重离子碰撞中的整体极化实验测量

徐庆华

山东大学

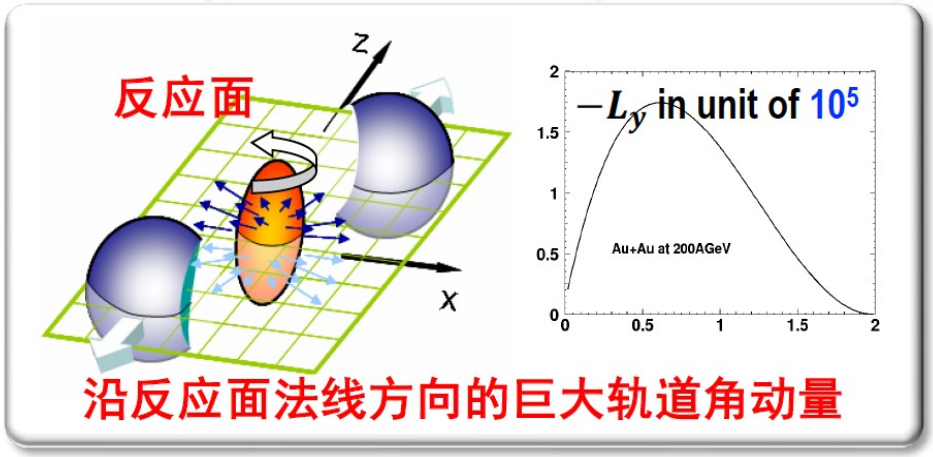
极端条件下的QCD研讨会

2026. 8. 18-20，烟台大学

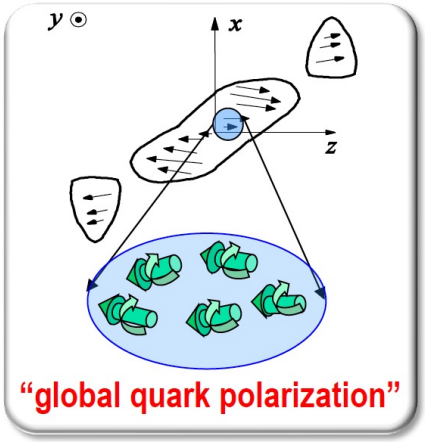
Λ Global polarization in heavy ion collisions

- Globally polarized quark gluon plasma (QGP) in non-central relativistic heavy ion collisions --> global polarization of hadrons

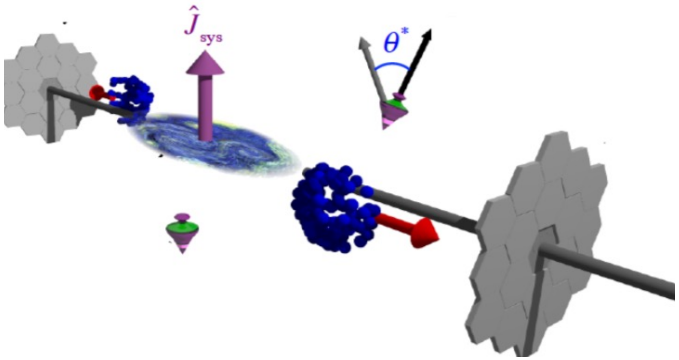
Zuo-tang Liang & Xin-Nian Wang, PRL94, 102301(2005); PLB629, 20(2005), 1000+ citation



QCD自旋—轨道相互作用导致



强子化导致（组合）



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

●超子整体极化

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

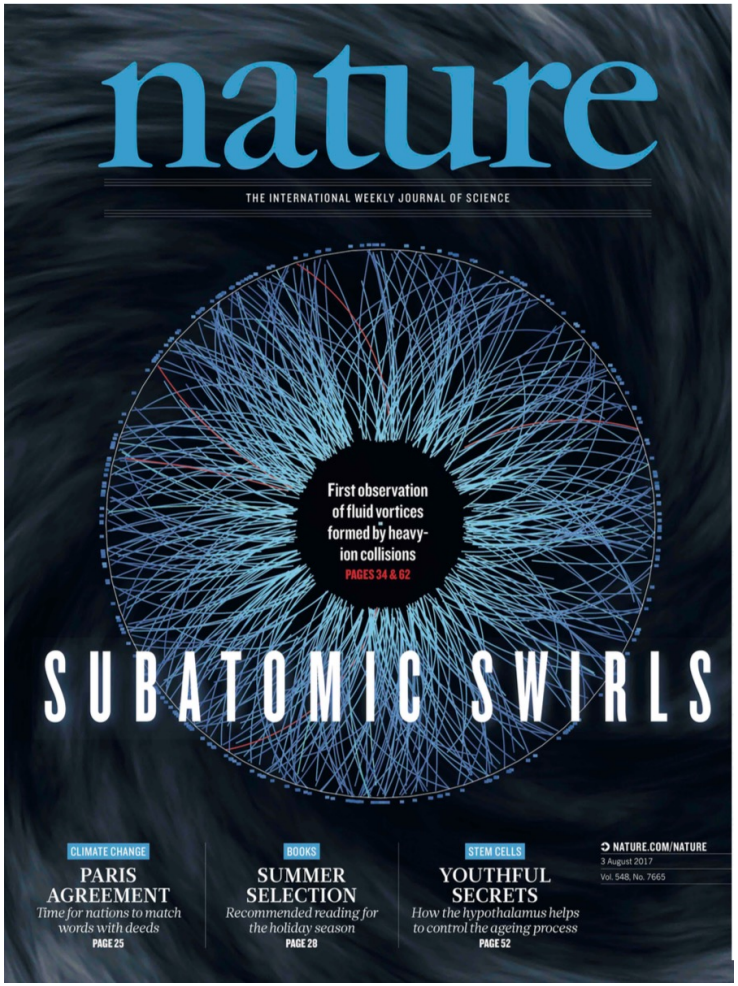
●矢量介子整体自旋排列

(spin alignment)

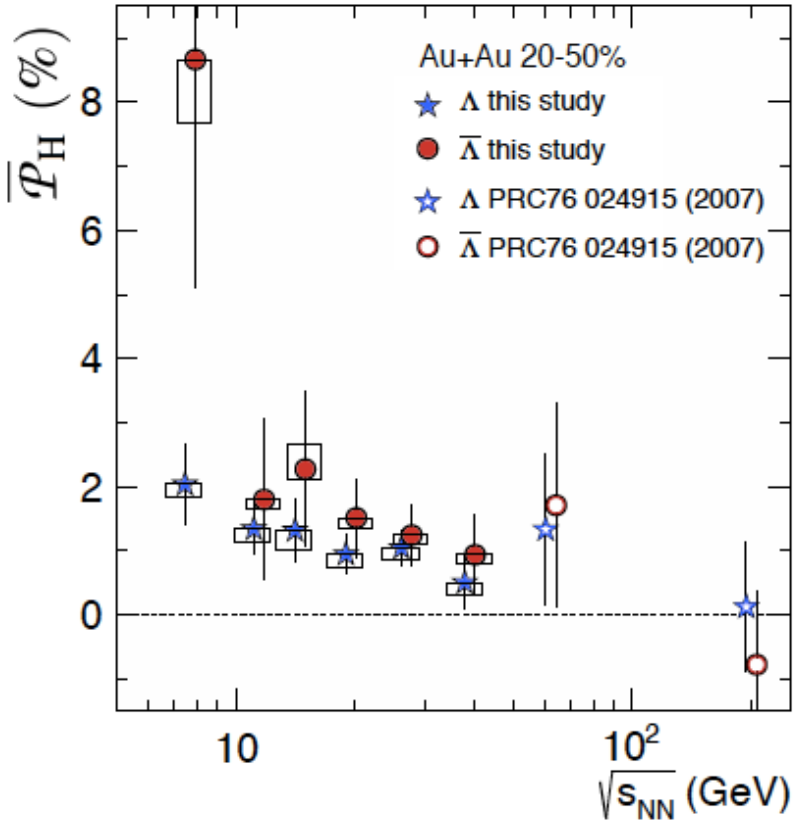
$$\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$$

Λ Global polarization in heavy ion collisions

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

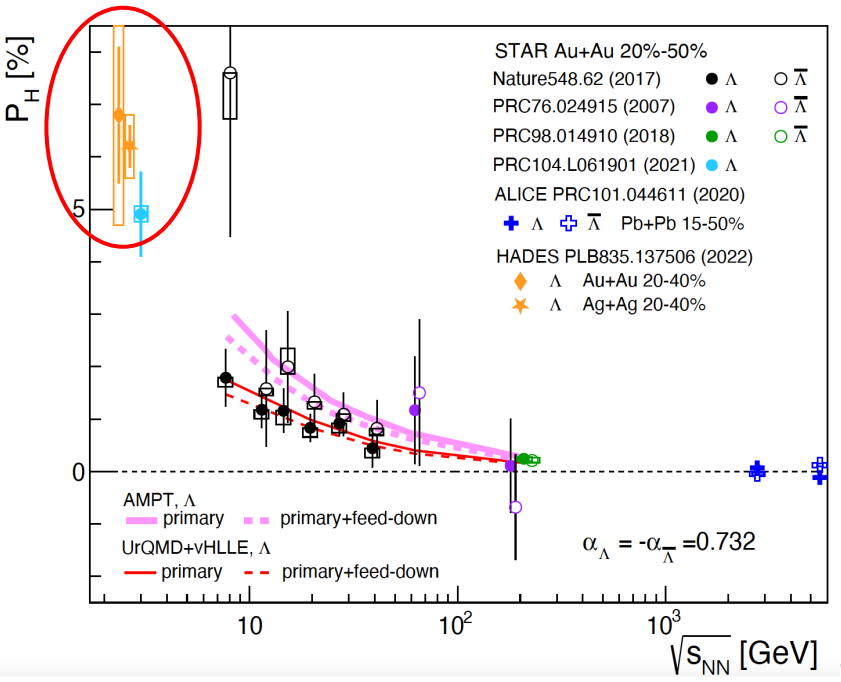


STAR, Nature 548 (2017)62



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

Energy dependence of global polarization

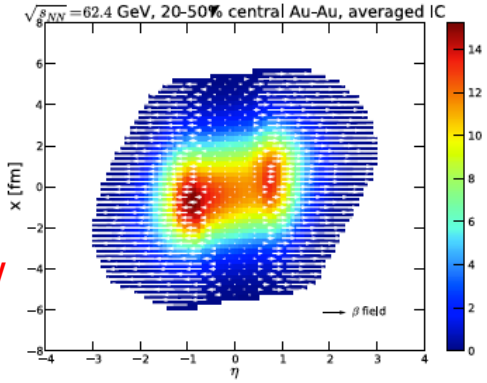


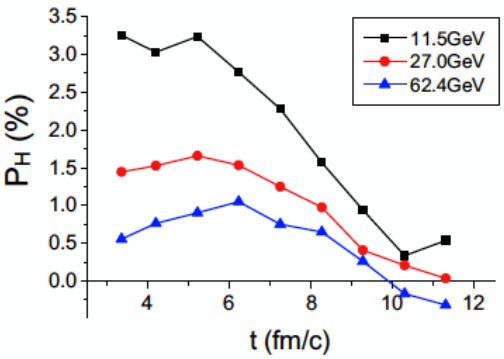
- HADES data at √s=2.4GeV Au+Au and 2.7 GeV Ag+Ag
- STAR data down to √s= 3 GeV
- ALICE results at 2.76 and 5.02 TeV Pb+Pb, consistent with zero within uncertainties

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

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

- Increasing trend toward lower energy described by various models
- Stronger shear flow in forward/ backward regions+ baryon stopping with limited acceptance
- Polarization continue to increase at low energy ?
- Connection to transverse polarization w.r.t. production plane? -> STAR FXT

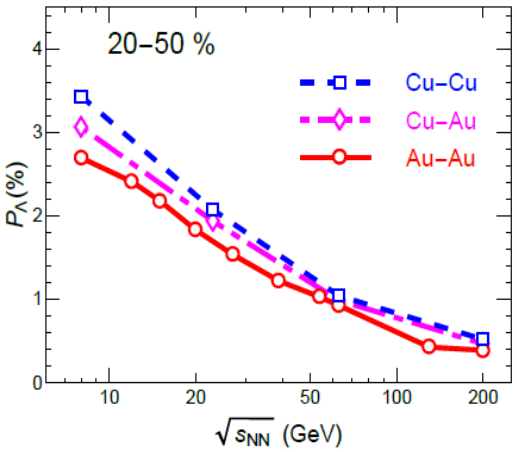




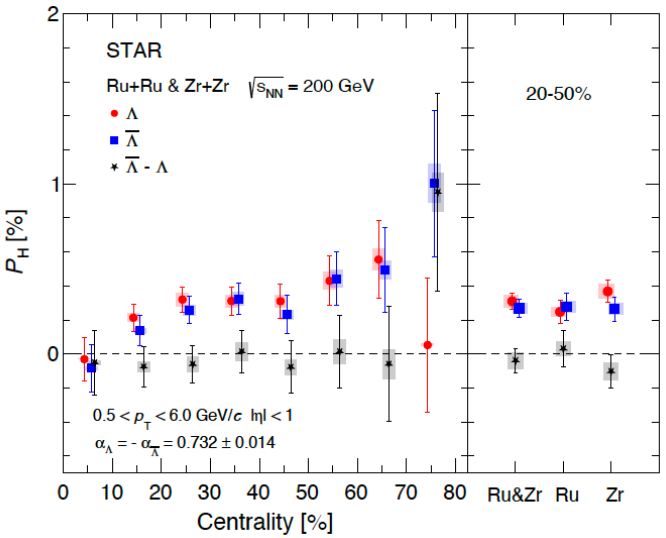
Global polarization in Ru+Ru and Zr+Zr collisions

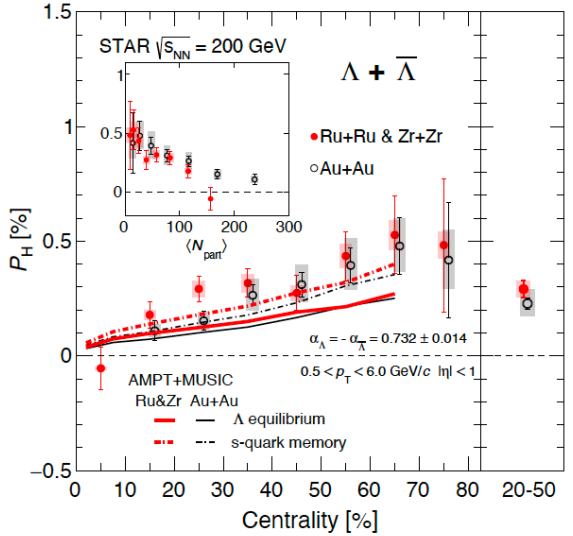
- Global polarization difference from different magnetic field in Zr+Zr and Ru+Ru?
- System size dependence of global polarization?

