2026 极端核物质前沿研讨会
April 24 -28 Workshop on extreme nuclear matter frontiers

Lambda polarization in pp collisions at STAR

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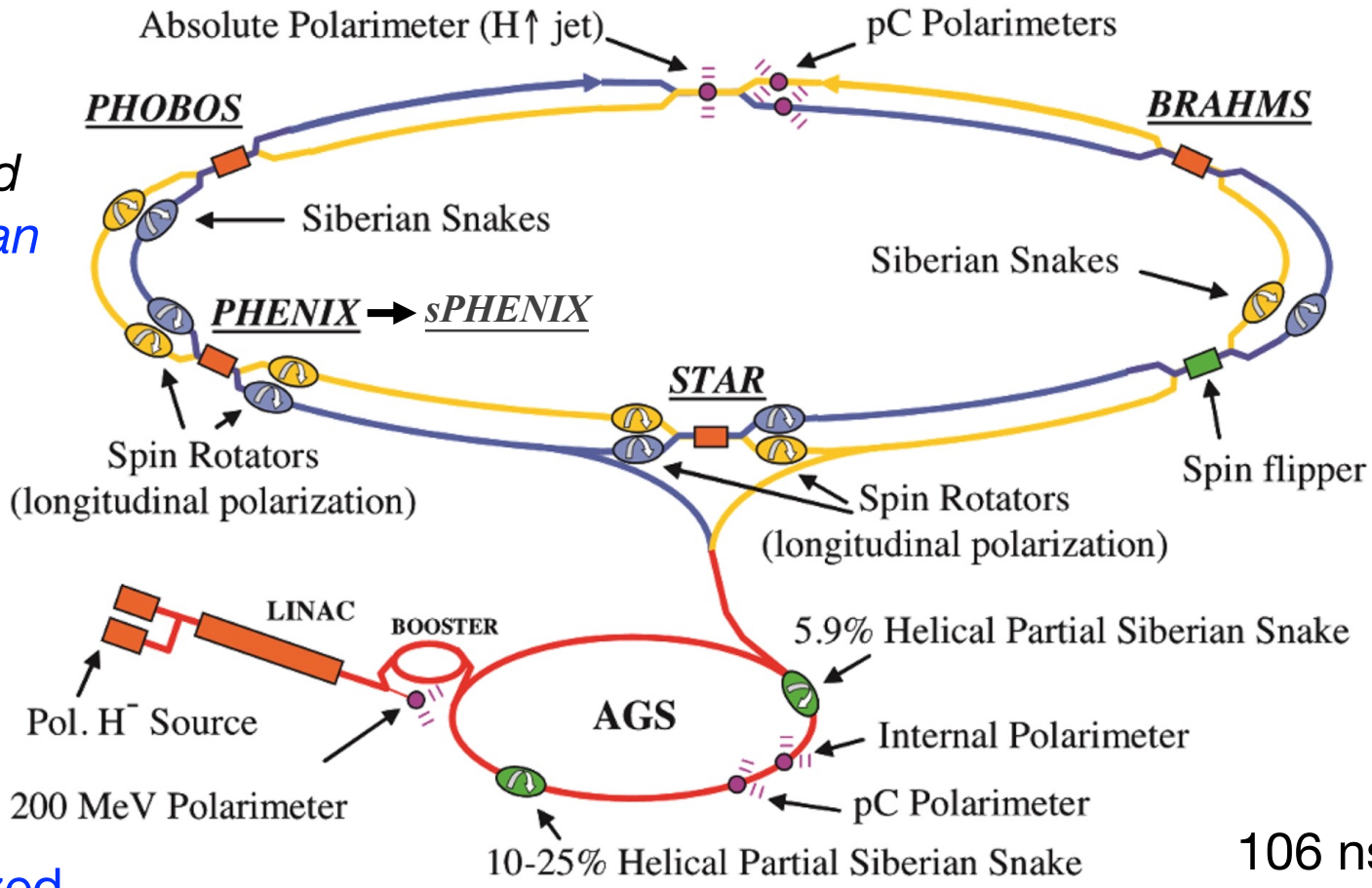
2026年4月27日

