Hydrodynamic contributions to spin polarization in AA and pA collisions

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Based on
- CY , X.Y. Wu, J. Zhu, S. Pu, G.Y. Qin, 2408.04296
- CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, Phys.Rev.C 109 (2024) 1, L011901
- X.Y. Wu, CY , G.Y. Qin, S. Pu, Phys.Rev.C 105 (2022) 6, 064909

Outline

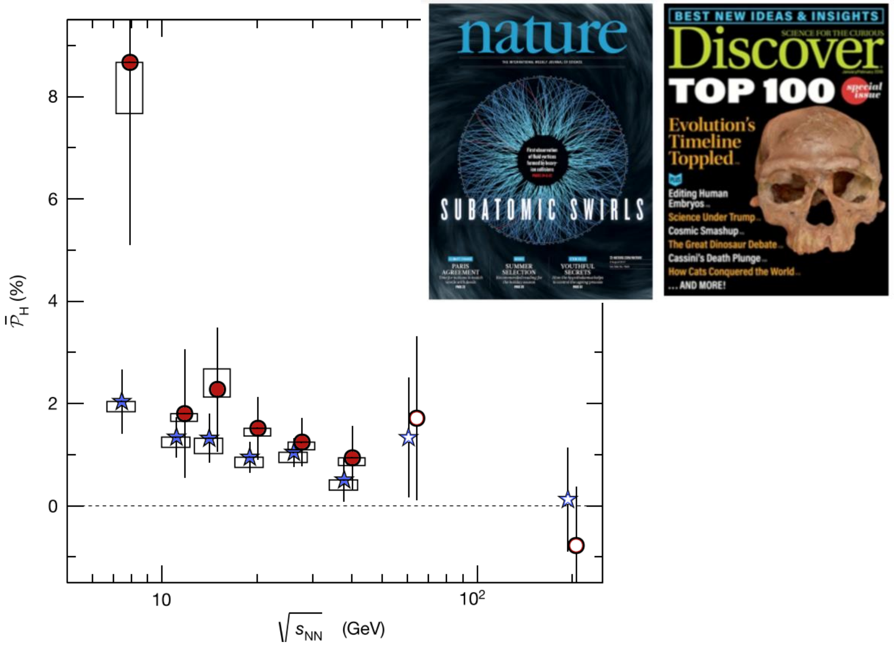
- **Introduction**
- **Spin polarization of Λ hyperons across RHIC-BES energies**
- **Spin polarization of Λ hyperons in p+Pb collisions**
- **Summary**

Global Polarization

- **Global Spin Polarization of Λ Hyperons**

Experiments

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

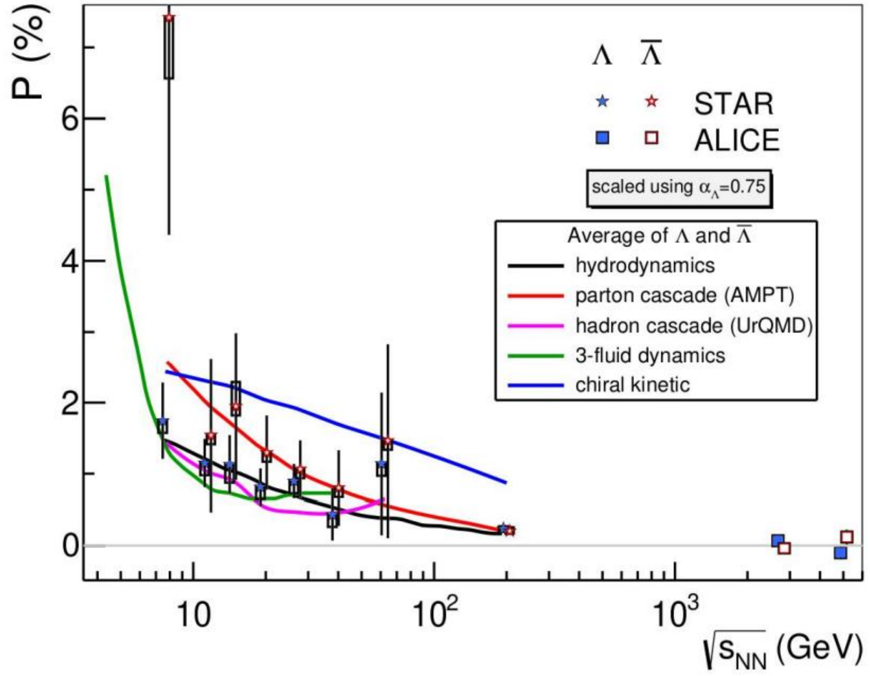


$$\omega = k_B T \left(\overline{P}_{\Lambda'} + \overline{P}_{\bar{\Lambda}'}\right)/\hbar \quad \sim \quad 10^{22} s^{-1}$$

Most vortical fluid so far !

Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. a94, 102301 (2005)
STAR, L. Adamczyk et al., Nature (London) 548, 62 (2017).

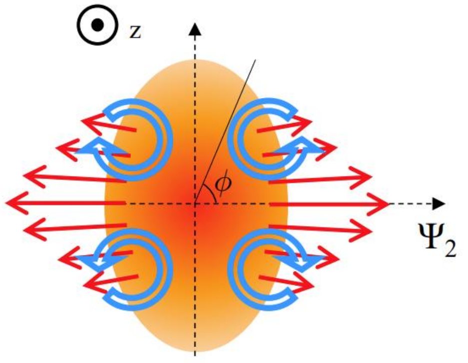
Theory

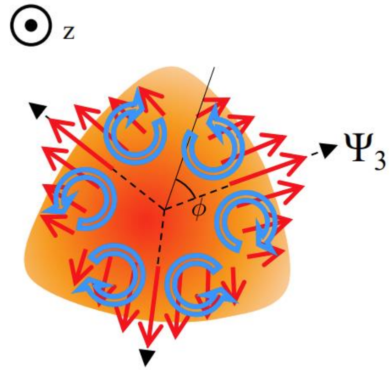


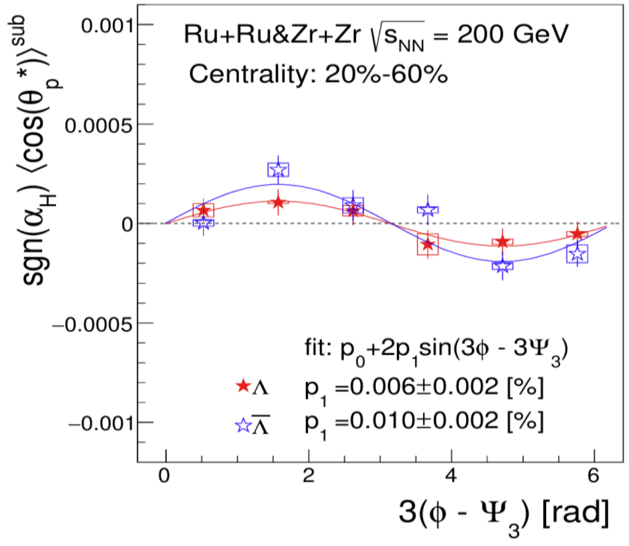
I. Karpenko and F. Becattini, Eur. Phys. J. C 77, 213 (2017).
H. Li, L.-G. Pang, Q. Wang, and X.-L. Xia, Phys. Rev. C 96, 054908 (2017).
Y. Xie, D. Wang, and L. P. Csernai, Phys. Rev. C 95, 031901(R) (2017).
Y. Sun and C. M. Ko, Phys. Rev. C 96, 024906 (2017)
S. Shi, K. Li, and J. Liao, Phys. Lett. B 788, 409 (2019).

