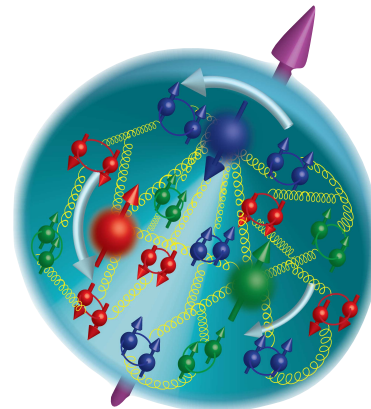


Measurements of Transverse Spin Dependent $\pi^+\pi^-$ Azimuthal Correlation Asymmetry and Unpolarized $\pi^+\pi^-$ Cross Section in p+p Collisions at STAR at RHIC

Bernd Surrow



(On behalf of the STAR Collaboration)



Supported in part by



DOE NP contract: DE-SC0013405

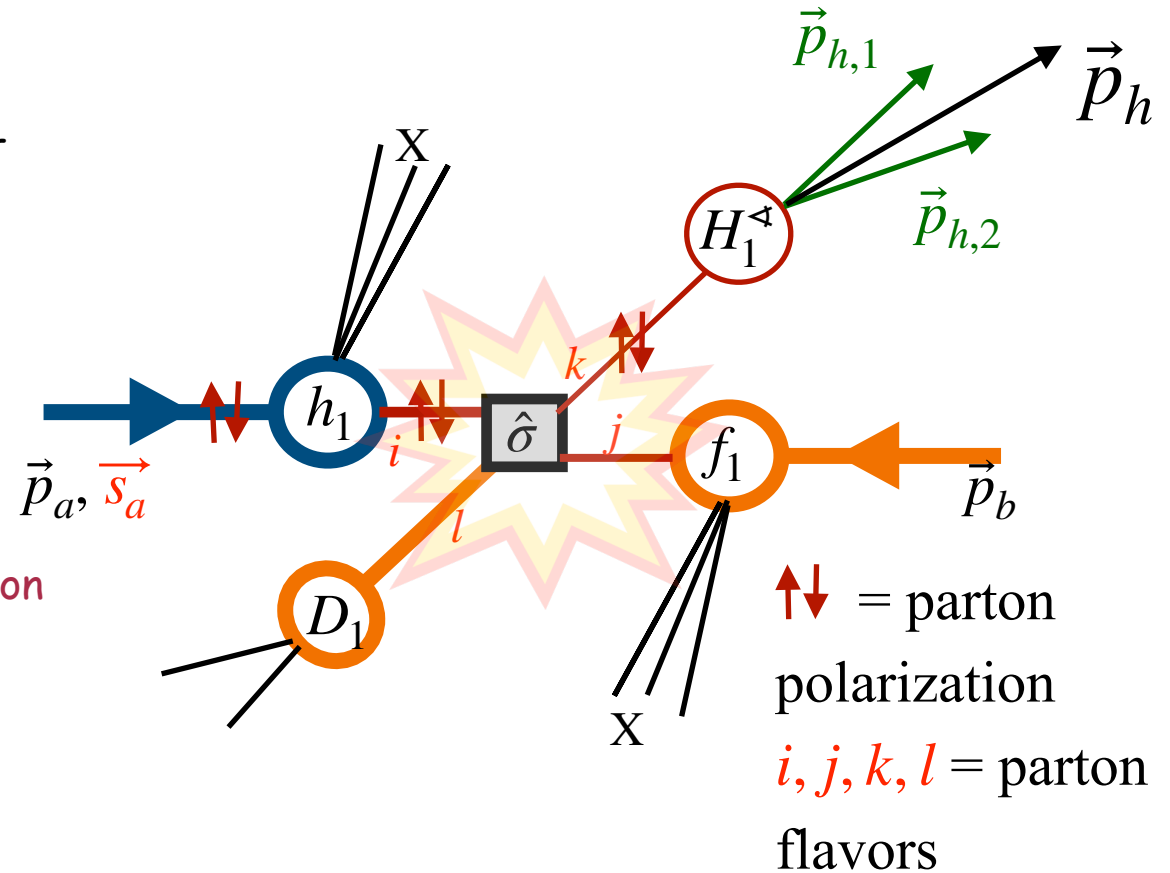
Bernd Surrow

DIS2024

XXXI International Workshop on Deep Inelastic Scattering
8-12 April 2024, Grenoble, France

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)**:

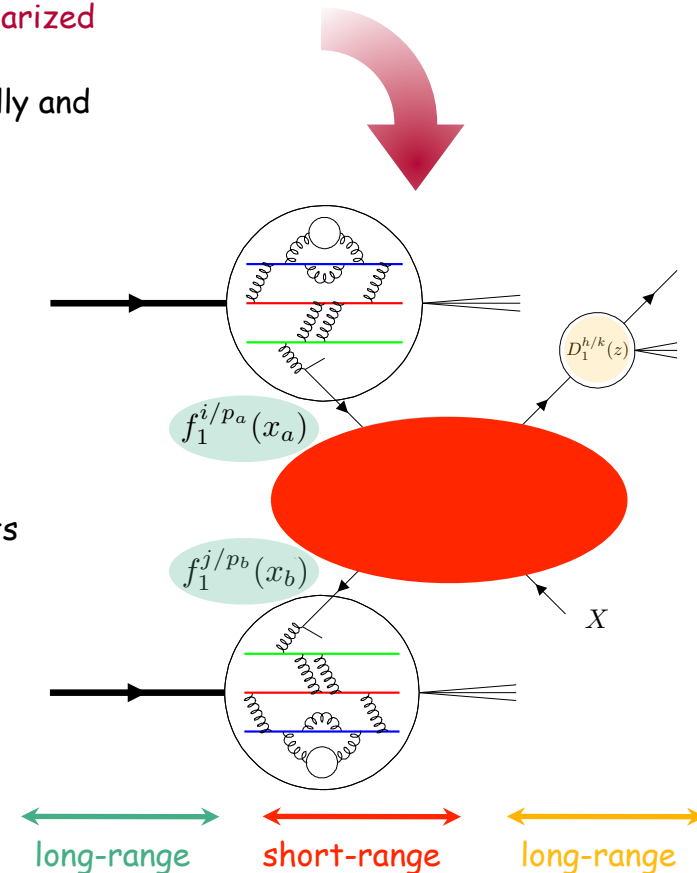
- **Collins TMD FFs**: Azimuthal single-spin asymmetries of charged pions in jets

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

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

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

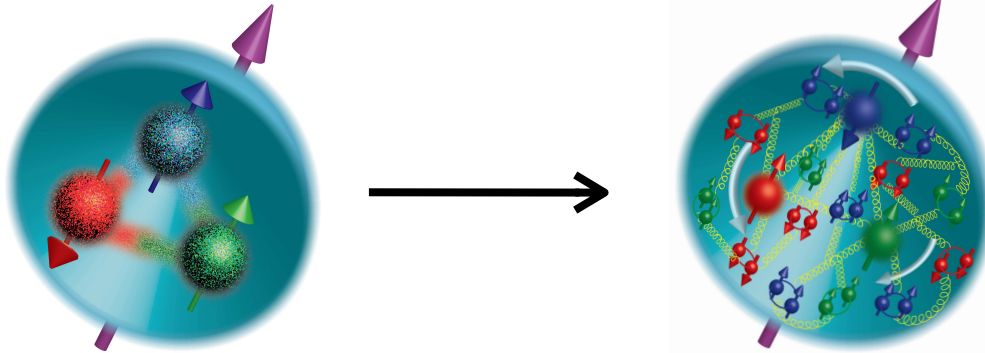
- Deepen our understanding concerning universality, factorization and evolution!



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	$g_{1T}^\perp = \rightarrow - \leftarrow$	$h_1 = \uparrow - \downarrow$ 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

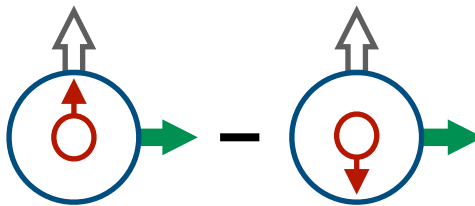
□ $h_1^q(x) =$ Transversity PDF

□ 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)**!

