Transverse Single Spin Asymmetry of Electromagnetic Jets at Forward Rapidity in $p^{\uparrow} + p$ Collisions at STAR

Weibin Zhang
for the STAR Collaboration

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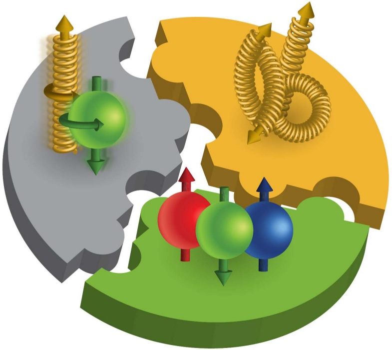
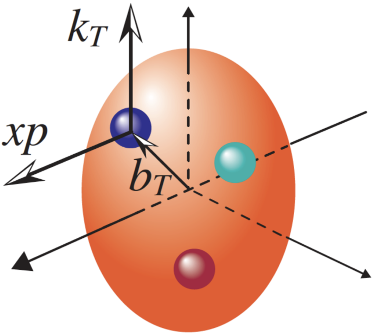
Proton Spin Puzzles

Too Small Puzzle



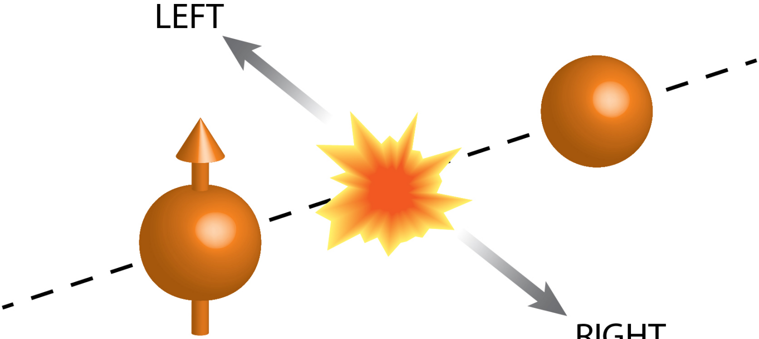
$$\frac{1}{2} = \sum_q S_q + \sum_g S_g + \sum_q L_q + \sum_g L_g$$

Too Large Puzzle



$$\mathrm{TSSA}_{\mathrm{exp}} >> \mathrm{TSSA}_{\mathrm{theory}}$$

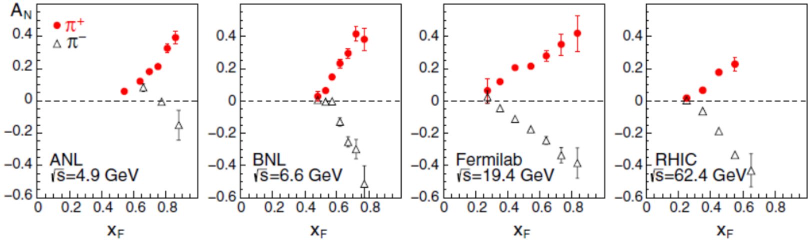
Transverse Single Spin Asymmetry (TSSA/A_N)



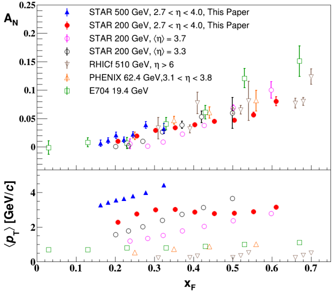
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Motivation

Aidala et al., Rev. Mod. Phys. 85, 655 (2013)



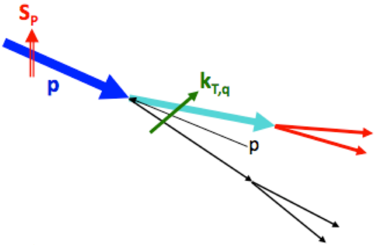
STAR Collaboration, PRD 103, 092009 (2021)



