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

25th International Spin Symposium (SPIN 2023)

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STAR

TEMPLE UNIVERSITY

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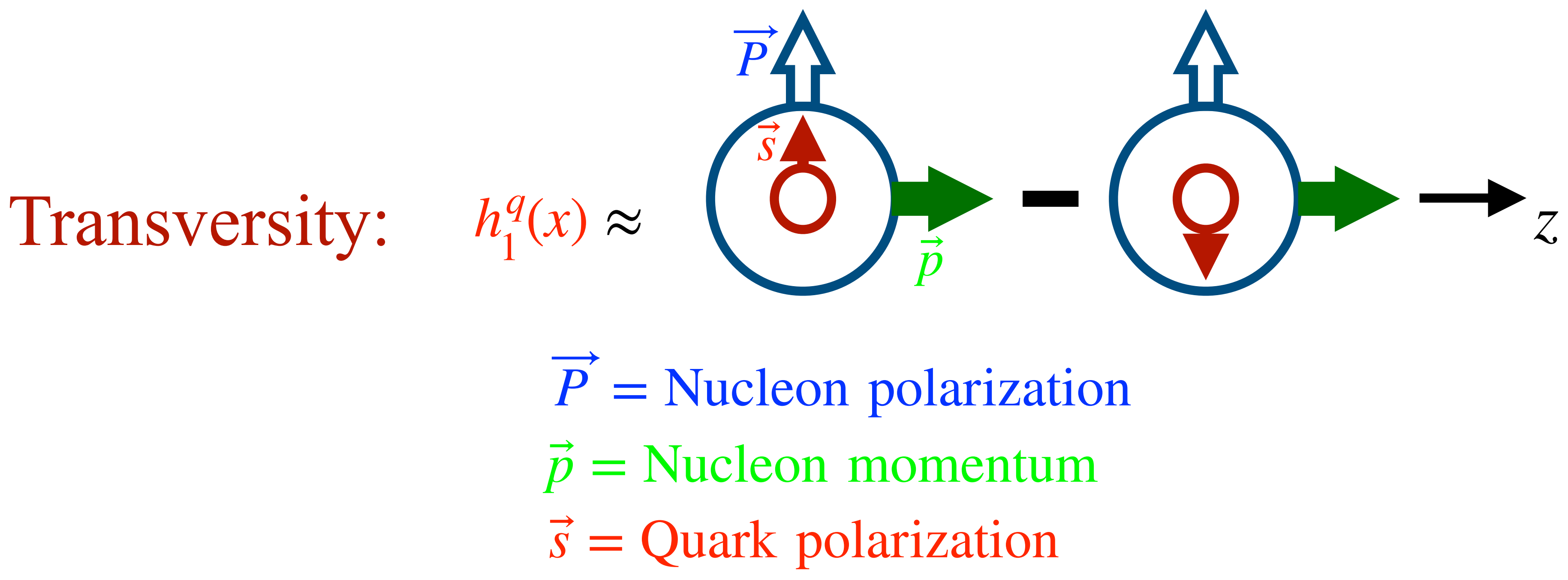
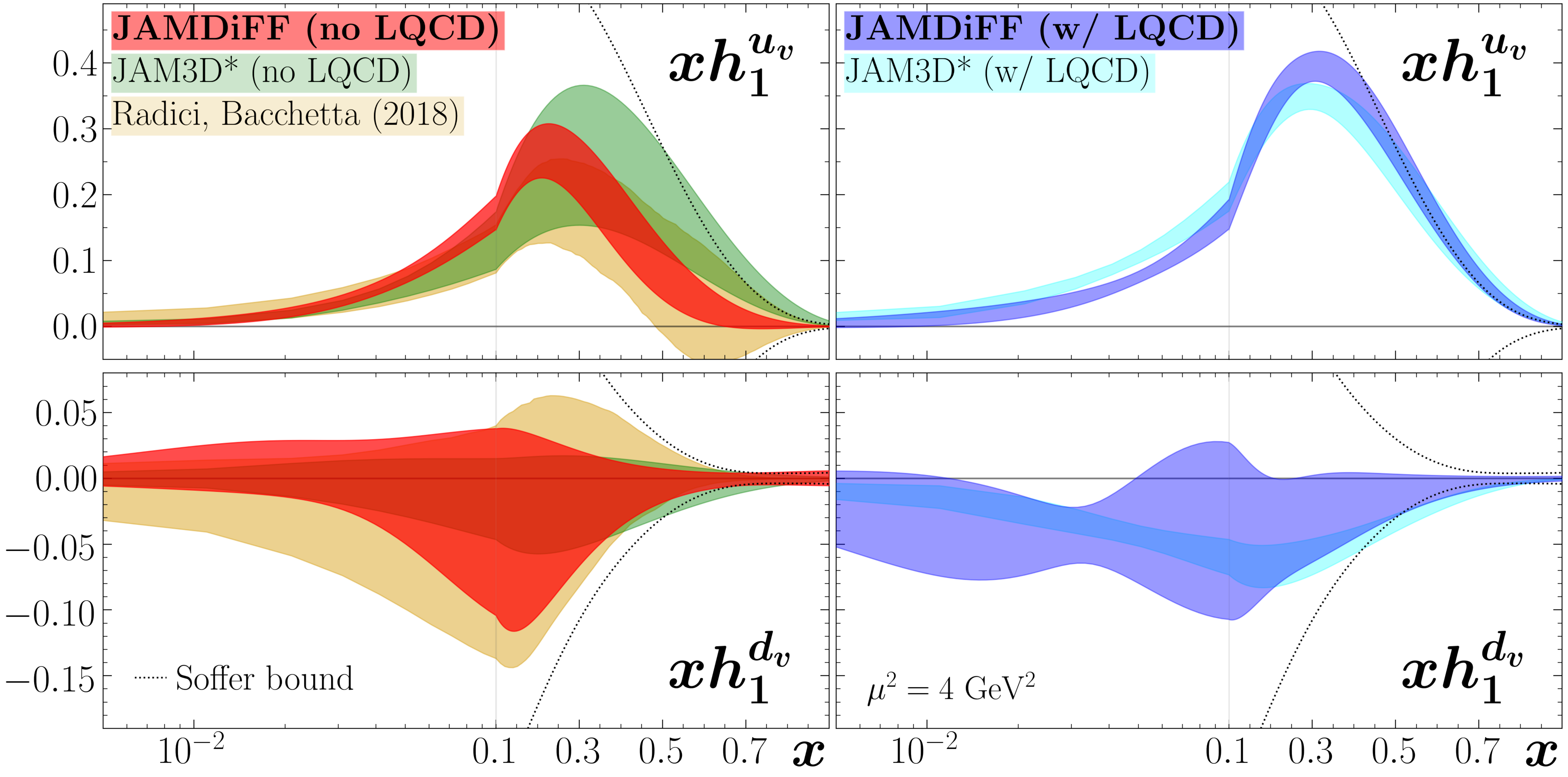
Transversity, $h_1^q(x)$

- Leading twist parton distribution function (PDF), which provides transverse spin structure of the nucleon.
- 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) in dihadron production channel.

Motivation: Measurement of observables in $\pi^+\pi^-$ channel to constrain $h_1^q(x)$ in the collinear framework in polarized *pp* collisions.



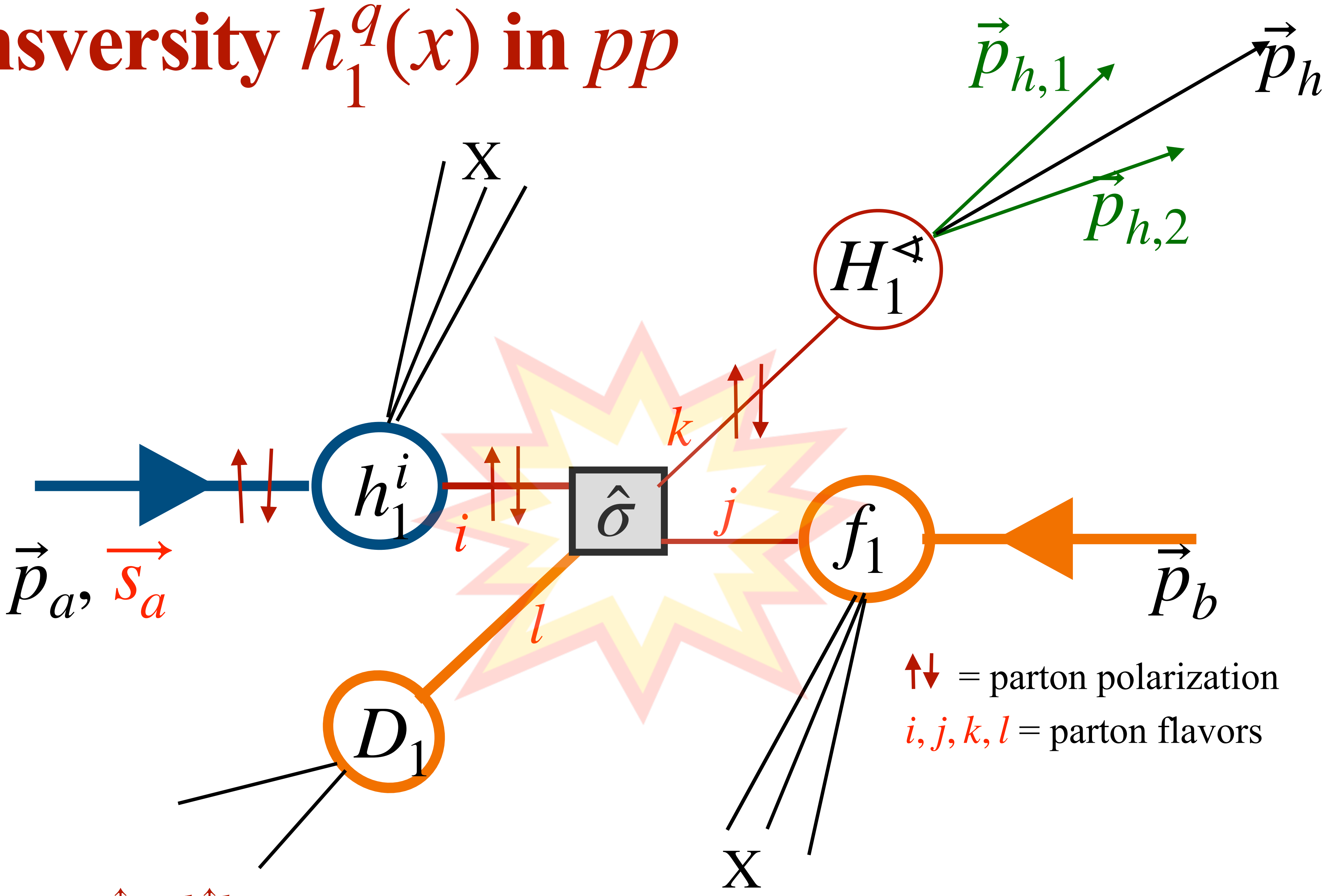


C. Cocuzza et. al., arXiv:2306.12998 [hep-ph]

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

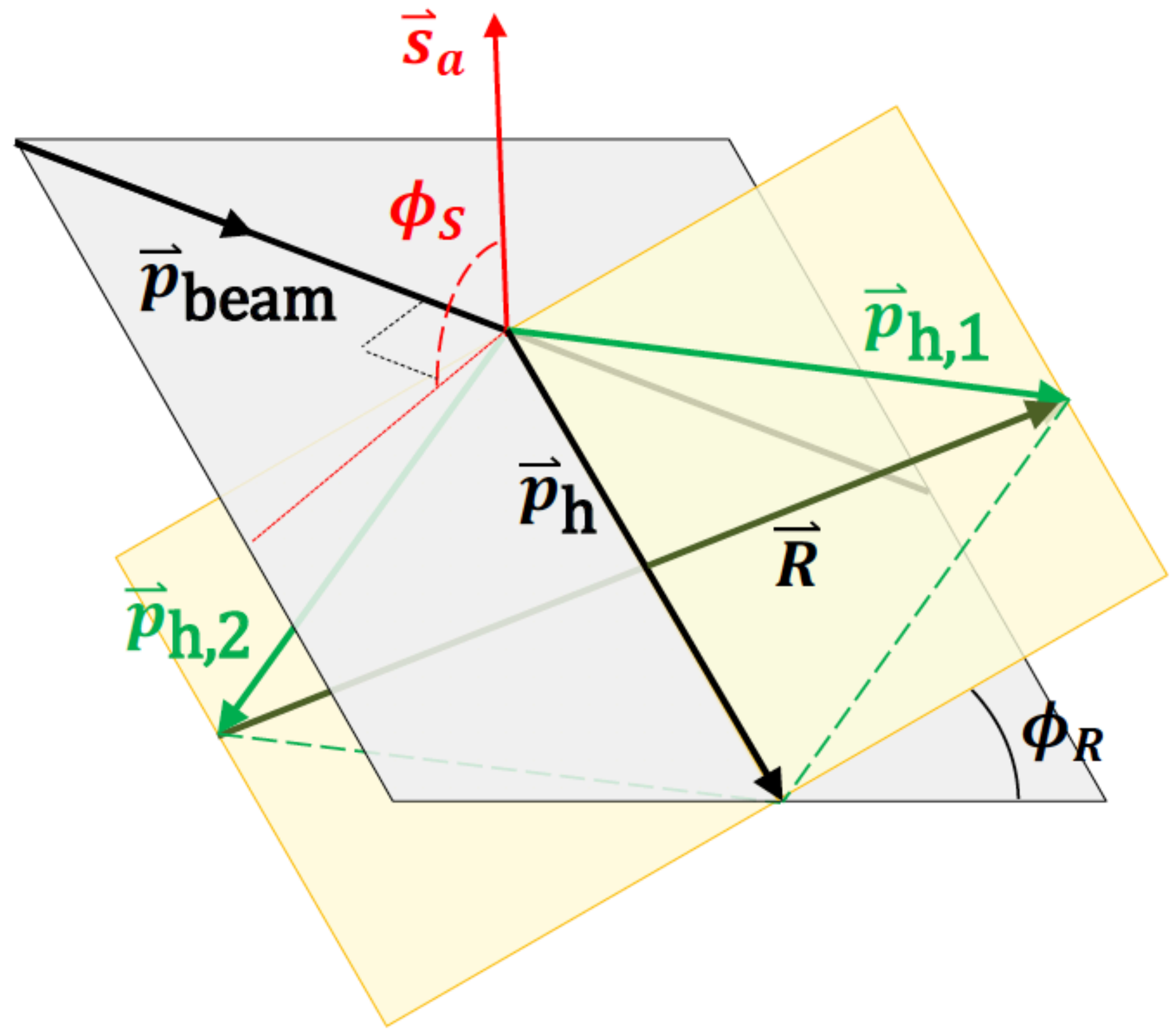
Dihadron Channel: $p^\uparrow + p \to h^+h^- + X$

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



Polarized Cross Section:

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



Unpolarized Cross Section:

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

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

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

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

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

  - Independent measurement of $H_1^{\sphericalangle}$ is required from e^+e^- experiments.
  - $D_1^{h_1h_2}$ is least known, specifically for gluon fragmentation.