Shuzhe Shi, Kangle Li, Jinfeng Liao
PLB 788(2019) 409413



STAR, PLB 870 (2025) 139891





- Significant global polarization observed, P_Λ and $P_{\bar{\Lambda}}$ increase with centrality.
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru/Zr+Zr and Au+Au

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

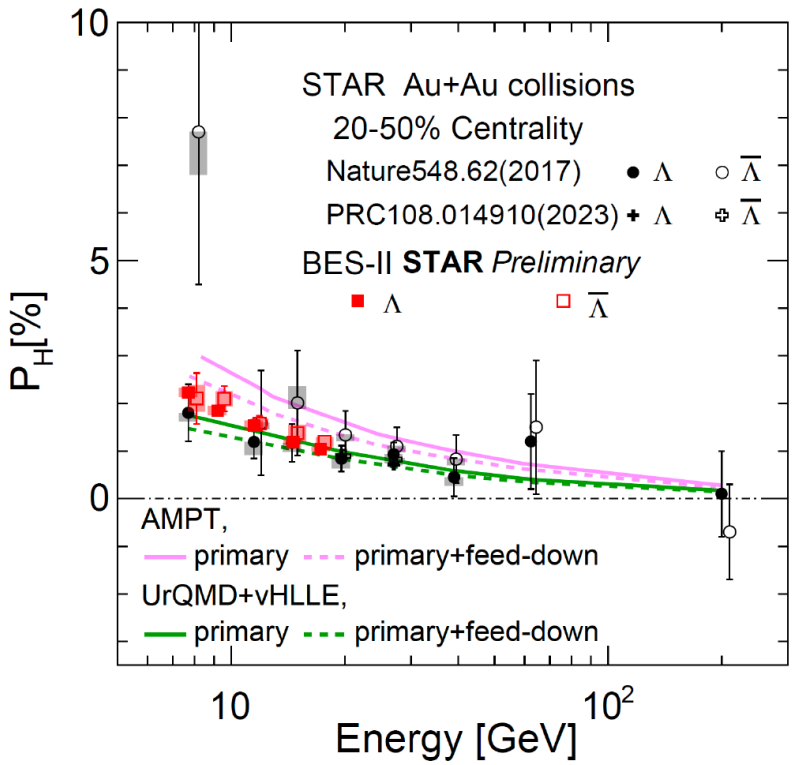
- Splitting of $\Lambda(\bar{\Lambda})$ global polarization due to the magnetic field ?

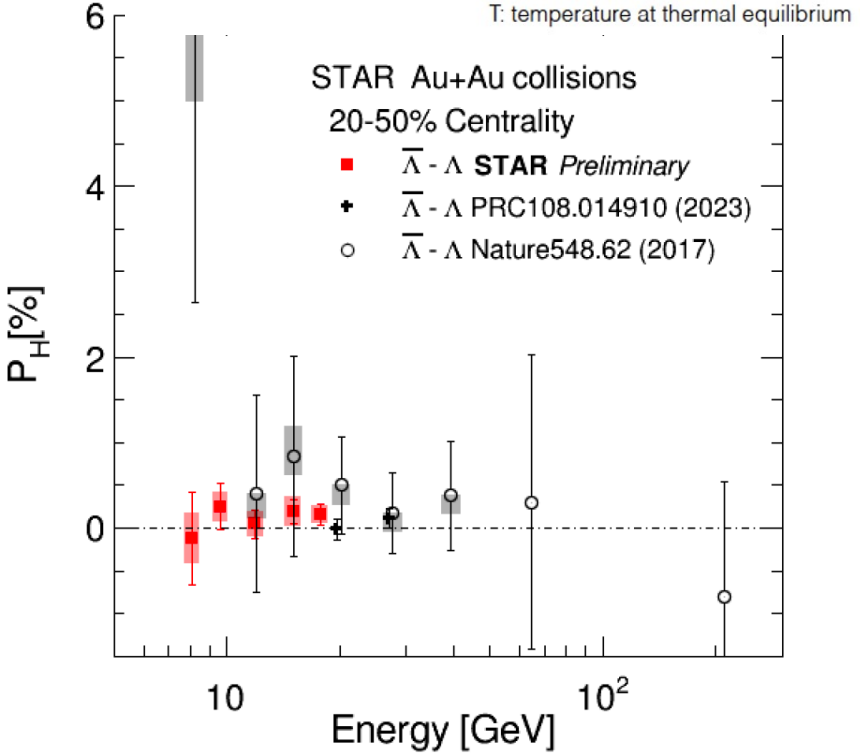
$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

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

μ_Λ: Λ magnetic moment

T: temperature at thermal equilibrium

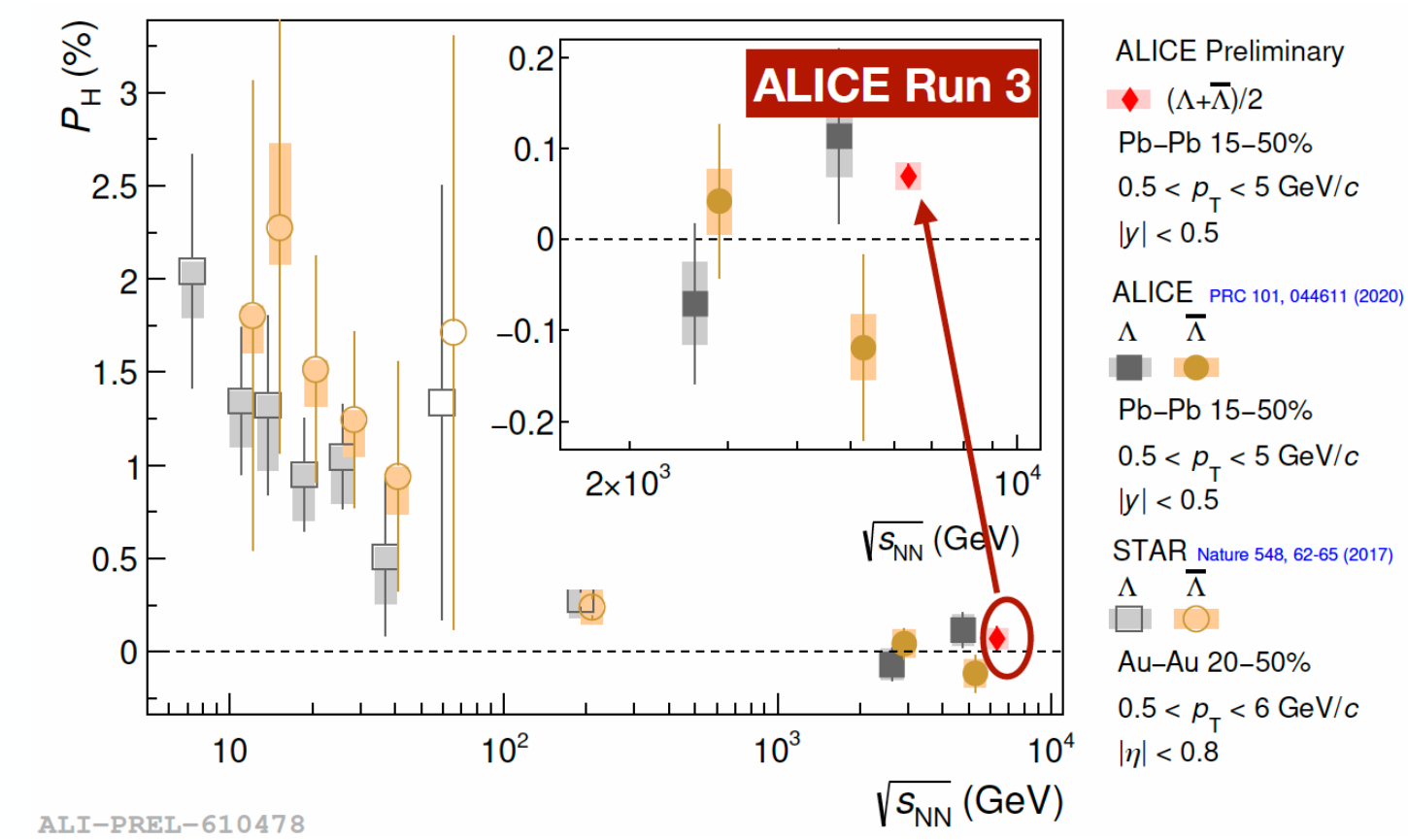




- ➢ No splitting between $\Lambda(\bar{\Lambda})$ polarization with 10 times more statistics than BES-I
- ➢ More data coming from STAR BES-II FXT with energy down to 3 GeV

$\Lambda(\overline{\Lambda})$ polarization from ALICE with high precision

- Observation of Λ global polarization at LHC energies with 5σ
  Consistent with the empirical prediction based on d*v*1/d*y*



Ξ and Ω global polarization at STAR

- 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

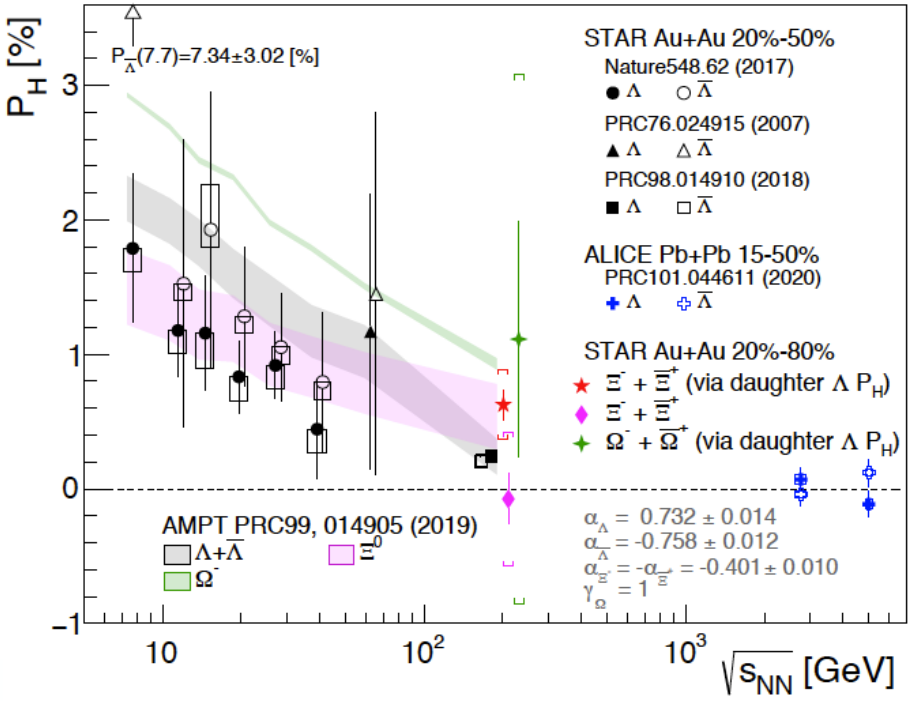
$$\mathbf{P}^*_\Lambda = C_{\Xi-\Lambda}\mathbf{P}^*_\Xi = \tfrac{1}{3}(1+2\gamma_\Xi)\,\mathbf{P}^*_\Xi. \qquad C_{\Xi-\Lambda} = +0.944$$

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

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

$$\alpha_\Omega^2 + \beta_\Omega^2 + \gamma_\Omega^2 = 1$$

STAR, PRL126, 162301 (2021)



- AMPT and hydro calculations capture the trend:

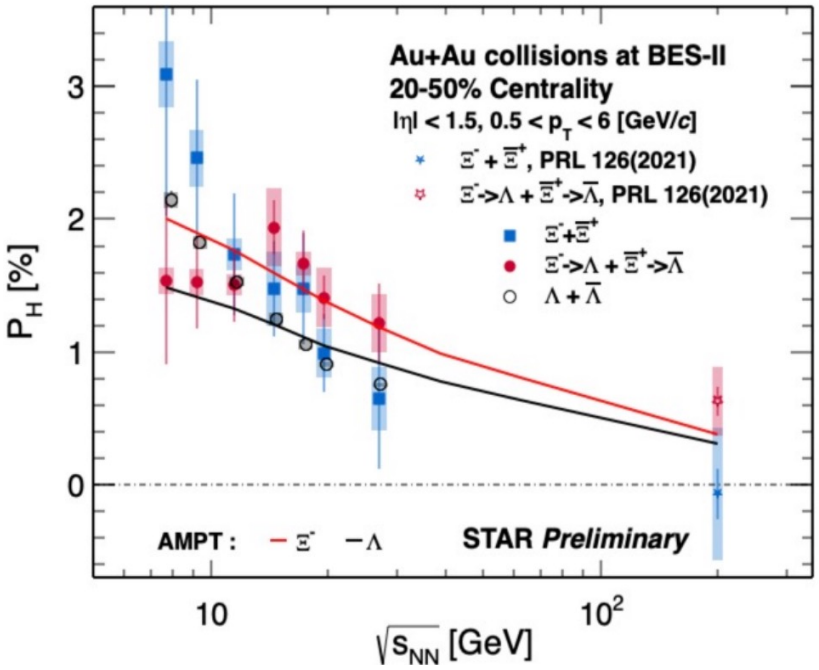
  D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)

