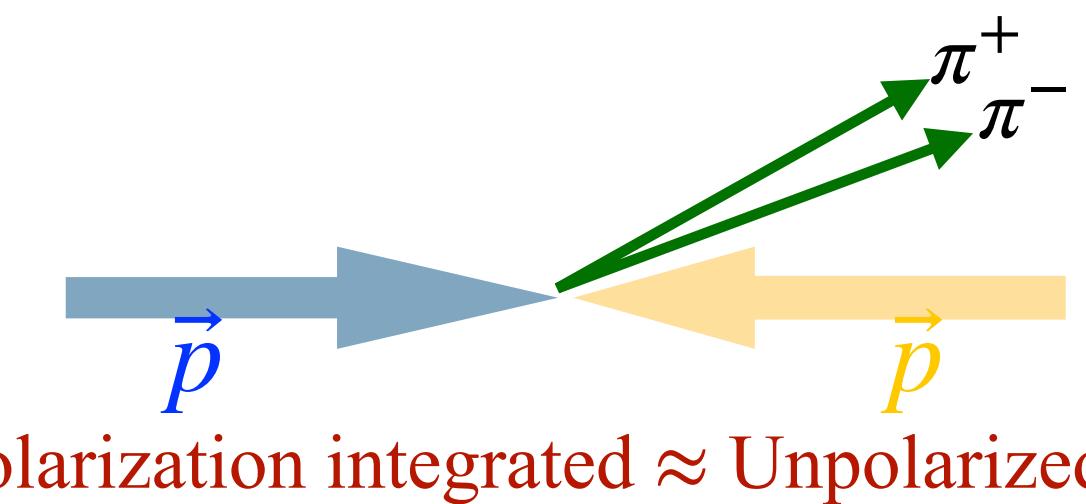
- Asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$, consistent with the previous measurement and theory prediction.
- Statistical precision is significantly improved in the new result.
- **Systematic uncertainty is dominated by the PID, which is expected to improve significantly when including TOF PID.**

Details in [SciPost Phys. Proc. 8 \(2022\) 047](#)

