Measurement of transverse polarization for $\Lambda/\bar{\Lambda}$ in p+p collisions at STAR

Part I : Transverse spin transfer in polarized p+p collisions

Part II: Transverse polarization in unpolarized p+p collisions

Taoya Gao(高涛亚), Shandong University

for the STAR collaboration

DIS2022, Santiago de Compostela, 2-6 May, 2022

Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

NSFC National Natural Science Foundation of China

Outline

- Motivation
- Introduction of RHIC and STAR
- Measurement of transverse spin transfer D_{TT}
- Measurement of polarizing Fragmentation Function (pFF)
- Summary

Motivation

Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

- Transverse spin transfer D_{TT} for $\Lambda(\bar{\Lambda})$ in p+p collisions:

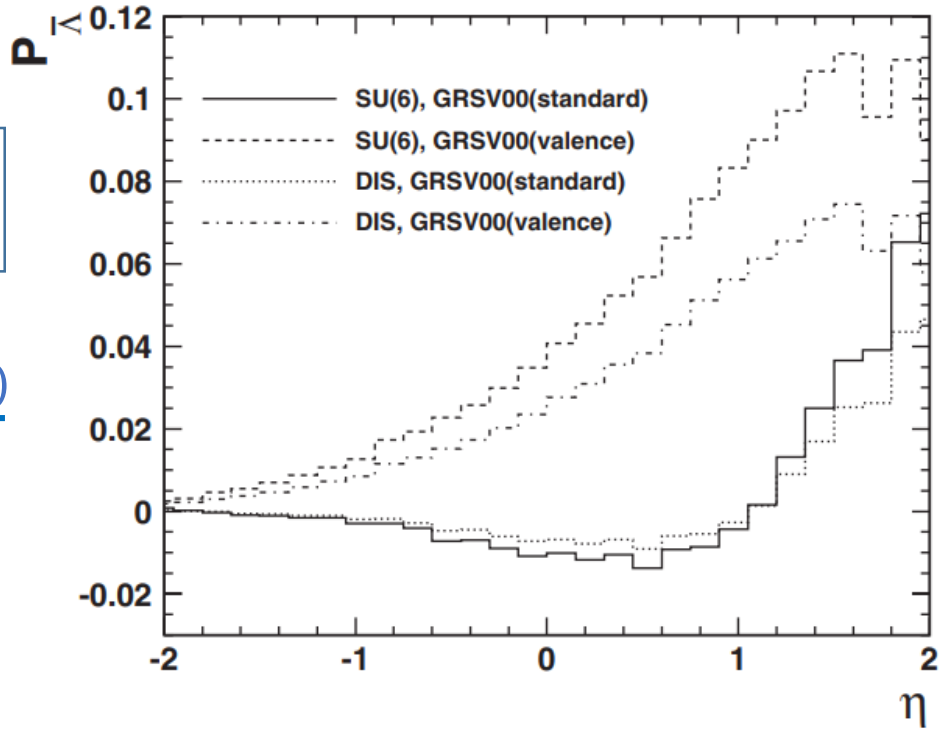
$$D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} - \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}}{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} + \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

Transversity FF also referred to as H_1

$$d\delta\sigma^{\Lambda} \propto \sum_{abcd} \int dx_a\, dx_b dz\, \delta f_a(x_a) f_b(x_b) \delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)} \delta D_c^{\Lambda}(z)$$

transversity distributions

pQCD

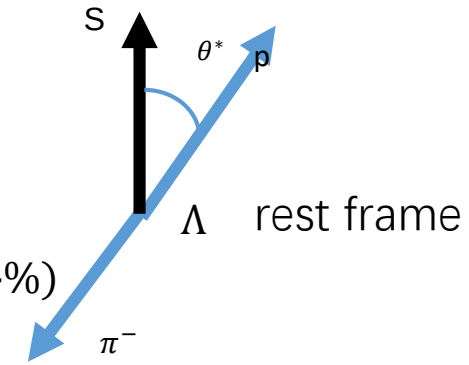


- D_{TT} provides connections to the transversity distributions and transversely polarized fragmentation functions.
- Λ polarization, P_{Λ}, can be determined through the angular distribution of its weak decay product:

$$\frac{dN}{d\cos\theta^*} \propto (1 + \alpha P \cos\theta^*)$$

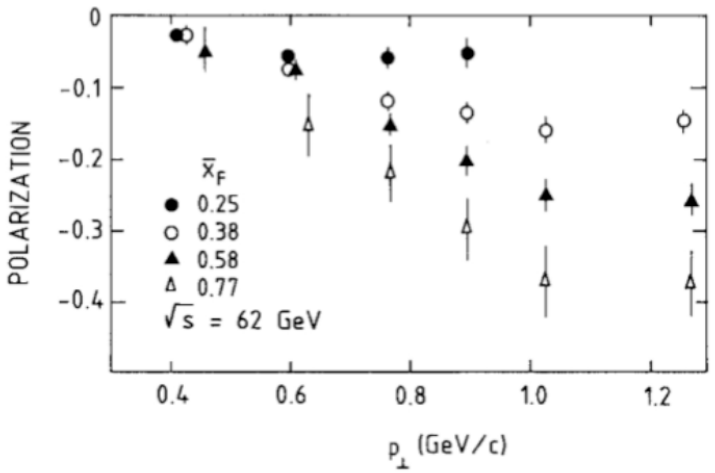
α: decay parameter

$\Lambda \to p + \pi^-(BR = 64\%)$

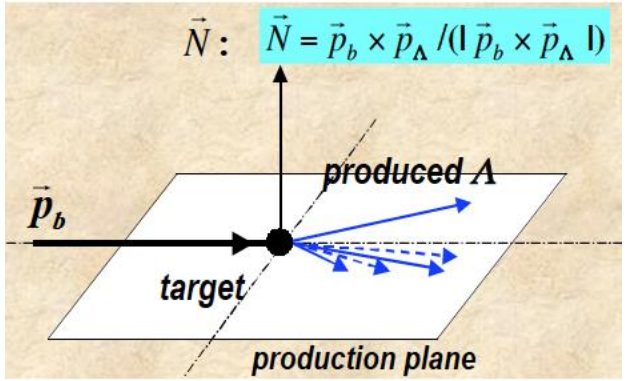


Motivation

- Large transverse polarization of hyperon was first observed in unpolarized hadron-hadron collisions in 1970s.
  - Along the normal vector of production plane
  - Not fully understood



A.D. Panagiotou, Int.J.Mod.Phys.A 5, 1197,(1990)



