# Measurement of transverse single spin asymmetry for forward $\pi^0$ in (non-)diffractive processes at RHICf and STAR

PacificSPIN2026

October/29/2026

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for the RHICf and STAR collaborations

Supported in part by

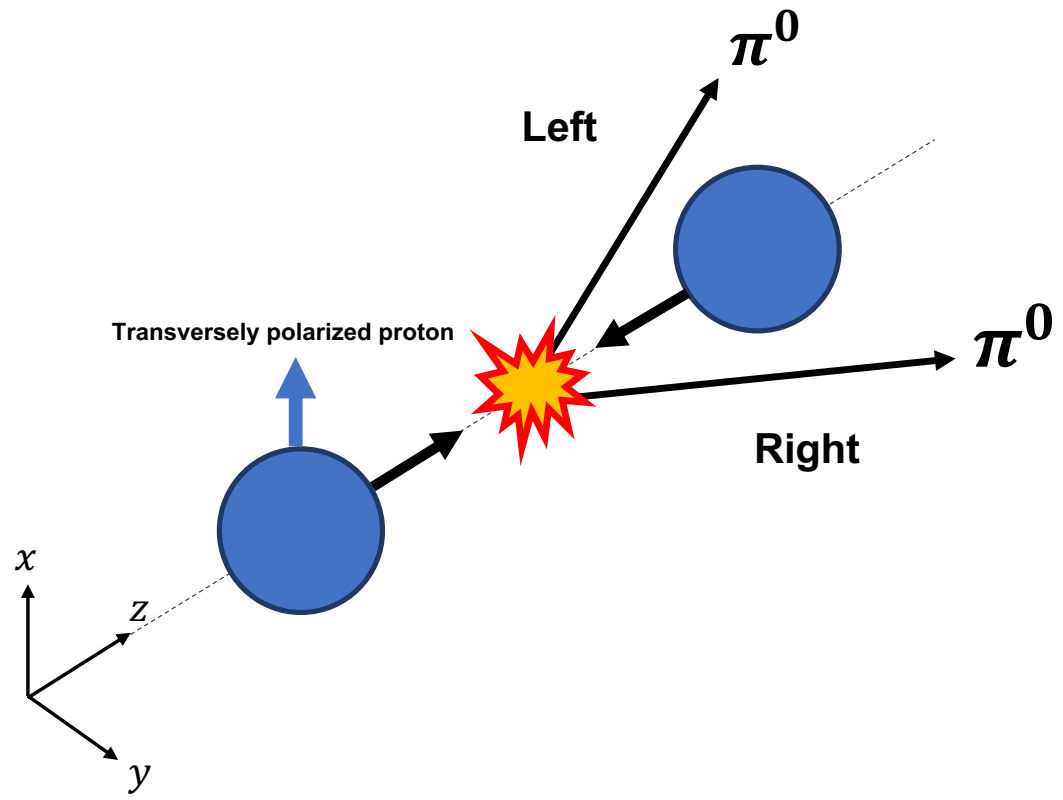
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# Transverse single spin asymmetry ($A_N$)

- **Definition**

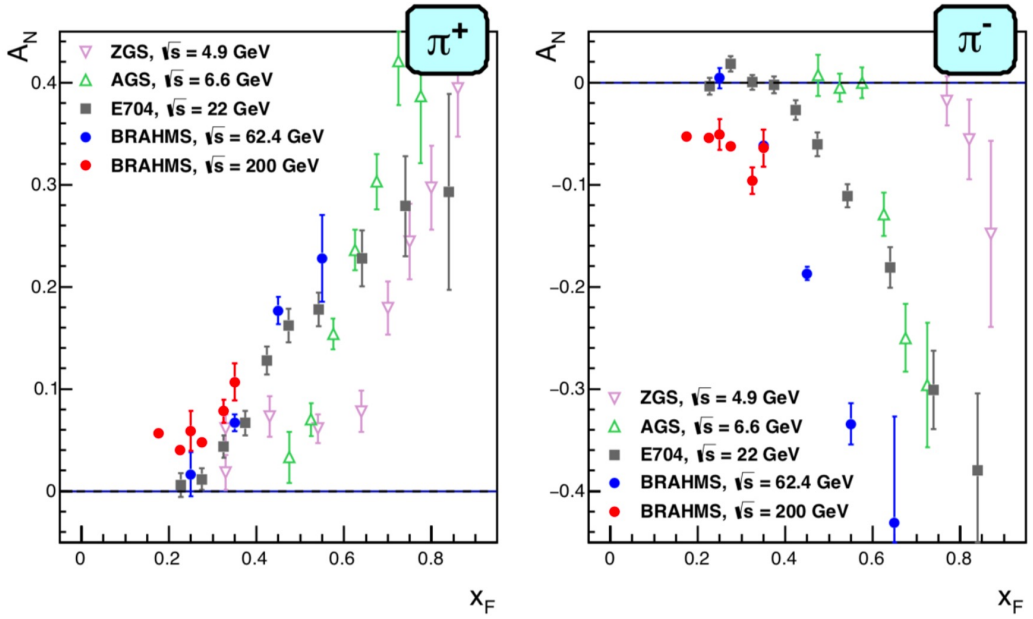
$$A_N \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



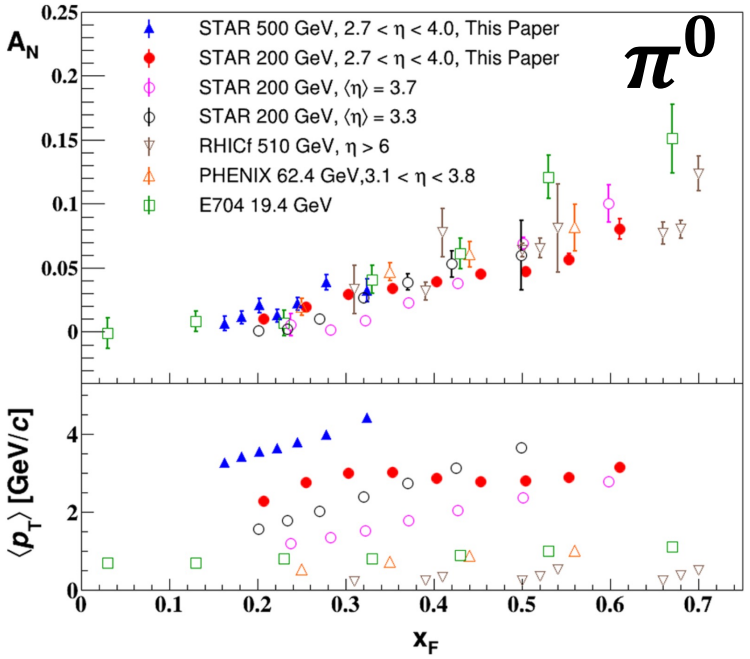

- The transverse single-spin asymmetry ($A_N$) represents a left-right asymmetry in particle production and reflects the underlying spin–transverse momentum correlations in a transversely polarized proton

# Transverse single spin asymmetry ($A_N$)

- **Measurements**




R. D. Klem et al., Phys. Rev. Lett. 36, 929 (1976)
D. L. Adams et al., Phys. Lett. B264, 462 - 466 (1991)
C. E. Allgowe et al., Phys. Rev. D 65, 092008 (2002)
I. Arsene et al., Phys. Rev. Lett. 101, 0420010 (2008)




