# Measurement of Transverse Single Spin Asymmetry at Forward Rapidity by the STAR Experiment at $\sqrt{s}$= 200 and 500 GeV

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# Outline

- Motivation
- Experiment setup
- Analysis:
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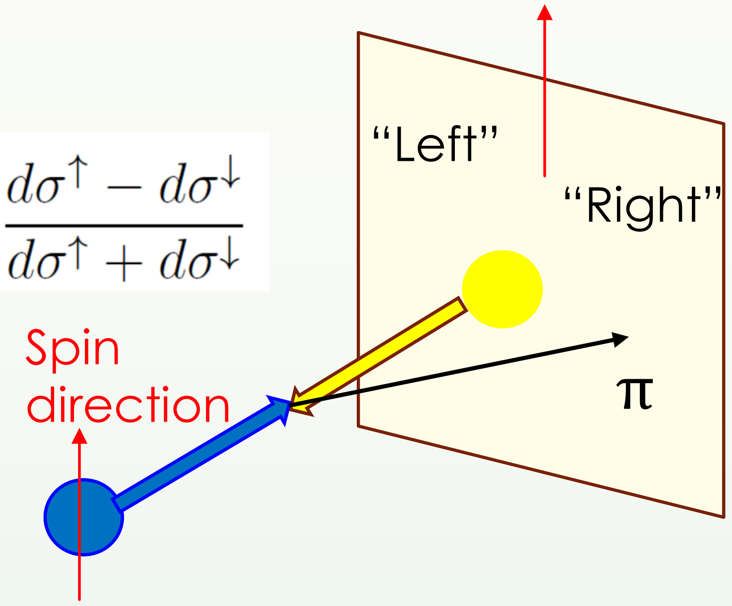
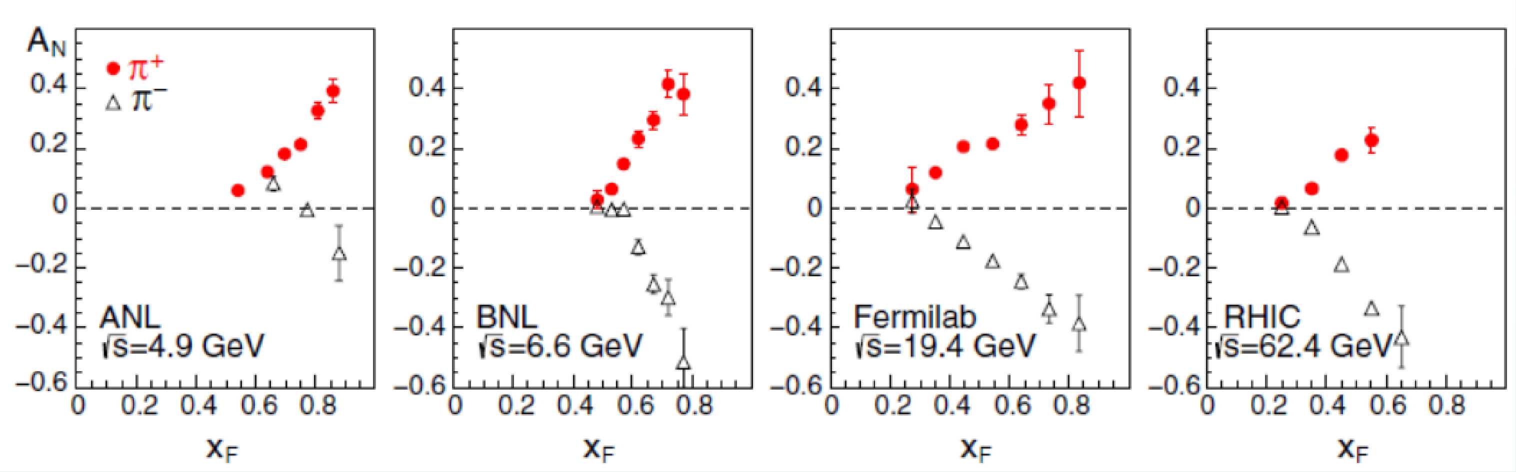
  - Photon/$\pi^0$ reconstruction
  - Asymmetry calculation
  - Systematic uncertainty
- Result and discussion
- Summary

# Motivation

- Transverse single spin asymmetry(TSSA/$A_N$)
- The phenomenon was first founded 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

The models have different energy scale requirements. But they share some similarities

- A decomposition of the contributions of 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**

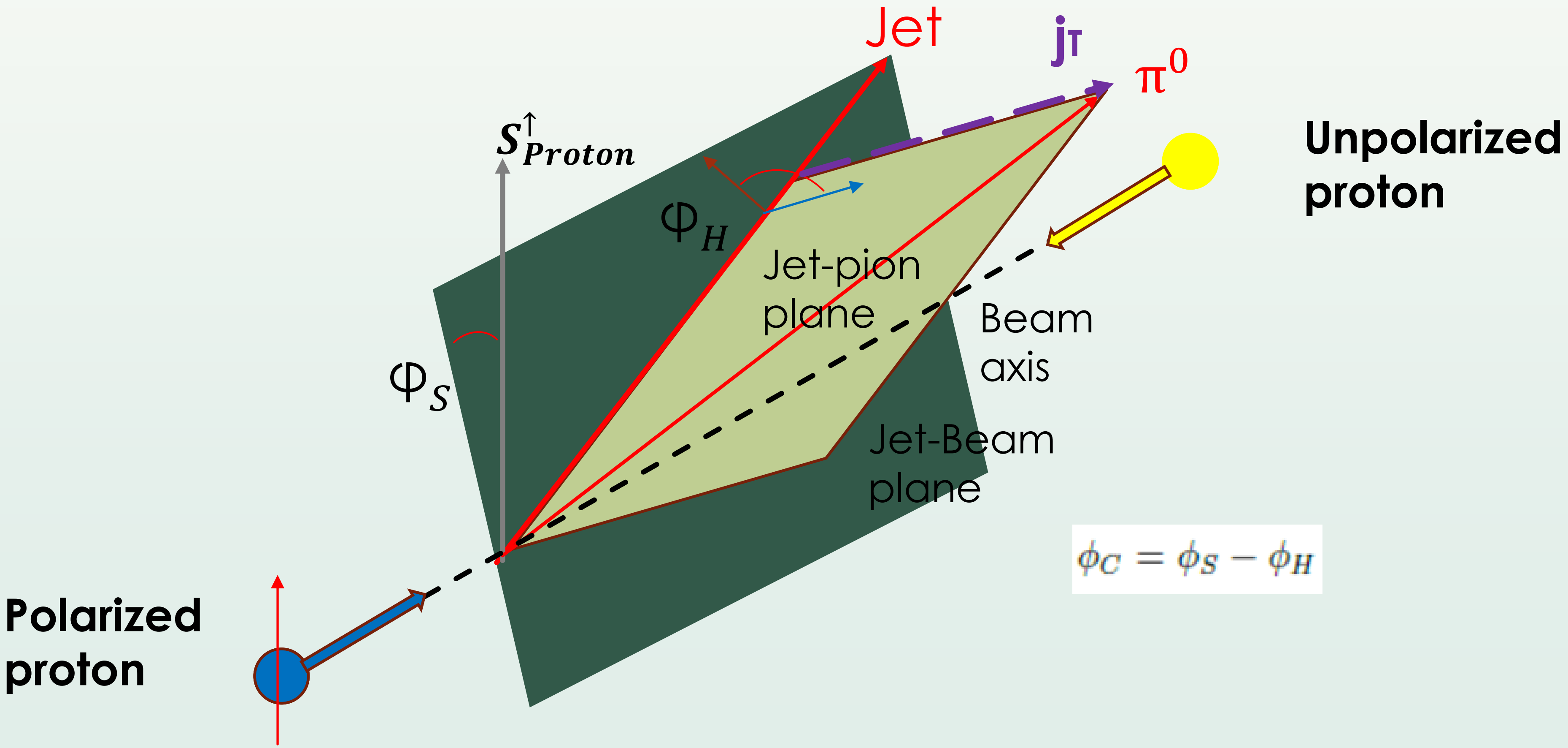
Both effects can contribute to the TSSA.