TMD FF

Quark polarization

Hardon polarization

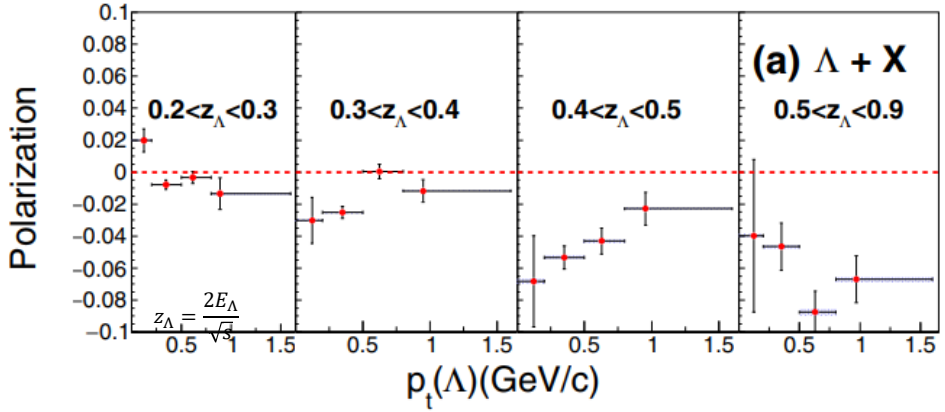
	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	$H_1, H_{1T}^\perp$

Polarizing FF: polarized hardon from unpolarized quark's fragmentation

- **One possible contribution could be from polarizing FFs**

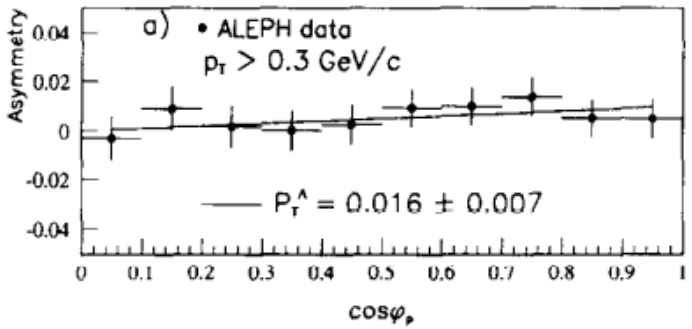
Precious results about polarizing FF

- Significant transverse polarization w.r.t. thrust axis observed in e^+e^- ($\sqrt{s} = 10.6\ GeV$) at BELLE.



BELLE, PRL 122(2019) 042001

- Measurements at LEP ($\sqrt{s} = 90\ GeV$) reported zero polarization → scale effect?



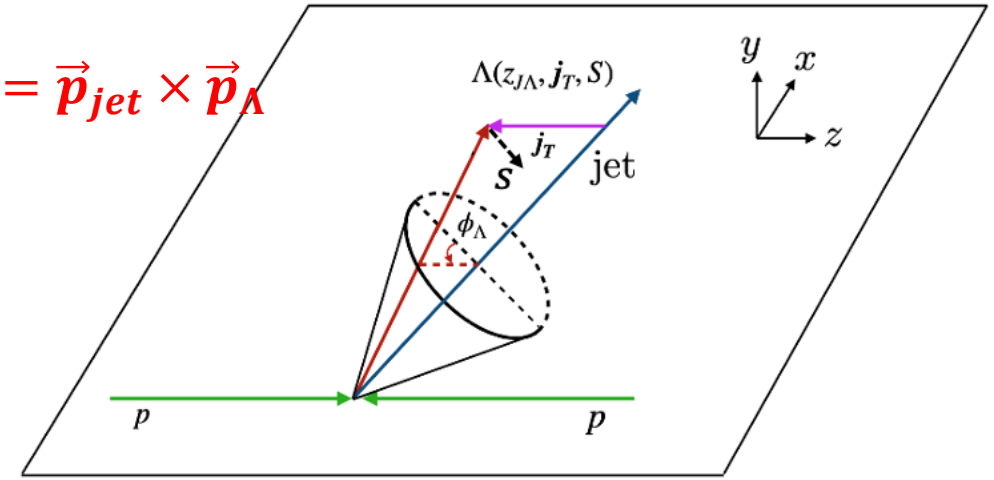
ALEPH, PLB 374, 319 (1996);

p_T (GeV/c)	P_T^Λ (%)
< 0.3	$-1.8 \pm 3.1 \pm 1.0$
$0.3 - 0.6$	$0.4 \pm 1.8 \pm 0.7$
$0.6 - 0.9$	$1.0 \pm 1.9 \pm 0.7$
$0.9 - 1.2$	$0.8 \pm 2.2 \pm 0.6$
$1.2 - 1.5$	$0.0 \pm 2.7 \pm 0.6$
> 1.5	$1.8 \pm 1.6 \pm 0.5$
> 0.3	$0.9 \pm 0.9 \pm 0.3$
> 0.6	$1.1 \pm 1.0 \pm 0.4$

OPAL, EPJC 2, 49 (1998)

- What can we do at RHIC?