(STAR) J. Adam et al., PRD 103, 092009 (2021)

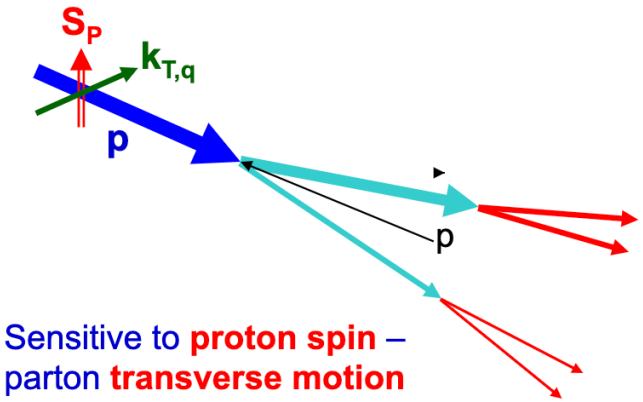
- Non-zero $A_N$ for $\pi^{\pm}$ and $\pi^0$ in forward region observed for the wide range of collision energies (4.9 - 510 GeV)

# Transverse single spin asymmetry ($A_N$)

- **Theoretical framework**

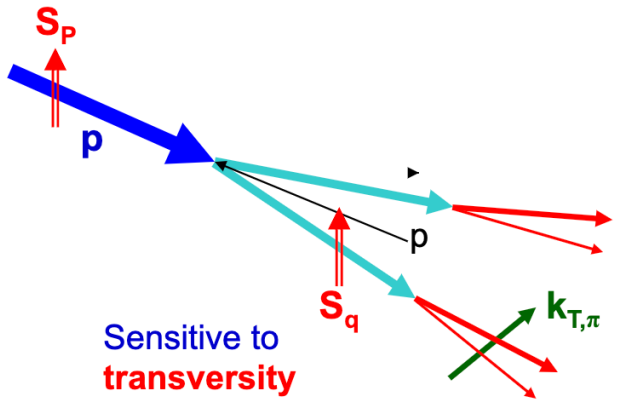
Sivers and Collins effects in pp collisions

**Sivers mechanism:** initial-state $k_T$ dependence in the parton distribution




Sensitive to **proton spin** – parton **transverse motion** correlations

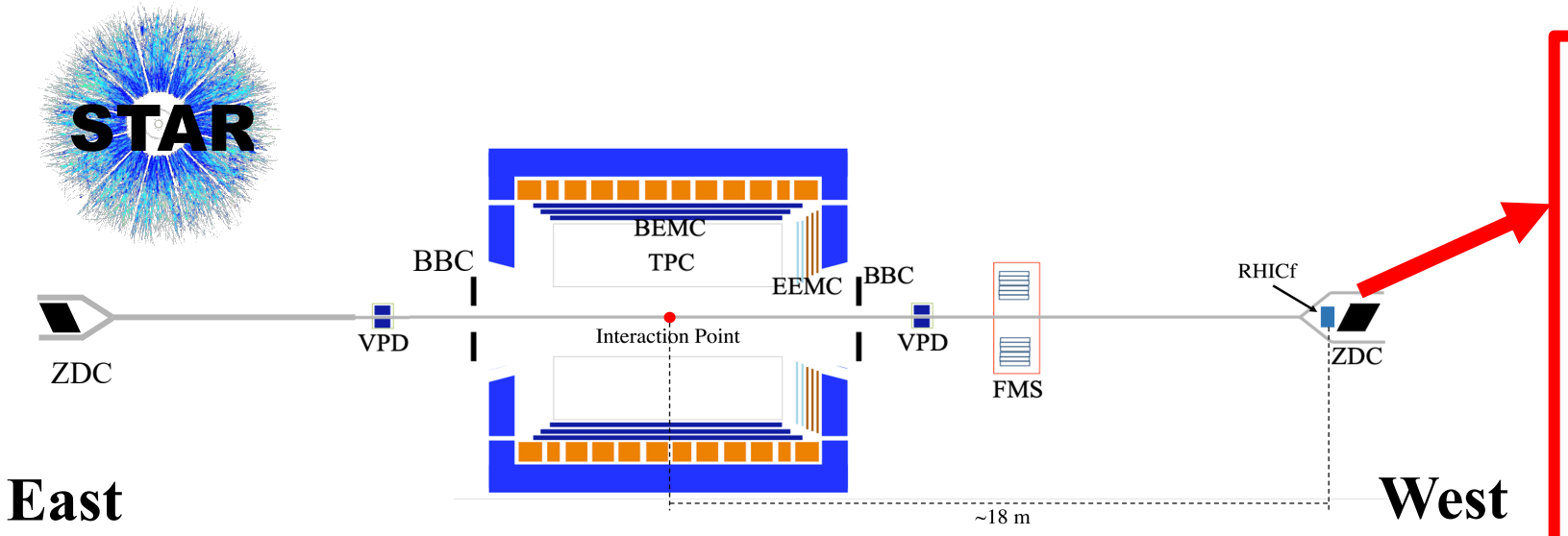
**Collins mechanism:** final-state asymmetry in the forward jet fragmentation

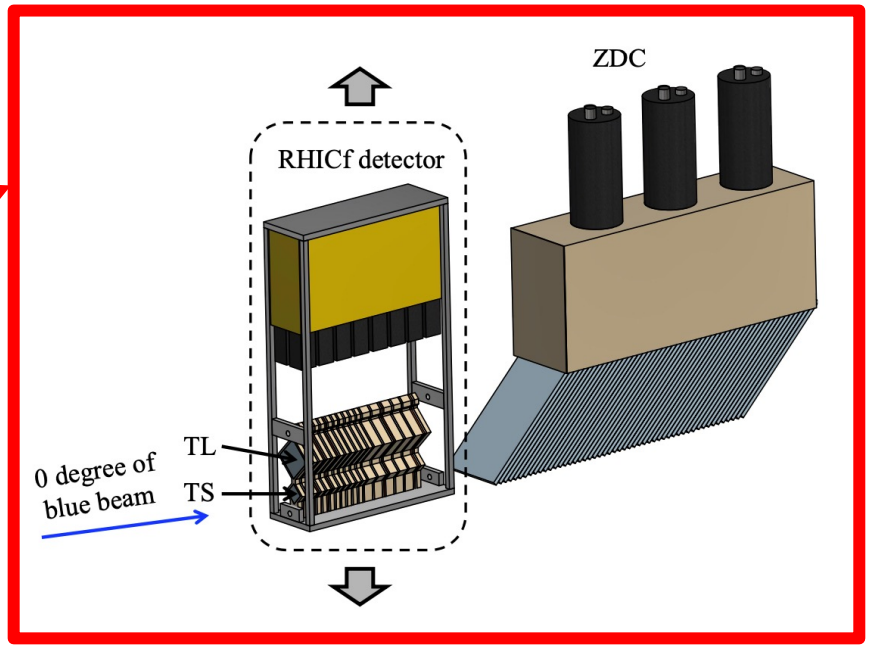



Sensitive to **transversity**

- These frameworks are related to the transverse spin structure of proton
- Sivers and Collins mechanisms could reproduce the large $A_N$ observed in experiments, which cannot be explained by standard collinear pQCD in which $A_N \approx 0$

