

第二届“旋转与磁场下的QCD物质研讨会”

Lambda Polarization in Cold QCD Processes

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2026年9月11-14日 安徽淮南



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SHANDONG UNIVERSITY

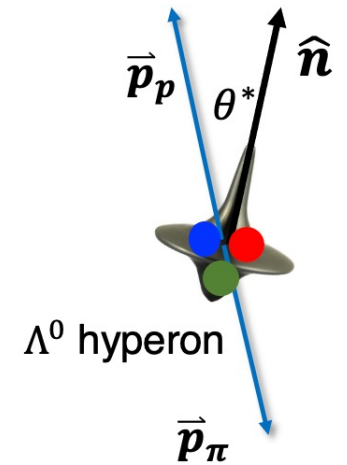


Lambda: final state “polarimetry”

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

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

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

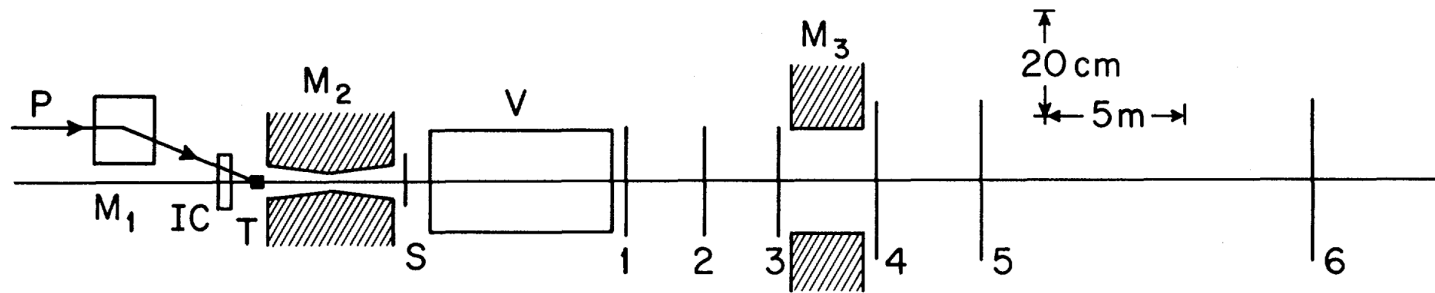


Puzzle since 1976

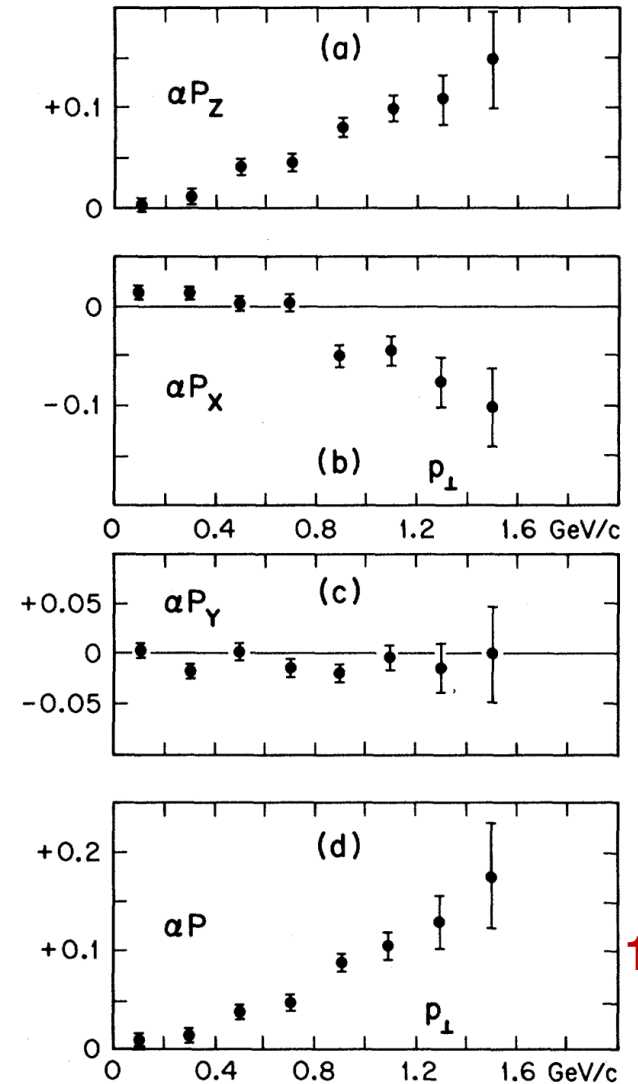
G. Bunce et al. PRL36, 1113 (1976)

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 Λ 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)

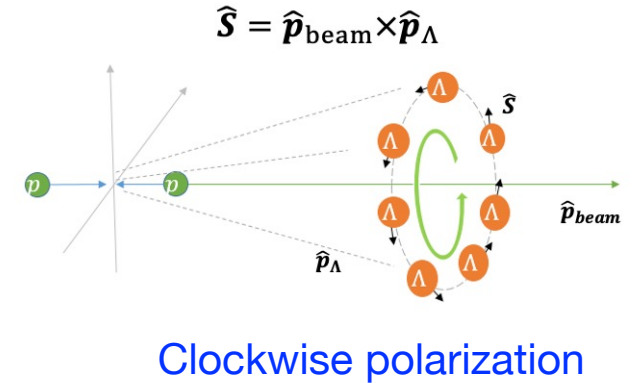
920 GeV proton + Carbon/Tungsten at DESY (HERA-B)

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

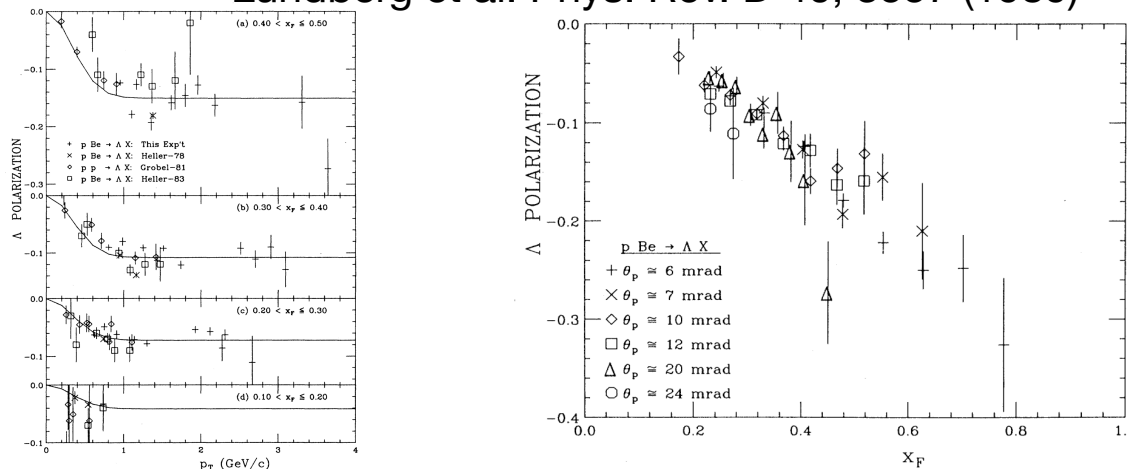
2.5 TeV proton + Neon at CERN (LHCb-SMOG)

