Measurement of transverse single spin asymmetry at forward rapidity by the STAR experiment in p+p collisions at $\sqrt{s} = 200$ and 500 GeV

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Light Cone 2021: Physics of Hadrons on the Light Front

Outline

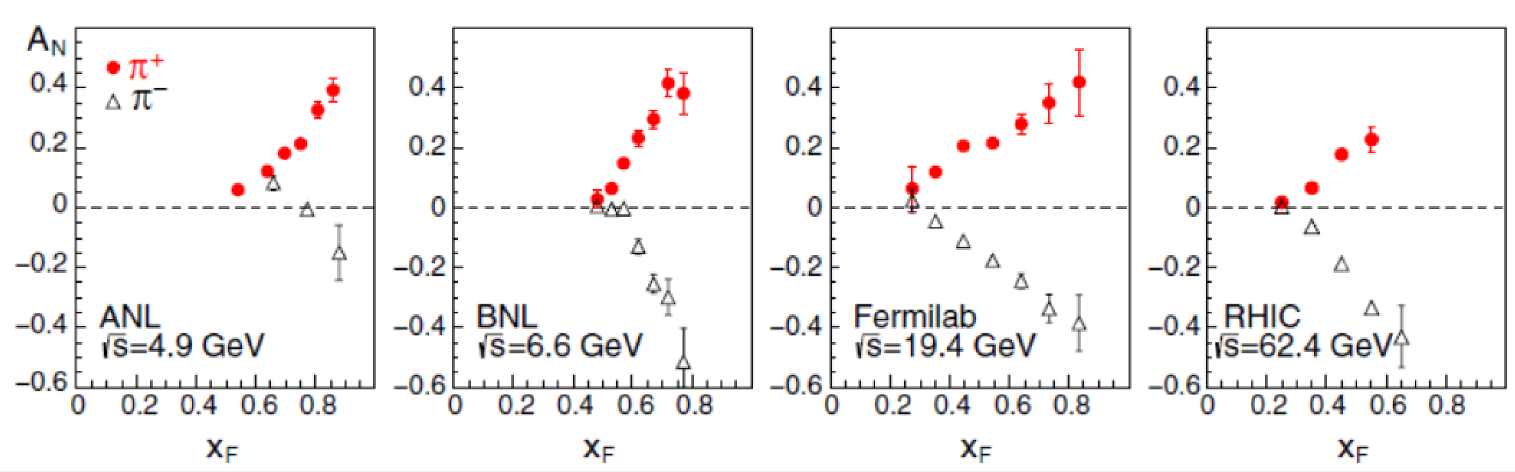
- Motivation
- Experiment setup
- Analysis
- Result and discussion
- Summary

This work has been Published in Phys. Rev. D 103, 092009 in 2021

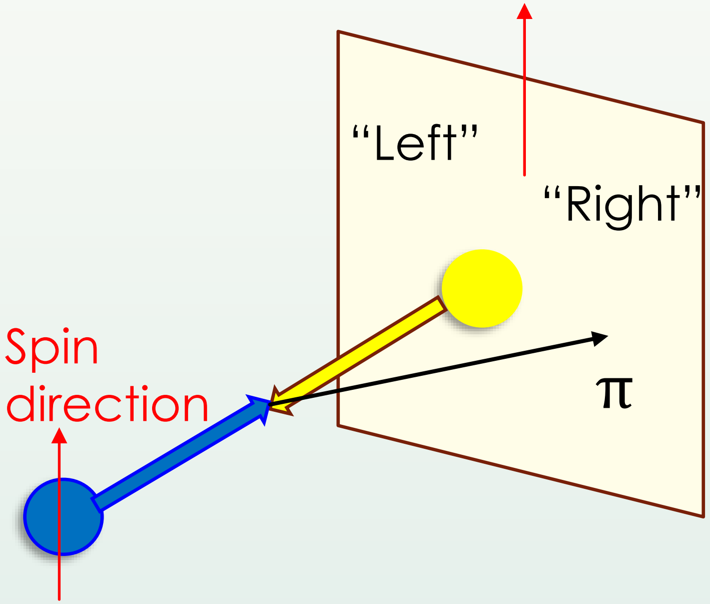
Motivation

- Transverse single spin asymmetry (TSSA/A_N)
- The large forward TSSA was first discovered in 1970s and can not be explained by LO QCD calculation

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



Aidala et al., Rev. Mod. Phys. 85, 655



Motivation

- Great progress has been made over the decades: Transverse momentum dependent PDF (TMD), Collinear twist-3 factorization and etc.

  In general, these models share some similarities that the TSSA originates from the **initial and final state effects**

- A decomposition of the contributions to TMD
  - **Initial state effect**: asymmetry originates from parton distribution function

$$\hat{f}_{q/p^\dagger}(x, \boldsymbol{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\dagger}(x, k_\perp)\, \boldsymbol{S} \cdot \left(\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_\perp\right)$$

Sivers function

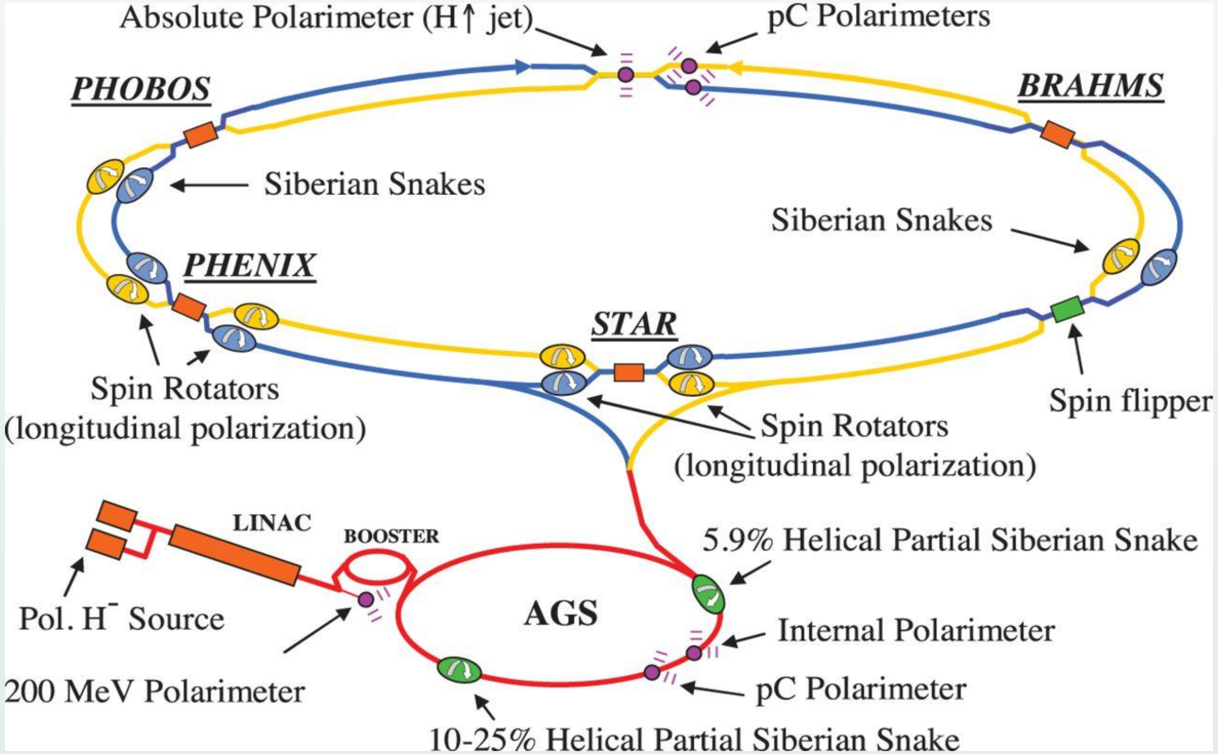
  - **Final state effect**: asymmetry originates from fragmentation