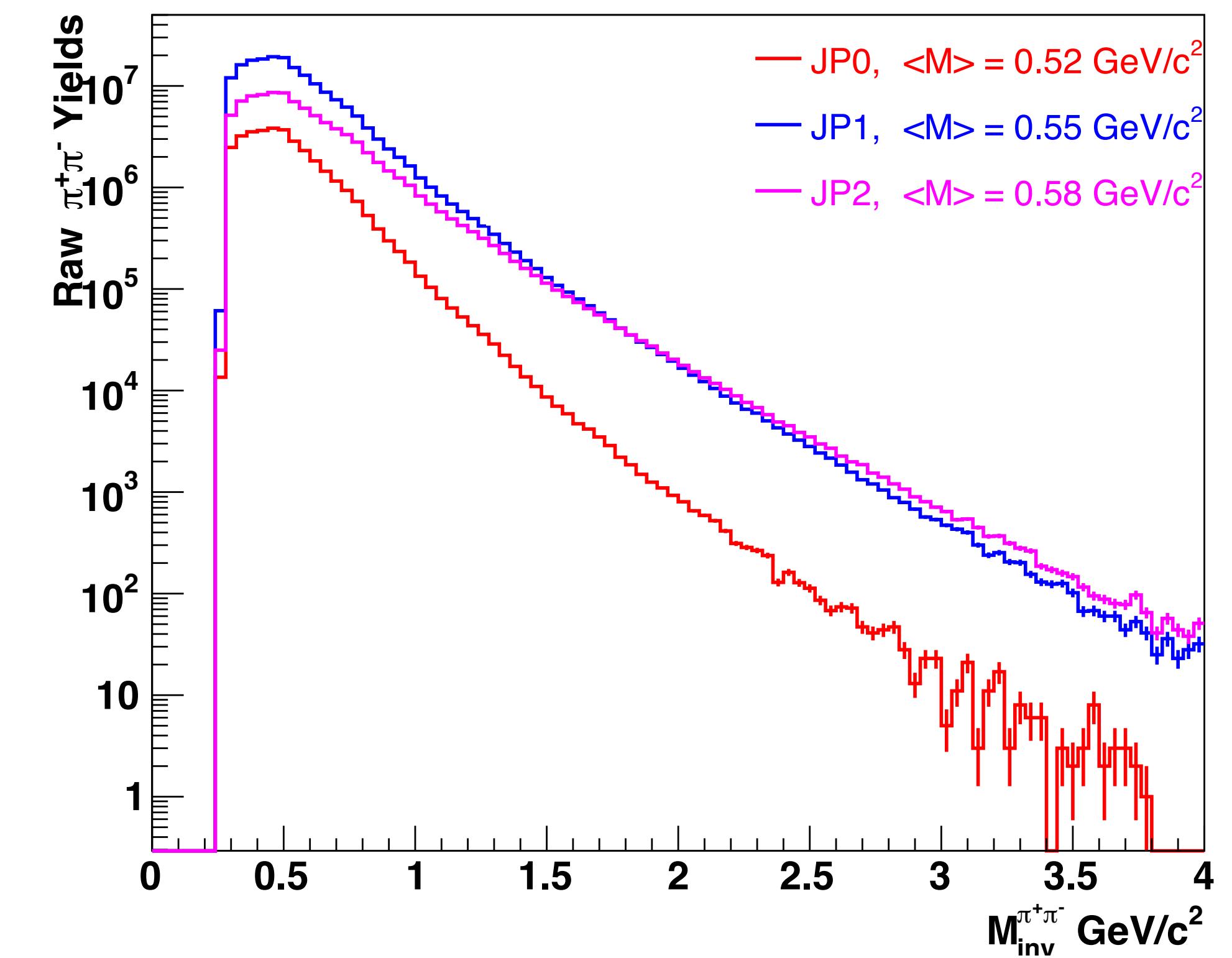


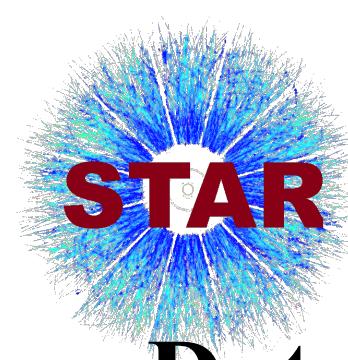
STAR Run 2012 Unpolarized $\pi^+\pi^-$ Cross-Section ($d\sigma_{UU}^{\pi^+\pi^-}$) Measurement

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



- Inclusive $\pi^+\pi^-$ differential cross section:
 - As a function of invariant mass, $M_{inv}^{\pi^+\pi^-}$, in $|\eta| < 1$.
 - Much needed for the $D_1^{h_1 h_2}$ extraction.
 - Access to $D_1^{h_1 h_2/g}$.
- STAR Run 2012 dataset @ $\sqrt{s} = 200$ GeV
- Trigger on high energy clusters in STAR calorimeters with varying threshold (JP0, JP1, and JP2)
 - Lower trigger threshold provides better gluon sensitivity than Run 2015.
- $\pi^+\pi^-$ construction is same as in the IFF analysis, except for the track $p_T > 0.5$ GeV/c.





STAR Run 2012 Unpolarized $\pi^+\pi^-$ Cross-Section ($d\sigma_{UU}^{\pi^+\pi^-}$) Measurement