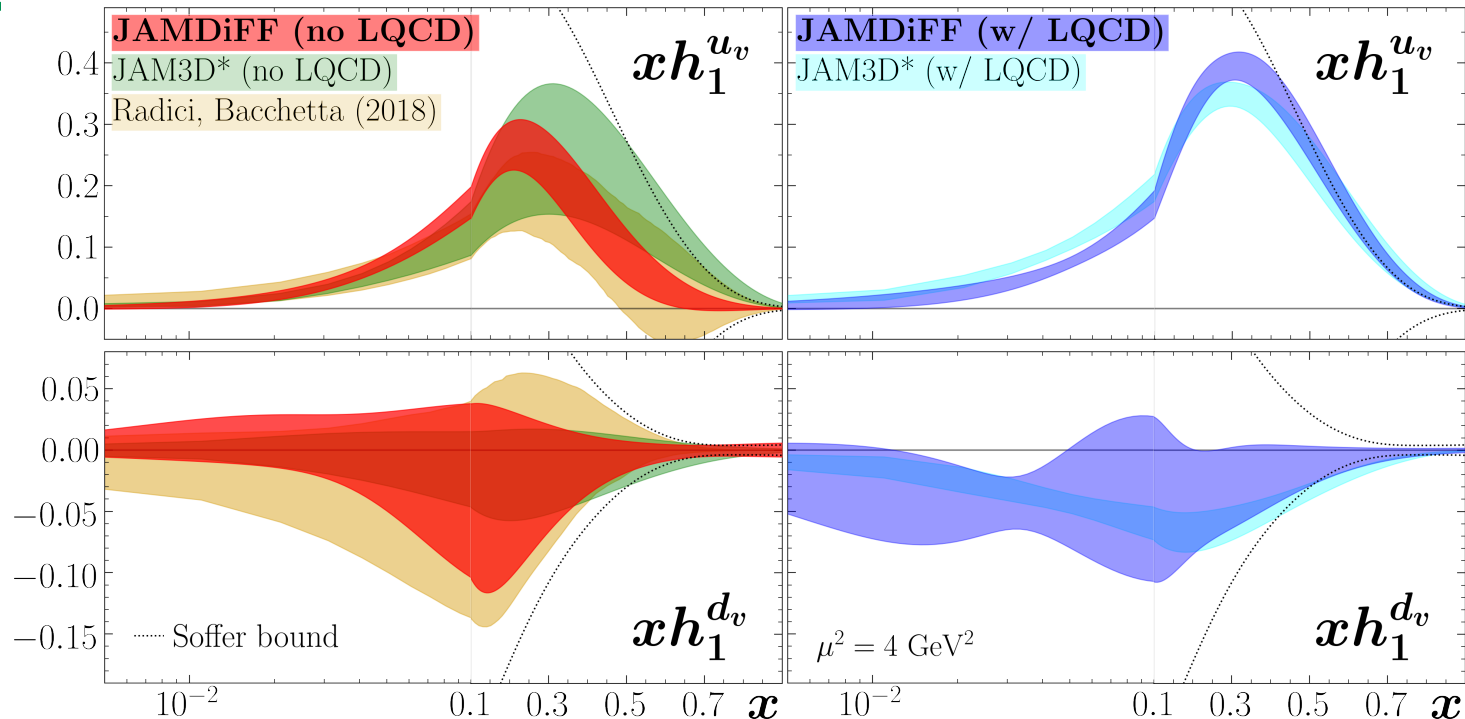
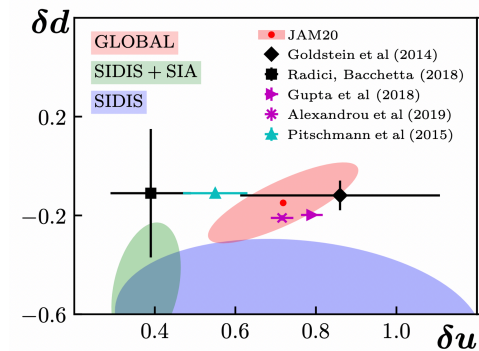
Theoretical Foundation

□ 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 (C. Cocuzza et al. (JAM Collaboration), Phys.Rev.D 109 (2024) 3, 034024)!
- Important connection to Lattice QCD!



Theoretical Foundation

Observables for transversity - Theoretical formulation

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

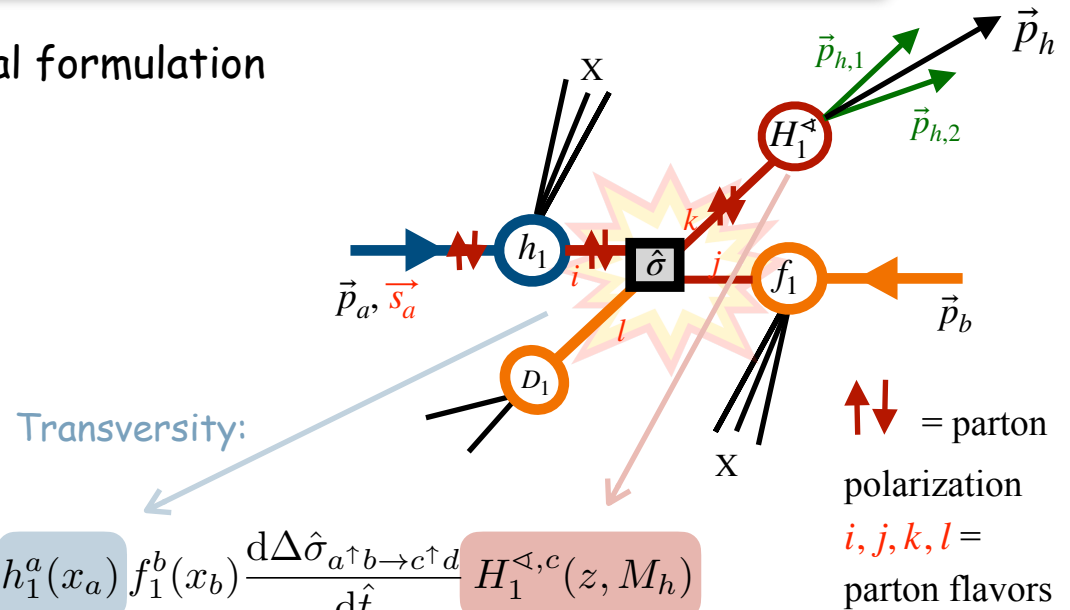
Asymmetry: $A_{UT}^{pp} = \frac{\mathcal{H}(M_h, P_{hT}, \eta)}{\mathcal{D}(M_h, P_{hT}, \eta)}$

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

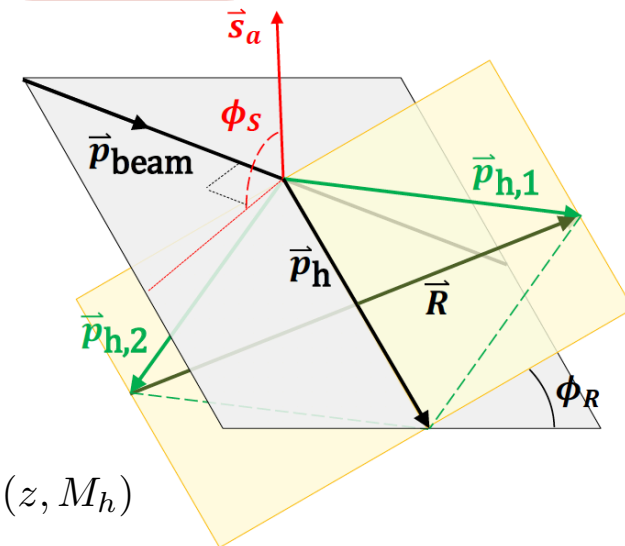
$$h_1 \leftrightarrow f_1, \quad H_1^{\langle a \rangle} \leftrightarrow D_1$$

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:



Theoretical Foundation

□ Observables for transversity - Experimental measurement

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

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

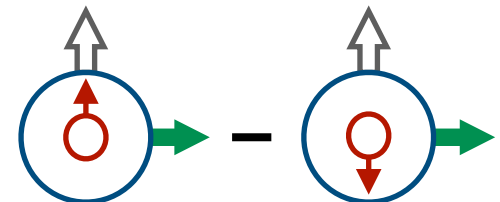
- Independent measurement of H_1^{\leftarrow} is required from $e^+ e^-$ experiments (e.g. BELLE!)
- $D_1^{h_1 h_2}$ is least known, specifically for gluon fragmentation (New constrain from STAR!)

- 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

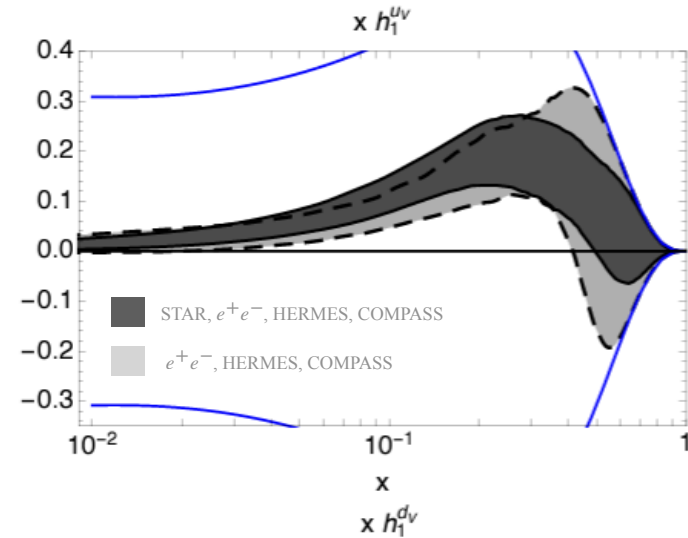
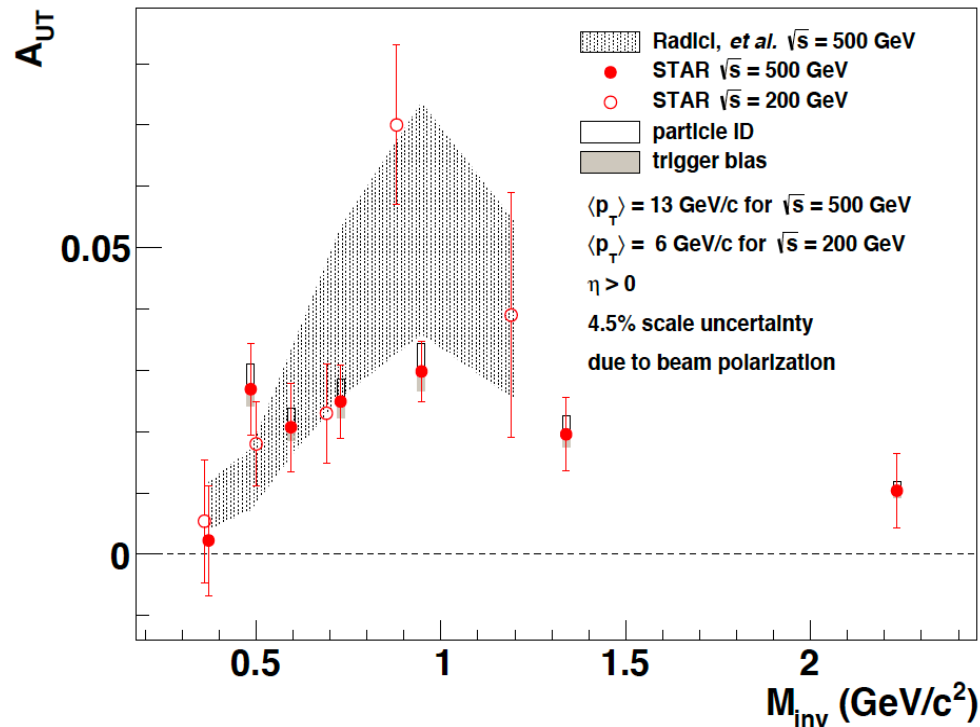
□ First proof-of-principle measurements at 200 GeV and 510 GeV