# RHICf experiment

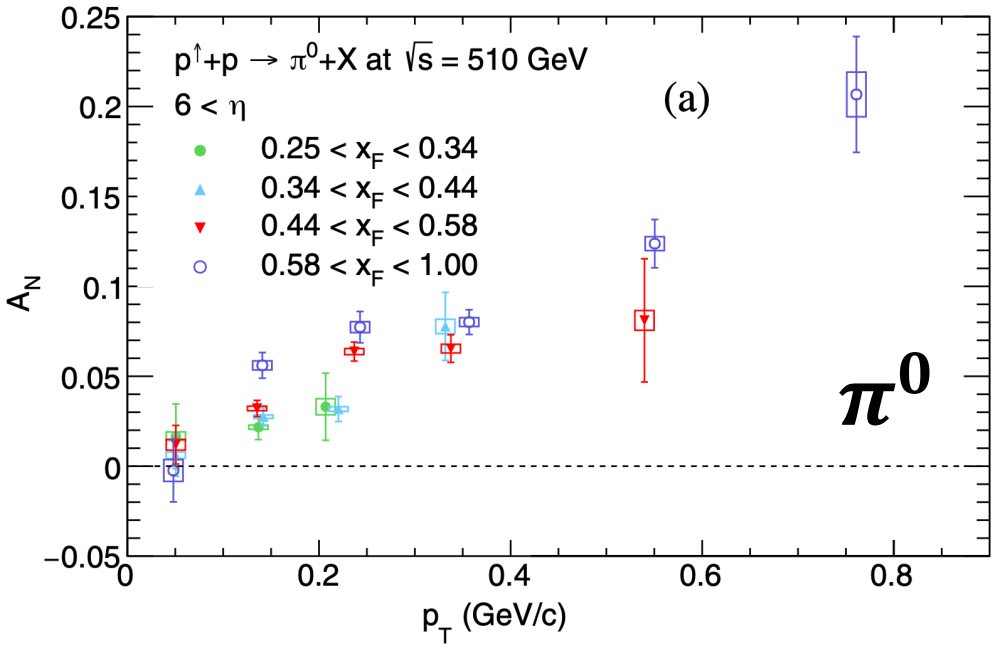


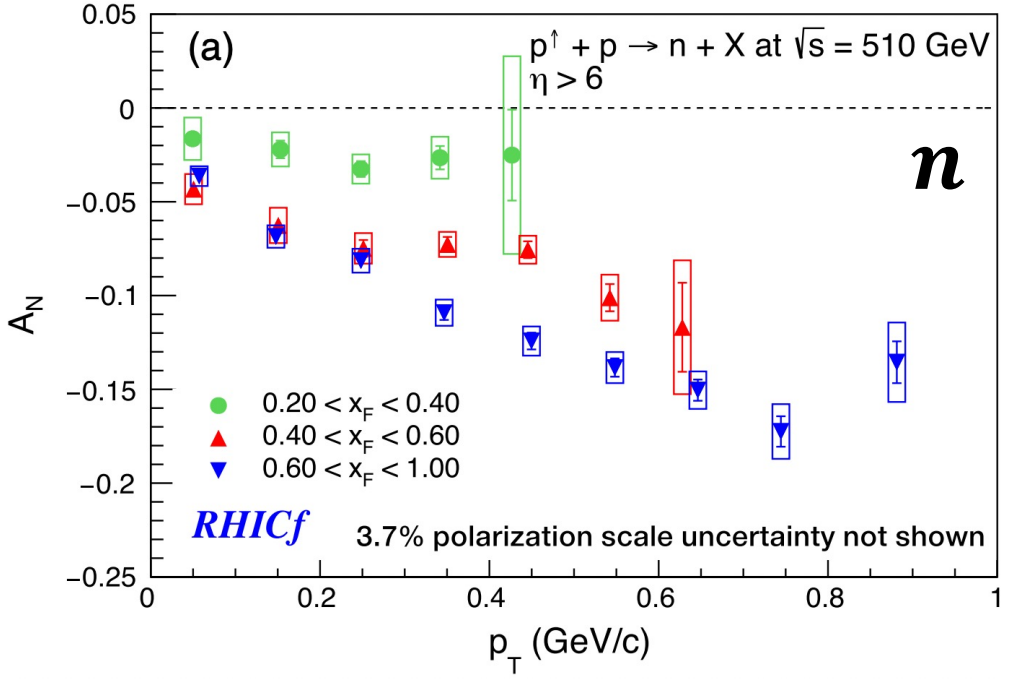

- RHICf detector was installed in the far forward ($\eta$ > 6) region of the STAR detector
- RHICf consists of a large tower (TL, 40mm) and a small tower (TS, 20 mm),
  Each tower is composed of 4 position layers (1 mm) and 16 scintillating plates
- RHICf operated to collect transversely polarized $p + p$ collisions at $\sqrt{s}$ = 510 GeV in 2017

# RHICf results

RHICf, PRL 124, 252501 (2020)



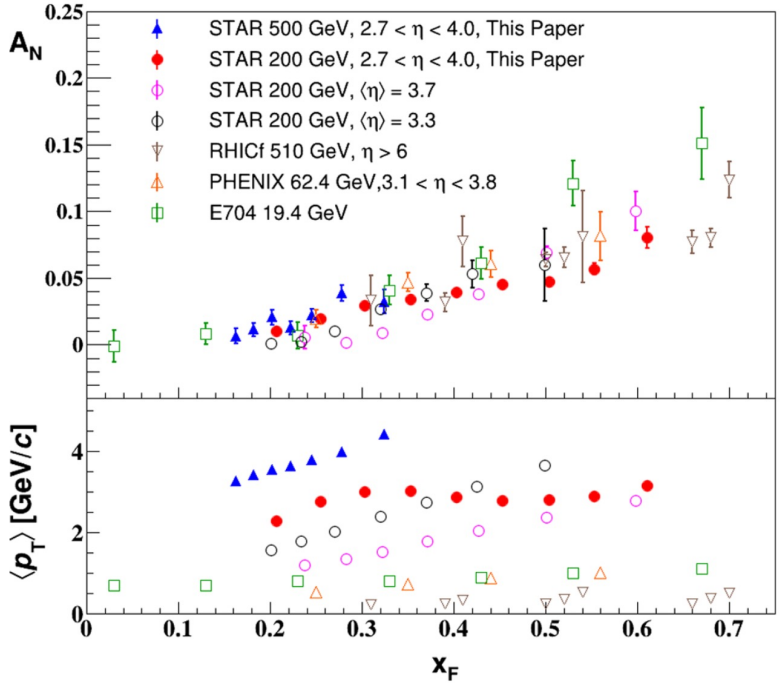

RHICf, PRD 109, 012003 (2024)

