Overview on spin polarization and correlation in pp collisions

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May 14, 2026

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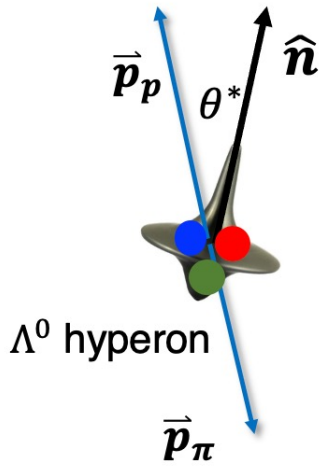
Outline

- 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%)



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

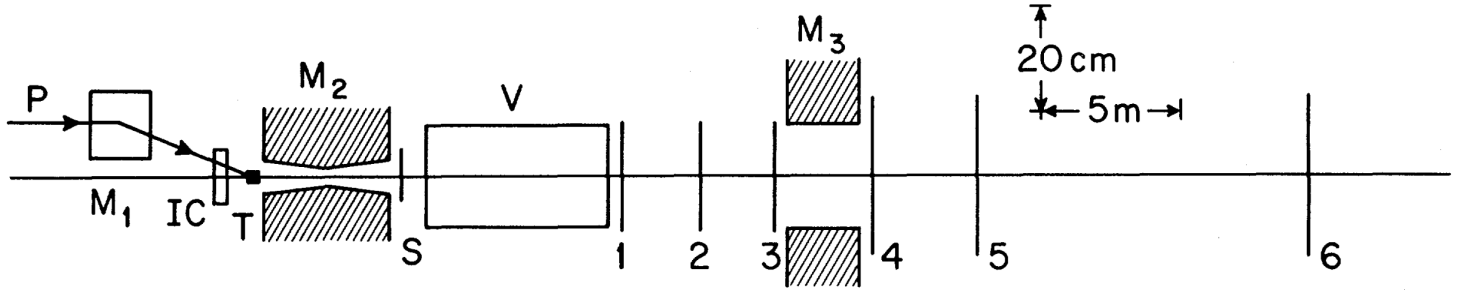
- Λ polarization plays an important role in spin physics
  - Hot QCD: vorticity, magnetic filed, medium effects, etc.
  - Cold QCD: spin structure, fragmentation, spin correlations

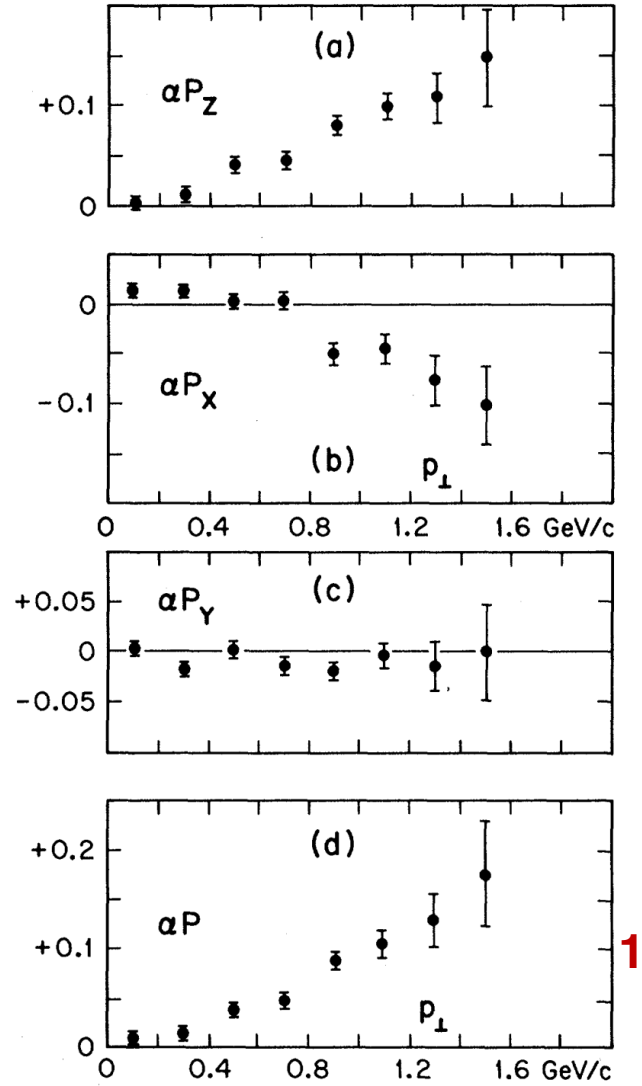
Puzzle since 1976

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

300 GeV unpolarized proton on unpolarized Beryllium target

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





10%

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.

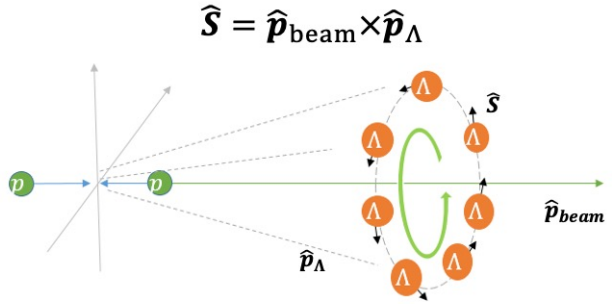
Follow-up measurements

incomplete list

Heller et al., Phys. Lett. B68 480 (1977)	24 GeV proton + Platinum at CERN
Heller et al., Phys. Rev. Lett. 41, 607 (1978)	400 GeV proton + Beryllium at Fermilab (different hyperon)
Erhan et al., Phys. Lett B82, 301 (1979)	$\sqrt{s}$ = 53, 62 GeV proton + proton at CERN (ISR)
Lomanno et al., Phys. Rev. Lett. 43, 1905 (1979)	28.5 GeV proton + Iridium at BNL (AGS)
Heller et al., Phys. Rev. Lett. 51, 2025 (1983)	400 GeV proton + Beryllium/Copper/Lead at Fermilab
Abe et al., Phys. Rev. Lett. 50, 1102 (1983)	12 GeV proton + Tungsten at KEK
Aleev et al., Z. Phys. C 36, 27 (1987)	~40 GeV neutron + Carbon/Aluminum/Copper
Lundberg et al., Phys. Rev. D 40, 3557 (1989)	400 GeV proton + Beryllium at Fermilab (higher pT)
Ramberg et al., Phys. Lett. B 338, 403 (1994)	800 GeV proton + Beryllium at Fermilab
Fanti et al., Eur. Phys. J. C 6 265 (1999)	450 GeV proton + Beryllium at CERN (SPS-NA48)
Abt et al., Phys. Lett. B 638, 415 (2006)	920 GeV proton + Carbon/Tungsten at DESY (HERA-B)
Aad et al., Phys. Rev. D 91, 032004 (2015)	$\sqrt{s}$ = 7 TeV proton + proton at CERN (ATLAS)
Abt et al., JHEP09, 082 (2024)	2.5 TeV proton + Neon at CERN (LHCb-SMOG)

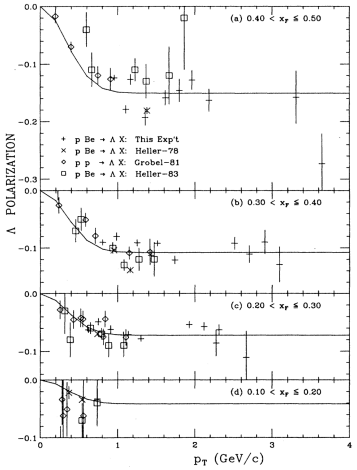
Features of lambda spontaneous polarization

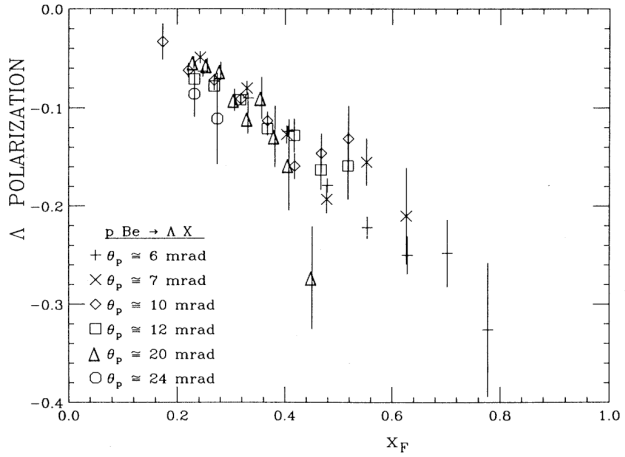
- Polarization is (almost) independent of beam energy.
- x_F and p_T dependence scales with energy.
- Weak target-mass dependence: pA ≈ pp, parton level reaction.
- Anti-lambda polarization is consistent with zero.



