Measurement of Transverse Spin-Dependent Azimuthal Correlation of Charged Pion Pairs in $p^{\uparrow}p$ Collisions at $\sqrt{s}$ = 200 GeV and 500 GeV at STAR

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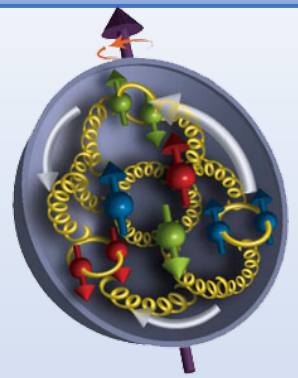
(For the STAR Collaboration)
05/03/2022

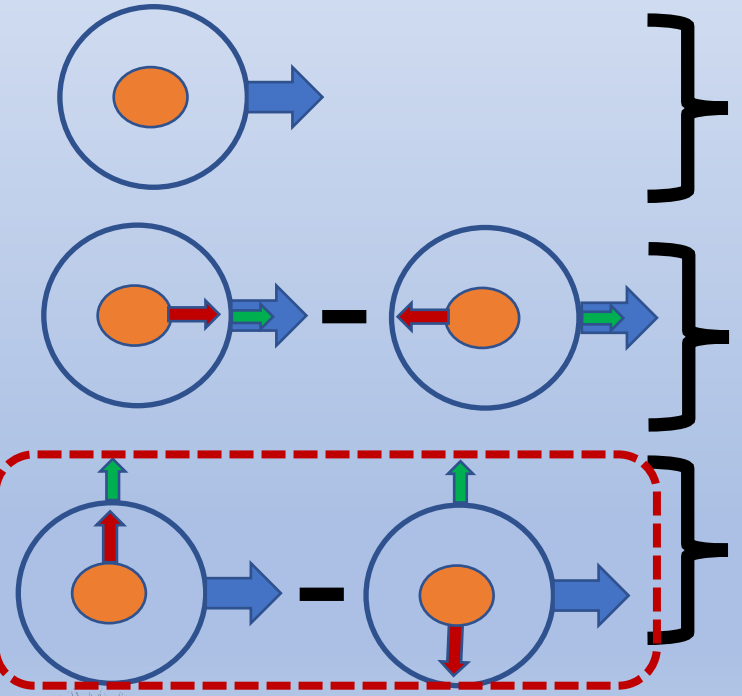
Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

Motivation

Nucleon Structure



Parton Distribution Functions(PDFs):



$Unpolarized\ (f_1(x))$

$Helicity\ (g_1(x))$

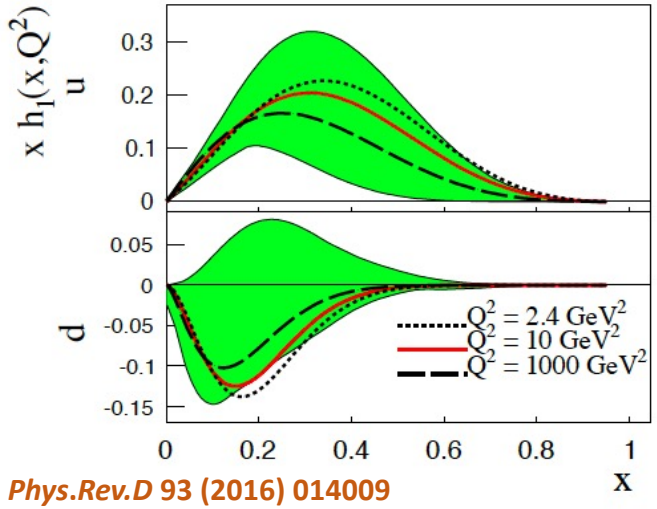
$Transversity\ (h_1(x))$

Nucleon Momentum

Nucleon Polarization

Parton Polarization

Transversity PDF



Phys.Rev.D 93 (2016) 014009

- Less known from experiments than $f_1(x)$ and $g_1(x)$
- Chiral-odd quantity
- Extraction requires coupling to another chiral-odd object, such as Fragmentation Functions (FF).
- For estimating tensor charge (g_T), a precise determination of transversity is necessary.

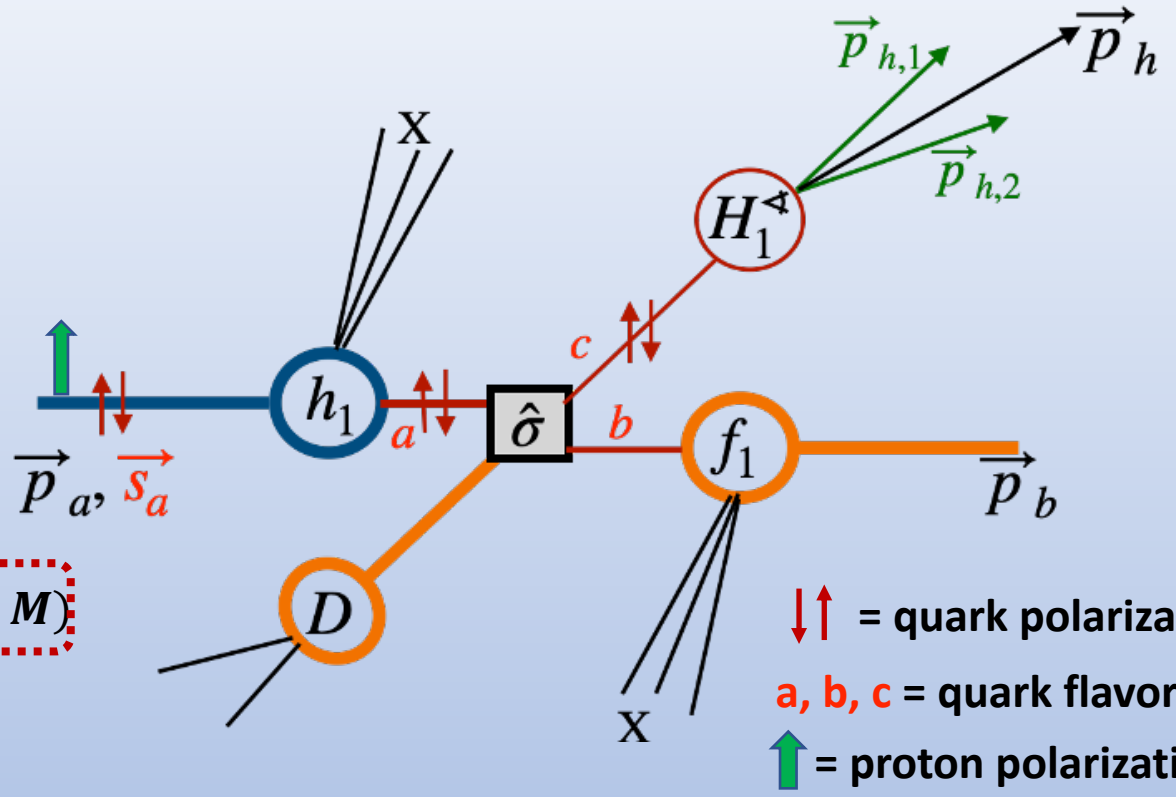
$$g_T = \int_0^1 dx[h_1^q(x) - h_1^{\bar{q}}(x)]$$