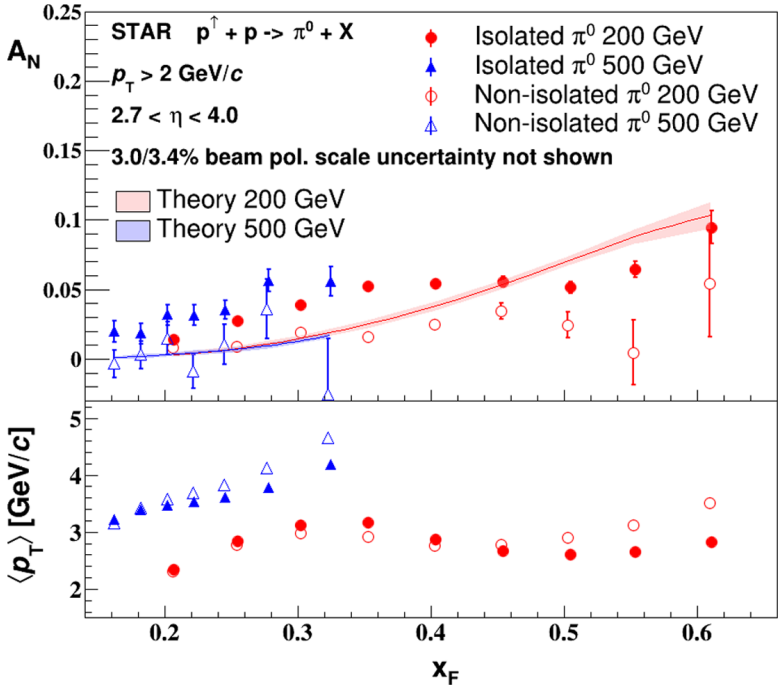



- RHICf Collaboration has successfully measured the $A_N$ of $\pi^0$ and $n$ in $p_T$ < 1.0 GeV/c and $\eta > 6$
- Non-zero $A_N$ for $\pi^0$ and $n$ at $\eta$ > 6 observed in the non-perturbative QCD regime

# $A_N$ for forward $\pi^0$ in different coverage

STAR, PRD 103, 092009 (2021)

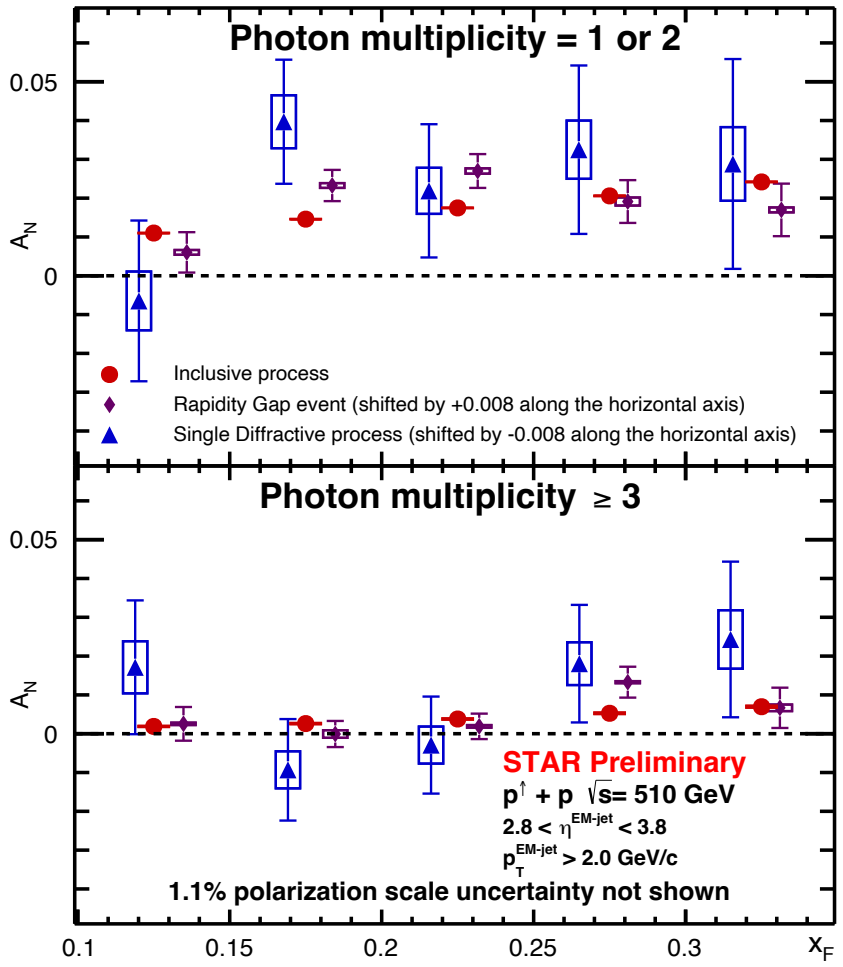



- $A_N$ for forward $\pi^0$ ($2.7 < \eta < 4$) and RHICf $\pi^0$ ( $\eta > 6$, $p_T < 0.2$ GeV/c) exhibit similar $x_F$ scaling behavior
- Large $A_N$ for forward and RHICf $\pi^0$ may arise from other mechanisms, e.g., diffraction or resonance particles
- Our goal is to isolate the diffractive contribution through a combined RHICf+STAR analysis