- Experimental data is very important in validating the factorizations and constraining the distribution functions

# Motivation

**Jet TSSA** – sensitive to the initial state effect.

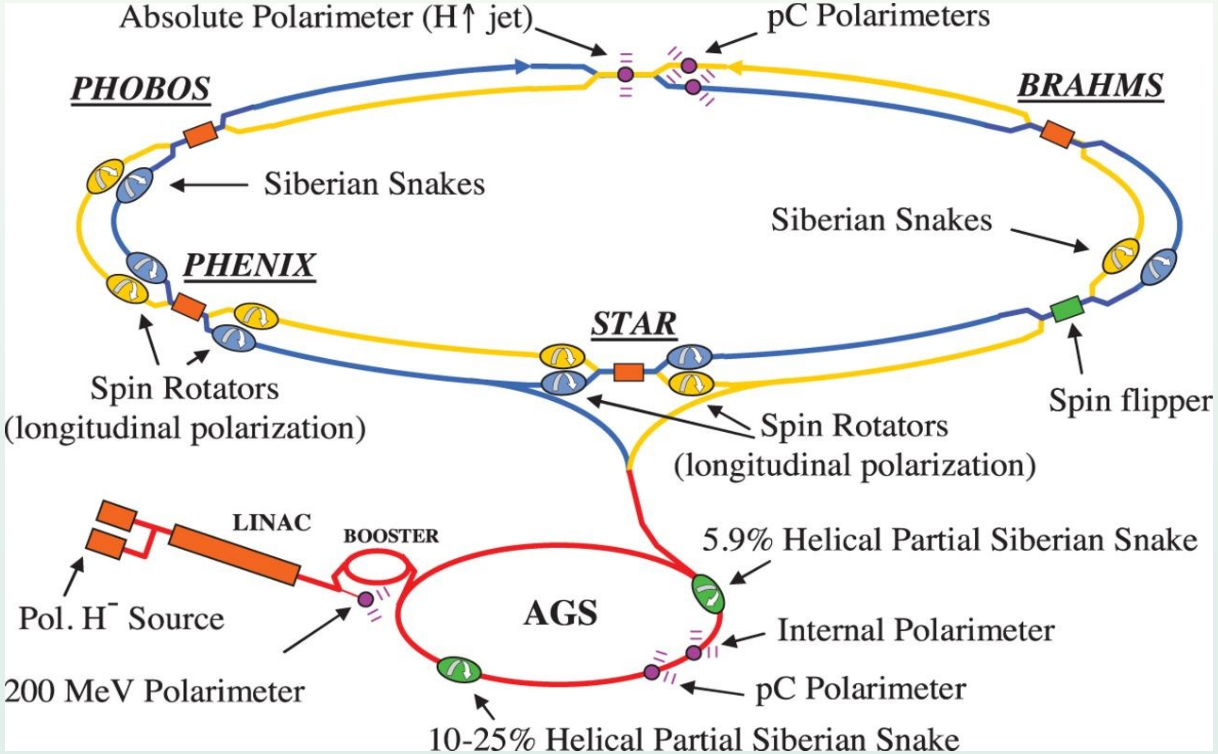
**Collins asymmetry** – sensitive to the final state effect.