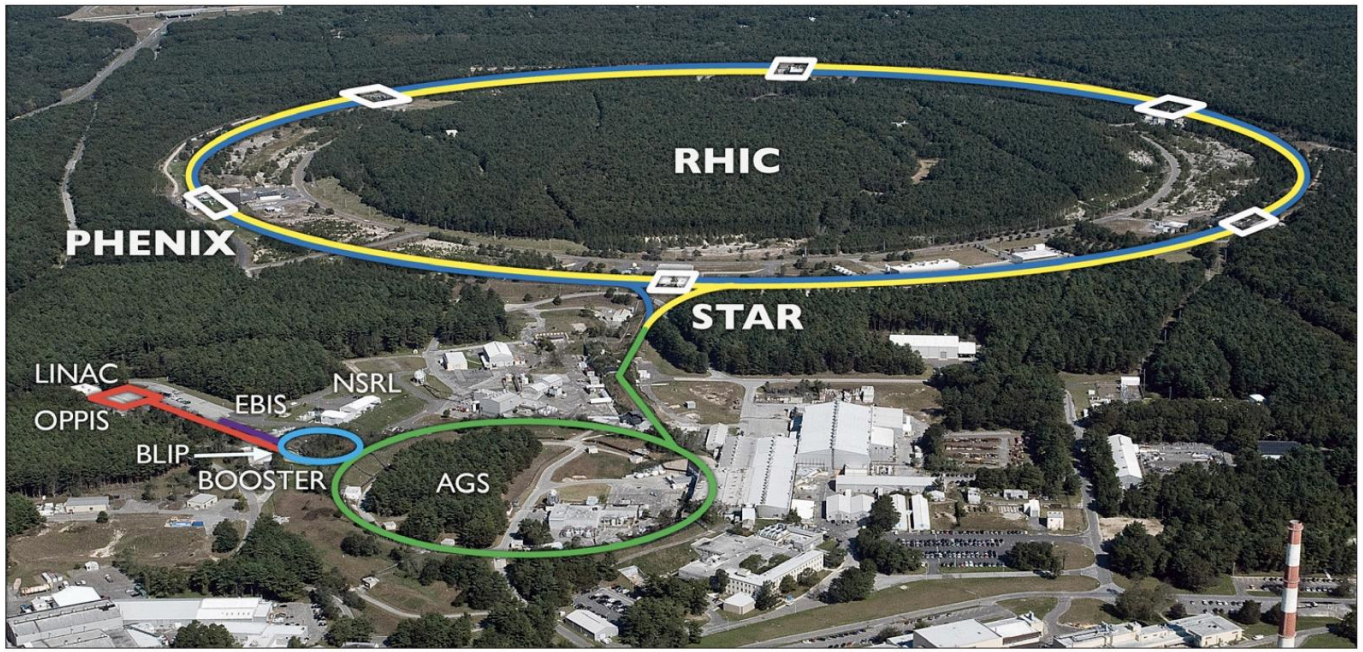
$$\vec{S} = \vec{p}_{jet} \times \vec{p}_\Lambda$$



$$p + p \rightarrow \Lambda^\uparrow + X$$

- In pp collisions, transverse polarization of Λ in jet can access polarizing FF
- Test the scale dependence

Relativistic Heavy Ion Collider



- **RHIC can provide all 4 collision patterns: ++, --, +-, -+.**

+ + - - + + - -

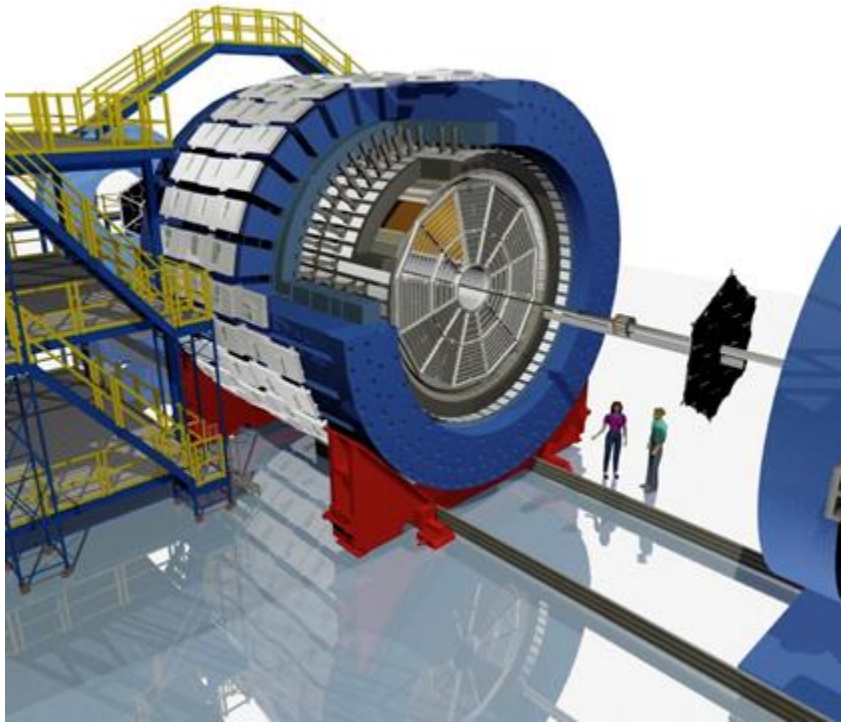
yellow beam

+ - + - + - + -

blue beam

- RHIC: world's first (and only) polarized hadron collider.
- For p+p, RHIC can run at $\sqrt{s} = 200\ \mathrm{GeV}$ and $500/510\ \mathrm{GeV}$ with beams longitudinally or transversely polarized
- Data set for D_{TT} :
  - transversely polarized collisions
  - energy: 200 GeV
  - luminosity: 52 pb^{-1}
- Data set for pFF:
  - unpolarized beam collision
  - energy: 200 GeV
  - luminosity: 104 pb^{-1}

Solenoidal Tracker At RHIC



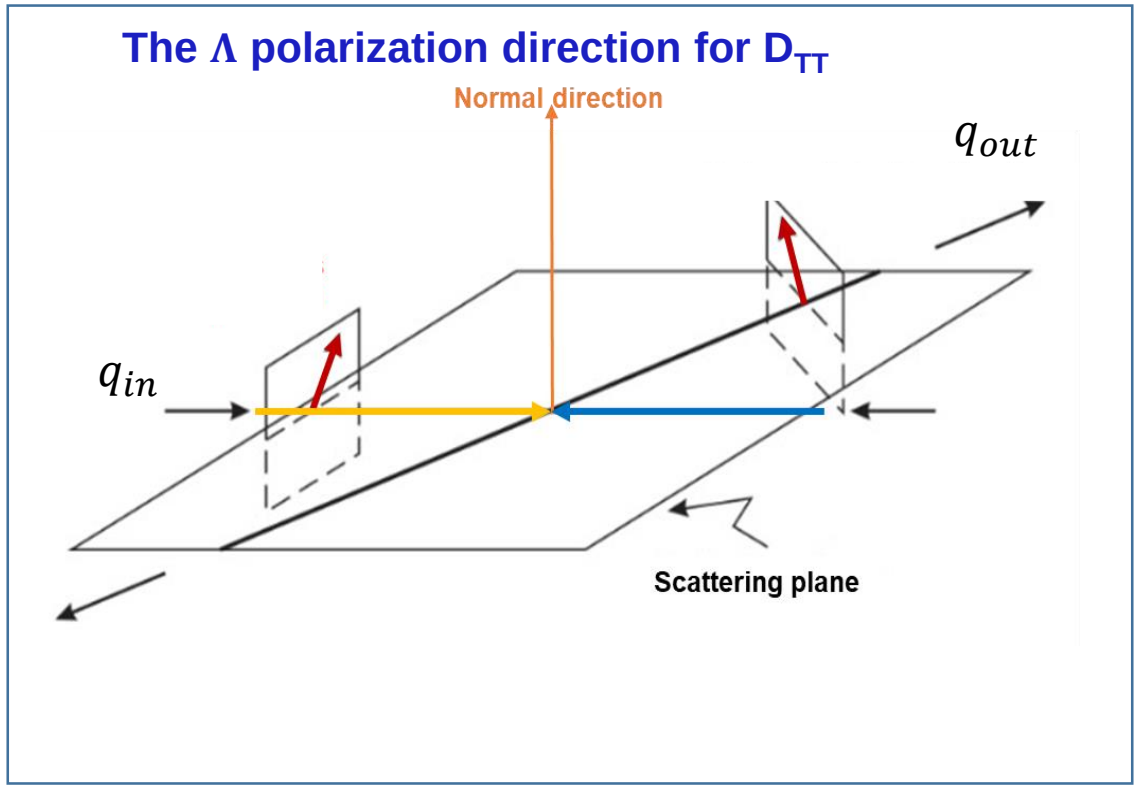
- For D_{TT} and pFFs analyses, the following sub-detectors are used:
  - **TPC:** the main detector for tracking and PID.
    - ✓ covering $|\eta| < 1.3$ and $\phi \in [0,2\pi]$.
  - **TOF:** used to improve PID.
    - ✓ covering $|\eta| < 1.0$ and $\phi \in [0,2\pi]$.
  - **EMC** includes:
    - ✓ BEMC (Barrel EMC) : covering $|\eta| < 1.0$ and $\phi \in [0,2\pi]$.
    - ✓ EEMC (Endcap EMC): covering $1.086 < \eta < 2.00$ and $\phi \in [0,2\pi]$.

