HIAF能区的自旋物理

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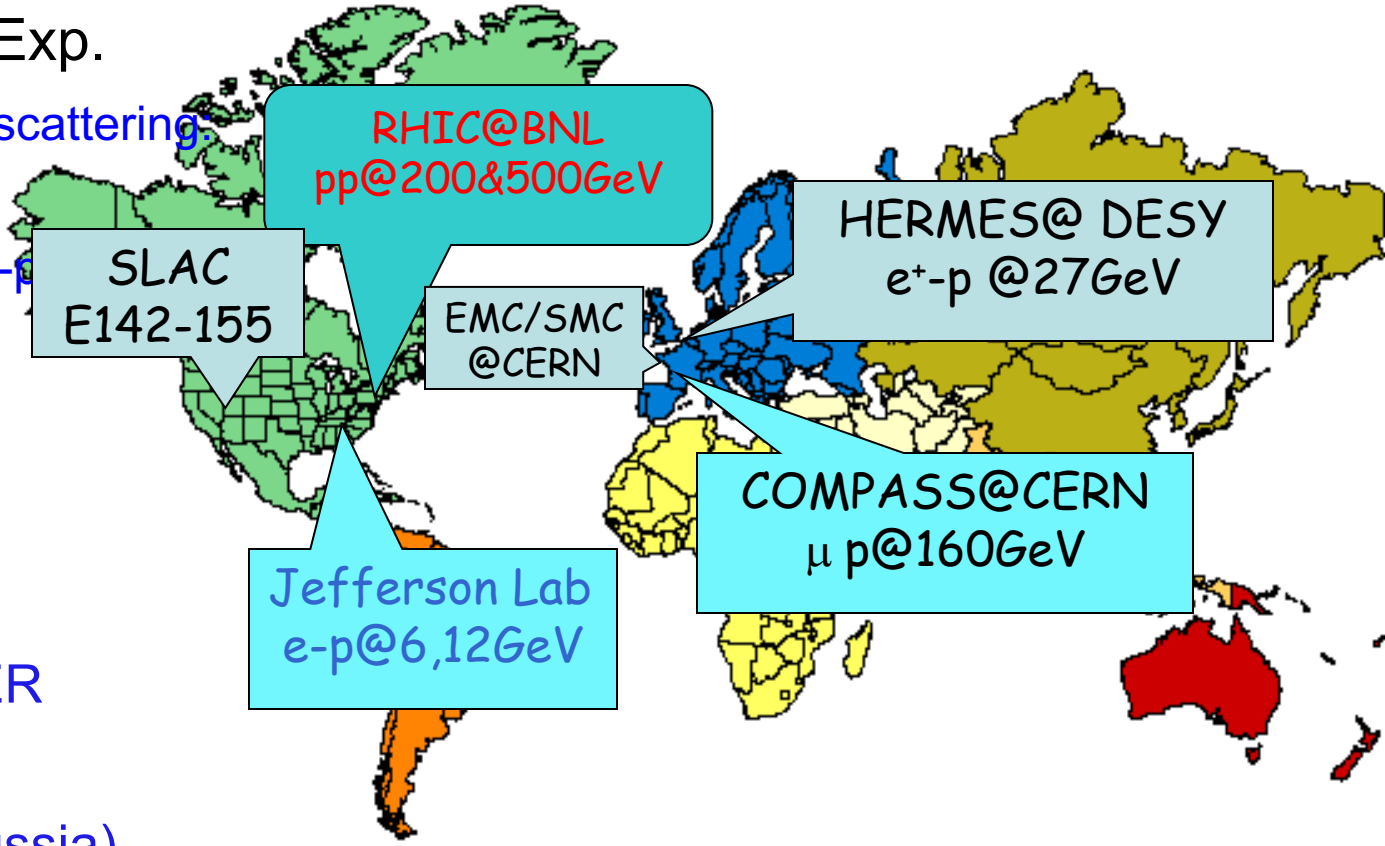
HIAF高能终端谱仪合作组会议，惠州

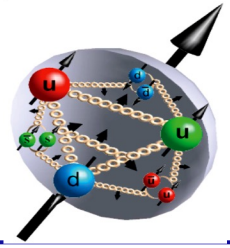
2024.11.16

World efforts for spin physics with polarized source

- Finished experiments: SLAC, EMC, SMC, HERMES, COMPASS
- Current running Exp.
  - Lepton-nucleon scattering: JLab
  - Polarized proton-p scattering, RHIC
- Future facilities
  - EIC (US, BNL)
  - EicC (China)
  - LHCspin/AFTER (CERN)
  - NICA-SPD (Russia)
  - JPARC (Japan)
  - GSI-FAIR (Germany)



Goal:
Nucleon spin structure



Spin physics with unpolarized source ?

- Yes! Two examples:
  - Lambda spontaneous polarization in hadron collisions
  - Global polarization in heavy ion collisions

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- Yes! Two examples:
  - Lambda spontaneous polarization in hadron collisions
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- HIAF高能终端自旋物理：9.3GeV的质子束流
  2.45～9.1GeV/u的重离子束流

Self analyzing Λ polarization via weak decay

- Λ polarization can be measured in experiment via weak decay:

Λ->$p\pi^-$(Br64%), Λ->$n\pi^0$(Br36%) ,

-T.D.Lee, C.N.Yang(1957)

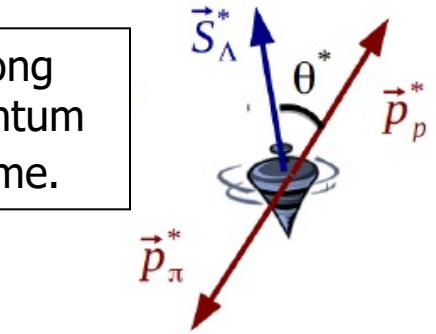
$$\frac{dN}{d\Omega} \propto 1 + \alpha (\vec{P}_\Lambda \cdot \hat{p}^*_p)$$

Unit vector along proton momentum in Λ's rest frame.

decay parameter

0.752

Λ polarization vector



$\Lambda \rightarrow p + \pi^+$

(BR: 63.9%, cτ~7.9 cm)

- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $\left|\Lambda^{\uparrow}\right\rangle = (ud)_{00}\, s^{\uparrow}$

- Λ polarization can serve as a powerful tool in spin physics of different field.

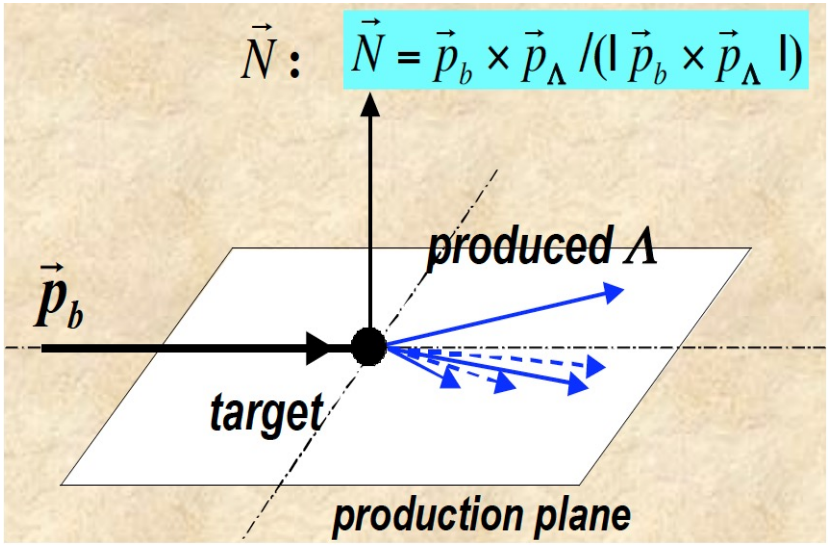
Induced transverse Λ polarization

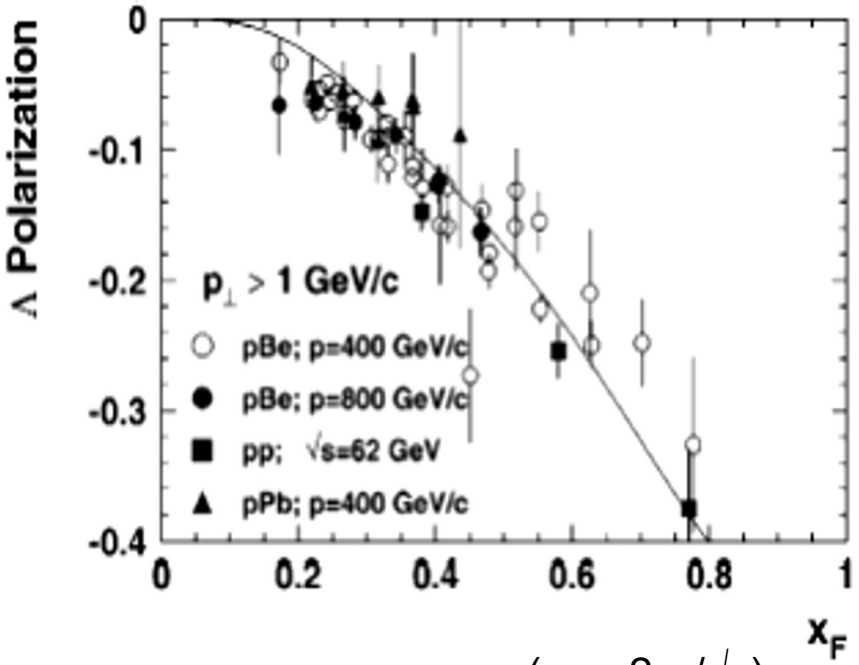
- Large polarization with unpolarized beam p + p $\rightarrow \Lambda^{\uparrow}$ + X , observed in different experiments.

  -G.Bunce *et al* PRL36,1113,(1976) -583 citations, followed by 50+ measurements

- pQCD calculation ~0 ($\propto m_q$).

  Kane, Pumplin & Repko, PRL41,1689(1978).