山东大学 SHANDONG UNIVERSITY

RHIC, as a polarized proton collider

Accelerate polarized protons with Siberian Snakes

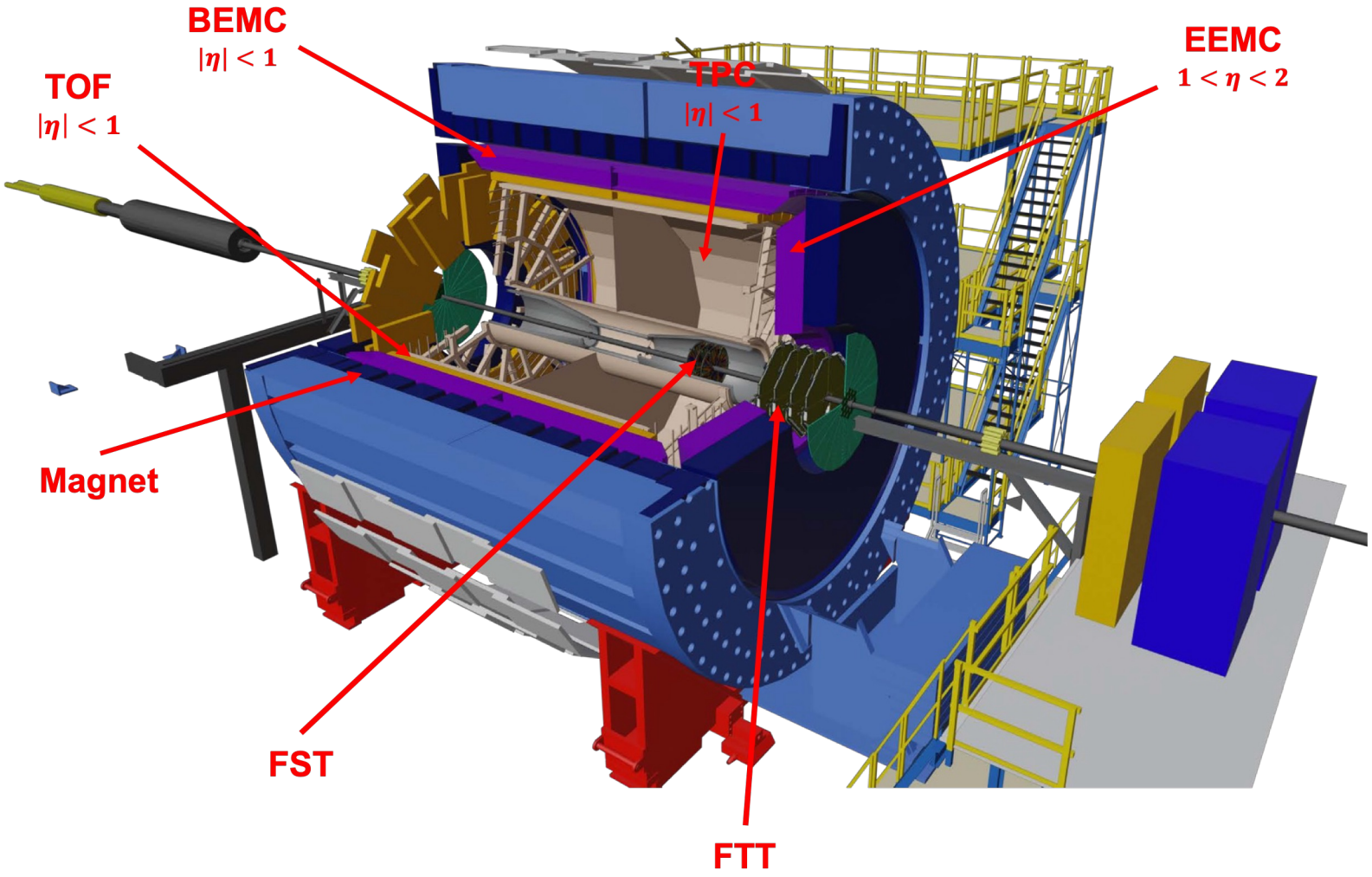


Manipulate spin direction with spin rotator

High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

STAR detector overview



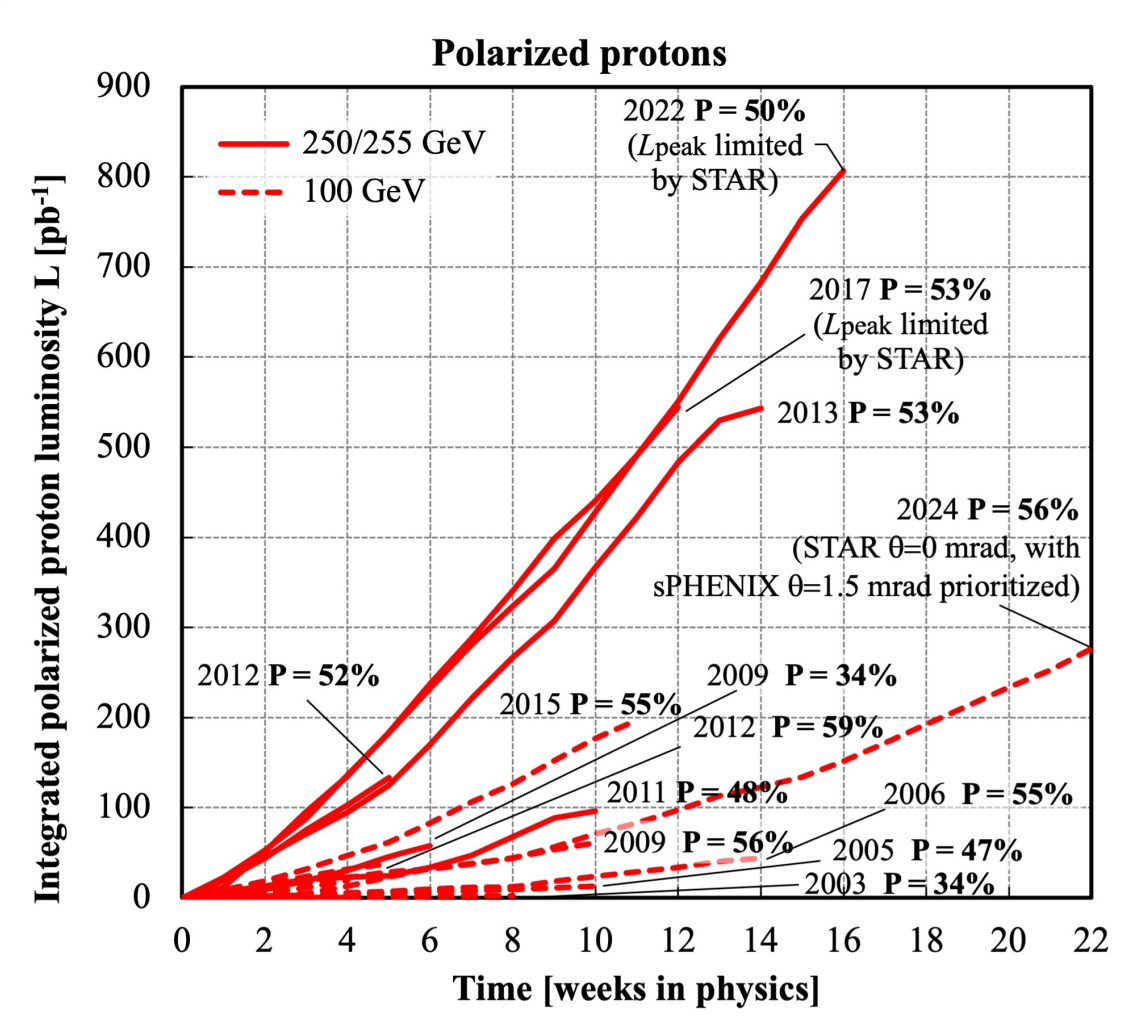
Tracking + PID

Time Projection Chamber
- charged track momentum msmt
- particle identification dE/dx,
- vertex reconstruction
- coverage $|\eta| < 1$

Time of Flight detector
- particle identification
- coverage $|\eta| < 1$

Barrel and Endcap E.M. Cal.
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $|\eta| < 1$ and $1 < \eta < 2$

RHIC pp data accumulation



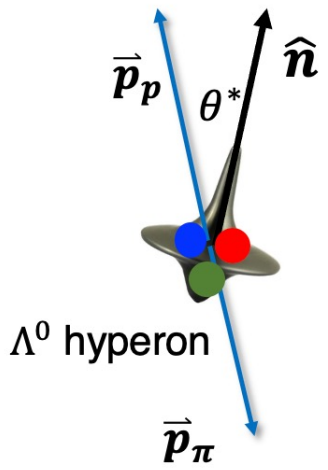
	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	52	53
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	52	53
	2017	510	350	55
	2022	508	400	52
	2024	200	164	55

by STAR

Lambda： final state “polarimetry”

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

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



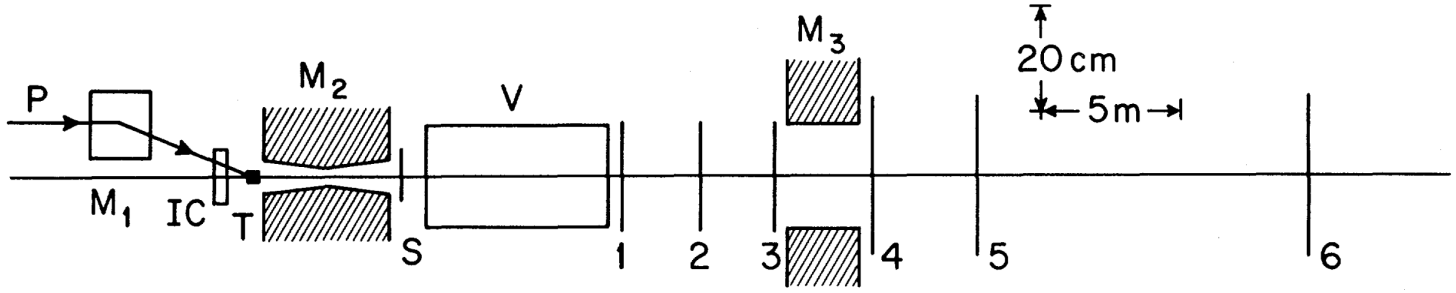
- Λ polarization plays an important role in spin physics
  - Hot QCD: vorticity, magnetic filed, medium effects, etc.
  - Cold QCD: spin structure, fragmentation, spin correlations

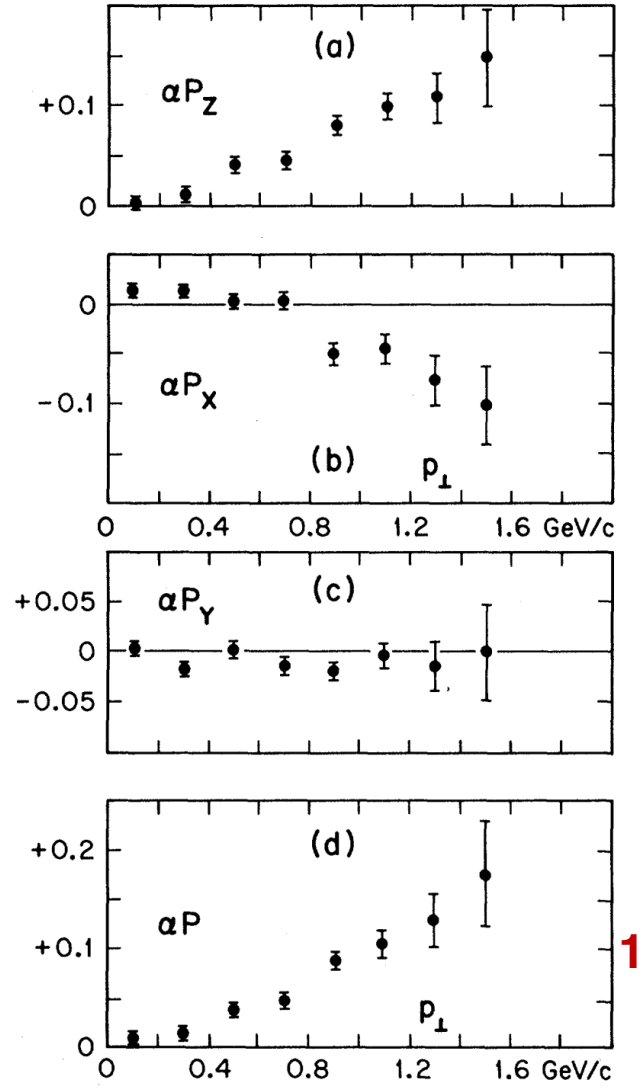
Puzzle since 1976

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

300 GeV unpolarized proton on unpolarized Beryllium target

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



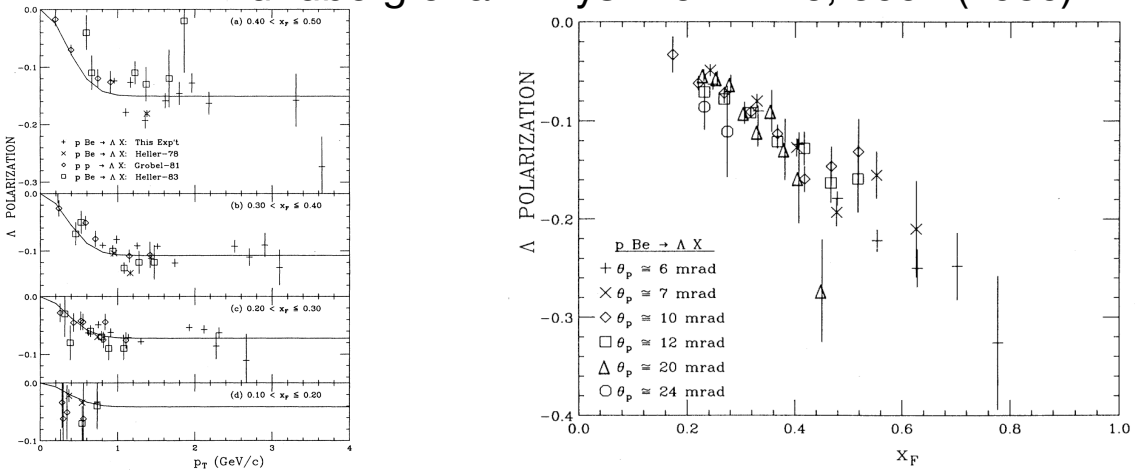


Since the first observations in fixed-target hadronic collisions, sizable transverse Λ polarization has been measured over a wide range of beam energies, collision systems, and experimental conditions, yet its underlying QCD mechanism remains not fully understood.

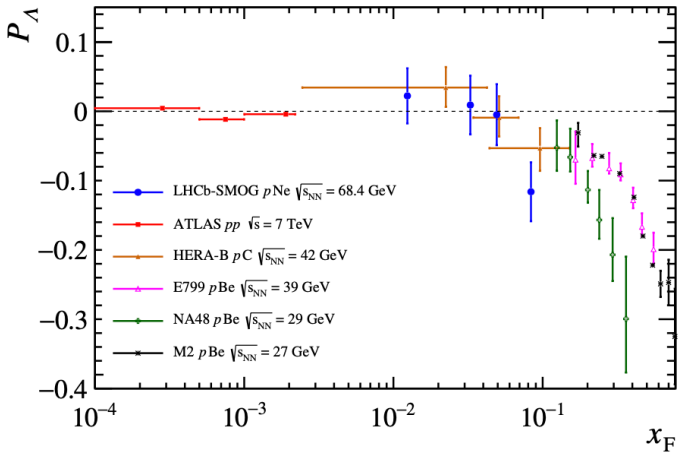
Features of lambda spontaneous polarization

- 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.

