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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Outline

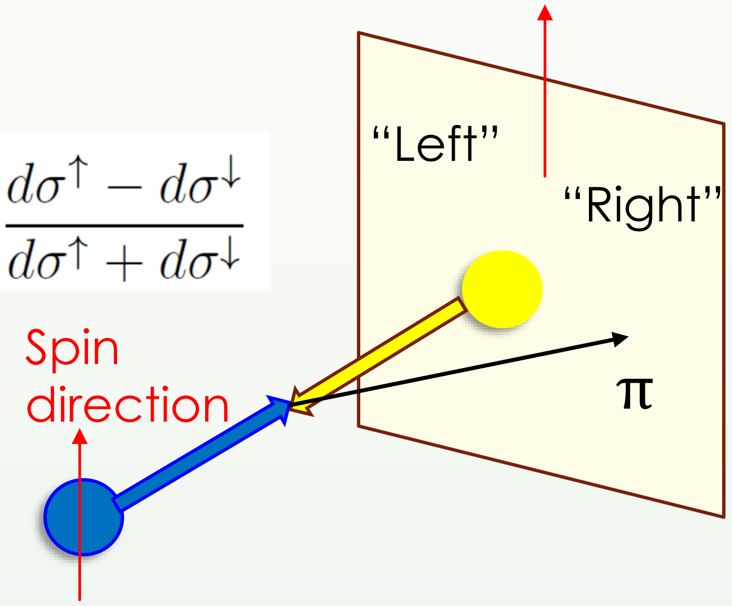
- Motivation
- Experiment setup
- Analysis:
    - Dataset
    - Asymmetry calculation
    - Systematic uncertainty
- Result and discussion
- Summary

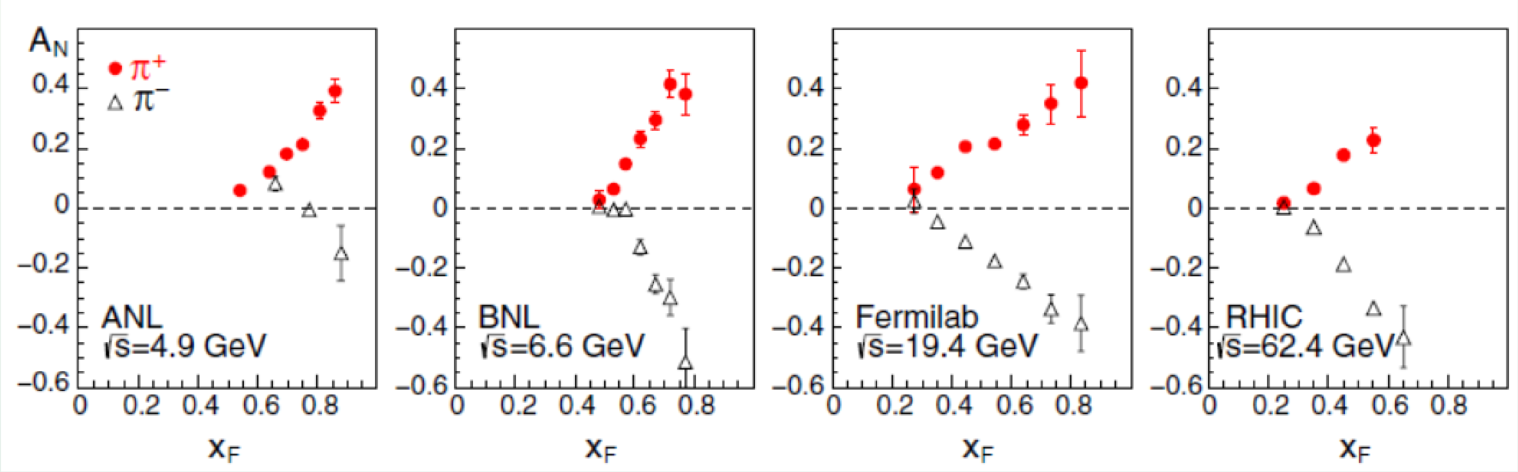
Preprint available in arXiv:2012.11428
Accepted for publication in PRD

Motivation

- Transverse single spin asymmetry(TSSA/A_N)
- The large forward TSSA was first found 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(2013)

- A lot of work was done to explore the underlying mechanisms in the past few decades

Motivation

- Transverse momentum dependent PDF(TMD)
- Collinear twist-3 factorization

These two models have different energy scale requirements, but they share some similarities

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

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

Sivers function

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

Transversity $\otimes$ **Collins function**

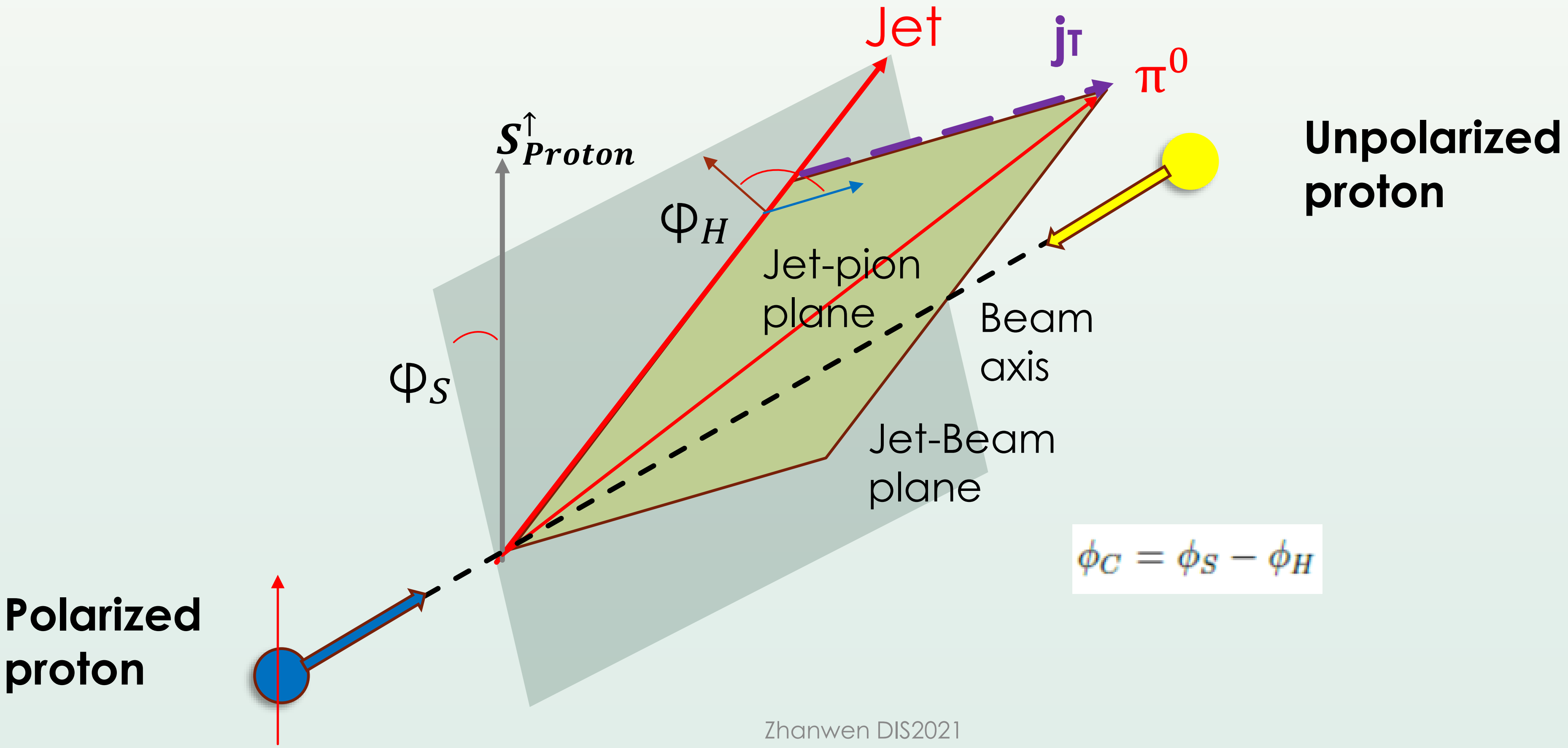
Both effects can contribute to the TSSA.