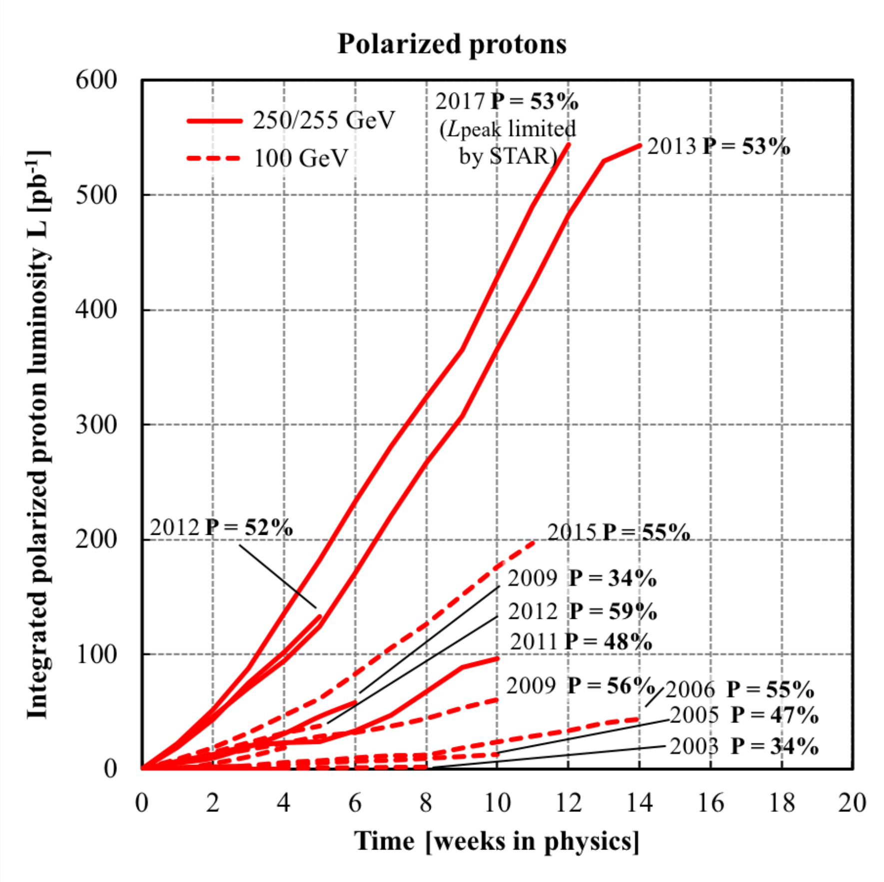
Transversity $\otimes$ **Collins function**

- Experimental data are very important in validating the factorization and constraining the PDFs

