

超子-核子谱仪物理研讨会

# Hyperon spin polarization and correlation in pp collisions

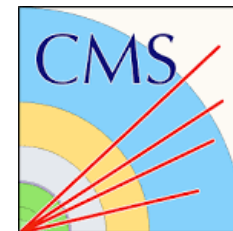
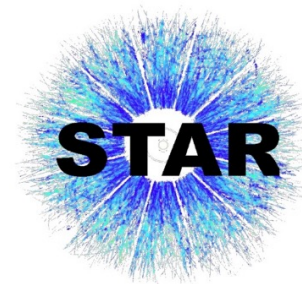
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山东大学

2026-8-15 天津



山东大学  
SHANDONG UNIVERSITY



# Outline

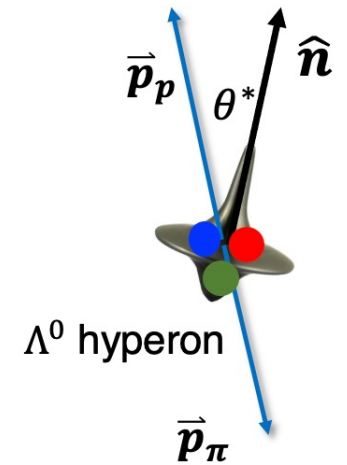
- Single-hyperon polarization in unpolarized pp collisions
- Spin correlation between initial state and final state
- Spin correlation between two hyperons at final state

# Lambda: final state “polarimetry”

- Self-analyzing weak decay: Lambda polarization can be measured from the angular distribution of its daughter particles: (Br~64%)

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

- $\Lambda$  polarization plays an important role in spin physics
  - Hot QCD: vorticity, magnetic field, medium effects, etc.
  - Cold QCD: spin structure, fragmentation, spin correlations

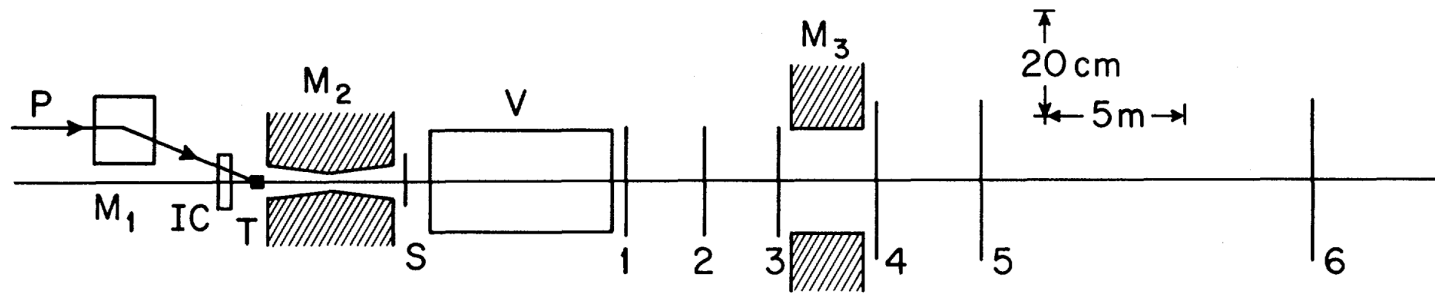


# Puzzle since 1976

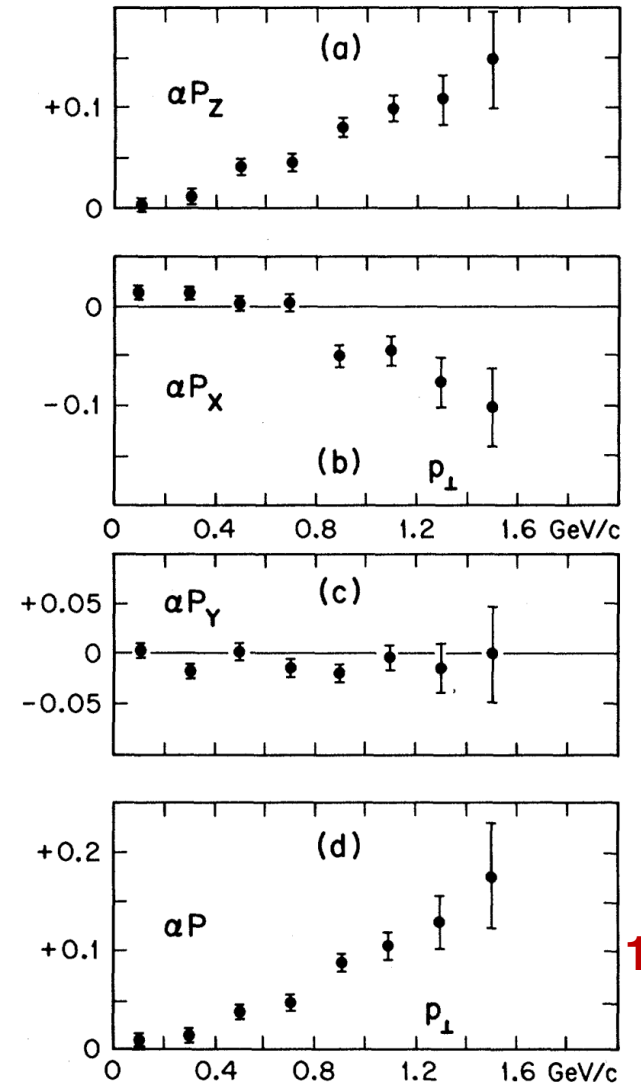
*G. Bunce et al. PRL36, 1113 (1976)*

300 GeV unpolarized proton on unpolarized Beryllium target

- 10% level polarization observed; increasing vs.  $p_T$



Since the first observations in fixed-target hadronic collisions, sizable transverse  $\Lambda$  polarization has been measured over a wide range of beam energies, collision systems, and experimental conditions, yet its underlying QCD mechanism remains not fully understood.



# Follow-up measurements

*incomplete list*

Heller et al., Phys. Lett. B68 480 (1977)

Heller et al., Phys. Rev. Lett. 41, 607 (1978)

Erhan et al., Phys. Lett B82, 301 (1979)

Lomanno et al., Phys. Rev. Lett. 43, 1905 (1979)

Heller et al., Phys. Rev. Lett. 51, 2025 (1983)

Abe et al., Phys. Rev. Lett. 50, 1102 (1983)

Aleev et al., Z. Phys. C 36, 27 (1987)

Lundberg et al., Phys. Rev. D 40, 3557 (1989)

Ramberg et al., Phys. Lett. B 338, 403 (1994)

Fanti et al., Eur. Phys. J. C 6 265 (1999)

Abt et al., Phys. Lett. B 638, 415 (2006)

Aad et al., Phys. Rev. D 91, 032004 (2015)

Abt et al., JHEP09, 082 (2024)

24 GeV proton + Platinum at CERN

400 GeV proton + Beryllium at Fermilab (different hyperon)

$\sqrt{s} = 53, 62$  GeV proton + proton at CERN (ISR)

28.5 GeV proton + Iridium at BNL (AGS)

400 GeV proton + Beryllium/Copper/Lead at Fermilab

12 GeV proton + Tungsten at KEK

~40 GeV neutron + Carbon/Aluminum/Copper

400 GeV proton + Beryllium at Fermilab (higher pT)

800 GeV proton + Beryllium at Fermilab

450 GeV proton + Beryllium at CERN (SPS-NA48)

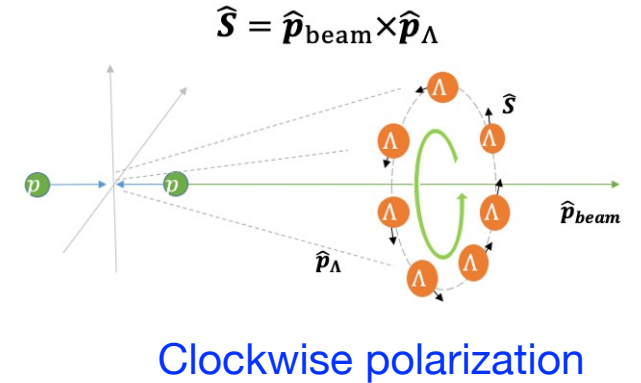
920 GeV proton + Carbon/Tungsten at DESY (HERA-B)

$\sqrt{s} = 7$  TeV proton + proton at CERN (ATLAS)