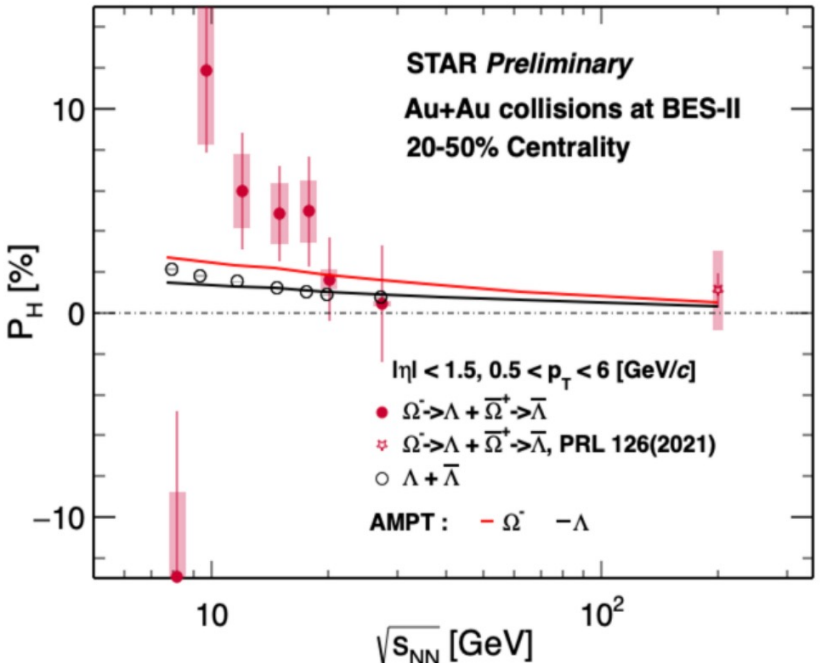
Ξ, Ω global polarization with STAR BES-II

- First measurement of Ξ, Ω polarization with BES data, significant Ξ polarization observed, decrease trend with collision energy
- No significant difference between Λ and Ξ global polarization within uncertainties
- A hint of larger Ω polarization than Λ and Ξ in low energies

$$P_\Omega \approx 5/3 P_\Lambda$$

Model: *H. Li et al , PLB 827, 136971 (2022)*

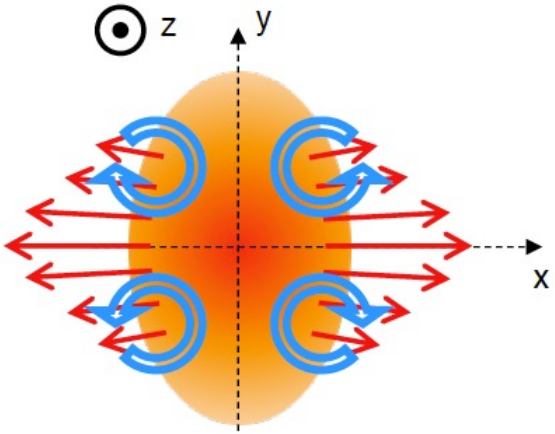


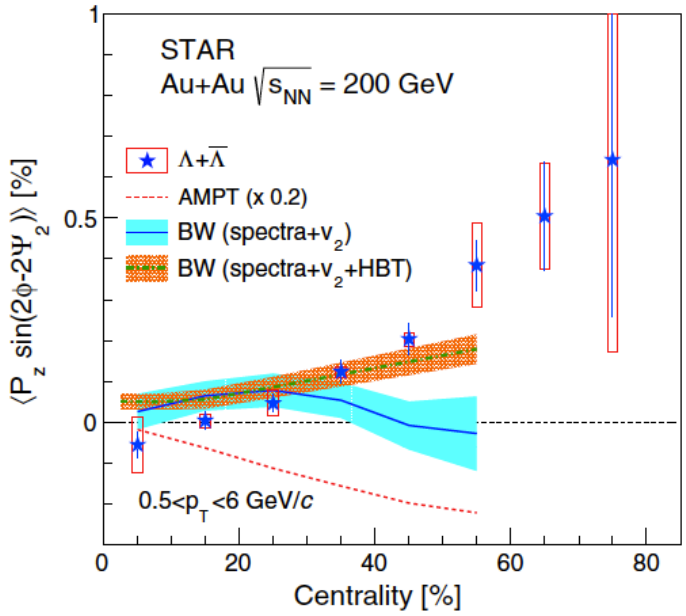


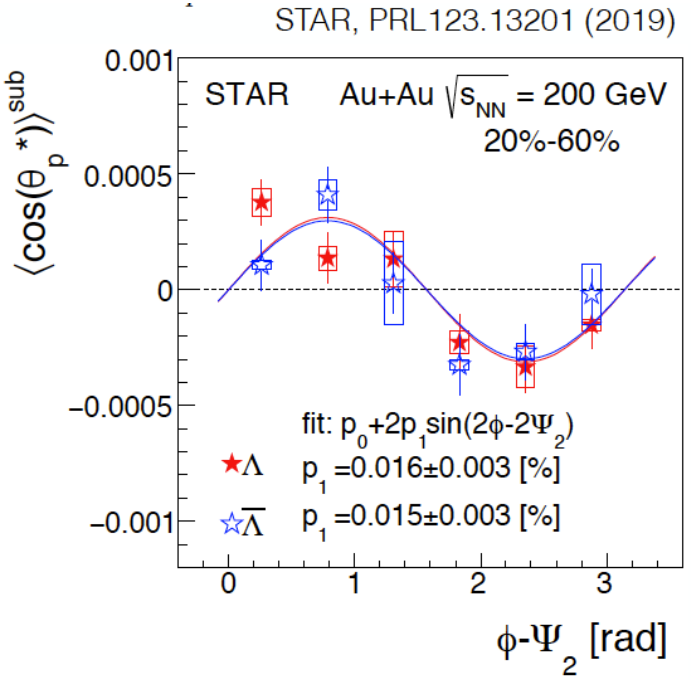
γ_Ω =1 is preferred, instead of -1, following the same trend as other hyperons

Polarization along the beam direction

"Local polarization"





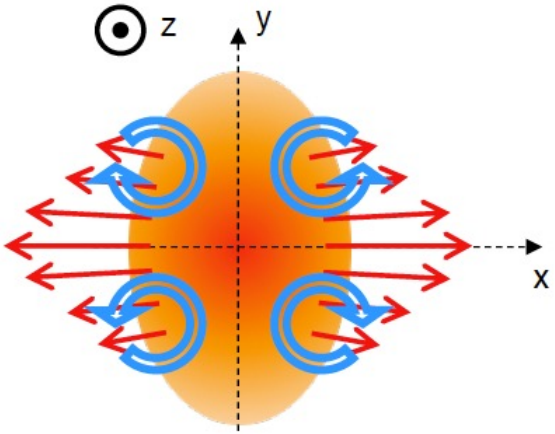


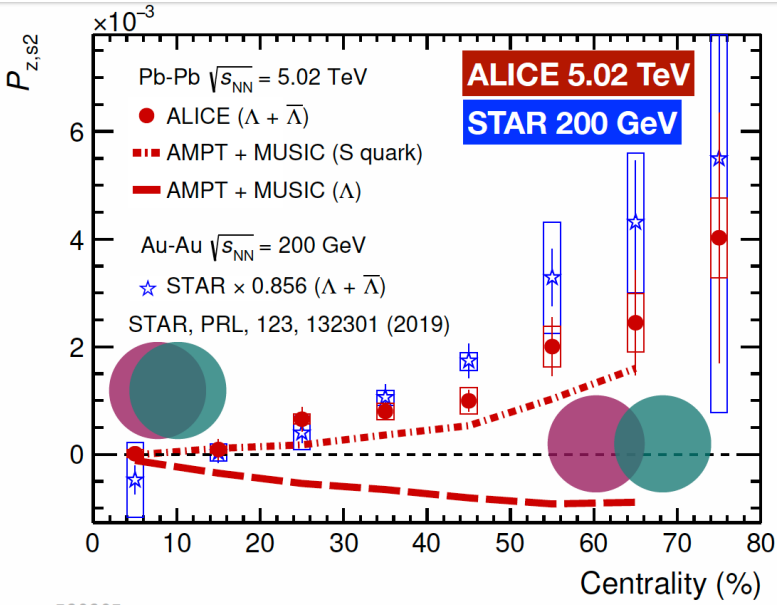
- Polarization along the beam direction expected from the "elliptic flow"
- STAR data indeed show such a longitudinal polarization Pz depending on azimuthal angle (sine function)
- Blast Wave model captures the trend with correct sign, while many others do not.

STAR, PRL123, 132301 (2019)

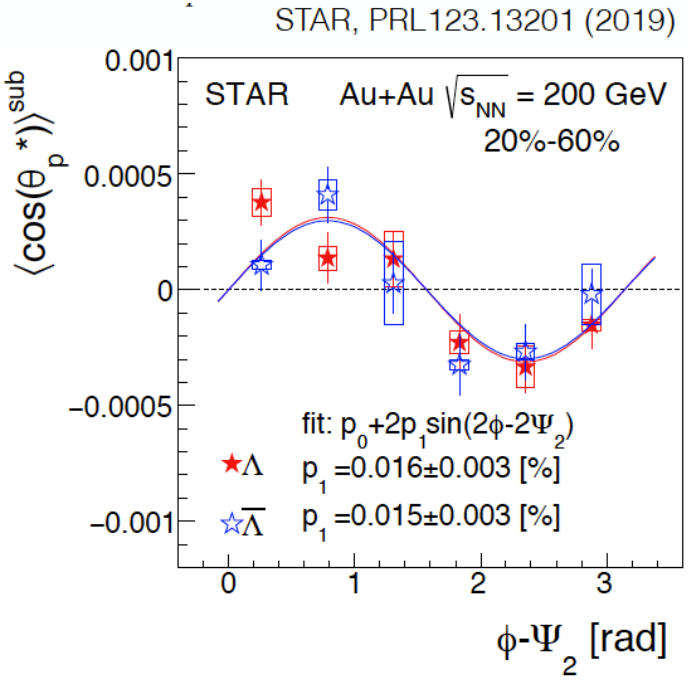
Polarization along the beam direction

"Local polarization"





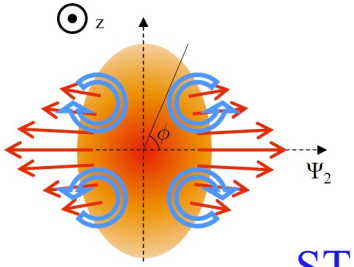
STAR, PRL123, 132301 (2019)
ALICE, PRL128, 172005 (2022)

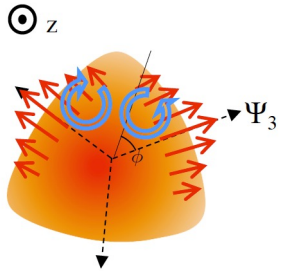


- Polarization along the beam direction expected from the "elliptic flow"
- STAR data indeed show such a longitudinal polarization Pz depending on azimuthal angle (sine function)
- Including a shear term may resolve the sign discrepancies

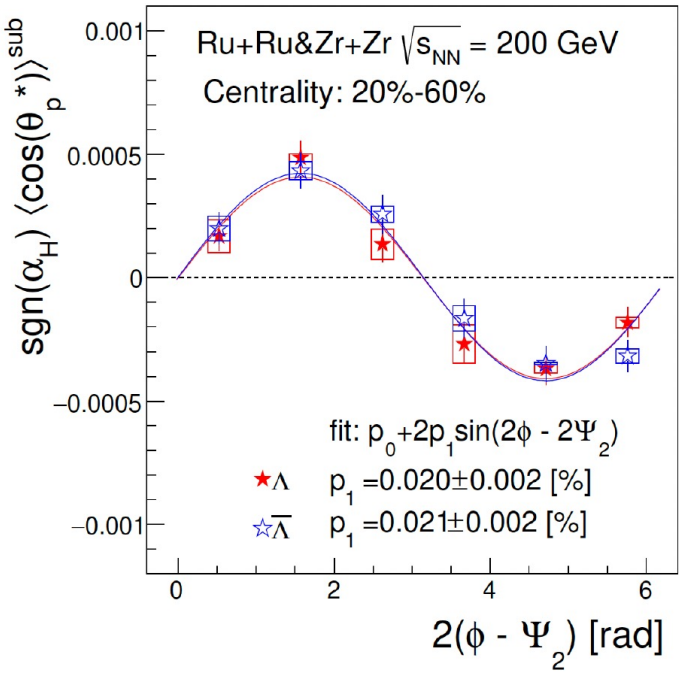
Λ polarization along the beam direction

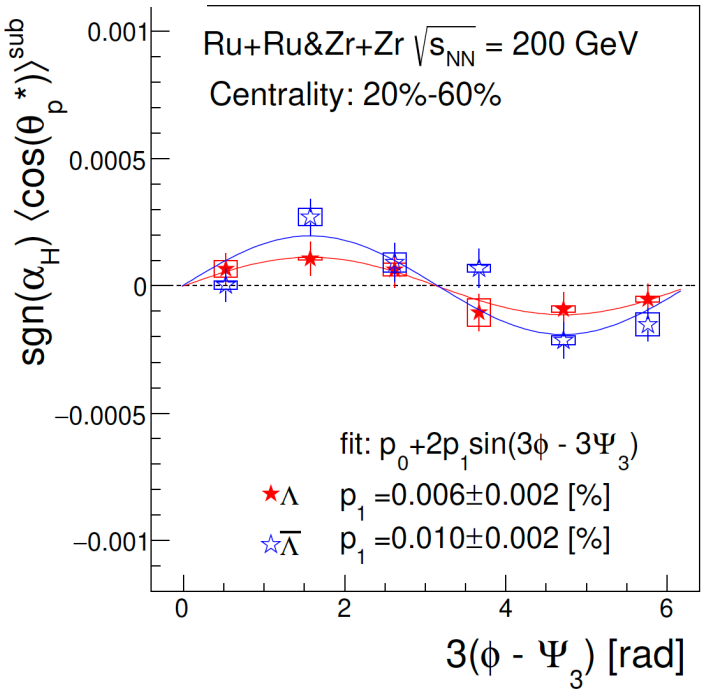
"Local polarization" in isobar collisions:





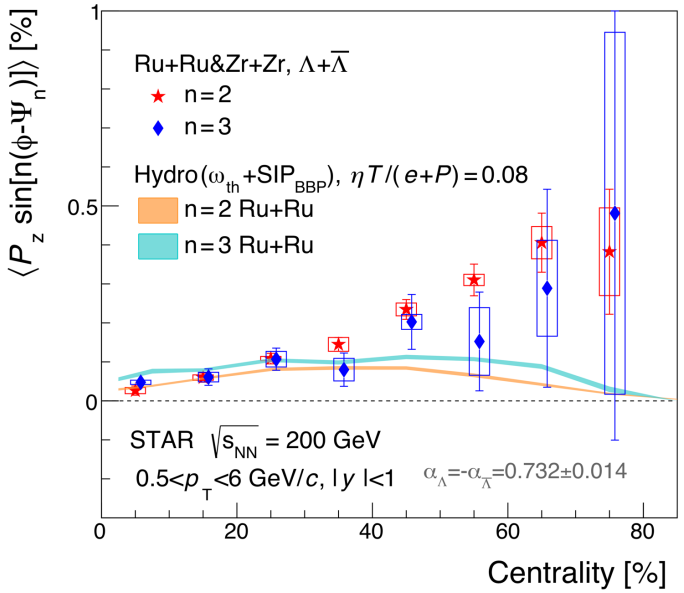
STAR, PRL131, 202301(2023)

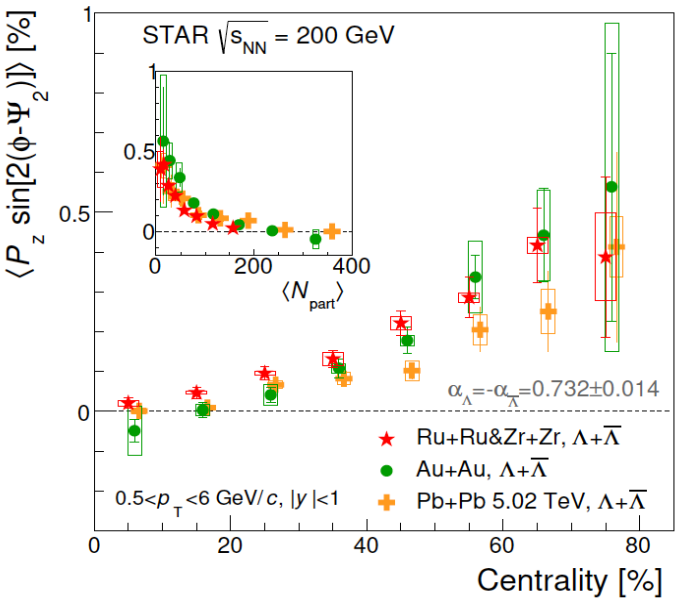




- First measurement relative to the 3^{rd}-order event plane Ψ_3
  - Similar pattern to the 2^{nd}-order, indicating v_3-driven polarization

Local polarization in Au+Au and iso-bar collisions

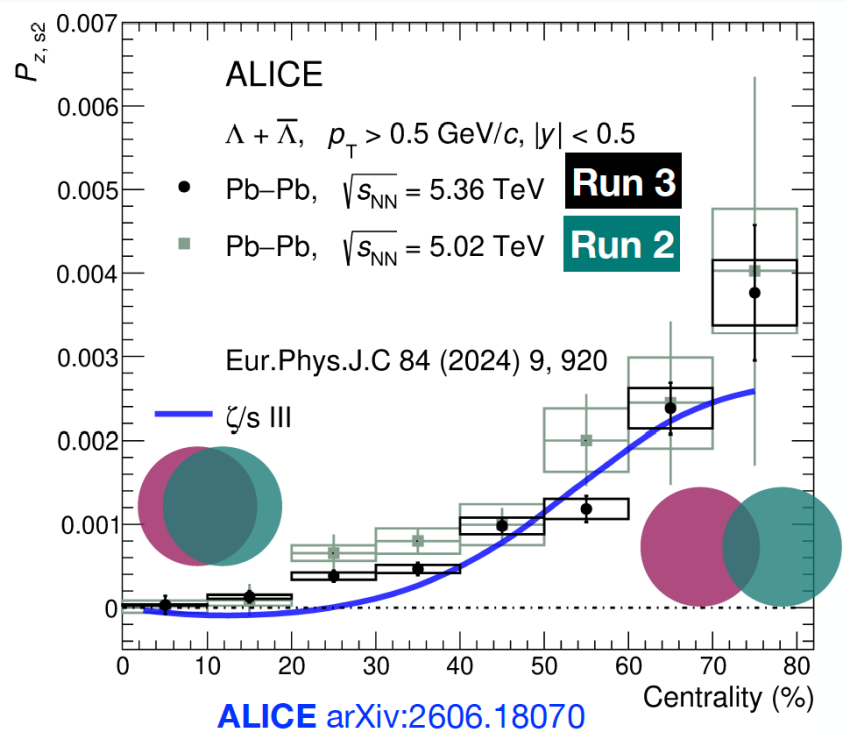


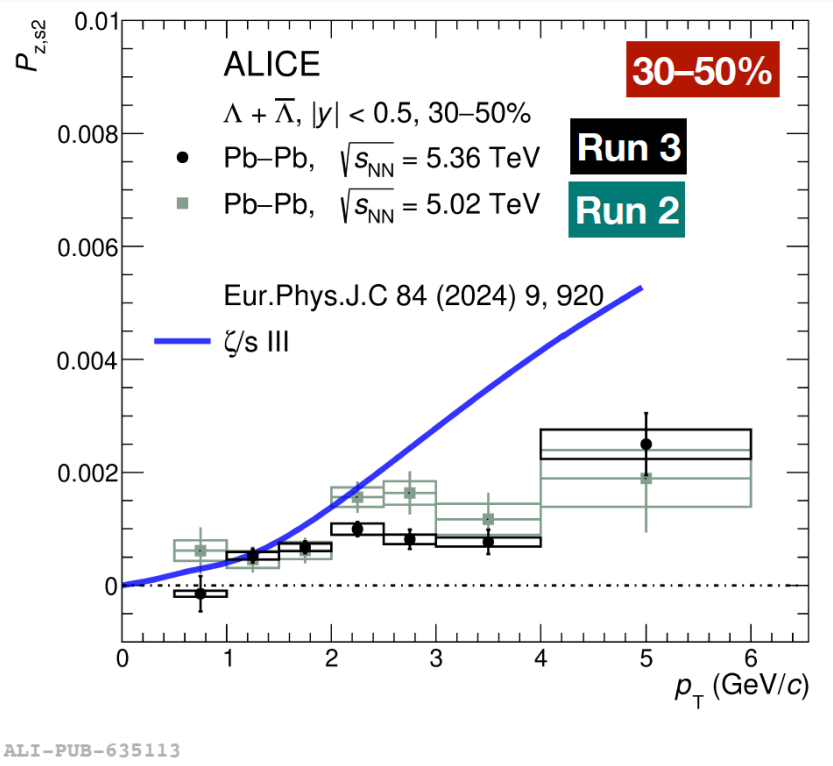


- Comparable 2^{nd} and 3^{rd} order sine coefficients of $P_{z,n}$, especially in most central events
- Hydrodynamic models with shear term reasonably describes the data for central collisions, but not for peripheral, Additional constraint on shear viscosity
- $P(z,n)$ from Isobar data comparable to Au+Au and Pb+Pb
  - ✓ A hint of system size dependence rather than energy dependence

ALICE, PRL128, 172005 (2022)
STAR, PRL131, 202301(2023)

New Results from ALICE on $\Lambda(\overline{\Lambda})$ local polarization

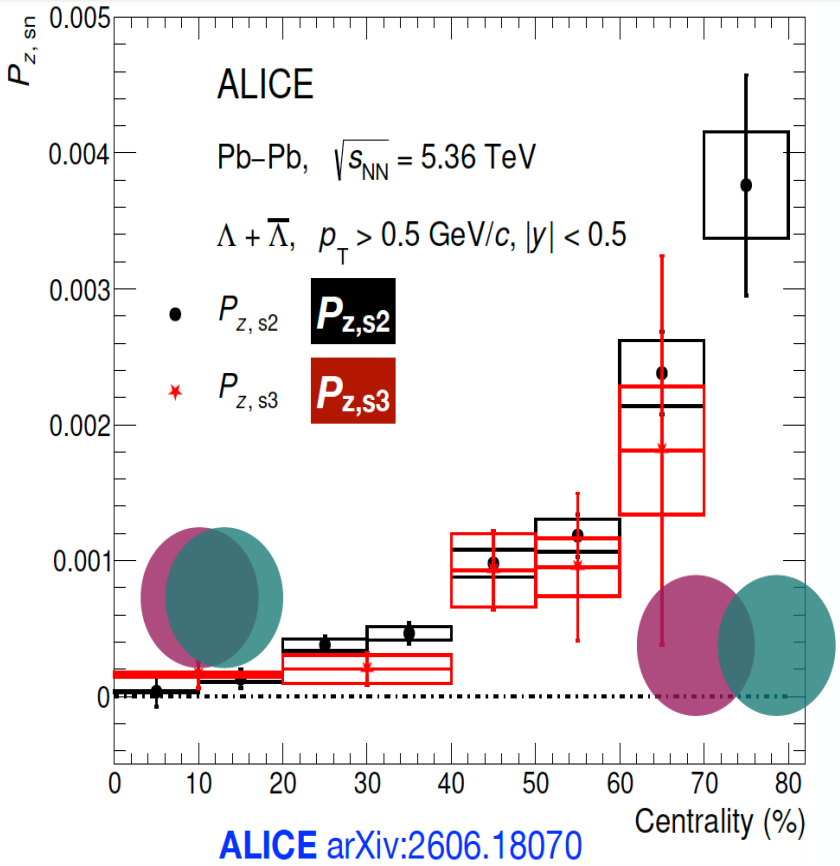


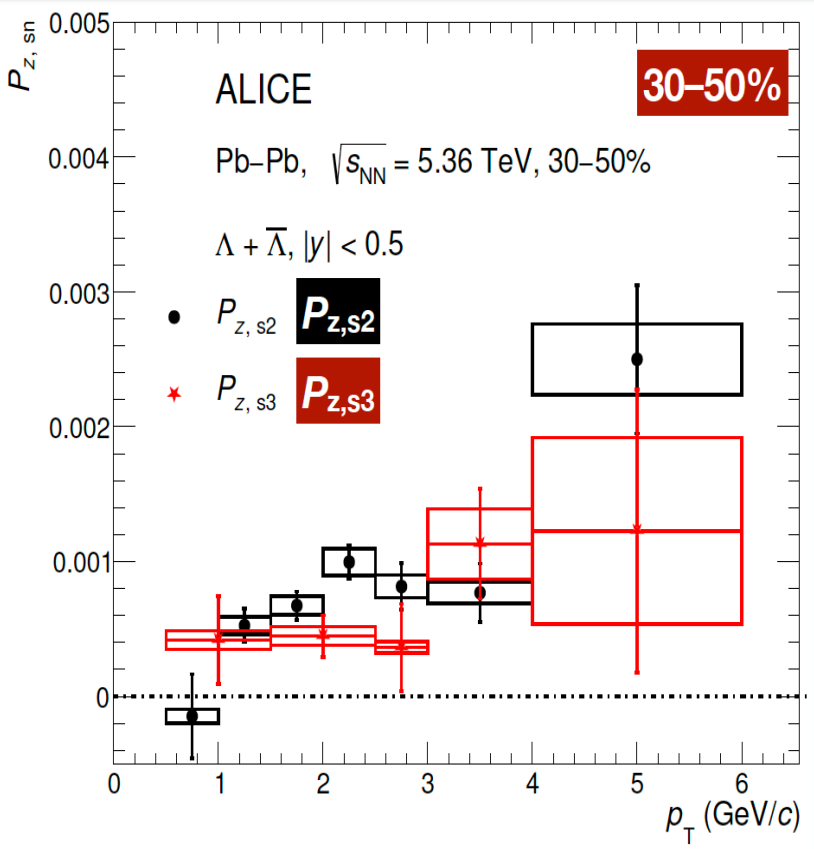


- Good agreement for data & model with shear-induced term on centrality dependence
- The measured p_T dependence is not fully described by the model

New Results from ALICE on $\Lambda(\overline{\Lambda})$ local polarization

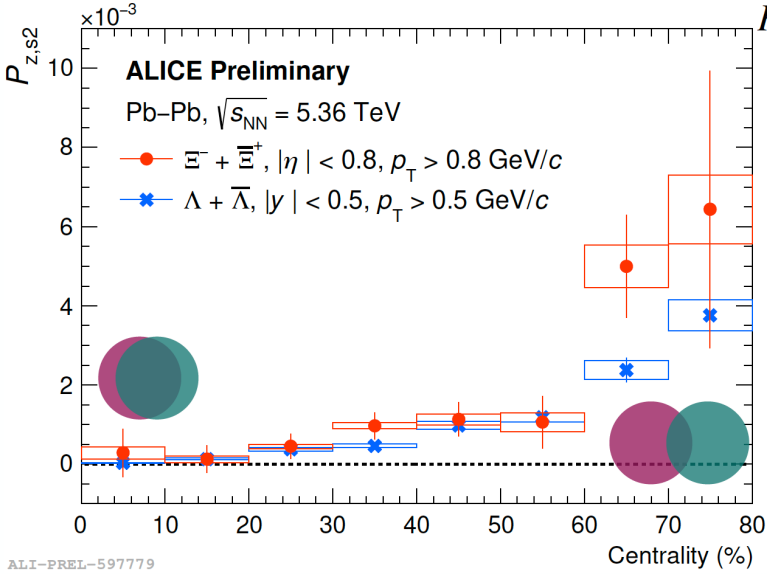
- Polarization induced by triangle flow
- $P_{z,s3}$ is compatible with $P_{z,s2}$, despite the v_3 is smaller v_2