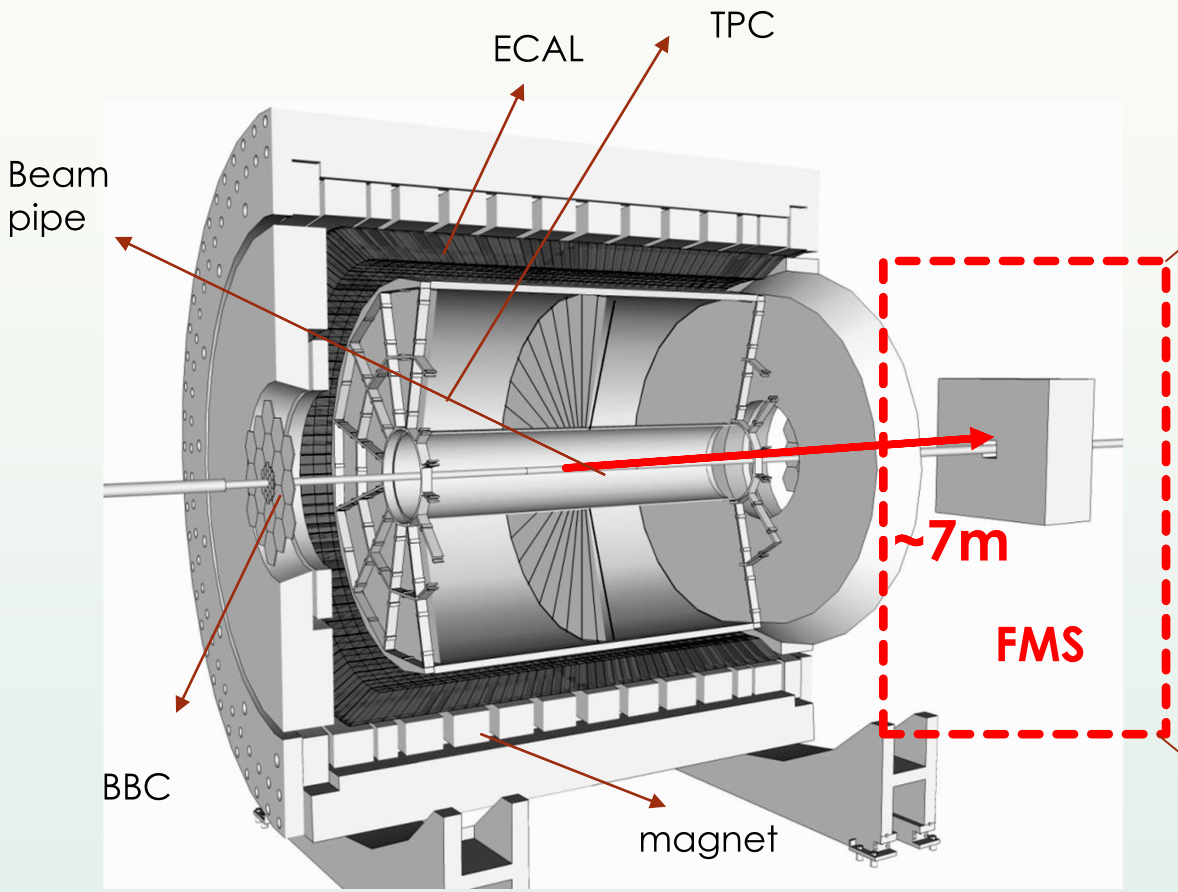
Experiment Setup- RHIC & STAR

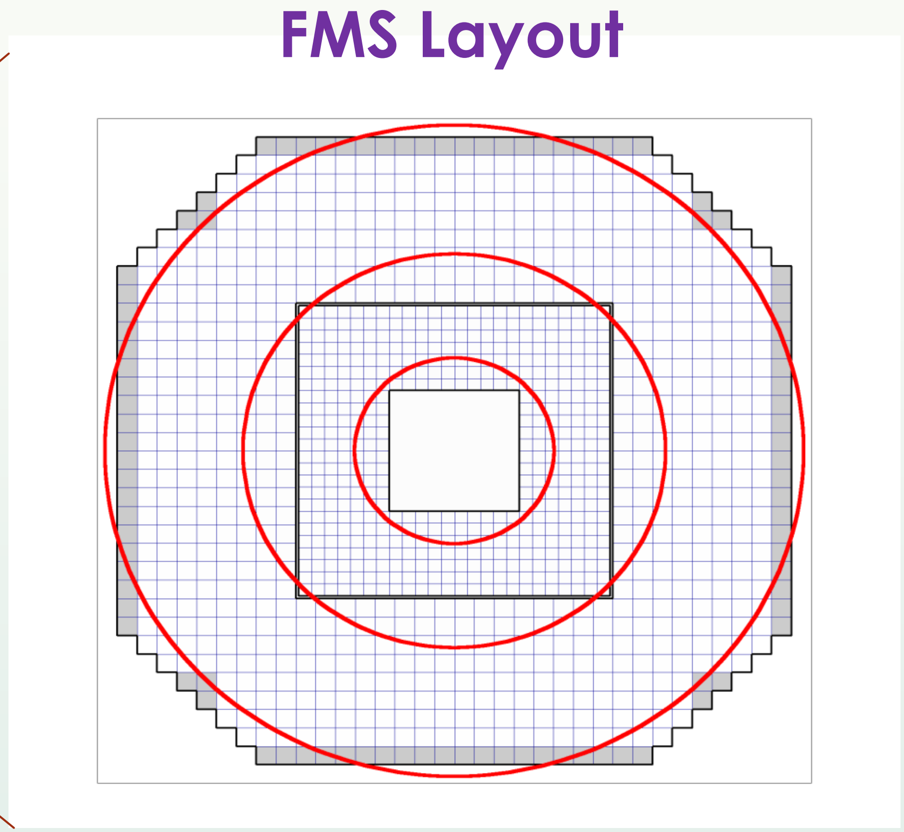
- The **Relativistic Heavy Ion Collider** at BNL provides unique opportunity to study spin physics because it is the world's only polarized proton-proton collider.





Experiment Setup- STAR & FMS





- EM-Calorimeter made of 1000+ lead glass cells
- Large pseudo-rapidity coverage in the forward direction 2.6-4.1
- Two cell types

Analysis- Dataset

- **Dataset:**

Transversely polarized proton-proton collisions

Year	Energy	Events
2011	500 GeV	165M
2015	200 GeV	569M

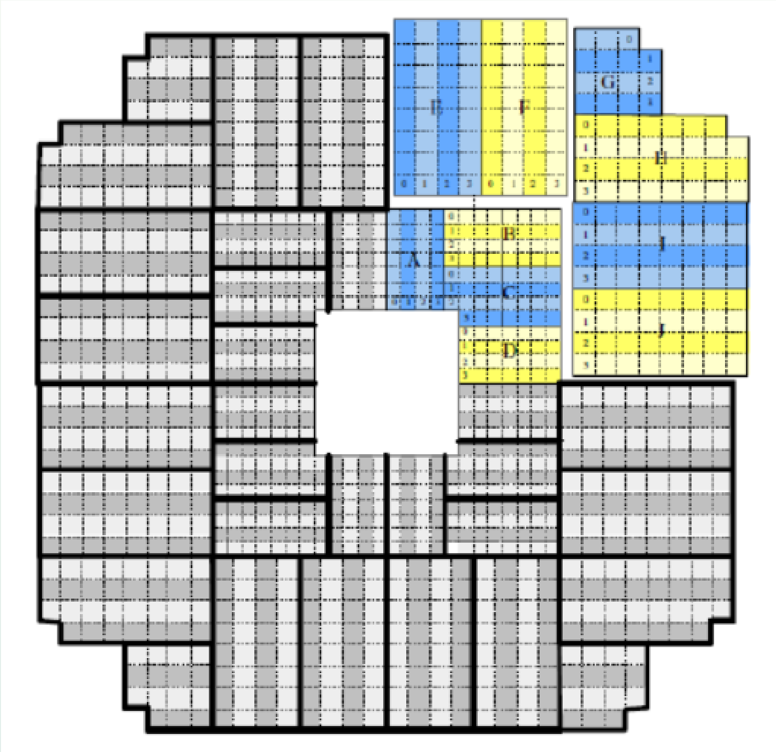
- **Beam polarization:**

52 / 57% (500 / 200 GeV)

- **Trigger:**

FMS-Board-sum and FMS-Jet-patch, both based on energy deposition in a defined region of the FMS

Trigger logic



Analysis- Asymmetry calculation

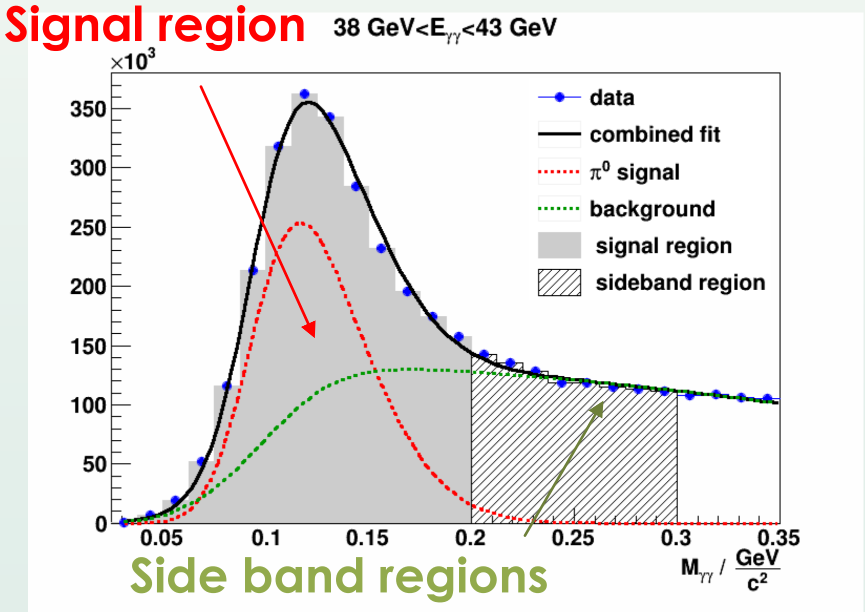
The **luminosity** and **detector efficiency** can be difficult to determine.

$$N^{\uparrow}(\phi) = \epsilon\mathcal{L}^{\uparrow}\sigma^{\uparrow}$$
$$= \epsilon\mathcal{L}^{\uparrow}\,(1 + pol * A_N\cos\phi)\ \ \sigma$$

- "Cross-ratio" method help eliminate those factors

$$pol \cdot A_N^{raw}\ \cos\phi = \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