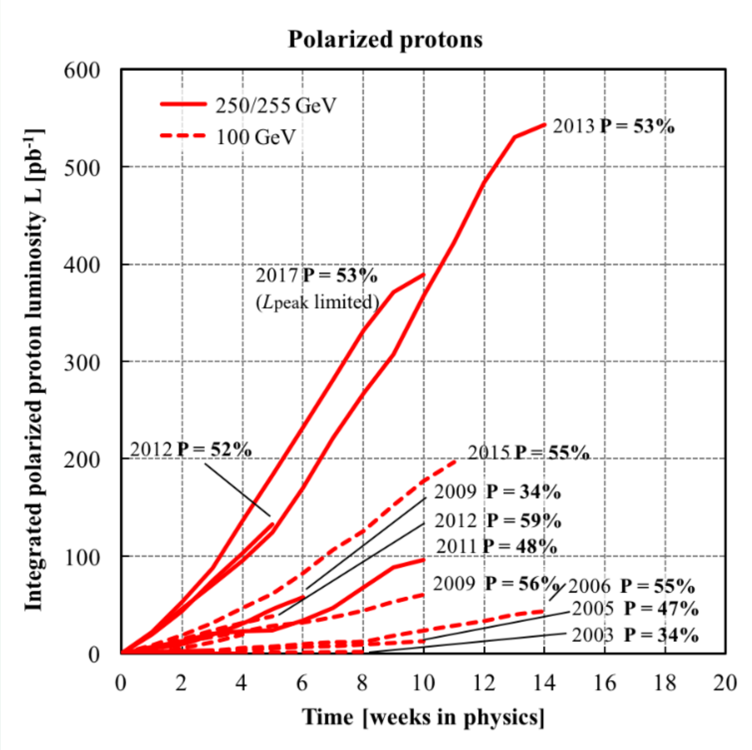



$$\phi_C = \phi_S - \phi_H$$

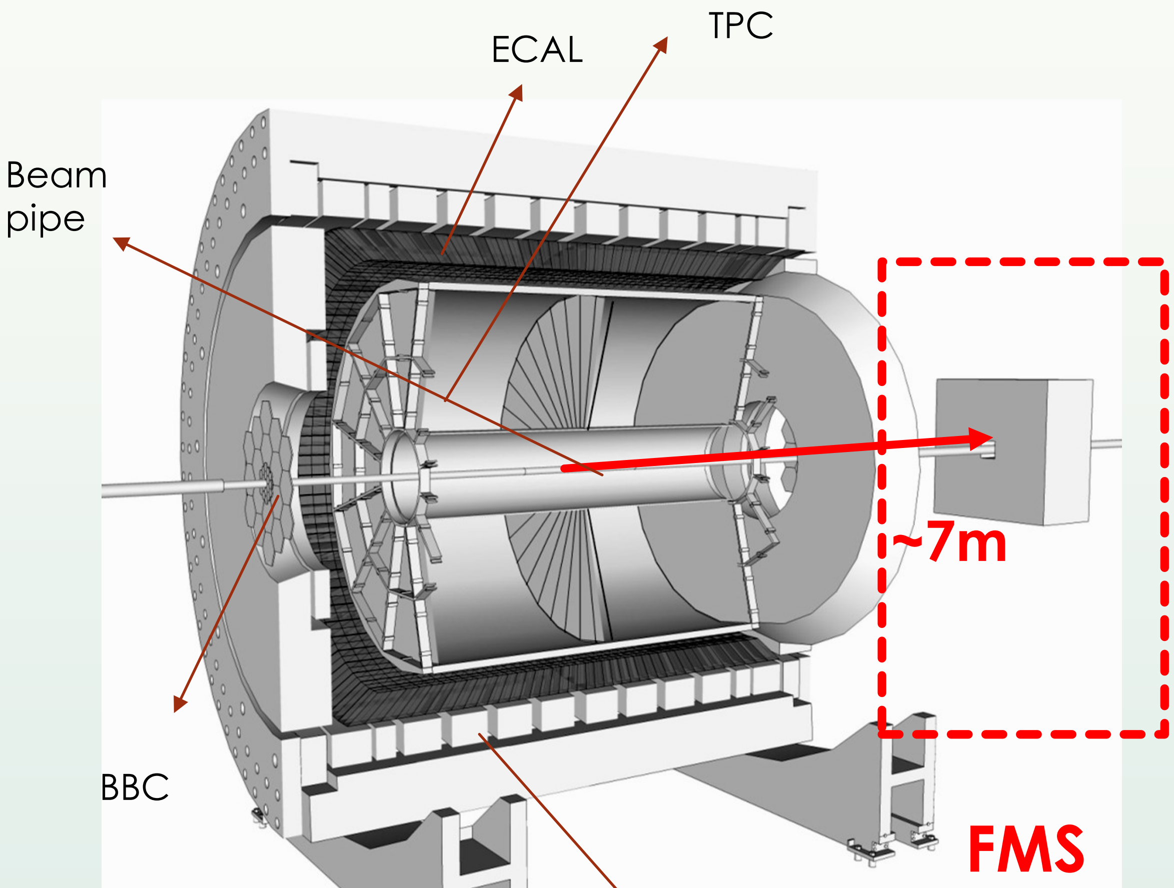
# Experiment Setup-RHIC & STAR

- The **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-RHIC & STAR




**Pseudo-rapidity 2.6 to 4.1**

The **Solenoid Tracker At RHIC** is powerful detector to conduct many different kinds of experiments.

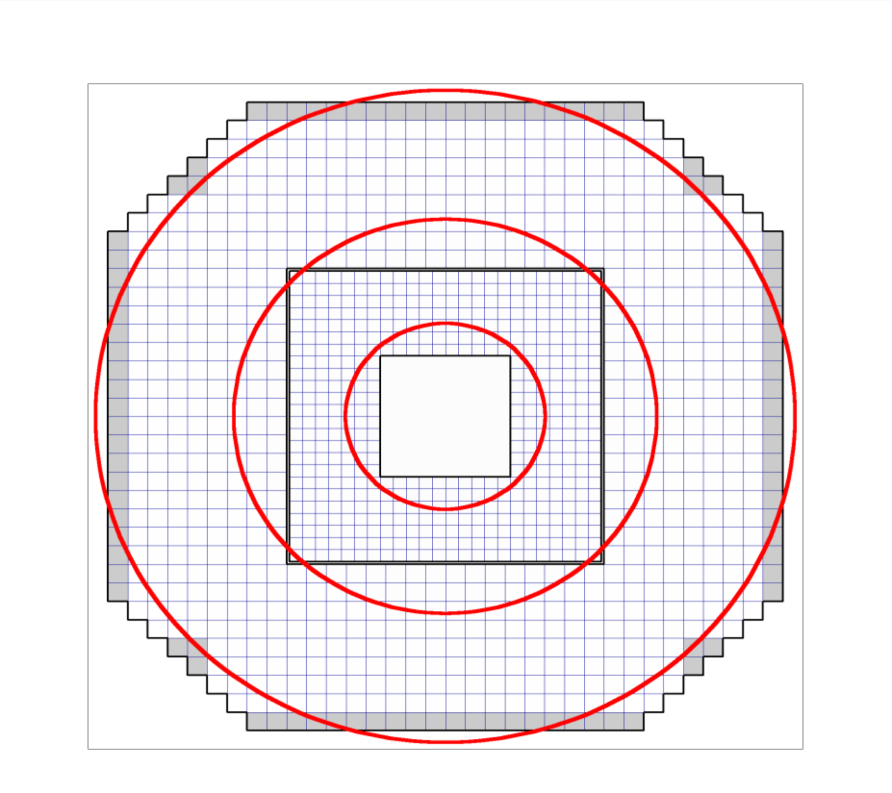
STAR installed **Forward Meson Spectrometer** in 2008. It can be used to reconstruct the neutral pion signals.

# Experiment Setup-FMS

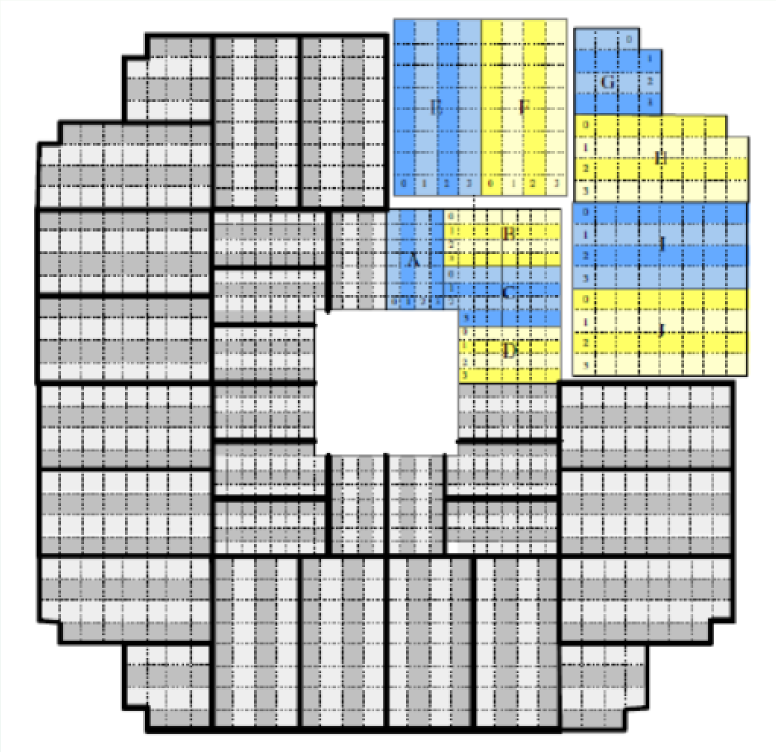
- EM-Calorimeter made out of lead glass
- Ideal way to detect photons from $\pi^0$ decays
- Large rapidity range in the forward direction
- Two cell types

| Cell Type | Radiation Length | Width | Length | Numbers |
|---|---|---|---|---|
| Small cell | 2.50 cm | 3.87 cm | 45.0 cm | 476 |
| Large cell | 3.75 cm | 5.81 cm | 60.2 cm | 788 |

