Measurements on longitudinal and transverse spin transfer to $\Lambda/\bar{\Lambda}$ in p+p collisions at STAR

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for the STAR Collaboration

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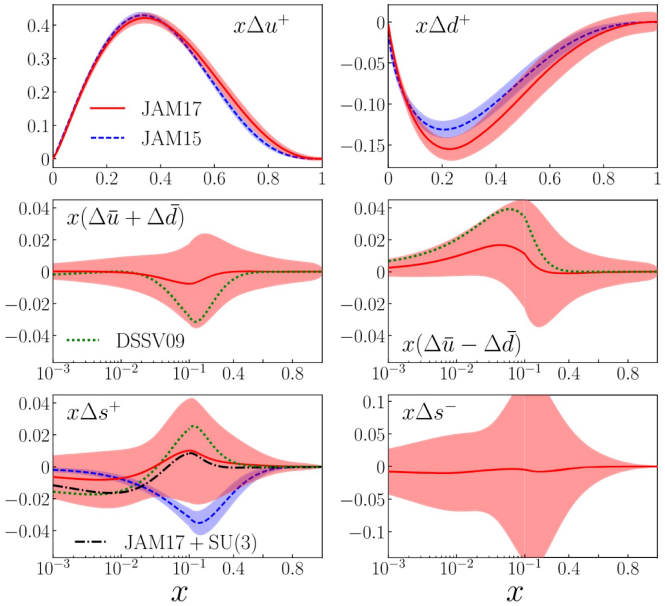
Longitudinal spin transfer D_{LL} predictions in p+p

- Longitudinal spin transfer of $\Lambda(\bar{\Lambda})$ in p+p:

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

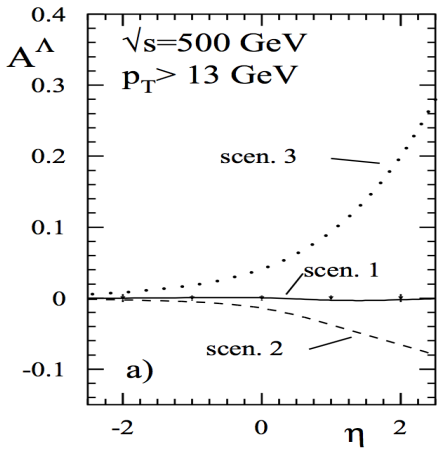
helicity distribution — pQCD calculable — polarized FF



J. Ethier et al, PRL**119**, 132001 (2017)

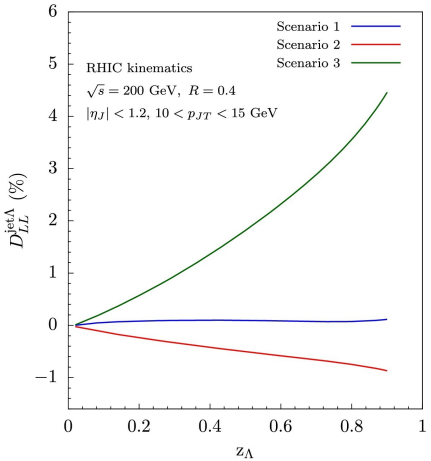
- Strong quark helicity not well constrained yet
- D_{LL} provides access to helicity distribution and polarized fragmentation function.

- D_{LL} predictions in p+p with modeling polarized fragmentation function:



D. de Florian et al, PRL 81, 530(1998)

Scen. 1: only s quark contribute to Λ spin.
Scen. 2: u, d contributes equally to Λ spin, opposite sign from s quark.
Scen. 3: u, d, s quarks have same contribution.



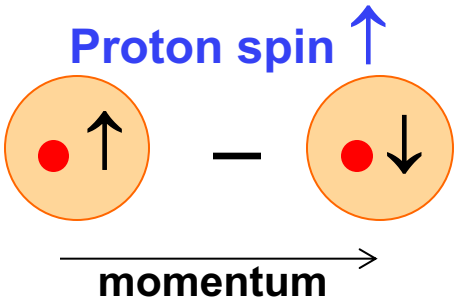
Z.-B. Kang et al, PLB 809, 135756 (2020).

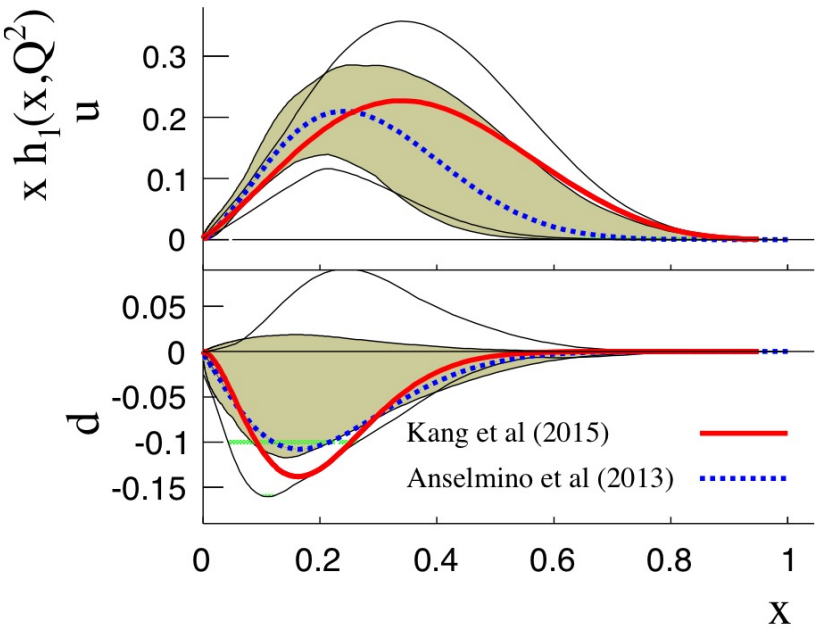
D_{LL} vs z can provides direct probe to the polarized fragmentation function

