Measurement of transverse spin transfer of Λ and $\bar{\Lambda}$ hyperons in p+p collisions at STAR

Qinghua Xu (Shandong University)

for the STAR Collaboration

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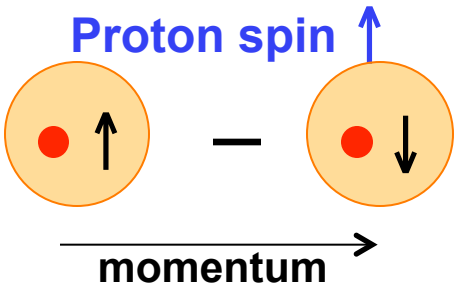
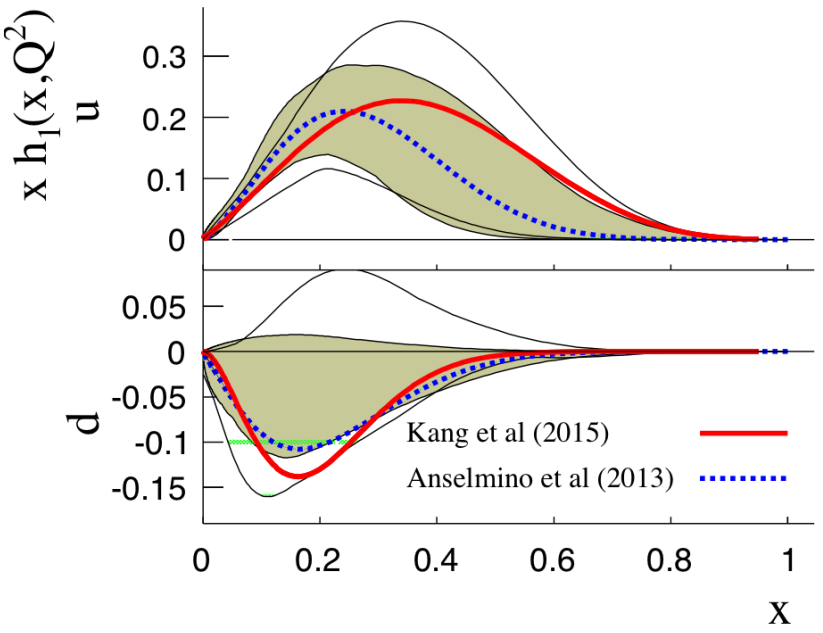
Transverse spin structure of nucleon

- Transversity- least known pdf among 3 leading twist pdfs.

$$\delta q(x,Q^2) = q^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2)$$





- Transversity involves helicity flip, thus no access in inclusive DIS process.

- Possible experimental measurements on δq(x):
  - Via Collins function (SIDIS, p+p), di-hadron production (SIDIS and p+p)
    Several Global fits available: Anselmino et al'13, Kang et al'15, M. Radici et al'18
  - Transversely polarized Drell-Yan process
  - Transverse spin transfer to hyperons (DIS, p+p) – this talk

What is special with Λ?

- Λ polarization can be measured in experiment via weak decay:

Λ->pπ⁻(Br64%), Λ->nπ⁰(Br36%) ,

-T.D.Lee, C.N.Yang(1957)

$$\frac{dN}{d\Omega} \propto 1 + \alpha (\vec{P}_\Lambda \cdot \hat{p}_p^*)$$

Unit vector along proton momentum in Λ's rest frame.

$\vec{P}_\Lambda \cdot \vec{p}_p^* = P_\Lambda \cos\theta^*$

decay parameter: 0.642(pπ⁻)

Λ polarization vector

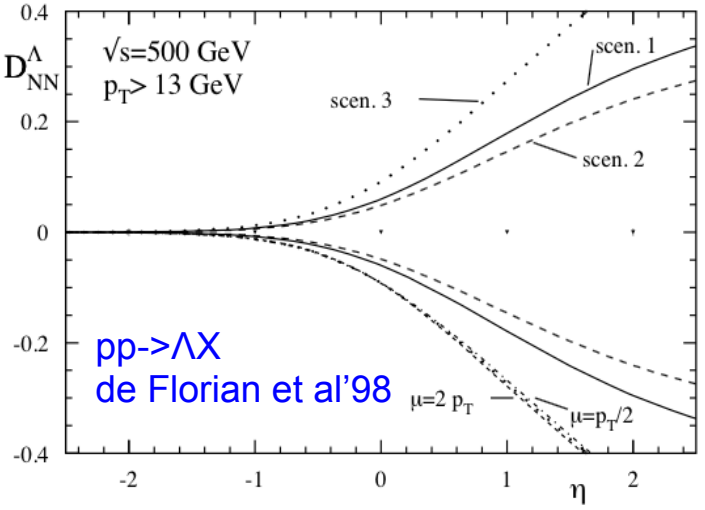
- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $\left|\Lambda^\uparrow\right\rangle = (ud)_{00} s^\uparrow$

Λ spin ~ *s* quark's spin

Transverse spin transfer of hyperons and δq(x)

- Transverse spin transfer of hyperons provide access to transversity and transversely pol. frag. function:

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



$$d\Delta_T\sigma^{(pp\to HX)} \propto \sum_{abcd}\int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T\hat{\sigma}^{(ab\to cd)}$$

transversity distribution

Transversely polarized fragmentation function

pQCD

- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

* Similarly, longitudinal spin transfer D_{LL} is connected to helicity pdf & frag.
-1st measurements of D_{LL} at RHIC STAR, PRD80, 111102(2009)