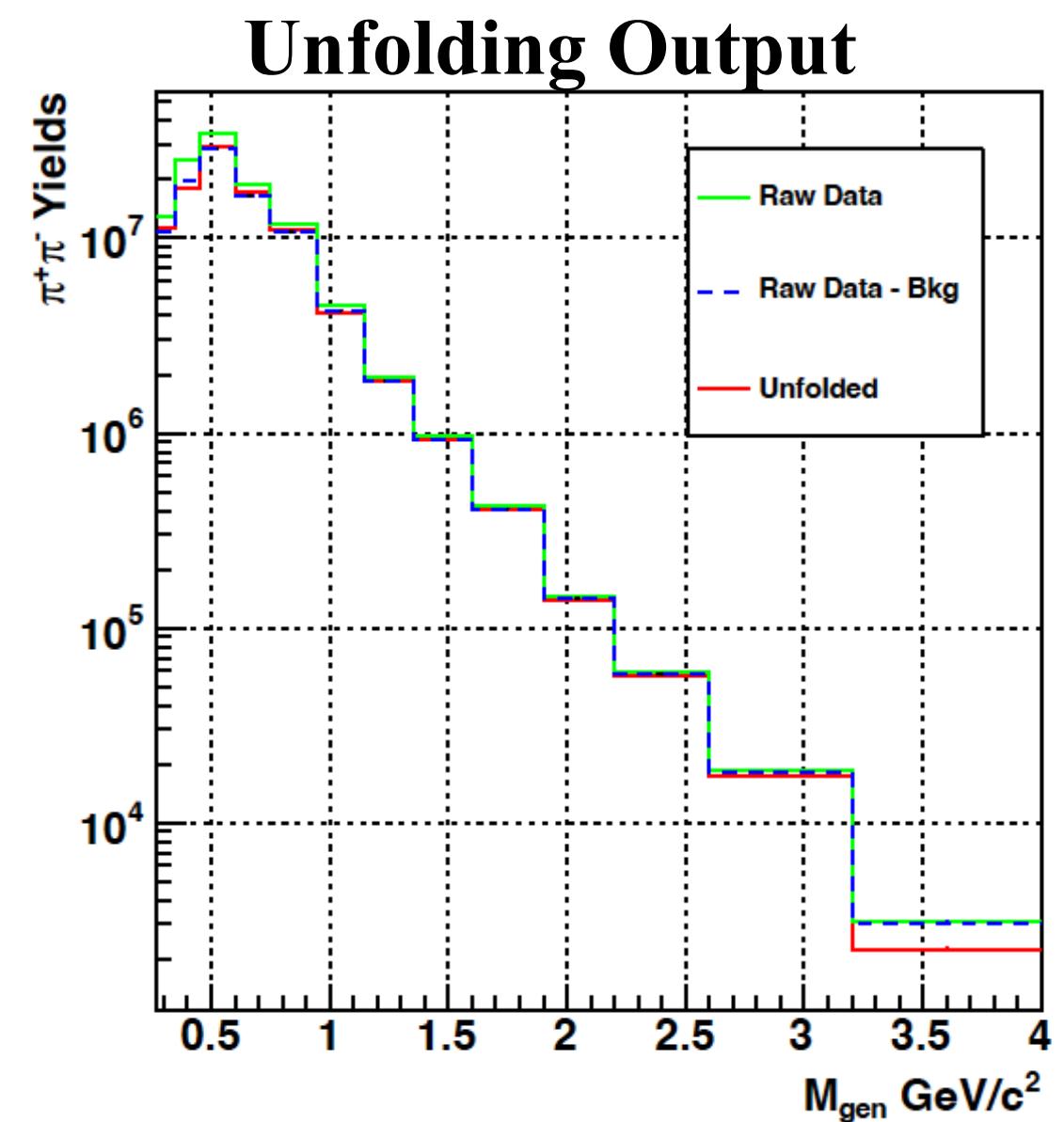
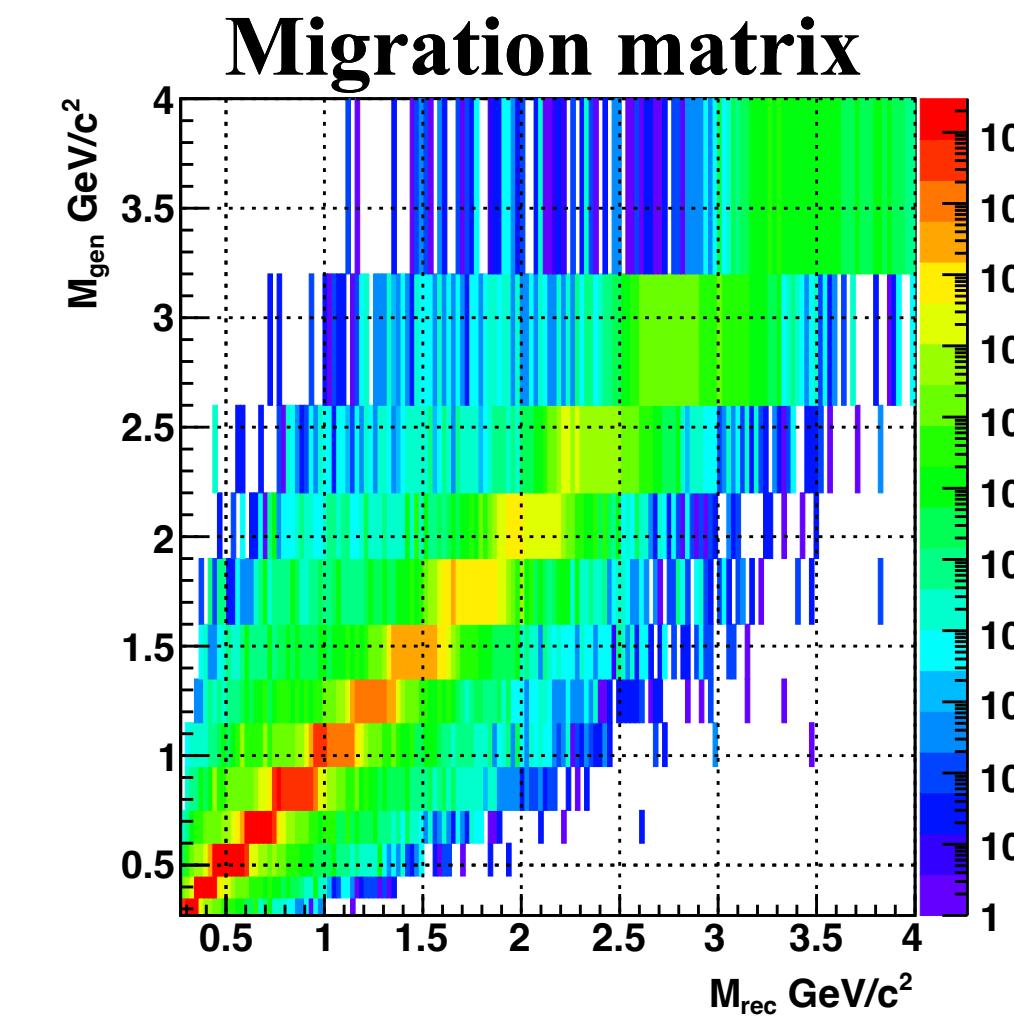
$$p + p \rightarrow \pi^+\pi^- + X \text{ at } \sqrt{s} = 200 \text{ GeV}$$