# $A_N$ with diffraction measurement

(STAR) Xilin Liang, DIS2025

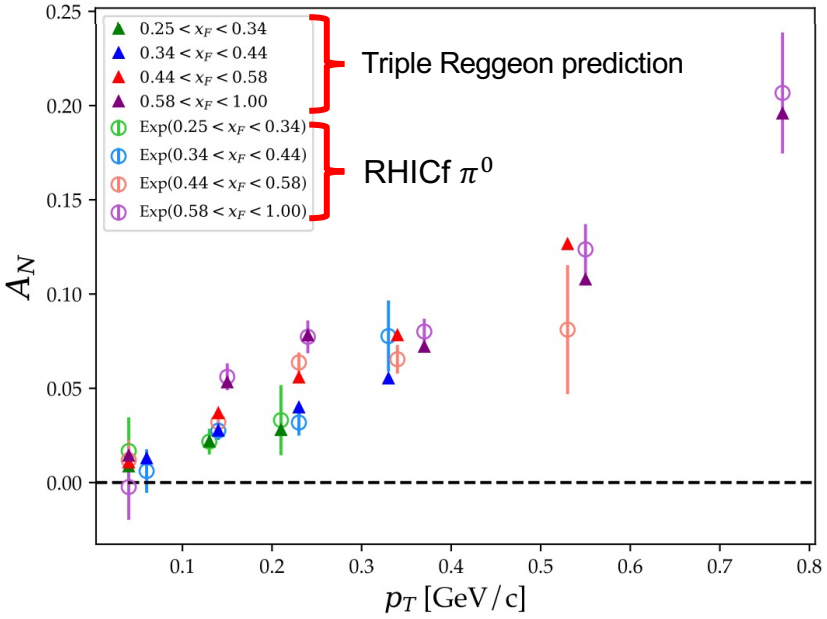


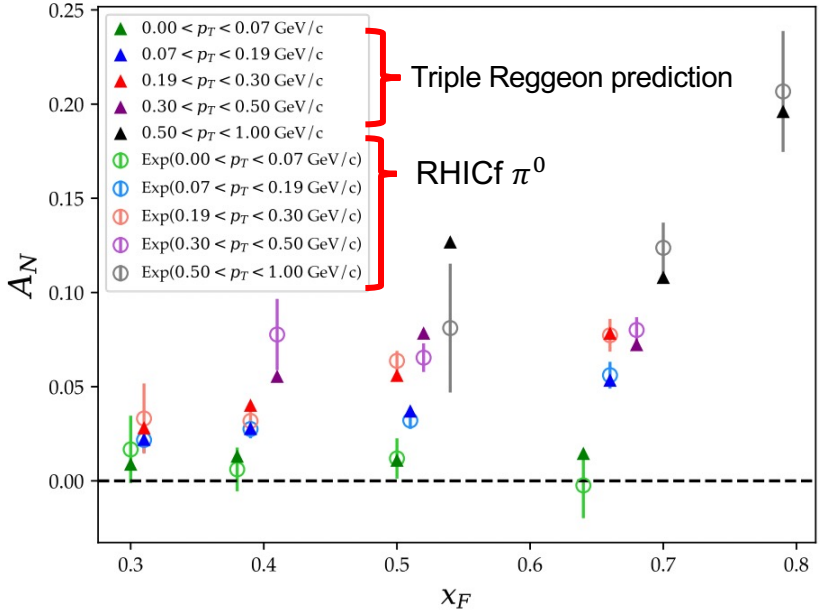

**For EM-Jet**

- It shows the $A_N$ with diffractive process within $p_{\mathrm{T}}^{\mathrm{EM-Jet}} > 2$ GeV/$c$ , $2.8 < \eta^{\mathrm{EM-Jet}} < 3.8$ (pQCD regime)
- $A_N$ for diffractive process is consistent with inclusive process

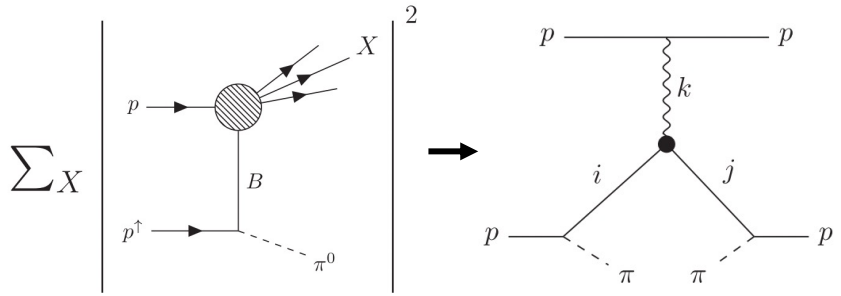
# Theoretical studies to explain the large $A_N$ of RHICf data

Hee-Jin Kim et al, PRD 106, 054001 (2022)



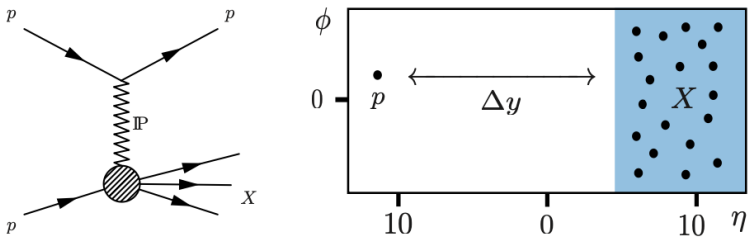




Triple Reggeon diagram

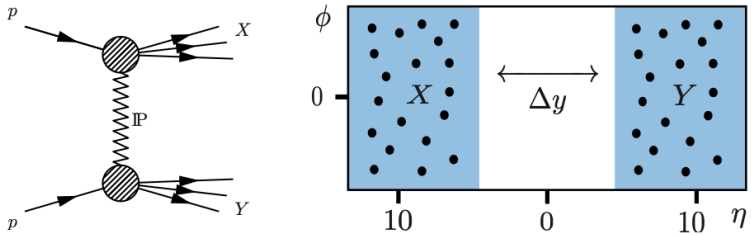



- The triple-Reggeon exchange model (diffraction) well describes the large $A_N$ measured by RHICf
- Suggests a significant contribution from baryonic triple-Regge exchanges

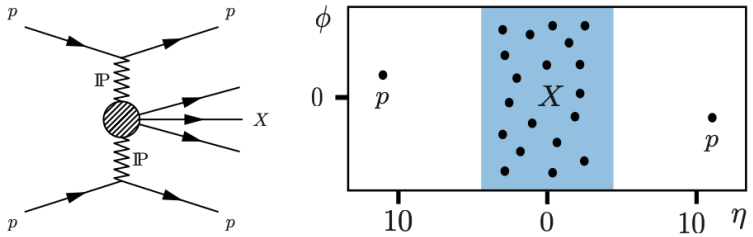
# Identification of diffractive p + p events




**Single Diffraction (SD)**




**Double Diffraction (DD)**




**Central Diffraction (CD)**

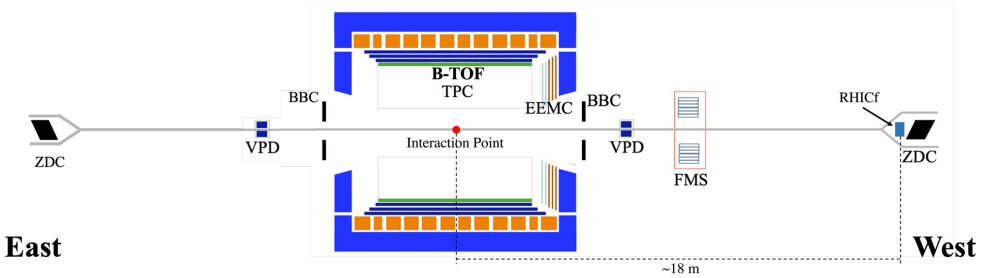
**Diffractive process features:**

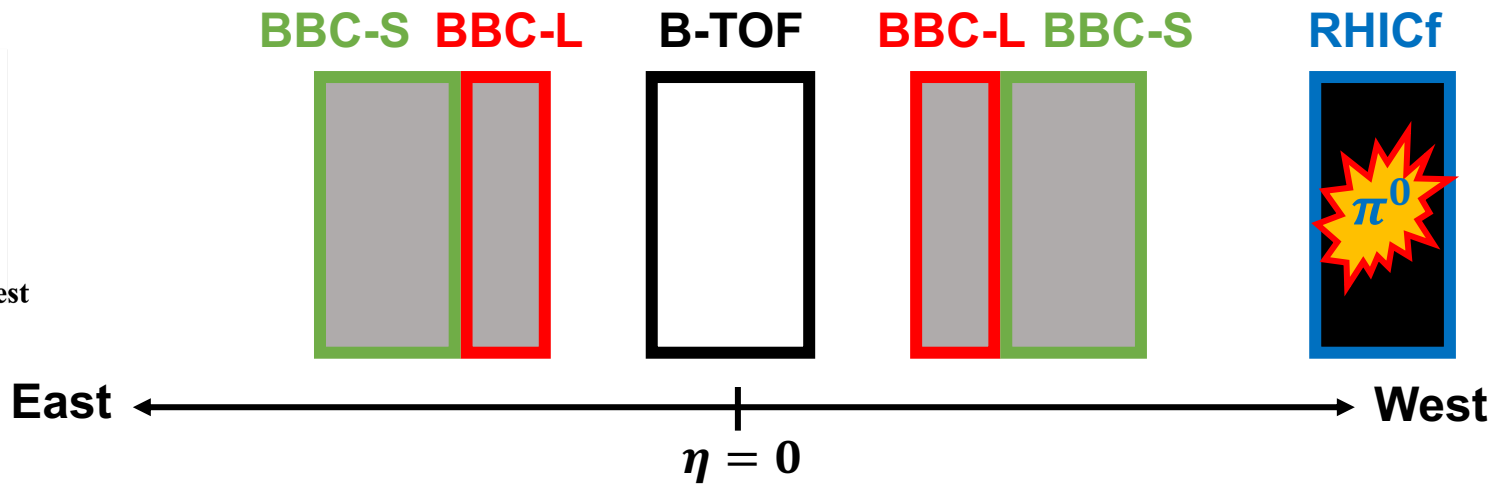
- Color Singlet Exchange (Pomeron exchange)
- Large Rapidity Gap
- Final state proton for SD

