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

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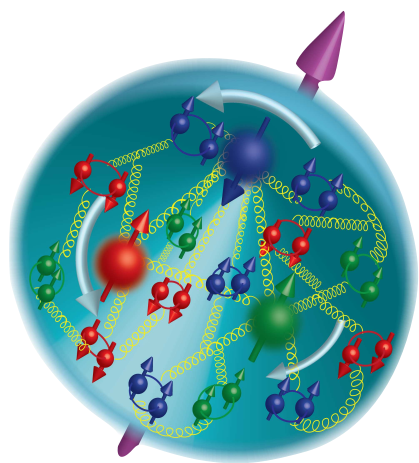

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- Theoretical Foundation
- RHIC Collider and STAR experiment
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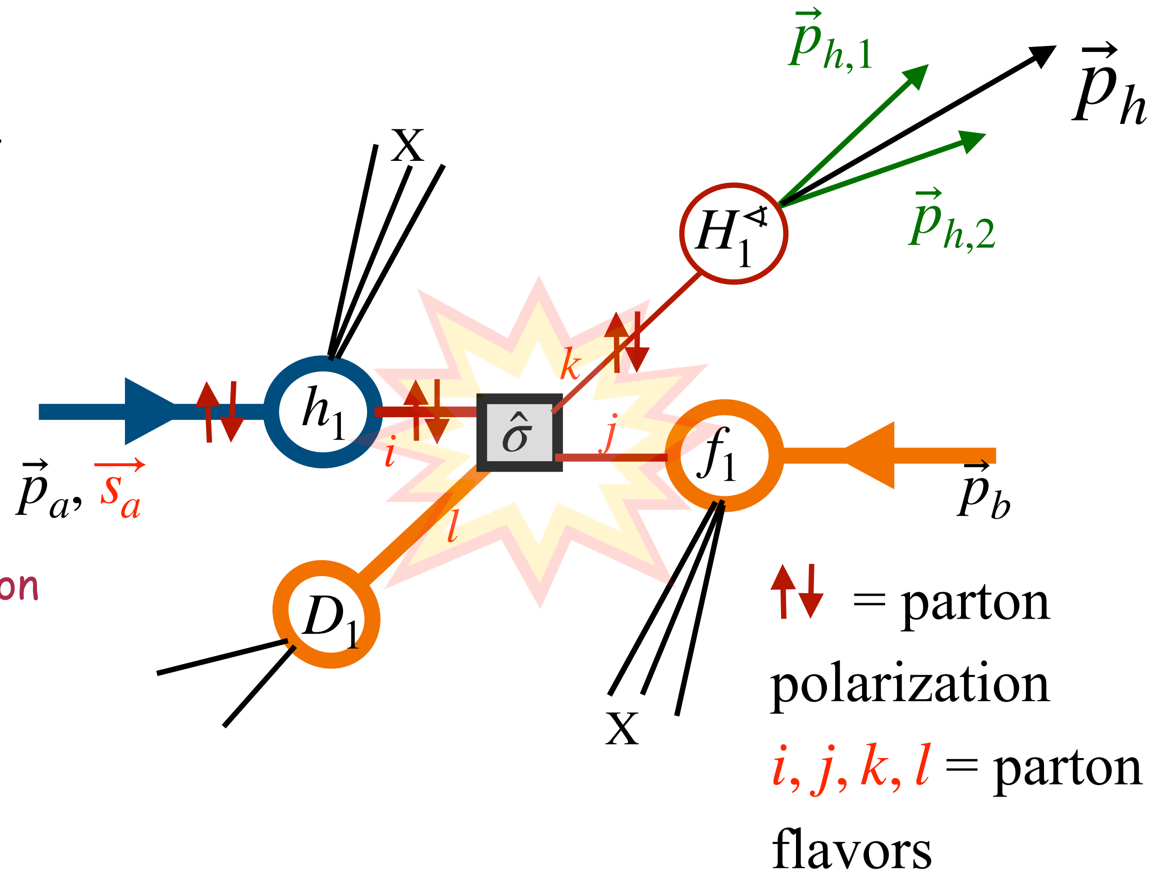
- $\pi^+\pi^-$ Asymmetry Results
- Analysis Details - $\pi^+\pi^-$ Cross-Section
- $\pi^+\pi^-$ Cross-Section Results
- Summary



Theoretical foundation

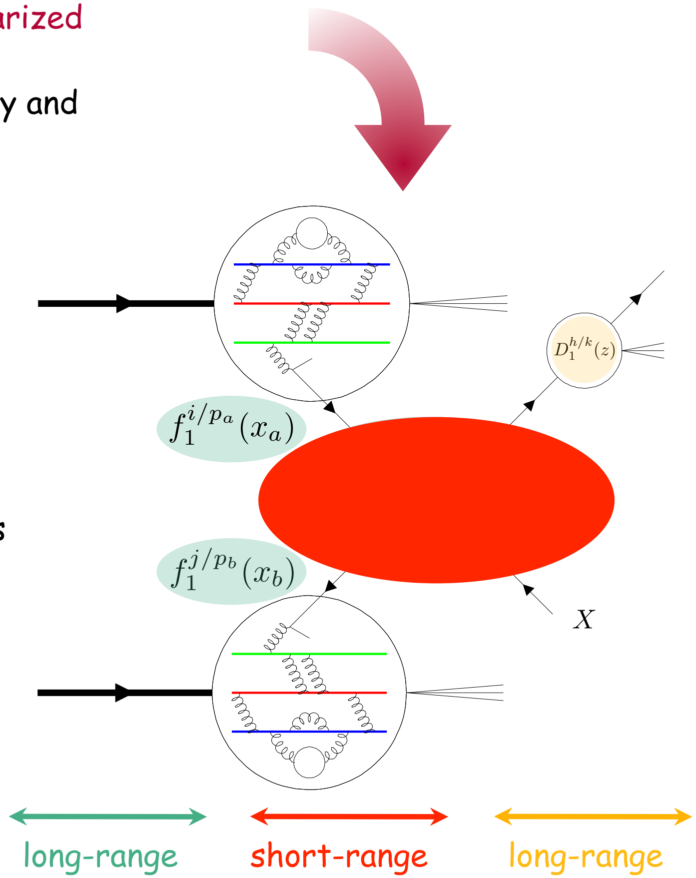
- Probe transverse proton spin structure using high-energy polarized p+p collisions
  - Important new insight into the transverse proton spin structure at STAR in polarized p+p collisions at high energies using well established processes both theoretically and experimentally involving jets / hadrons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

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

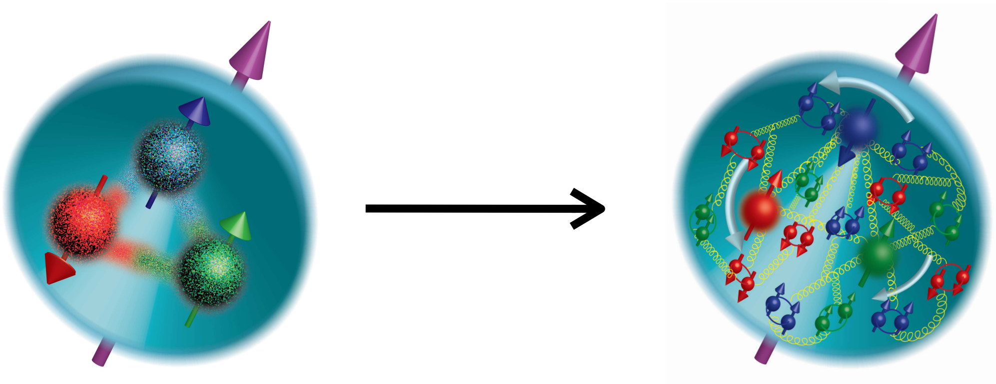
  - Deepen our understanding concerning universality, factorization and evolution!

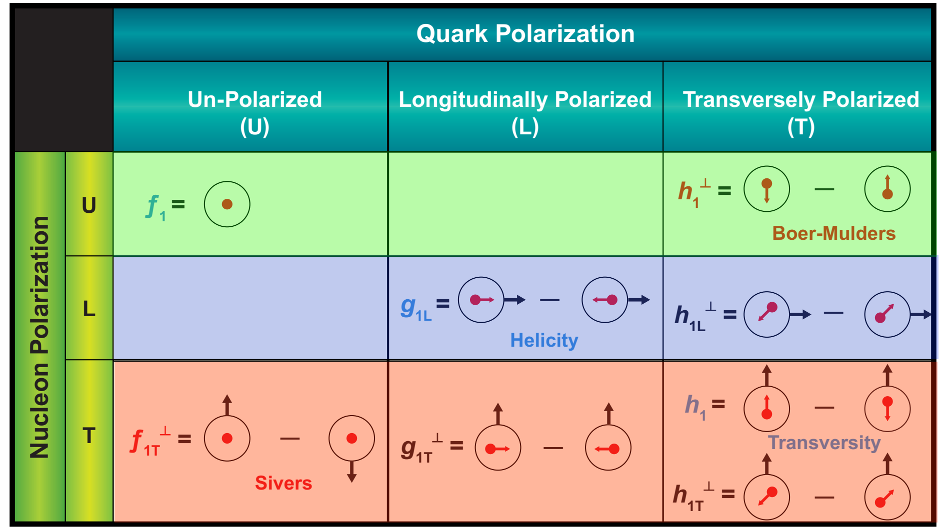


FF Review: A. Metz and A. Vossen, Prog. Part. Nucl. Phys. 91 (2016) 136.