Transverse spin structure of nucleon

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

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





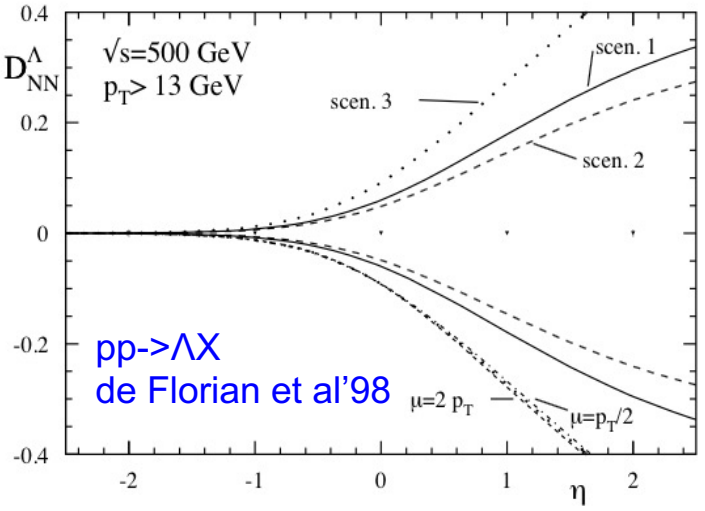
- Transversity involves helicity flip, thus no access in inclusive DIS process.

- Possible experimental measurements on $\delta q(x)$:
  - Via Collins function (SIDIS, p+p), di-hadron production (SIDIS and p+p)
  - Transversely polarized Drell-Yan process
  - Transverse spin transfer to hyperons (DIS, p+p)

Transverse spin transfer of hyperons and δq(x)

- Transverse spin transfer of hyperons provides access to transversity and transversely polarized fragmentation function:

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



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

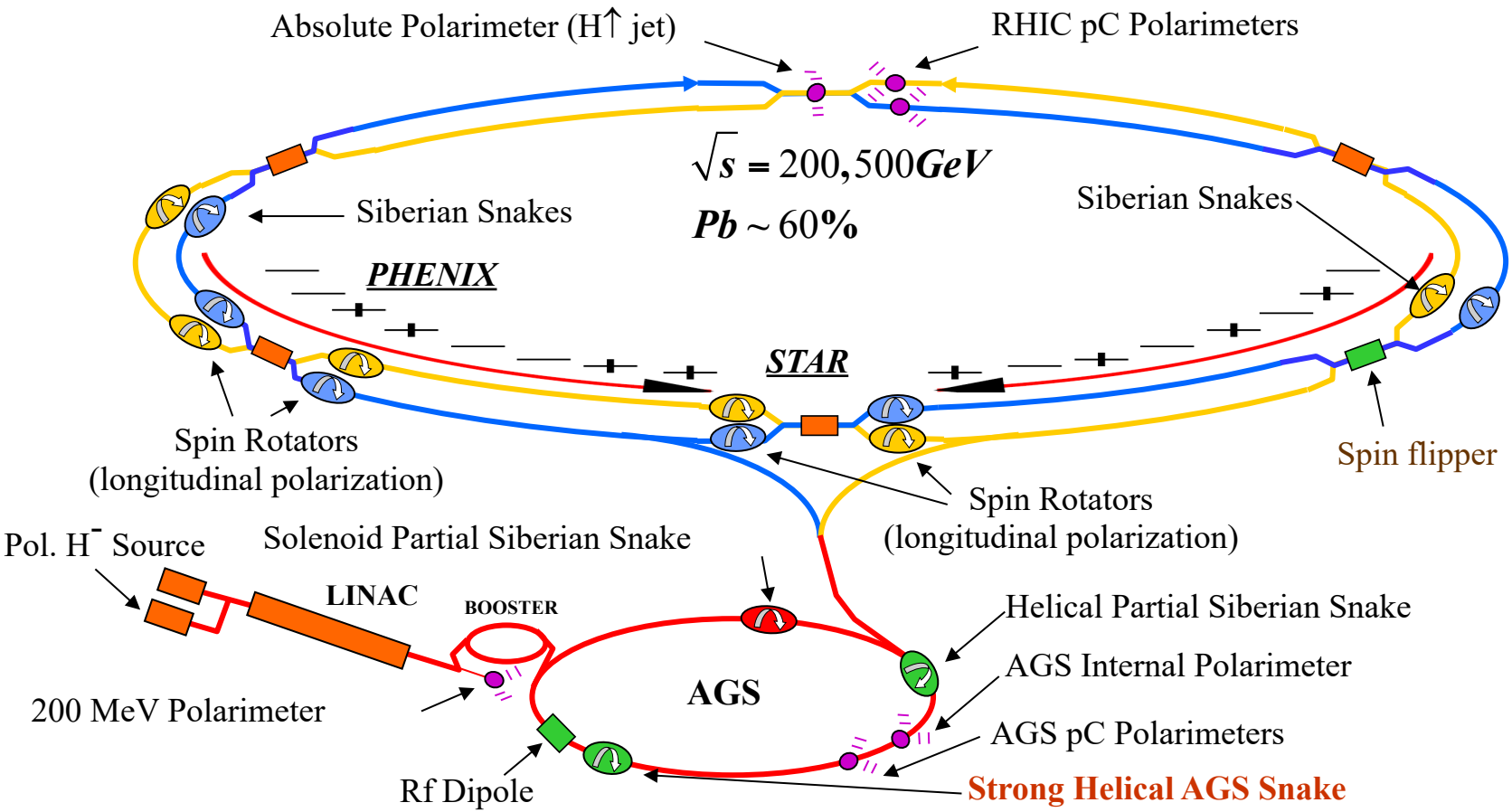
transversity distribution

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).