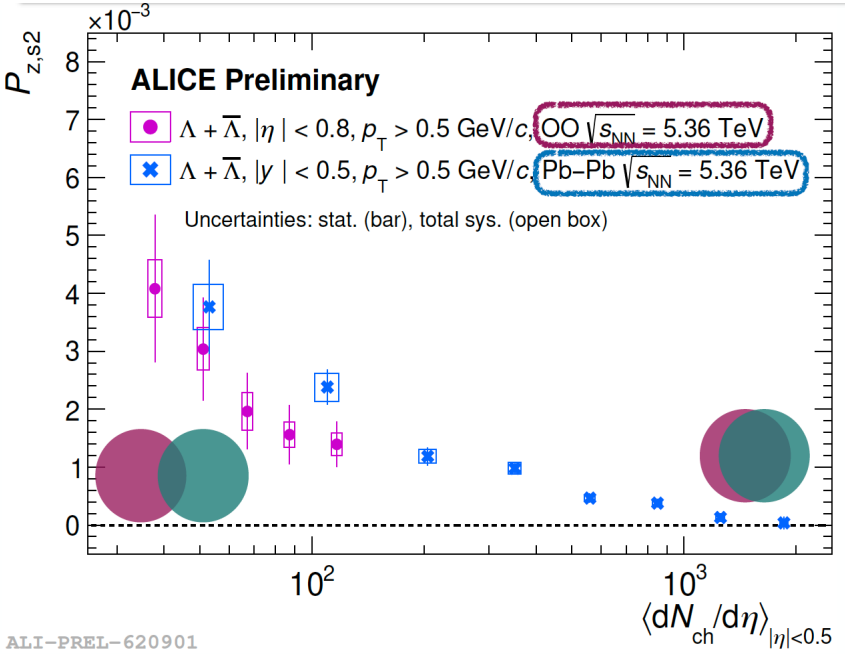


New Results from ALICE on local polarization

- 1st results of local polarization of Ξ in Pb+Pb



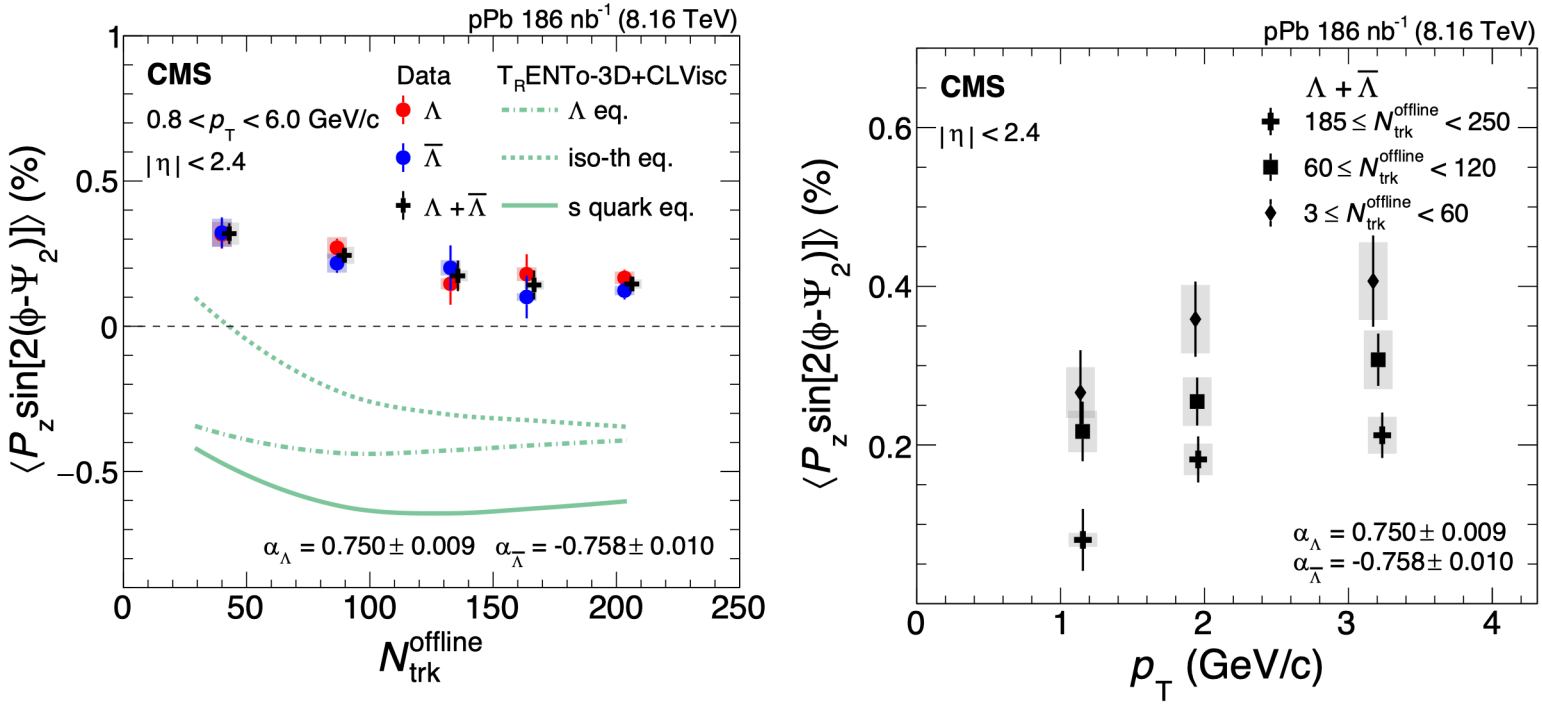
- First measurement of Λ longitudinal polarization in O+O collisions
- Significantly non-zero values for 0–50% centrality



Longitudinal polarization in p+Pb at CMS

- First Λ polarization measurement in small collision systems

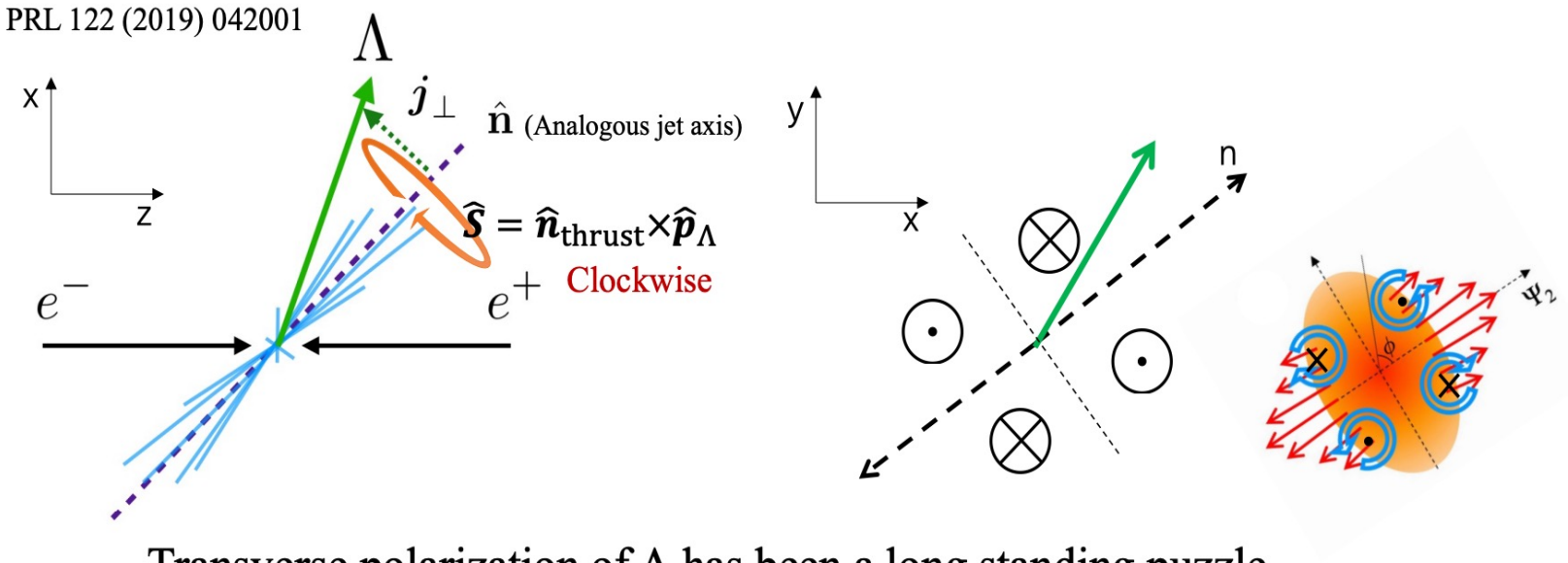
CMS, PRL 135 (2025) 132301



- Significant Λ local polarization observed in p+Pb collisions
- Challenge the current interpretation for polarization mechanism in heavy ion collisions

Longitudinal polarization in small system at CMS

- Is it from cold-QCD effect like polarizing fragmentation function ?



Transverse polarization of Λ has been a long standing puzzle
Recent Belle measurement in e^+e^- shows a significant signal wrt thrust axis
Projection into x-y plane introduce a P_z wrt thrust axis (n)
Thrust axis coincide with 2nd order event plane at low multiplicity

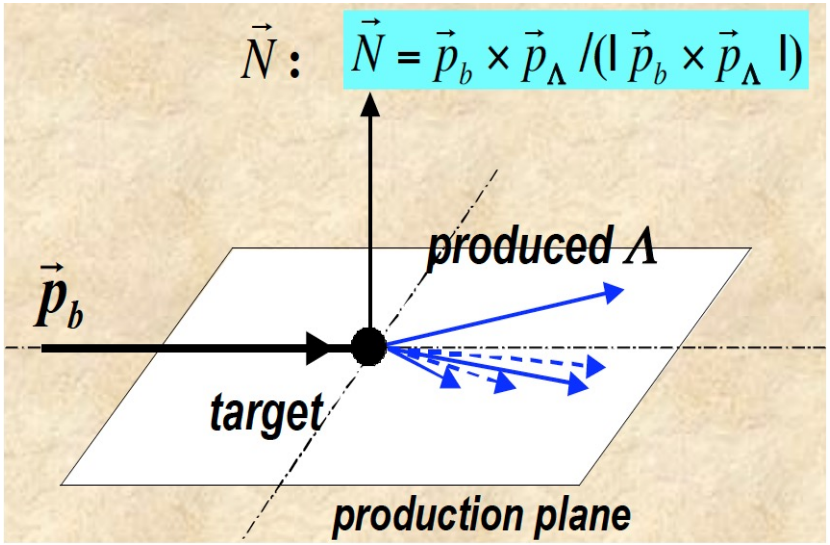
Induced transverse Λ polarization

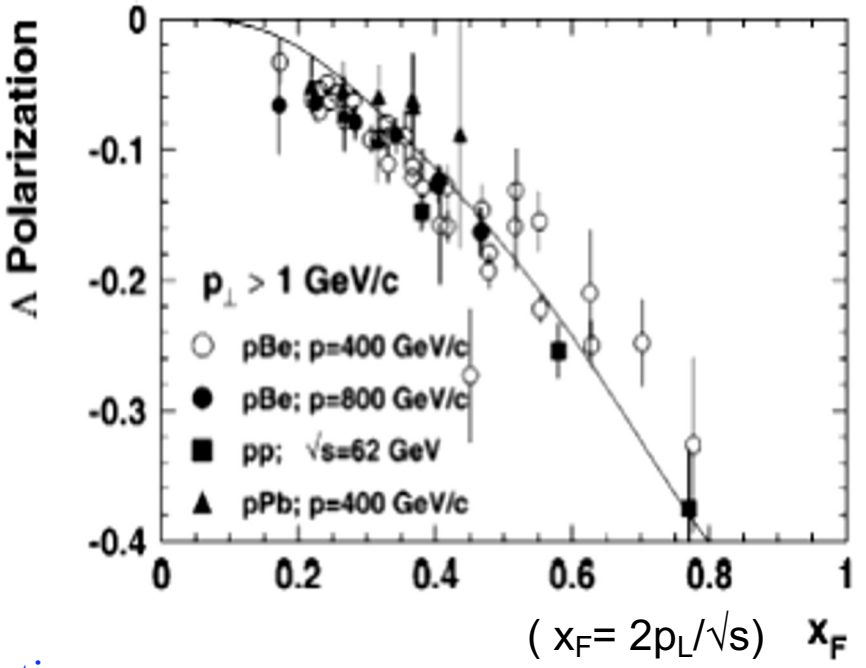
- Large polarization with unpolarized beam p + p/A $\rightarrow \Lambda^{\uparrow}$ + X , observed in different experiments.