○ STAR observed significant $\pi^+\pi^-$ correlation asymmetry, A_{UT} , using 200 GeV and 500 GeV

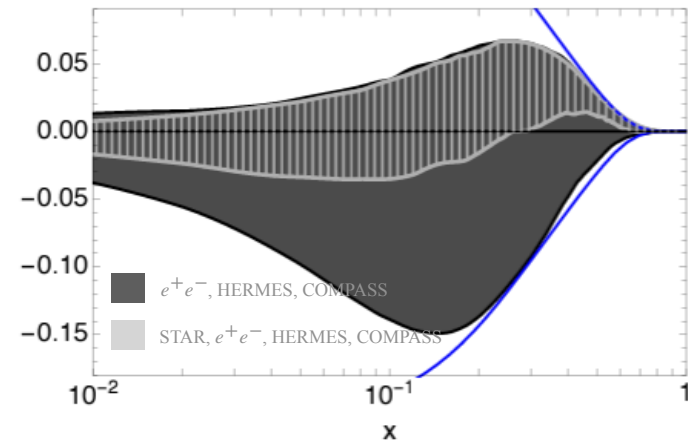
○ $A_{UT} \propto h_1^q(x) H_1^{\langle \pi^+\pi^- \rangle}(z, M_h^2)$

○ A_{UT} enhanced around ρ -mass region.

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



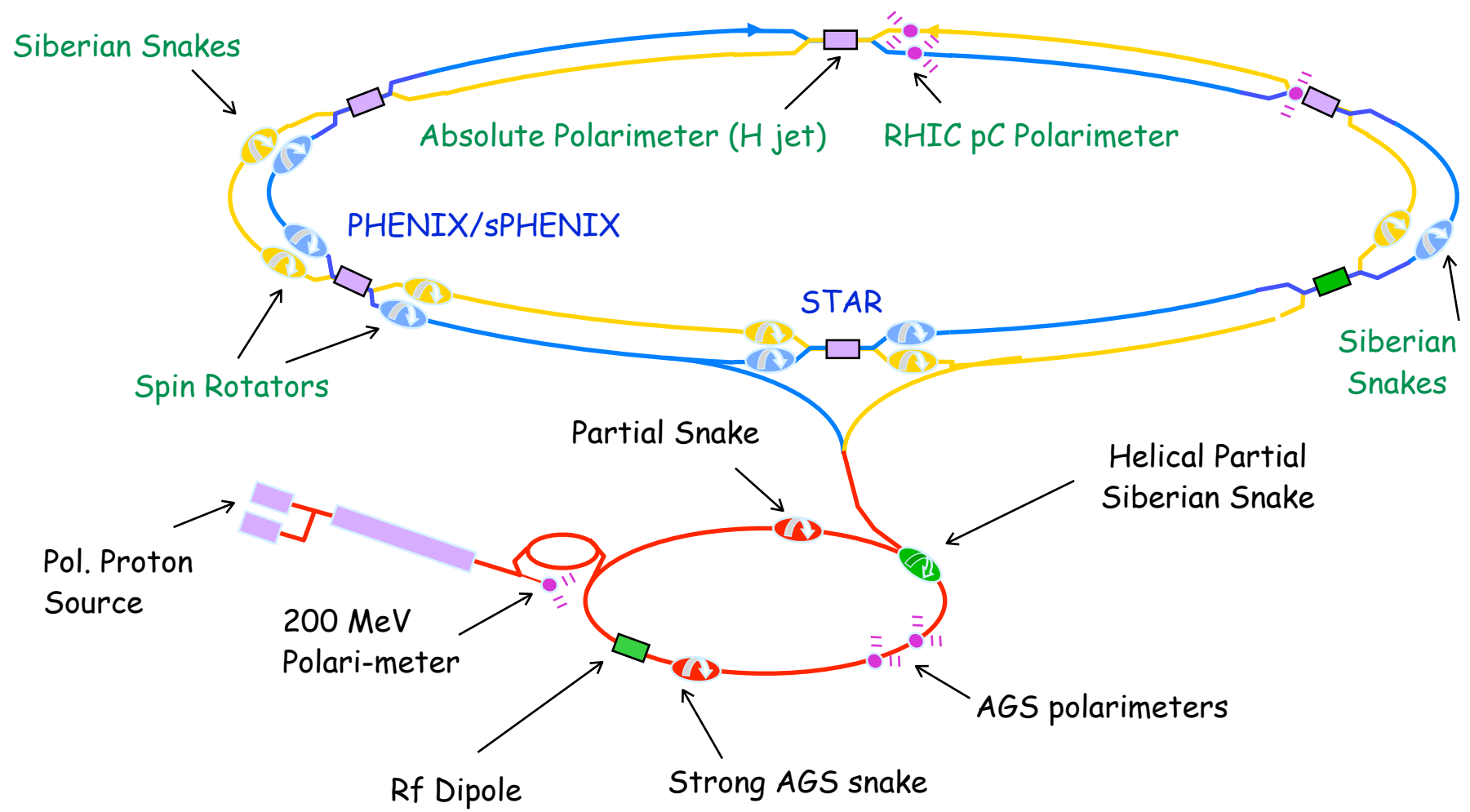
Significant
 impact on
 $h_1^q(x)$ from
 STAR data
 at
 $\sqrt{s} = 200$ GeV