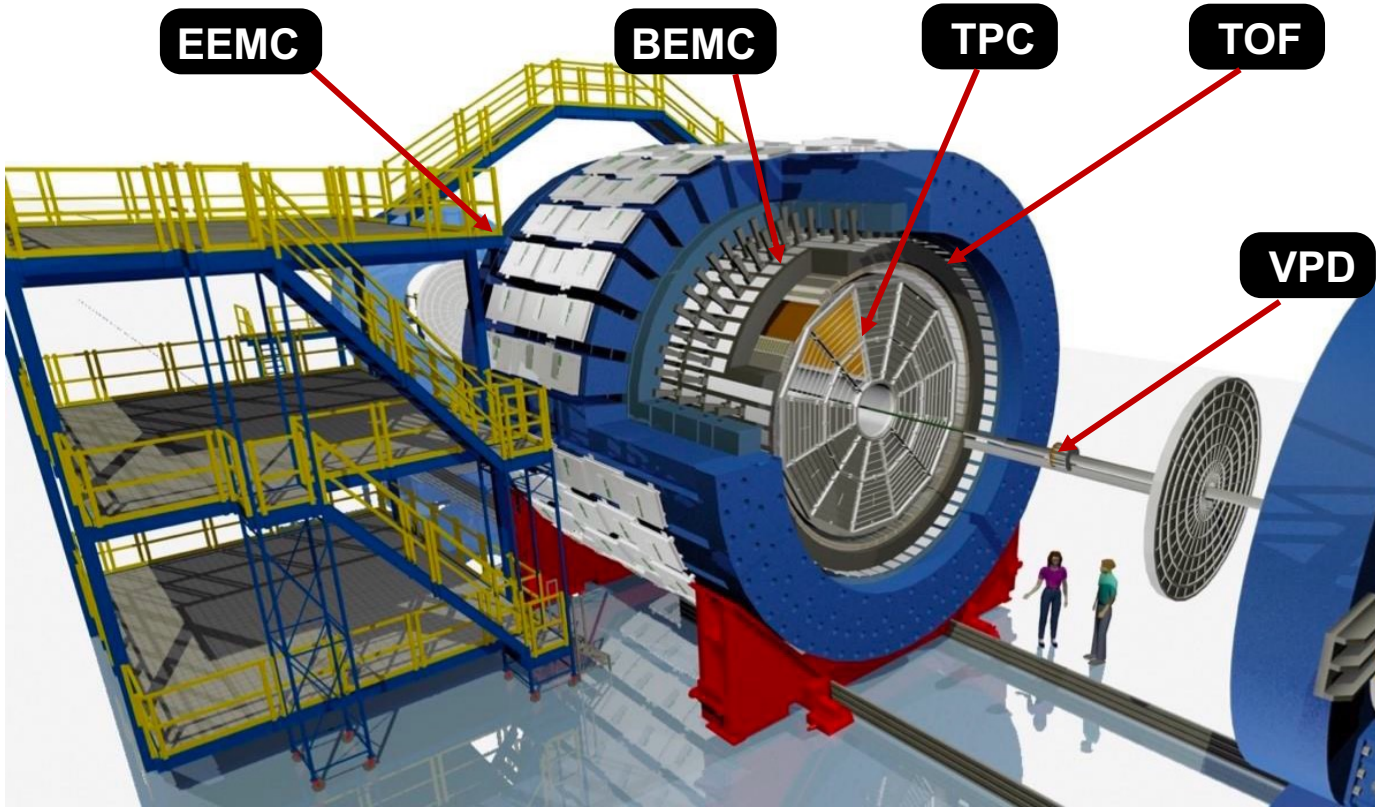
RHIC- a polarized proton+proton collider



- Data sample I: longitudinally polarized p+p collisions at 200GeV with STAR in 2015, ~52pb^{-1}, beam polarization ~53%. -> D_{LL}
- Data sample II: transversely polarized p+p collisions at 200GeV with STAR in 2015, ~52pb^{-1}, beam polarization ~57%. -> D_{TT}

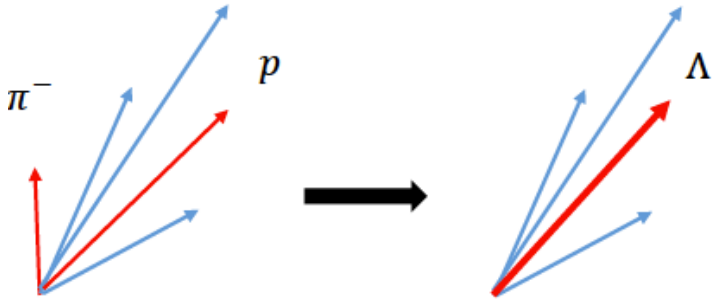
STAR - Solenoid Tracker At RHIC

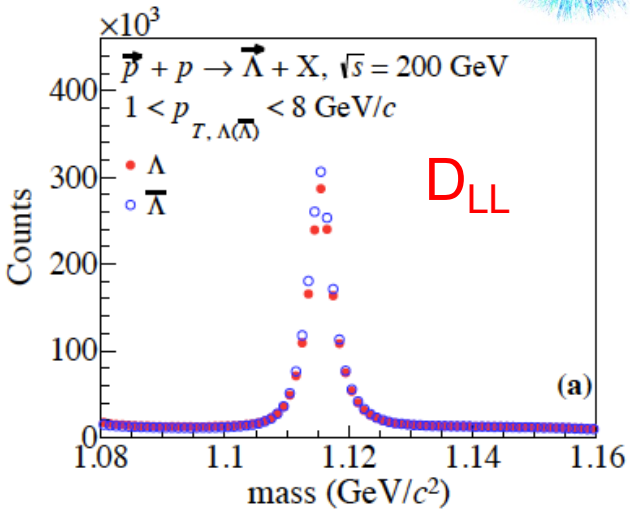
- **Time Projection Chamber (TPC)**
  - $|\eta| < 1.3$ with 2π azimuthal coverage
  - Tracking and particle identification.
- **Time of Flight (TOF)**
  - $|\eta| < 1.0$ with 2π azimuthal coverage
  - Particle identification.
- **Electromagnetic Calorimeter (EMC)**
  - Barrel EMC (BEMC): $|\eta| < 1.0$
  - Endcap EMC (EEMC): $1.086 < \eta < 2.0$
  - Photon, π^0 , also serve as trigger detectors.
- **Vertex Position Detector (VPD)**
  - $4.2 < |\eta| < 5.1$
  - Vertex & relative luminosity.