  -G.Bunce *et al* PRL36,1113,(1976) -620 citations, followed by 50+ measurements

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

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



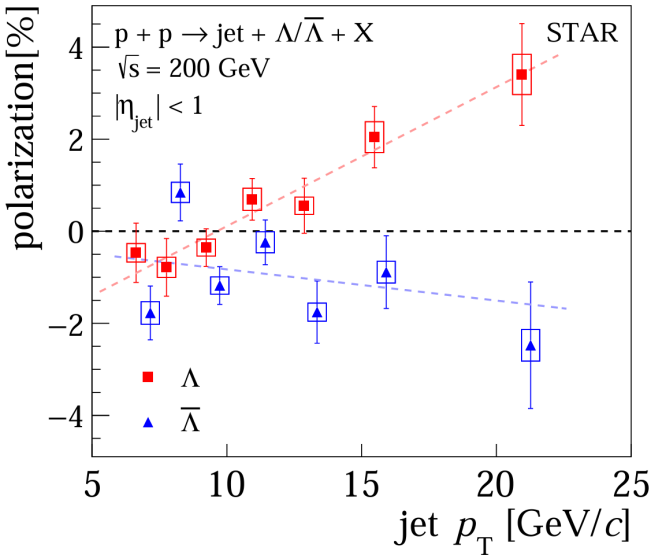


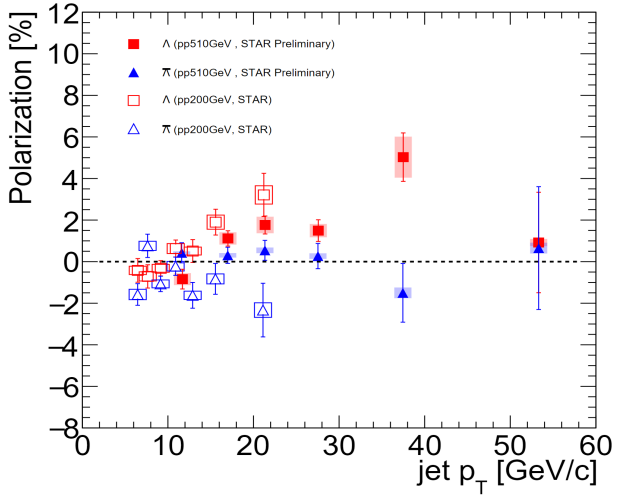
➢ Polarization has to come from non-perturbative processes
- polarizing fragmentation or parton distribution

Λ polarization in jets in unpolarized p+p collision

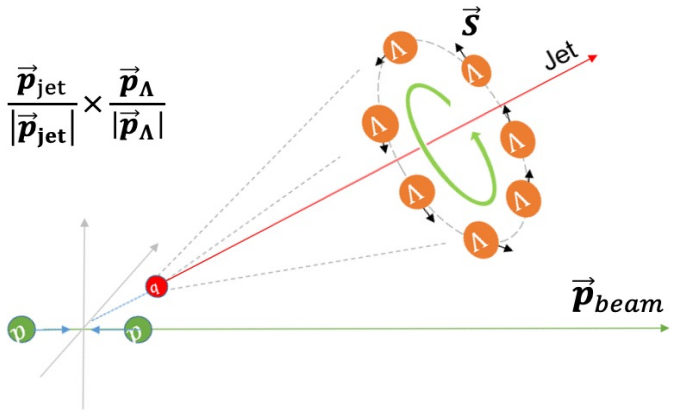
- Λ polarization in jets in p+p -> polarizing fragmentation function at STAR:

STAR, JHEP 06 (2026)050



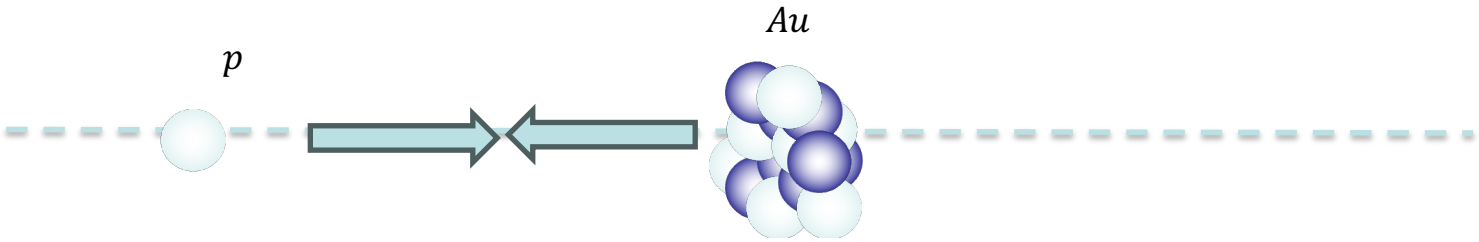


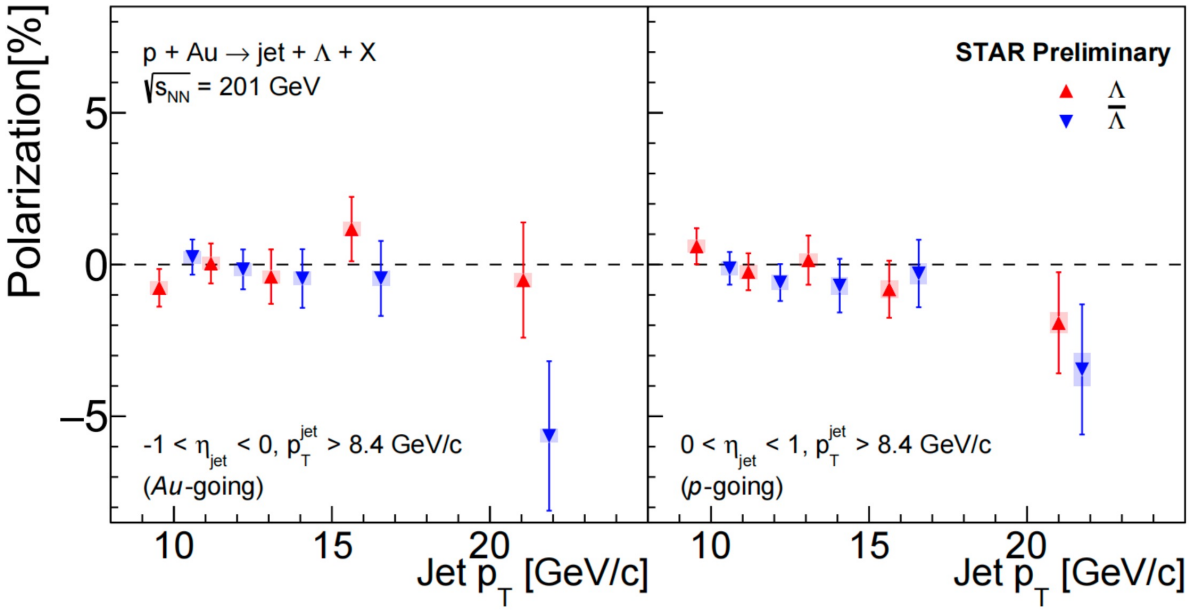
$$\vec{S} = \frac{\vec{p}_{\text{jet}}}{|\vec{p}_{\text{jet}}|} \times \frac{\vec{p}_{\Lambda}}{|\vec{p}_{\Lambda}|}$$



- **First measurement of Λ polarization in jets in pp collisions**
  - ✓ Clear jet p_T dependence of Λ polarization
  - ✓ First constraints on gluon PFF

Λ polarization in jets in unpolarized p+Au collision





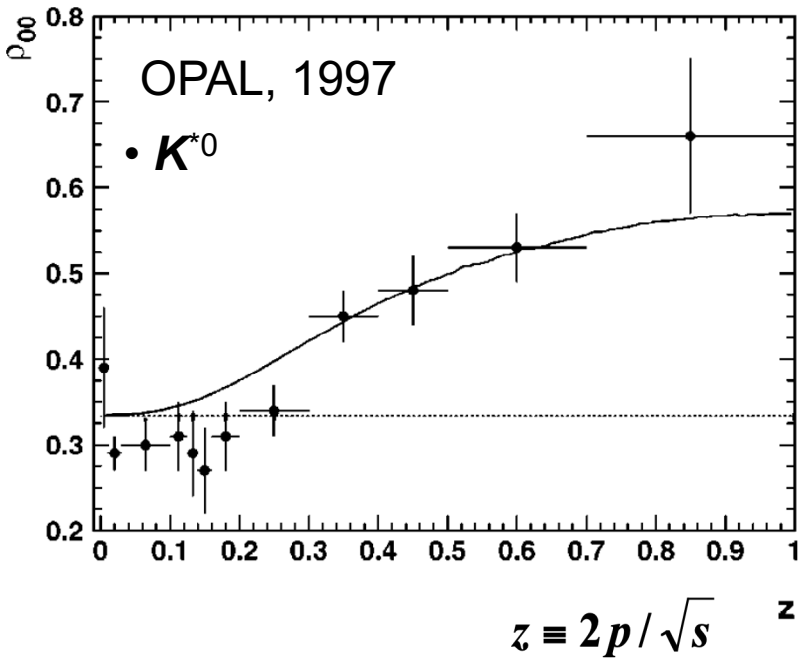
- Polarization studied for *p* and *Au* side, for possible nuclear effect
- No significant transverse polarization is observed in p-Au collisions
- An indication of nuclear medium effects in p-Au collisions

Spin alignment of vector meson

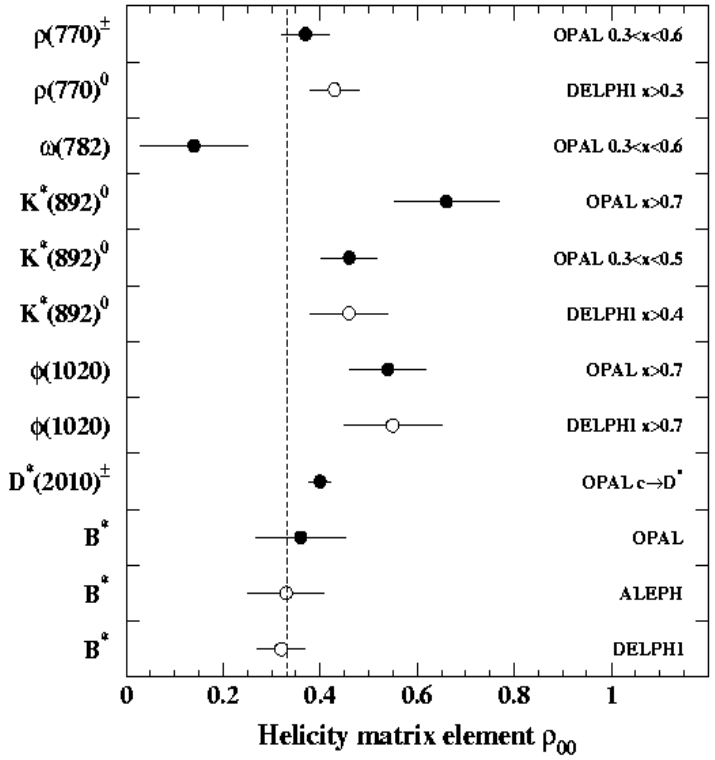
- **Spin alignment**: $W(\cos\theta^*) = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$

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

- Spin alignment data at LEP (e^+e^- at 90GeV):



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



➢ Global spin alignment measurement in A+A collisions?

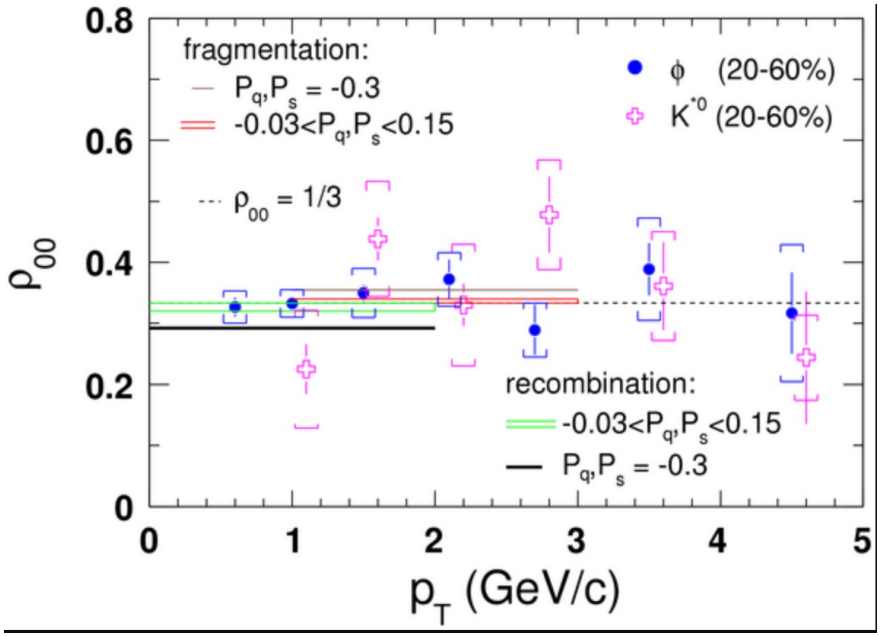
Z. T. Liang, X.N. Wang, Phys.Lett.B629, (2005)

1st STAR paper on spin alignment

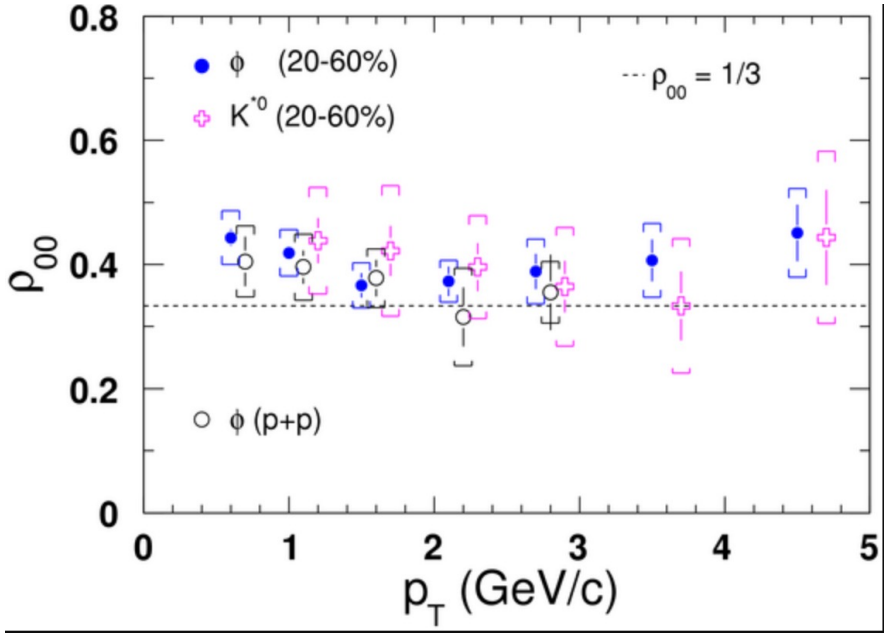
Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