- Hard scattering events were selected by jet trigger based on energy deposits in EMC.

Transverse spin transfer D_{TT} extraction at STAR

- In hard partonic scattering, the direction of transverse polarization is rotated along the normal direction of the scattering plane.
- **Jet axis** is used to obtain the polarization direction after rotation.
  - The anti-k_T algorithm with $R = 0.6$ to reconstruct jets.
  - $\Delta R < 0.6$ is used to correlate $\Lambda(\bar{\Lambda})$ candidate with a jet.

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2};\ \Delta\phi = \phi_\Lambda - \phi_{jet};\ \Delta\eta = \eta_\Lambda - \eta_{jet}$$



J.Collins, S.Heppelmann, G.Ladinsky, NPB420 (1994)565

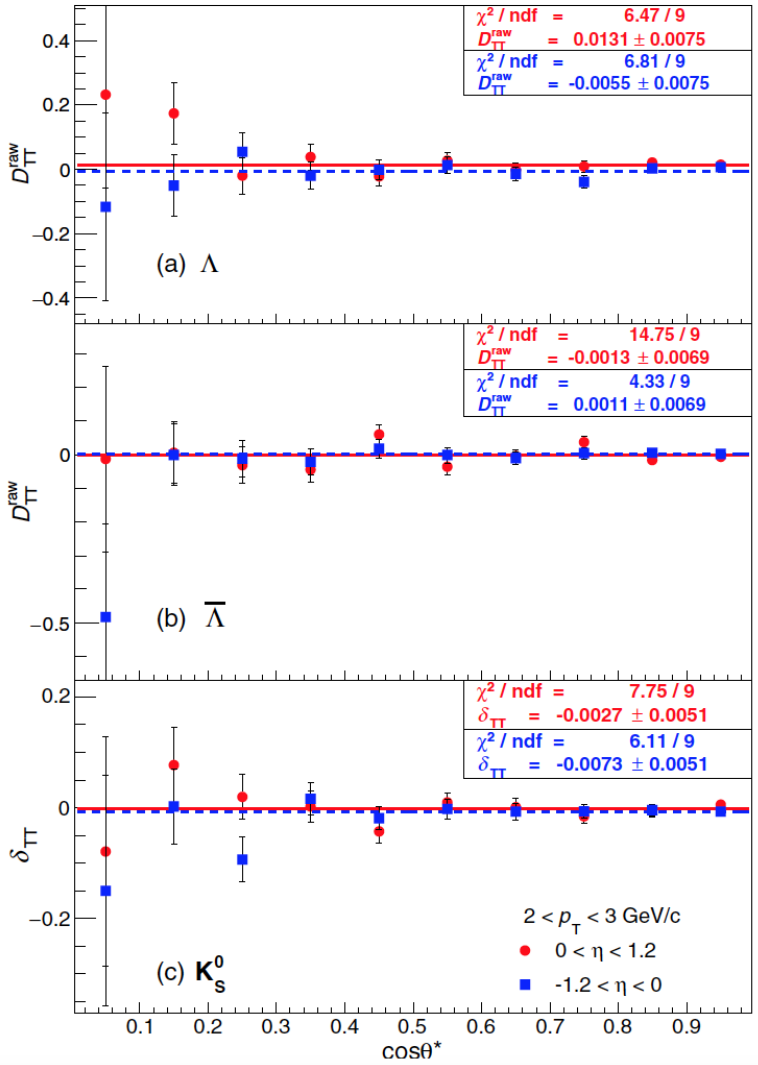
Cross-ratio method for D_{TT}

- D_{TT} is extracted from a cross-ratio asymmetry using Λ counts with opposite beam polarization configurations within a small interval of $cos\theta^*$:

$$D_{TT} = \frac{1}{\alpha P_{beam}\langle cos\theta^*\rangle}\frac{\sqrt{N^{\uparrow}(cos\theta^*)N^{\downarrow}(-cos\theta^*)} - \sqrt{N^{\uparrow}(-cos\theta^*)N^{\downarrow}(cos\theta^*)}}{\sqrt{N^{\uparrow}(cos\theta^*)N^{\downarrow}(-cos\theta^*)} + \sqrt{N^{\uparrow}(-cos\theta^*)N^{\downarrow}(cos\theta^*)}}$$

STAR, PRD 98, 091103R (2018)

  - $N^{\uparrow/\downarrow}$: number of Λ hyperon when the beam polarization is $\uparrow/\downarrow$
  - α: decay parameter
  - P_{beam} : beam polarization
- The relative luminosity and the detector acceptance are both canceled.
- K_S^0 was used to do a null check
  - α of K_S^0 is assumed equal to 1



STAR, PRD98, 091103R (2018)

$\Lambda/\bar{\Lambda}$ reconstruction and background subtraction

- Reconstruction of the Λ and $\bar{\Lambda}$ candidates with TPC tracks:

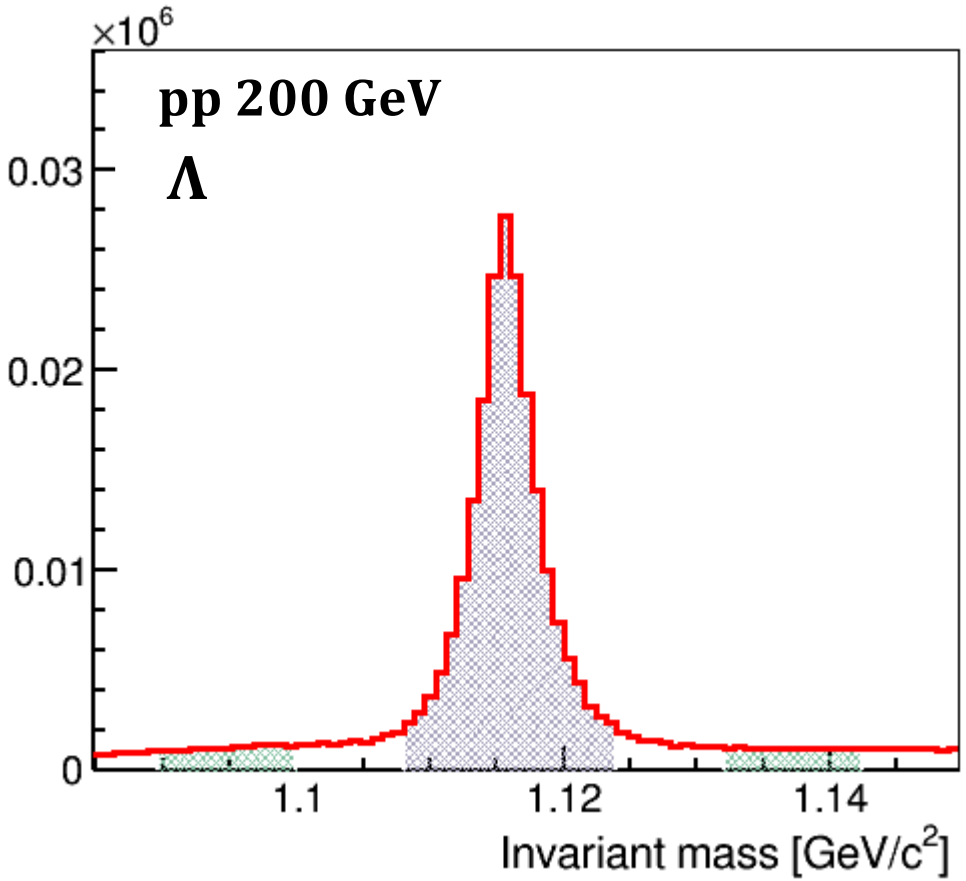
$$\Lambda \rightarrow p + \pi^{-}; \bar{\Lambda} \rightarrow \bar{p} + \pi^{+}$$

  - ✓ Topological cuts to reduce the background.
  - ✓ Side-band method to estimate the background fraction

- The spin transfer signal is extracted by:

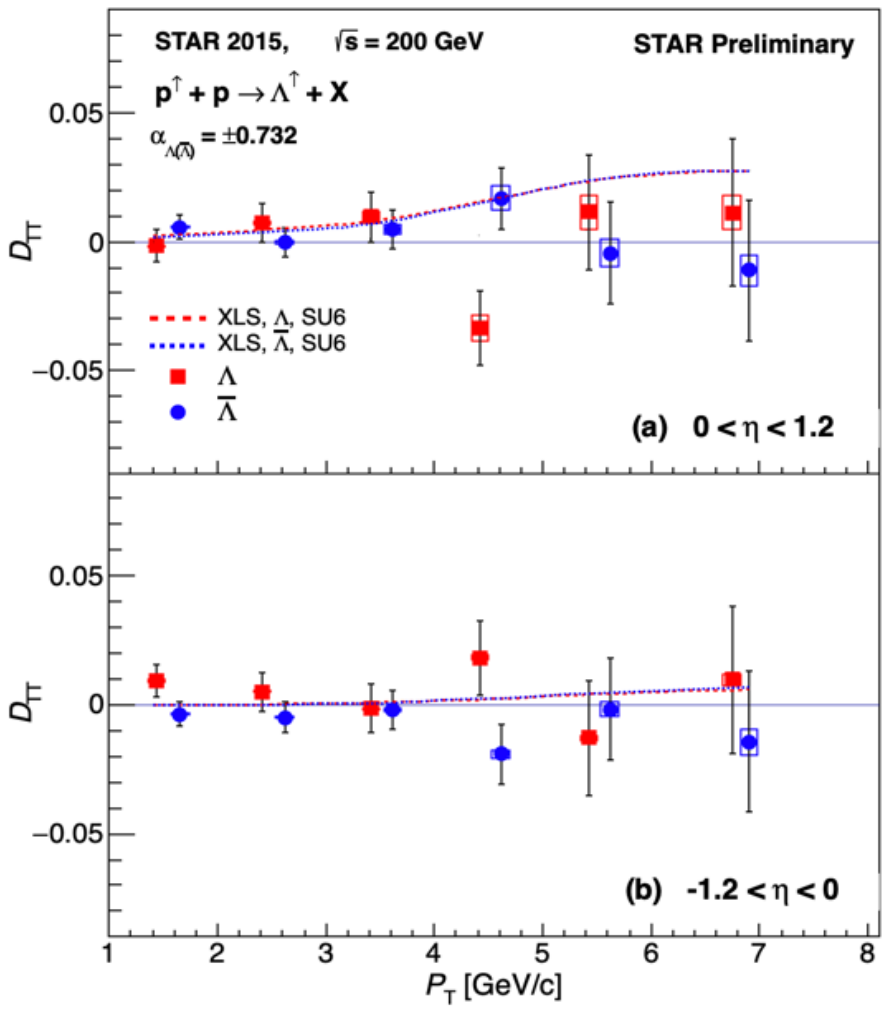
$$\boldsymbol{D_{TT} = \frac{D_{TT}^{raw} - r D_{TT}^{bkg}}{1 - r}}$$