Direction of transverse polarization

- Transverse polarization direction - azimuthal angle determination

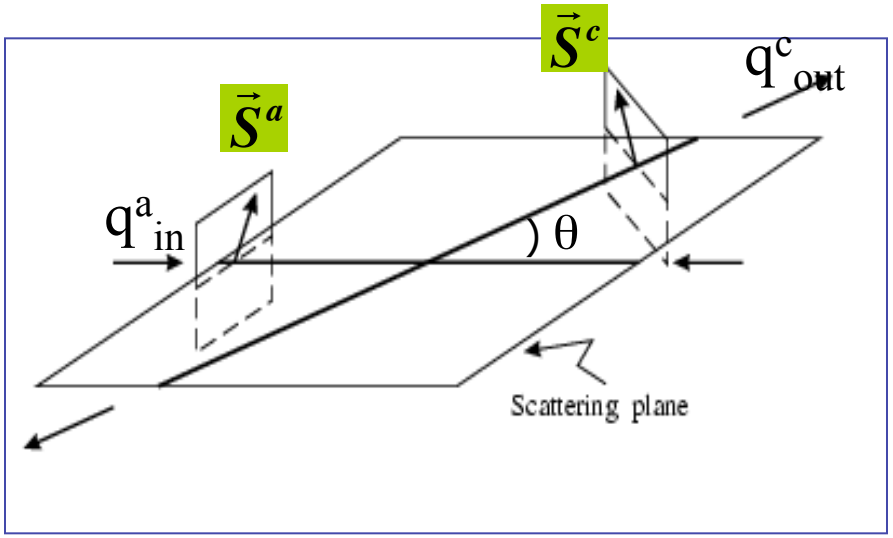
  Helicity density matrix of spin ½ particle (transversely polarized) :

$$\rho^{a}_{in} = \frac{1}{2}\begin{pmatrix} 1 & P_{aT}e^{-i\phi} \\ P_{aT}e^{i\phi} & 1 \end{pmatrix}$$

P_{aT}: transverse polarization

ϕ: azimuthal angle of pol. vector

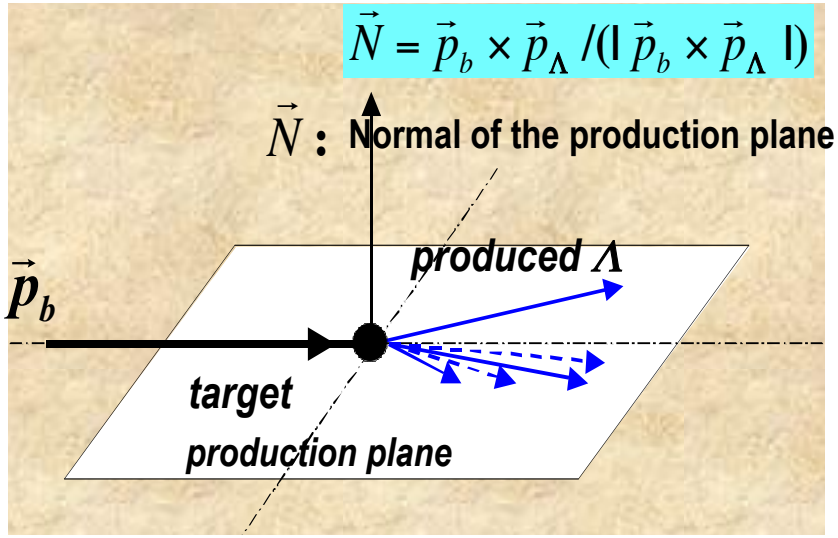
- The direction of transverse polarization is rotated along the normal of scattering plane in partonic scattering:

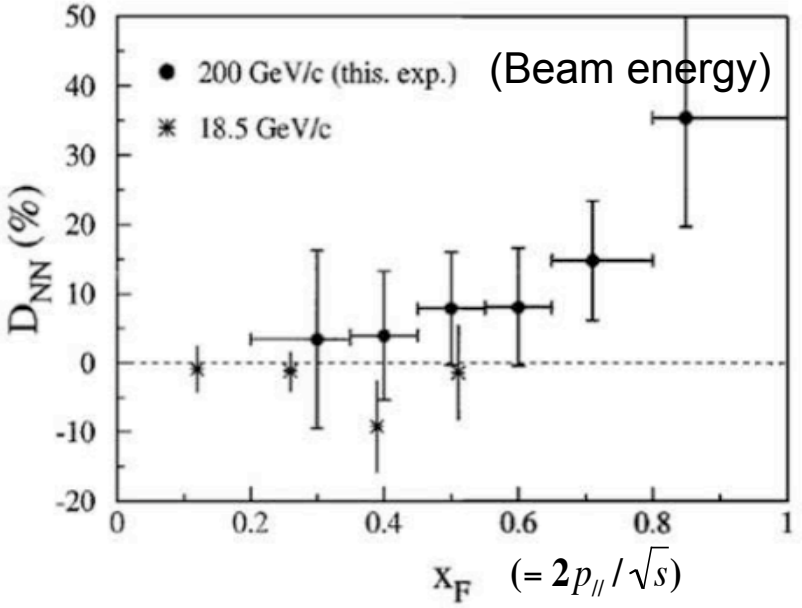


J.Collins, S.Heppelmann, G.Ladinsky, NPB420 (1994)565

How to measure transverse spin transfer ?