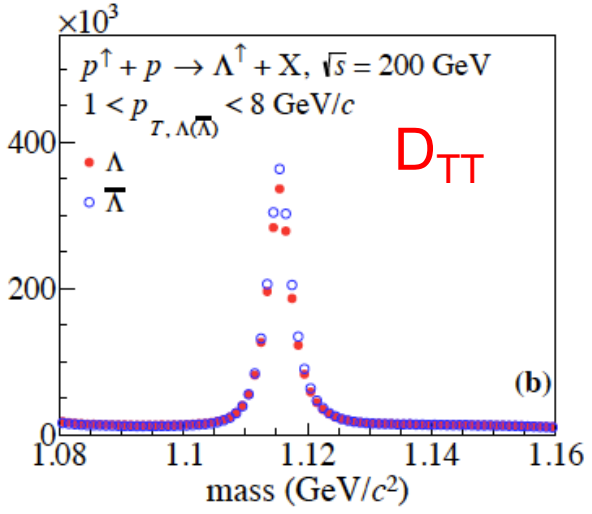


Hyperon & jet reconstruction

- Select hard scattering events using a jet trigger based on the energy deposits in the EMC
- $\Lambda(\overline{\Lambda})$ reconstruction: $\Lambda \to p + \pi^-$; $\overline{\Lambda} \to \overline{p} + \pi^+$
  - Topological cuts to reduce background
  - Side-band method to estimate residual background.
- **Require hyperons to be part of a jet:**
  - Jets reconstructed with anti-k_T algorithm (R=0.6) with TPC tracks, EMC energy deposits, and $\Lambda(\overline{\Lambda})$







- Background subtraction: $D_{LL} = \dfrac{D_{LL}^{raw} - r D_{LL}^{bkg}}{1 - r}$

r : background fraction (~10%)

Extraction of spin transfer D_{LL} in p+p

- Λ polarization is usually extracted from the angular distribution of its weak decay ($\Lambda \rightarrow p\pi^-$):

$$dN = \frac{N_{tot}}{2} A(\cos\theta^*)(1 + \alpha P_\Lambda \cos\theta^*) \qquad \cos\theta^* \propto \vec{P}_\Lambda \cdot \vec{p}_p^{\,*}$$

α: decay parameter
A(cosθ*): detector acceptance

- D_{LL} has been extracted from Λ counts with opposite beam polarization within a small interval of cosθ*: -STAR, PRD80, 111102 (2009)

$$D_{LL} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$, where the acceptance cancels.

$$N^+ = N^{++} \frac{L_{--}}{L_{++}} + N^{+-} \frac{L_{--}}{L_{+-}}$$

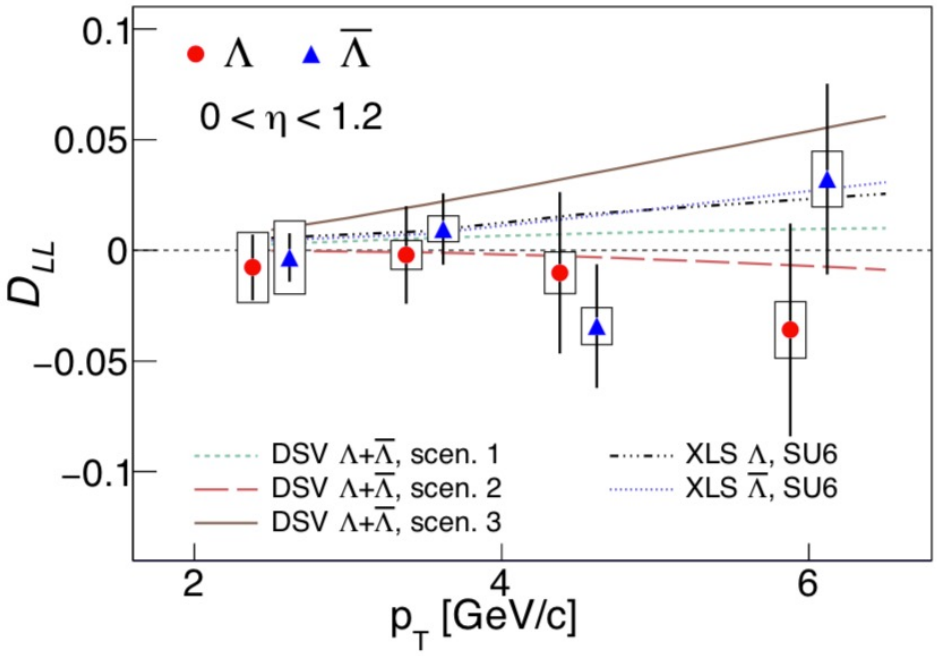
$$N^- = N^{-+} \frac{L_{--}}{L_{-+}} + N^{--}$$

Relative luminosity ratio measured with VPD, ZDC, and P_{beam} in RHIC.

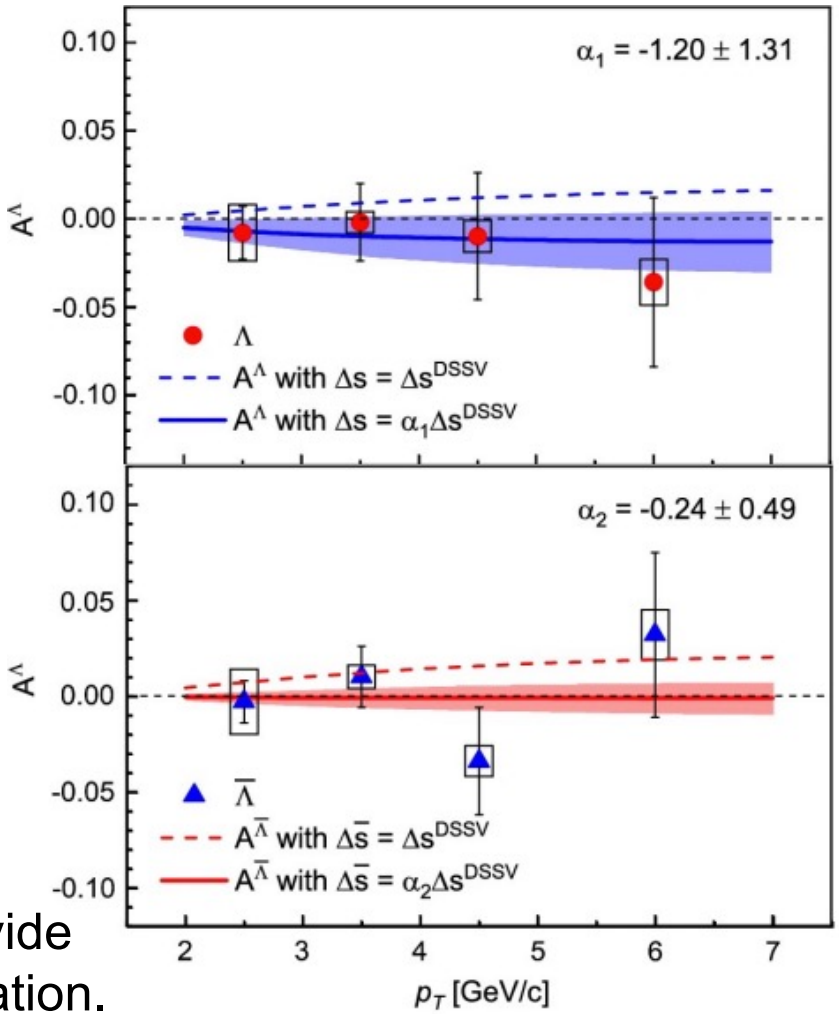
Previous D_{LL} results with STAR 2009 data