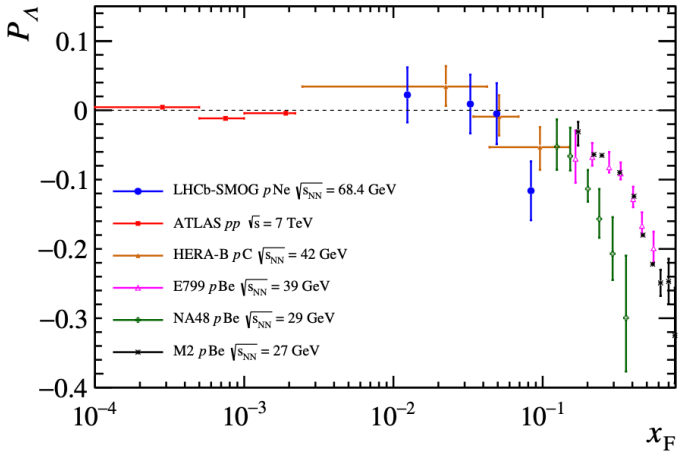
Clockwise polarization

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





Abt et al, JHEP09, 082 (2024)

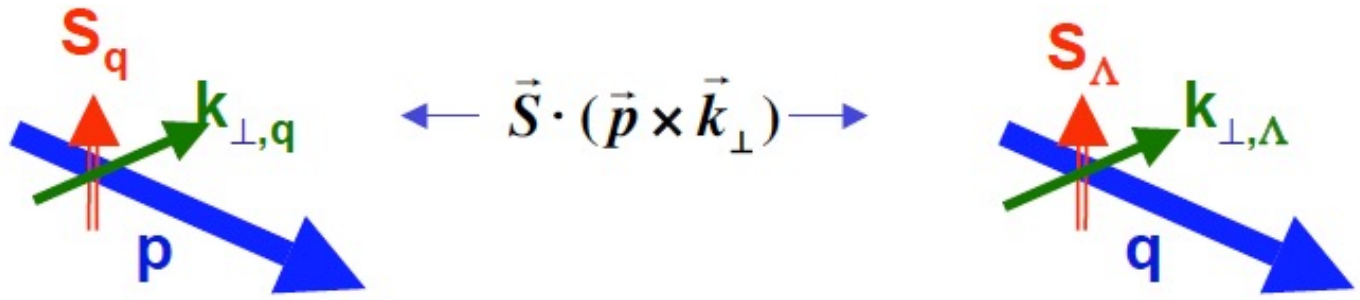


Initial- and final-state sources of Λ polarization

Partonic scattering (pQCD) cannot explain the large polarization.

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

Parton distributions



Parton fragmentations

Different collision systems provide complementary constraints.

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

Measurements in e^+e^- annihilation

- LEP ($\sqrt{s} = 90$ GeV): no significant polarization
  - ALEPH $P_T^{\Lambda,\bar{\Lambda}} = 0.016 \pm 0.007$

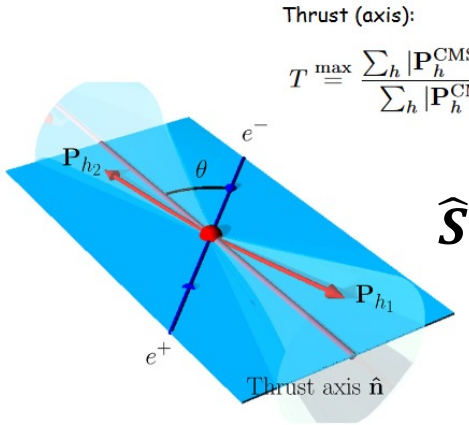
  ALEPH, PLB 374, 319 (1996)
  - OPAL $P_T^{\Lambda} = 0.019 \pm 0.014$ ($p_T > 0.3$ GeV/c)

  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)

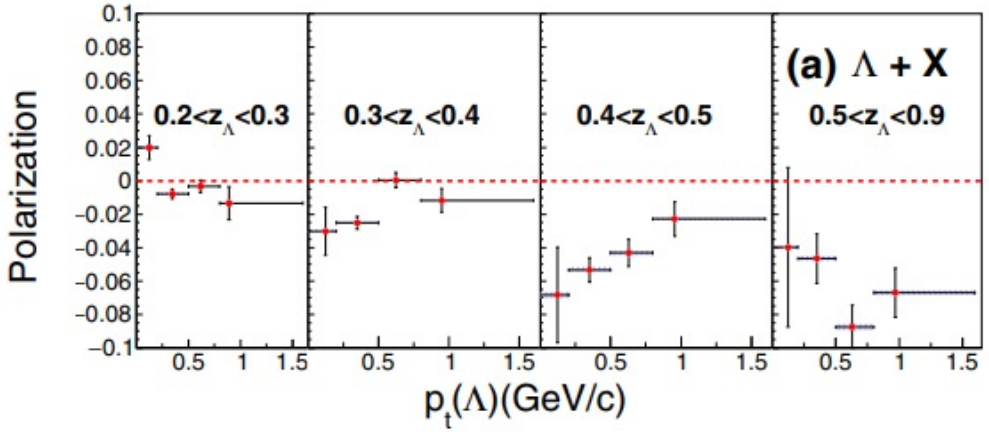
  D'Alesio, Murgia, Zaccheddu, PRD 102, 054001 (2020)

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



$$\hat{\boldsymbol{S}} = \hat{\boldsymbol{n}}_{\mathrm{thrust}} \times \hat{\boldsymbol{p}}_{\Lambda}$$

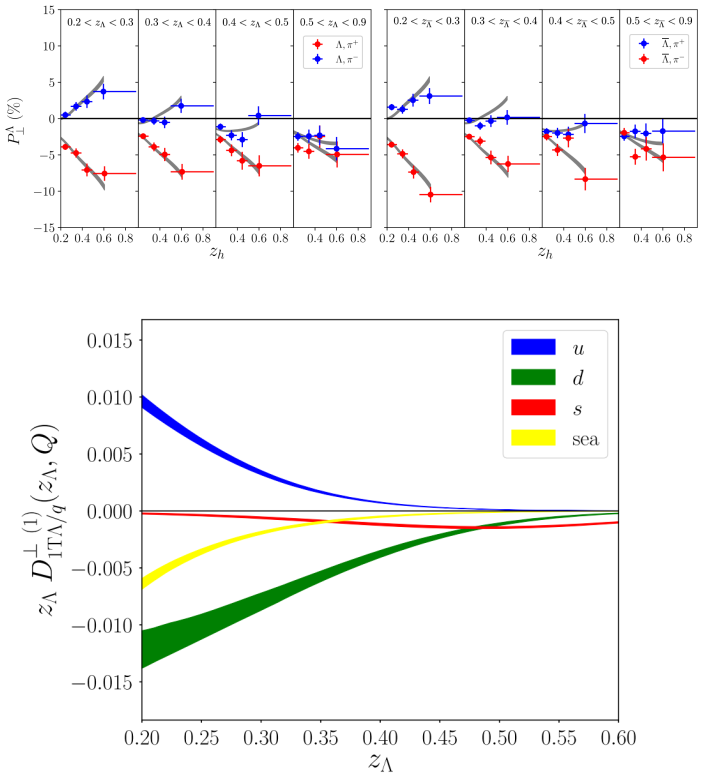
$$z_\Lambda = \frac{2E_\Lambda}{\sqrt{s}}$$



Global analyses of Belle results

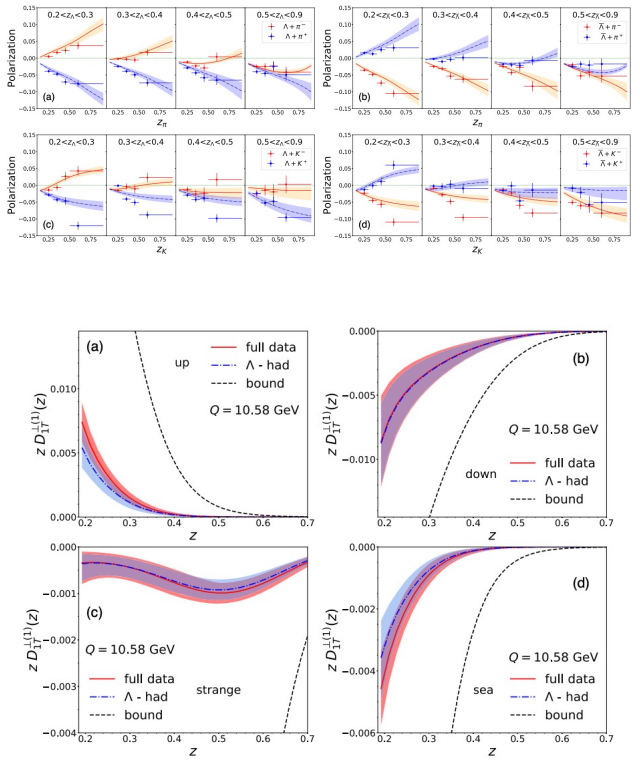
Callos, Kang, Terry,

PRD 102, 096007 (2020)



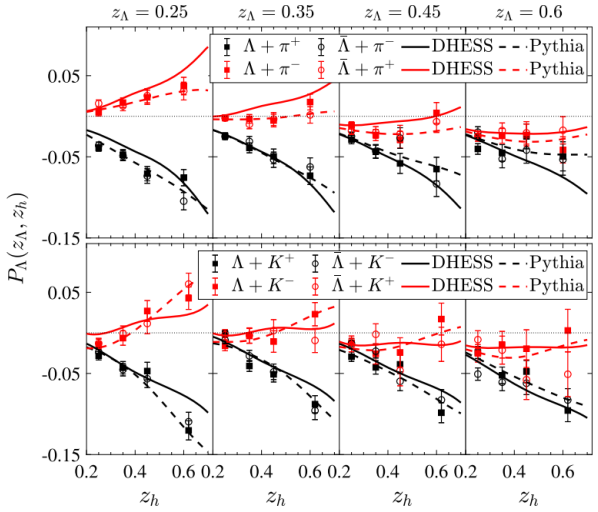
D'Alesio, Murgia, Zaccheddu,

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?