Typical di-photon mass spectrum



STAR, Phys. Rev. D 103, 092009

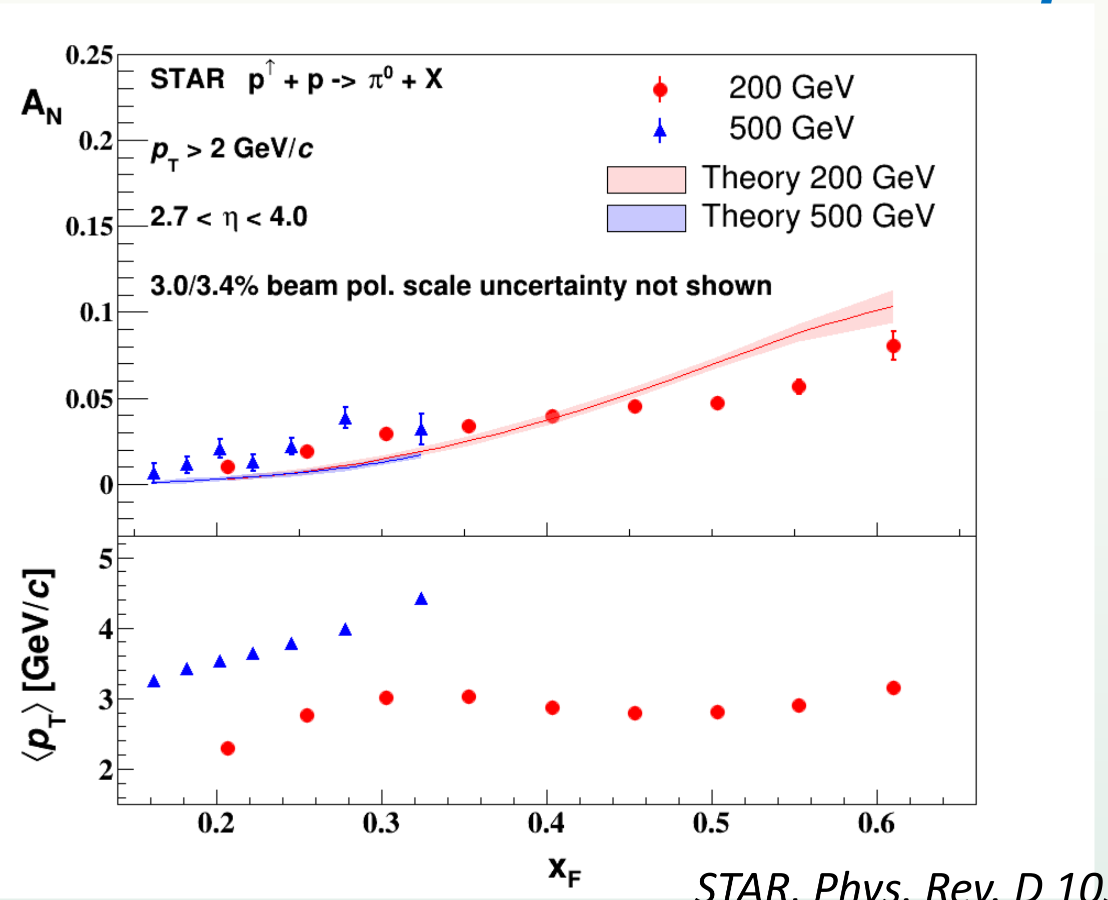
- Background subtraction

The fraction comes from the fitting of the mass spectrum

Signal/background shapes are from simulation

$$A_N^{\mathrm{raw}_{sig}} = f_{\mathrm{sig}_{sig}} * A_N^{\pi^0} + (1 - f_{\mathrm{sig}_{sig}}) * A_N^{bkg}$$
$$A_N^{\mathrm{raw}_{sb}} = f_{\mathrm{sig}_{sb}} * A_N^{\pi^0} + (1 - f_{sig_{sb}}) * A_N^{bkg}$$

Result- π^0 TSSA vs. x_F

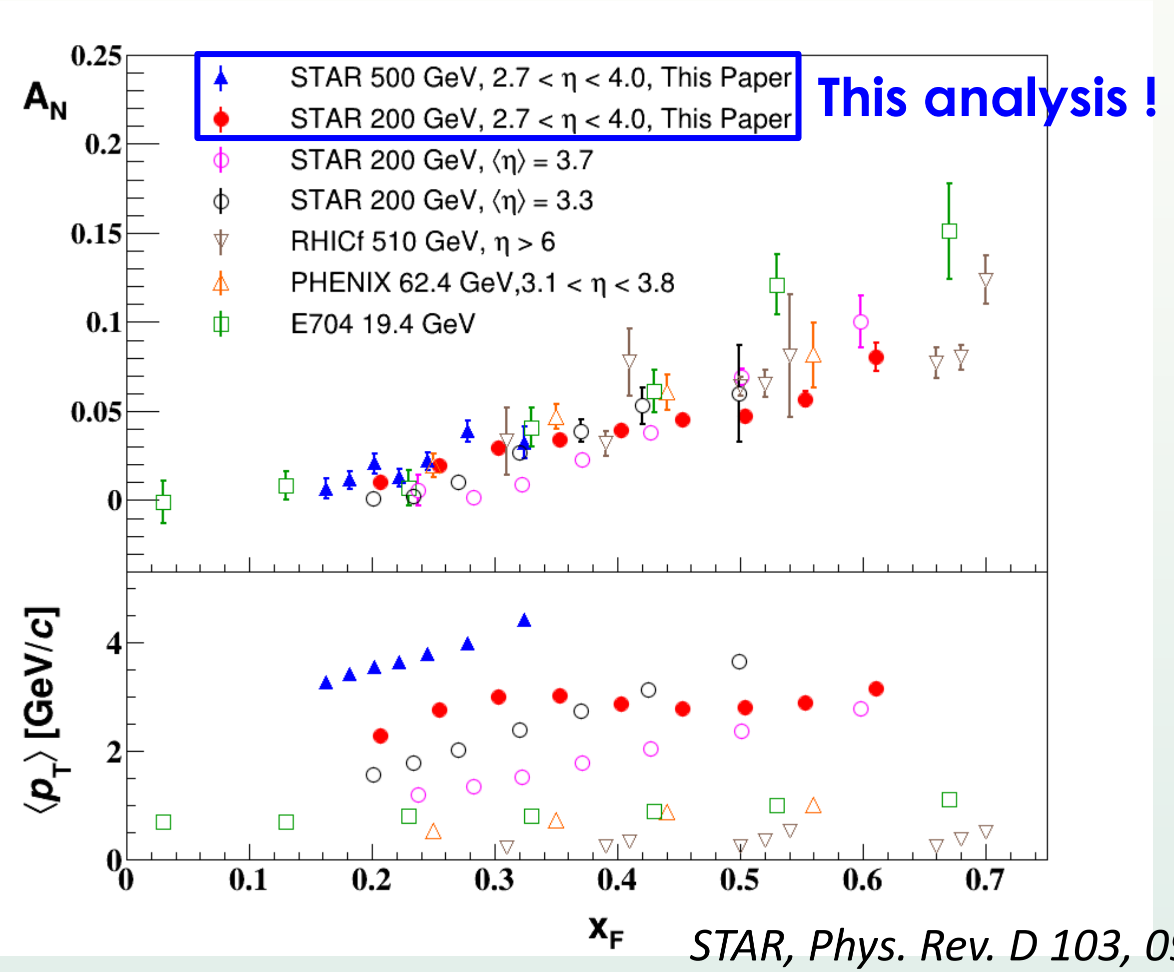


Theory curves:
J. Cammarota et al.,
Phys.Rev.D 102, 054002

STAR, Phys. Rev. D 103, 092009

- ❑ The π^0 TSSA increases with x_F.
- ❑ Consistent between 200 GeV and 500 GeV. Energy dependence is weak.