Features of lambda spontaneous polarization

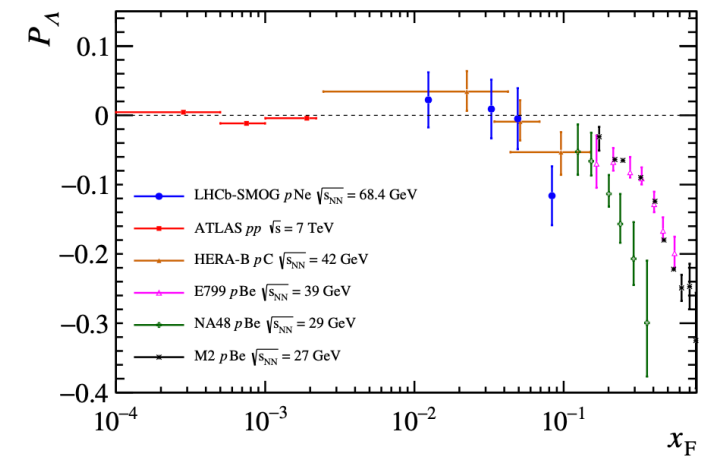
- Polarization is (almost) independent of beam energy.
- x_F and p_T dependence scales with energy.
- Weak target-mass dependence: $pA \approx pp$, parton level reaction.
- Anti-lambda polarization is consistent with zero.



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



Abt et al, JHEP09, 082 (2024)

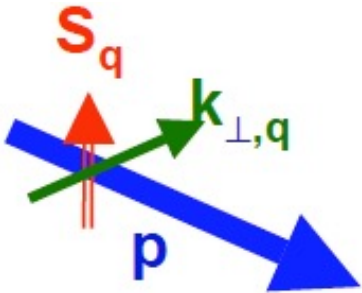


Initial- and final-state sources of Λ polarization

Partonic scattering (pQCD) cannot explain the large polarization.

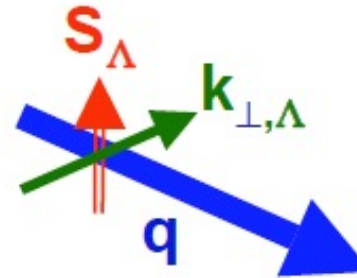
Then, must be non-pQCD effects from *initial state and/or final state*.

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

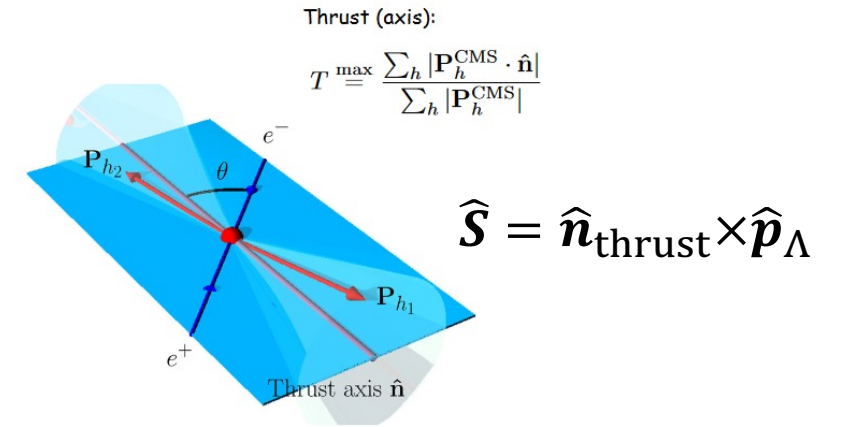
Measurements in e^+e^- annihilation

- 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)

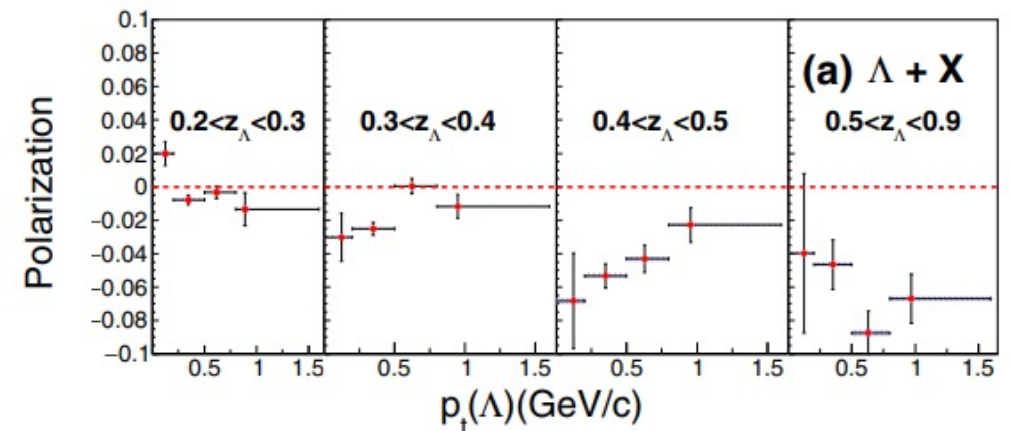
Callos, Kang, Terry, PRD 102, 096007 (2020)

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

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

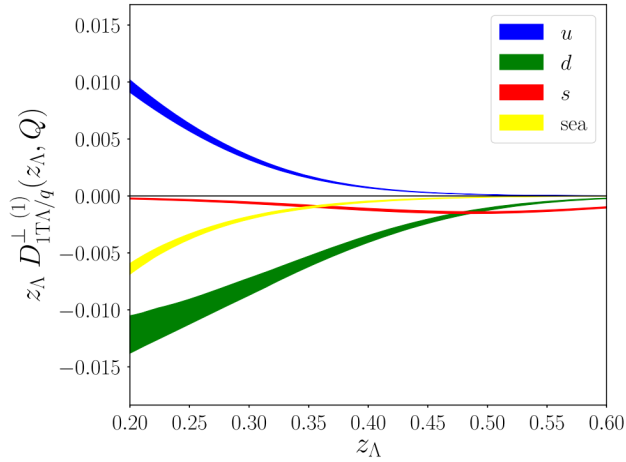
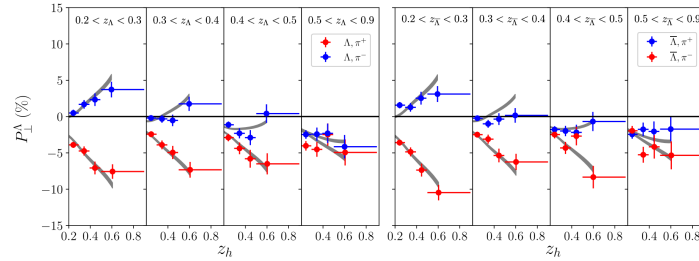