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

Motivation

Jet TSSA – sensitive to the initial state effect.

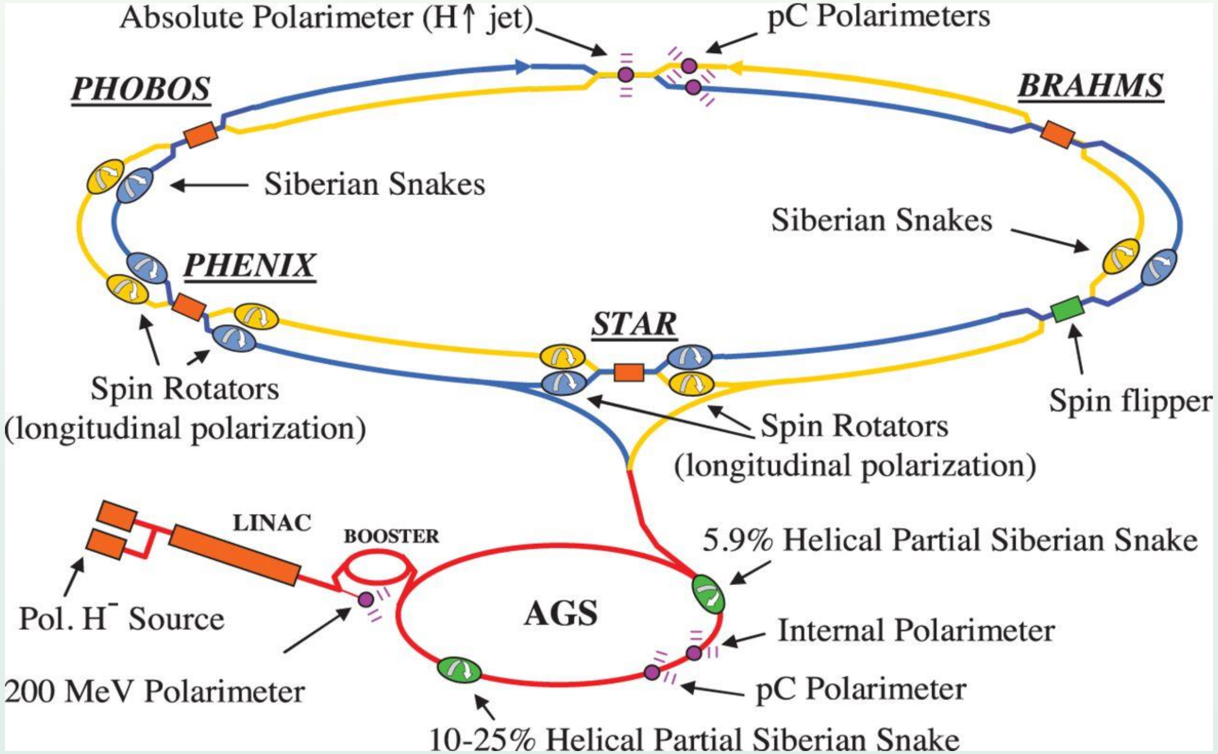
Collins asymmetry – sensitive to the final state effect.