Theoretical Foundation

- Proton spin structure



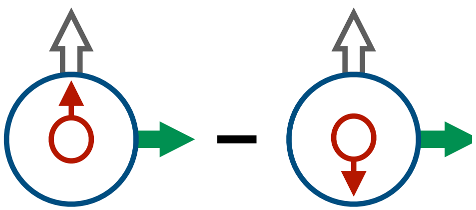


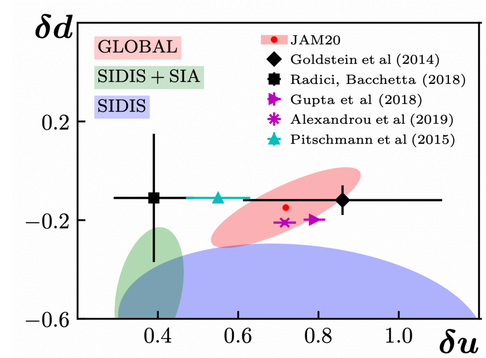
- Proton spin structure in terms of parton distribution functions (PDFs)
- Three leading twist collinear PDFs, integrated over parton transverse momenta k_T:
  - $f_1(x)$ = Unpolarized PDF
  - $g_1(x)$ = Helicity PDF
  - $h_1^q(x)$ = Transversity PDF
- Motivation: Measurement of observable to constrain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

Theoretical Foundation

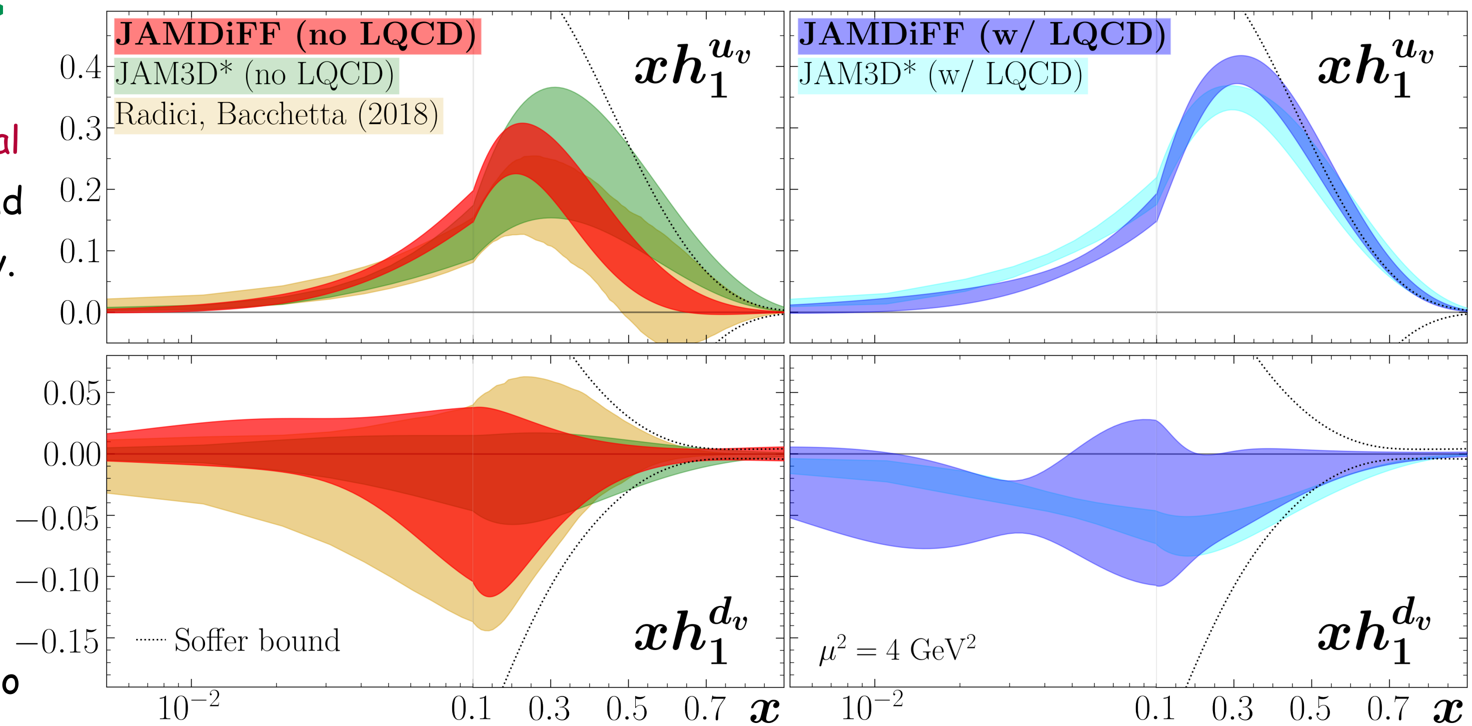
- Transversity

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



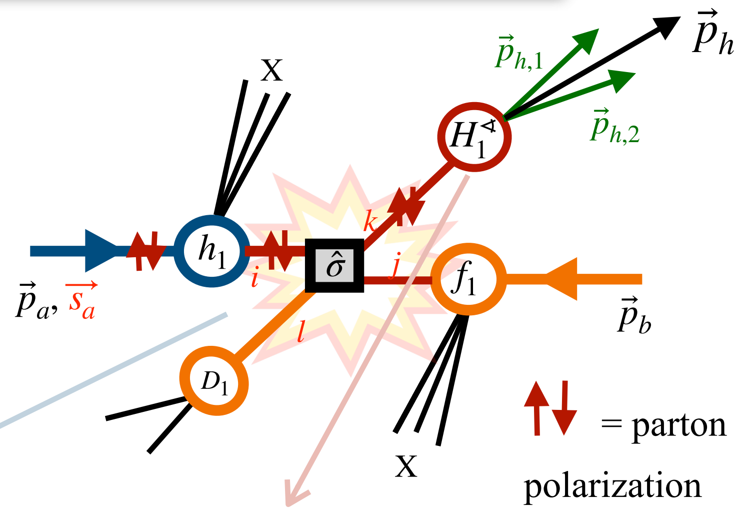


- First transversity global analysis by M. Radici and A. Bacchetta (Phys. Rev. Lett. 120, 192001 (2018))
- New global analysis by JAM global analysis (arXiV 2308.14857)!
- Important connection to Lattice QCD!



Theoretical Foundation

- Observables for transversity - Theoretical formulation



= parton polarization

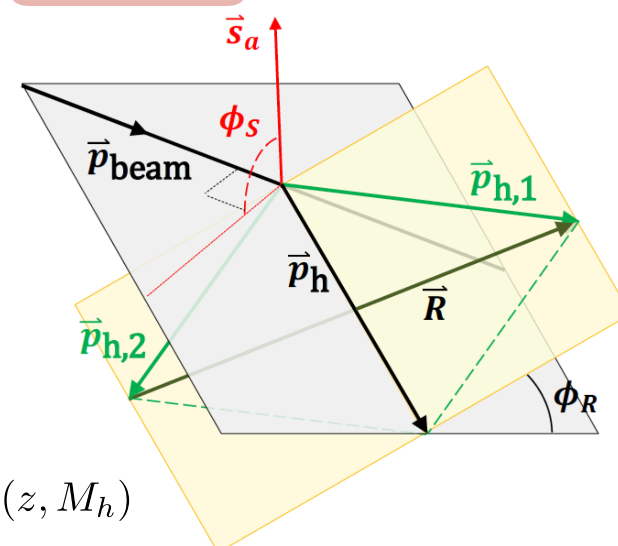
i, j, k, l = parton flavors

- Di-hadron channel: $p\uparrow + p \rightarrow h^+h^- + X$
- Asymmetry: $A_{UT}^{pp} = \dfrac{\mathcal{H}(M_h, P_{hT}, \eta)}{\mathcal{D}(M_h, P_{hT}, \eta)}$

Transversity:

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

$$h_1 \leftrightarrow f_1, \quad H_1^{\sphericalangle} \leftrightarrow D_1$$



- Unpolarized cross-section:

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

Theoretical Foundation

- Observables for transversity - Experimental measurement

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

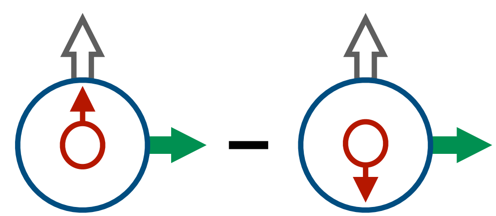
$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z,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

    - Independent measurement of $H_1^{\sphericalangle}$ is required from e^+e^- experiments (e.g. BELLE!)
    - $D_1^{h_1h_2}$ 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 $D_1^{h_1h_2}$ providing access to quarks and gluons