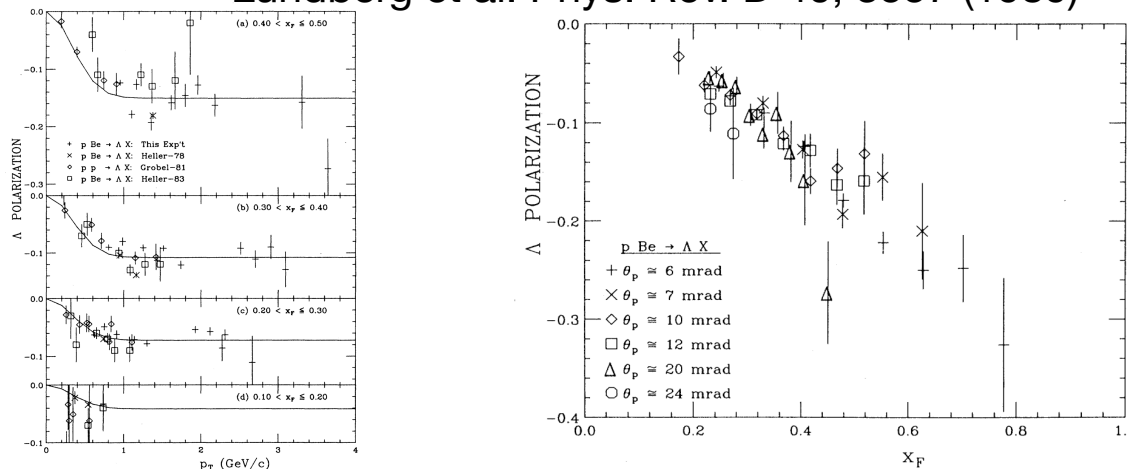
2.5 TeV proton + Neon at CERN (LHCb-SMOG)

# Features of lambda spontaneous polarization

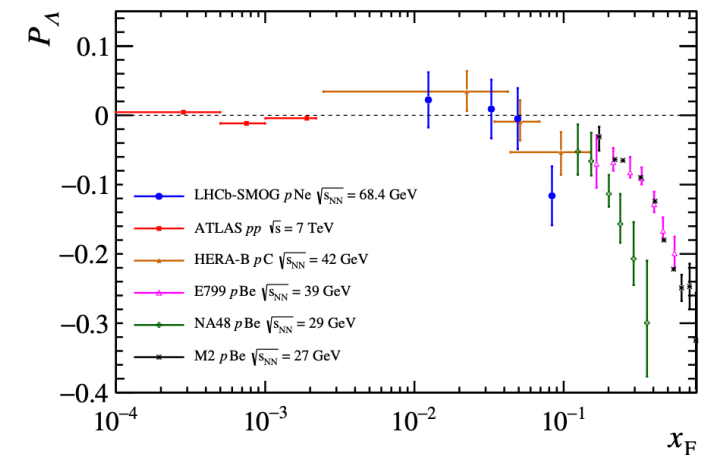
- Polarization is (almost) independent of beam energy.
- $x_F$  and  $p_T$  dependence scales with energy.
- Weak target-mass dependence:  $pA \approx pp$ , parton level reaction.
- Anti-lambda polarization is consistent with zero.



Lundberg et al. Phys. Rev. D 40, 3557 (1989)



Abt et al, JHEP09, 082 (2024)

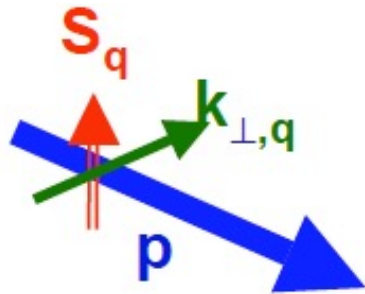


# Initial- and final-state sources of $\Lambda$ polarization

Partonic scattering (pQCD) cannot explain the large polarization.

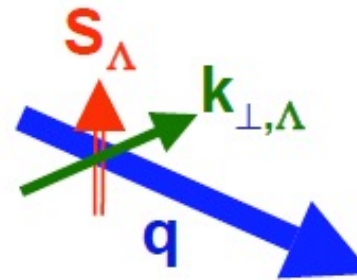
Then, must be non-pQCD effects from *initial state and/or final state*.

Parton distributions



$$\leftarrow \vec{S} \cdot (\vec{p} \times \vec{k}_{\perp}) \rightarrow$$

Parton fragmentations



Different collision systems provide complementary constraints.

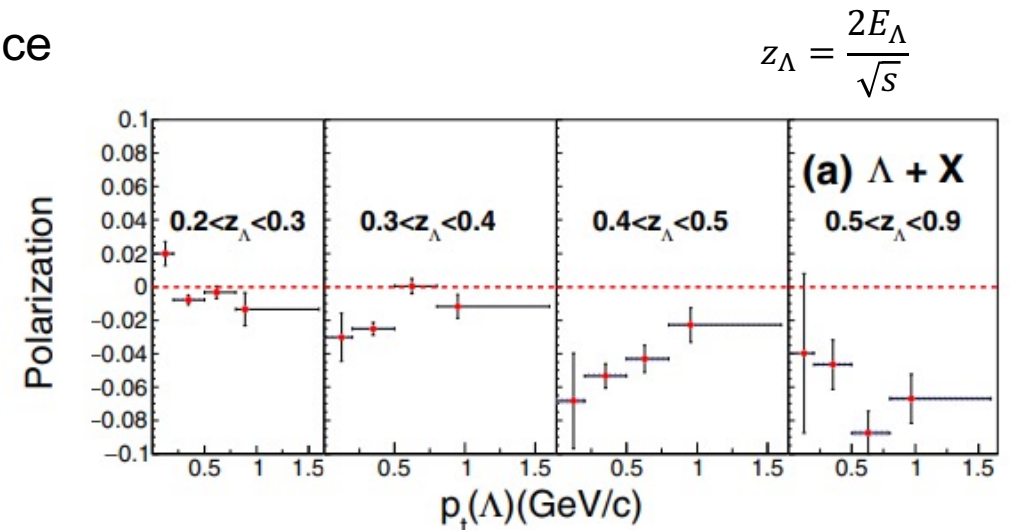
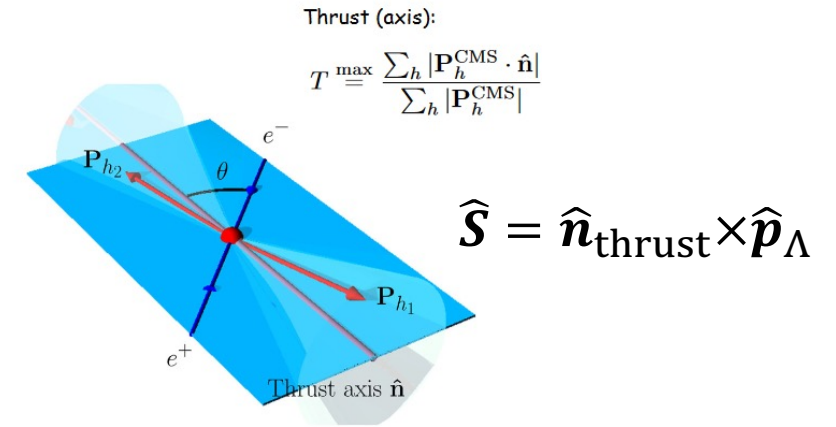
- Spin transfer from initial state: parton is polarized in unpolarized proton
- Polarization arising at final state: parton is unpolarized but fragmenting into polarized hadron.

Boer-Mulders

Polarizing FFs

# Measurements in $e^+e^-$ annihilation

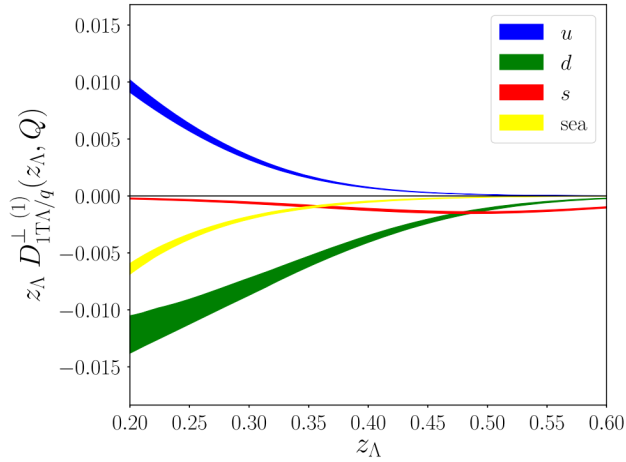
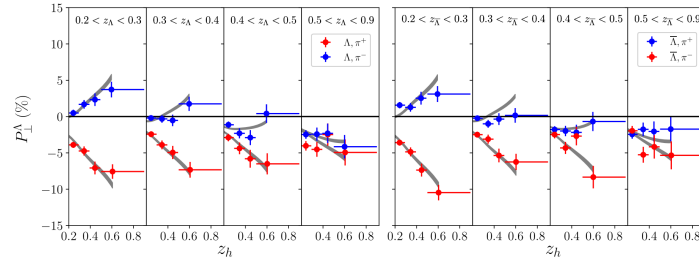
- LEP ( $\sqrt{s} = 90$  GeV): no significant polarization
  - ALEPH  $P_T^{\Lambda, \bar{\Lambda}} = 0.016 \pm 0.007$   
ALEPH, PLB 374, 319 (1996)
  - OPAL  $P_T^{\Lambda} = 0.019 \pm 0.014$  ( $p_T > 0.3$  GeV/c)  
OPAL, EPJC 2, 49 (1998)
- At Belle ( $\sqrt{s} = 10.6$  GeV) Belle, PRL 122, 042001 (2019)
  - Significant polarization with fractional energy  $z$  dependence
- Extraction of polarizing Fragmentation Function(pFFs)  
Callos, Kang, Terry, PRD 102, 096007 (2020)  
D'Alesio, Murgia, Zaccheddu, PRD 102, 054001 (2020)  
Chen, Liang, Pan, Song, Wei, PLB 816, 136217 (2021)