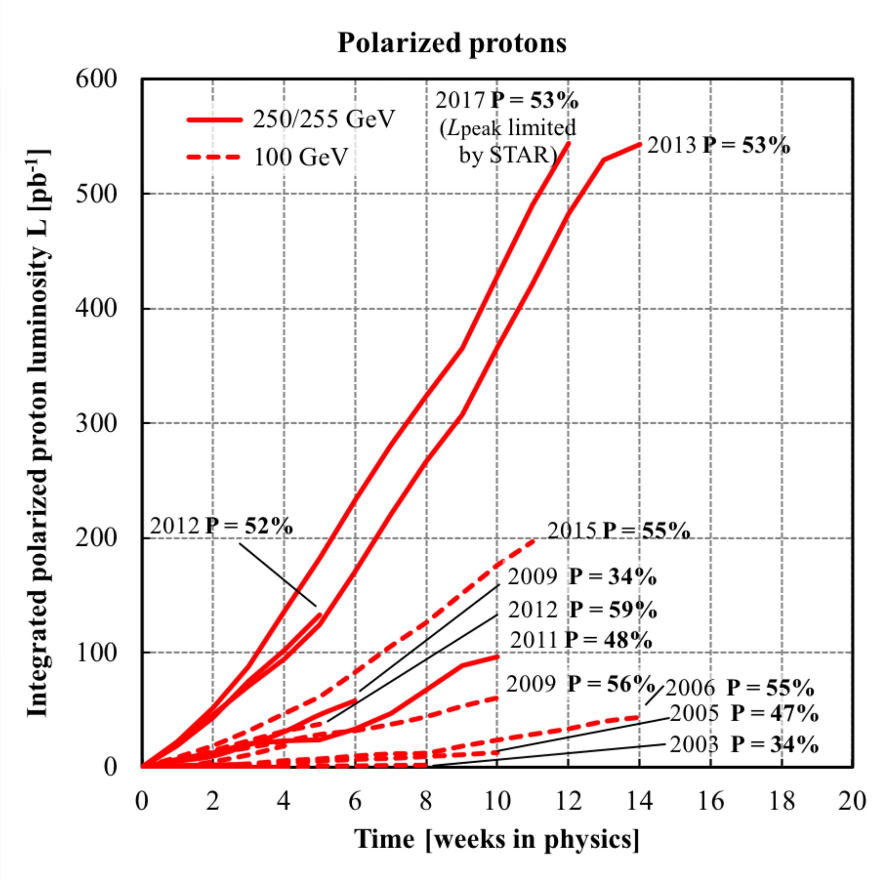


$$\phi_C = \phi_S - \phi_H$$

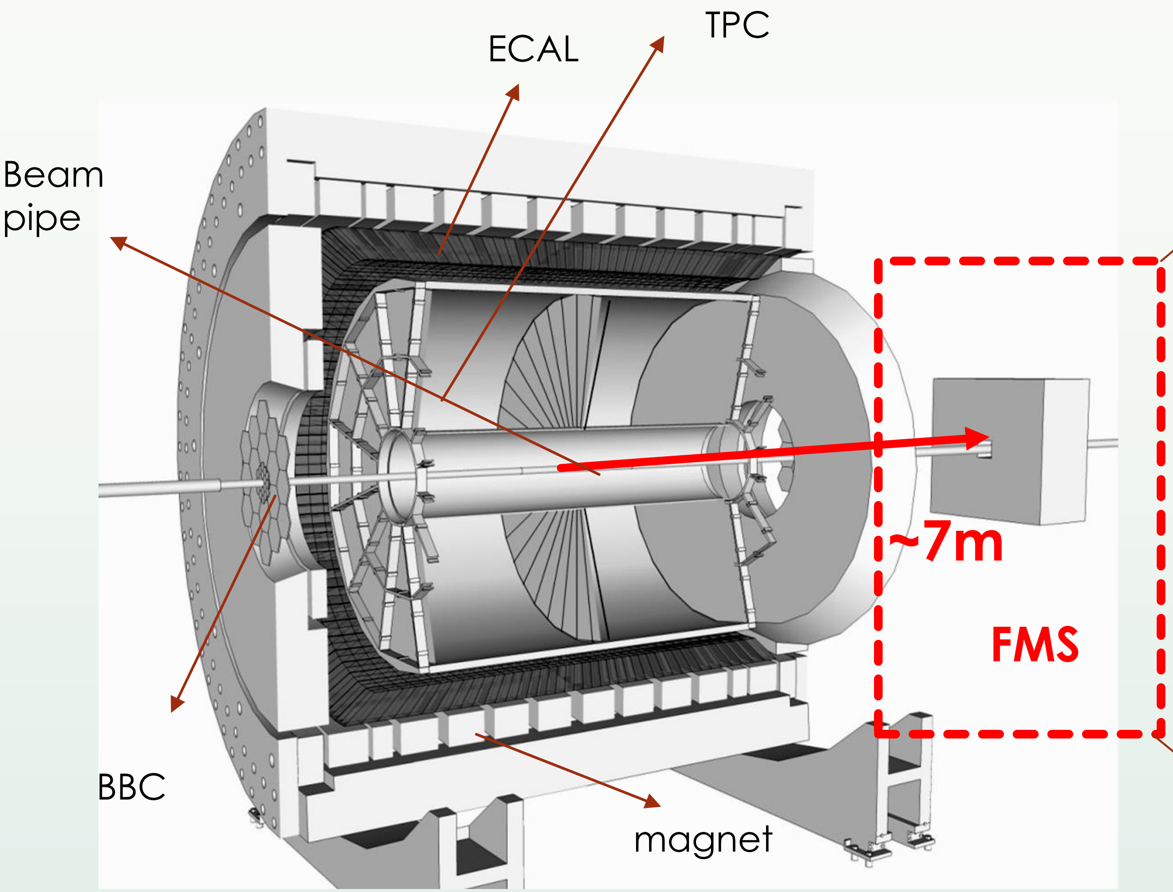
Experiment Setup- RHIC & STAR

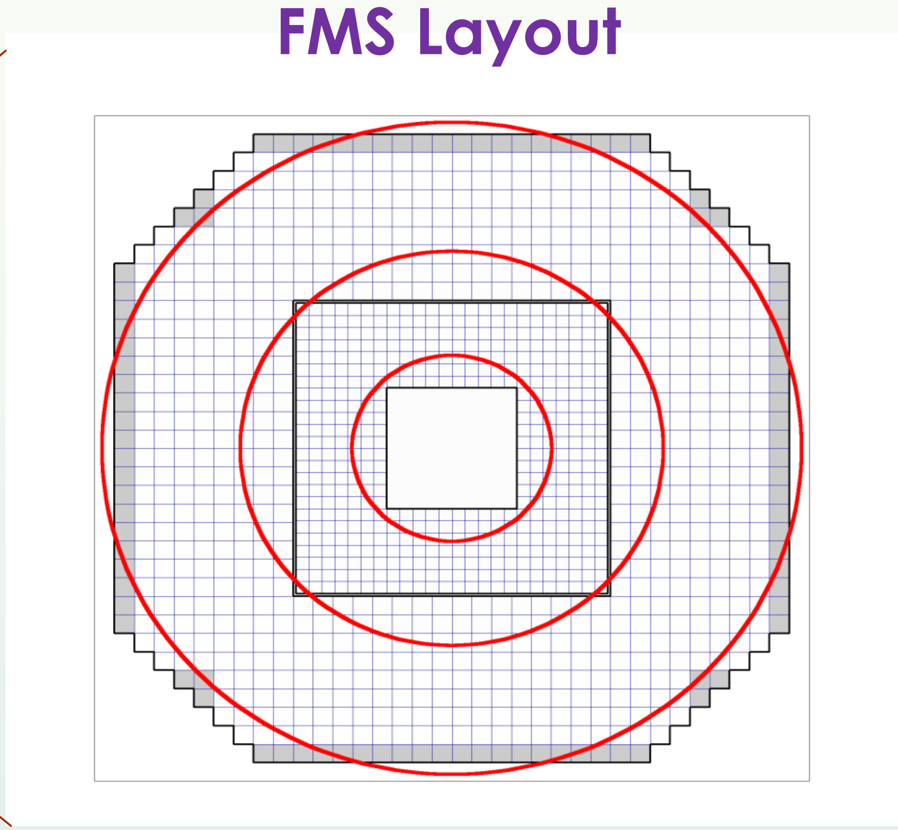
- The **R**elativistic **H**eavy **I**on **C**ollider at BNL provides unique opportunity to study spin physics because it is the world's only polarized proton-proton collider.