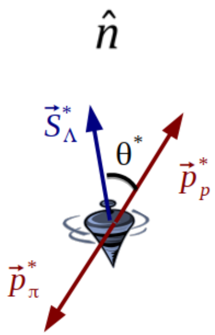
Local Polarization

- **Local Vortical Structure**





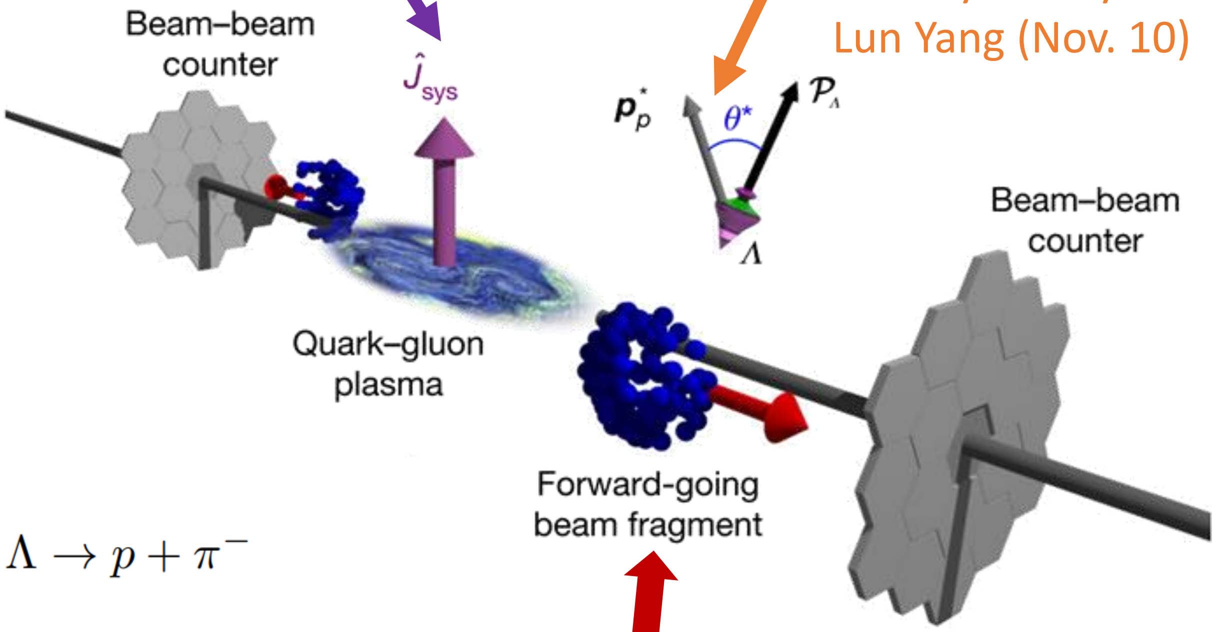




Total angular monetum (Out-plane direction)

Helicity polarization (particle's momentum)

Plenary talk by Prof. Di-Lun Yang (Nov. 10)



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

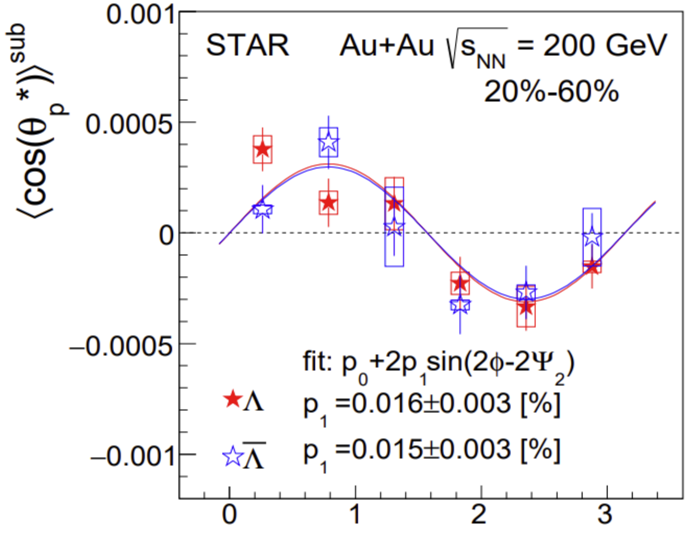
Beam direction polarization

STAR, L. Adamczyk et al., Nature (London) 548, 62.
STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301.

“Sign” Problem& shear induced polarization

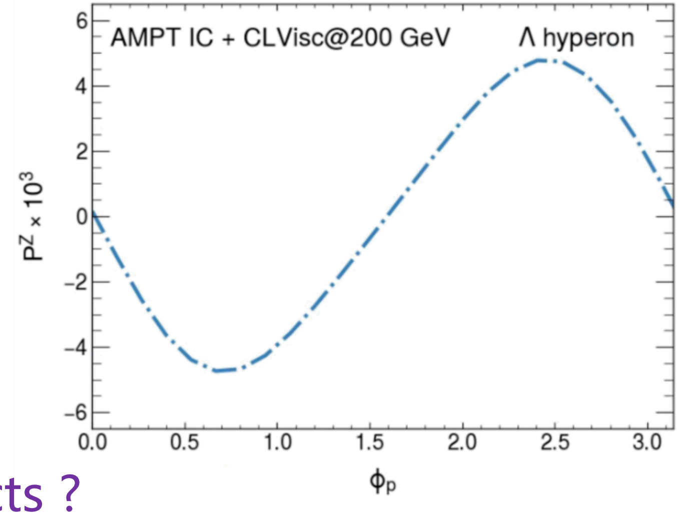
STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301

F. Becattini and I. Karpenko, Phys. Rev. Lett. 120, 012302
X.-L. Xia, H. Li, Z.-B. Tang, and Q. Wang, Phys. Rev. C 98, 024905