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



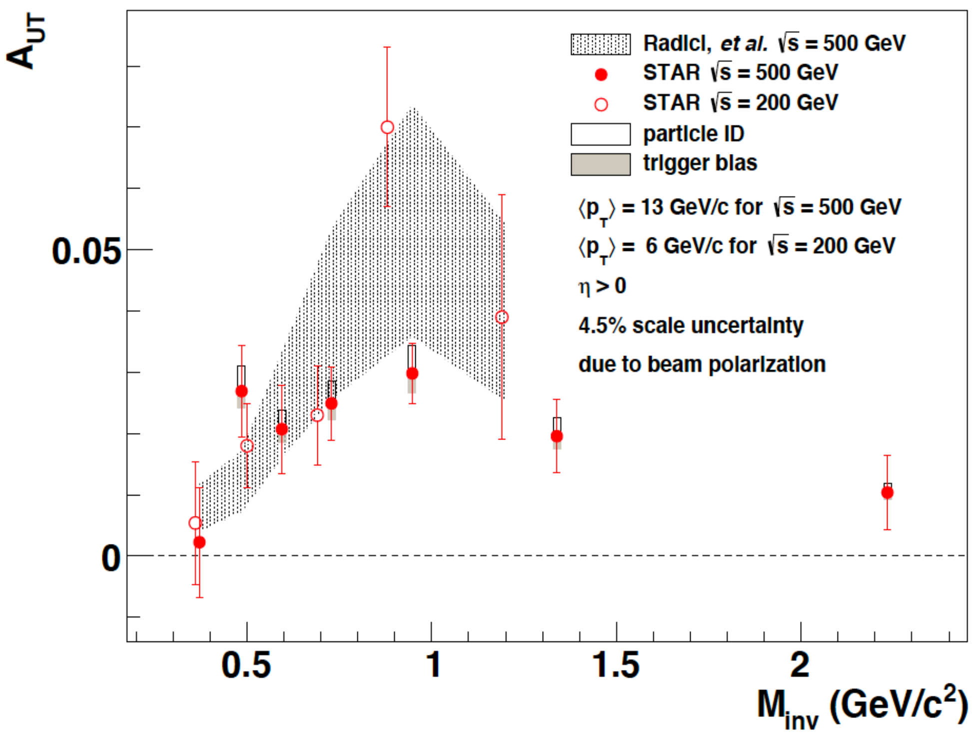
Theoretical Foundation

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

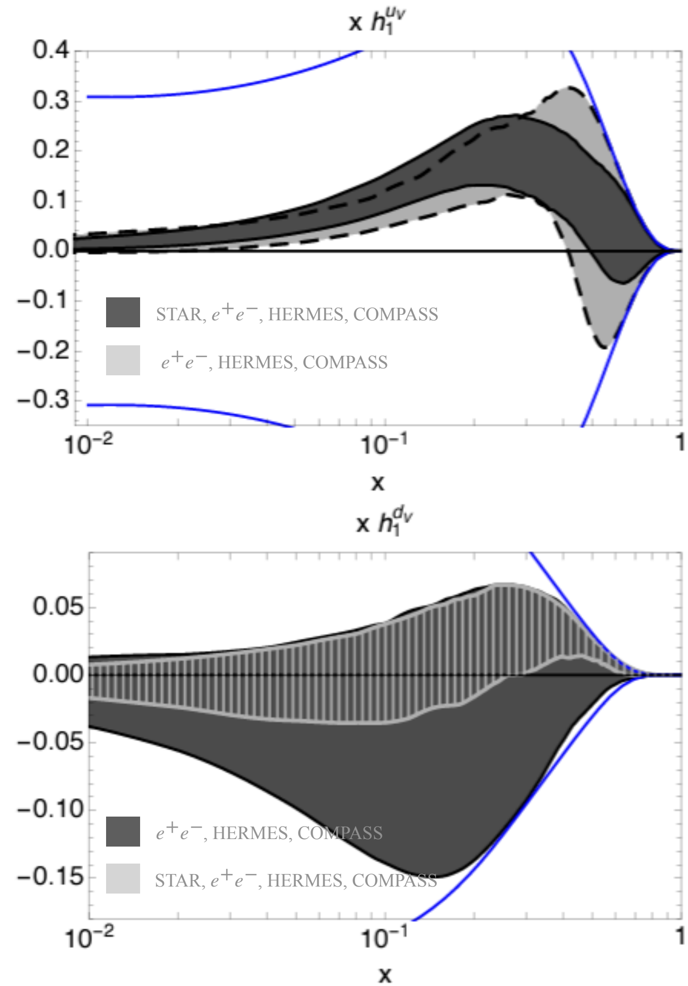
Radici et. al. Phys. Rev. Lett. 120 (2018), 19 192001

  - STAR observed significant $\pi^+\pi^-$ correlation asymmetry, A_{UT}, using 200 GeV and 500 GeV
  - $A_{UT} \propto h_1^q(x) H_1^{\sphericalangle \pi^+\pi^-}(z, M_h^2)$
  - A_{UT} enhanced around ρ-mass region.