Data Unfolding

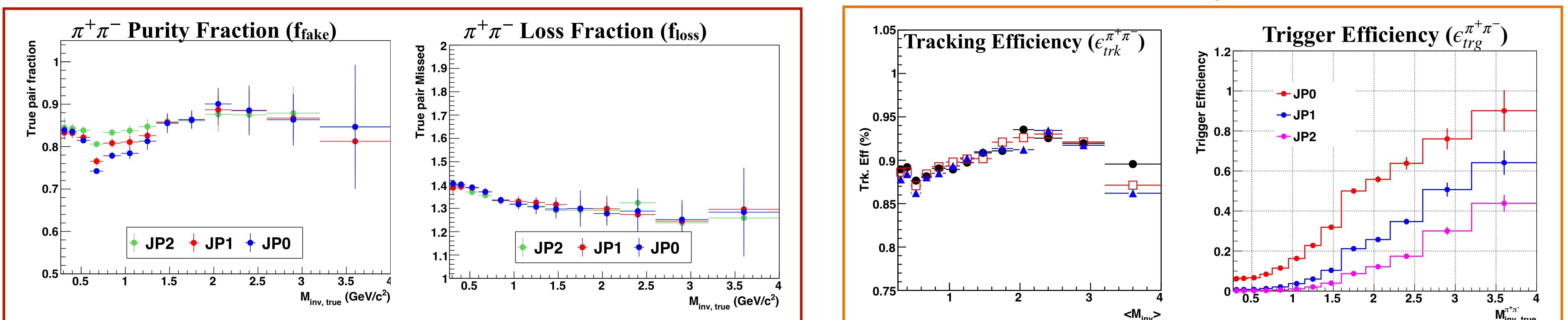
- One can extract underlying hadron-level properties from reconstructed pairs using a regularized unfolding, as implemented in TUnfold.
- It takes **migration matrix** as input, which is derived from PYTHIA and GEANT simulation.
- **Small shape change in the unfolding output than the input.**

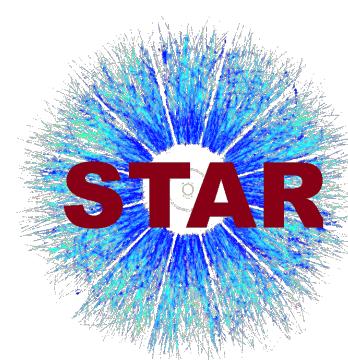
PID Corrections

- f_{fake} accounts for the $\pi^+\pi^-$ impurity (due to other particle contamination).
- f_{loss} accounts for the $\pi^+\pi^-$ loss due to **restrictive PID cuts**.



Efficiency Corrections





STAR Run 2012 Unpolarized $\pi^+\pi^-$ Cross-Section ($d\sigma_{UU}^{\pi^+\pi^-}$) Measurement