Transversity $(h_1(x))$ in $p^{\uparrow}p$ Collisions

Interference Fragmentation Function($H_1^{\sphericalangle}$) Channel :

$$p\uparrow + p \rightarrow h^+h^- + X$$

- No jet reconstruction required
- Collinear framework preserved
- Better access to d-quark than SIDIS



$$d\sigma_{UT} \propto \sin(\phi_s - \phi_R) \int dx_a dx_b f_1(x_a) h_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

A. Bacchetta and M. Radici
Phys. Rev. D 70 (2004) 094032

Di-hadron correlation Asymmetry

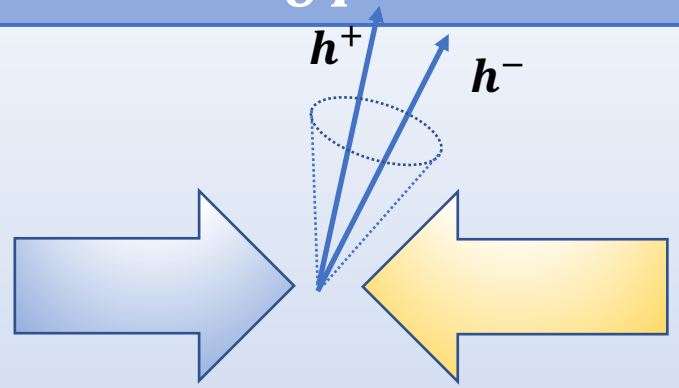
$$A_{UT} = \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\downarrow} \propto h_1 H_1^{\sphericalangle}(z, M)$$

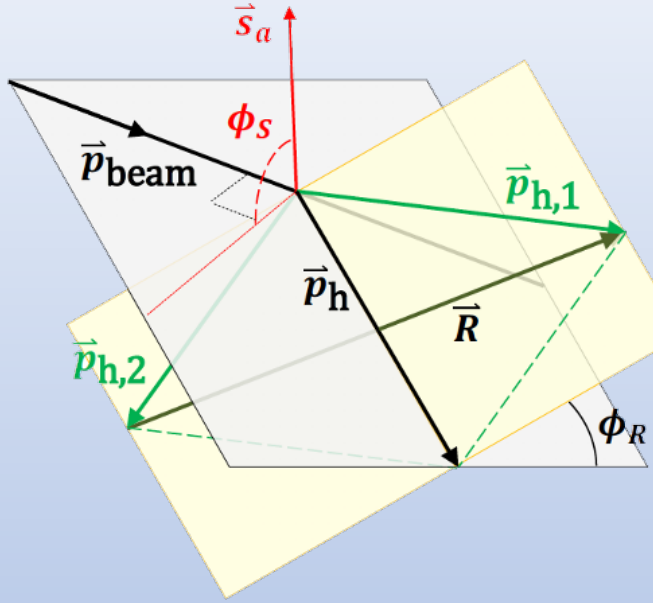
$z = \frac{E^{h^+h^-}}{E^{parton}}$, M_{inv} = Invariant mass of hadron pair

Cross-ratio Method for A_{UT} Extraction

A_{UT} can be extracted from cross-ratio formula

$$A_{UT}\sin(\phi_s - \phi_R) = \frac{1}{P}\frac{\sqrt{N^{\uparrow}_{1,\alpha}N^{\downarrow}_{1,\beta}} - \sqrt{N^{\downarrow}_{1,\alpha}N^{\uparrow}_{1,\beta}}}{\sqrt{N^{\uparrow}_{1,\alpha}N^{\downarrow}_{1,\beta}} + \sqrt{N^{\downarrow}_{1,\alpha}N^{\uparrow}_{1,\beta}}}$$

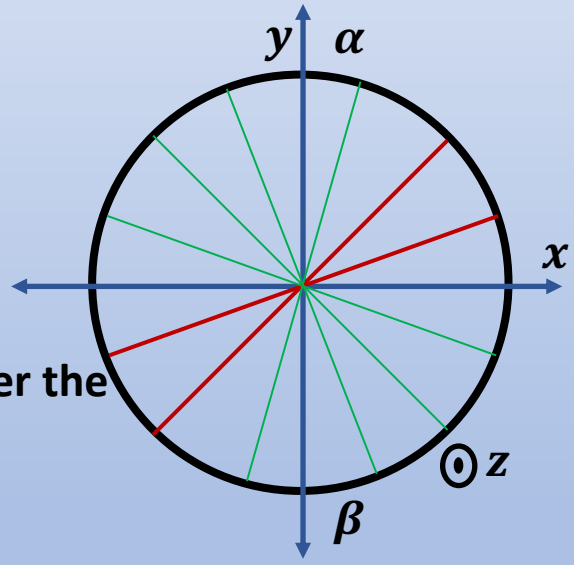




Free from detector efficiencies and spin-dependent luminosities, reduces the systematic uncertainties.

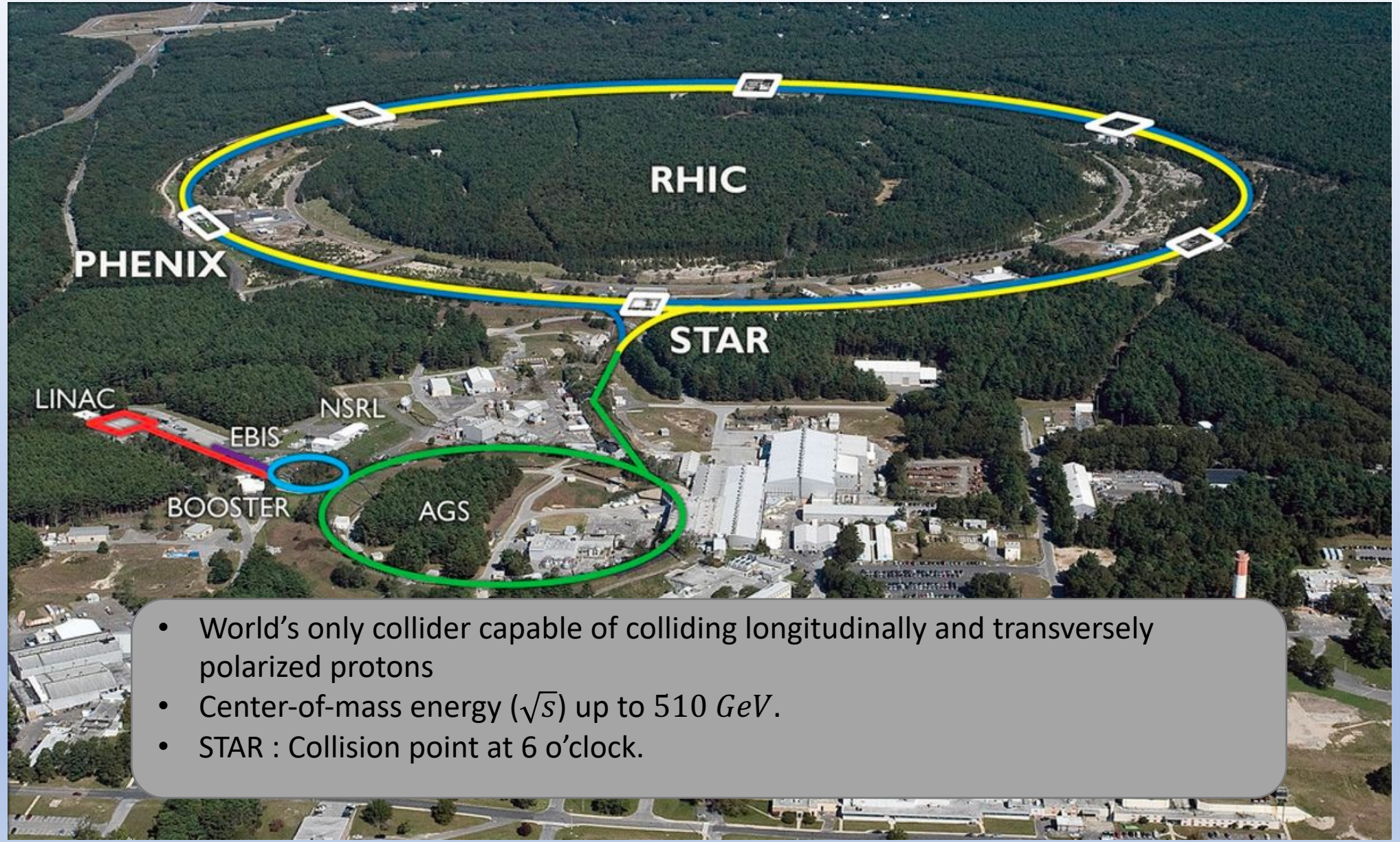
$N^{\uparrow}_{1,\alpha(\beta)}$ # of h^+h^- in upper, α (lower, β) half of the detector when beam polarization is up(↑) (down(↓)).