Comparison to previous measurements

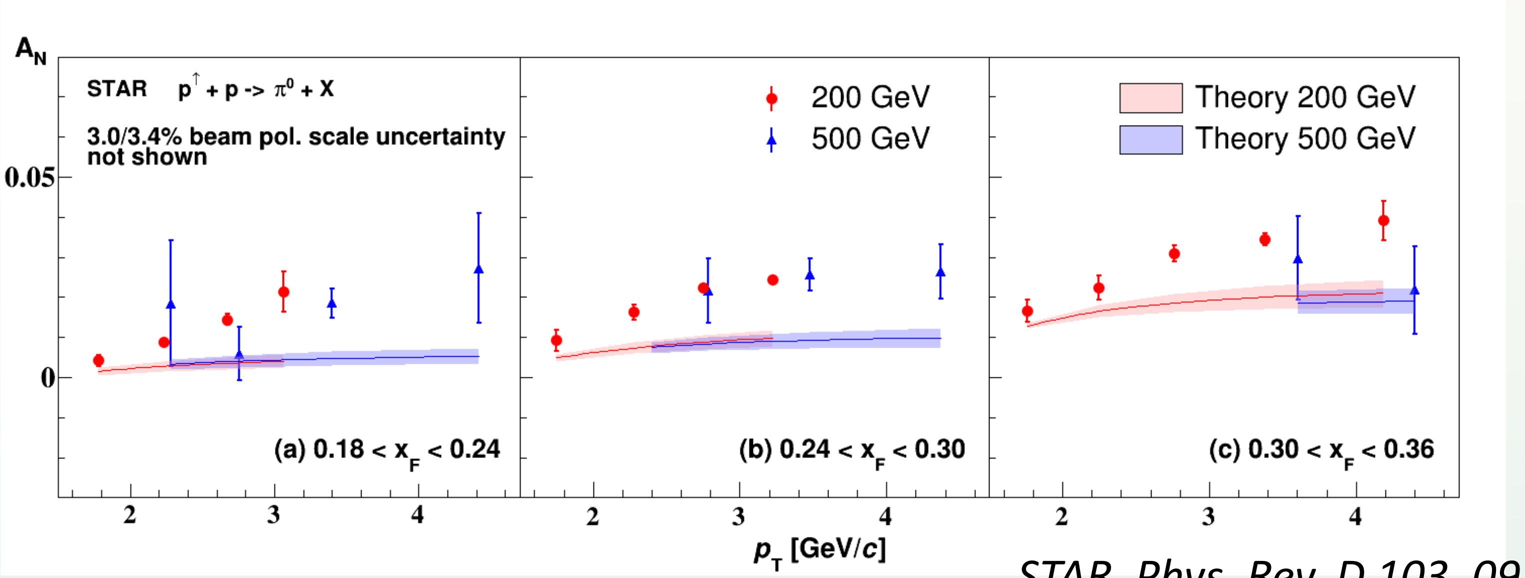


$$x_F = \frac{E_L^{\pi^0}}{E_{beam}}$$

STAR, Phys. Rev. D 103, 092009
STAR 2008 data:
STAR, Phys.Rev.Lett. 101, 222001

- ❑ Weak collision energy dependence of the π^0 TSSA from 19.4 to 500 GeV
- ❑ **Other observables are needed to disentangle the initial and final state effect.**

Result- π^0 TSSA vs. p_T



Theory curves:
J. Cammarota et al., Phys.Rev.D 102, 054002

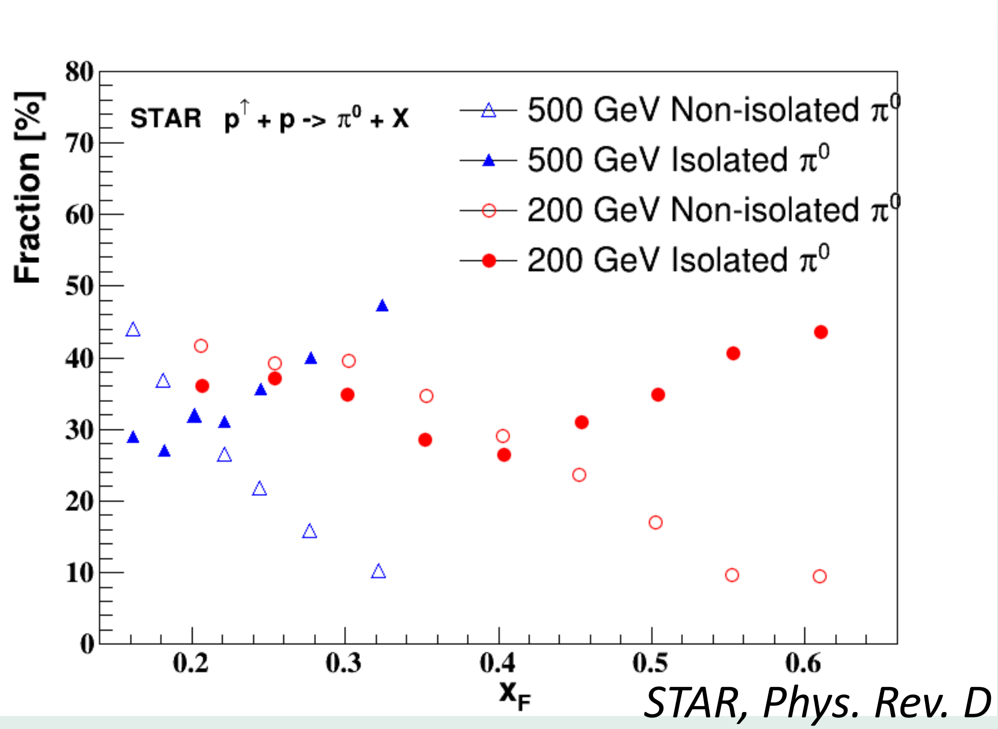
STAR, Phys. Rev. D 103, 092009

- ❑ Overlapping x_F region between 200 GeV and 500 GeV results.
- ❑ The 200 GeV data shows a significant increase of TSSA below 3 GeV, which explains the higher TSSA than 2008 STAR data in the previous slide.
- ❑ The 500 GeV data are flat over the p_T range.