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

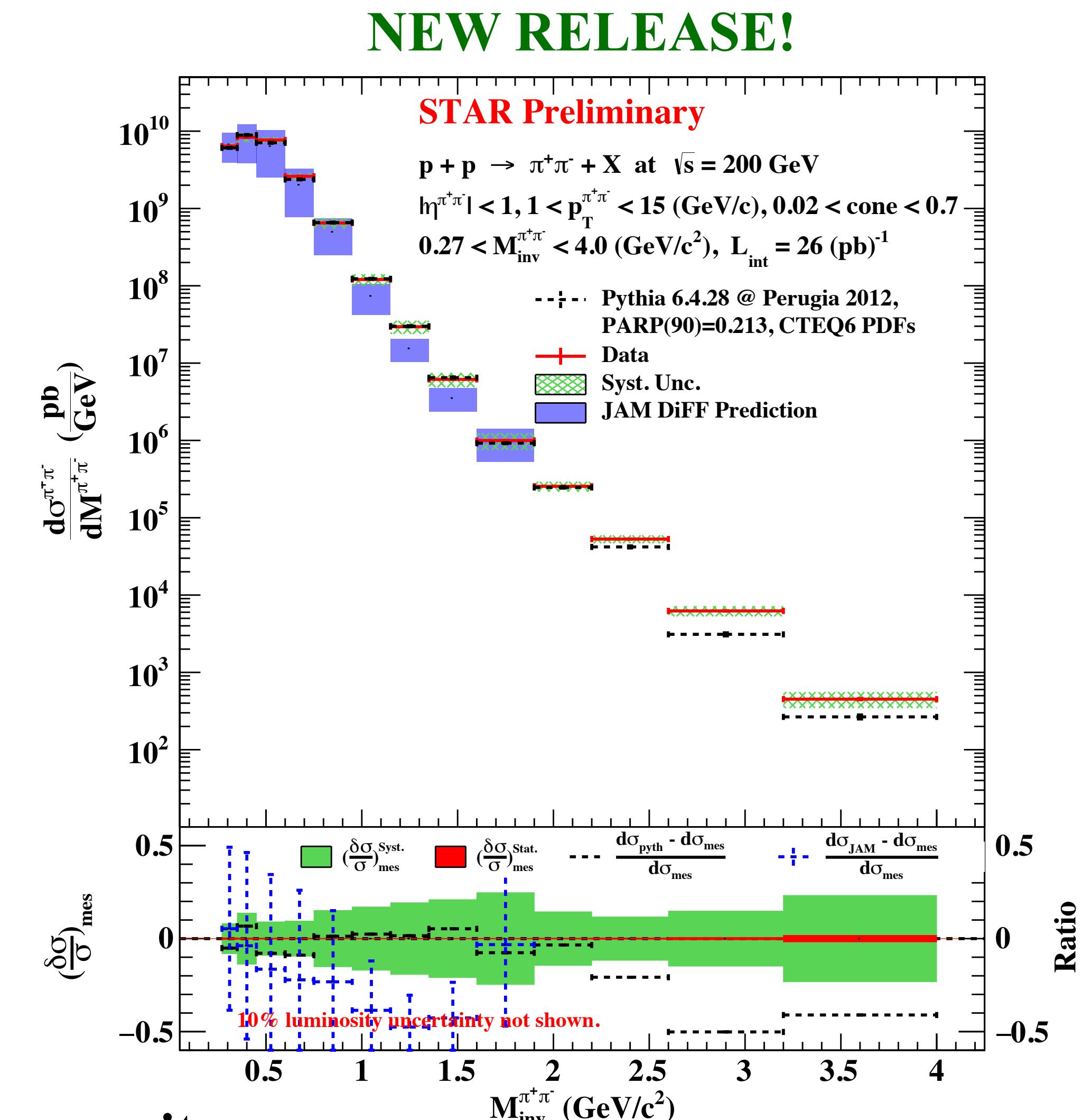
STAR Preliminary

Top panel:

- First unpolarized cross-section measurement in pp via $\pi^+\pi^-$ channel.
- The **measured cross-section** is in good agreement with the cross-section from the **PYTHIA simulation** and **JAM DiFF prediction**.

Bottom panel:

- Systematic uncertainty (green band)
- Measured cross-section compared with PYTHIA (dashed black) and with JAM DiFF (Blue) cross-sections
- Statistical uncertainty (red band)
- This measurement provides access to $D_1^{h_1 h_2}$ for gluons.
- Together with the Belle measurements, A_{UT} and $d\sigma_{UU}$ in pp opens up a path for the **model-independent extraction of transversity**.