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

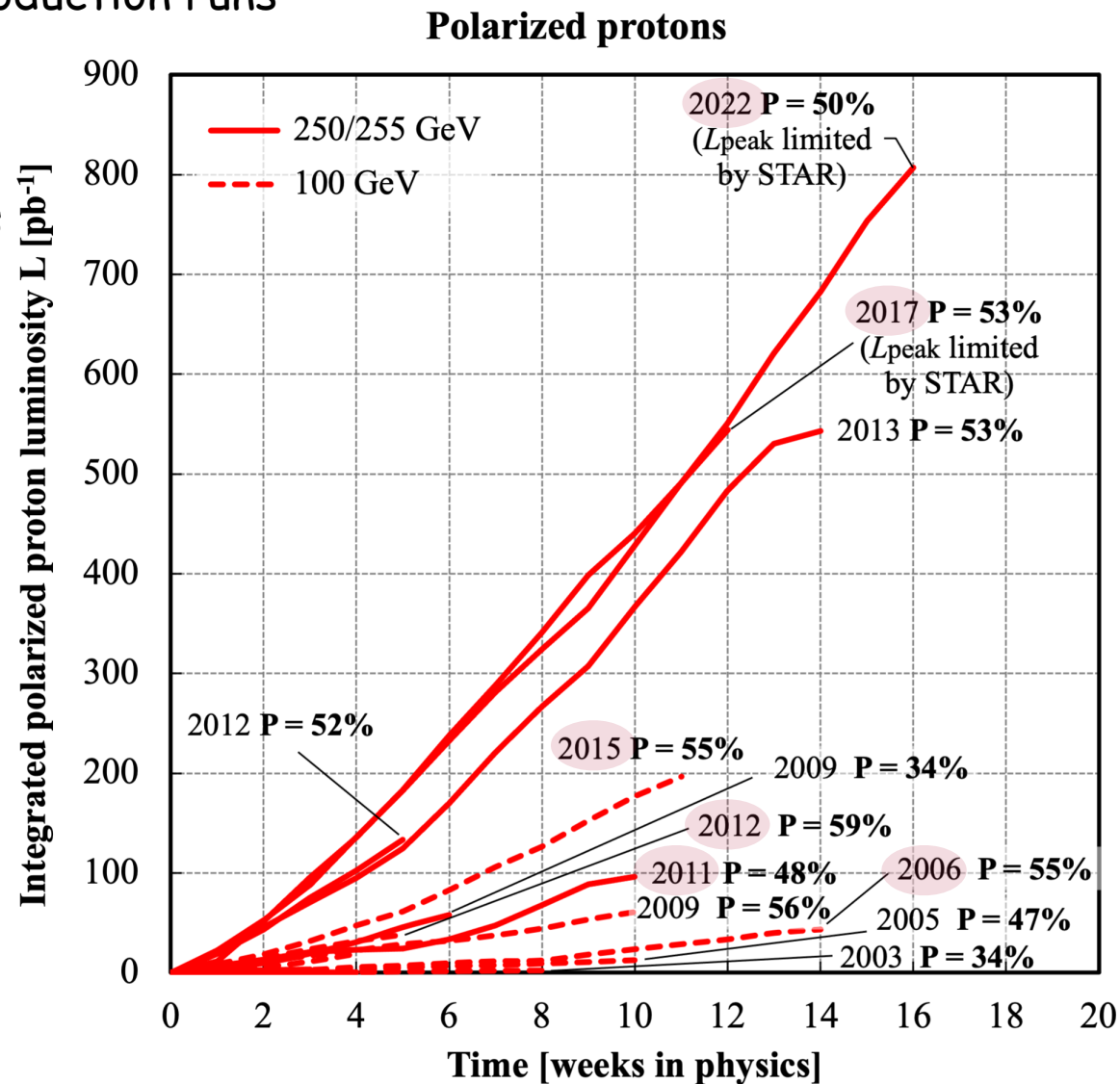
200GeV and 2011 at 500GeV

measurements

- Large data samples in 2015 at

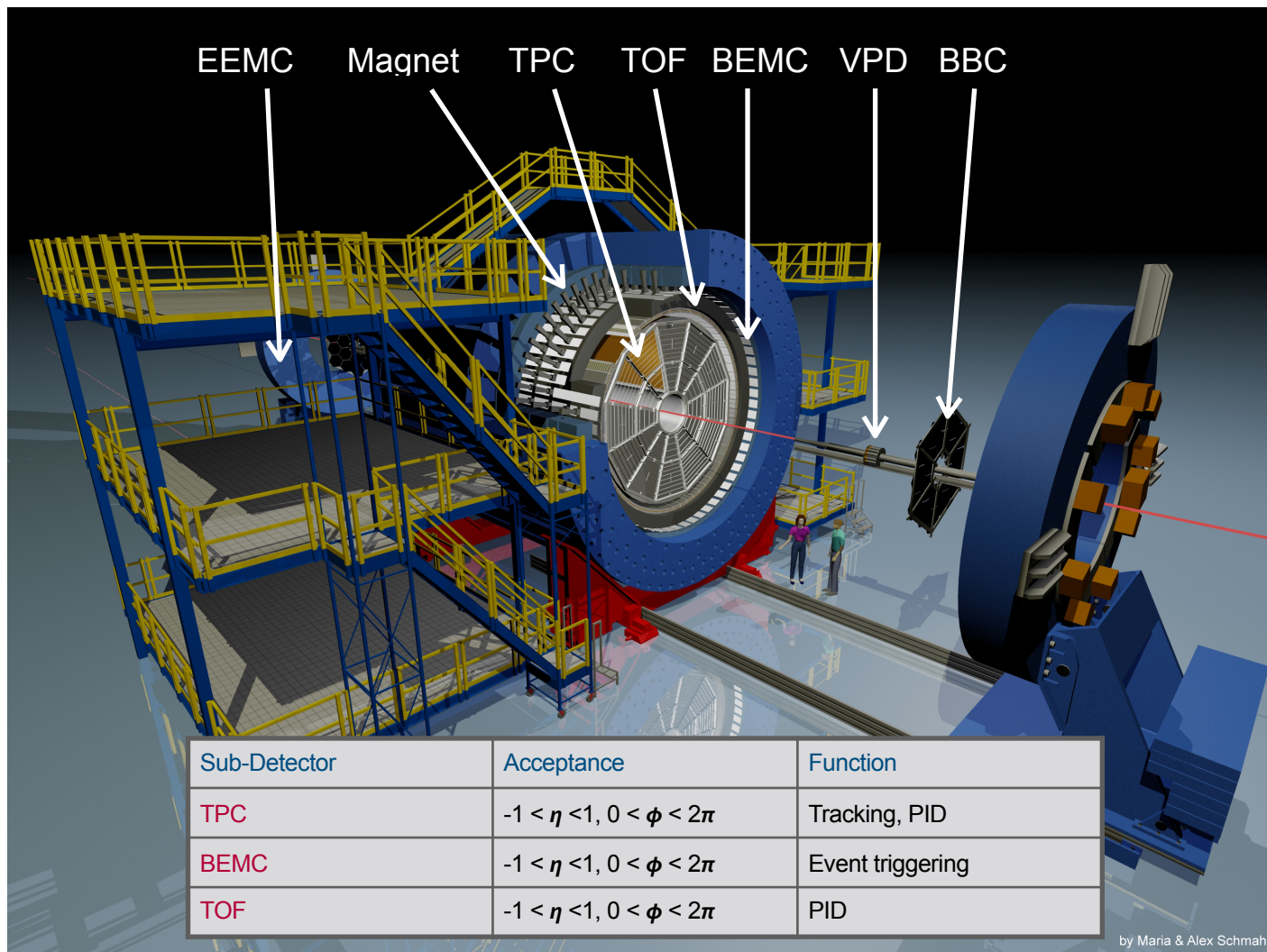
200GeV and 2017 / 2022 at

510GeV!



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_{int} (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)

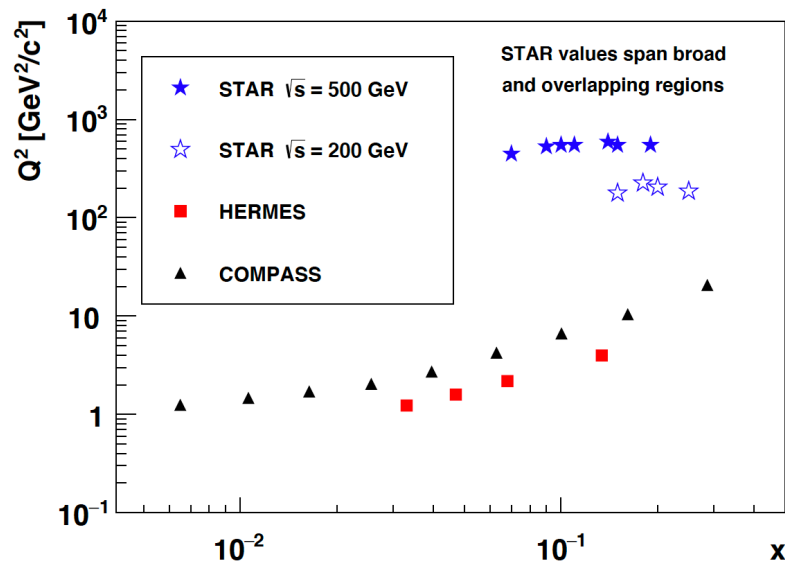
STAR IFF
 Preliminary @
 $\sqrt{s} = 510$ GeV

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_{int} (pb^{-1})	~ 1.8	~ 25	~ 22	~ 52	~ 320	~ 400	~ 190
$\langle P_{\text{beam}} \rangle$ (%)	~ 60	~ 53	~ 57	~ 57	~ 55	~ 52	



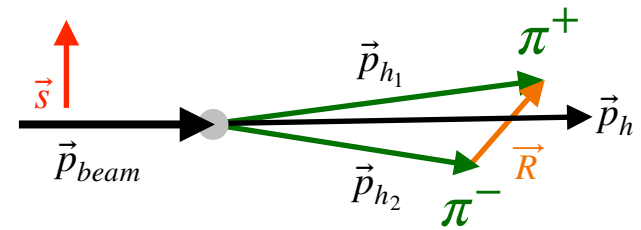
STAR Kinematic Coverage:

- 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 $\vec{R} = \frac{1}{2}(\vec{p}_{h_1} - \vec{p}_{h_2})$

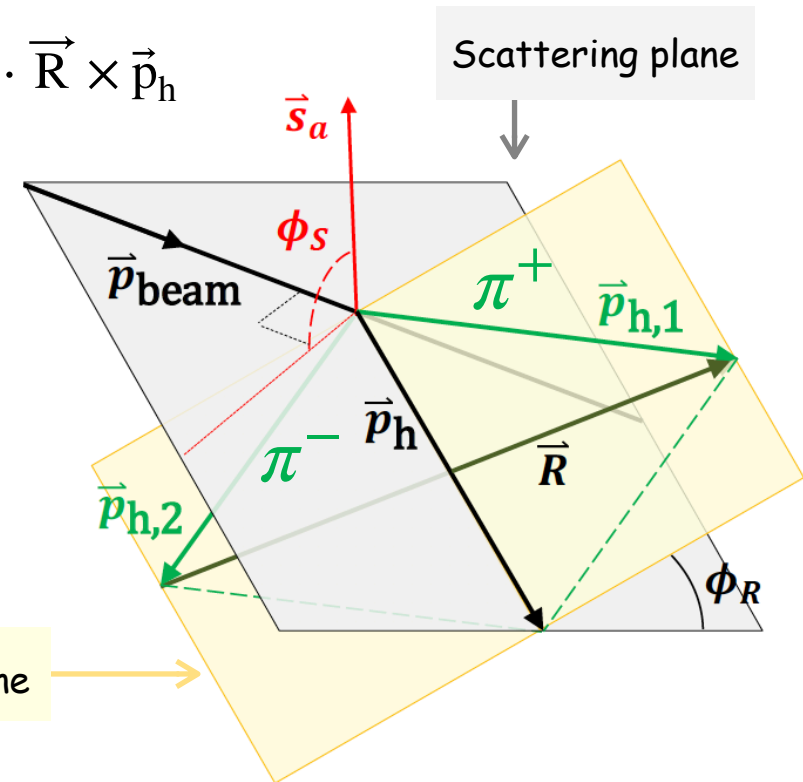
○ Access to the quark polarization via correlation: $\vec{S} \cdot \vec{R} \times \vec{p}_h$