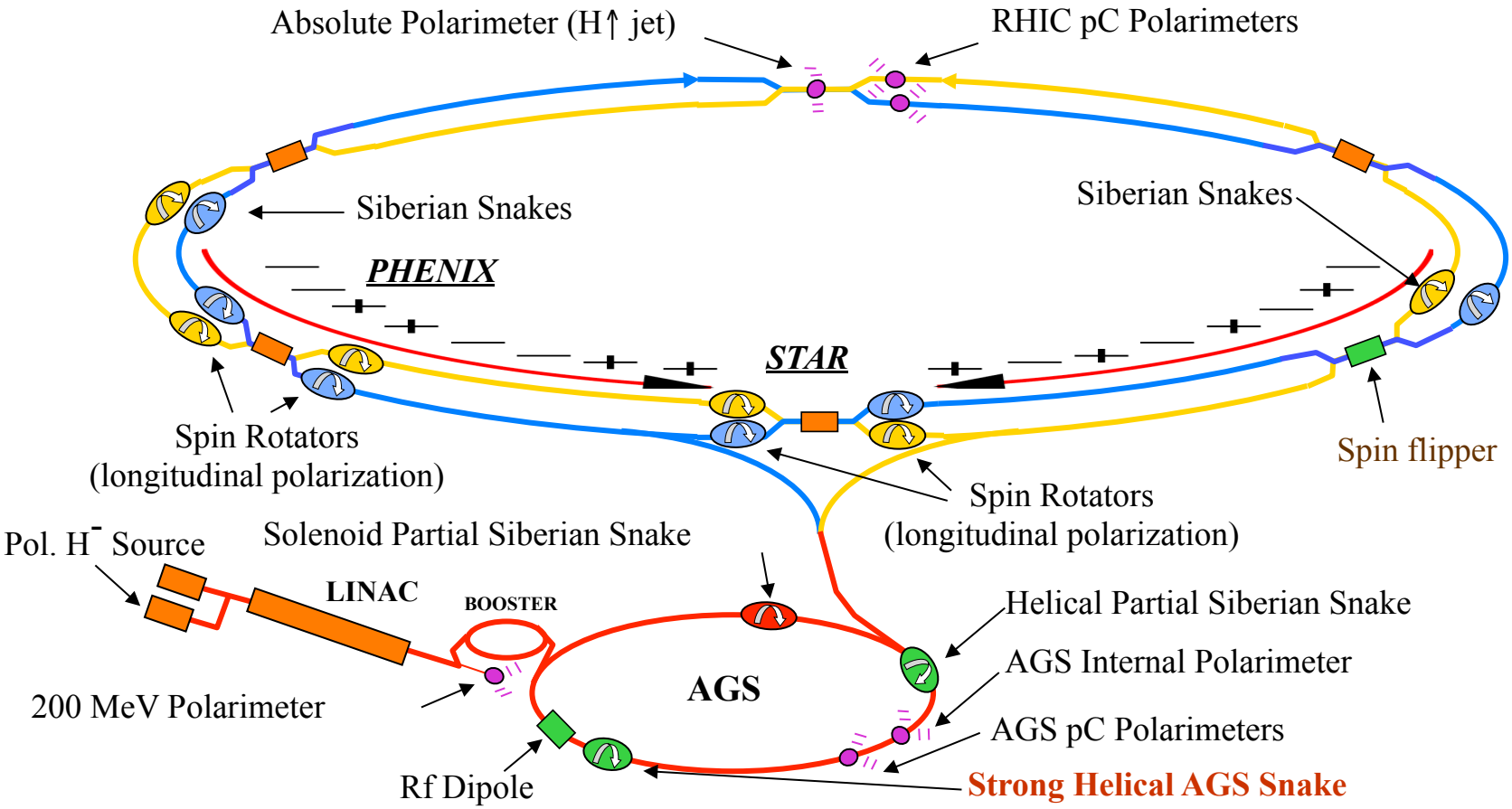
- Possible measurements on transverse spin transfer:
  - D_{TT} : final state polarization along the pol. of outgoing hard quark (considering the rotation in scattering plane)--- jet correlation
  - D_{NN} : spin transfer w.r.t. production plane
    - precision reduced ~ one half (beam pol. projected to N.)
    - production plane close to hard scattering plane at high p_T
    - in principle $D_{TT}=D_{NN}$





E704, PRL78, 4003(1997)

RHIC- a polarized proton+proton collider



- ✓ Data sample: transversely polarized p+p collisions at 200GeV taken with STAR detector in 2012, ~19pb^{-1}.
- ✓ RHIC Beam polarization: Blue beam: 64%, Yellow beam: 58%.