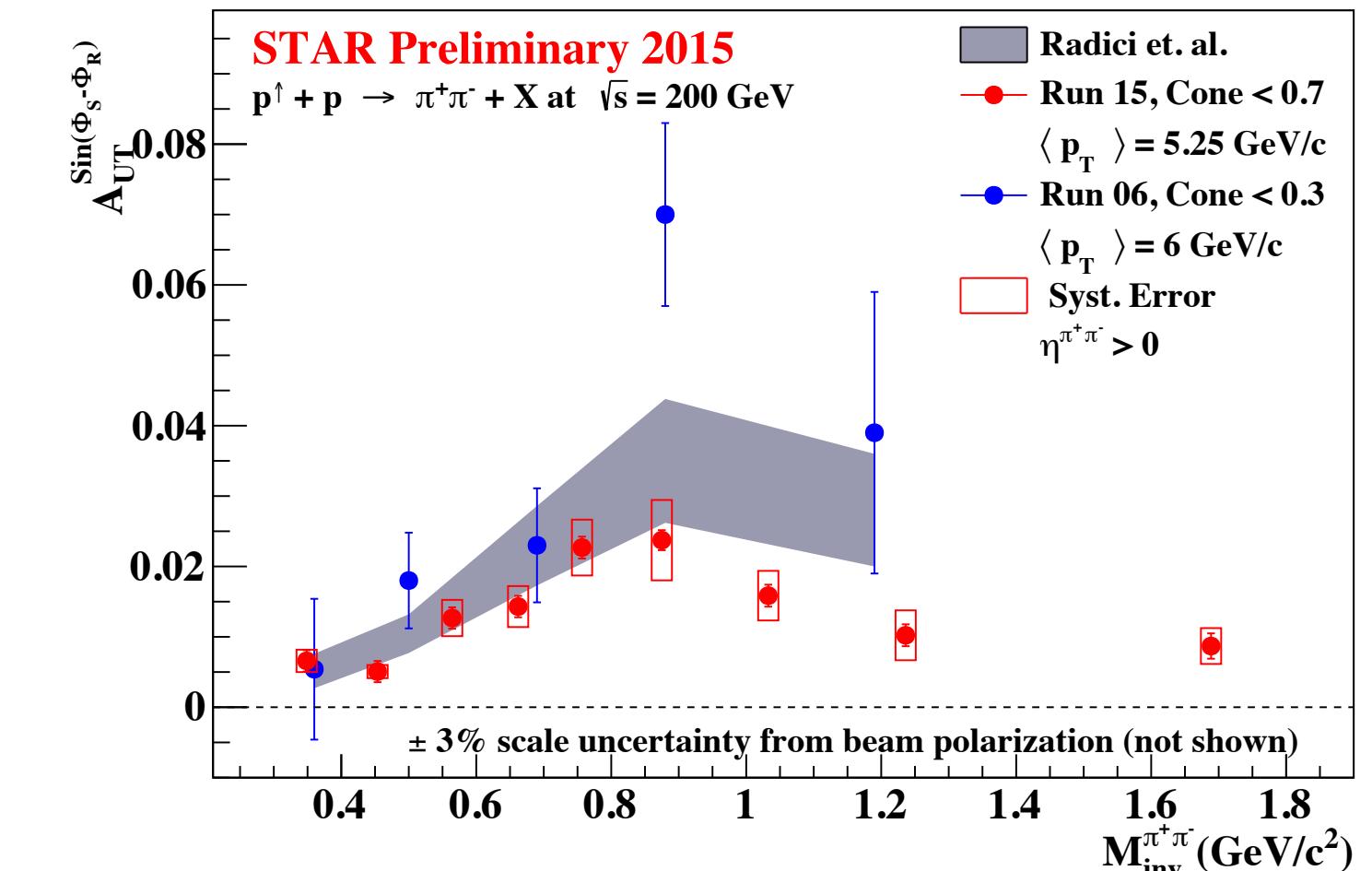


Summary and Outlook

- Precision $\pi^+\pi^-$ IFF asymmetry measurement

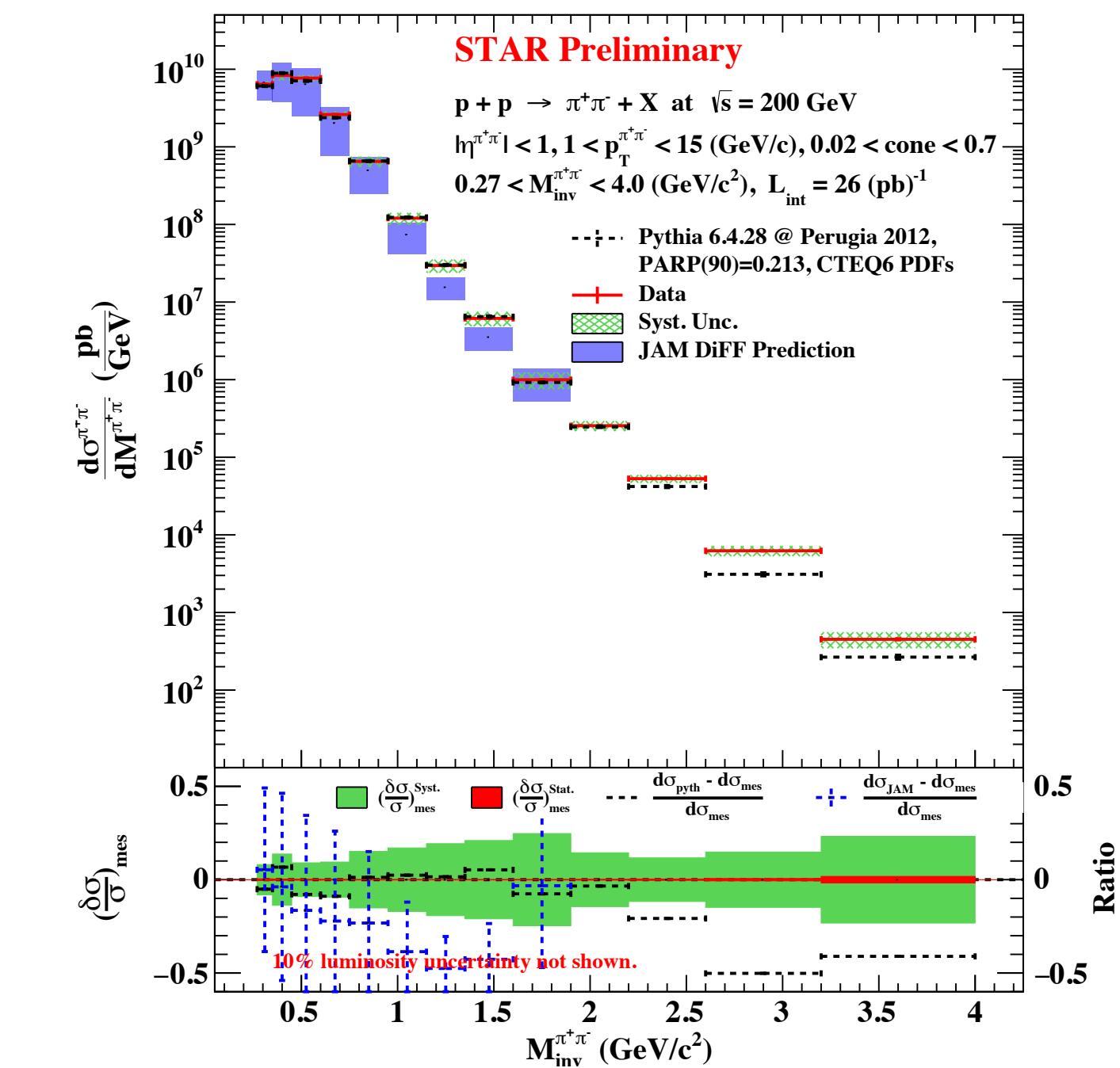
- Probes valence quarks (u and d) transversity.
- Dominant PID systematic uncertainty expected to shrink comparable to the statistical uncertainty, including TOF.

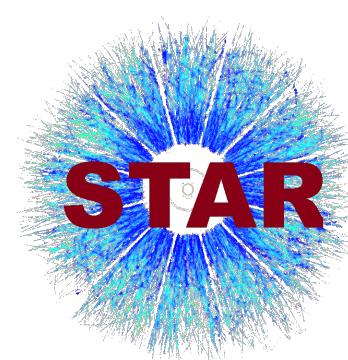
$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{h_1 h_2/k}(z, M_h^2)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z, M_h^2)}$$



