

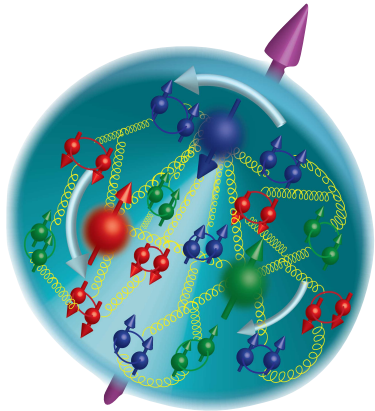


# Measurements of Transverse Spin Dependent $\pi^+\pi^-$ Azimuthal Correlation Asymmetry and Unpolarized $\pi^+\pi^-$ Cross Section in p+p Collisions at STAR at RHIC

Bernd Surrow



(On behalf of the STAR Collaboration)



**Transversity 2024**  
 7th International Workshop on transverse phenomena in hard processes  
<https://l.infn.it/transversity2024>

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Jun 3 – 7, 2024, Trieste, Italy

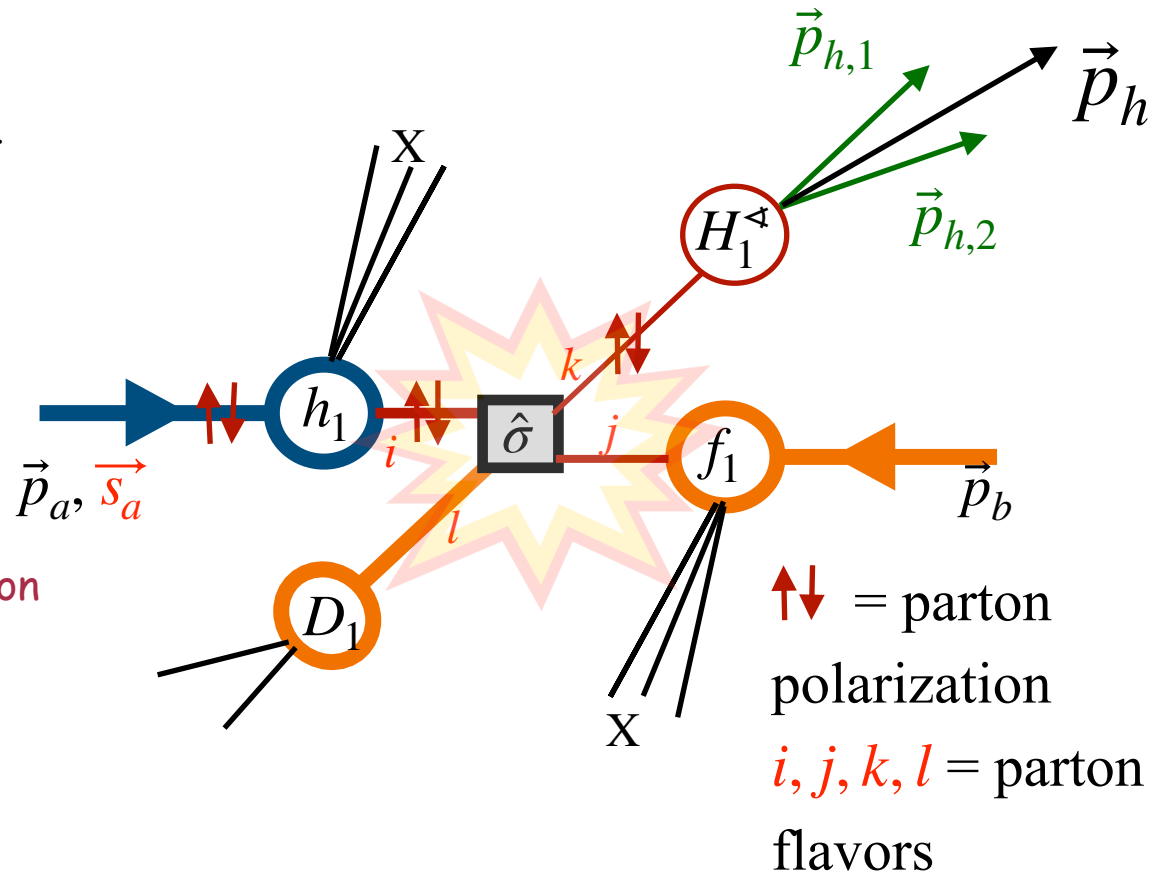


DOE NP contract: DE-SC0013405

Bernd Surrow

# Outline

- Theoretical Foundation
- RHIC Collider and STAR experiment
- Analysis Details -  $\pi^+\pi^-$  Asymmetry
- $\pi^+\pi^-$  Asymmetry Results
- Analysis Details -  $\pi^+\pi^-$  Cross-Section
- $\pi^+\pi^-$  Cross-Section Results
- Summary



# Theoretical foundation

## □ Probe transverse proton spin structure using high-energy polarized p+p collisions

- Important new insight into the **transverse proton spin structure** at STAR in **polarized p+p collisions at high energies** using **well established processes** both theoretically and experimentally **involving jets / hadrons**

- **Transversity-related measurements:** Important insight into transverse spin structure - **Need coupling of transversity ( $h_1$ ) to chiral-odd transverse spin dependent fragmentation function (FF):**

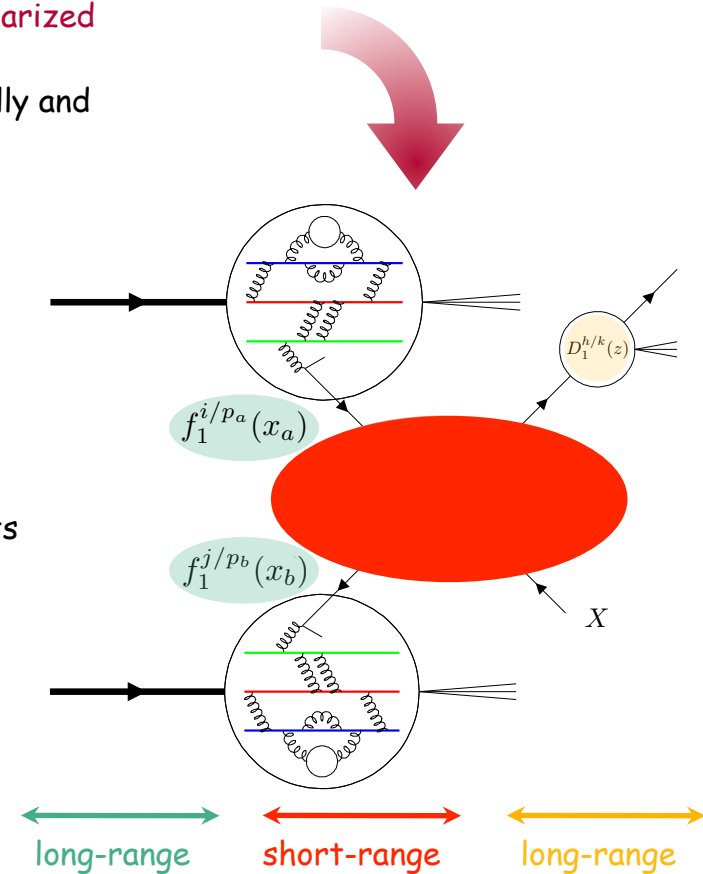
- **Collins TMD FFs:** Azimuthal single-spin asymmetries of charged pions in jets

$$\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^\perp{}^{h/k}(z, k_T)$$

- **Di-hadron FFs:** Azimuthal correlations of charged pion pairs

$$\sum_{i,j,k} h_1^{i/p_a}(x_a) \otimes f_1^{j/p_b}(x_b) \otimes H_1^\triangleleft{}^{h_1 h_2/k}(z, M_h)$$

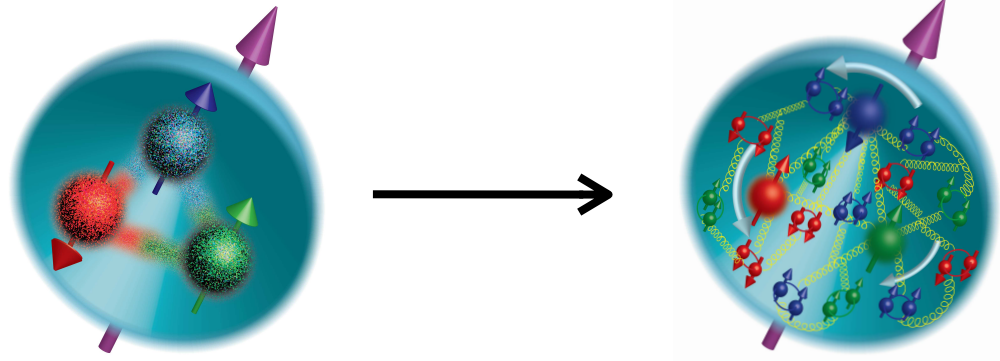
- Deepen our understanding concerning universality, factorization and evolution!



FF Review: A. Metz and A. Vossen, Prog. Part. Nucl. Phys. 91 (2016) 136.

# Theoretical Foundation

□ Proton spin structure



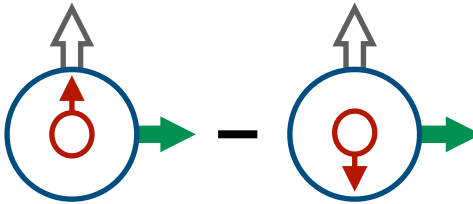
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \uparrow - \downarrow$ Boer-Mulders
	L		$g_{1L} = \rightarrow - \leftarrow$ Helicity	$h_{1L}^\perp = \rightarrow - \leftarrow$
	T	$f_{1T}^\perp = \uparrow - \downarrow$ Sivers	$g_{1T}^\perp = \uparrow - \leftarrow$	$h_1 = \uparrow - \downarrow$ Transversity $h_{1T}^\perp = \rightarrow - \leftarrow$

- Proton spin structure in terms of parton distribution functions (PDFs)
- Three leading twist collinear PDFs, integrated over parton transverse momentum  $k_T$ :
  - $f_1(x)$  = Unpolarized PDF
  - $g_1(x)$  = Helicity PDF
  - $h_1^q(x)$  = Transversity PDF
- Motivation: Measurement of **observable to constrain  $h_1^q(x)$  in collinear framework** in polarized p+p collisions **employing chiral-odd di-hadron fragmentation function (DiFF)**!