## Layout



## Trigger logic



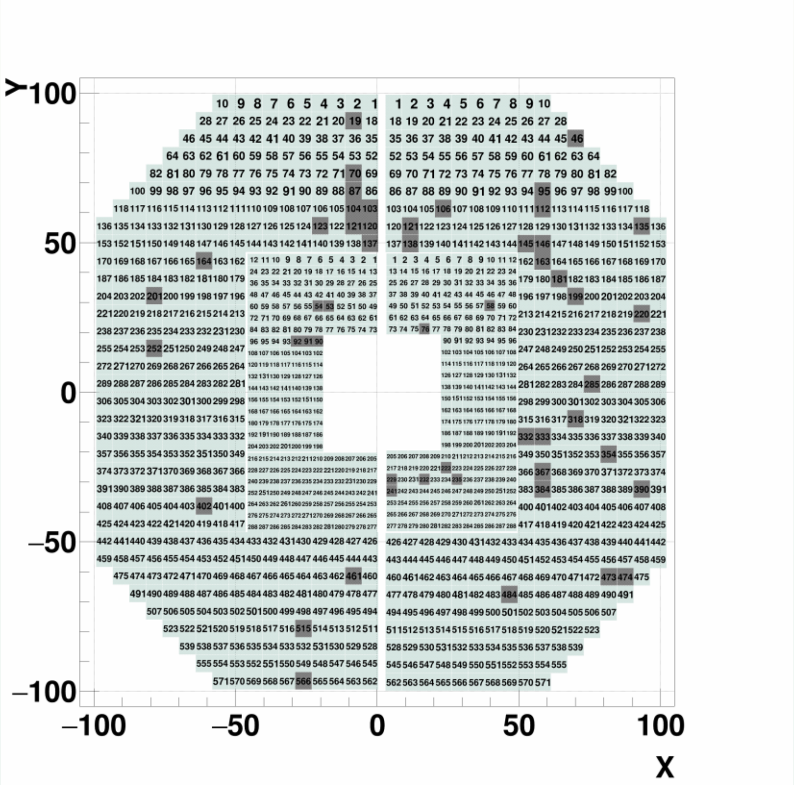
# Analysis- Dataset

## ➨ Dataset:

STAR transversely polarized proton-proton collisions

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

Bad channels in Run11




## ➨ Beam polarization:

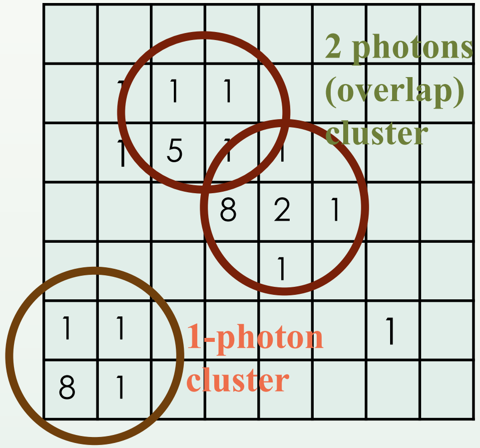
52 / 57% (500 / 200 GeV)

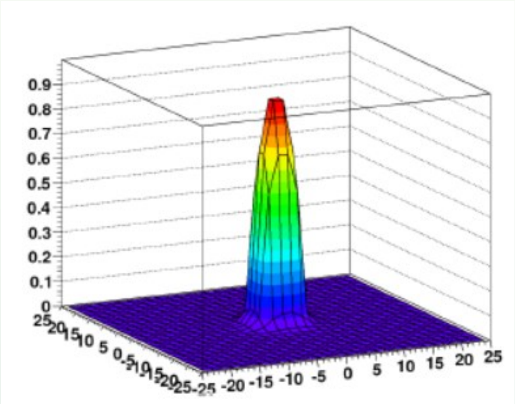
## ➨ Trigger:

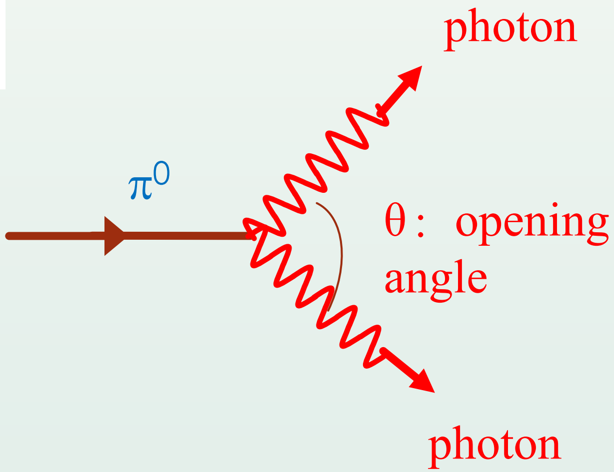
FMS-Board-sum and FMS-Jet-patch

# Analysis- Photon/$\pi^0$ reconstruction

**1) Cluster finding** → **2)Clusters classification** → **3) Shower shape fitting** → **Photon candidates**






$$\pi^0 \rightarrow \gamma\gamma$$

$$M_{\gamma\gamma} = \sqrt{2 * E_1 * E_2 * (1 - \cos(\theta))} \approx \sqrt{E_1 * E_2} * \theta$$