STAR - Solenoid Tracker At RHIC

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

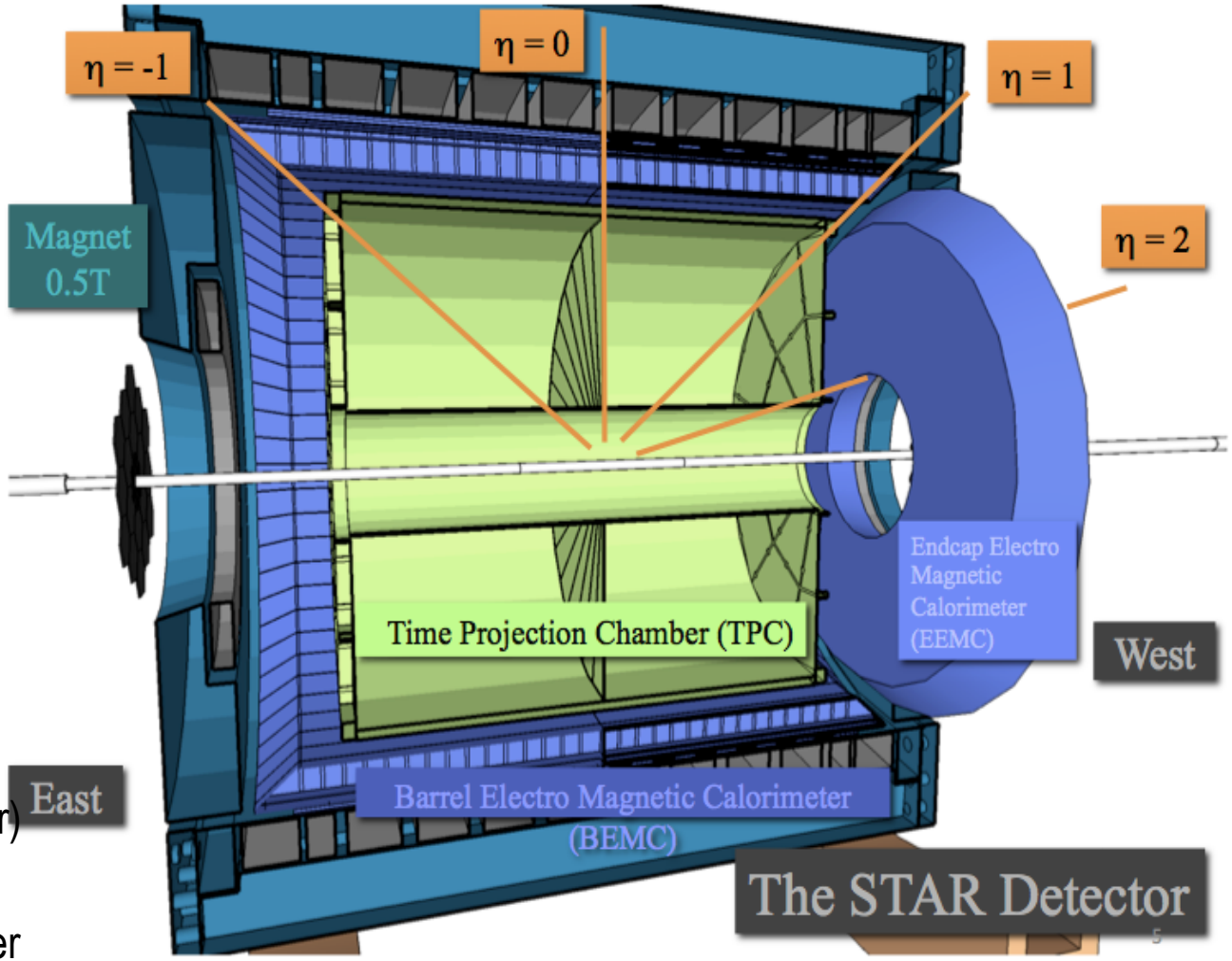
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Central Tracking

- Large-volume TPC
  - $|\eta| < 1.3$

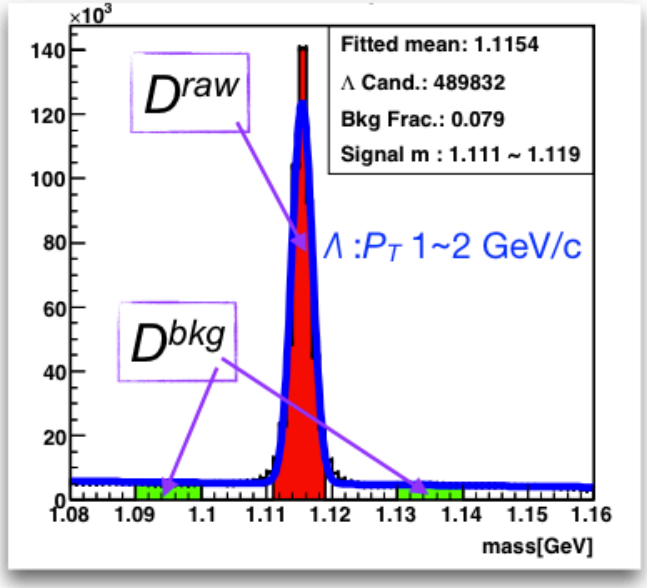
Calorimetry

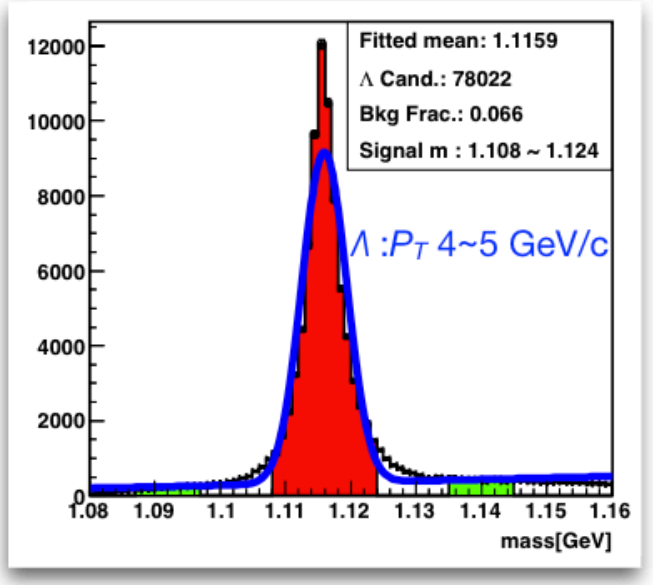
- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
- Forward Meson Spectrometer
  - $2.5 < \eta < 4.0$



Lambda hyperon reconstruction at STAR

- Λ and $\bar{\Lambda}$ are reconstructed via decay channels to (anti-)proton and pion:





- Residual backgrounds are subtracted with D_{TT} extraction:

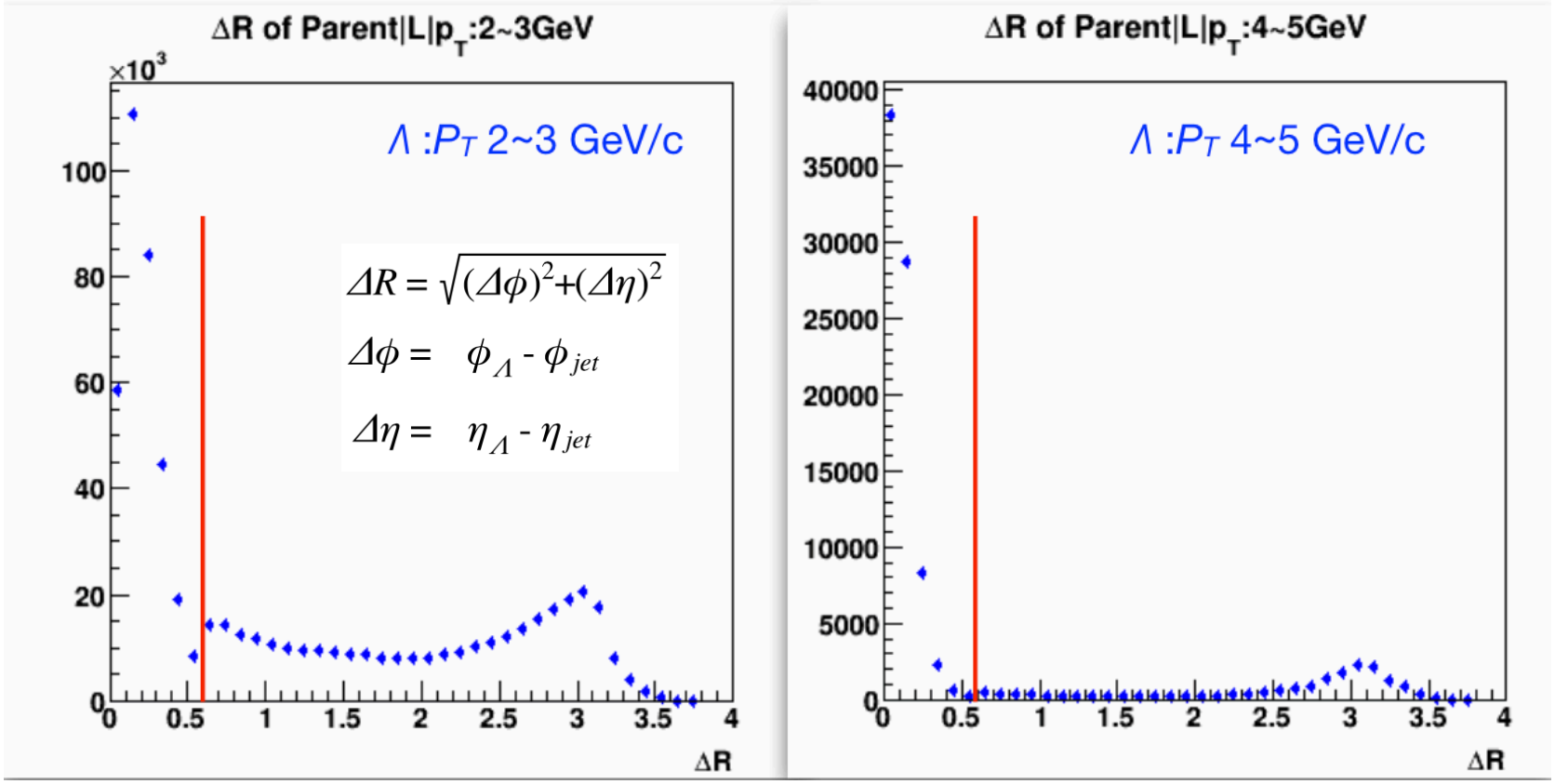
$$D_{TT} = \frac{D_{TT}^{raw} - rD_{TT}^{bkg}}{1-r}$$

$$\delta D_{TT} = \frac{\sqrt{(\delta D_{TT}^{raw})^2 + \left(r\delta D_{TT}^{bkg}\right)^2}}{1-r}$$

- r: the residual background fraction, estimated with side-band method, <10%

Jet Correlation with hyperons

- Anti-Kt algorithm is used in jet reconstruction; ΔR is calculated to make correlation between (anti-)Lambda candidate and jet.
- Require η_{jet} ~ (-0.7, 0.9), p_T > 5.0 GeV/c. If $\Delta R < 0.6$ for a hyperon, corresponding jet axis is used as outgoing quark direction to get the quark's transverse polarization direction.



Extraction of transverse spin transfer D_{TT}

- Momentum distribution of Λ weak decay in its rest frame:

$$dN/d\cos\theta^* \sim A(\cos\theta^*)(1+\alpha P_\Lambda \cos\theta^*)$$

$$\cos\theta^* \propto \vec{P}_\Lambda \cdot \vec{p}_p^{\,*}$$

α: decay parameter, 0.642 for Λ

$\vec{P}_\Lambda$: Λ polarization vector

$\vec{p}_p^{\,*}$: momentum of proton in Λ rest frame

- D_{TT} can be extracted from Λ counts with opposite beam polarization within a small interval of cosθ*:

$$D_{TT} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}$$

$N^{\uparrow}$: $\Lambda\,(\bar{\Lambda})$ counts with positive beam polarization

$N^{\downarrow}$: $\Lambda\,(\bar{\Lambda})$ counts with negative beam polarization