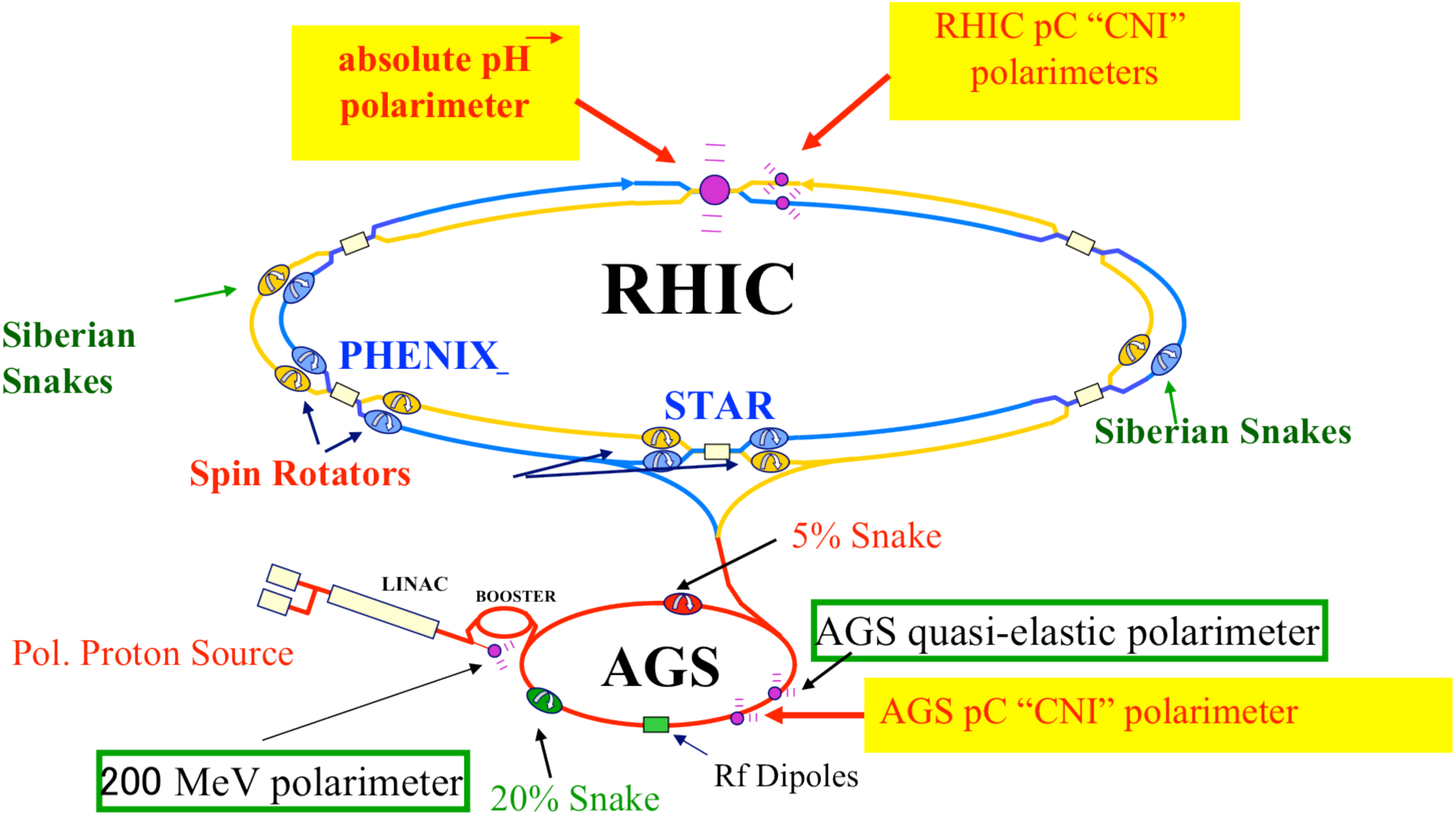
- **Unpolarized Dihadron Cross-Section, $d\sigma_{UU}$, in $p + p \rightarrow h^+h^- + X$**

  - $d\sigma_{UU}$ is crucial for the $D_1^{h_1h_2}$, which provides equal access to quarks and gluons.

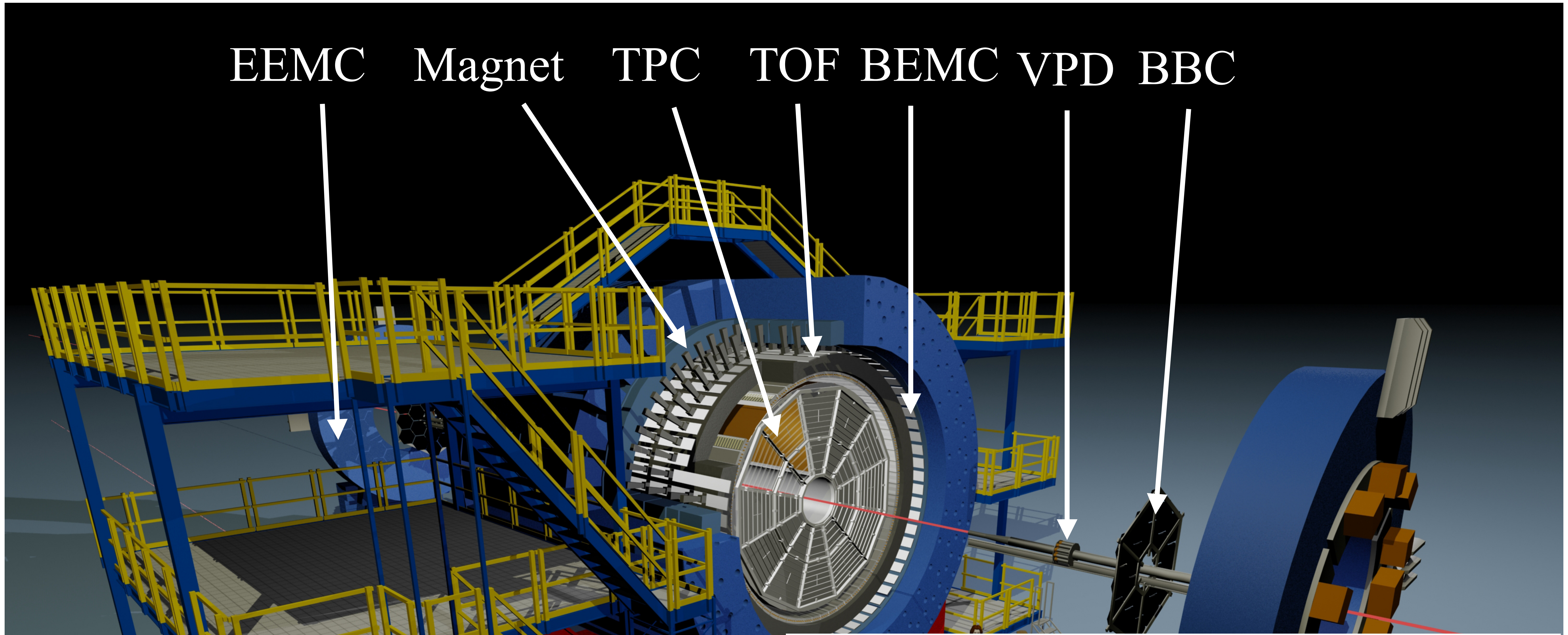
- **$d\sigma_{UU}$ and A_{UT} allows model-independent extraction of $h_1(x)$.**

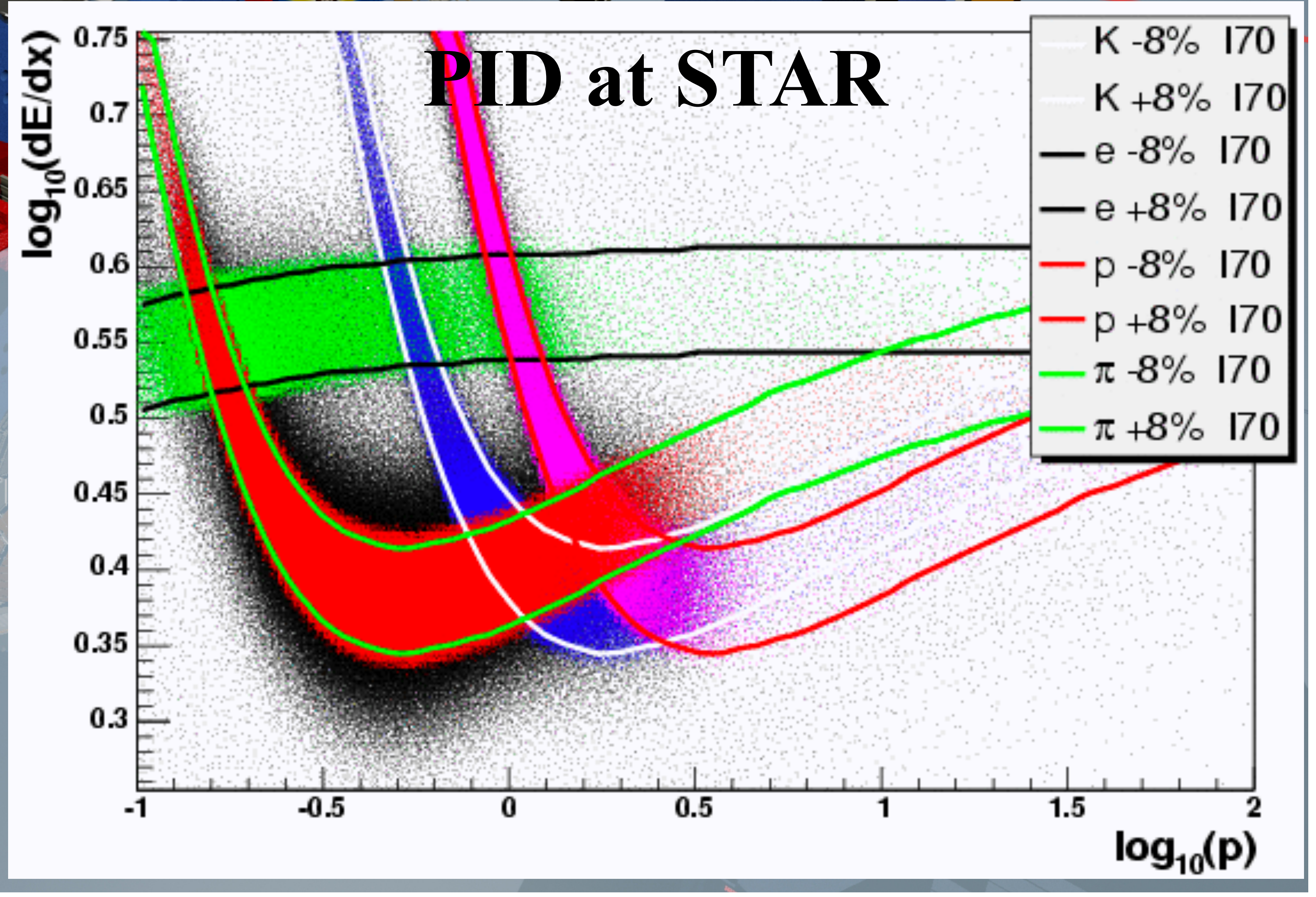
Bachhetta & Radici
Phys.Rev.D 70 (2004) 094032

Relativistic Heavy Ion Collider (RHIC)



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

IFF Studies at STAR

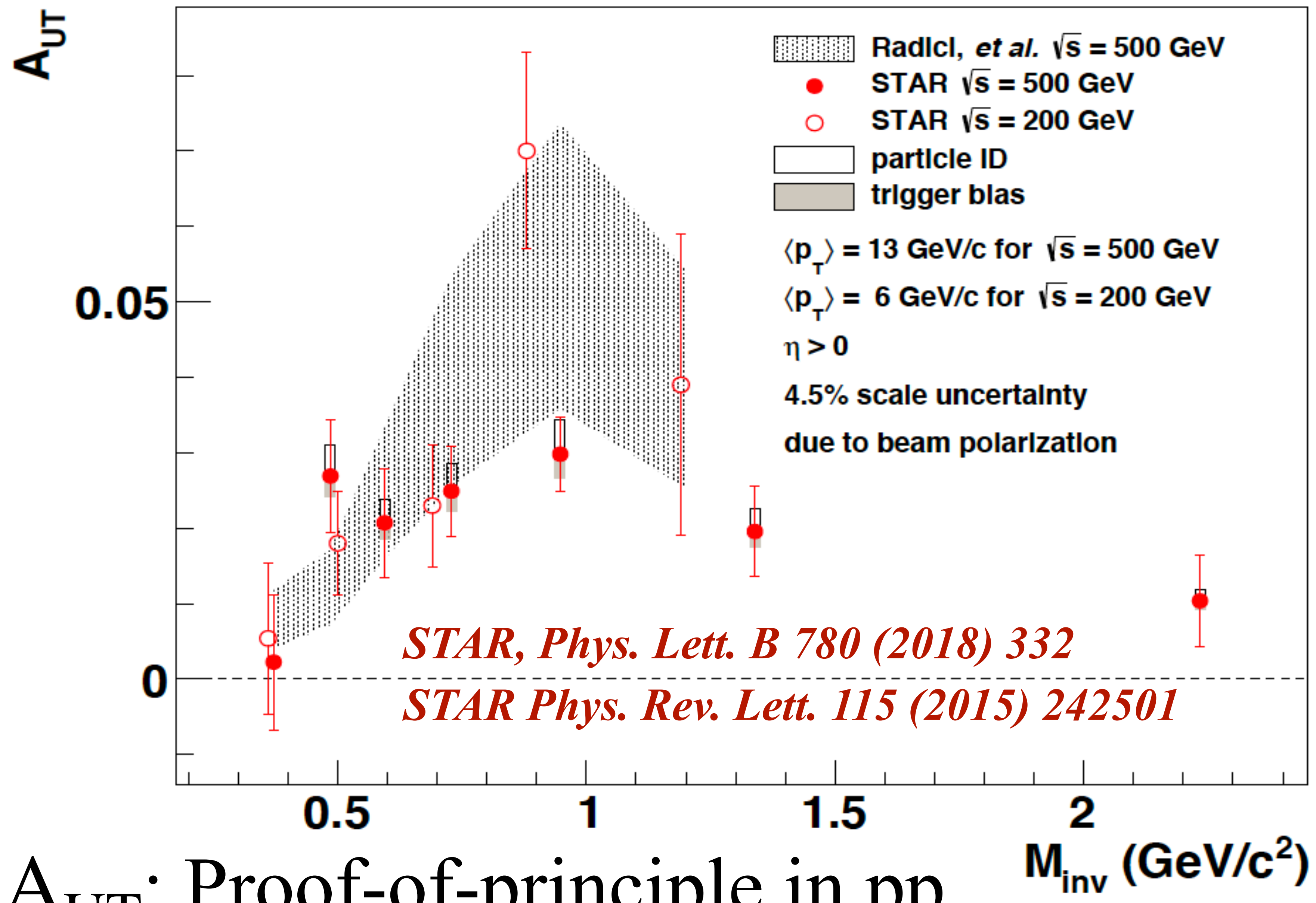
Collision	proton-proton						
Polarization	transverse						
Year	2006	2011	2012	2015	2017	2022	2024
$\sqrt{s}$ (GeV)	200	500	200	200	510	508	200
L_{int} (pb^{-1})	~ 1.8	~ 25	~ 22	~ 52	~ 350	~ 400	??
$< P_{beam} >$ (%)	~ 60	~ 53	~ 57	~ 57	~ 55	~ 52	??