A_{UT} is measured using a transversely polarized beam colliding with another unpolarized beam (integrating over the bunches with all spin states).



ϕ_s = angle between quark spin vector, $\overrightarrow{s_a}$ and scattering plane(spanned by $\vec{p}_{beam}$ and $\vec{p}_h$)
ϕ_R = angle between scattering plane and di-hadron plane ($\vec{p}_{h,1}$ and $\vec{p}_{h,2}$)

Relativistic Heavy Ion Collider(RHIC)

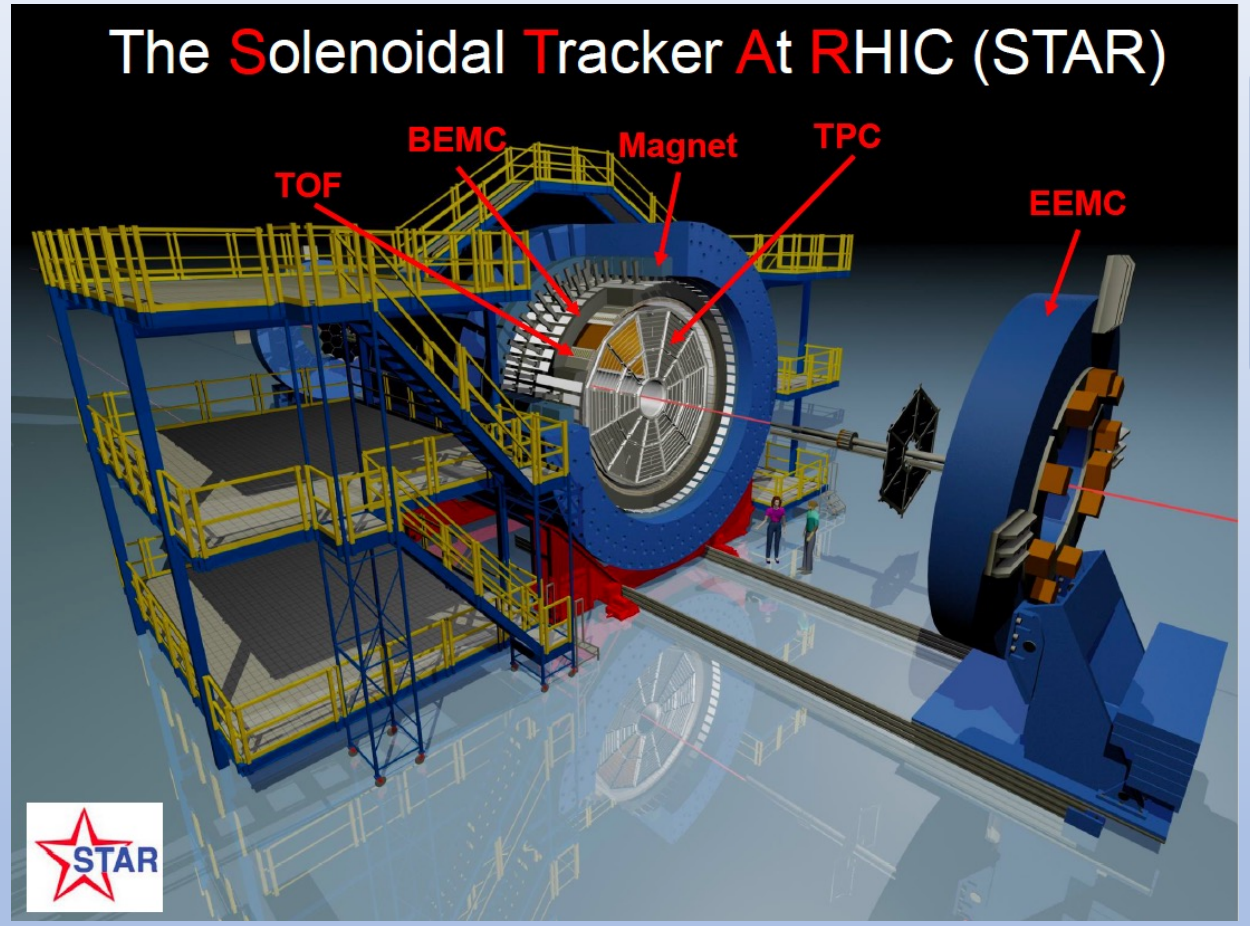


- World's only collider capable of colliding longitudinally and transversely polarized protons
- Center-of-mass energy ($\sqrt{s}$) up to $510\ GeV$.
- STAR : Collision point at 6 o'clock.

Solenoidal Tracker At RHIC(STAR)

Magnet

- Uniform magnetic field of 0.5 T



Time Projection Chamber(TPC)

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Charge determination and particle momentum reconstruction
- PID via measuring ionization energy loss

Barrel Electromagnetic Calorimeter(BEMC)

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Event triggering

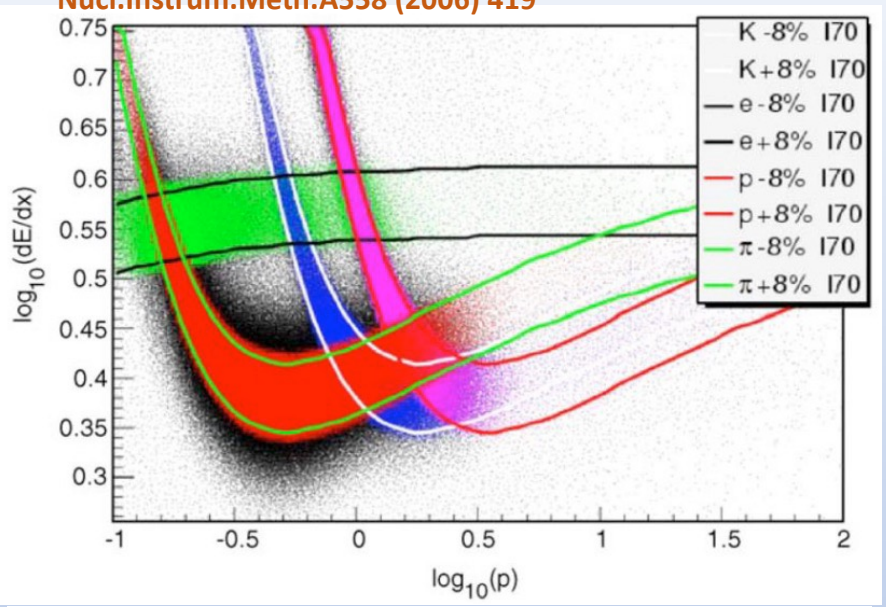
Time Of Flight(TOF):