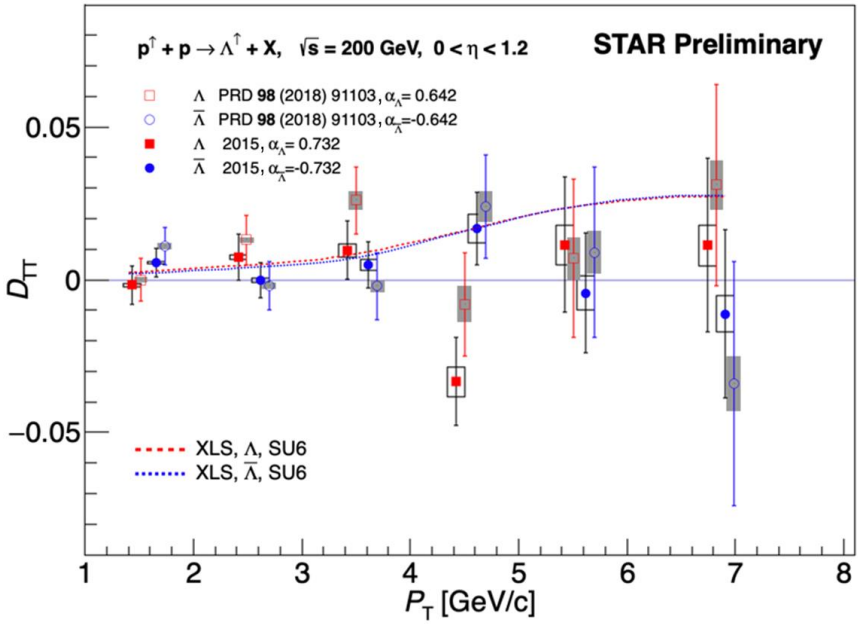
$\boldsymbol{r}$ is the background fraction, <10%



Example of invariant mass distribution for D_{TT} of Λ in p_T 3~4 GeV at 200 GeV

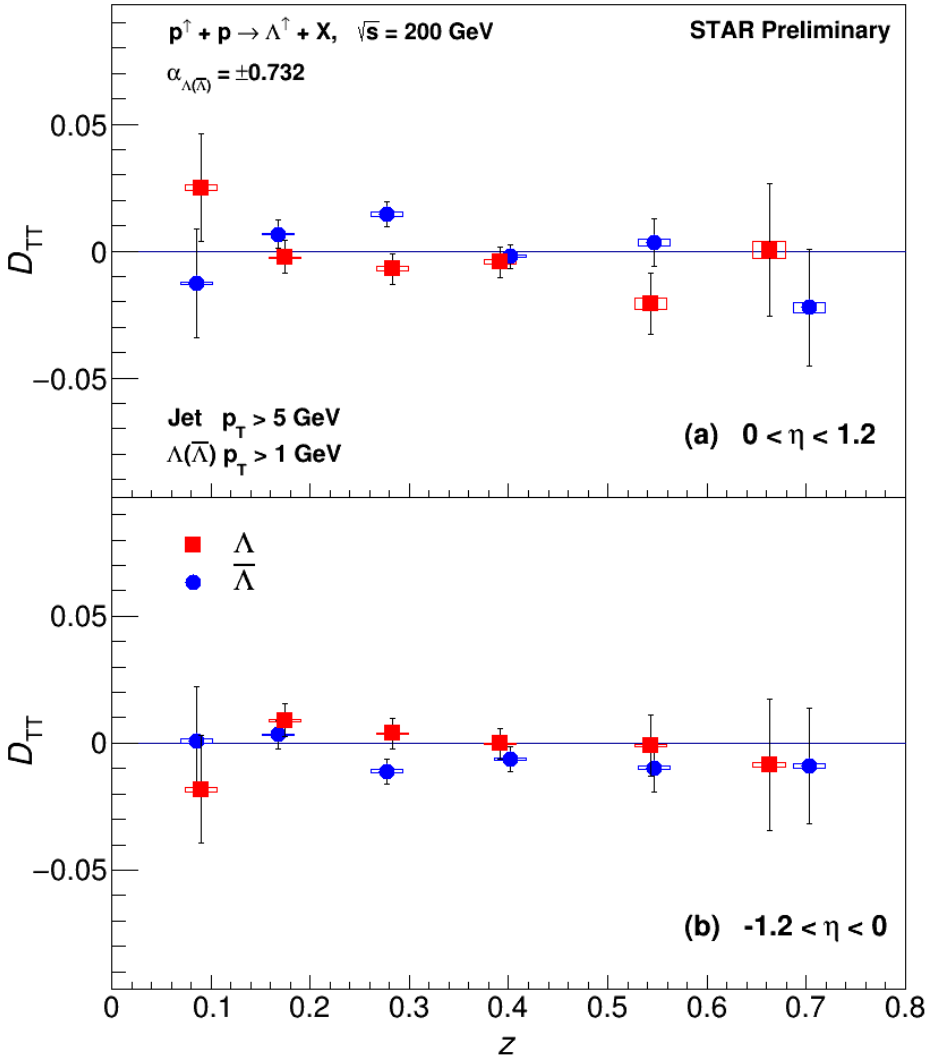
D_{TT} vs p_T results from STAR 2015 data





- D_{TT} is consistent with the model predictions, also consistent with zero within uncertainties
- D_{TT} results from 2015 are consistent with previous 2012 data, with twice the statistics.

D_{TT} vs z results from STAR 2015 data



$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

- **First measurement of D_{TT} vs. z** for $\Lambda(\bar{\Lambda})$ in p+p collisions.
- Results are consistent with zero within uncertainties.
- May indicate that the strange quark transversity distribution and/or the polarized fragmentation function of $\Lambda(\bar{\Lambda})$ is small.

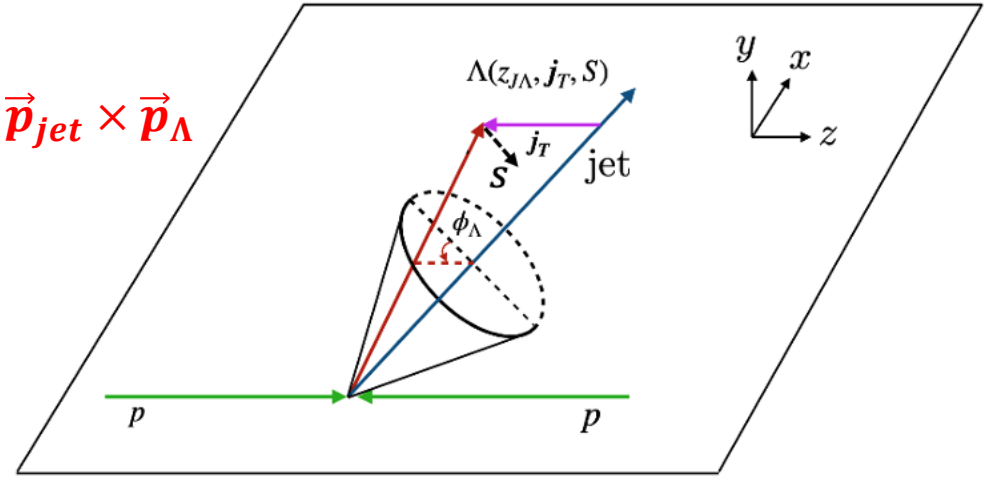
Transverse Λ polarization w.r.t. jet in unpolarized pp