○ 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 π^- to π^+ A_{UT} gets otherwise diluted

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



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

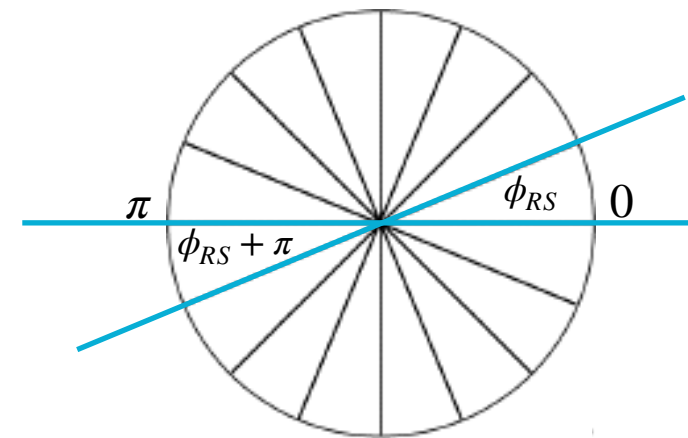
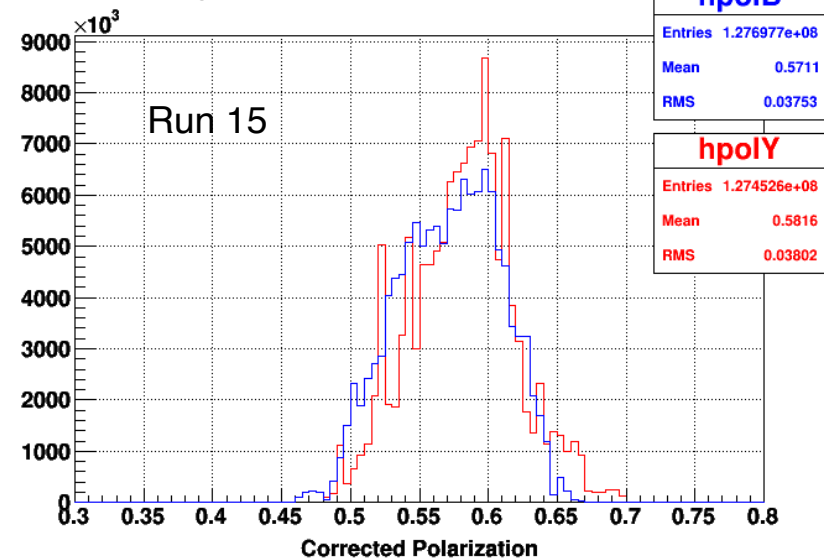
□ Asymmetry determination

- Cross-ratio formula: ϕ_{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 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: $N^\uparrow(\phi_{RS}), N^\downarrow(\phi_{RS})$.

$P \equiv$ Average beam polarization

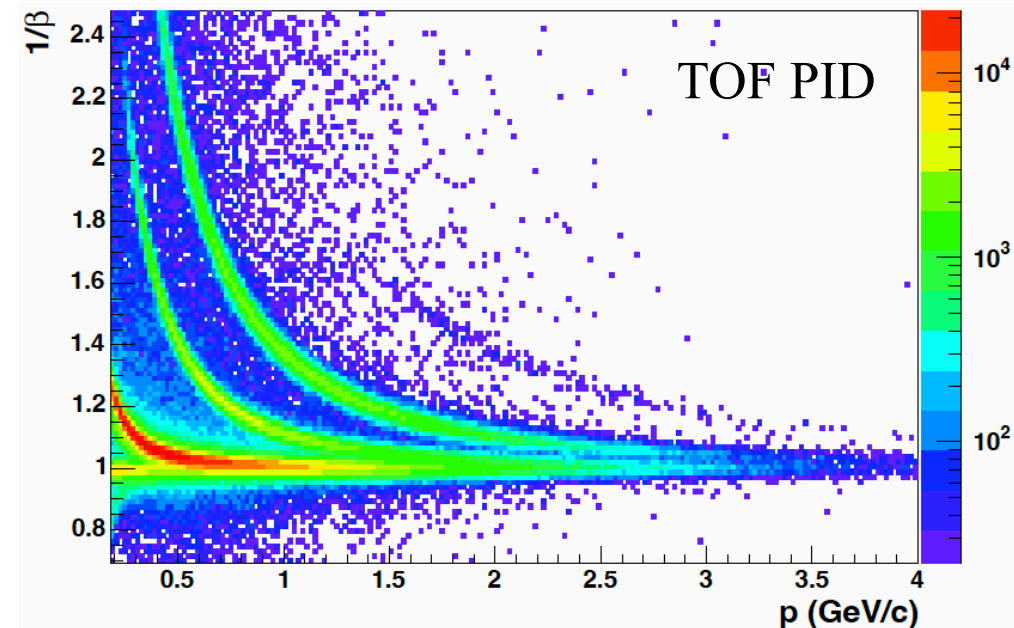
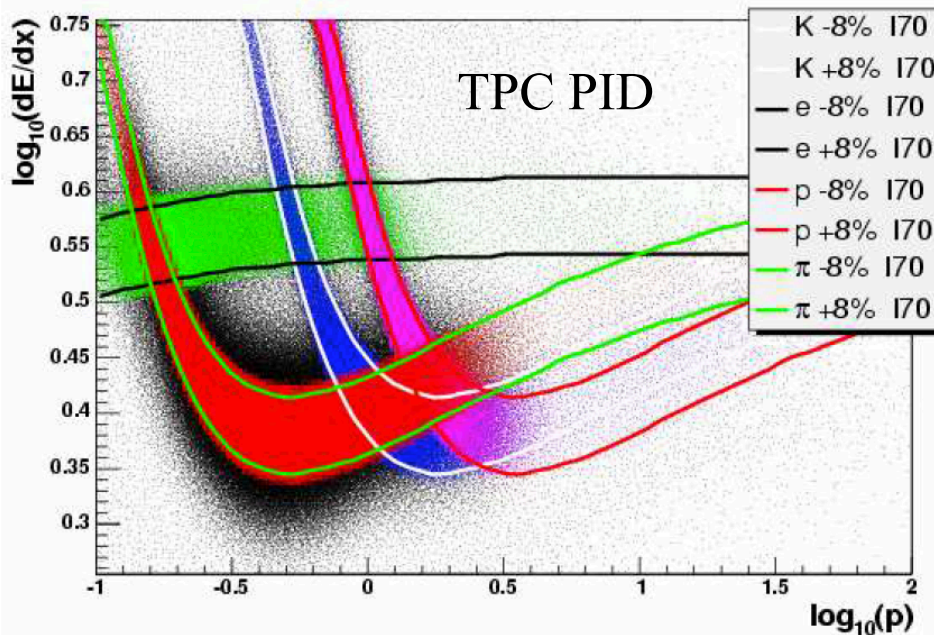