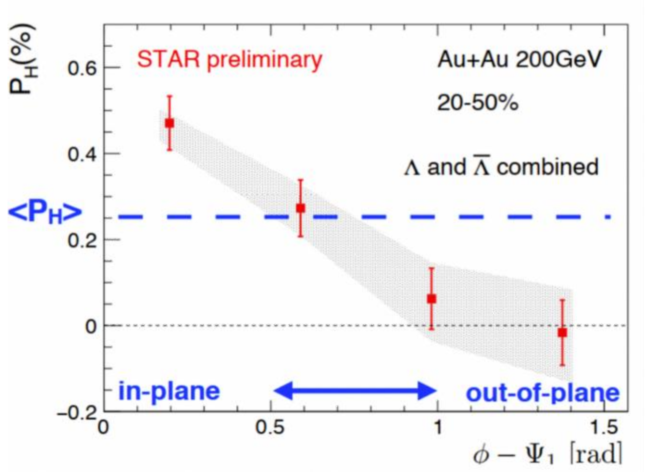


Beam direction Polarization

Opposite Sign!

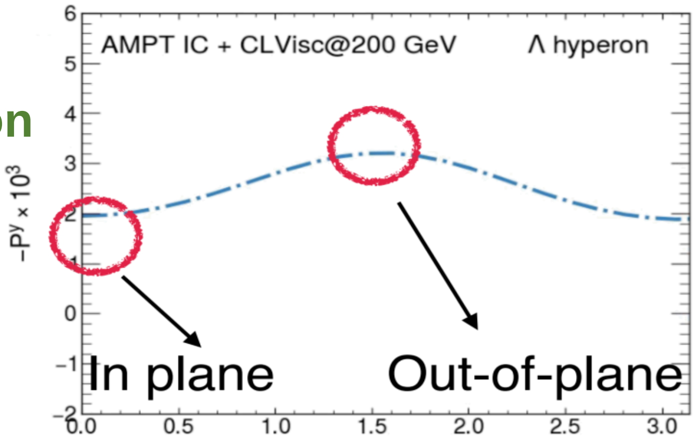


Out of global equilibrium effects ?



Local Transverse Polarization

Opposite Trend!



Hydrodynamic Effects

Recalling the original spin polarization distribution in phase space

$$\mathcal{S}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p \mathcal{J}_5^\mu(p,X)}{2m_\Lambda \int d\Sigma \cdot \mathcal{N}(p,X)},$$

Axial current ($\mathcal{J}_5^\mu$)

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. 338, 32 (2013).
R.-H. Fang, L.-G. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C94, 024904 (2016)

The axial currents at the local equilibrium can be decomposed as

$$\mathcal{J}^\mu_{\rm thermal} = a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T},$$

Thermal vorticity

$$\mathcal{J}^\mu_{\rm shear} = -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta p^\sigma\partial_{<\sigma}u_{\nu>}$$

Shear viscous tensor
Shear Induced Polarization(SIP)

$$\mathcal{J}^\mu_{\rm accT} = -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\left(Du_\beta - \frac{1}{T}\partial_\beta T\right).$$

Fluid acceleration

$$\mathcal{J}^\mu_{\rm chemical} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\partial_\nu\frac{\mu}{T},$$

Gradient of chemical potential
Spin Hall Effect (SHE)

New effects!

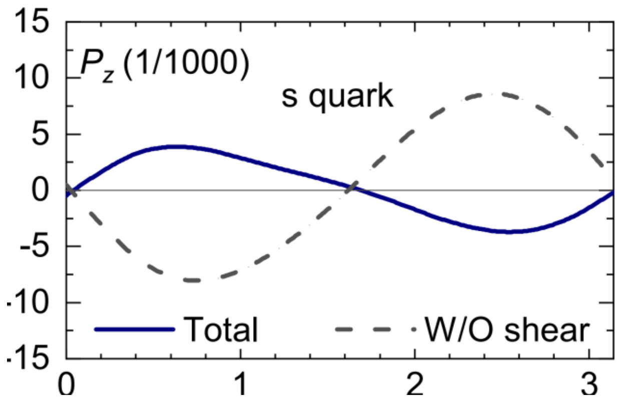
$$\mathcal{J}^\mu_{\rm EB} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta E_\nu,$$