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



Abt et al, JHEP09, 082 (2024)

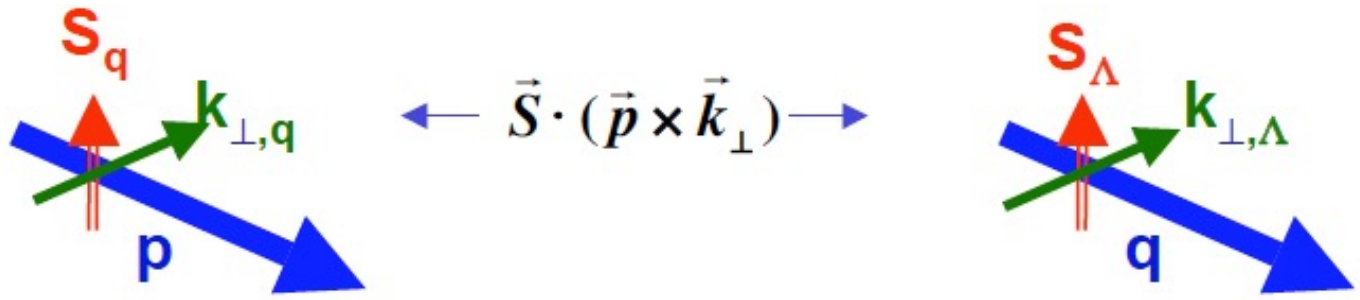


Initial- and final-state sources of Λ polarization

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 polarized proton — Helicity/Transiversity
  parton is polarized in unpolarized proton — Boer-Mulders
- Polarization arising at final state: parton is unpolarized but fragmenting into polarized hadron. — Polarizing FFs

Transverse spin transfer in polarized pp collision

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

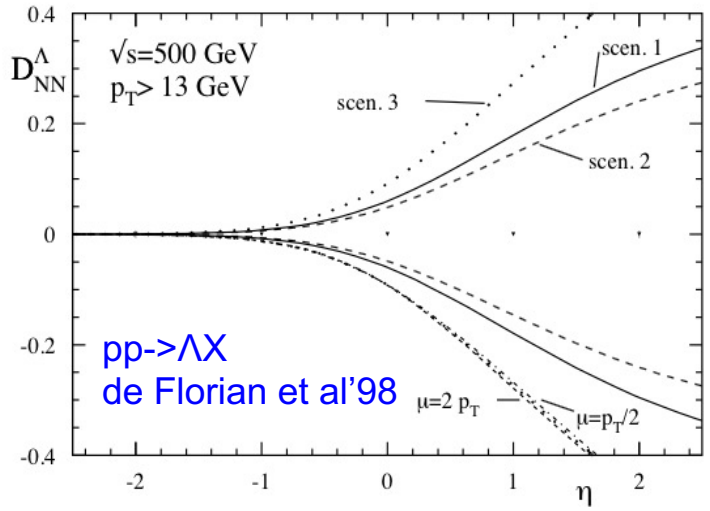
$$D_{TT} \equiv \frac{d\sigma^{(p^{\uparrow}p\to H^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p\to H^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p\to H^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p\to H^{\downarrow}X)}} = \frac{d\Delta_T\sigma}{d\sigma}$$

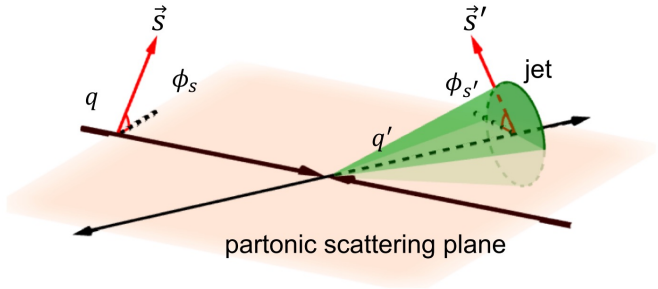
$$d\Delta_T\sigma^{(pp\to HX)} \propto \sum_{abcd}\int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T\hat{\sigma}^{(ab\to cd)}$$

transversity distribution

Transversely polarized fragmentation function

pQCD

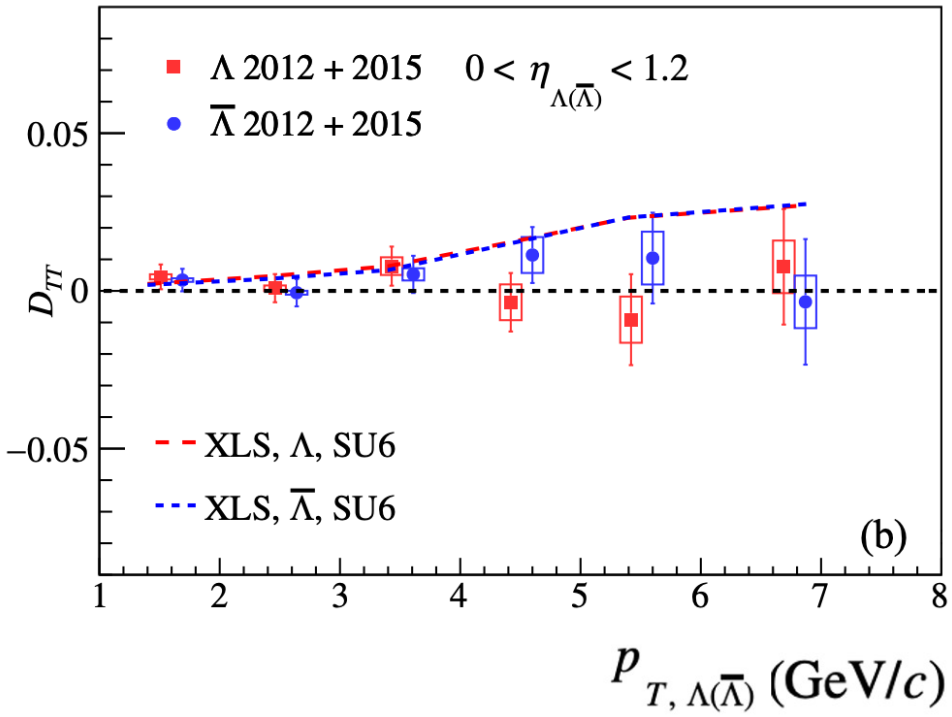


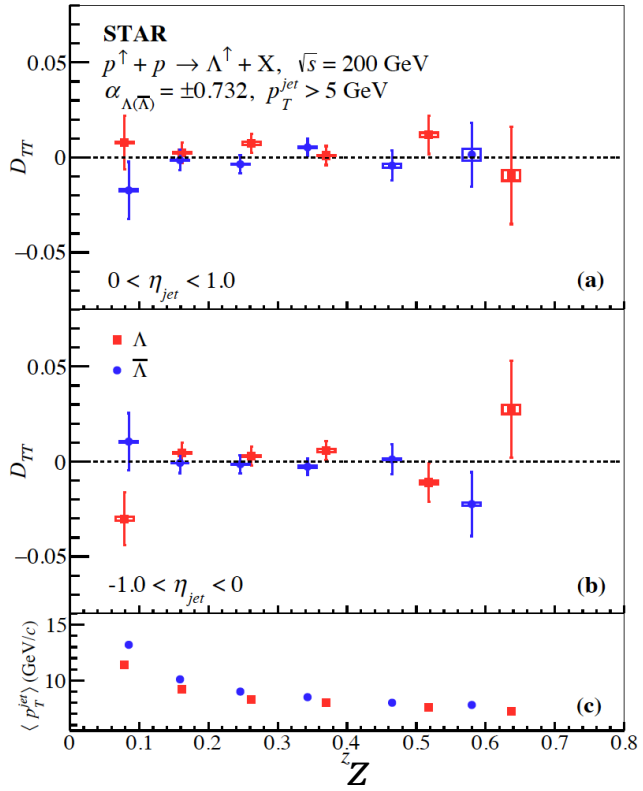


- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

Latest D_{TT} measurements at RHIC

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.

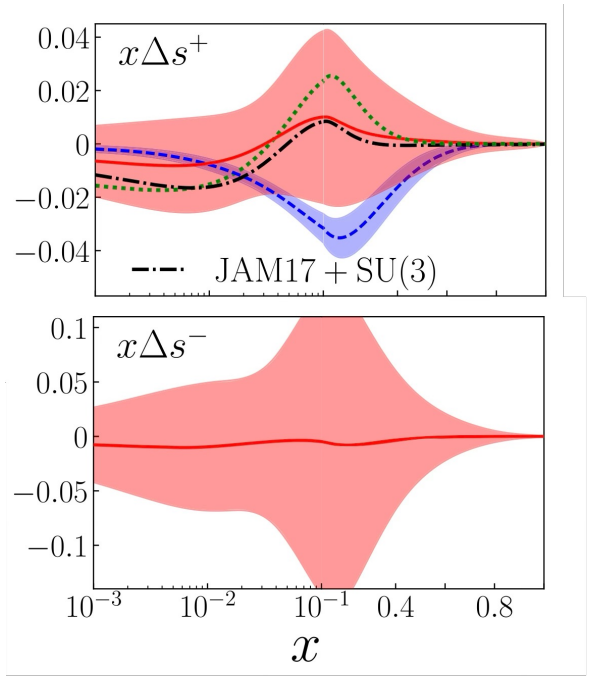
Longitudinal spin transfer in polarized pp collision