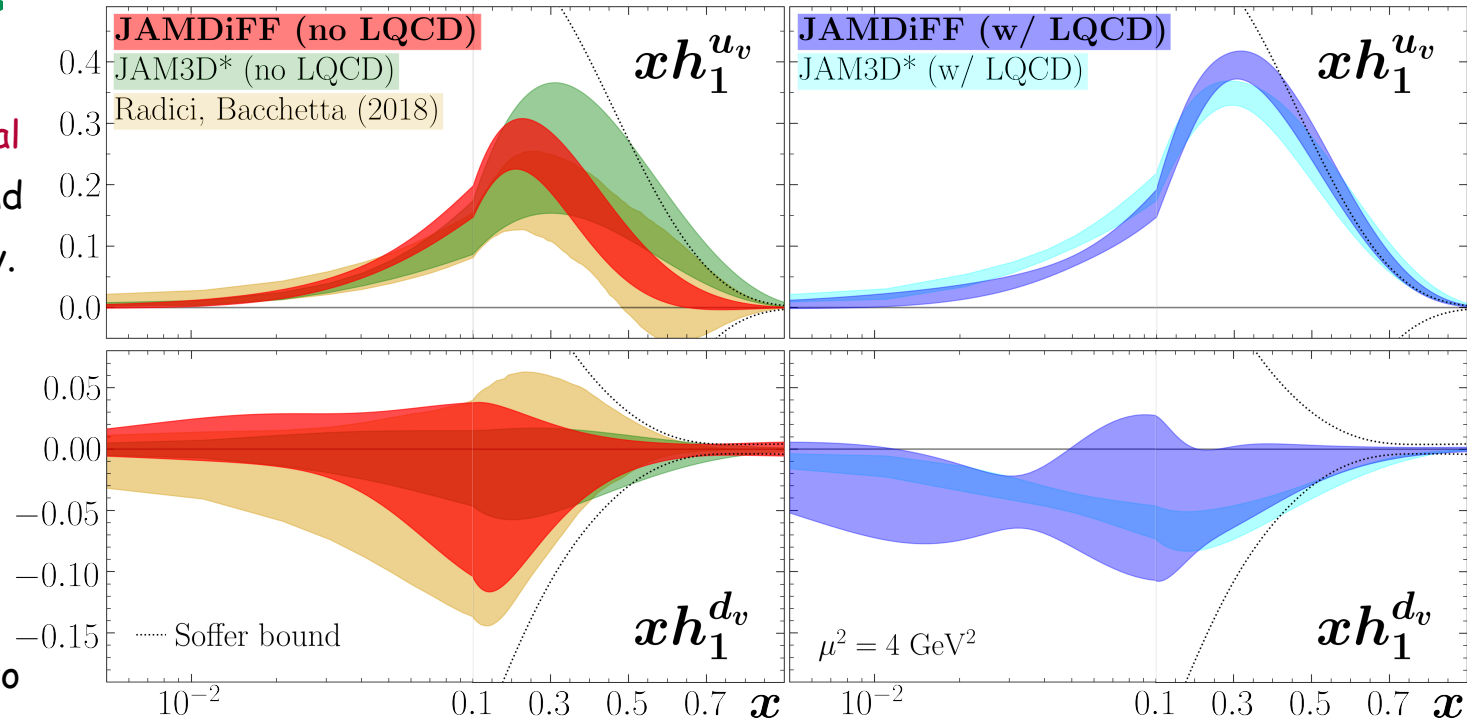
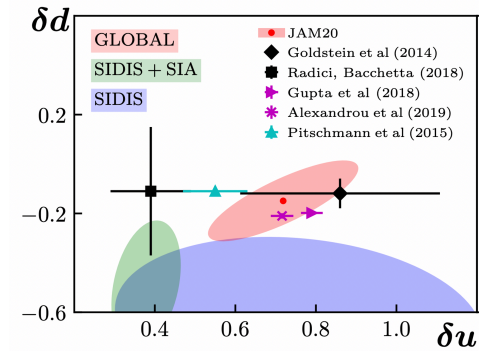
# Theoretical Foundation

## □ Transversity

Correlation between nucleon transverse polarization and transverse polarization of quarks - no gluon transversity!



- First transversity global analysis by M. Radici and A. Bacchetta (Phys. Rev. Lett. 120, 192001 (2018))
- New global analysis by JAM global analysis (arXiv 2308.14857)!
- Important connection to Lattice QCD!



# Theoretical Foundation

## Observables for transversity - Theoretical formulation

Di-hadron channel:  $p \uparrow + p \rightarrow h^+ h^- + X$

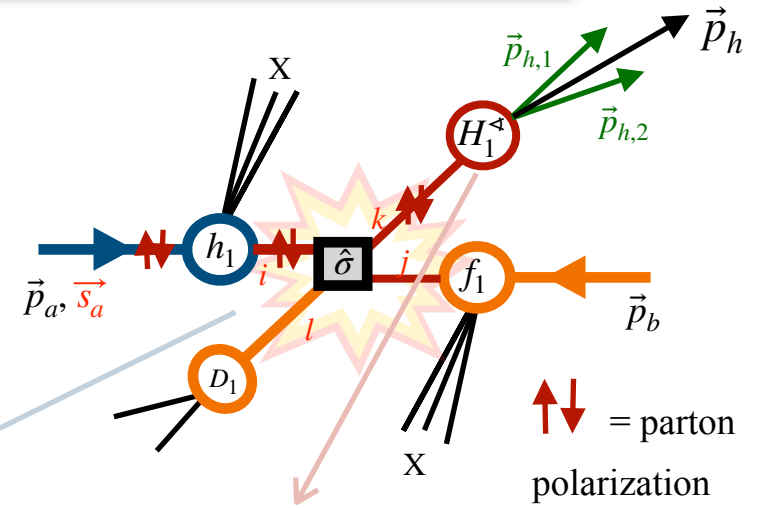
Asymmetry:  $A_{UT}^{pp} = \frac{\mathcal{H}(M_h, P_{hT}, \eta)}{\mathcal{D}(M_h, P_{hT}, \eta)}$

$$\mathcal{H}(M_h, P_{hT}, \eta) = 2P_{hT} \sum_i \sum_{a,b,c,d} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \frac{dx_b}{z} h_1^a(x_a) f_1^b(x_b) \frac{d\Delta \hat{\sigma}_{a \uparrow b \rightarrow c \uparrow d}}{d\hat{t}} H_1^{\langle a,c \rangle}(z, M_h)$$

$$h_1 \leftrightarrow f_1, H_1^{\langle a \rangle} \leftrightarrow D_1$$

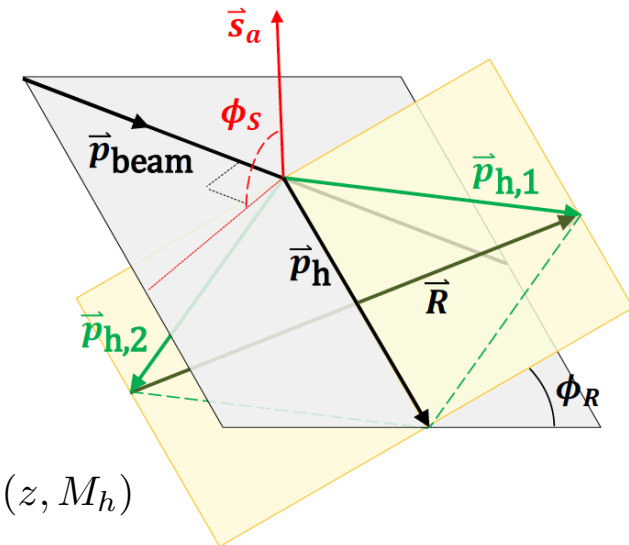
Unpolarized cross-section:

$$\mathcal{D}(M_h, P_{hT}, \eta) = 2P_{hT} \sum_i \sum_{a,b,c,d} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \frac{dx_b}{z} f_1^a(x_a) f_1^b(x_b) \frac{d\hat{\sigma}_{ab \rightarrow cd}}{d\hat{t}} D_1^c(z, M_h)$$



Transversity:

$\uparrow \downarrow$  = parton polarization  
 $i, j, k, l$  = parton flavors



# Theoretical Foundation

## □ Observables for transversity - Experimental measurement

- Di-hadron azimuthal correlation asymmetry,  $A_{UT}$ , for  $p \uparrow + p \rightarrow h^+ h^- + X$ :

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

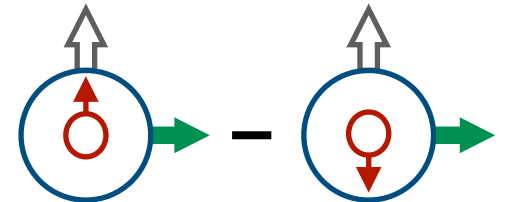
- Independent measurement of  $H_1^{\leftarrow}$  is required from  $e^+ e^-$  experiments (e.g. BELLE!)
- $D_1^{h_1 h_2}$  is least known, specifically for gluon fragmentation (New constrain from STAR!)

- Unpolarized di-hadron cross-section,  $d\sigma_{UU}$ , for  $p \uparrow + p \rightarrow h^+ h^- + X$ :