ϕ_{RS} binning scheme

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

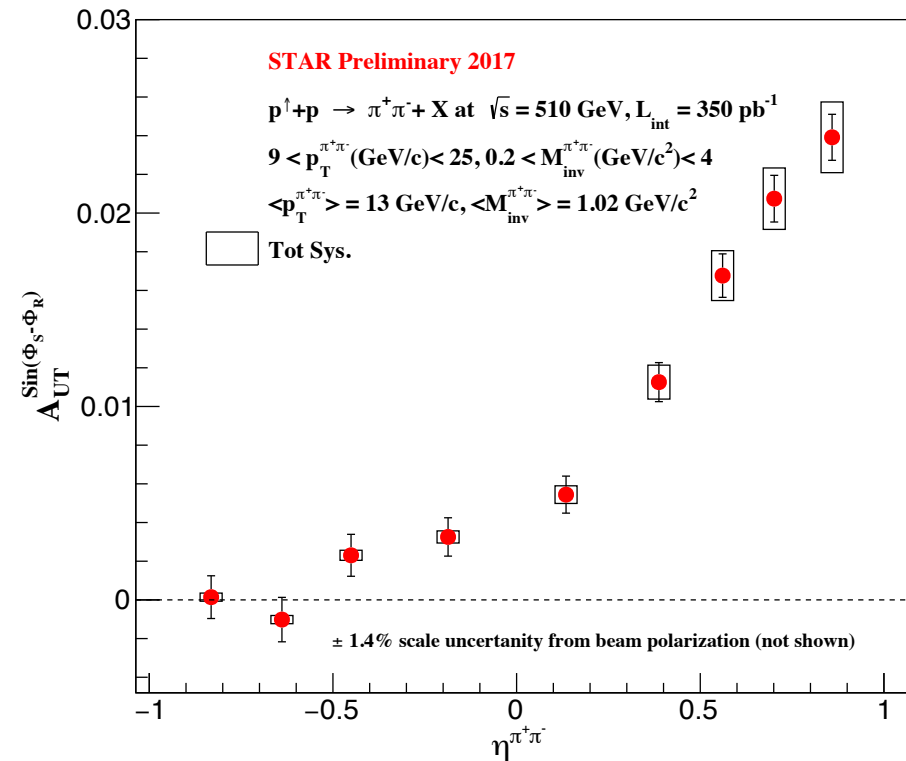
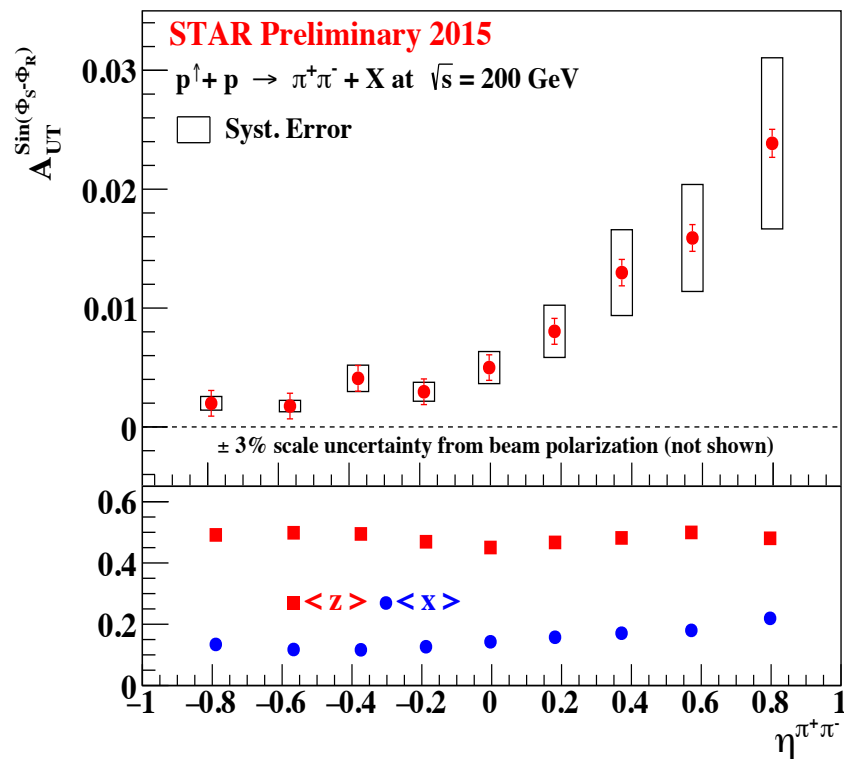
□ Systematic uncertainties

- 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

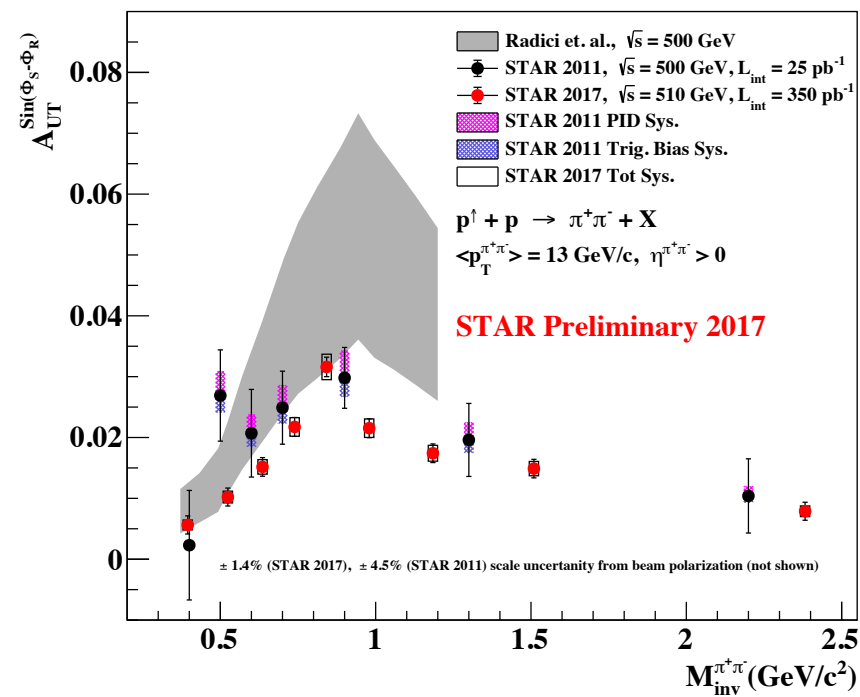
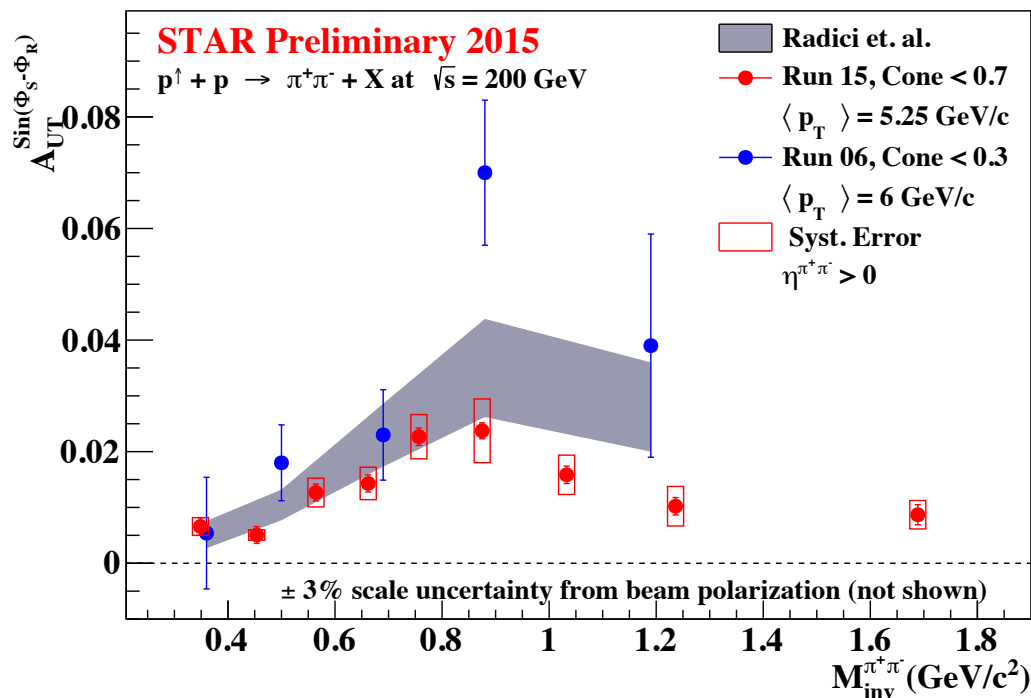
- Asymmetry vs. pseudo-rapidity $\eta^{\pi^+\pi^-}$ at 200GeV and 510GeV



- A_{UT} increases with η 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

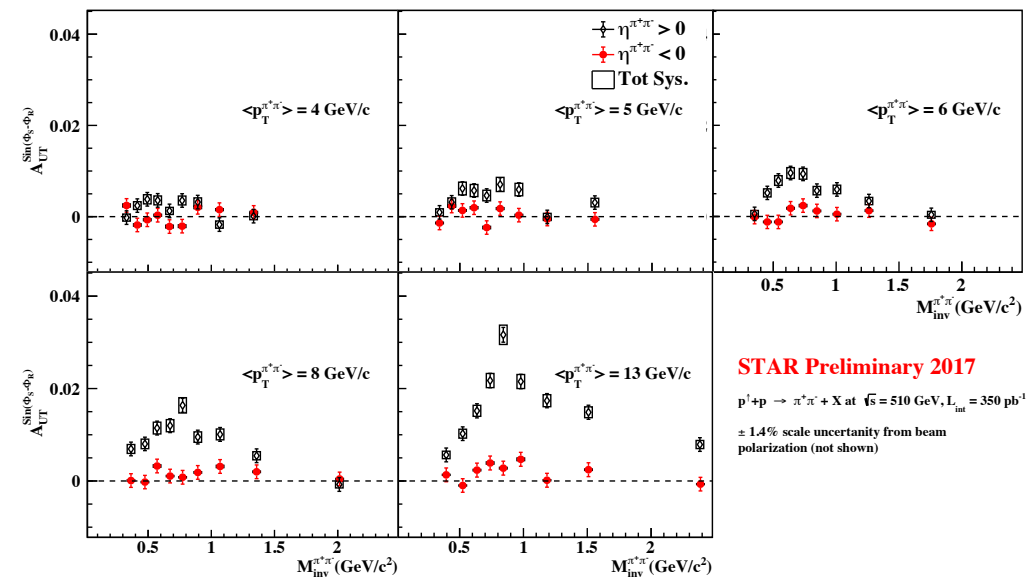
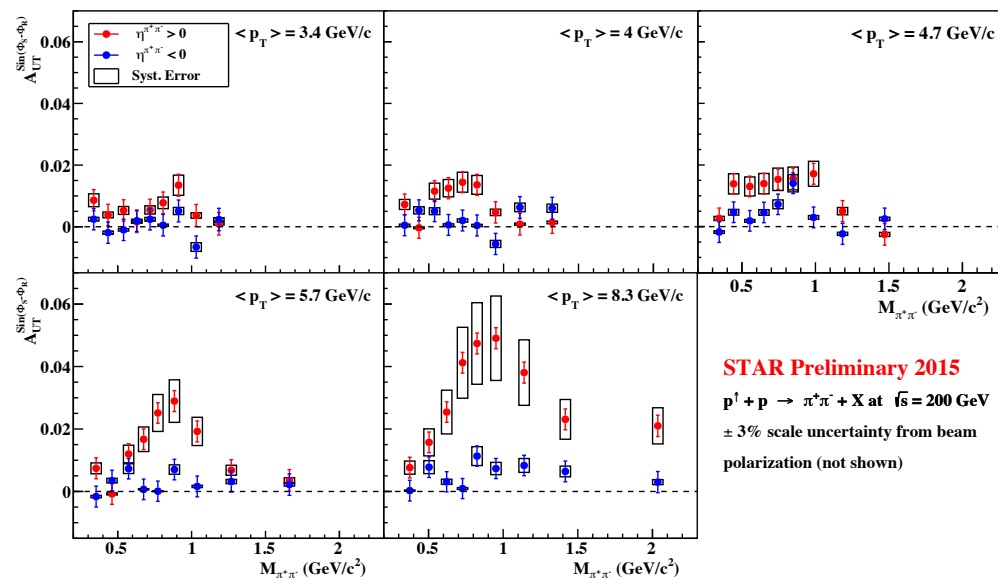
- Asymmetry vs. invariant mass $M_{inv}^{\pi^+\pi^-}$ integrated in p_T at 200GeV and highest p_T bin at 510GeV



