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Longitudinal and Transverse Spin Transfers of Λ and $\bar{\Lambda}$ Hyperons in polarized p-p Collisions at $\sqrt{s} = 200$ GeV at RHIC-STAR

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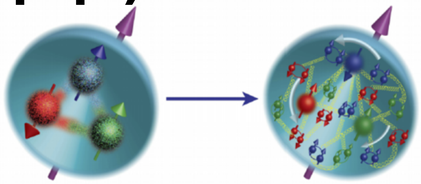
Outline

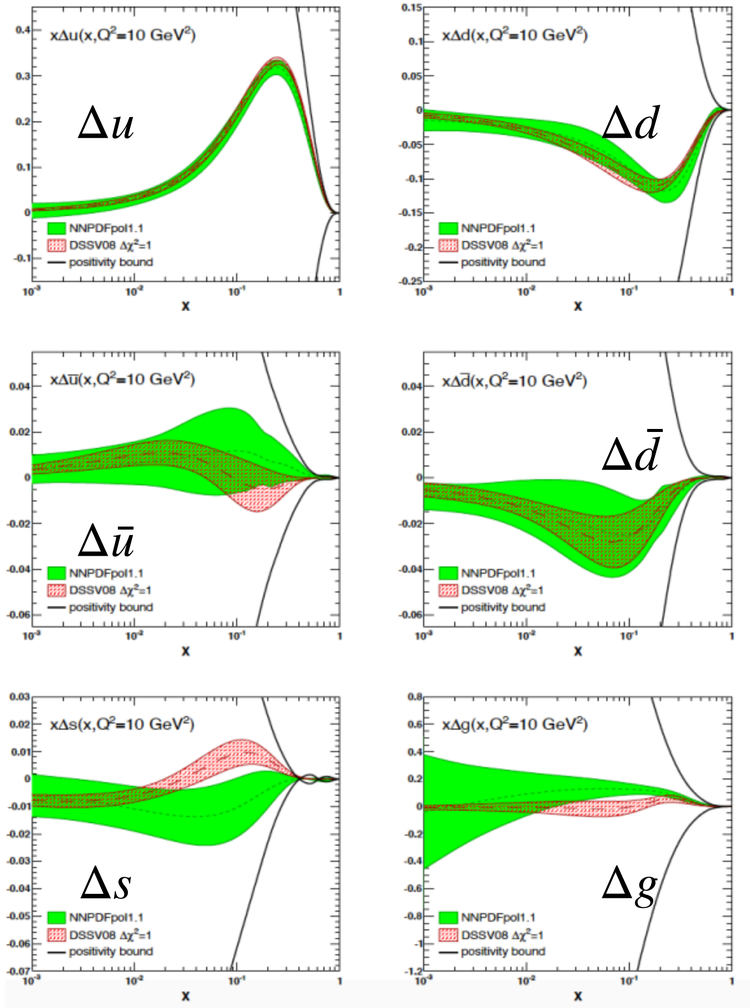
- Motivation
- Introduction to RHIC & STAR
- Reconstructions of Λ and $\bar{\Lambda}$
- Measurements of Longitudinal Spin Transfer, D_{LL}
- Measurements of Transverse Spin Transfer, D_{TT}
- Summary

Motivation

Nucleon Spin Structure (from DIS and p-p)

- Spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$.
- Valence quark helicity distributions are well known.
- Poor knowledge on sea quarks, especially for strange quark.





NNPDFpol1.1, Nucl. Phys. B887,276 (2014)

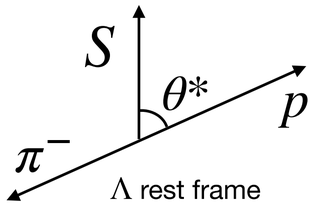
Why choose Λ ?

- The spin of Λ is expected to be carried mostly by its constituent strange quark.
- The weak decay of Λ provides a way to measure its polarization.

$$dN \sim (1 + \alpha P_\Lambda cos\theta^*) dcos\theta^*$$

α : weak decay parameter of Λ

P_Λ: the polarization of Λ



Longitudinal spin transfer D_{LL} in p-p collisions

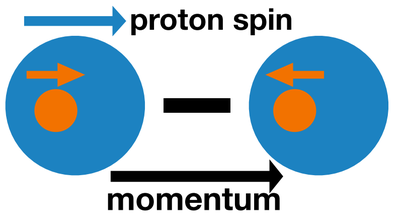
- D_{LL} is defined as the **cross-section asymmetry**

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

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

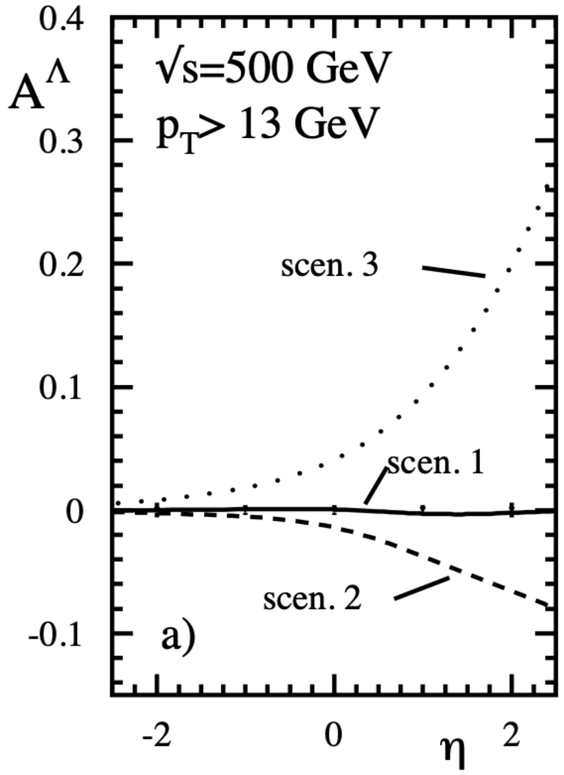
helicity distribution — pQCD calculable — polarized FF