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

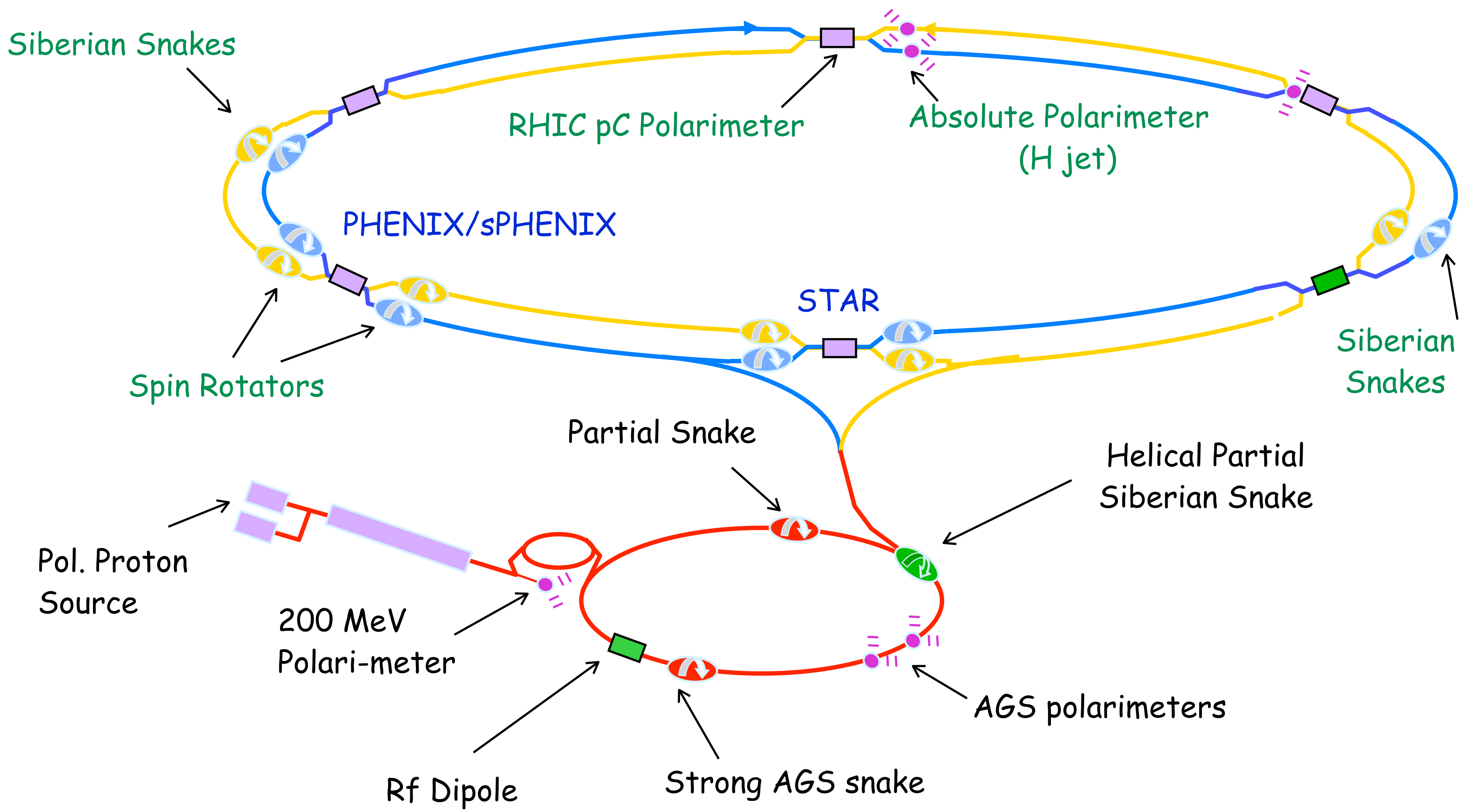


Significant impact on $h_1^q(x)$ from STAR data at $\sqrt{s} = 200$ GeV



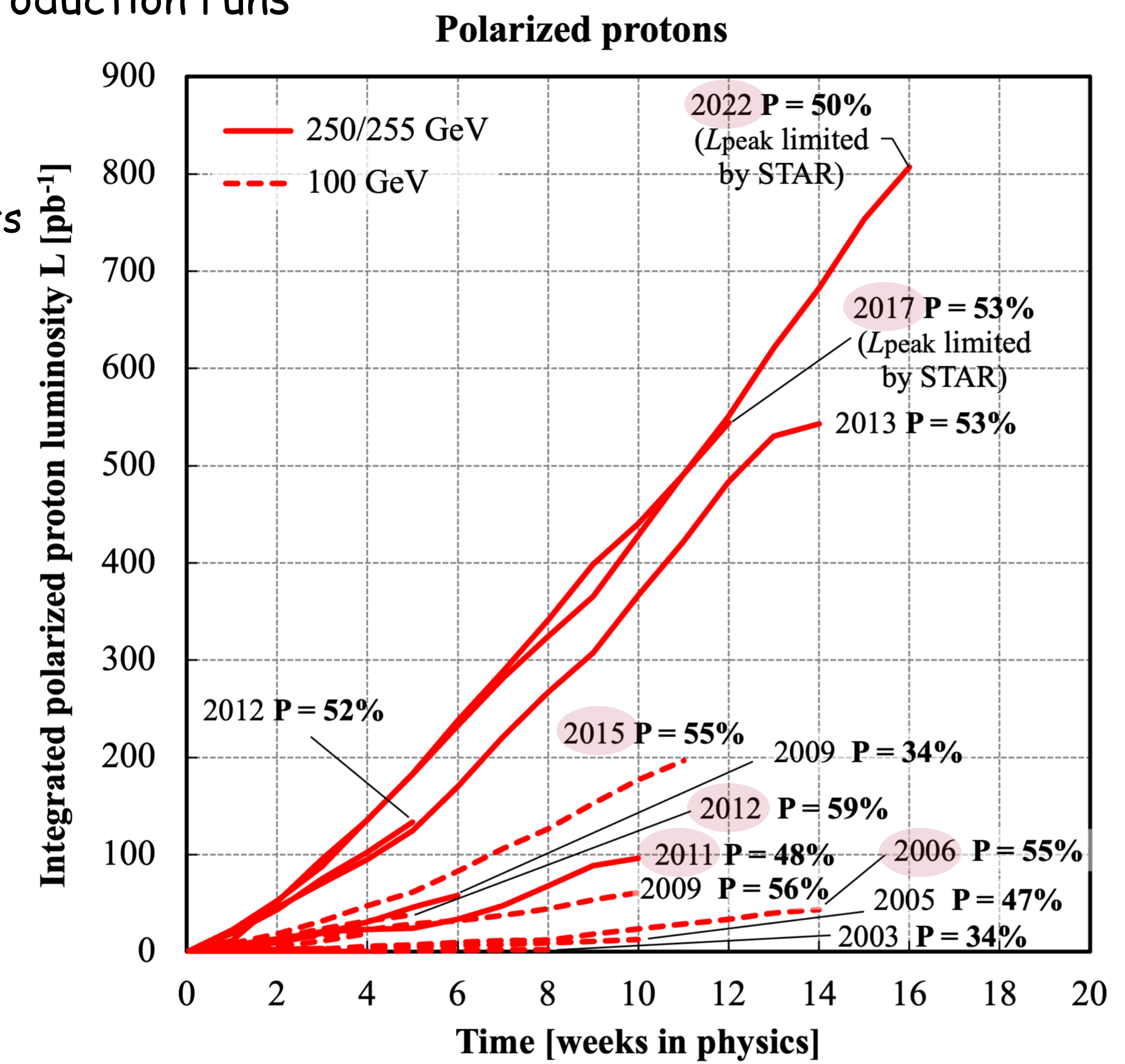
RHIC Collider and STAR Experiment

- Polarized p+p collider facility at BNL



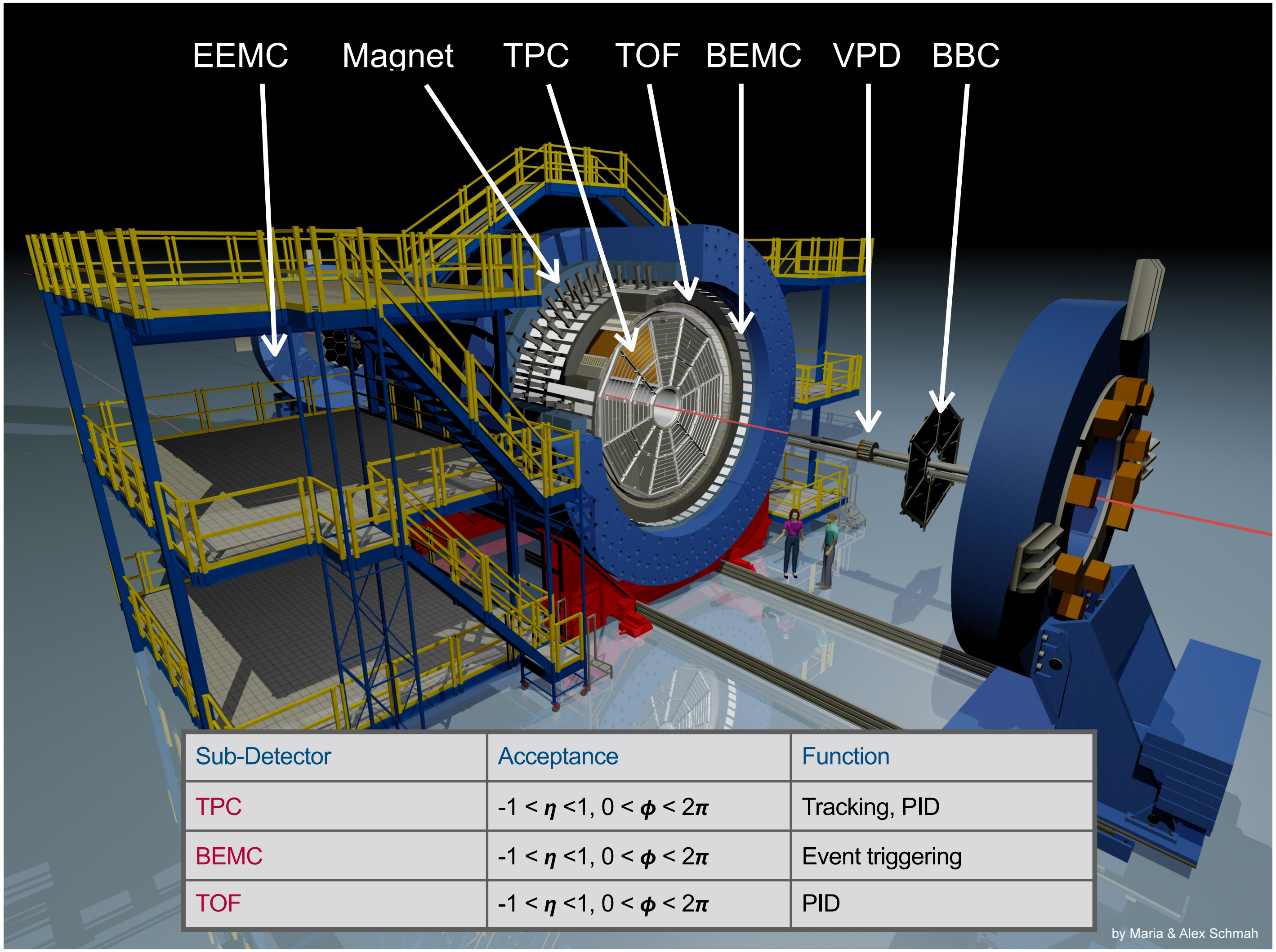
RHIC Collider and STAR Experiment

- 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



Sub-Detector	Acceptance	Function
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

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	~ 350	~ 400	~ 190
$\langle P_{beam} \rangle$(%)	~ 60	~ 53	~ 57	~ 57	~58	~58	

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						
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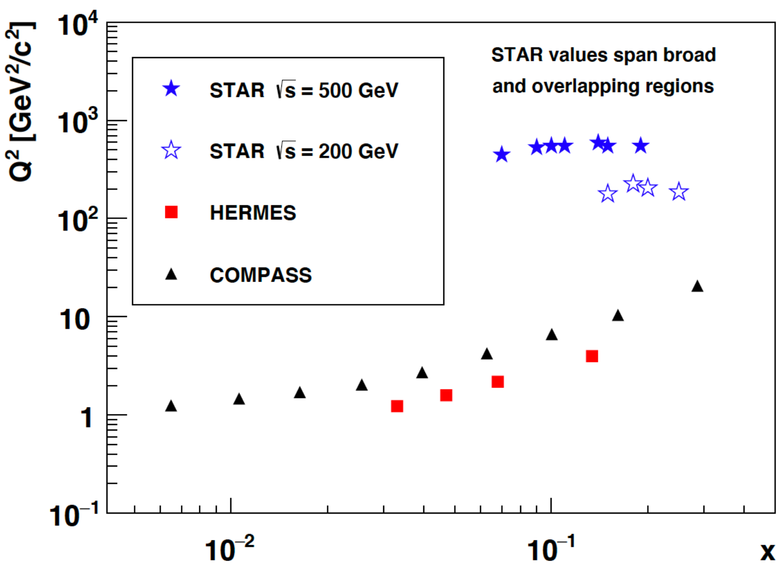
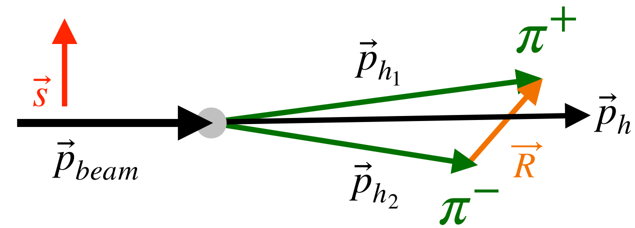


STAR Kinematic Coverage:

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

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

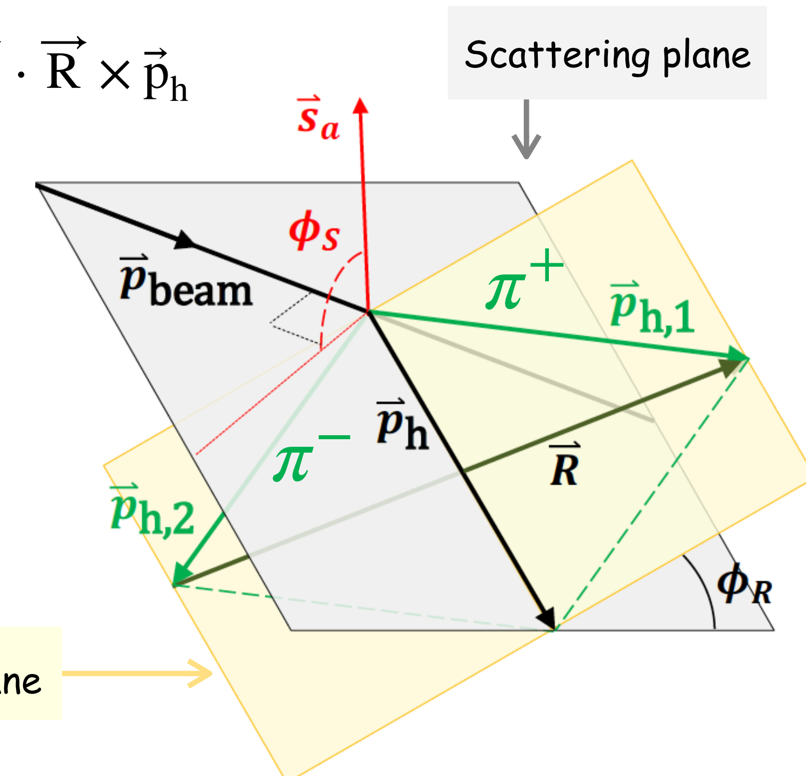
- Kinematic variables and selection cuts



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: $\vec{\mathrm{S}} \cdot \vec{\mathrm{R}} \times \vec{\mathrm{p}}_{\mathrm{h}}$
- 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 $\vec{\mathrm{R}}$ always points from π^- to π^+ $\mathrm{A_{UT}}$ gets otherwise diluted



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

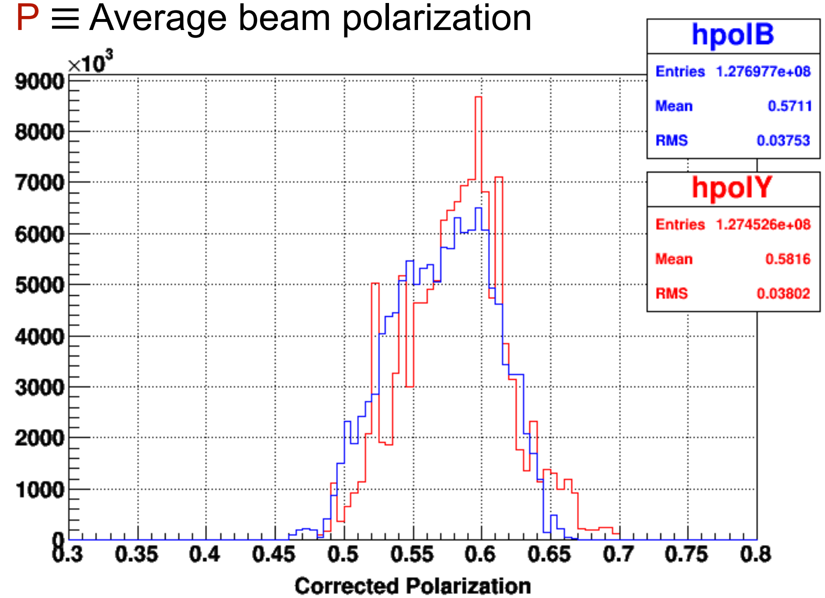
Analysis details - $\pi^+\pi^-$ Asymmetry