- $|\eta| < 1, 0 \leq \phi \leq 2\pi$
- Stopwatch for particles
- Helps to improve PID

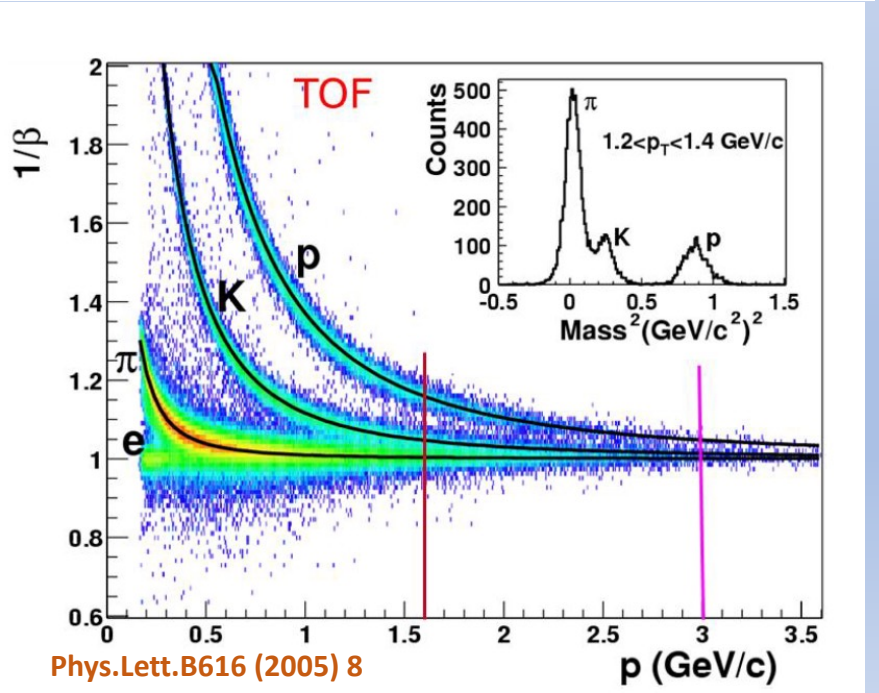
PID at STAR

- At STAR PID is done by measuring average specific ionization energy loss $\left\langle \frac{dE}{dx} \right\rangle$ in TPC
- Poor $\frac{dE}{dx}$ resolution for p > 1 GeV/c

Nucl.Instrum.Meth.A558 (2006) 419



- When the $\frac{dE}{dx}$ vs p bands for two different particle types are close together or cross, TOF is extremely useful for PID.
  - TOF detector has a high capability of separating proton from kaon and pion for momenta up to 3 GeV/c.



Phys.Lett.B616 (2005) 8

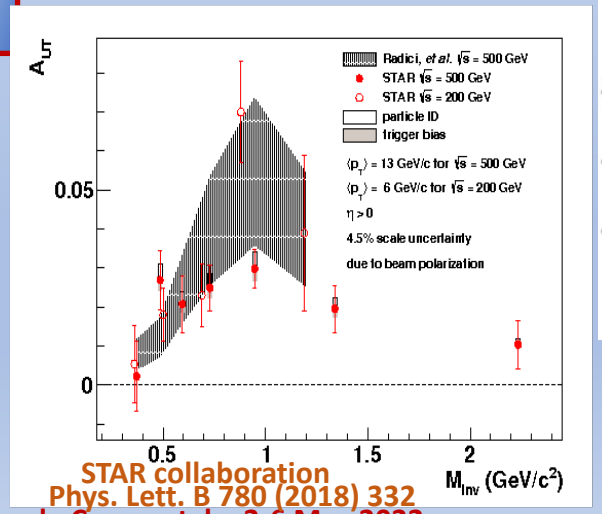
A_{UT} at STAR

- A non-zero A_{UT} singal has been observed against different kinematic observables ($\eta_{pair}, p_{T_{pair}}, M_{inv}$) of the pion pairs ($\pi^+\pi^-$) in final state.

A_{UT} with $p^{\uparrow}p$ at STAR				
Year	2006	2011	2015	2017
$\sqrt{s}$ (GeV)	200	500	200	510
$L_{int}(pb^{-1})$	~1.8	~25	~52	~350
	Published		STAR Preliminary	On-going

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

- The published results agree with the IFF model calculation which predicts enhancement of A_{UT} near ρ mass region.
- The statistical precision of the 2017 dataset is expected to be four times better than that of the 2011 dataset.
- STAR just completed taking another large pp dataset at 510 GeV (2022) ($L_{int}(pb^{-1})$~400) and is planning to take another pp 200 GeV ($L_{int}(pb^{-1})$~265) data set in 2024.



STAR collaboration
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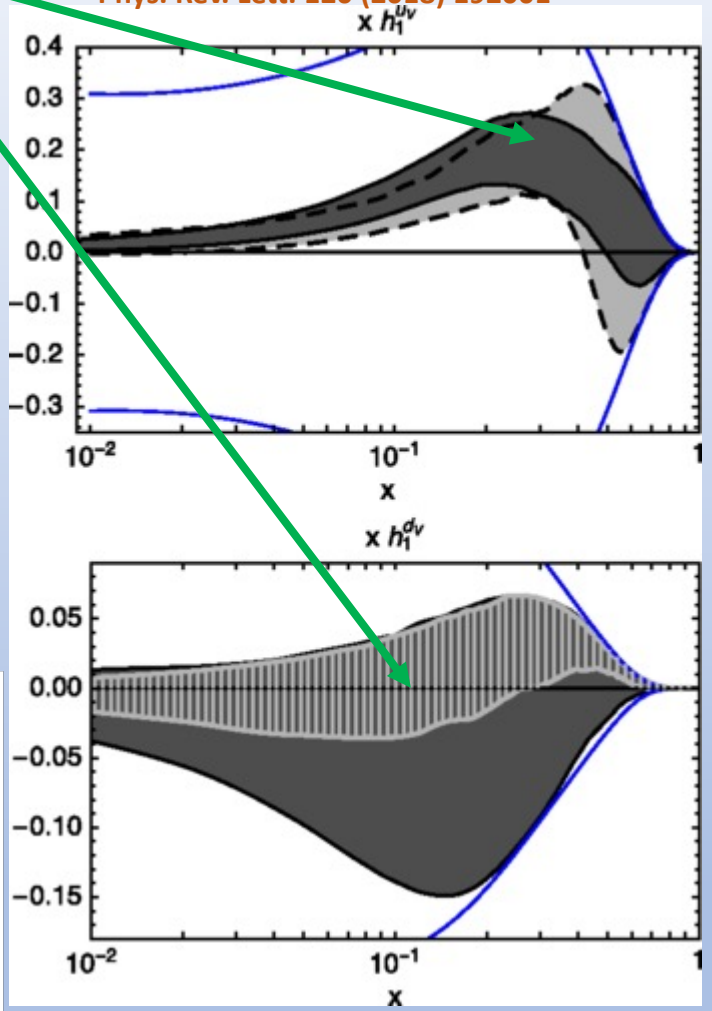
M. Radici and A. Bacchetta
Phys. Rev. Lett. 120 (2018) 192001