Experiment Setup- STAR & FMS





- EM-Calorimeter made of 1000+ lead glass cells
- Large pseudo-rapidity range 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

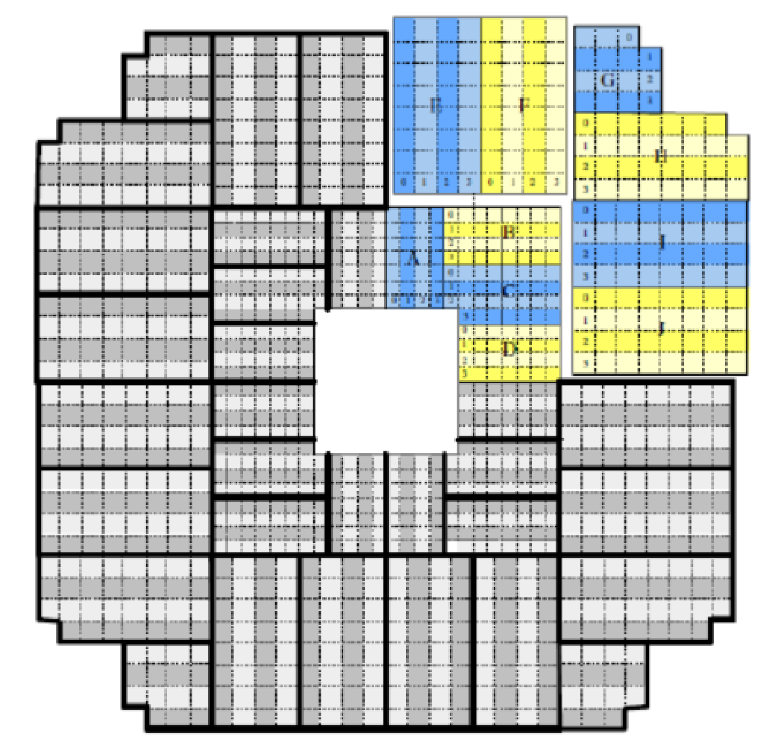
Beam polarization:

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



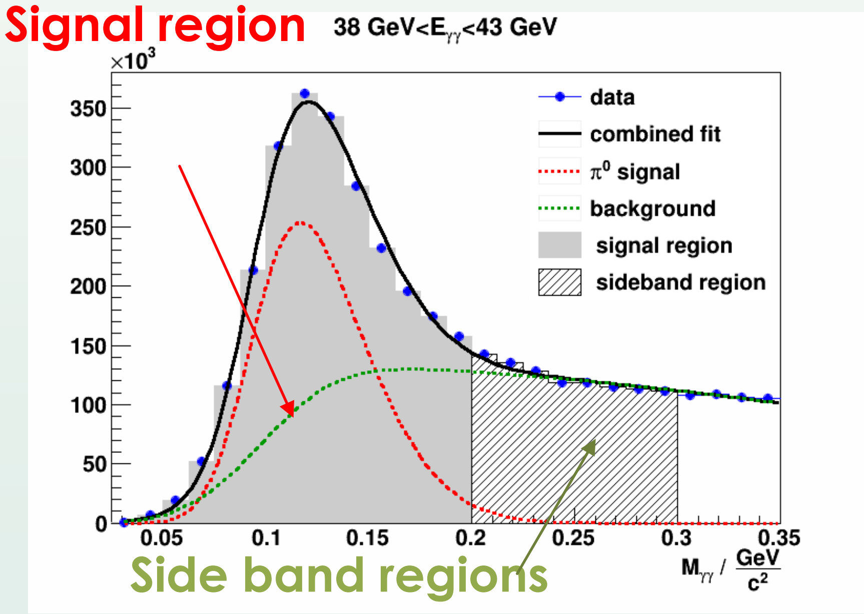
Analysis- Asymmetry calculation

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

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



STAR, arXiv:2012.11428

- Background subtraction

The fraction comes from the fitting of the mass spectrum

Signal/background shapes are from simulation

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

Analysis- Collins Asymmetry

π^0 /EM-jet TSSA

vs.

Collins asymmetry

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

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

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

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

For jet reconstruction:

- Anti-kT R=0.7
- $p_T > 2$ GeV

For π^0 in a jet :

- $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.04$

The jet is only "electromagnetic jet"

Analysis- Systematic uncertainty

Uncertainties:

- π^0/jet energy scale uncertainty (x_F and z_{em}): calibration, non-linear response, radiation damage
- π^0 TSSA: background subtraction
- Beam polarization

Analysis	Uncertainties types (Run-11/Run15)		
π^0 TSSA	x_F	Asymmetry	Beam polarization
	4.4%/3.0%	5.8%	3.4%/3.0%
Jet TSSA	x_F	Asymmetry	Beam polarization
	7.8%/8.5%	–	3.4%/3.0%
Collins Asymmetry	z_{em}	Asymmetry	Beam polarization
	8.9%/9.0%	–	3.4%/3.0%

Corrections:

- Jet TSSA: background correction, underlying event correction, correction to particle level
- Collins asymmetry: Collins angle resolution correction