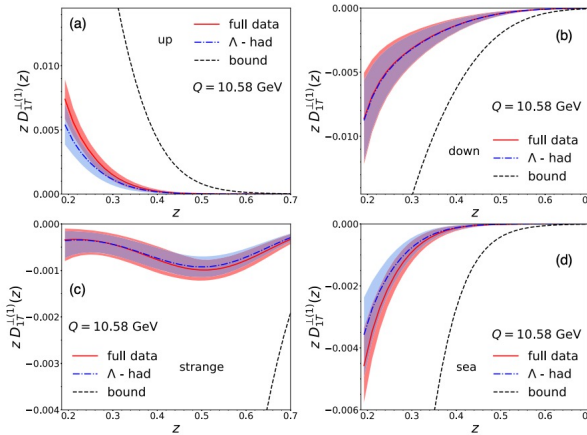
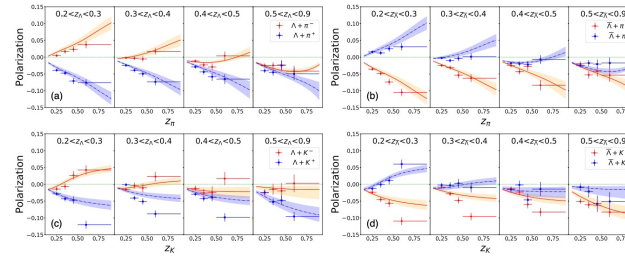
See Yinghui Guan's talk

# Global analyses of Belle results

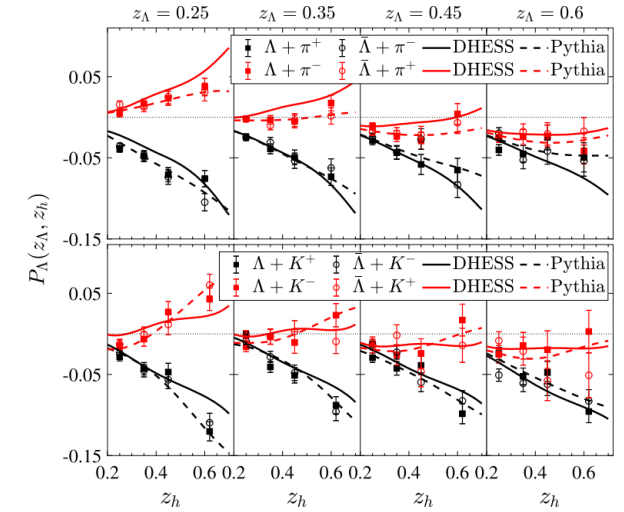
Callos, Kang, Terry,  
PRD 102, 096007 (2020)



D'Alesio, Murgia, Zaccheddu,  
PRD 102, 054001 (2020)



Chen, Liang, Pan, Song, Wei,  
PLB 816, 136217 (2021)



Isospin symmetry  
constrained

$$D_{1Tu}^{\perp\Lambda} = D_{1Td}^{\perp\Lambda}$$

Also Twist-3 FF: Gamberg, Kang, Shao, Terry, Zhao, PLB818, 136371 (2021)

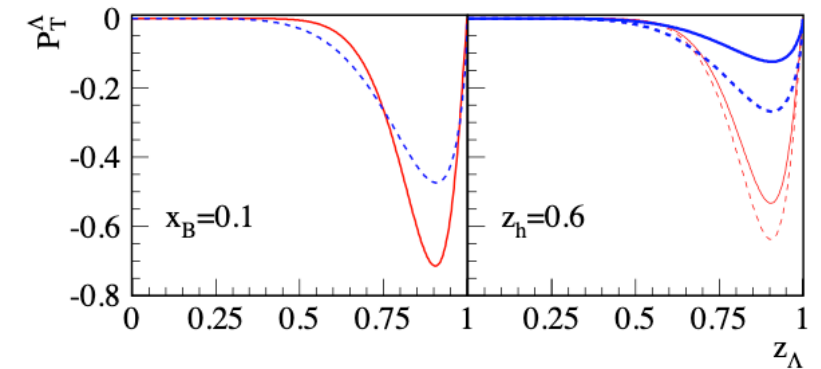
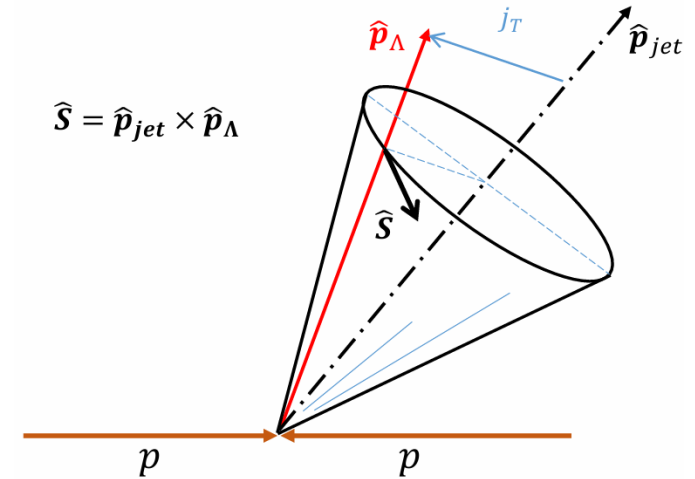
# What can we do in pp/pA collision at RHIC and LHC?

- Polarizing Fragmentation Functions(pFFs) can be accessed by transverse polarization of  $\Lambda$ -in-jet in pp collision

*Boer et al, PLB 671, 91-98 (2008)*

*Kang, Lee, Zhao, PLB 809, 135756 (2020)*

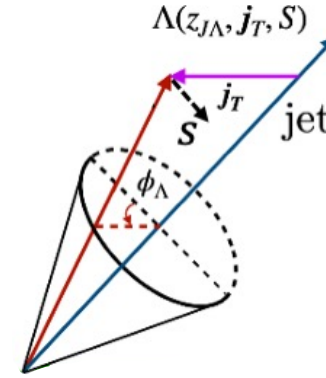
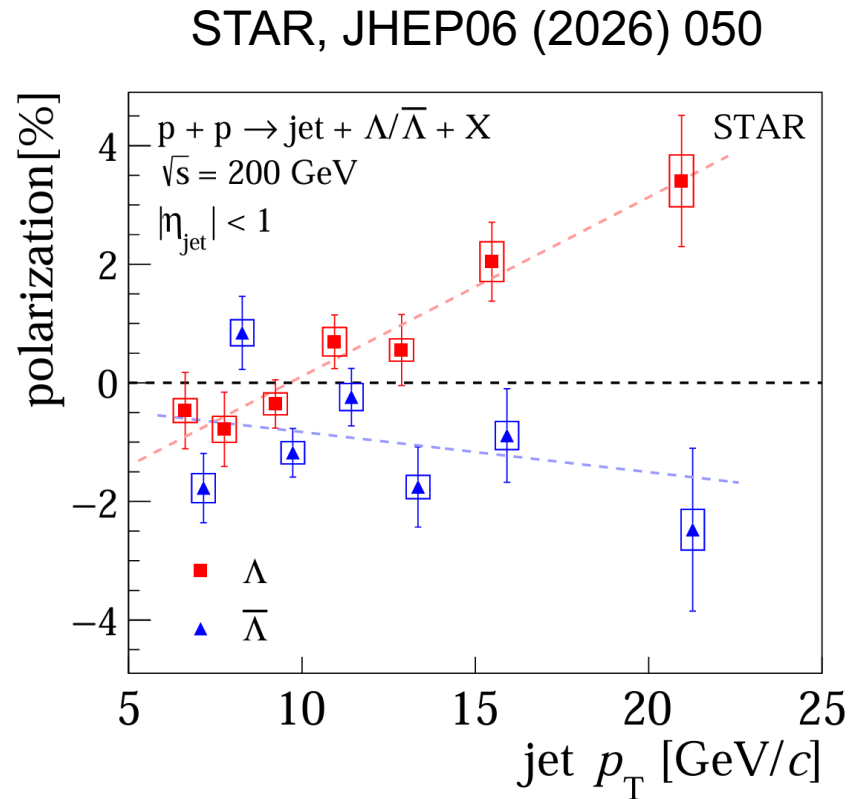
- Polarization direction normal to the production plane constructed by jet and  $\Lambda$  momentum
- Complement to  $e^-e^+$ :
  - Cover a wide range of jet  $p_T$ : 5~50 GeV at RHIC and higher at LHC
  - Test universality of pFFs