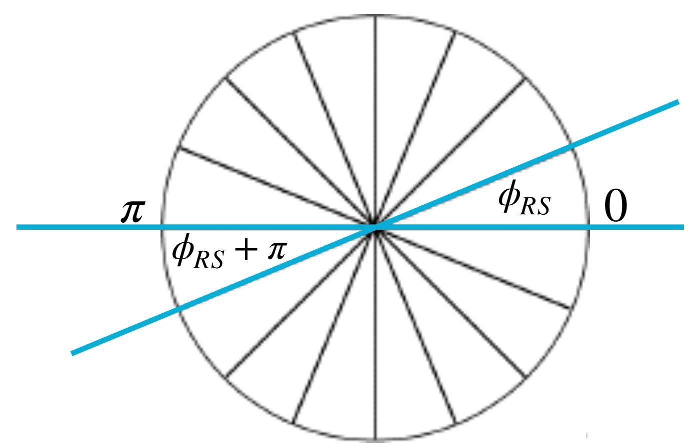
- Asymmetry determination
  - Cross-ratio formula: ϕ_{RS} binning in A_{UT} extraction

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

  - 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

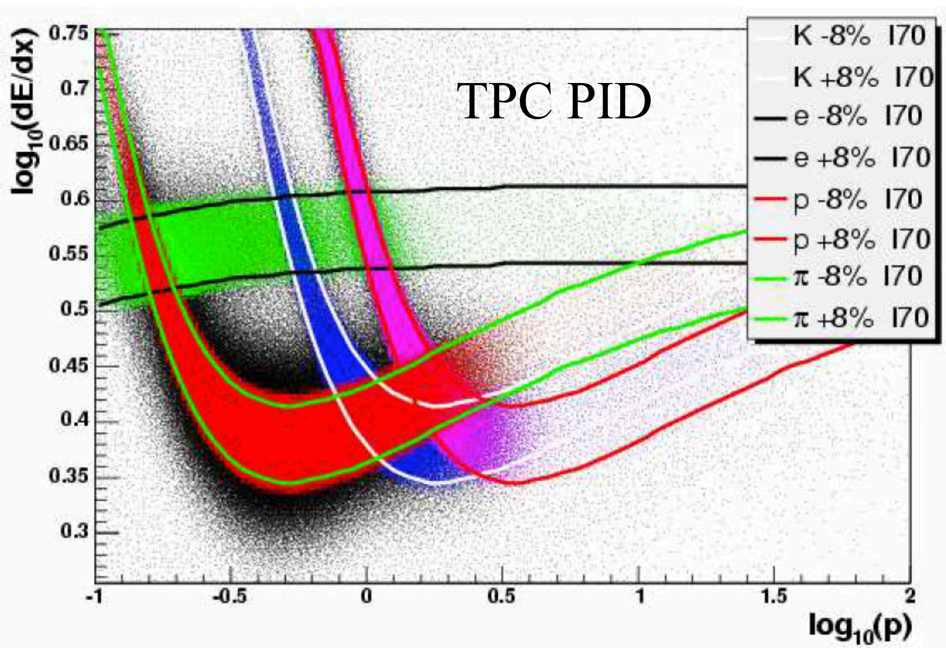


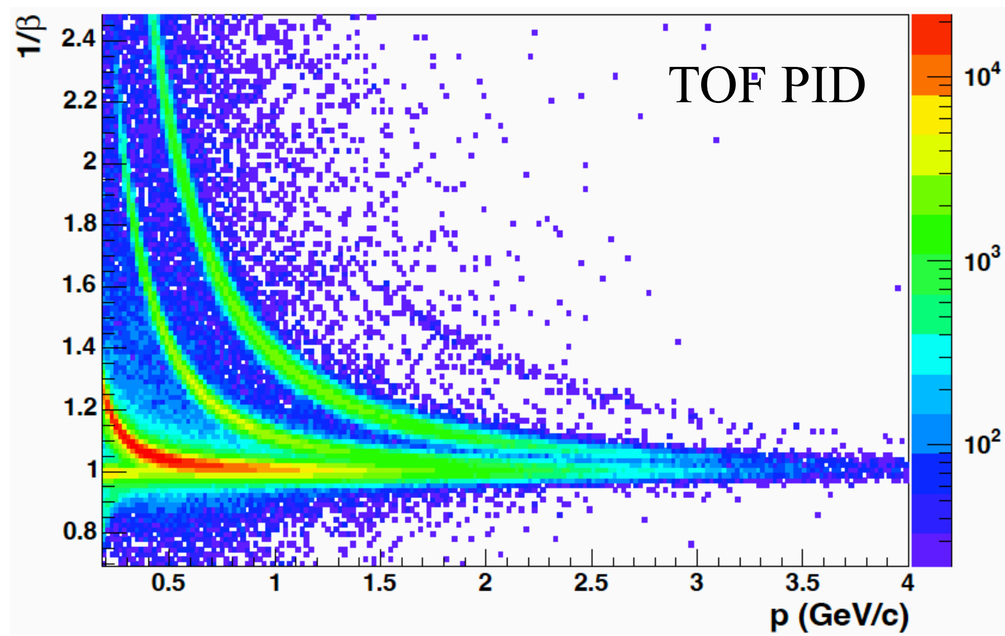


ϕ_{RS} binning scheme

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

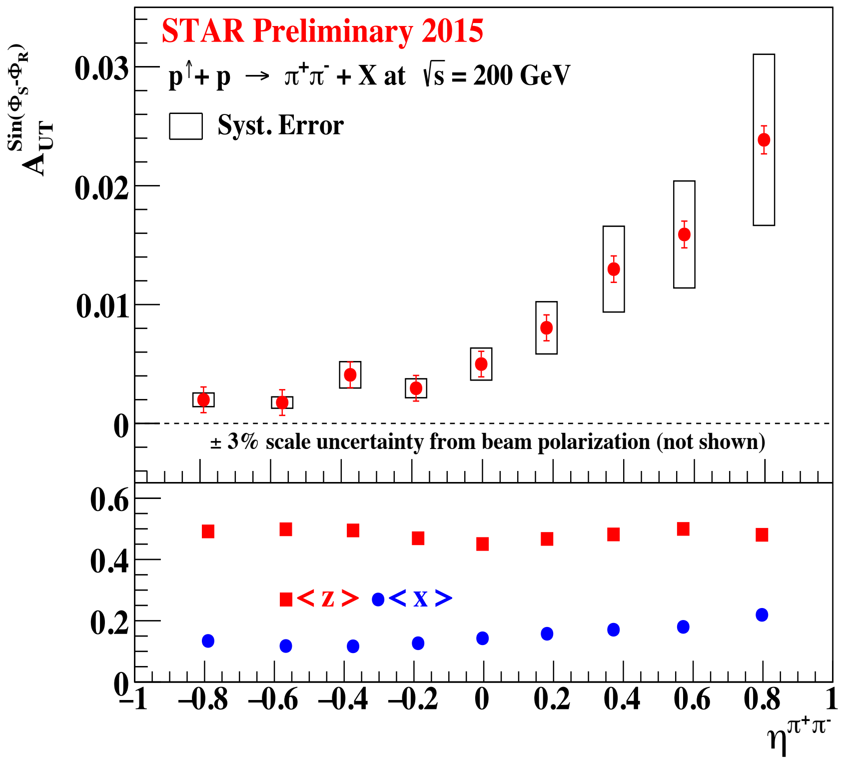
- Systematic uncertainties
  - STAR PID relies on the measured ionization energy loss (dE/dx) by the TPC at low p_T.
  - Time of Flight (TOF) helps to improve the STAR PID, in conjunction with the TPC via dE/dx
  - The fraction of proton, kaon, and electron (backgrounds) in the pion signal region estimates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

