Experiment: Spin physics II

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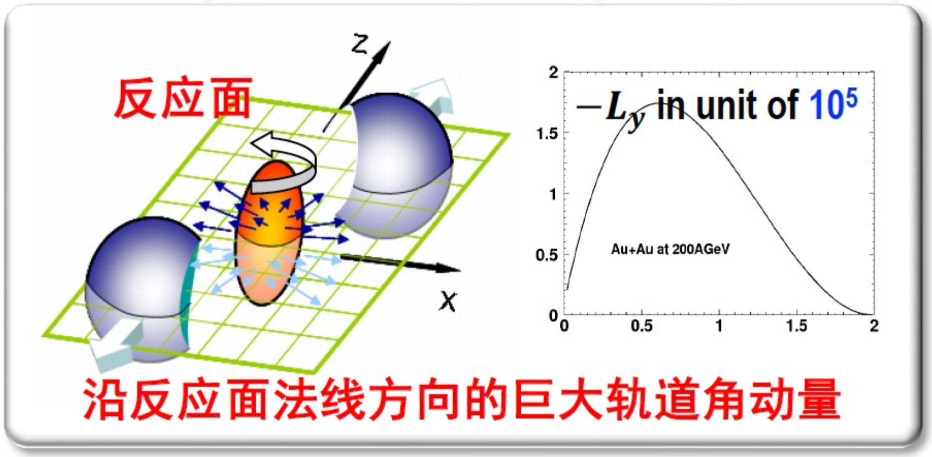
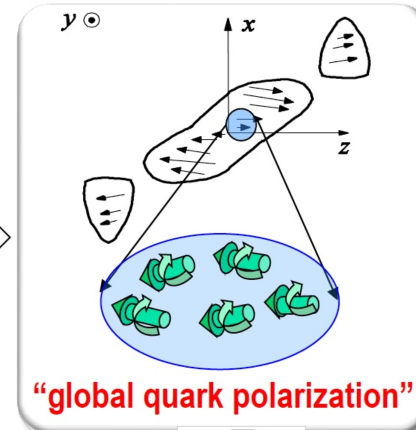
Λ Global polarization in heavy ion collisions

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

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



QCD自旋—轨道
相互作用导致



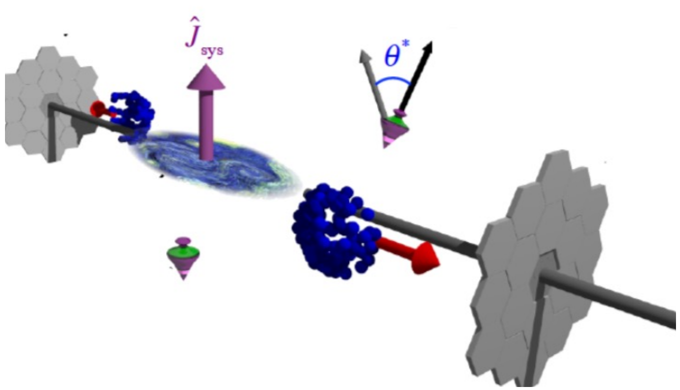
强子化导致
（组合）

● 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)

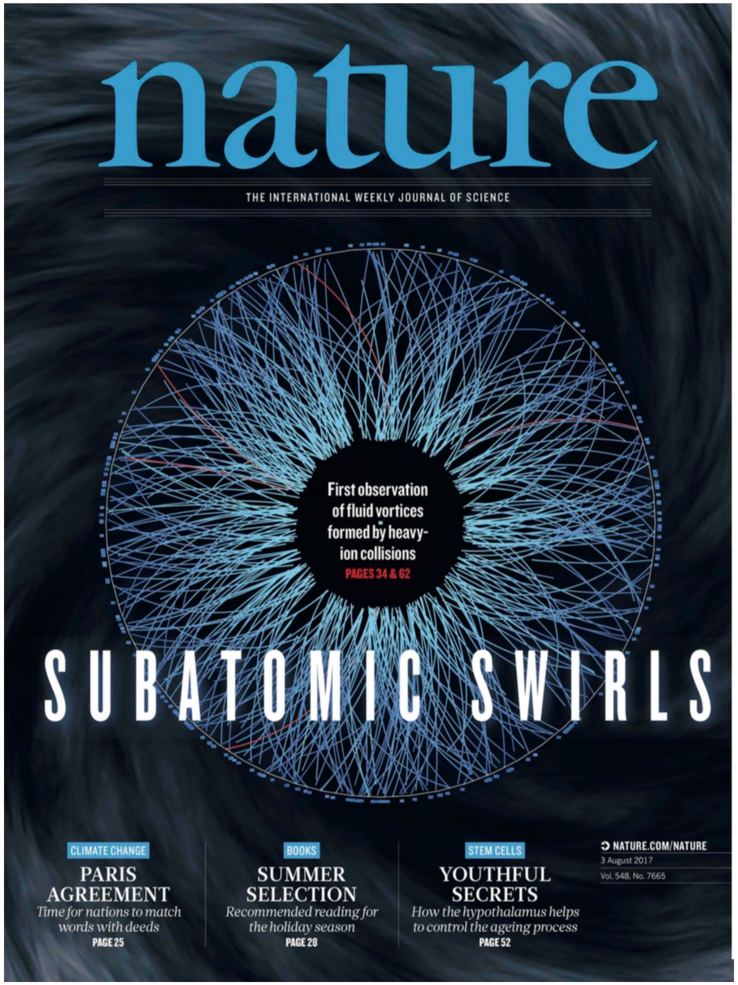
$$\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$$



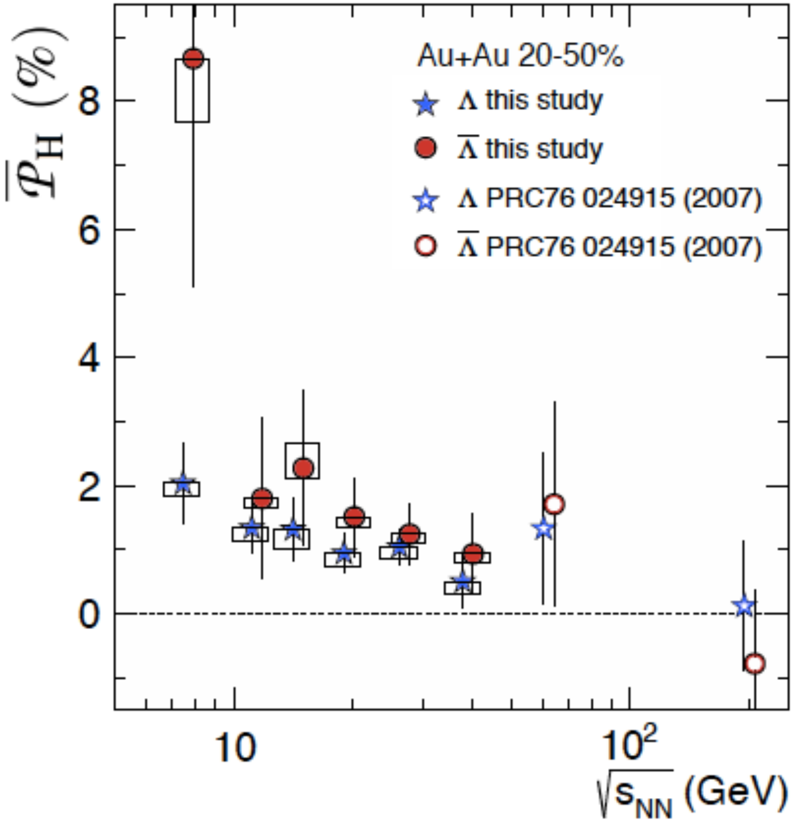
-Measurements started soon after the prediction, first data available in 2007 from RHIC-STAR

Λ Global polarization in heavy ion collisions

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



STAR, Nature 548(2017)62



Measurement of global polarization at STAR

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

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

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

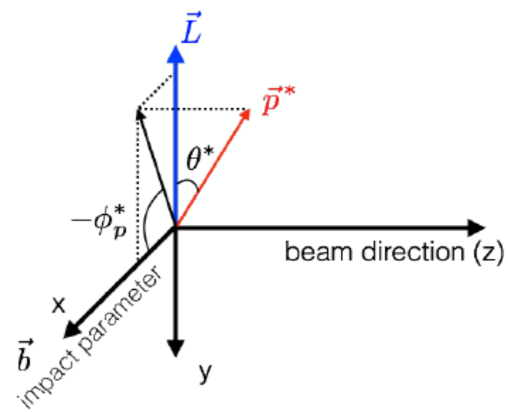
- At STAR, the global polarization has been extracted with

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

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

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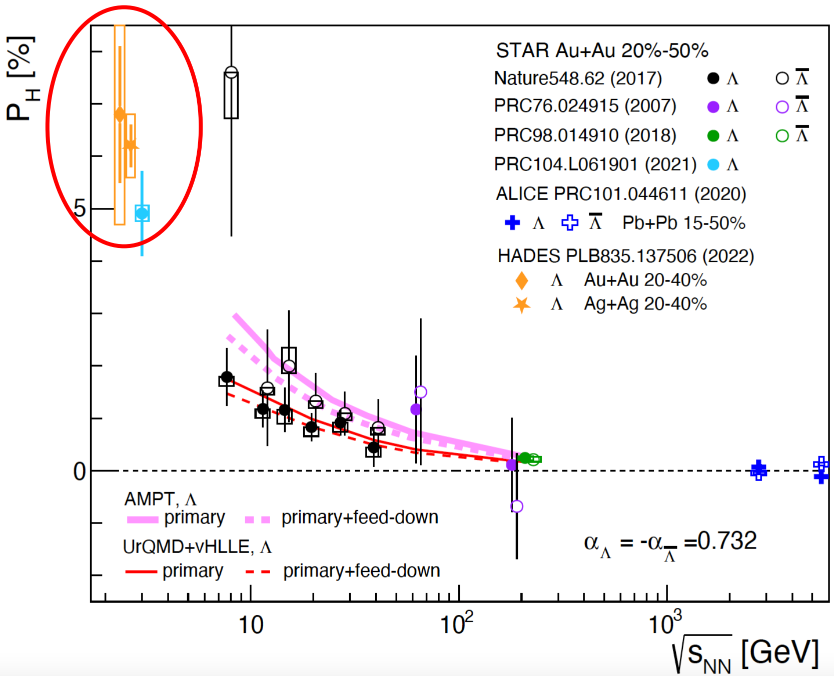
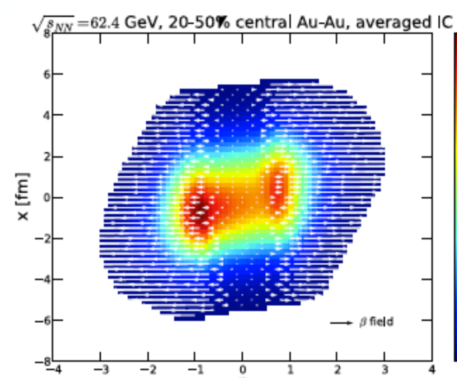
Energy dependence of global polarization

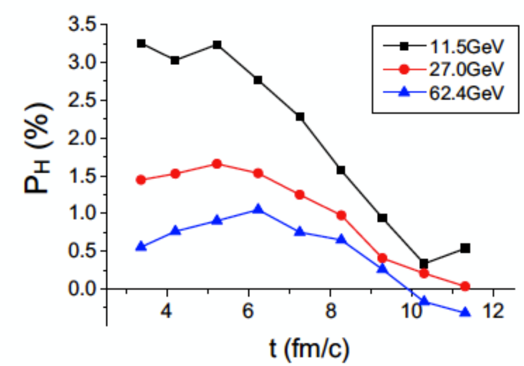


- HADES data at √s=2.4GeV Au+Au and 2.7 GeV Ag+Ag
- STAR data down to √s= 3 GeV
- ALICE results at 2.76 and 5.02 TeV Pb+Pb, consistent with zero within uncertainties

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 (related to rapidity dependence)
- Polarization continue to increase at low energy ?

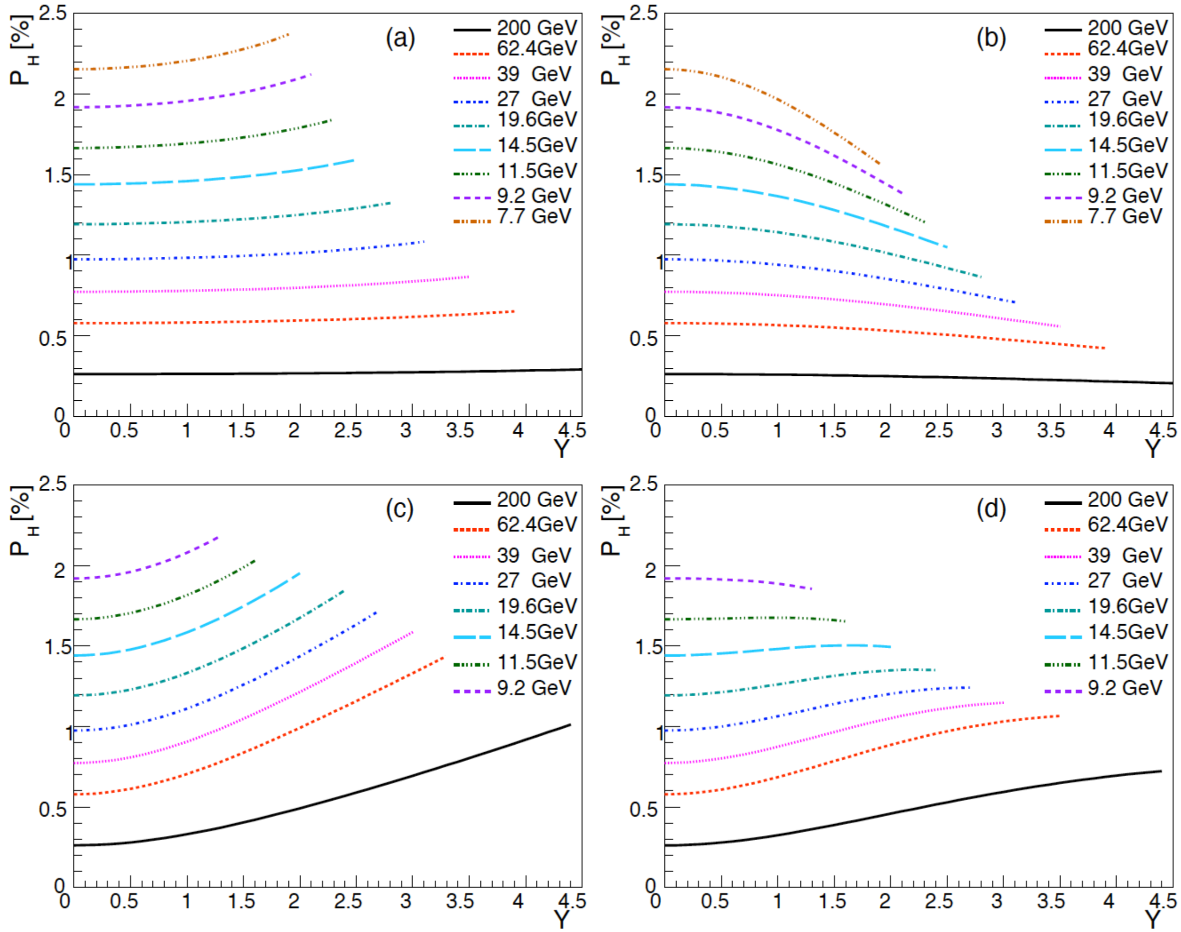




- Y. Ivanov, Phys. Rev. C103, 031903(2021)