**Selection for the analysis**

- $Pt > 2GeV$
- $2.8 < \eta < 4.0$
- $M_{\gamma\gamma} < 0.3GeV$
- $Z_{\gamma\gamma} < 0.7$

$$Z_{\gamma\gamma} = \frac{E_1 - E_2}{E_1 + E_2}$$

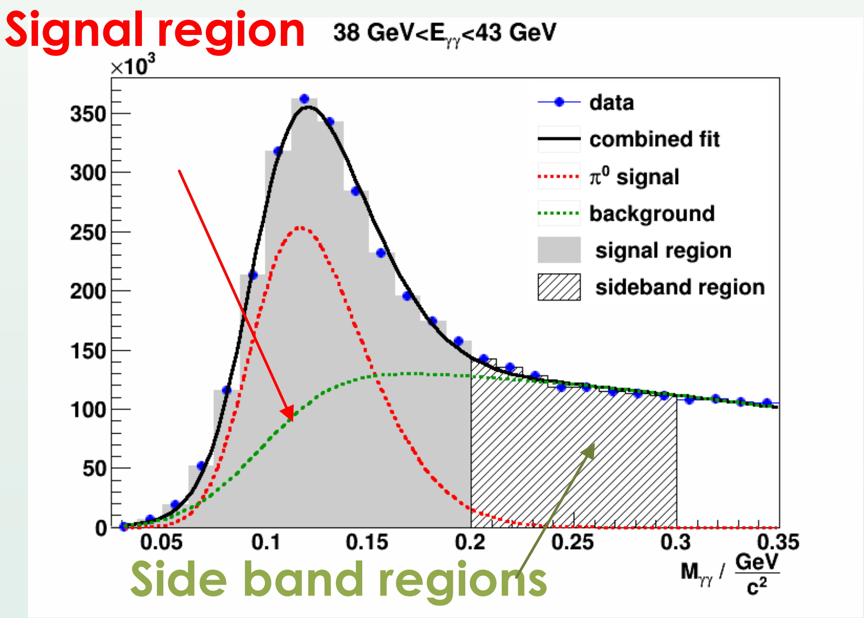
# Analysis- Asymmetry calculation

The **relative luminosity** and **detector efficiency** can be difficult to determined.

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

- "Cross-ratio" method help eliminates those factors

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




- Background subtraction

The fraction comes from the fitting of the mass spectrum

Signal/background shapes are from simulation

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

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

# Analysis- Collins Asymmetry

TSSA vs. Collins asymmetry

**TSSA**

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

- Azimuthal angle
- All $\pi^0$ candidates
- Background subtraction

**Collins asymmetry**

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

- Collins angle
- Only $\pi^0$ within a jet
- No Background subtraction

For jet reconstruction:

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

For $\pi^0$ in a jet :

- $\Delta R > 0.04$

**The jet is only "electromagnetic Jet"**

# Analysis- Systematic uncertainty

Uncertainties:

- $\pi^0$/jet energy uncertainty($x_F$ an $z_{em}$):

  calibration, non-linear response, radiation damage

- $\pi^0$ TSSA: background subtraction
- Beam Polarization

| Analysis | Uncertainties types (Run-11/Run15) | | |
|---|---|---|---|
| $\pi^0$ TSSA | $x_F$ | Asymmetry | Beam polarization |
| | <4.4%/3.0% | < 5.8% | <3.4%/3.0% |
| Jet TSSA | $x_F$ | Asymmetry | Beam polarization |
| | <6.7%/4.2% | — | <3.4%/3.0% |
| Collins asymmetry | $z_{em}$ | Asymmetry | Beam polarization |
| | $<7.9\%/5.1\%\times(1-z_{em})$ | — | <3.4%/3.0% |

Corrections:

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

# Analysis- Observables

All measurements are done in 200 GeV (Run-15) and 500 GeV (Run-11)

- 1) $\pi^0$ TSSA: **initial+final** state effect

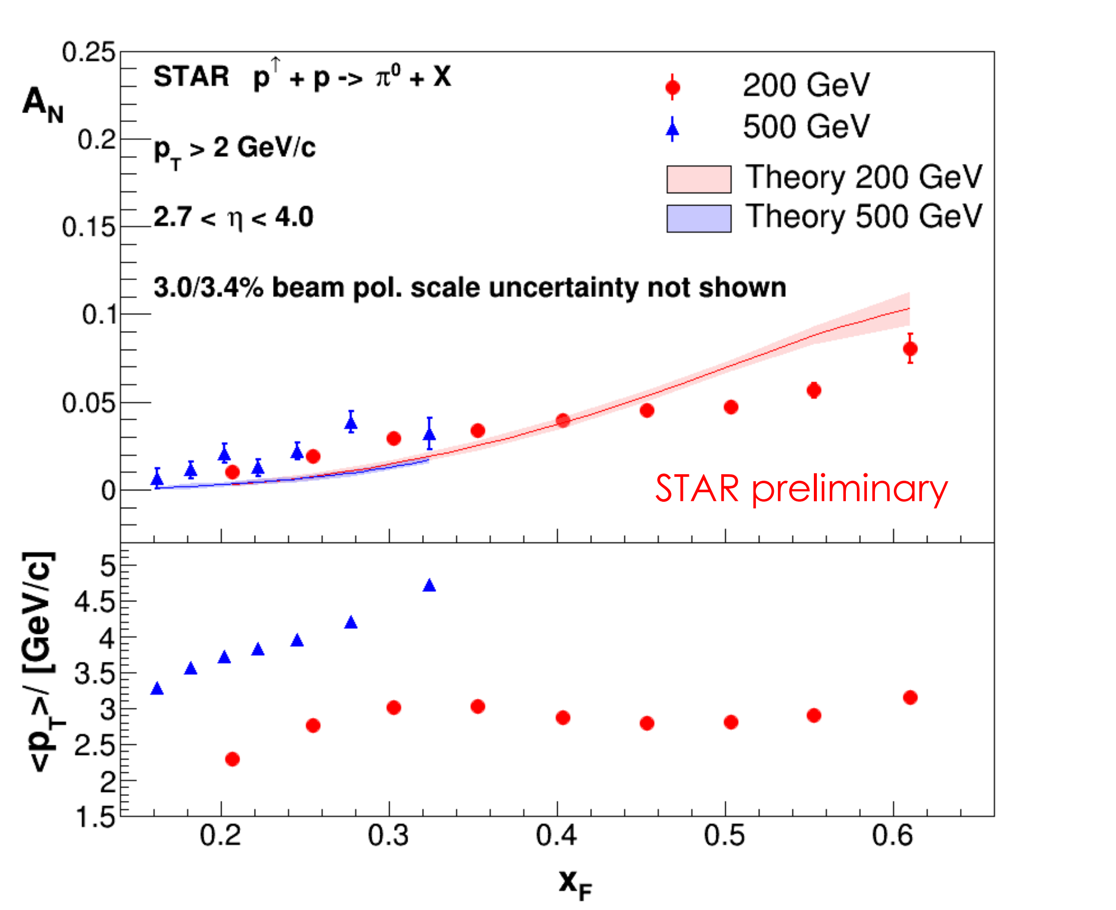
  TSSA as function of Feynman-x ($x_F$) ; $x_F = \frac{E_{\pi L}}{E_{beam}}$

  TSSA as function of $p_T$ ;

  Isolated/non-isolated $\pi^0$ $A_N$ as 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) in the analysis