$$z_{\Lambda} = \frac{2E_{\Lambda}}{\sqrt{s}}$$

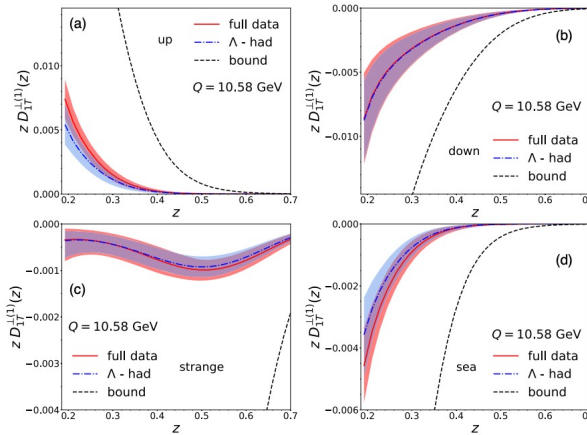
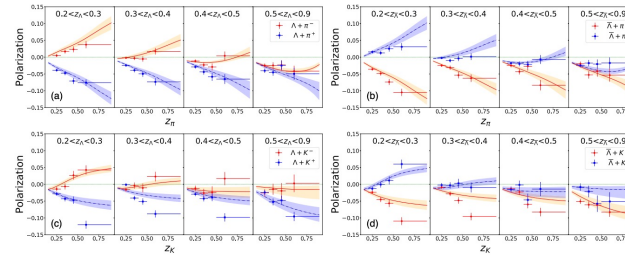


Global analyses of Belle results

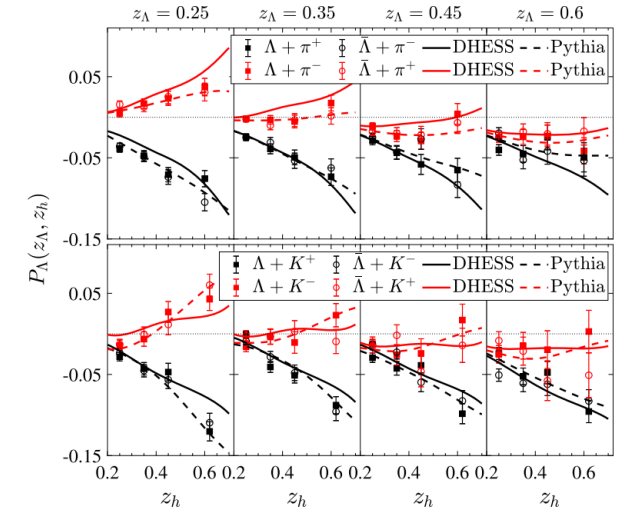
Callos, Kang, Terry,
PRD 102, 096007 (2020)



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)

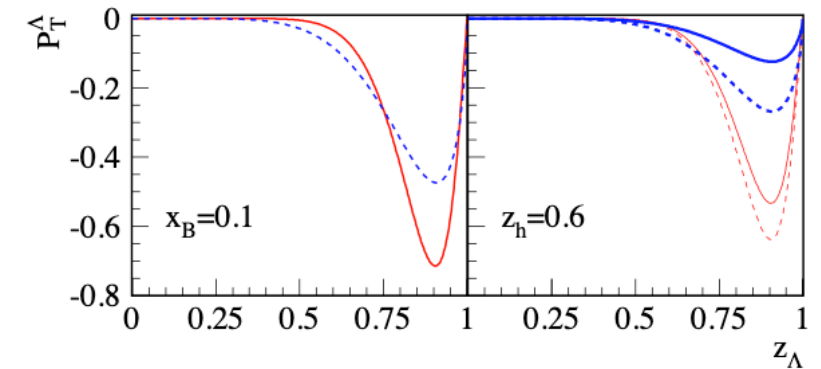
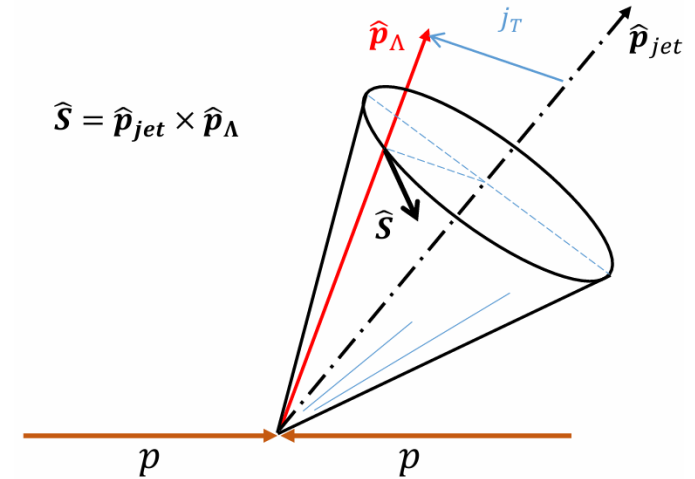
What can we do in pp/pA collision at RHIC and LHC?

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

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

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

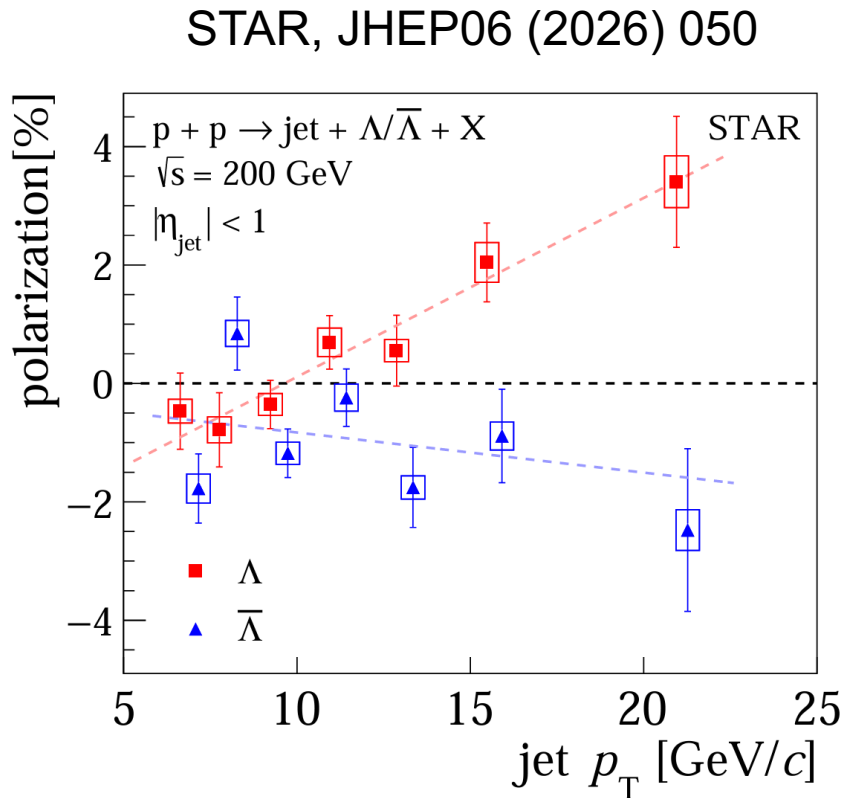
- Polarization direction normal to the production plane constructed by jet and Λ momentum
- Complement to e^-e^+ :
 - Cover a wide range of jet p_T : 5~50 GeV at RHIC and higher at LHC
 - Test universality of pFFs