Rapidity dependence of global polarization

- Zuo-Tang Liang, Jun Song, Isaac Upsal, Qun Wang and Zhang-Bu Xu*, Chin. Phys.C* 45 (2021), 014102

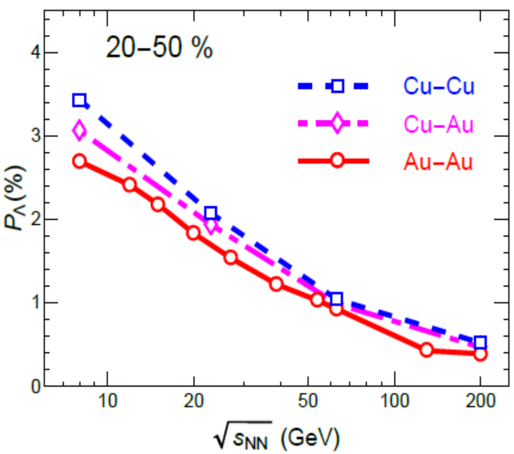


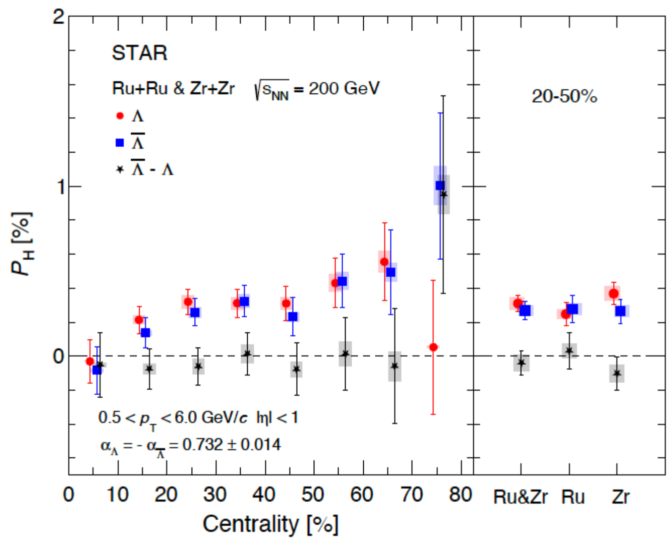
Global polarization in Ru+Ru and Zr+Zr collisions

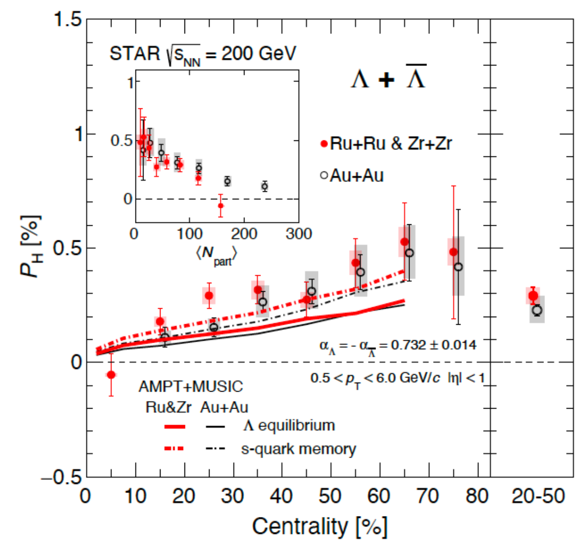
- Global polarization difference from different magnetic field in Zr+Zr and Ru+Ru?
- System size dependence of global polarization?

STAR, arXiv:2505.05046, to appear in PLB

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







- ➢ Significant global polarization observed, P_Λ and $P_{\bar{\Lambda}}$ increase with centrality.
- ➢ No significant difference between P_Λ and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions.
- ➢ 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

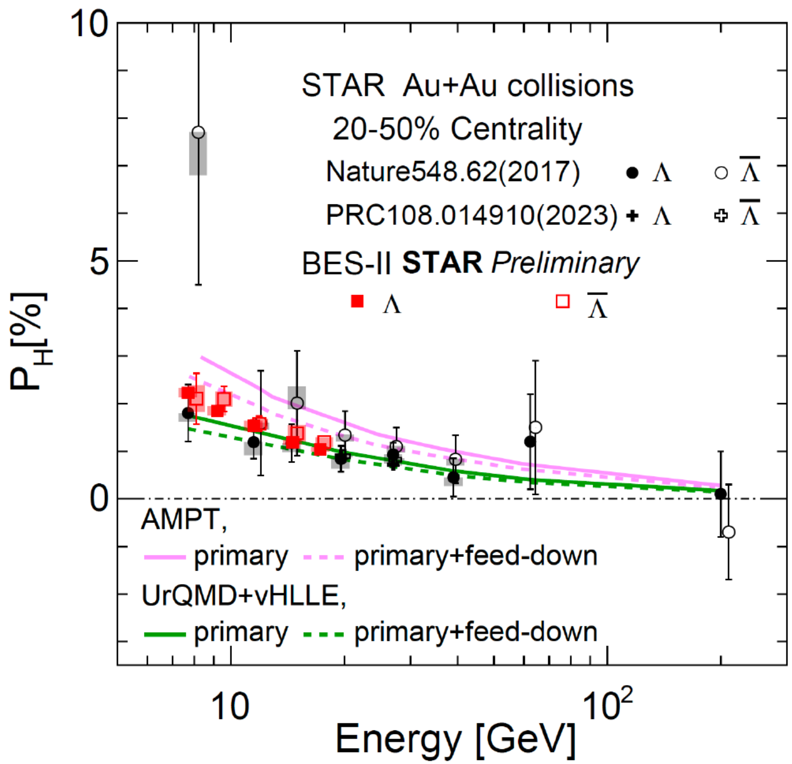
- Splitting of $\Lambda(\bar{\Lambda})$ global polarization due to the magnetic field ?

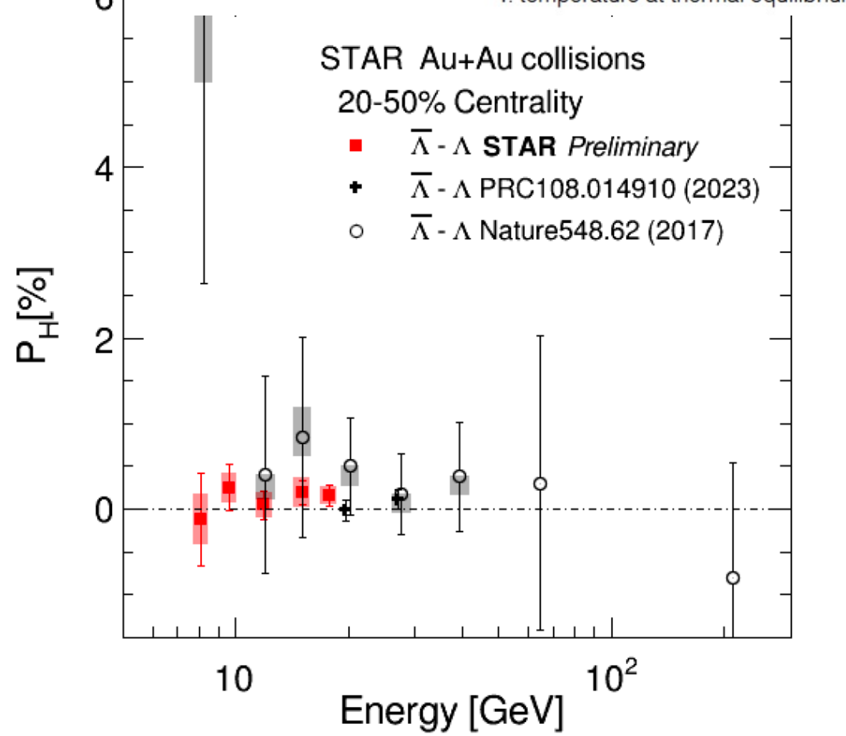
$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

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

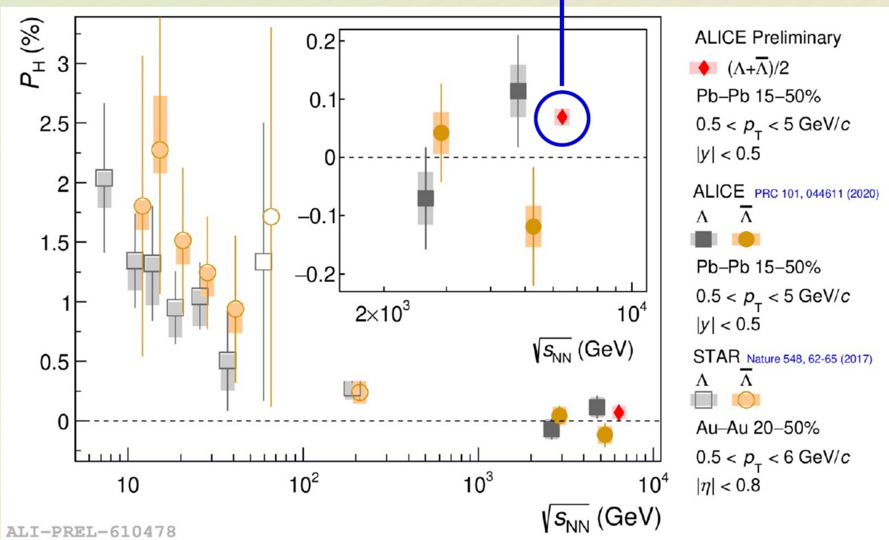
➢ More data coming from STAR BES-II FXT with energy down to 3 GeV

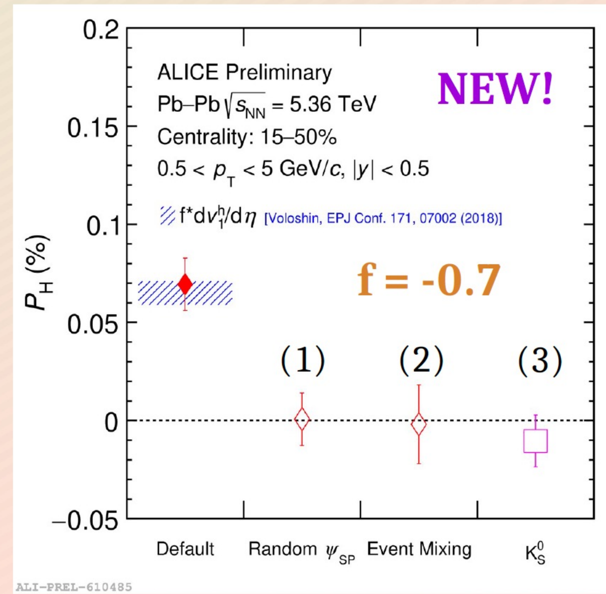
New Results from ALICE on $\Lambda(\bar{\Lambda})$ global polarization

- Prottay Das @ SPIN2025

Global polarization measurement at LHC

NEW!





- ✓ **First observation of non-zero polarization of hyperons at LHC energies with 5σ significance**
- ✓ **Vorticity at LHC energy: (3.27± 0.66) 10^{20} s^{-1}**
- ✓ Average polarization consistent with the empirical prediction based on directed flow slope at mid-rapidity
- ✓ Several null hypothesis tests (1, 2, 3) performed succesfully

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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

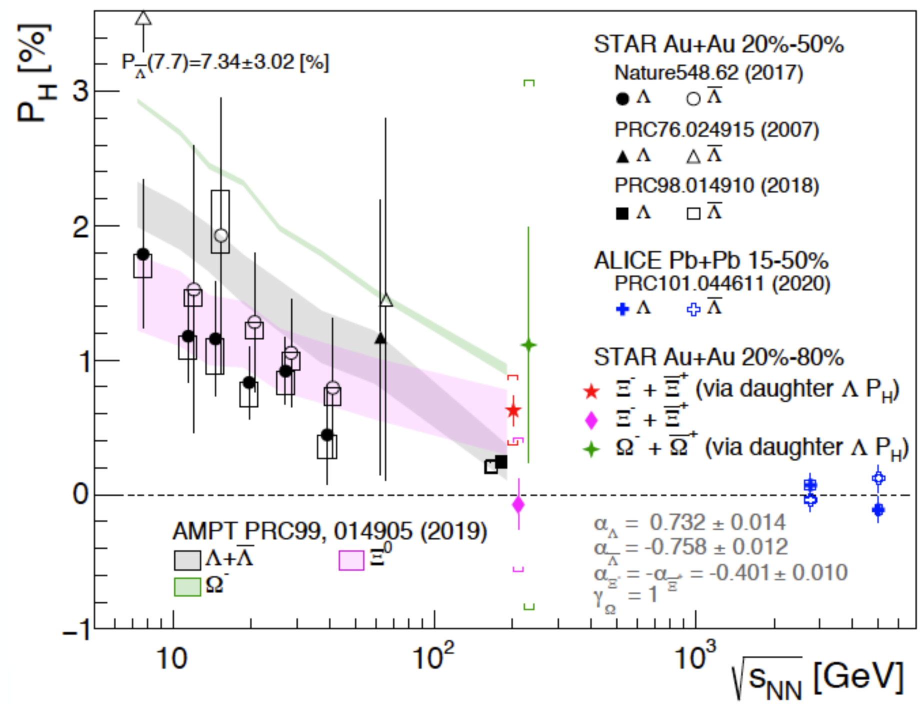
$$\mathbf{P}_{\Lambda}^{*} = C_{\Xi^- \Lambda} \mathbf{P}_{\Xi}^{*} = \frac{1}{3}\left(1 + 2\gamma_{\Xi}\right) \mathbf{P}_{\Xi}^{*}. \quad C_{\Xi^- \Lambda} = +0.944$$

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

-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:

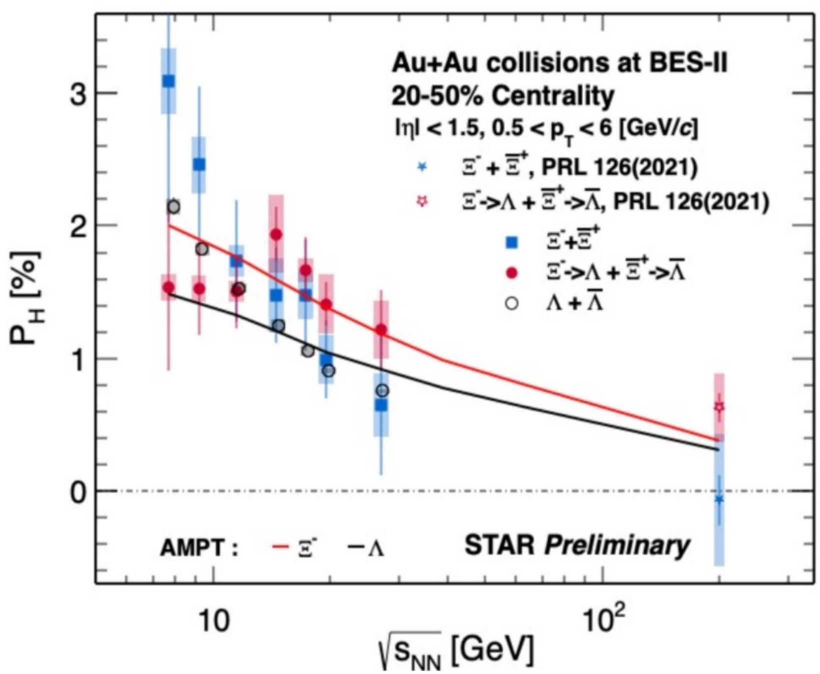
D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)