Including STAR 2006 results



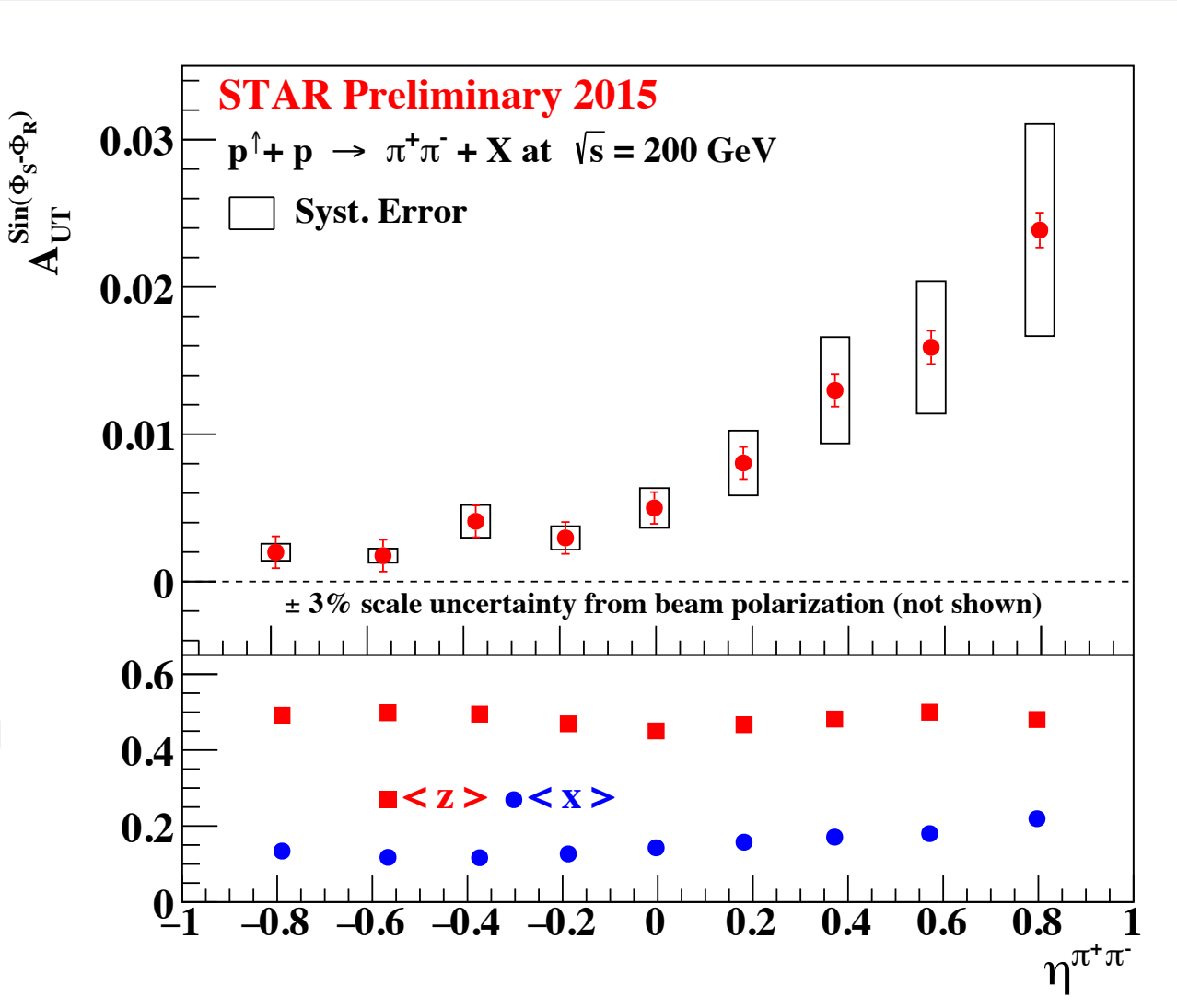
STAR results play a crucial role in constraining the global fit of transversity.

STAR Preliminary: A_{UT} vs η_{pair}

- A_{UT} as function of η_{pair} integrated over $p_{T_{pair}}$ and M_{inv}
  - Strong rise of A_{UT} signal towards higher η_{pair} where we reach the highest value of x.
  - η_{pair} direction is relative to the polarized beam.

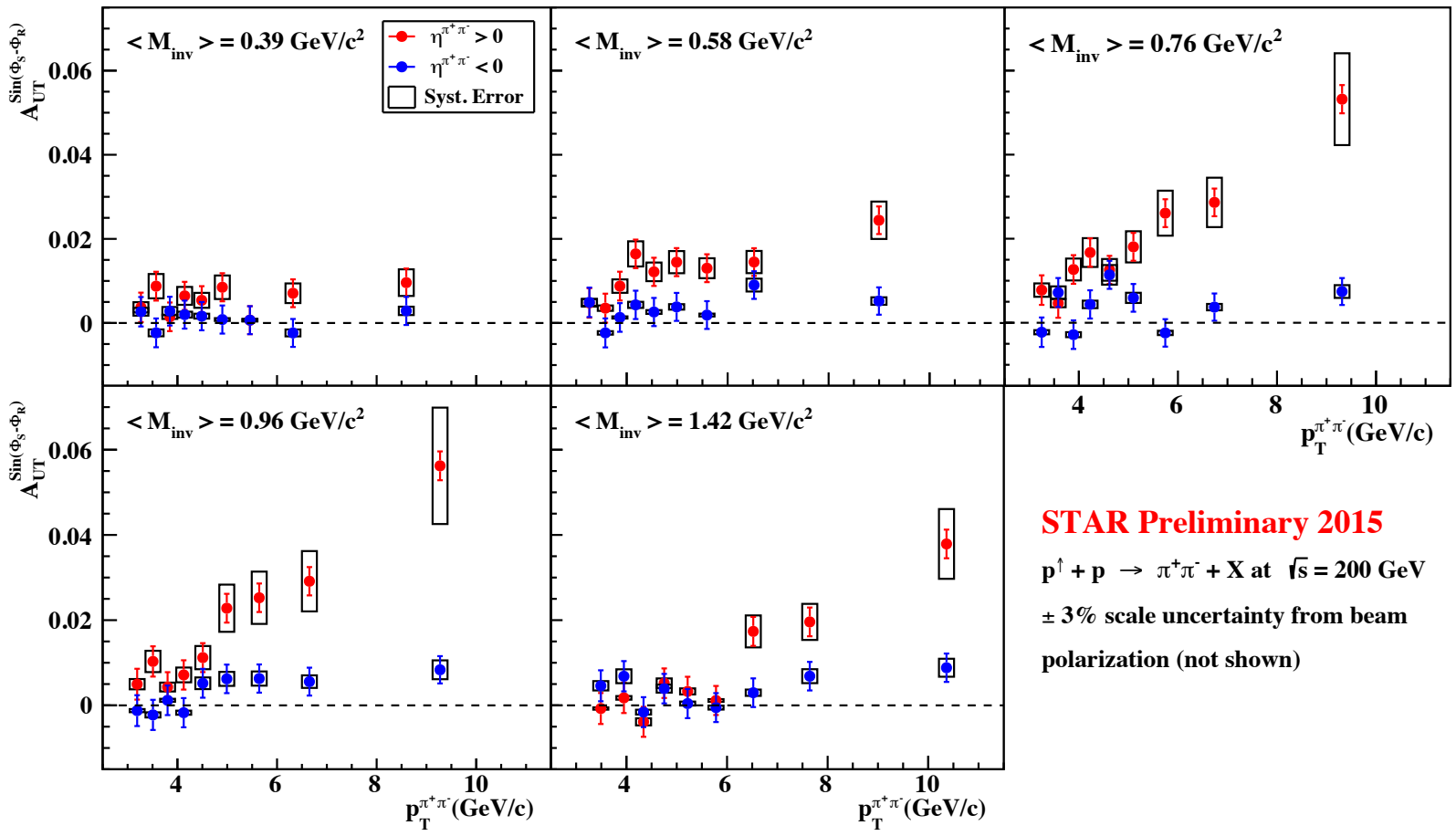
- x, fractional momentum of proton carried by quark, and z, fractional energy of struck quark carried by pion pair as a function of η_{pair}
- x, z are estimated by simulation.