Result- isolated π^0 TSSA

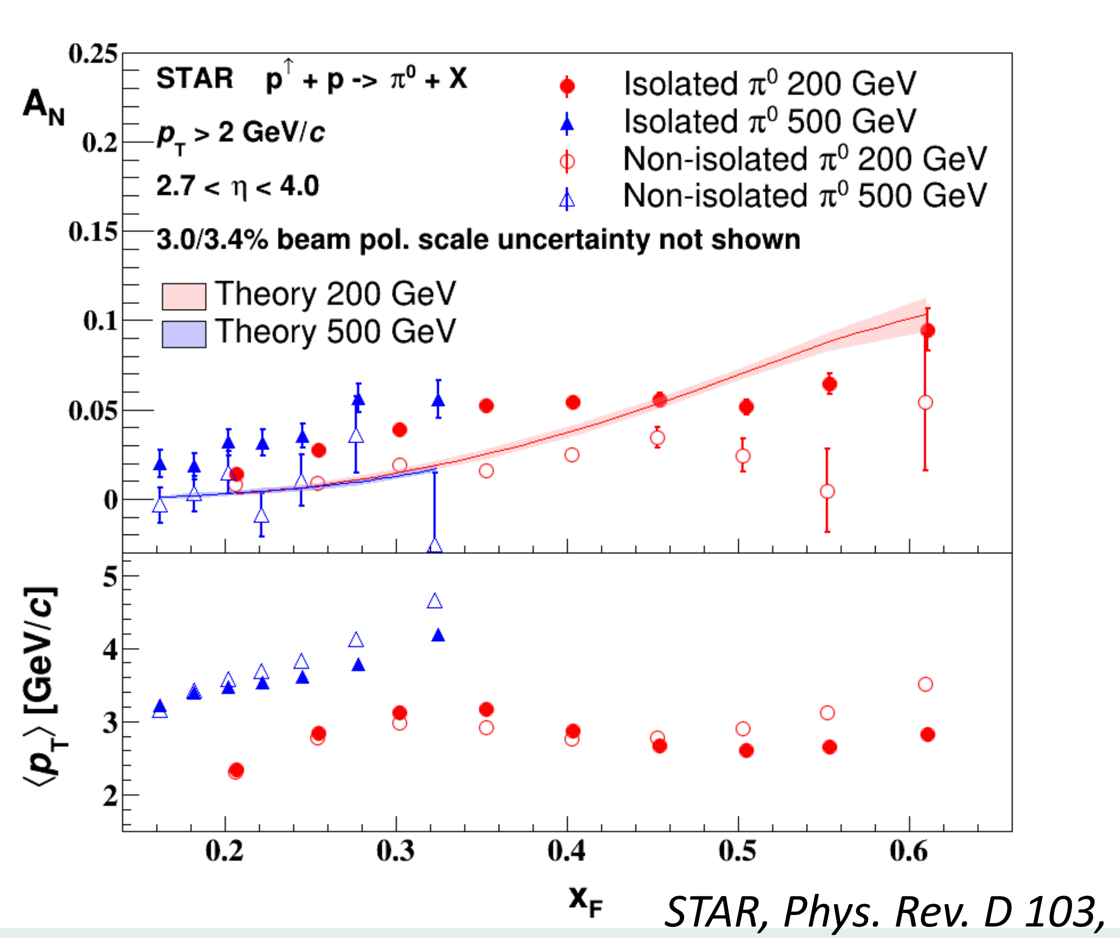
- Motivation: investigate the π^0 event topology (π^0 with no other particle around)
- Method: in a surrounding area (in η-φ space, R=0.7), if the π^0 energy fraction > 98%, it is defined as isolated. If the π^0 energy fraction < 90%, it is defined as non-isolated

Fractions of different types of π^0 event in the overall sample



STAR, Phys. Rev. D 103, 092009

Result- isolated π^0 TSSA



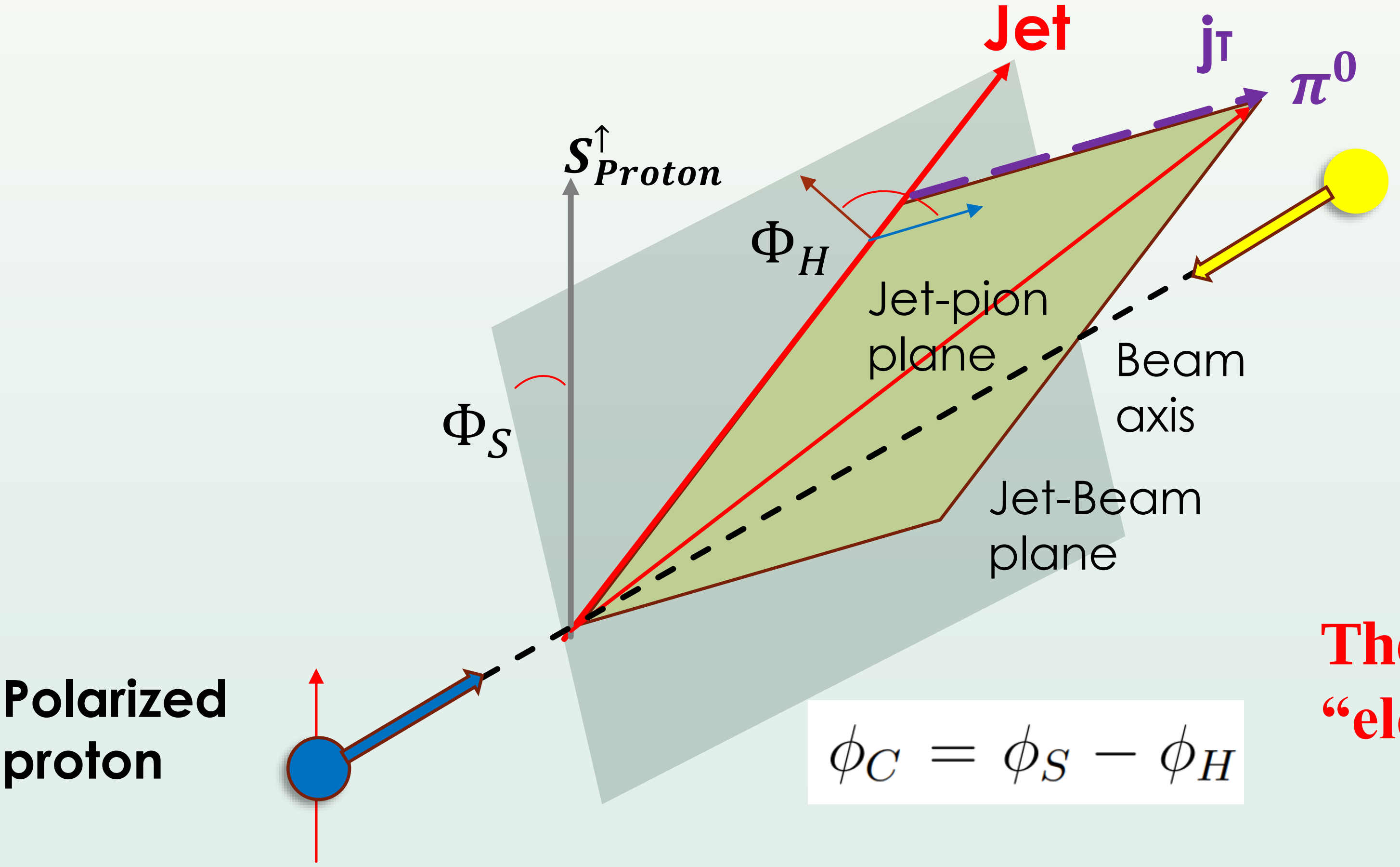
- The TSSAs of the two types of π^0 are significantly different. Isolated π^0 TSSA dominates.
- The physical origin and mechanism accounting for higher TSSA of isolated π^0 is not known yet – implication of a third origin? Diffractive process is a potential candidate.

STAR, Phys. Rev. D 103, 092009
Theory curves:
J. Cammarota et al., Phys.Rev.D 102, 054002

More observables

Jet TSSA – sensitive to the initial state effect.