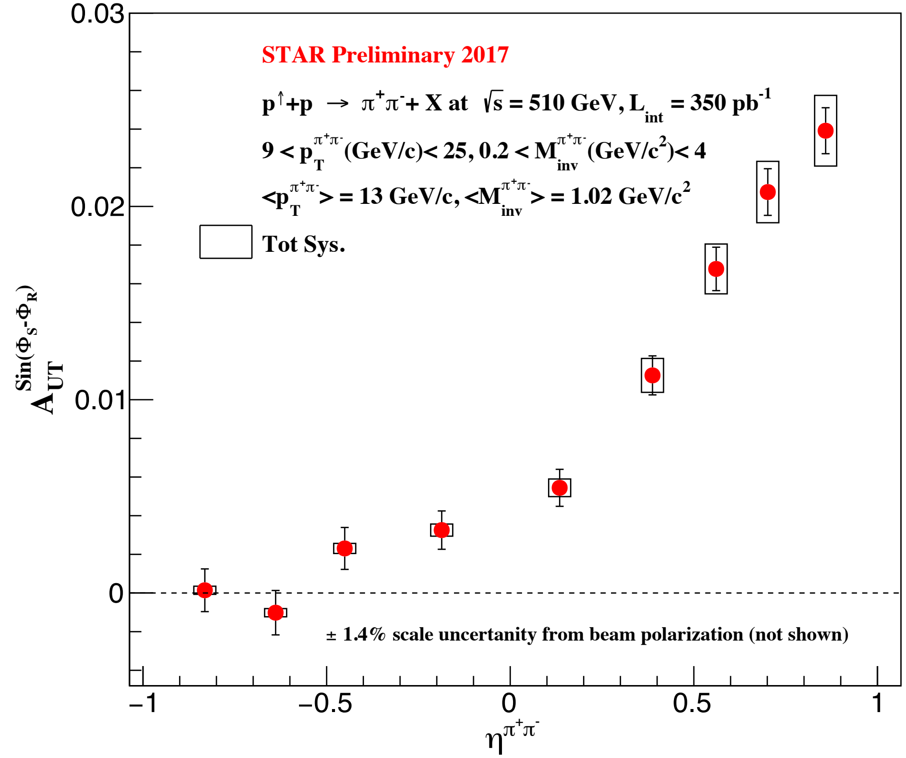




$\pi^+\pi^-$ Asymmetry Results

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

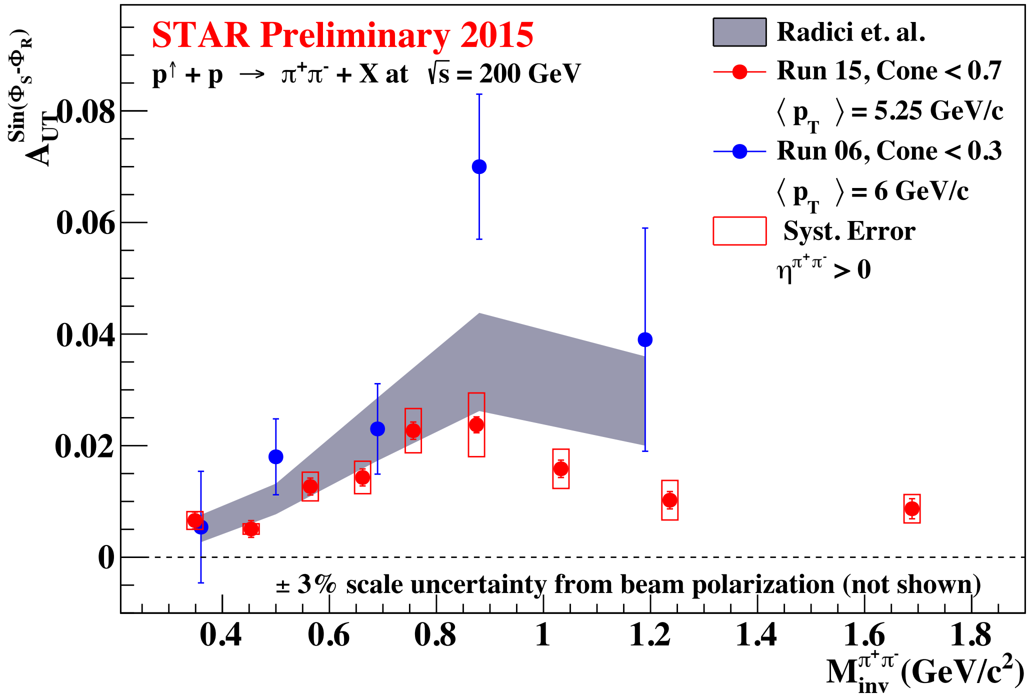


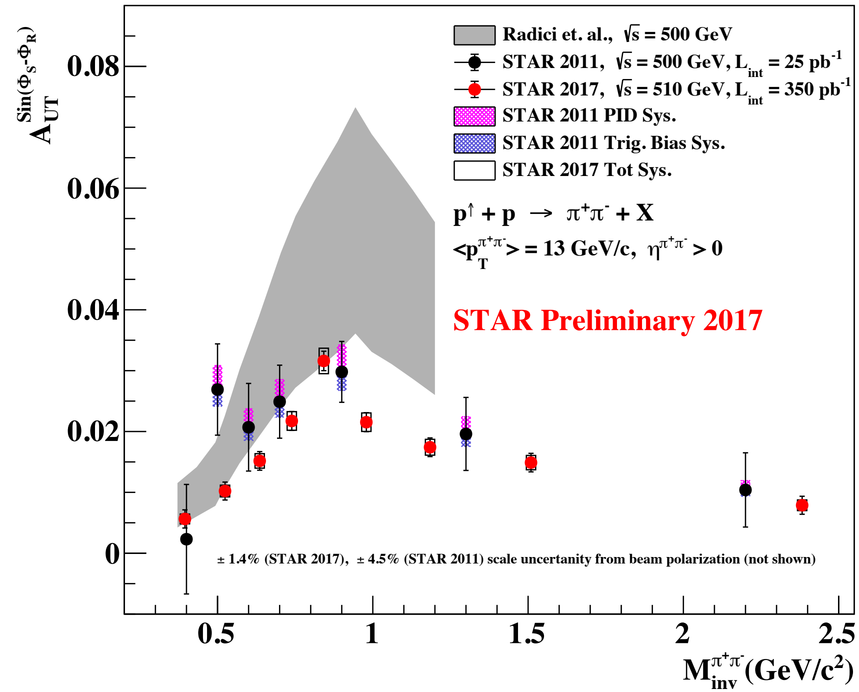


- A_{UT} increases with η at 200GeV (Run 15) and 510GeV (Run 17) - Sizable $h_1^q(x)$ expected for $\eta > 0$, i.e. large x!
- Improved PID treatment for 510GeV (Run 17) using TPC/TOF, whereas 200GeV (Run 15) based on TOF PID only so far
- Systematic uncertainties: PID and Trigger bias

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

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

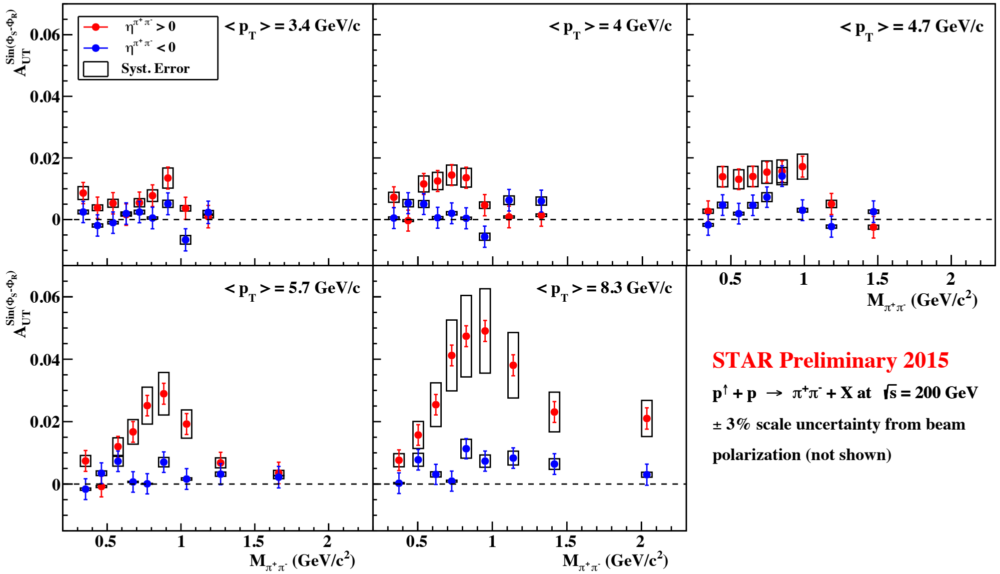


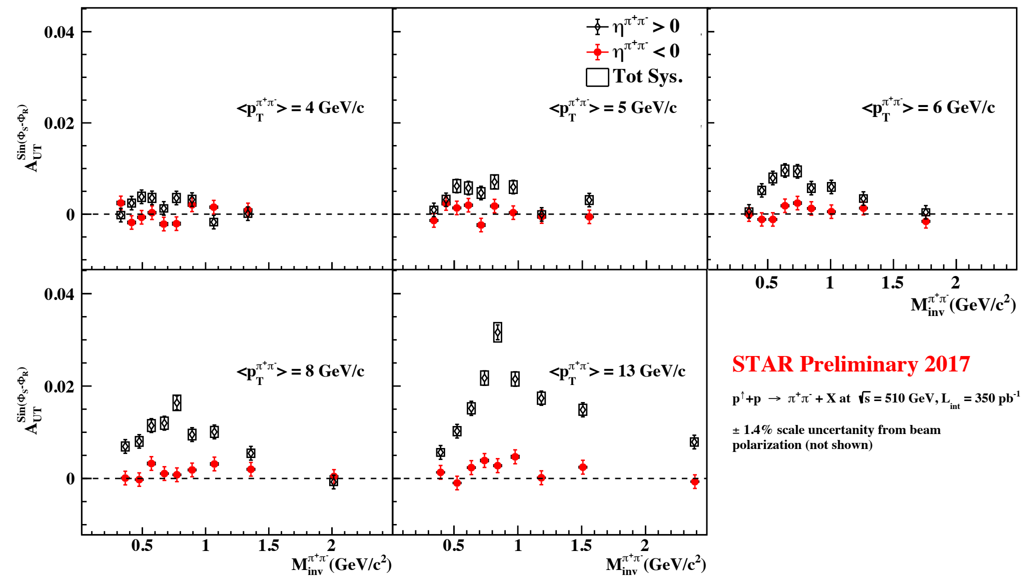


- A_{UT} asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-}$ ~ 0.8, consistent with the previous measurement and theory prediction
- Theory calculations overshoots the new measurement beyond the ρ resonance peak
- Statistical precision is significantly improved by the new result