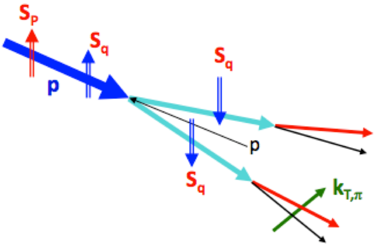
- Perturbative-QCD predicts small contributions from hard scattering: $A_N \sim m_q/p_T \sim O(10^{-4})$
- Large A_N observed $\sim O(10^{-1})$
- Compels inclusion of TMD/twist-3 mechanisms and diffractive effects beyond collinear pQCD

Theoretical Explanation: TMD ($p_T << Q$)

Initial State Effect
Sivers mechanism



Final State Effect
Collins mechanism



Spin-momentum coupling between the proton's $\vec{S}_\perp$ and the $\vec{k}_\perp$ of its unpolarized partons

Correlation between a quark's $\vec{S}_\perp$ and the $\vec{k}_\perp$ of unpolarized hadrons produced in its fragmentation

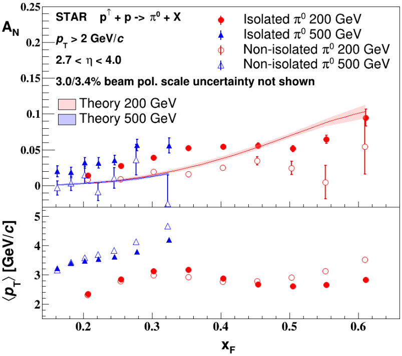
Theoretical Explanation: Twist-3 ($p_T \sim Q$)

- Incorporates quark–gluon–quark correlations in the parton distribution or in fragmentation
- No explicit parton k_T; instead, multi-parton correlators encode spin–momentum correlations
- Qiu–Sterman function $T_F(x,x)$ (ETQS matrix element) in the initial state, and analogous $\hat{H}(z)$-type functions in fragmentation
- $\mathrm{A_N}$ scales as $1/\mathrm{p_T}$, consistent with observed trends at high $\mathrm{p_T}$

$$\mathrm{A_N} \sim \frac{T_F(x,x) \otimes H}{f(x) \otimes \hat{H}}$$

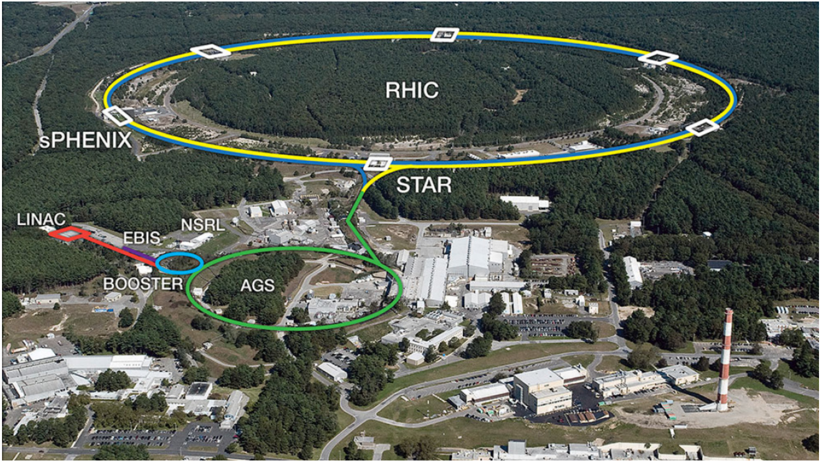
TSSA in Electromagnetic (EM) Jets

STAR Collaboration, PRD 103, 092009 (2021)



- Isolated π^0 has a larger A_N than non-isolated π^0
- EM-jets: jets with only photons
- Explore the potential source of large A_N
  - Diffractive processes
- Characterize A_N in terms of EM-jet p_T, energy and photon multiplicities