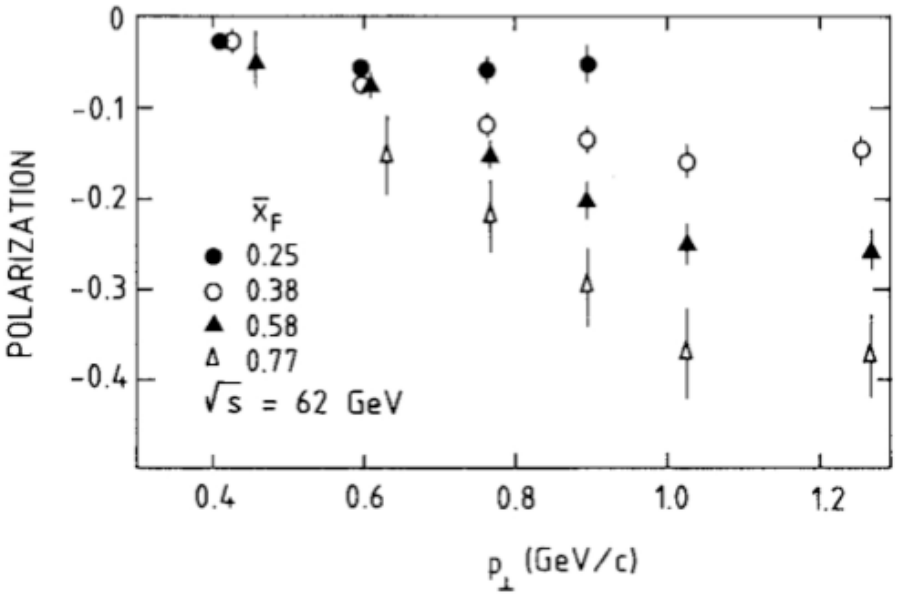


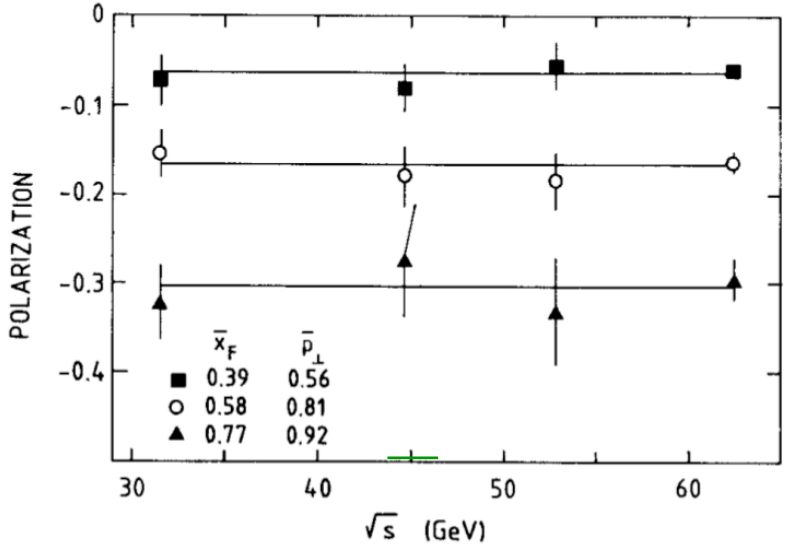


($x_F = 2p_L/\sqrt{s}$)

What did the data tell us?

- Polarization increase linearly with x_F, ~40% at large x_F !
- Polarization increase with $p_\perp$ <1 GeV and saturates at $p_\perp > 1$ GeV
- Small energy dependence (P_b→12-2000 GeV)
- Anti-Lambda polarization much smaller, ~0
- Extended to Xi, Sigma polarization



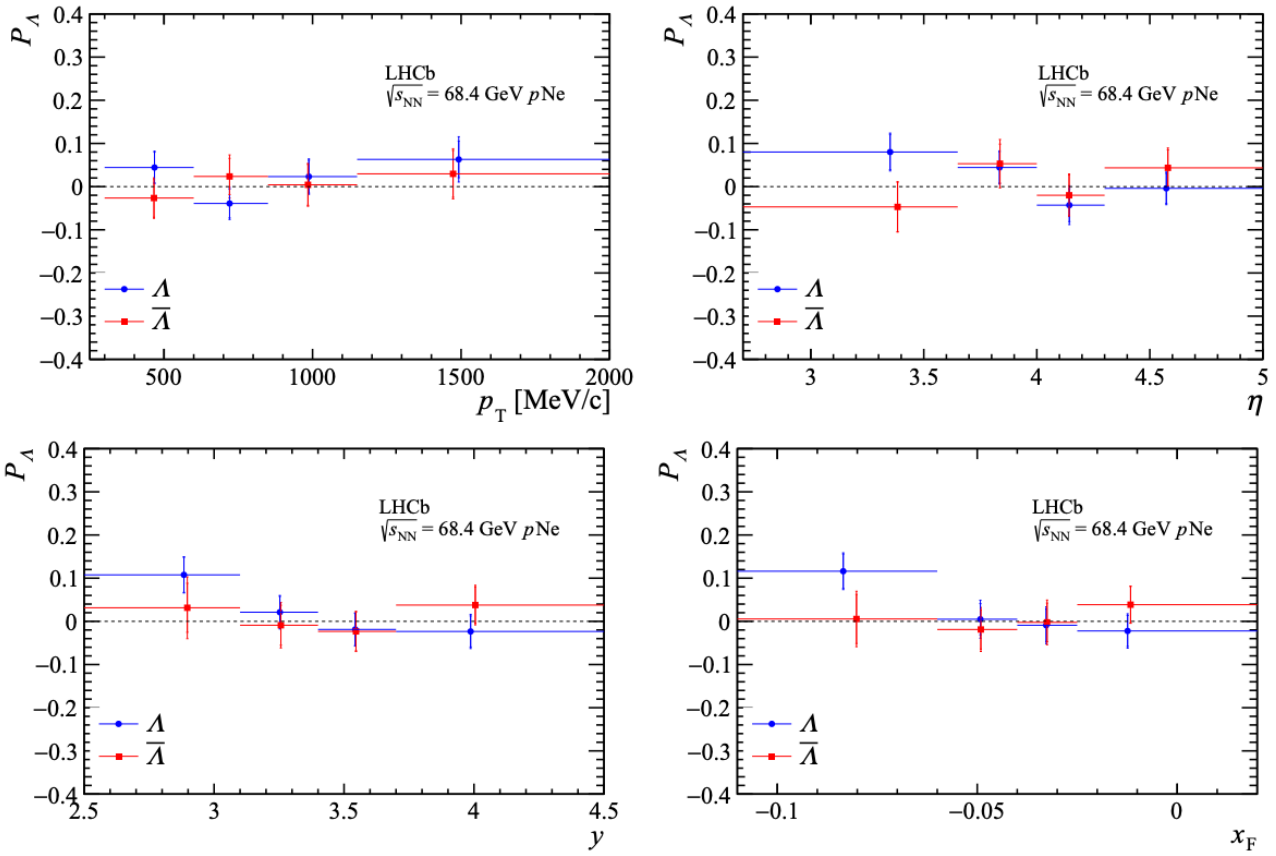


-- Data review, i.e., A.D. Panagiotou, Int.J.Mod.Phys.A 5, 1197,(1990)

➢ More recent measurements at LHC, Belle, RHIC, JLab …

Transverse polarization measurement of Λ hyperons in pNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.4\,\mathrm{GeV}$ with the LHCb detector

LHCb, JHEP 09 (2024) 082



Theoretical understanding - history

- pQCD calculation leads to P~ 0 ($\propto \alpha_s m_q$) at parton level
- Available Models (mostly based on recombination of a ud diquark from the proton and a s quark from the sea):
  - ✓ Lund string fragmentation (B.Andersson et al, 1979)
  - ✓ De Grand-Mietinnen precession model (1981)
  - ✓ Angular momentum of valence quarks (Boros, Meng, Liang,1993)

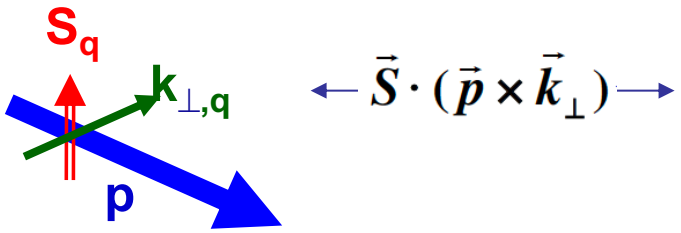
- Most models give qualitative descriptions for data with p_T<1GeV.
- No coherent description of all pheonomena!

-review of models by J. Felix, Mod.Phys.Lett.A 14 (1999) 827

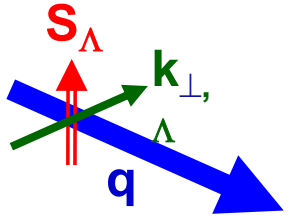
Theoretical understanding – QCD framework

- Within QCD framework:
  - polarization originates from non-perturbative processes->

Polarizing distribution function	Polarizing fragmentation function



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



-Boer-Mulders function : pol. parton in unpol. hadron

-pFF: unpol. parton fragment into pol. hadron

- Chiral odd contribution
- Boer-Mulders function

  D. Boer, P. J. Mulders, PRD 57, 5780303 (1998),

- Fit of data: M. Anselmino *et al*, PRD63 (2001) 054029;
- Predictions of pol. within a jet:

  D.Boer *et al*, PLB 659 (2008) 127.

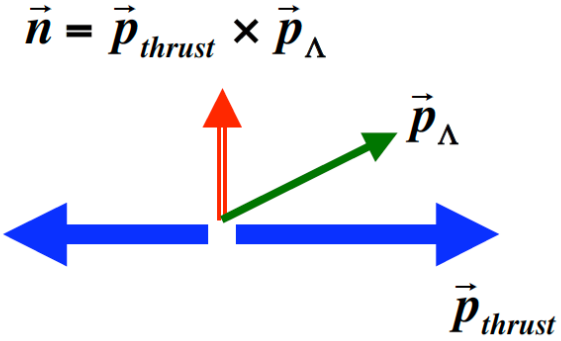
  Z.B. Kang *et al*, PLB 809, 135756 (2020).