$$\Delta f_a(x_a) = f_a^+(x_a) - f_a^-(x_a)$$



- Λ D_{LL} can shed light on both **helicity distributions** of $s(\bar{s})$ and the **polarized fragmentation functions (FF)**.

Prediction of D_{LL} at RHIC



D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 4 (1998).

Transverse spin transfer D_{TT} in p-p collisions

- D_{TT} **is defined as the cross-section asymmetry**

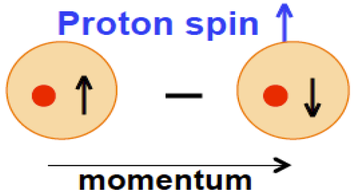
$$D_{TT}^{\Lambda} = \frac{d\sigma(p^{\uparrow}p \to \Lambda^{\uparrow}X) - d\sigma(p^{\uparrow}p \to \Lambda^{\downarrow}X)}{d\sigma(p^{\uparrow}p \to \Lambda^{\uparrow}X) + d\sigma(p^{\uparrow}p \to \Lambda^{\downarrow}X)} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

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

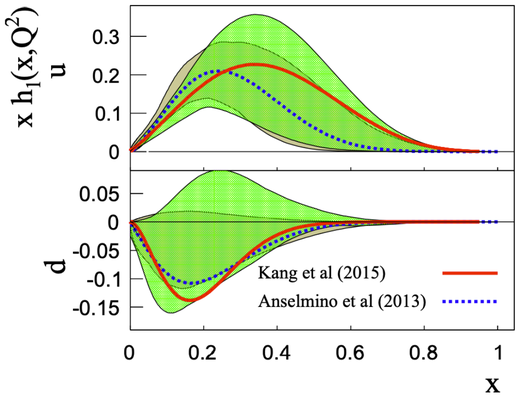
transversity distribution | pQCD calculable | polarized FF

- **Little experimental constraint of the transversity.**

$$\delta f_a(x_a) = f_a^{\uparrow}(x_a) - f_a^{\downarrow}(x_a)$$

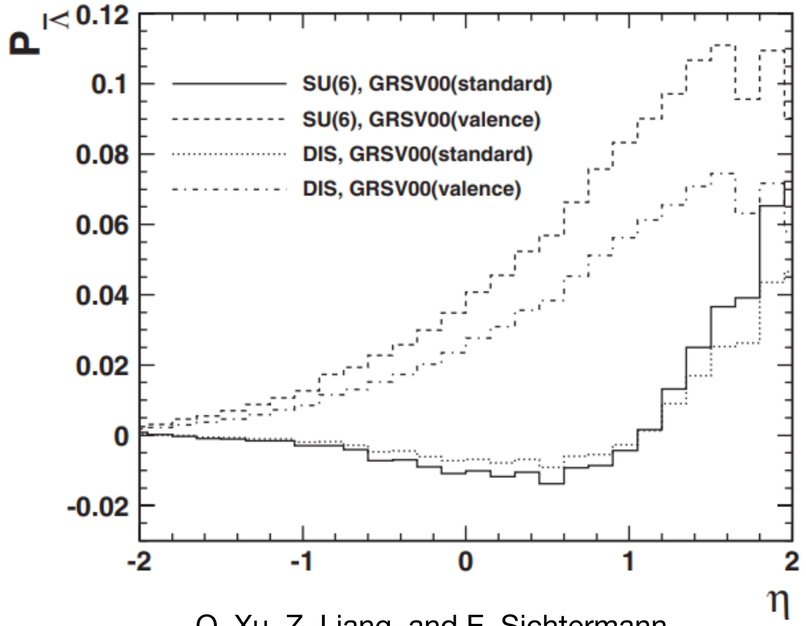


No constraint for strange quark



Kang, Z.-B., Prokudin, A., Sun, P. & Yuan, F. *Phys. Rev. D* **93**, 014009 (2016).

Polarization of $\bar{\Lambda}$ in transversely polarized p-p collisions



Q. Xu, Z. Liang, and E. Sichtermann, Phys. Rev. D **73**, 077503 (2006).

- Λ D_{TT} can shed light on both **transversity distribution** of $s(\bar{s})$ and the **polarized fragmentation functions (FF)**.