- D_{LL} measurements from STAR 2009 data, statistically limited.

-STAR, PRD98, 112009 (2018)



- D.de Florian, M.Stratmann, W.Vogelsang, PRL81,530(1998)
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503(2006)



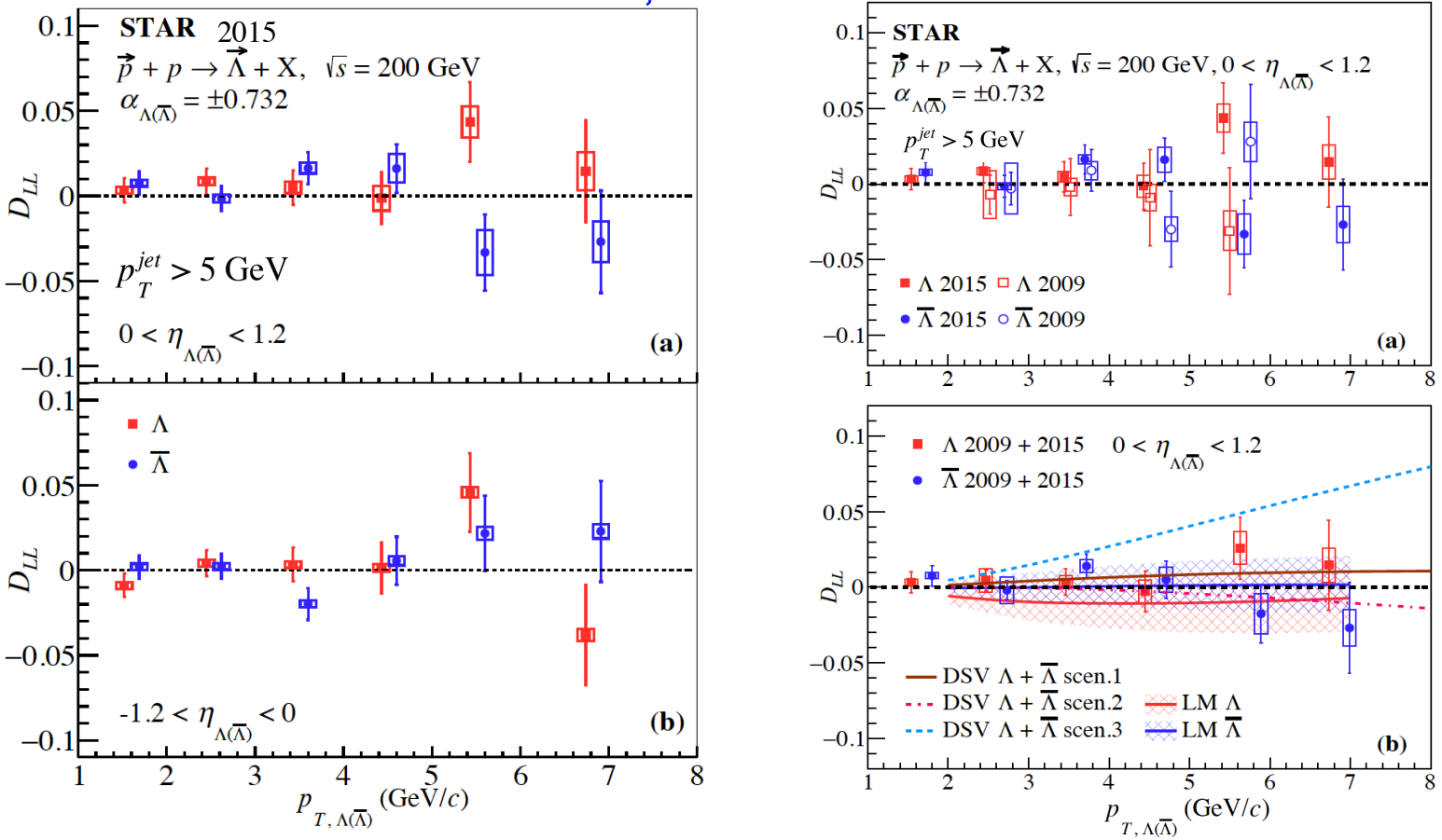
- X.N. Liu, B.Q. Ma, EPJC 79,409 (2019)

- Theoretical models, when fit to data, provide constraints to (anti)strange quark polarization.

New D_{LL} results with STAR 2015 data

- New results are in agreement with previous measurements, with twice statistics. No clear difference observed between Λ and $(\overline{\Lambda})$.
- Results are in agreement with various model predictions, except "DSV" calculation with "scen. 3" of polarized fragmentation function.