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

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

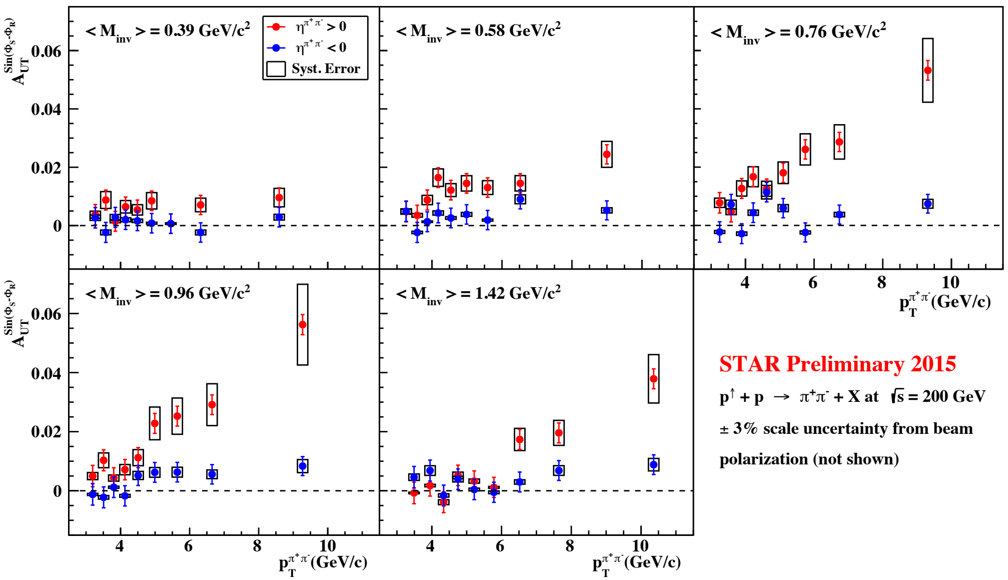


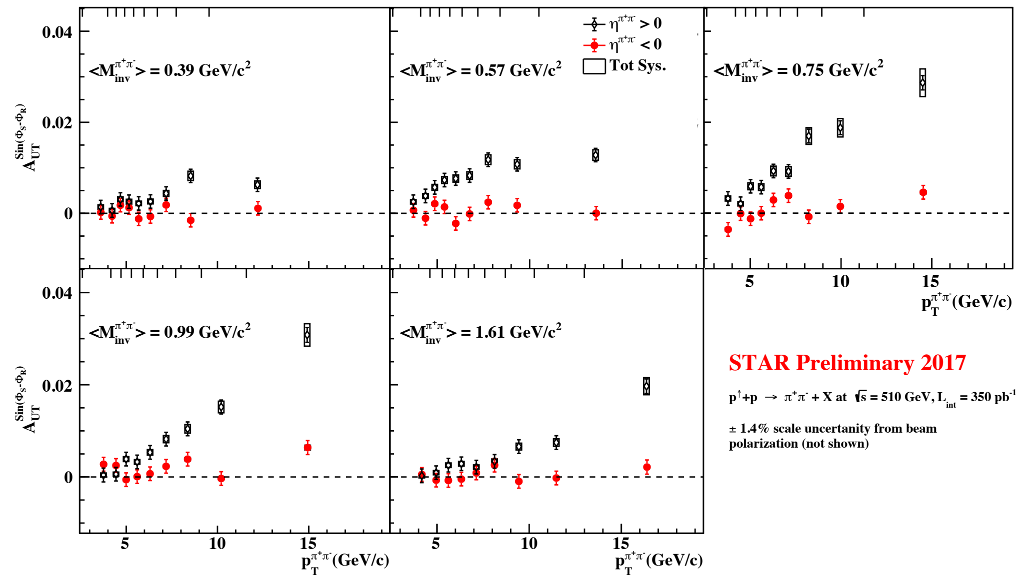


- $A_{UT}^{\sin(\phi_{RS})}$ vs $M_{\text{inv}}^{\pi^+\pi^-}$ in different p_T and $\eta^{\pi^+\pi^-}$ bins
- Signal grows stronger at higher p_T in forward $\eta^{\pi^+\pi^-}$ region / Resonance peak around $M_{\text{inv}}^{\pi^+\pi^-} \sim 0.8\ \text{GeV}/c^2 \sim M_\rho$.
- Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from polarized beam

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

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

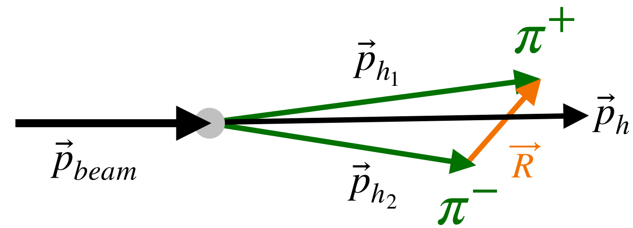


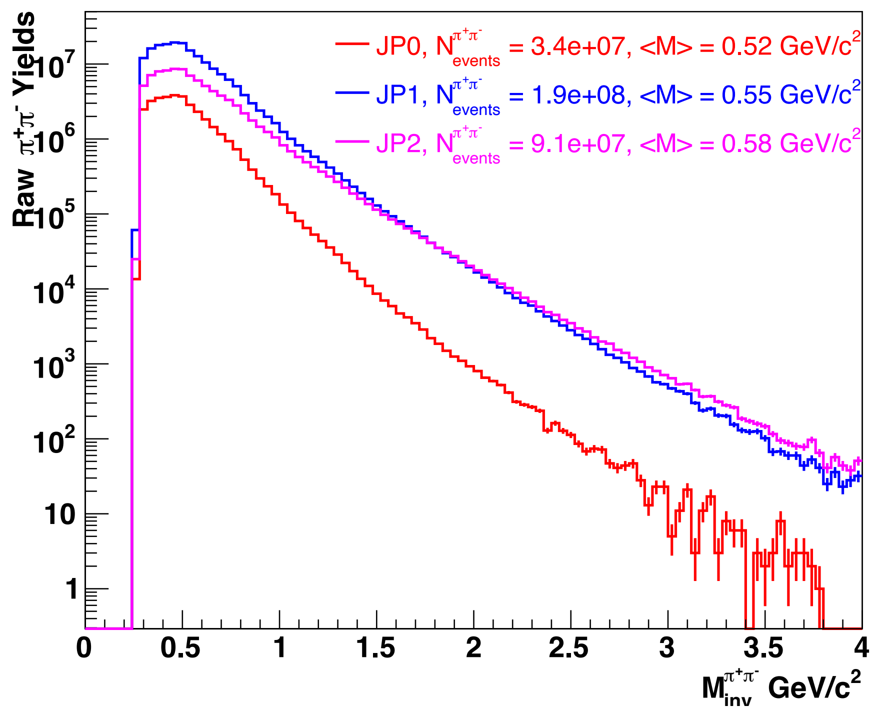


- Large asymmetry signal at higher $\mathrm{p_T}$ in forward $\eta^{\pi^+\pi^-}$ region. Stronger signal when $\langle \mathrm{M_{inv}} \rangle \sim \mathrm{M}_\rho$.
- Backward $\eta^{\pi^+\pi^-}$ signal ($\eta^{\pi^+\pi^-} < 0$) is small, mainly from low x quarks from polarized beam.

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

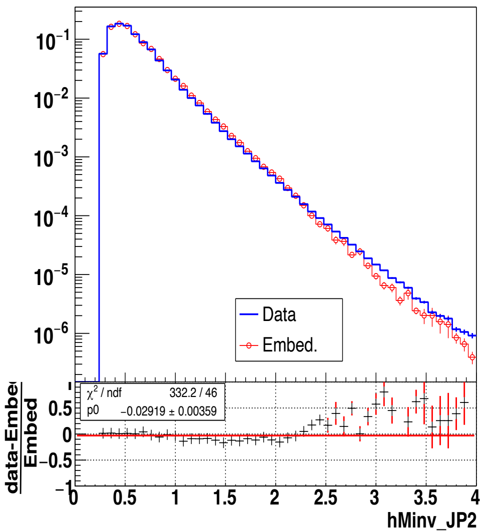
- Selection criteria
  - Di-hadron channel, $p + p \to \pi^+\pi^- + X$:
  - Inclusive $\pi^+\pi^-$ differential cross section:
    - As a function of invariant mass, $M_{inv}^{\pi^+\pi^-}$, in $|\eta|$<1 .
    - Much needed for the $D_1^{h_1h_2}$ extraction.
    - Access to $D_1^{h_1h_2/g}$.
  - STAR Run 2012 dataset @ $\sqrt{s} = 200$ 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.

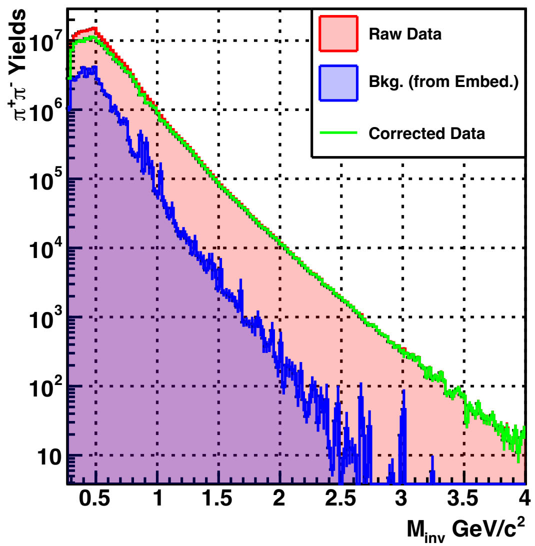


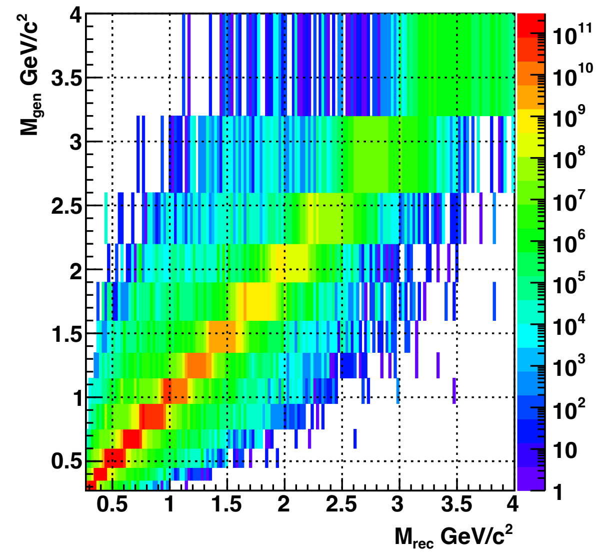


Analysis details - $\pi^+\pi^-$ Cross-Section

- Cross-section determination and systematic uncertainties







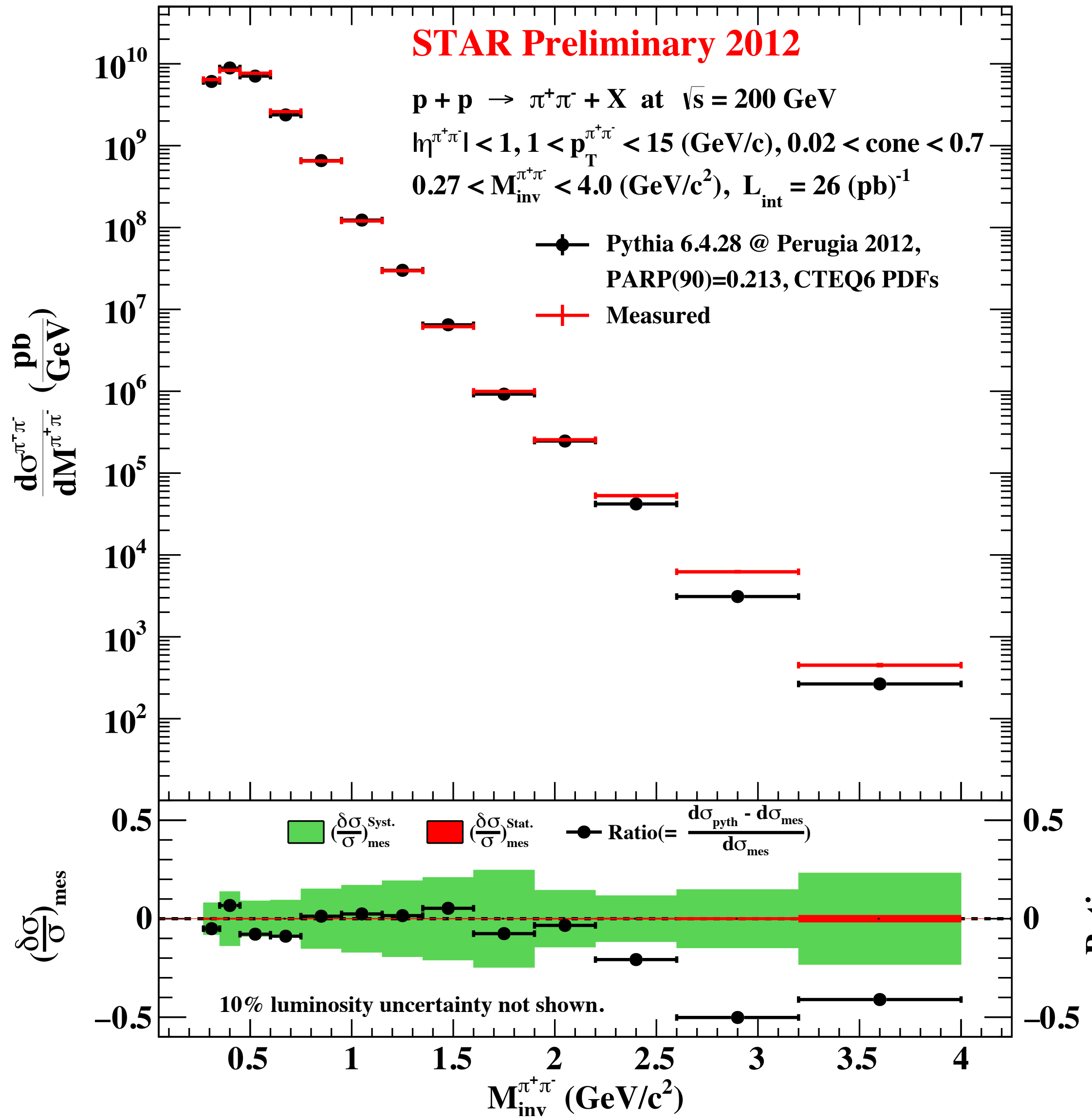
- PYTHIA simulated events, reconstructed through GEANT package embedded with real collision events to effectively reconstruct STAR detector responses (Embedding)
- Unfolding accounts for the bin migration effect and backgrounds
- Unfolding is performed for each trigger, allowing independent measurement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