P_{beam} : polarization of beam

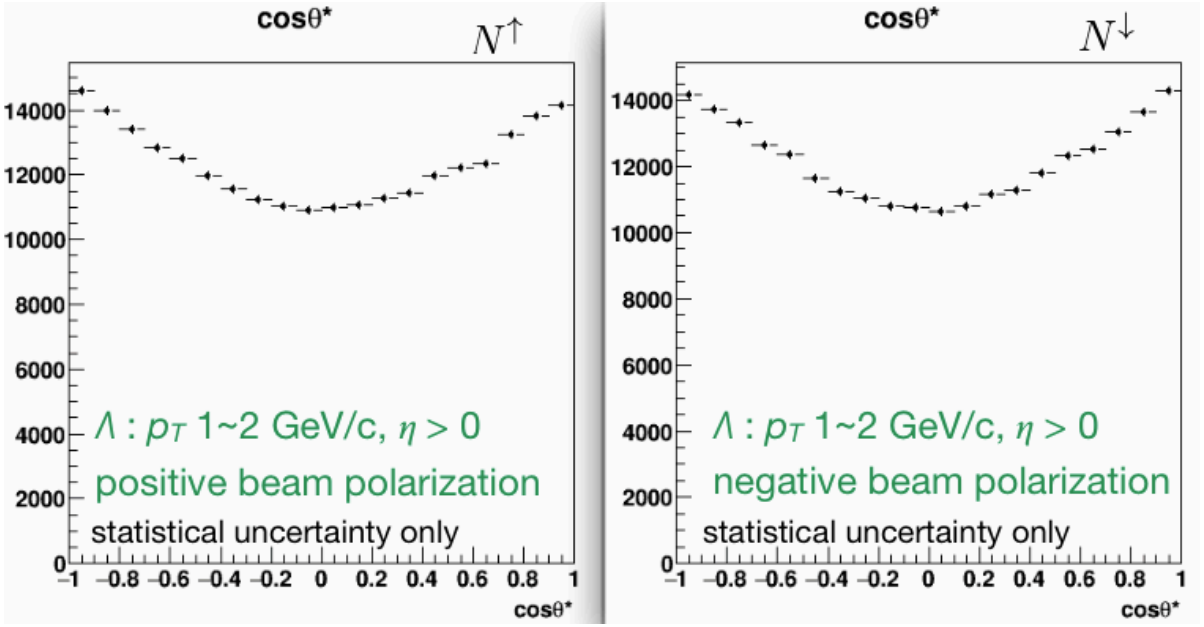
<cosθ*> : mean in each cosθ* bin

- Acceptance of reverse beam polarization is expected to be the same in each cosθ* bin, thus cancelled
- *R*: relative luminosity, obtained with non-hyperon events.

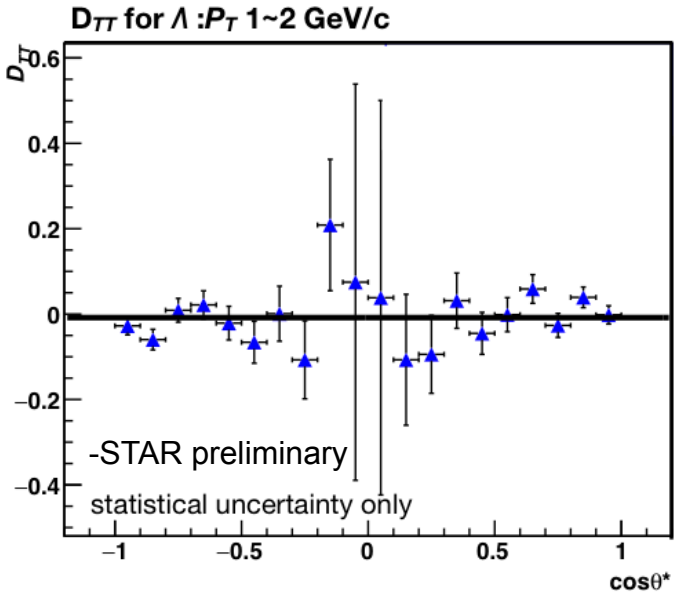
Extraction of transverse spin transfer D_{TT}

- Lambda counts versus cosθ^* for opposite beam spin:

$$D_{TT} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}$$

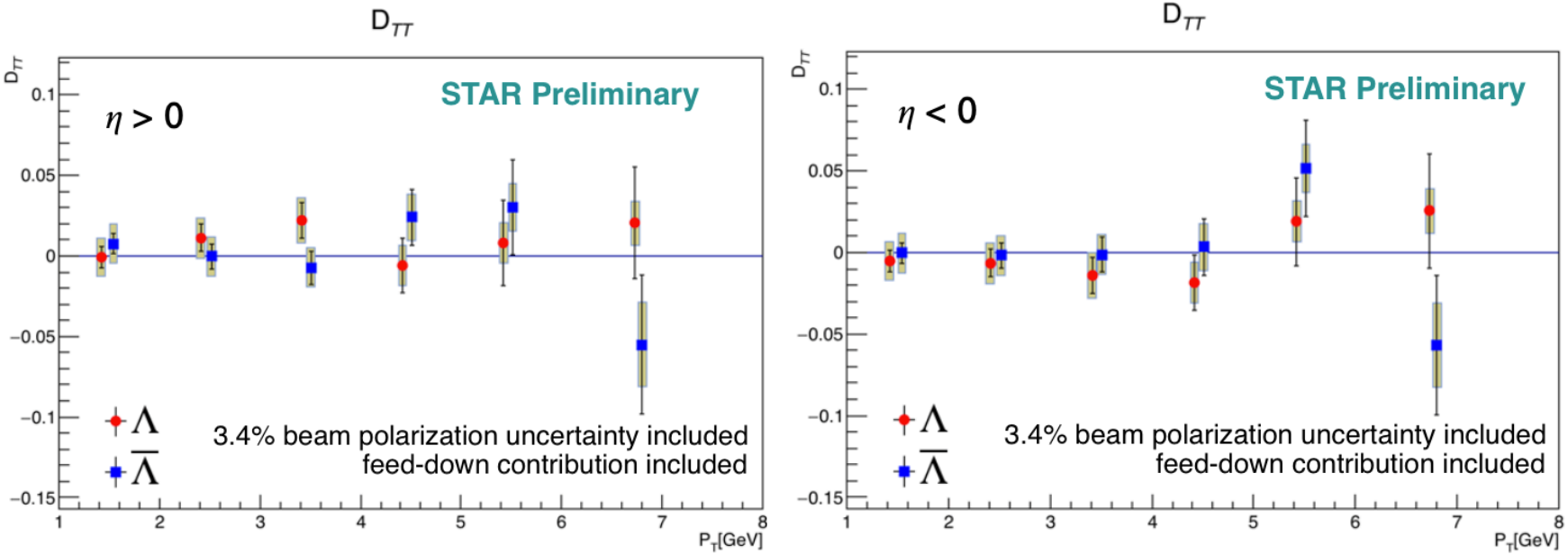


- Extract D_{TT} in each cosθ^* bin, then average over whole cosθ^* range.
- Background subtraction.
- The method passed the null check with K_s^0 ->π^+ π^-