- $d\sigma_{UU}$  is crucial for  $D_1^{h_1 h_2}$  providing access to quarks and

gluons

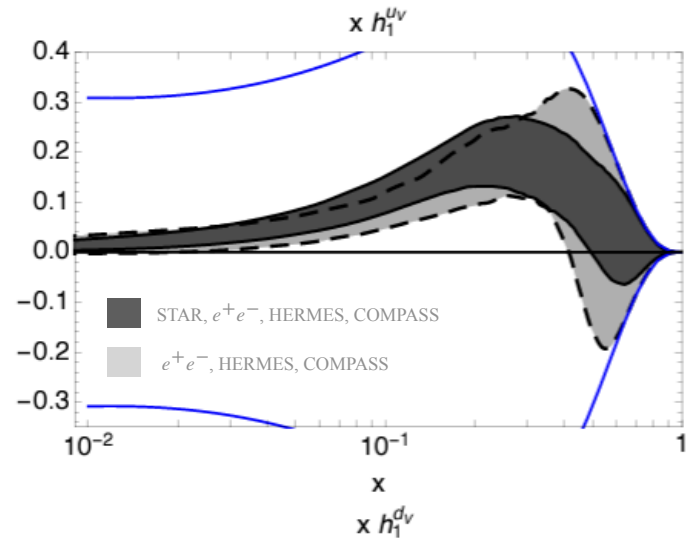
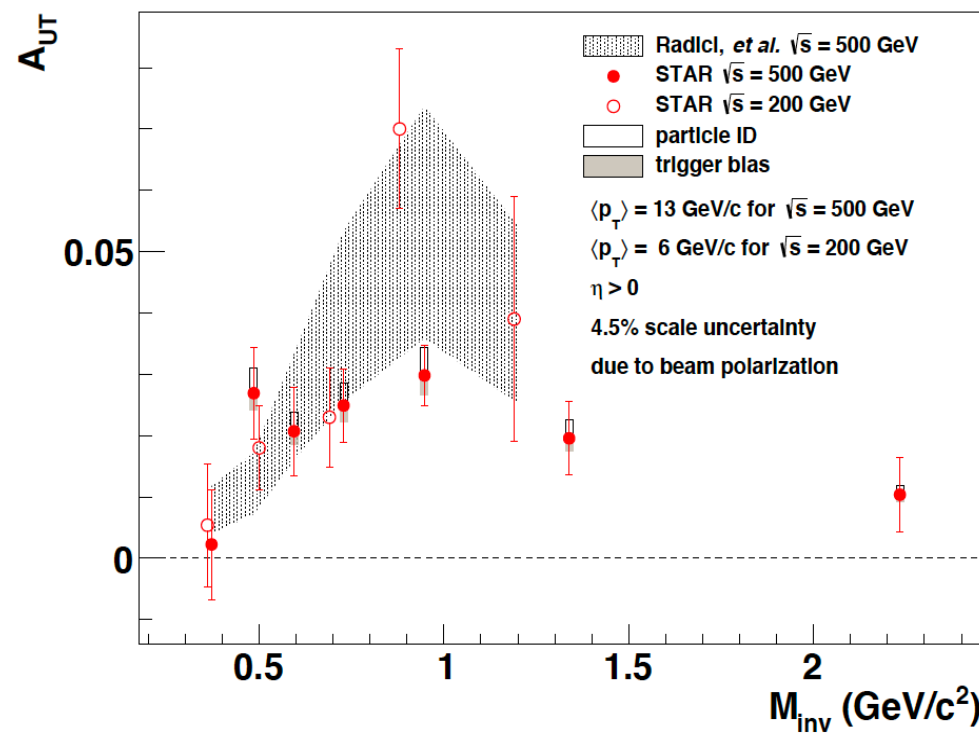
- $d\sigma_{UU}$  and  $A_{UT}$  allow model-independent extraction of transversity,  $h_1^q(x)$ !



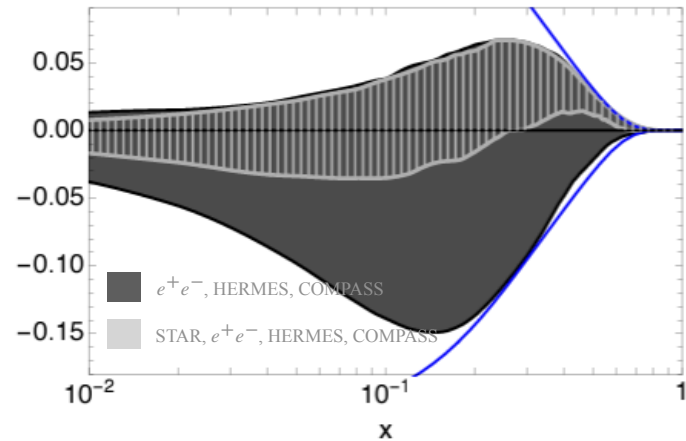
# Theoretical Foundation

- First proof-of-principle measurements at 200 GeV and 510 GeV
- STAR observed significant  $\pi^+\pi^-$  correlation asymmetry,  $A_{UT}$ , using 200 GeV and 500 GeV
- $A_{UT} \propto h_1^q(x)H_1^{\leq\pi^+\pi^-}(z, M_h^2)$
- $A_{UT}$  enhanced around  $\rho$ -mass region.