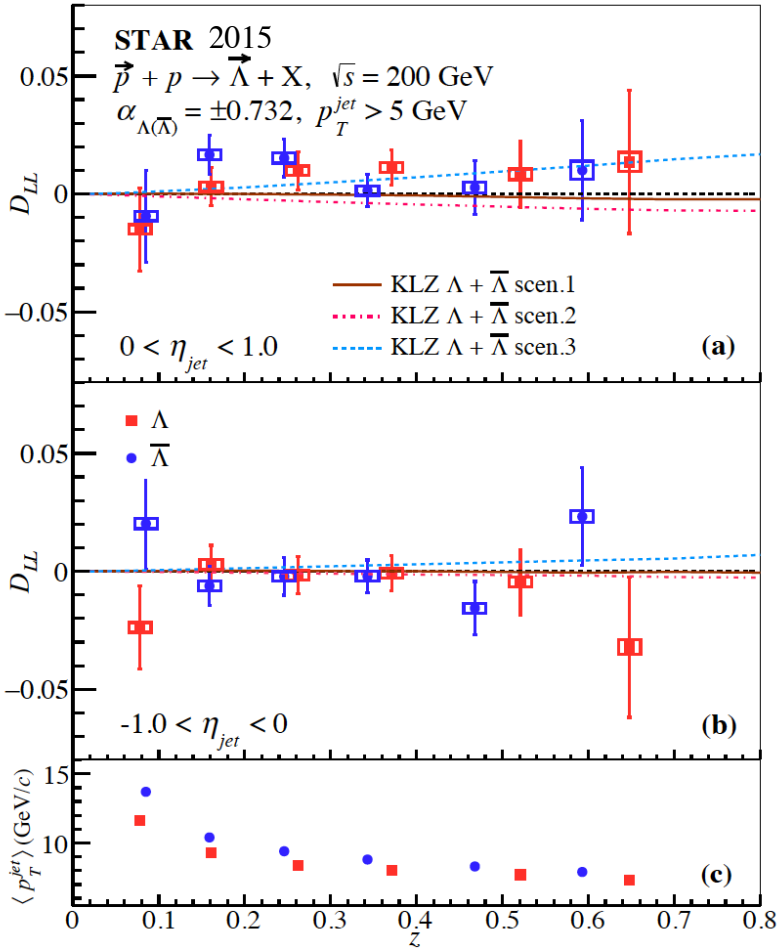
STAR, arXiv:2309.14220



- D.de Florian, M.Stratmann, W.Vogelsang, PRL81,530(1998); - X.N. Liu, B.Q. Ma, EPJC 79,409 (2019)

D_{LL} vs z results with STAR 2015 data

- First measurements of D_{LL} vs z in polarized p+p collisions, directly probing the polarized fragmentation functions.
- The results are comparable to model prediction within uncertainties.



STAR, arXiv: 2309.14220

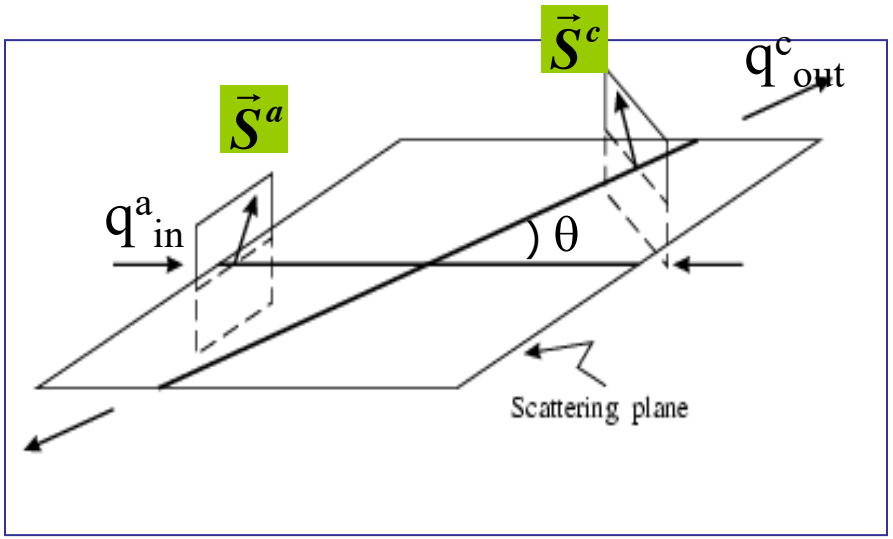
$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

z: Jet momentum fraction carried by hyperon

- Z.-B. Kang, K. Lee, F. Zhao, Phys. Lett. B **809**, 135756 (2020).

Direction of transverse polarization

- The direction of transverse polarization is rotated along the normal of scattering plane in partonic scattering, using reconstructed jet axis



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

- 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

Extraction of transverse spin transfer D_{TT}

- D_{TT} is extracted from a cross-ratio asymmetry using Λ counts with opposite beam polarization within a small interval of cosθ* :

-STAR, PRD 98, 091103R (2018)