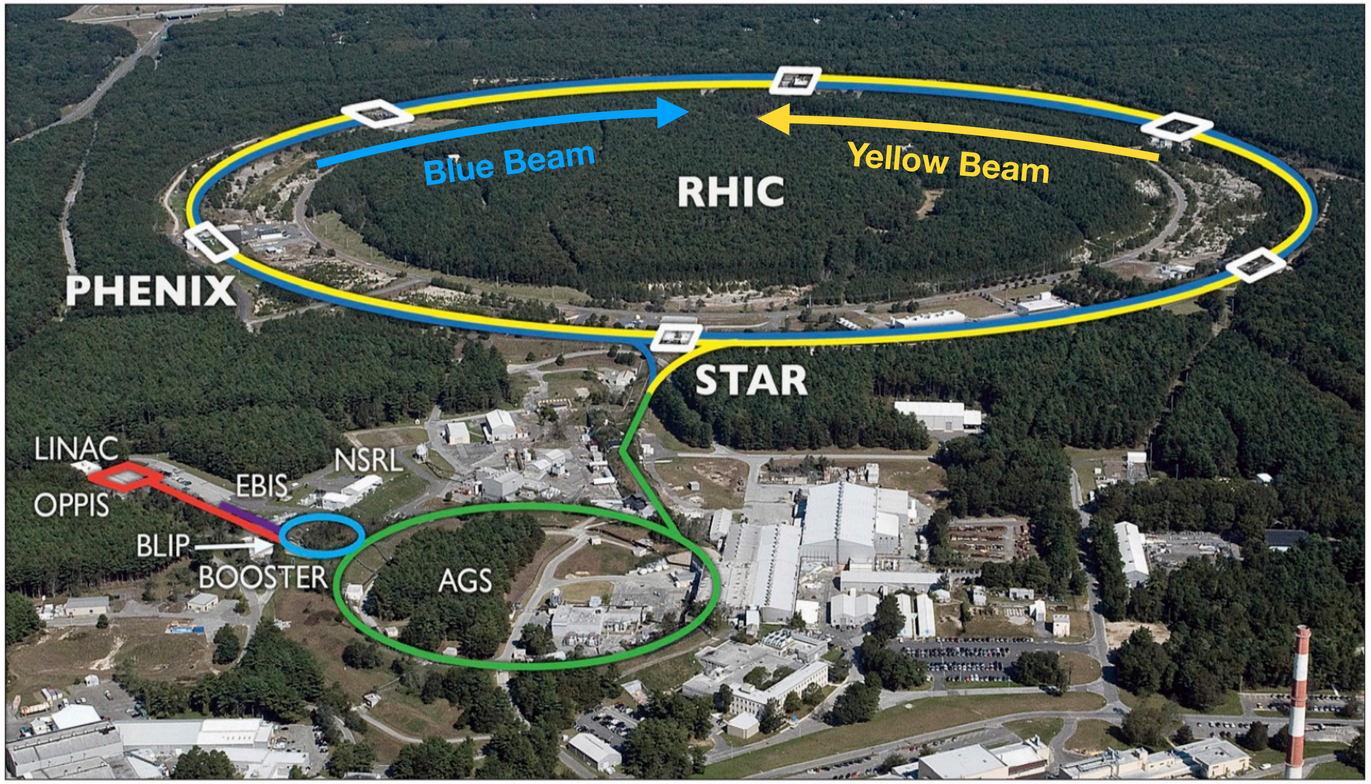
Relativistic Heavy Ion Collider

RHIC as a polarized p-p collider

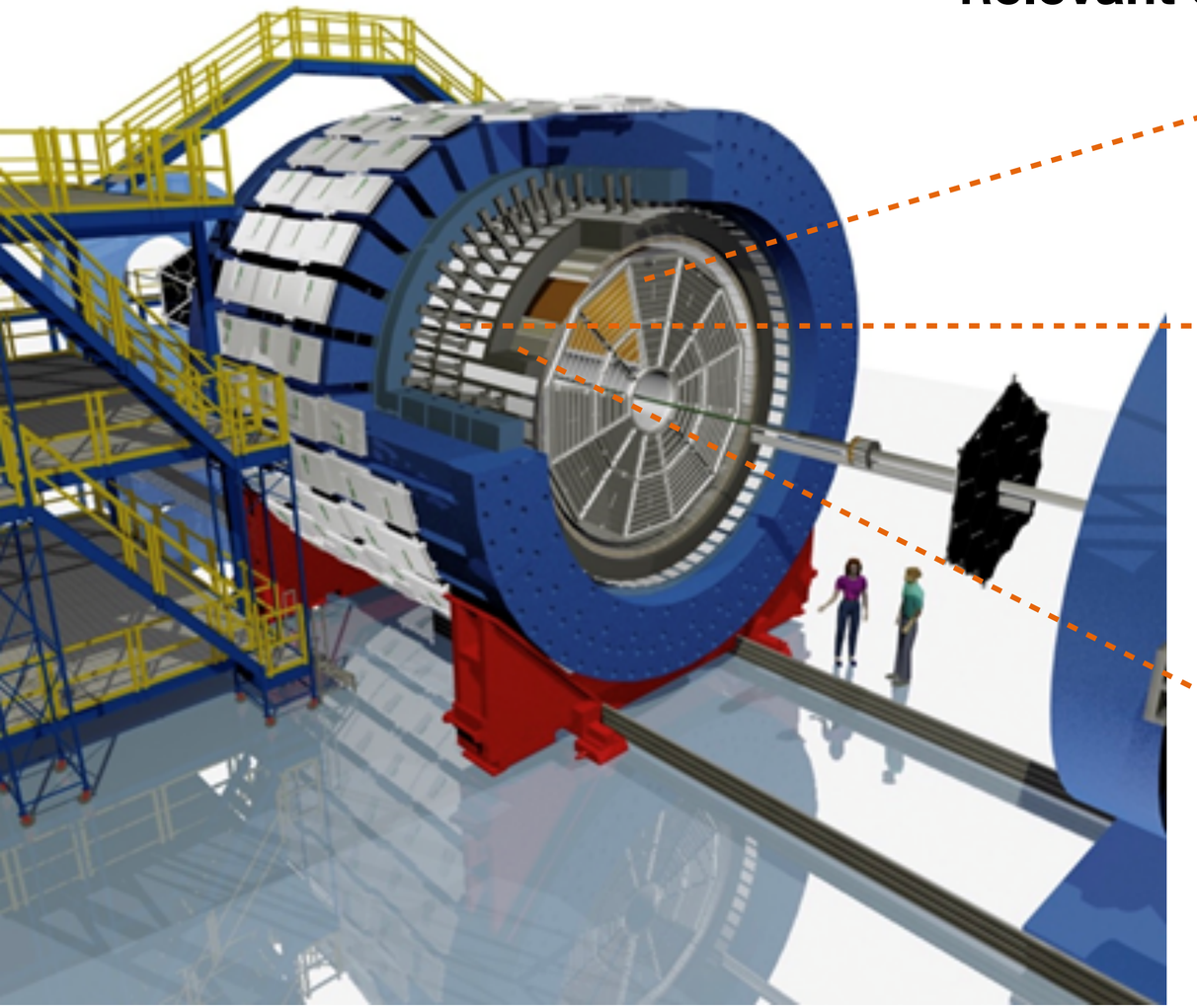
- The world's first and only polarized p-p collider.
- Collides both transversely and longitudinally polarized proton beams at $\sqrt{s} = 200$ and $500/510$ GeV.