Boer et al, Phys.Rev. Lett. 105.202001 (2010)

# Results from 200 GeV pp collision

## Polarization as a function of jet $p_T$



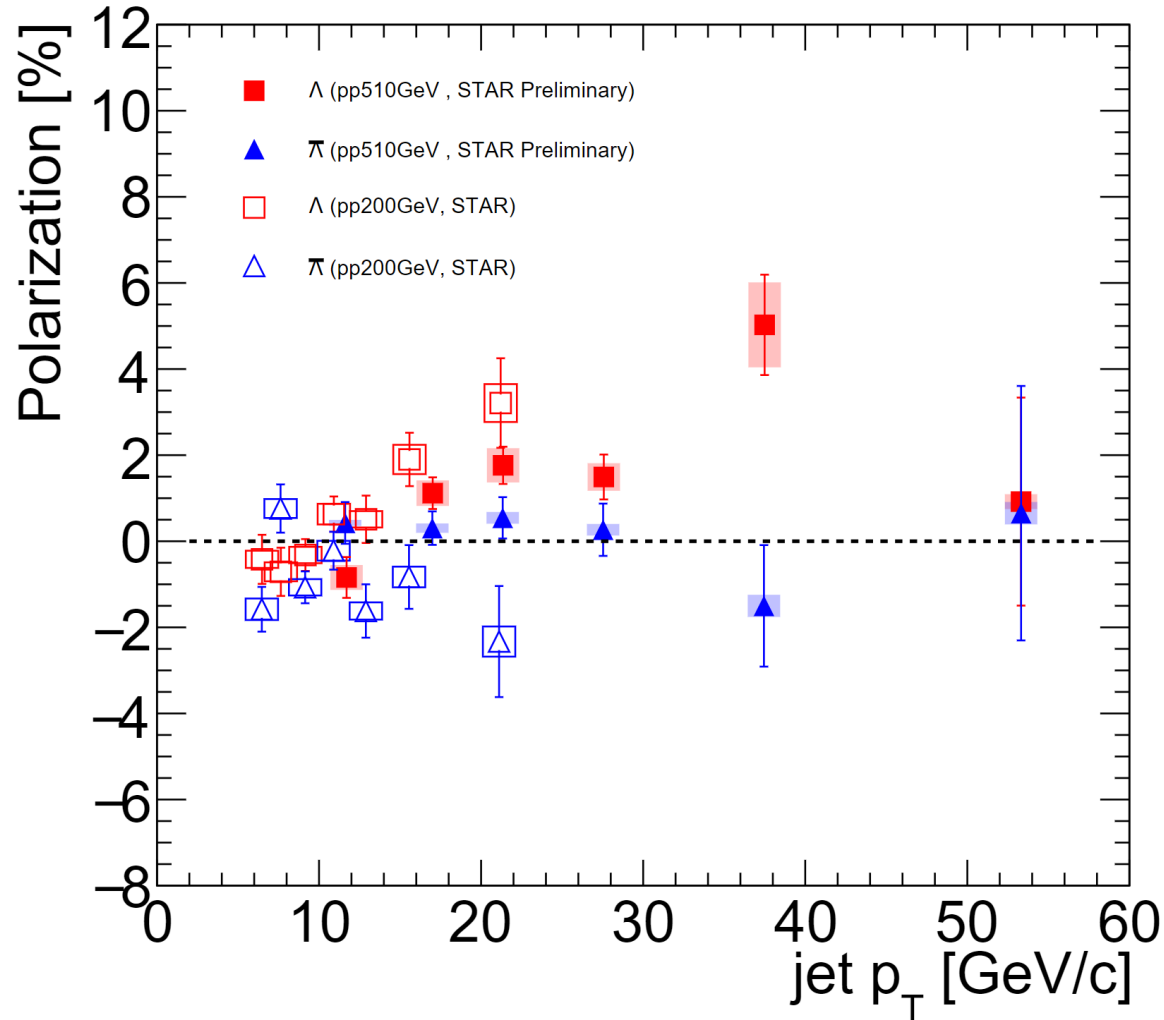
$$\hat{\mathbf{S}} = \hat{\mathbf{p}}_{\text{jet}} \times \hat{\mathbf{p}}_{\Lambda}$$

- Cover jet  $p_T$  range: 8~25 GeV/c
- significant jet  $p_T$  dependence for  $\Lambda$
- Indication of non-zero  $\bar{\Lambda}$  polarization ( $\sim 2\sigma$ ) from average value

Note:  $\Lambda(\bar{\Lambda})$  jet  $p_T$  corrected to particle level

# Preliminary Results from 510 GeV pp collision

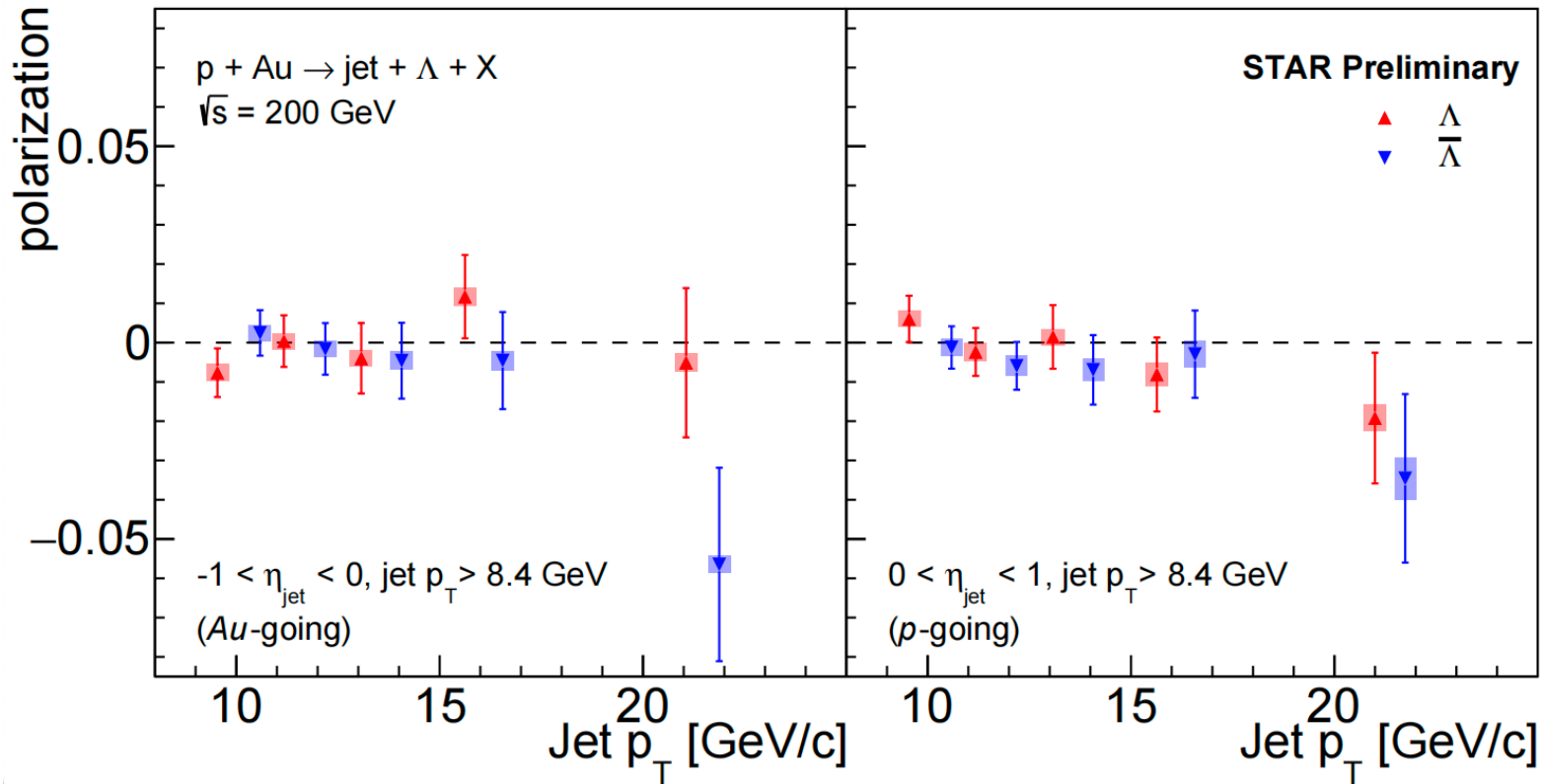
STAR, SPIN2025 (Jinhao He)