Collins asymmetry – sensitive to the final state effect.



$$\phi_C = \phi_S - \phi_H$$

The jet here refers to "electromagnetic jet"

More observables

π^0 /EM-jet TSSA vs. Collins asymmetry

$$N^{\uparrow}(\phi) = \epsilon\mathcal{L}^{\uparrow}\sigma^{\uparrow}$$
$$= \epsilon\mathcal{L}^{\uparrow}\,(1 + pol * A_N \cos\phi)\ \ \sigma$$

- Azimuthal angle ϕ
- All π^0 candidates
- Background subtraction for π^0

Collins asymmetry

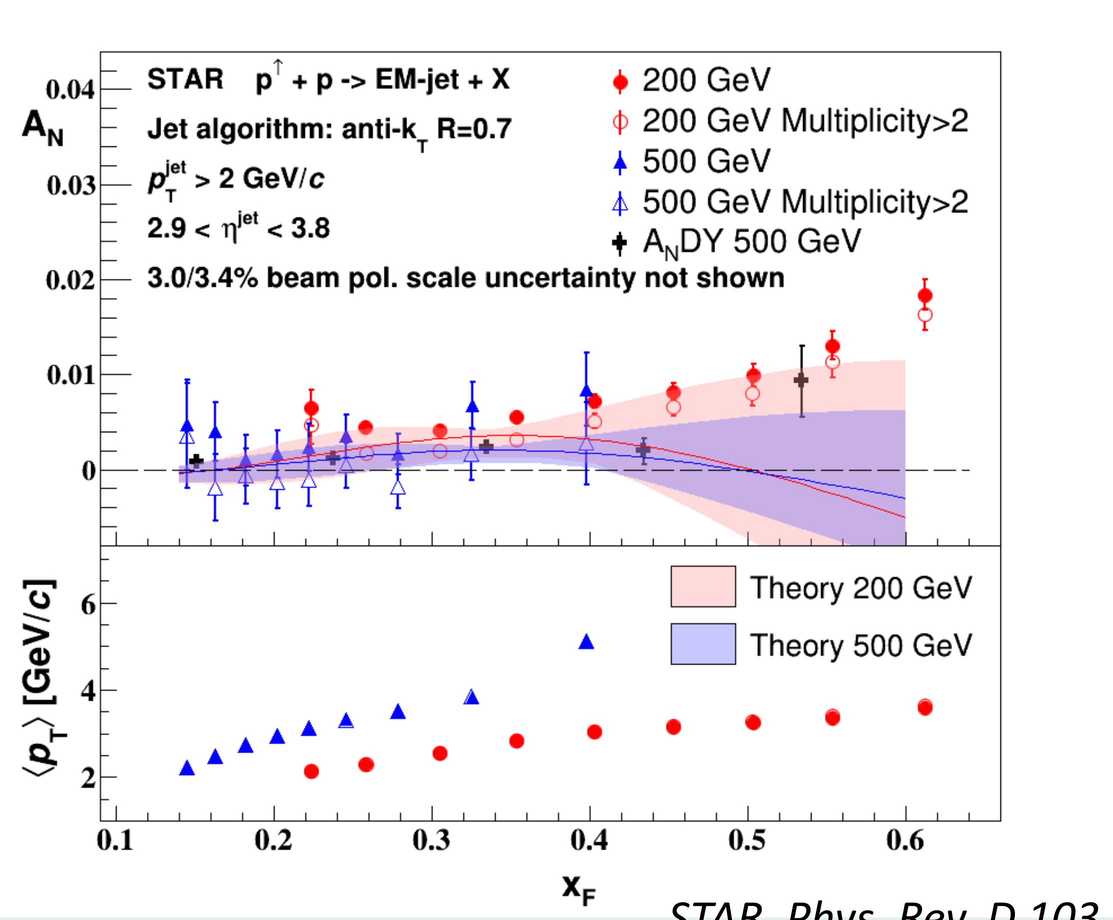
$$N^{\uparrow}(\phi_c) = \epsilon\mathcal{L}^{\uparrow}\sigma^{\uparrow}$$
$$= \epsilon\mathcal{L}^{\uparrow}\,(1 + pol * A_{UT} \sin\phi_c)\ \ \sigma$$

- Collins angle ϕ_c
- Only π^0 within a jet
- No background subtraction

For jet reconstruction and π^0 in a jet :

- anti-k_T R=0.7
- p_T > 2 GeV
- $\sqrt{(\phi_{\pi^0} - \phi_{jet})^2 + (\eta_{\pi^0} - \eta_{jet})^2} < 0.04$

Result- jet TSSA

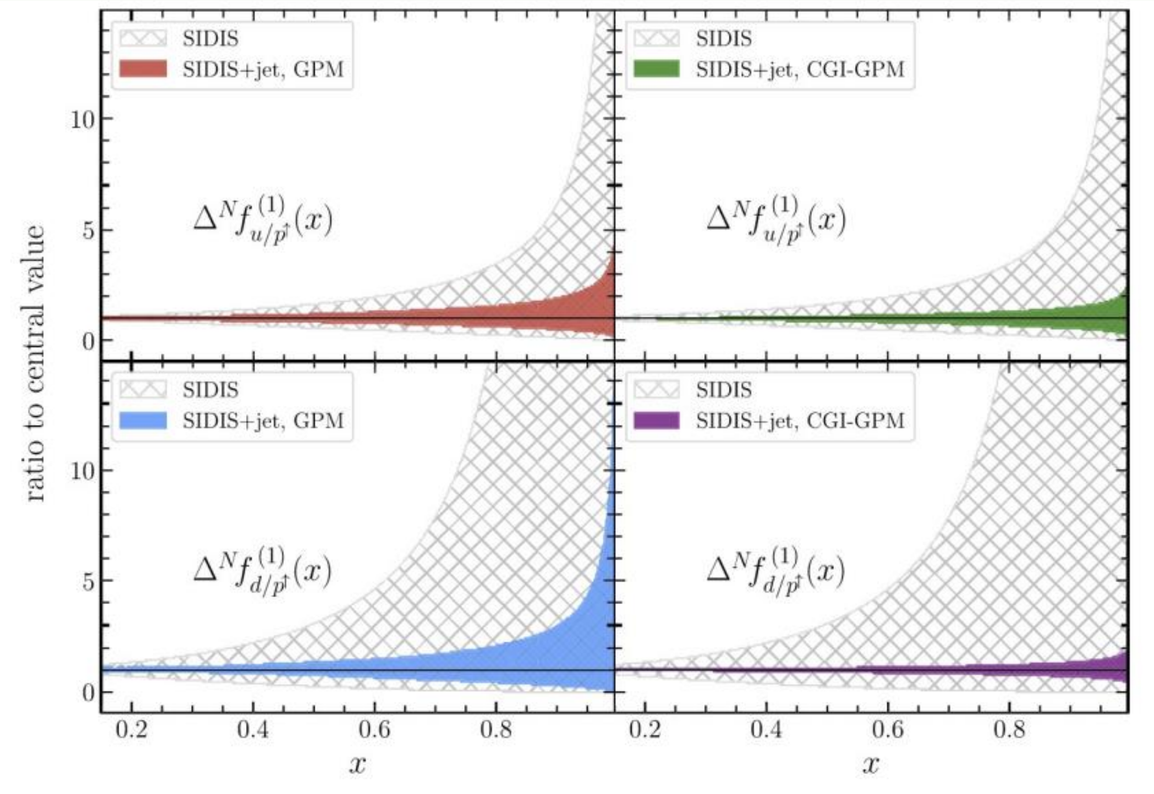


- The jet TSSA is a few times smaller than the π^0 TSSA in the same x_F bin.
- Jets with minimum photon multiplicity requirement have significantly smaller TSSA.
- The $A_N DY$ result shows the TSSA of full jets, and is consistent with the result of the EM-jets having at least 3 photons.