- First unpolarized $\pi^+\pi^-$ cross-section measurement in pp

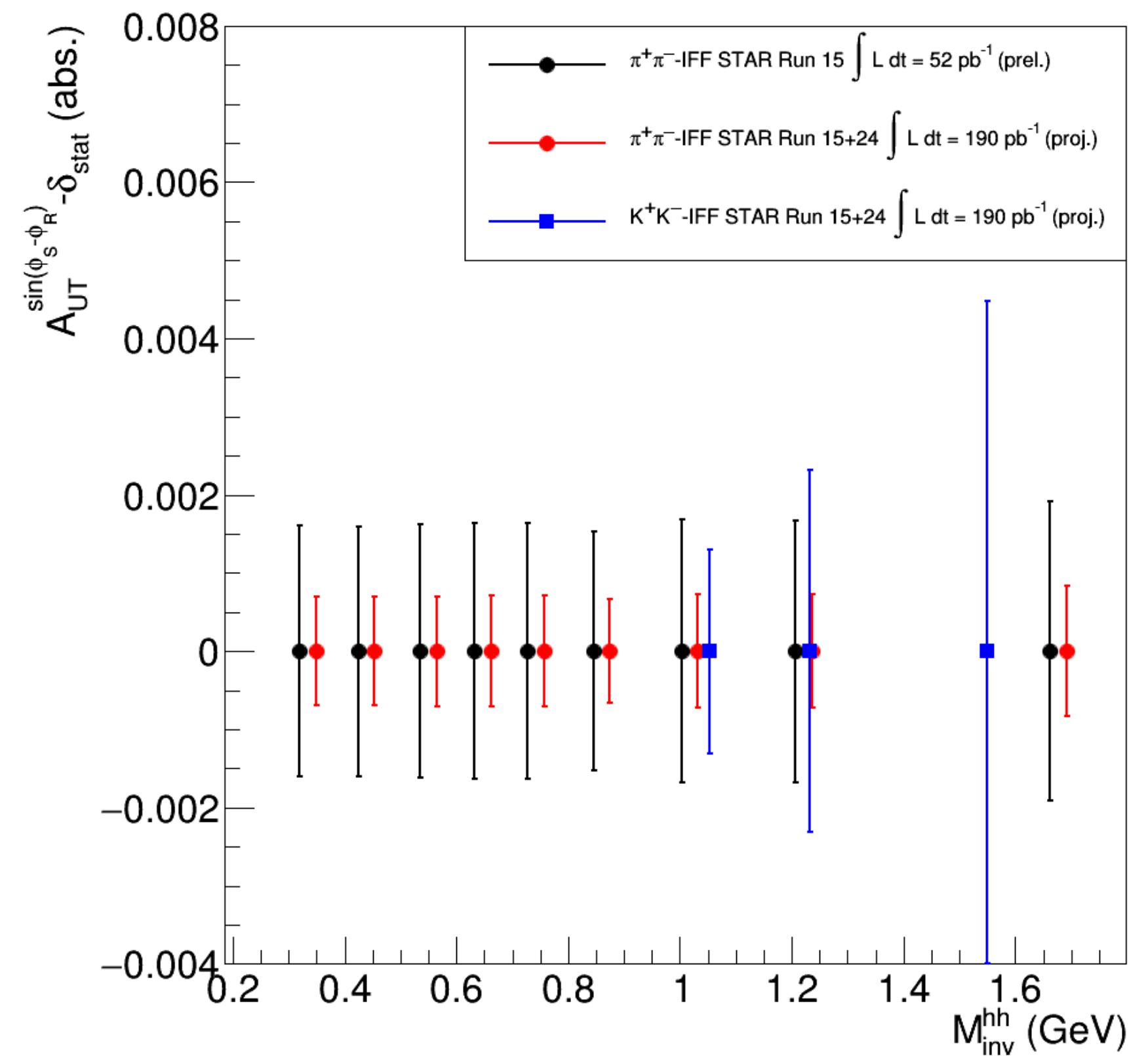
- Provides access to $D_1^{h_1 h_2}$ for gluons.
- Path to the model-independent extraction of $h_1(x)$.
- Planned double differential cross-section in $M_{inv}^{\pi^+\pi^-}$ and $p_T^{\pi^+\pi^-}$.



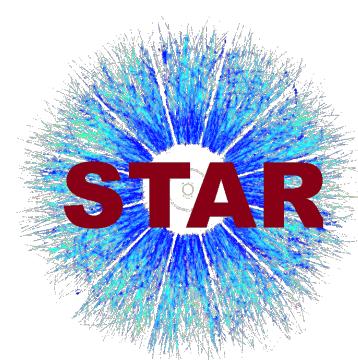


Summary and Outlook

- Precision IFF asymmetries @ $\sqrt{s} = 200$ GeV probing transversity beyond valence quarks
 - Precision $\pi^+\pi^-$ IFF asymmetry from Run 2015+2024
 - Proposed K^+K^- IFF asymmetry, sensitive to the “strange quark” transversity.



Thank you for your attention!



Backup

Unpolarized $\pi^+\pi^-$ Cross Section Measurement

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

Corrections (Bin by bin)

1. $\pi^+\pi^-$ Purity Fraction (f_{fake})
2. $\pi^+\pi^-$ Loss Fraction (f_{loss})
3. Tracking Efficiency ($\epsilon_{\text{trk}}^\pi$)
4. Trigger Efficiency ($\epsilon_{\text{trg}}^{\pi^+\pi^-}$)

Triggered Cross Sections

$$\frac{d\sigma^{pp \rightarrow \pi^+\pi^-}}{dM^{\pi^+\pi^-}} = \frac{f_{\text{fake}} \cdot f_{\text{loss}}}{L \cdot \epsilon_{\text{trk}}^{\pi^+} \cdot \epsilon_{\text{trk}}^{\pi^-} \cdot \epsilon_{\text{trg}}^{\pi^+\pi^-}} \cdot \frac{dN_{\text{true}}^{\pi^+\pi^-}}{dM^{\pi^+\pi^-}}$$

- Good agreement between triggered cross-sections; disagreement is considered as “Trigger Inefficiency”.
- Final cross-section (“Comb.” in the figure) is the weighted average of triggered cross-sections.