- The preliminary results at  $\sqrt{s}=510$  GeV cover jet  $p_T$  up to 50 GeV
- $\Lambda$  polarization as a function of jet  $p_T$  consistent with the trend at  $\sqrt{s} = 200$  GeV
- The relative contribution from different partons is different from  $\sqrt{s}= 200$  GeV and  $\sqrt{s}=510$  GeV even at same jet  $p_T$

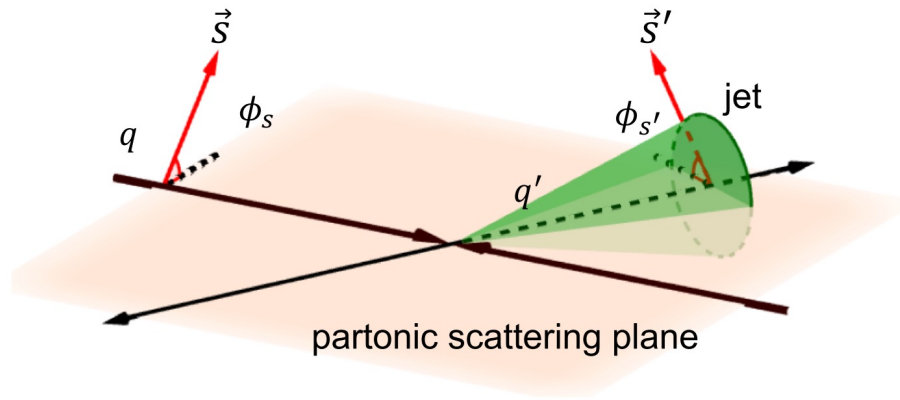
# Preliminary Results from 201 GeV pAu collision

STAR, DIS2026 (Xiaohui Liu)



- Polarization is studied separately on the **Au-going side ( $\eta < 0$ )** and the **proton-going side ( $\eta > 0$ )**.
- No significant transverse polarization is observed in pAu collisions.

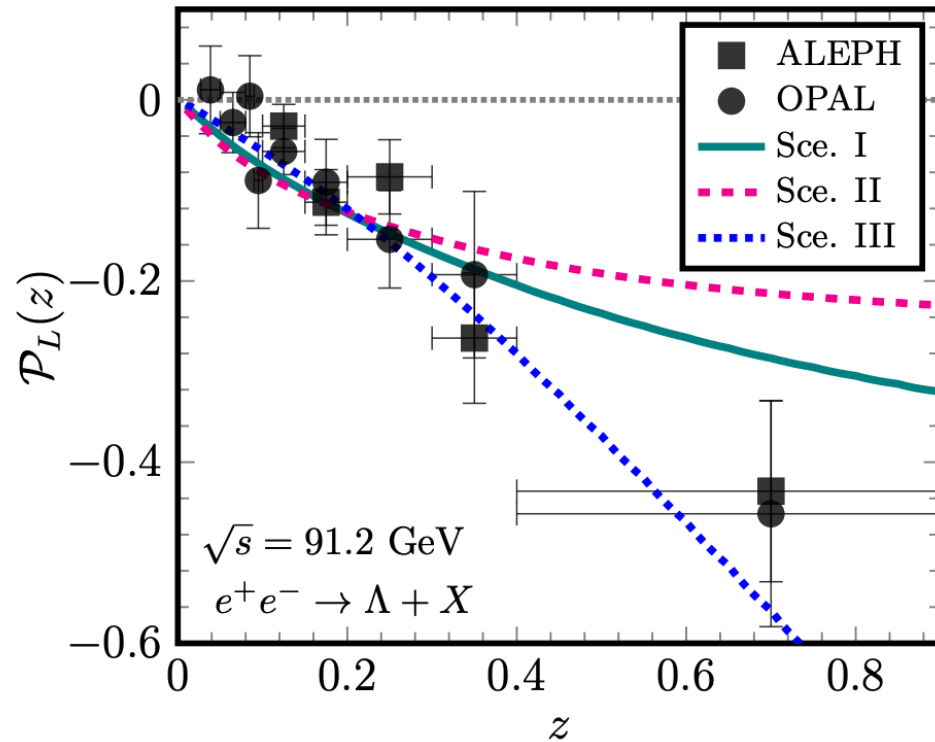
# Spin correlation between initial state and final state



- Polarized beam provides a controlled initial spin direction
- Parton polarization governed by polarized PDFs in the proton
- Hard scattering determines the spin-dependent partonic subprocess
- Fragmentation transfers parton spin information to the final-state  $\Lambda$
- $D_{LL}$  and  $D_{TT}$ : longitudinal and transverse spin transfer

$$\frac{d\sigma^{p^+p \rightarrow \Lambda^+X} - d\sigma^{p^+p \rightarrow \Lambda^-X}}{d\sigma^{p^+p \rightarrow \Lambda^+X} + d\sigma^{p^+p \rightarrow \Lambda^-X}}$$

# LEP $Z^0$ -pole data: evidence for $\Lambda$ spin transfer



- $Z^0$  decay produces strongly polarized primary quarks
- Large longitudinal  $\Lambda$  polarization observed
- Evidence for quark-to- $\Lambda$  spin transfer
- Key constraint for DSV polarized  $\Lambda$  fragmentation functions

D. de Florian, M. Stratmann, W. Vogelsang,  
Phys. Rev. D 57, (1998)5811–5824  
K. B. Chen, W. H. Yang, Y. J. Zhou and Z. T. Liang,  
Phys. Rev. D 95 (2017)3, 034009

# Earlier transverse spin transfer in fixed-target pp collisions

Bonner et al, *Phys. Rev. Lett.* 58, 447 (1987) Transversely polarized proton 13.3/18.5 GeV

E704, *Phys. Rev. Lett.* 78, 4003 (1997)

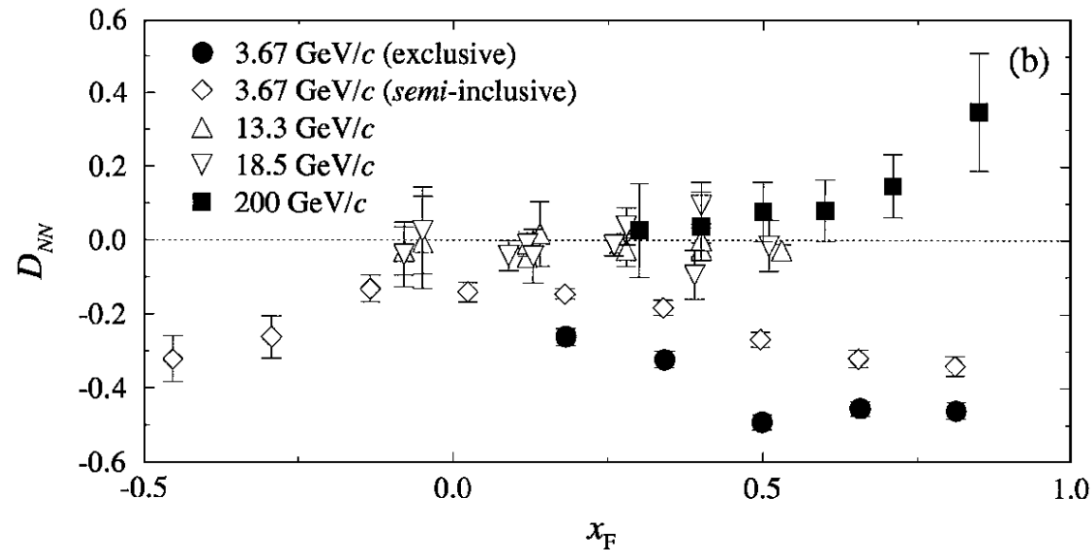
Transversely polarized proton 200 GeV

Low pT

DISTO, *Phys. Rev. Lett.* 83, 1534 (1999)

Transversely polarized proton 3.67 GeV Exclusive/Simi-inclusive

$$D_{NN} = \frac{E \frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} - E \frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}{E \frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} + E \frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}$$



Spin transfer shows strong dependence on reaction mechanism and kinematics.