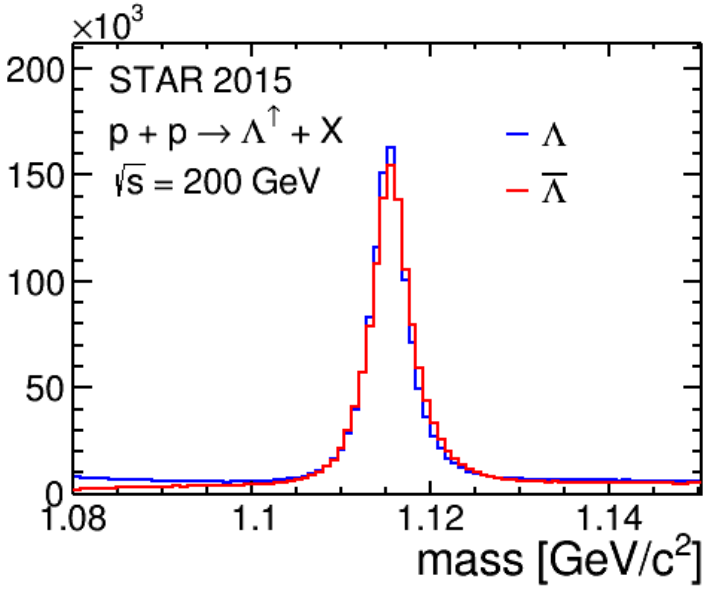
- To determine the Λ polarization along the normal of jet-Λ plane, both Λ and jet reconstruction are needed.
- The detector acceptance & efficiency is required to extract the polarization, which can only be obtained via MC simulation.

- Λ jet reconstruction
  - anti-k_T
  - $R = 0.6$
  - $\Lambda, \bar{\Lambda}$ as input instead of daughter tracks

$$\frac{dN}{d\cos\theta^*} = A(\cos\theta^*)(1 + \alpha P \cos\theta^*)$$

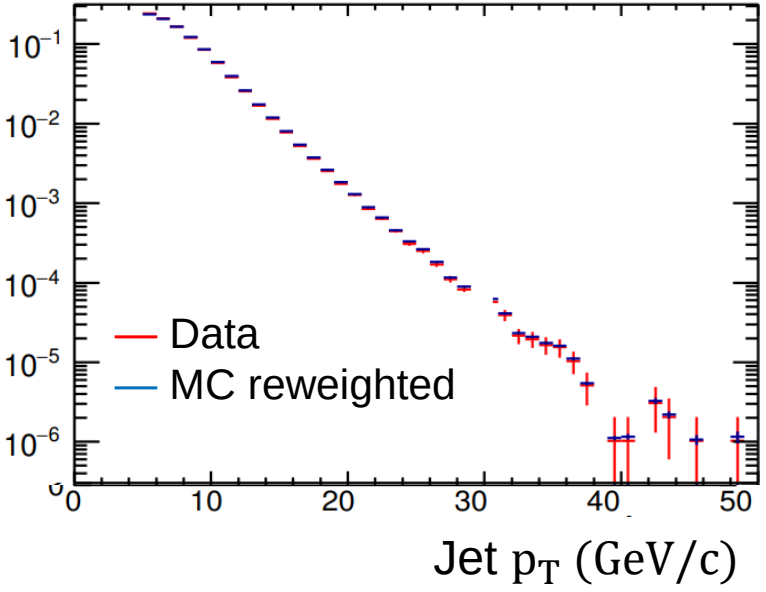
$$\vec{S} = \vec{p}_{jet} \times \vec{p}_{\Lambda}$$

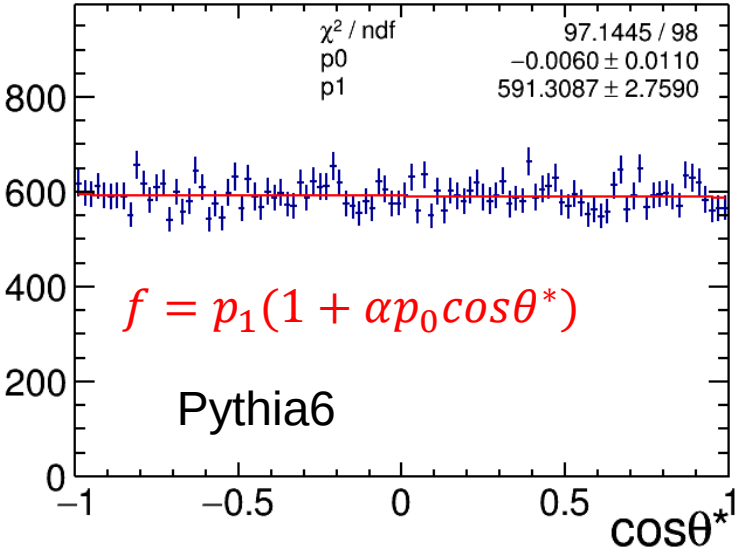


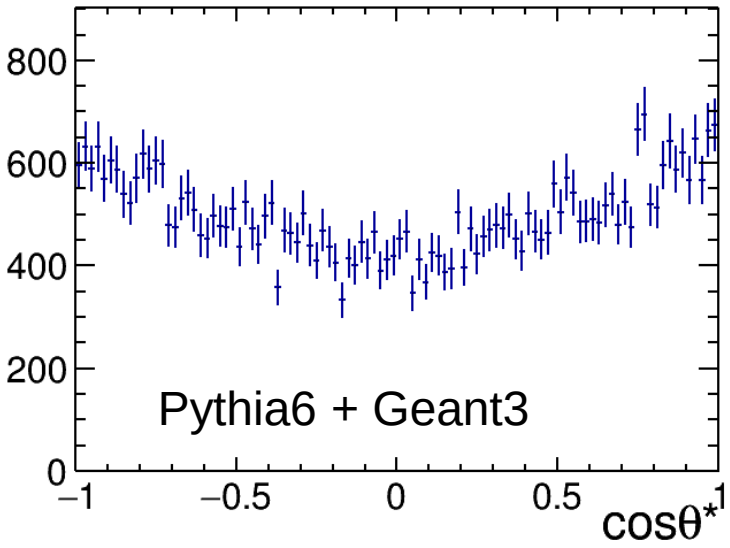


Embedding MC simulation

- Generator: Pythia 6.4.28
- Full Geant3 simulation of detector response
- Pythia events were embedded into STAR “zero bias” events
- Same analysis algorithm as data applied for MC sample