B. I. Abelev *et al.* (STAR Collaboration)
Phys. Rev. C **77**, 061902(R) – Published 12 June 2008

J.H. Chen, Z.B. Tang et. al.



w.r.t. reaction plane

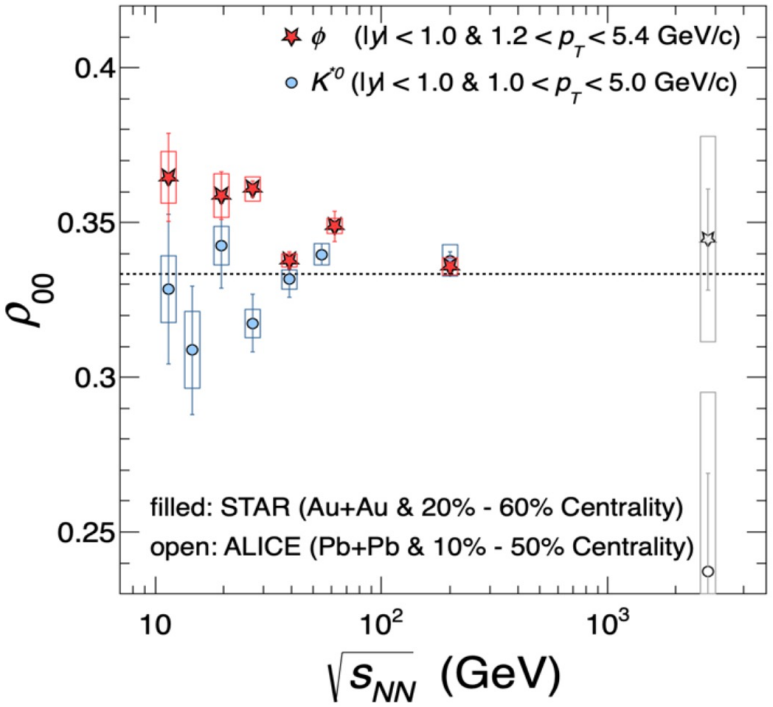


w.r.t. production plane

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

J.P. Lv, Z.H. Yu, Z.T. Liang, Q. Wang, X.N. Wang, PRD 109, 114003 (2024)

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

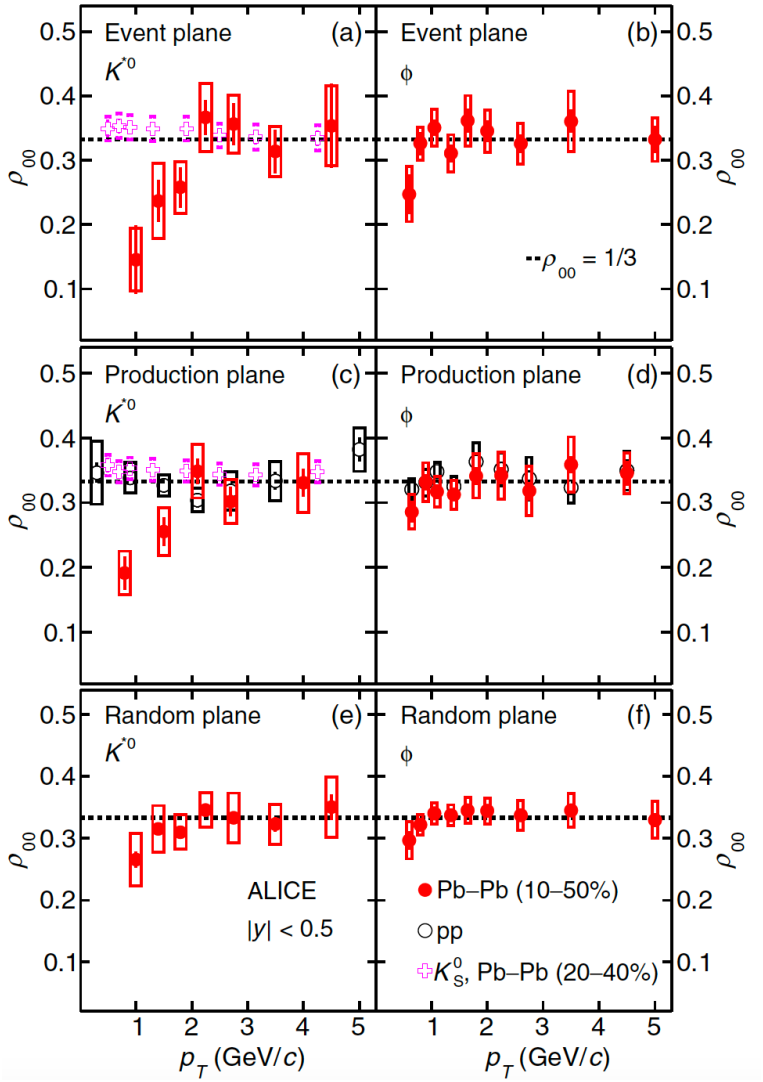
- Polarization by a strong force field of vector meson

X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

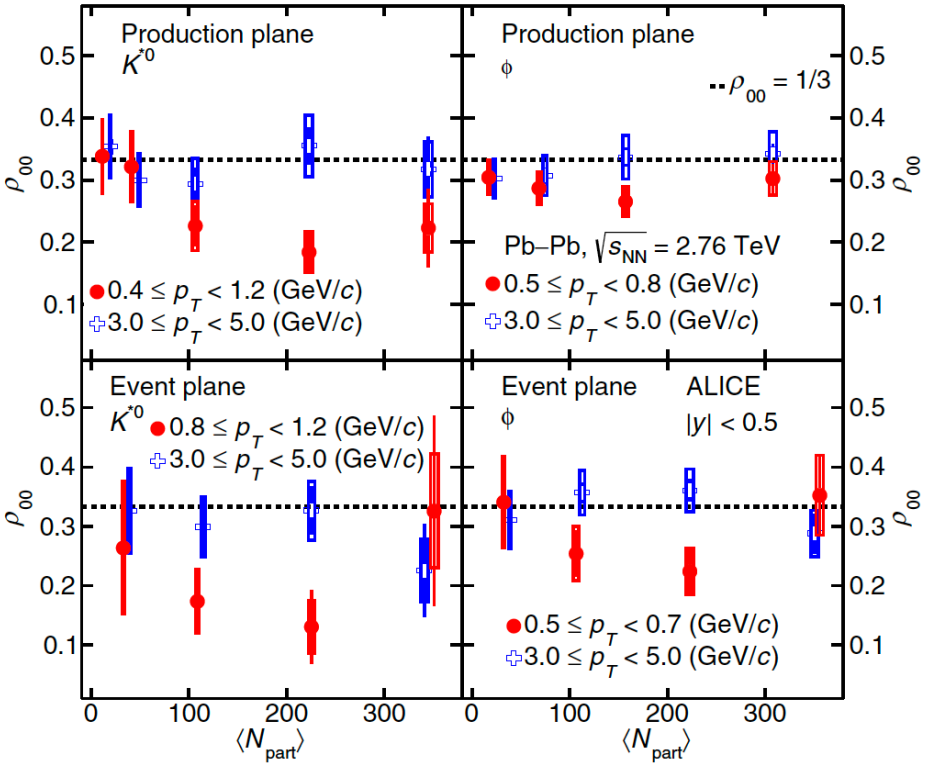
Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

ALICE, PRL125, 012301 (2020)

S. Acharya *et al.*[*]
(The ALICE Collaboration)



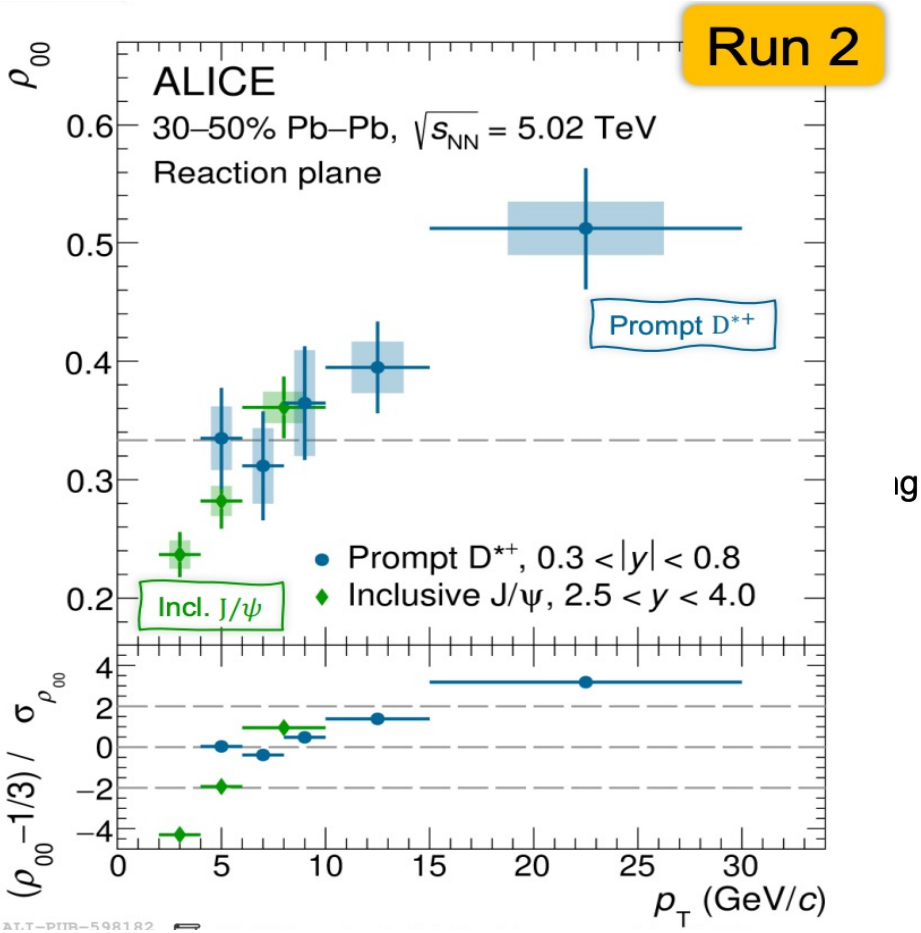
- ρ_{00} are found to be <1/3 at low p_T<2 GeV for K*0 and ϕ in Pb-Pb at 2.76 TeV

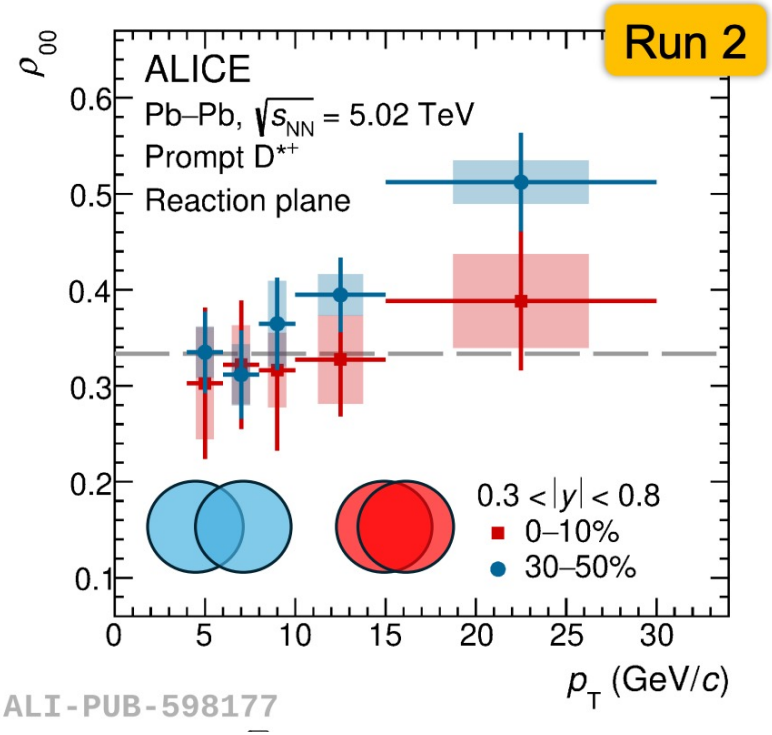


D* spin alignment in Pb+Pb at ALICE

D^{*+} spin alignment in Pb–Pb collisions

First measurement of D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions





ALICE, JHEP 10 (2025) 094

J/ψ global spin alignment in heavy ion

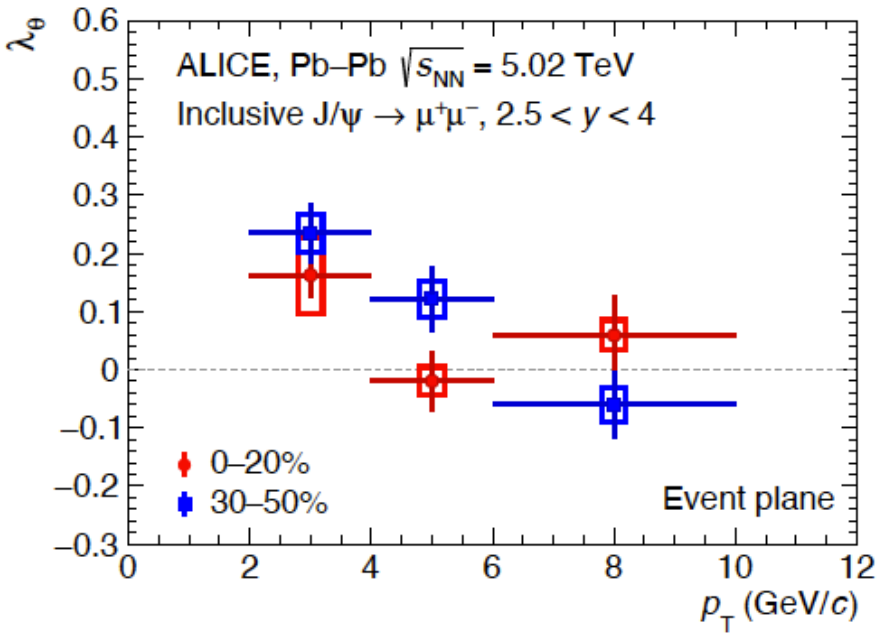
- J/ψ production mechanism different as ϕ , its global spin alignment could provide new insights