- Published IFF A_{UT}

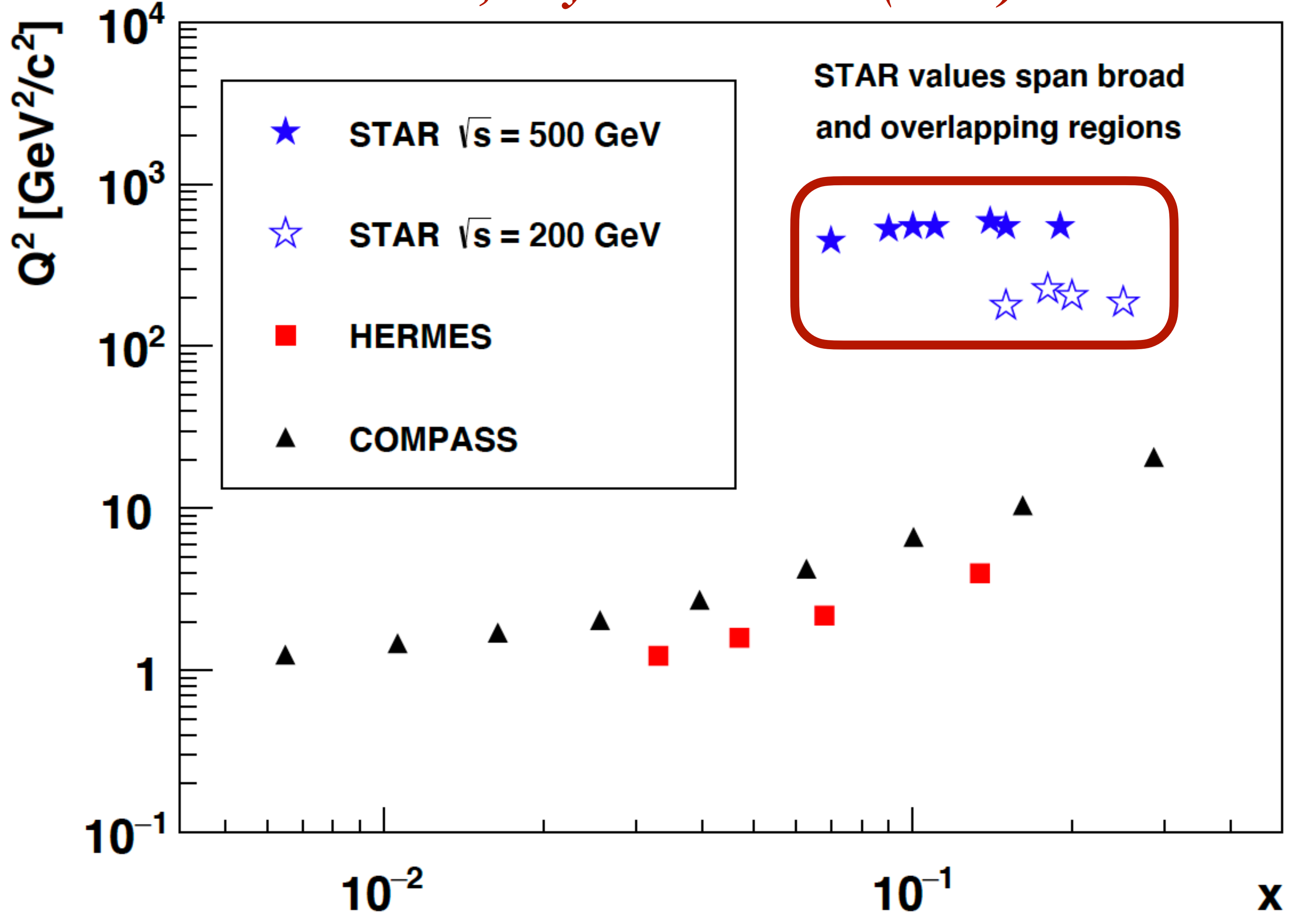
STAR, Phys. Lett. B 780 (2018) 332

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

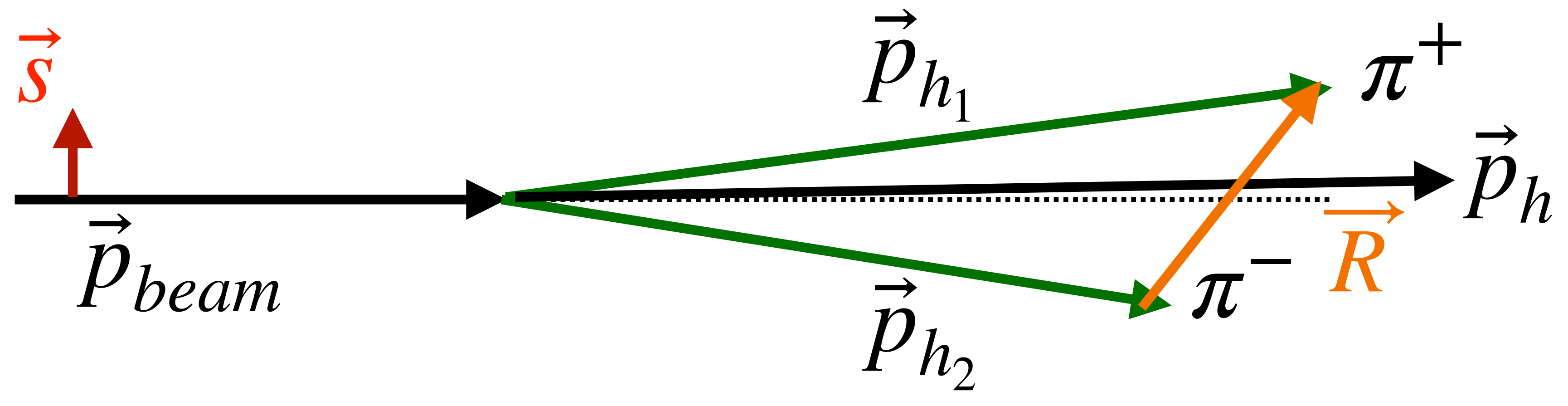


STAR Kinematic Coverage

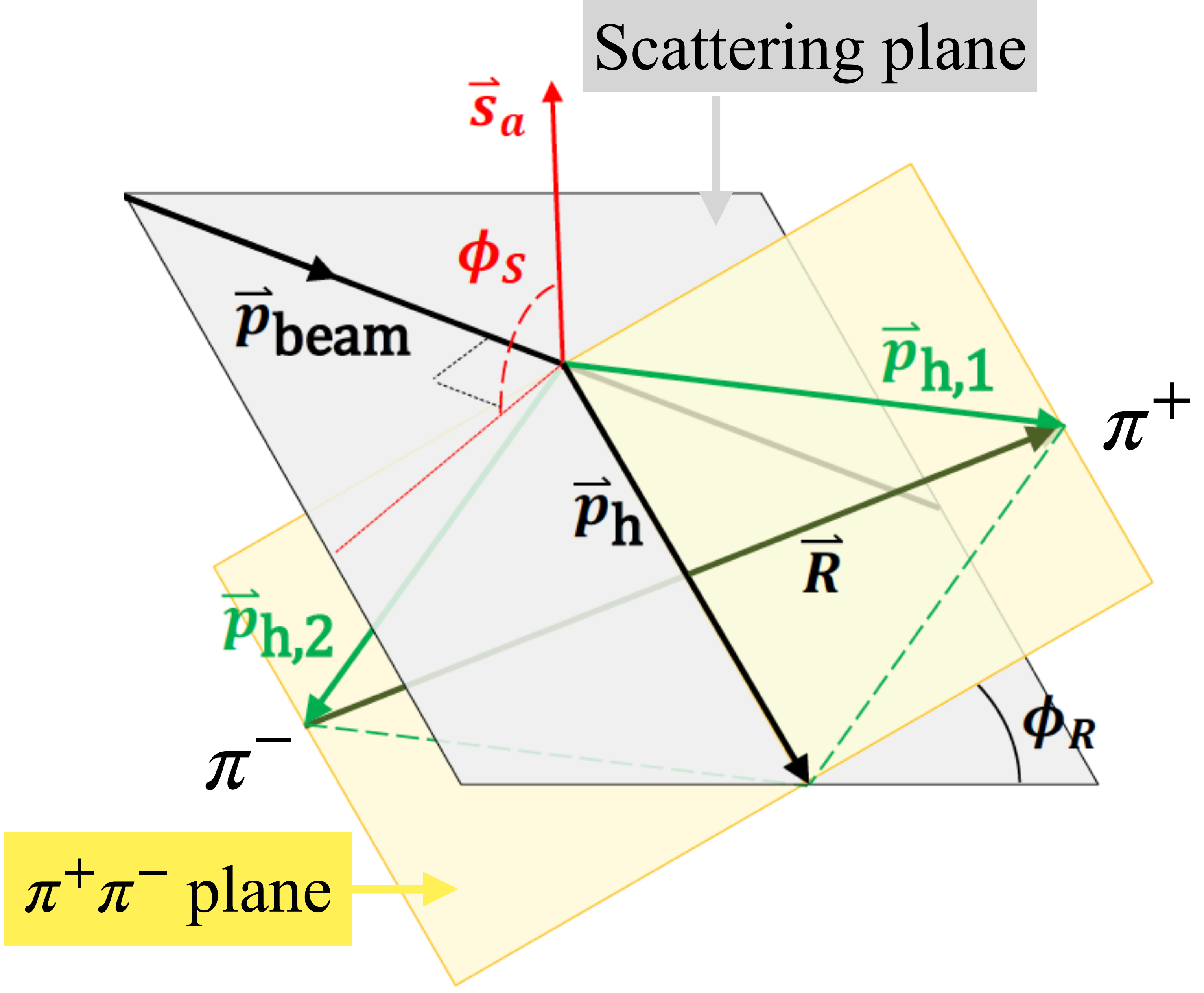
STAR Run 2015 $\pi^+\pi^-$ Asymmetry Analysis

$p^\uparrow + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ 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 ~ $\vec{S} \cdot \vec{R} \times \vec{p}_h$.
- Pion identification by measuring the ionization energy loss (dE/dx) with $p_T^\pi > 1.5$ 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

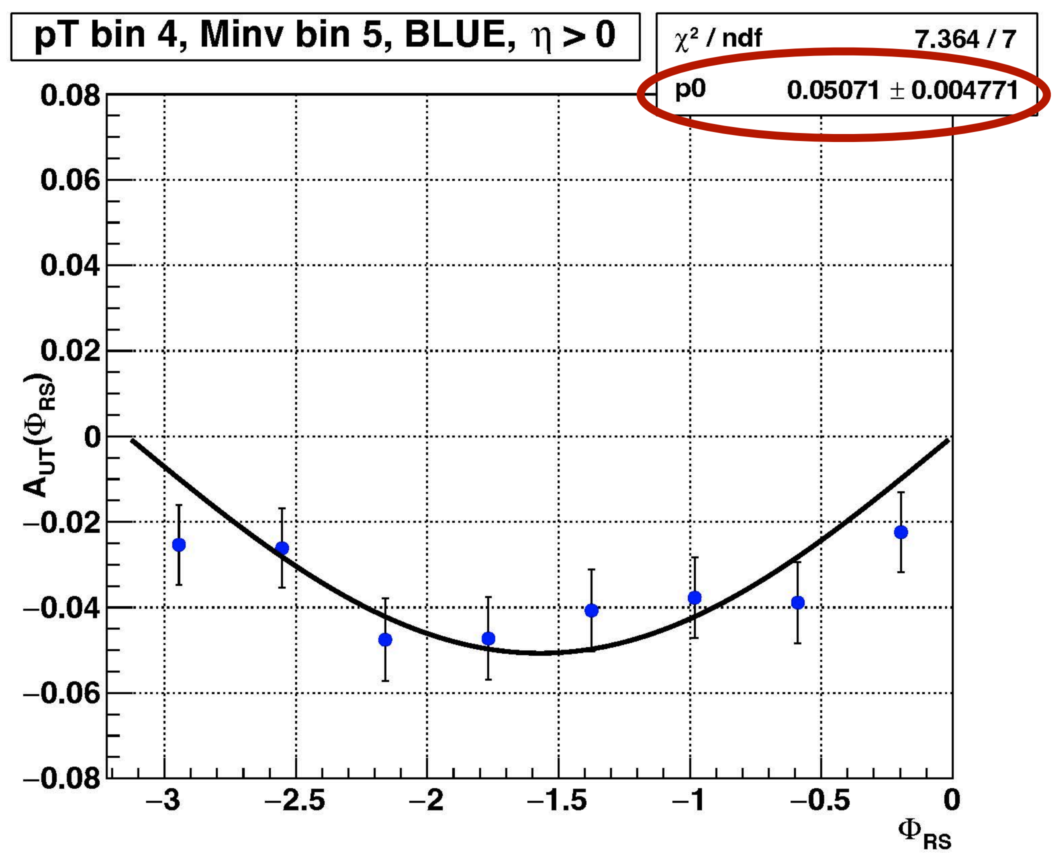
$$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X \text{ at } \sqrt{s} = 200 \text{ GeV}$$

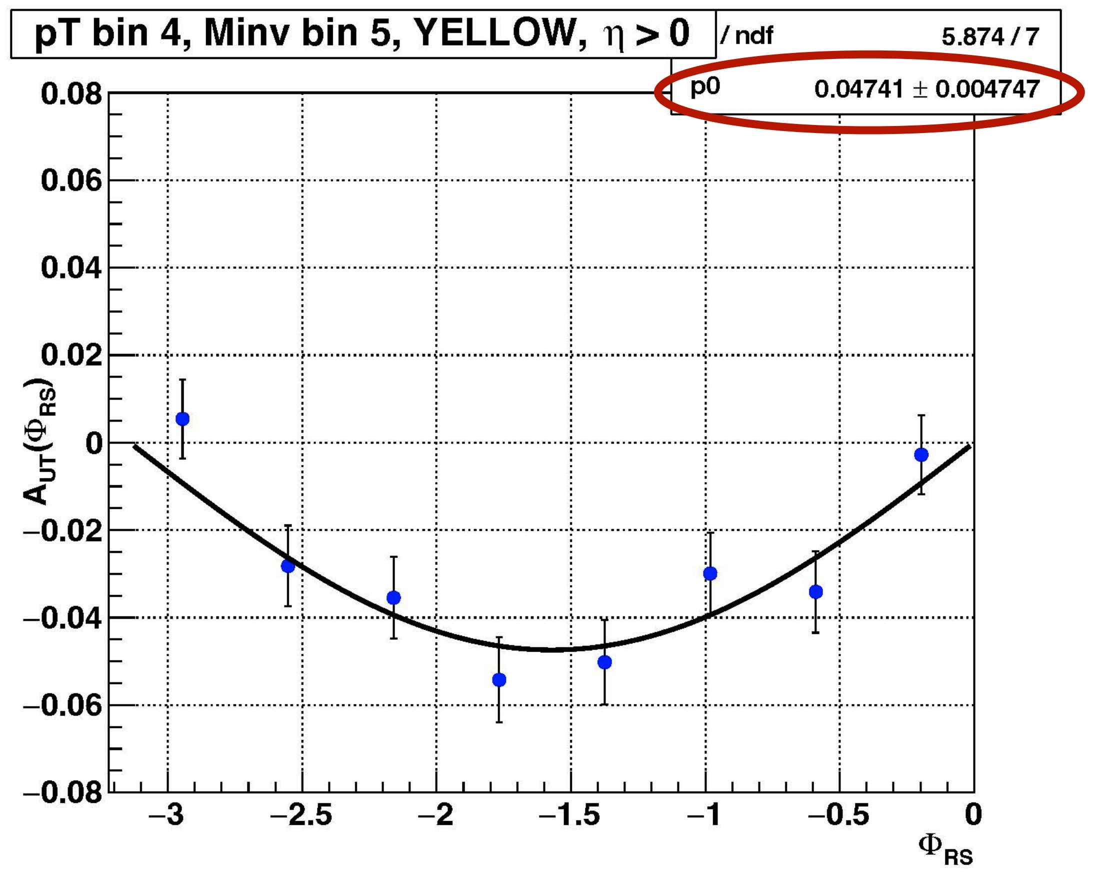
- $A_{UT}^{\sin(\phi_{RS})}$ extracted as a function of $M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$, and $\eta^{\pi^+\pi^-}$.