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

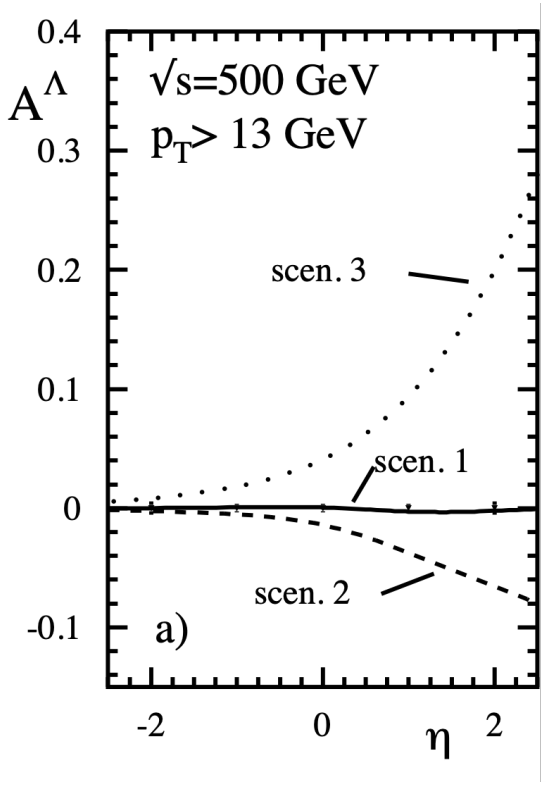


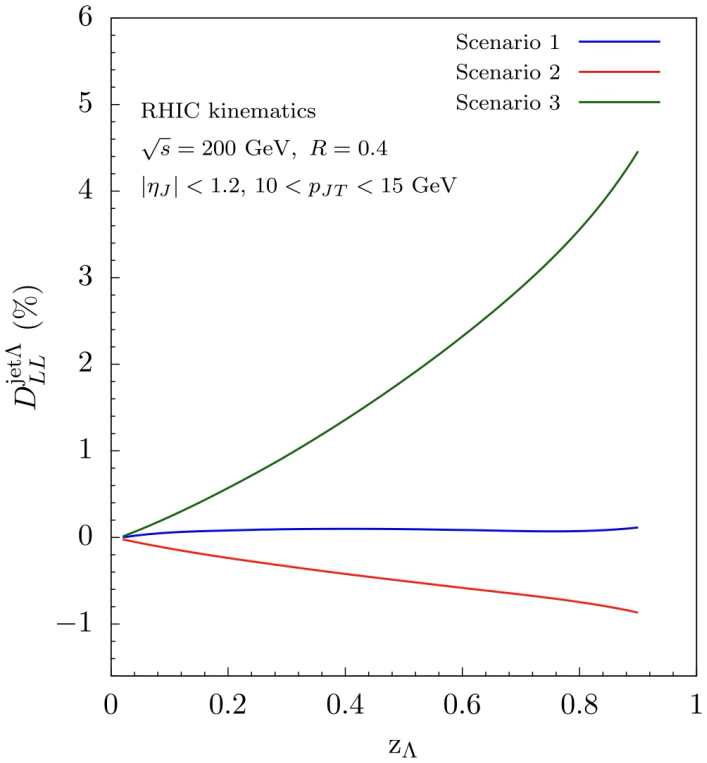
JAM, Phys. Rev. Lett. **119**, 132001 (2017).

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).

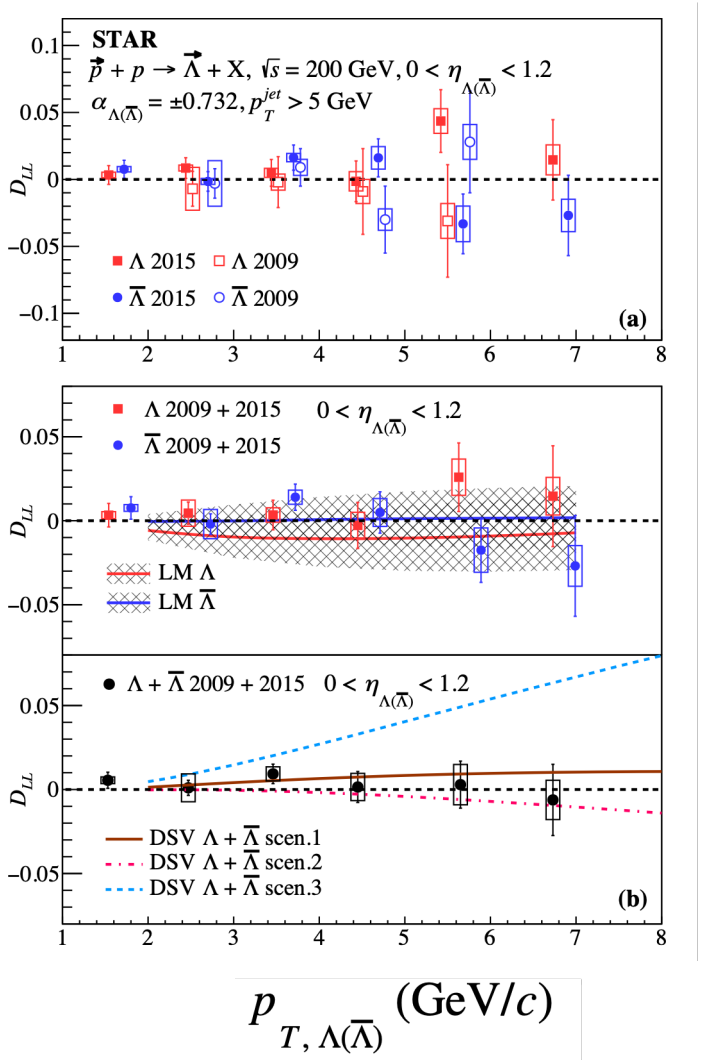
Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

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

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).

Measurements in e^+e^- annihilation

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

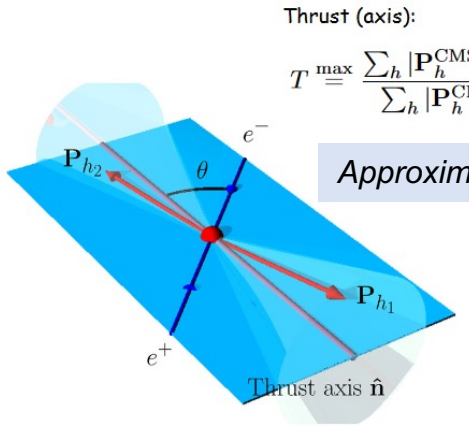
  ALEPH, PLB 374, 319 (1996)
  - OPAL $P_T^{\Lambda} = 0.019 \pm 0.014$ ($p_T > 0.3$ GeV/c)

  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)

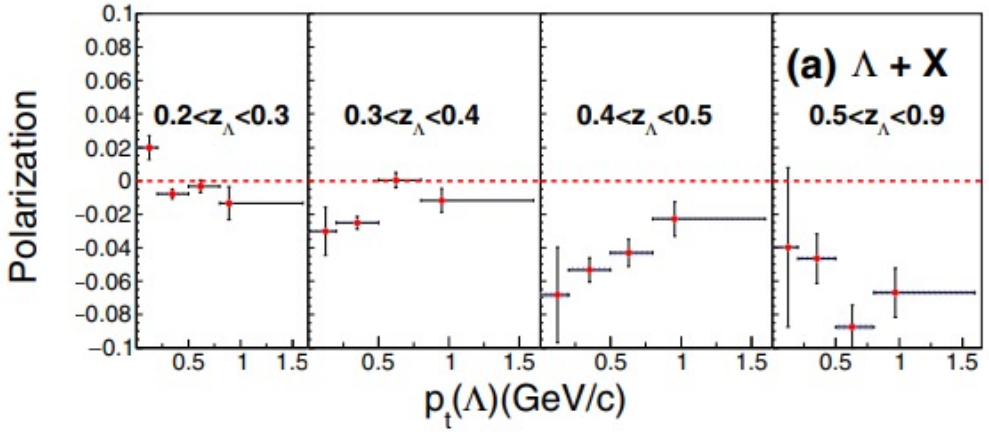
  Chen, Liang, Pan, Song, Wei, PLB 816, 136217 (2021)



Approximate jet axis

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

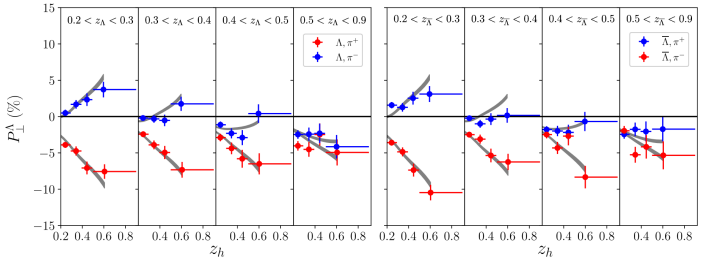
$$z_{\Lambda} = \frac{2E_{\Lambda}}{\sqrt{s}}$$

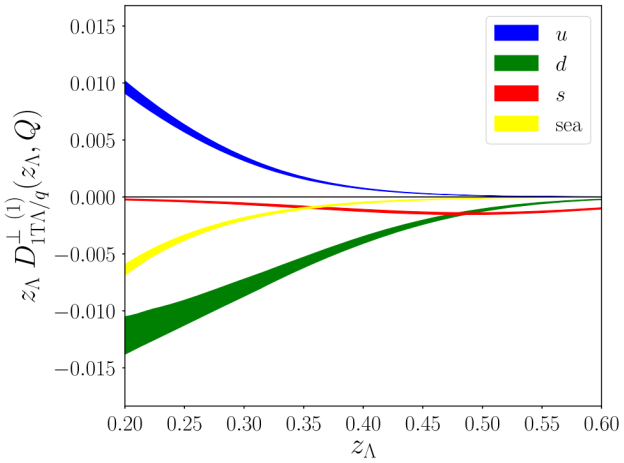


Global analyses of Belle results

Callos, Kang, Terry,

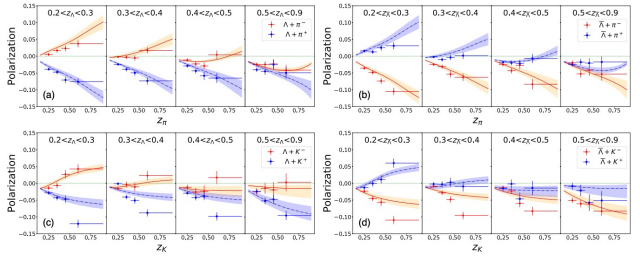
PRD 102, 096007 (2020)

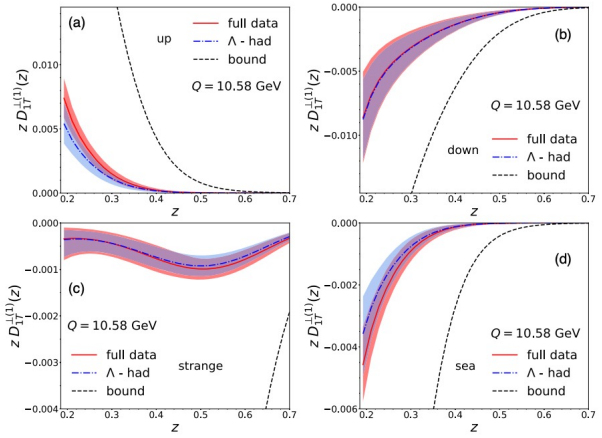




D'Alesio, Murgia, Zaccheddu,

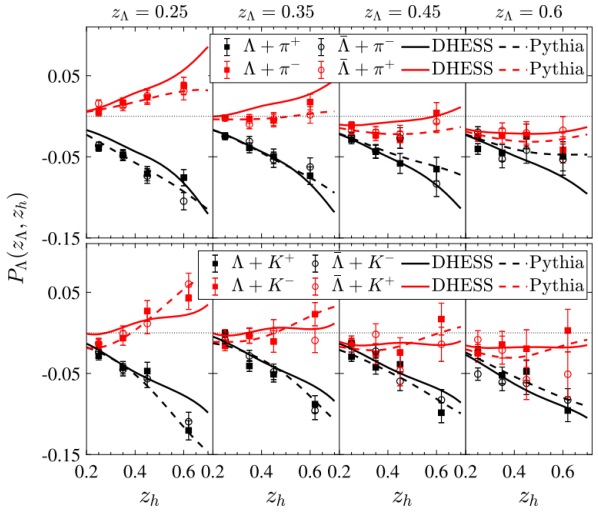
PRD 102, 054001 (2020)





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?