Electromagnetic fields

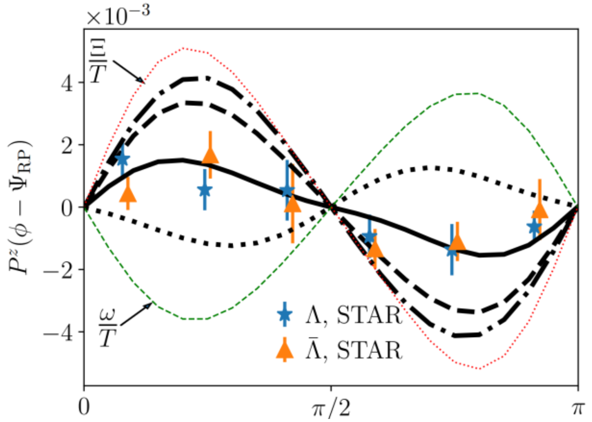
Y. Hidaka, S. Pu, and D.-L. Yang, Phys. Rev. D97, 016004 (2018)
S. Y. F. Liu, Y. Yin, PRD 104, 054043 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519
S. Y. F. Liu, Y. Yin, JHEP 07 (2021) 188.

Spin polarization in very high energy collisions

- **Hydrodynamic contribution to the local spin polarization**



B. Fu, et al. Phys. Rev. Lett. 127, 142301



F. Becattini et al, Phys. Rev. Lett. 127, 272302

Also see: CY, S. Pu, and D.-L. Yang, Phys. Rev. C 104, 064901.
S. Ryu, V. Jupic, and C. Shen, Phys. Rev. C 104, 054908
X.-Y. Wu, CY, G.-Y. Qin, and S. Pu, Phys. Rev .C 105 6, 064909
B. Fu, L. Pang, H. Song, and Y. Yin, (2022), 2201.12970.
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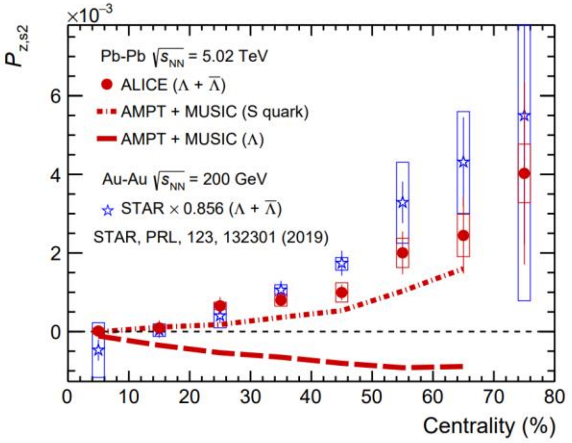
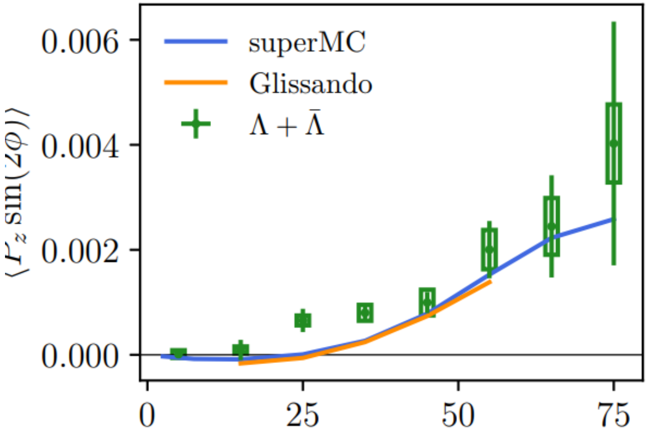


ALICE, Phys. Rev. Lett. 128, 172005(2022)



A. Palermo, et al. Eur.Phys.J.C 84 (2024) 9, 920

Considering shear induced Polarization under some assumptions, the theoretical calculations qualitatively/quantitatively agree with the experimental data at RHIC top energy and 5.02 TeV Pb+Pb collision. The results are sensitive to the approximations and parameters.

Outline

- Introduction
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Setup of simulation

- ## (3+1) dimensional viscous hydrodynamic framework CLVisc

Solve the Energy-momentum conservation and net baryon current:

$$\nabla_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\nabla_\mu J^\mu = 0 \qquad J^\mu = nU^\mu + V^\mu$$