Data sets in 2015

	$\sqrt{s}\ (GeV)$	$L_{int}\ (pb^{-1})$	P_{beam}
Longitudinal	200	50	52% / 56%
Transverse	200	52	57% / 57%



Solenoidal Tracker At RHIC

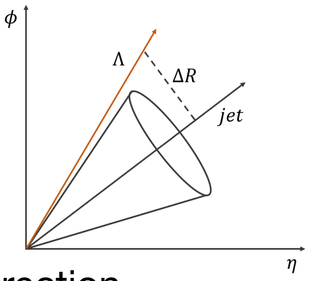


Relevant detectors for the D_{LL} and D_{TT} measurements

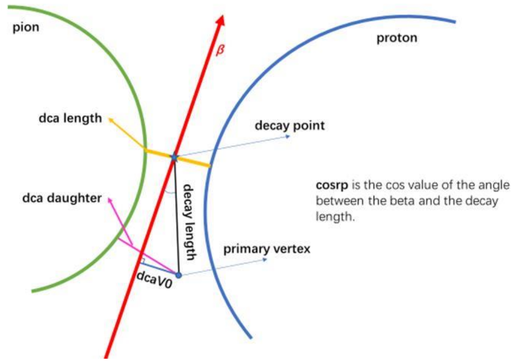
- **Time Projection Chamber (TPC)**
  - $|\eta| < 1.3$ and $0 \leq \phi \leq 2\pi$.
  - Tracking and PID.
- **Electromagnetic Colorimeter (EMC)**
  - Barrel EMC (BEMC): $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$.
  - Endcap EMC (EEMC): $1.086 < \eta < 2.0$ and $0 \leq \phi \leq 2\pi$.
  - Jet reconstruction, direct photon …
  - Can serve as the trigger detectors.
- **Time of Flight Detector (TOF)**
  - $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$.
  - PID.

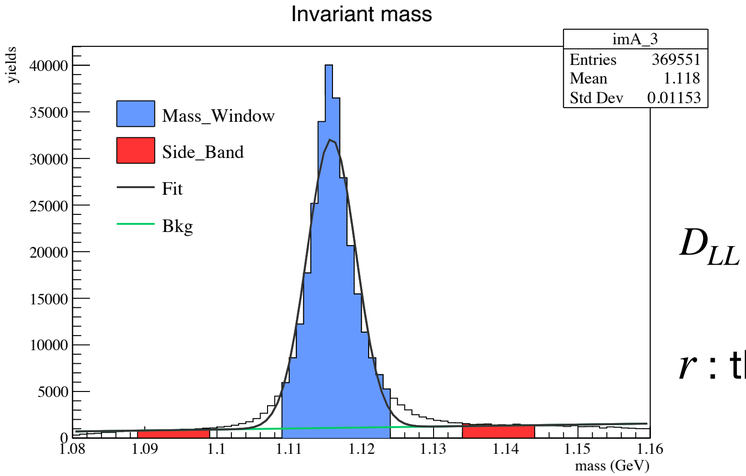
Reconstruction of Λ and $\bar{\Lambda}$

- Apply a set of topological cuts to reduce the background (below 10%).
- Side-band method is used to estimate the residual background.
- Require hyperons to be associated with a jet.
  - Reconstruct jets with $anti-k_T$ algorithm with $R = 0.6$.
  - $\Delta R = \sqrt{(\eta_\Lambda - \eta_{jet})^2 + (\phi_\Lambda - \phi_{jet})^2} < 0.6$
  - Jet axis is used to determine the transverse polarization direction.