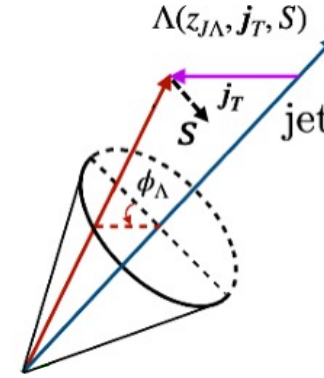
Boer et al, Phys.Rev. Lett. 105.202001 (2010)

Results from 200 GeV pp collision

Polarization as a function of jet p_T



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

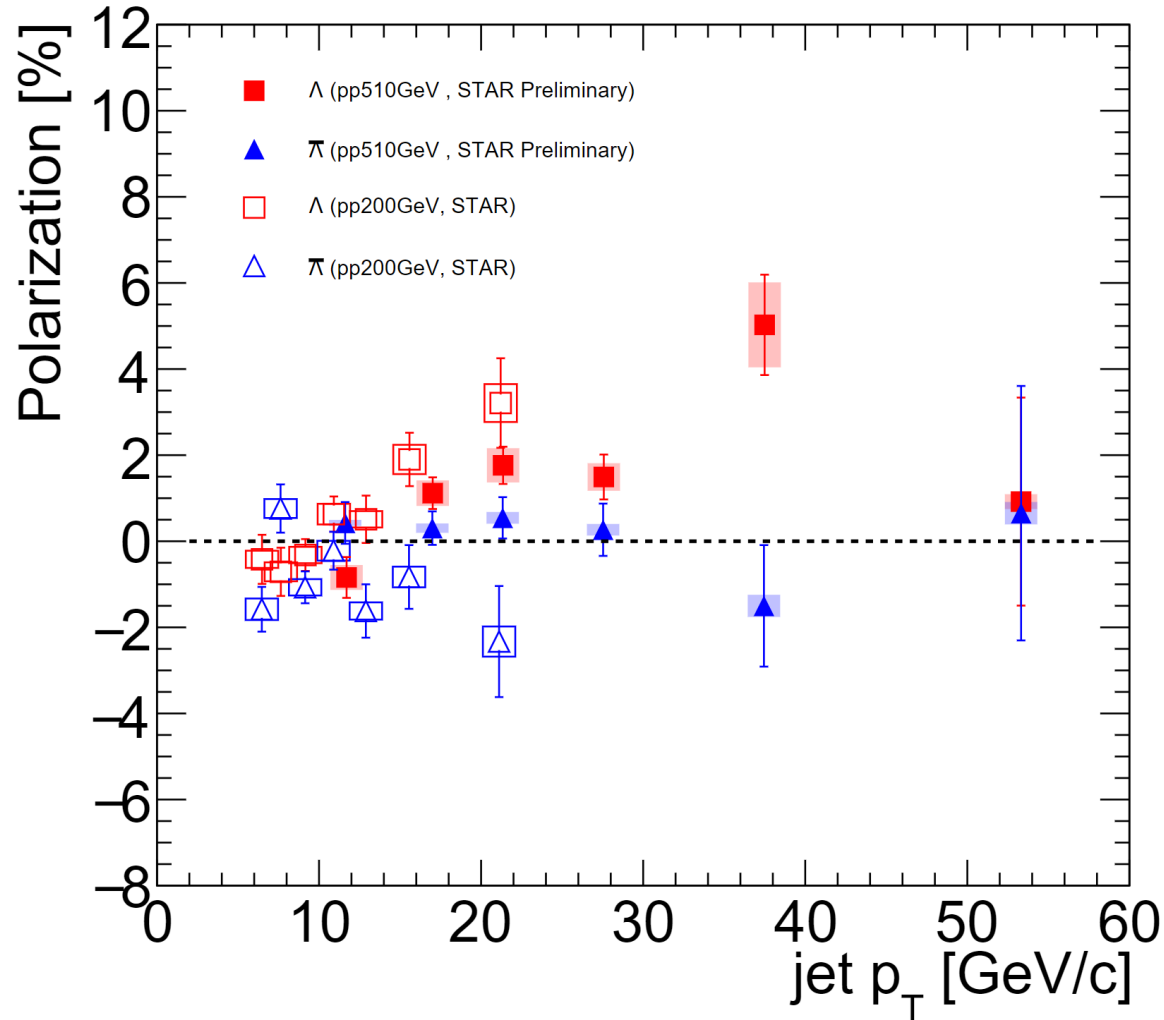


$$\hat{\mathbf{S}} = \hat{\mathbf{p}}_{\text{jet}} \times \hat{\mathbf{p}}_{\Lambda}$$