- A_{UT} asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$ GeV/c 2 , consistent with the previous measurement and theory prediction
- Theory calculations overshoots the new measurement beyond the ρ resonance peak
- Statistical precision is significantly improved by the new result

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

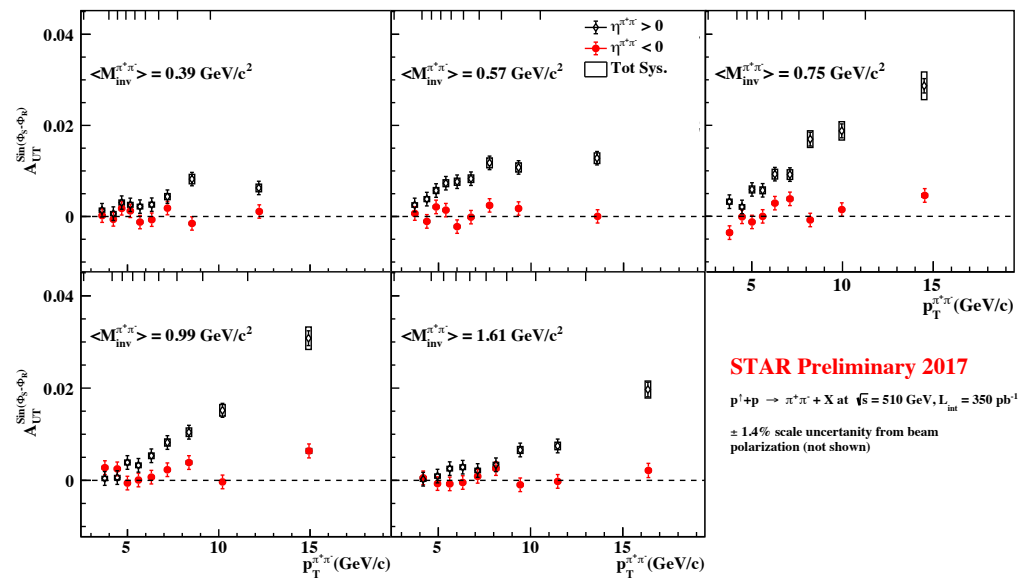
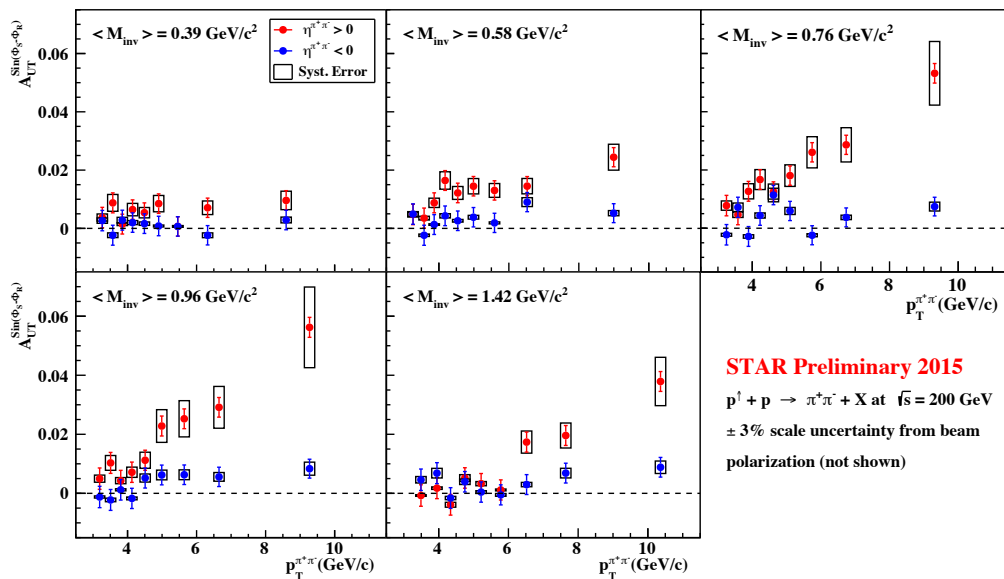
- Asymmetry vs. invariant mass $M_{\text{inv}}^{\pi^+\pi^-}$ in p_T bins at 200 GeV and 510 GeV



- $A_{\text{UT}}^{\sin(\phi_{\text{RS}})}$ 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

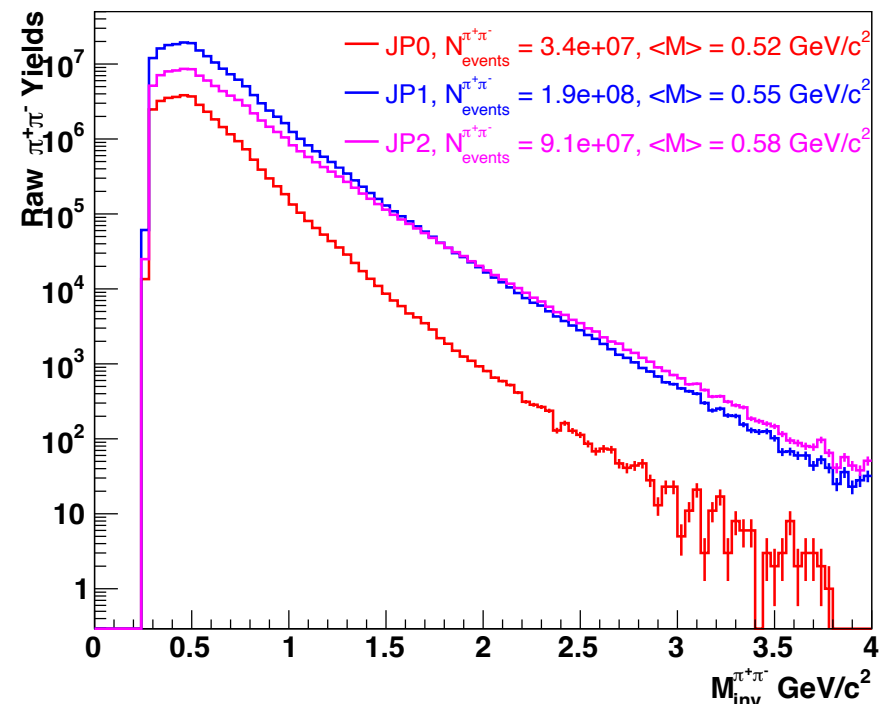
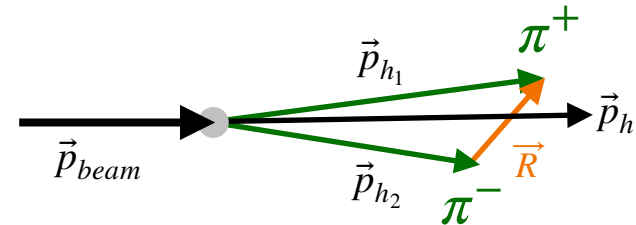


- Large asymmetry signal at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Stronger signal when $\langle M_{inv} \rangle \sim M_\rho$.
- Backward $\eta^{\pi^+\pi^-}$ signal ($\eta^{\pi^+\pi^-} < 0$) is small, mainly from low x quarks from polarized beam.