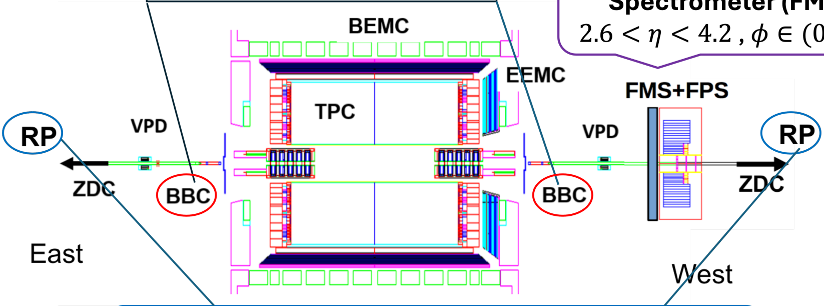
The STAR Experiment at RHIC



The STAR Detector

Beam-Beam Counter (BBC)
$2.1 < |\eta| < 5$

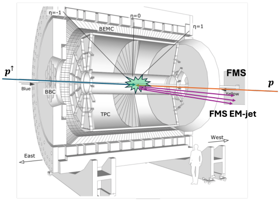
Forward Meson Spectrometer (FMS)
$2.6 < \eta < 4.2$, $\phi \in (0, 2\pi)$



Roman Pot (RP)
On both sides, about 15 m away from Interaction Point
Only east side RP is used for these analyses

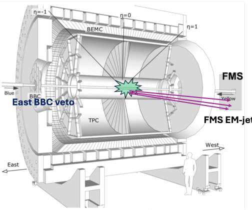
Inclusive and Diffractive Processes

Inclusive



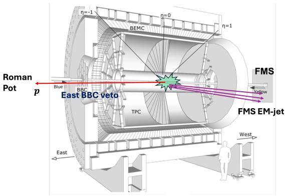
- EM-jets at FMS

Rapidity Gap



- One EM-jet at FMS
- Veto on east BBC

Single Diffractive



- One EM-jet at FMS
- Veto on east BBC
- One proton at east RP

Dataset and Event Selection

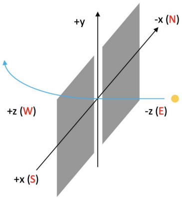
Dataset

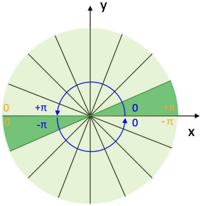
- 2015: pp collisions at $\sqrt{s} = 200$ GeV, P = 57%
- 2017: pp collisions at $\sqrt{s} = 510$ GeV, P = 60%

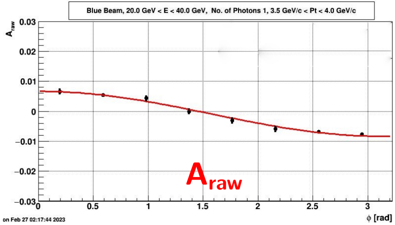
Event Selection

- $|z| \leq 80$ cm
- Photon: $E > 1$ GeV
- EM-jet: Anti-k_T clustering, $R = 0.7$, $\mathrm{p_T} > 2$ GeV, $2.8 < \eta < 3.8$
- $\mathrm{p_T}$ is corrected for underlying event using off-axis cone method [STAR Collaboration, PRD, 100, 052005 (2019)]
- Energy is unfolded to particle level