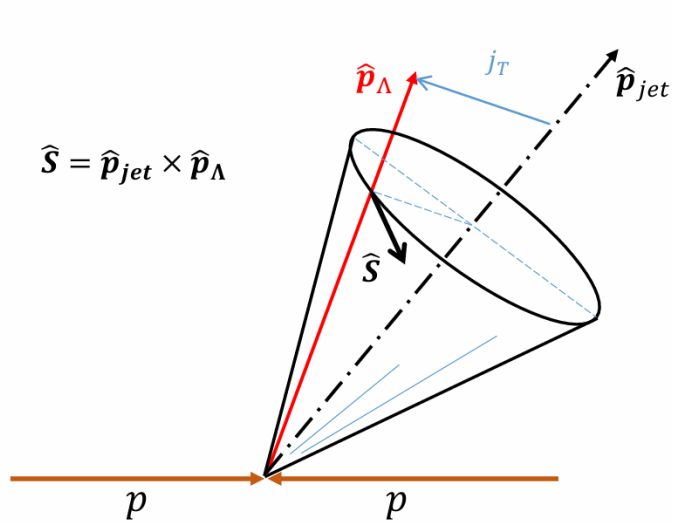
- Polarizing Fragmentation Functions(pFFs) can be accessed by transverse polarization of Λ-in-jet in pp collision

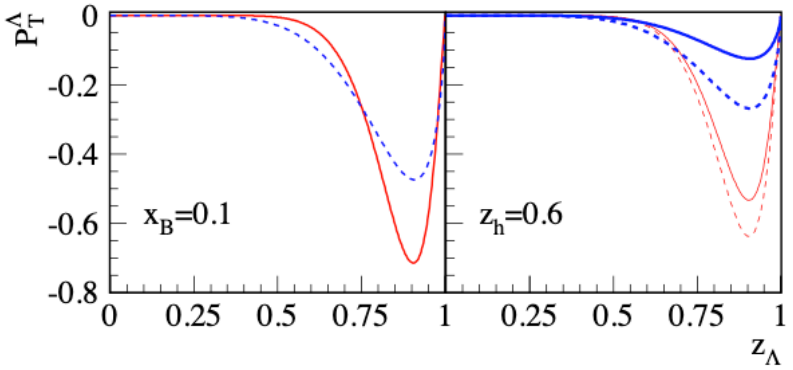
  Boer et al, PLB 671, 91-98 (2008)

  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

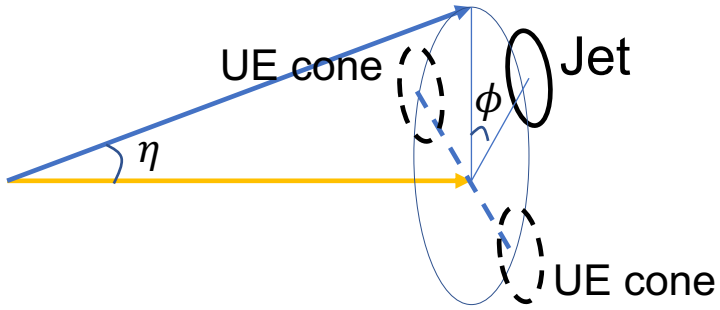


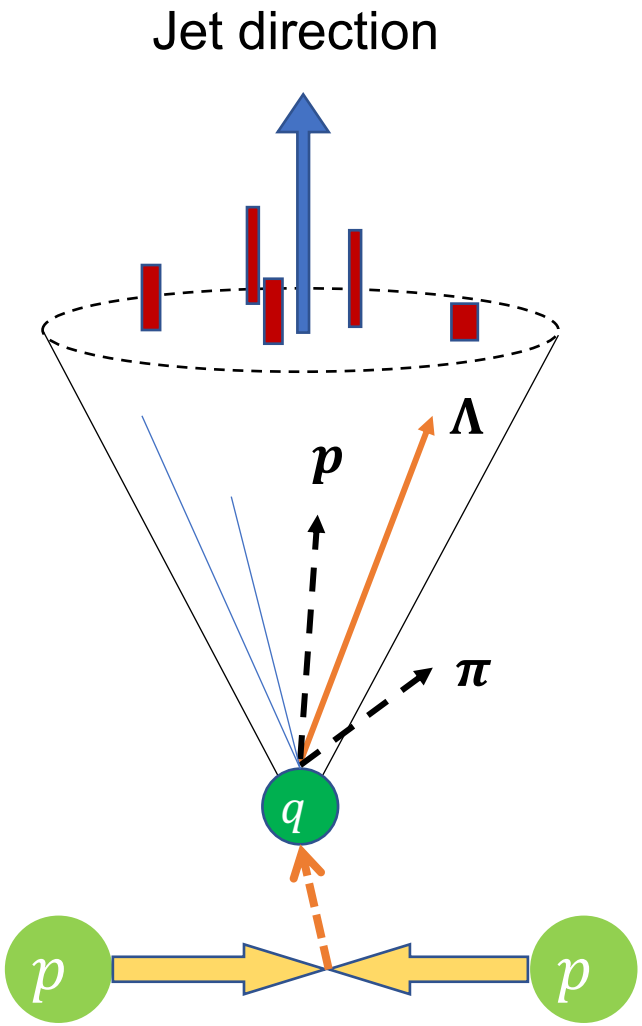


Boer et al, Phys.Rev. Lett. 105.202001 (2010)

V0-jet reconstruction

- Jet reconstruction
  - Anti-k_T with $\mathrm{R} = 0.6$
  - Particle list: TPC tracks and EMC energy deposit
  - $\Lambda, \overline{\Lambda}$ as input particles
- Underlying event correction by off-axis method