- Color Singlet (such as photon or pomeron) exchange may contribute to the $A_N$

# Event classification method

## ◆Condition definition



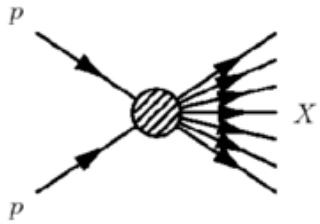




- Detector signal on/off thresholds are determined using minimum-bias trigger events
- Events are classified using rapidity-gap signatures of diffractive processes

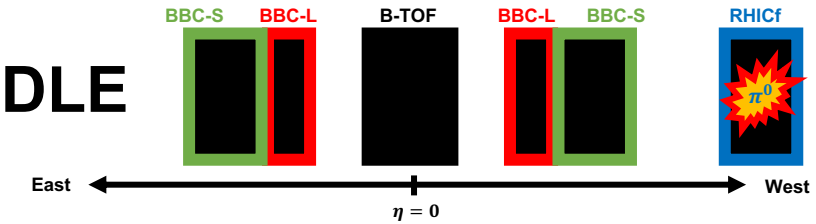
**Legend:**

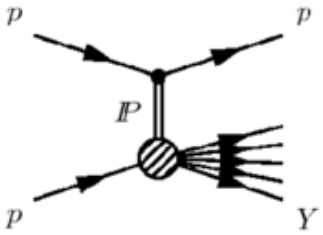
- **Always signal**
- **signal or not**
- **No signal**