STAR, Phys. Rev. D 103, 092009
Theory curves:
L. Gamberg et al., Phys.Rev.Lett. 110,232301

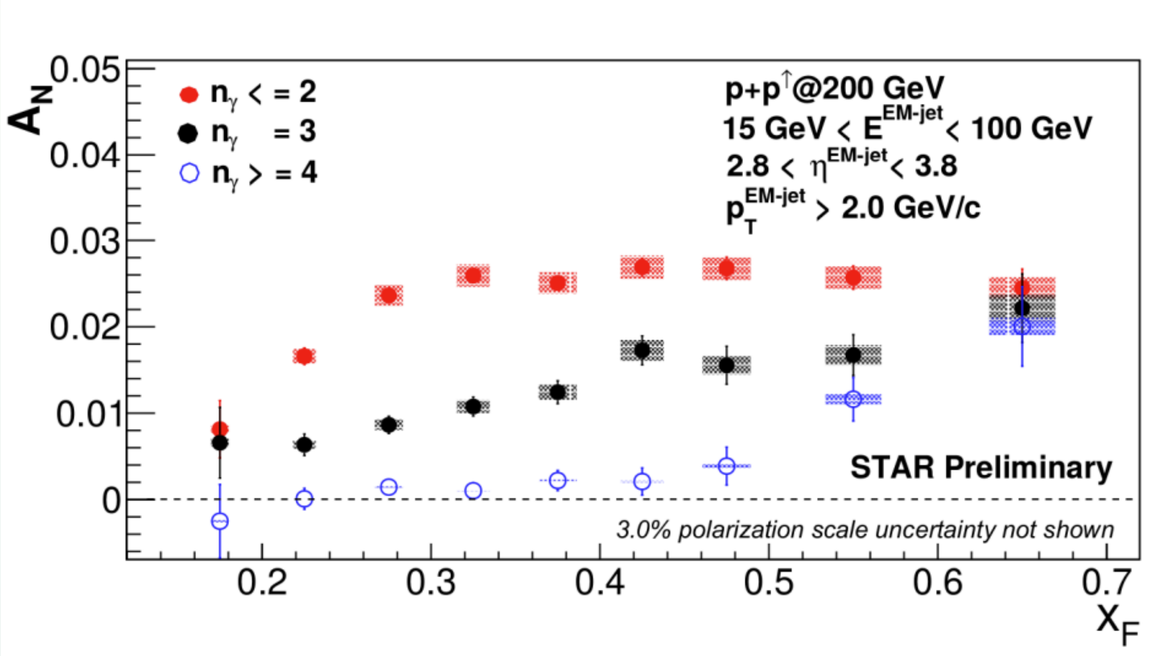
Result- jet TSSA

- Impact: greatly reduce the uncertainty of the u/d quark Sivers function at large x

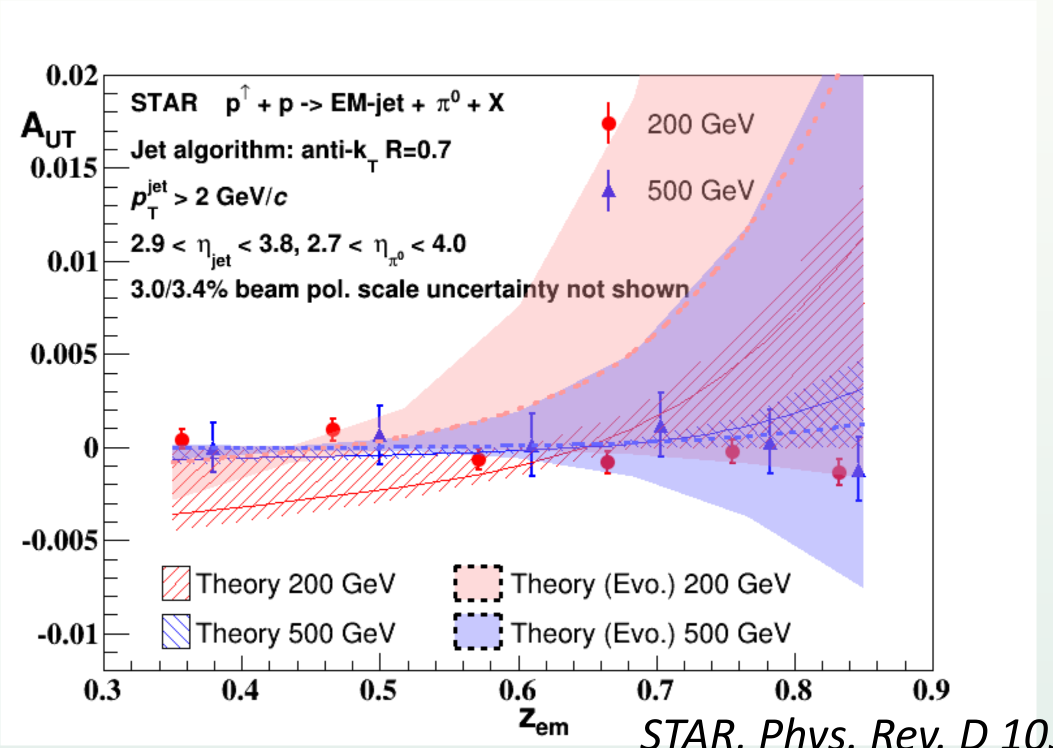


M. Boglione et al., Phys.Lett.B 815, 136135

- Follow up work at STAR: EM-jet TSSA decreases with increasing photon multiplicity (more "jet-like")



Result- Collins asymmetry for π^0 in a jet



$$Z_{em} = \frac{E_{\pi}}{E_{jet}}$$

STAR, Phys. Rev. D 103, 092009
Theory curves:
Z. Kang et al., Phys.Lett.B 774,635

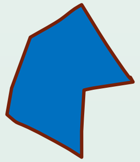
- The Collins asymmetries are very small at both energies, which reflects the cancellation of the Collins effect of the u/d quark

The whole landscape

The π^0 TSSAs have multiple sources. Interesting things happen when we break it down:

π^0 TSSA = Initial state effect + Final state effect + Unclear source

Jet TSSA

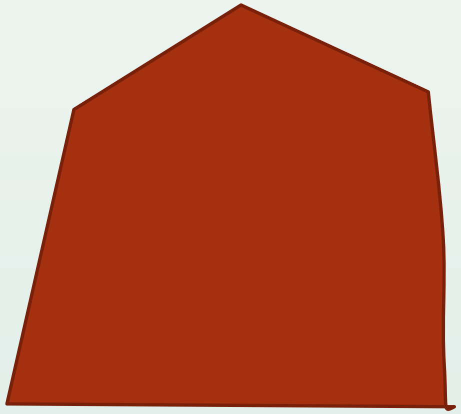


Initial state effect

Collins asymmetry

Final state effect

Isolated π^0 TSSA



Unclear source
(Diffractive process?)

Summary

- We measured the π^0 /jet TSSA and Collins asymmetry using the FMS in STAR 200 and 500 GeV p-p data
- We investigated the π^0 event topology. The mechanism for the higher TSSAs of the isolated π^0 remains unclear. It offers new perspectives to the origin of TSSA
- We measured the jet TSSAs and Collins asymmetry to separate contributions from initial and final state effects, both of which are small
- These measurements together provide important inputs for further investigation for TSSA
- This work has been Published in Phys. Rev. D 103, 092009 in 2021