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



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

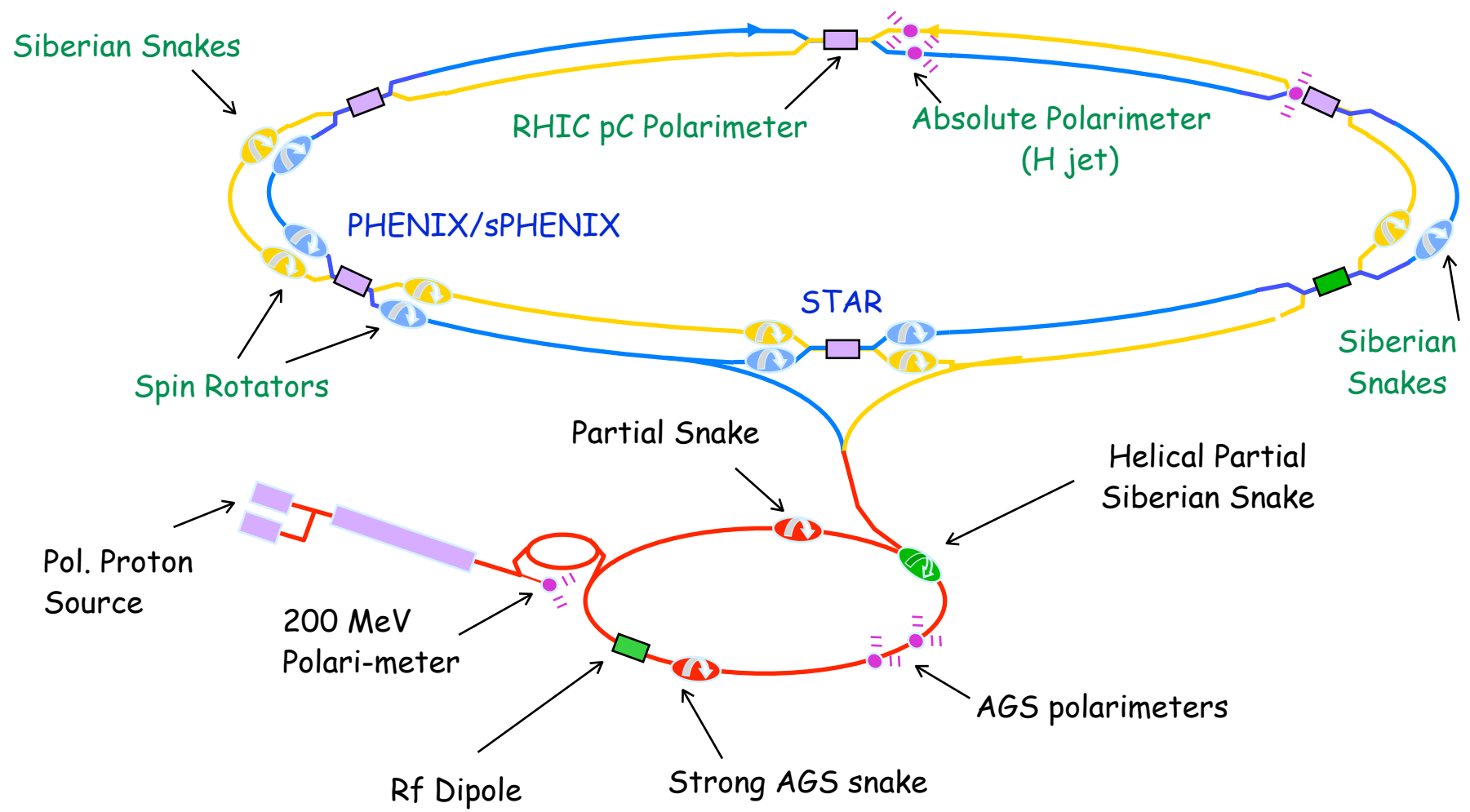


STAR, Phys. Lett. B 780 (2018) 332  
 STAR Phys. Rev. Lett. 115 (2015) 242501



# RHIC Collider and STAR Experiment

- Polarized p+p collider facility at BNL

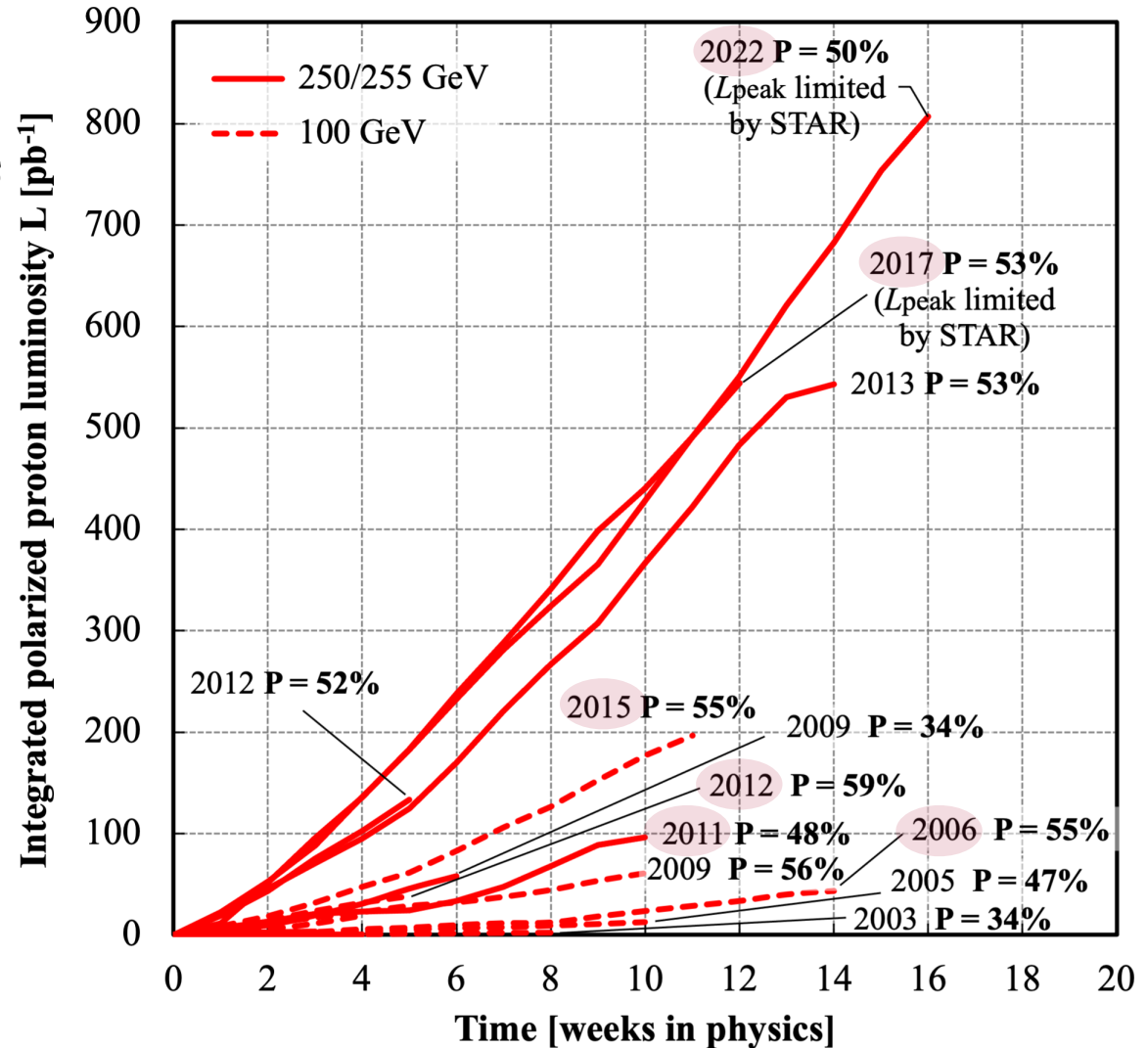


# RHIC Collider and STAR Experiment

## □ Transverse spin-polarized p+p production runs

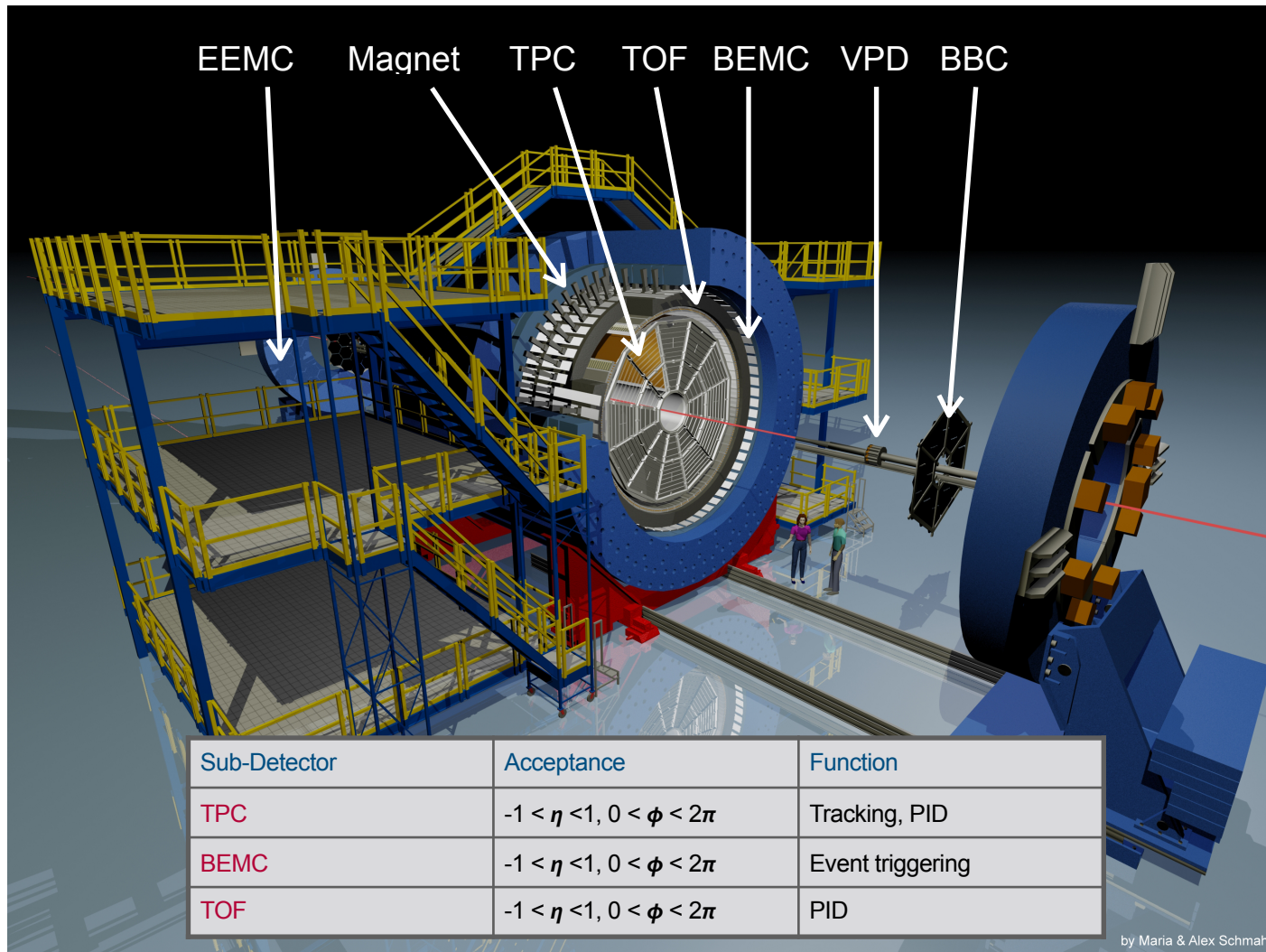
- Di-hadron FFs: 2006 at 200GeV and 2011 at 500GeV measurements and updates presented here!
- TMD Collins FFs: 2012 / 2015 at 200GeV and 2011 at 500GeV measurements
- Large data samples in 2015 at 200GeV and 2017 / 2022 at 510GeV!

### Polarized protons



# RHIC Collider and STAR Experiment

## □ Overview of STAR experiment



# RHIC Collider and STAR Experiment

## □ Polarized p+p data samples and kinematic coverage

Collision mode	proton-proton						
Polarization type	transverse						
Year	2006	2011	2012	2015	2017	2022	2024
$\sqrt{s}$ (GeV)	200	500	200	200	510	508	200
$L_{\text{int}}$ ( $\text{pb}^{-1}$ )	~1.8	~25	~22	~52	~320	~400	~190
$\langle P_{\text{beam}} \rangle$ (%)	~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  
 Unpolarized  $\pi^+\pi^-$   
 Cross Section (2012)  
 IFF Asymmetry (2015)

STAR IFF  
 Preliminary @  
 $\sqrt{s} = 510$  GeV

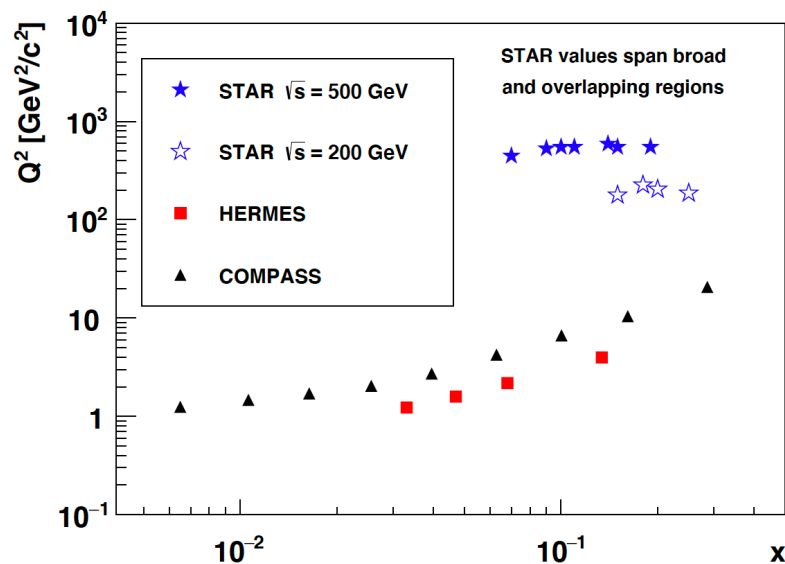
Planned IFF and  
 Cross Section  
 Measurements



# RHIC Collider and STAR Experiment

## □ Kinematic coverage

Collision mode	proton-proton						
Polarization type	transverse						
Year	2006	2011	2012	2015	2017	2022	2024
$\sqrt{s}$ (GeV)	200	500	200	200	510	508	200
$L_{\text{int}}$ (pb <sup>-1</sup> )	~1.8	~25	~22	~52	~320	~400	~190
$\langle P_{\text{beam}} \rangle$ (%)	~60	~53	~57	~57	~55	~52	



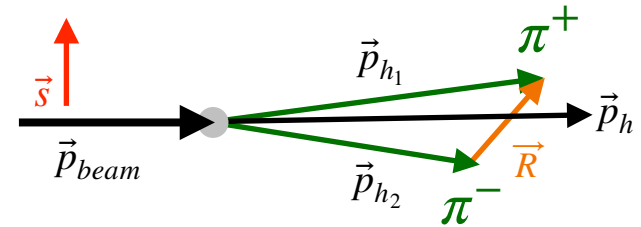
## STAR Kinematic Coverage:

- Covers **larger  $Q^2$  values** compared to HERMES and COMPASS.
- **Intermediate  $x$  coverage**, probing predominantly **valence quark region**.

# Analysis details - $\pi^+\pi^-$ Asymmetry

## □ Kinematic variables and selection cuts

Polarized parton fragments to  $\pi^+\pi^-$  :



Two crucial vectors:  $\vec{p}_h = \vec{p}_{h_1} + \vec{p}_{h_2}$  and  $\vec{R} = \frac{1}{2}(\vec{p}_{h_1} - \vec{p}_{h_2})$

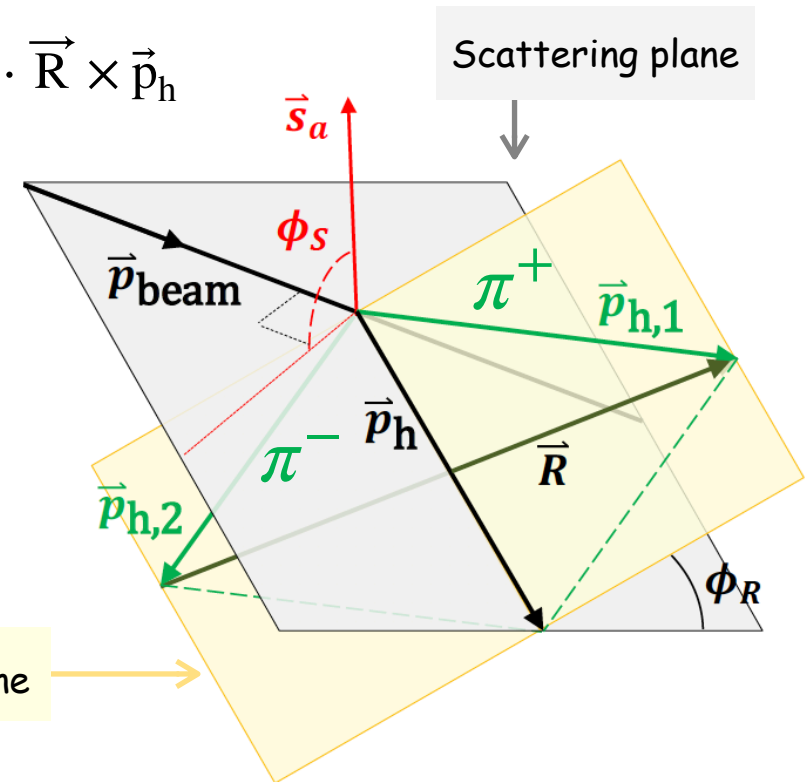
○ Access to the quark polarization via correlation:  $\vec{S} \cdot \vec{R} \times \vec{p}_h$