# (Non-)Diffractive-Like-Event (DLE)

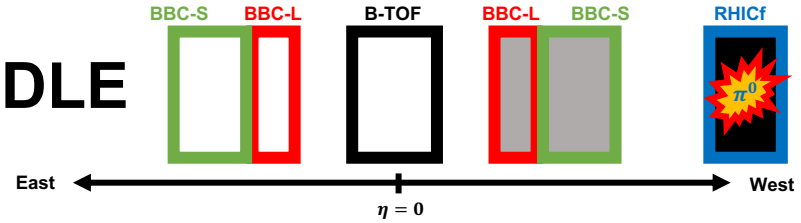


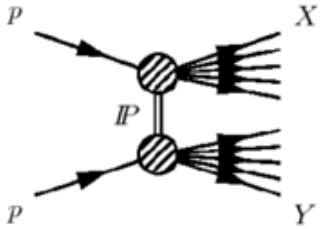

**Non Diff.** ⟷ **NDLE**



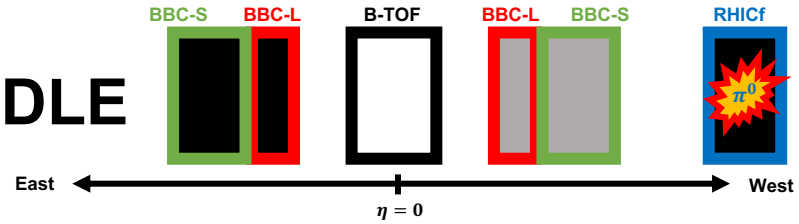




**Single Diff.** ⟷ **SDLE**




**Double Diff.** ⟷ **DDLE**



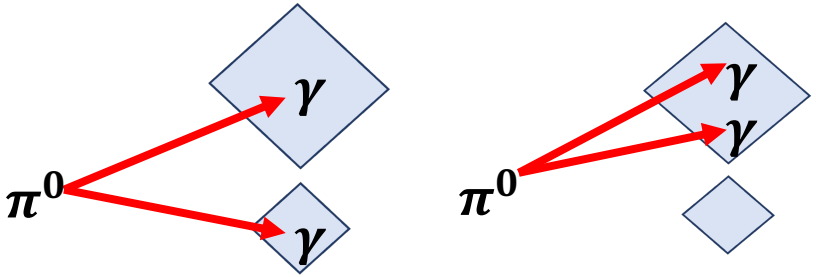

**Legend:**

- **Always signal**
- **signal or not**
- **No signal**

- We classified the three different processes with detector correlations

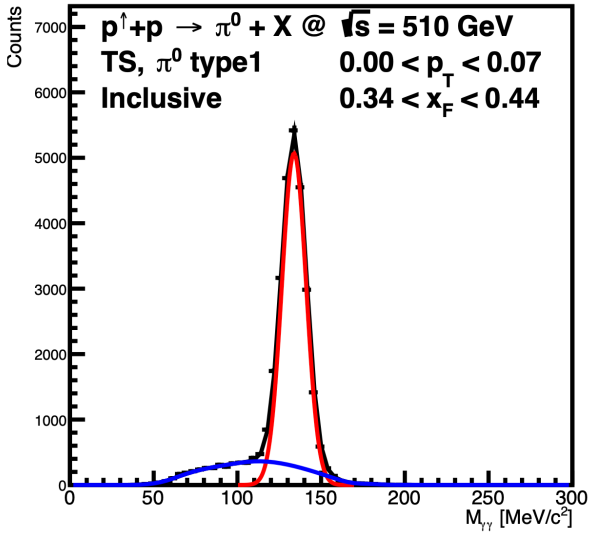
# RHICf $\pi^0$ measurement

◆ **Definition of RHICf $\pi^0$ type**

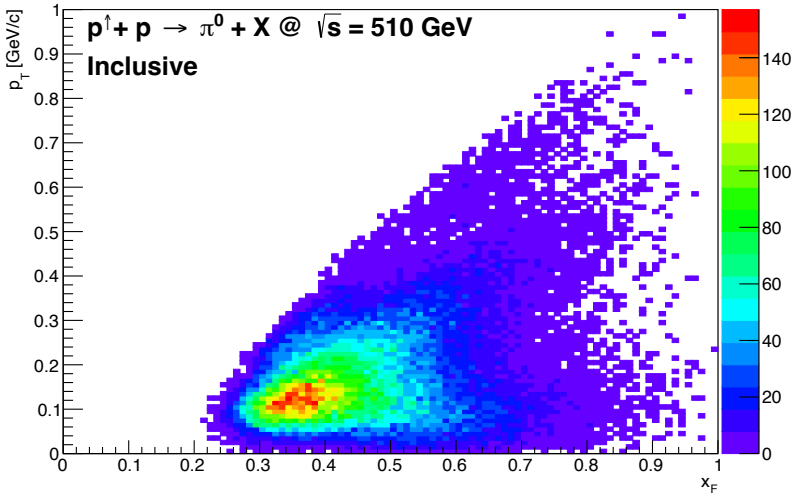



Type-1 $\pi^0$ Type-2 $\pi^0$

**Two $\gamma$ invariant mass**




**$p_T$ and $x_F$ correlations for $\pi^0$**



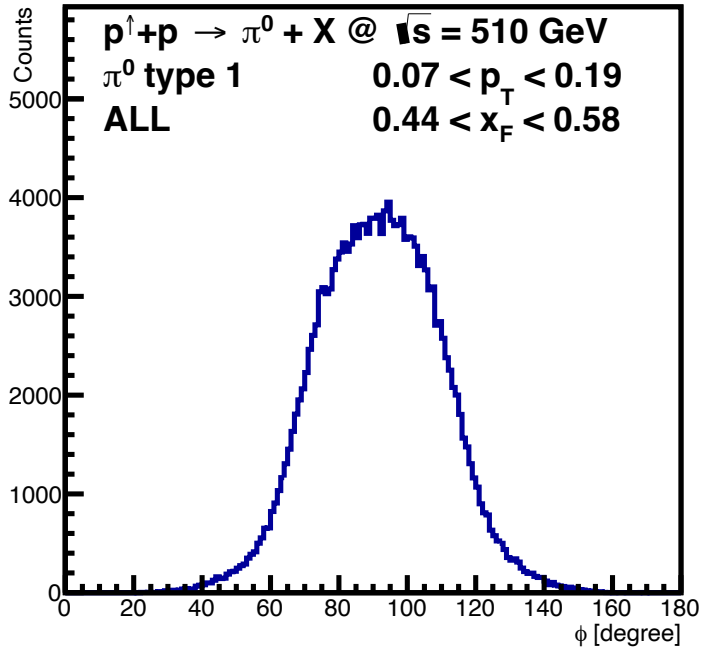

- $\pi^0$ candidates are selected based on the two-gamma invariant mass
- Background estimation has been conducted by using Gaussian Process Regression method
- Energy resolution $\sigma_E$ ~3.5% and transverse momentum resolution $\sigma_{p_T}$ ~4.5% for $\pi^0$ are observed

*RHICf, PRL 124, 252501 (2020)*

# $A_N$ of RHICf $\pi^0$ calculation

$$A_N = \frac{1}{P\, D_\phi}\left(\frac{N_L^\uparrow - R\, N_R^\downarrow}{N_L^\uparrow + R\, N_R^\downarrow}\right)$$

**Azimuthal angle distribution**




$P$ = Beam polarization

$D_\phi$ = Dilution factor

$R$ = Relative luminosity

$$D_\phi = \frac{1}{N}\sum \sin\phi$$

$N_{L(R)}^{\uparrow(\downarrow)}$ = Number of reconstructed $\pi^0$ events detected on the left (right) side of beam polarization direction for spin-up(down) bunches

- $A_N$ was calculated using the luminosity-based formula
- A dilution factor was applied to correct for the $\phi$ modulation of $\pi^0$ due to the finite detector acceptance

# Background $A_N$ of RHICf $\pi^0$ subtraction

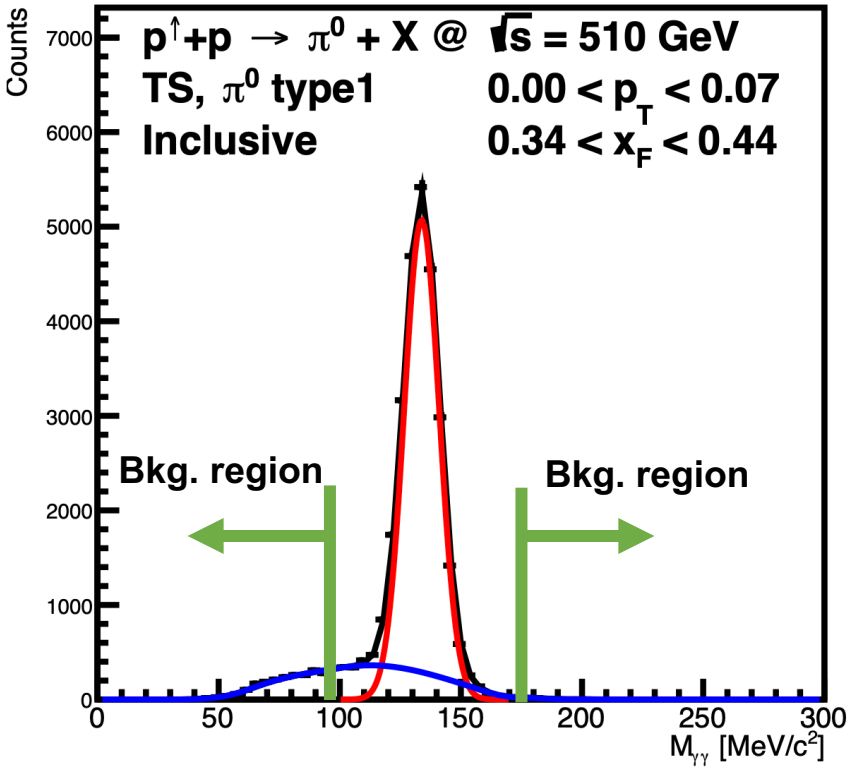
$$A_N^S = \left(1 + \frac{N_B}{N_S}\right) A_N^{S+B} - \left(\frac{N_B}{N_S}\right) A_N^B$$

$A_N^{S+B}$ = Signal + background $A_N$ withtin $3\sigma$

$A_N^B$ = Background $A_N$ in $5\sigma$ away from mass peak

$A_N^S$ = Subtracted $A_N$

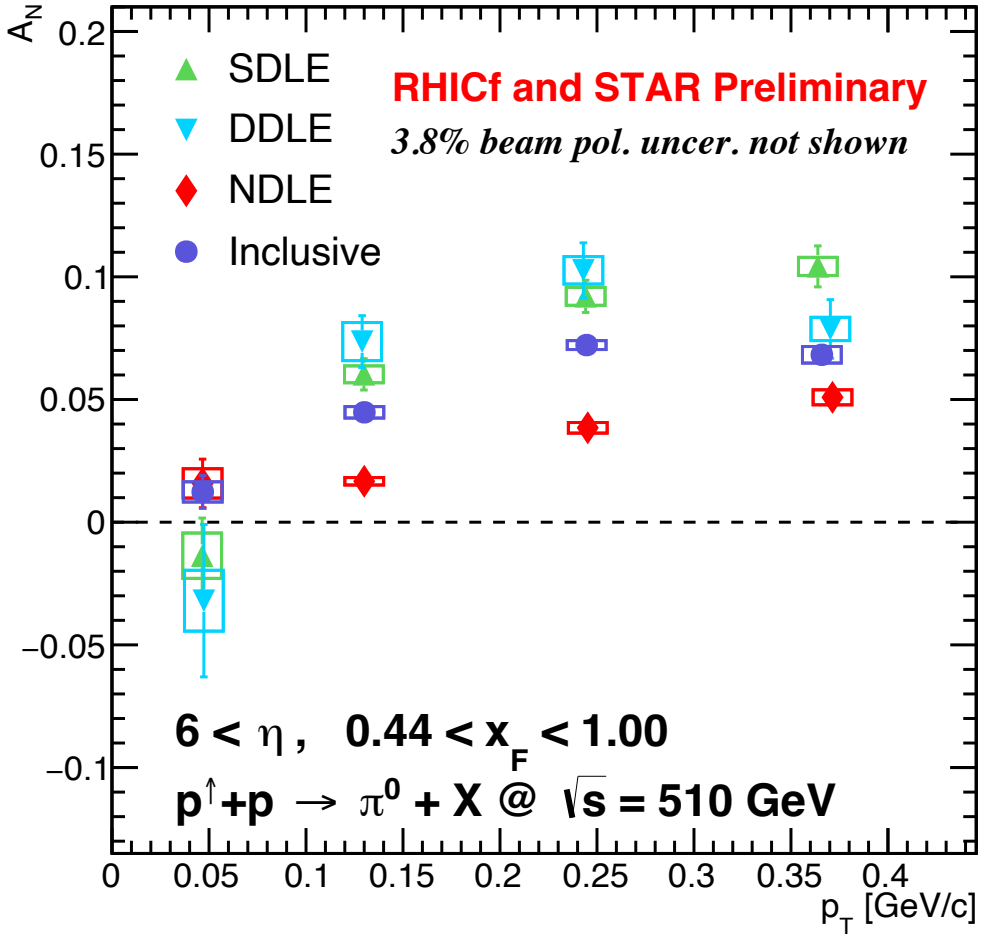
$N_{B(S)}$ = Integrated counts of background (signal) within $3\sigma$