- **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!)



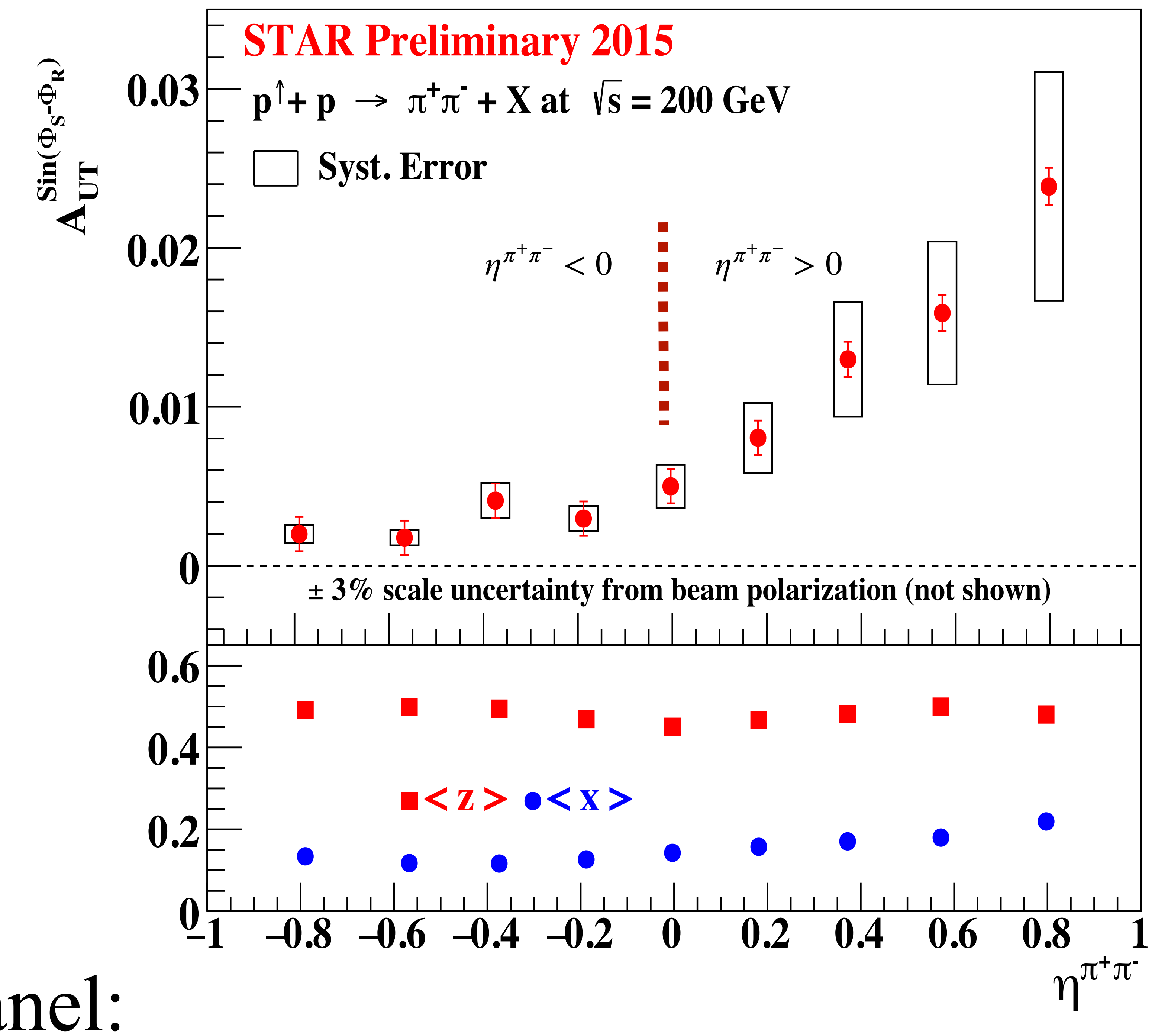


- Two transverse polarization states: ↑, ↓
- 16 ϕ_{RS} bins of uniform widths over $[-\pi, \pi]$.
- Symmetry between $[-\pi, 0]$ and $[0, \pi]$ hemispheres.
- Count $\pi^+\pi^-$ yields in each 16 ϕ_{RS} bins for each polarization states: $N^{\uparrow}(\phi_{RS})$, $N^{\downarrow}(\phi_{RS})$.

- Amplitude of the fit in $[-\pi, 0]$ gives the A_{UT} .
- A_{UT} extracted for Blue and Yellow beams separately. Final A_{UT} is the weighted average of both.

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

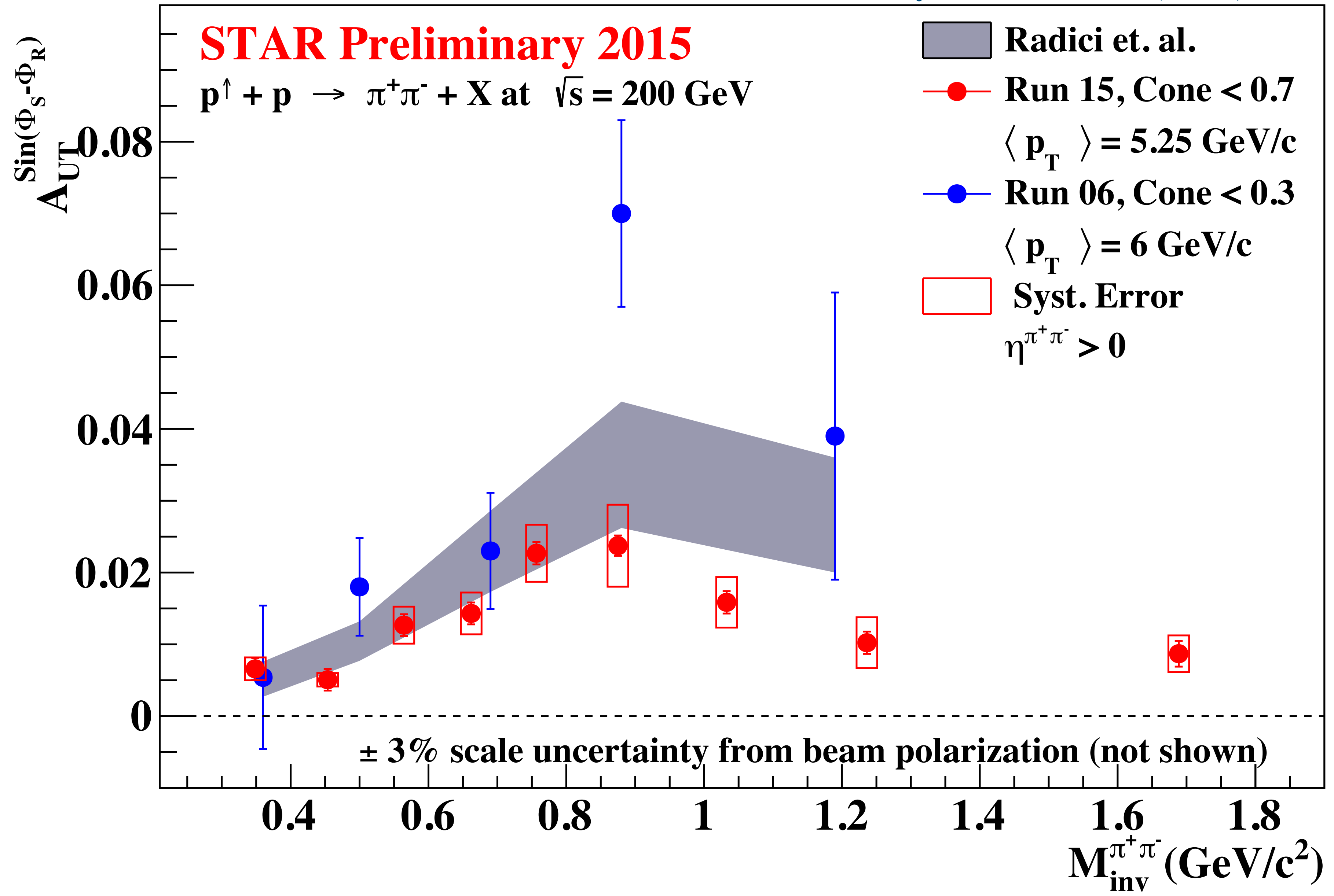
$$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X \text{ at } \sqrt{s} = 200 \text{ GeV}$$



$$z \rightarrow \frac{E_{\pi^+\pi^-}}{E_{quark}}$$

$$x = \frac{\vec{p}_{quark}}{\vec{p}_{proton}}$$

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:

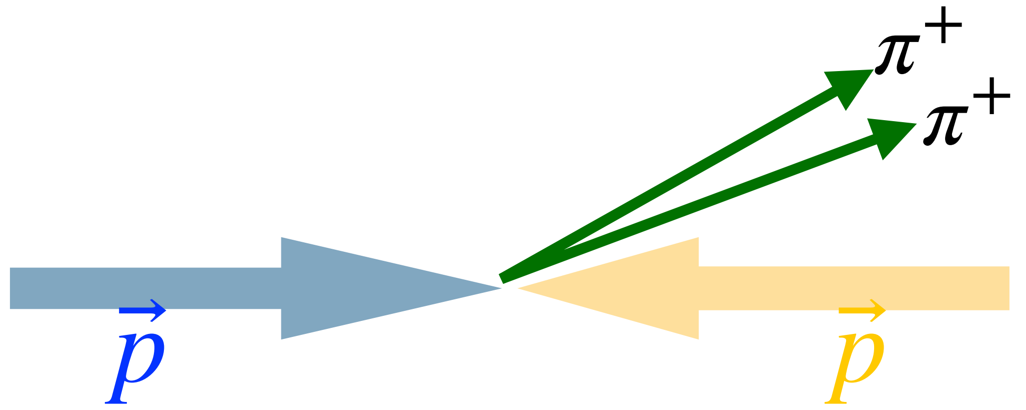
- Mean x and z from simulation.
- $0.1 < \langle x \rangle < 0.22$, $\langle z \rangle \sim 0.46$

- 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

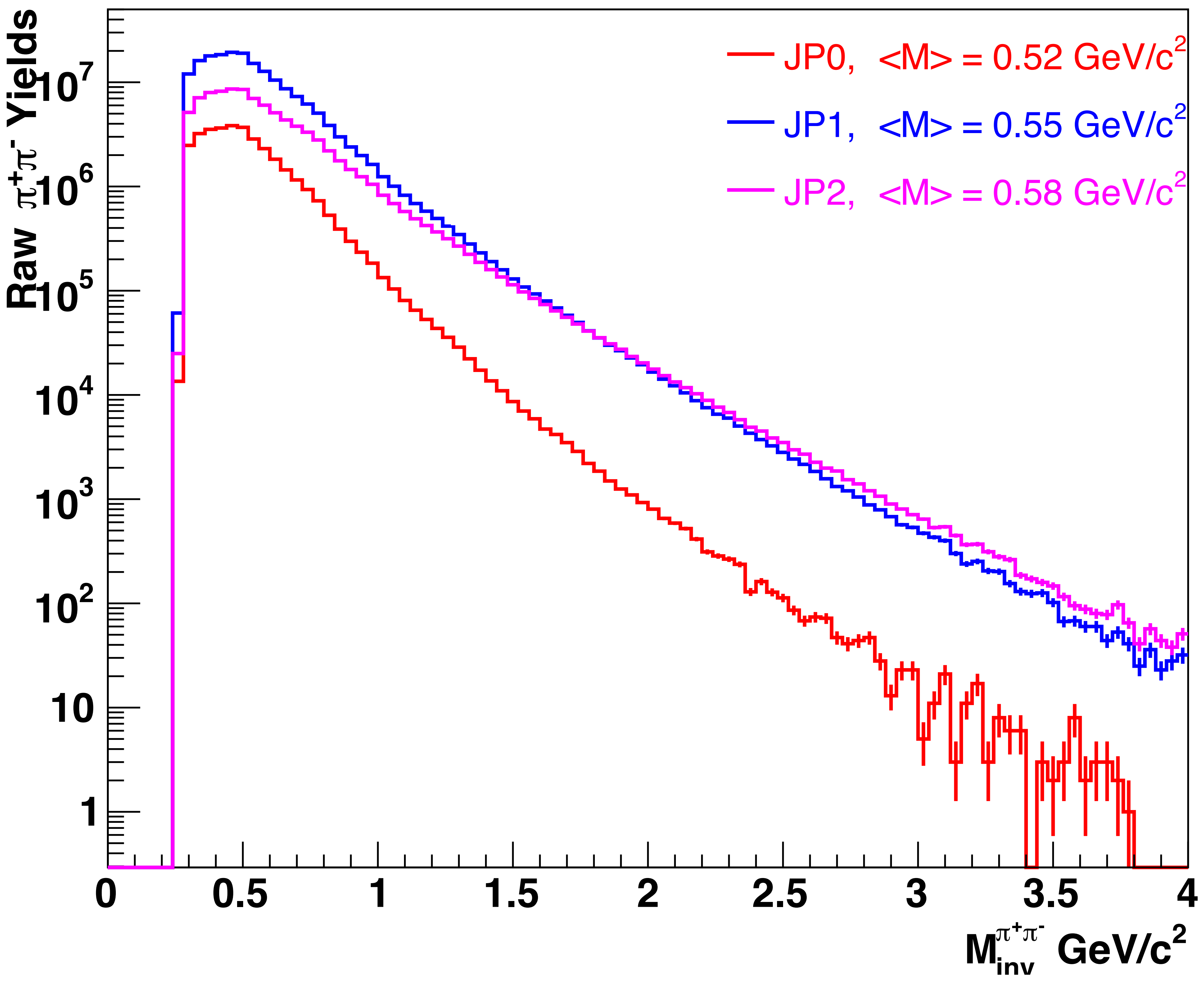
STAR Run 2012 Unpolarized $\pi^+\pi^-$ Cross-Section ($d\sigma_{UU}^{\pi^+\pi^-}$) Measurement

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



Polarization integrated ≈ Unpolarized

- 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 $D_1^{h_1h_2/g}$.
- STAR Run 2012 dataset @ $\sqrt{s} = 200$ GeV
- Triggers: JP0, JP1, 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