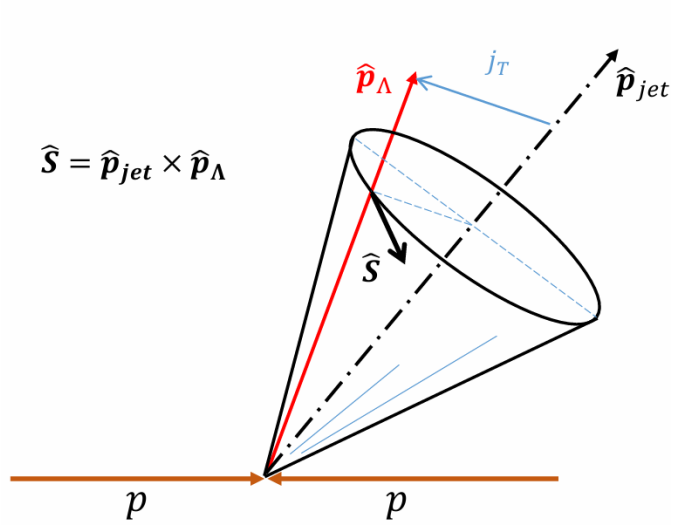
- Polarizing Fragmentation Functions(pFFs) can be accessed by transverse polarization of Λ-in-jet in pp collision

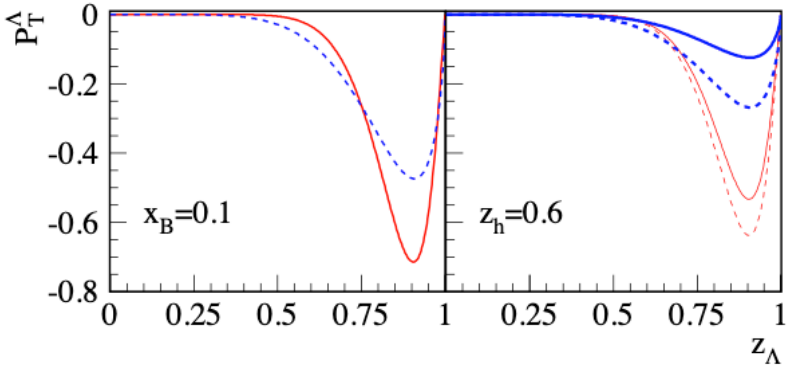
  Boer et al, PLB 671, 91-98 (2008)

  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

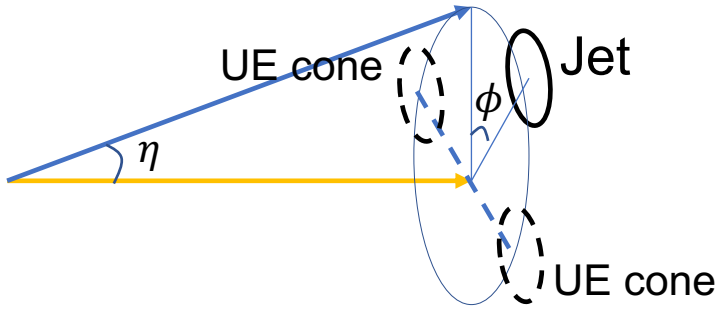


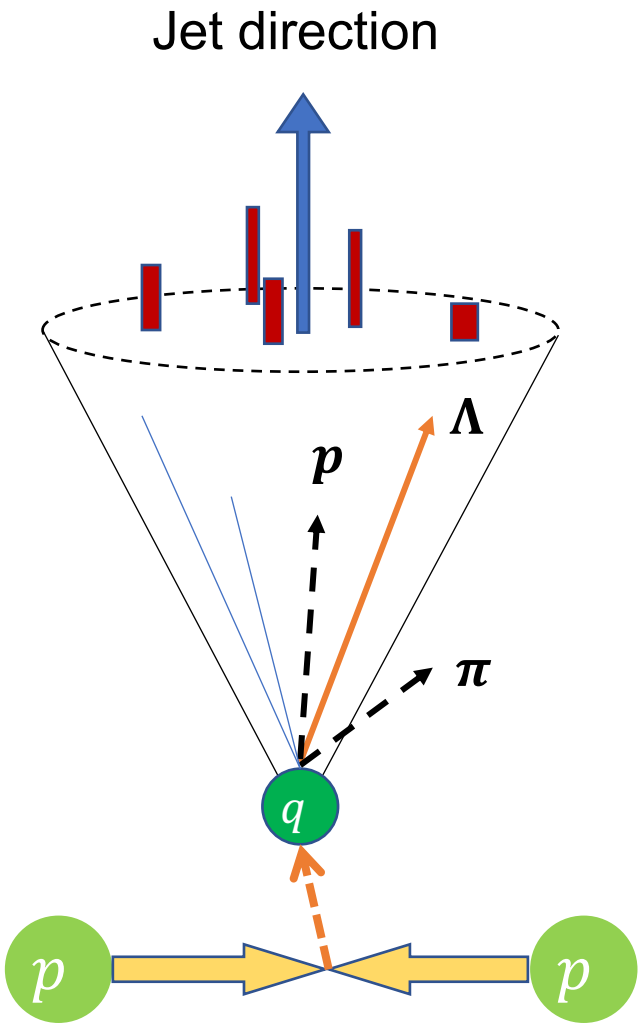


Boer et al, Phys.Rev. Lett. 105.202001 (2010)

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





Acceptance correction and polarization extraction

Mixed events

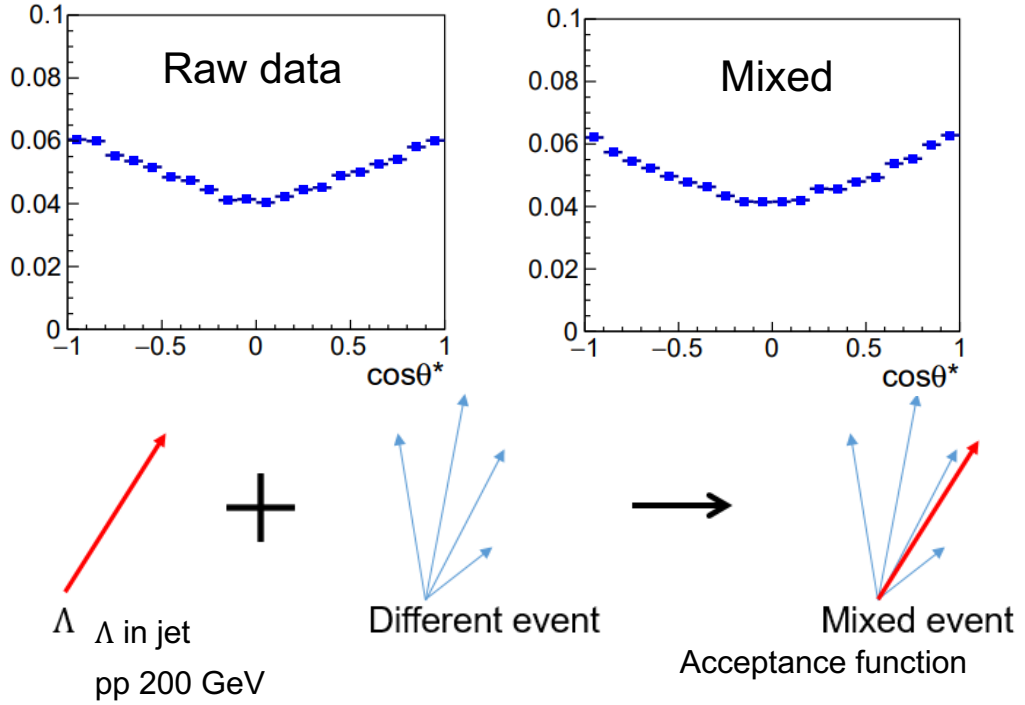
- Mixed Λ with jet from different events
- Difference of V_z: $|\Delta V_z| \leq 5$ cm
- The same trigger

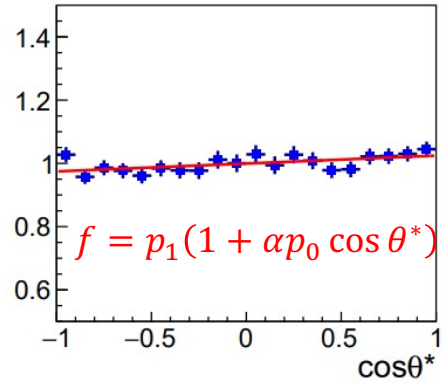
Acceptance correction

- Reweighting 3D distribution of $\Delta\eta, \Delta\phi$ between Λ and jet, and η_{jet}
- Correction $\dfrac{N(cos\theta^*)_{Data}}{N(cos\theta^*)_{Mixed}}$