Equation of motion of dissipative current:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha\langle}\sigma^{\mu\nu\rangle}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}$$

$$\Delta^{\mu\nu} DV_\mu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

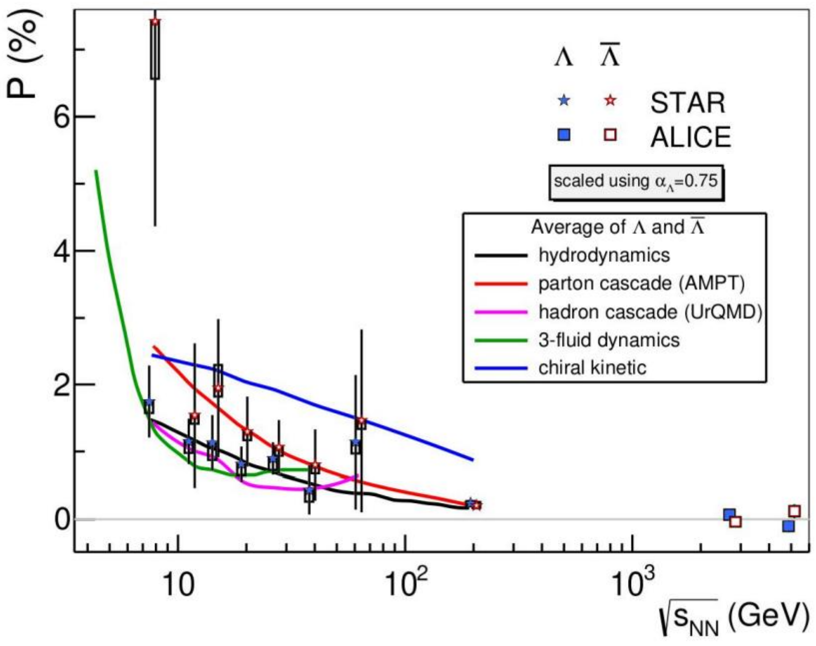
- ## Setup

initial condition: AMPT, SMASH
freeze out condition : e<0.4GeV/fm^3
Equation of State: NEOS BQS

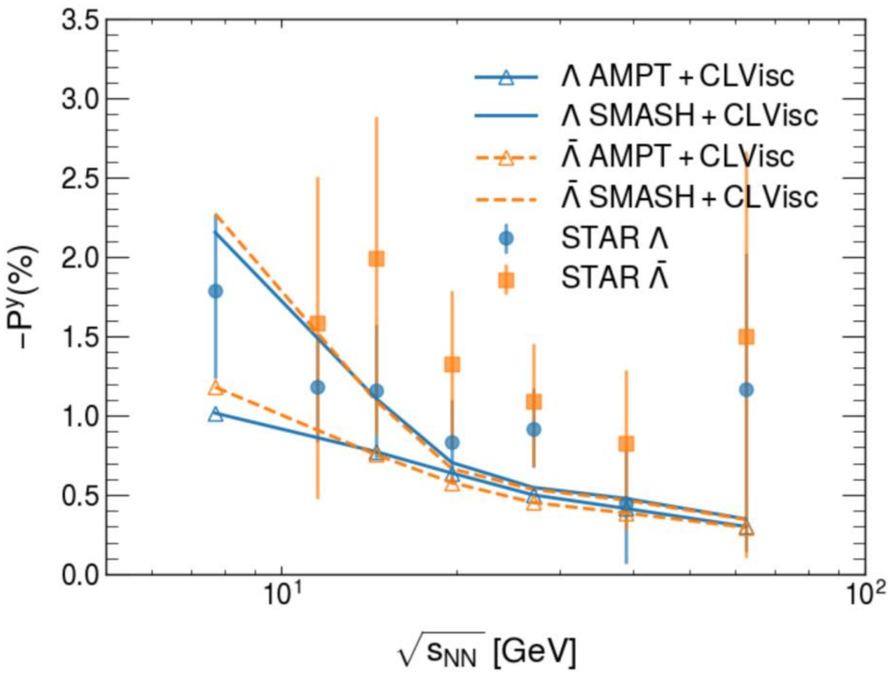
L. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C 86, 024911
X.-Y. Wu, G.-Y. Qin, L.-G. Pang, and X.-N. Wang, Phys. Rev. C 105, 034909

Global Polarization

Thermal vorticity only



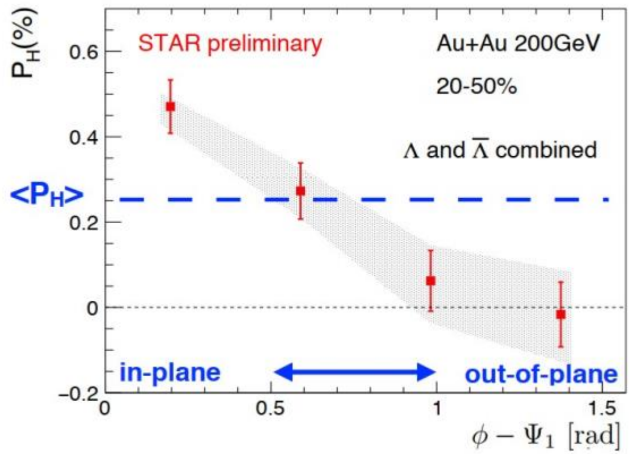
$$\mathcal{J}_5^\mu = \mathcal{J}_{\rm thermal}^\mu + \mathcal{J}_{\rm shear}^\mu + \mathcal{J}_{\rm accT}^\mu + \mathcal{J}_{\rm chemical}^\mu .$$