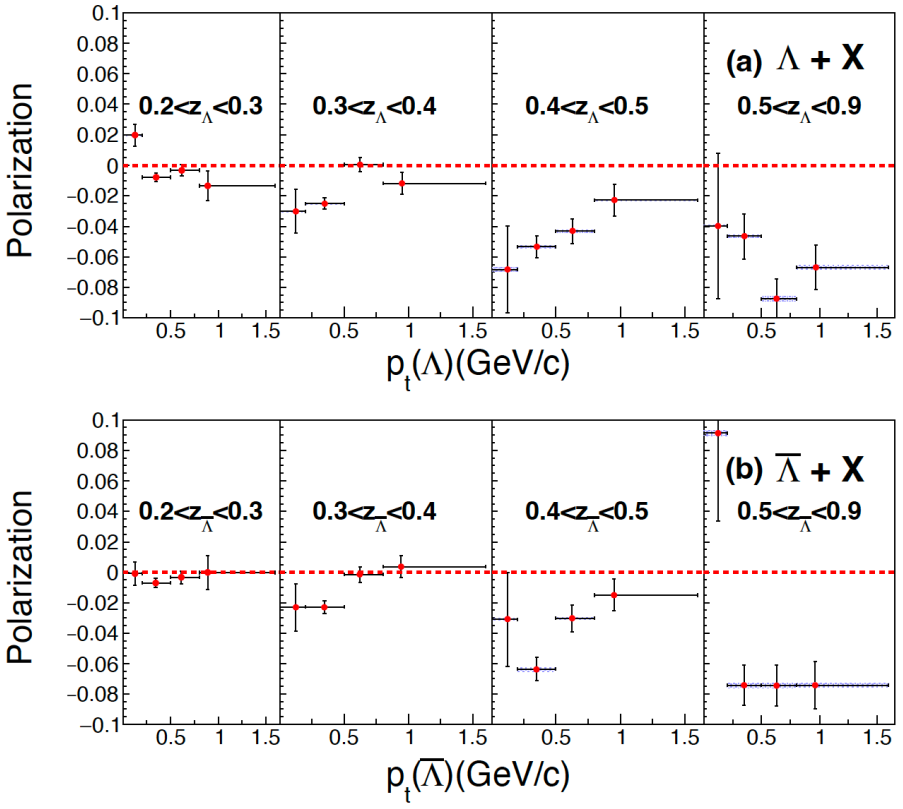
- High twist framework: high twist correlation, high twist fragmentation
  - Y. Kanazawa & Y. Koike, PRD 64, 034019 (2001).
  - J.Zhou, F.Yuan, Z.Liang, PRD78 (2008)114008;

Λ polarization in e^+e^-– study of pFF

- Belle experiment observed significant polarization of $\Lambda/\overline{\Lambda}$ transverse to $\Lambda/\overline{\Lambda}$ - thrust axis plane in unpolarized e^+e^- annihilation ($\sqrt{s} = 10.6\ GeV$)

Belle, PRL 122(2019) 042001





Extraction/modelling of pFF:

U. D'Alesio, F. Murgia, M. Zaccheddu, Phys. Rev. D 102 (5) (2020) 054001

D. Callos, Z.B. Kang, J. Terry, Phys. Rev. D 102 (9) (2020) 096007

K.B. Chen, Z.T. Liang, Y.L. Pan, Y.K. Song, S.Y. Wei, Phys. Lett. B 816 (2021) 136217

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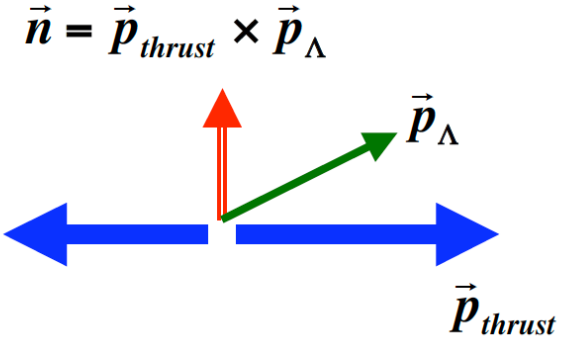
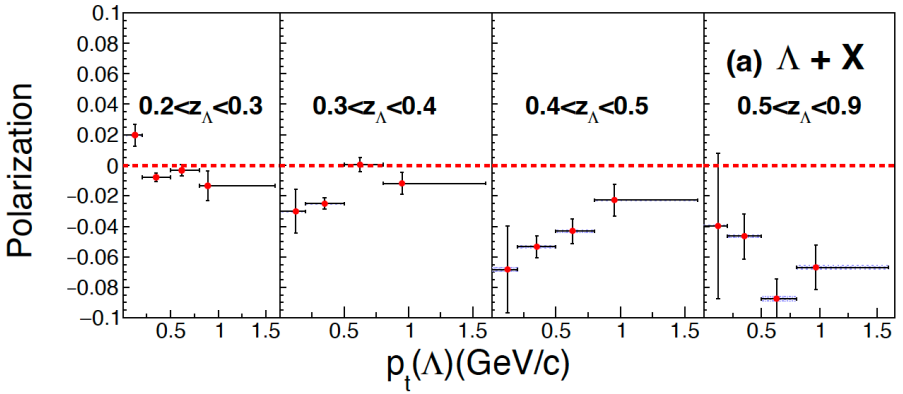




- No polarization at LEP ?!

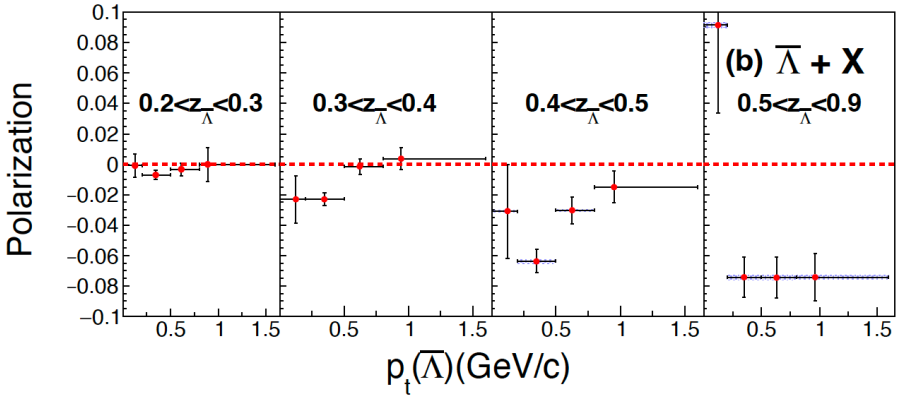
$P_T^{\Lambda} = 0.019 \pm 0.014$ (OPAL)

$P_T^{\overline{\Lambda}} = 0.015 \pm 0.014$

$P_T^{\Lambda+\overline{\Lambda}} = 0.016 \pm 0.007$ (ALEPH)

-ALEPH, Phys. Lett. B374, 319 (1996)

-OPAL, Eur. Phys. J. C2, 49 (1998)



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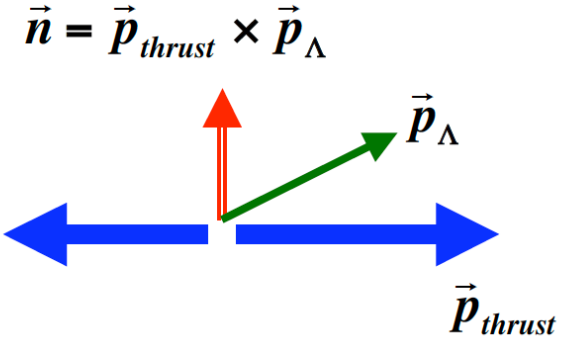
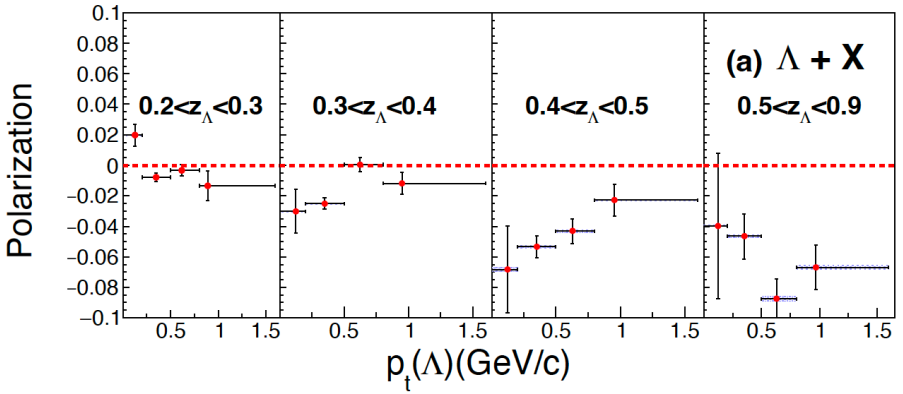
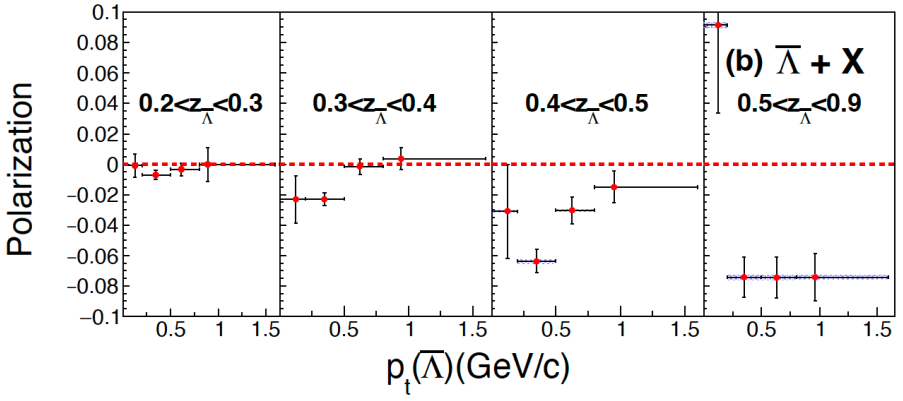
Belle, PRL 122(2019) 042001







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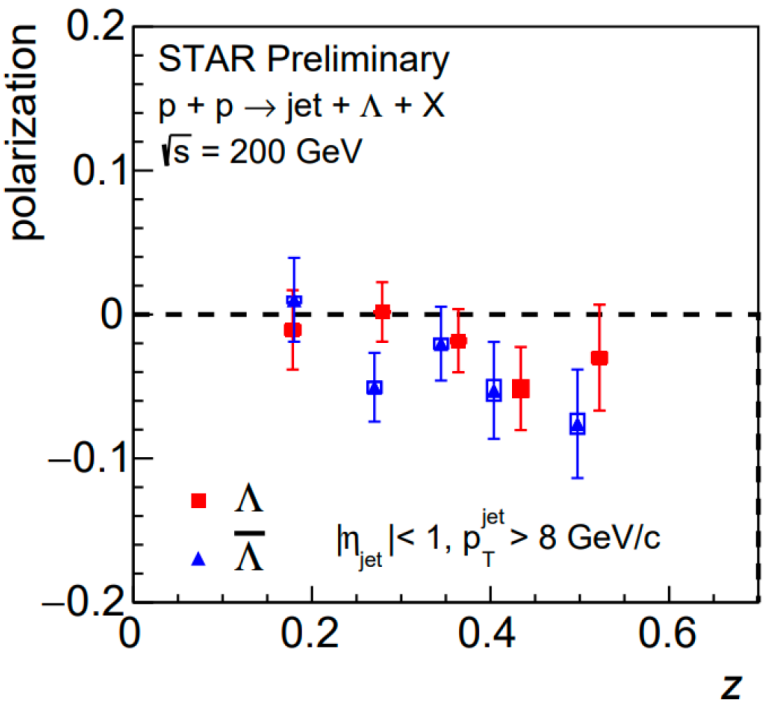
-ALEPH, Phys. Lett. B374, 319 (1996)

-OPAL, Eur. Phys. J. C2, 49 (1998)

➢ Jet energy evolution effect ? Λ pol. in jet in pp at higher jet energy at RHIC?