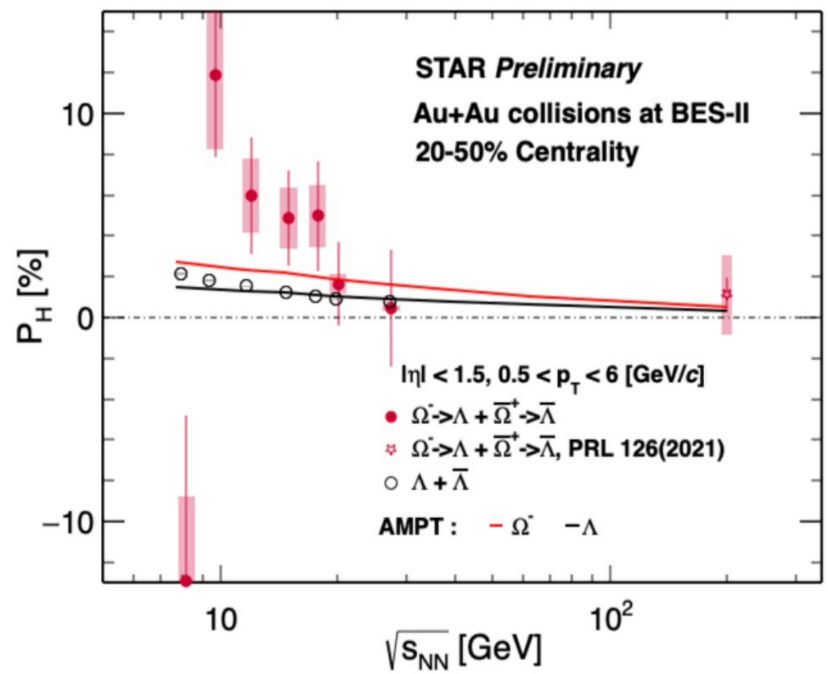
Ξ, Ω global polarization with STAR BES-II

- 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 Phys. Lett. B827, 136971 (2022)*





1
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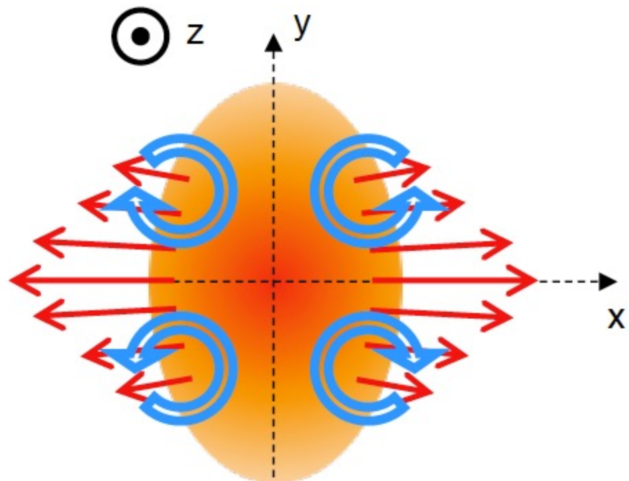
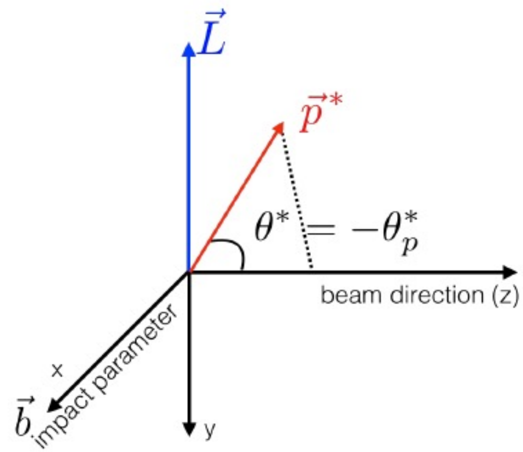
Polarization along the beam direction

"Local polarization"

F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, SQM2017





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\mathrm{H}} \mathbf{P_H} \cdot \mathbf{p}_p^*)$$

$$\langle \cos\theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos\theta_p^* d\Omega^*$$

$$= \alpha_{\mathrm{H}} P_z \langle (\cos\theta_p^*)^2 \rangle$$

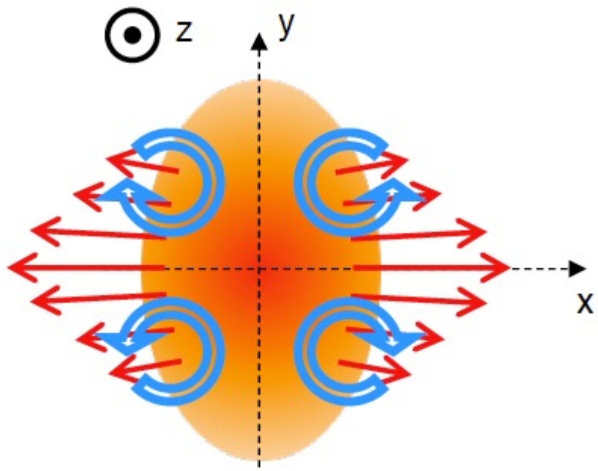
$$\therefore \; P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}} \langle (\cos\theta_p^*)^2 \rangle}$$

$$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}}} \quad \text{(if perfect detector)}$$

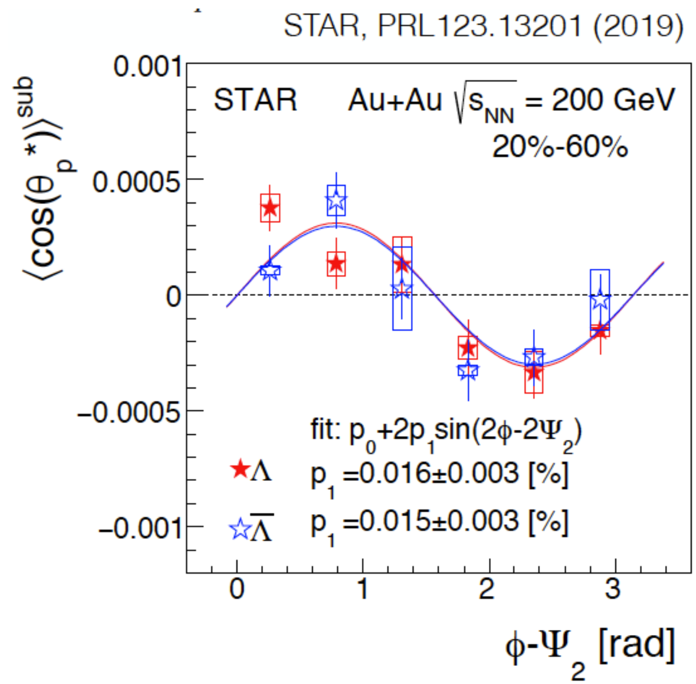
- Stronger flow in in-plane than in out-of-plane, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.

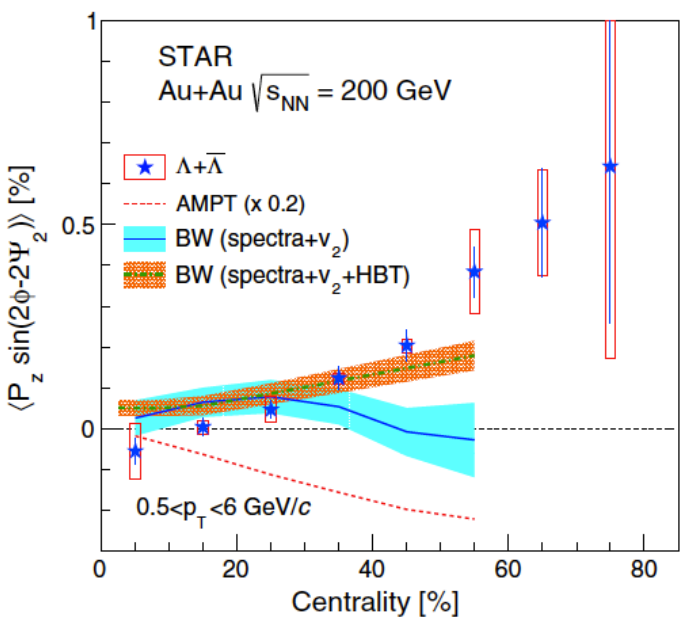
Polarization along the beam direction

"Local polarization"



STAR, PRL123.13201 (2019)

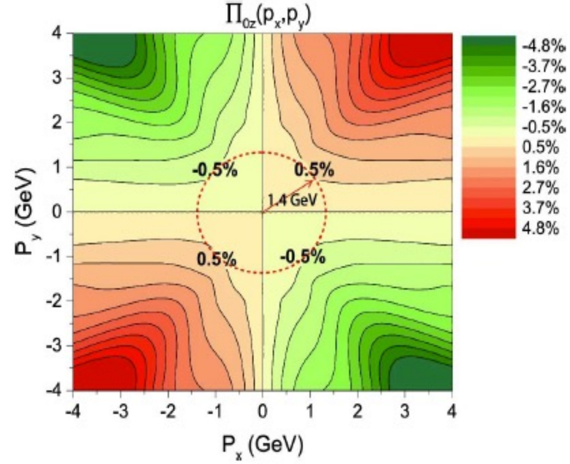


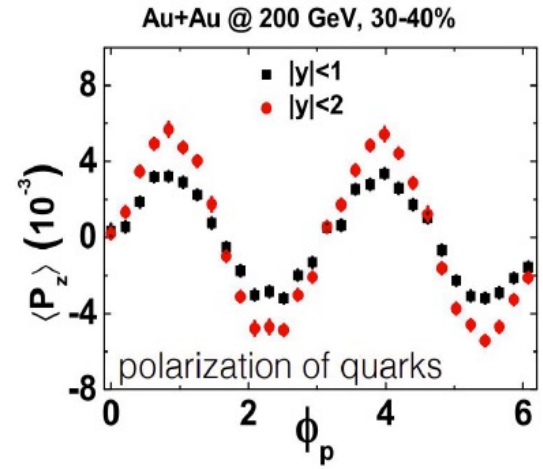


- Polarization along the beam direction expected from the "elliptic flow"
- STAR data indeed show such a longitudinal polarization Pz depending on azimuthal angle (sine function)
- Blast Wave model captures the trend with correct sign, while many others do not.

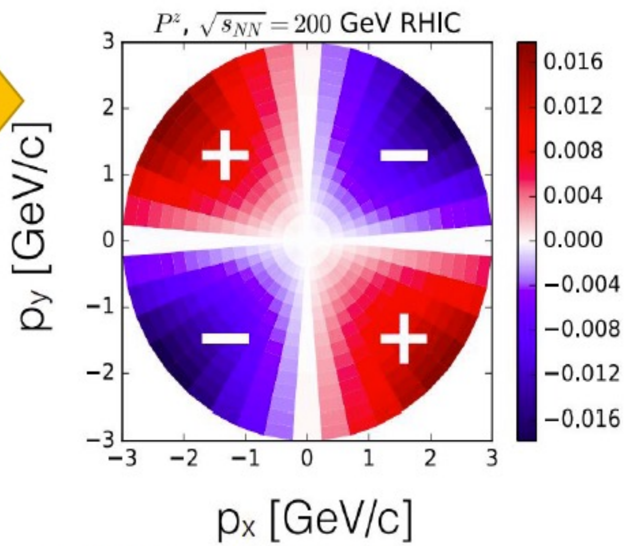
P_z: sign problem

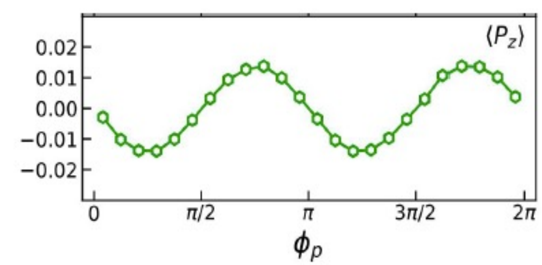
- Some model studies predicted this behavior with the correct sign
  - (3+1)D PICR hydro.: Y. Xie, *et. al.*, EPJ C 80, 39 (2020)
  - Chiral kinetic: Y. Sun, *et. al.*, PRC 99, 011903(R) (2019)

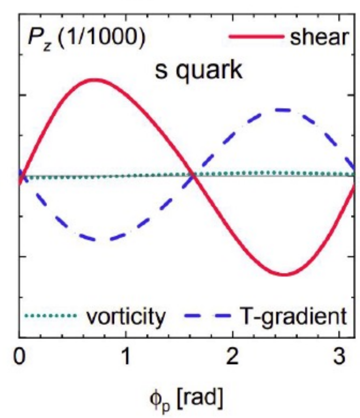




- Others predicted the incorrect sign
  - UrQMD+hydro: F. Becattini, *et. al.*, PRL.120.012302 (2018)
  - AMPT: X. Xia, *et. al.*, PRC98.024905 (2018)







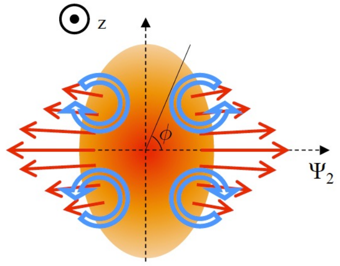
- Recent considerations of a shear term may resolve the sign discrepancies

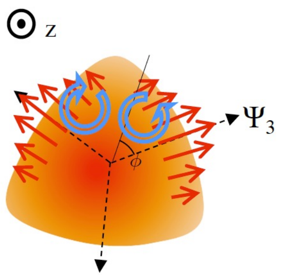
B. Fu et al., PRL 127 (2021) 14, 142301
F. Becattini et al., PRL 127, 272302 (2021)

-J. Adams, QM 2022

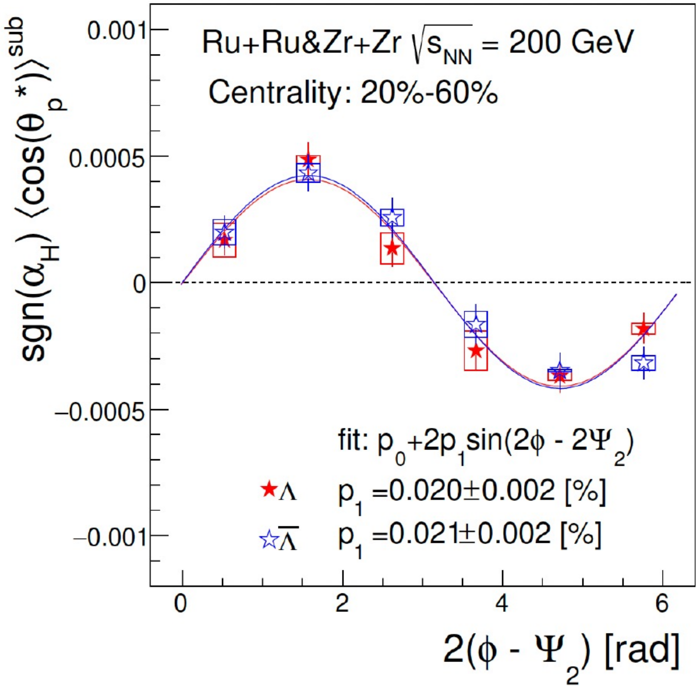
Λ polarization along the beam direction

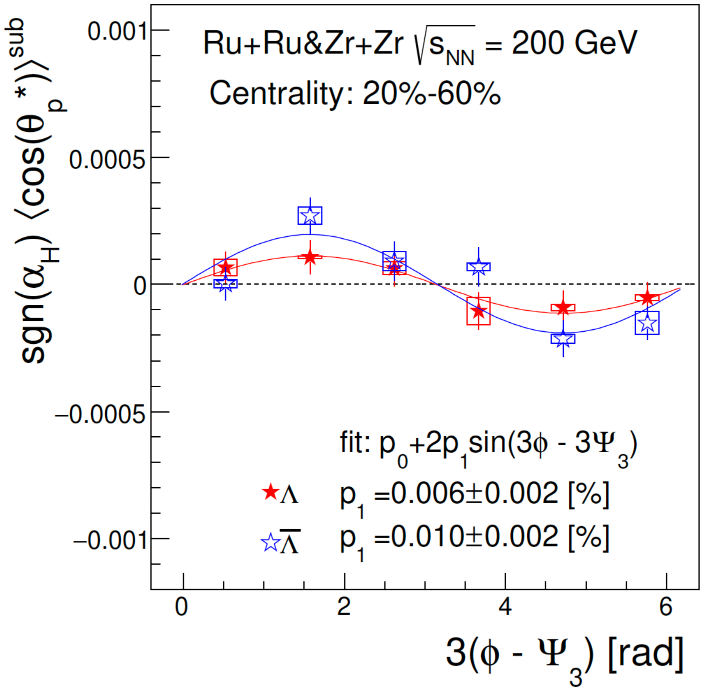
"Local polarization" in isobar collisions:





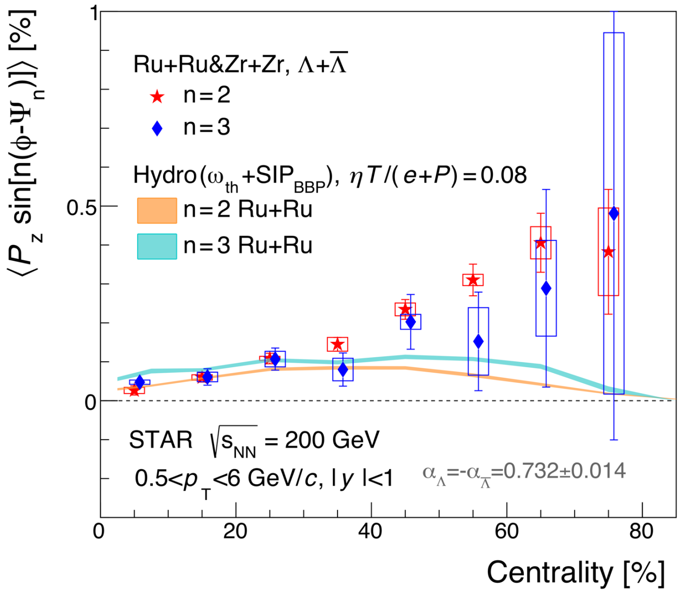
STAR, PRL131, 202301(2023)

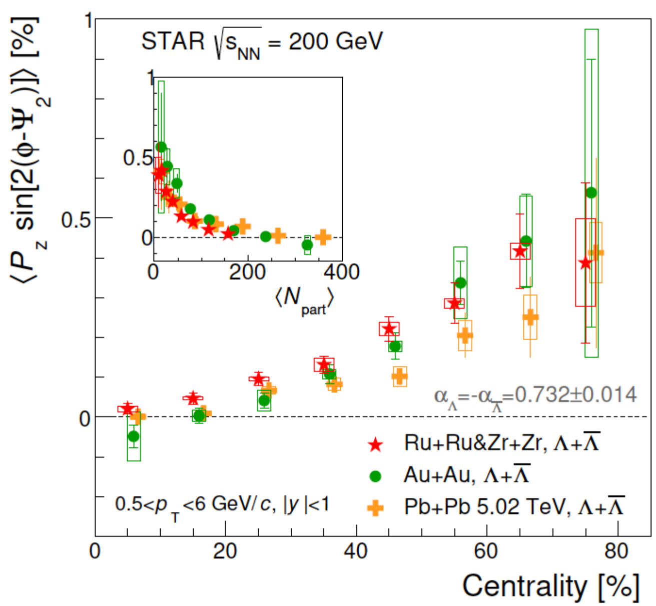




- First measurement relative to the 3^{rd}-order event plane Ψ_3
  - Similar pattern to the 2^{nd}-order, indicating v_3-driven polarization

Local polarization in iso-bar collisions





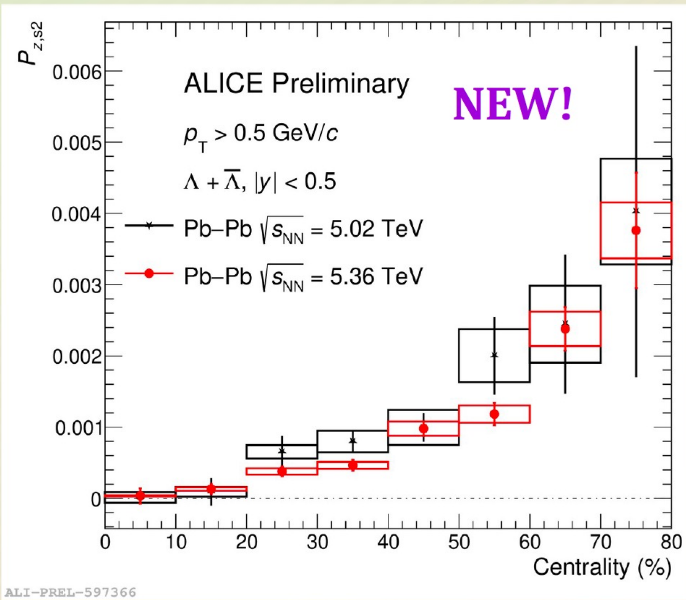
- Comparable 2^{nd} and 3^{rd} order sine coefficients of $P_{z,n}$, especially in most central events
- Hydrodynamic models with shear term reasonably describes the data for central collisions, but not for peripheral, Additional constraint on shear viscosity
- $P(z,n)$ from Isobar data comparable to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

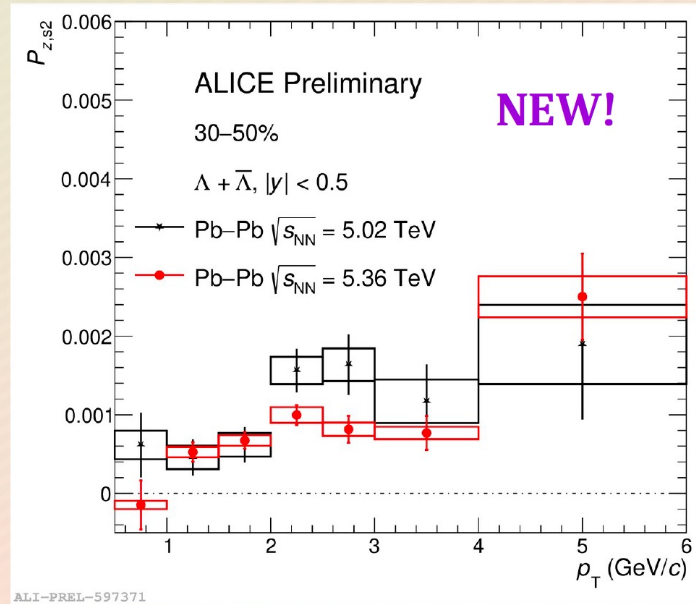
STAR, PRL131, 202301(2023)

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

- Prottay Das @ SPIN2025

Longitudinal second order polarization of Λ



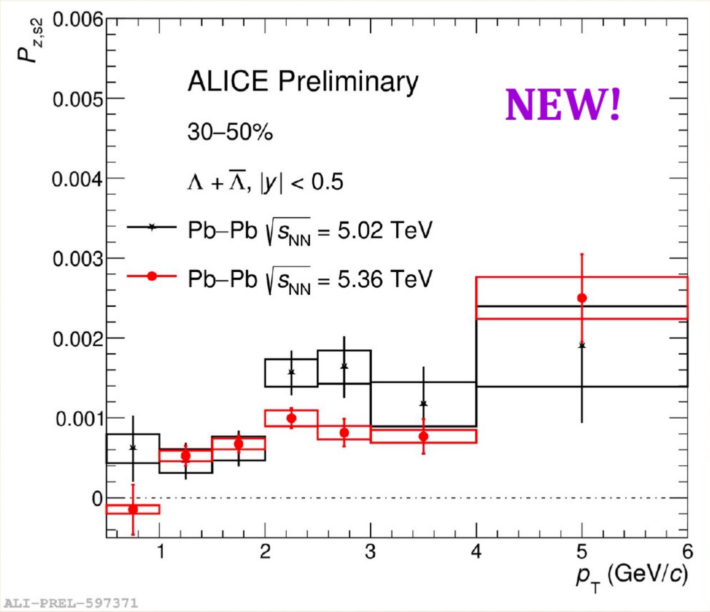


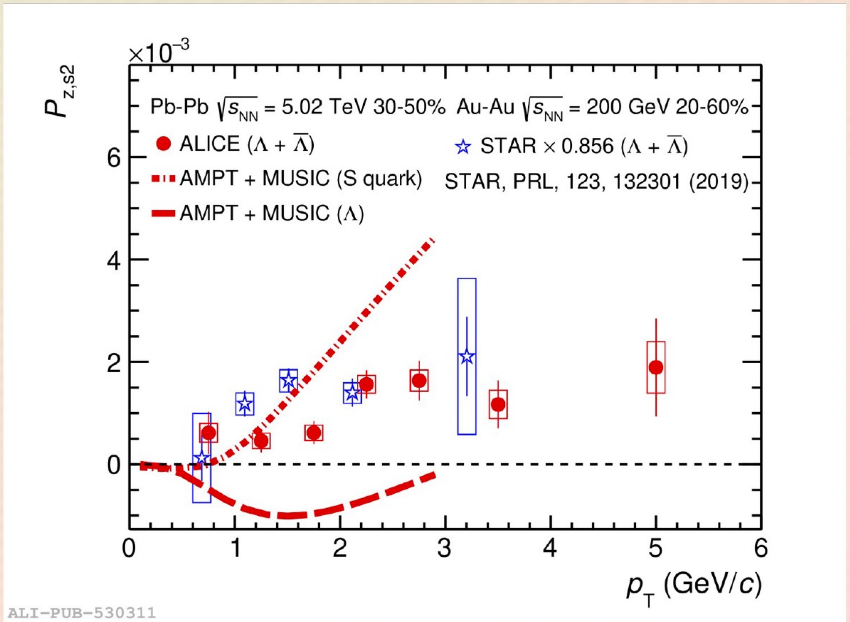
- ✓ $P_{z,s2}$ increases from central to peripheral collisions due to increasing anisotropy
- ✓ $P_{z,s2}$ increases mildly with p_T
- ✓ Run 3 results are compatible with Run 2 with much smaller statistical uncertainties due to x20 data sample

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

- Prottay Das @ SPIN2025

Comparison with STAR energy and model predictions





ALICE Collaboration, Phys. Rev. Lett. 128, 172005 (2022)

- ✓ $P_{z,s2}$ at the LHC is smaller in magnitude to top RHIC energy at low p_T
- ✓ 3+1 D hydro model MUSIC + AMPT initial conditions predicts correct sign polarization if shear-induced polarisation is included and the inherits quark s polarisation at the hadronisation stage

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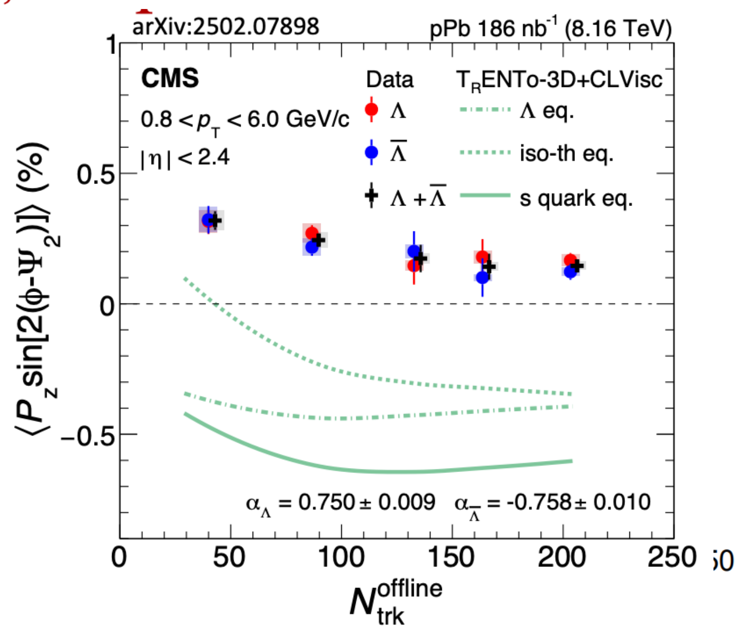
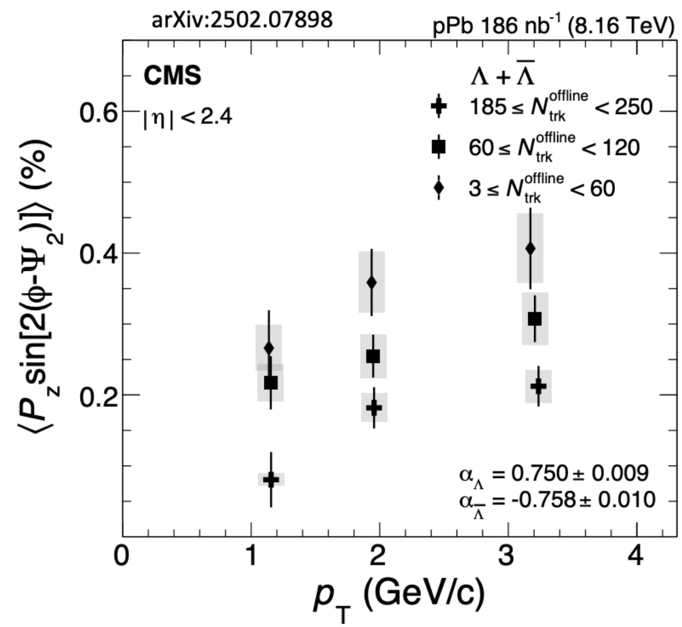
B.Fu et al., Phys. Rev. Lett. 127, 142301 (2021)

Longitudinal polarization in small system at CMS

- Chenyan Li @ SPIN2025

$P_{z,s2}$ in pPb collisions





Significant positive $P_{z,s2}$ signal observed for the entire multiplicity range

$P_{z,s2}$ values for Λ, $\bar{\Lambda}$ are consistent

$P_{z,s2}$ decrease as function of multiplicity, increase as function of p_T

Hydro calculation is not consistent with data
Not consistent with the trend of v2

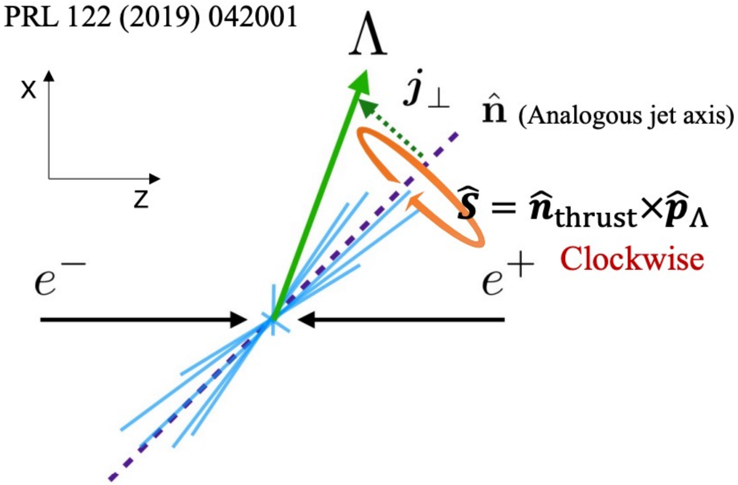
Longitudinal polarization in small system at CMS

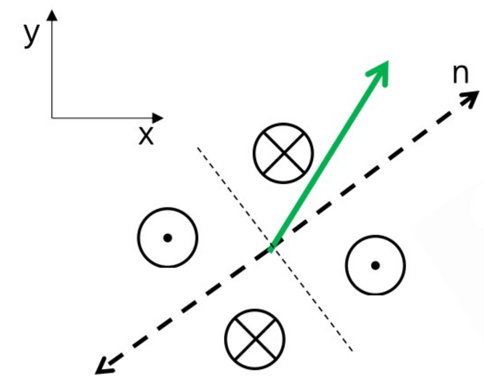
- Is it from cold-QCD effect like polarizing fragmentation function ?