$$\Lambda \to p + \pi^-$$
$$\bar{\Lambda} \to \bar{p} + \pi^+$$





$\bar{\Lambda}$ Invariant mass

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

r : the background fraction

Measurements of D_{LL}

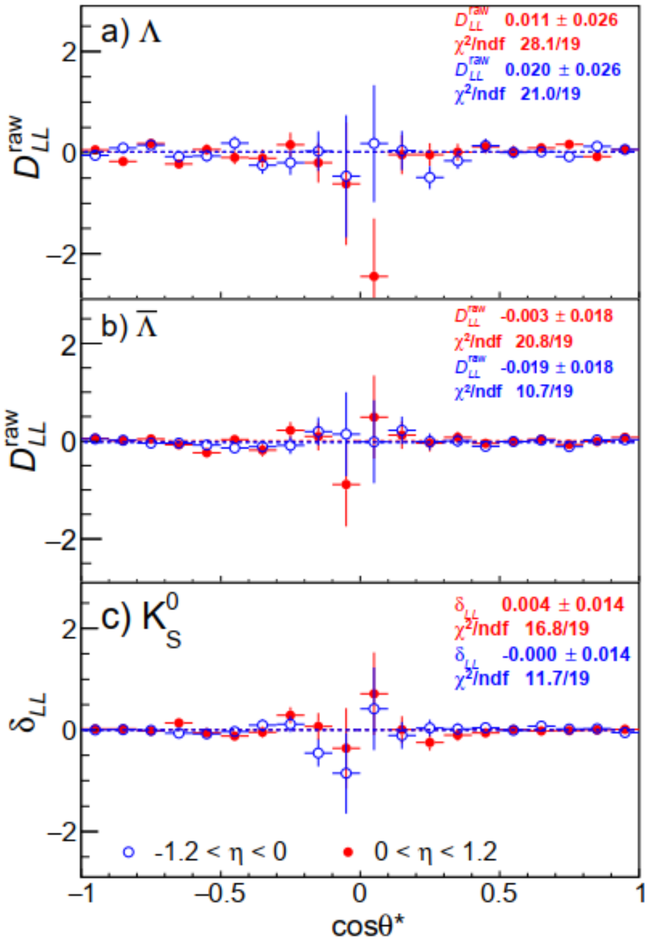
- D_{LL} is measured through the **asymmetry of the Λ yields** with different beam helicities in small $cos\theta^*$ bins

$$D_{LL} = \frac{1}{\alpha P_{beam} < cos\theta^* >} \frac{N^+ - RN^-}{N^+ + RN^-}$$ → Acceptance canceled

  - $N^{+(-)}$ are the Λ yields with positive and negative beam helicities, respectively.
  - R is the relative luminosity measured by the VPD.
  - $\alpha = 0.732$ is the decay parameter of Λ hyperon.
  - P_{beam} is the beam polarization.

- δ_{LL} of K^0_S as a **null check.**
  - Same method as D_{LL} measurement, with an artificial decay parameter $\alpha = 1$.
  - Results are consistent with zero as expected.

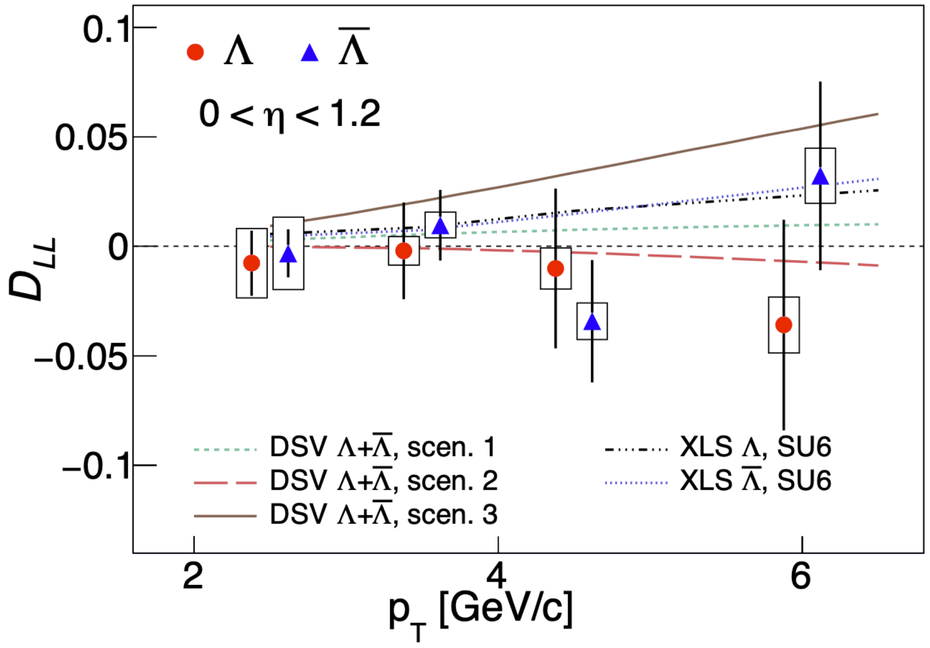
Adam, J. *et al.* [STAR Collaboration], *Phys. Rev. D* **98**, 032011 (2018).