Polarization extraction

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

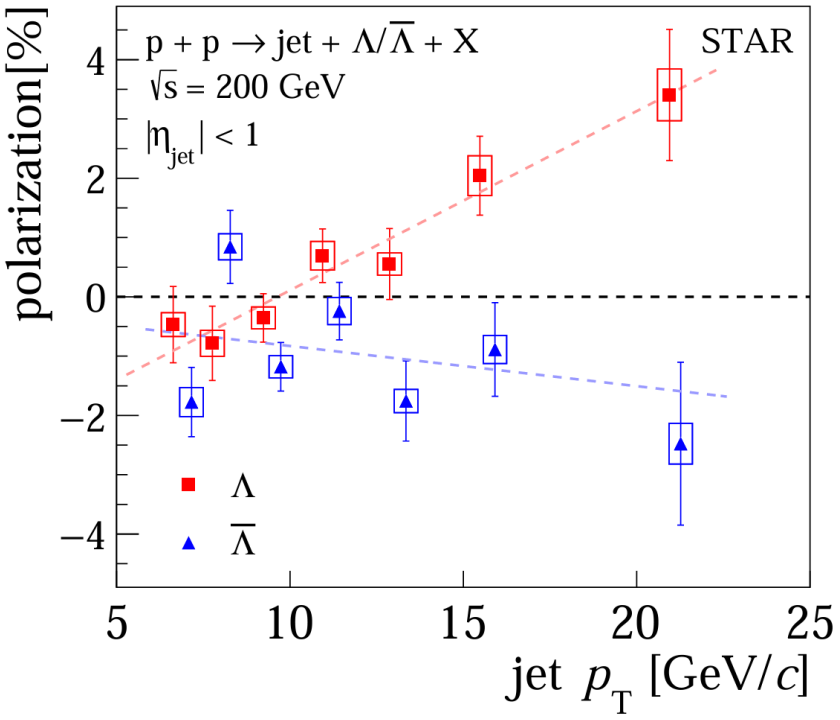


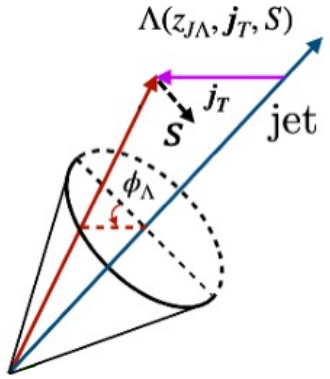


Results from 200 GeV pp collision

Polarization as a function of jet p_T

STAR,arXiv: 2509.17487





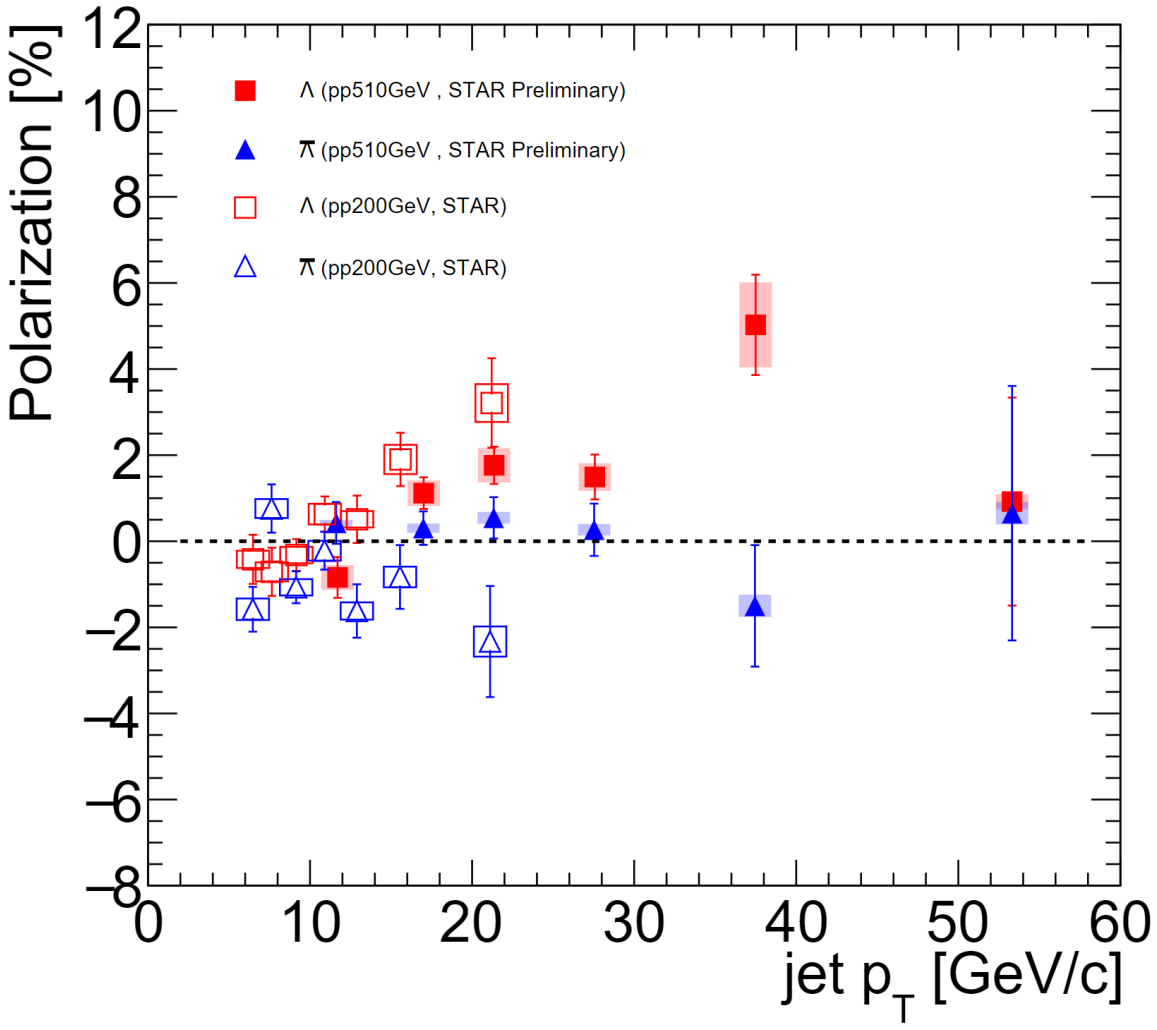
$$\hat{\boldsymbol{S}} = \hat{\boldsymbol{p}}_{jet} \times \hat{\boldsymbol{p}}_{\Lambda}$$

- 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

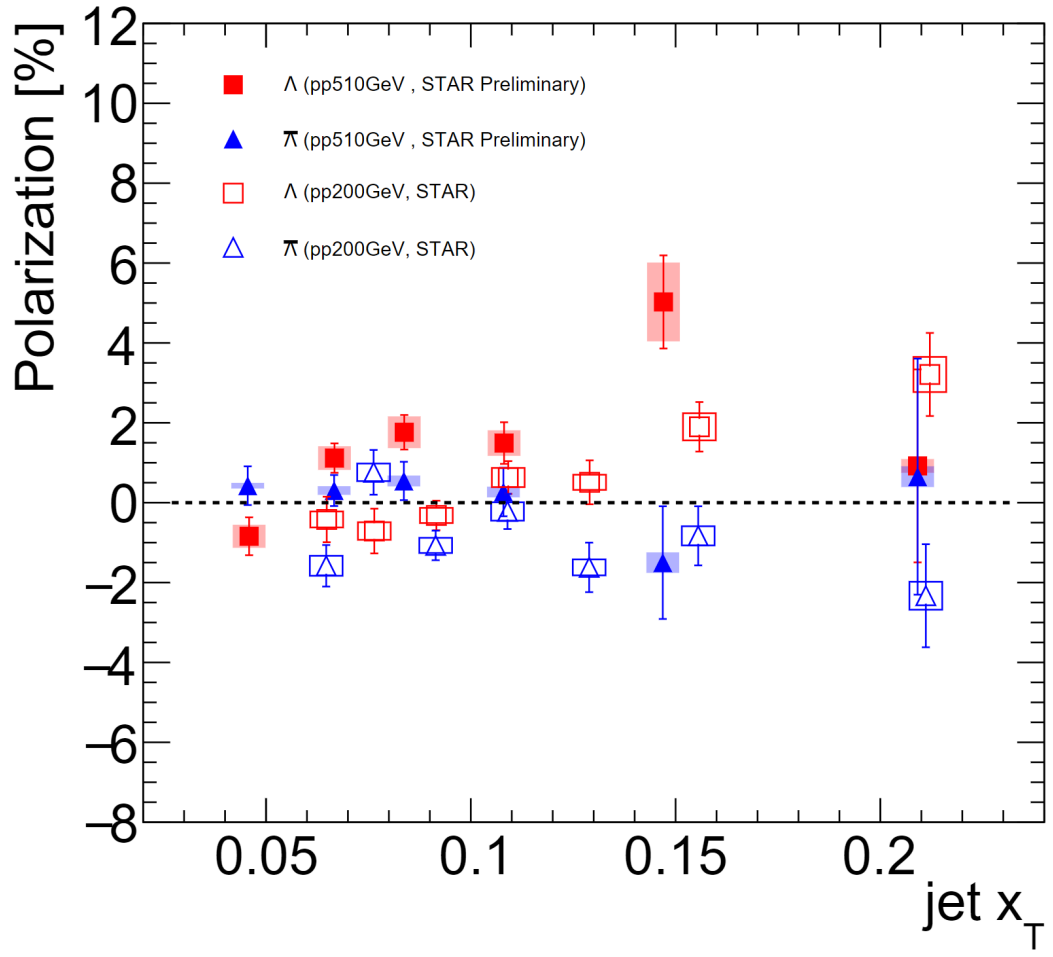
Preliminary Results from 510 GeV pp collision