Λ polarization within jet in unpolarized pp collision

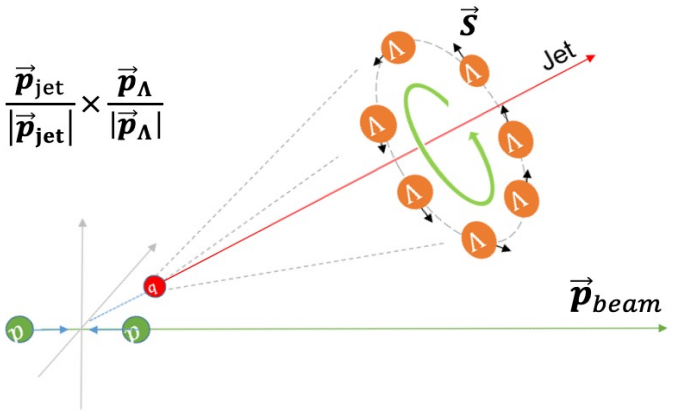
- Λ polarization in jet -> polarizing fragmentation function at STAR:



$$z = \frac{p_\Lambda * p_{jet}}{|p_{jet}| * |p_{jet}|}$$

Jet momentum fraction carried by $\Lambda(\bar{\Lambda})$

$$\vec{S} = \frac{\vec{p}_{\text{jet}}}{|\vec{p}_{\text{jet}}|} \times \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}$$

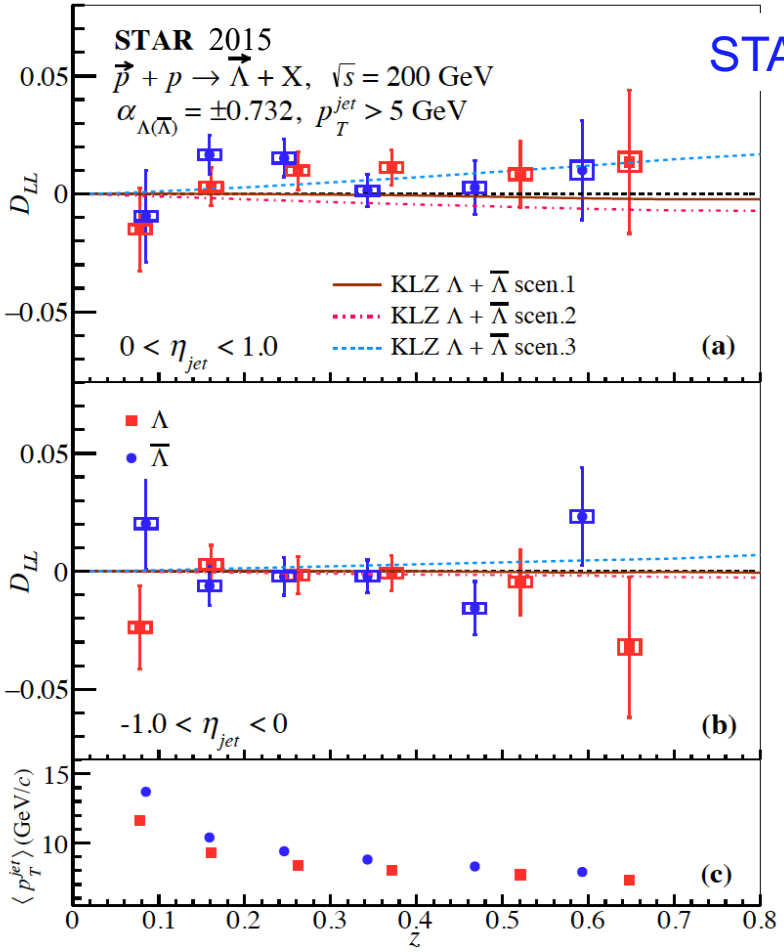


- Constraint for collinear fragmentation functions
- Λ polarization is consistent with 0
- Indication of negative transverse polarization of $\bar{\Lambda}$ $(\sim 2.6\sigma)$

➢ More data are being analyzed at both 200 GeV and 500 GeV at STAR, with a wide range of jet momentum, to test universality and scale dependence

Spin transfer measurement at RHIC-STAR

- First measurements of D_{LL} vs z in polarized p+p collisions, directly probing the polarized fragmentation functions.
- The results are comparable to model prediction within uncertainties.



STAR, PRD109, 012004 (2024)

$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

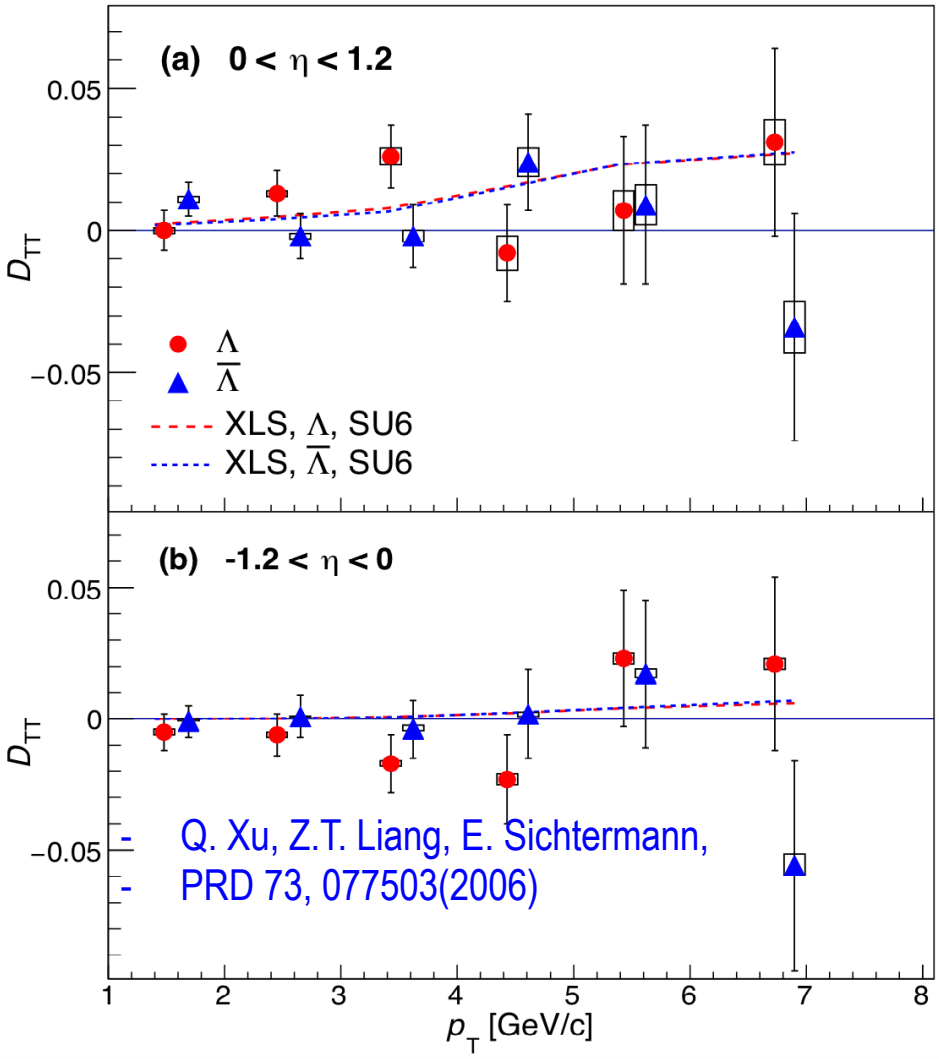
z: Jet momentum fraction carried by hyperon

- Z.-B. Kang, K. Lee, F. Zhao, Phys. Lett. B **809**, 135756 (2020).

Transverse spin transfer D_{TT} results at STAR

- First D_{TT} measurements in p+p collision at 200 GeV at RHIC:

-STAR, PRD98, 091103R (2018)



- ✓ 1st transverse spin transfer measurement in p+p collisions at RHIC.
- ✓ Most precise measurement on hyperon polarization in p+p collision at RHIC, which reach p_T ~6.7 GeV/c with statistical uncertainty of 0.04.
- ✓ D_{TT} of $\Lambda / \overline{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

Spin polarization of vector meson

- Spin density matrix of a vector meson: $\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$

$$(\rho = \sum_i P_i \,|\, i >< i \,|)$$

ρ_{11}: the probability to be in *h=1* state, similar for ρ_{-1-1} and ρ_{00}.

- Spin polarization information of vector meson can be extracted via it decay
  - For $V \rightarrow M_1 + M_2$, M_1 and M_2 are two pseudo-scalar mesons,

$$W(\cos\theta^*) = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

"Spin alignment", J.F. Donoghue, PRD19, 1979.

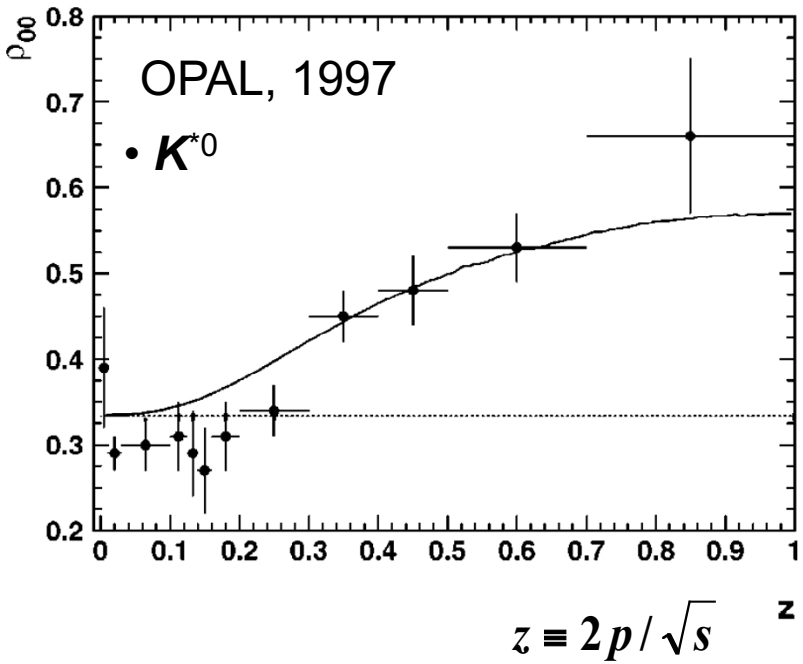
Θ*: angle between decay daughter M and the quantization axis in rest frame of V