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

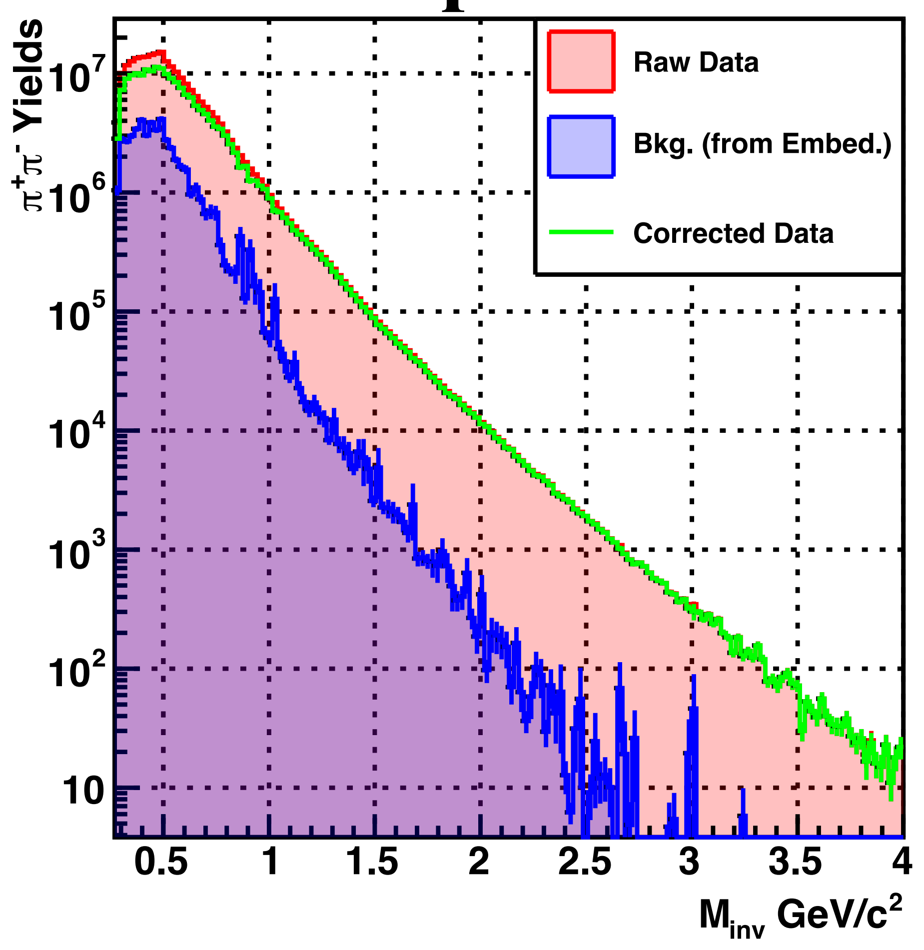
- Unfolding accounts for the **bin migration effect.**
- **Embedding (PYTHIA** simulated events, reconstructed through the **GEANT 3** package embedded in the zero-bias events) are used for the unfolding.
- **Backgrounds** are subtracted before unfolding.

Unfolding Using TUnfoldDensity

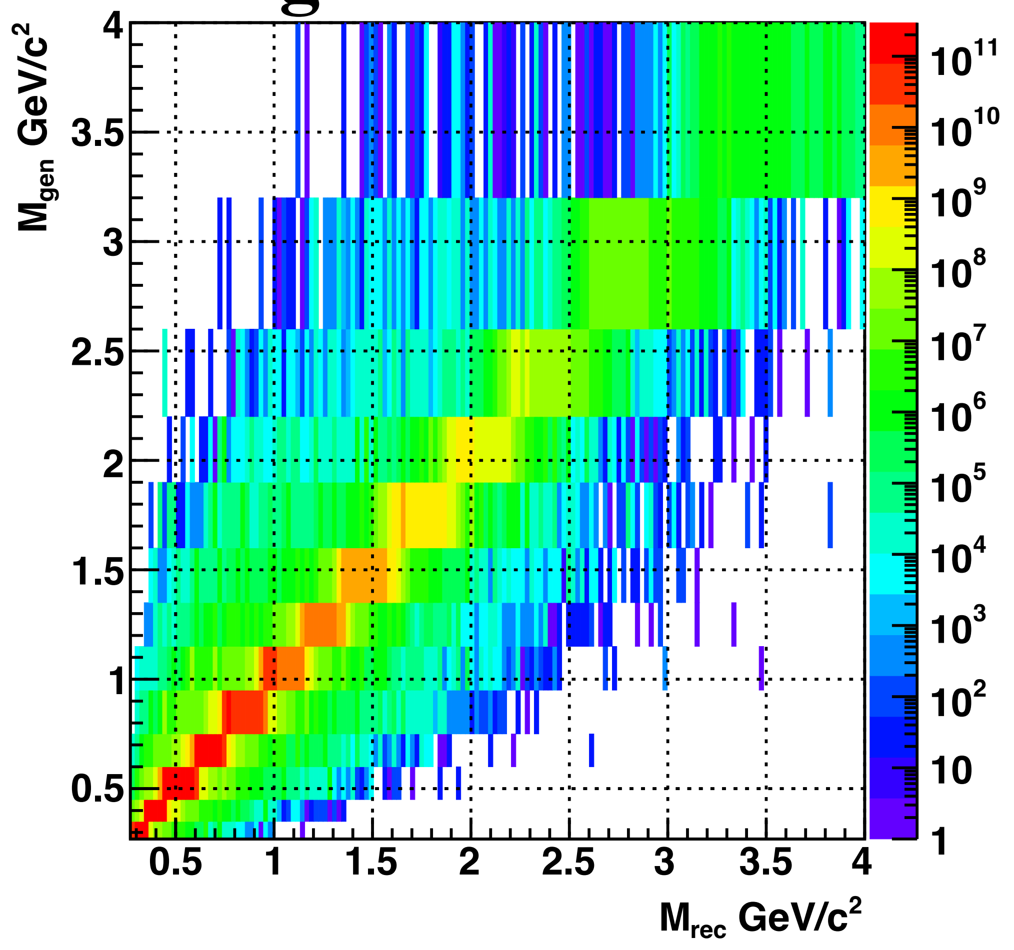
- TUnfoldDensity is based on least square fit with Tikhonov regularization.
- Input $\equiv$ Background corrected data.
- **Migration matrix** transforms the "detector" yields to the "true" yields.
- Output $\equiv$ "True" yields

- Small shape change in the unfolding output than the input.
- Unfolding is performed for each trigger, allowing independent measurement of triggered cross-section.

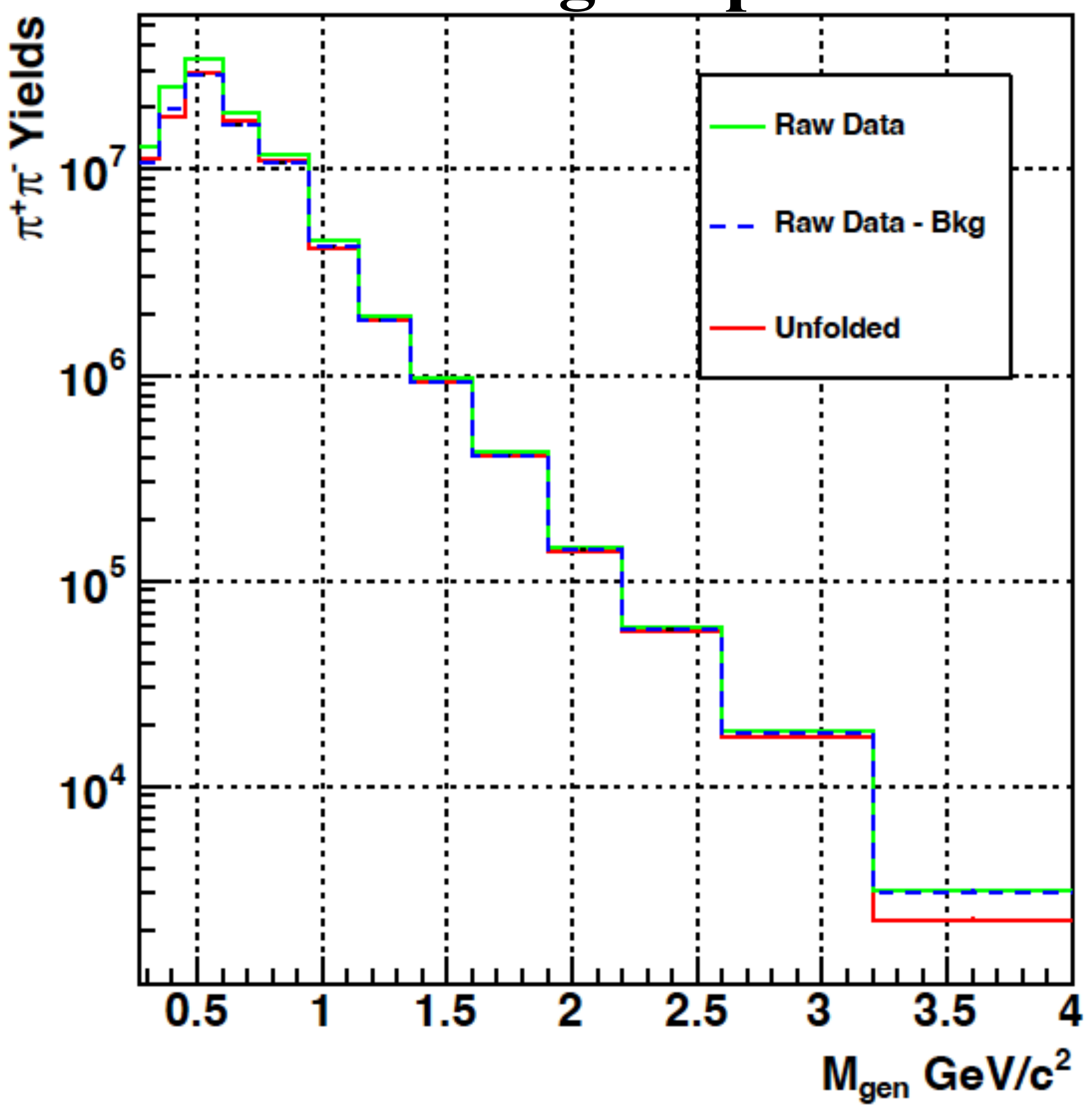
Input



Migration matrix



Unfolding output



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

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

- All the corrections are **embedding** driven.

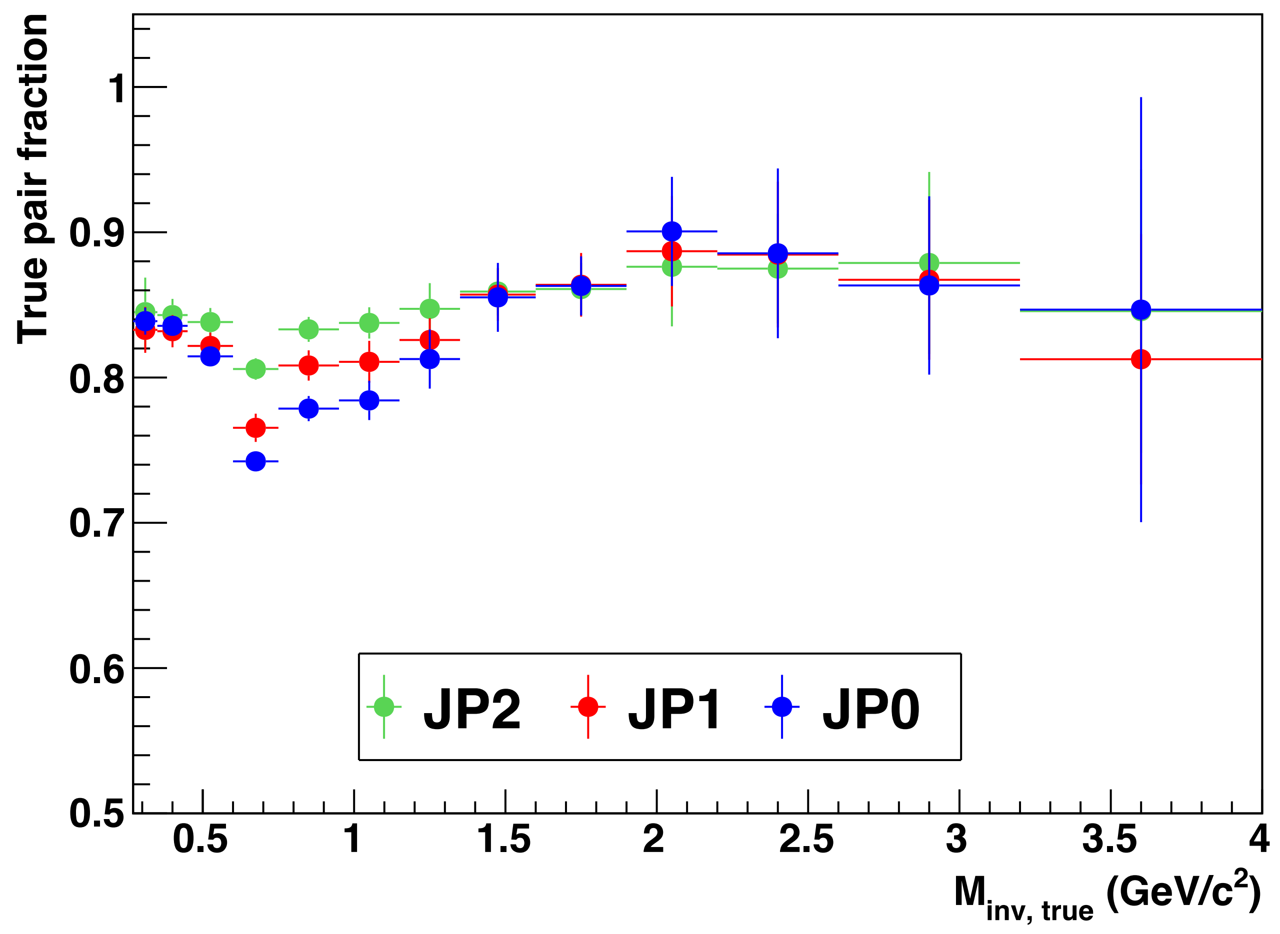
PID Corrections

- 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**.