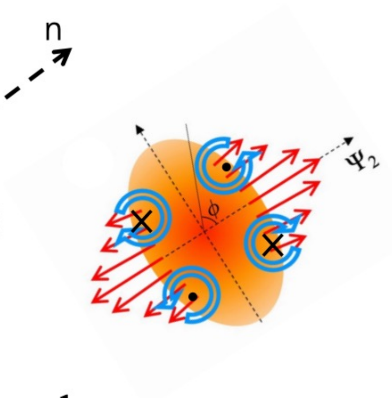
Is it from spin physics?

- Chenyan Li @ SPIN2025

PRL 122 (2019) 042001







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

Opposite direction than our signal; but could have a z_Λ dependence

Diluted towards high multiplicity

Spin polarization of vector meson

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

$$(\rho = \sum_i P_i \,|\, i \rangle\langle i \,|)$$

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,

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

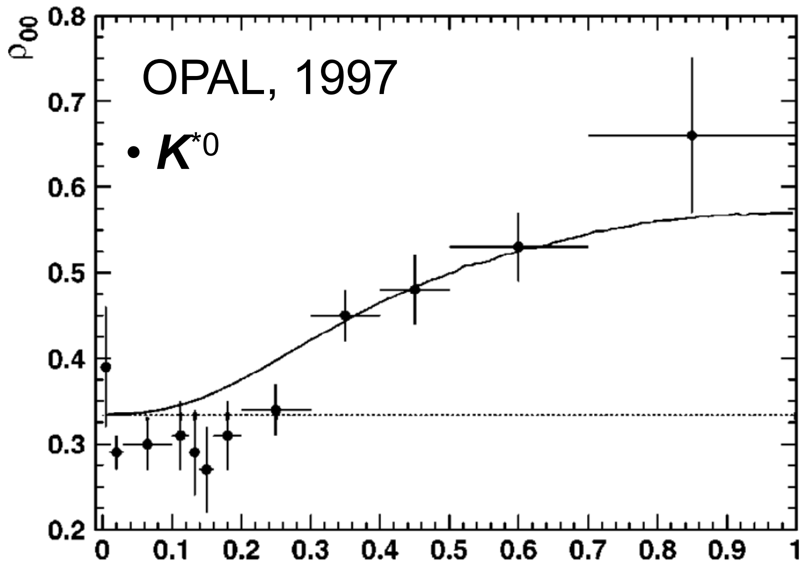
"Spin alignment", J.F. Donoghue, PRD19, 1979.

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

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

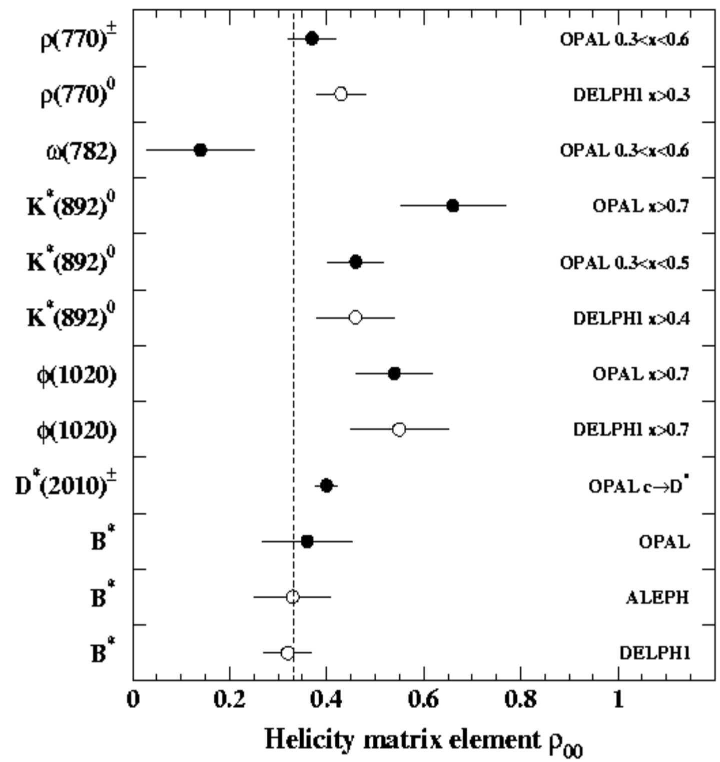
• Spin alignment: $$\mathbf{W}(\cos\theta) = \frac{3}{4}[(1-\rho_{00}) + \boxed{(3\rho_{00}-1)}\cos^2\theta^*]$$

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



$z \equiv 2p/\sqrt{s}$

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)

Global spin alignment in heavy ion

- Spin alignment of ϕ, K* meson in Au+Au collision at STAR:

Yield of ϕ, K* is corrected for efficiency and acceptance using STAR embedding simulations, then fitted with decay angle distribution:

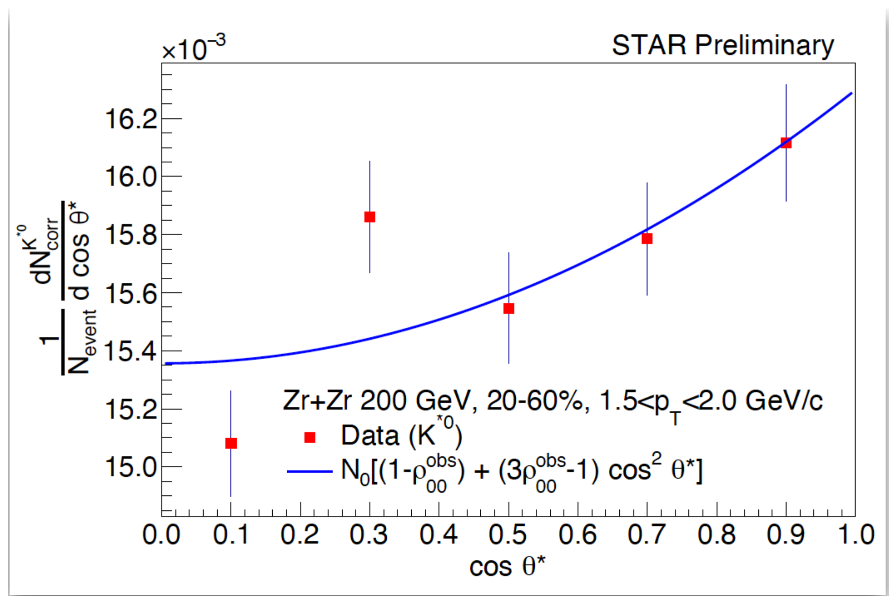
- Observed ρ_{00}^{obs} is calculated from fitting the yield with function:

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}^{obs}) + (3\rho_{00}^{obs} - 1)\cos^2\theta^*\right]$$

- Observed ρ_{00}^{obs} is corrected for TPC event plane resolution (R)

$$\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}\left(\rho_{00}^{\mathrm{obs}} - \frac{1}{3}\right)$$

Tang et. al., Phys. Rev. C 98, 044907 (2018)

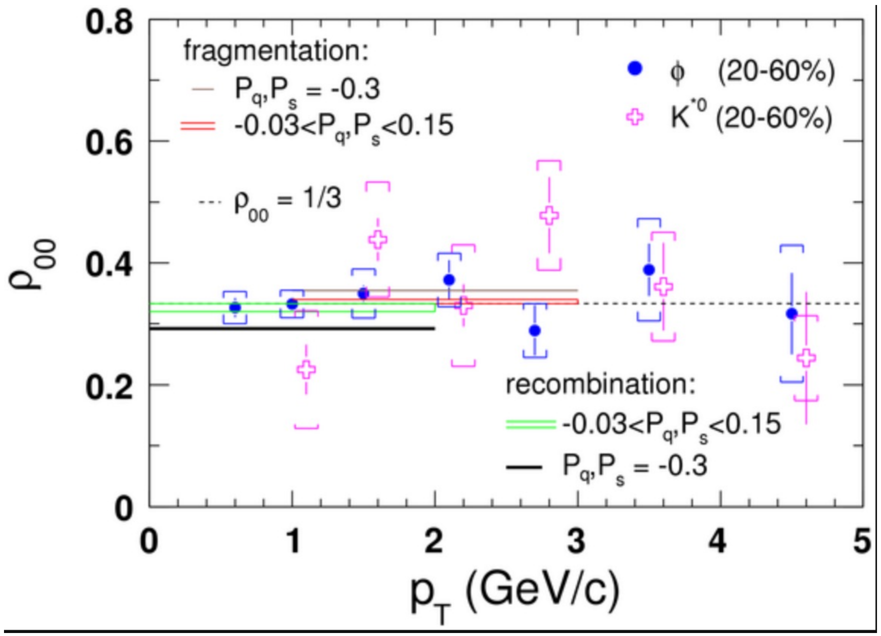


1st STAR paper on spin alignment

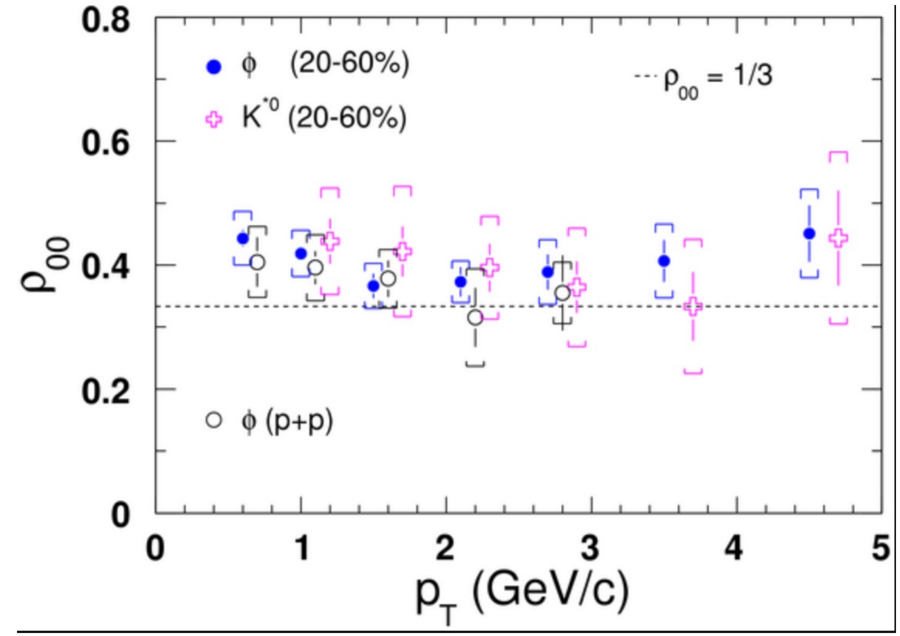
Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

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



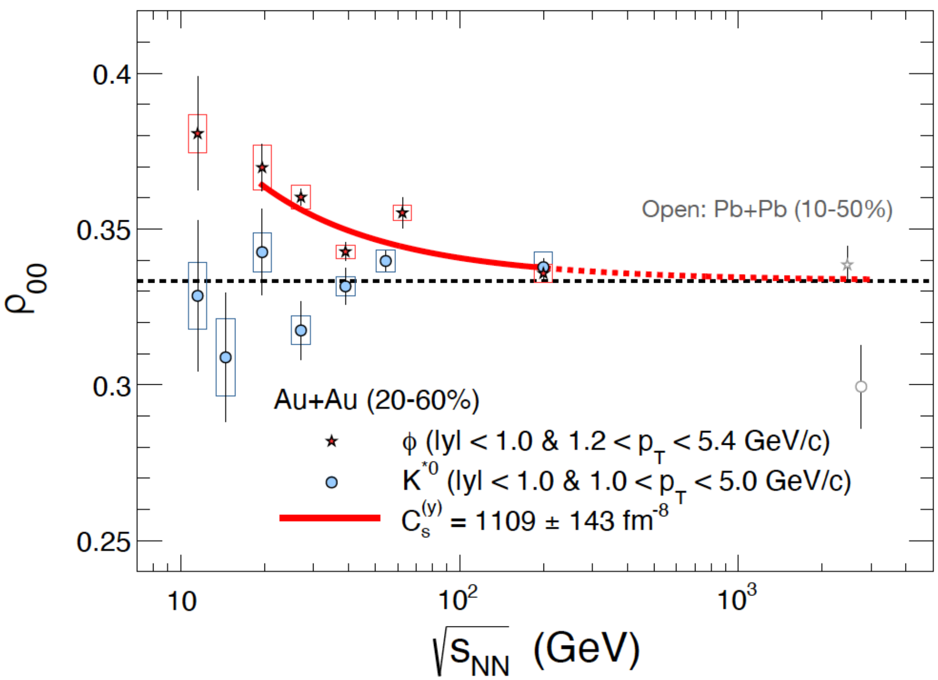
w.r.t. production plane

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

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

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!

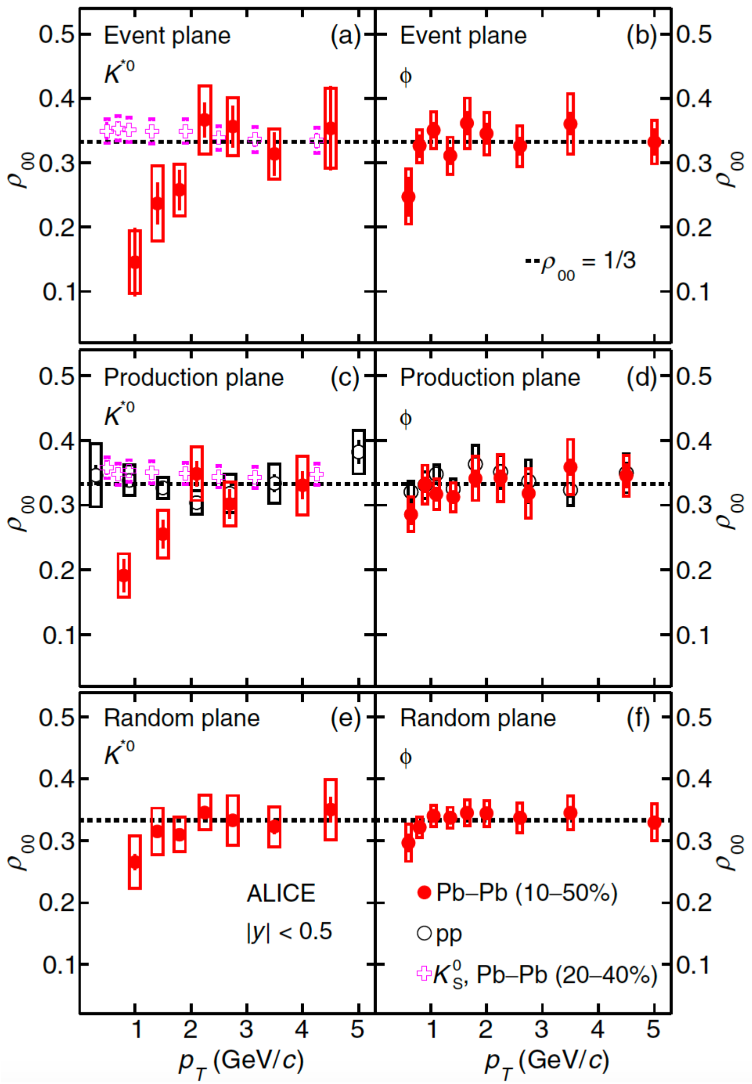
- Polarization by a strong force field of vector meson