Previous result with STAR 2009 data

- Previous measurement with 2009 data

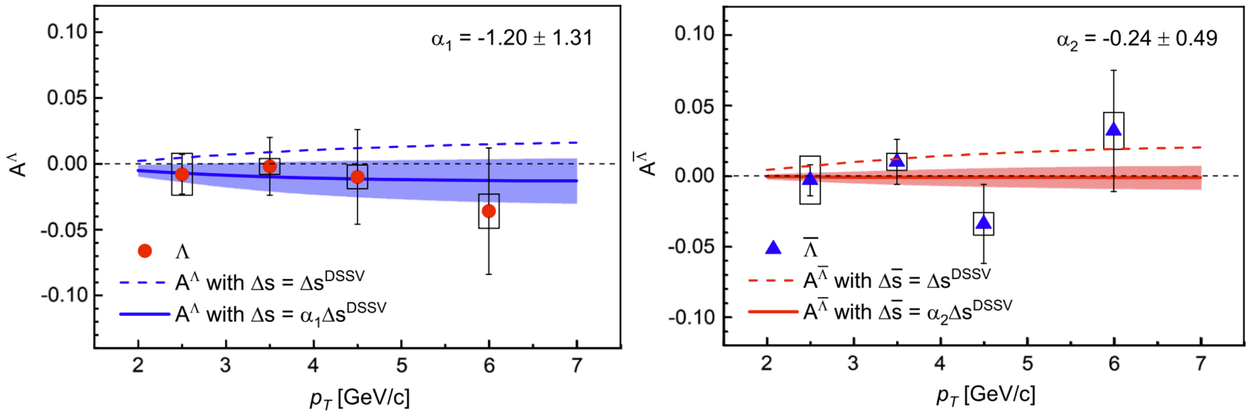
Adam, J. *et al*. [STAR Collaboration], *Phys. Rev. D* **98**, 112009 (2018).



- The results are consistent with zero
- In agreement with several models

- Theoretical studies, when fit to data, show indications of asymmetry of strange quark and anti-quark polarization

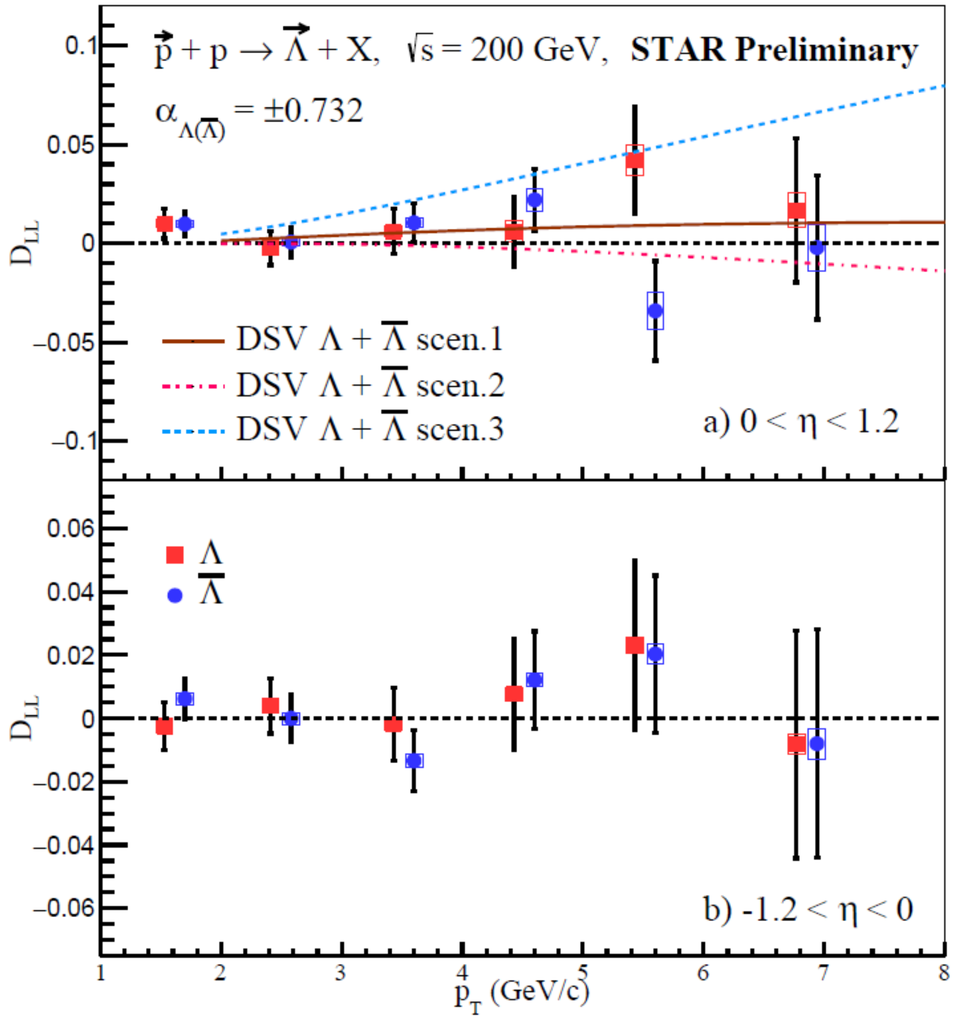
X.N. Liu, B.Q. Ma. *Eur. Phys. J. C* 10 (2019).



(a) Longitudinal spin transfer to Λ. **(b)** Longitudinal spin transfer to $\bar{\Lambda}$.