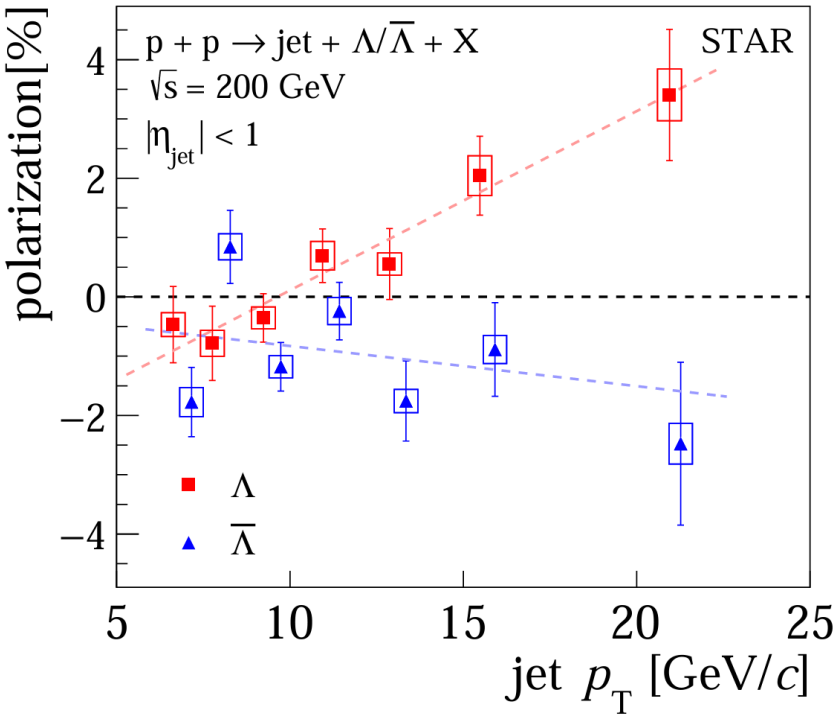


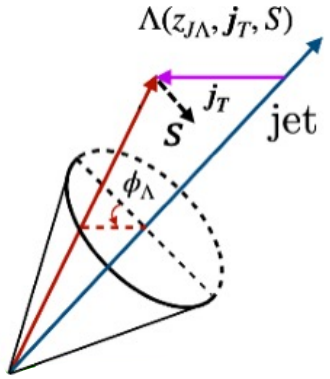


Results from 200 GeV pp collision

Polarization as a function of jet p_T

STAR, arXiv: 2509.17487





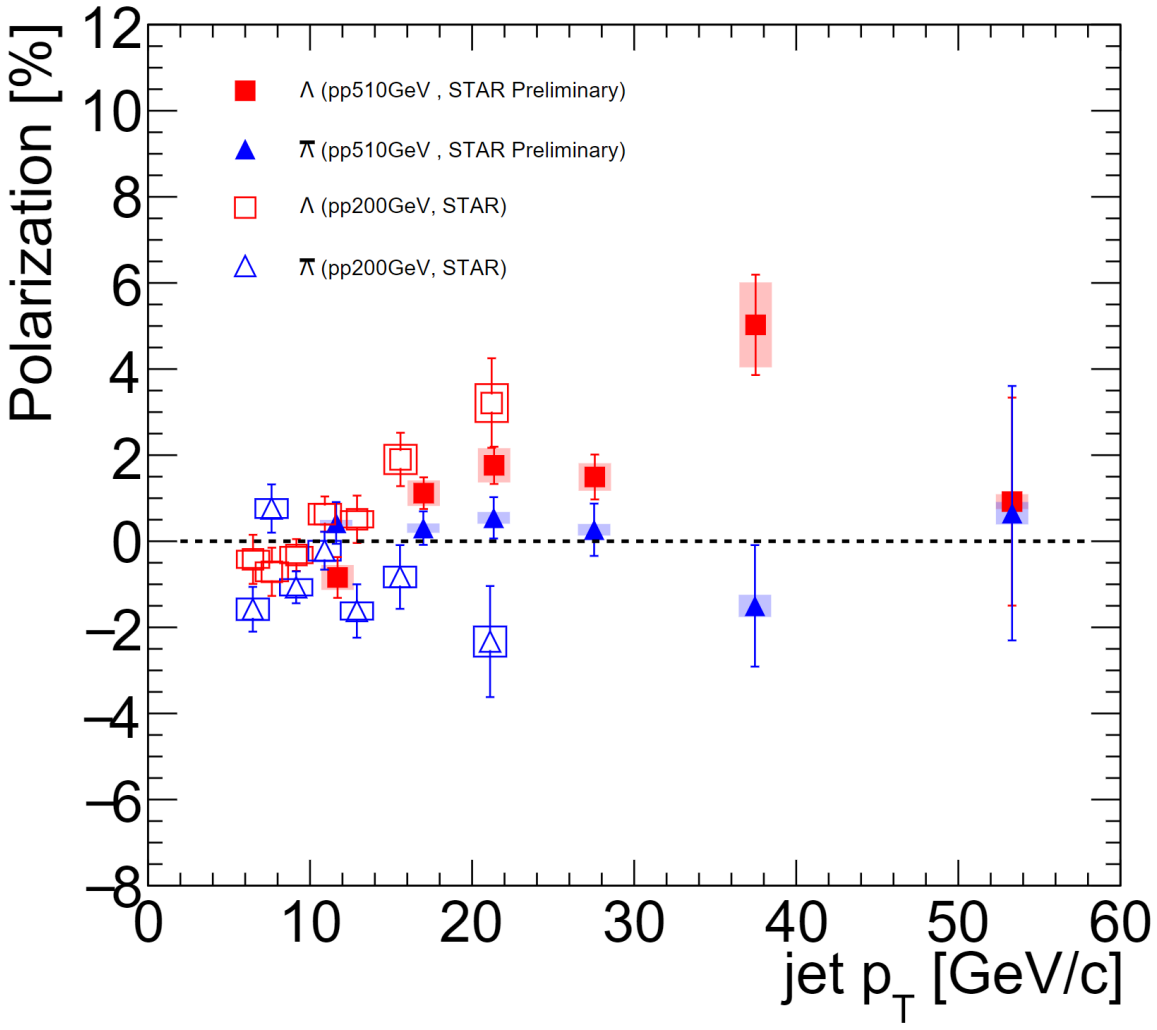
$$\hat{\boldsymbol{S}} = \hat{\boldsymbol{p}}_{jet} \times \hat{\boldsymbol{p}}_{\Lambda}$$

- 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

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

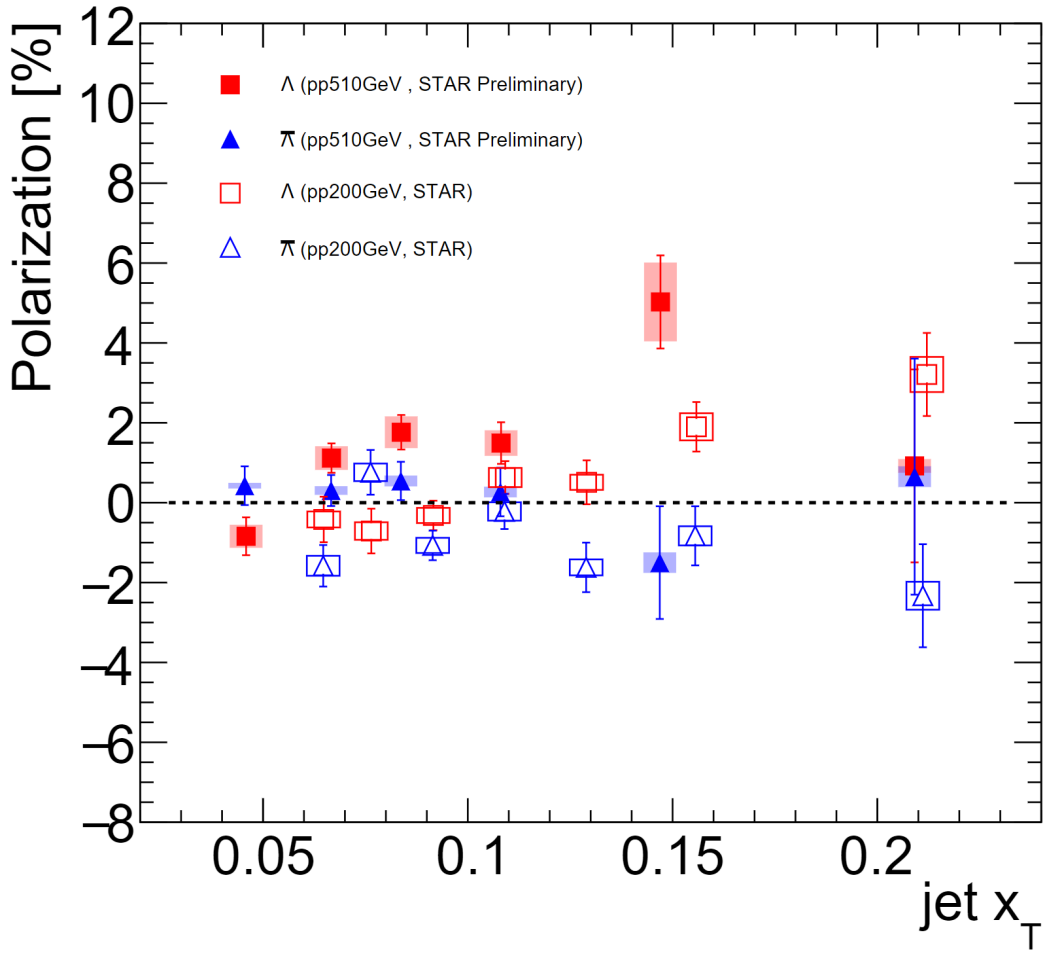
Preliminary Results from 510 GeV pp collision

STAR, SPIN2025 (Jinhao He)