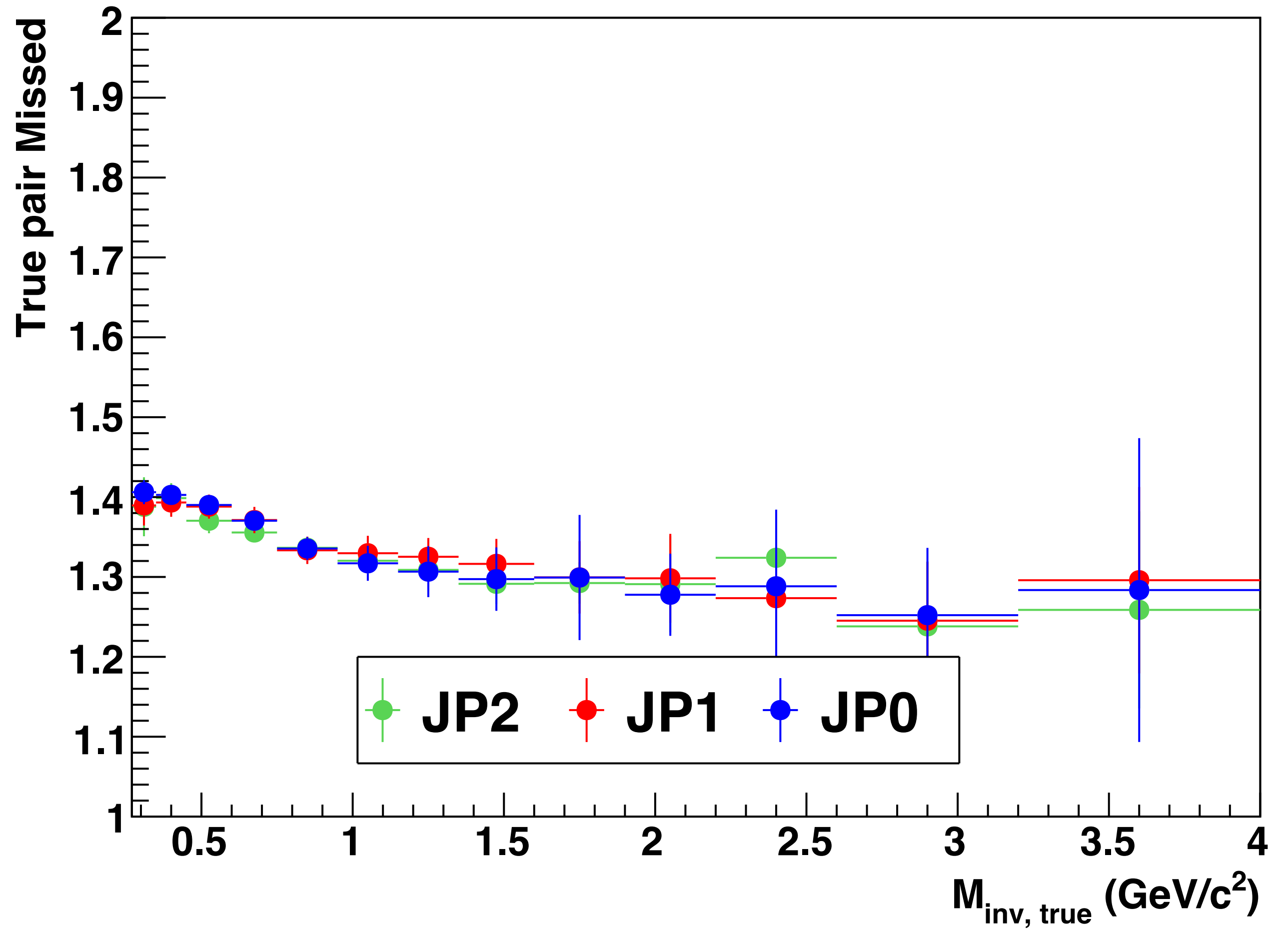
Efficiency Corrections

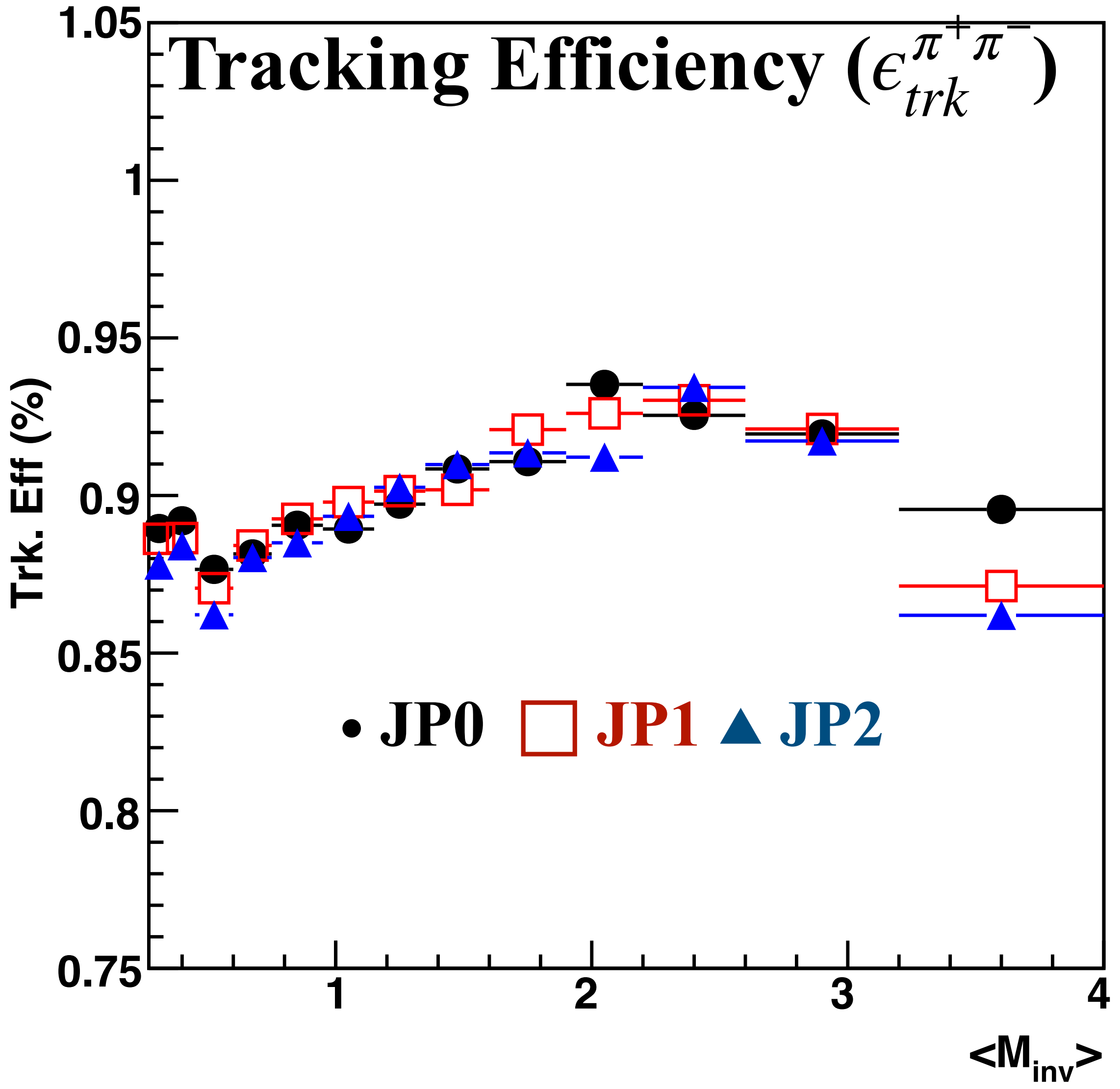
- Tracking Efficiency ($\epsilon_{trk}^{\pi^+\pi^-}$)
- Trigger Efficiency ($\epsilon_{trg}^{\pi^+\pi^-}$)

$\pi^+\pi^-$ Purity Fraction (f_{fake})

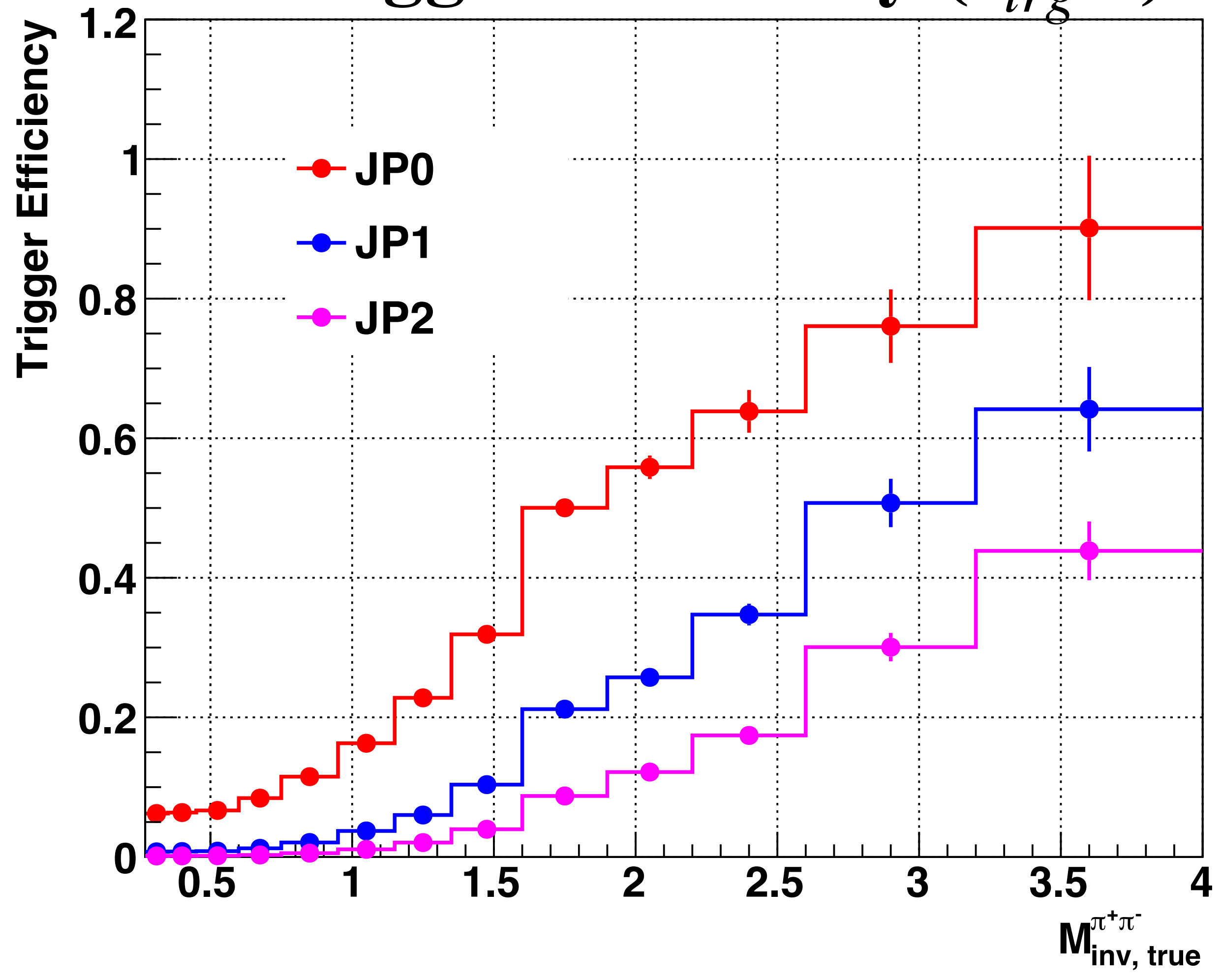


$\pi^+\pi^-$ Loss Fraction (f_{loss})





Trigger Efficiency ($\epsilon_{trg}^{\pi^+\pi^-}$)



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

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

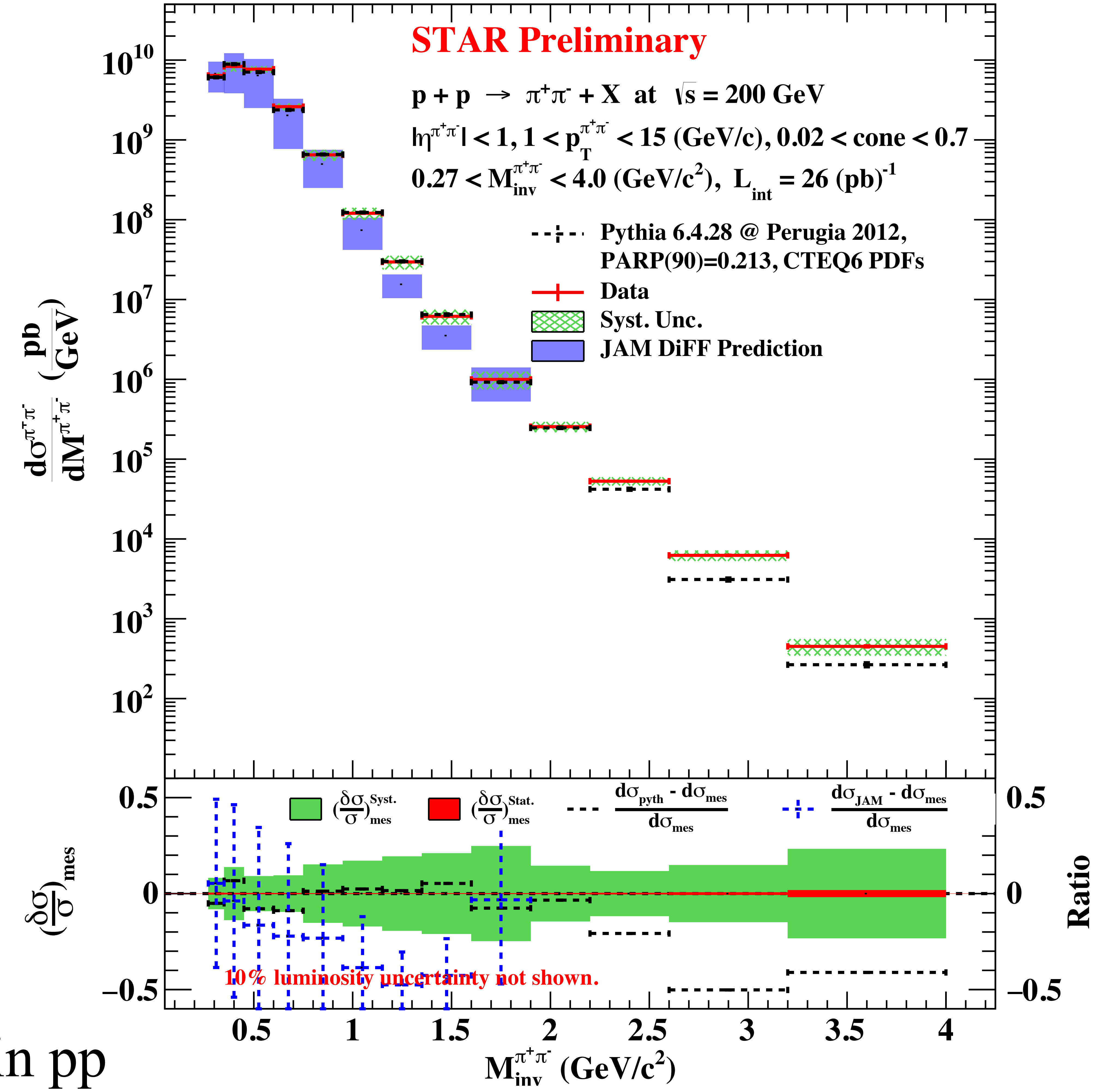
STAR Preliminary

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) (Details in backup!)
- Relative difference between PYTHIA and measured cross-section (closed circle).
- Statistical uncertainty (red band).