STAR, SPIN2025



- 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

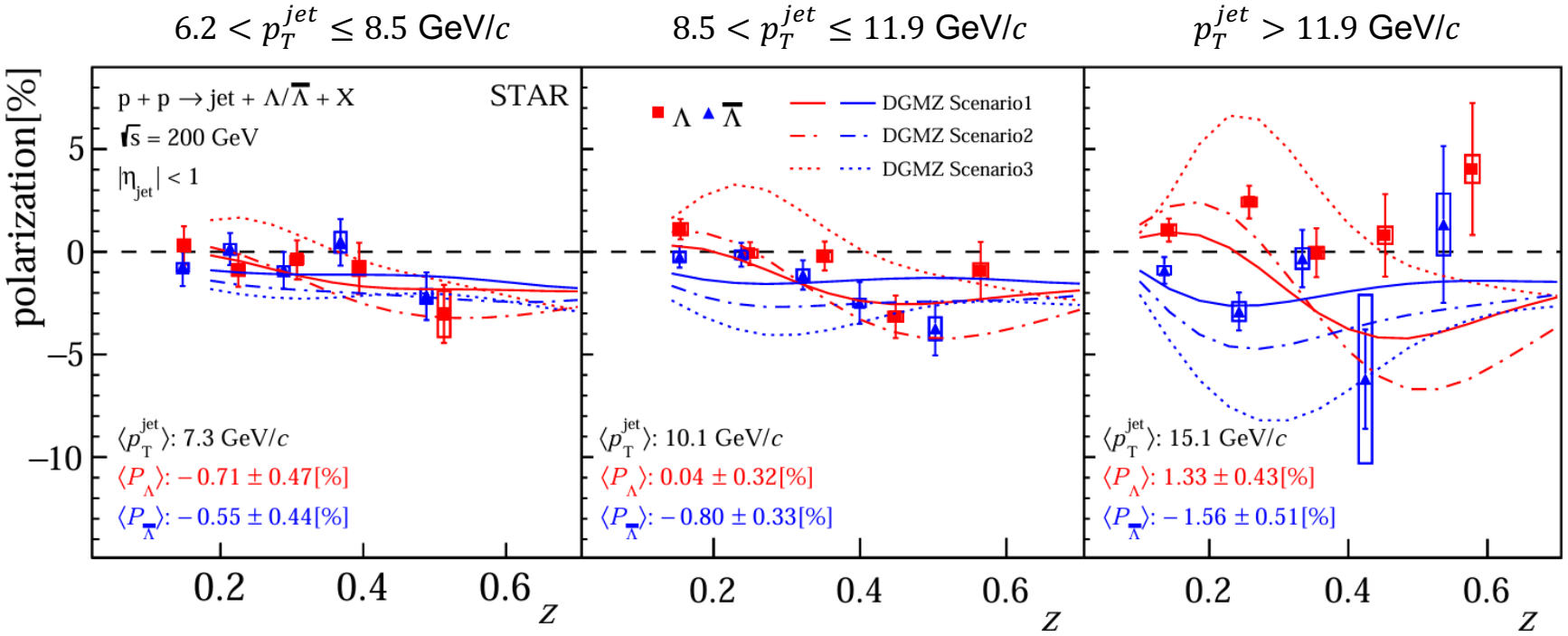


$$x_T = \frac{2p_T}{\sqrt{s}}$$

- 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

Results as function of z

STAR, arXiv:2509.17487



DGMZ model:

D'Alesio, Gamberg, Murgia, Zaccheddu, Phys. Lett. B 851 (2024) 138552

Scenario 1: Different PFF for u, d, s and their antiquarks

Scenario 2: Same as in Sc. 1 including charm in unpolarized x-section

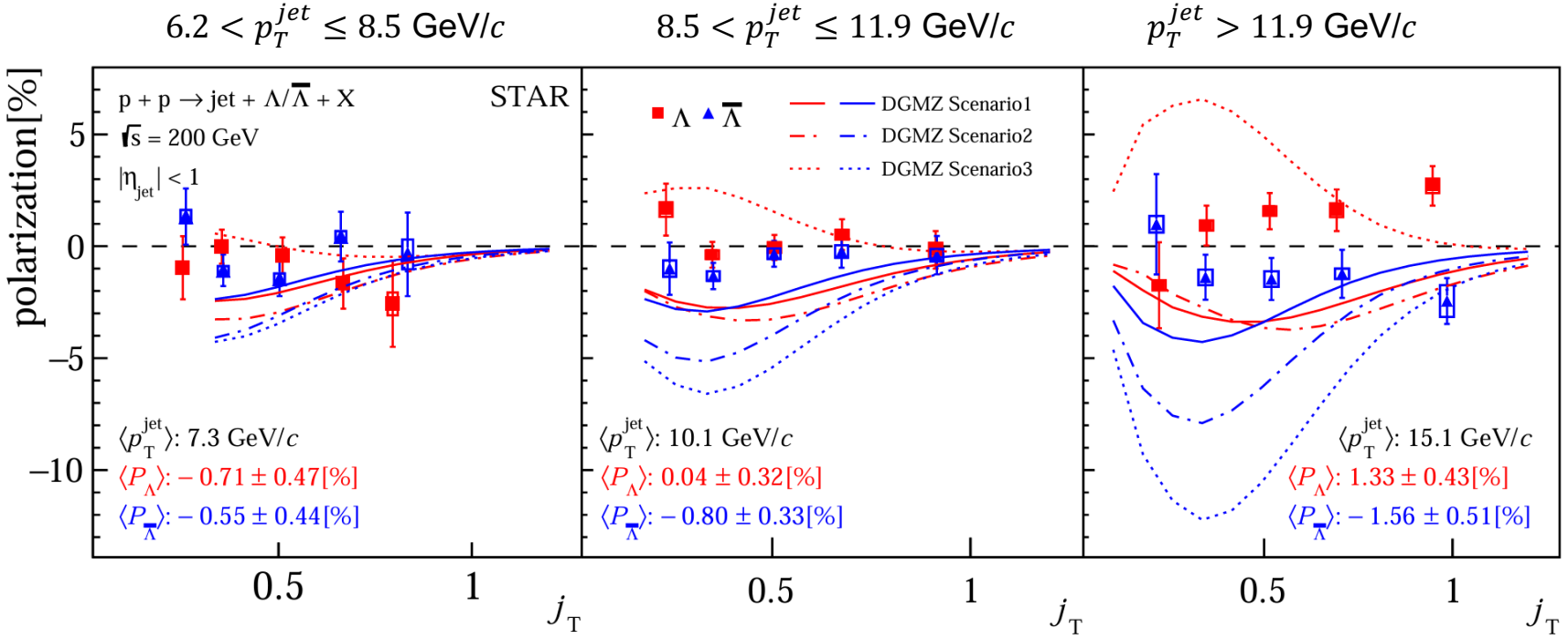
Scenario 3: Including $SU(2)$ isospin symmetry based on Sc. 2

z: jet longitudinal momentum fraction carried by Λ

- Provide the first experimental constraints for PFF from pp collisions
- Possible z dependences are observed at different jet p_T ranges
- Good agreement between data and model at low jet p_T range

Results as function of j_T

STAR, arXiv:2509.17487



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Scenario 1: Different PFF for u, d, s and their antiquarks

Scenario 2: Same as in Sc. 1 including charm in unpolarized x-section

Scenario 3: Including $SU(2)$ isospin symmetry based on Sc. 2

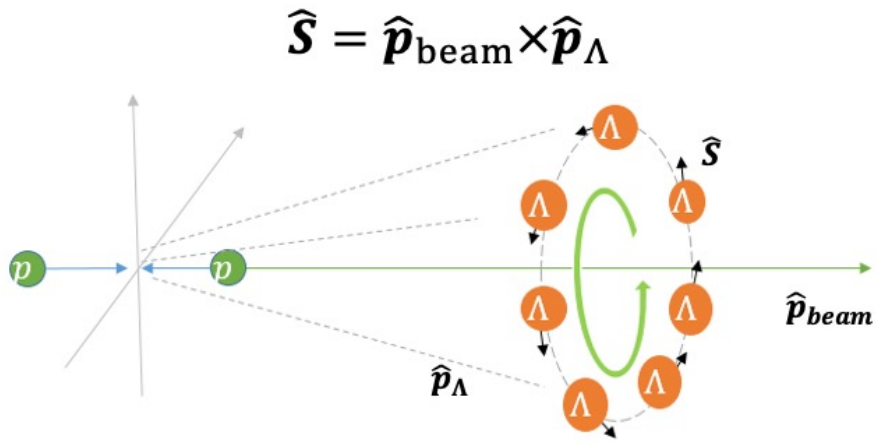
j_T: transverse momentum of Λ relative to jet

$$j_T = \frac{p_\Lambda \times p_{jet}}{|p_{jet}|}$$

- Provide the first experimental constraints for PFF from pp collisions
- Possible z dependences are observed at different jet p_T ranges
- Good agreement between data and model at low jet p_T range
- No significant dependence on j_T at all jet p_T ranges
- Opposite sign of Λ and $\overline{\Lambda}$ polarization at high jet p_T

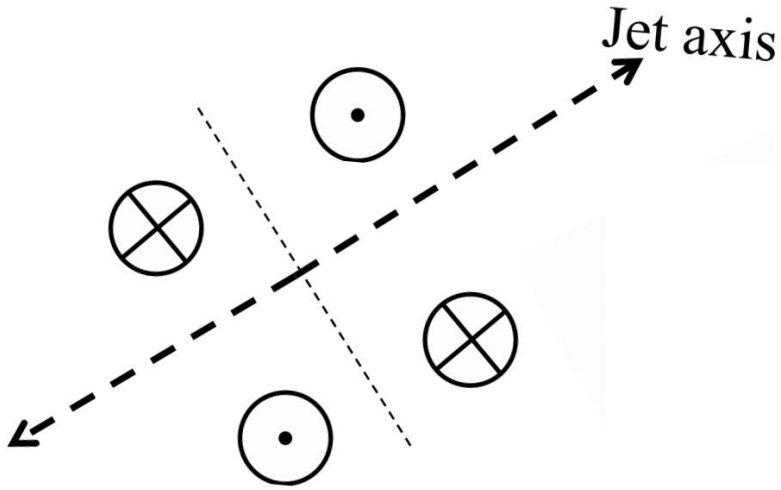
Possible connection to other observables?