Spin alignment of vector meson in e^+e^-

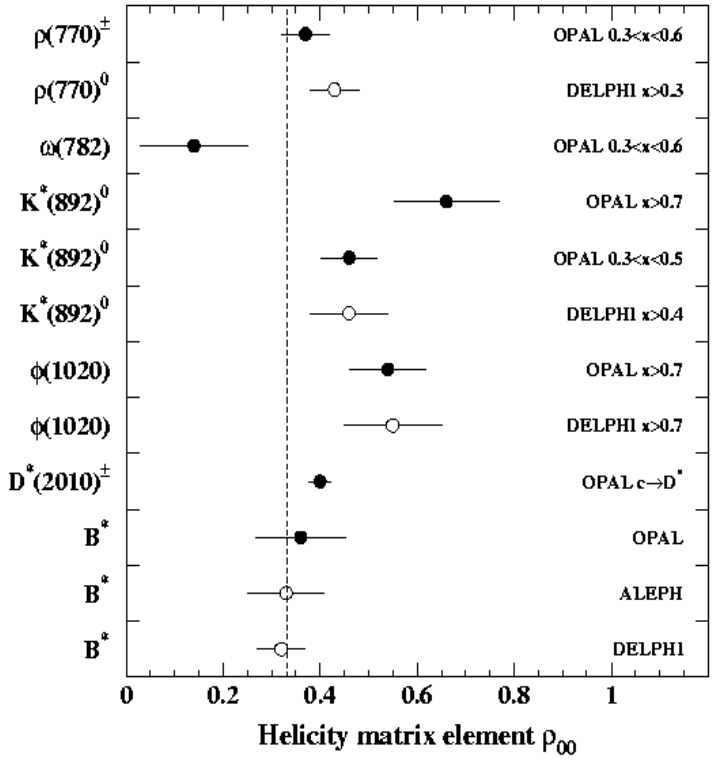
- Spin alignment:

$$W(\cos\theta) = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

- Lot of spin alignment data at LEP (e^+e^- at 90GeV):



Q. Xu, Z. Liang, PRD63(2001)111301



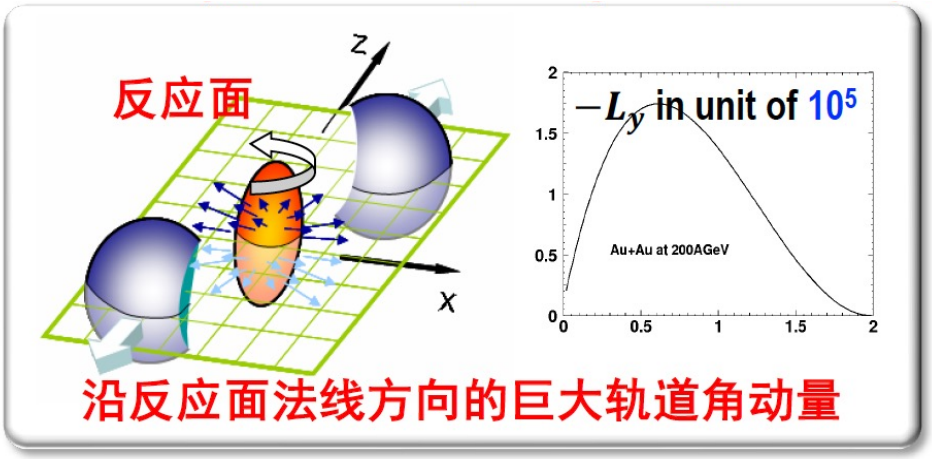
➢ Spin alignment measurement in hadron collisions at HIAF?

Λ Global polarization in heavy ion collisions

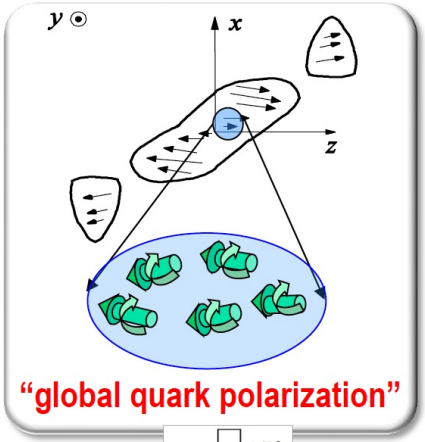
- Globally polarized quark gluon plasma (QGP) in non-central relativistic heavy ion collisions

- 800+ citation

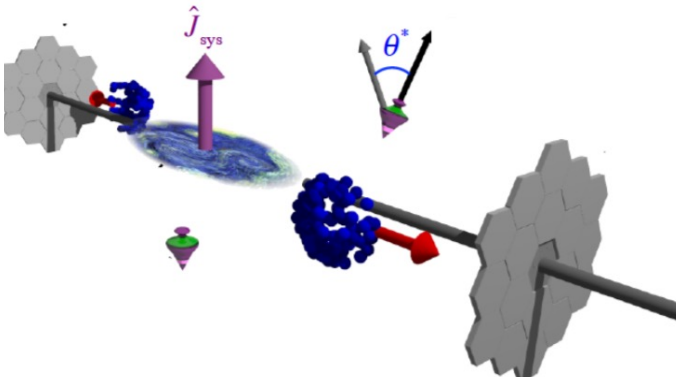
Zuo-tang Liang & Xin-Nian Wang, PRL94, 102301(2005); PLB629, 20(2005).



QCD自旋—轨道相互作用导致



强子化导致（组合）



●超子整体极化

$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

●矢量介子整体自旋排列

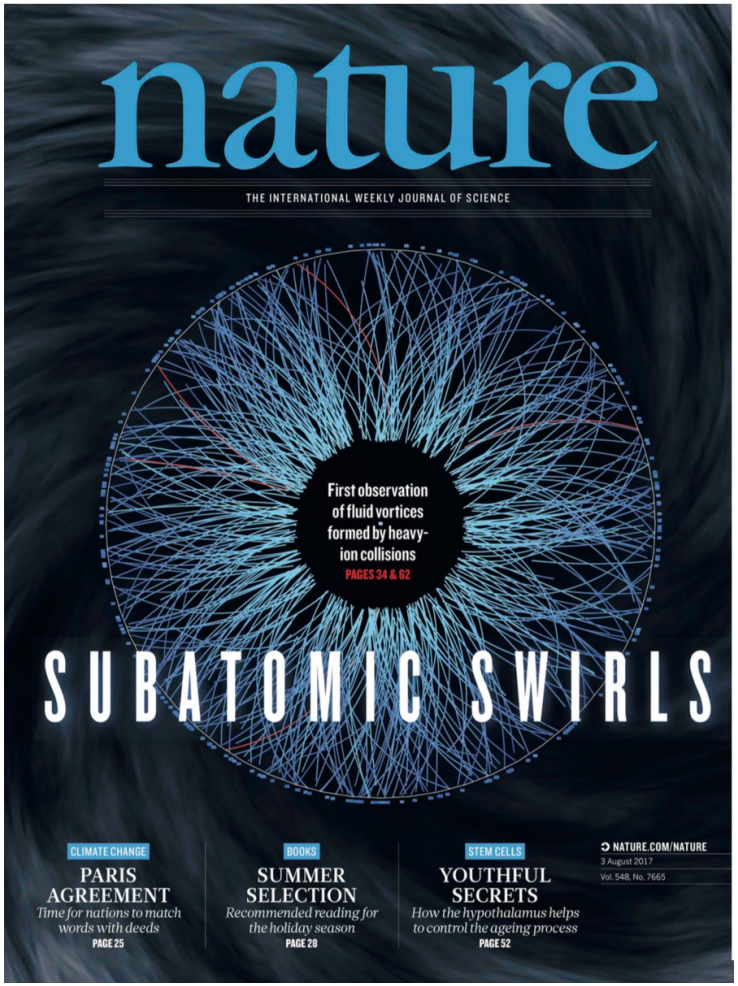
(spin alignment)

$$\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$$

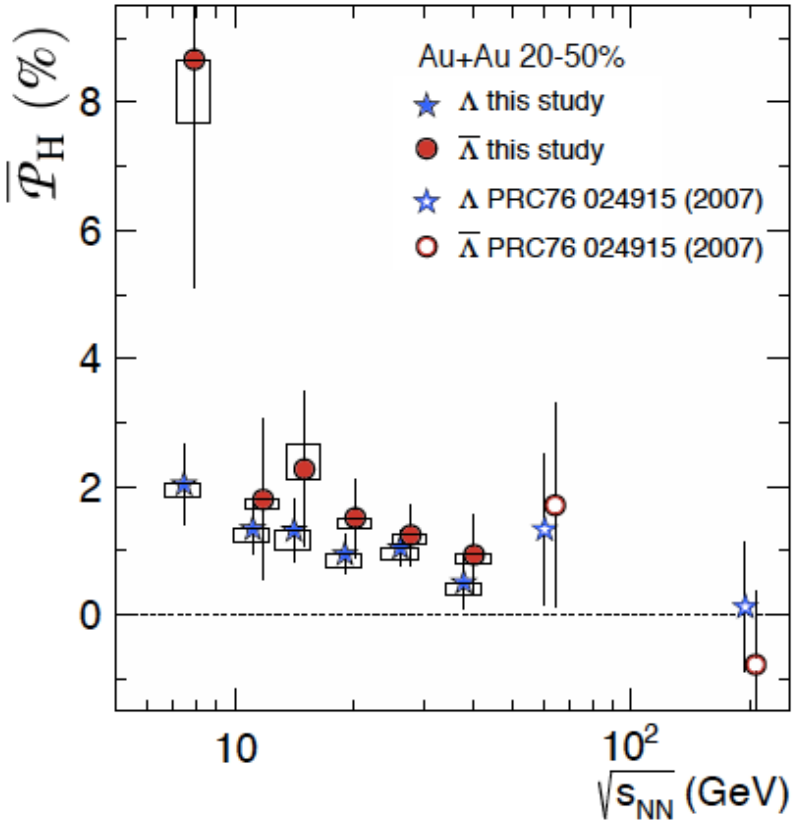
-Measurements started soon after the prediction, first data available in 2007 from RHIC-STAR

Λ Global polarization in heavy ion collisions

- Λ global polarization observed with STAR BES-I (Nature cover), *new hot topic* – spin physics in heavy ion



STAR, Nature 548(2017)62



物理学报专题：高能重离子碰撞中的自旋与手征效应

客座编辑：梁作堂、王群、马余刚

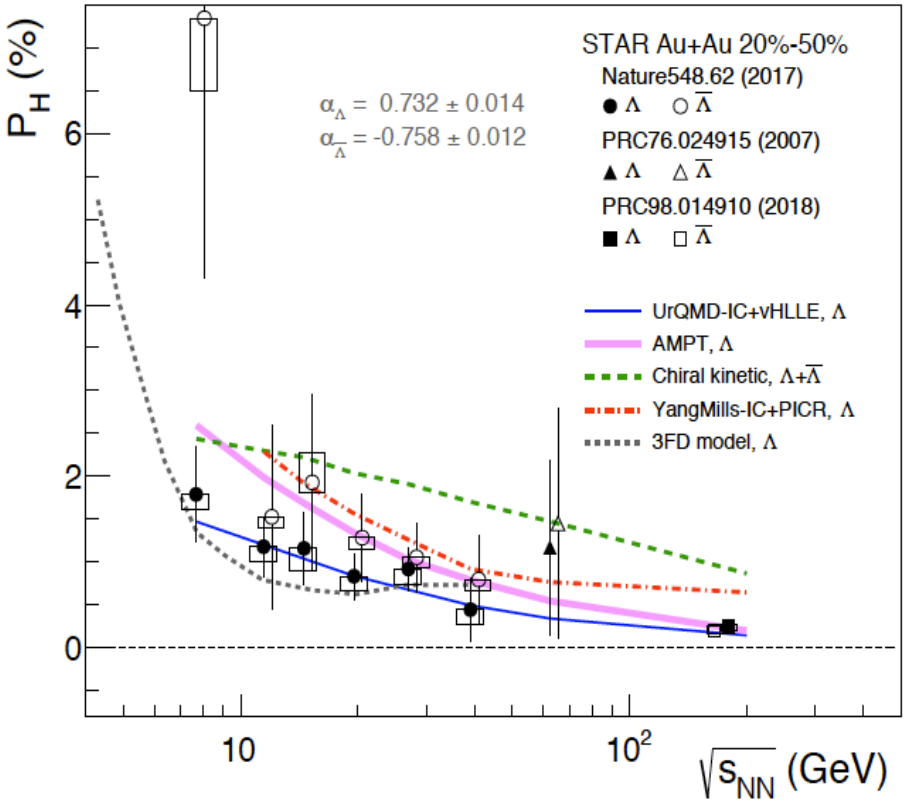
物 理 学 报

第 72 卷 第 7 期 2023 年 4 月 5 日

Global polarization in heavy ion collisions

- Spin-orbit coupling leads to spin polarization of produced particles, like Λ
- Effects to global polarization from the magnetic field