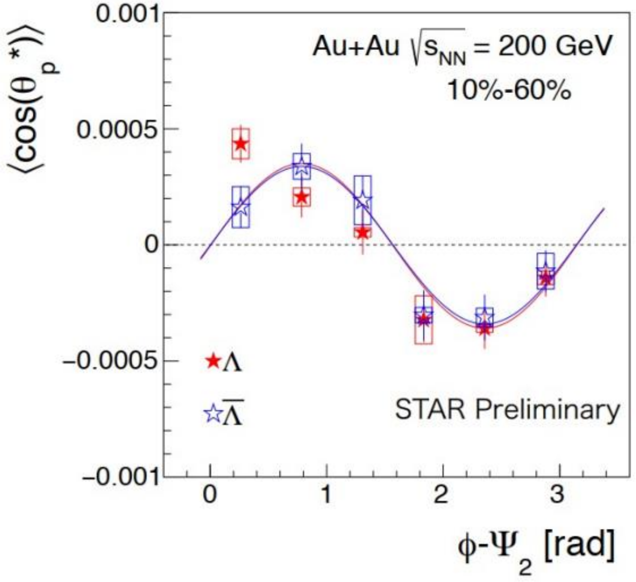
X.-Y. Wu, CY, G.-Y. Qin, and S. Pu, Phys. Rev .C 105 6, 064909

- **The influence of these new effects on the global polarization is small. The theoretical calculations are consistent with the experimental results under both two cases.**