# Result- $\pi^0$ TSSA vs. $x_F$

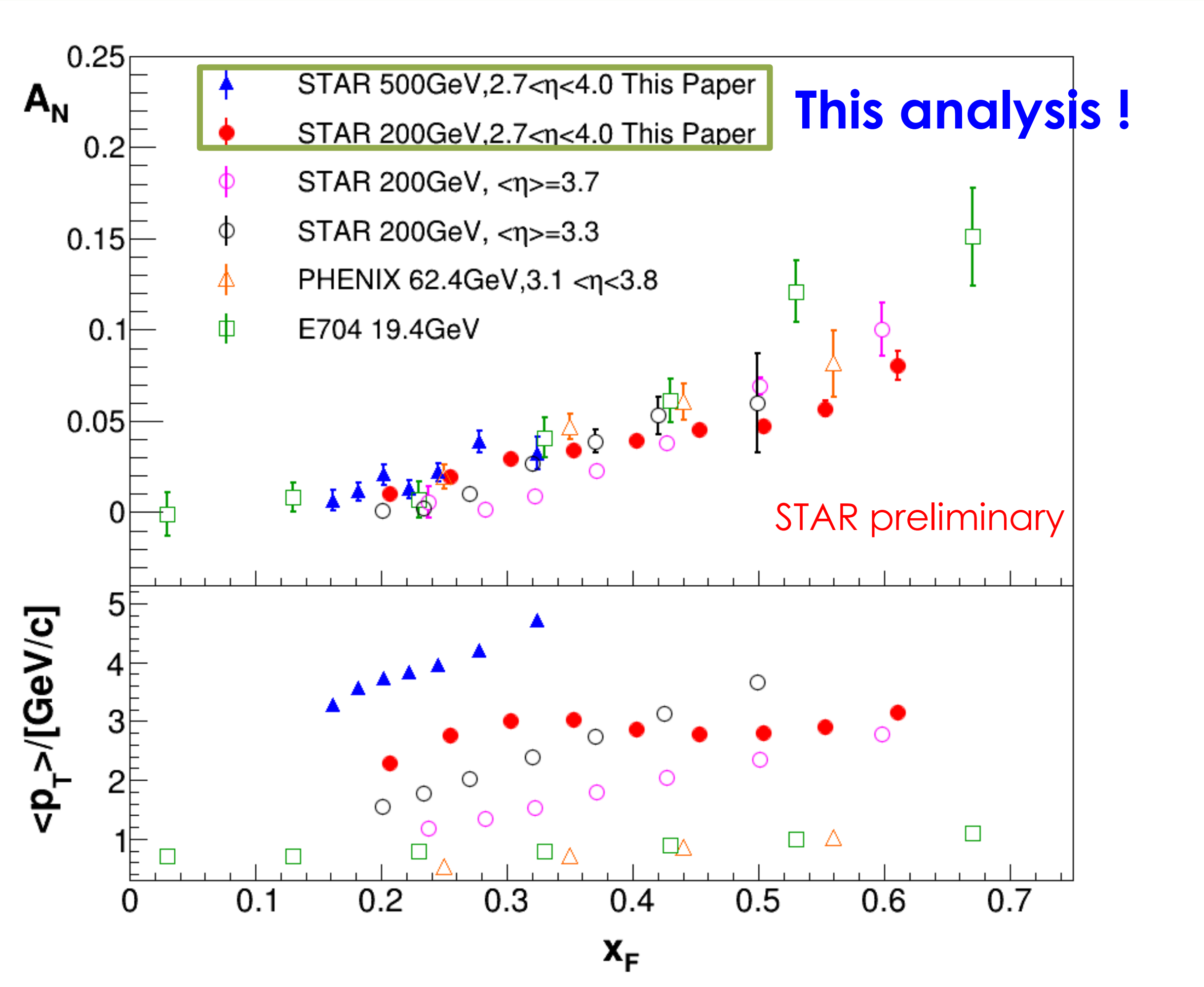



*Theory curves:*
*J. Cammarota, et al.*
*arXiv:2002.08384(2020)*

$$x_F = \frac{E_{\pi L}}{E_{beam}}$$

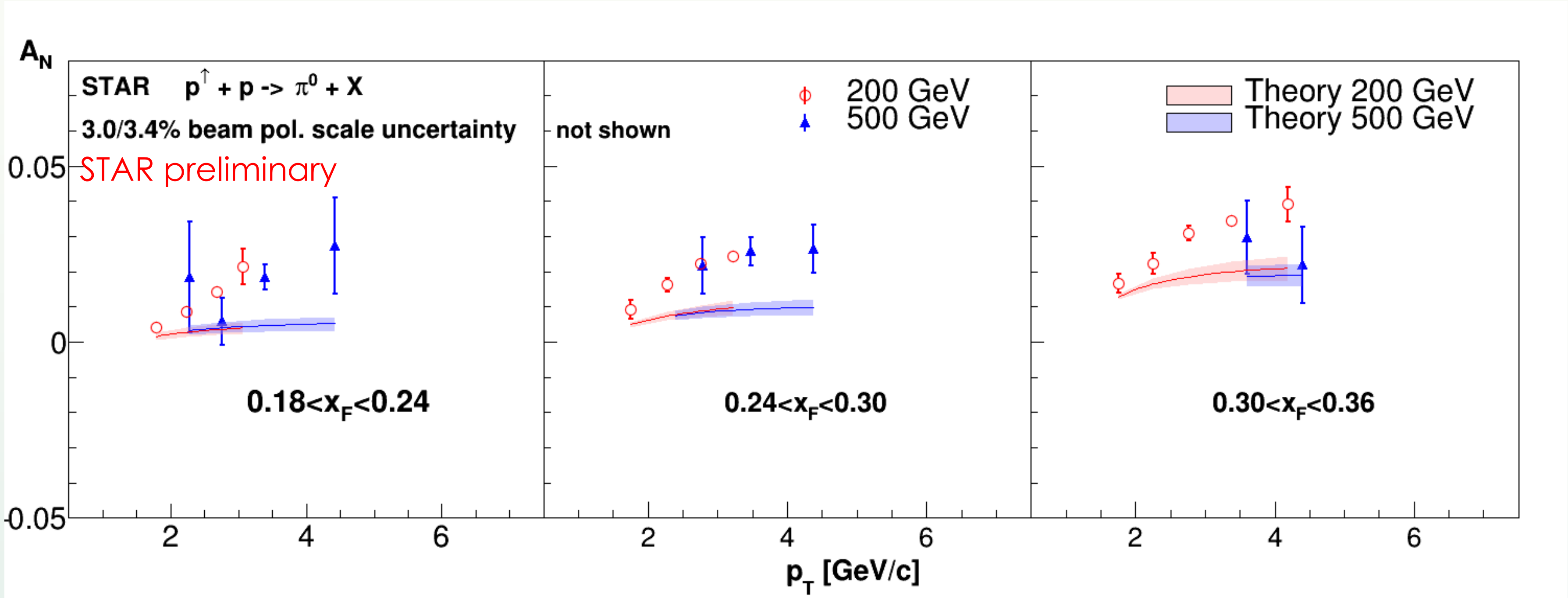
- The $\pi^0$ TSSA increases with $x_F$.
- Consistent in 200 GeV and 500 GeV. Energy dependence is weak.