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

Polarization as function of jet x_T at $\sqrt{s}$ = 510 GeV

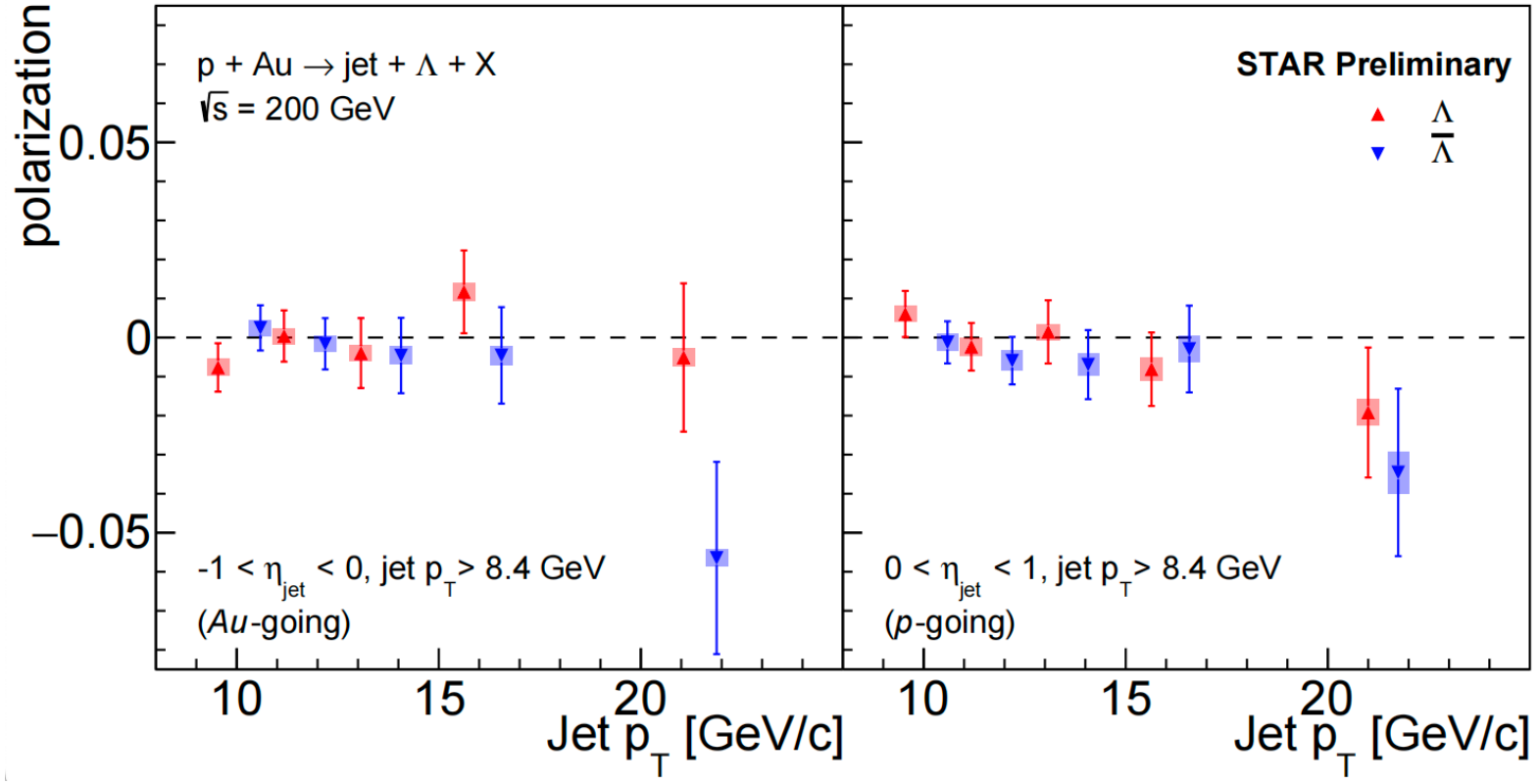


$$x_T = \frac{2p_T}{\sqrt{s}}$$

- x_T approximate to the momentum fractions of scattering partons at $\sqrt{s}$ = 200 and 510 GeV
- The comparison between $\sqrt{s}$ = 200 GeV and 510GeV at same x_T, then reflects the scale dependence; with a factor of 2.55 difference

Preliminary Results from 201 GeV pAu collision

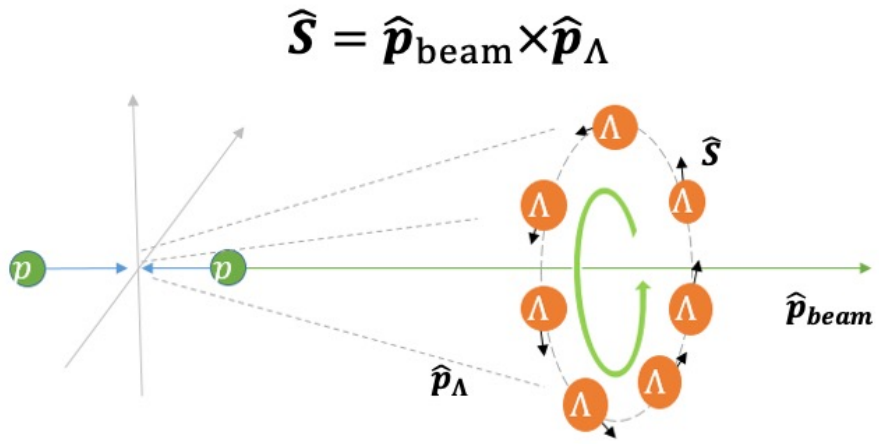
STAR, DIS2026 (Xiaohui Liu)



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

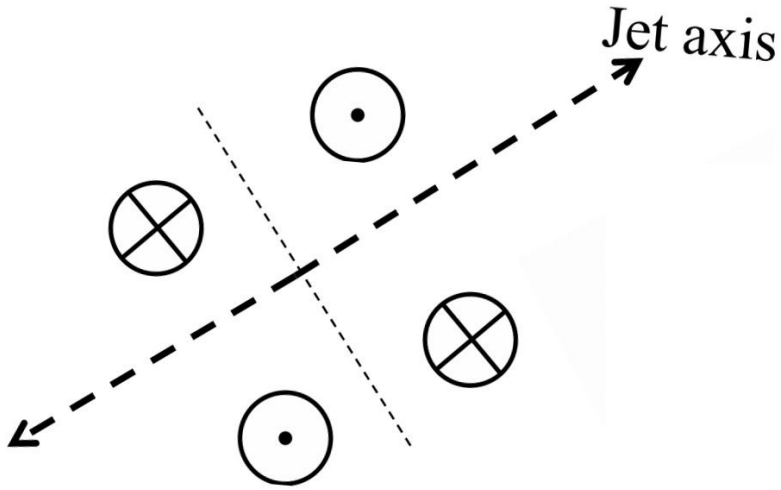
Possible connection to other observables?

To production plane polarization



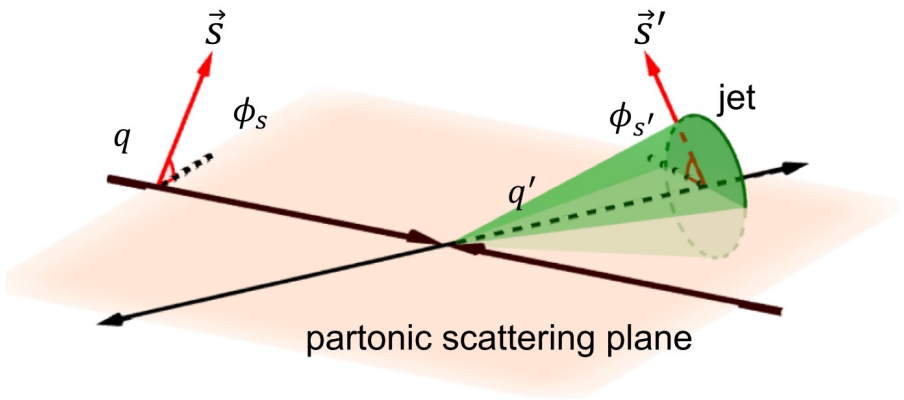
When Lambda-in-Jet is selected with bias, production planes spanned by beam and lambda consistent with by jet axis and lambda

To local polarization with low multiplicity



When (leading) di-jet or mutli-jet impact event plan reconstruction, polarization surrounding jet axis can be observed as “local polarization”

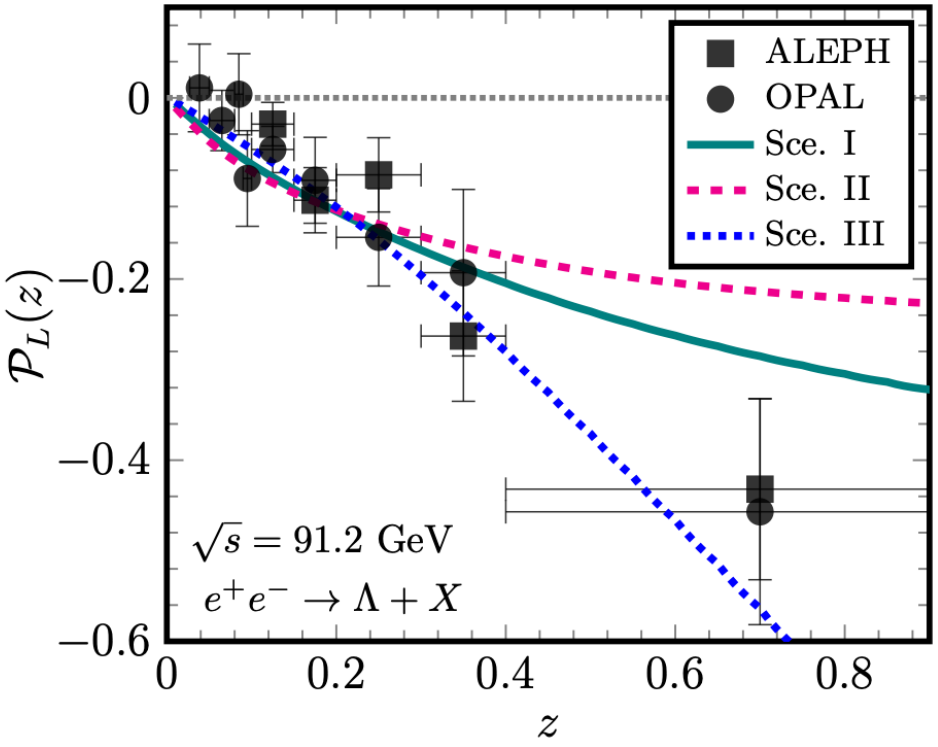
Spin correlation between initial state and final state