A_N Extraction



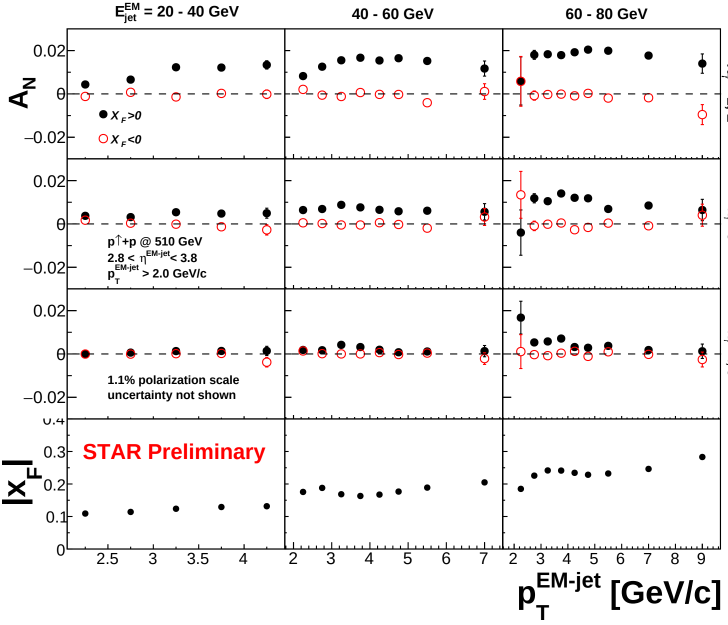




$$A_{raw} = A_N \times P \times \cos(\phi) \approx \frac{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} - \sqrt{N_\phi^\downarrow N_{\phi+\pi}^\uparrow}}{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} + \sqrt{N_\phi^\downarrow N_{\phi+\pi}^\uparrow}}$$

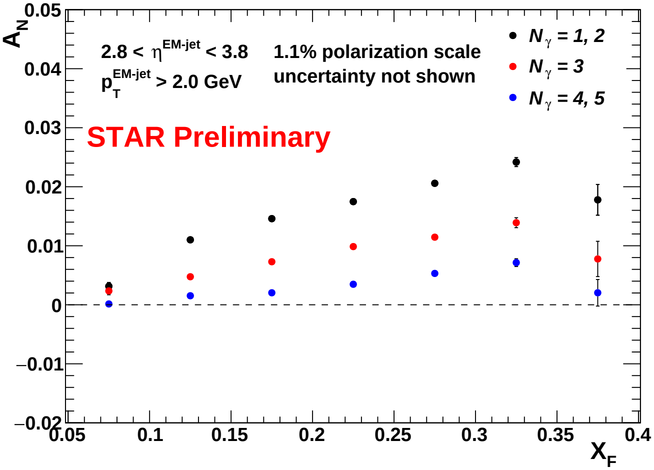
P = beam polarization $\quad \phi$ = azimuthal angle

Inclusive: A_N vs p_T at pp $\sqrt{s} = 510$ GeV



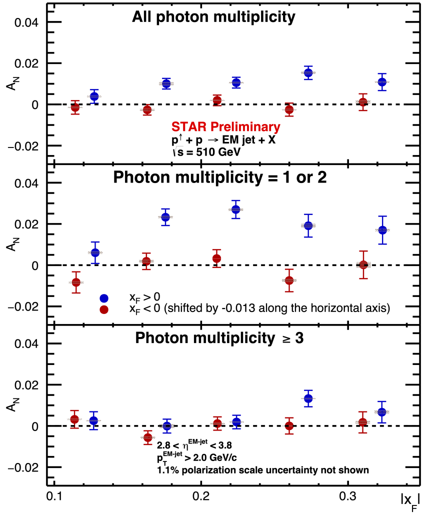
Inclusive: A_N vs x_F at pp $\sqrt{s} = 510$ GeV

- A_N increases with x_F (except the last x_F bin)
- A_N decreases with increasing photon multiplicity