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

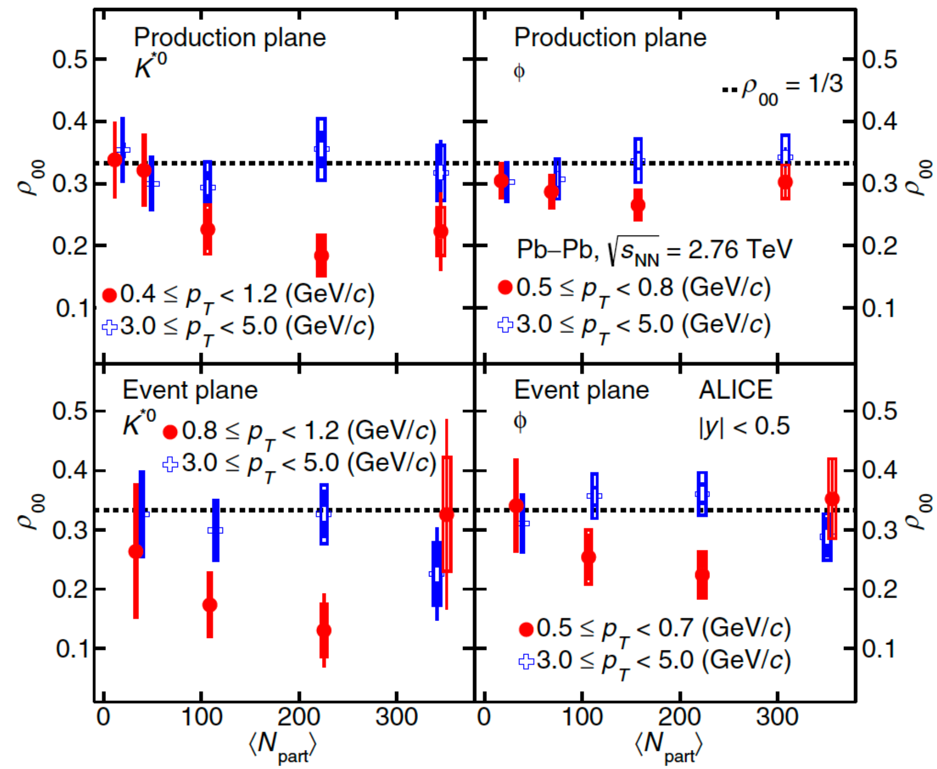
Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

ALICE, PRL125, 012301 (2020)

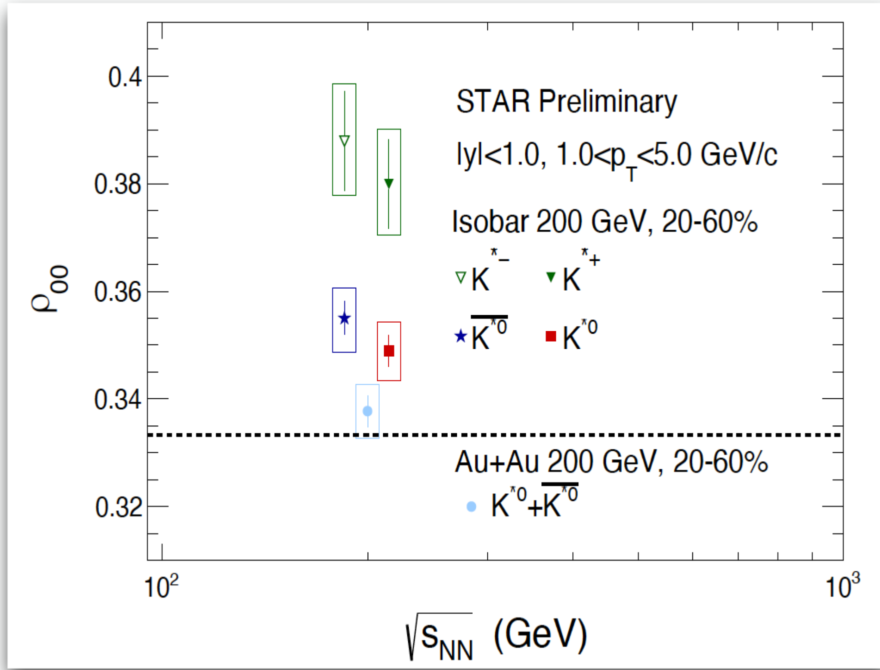
S. Acharya *et al.*[*]
(The ALICE Collaboration)



- 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



K* ρ_{00} from Isobar collisions



- $K^{*+/-}$: First measurement of global ρ_{00}
- K^{*0} vs. $K^{*+/-}$: ~ 2.5σ difference
  - Ordering opposite to the expectation from **B** field *Yang, et. al., Phys Rev C 97, 034917 (2018)*
  - Effects from vector meson strong force field?

- Need inputs from theory to understand this behavior

19

Subhash Singha @ QM 2022

Spin alignment becomes a new hot topic in heavy ion physics!

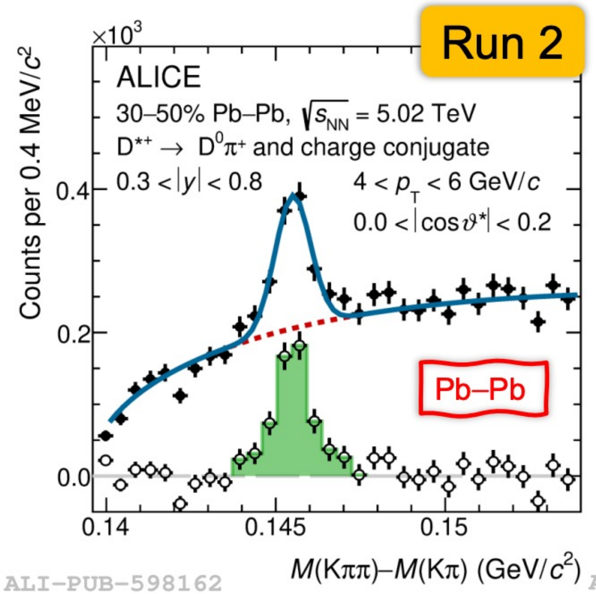
D* spin alignment at ALICE

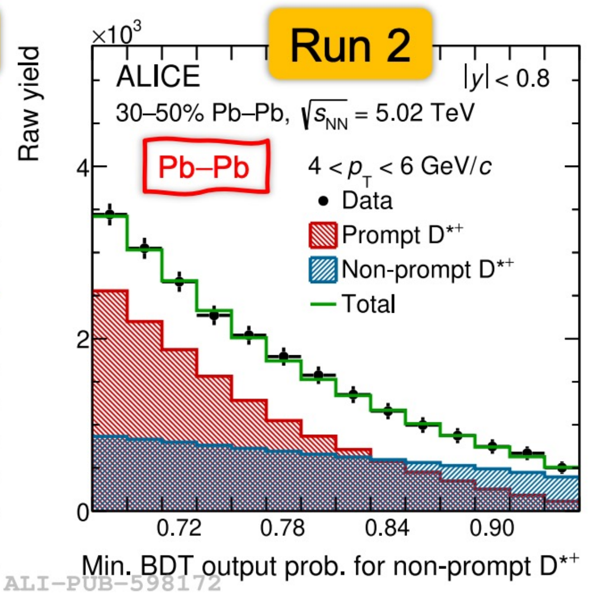
- Mingze Li @ SPIN2025

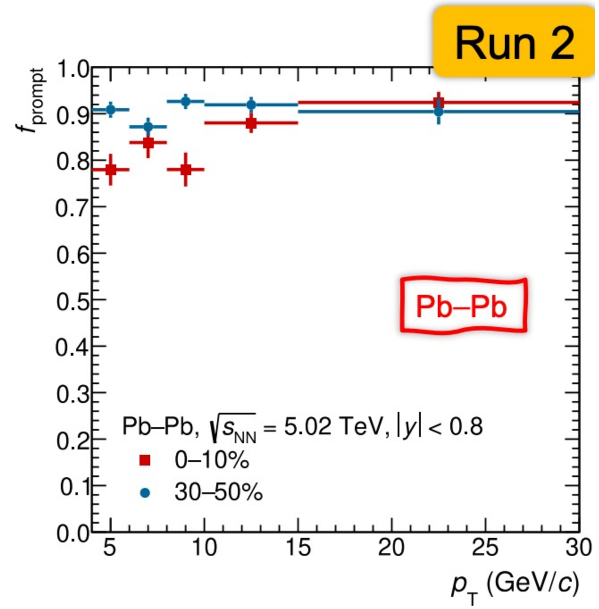
D^{*+} yield extraction

For D^{*+} analysis in pp and Pb–Pb collisions, Boosted Decision Trees (BDT) with 3-class (prompt, non-prompt, background) classification are used to:

- Reduce the combinatorial background
- Separate prompt and non-prompt charm hadrons







D* spin alignment at ALICE

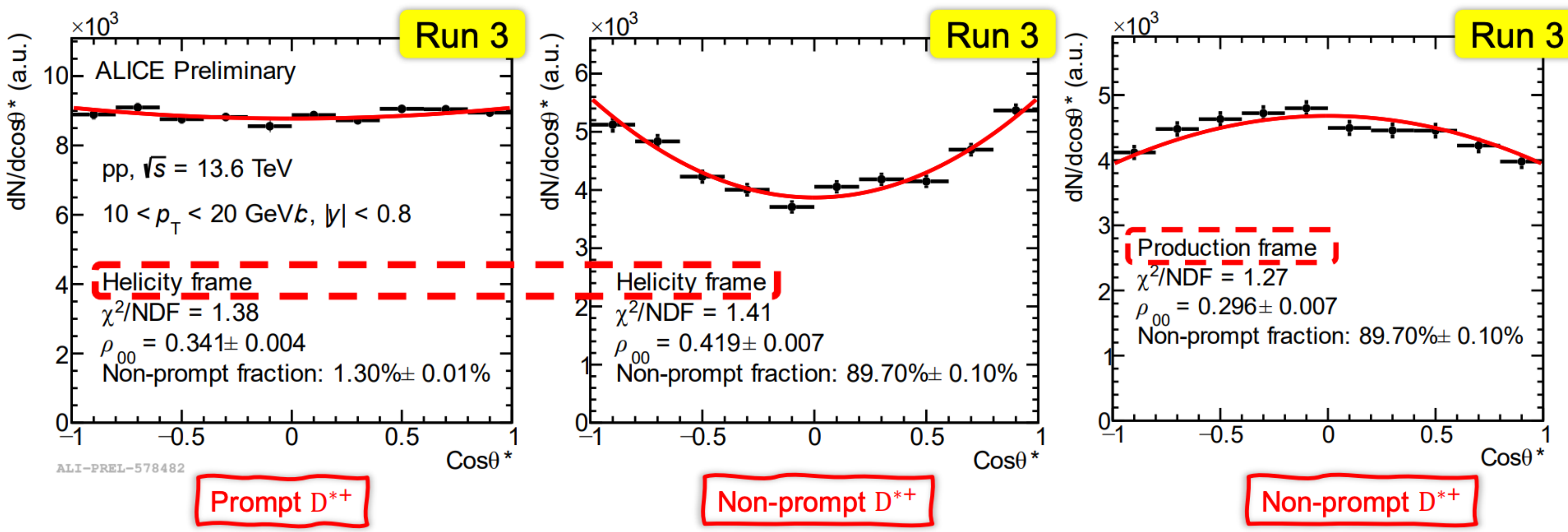
- Mingze Li @ SPIN2025

ρ_{00} extraction

- **Helicity:** Direction of vector meson momentum
- **Production:** Direction perpendicular to vector meson momentum and beam axis

Spin alignment:

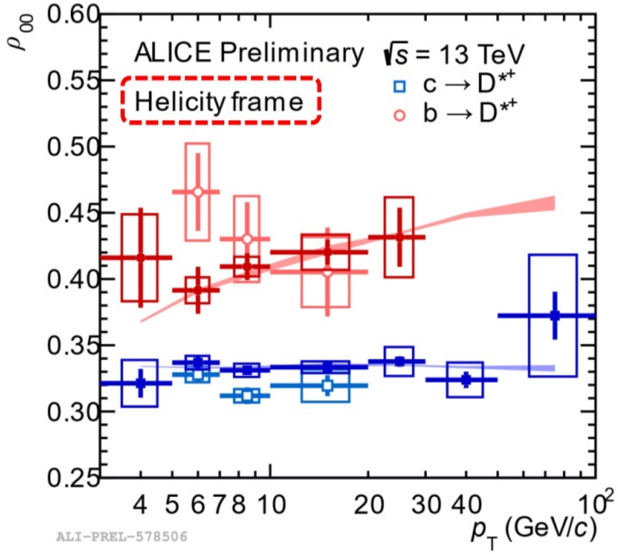
$$\frac{dN}{d\cos\theta^*} = N_0[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

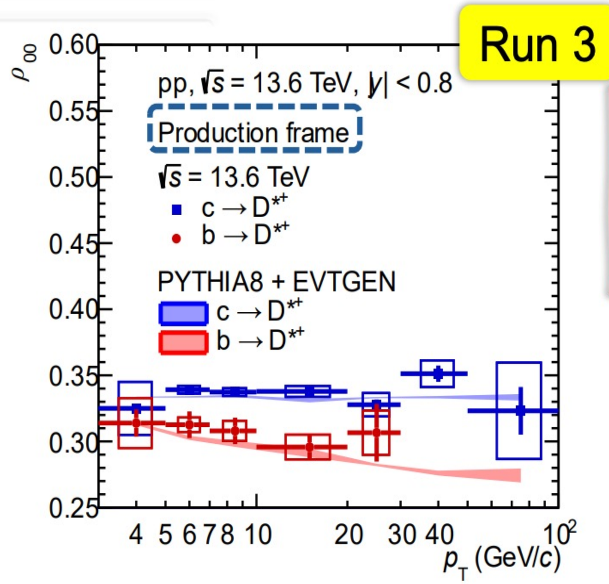


D* spin alignment in pp at ALICE

- Mingze Li @ SPIN2025

D^{*+} spin alignment in pp collisions





Measurement in agreement with prediction of PYTHIA 8.3+EVTGEN

PYTHIA 8.3: SciPost Phys.Codeb. 2022 (2022), 8

EVTGEN: EPJ Web Conf. 295 (2024), 03012

- **Prompt D^{*+}**
  - ⇒ No significant deviation from ρ_{00}= ⅓
  - ⇒ Not supporting any hadronization scenario employing spin-dependent FFs
- **Non-prompt D^{*+}**
  - ⇒ ρ_{00} larger than ⅓ for helicity frame
  - ⇒ Helicity conservation in weak decays of beauty hadrons

D* spin alignment in Pb+Pb at ALICE

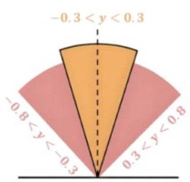
- Mingze Li @ SPIN2025

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

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

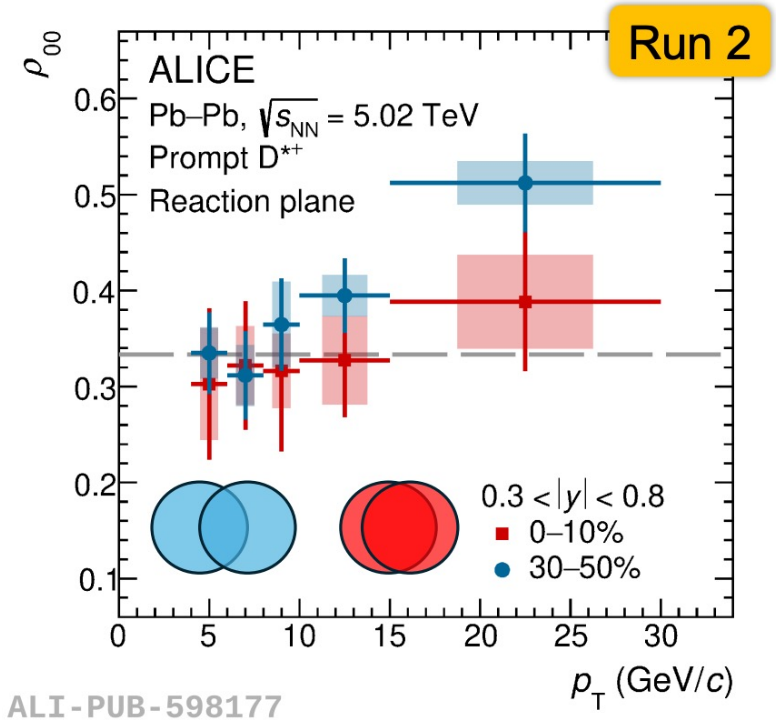
Extracted ρ_{00} parameter for **prompt D^{*+}**