STAR, Nature 548, 62 (2017)
STAR, PRC90, 014910 (2018)



- Indication of thermal vorticity

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

F. Becattini et al., PRC95.054902 (2017)

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- Increasing trend toward lower energies, described well by various theoretical models

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model

- Possible difference between Λ and anti-Λ

$\Lambda(\bar{\Lambda})$ global polarization from STAR BES-II

- Splitting of $\Lambda(\bar{\Lambda})$ global polarization due to the magnetic field ?

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

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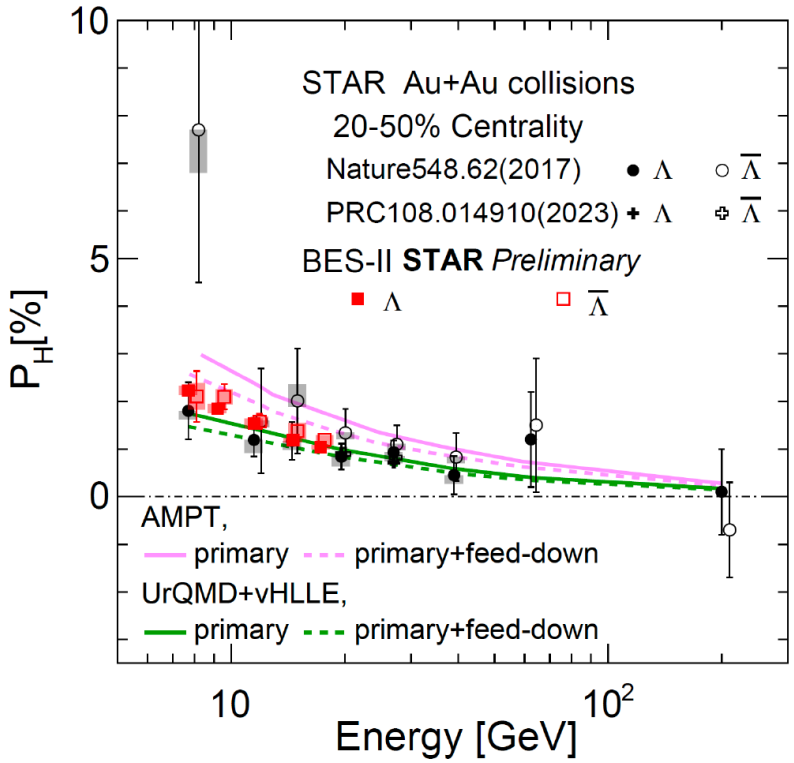
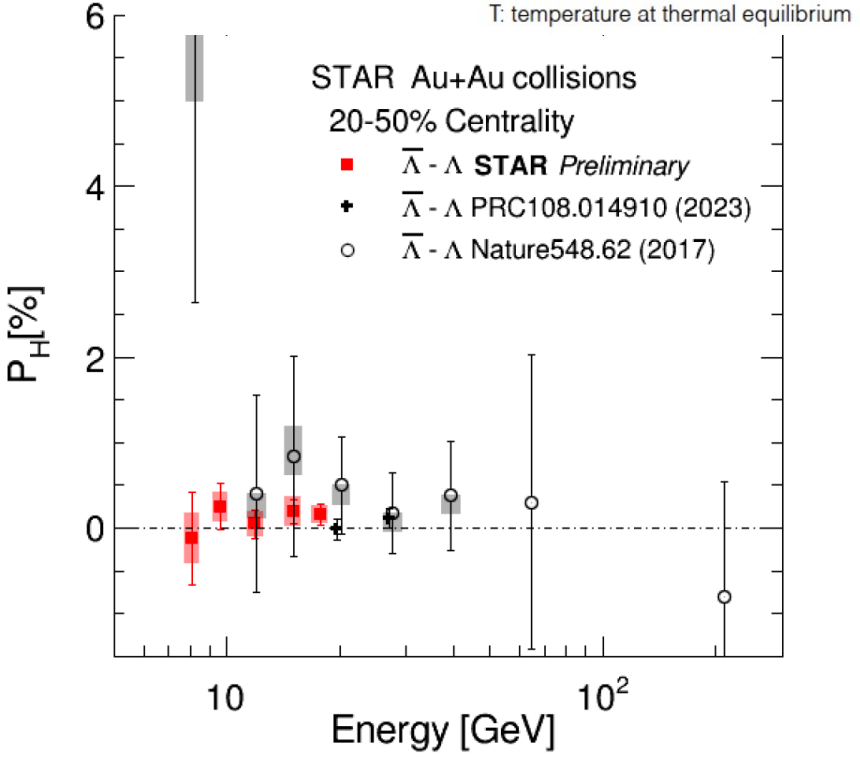
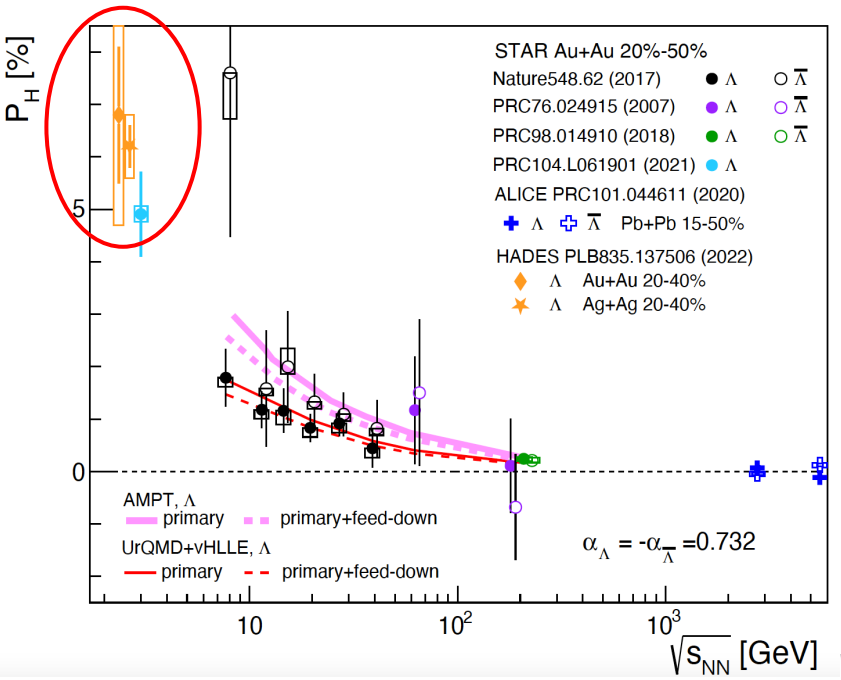




- No splitting between $\Lambda(\bar{\Lambda})$ global polarization within uncertainties
- More data coming from STAR BES-II FXT with energy down to 3 GeV

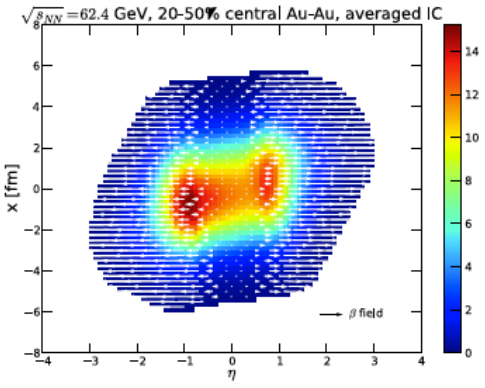
Energy dependence of global polarization

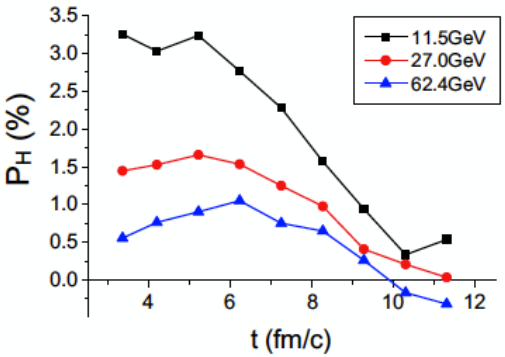


- HADES data at √s=2.4GeV Au+Au and 2.7 GeV Ag+Ag
- STAR data down to √s= 3 GeV
- ALICE results at 2.76 and 5.02 TeV Pb+Pb, consistent with zero within uncertainties

I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)

- Stronger shear flow in forward/ backward regions+ baryon stopping with limited acceptance (related to rapidity dependence)
- Polarization continue to increase at low energy ?
  - ➢ Good chance at HIAF in AA
    √s: 2.5~4.3GeV





- Y. Ivanov, Phys. Rev. C103, 031903(2021)

Ξ and Ω global polarization measurement

- Two possible ways of measurement:

1) Direct measurement via weak decay, but subject to small decay parameters.