○ 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  $\vec{R}$  always points from  $\pi^-$  to  $\pi^+$   $A_{UT}$  gets otherwise diluted

$\pi^+\pi^-$  reaction plane



# Analysis details - $\pi^+\pi^-$ Asymmetry

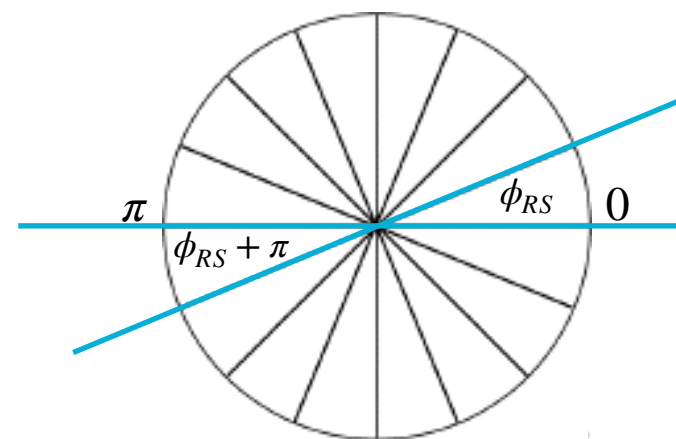
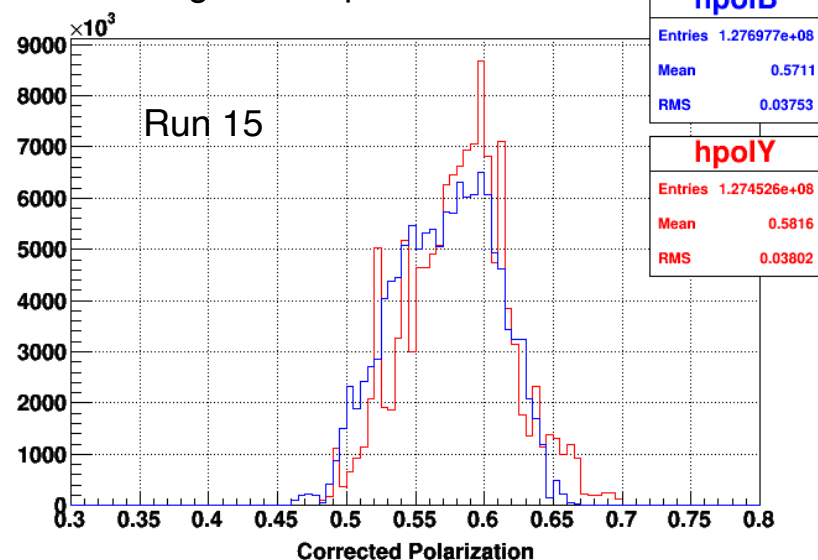
## □ Asymmetry determination

- Cross-ratio formula:  $\phi_{RS}$  binning in  $A_{UT}$  extraction

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

- Free from relative luminosity terms (cancels out in symmetric detector system!)
- Two transverse polarization states:  $\uparrow, \downarrow$
- 16  $\phi_{RS}$  bins of uniform widths over  $[-\pi, \pi]$ .
- Symmetry between  $[-\pi, 0]$  and  $[0, \pi]$  hemispheres.
- Count  $\pi^+\pi^-$  yields in each 16  $\phi_{RS}$  bins for each polarization states:  $N^\uparrow(\phi_{RS}), N^\downarrow(\phi_{RS})$ .

$P \equiv$  Average beam polarization



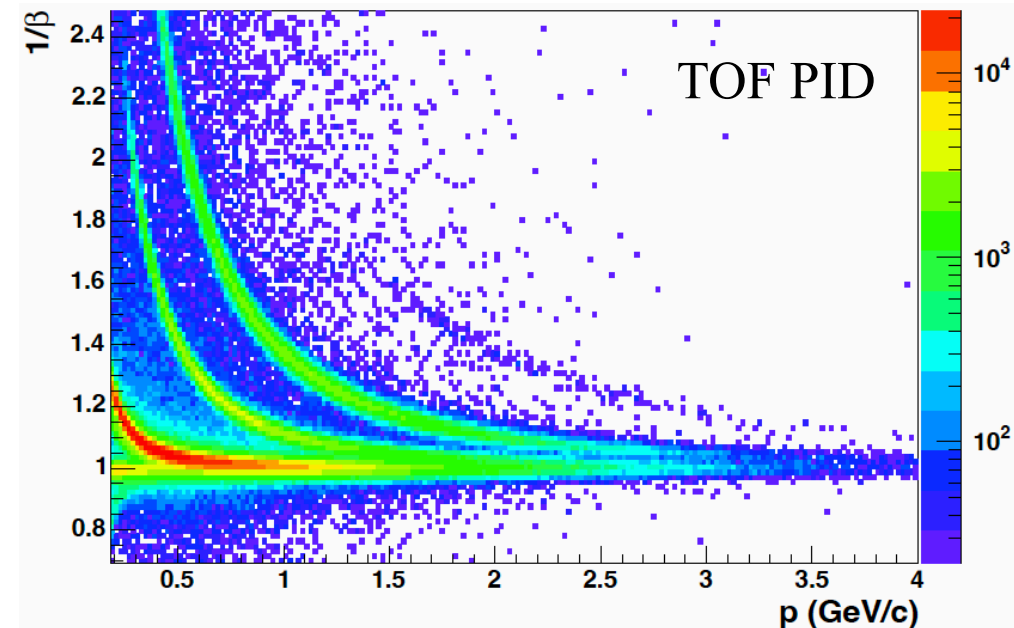
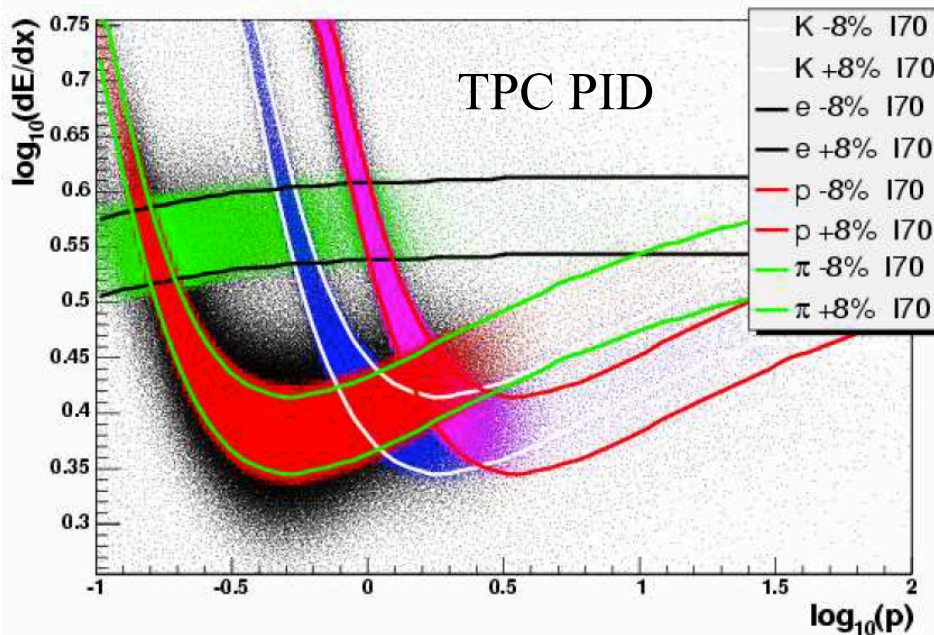
$\phi_{RS}$  binning scheme