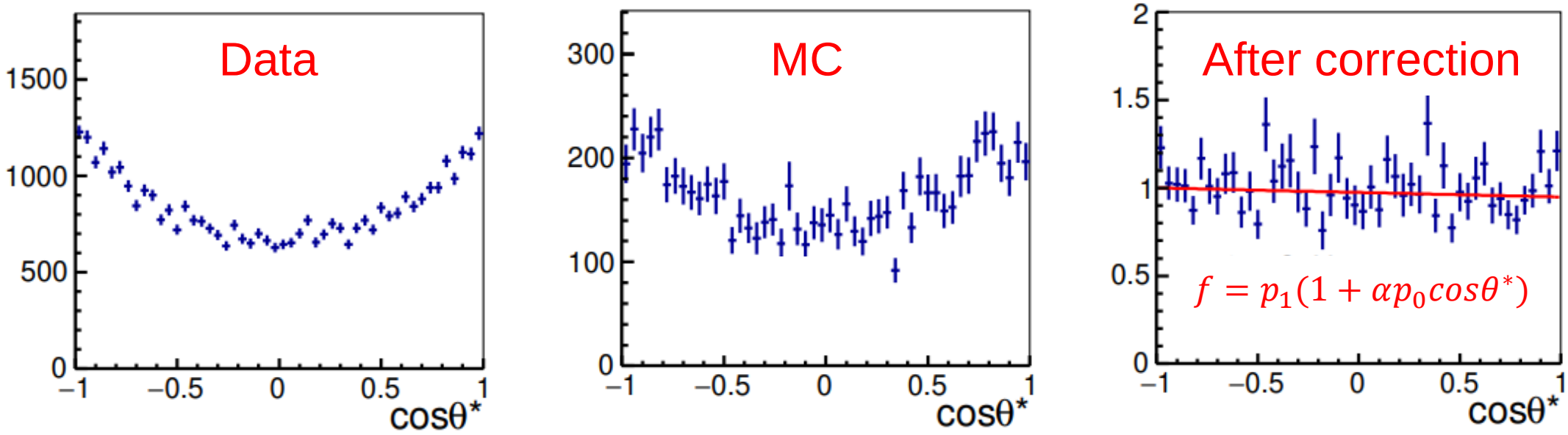






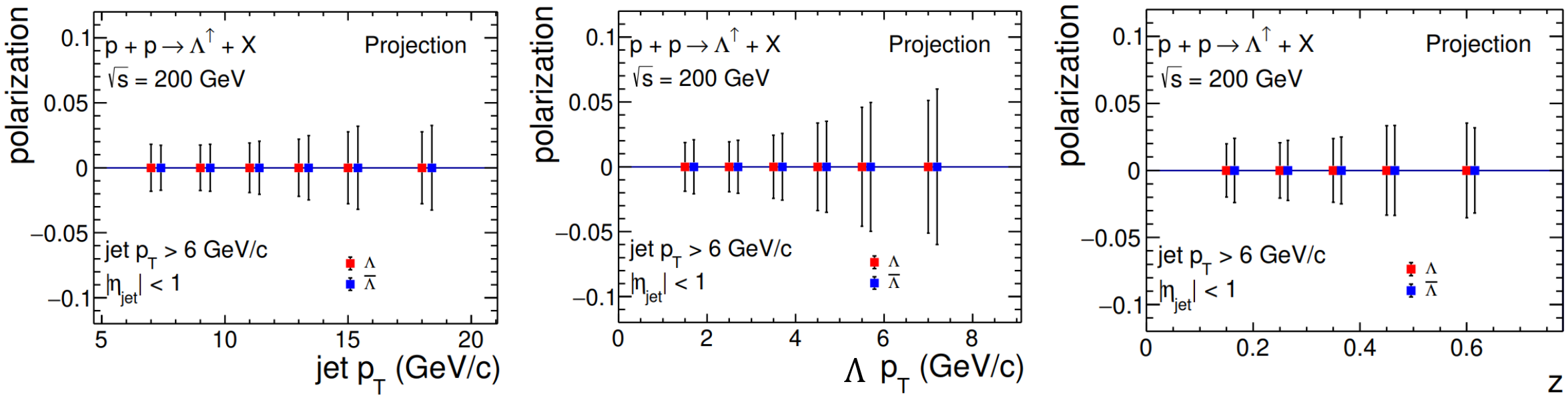
Λ polarization extraction

- Acceptance corrected $\cos\theta^*$ distribution: $\frac{cos\theta^*(data)}{cos\theta^*(MC)}$
- Extract polarization through fitting: $\frac{dN}{d\cos\theta^*} = N_0(1 + \alpha P \cos\theta^*)$



Precision projection of Λ polarization

- Projected precision of Λ polarization measurement in pp collisions :



- The analysis is ongoing

Summary

- The transverse spin transfer, D_{TT} , has been measured for $\Lambda(\bar{\Lambda})$ in p+p collisions at $\sqrt{s} = 200$ GeV at STAR:
  - Preliminary results of D_{TT} for $\Lambda(\bar{\Lambda})$ versus hyperon p_T up to 8GeV/c, with improved precision, are consistent with zero within uncertainties.
  - The first measurement of D_{TT} versus z, can provide direct information on the transversely polarized fragmentation functions.
- Polarizing fragmentation function, pFF, may contribute to the transverse polarization of $\Lambda(\bar{\Lambda})$ in unpolarized hadron collisions:
  - pFF is being studied in p+p collisions, by measuring $\Lambda(\bar{\Lambda})$ polarization within jets, which covers different momentum scales as BELLE and LEP.
  - pFF measurement at STAR is underway, 1~2% statistical precision is expected.

Thank you

Back Up

Λ in jet and z determination

- z definition:

$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

  - ✓ **detector z**: Jets are reconstructed using TPC tracks and EMC energy deposits
  - ✓ **particle z**: In theoretical calculations, all the particles are used for the jet

- **Measuring D_{TT} vs. particle z**
  - ✓ Obtain the detector z and D_{TT} in each detector z bin
  - ✓ Correct the average detector z to particle z (using correction factors obtained from MC simulation based on Pythia6 + Geant)