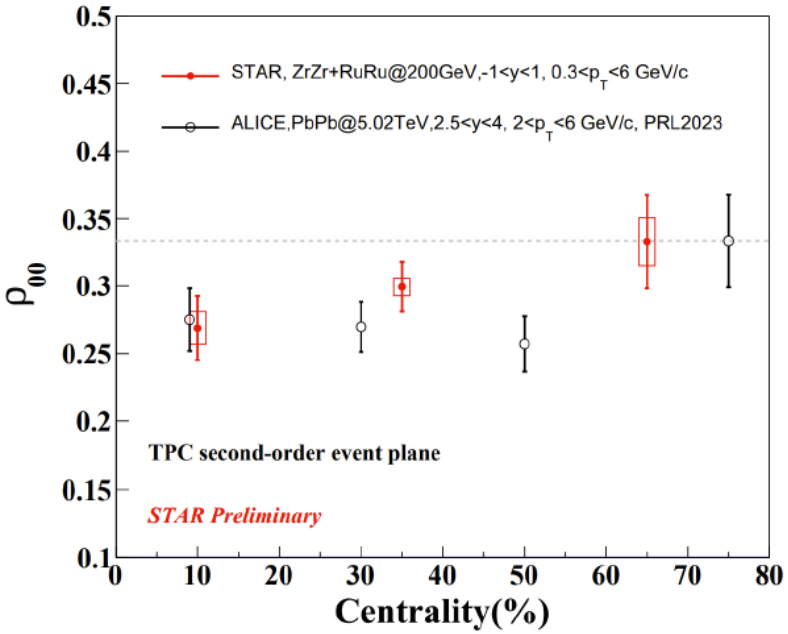
$$W(\theta) \propto [(1+\rho_{00}) + (1-3\rho_{00})cos^2\theta]$$

$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right),$$

λ_θ=(1-3ρ_{00})/ (1+ρ_{00})

- Measurements at ALICE and STAR





ALICE, PRL131 (2023) 042303

Spin observables probing quark spin quantities

- Complete list of spin observables in A+A 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

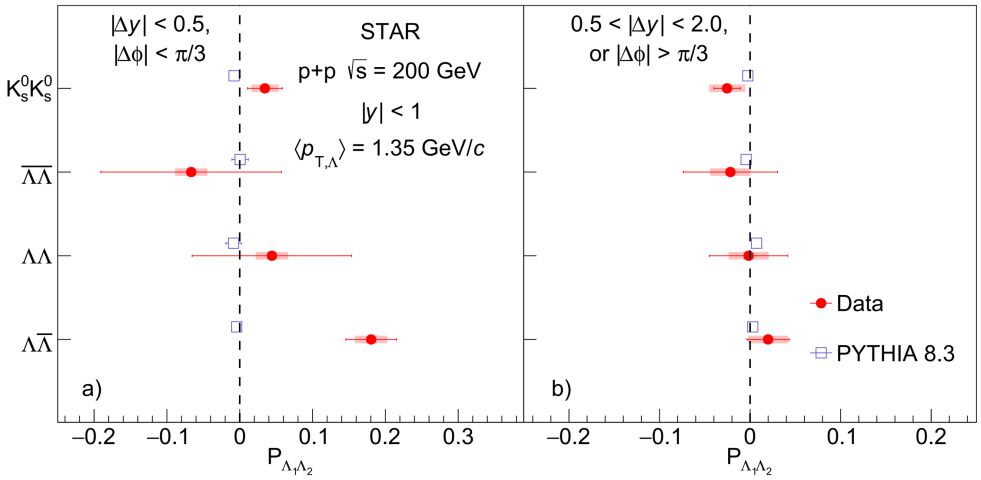
Systematic studies of quark spin correlations in QGP!

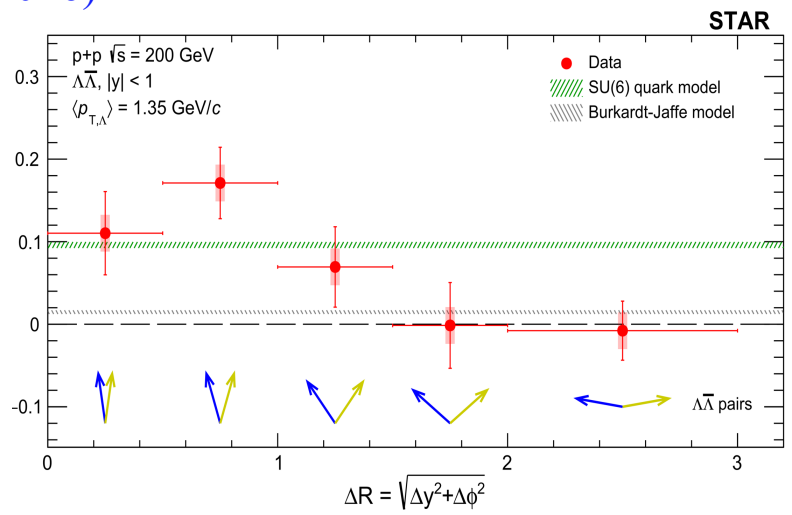
- Slides from Z. T. Liang

$\Lambda\bar{\Lambda}$ spin correlations in p+p collision at STAR

- Evidence of spin-spin correlation for short range $\Lambda\bar{\Lambda}$ pairs
- Correlation consistent with zero for long range pairs and other pairs

STAR, Nature 650, 65(2026)





$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

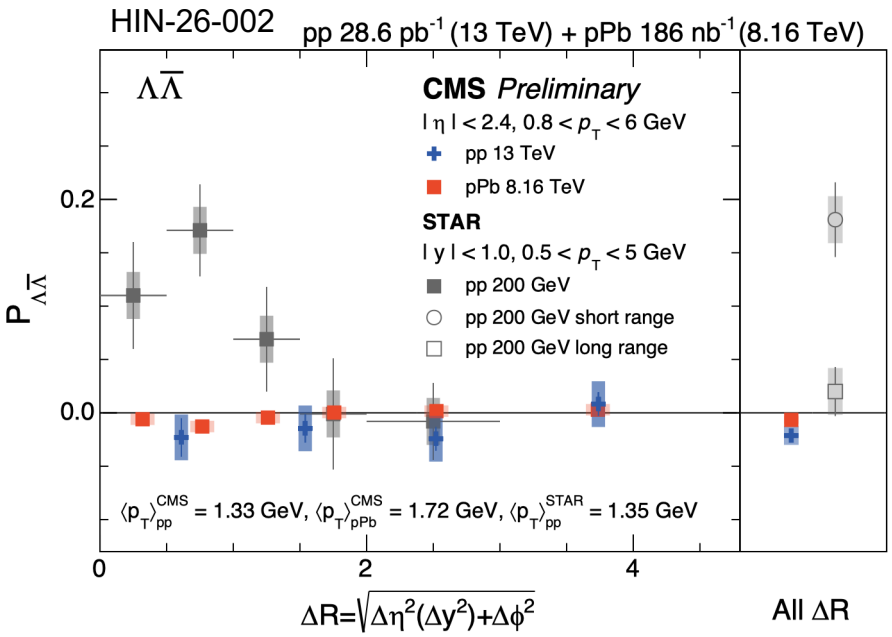
$$P_{\Lambda 1 \Lambda 2} = C_{12} = (\mathrm{Cxx} + \mathrm{Cyy} + \mathrm{Czz})/3$$

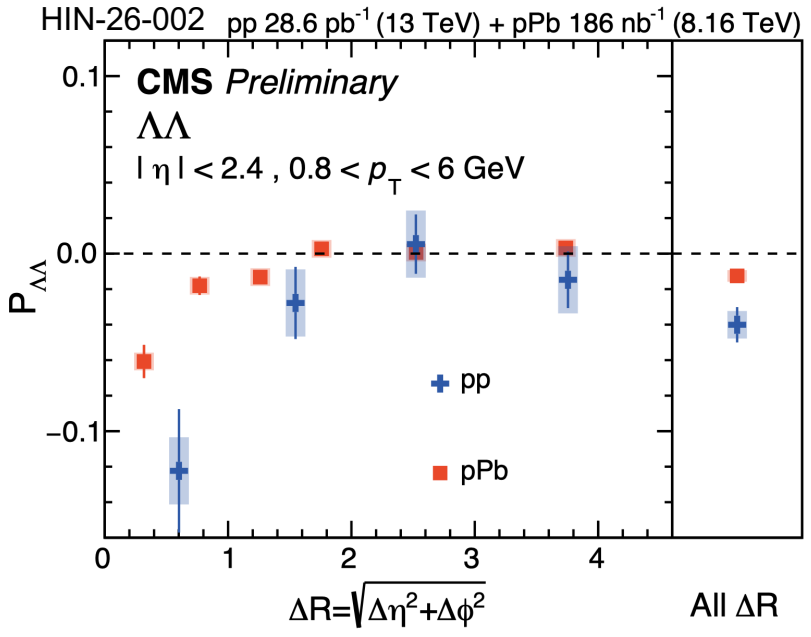
θ* - Angle between decay protons in rest frames of parent Λ's

➢ Possible source: maximally entangled s-sbar spin correlation of pairs from QCD vacuum ?

Lambda spin correlation in p+p & p+Pb at CMS

- Spin correlation measurement at LHC energies



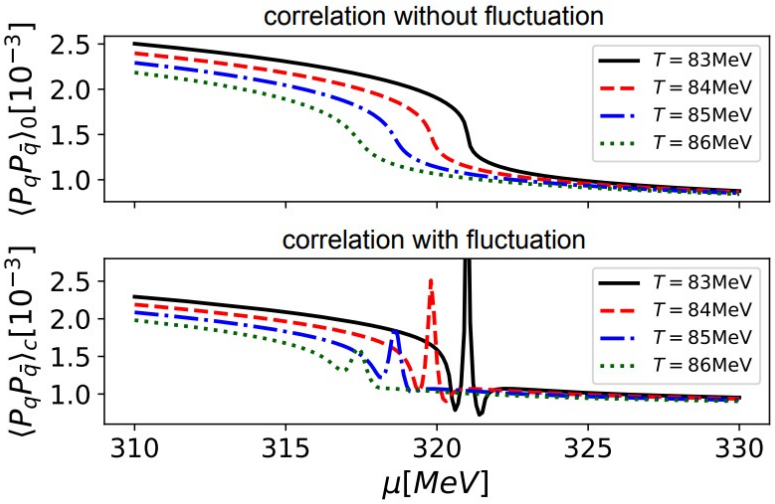


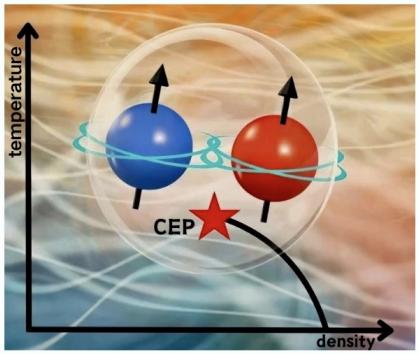
- ➢ Different behavior observed than at RHIC energies ?
- ➢ Might indicate energy dependence of the underlying mechanism

Lambda-Lambda spin-spin correlation in A+A

- Spin correlation could be sensitive to the CEP in the QCD phase diagram

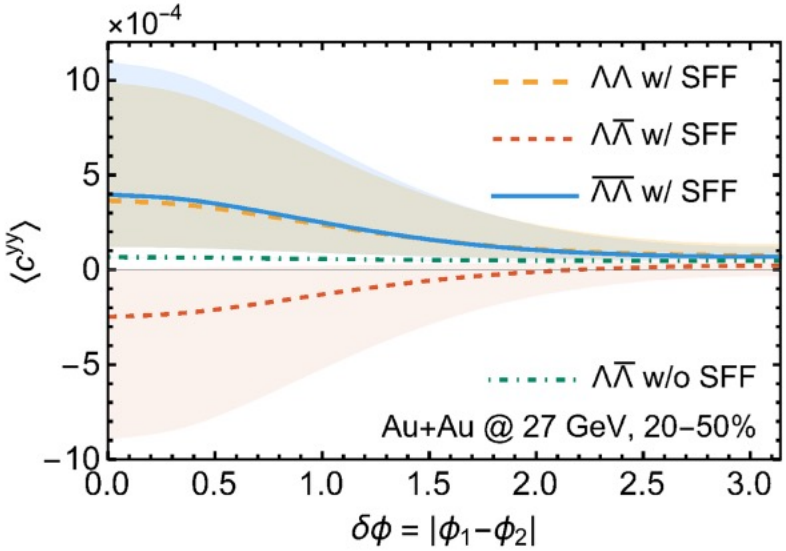
Hao-Lei Chen, et. al, PRL 135. 032302 (2025)





- Different spin correlation behaviors of $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs predicted

Xin-Li Sheng, et. al, PRL136 (2026) , 082301



➢ Data analyses at LHC and RHIC are underway

Summary

- Spin polarization: a new avenue of high energy nuclear physics

- **Global hyperon** polarization observed, clear energy dependence, extended from Lambda, to Xi, Omega
- **Local polarization**, significant, sensitive to the fluctuation of vorticity and bulk properties
- **Hyperon polarization in small system** not fully understood, could have connection with cold QCD effect like fragmentation
- **Vector meson global spin alignment** observed with a significant pattern for φ, potentially related to quark field or quark spin correlation
- **Spin-spin correlation** observed in p+p, p+A, analyses in A+A ongoing, rich and exciting physics to be explored

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谢谢！