To production plane polarization



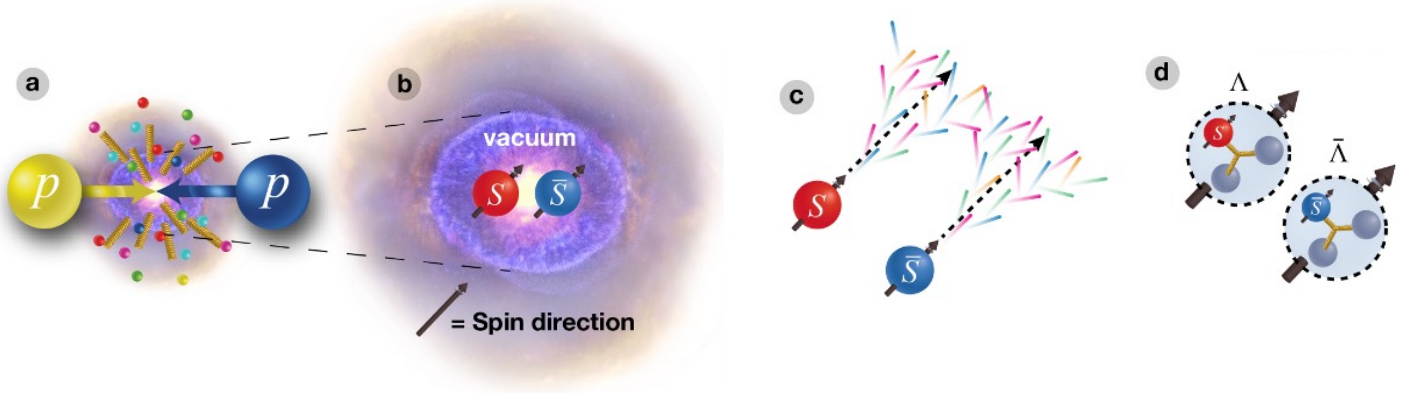
When Lambda-in-Jet is selected with bias, production planes spanned by beam and lambda consistent with by jet axis and lambda

To local polarization with low multiplicity

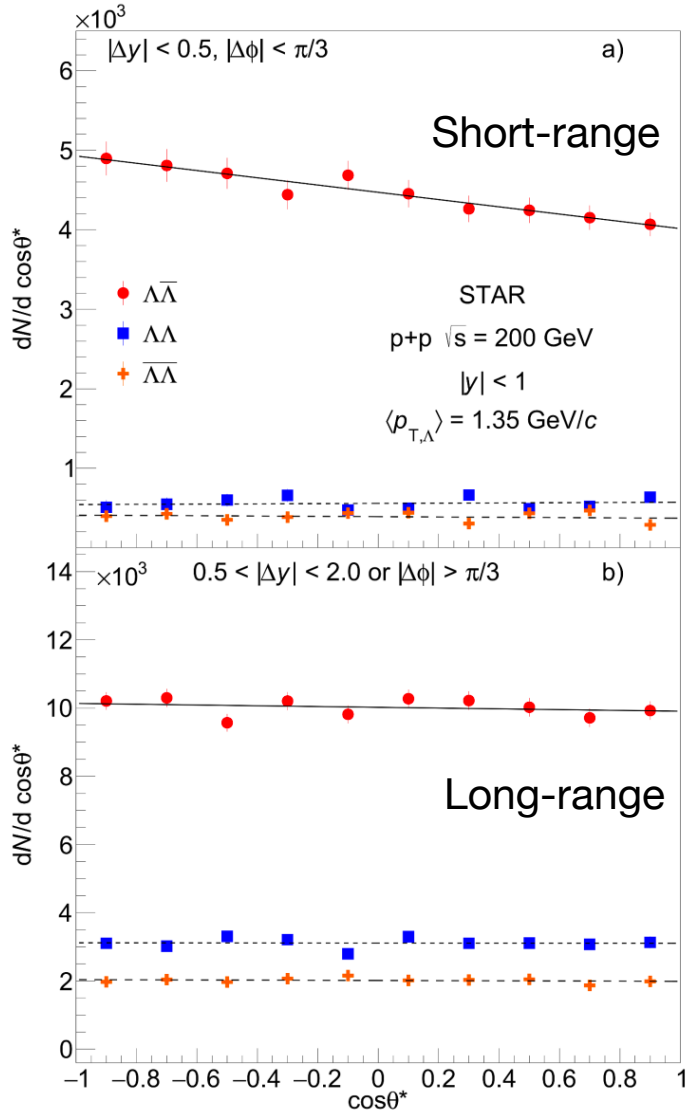


When (leading) di-jet or mutli-jet impact event plan reconstruction, polarization surrounding jet axis can be observed as “local polarization”

Spin correlation



STAR, Nature 650, 65–71 (2026)



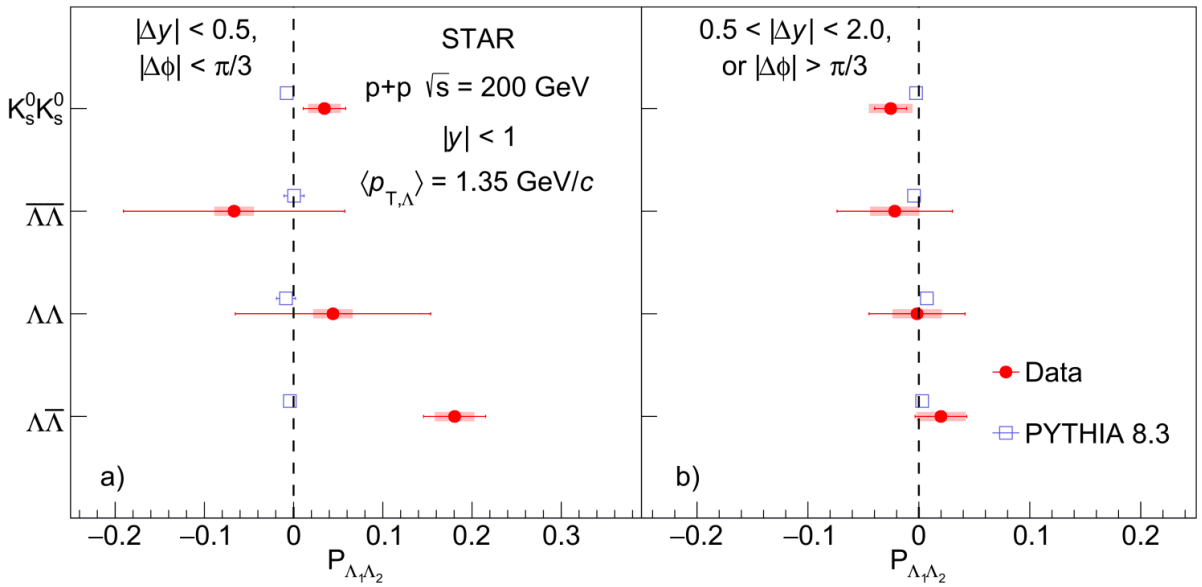
Spin correlation of $\Lambda/\bar{\Lambda}$ hyperon pairs measured in p+p collisions to study the hadronization of the entangled $s/\bar{s}$ quark pairs from the QCD vacuum.

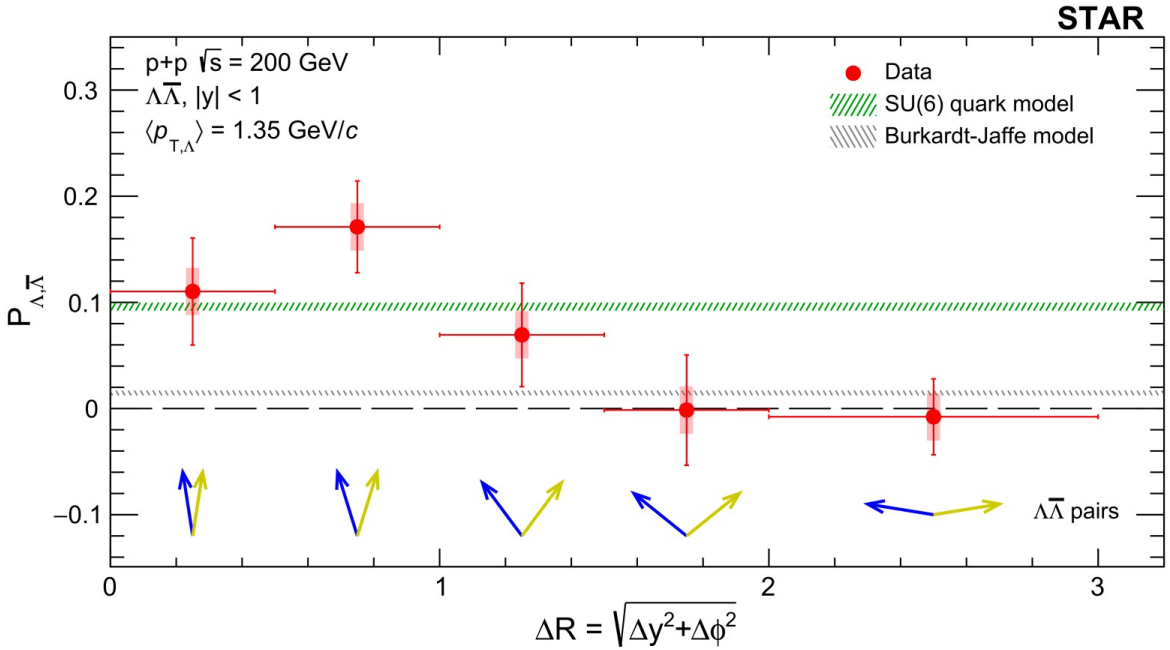
$$dN/d\cos(\theta*) = A\,(1 + B\cos\theta*)$$

A: normalization, B: $\alpha_1\alpha_2 P_{\Lambda 1 \Lambda 2}$

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

Summary

- Lambda “spontaneous” polarization: ~50 years puzzle
- Lambda spin transfer results could constrain pPDFs and pFFs, in global analysis.
  - 200 GeV data analyzed;
  - 500 GeV on disk to be analyzed.
- Polarization of Lambda in jet could access polarizing FFs and hopefully answer some puzzling questions.
  - Completing analysis of pp 200 GeV and 510 GeV;
  - Ongoing analysis for pAu 200 GeV and pPb 8.26 TeV.
- Spin correlation between $\Lambda/\overline{\Lambda}$ pairs provides new insight into the $\mathbf{\Lambda}$ hyperon polarization puzzle.

Thanks for your attention!