# Longitudinal spin transfer in polarized pp collision at STAR

The factorized framework enables perturbative description

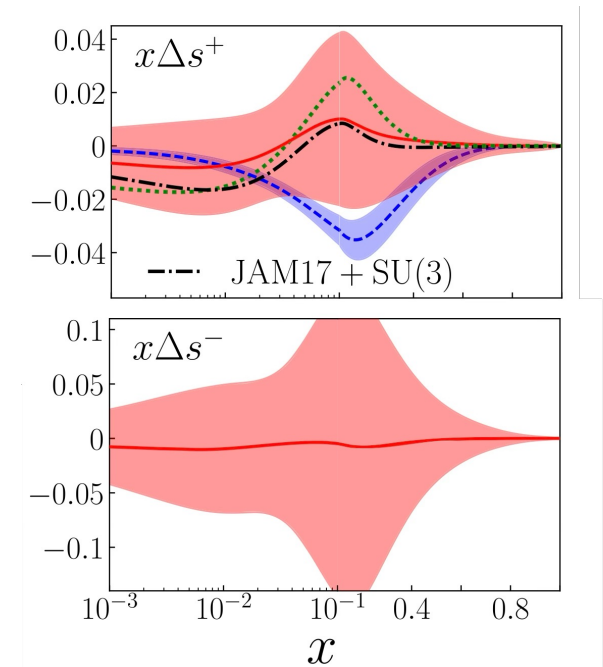
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma^{p^+p \rightarrow \Lambda^+X} - d\sigma^{p^+p \rightarrow \Lambda^-X}}{d\sigma^{p^+p \rightarrow \Lambda^+X} + d\sigma^{p^+p \rightarrow \Lambda^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

$$d\Delta\sigma \propto \Delta f_a(x_a) f_b(x_b) \Delta\sigma^{ab \rightarrow cd} \Delta D^{\Lambda}(z)$$

helicity  
distribution

pQCD  
calculable

longitudinally  
polarized FFs

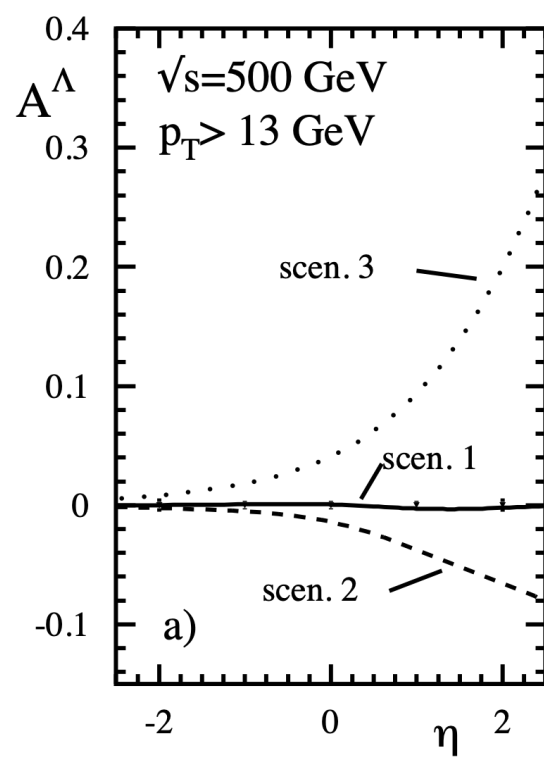


JAM, Phys. Rev. Lett. **119**, 132001 (2017).

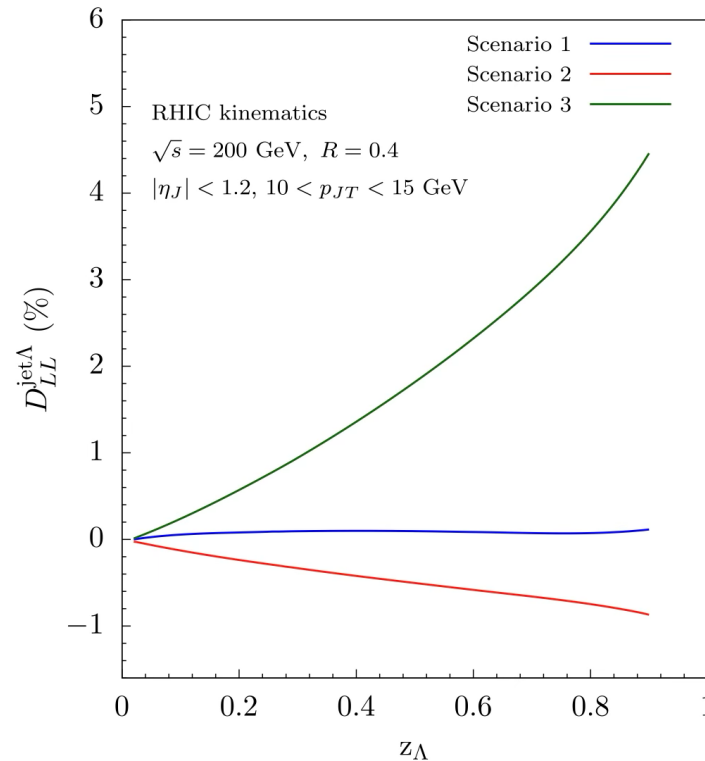
$D_{LL}$  can provide constraints on both polarized FFs and polarized PDFs of s and s-bar

$D_{LL}$  vs z can provide direct probe to the polarized FFs

# $D_{LL}$ predictions for pp at RHIC



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



Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

**scenario 1:** only s quark can contribute to polarization.

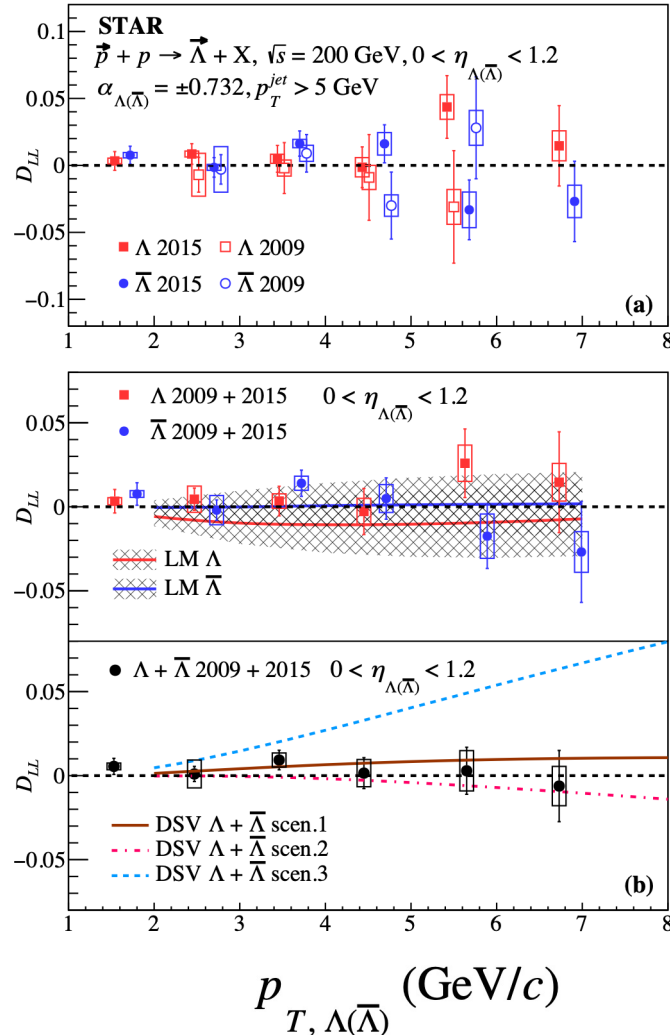
**scenario 2:** u and d quarks have the same contribution to polarized but u and d have an opposite sign from s quark.

**scenario 3:** u, d and s quarks have the same contribution to the polarized

Dramatic different predictions between different extreme scenarios

# Latest $D_{LL}$ results in pp at STAR

STAR, Phys. Rev. D **109**, 012004 (2024)



- Twice statistics larger as STAR 2009 data
- Most precise measurements up to date.
- Consistent results between Lambda and Anti-lambda
- Two year's results are consistent
- Results are consistent with LM calculation
- Strong disfavor of the scenario 3 for the polarized FFs

Model predictions:

- X.N. Liu, B.Q. Ma. Eur. Phys. J. C 10 (2019).
- D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. 81, 530 (1998).