Transverse spin transfer D_{TT} results at STAR

- Results of transverse spin transfer D_{TT} in p+p collision at 200 GeV:



- ✓ 1st transverse spin transfer measurement in p+p collisions at RHIC.
- ✓ Most precise measurement on (anti-)Lambda polarization in p+p collision at RHIC, which reach p_T ~6.7 GeV/c with statistical uncertainty of 0.04.
- ✓ D_{TT} of Lambda and anti-Lambda are consistent with each other and consistent with zero at current precision.

Reducing systematic/statistical uncertainty

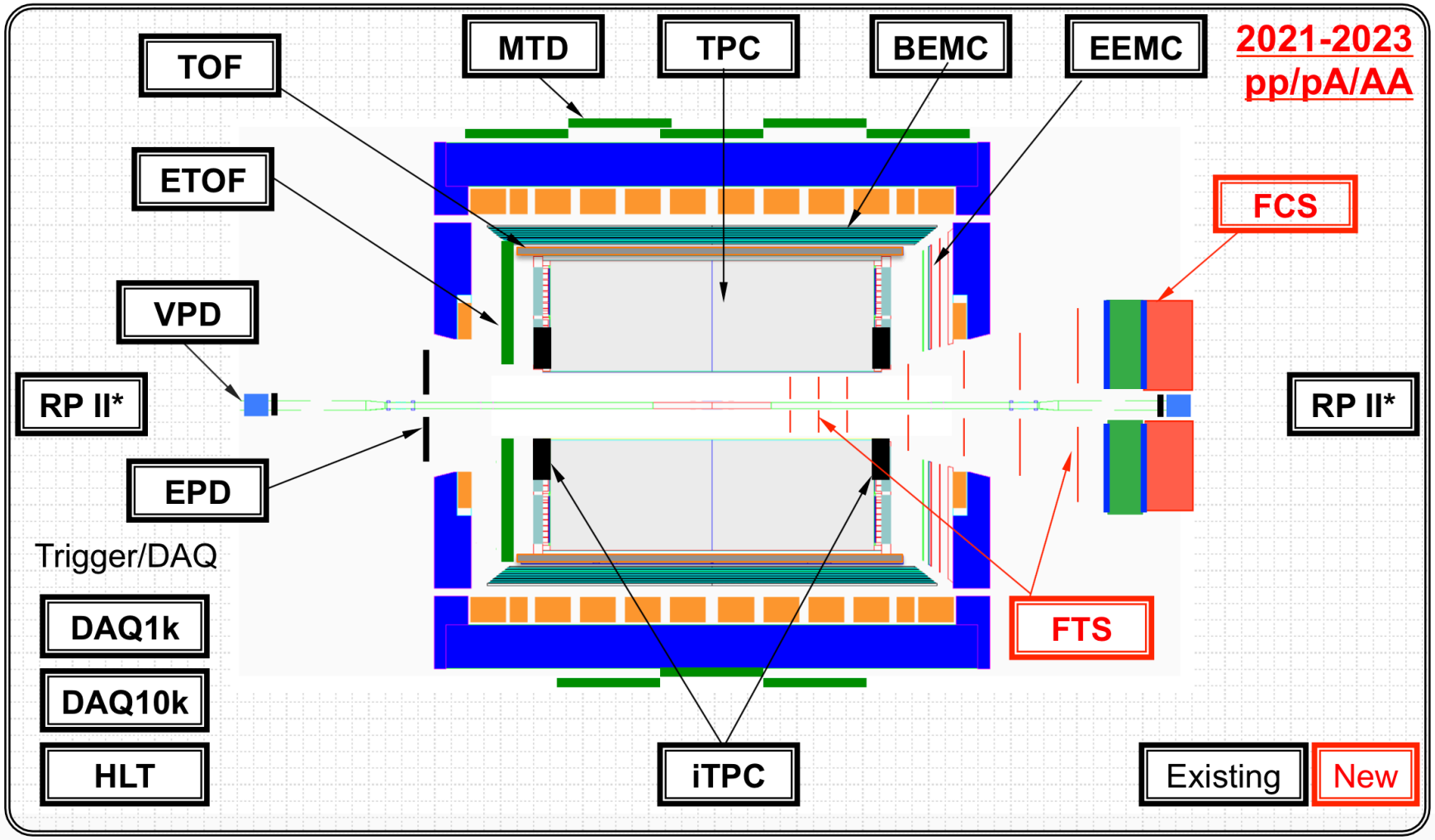
- List of systematic uncertainty to current D_{TT} results:
  - ✓ 3.4% scale uncertainty from RHIC beam polarization measurement.
  - ✓ 2% from decay parameter (0.642 ± 0.013).
  - ✓ 0.012 from relative luminosity measurement -> dominant source
  - ✓ Residual background fraction estimation (<0.003).
  - ✓ Pile up effect, estimated to be <0.005.
  - ✓ Trigger bias estimated from MC simulation (<0.008).
- Reduce the systematic uncertainty with cross-ratio method:

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

  - ✓ Both acceptance and luminosity dependences are canceled mostly.
  - ✓ Consistent D_{TT} results, with systematic uncertainty significantly reduced.
  - ✓ Underway, results to be released soon.
- Statistical uncertainty will be improved with 2015 STAR data (~50 pb^{-1})