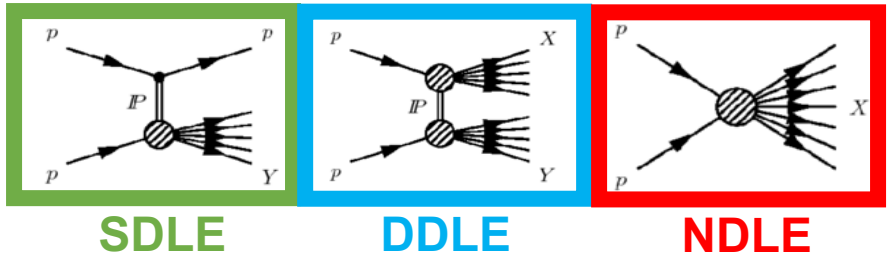



- Background subtraction was performed using $A_N^B$ and the background-to-signal ratio (B/S ratio) within the $3\sigma$ of the mass peak

- $A_N^B$ was estimated from background events located more than $5\sigma$ away from the mass peak.

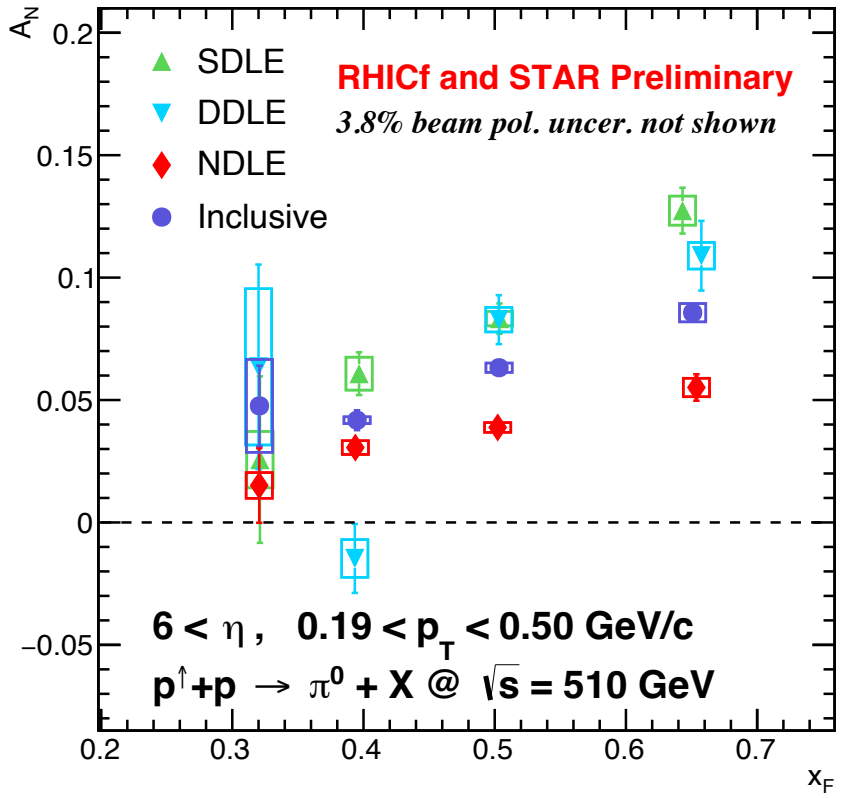
# Results

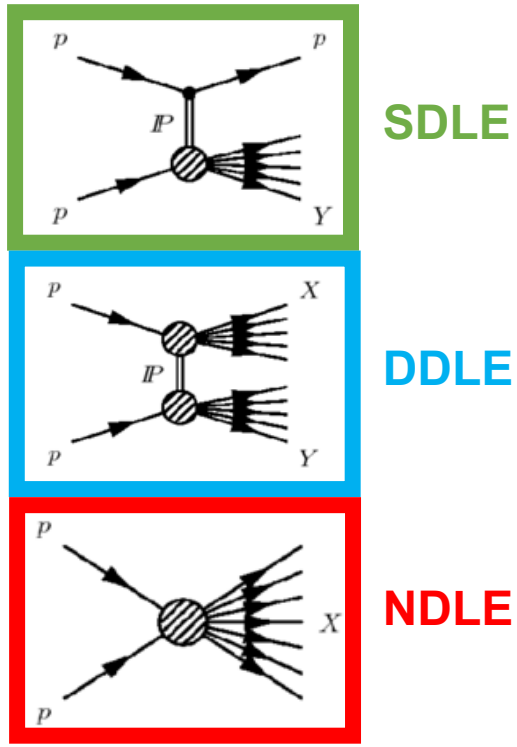



- We observe the non-zero $A_N$ of RHICf $\pi^0$ under the SDLE, DDLE and NDLE conditions
- The SDLE and DDLE show similar behavior and exhibit a more enhanced $A_N$ compared to the inclusive result
- NDLE condition shows a suppressed $A_N$ relative to the inclusive result

# Results




- It shows different $A_N$ values for S/DDLE and NDLE compared with inclusive result as a function of $x_F$

- Diffractive process may contribute to the large $A_N$ in $\eta > 6$ region

# Summary

- $A_{\mathrm{N}}$ is measured for (non-)diffractive like events in $p^{\uparrow} + p$ collision at $\sqrt{s} = 510$ GeV at RHICf and STAR experiments

- Non-zero $A_{\mathrm{N}}$ values of RHICf $\boldsymbol{\pi^0}$ are observed across all classified event types

- $A_{\mathrm{N}}$ values for SDLE and DDLE show an enhancement relative to the inclusive events
  In contrast, $A_{\mathrm{N}}$ for NDLE is suppressed compared to the inclusive events

- Our new results provide strong evidence for the diffractive origin of the large forward $A_{\mathrm{N}}$