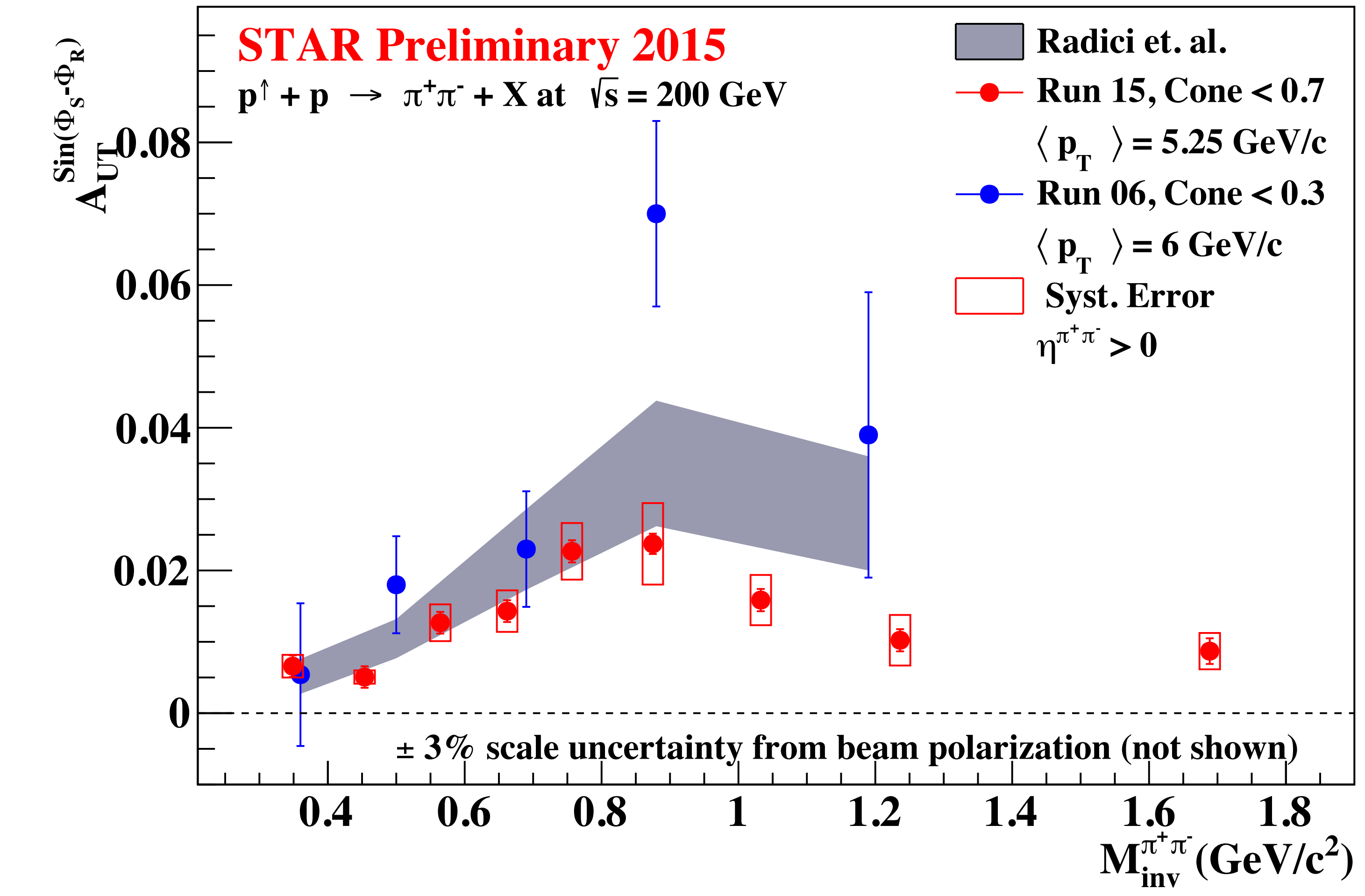


- This measurement **provides access to $D_1^{h_1h_2}$ for gluons**.
- Together with the Belle measurements, IFF and cross-section in pp opens up a path for the **model-independent extraction of transversity**.

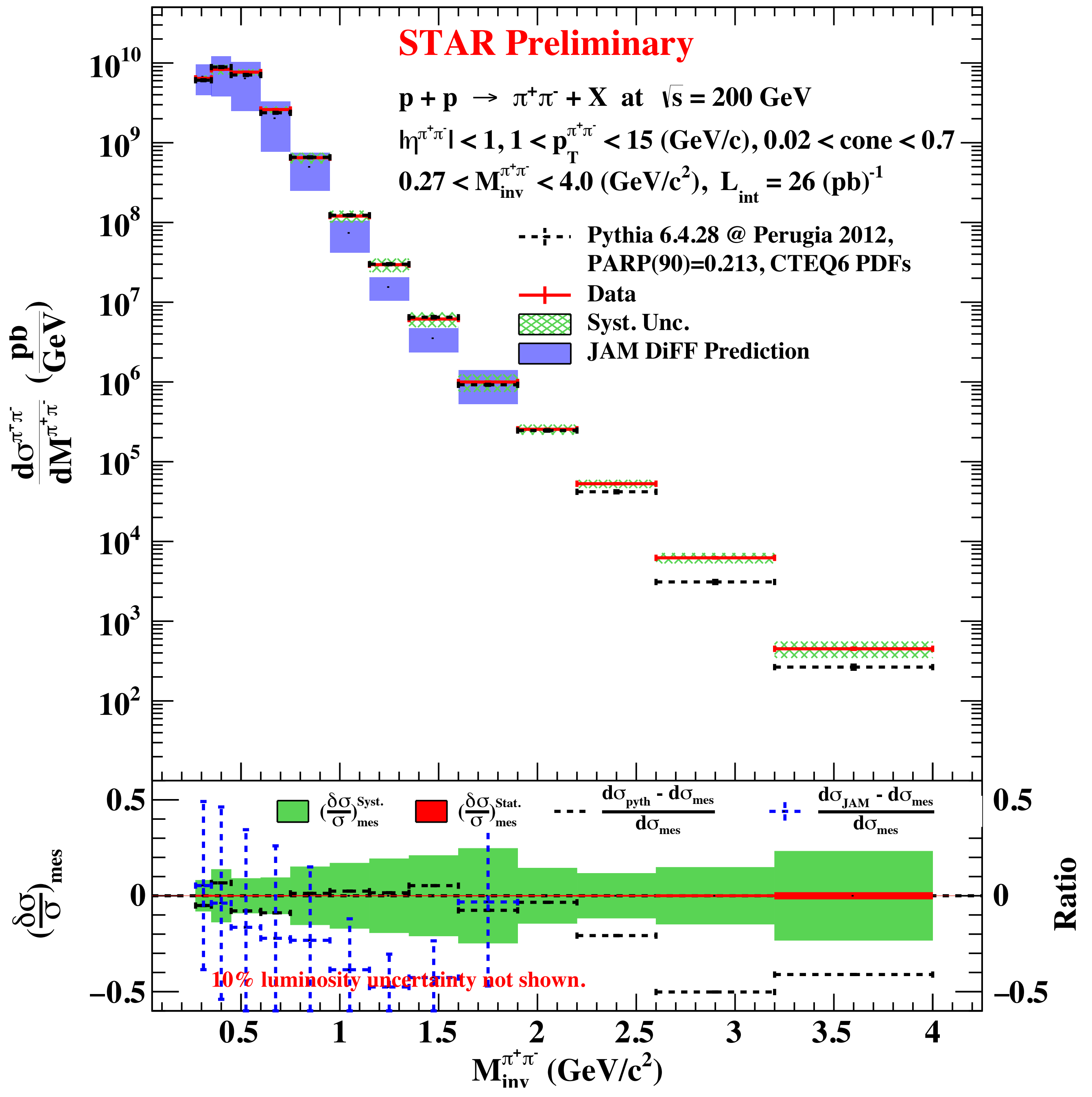
Summary and Outlook

- **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.

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

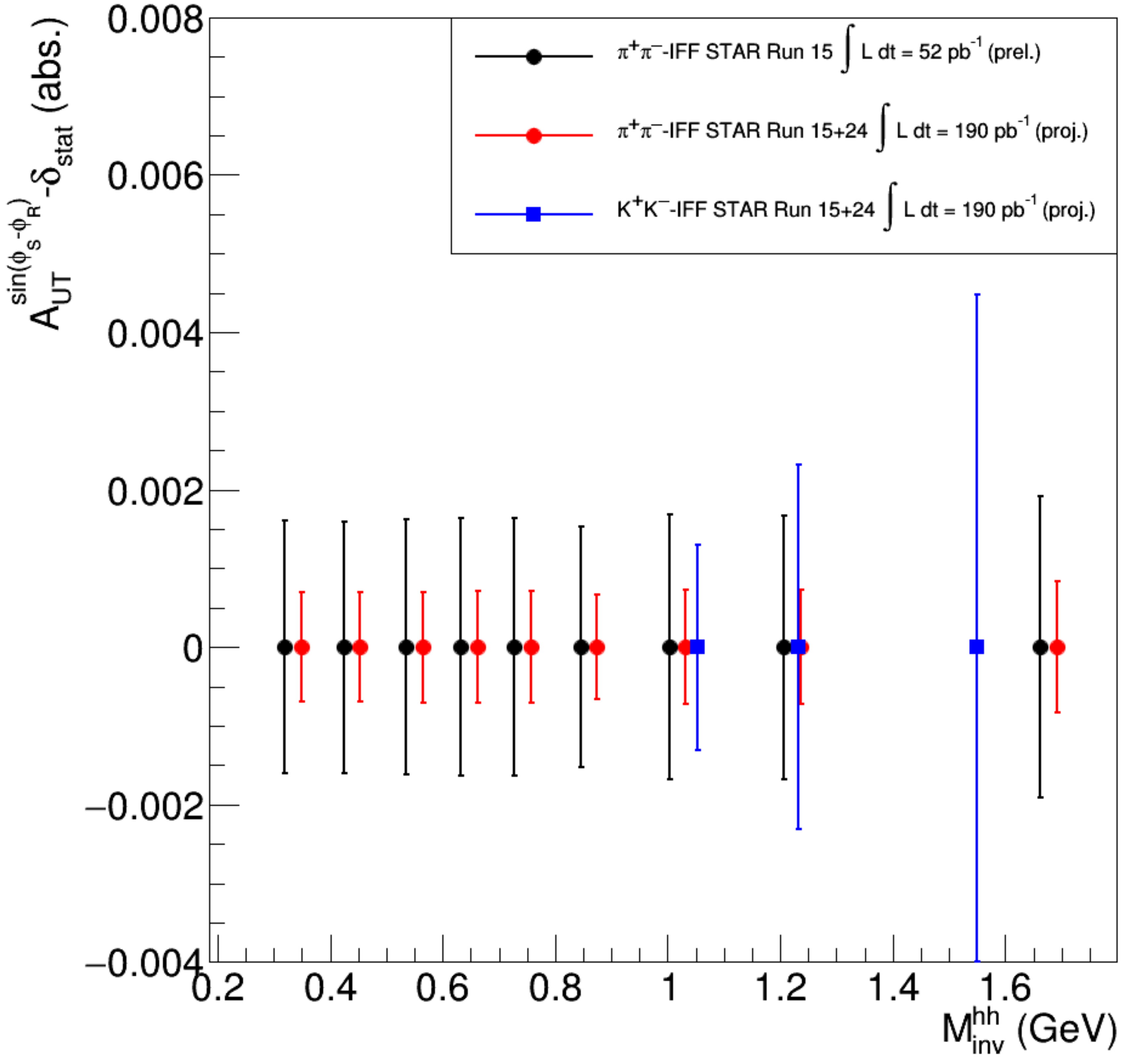


- **First unpolarized $\pi^+\pi^-$ cross-section measurement in *pp***
  - Provides access to $D_1^{h_1 h_2}$ for gluons.
  - Path to the model-independent extraction of $h_1(x)$.
  - Planned double differential cross-section in $\mathrm{M}_{\mathrm{inv}}^{\pi^+\pi^-}$ and $p_T^{\pi^+\pi^-}$.



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

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

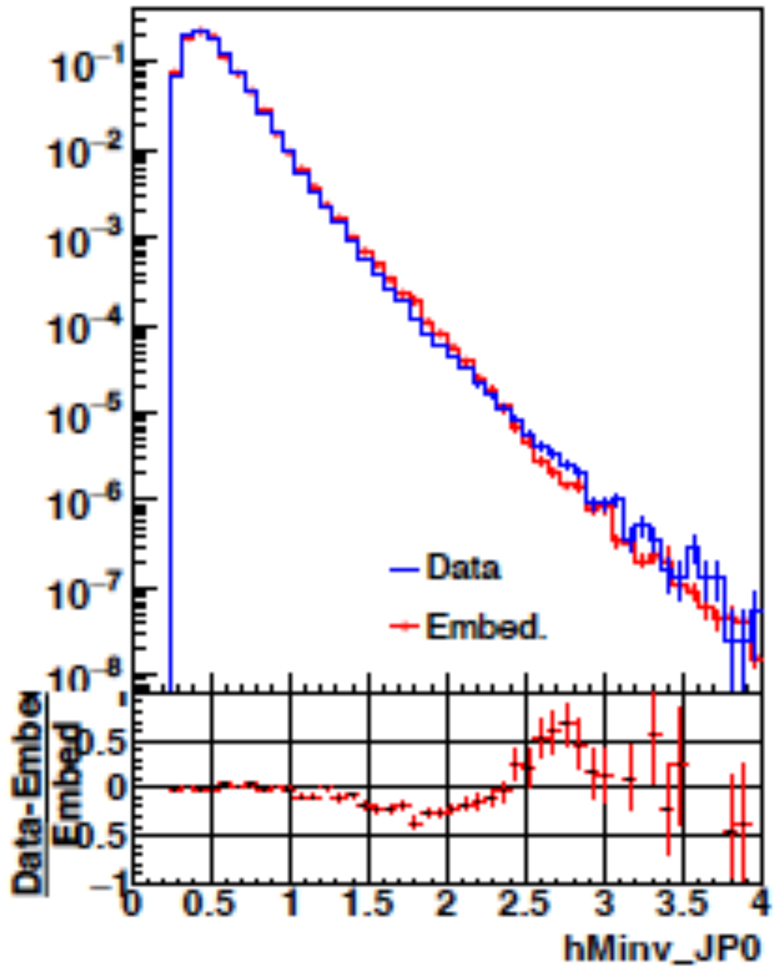
$p + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

Simulation and Embedding Sample

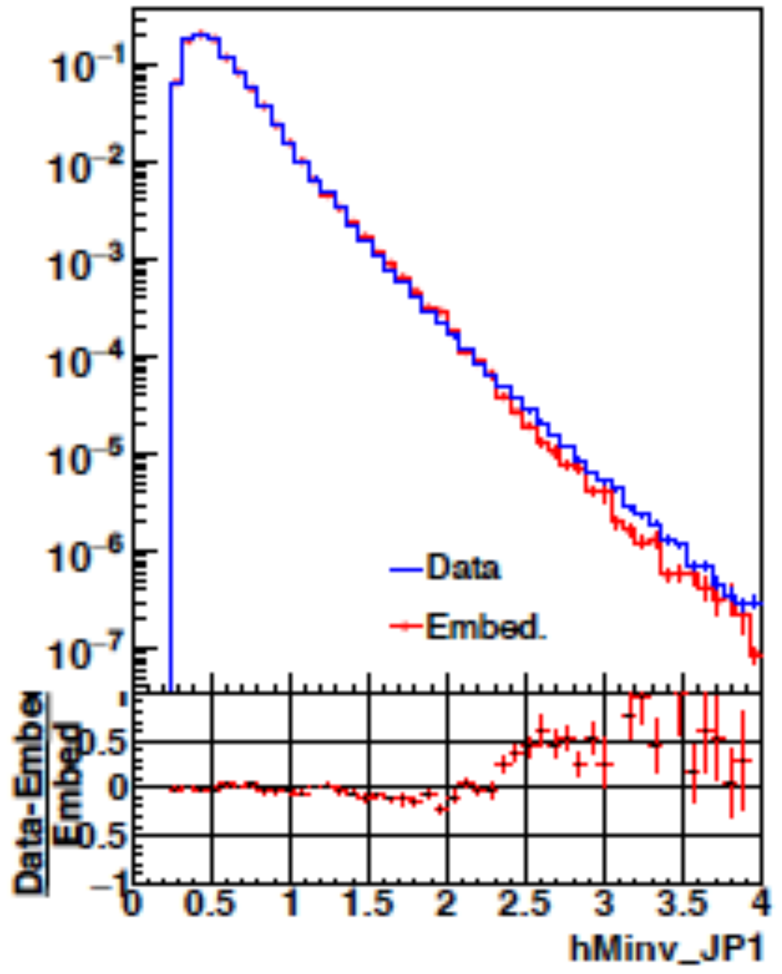
- Simulation and Embedding sample needed for:
  - Data unfolding
  - PID corrections
  - Efficiency analysis
  - Systematic studies

- **PYTHIA** simulated events, reconstructed through the **GEANT 3** package embedded in the zero-bias events to effectively reconstruct STAR detector responses (Embedding).