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

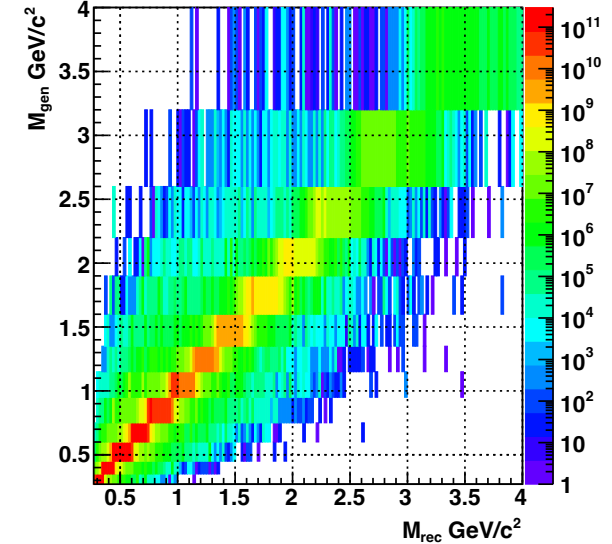
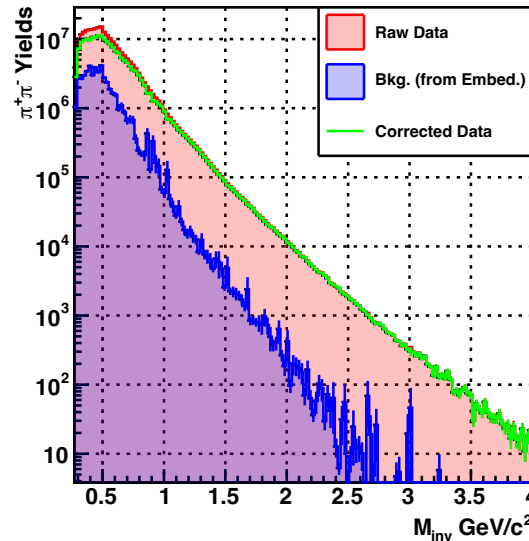
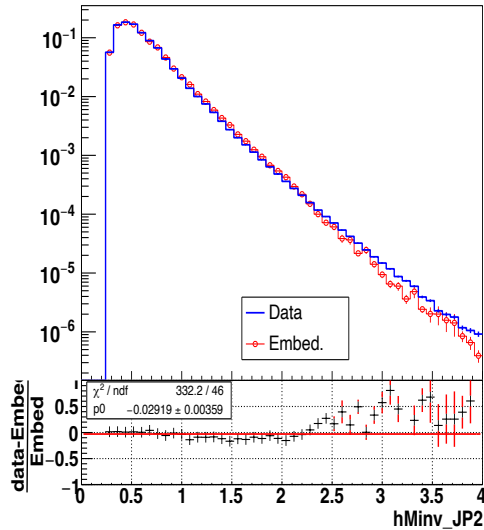
□ Selection criteria

- 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:

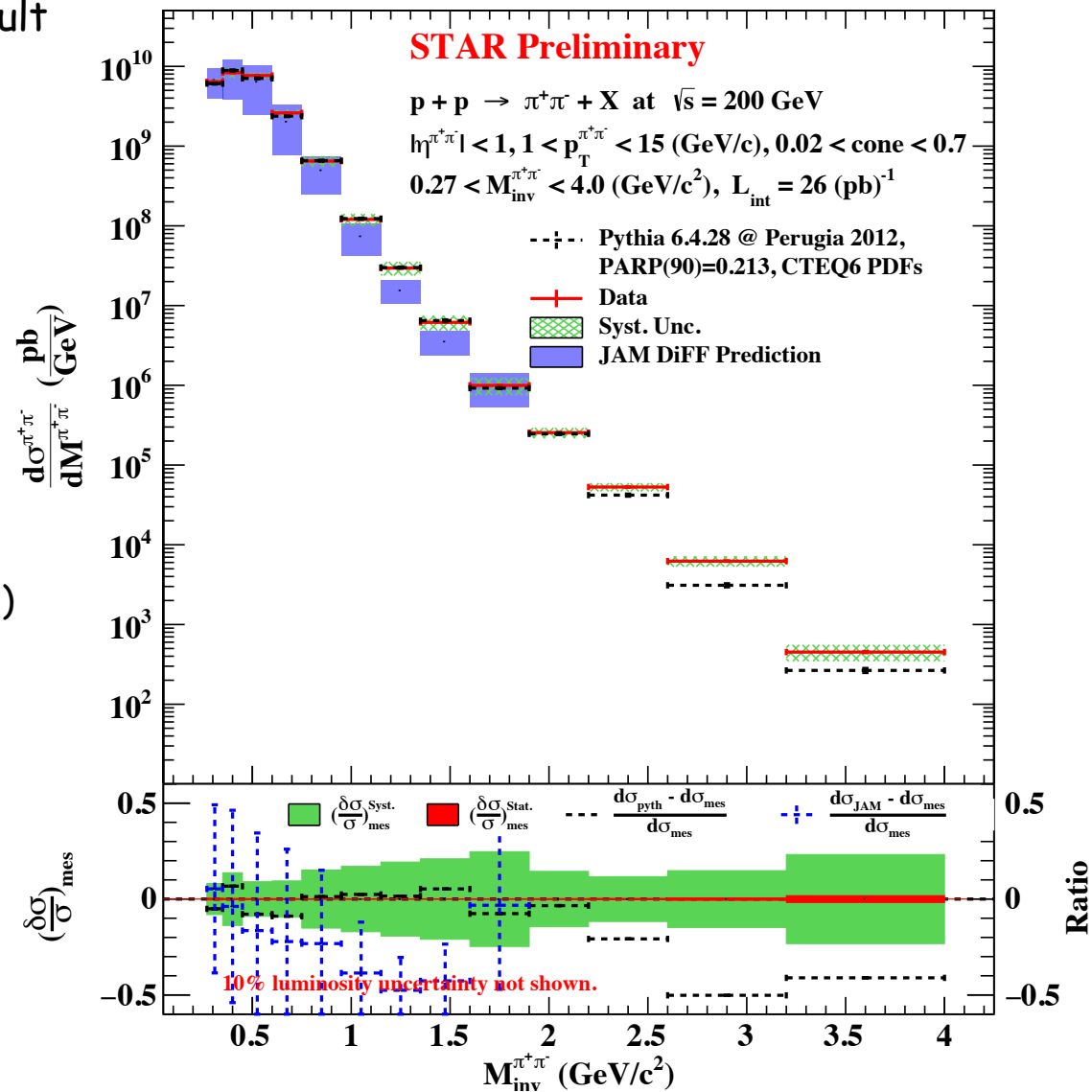
- First unpolarized $\pi^+\pi^-$ cross-section measurement
- Good agreement in comparison to PYTHIA simulation and JAMDiFF prediction

○ 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

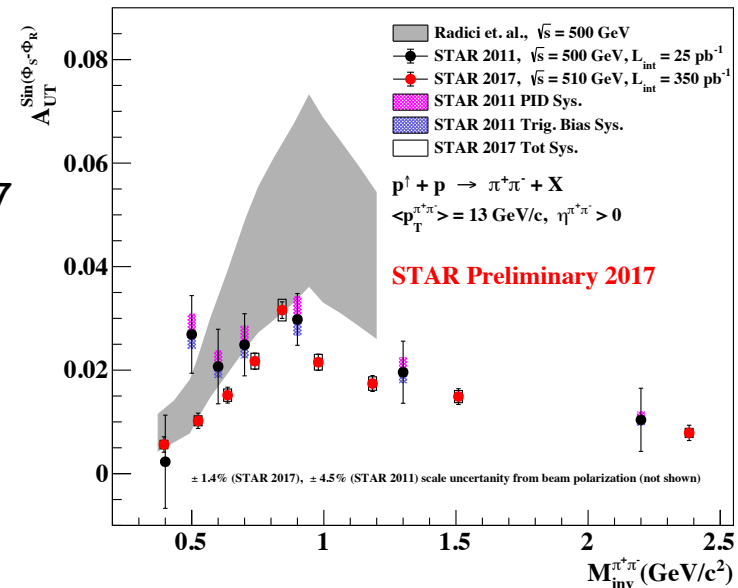
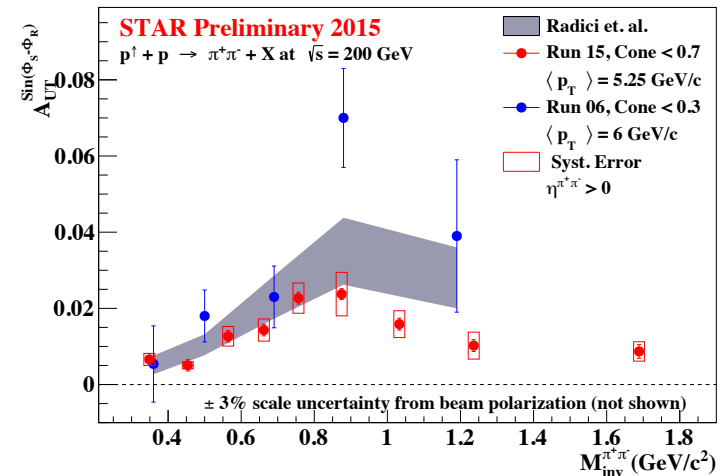
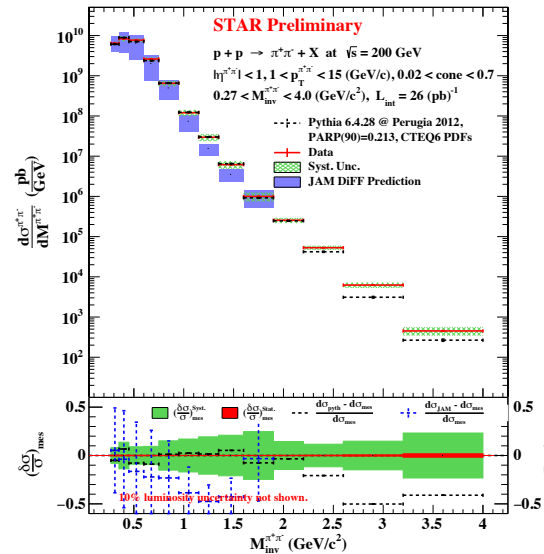
○ Path to model-independent extraction of $h_1(x)$



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