# Comparison to previous measurements




- ❑ Weak collision energy dependence of the $\pi^0$ TSSA from 19.4 to 500 GeV
- ❑ Comparison to the former FPD results at STAR shows higher TSSA in current measurement, which can be explained by the higher average $p_T$

# Result- $\pi^0$ TSSA vs. $p_T$

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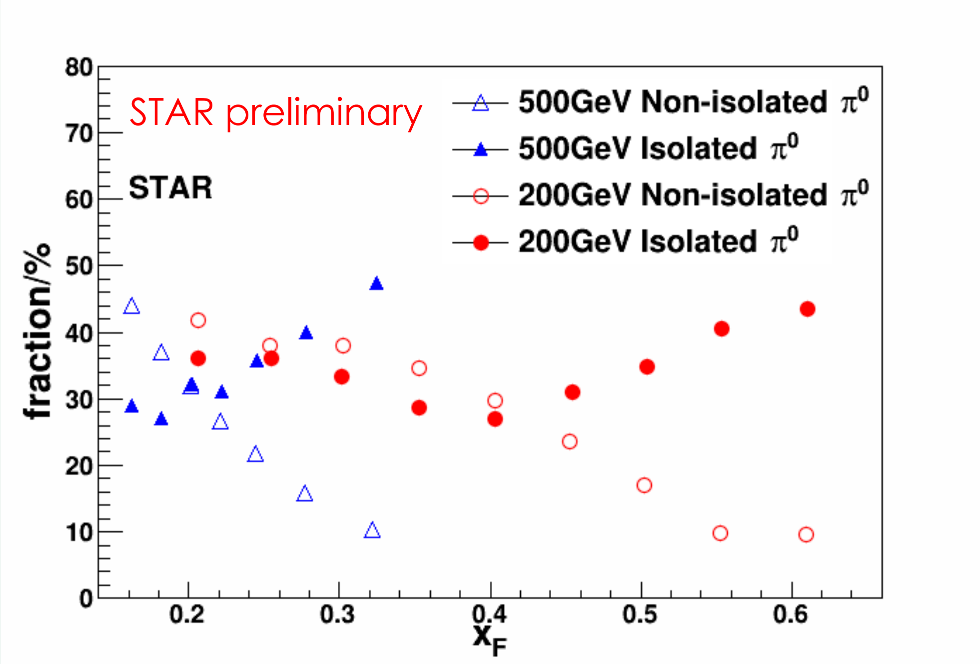
- ❑ This measurement was done in the overlap $x_F$ regions.
- ❑ The 200 GeV data shows significant increase of TSSA below 3 GeV.
- ❑ The 500 GeV data flattens over the $p_T$ range.

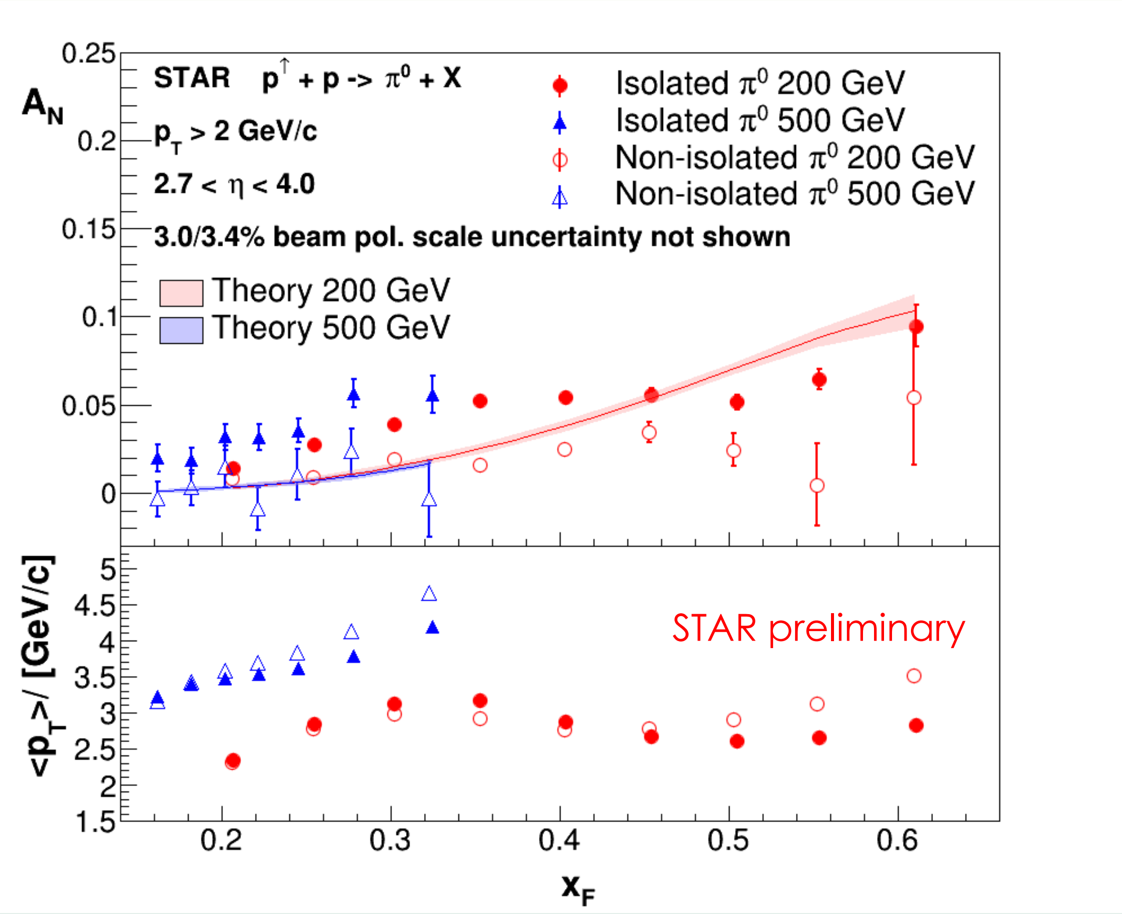
# Result: isolated $\pi^0$ TSSA

- Motivation: investigate the $\pi^0$ event topology ($\pi^0$ with no other particle around)
- Method: in a surrounding area (in η-φ space, R=0.7), if the $\pi^0$ 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 $\pi^0$ event in the overall sample