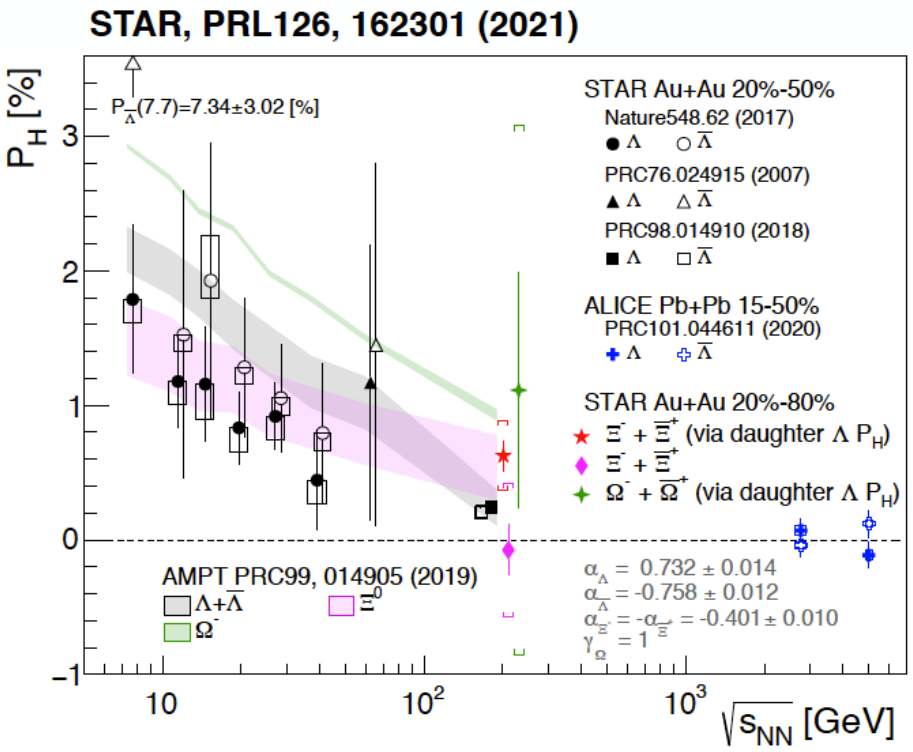
hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \to p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \to \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \to \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2

2) Through the polarization transfer to daughter Λ in the decay process

$$\mathbf{P}^*_\Lambda = C_{\Xi-\Lambda}\mathbf{P}^*_\Xi = \tfrac{1}{3}(1+2\gamma_\Xi)\,\mathbf{P}^*_\Xi. \qquad C_{\Xi-\Lambda} = +0.944$$

$$\mathbf{P}^*_\Lambda = C_{\Omega-\Lambda}\mathbf{P}^*_\Omega = \tfrac{1}{5}(1+4\gamma_\Omega)\,\mathbf{P}^*_\Omega.$$

-γ_Ω is not known, with estimation ~1, C~1



➢ AMPT and hydro calculations capture the trend:

D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)

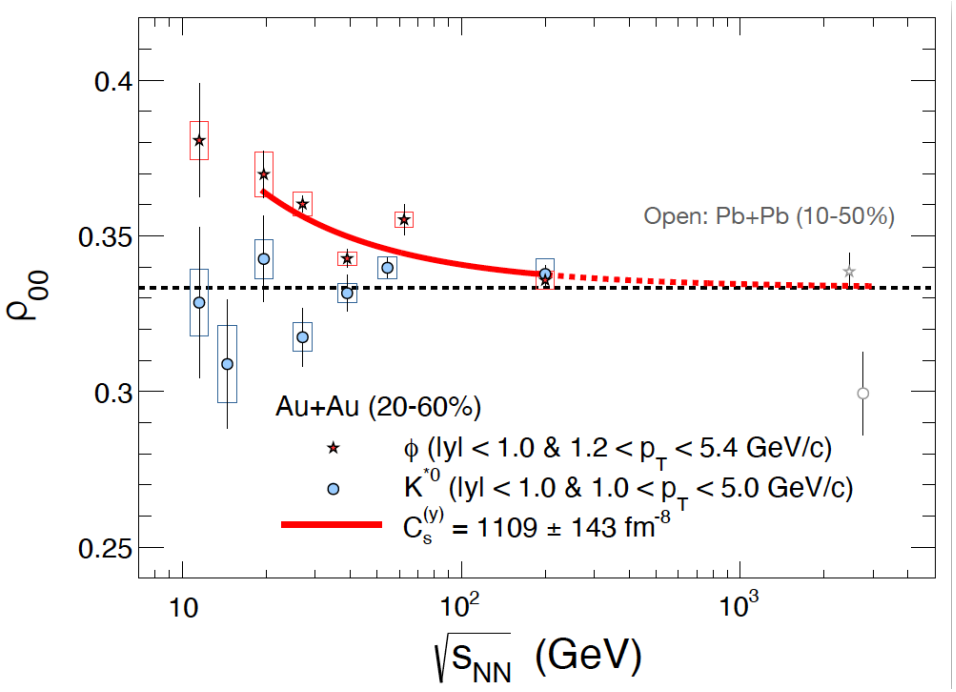
➢ Can also be measured at HIAF energy

Global spin alignment in heavy ion collision

- Vector mesons' ρ_{00} from Au+Au at STAR BES-I:

STAR, Nature **614**, 244 (2023)

Z. T. Liang, X.N. Wang, Phys.Lett.B629, (2005)



for $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

$$\rho_{00}^{V} = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle} \neq \frac{1 - \langle P_q \rangle \langle P_{\bar{q}} \rangle}{3 + \langle P_q \rangle \langle P_{\bar{q}} \rangle}$$

two folded average

$$\langle P_q P_{\bar{q}} \rangle = \left\langle \langle P_q P_{\bar{q}} \rangle_V \right\rangle_S$$

inside the meson V

over the system S

STAR Data indicate: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$ **simply means correlation!**

➢ Vector meson spin alignment at HIAF energy

Lambda-(anti)Lambda spin-spin correlation

- Angular distribution of Lambda-(anti)Lambda pair production in pp/AA:

$$\frac{dN}{d\cos\theta_i^* d\cos\theta_j^*} = f_{\uparrow\uparrow}\frac{dN_{\uparrow\uparrow}}{d\cos\theta_i^* d\cos\theta_j^*} + f_{\downarrow\downarrow}\frac{dN_{\downarrow\downarrow}}{d\cos\theta_i^* d\cos\theta_j^*} + f_{\uparrow\downarrow}\frac{dN_{\uparrow\downarrow}}{d\cos\theta_i^* d\cos\theta_j^*} + f_{\downarrow\uparrow}\frac{dN_{\downarrow\uparrow}}{d\cos\theta_i^* d\cos\theta_j^*}$$
$$= \frac{1}{4}\left[1 + A\alpha_\Lambda \cos\theta_i^* + B\alpha_\Lambda \cos\theta_j^* + C\alpha_\Lambda^2 \cos\theta_i^* \cos\theta_j^*\right],$$

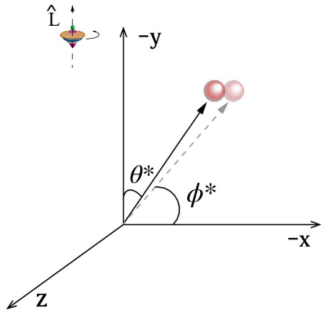
$\boldsymbol{\theta}_i^*$: angle between decayed (anti)proton *i* and spin direction in each hyperon's rest frame

➢ In particular for global polarization in heavy ion collision:

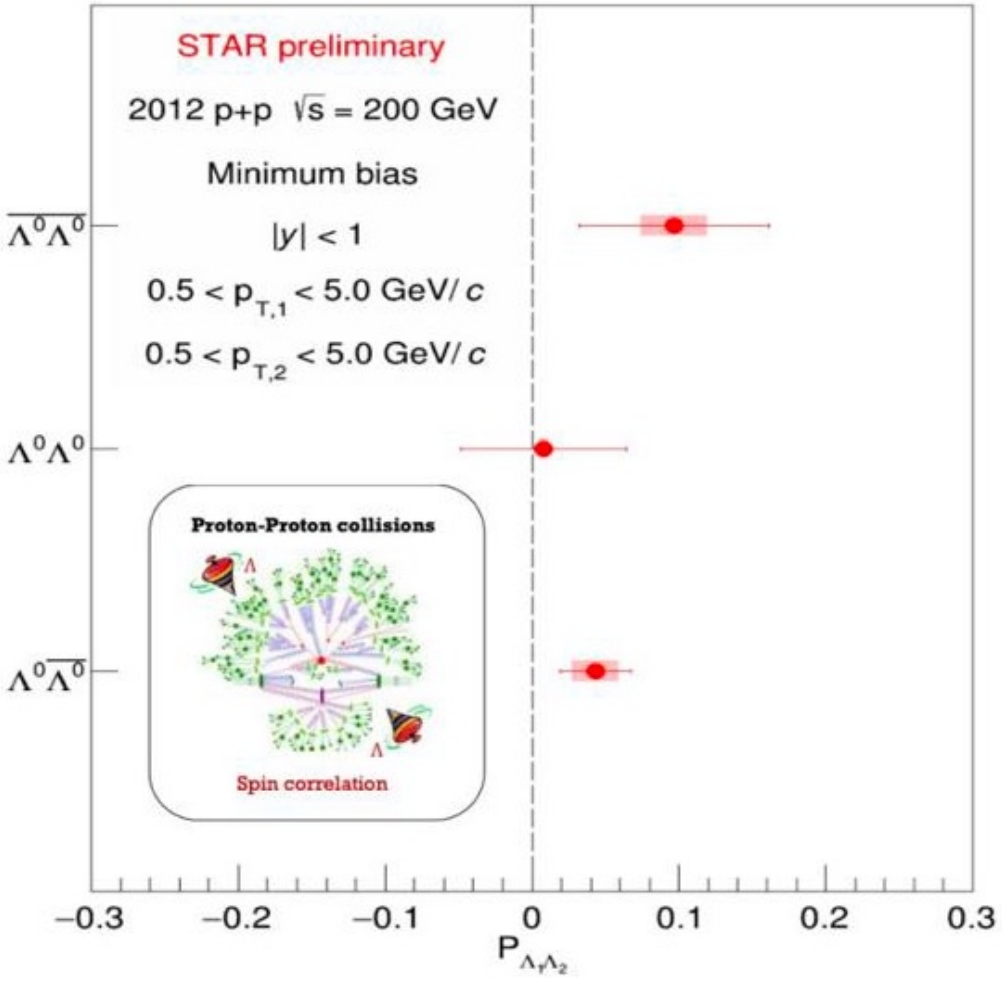
$$c'_{\Lambda\Lambda} = \frac{9}{\alpha_\Lambda^2}\langle\cos\theta_i^* \cos\theta_j^*\rangle - P_\Lambda^2. \quad \text{Or} \quad c'_{\Lambda\Lambda} = \frac{64}{\pi^2\alpha_\Lambda^2}\langle\sin\Delta\phi_i^* \sin\Delta\phi_j^*\rangle - P_\Lambda^2,$$

$P_{\boldsymbol{\Lambda}}$: hyperon global polarization along reaction plane
$\Delta\Phi^*$: azimuthal angle of decay proton relative to the reaction plane

- D.Y. Shen, J.H. Chen, A.H. Tang, arXiv:2407.21291
- H.C Zhang, S.Y. Wei, Phys.Lett.B 839 (2023) 137821



- Lambda-(anti)Lambda spin correlation in pp at 200GeV at STAR:



- An indication of $\Lambda - \overline{\Lambda}$ spin correlation in pp, analysis in AA ongoing at STAR

Spin observables probing quark spin quantities

- Complete list of spin observables in AA collisions, including spin correlations of hyperon pair production !