# Transverse spin transfer in polarized pp collision

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

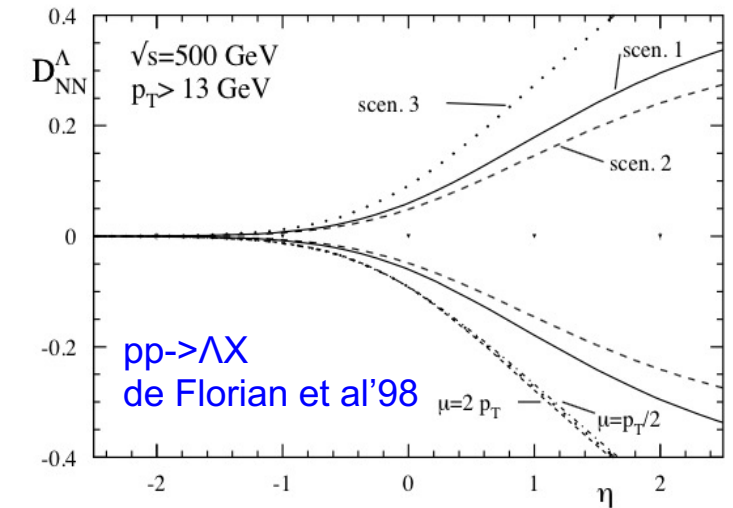
$$D_{TT} \equiv \frac{d\sigma^{(p^\uparrow p \rightarrow H^\uparrow X)} - d\sigma^{(p^\uparrow p \rightarrow H^\downarrow X)}}{d\sigma^{(p^\uparrow p \rightarrow H^\uparrow X)} + d\sigma^{(p^\uparrow p \rightarrow H^\downarrow X)}} = \frac{d\Delta_T \sigma}{d\sigma}$$

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

transversity distribution

Transversely polarized  
fragmentation function

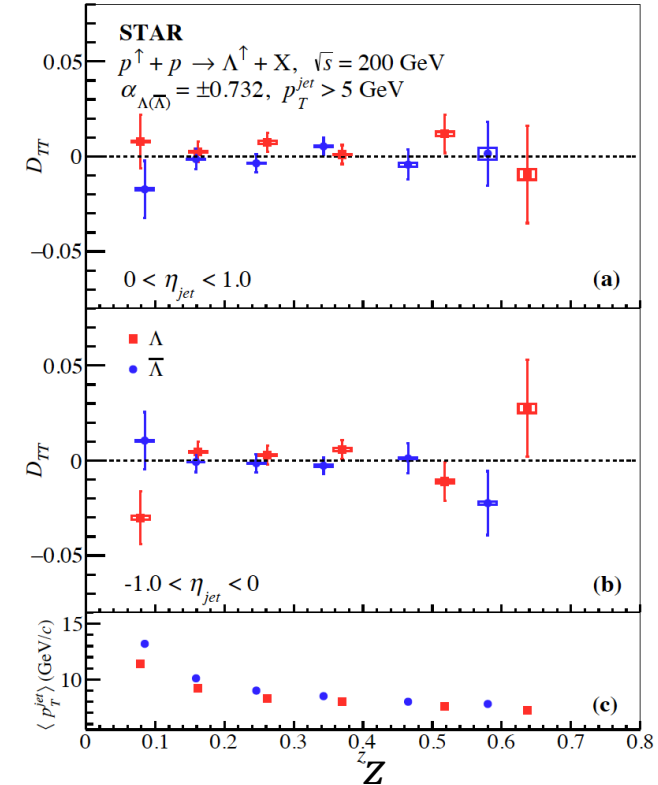
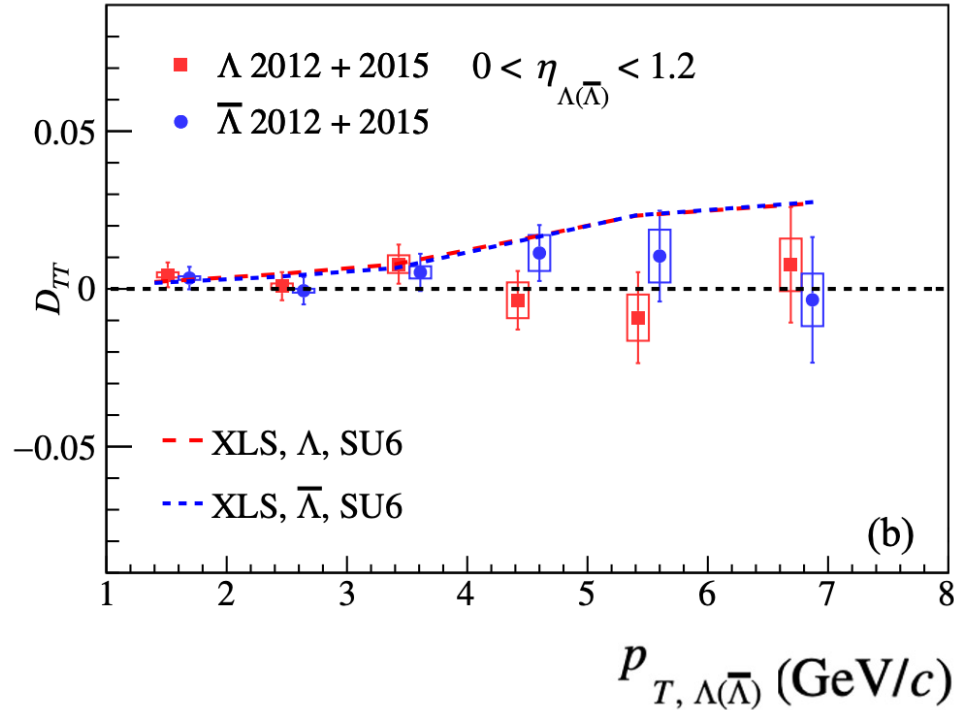
pQCD



- 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).

# Latest $D_{TT}$ measurements at STAR

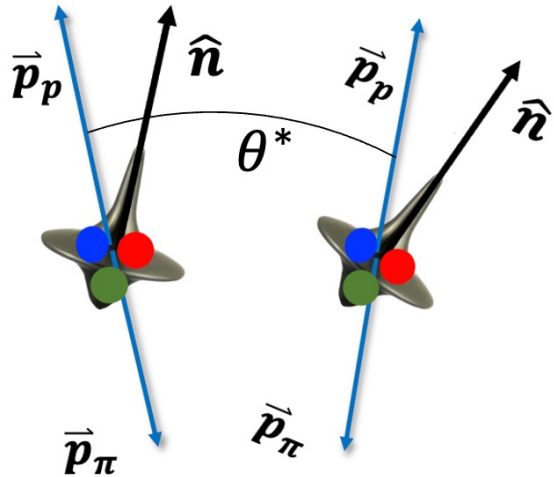
STAR, PRD109, 012004 (2024)



- The  $D_{TT}$  results are consistent with model calculations within uncertainties, also consistent with 0.
- First measurement of  $D_{TT}$  vs.  $z$  in p+p collisions, providing constraints on transversely polarized fragmentation functions.

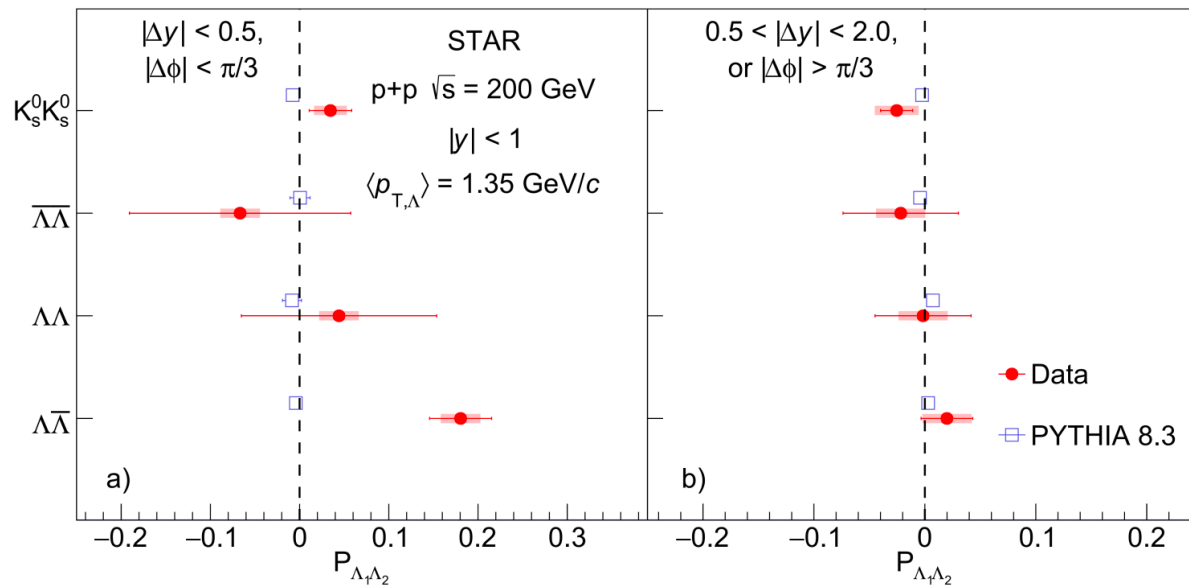
# Spin correlation between two hyperons at final state

- Single hyperon spin polarization measures how one hyperon acquires spin
- Spin transfer measures how initial spin is connected to one final hyperon
- Pair correlation measures whether two final hyperons share correlated spin information
- Pair type and angular separation help identify the underlying production mechanism
- A nonzero correlation can reveal spin-dependent structure beyond single-particle observables