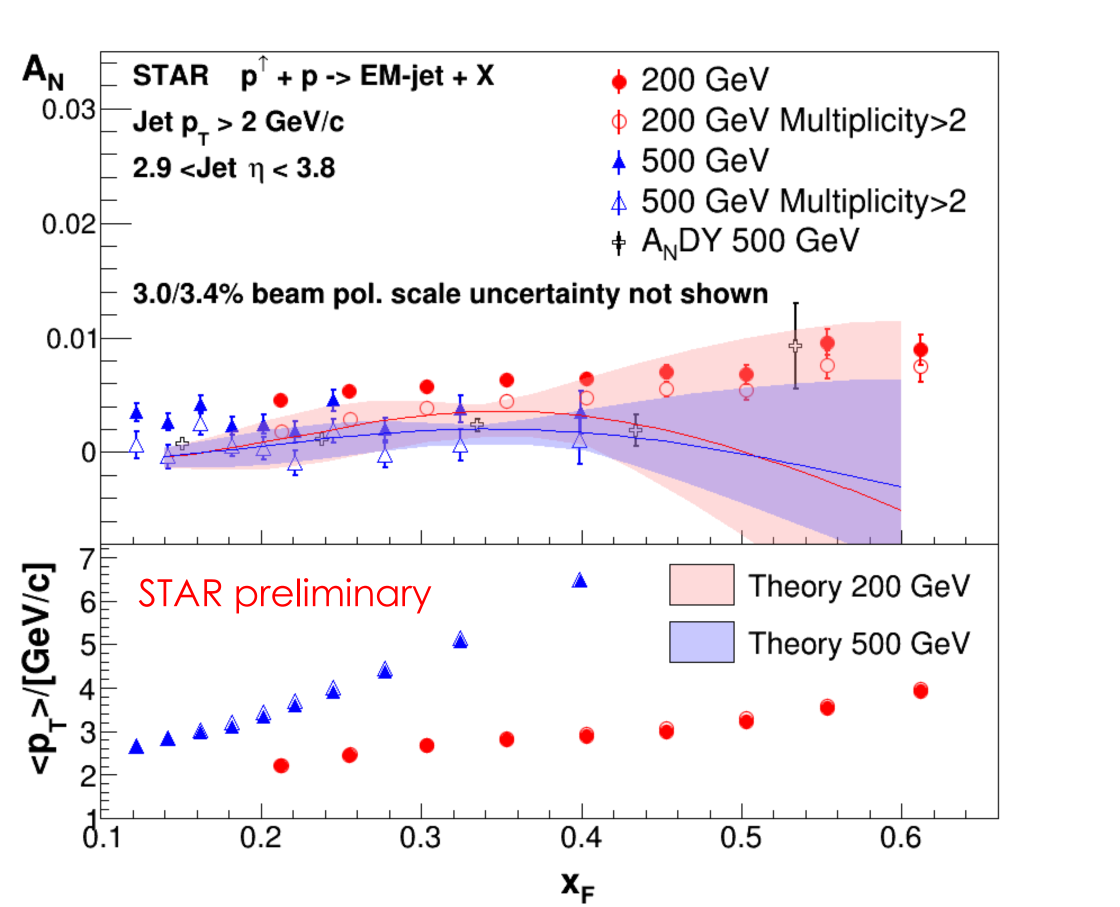
# Result: isolated $\pi^0$ TSSA




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

*Theory curves:*
*J. Cammarota et al.*
*arXiv:2002.08384(2020)*

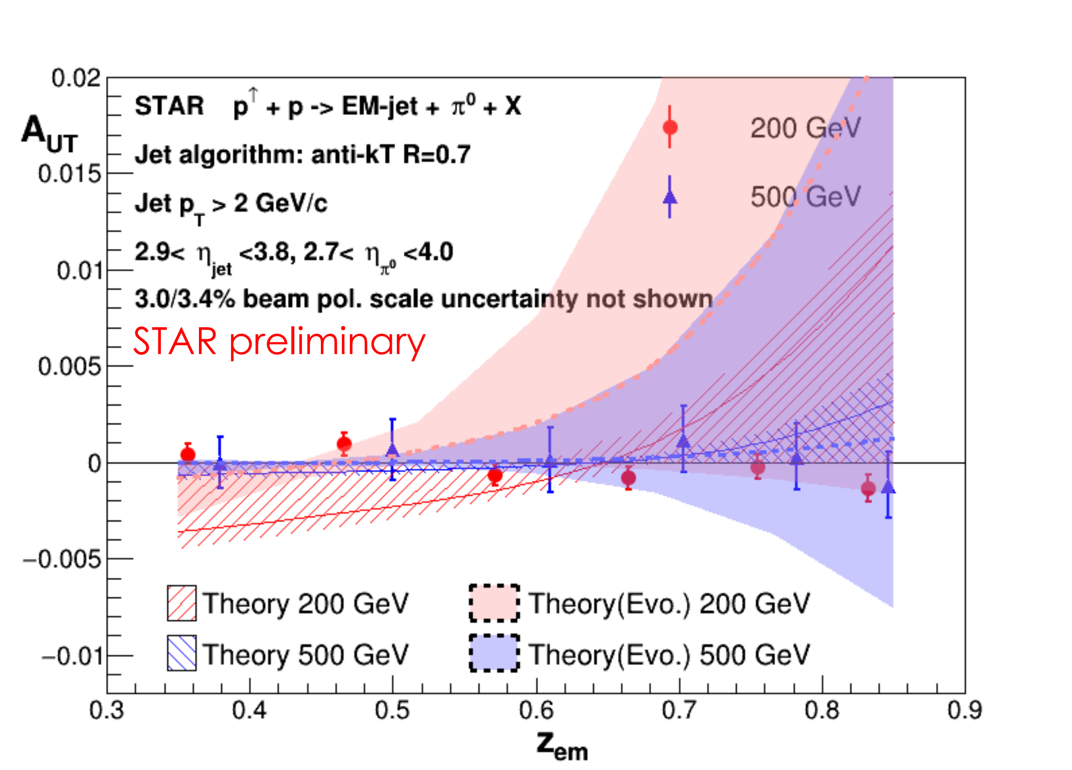
# Result: jet TSSA




- The jet TSSA is a few times smaller than the $\pi^0$ TSSA in the same $x_F$ bin.
- Energy dependence is more prominent
- The jet with photon multiplicity minimum requirement has significantly smaller TSSA.
- The $A_N DY$ result shows the TSSA of the full jet, and is consistent with the result of the EM-jet which has at least 3 photons.

*Theory curves:*
*L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett.110(2013)23,232301*

# Result: Collins Asymmetry for $\pi^0$ in a jet




*Theory curves:*
*Z. Kang , et al.*
*Phys.Lett.B* 774,635(2017)

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

- ❑ The Collins asymmetries are very small in both energies
- ❑ This reflects the cancellation of the Collins function of the u/d quark

# Summary

- We measured the $\pi^0$ /jet TSSA and Collins asymmetry using the FMS in STAR 200 and 500 GeV p-p data
- The $\pi^0$ TSSA results show weak energy dependence through 20 to 500 GeV
- We investigated the $\pi^0$ event topology. The isolated $\pi^0$ TSSAs are significantly larger than the non-isolated $\pi^0$ , the mechanism of which remains unclear. It offer a new perspectives of the origin of TSSA
- We measured the jet TSSAs and Collins asymmetry to separate contribution from the initial and final state effect, both of which are small
- These measurements will provide important inputs for further theory investigation for TSSA