Forward Λ physics with STAR forward upgrade

- STAR forward detector upgrade enables forward Λ reconstruction:
  - with forward tracking system and forward calorimeter system in 2021+



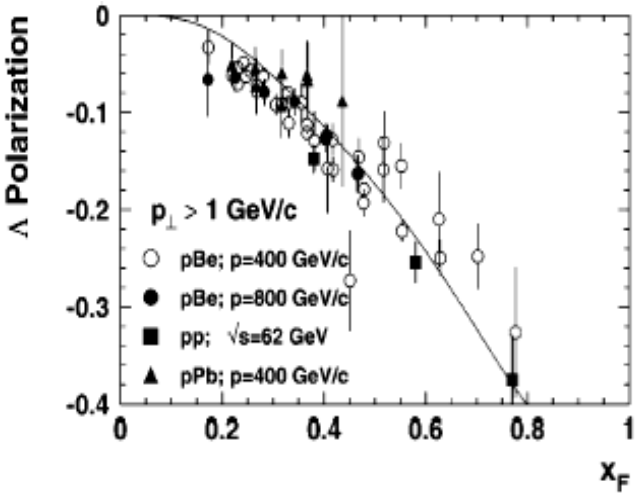
* FTS: Forward Tracking System; FCS: Forward Calorimeter System

Forward Λ physics with STAR forward upgrade

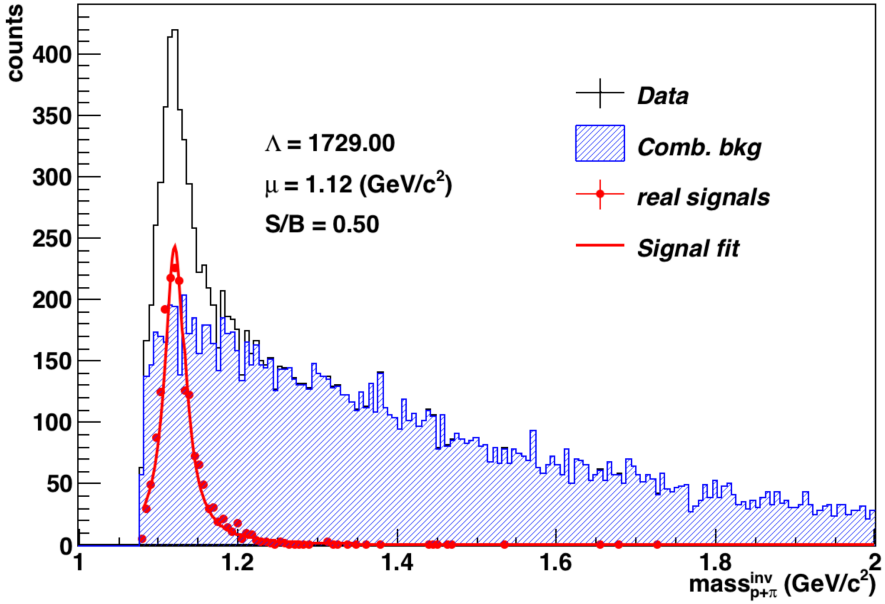
- STAR forward detector upgrade enables forward Λ reconstruction:
  - with forward tracking system and forward calorimeter system in 2021+

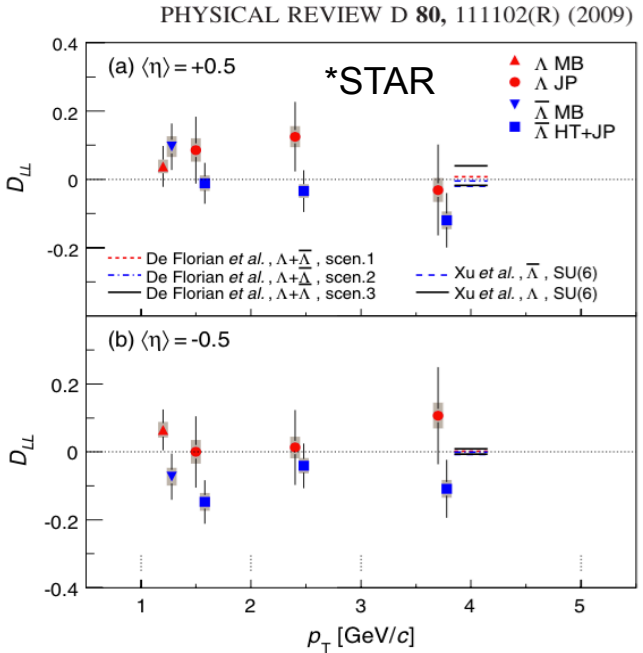
  ✓ Induced polarization in unpolarized p+p

  ✓ Spin transfer in both longitudinal and transverse polarized pp : D_{LL} & D_{TT}



- Simulation of Λ reconstruction with FCS+FTS in p+p at STAR:





Summary and Outlook

- First measurement of $\Lambda/\bar{\Lambda}$ transverse spin transfer (D_{TT}) in p+p collisions at RHIC, sensitive to transversity and transversely polarized fragmentation function.
- The largest $\Lambda/\bar{\Lambda}$ sample so far in p+p collision at RHIC and the D_{TT} precision is ~0.04 at $\langle p_T \rangle$ ~6.7 GeV and $\langle \eta \rangle$~0.5.
- D_{TT} of $\Lambda/\bar{\Lambda}$ are consistent with each other at current precision.
- STAR p+p data taken in 2015 with transverse polarization is two times larger, and better D_{TT} precision is expected.
- STAR forward detector upgrade enables rich forward Λ physics, by reconstructing Λ's with forward tracking system and forward calorimeter system in 2021^{+} at STAR.