Coefficient	Value	Δs	$\Delta \bar{s}$	$\chi^2_{\min}$
α_1	-1.20 ± 1.31	-0.014 ± 0.015		0.37
α_2	-0.24 ± 0.49		-0.003 ± 0.005	2.48

New D_{LL} results with STAR 2015 data

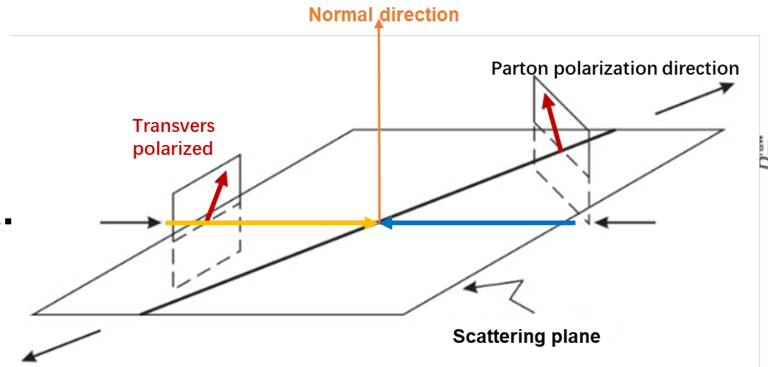


- D_{LL} as a function of hyperon p_T, with small offset applied for better visibility.
- The results are the most precise measurements to date with twice the statistics of the 2009 data set.
- The hyperon p_T range is extended up to 7 GeV/c.
- Results show consistency between Λ and $\bar{\Lambda}$.
- The data are also in agreement with various models within uncertainties.

For model calculation see
D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 4 (1998).

Measurement of D_{TT}

- D_{TT} measures the spin transfer to the final state polarization along the polarization direction of outgoing quark.
- Jet axis is required to determine the transverse polarization direction.

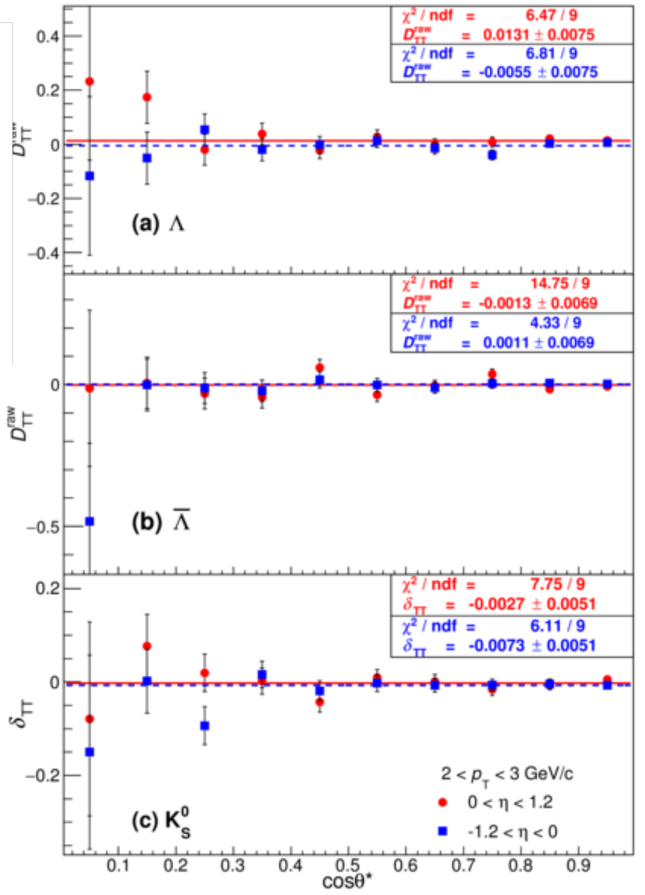


- D_{TT} is measured with **cross-ratio method** in small $cos\theta^*$ bins.

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

The relative luminosity and the acceptance are both canceled.

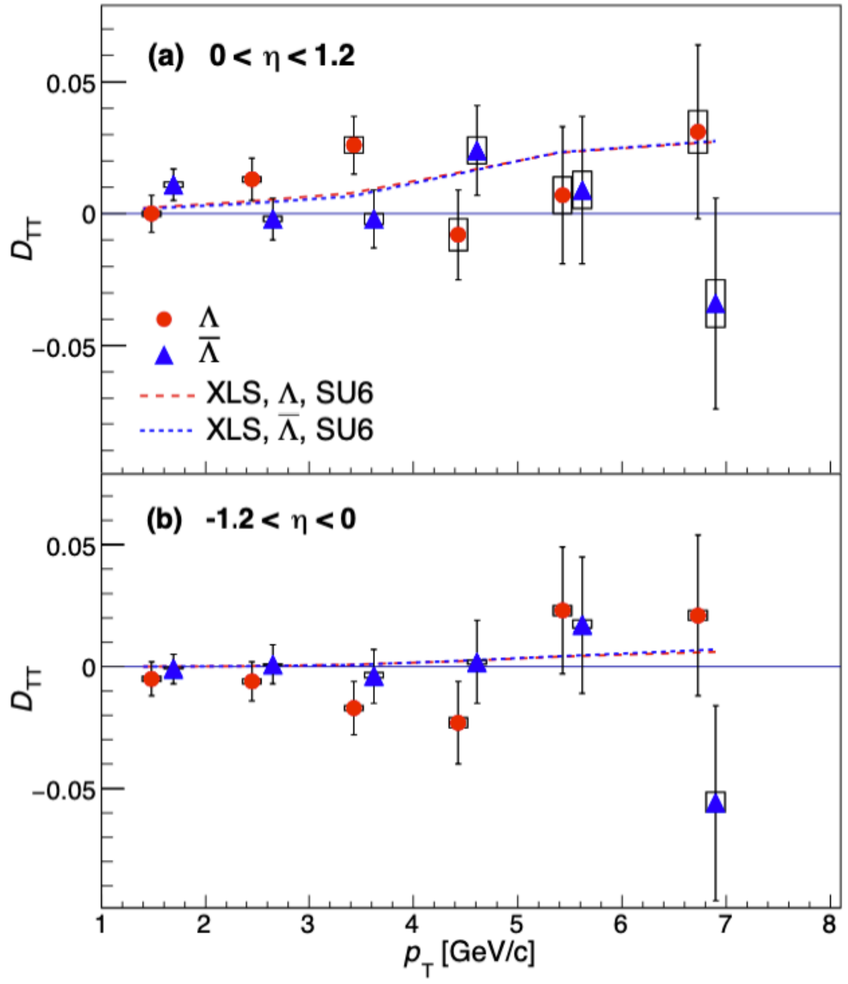
- δ_{TT} of K^0_S as a **null check.**
  - The results are consistent with zero as expected.