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

Preliminary Results from 510 GeV pp collision

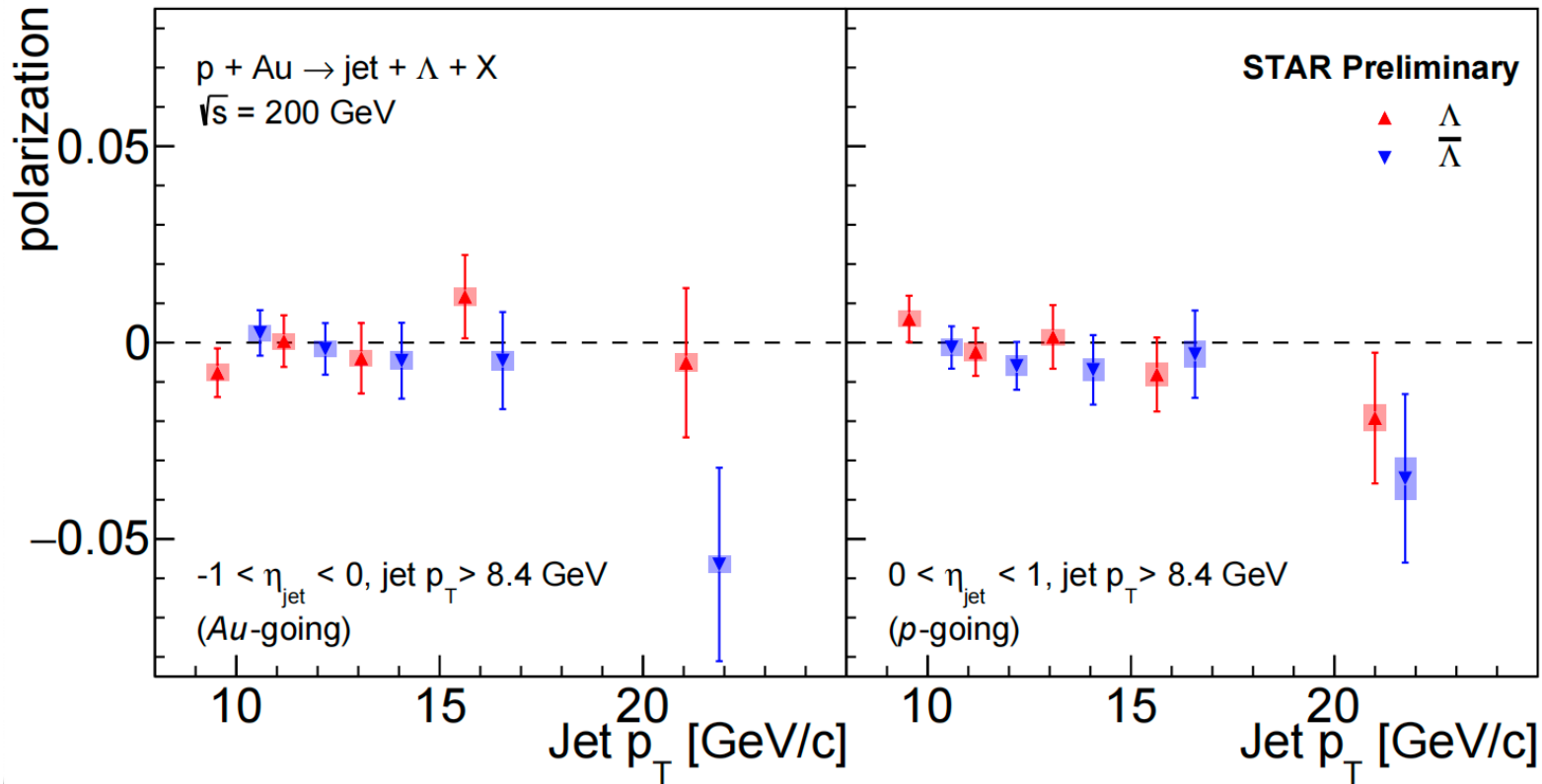
STAR, SPIN2025 (Jinhao He)



- The preliminary results at $\sqrt{s}=510$ GeV cover jet p_T up to 50 GeV
- Λ 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

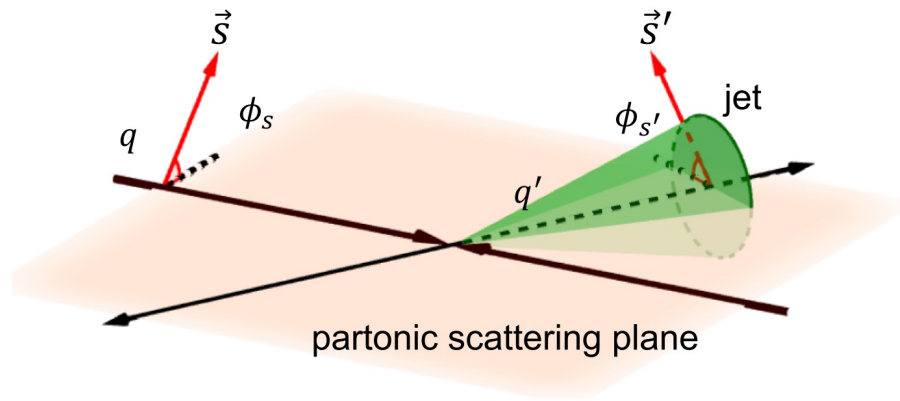
Preliminary Results from 201 GeV pAu collision

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.

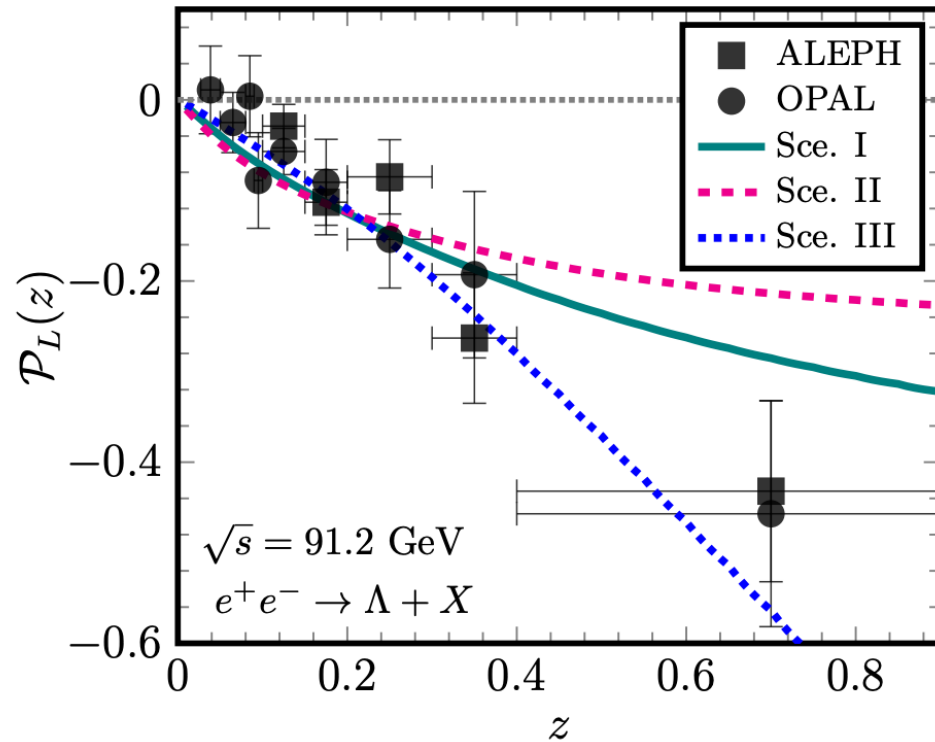
Spin correlation between initial state and final state



- 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 Λ
- 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 Λ spin transfer



- Z^0 decay produces strongly polarized primary quarks
- Large longitudinal Λ polarization observed
- Evidence for quark-to- Λ spin transfer
- Key constraint for DSV polarized Λ 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)