- In less central rapidity regions $\boxed{0.3 < |y| < 0.8}$
  - Central collisions (0-10%):
    Consistent with ρ_{00}= ⅓
  - Non-central collisions (30-50%):
    Evidence of ρ_{00} larger than ⅓ at high p_T
    ⇒ Consistent with the scenario of polarized charm quarks hadronizing via fragmentation



$$\boxed{\rho_{00} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3}$$

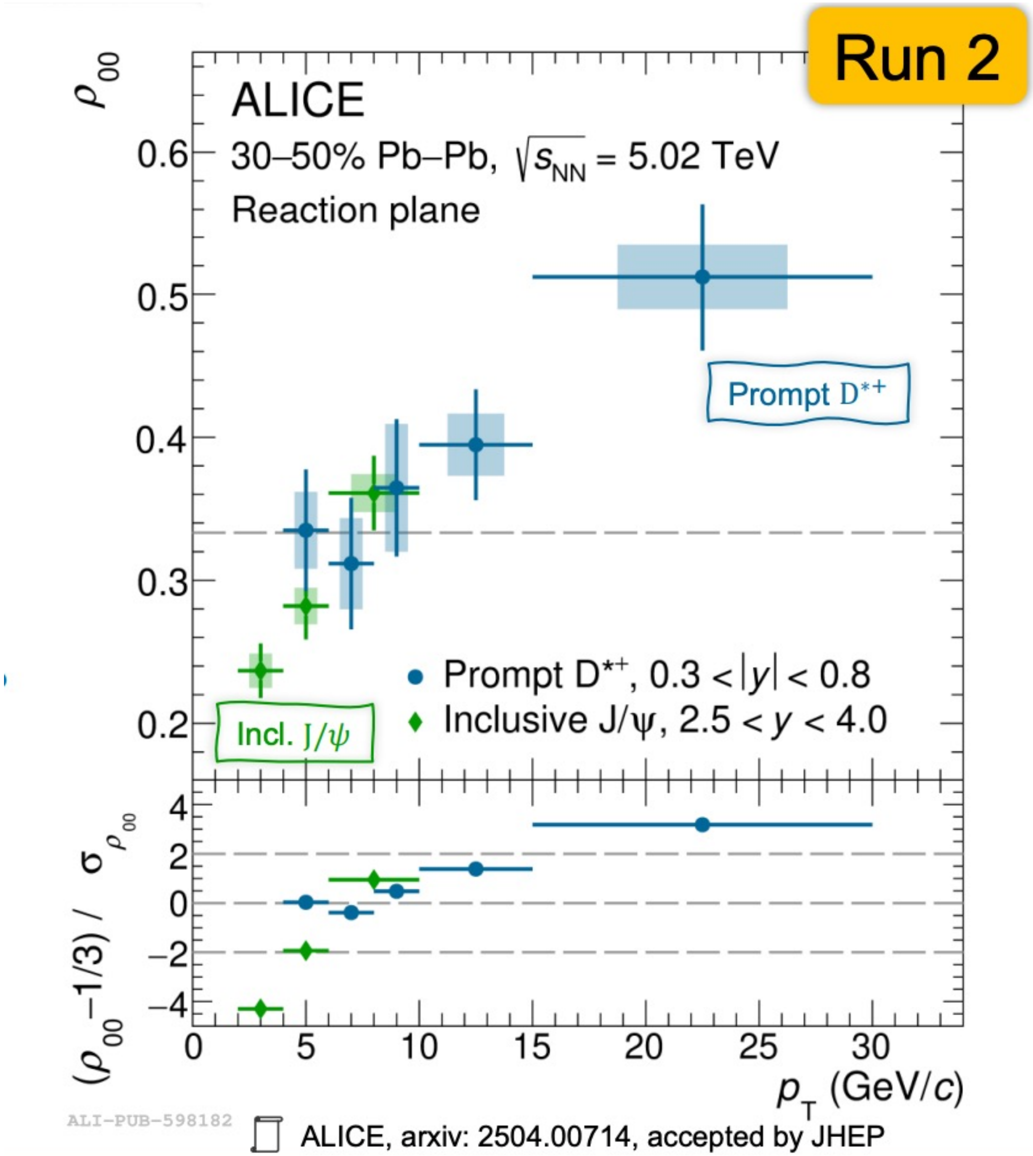
Liang et al, Physics Letters B 629 (2005) 20–26

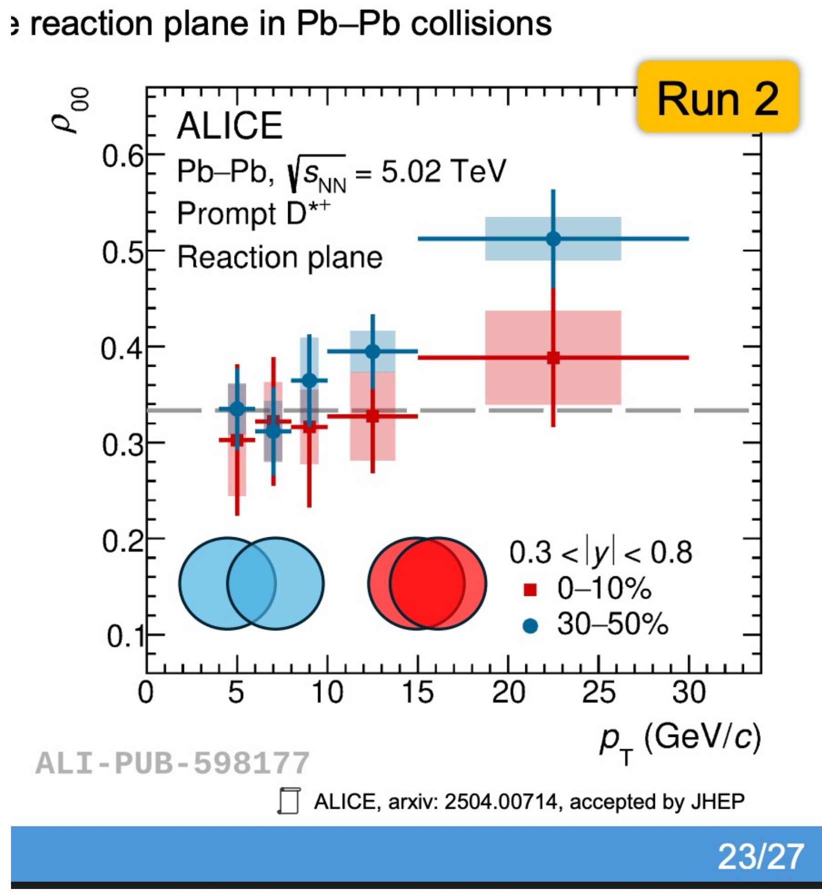


ALICE, arxiv: 2504.00714, accepted by JHEP

D* spin alignment in Pb+Pb at ALICE

- Mingze Li @ SPIN2025

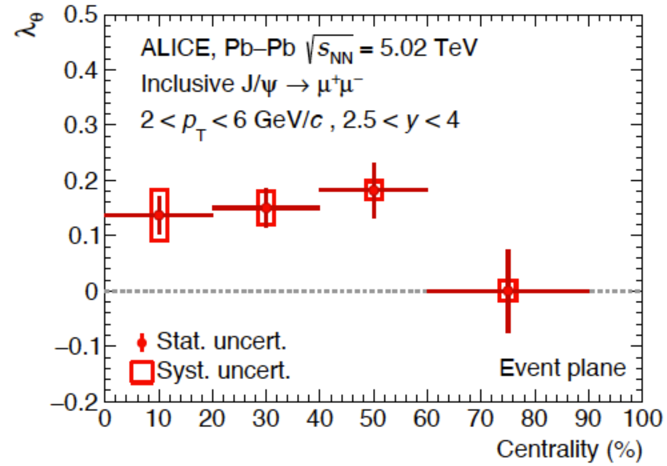




Global spin alignment of J/ψ

- J/ψ production mechanism：

ALICE, PRL131 (2023) 042303



J/ψ 介子

再产生效应 — QGP中 — 能量依赖性
硬散射产生 — 碰撞早期 — 强磁场

ϕ介子

再产生效应 — QGP中

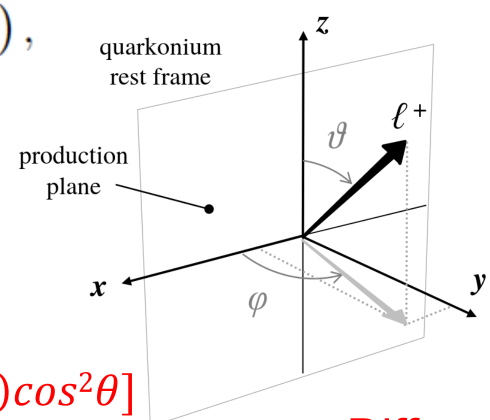
- J/ψ spin alignment determination, along angular momentum direction

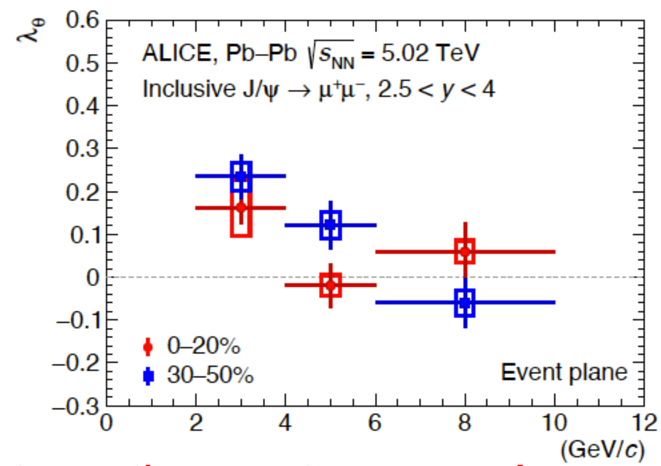
Decay channel : $J/\psi \rightarrow e^+e^-$

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

λ_θ=(1-3ρ_{00})/ (1+ρ_{00})

λ_θ = 1: transverse polarization
λ_θ = -1: longitudinal polarization
λ_θ = 0: no polarization





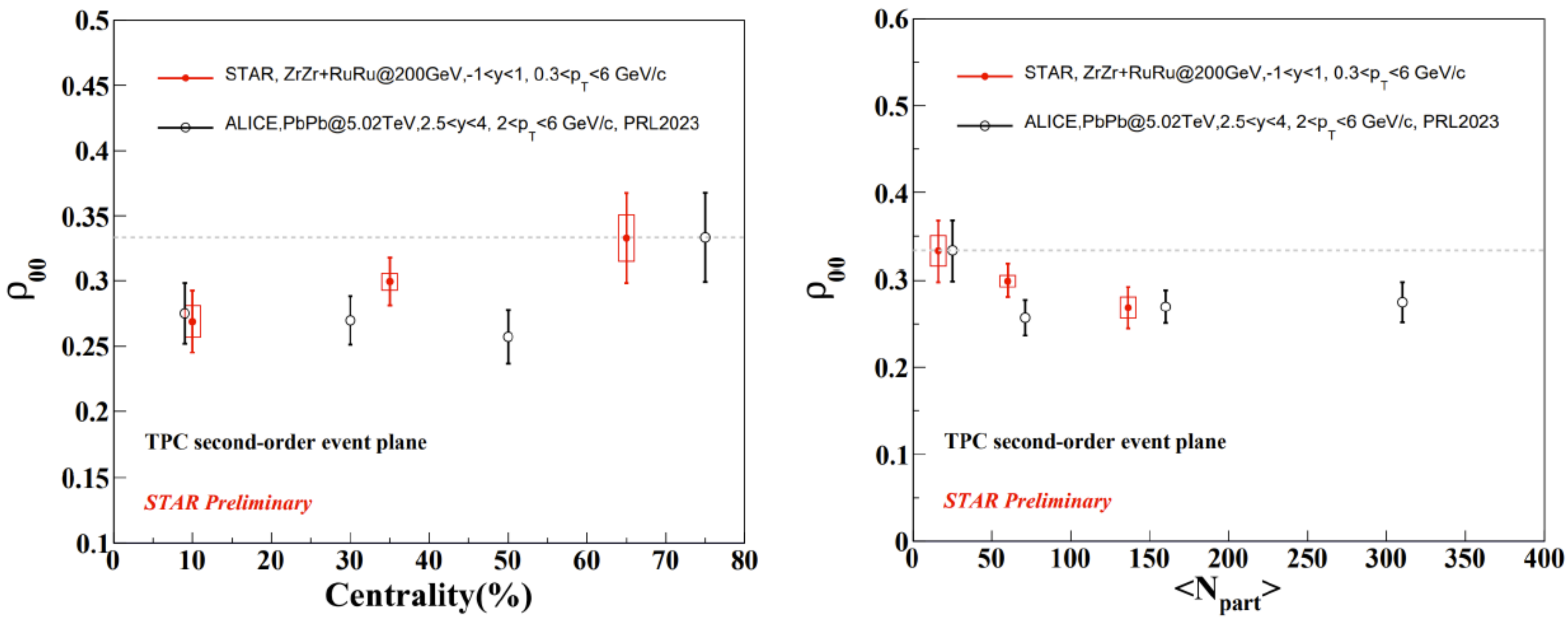
$W(\theta) \propto [(1+\rho_{00}) + (1-3\rho_{00})cos^2\theta]$

->Different as other vector meson!