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

- 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

LEP Z^0-pole data: evidence for Λ spin transfer



- Z^0decay 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

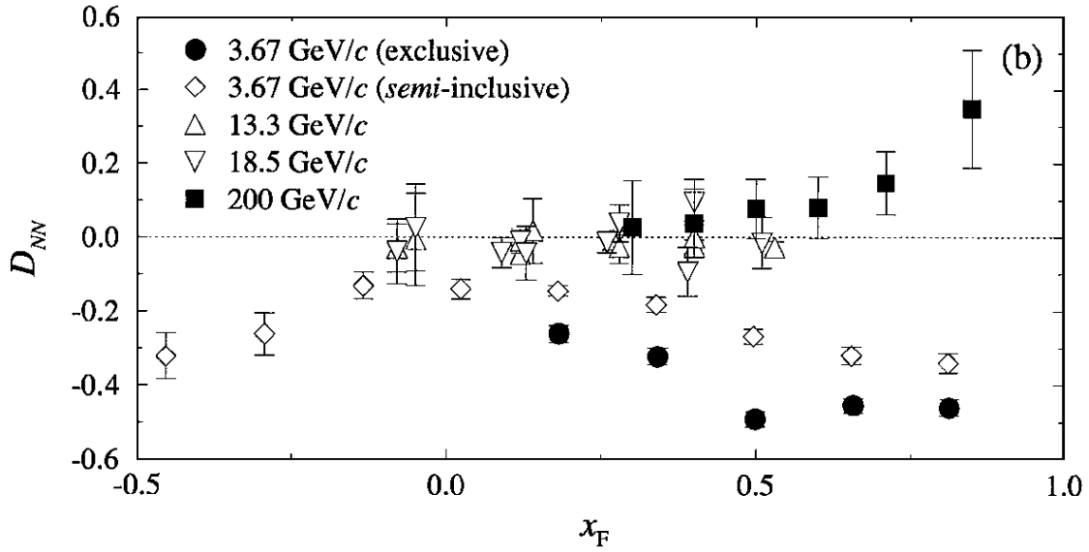
E704, Phys. Rev. Lett. 78, 4003 (1997) Transversely polarized proton 200 GeV

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.

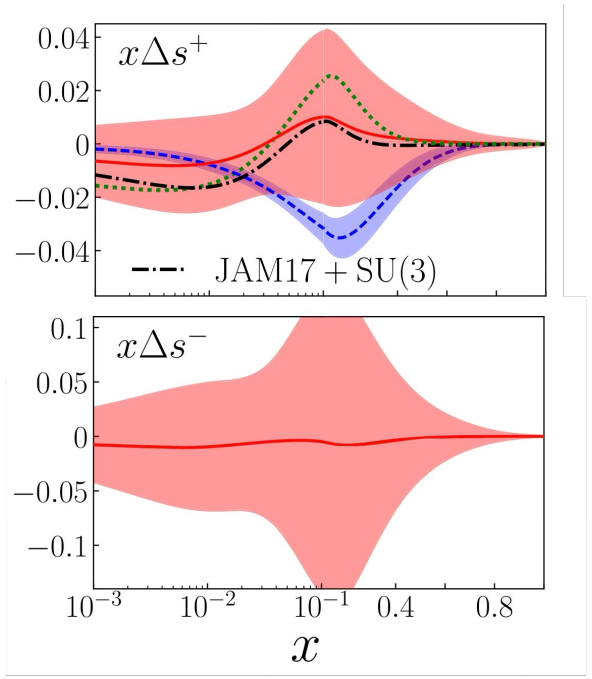
Longitudinal spin transfer in polarized pp collision at STAR

The factorized framework enables perturbative description

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

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

helicity distribution — pQCD calculable — longitudinally polarized FFs

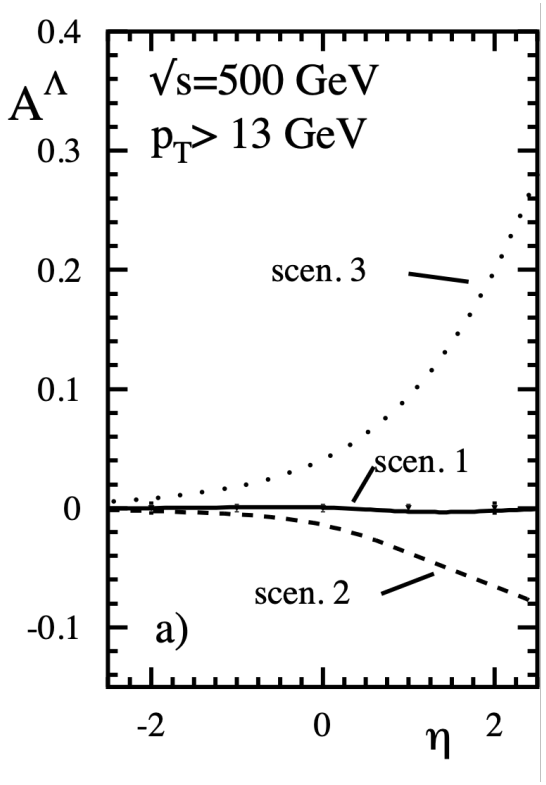


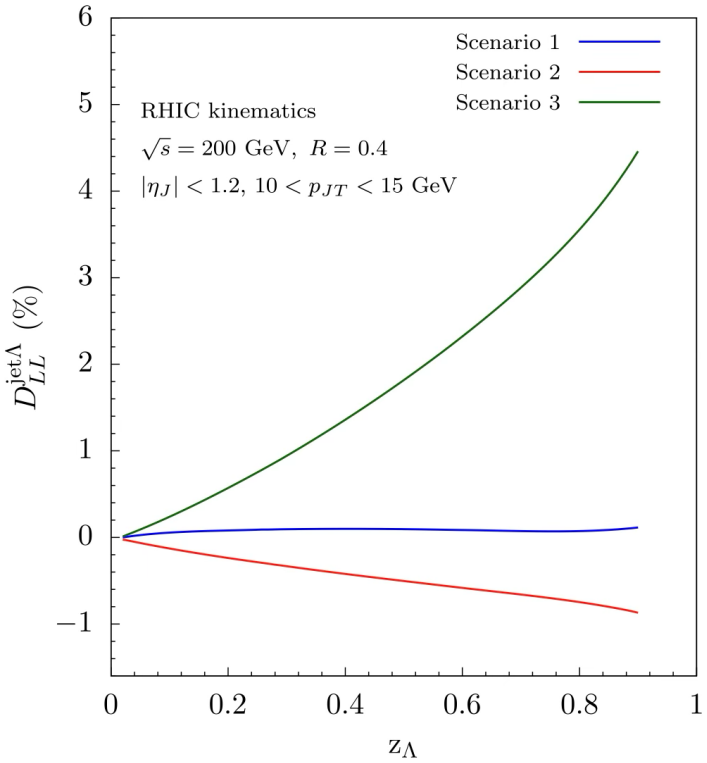
JAM, Phys. Rev. Lett. **119**, 132001 (2017).

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).

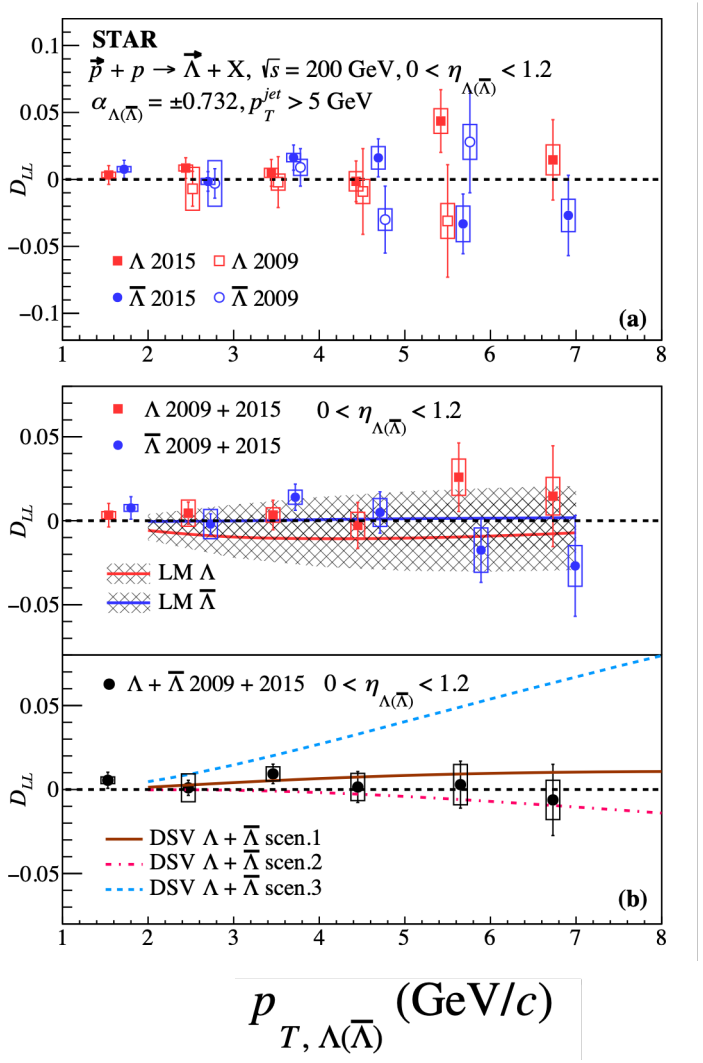
Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