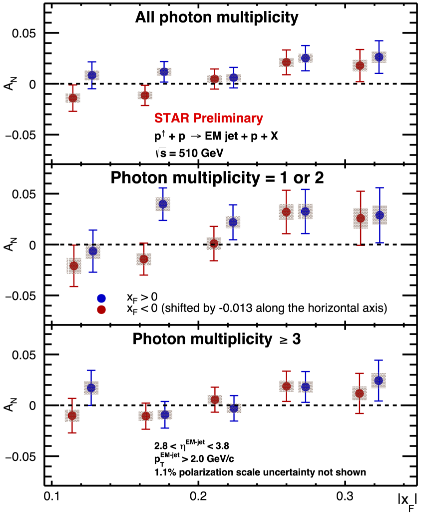


Diffractive: A_N vs x_F at pp $\sqrt{s} = 510$ GeV

Rapidity Gap

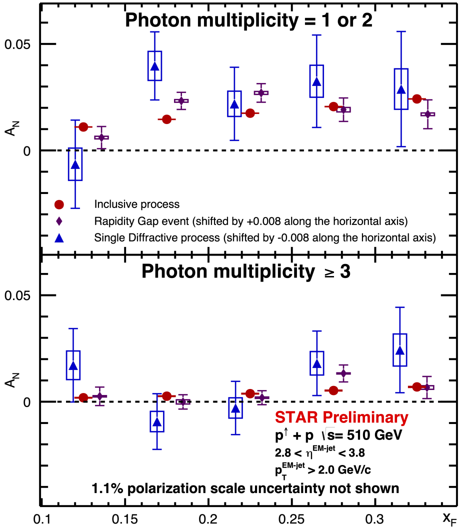


Single Diffractive



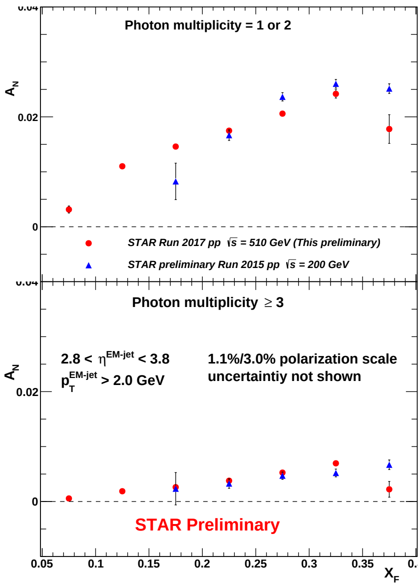
A_N vs x_F at pp $\sqrt{s} = 510$ GeV

- Rapidity gap event and single diffractive process exhibit similar A_N to inclusive process
- In all three processes, EM-jets with large photon multiplicity (≥ 3) display very small A_N

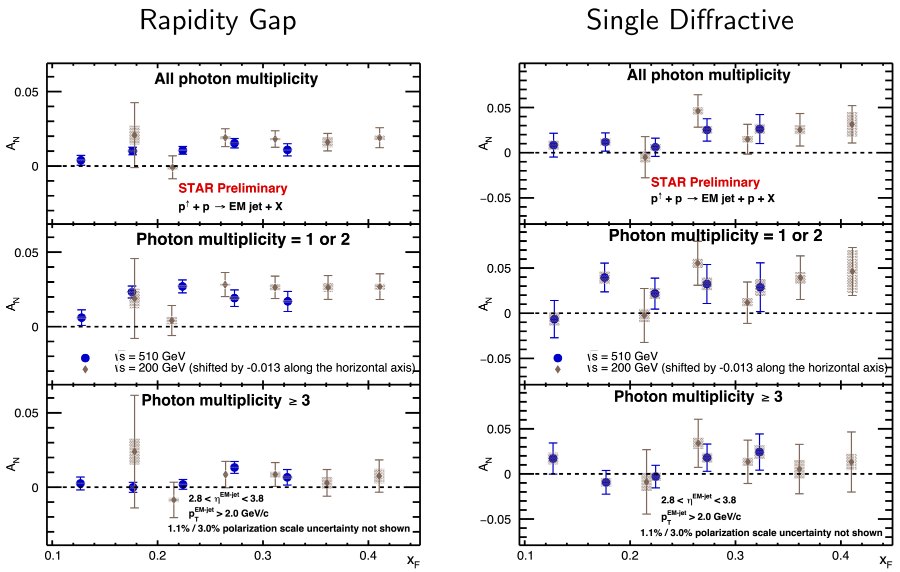


Inclusive: pp $\sqrt{s} = 510$ GeV vs 200 GeV

- Inclusive process shows similar A_N at $\sqrt{s} =$ 510 GeV and 200 GeV in the overlapping x_F region, while the 500 GeV data extend coverage to lower x_F
- At both $\sqrt{s} = 510$ GeV and 200 GeV, A_N primarily arises from low photon multiplicity EM-jets



Diffractive: pp $\sqrt{s} = 510$ GeV vs 200 GeV



Summary

- A_N is extracted for inclusive and diffractive processes at $\sqrt{s} =$ 200 and 510 GeV
- A_N increases with EM-jet's energy and x_F, varies with its p_T and decreases with its photon multiplicity
- Similar A_N is observed for all three processes at $\sqrt{s} =$ 200 GeV and 510 GeV
- Diffractive processes alone cannot account for the large A_N observed in inclusive events.