Adam, J. *et al.* [STAR Collaboration], *Phys. Rev. D* **98**, 091103 (2018).

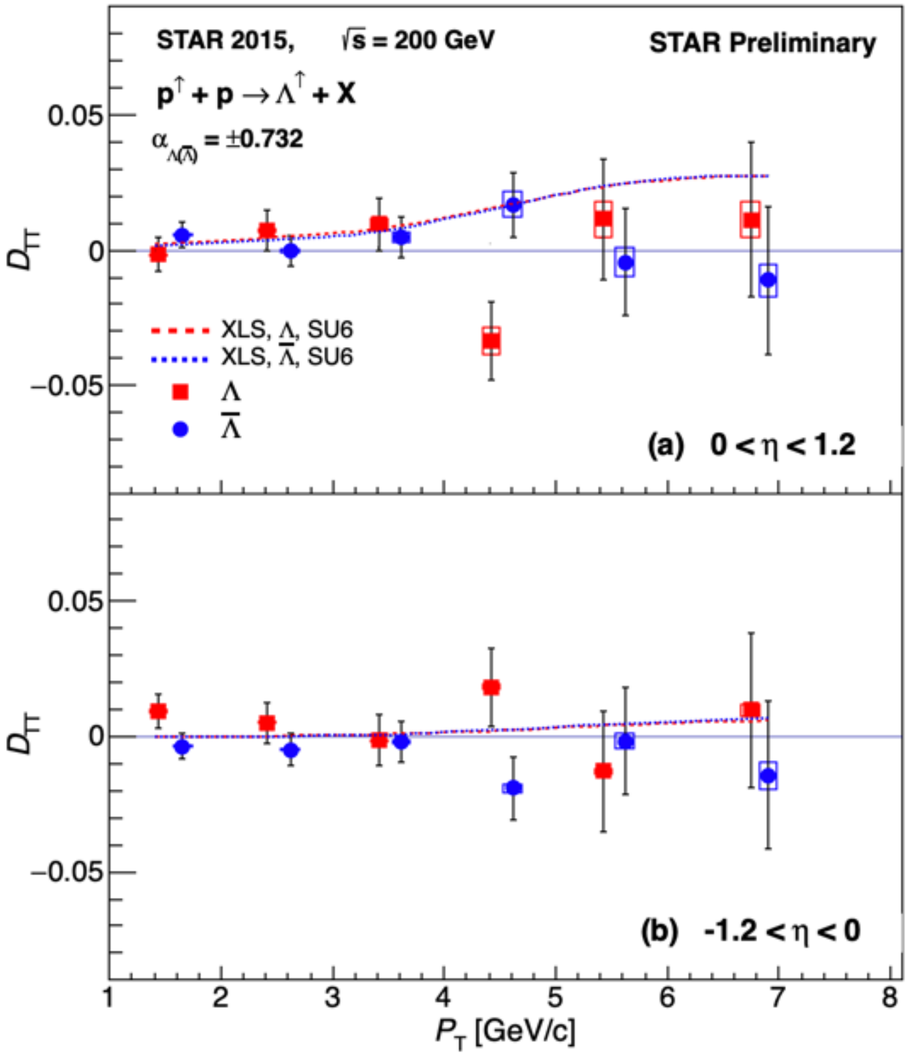
Previous result with STAR 2012 data

Adam, J. *et al.* [STAR Collaboration]. *Phys. Rev. D* **98**, 091103 (2018).



- First measurement on the D_{TT}
- Hyperon p_T range is up to 7 GeV/c
- The results are consistent with the model prediction.

New D_{TT} results with STAR 2015 data



- D_{TT} as a function of hyperon p_T, with small offset applied for better visibility.
- The new results have a factor of $\sim\sqrt{2}$ improvement in statistical precision.
- The results are consistent with the model prediction.
- Indicate small transversity distributions and/or small polarized FF.

Summary

- The measurements of D_{LL} and D_{TT} in the polarized p-p collisions can provide insights into the polarized PDFs for strange quark and also polarized FF.
- Polarized p-p data taken in 2015 at STAR provide about two times the statistics as compared to previous measurements.
- New results are consistent with previous measurements and also consistent with zero, which indicate small polarized PDFs for strange quark and/or polarized FF.
- STAR forward detector upgrade will enable Λ measurements in the forward pseudo-rapidity region ($2.5 < \eta < 4$). More transversely polarized p-p collisions will be collected in 2022 at 510 GeV and in 2024 at 200 GeV.