P. Faccioli et al., Eur. Phys. J. C (2010) 69: 657

J/ψ global spin alignment in iso-bar at STAR

- Dandan Shen @ SPIN2023



➢ The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different collision energy, systems and rapidity

09/26/2023 Dandan Shen @ SPIN 2023 19

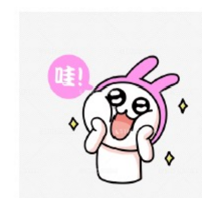
Spin observables probing quark spin quantities

- 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-(anti)Lambda spin-spin correlation

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

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

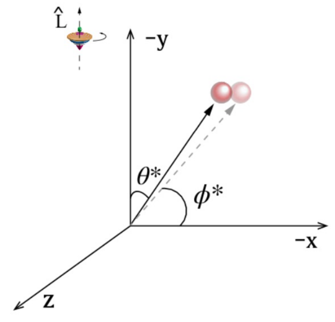
$\boldsymbol{\theta}_i$* : angle between decayed (anti)proton *i* and spin direction in each hyperon's rest frame

- In particular for global polarization in heavy ion collision:

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

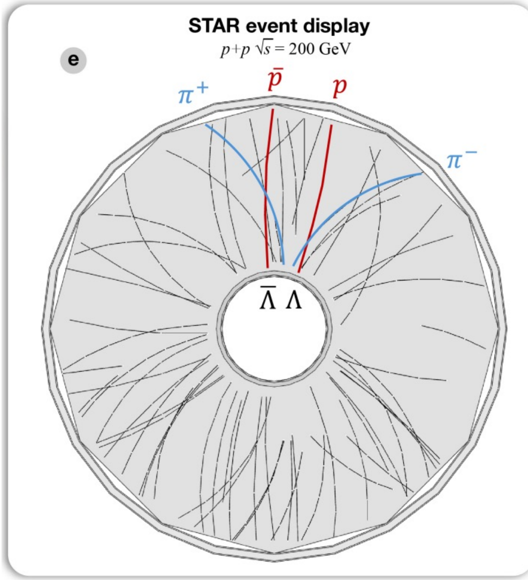
P_Λ: hyperon global polarization along reaction plane
$\Delta\Phi$*: azimuthal angle of decay proton relative to the reaction plane

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

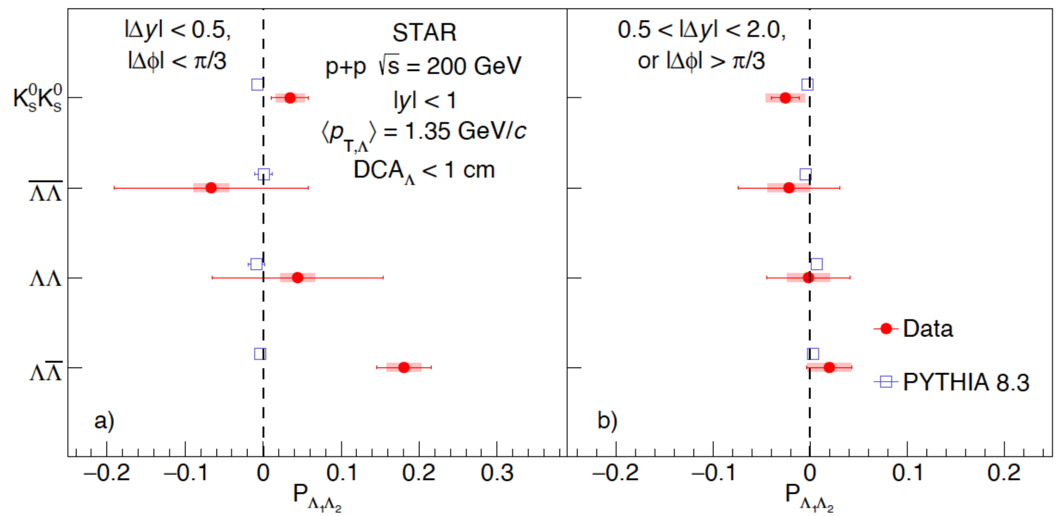


Lambda-Lambda spin-spin correlation in pp

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



STAR, arXiv:2506.05499



- Spin correlation $C^S_{\Lambda_1\Lambda_2}(\mathrm{P}_{\Lambda_1\Lambda_2})$ can be determined as:

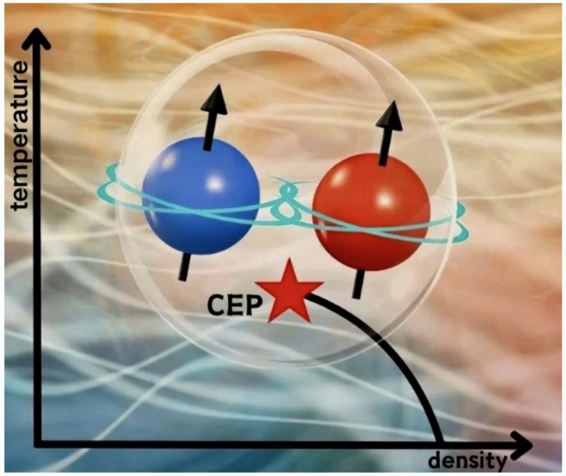
$$\frac{1}{N}\frac{dN}{d\cos\theta^*_{1,2}} = \frac{1}{2}[1+\alpha_1\alpha_2 C^S_{\Lambda_1\Lambda_2}\cos\theta^*_{1,2}]$$

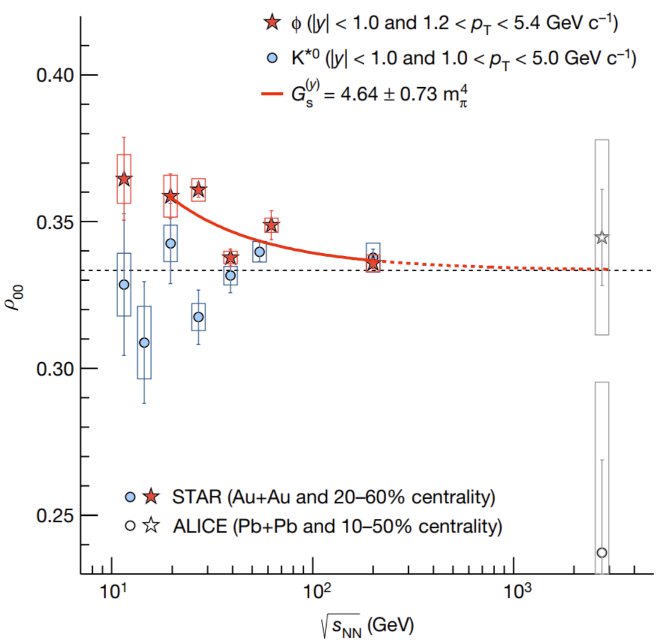
$\theta^*_{1,2}$ is the angle between the momentum of the protons, each boosted to the rest frame of their parent particle

- A nonzero spin correlation is observed in $\Lambda\bar{\Lambda}$ pairs
- ***How about heavy ion collisions? Data analysis at STAR is ongoing***

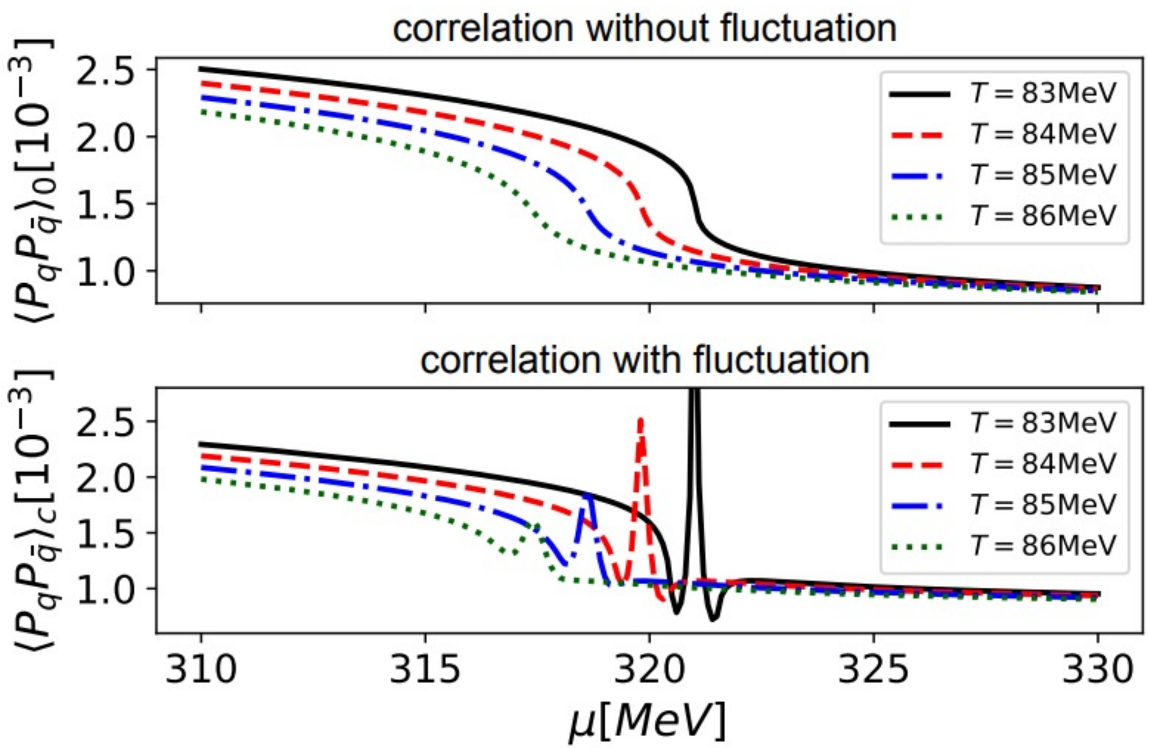
Lambda-Lambda spin-spin correlation & CEP

- Hyperon spin correlation could be sensitive to the CEP in the QCD phase





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

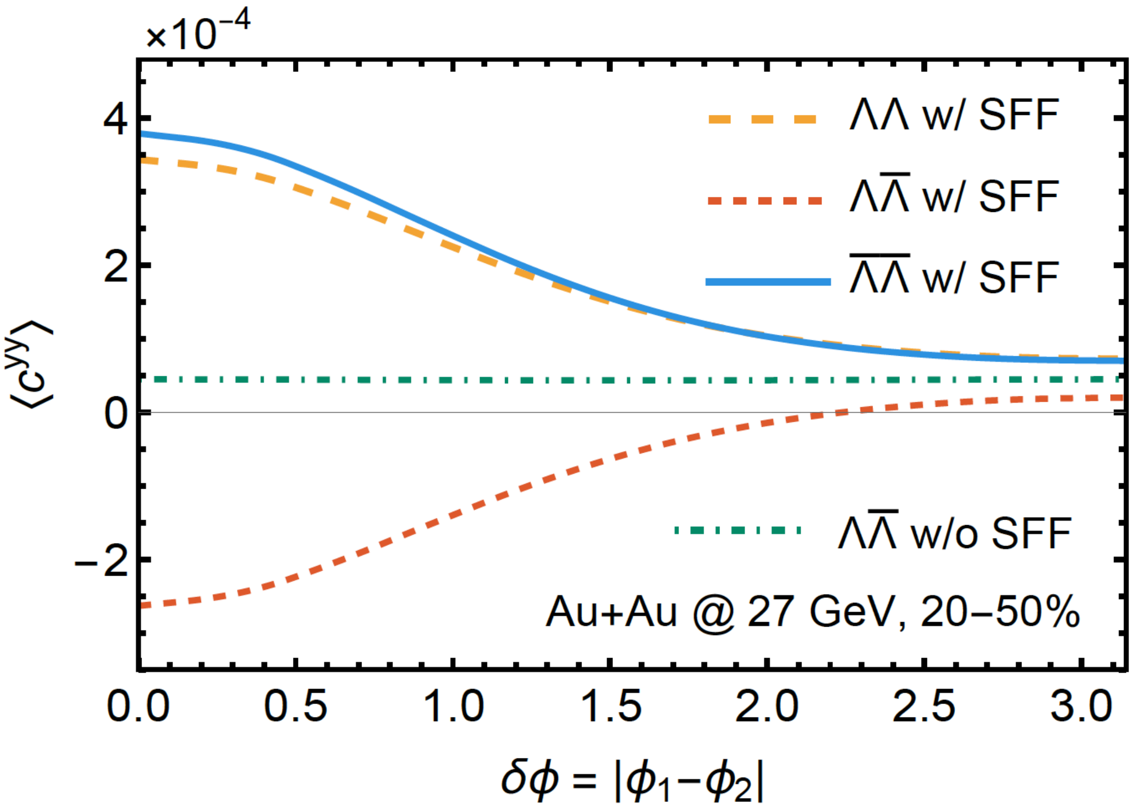


$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$$

Lambda-Lambda spin-spin correlation in AA

- Different spin correlation behaviors of $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs are predicted by theoretical model

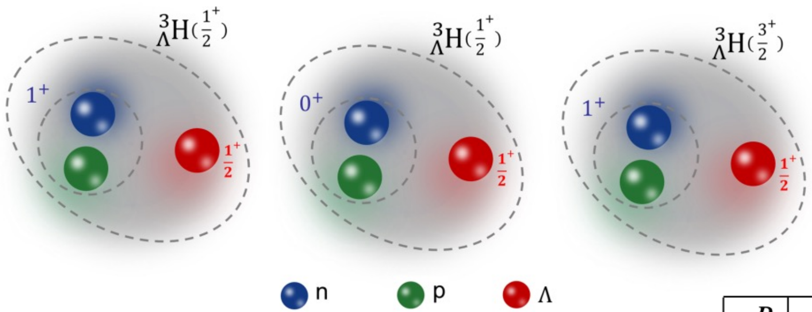
Xin-Li Sheng, et. al, arXiv: 2508.03496



Global polarization of hyper-nuclei in AA collision

- Possible spin structure of hypertriton:

- K.J. Sun et. al. PRL134 (2025), 022301

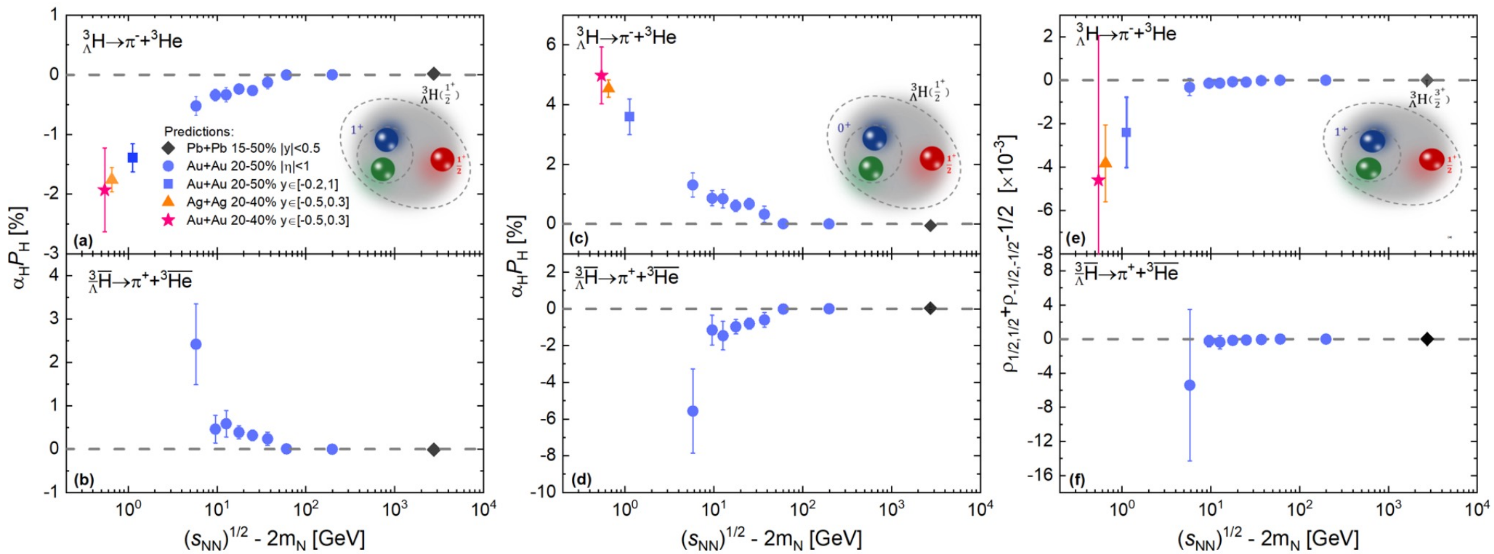


$$^3_\Lambda H \rightarrow \pi^- + ^3He$$

- Angular distribution via hypertriton decay:

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

- Polarization predictions:



Summary

- Exciting spin measurements in heavy ion collisions
  - ➢ Polarization to study QCD medium property in heavy ion collisions
    - ✓ hyperon global polarization
    - ✓ hyperon local polarization
    - ✓ Vector meson spin alignment
    - ✓ Di-hadron spin correlation
  - ➢ Polarization measurements to study QCD effect in pp
    - ✓ hyperon polarization relative to reaction plane
    - ✓ Vector meson spin alignment