- Systematic uncertainties arise from PID (TPC alone) and trigger bias effect.
  - Significant reduction of the PID uncertainty is expected by including TOF.



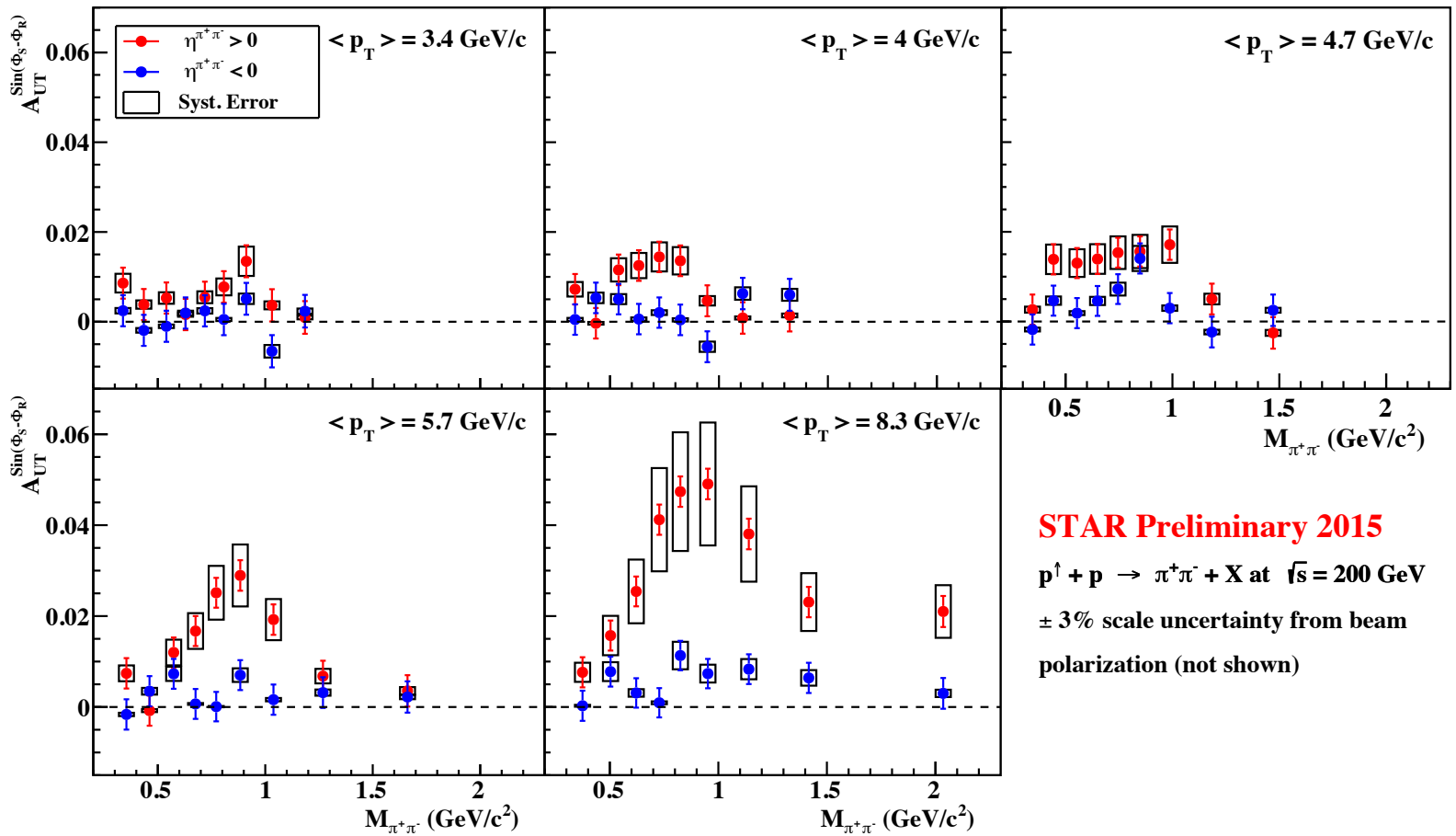
STAR Preliminary: A_{UT} vs $p_{T_{pair}}$

- A_{UT} vs $p_{T_{pair}}$ for different M_{inv} and η_{pair} bins
  - Larger A_{UT} at higher $p_{T_{pair}}$ for $\eta_{pair} > 0$
  - Stronger signal when M_{inv} is around $M_\rho \sim 0.8\ GeV/c^2$