Analysis- Observables

All measurements are done in 200 GeV (2015) and 500 GeV (2011) p+p collision

- 1) π^0 TSSA: **initial+final** state effect

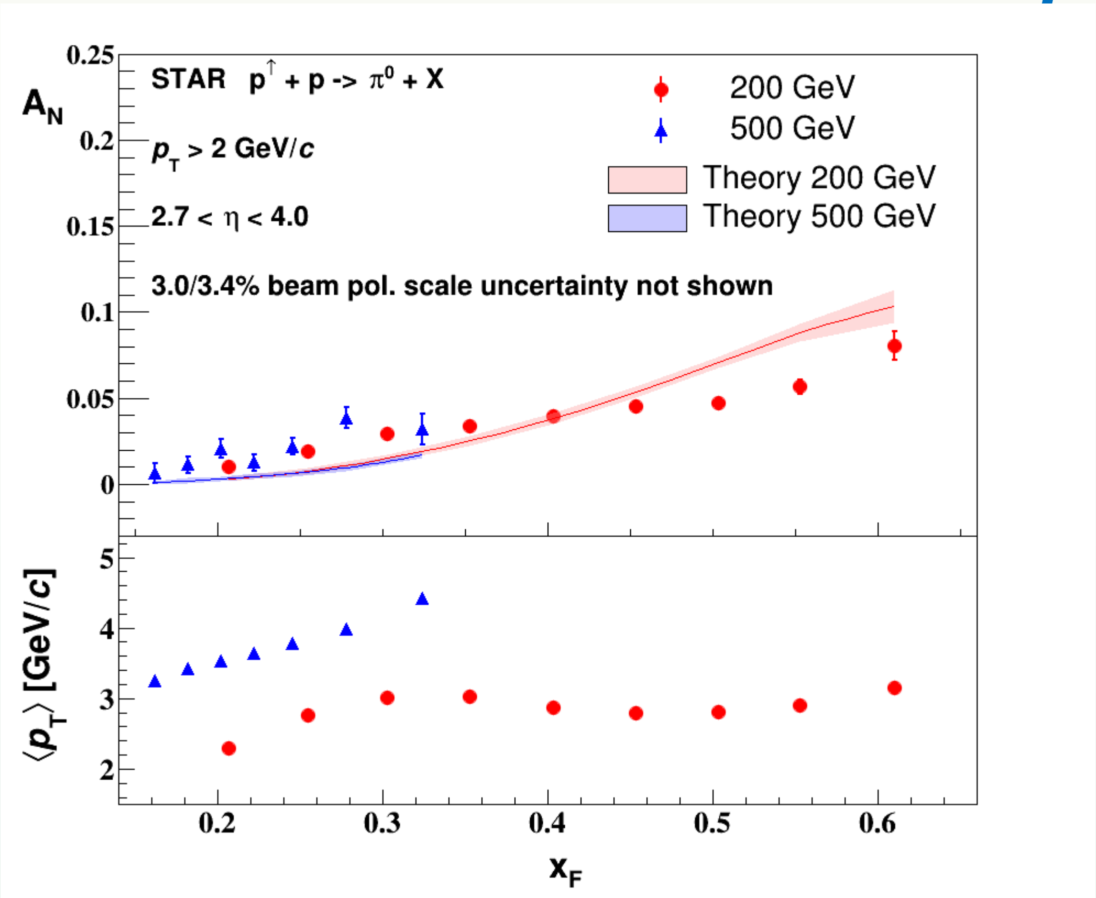
  TSSA as a function of Feynman-x (x_F) ; $x_F = \frac{E_L^{\pi^0}}{E_{beam}}$

  TSSA as a function of p_T ;

  Isolated/non-isolated π^0 A_N as a function of Feynman-x
- 2) Jet TSSA : **initial** state effect
- 3) Collins Asymmetry : **final** state effect

The jets used in 2) 3) are electromagnetic jet (EM-jet)