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

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

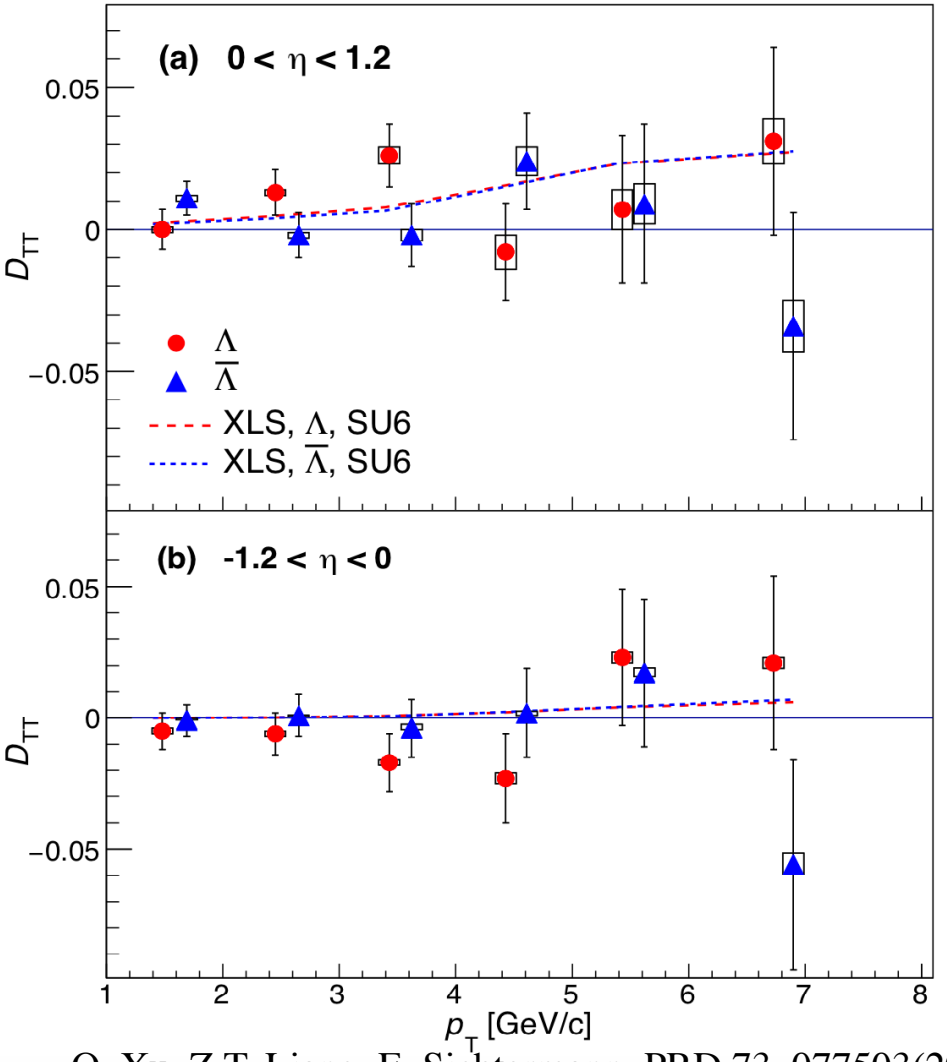
P_{beam} : polarization of beam
<cosθ*> : mean in each cosθ* bin

- Acceptance of reverse beam polarization is expected to be the same in each cosθ* bin, thus cancelled
- Luminosity is also cancelled in the cross-ratio asymmetry

Previous D_{TT} results with STAR 2012 data

- D_{TT} measurements in p+p collision at 200 GeV with STAR 2012 data:

  -STAR, PRD98, 091103R (2018)



- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503(2006)

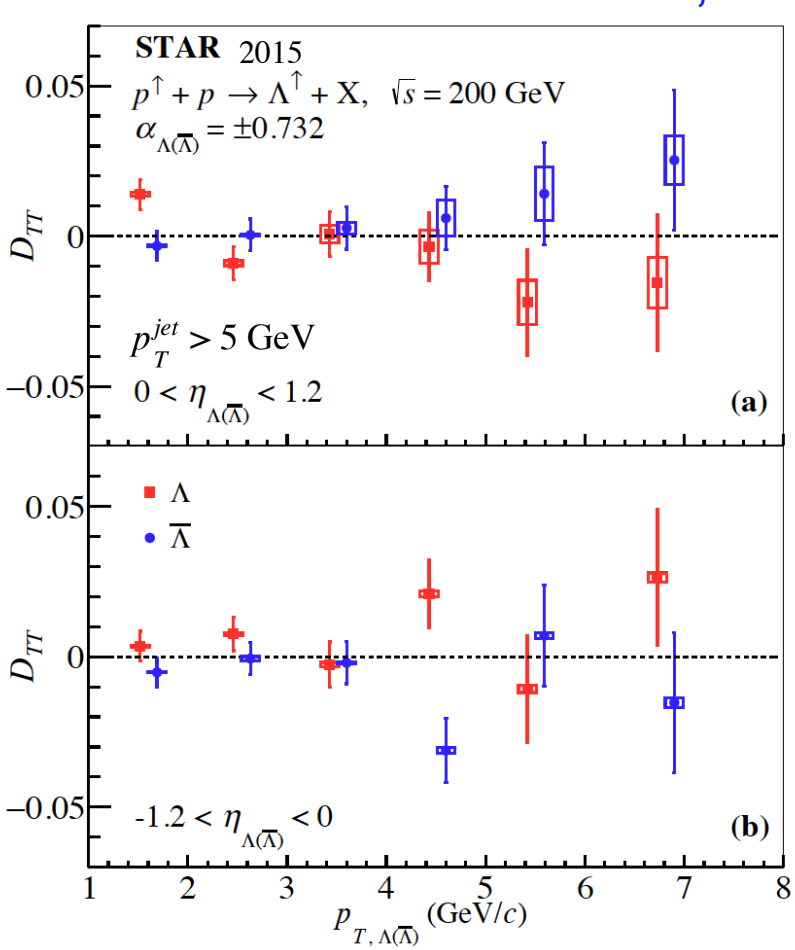
- First D_{TT} Measurement in p+p , reaches p_T ~6.7 GeV/c with statistical uncertainty of 0.04.