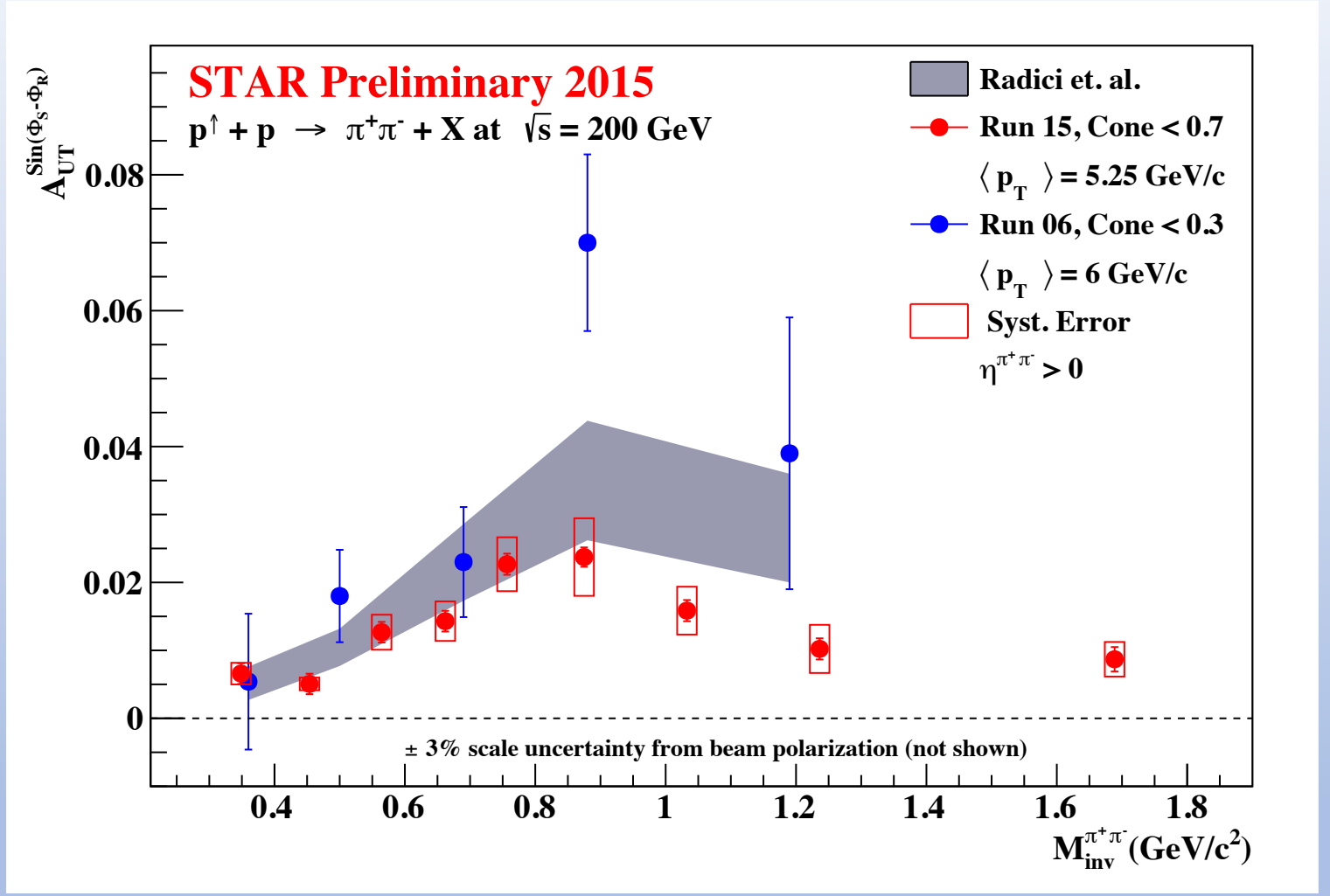
STAR Preliminary: A_{UT} vs M_{inv}

- A_{UT} vs M_{inv} for different $p_{T_{pair}}$ and η_{pair} bins
  - A_{UT} signal increase as <$p_{T_{pair}}$> increases.
  - Significant A_{UT} signal is seen in the highest $p_{T_{pair}}$ bin, with enhancement near the ρ mass region.



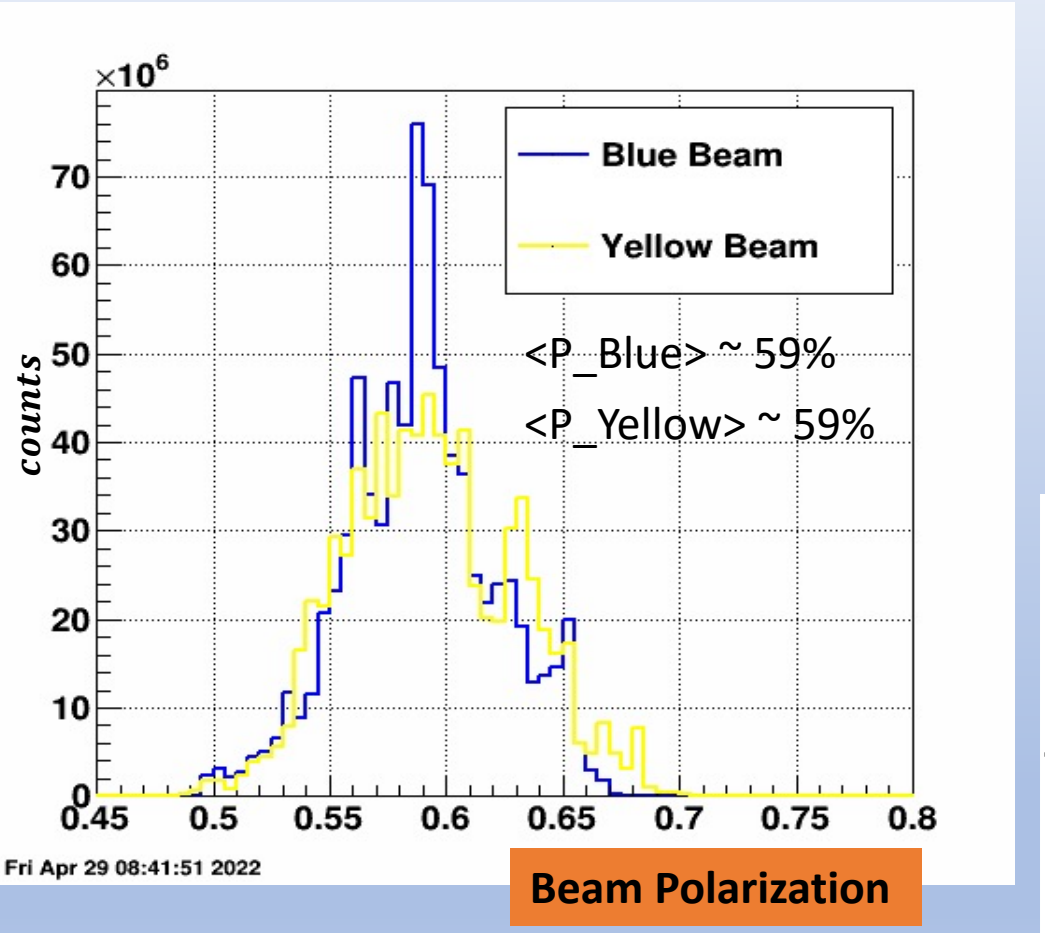
STAR Preliminary: A_{UT} vs M_{inv} with $p_{T\,pair}$ Integrated

- A_{UT} vs M_{inv} integrated over $p_{T\,pair}$ for η_{pair} >0
  - Enhancement of A_{UT} around ρ mass, consistent with the previous measurement with improved precision and theoretical calculations.



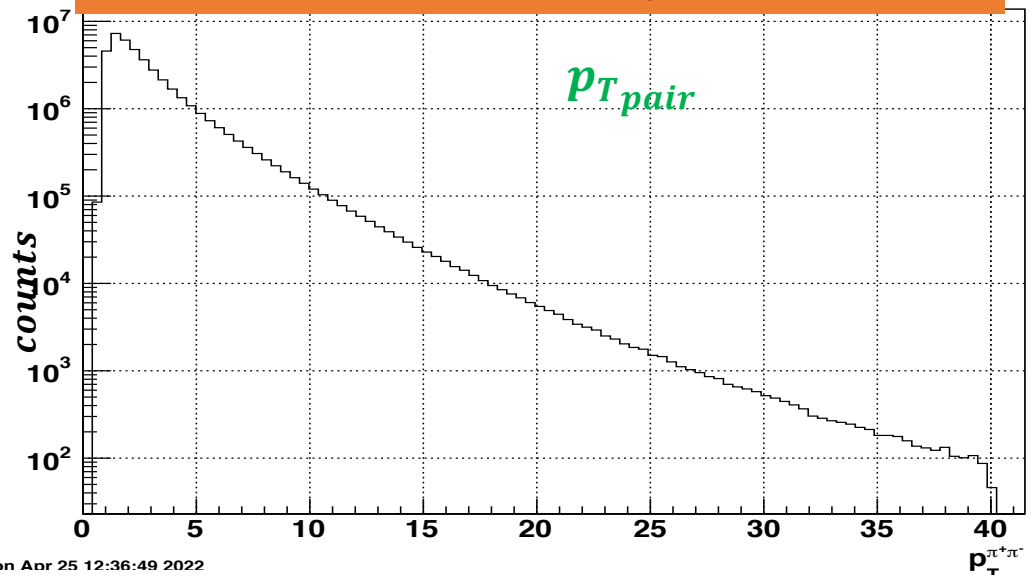
STAR 2017 $p^{\uparrow}p$ collisions @ 510 GeV