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

- Cross-section result

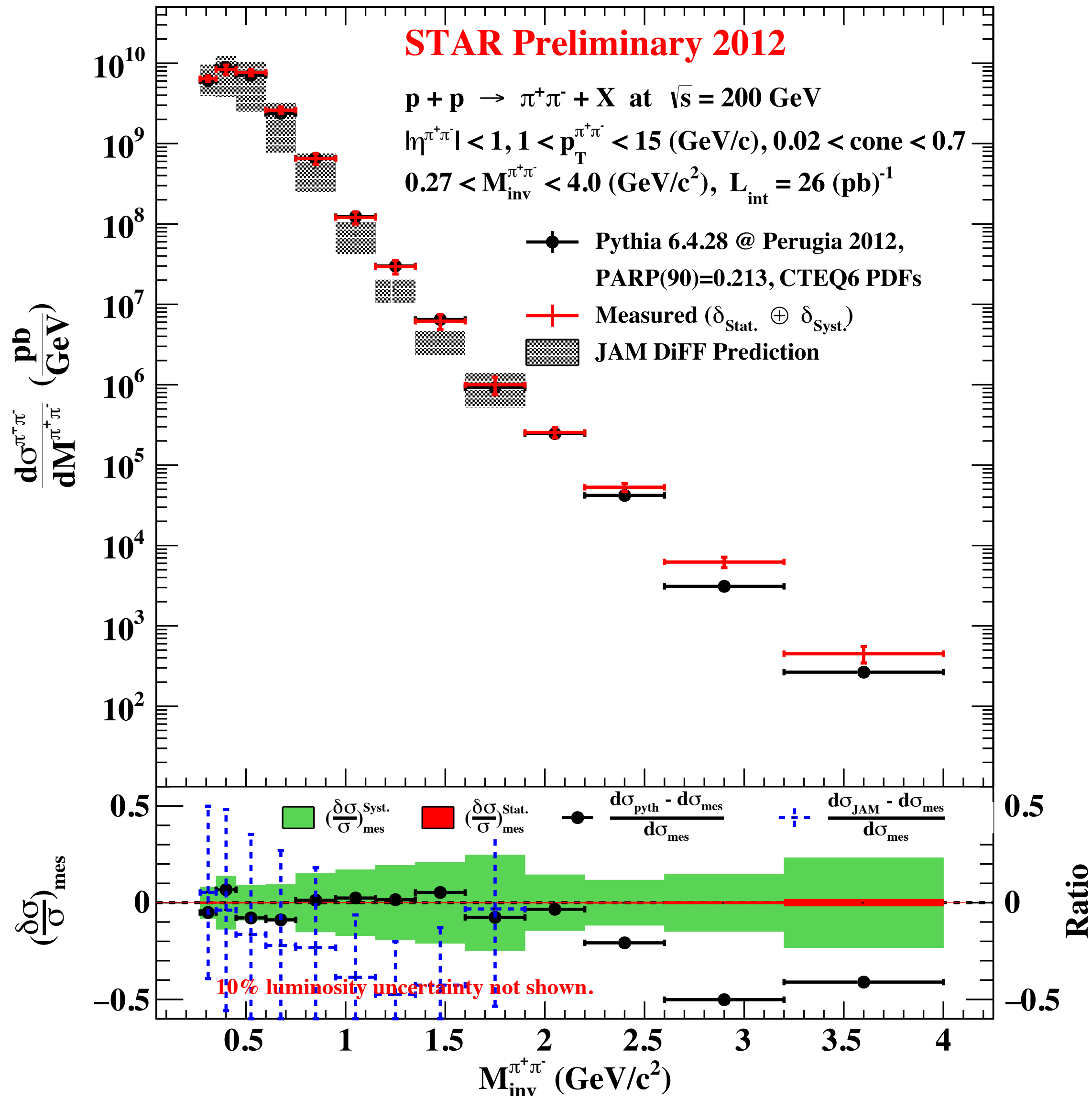
$$\frac{d\sigma^{pp\to\pi^+\pi^-}}{dM^{\pi^+\pi^-}} = \frac{f_{fake}\cdot f_{loss}}{L\cdot \epsilon_{trk}^{\pi^+}\cdot \epsilon_{trk}^{\pi^-}\cdot \epsilon_{trg}^{\pi^+\pi^-}}\cdot \frac{dN_{true}^{\pi^+\pi^-}}{dM^{\pi^+\pi^-}}$$

  - Corrections:
    - $\pi^+\pi^-$ Purity Fraction (f_{fake})
    - $\pi^+\pi^-$ Loss Fraction (f_{loss})
    - Tracking Efficiency (ϵ_{trk}^{π})
    - Trigger Efficiency ($\epsilon_{trg}^{\pi^+\pi^-}$)
  - First cross-section measurement: Provides needed constrain of $D_1^{h_1h_2}$ for gluons.
  - Path to model-independent extraction of $h_1(x)$!



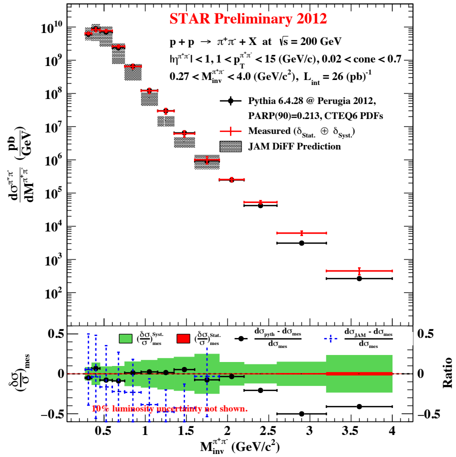
Analysis details - $\pi^+\pi^-$ Cross-Section

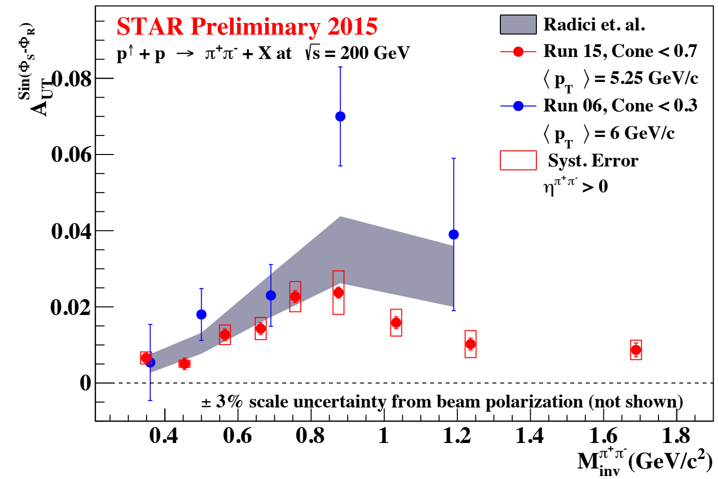
- Cross-section result
  - First cross-section measurement: Provides access to $D_1^{h_1 h_2}$ for gluons.
  - Path to model-independent extraction of $h_1(x)$
  - Final Result with PYTHIA and JAM-pdf DiFF cross-section!

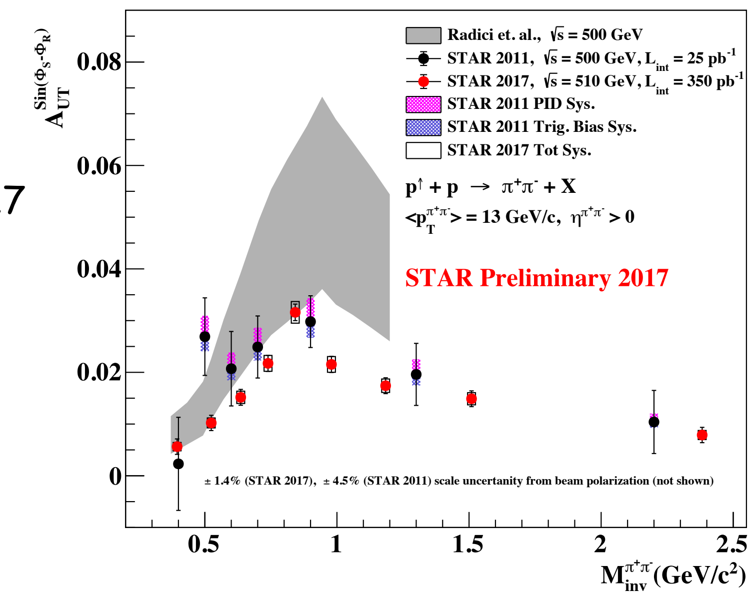


Summary and Outlook

- 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