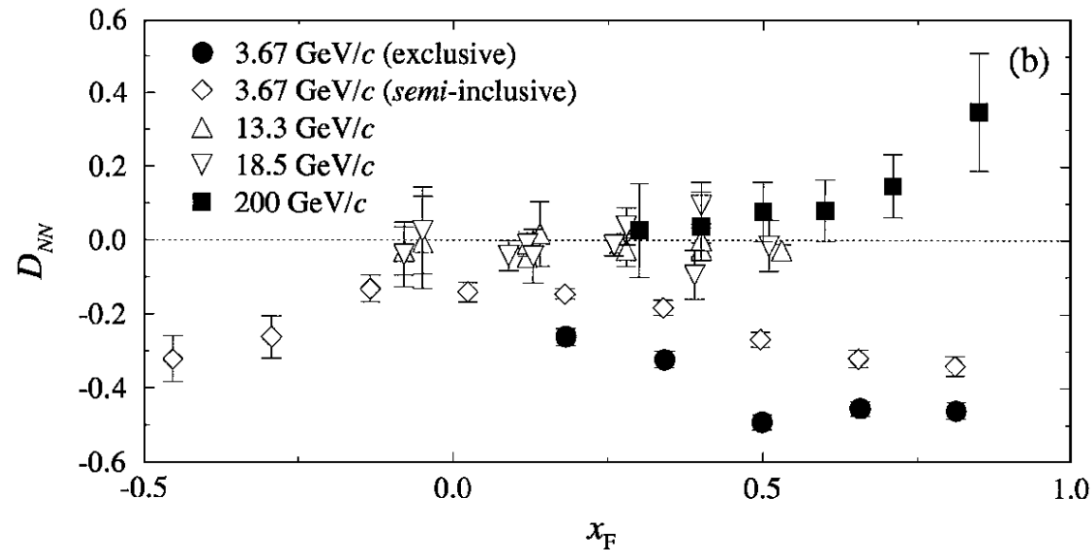
Transversely polarized proton 200 GeV

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

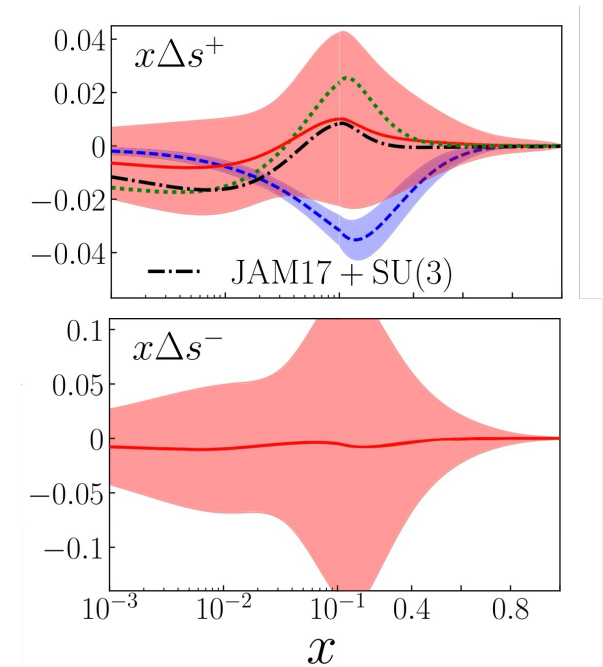
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma^{p^+p \rightarrow \Lambda^+X} - d\sigma^{p^+p \rightarrow \Lambda^-X}}{d\sigma^{p^+p \rightarrow \Lambda^+X} + d\sigma^{p^+p \rightarrow \Lambda^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

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

helicity
distribution

pQCD
calculable

longitudinally
polarized FFs

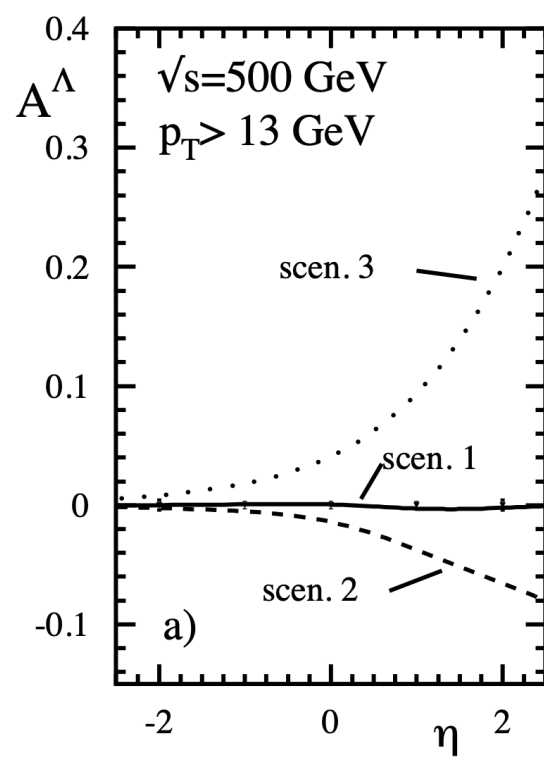


JAM, Phys. Rev. Lett. **119**, 132001 (2017).

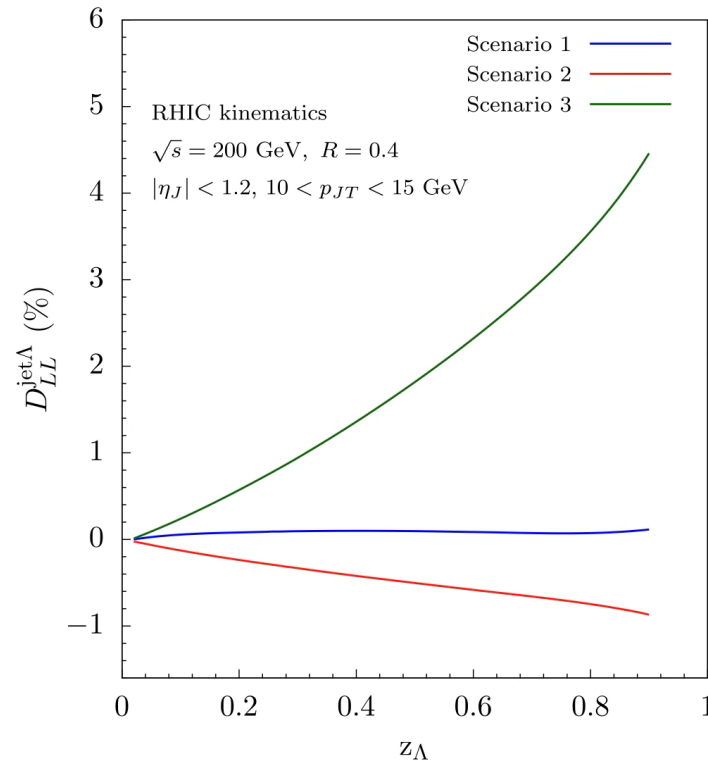
D_{LL} can provide constraints on both polarized FFs and polarized PDFs of s and s-bar

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.