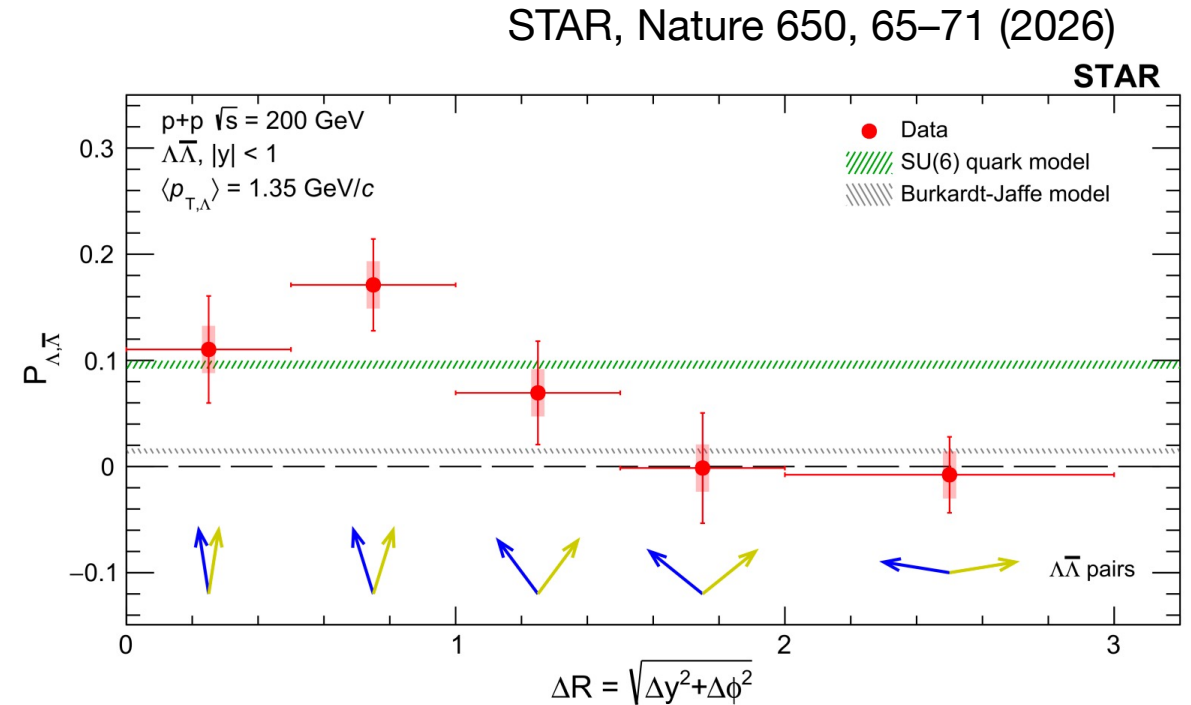
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2} \cos\theta^*$$

# Results of spin correlations in pp 200 GeV



Short-range  $\Lambda\bar{\Lambda}$  pairs show non-zero spin correlation

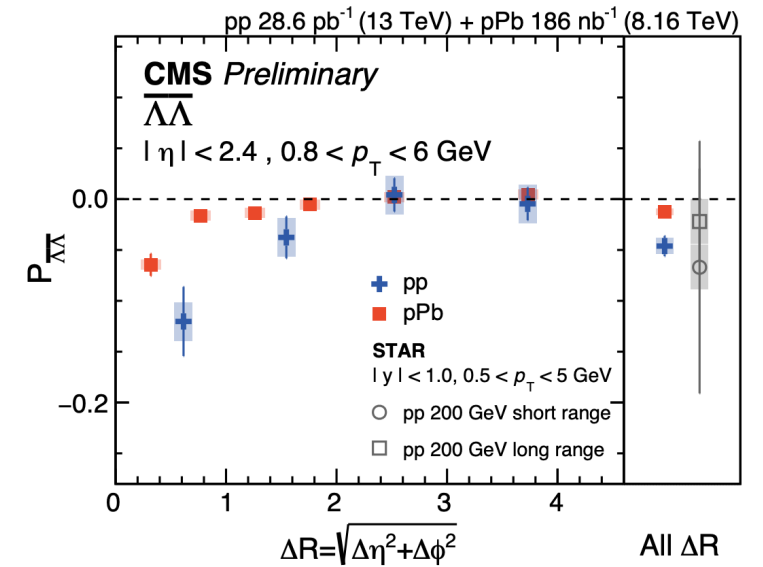
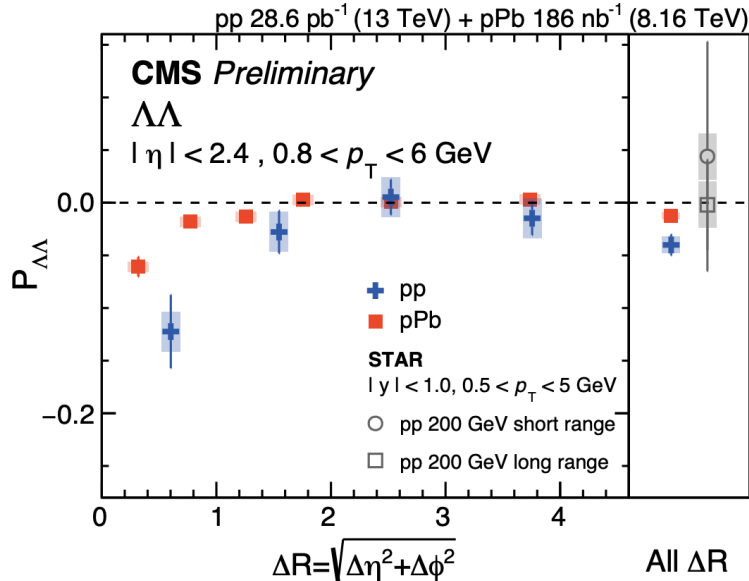
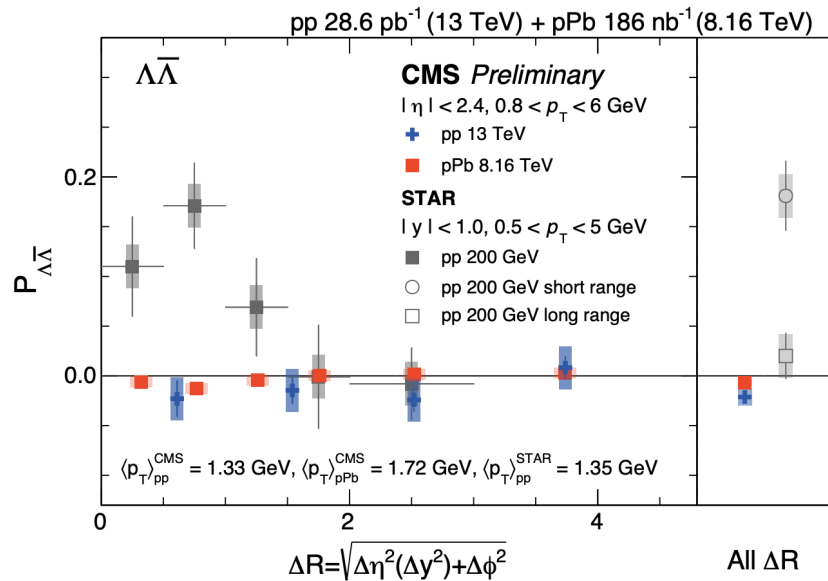
All other pairs are consistent with zero



Spin correlation of  $\Lambda\bar{\Lambda}$  pairs as a function of  $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$

# Preliminary results from CMS in pp and pPb

CMS, DIS2026 (Jieke Wang)



[CMS-PAS-HIN-26-002](#)

- $\Lambda\bar{\Lambda}$  spin correlation consistent with zero, with a hint of negative value
- Negative correlations found for  $\Lambda\Lambda$  and  $\Lambda\bar{\Lambda}$  at small  $\Delta R$  (Short-range)

# Summary

| Measurement            | What it probes                               | Results or Status                                                                                                                                                                                                                              |
|------------------------|----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Inclusive polarization | Polarization w.r.t production plane          | Large transverse polarization observed; 50-year puzzle                                                                                                                                                                                         |
| Spin transfer          | Initial-to-final spin transfer; PDFs/FFs     | Non-zero at large $x_F$<br>Consistent with 0 at small $x_F$                                                                                                                                                                                    |
| Lambda-in-jet          | Polarizing FFs                               | STAR pp: Jet $p_T$ dependence and different for $\Lambda$ and $\bar{\Lambda}$<br>STAR pAu: consistent with zero at both sides                                                                                                                  |
| Pair spin correlation  | correlation in hadronization / fragmentation | STAR pp: non-zero for $\Lambda\bar{\Lambda}$ at small $\Delta R$ and consistent with 0 for all the rest<br>CMS pp/pPb: small for $\Lambda\bar{\Lambda}$ but negative for $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ at small $\Delta R$ |

More measurements (first or precision) ongoing, please stay tuned.

Thanks for your attention!