# Analysis details - $\pi^+\pi^-$ Asymmetry

## □ Systematic uncertainties

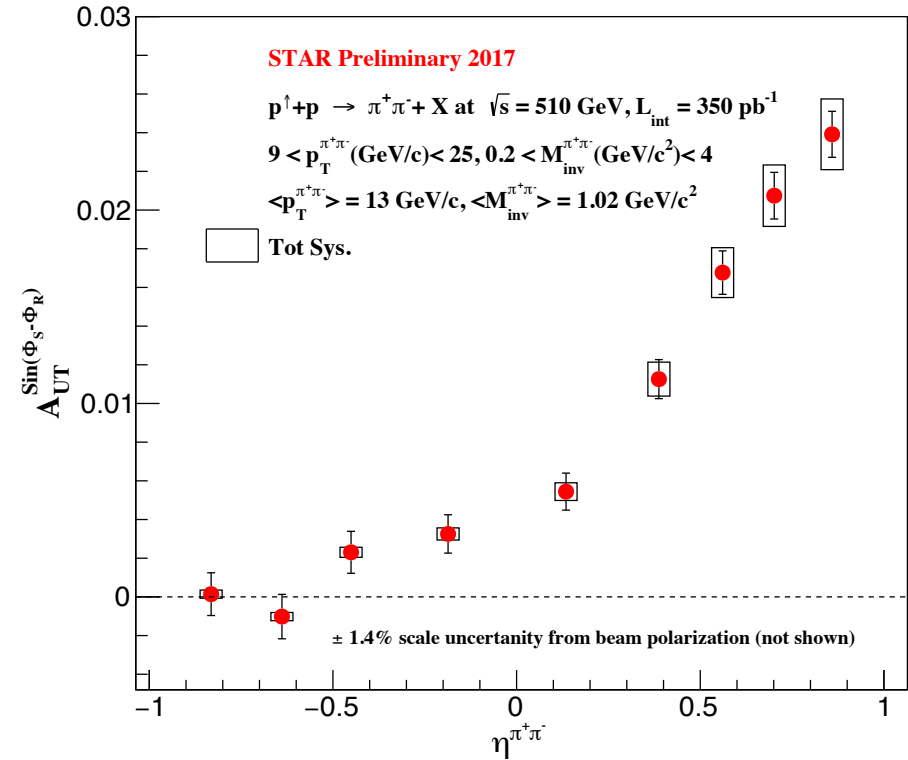
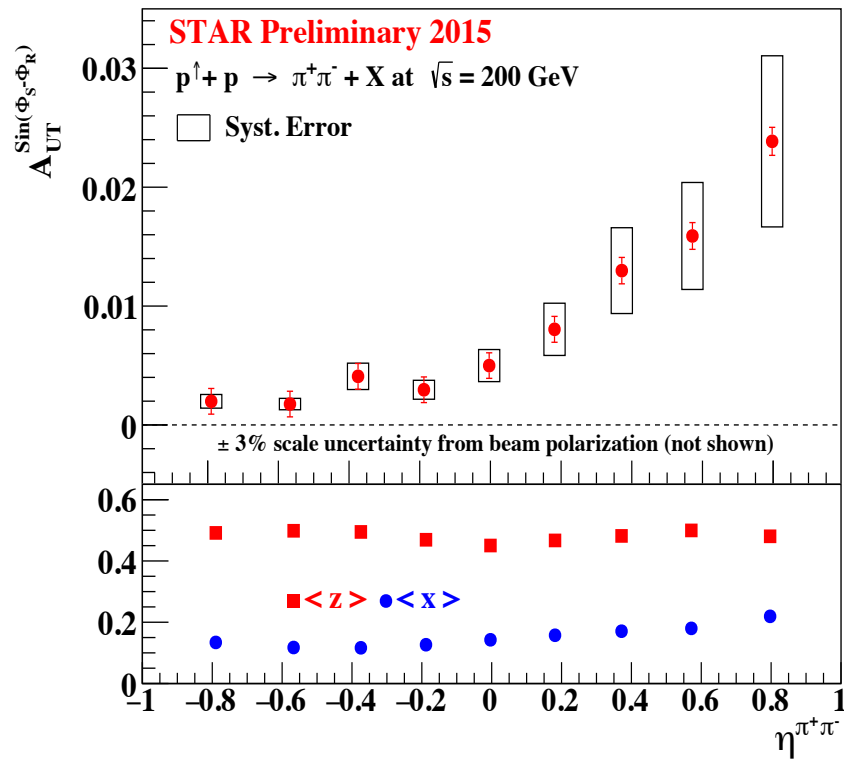
- STAR PID relies on the measured ionization energy loss ( $dE/dx$ ) by the TPC at low  $p_T$ .
- Time of Flight (TOF) helps to improve the STAR PID, in conjunction with the TPC via  $dE/dx$
- The fraction of proton, kaon, and electron (backgrounds) in the pion signal region estimates the PID systematic uncertainty





# $\pi^+\pi^-$ Asymmetry Results

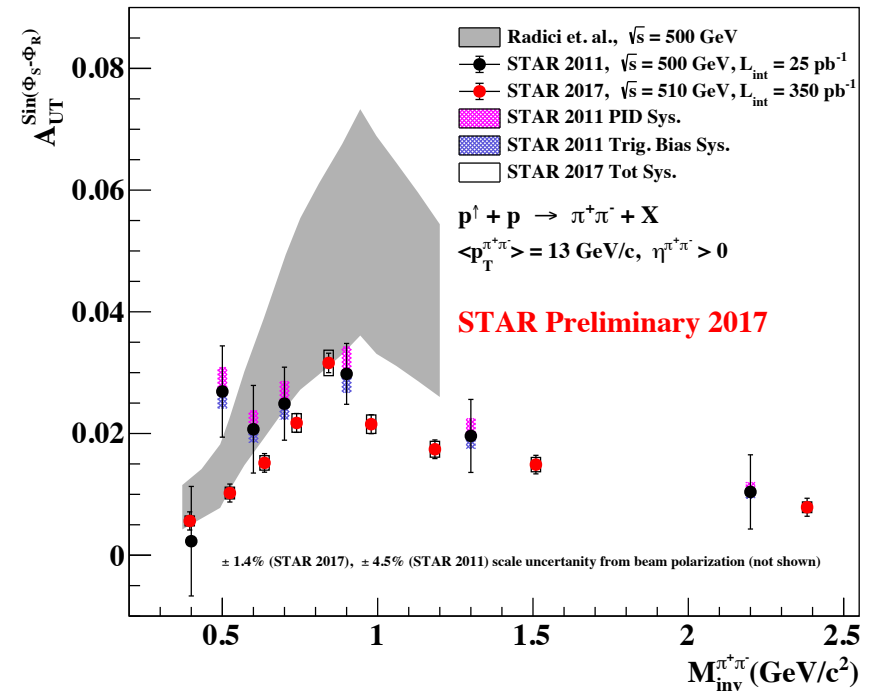
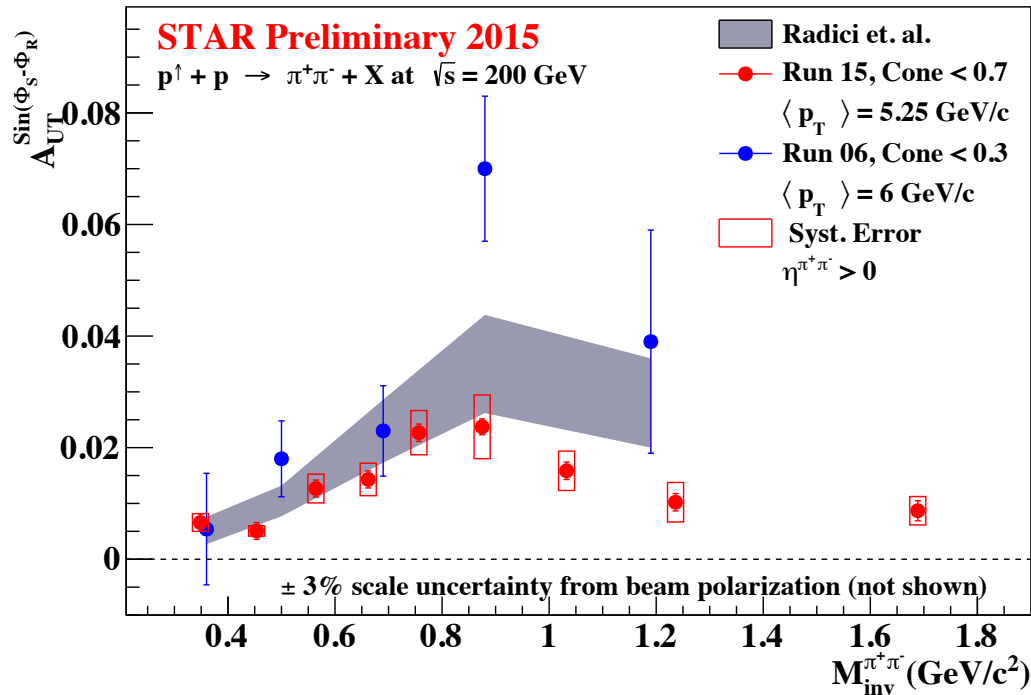
- Asymmetry vs. pseudo-rapidity  $\eta^{\pi^+\pi^-}$  at 200GeV and 510GeV



- $A_{UT}$  increases with  $\eta$  at 200GeV (Run 15) and 510GeV (Run 17) - Sizable  $h_1^q(x)$  expected for  $\eta > 0$ , i.e., large  $x$ !
- Improved PID treatment for 510GeV (Run 17) using TPC/TOF, whereas 200GeV (Run 15) based on TPC PID only so far, TOF PID incl. for final result for 200GeV (Run 15)
- Systematic uncertainties: PID and Trigger bias

# $\pi^+\pi^-$ Asymmetry Results

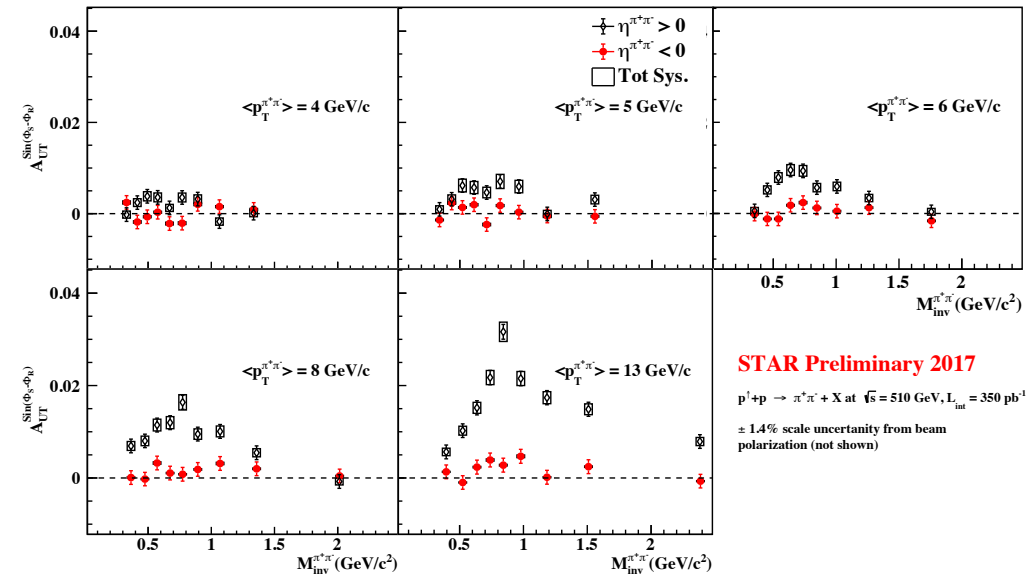
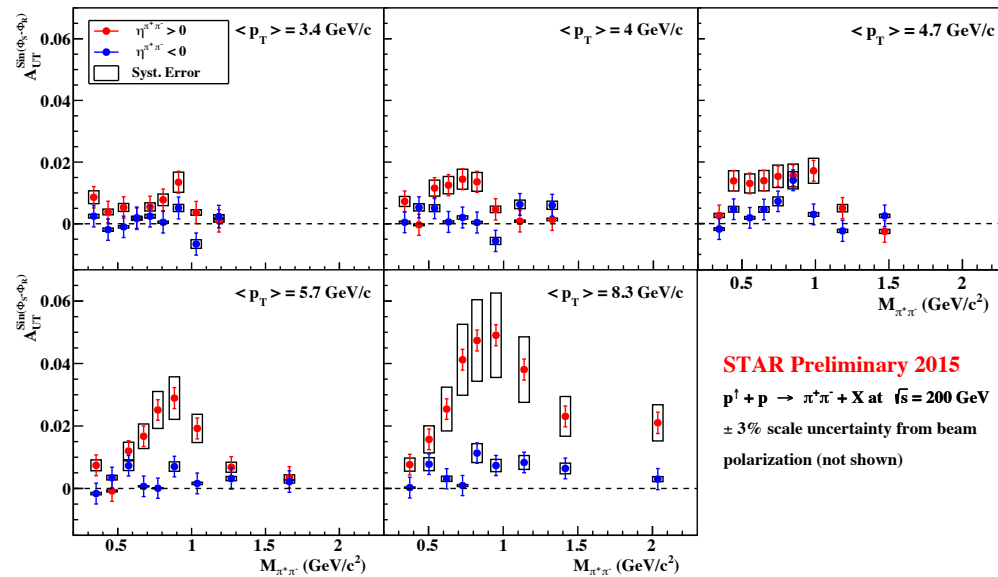
- Asymmetry vs. invariant mass  $M_{inv}^{\pi^+\pi^-}$  integrated in  $p_T$  at 200GeV and highest  $p_T$  bin at 510GeV