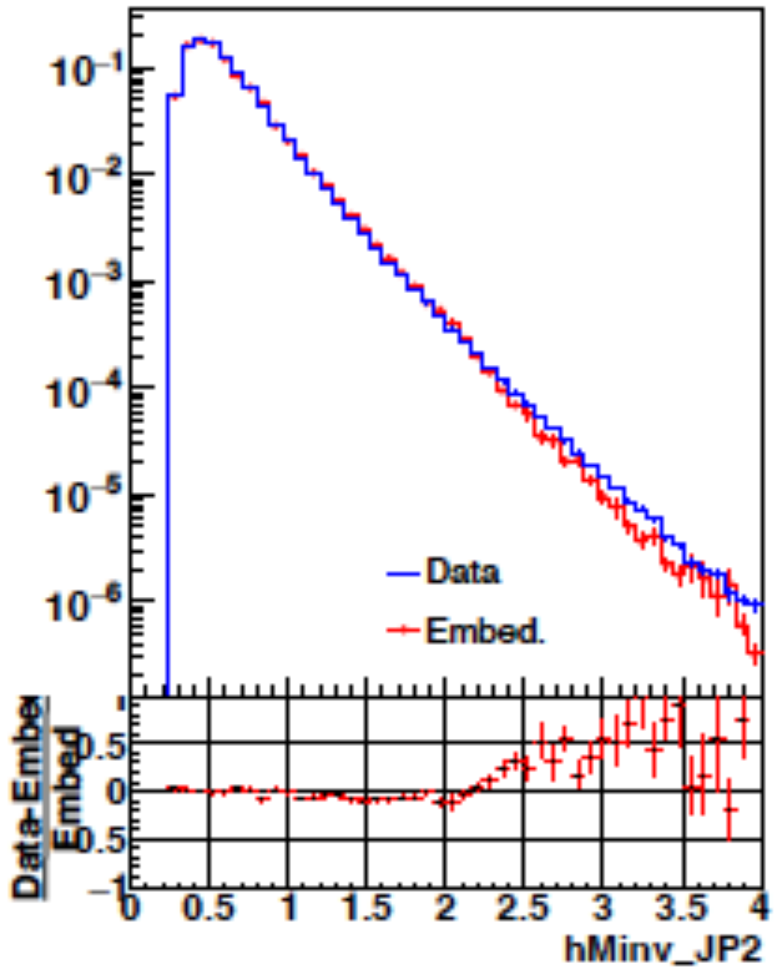
- Good agreement between the data and embedding.



(a) $M_{inv}^{\pi^+\pi^-}$ comparison for JP0 trigger.



(b) $M_{inv}^{\pi^+\pi^-}$ comparison for JP1 trigger.



(c) $M_{inv}^{\pi^+\pi^-}$ comparison for JP2 trigger

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

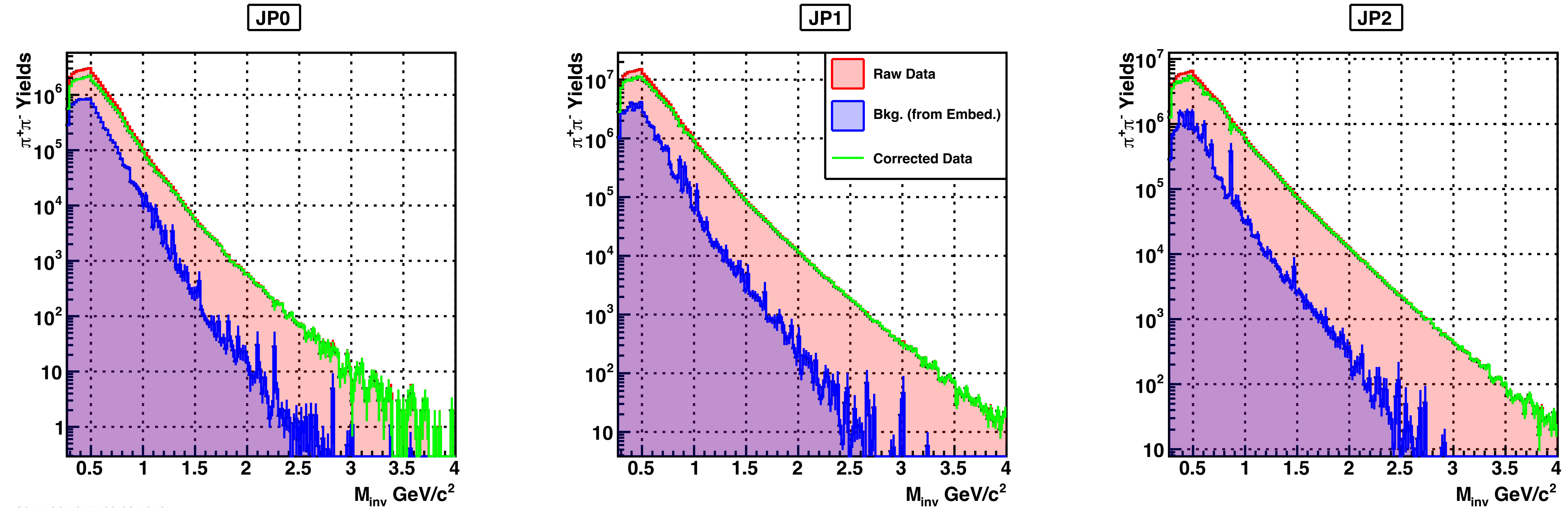
$p + p \to \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

- Unfolding accounts for the bin migration effect and backgrounds.

$$y_i = \sum_{j=1}^{m} A_{ij} x_i + b_i \; , \; 1 \leq i \leq n, \; n \geq m$$

$\boldsymbol{y}$ = detector level, $\boldsymbol{x}$ = truth level

$\boldsymbol{A}$ = Migration matrix , $\boldsymbol{b}$ = background

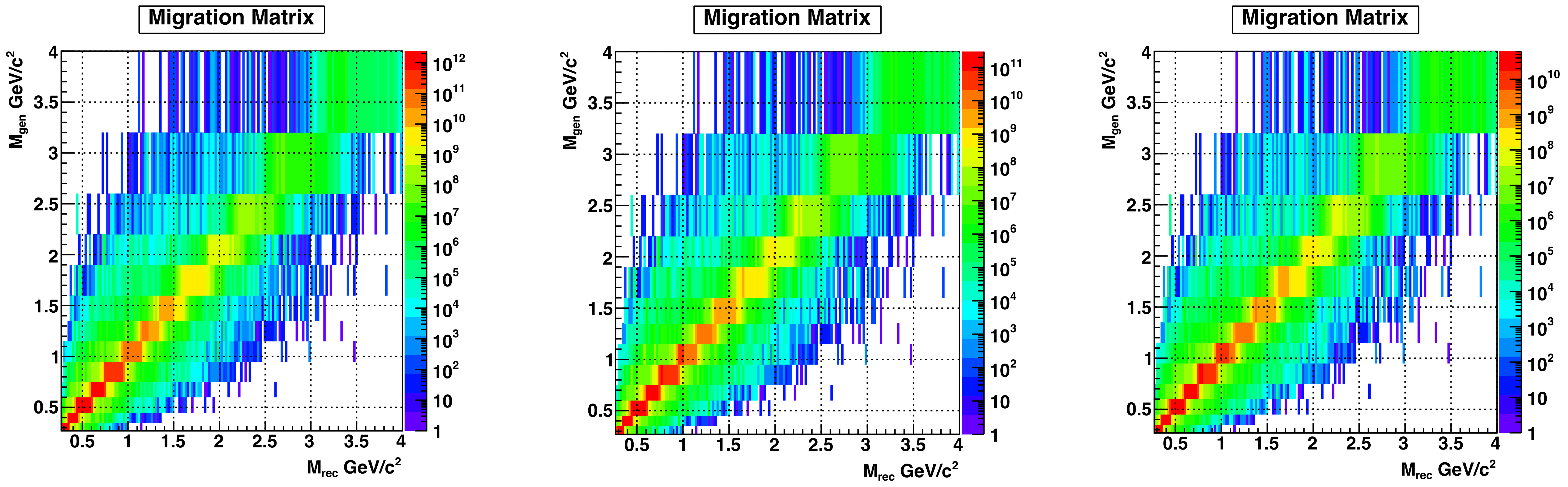


$b \equiv$ Backgrounds $y \equiv$ Raw yields $y - b \equiv$ Raw yields − Backgrounds

Unfolding Using TUnfoldDensity

- TUnfoldDensity is based on least square fit with Tikhonov regularization.
- Input ($\boldsymbol{y}$) ≡ Raw detector yields.
- Migration matrix transforms the "detector" yields to the "true" yields.
- Output ($\boldsymbol{x}$) ≡ "True" yields

A_{JP0} A_{JP1} A_{JP2}



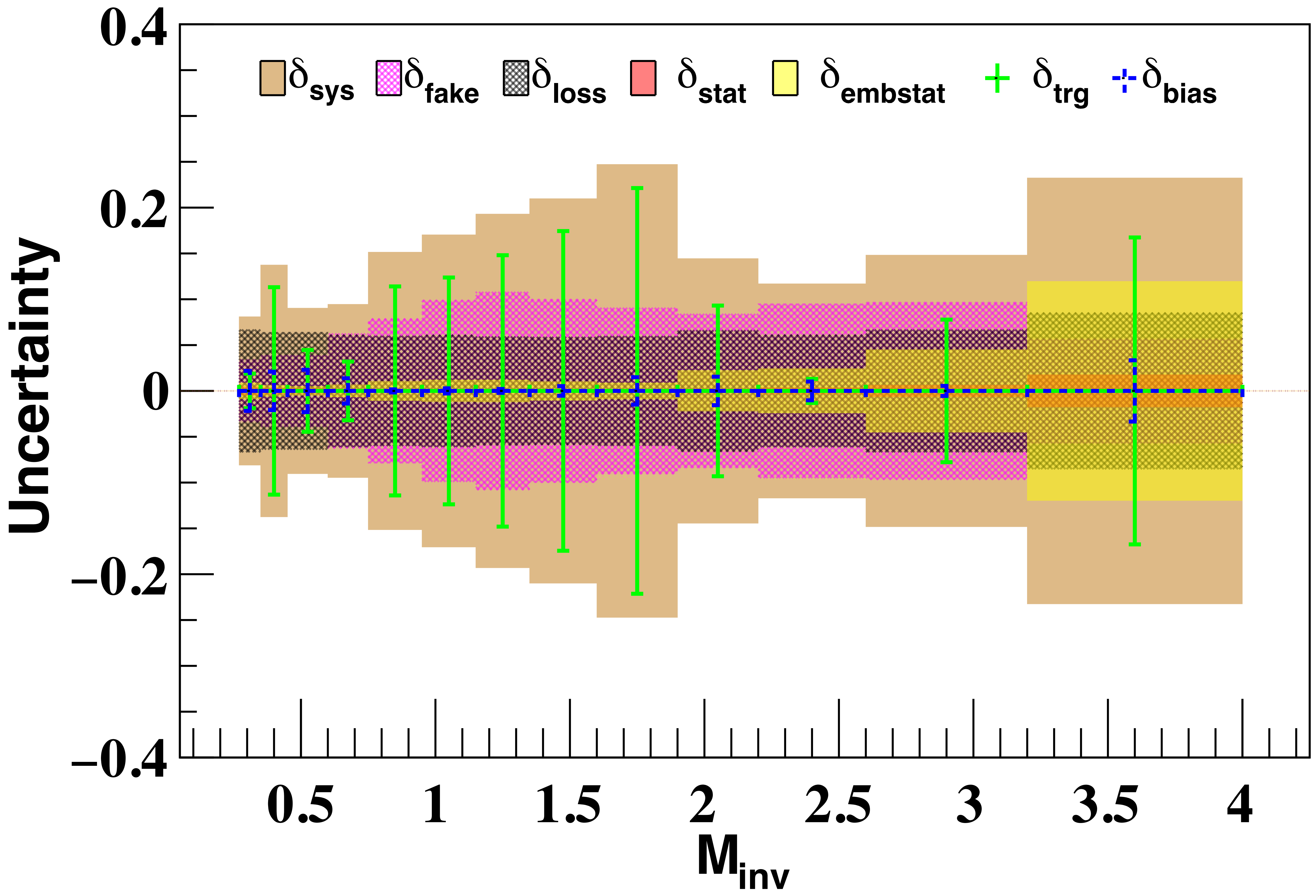
STAR Run 2012 Unpolarized $\pi^+\pi^-$ Cross-Section ($d\sigma_{UU}^{\pi^+\pi^-}$) Measurement

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

Systematic uncertainties

1. $\pi^+\pi^-$ Purity Fraction (δ_{fake})
2. $\pi^+\pi^-$ Loss Fraction (δ_{loss})
3. Trigger Dependence (δ_{trg})
4. Trigger Bias (δ_{bias})
5. Simulation Statistics (δ_{embstat})

$$\delta_{\text{sys}} = \sqrt{\delta_{\text{fake}}^2 + \delta_{\text{loss}}^2 + \delta_{\text{trg}}^2 + \delta_{\text{bias}}^2 + \delta_{\text{embstat}}^2}$$



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 (ϵ^{π}_{trk})
4. Trigger Efficiency ($\epsilon^{\pi^+\pi^-}_{trg}$)

Triggered Cross Sections

$$\frac{d\sigma^{pp\rightarrow\pi^+\pi^-}}{dM^{\pi^+\pi^-}} = \frac{f_{fake} \cdot f_{loss}}{L \cdot \epsilon^{\pi^+}_{trk} \cdot \epsilon^{\pi^-}_{trk} \cdot \epsilon^{\pi^+\pi^-}_{trg}} \cdot \frac{dN^{\pi^+\pi^-}_{true}}{dM^{\pi^+\pi^-}}$$

- 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.