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:

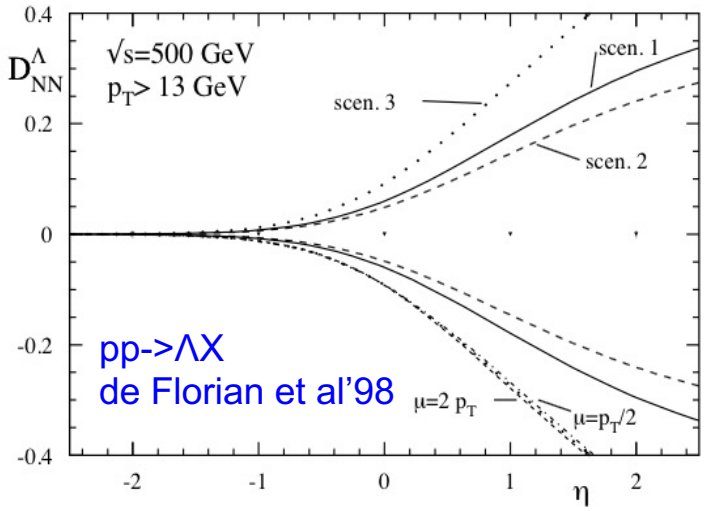
$$D_{TT} \equiv \frac{d\sigma^{(p^{\uparrow}p\to H^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p\to H^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p\to H^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p\to H^{\downarrow}X)}} = \frac{d\Delta_T\sigma}{d\sigma}$$

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

transversity distribution

Transversely polarized fragmentation function

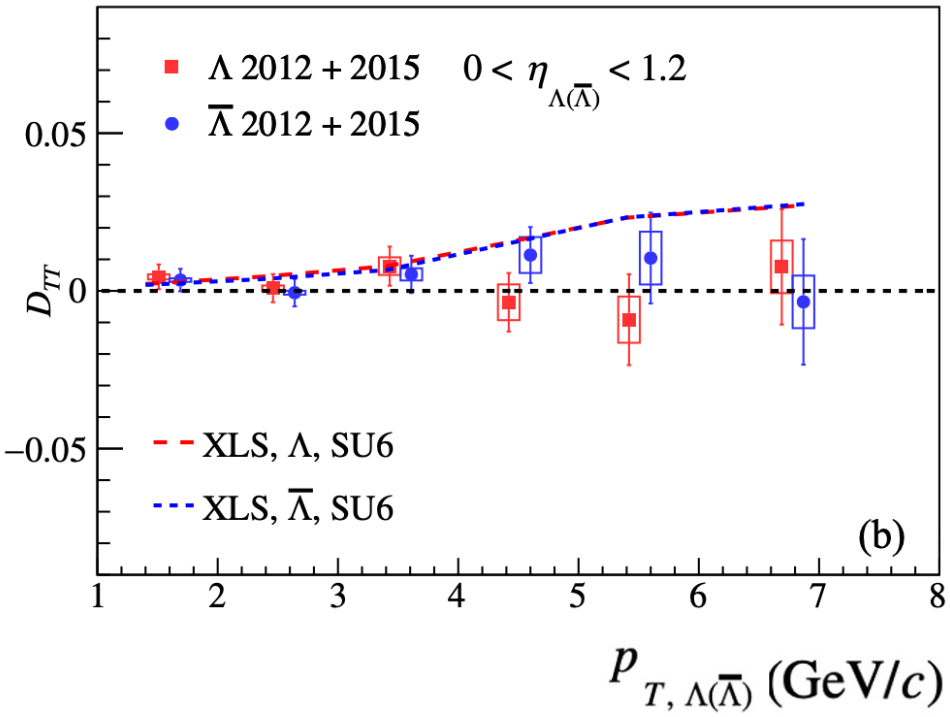
pQCD

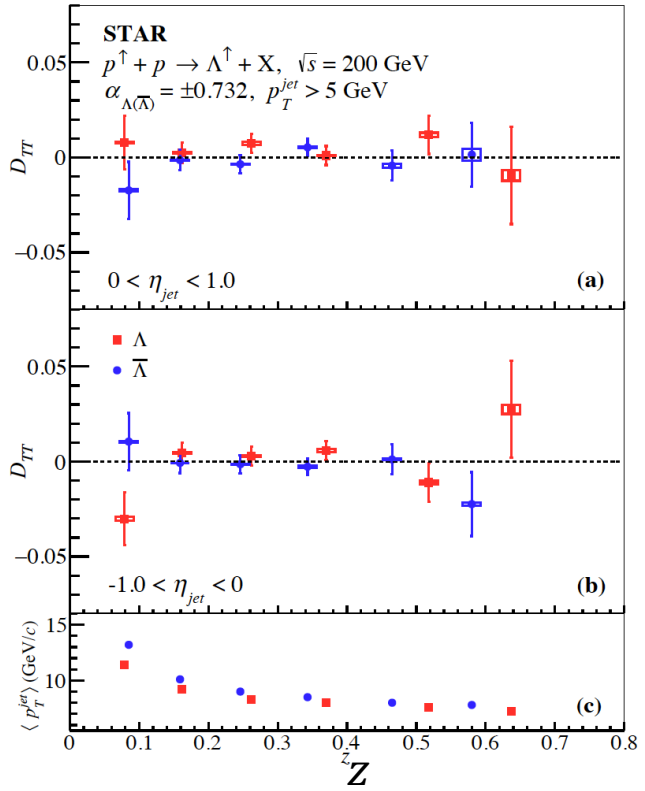


- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

Latest D_{TT} measurements at STAR

STAR, PRD109, 012004 (2024)

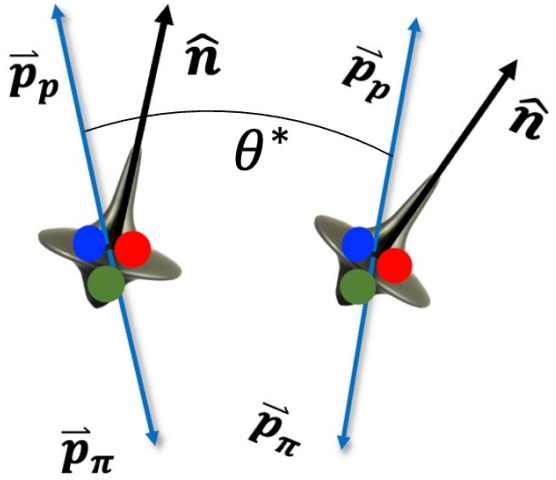




- The D_{TT} results are consistent with model calculations within uncertainties, also consistent with 0.
- First measurement of D_{TT} vs. z in p+p collisions, providing constraints on transversely polarized fragmentation functions.

Spin correlation between two hyperons at final state

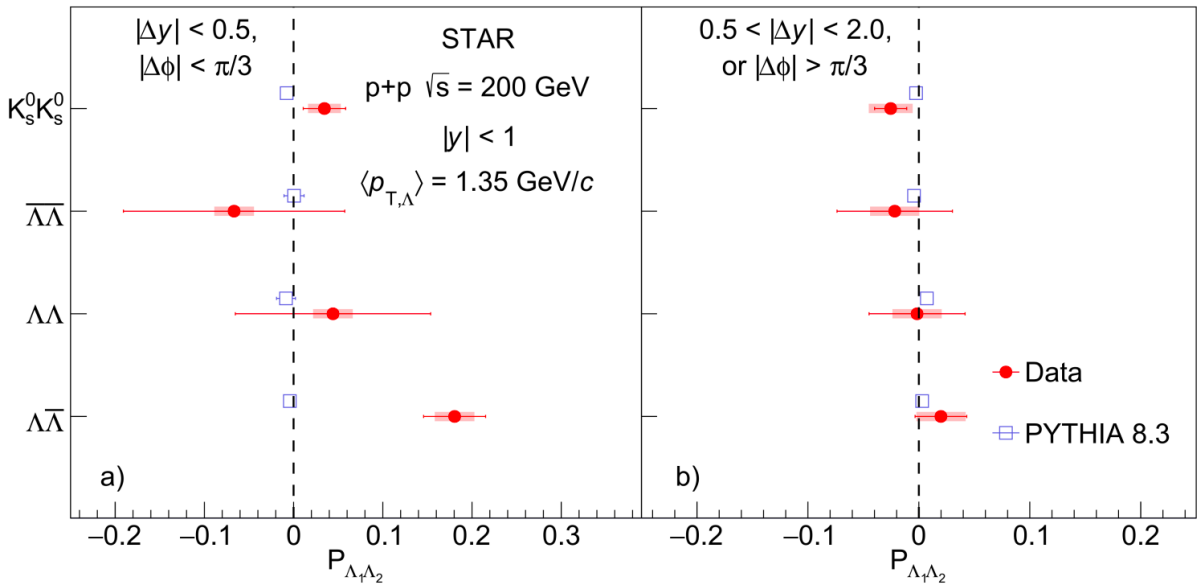
- Single hyperon spin polarization measures how one hyperon acquires spin
- Spin transfer measures how initial spin is connected to one final hyperon
- Pair correlation measures whether two final hyperons share correlated spin information
- Pair type and angular separation help identify the underlying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