Result- π^0 TSSA vs. x_F



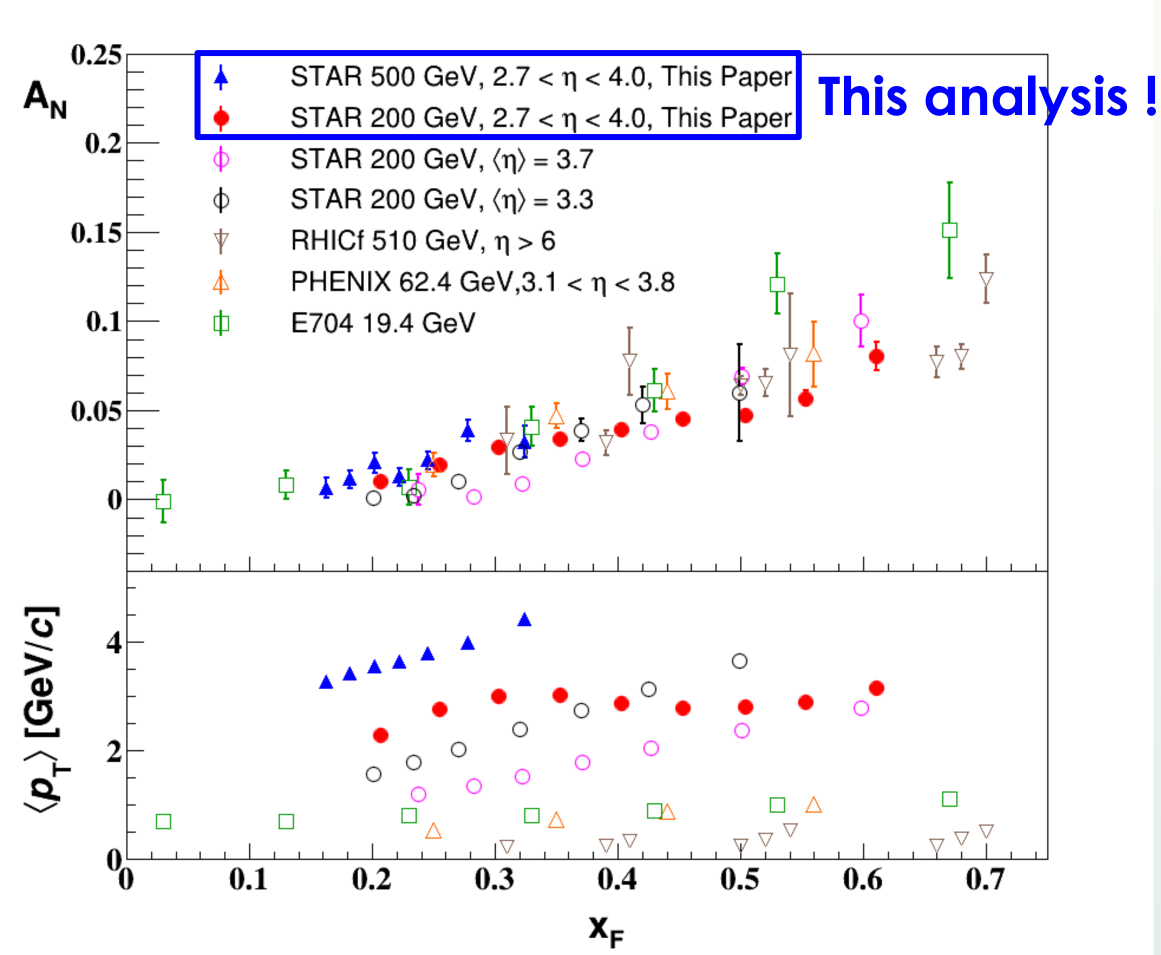
STAR, arXiv:2012.11428

Theory curves:
J. Cammarota, et al.
Phys.Rev.D.102.054002

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

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

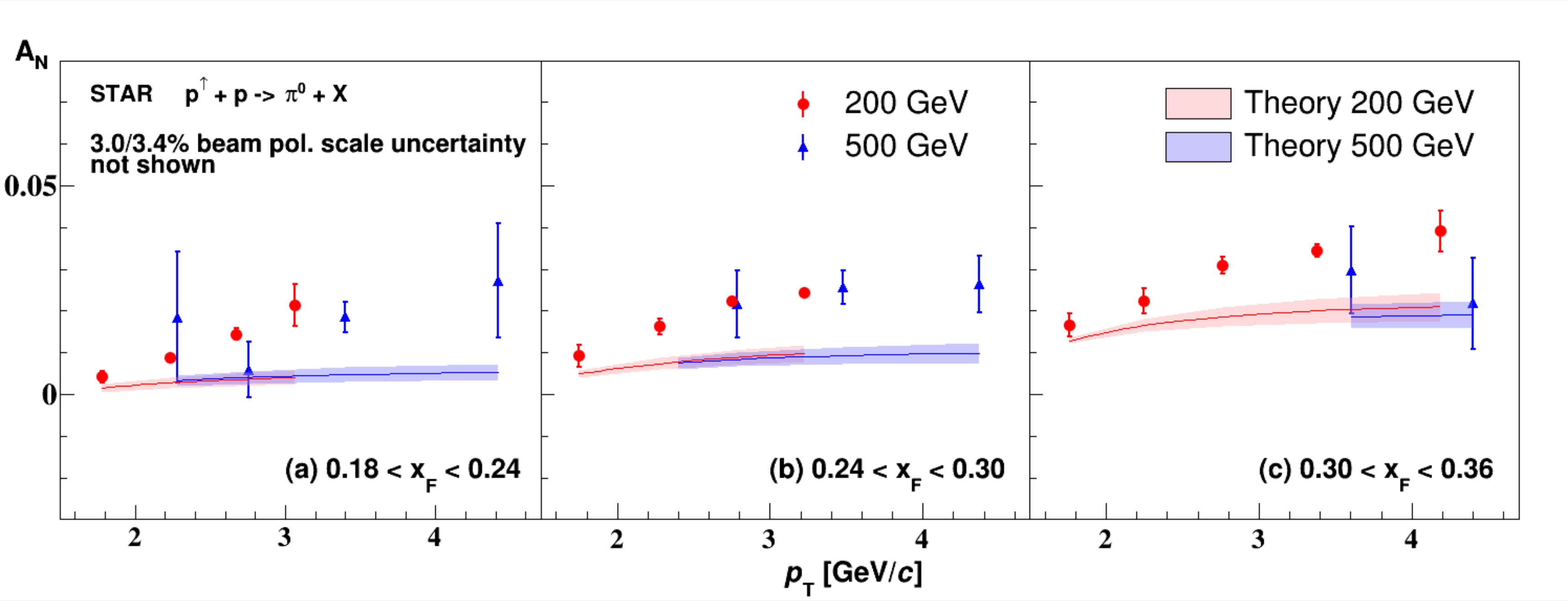
Comparison to previous measurements



STAR, arXiv:2012.11428

- Weak collision energy dependence of the π^0 TSSA from 19.4 to 500 GeV
- Comparison to the previous Forward Pion Detector results at STAR shows larger TSSA in current measurement, which can be explained by the higher average p_T

Result- π^0 TSSA vs. p_T



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Phys.Rev.D.102.054002

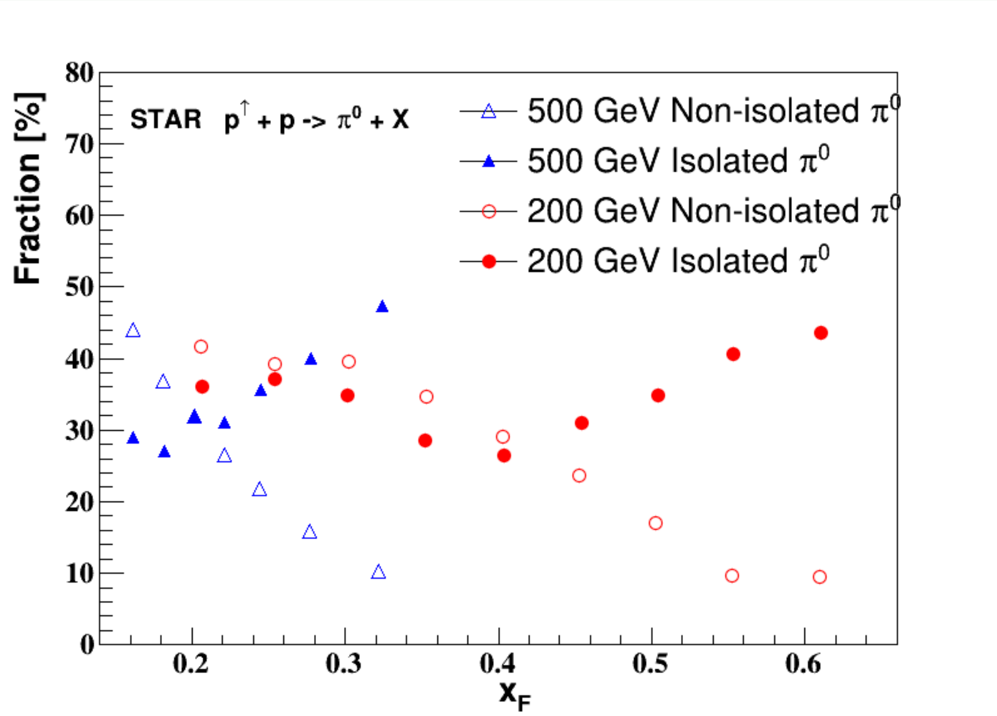
STAR, arXiv:2012.11428

- ❑ Overlapping x_F region between 200 GeV and 500 GeV results.
- ❑ The 200 GeV data shows significant increase of TSSA below 3 GeV.
- ❑ The 500 GeV data flattens 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 takes most of the total energy, it is defined as isolated. The cut is placed at an energy fraction z=0.9 and 0.98