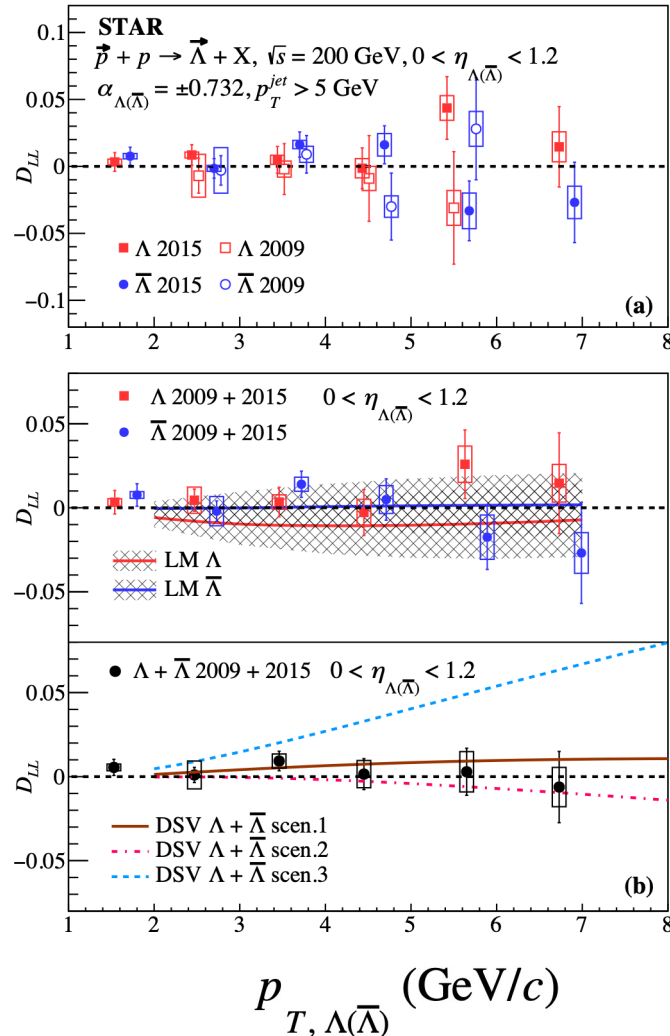
scenario 2: u and d quarks have the same contribution to polarized but u and d have an opposite sign from s quark.

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:

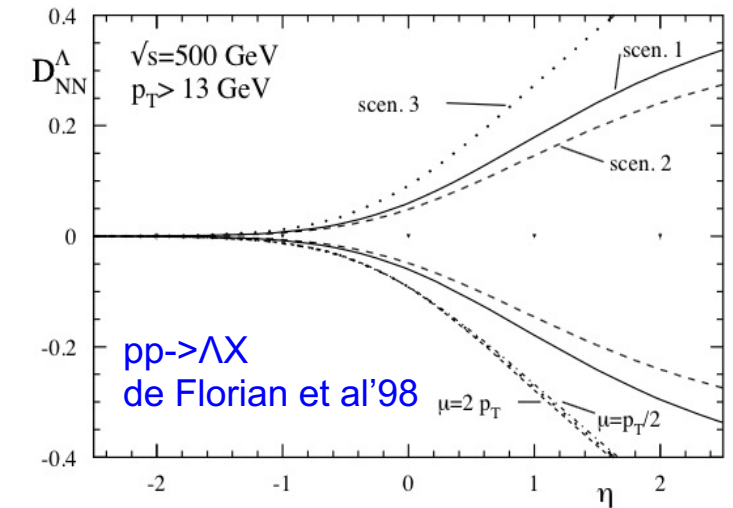
$$D_{TT} \equiv \frac{d\sigma^{(p^\uparrow p \rightarrow H^\uparrow X)} - d\sigma^{(p^\uparrow p \rightarrow H^\downarrow X)}}{d\sigma^{(p^\uparrow p \rightarrow H^\uparrow X)} + d\sigma^{(p^\uparrow p \rightarrow H^\downarrow X)}} = \frac{d\Delta_T \sigma}{d\sigma}$$

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

transversity distribution

Transversely polarized
fragmentation function

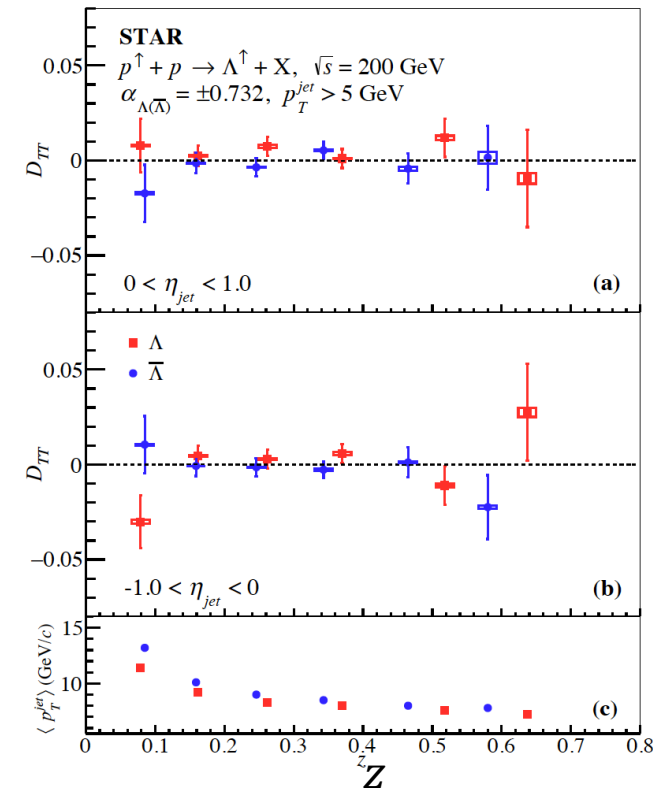
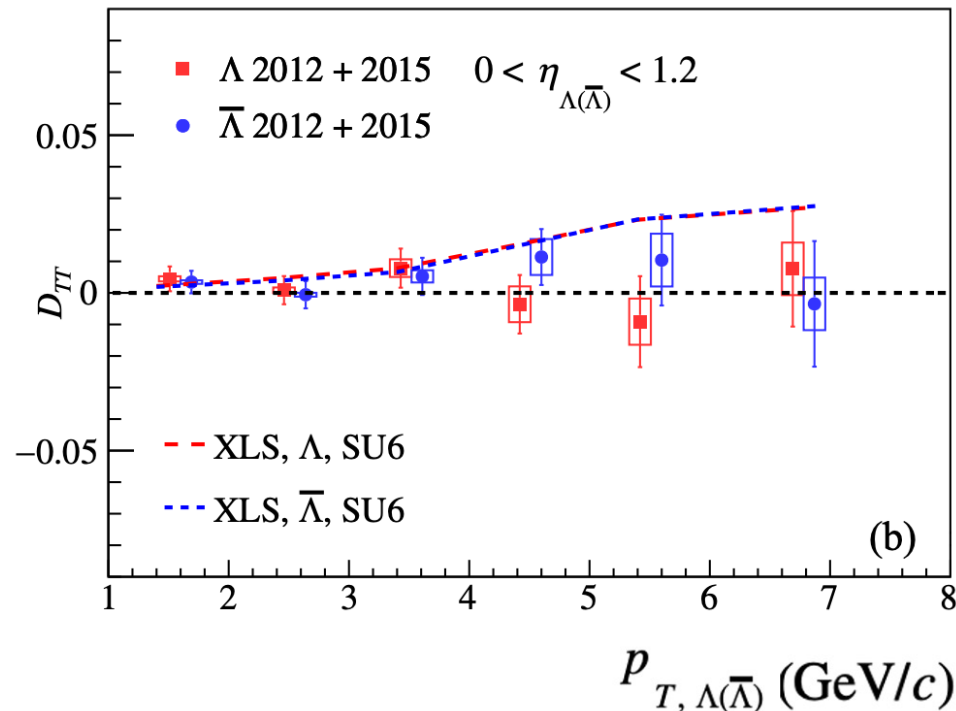
pQCD



- 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).