Hadron	Measurables	Sensitive quantities
Spin 1/2 (hyperon H)	Hyperon polarization P_H	average quark polarization $\langle P_q \rangle$
	Hyperon spin correlation $c_{H_1H_2}, c_{H_1\bar{H}_2}$	long range spin correlations $c_{qq}, c_{q\bar{q}}$
Spin 1 (Vector mesons)	Spin alignment ρ_{00}	local spin correlations $c_{q\bar{q}}$
	Off diagonal elements $\rho_{m'm}$	local spin correlations $c_{q\bar{q}}$
Spin 3/2 $J^P = \left(\frac{3}{2}\right)^+$ baryons	Hyperon polarization P_{H^*} or S_L	average quark polarization $\langle P_q \rangle$
	Rank 2 tensor polarization S_{LL}	local spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	local spin correlations c_{qqq}

Z. Zhang, J.P. Lv, Z.H. Yu, and Z.T. Liang, arXiv: 2406.03840

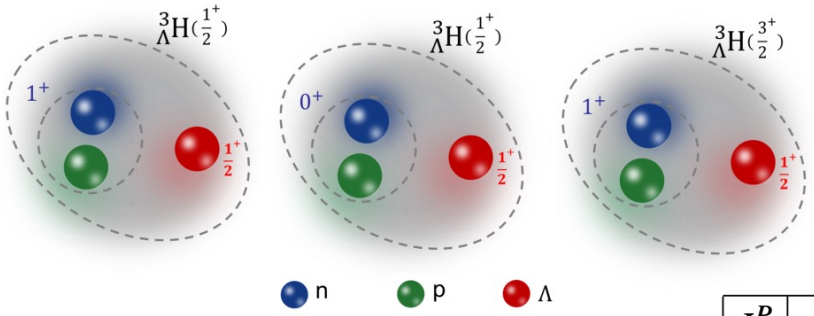
Systematic studies of quark spin correlations in QGP!

- Slides from Z. T. Liang

Global polarization of hyper-nuclei in AA collision

- Possible spin structure of hypertriton:

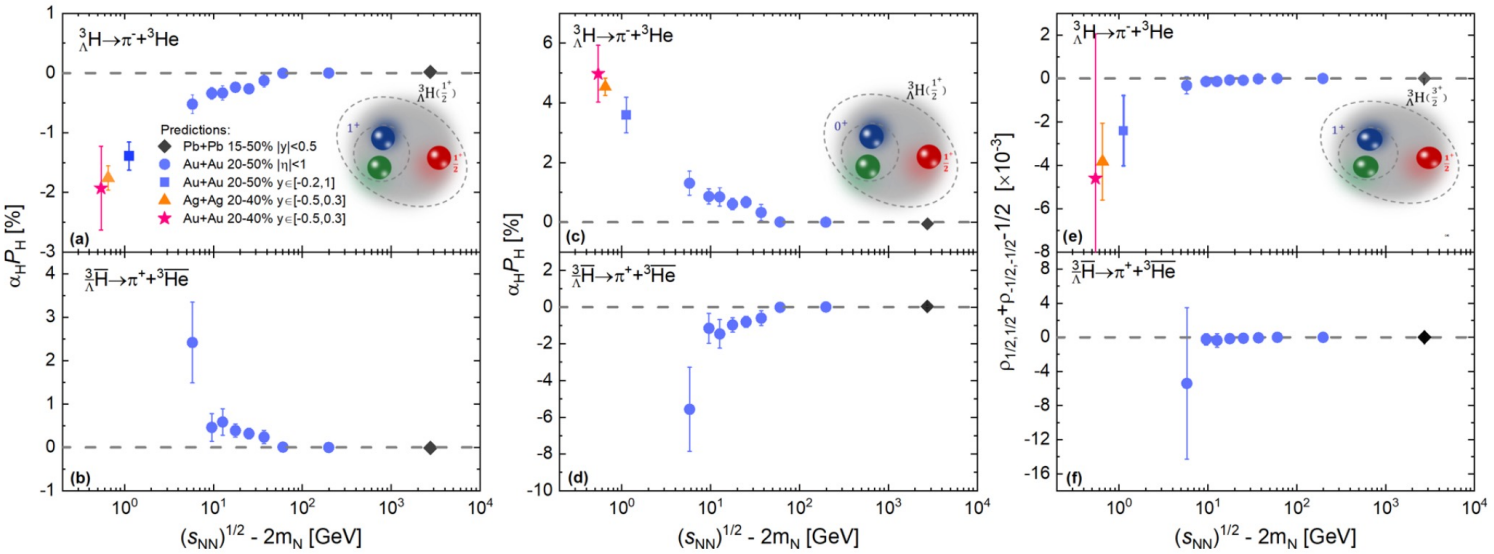
- K.J. Sun et. al. arXiv: 2405.12015



$$^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\mathrm{He}$$

- Angular distribution via hypertriton decay:
- Polarization predictions:

J^P	structure	decay mode	$\frac{dN}{d\cos\theta^*}$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{3}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}\left(1 - \mathcal{P}_\Lambda^2(3\cos^2\theta^* - 1)\right)$



Summary

- Lot of interesting spin measurements can be done at HIAF energy
  - Spontaneous polarization to study QCD effect with proton beam
    - ✓ Λ, Ξ hyperon polarization
    - ✓ Vector measurement spin alignment
  - Global polarization to study QCD medium property in heavy ion collisions with ion beam
    - ✓ Λ, Ξ hyperon polarization
    - ✓ Vector measurement spin alignment
    - ✓ Di-hadron spin correlation
- With polarized target, more spin physics can be performed (not covered)

Summary

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谢谢！

Measurement of global polarization at STAR

- The Λ polarization can be determined through the angular distribution of its weak decay product.

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \boldsymbol{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*)$$

$\boldsymbol{P}_H$: hyperon polarization
$\hat{\boldsymbol{p}}_B$: unit vector of daughter baryon momentum
α_H: hyperon decay parameter

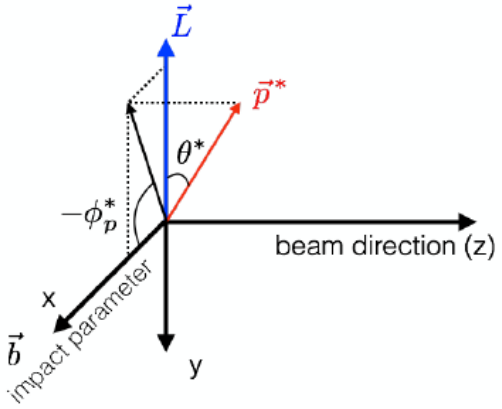
- At STAR, the global polarization has been extracted with

First adopted in PRC76, 024915 (2007)

$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{1}{A_0} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{Res(\Psi_1)}$$

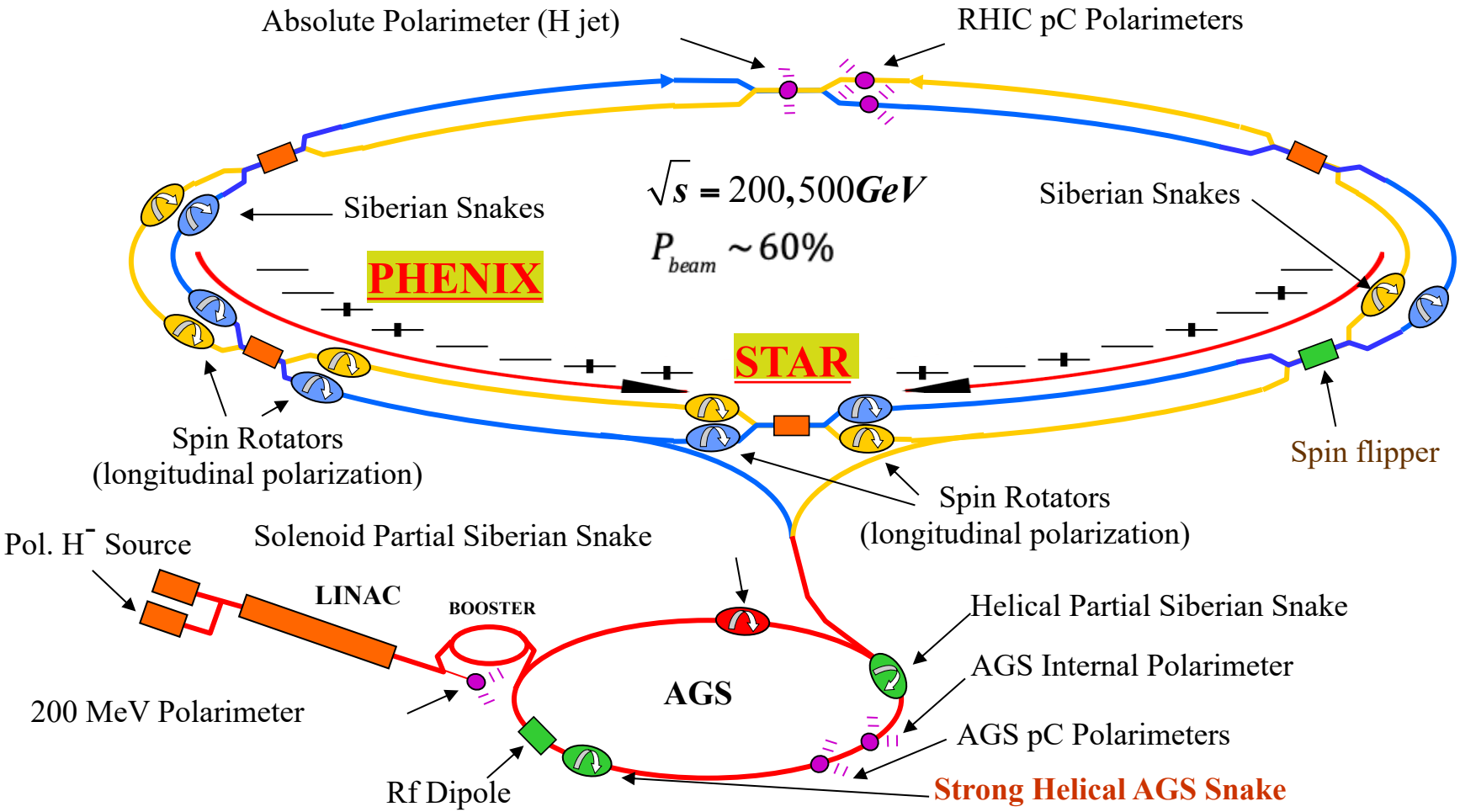
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$

Ψ_1: azimuthal angle of 1st order reaction plane



-In this way, the detector acceptance is largely avoided, but rather a scale effect with A_0

RHIC- 1st polarized proton-proton collider



- Spin direction changes from bunch to bunch, longitudinal or transverse
- Two main experiments: sPHENIX (PHENIX) & STAR