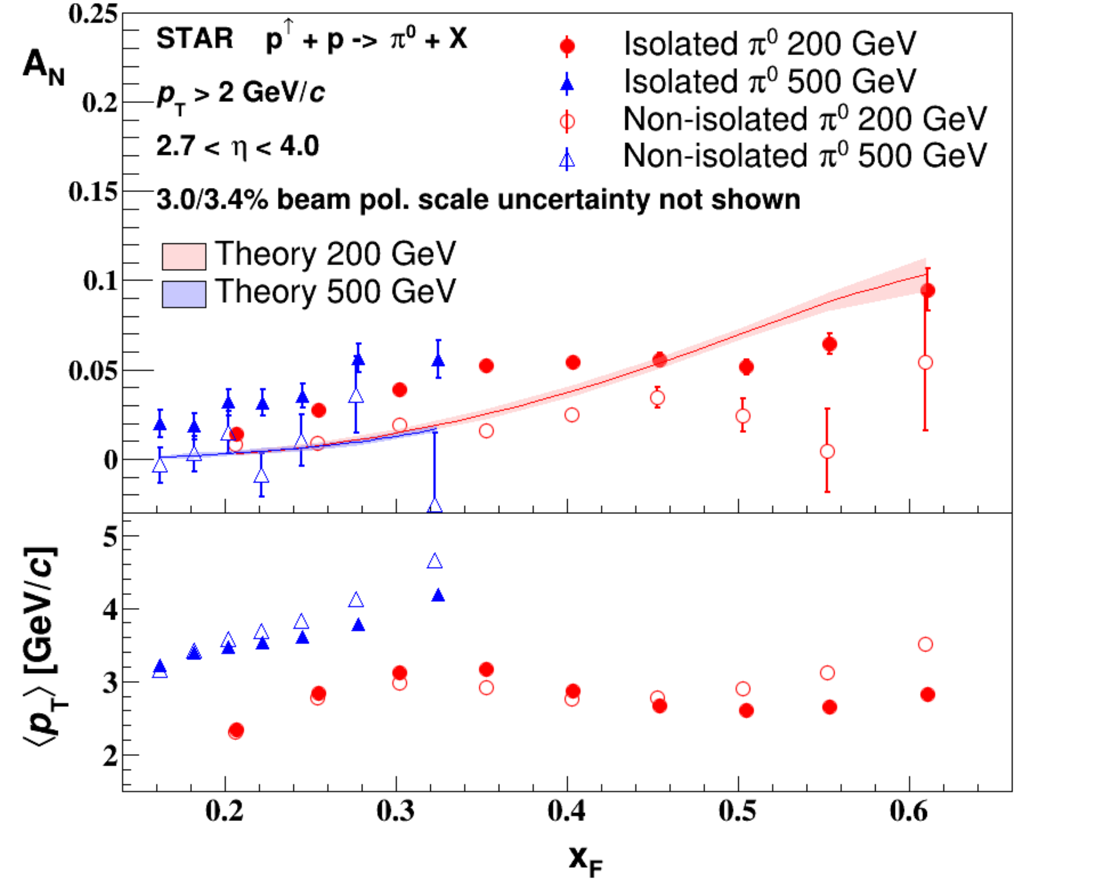
Fractions of different types of π^0 event in the overall sample



STAR, arXiv:2012.11428

Result- isolated π^0 TSSA

STAR, arXiv:2012.11428

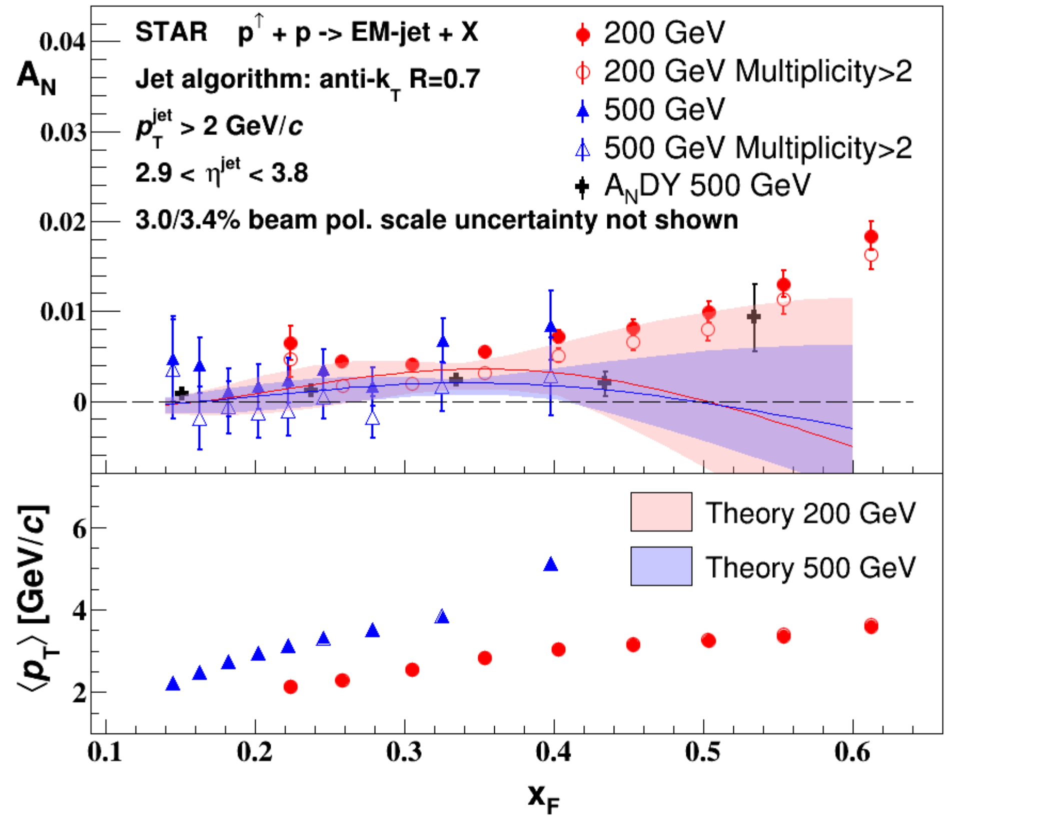


Theory curves:
J. Cammarota, et al.
*Phys.Rev.D.*102.054002

- 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?