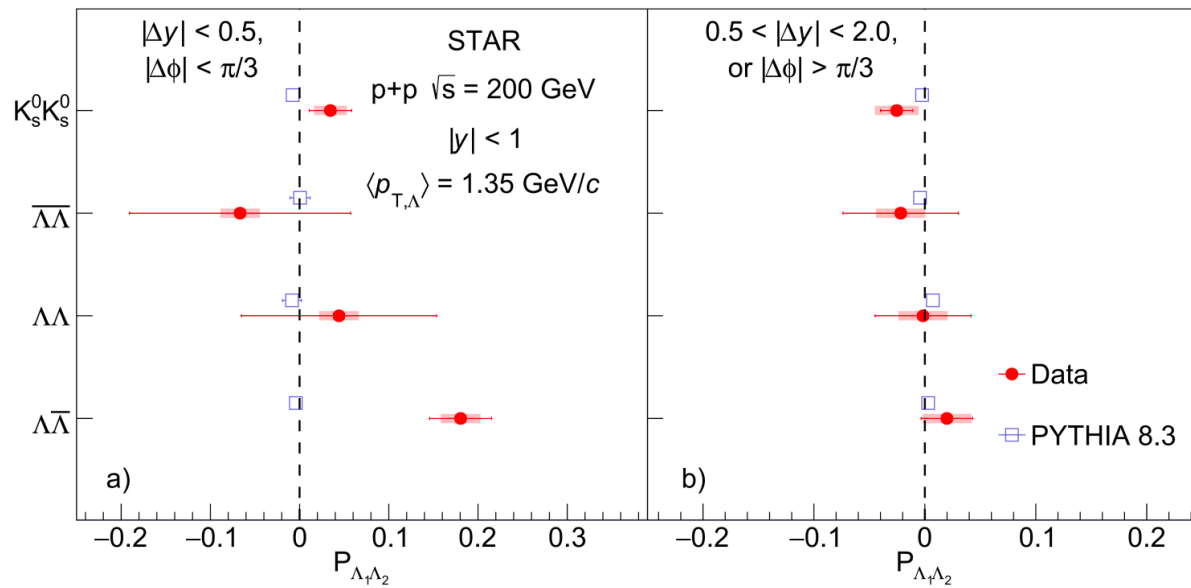
Latest D_{TT} measurements at STAR

STAR, PRD109, 012004 (2024)



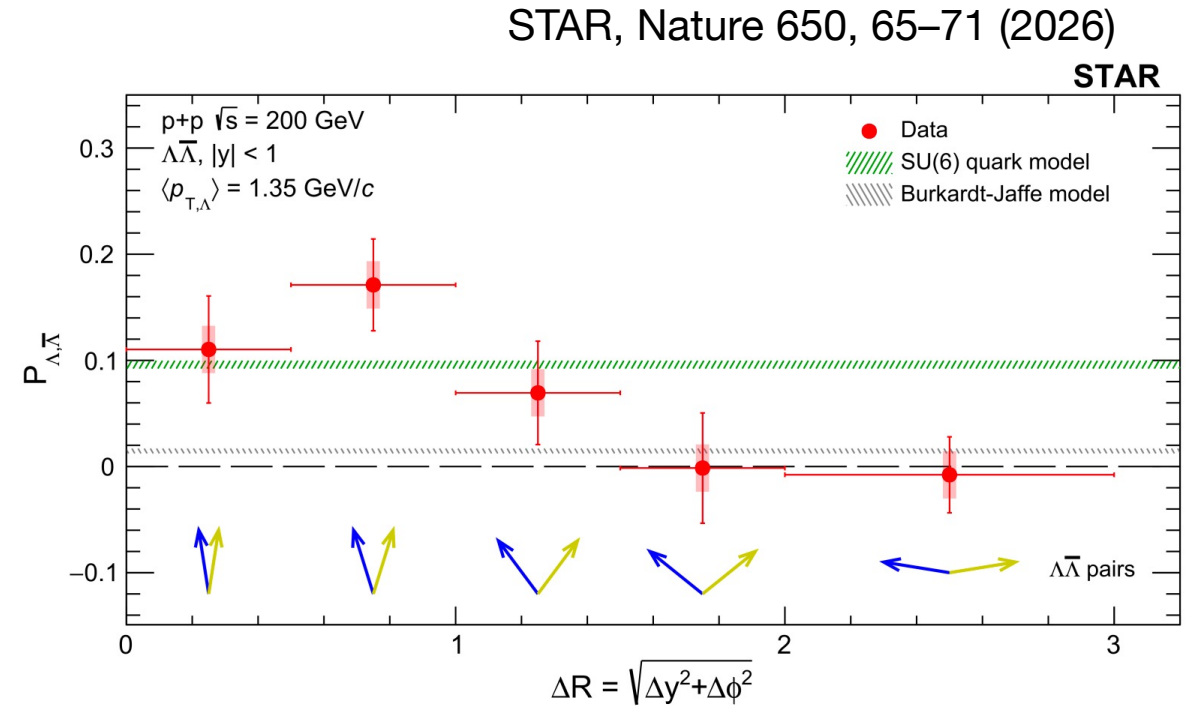
- The D_{TT} results are consistent with model calculations within uncertainties, also consistent with 0.
- First measurement of D_{TT} vs. z in p+p collisions, providing constraints on transversely polarized fragmentation functions.

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 $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$

Lambda polarization in cold QCD processes

Process	Experiments	Main results	Physics sensitivity
Inclusive pp/pA	Fixed-target, ATLAS, HERA-B, LHCb	Large polarization; x_F and p_T dependence; scales with energy	Polarization mechanisms; kinematic and nuclear dependence
e^+e^-	LEP 91 GeV	Large longitudinal Λ polarization	Polarization transfer in fragmentation
e^+e^-	Belle 10.6 GeV	Significant transverse polarization	Quark polarizing fragmentation functions
DIS	HERMES, COMPASS, CLAS12, NOMAD	Longitudinal spin transfer smaller than expectation; transverse spin transfer consistent with zero	Flavor-dependent polarized fragmentation; current and target fragmentation
Polarized pp	STAR 200 GeV	Consistent with zero	Helicity and transversity distributions; polarized fragmentation functions
pp/pA to Λ -in-jet	STAR 200/500 GeV	Dependence on jet p_T ; pA is different from pp	Quark and gluon polarizing fragmentation; TMD evolution and universality

Summary

- Λ hyperons are powerful spin probes.
- Old puzzles persist; new ones emerge.
- Polarizing fragmentation is nonzero; flavor and gluon contributions remain unclear.
- Systematic studies need varied systems, energies, and flavor tagging.
- Limited detector acceptance motivates dedicated instrumentation.

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Thanks for your attention!