- $A_{UT}$  asymmetry is enhanced around  $M_{inv}^{\pi^+\pi^-} \sim 0.8$ , consistent with the previous measurement and theory prediction
- Theory calculations overshoots the new measurement beyond the  $\rho$  resonance peak
- Statistical precision is significantly improved by the new result

# $\pi^+\pi^-$ Asymmetry Results

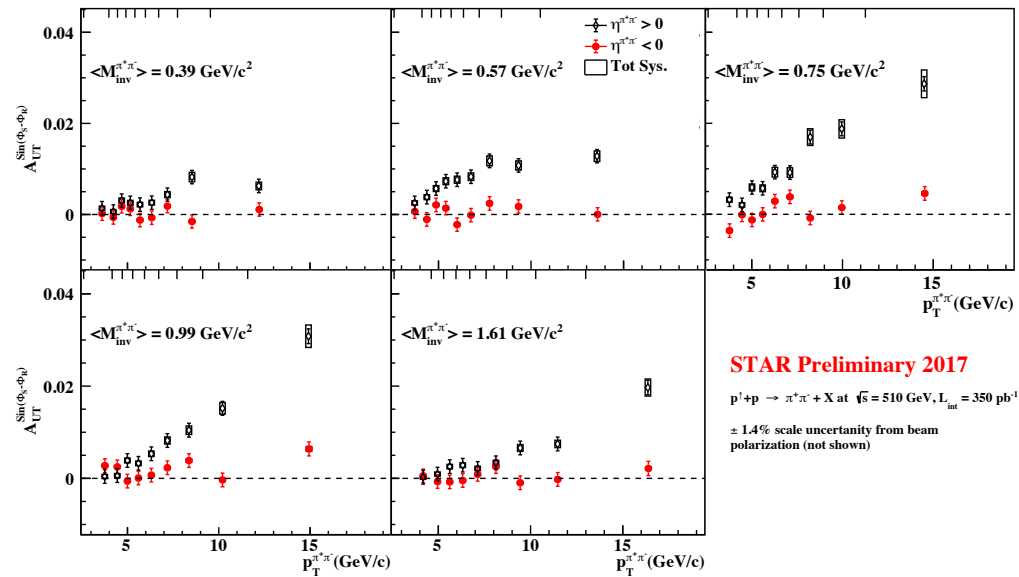
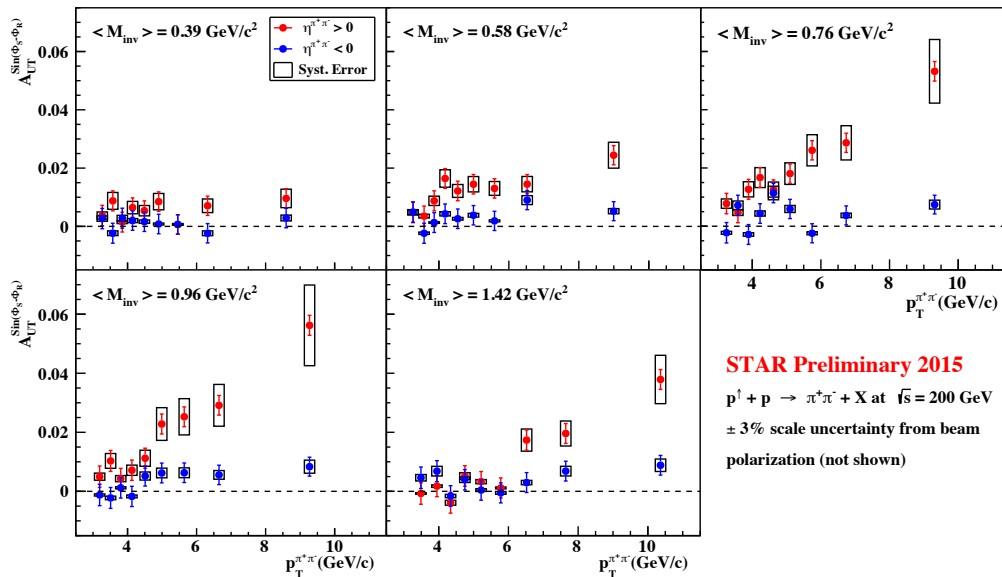
- Asymmetry vs. invariant mass  $M_{\text{inv}}^{\pi^+\pi^-}$  in  $p_T$  bins at 200GeV and 510GeV



- $A_{\text{UT}}^{\sin(\phi_{\text{RS}})}$  vs  $M_{\text{inv}}^{\pi^+\pi^-}$  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  $M_{\text{inv}}^{\pi^+\pi^-} \sim 0.8 \text{ GeV/c}^2 \sim M_\rho$ .
- Backward  $\eta^{\pi^+\pi^-}$  signal is small, mainly from low  $x$  quarks from polarized beam

# $\pi^+\pi^-$ Asymmetry Results

- Asymmetry vs. transverse momentum  $p_T$  in  $M_{inv}^{\pi^+\pi^-}$  bins at 200GeV and 510GeV

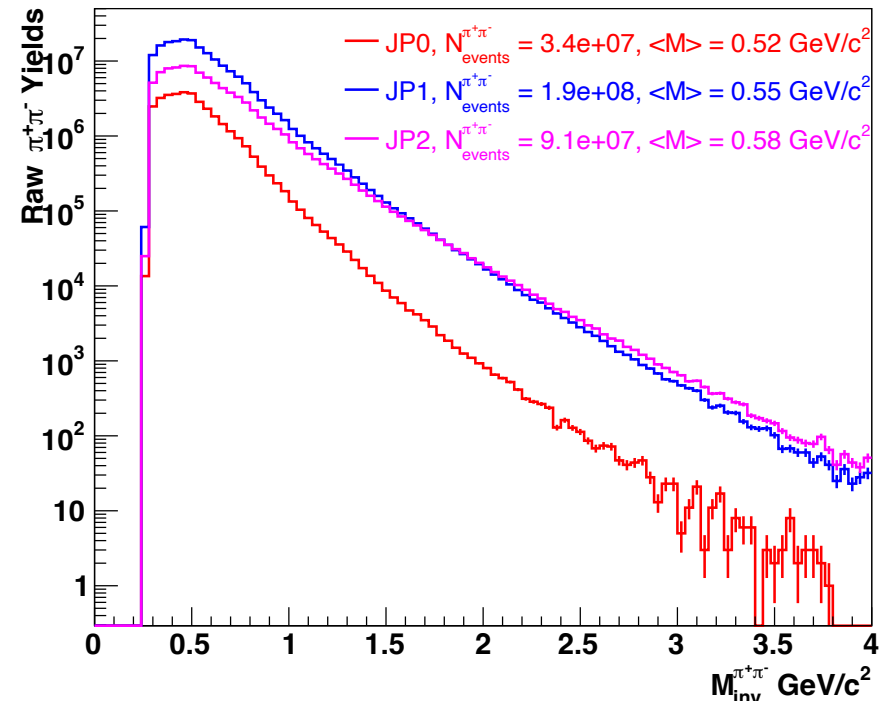
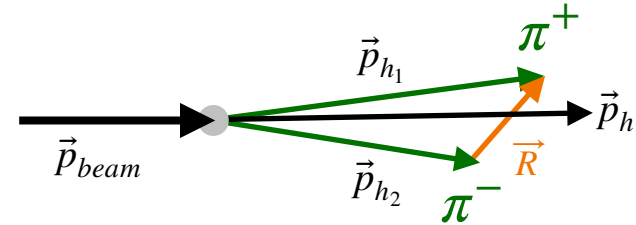


- Large asymmetry signal at higher  $p_T$  in forward  $\eta^{\pi^+\pi^-}$  region. Stronger signal when  $\langle M_{inv} \rangle \sim M_\rho$ .
- Backward  $\eta^{\pi^+\pi^-}$  signal ( $\eta^{\pi^+\pi^-} < 0$ ) is small, mainly from low  $x$  quarks from polarized beam.

# Analysis details - $\pi^+\pi^-$ Cross-Section

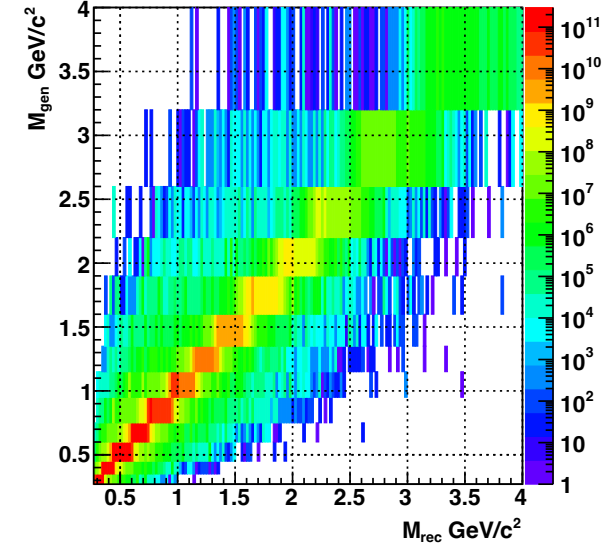
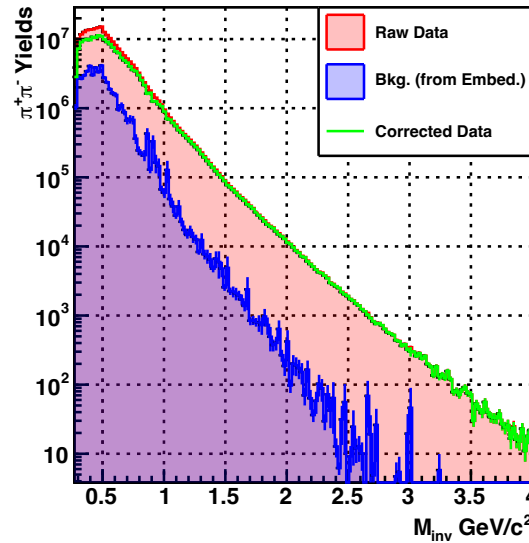
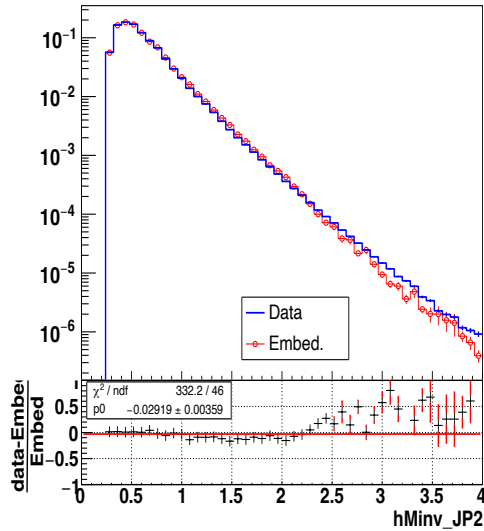
## □ Selection criteria

- Di-hadron channel,  $p + p \rightarrow \pi^+\pi^- + X$ :
- 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 @  $\sqrt{s} = 200 \text{ GeV}$
- 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  $p_T > 0.5 \text{ GeV}/c$ .