Result- jet TSSA

STAR, arXiv:2012.11428

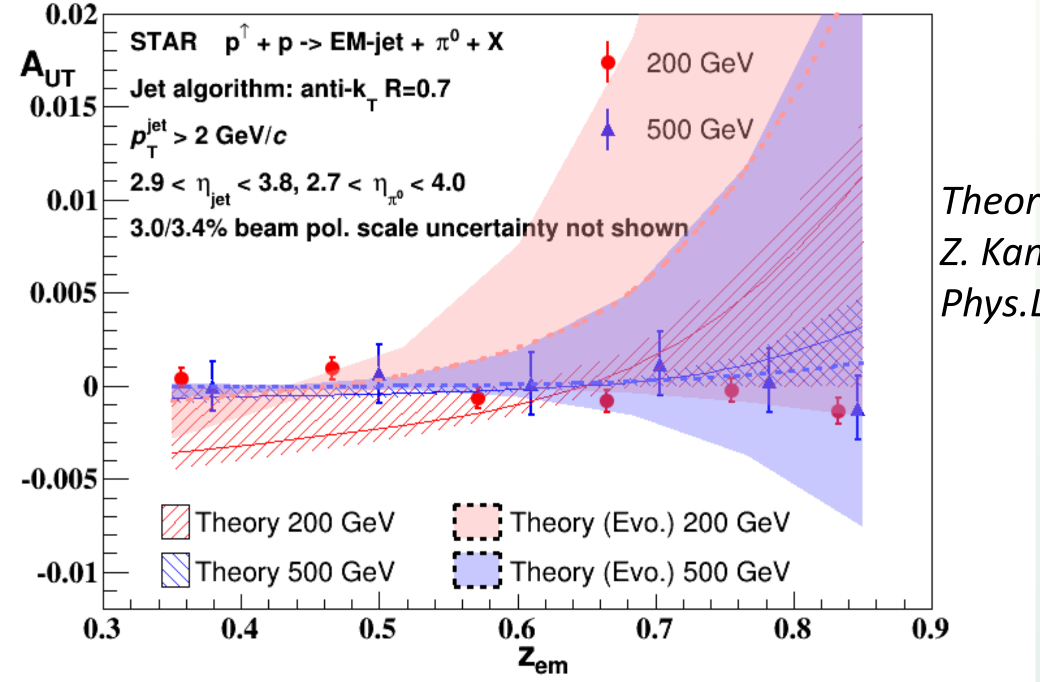


- The jet TSSA is a few times smaller than the π^0 TSSA in the same x_F bin.
- Jets with minimum photon multiplicity requirement have significantly smaller TSSA.
- The $A_N DY$ result shows the TSSA of full jets, and is consistent with the result of the EM-jet having at least 3 photons.

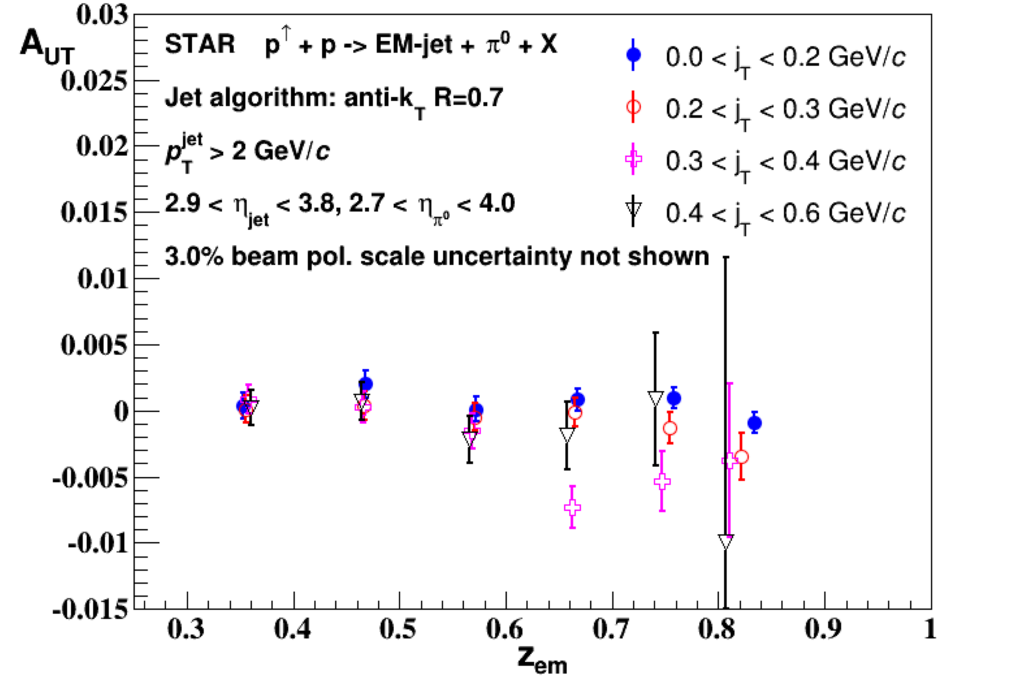
Theory curves:
L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.110,232301

Result- Collins Asymmetry for π^0 in a jet

STAR, arXiv:2012.11428



Theory curves:
Z. Kang , et al.
Phys.Lett.B774,635 (2017)



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

$$j_T = E_\pi \ \text{projection perpendicular to jet}$$

- ❑ The Collins asymmetries are very small at both energies
- ❑ This reflects the cancellation of the Collins effect of the u/d quark
- ❑ Weak j_T dependence is observed

Summary

- We measured the π^0 /jet TSSA and Collins asymmetry using the FMS in STAR 200 and 500 GeV p-p data
- The π^0 TSSA results show weak energy dependence through 20 to 500 GeV
- We investigated the π^0 event topology. The isolated π^0 TSSAs are significantly larger than the non-isolated π^0 , the mechanism of which 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 provide important inputs for further investigation for TSSA