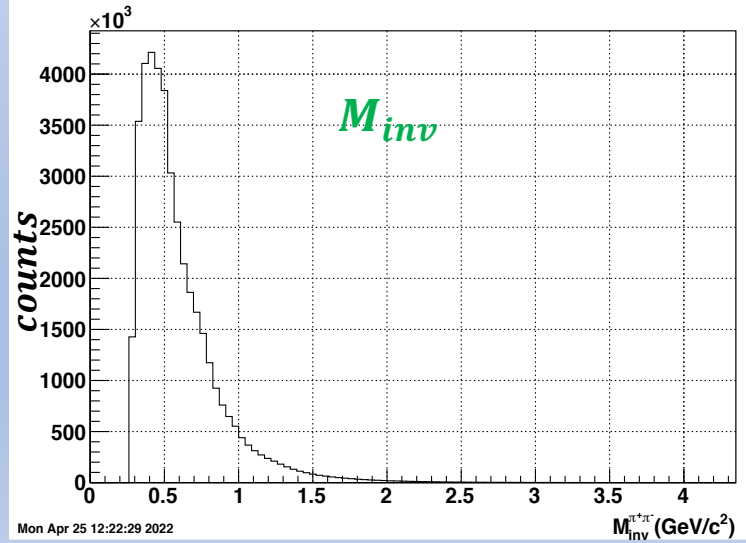
- **IFF analysis of STAR 2017 $p^{\uparrow}p$ at $\sqrt{s} = 510$ GeV is underway.**

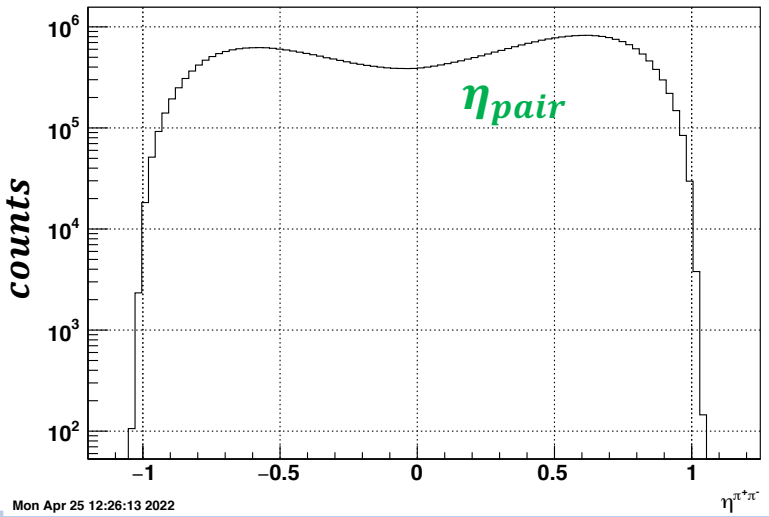


Beam Polarization

Kinematic Observable for A_{UT} measurement



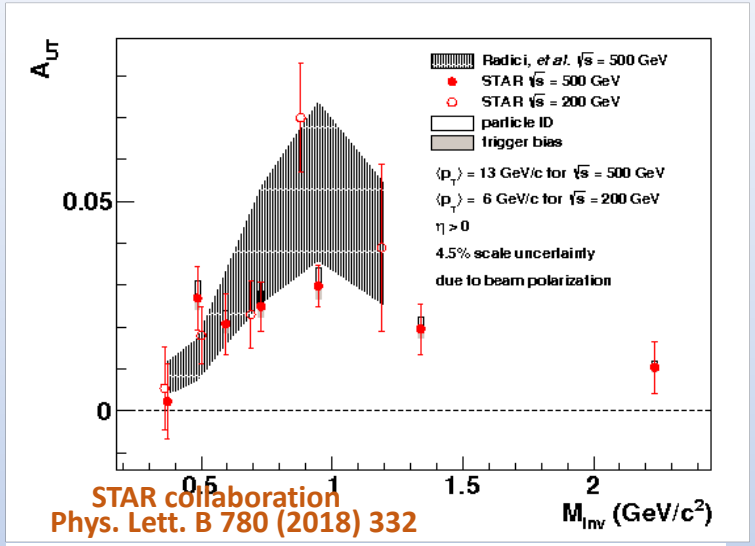




STAR 2017 $p^{\uparrow}p$ collisions @ 510 GeV

- Previous STAR 2011 A_{UT} results are statistically limited.
- Figure of merit $(P^2 L_{int})$ for 2017 data is ~15 times larger than that of 2011 data.
- The statistical precision improvement by about a factor of 4 is expected compared to that of 2011 dataset.

- Data analysis is ongoing.
- Systematics uncertainty is expected to improve with TPC and TOF PID.



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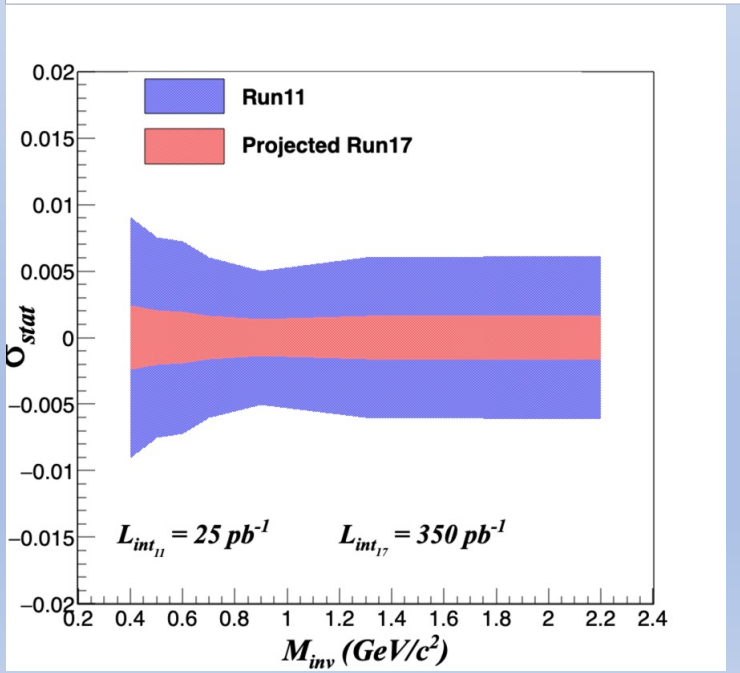

Summary

- Di-hadron azimuthal correlation asymmetry, A_{UT}, sensitive to transversity, has been measured as a function of various kinematic observables (η_{pair} , $p_{T_{pair}}$, M_{inv}) for the final state pion pairs.
  - A_{UT} enhances around the ρ mass region, and rises with $p_{T_{pair}}$ and η_{pair}.

- STAR 2006 A_{UT} results showed a huge impact in constraining transversity through first ever global fit of transversity.
- With 200 GeV and 500 GeV data, the STAR A_{UT} results will aid in the extraction of transversity evolution around the valence quark region.

- PID systematic uncertainties are expected to improve by including TOF PID in addition to TPC PID.
- Planning unpolarized di-hadron cross-section measurement at 200 GeV and 500 GeV, which could reduce the uncertainties in transversity extraction.