# Analysis details - $\pi^+\pi^-$ Cross-Section

- Cross-section determination and systematic uncertainties



- PYTHIA simulated events, reconstructed through GEANT package embedded with real collision events to effectively reconstruct STAR detector responses (Embedding)
- Unfolding accounts for the bin migration effect and backgrounds
- Unfolding is performed for each trigger, allowing independent measurement of triggered cross-section

# Analysis details - $\pi^+\pi^-$ Cross-Section

## □ Preliminary di-hadron cross-section result

### ○ Top Panel:

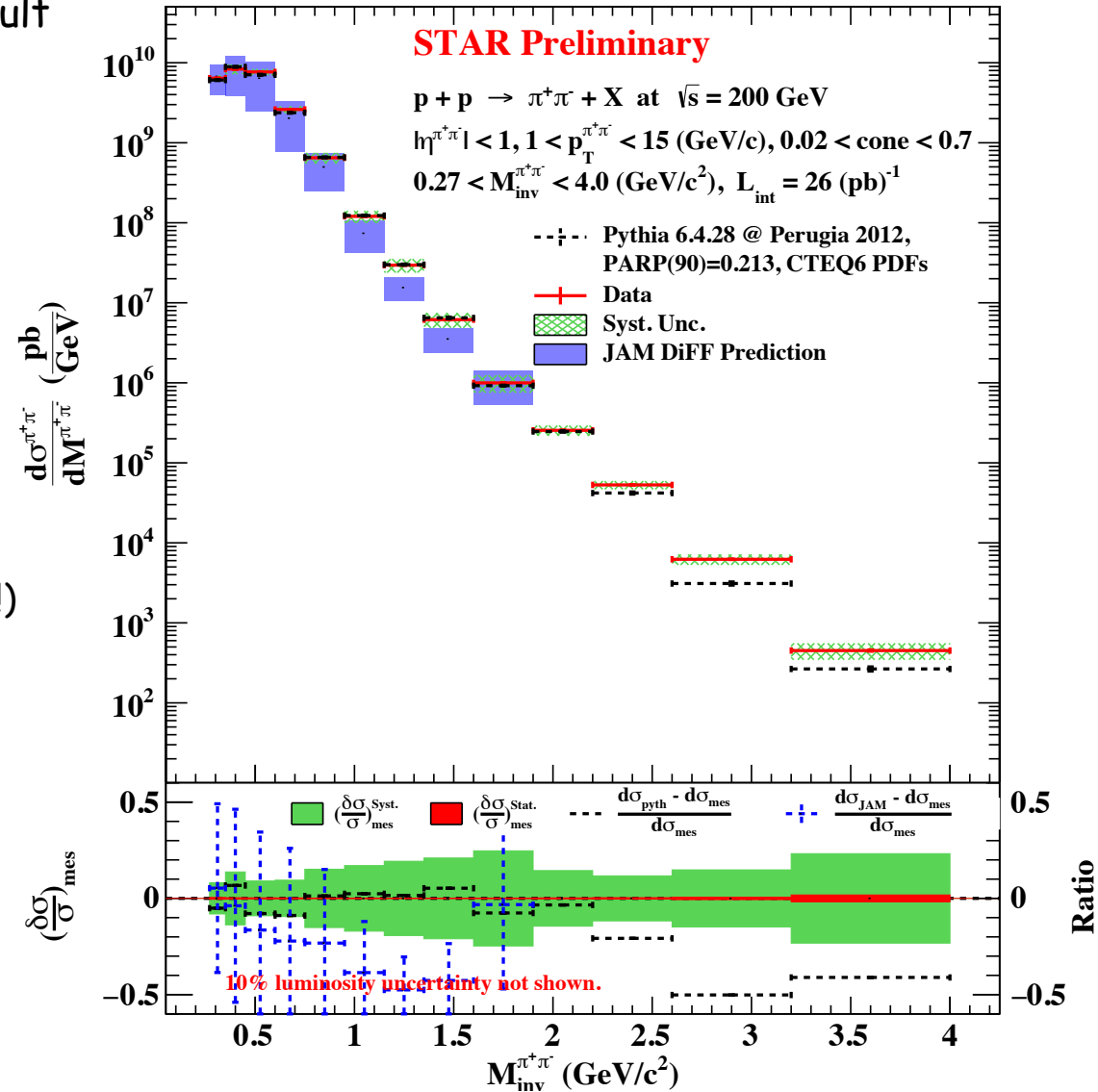
- First unpolarized  $\pi^+\pi^-$  cross-section measurement
- Good agreement in comparison to PYTHIA simulation and JAMDiFF prediction

### ○ Bottom Panel:

- Systematic uncertainties (Green band!)
- Statistical uncertainties (Red band!)
- Relative difference to PYTHIA / JAMDiFF shown in black/blue

### ○ Access to $D_1^{h_1 h_2}$ for gluons

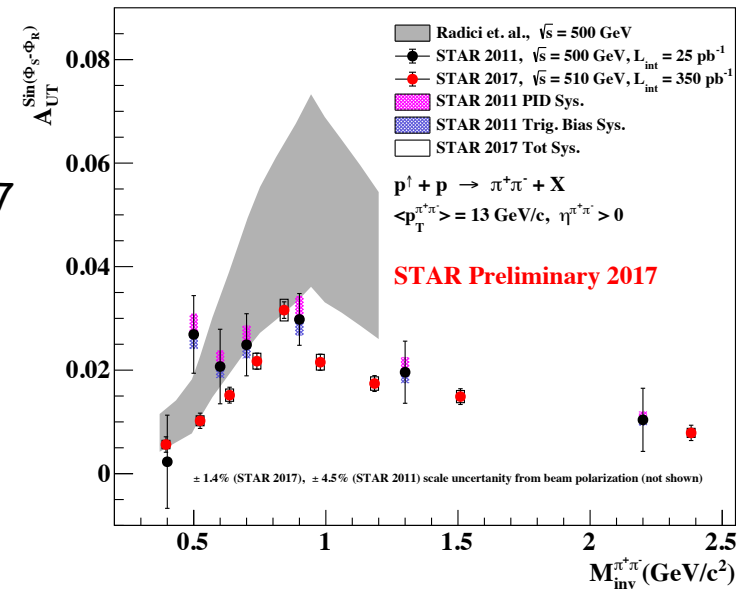
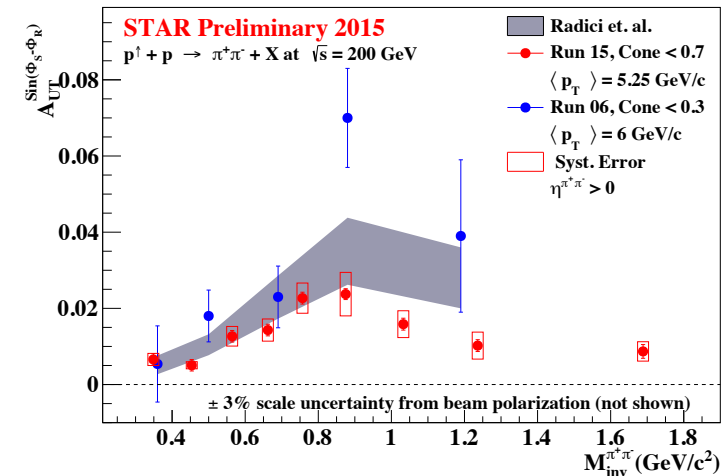
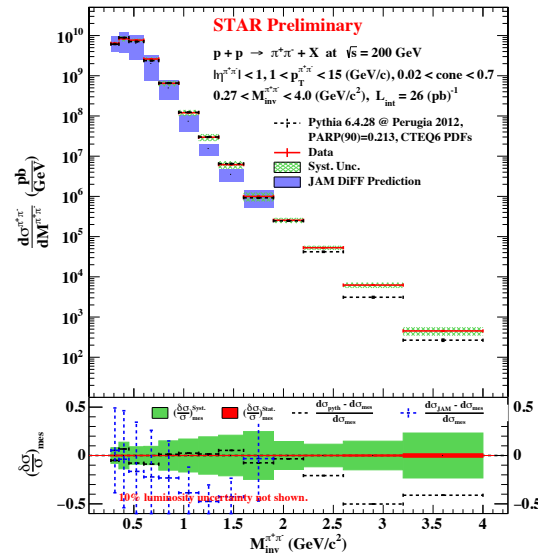
### ○ Path to model-independent extraction of $h_1(x)$



# Summary and Outlook

## □ Summary

- New measurements of IFF di-pion asymmetries at 200GeV (2015) and 510GeV (2017)
- First di-pion cross-section measurement at 200GeV (2012)
- Improved PID systematics (Combination of TPC+TOF) for Run 17 data at 510GeV, to be applied to 200GeV measurement
- Publication of 200GeV and 510 di-pion measurements: Input to global analysis for transversity extraction!





# Summary and Outlook

## □ Outlook

- Precision measurement of IFF asymmetries for pions / kaons from 2015+2024 at 200GeV and 2017+2022 at 510GeV
- Planned cross-section measurements for pions at 510GeV and Kaons at 200/510GeV