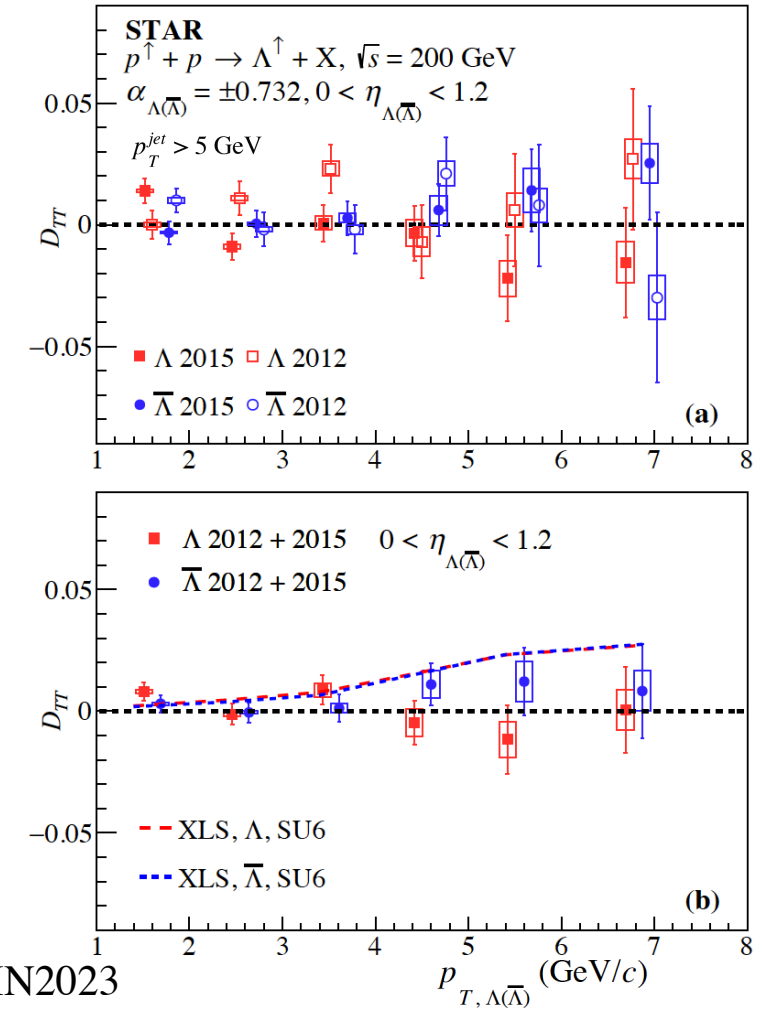
- D_{TT} of $\Lambda / \bar{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

New D_{TT} results with STAR 2015 data

- New D_{TT} results from 2015 are consistent with previous 2012 data, with twice statistics. Most precise data up to date.
- D_{TT} is consistent with the model predictions within uncertainties.

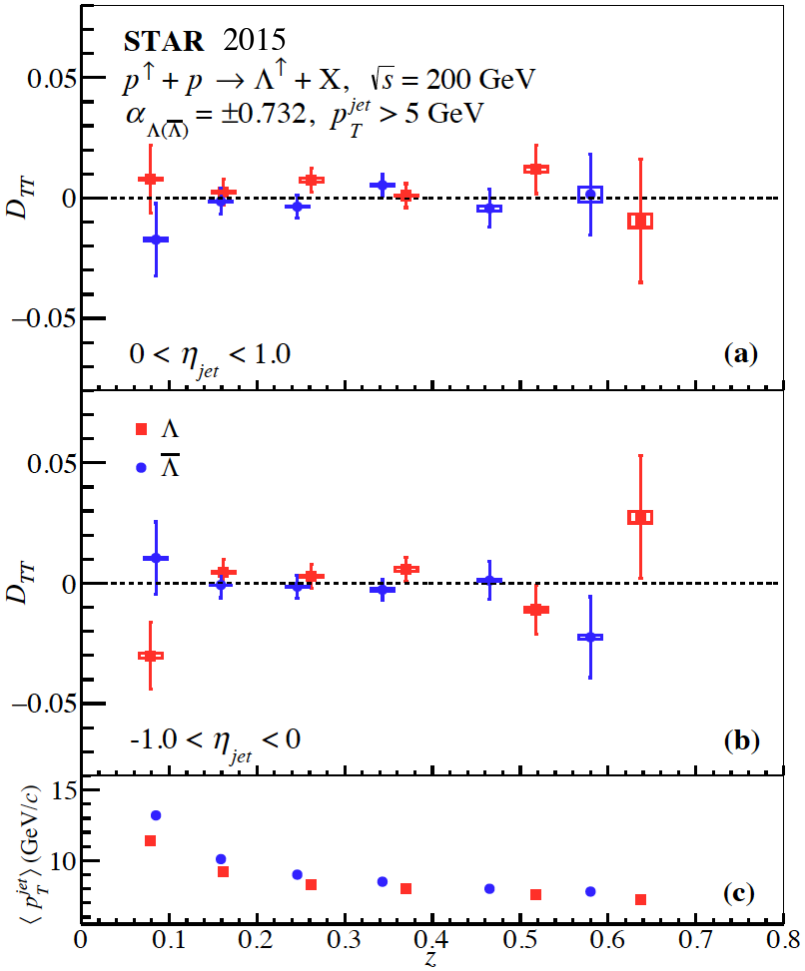
STAR, arXiv: 2309.14220





New D_{TT} results STAR 2015 data

- First measurement of D_{TT} vs. z for $\Lambda(\overline{\Lambda})$ in p+p collisions, providing constraints on transversely polarized fragmentation functions.
- Results are consistent with zero within uncertainties.



STAR, arXiv: 2309.14220

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

z: Jet momentum fraction carried by hyperon

Summary and Outlook

- The longitudinal spin transfer, D_{LL}, for $\Lambda(\bar{\Lambda})$ in p+p at 200 GeV at STAR:
  - Measurement of D_{LL} for $\Lambda(\bar{\Lambda})$ versus hyperon p_T up to 8GeV/c, with twice statistics of previous publication. One scenario of polarized fragmentation function is disfavored.
  - The first measurement of D_{LL} versus z, provide direct information on the longitudinal polarized fragmentation functions.
- The transverse spin transfer, D_{TT}, for $\Lambda(\bar{\Lambda})$ in p+p at 200 GeV at STAR:
  - D_{TT} for $\Lambda(\bar{\Lambda})$ versus hyperon p_T up to 8GeV/c, with twice statistics of previous publication. Results consistent with zero within uncertainty.
  - The first measurement of D_{TT} versus z, provide direct constraints on the transversely polarized fragmentation functions.
- Large data samples of longitudinally polarized p+p taken in 2013, and transversely polarized p+p in 2017, 2022 at 510 GeV at STAR will improve the precision of spin transfer measurements significantly.

Summary and Outlook

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  - The first measurement of D_{LL} versus z, provide direct information on the longitudinal polarized fragmentation functions.

-Talk on A_{LL} of $\Lambda\ (\bar{\Lambda}, K_0^s)$, Yi Yu, Sep 26, 3pm, Helicity session

- The transverse spin transfer, D_{TT}, for $\Lambda(\bar{\Lambda})$ in p+p at 200 GeV at STAR:
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