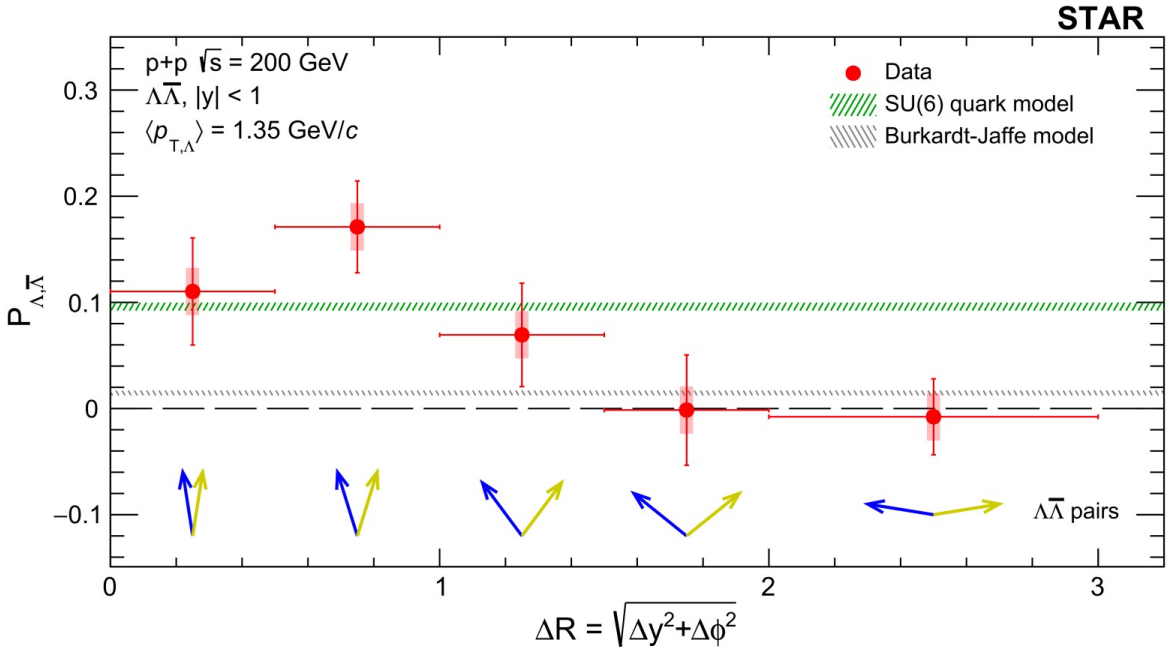


$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_1\alpha_2 P_{\Lambda 1 \Lambda 2} \cos\theta^*$$

Results of spin correlations in pp 200 GeV

STAR, Nature 650, 65–71 (2026)





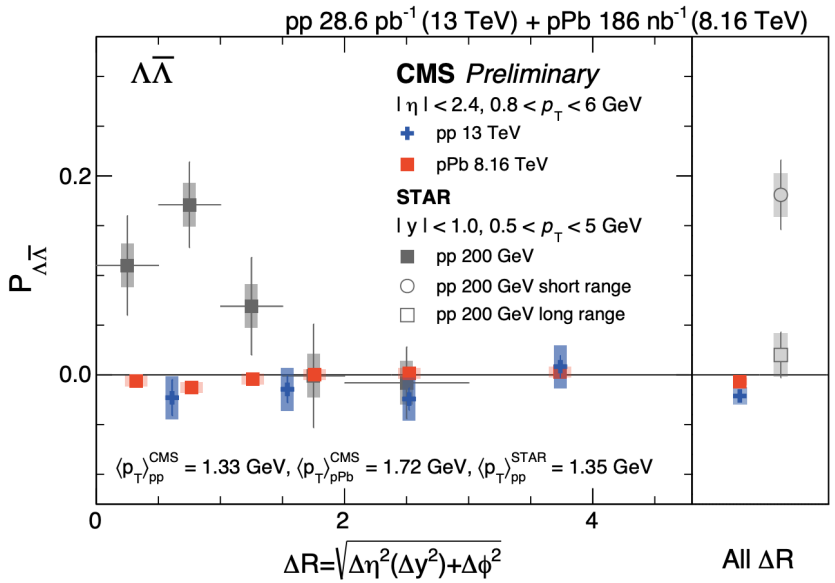
Short-range $\Lambda\overline{\Lambda}$ pairs show non-zero spin correlation

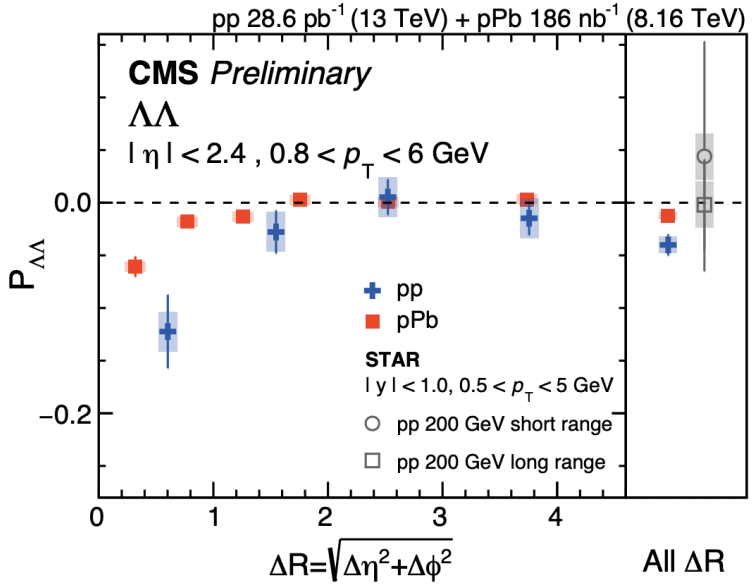
All other pairs are consistent with zero

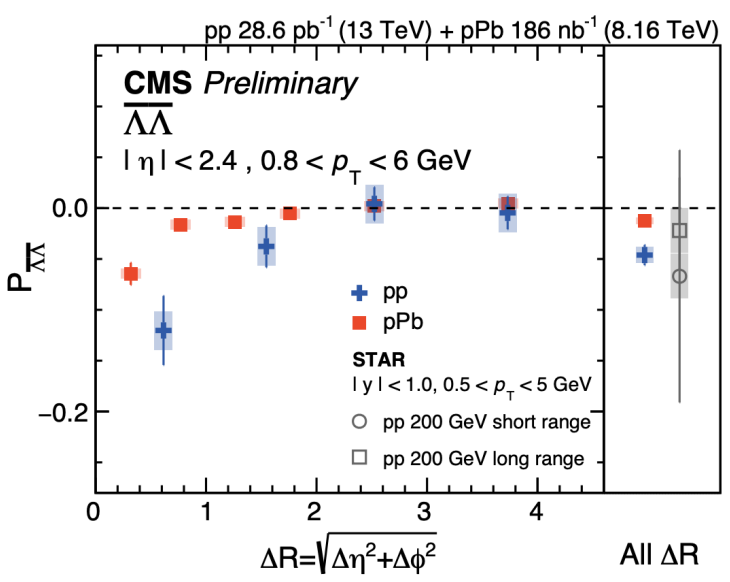
Spin correlation of $\Lambda\overline{\Lambda}$ pairs as a function of $\Delta R = \sqrt{\Delta\eta^2+\Delta\phi^2}$

Preliminary results from CMS in pp and pPb

CMS, DIS2026 (Jieke Wang)







CMS-PAS-HIN-26-002

- $\Lambda\overline{\Lambda}$ spin correlation consistent with zero, with a hint of negative value
- Negative correlations found for $\Lambda\Lambda$ and $\overline{\Lambda\Lambda}$ at small ΔR (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 Consistent with 0 at small x_F
Lambda-in-jet	Polarizing FFs	STAR pp: Jet p_T dependence and different for Λ and $\bar{\Lambda}$ 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 ΔR and consistent with 0 for all the rest CMS pp/pPb: small for $\Lambda\bar{\Lambda}$ but negative for $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ at small ΔR

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

Thanks for your attention!