$P_{2,y}$ and $P_{2,z}$ across BES

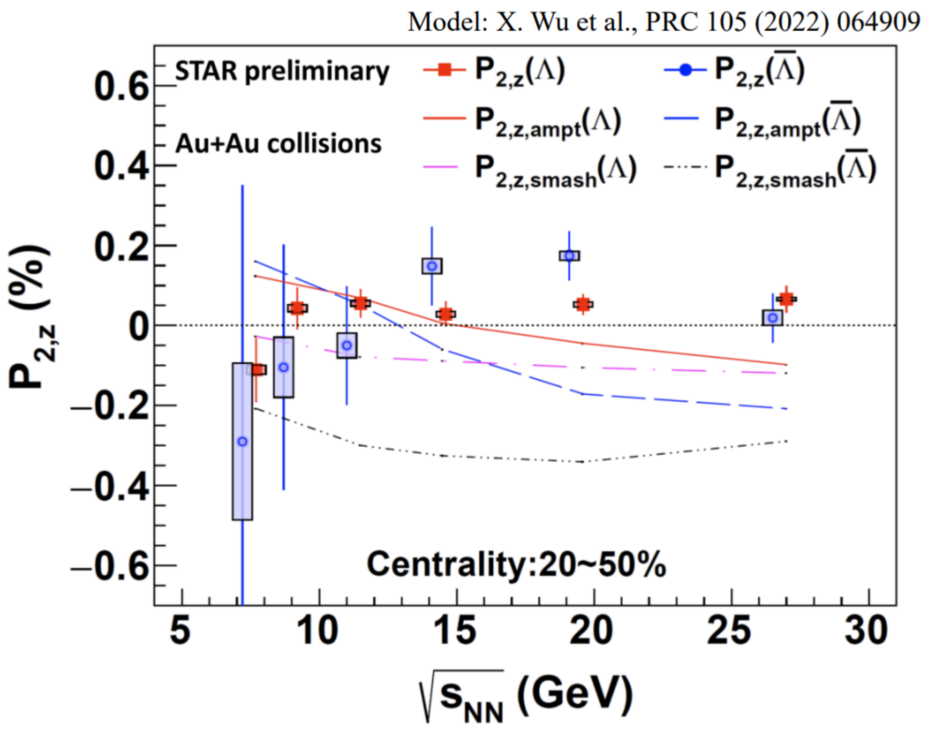


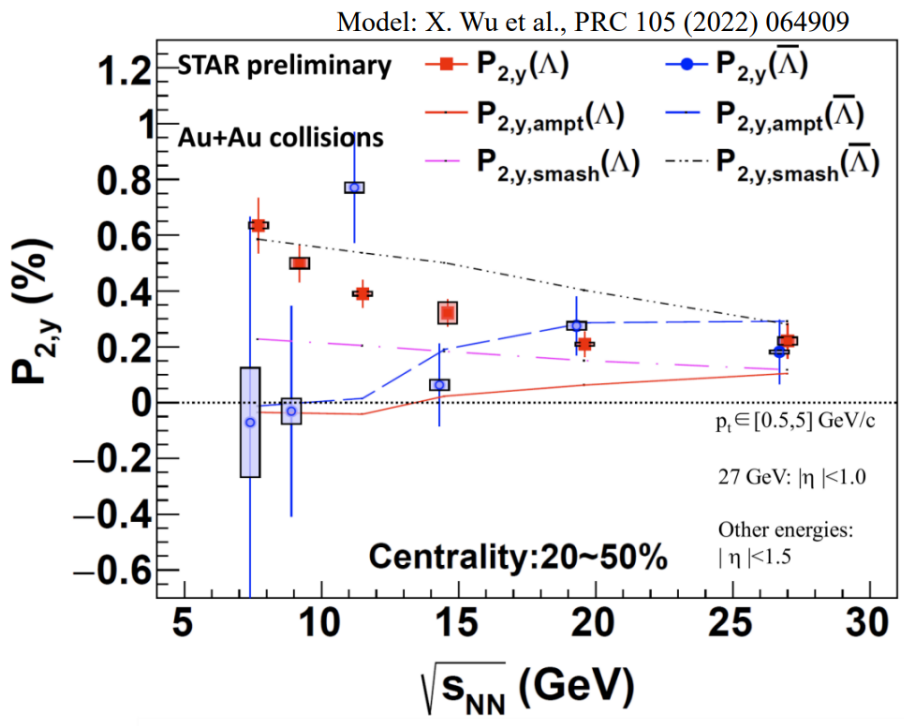
$$P_{2,y} \equiv \langle P_y \cos[2(\phi_\Lambda - \Psi_2)] \rangle$$



$$P_{2,z} \equiv \langle P_z \sin[2(\phi_\Lambda - \Psi_2)] \rangle$$

$P_{2,y}$ and $P_{2,z}$ across BES





Qiang Hu, Talks on SQM 2024

- **The sign of the spin polarization will change at the lower collision energy**
- **P2,y of Λ increase with decreasing energy and current models cannot describe the results**

Outline

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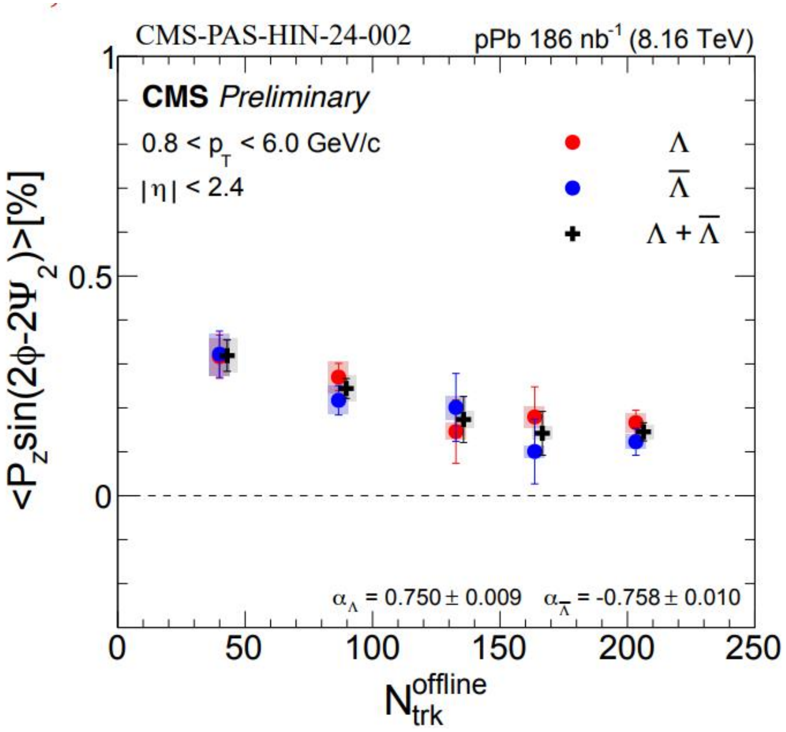
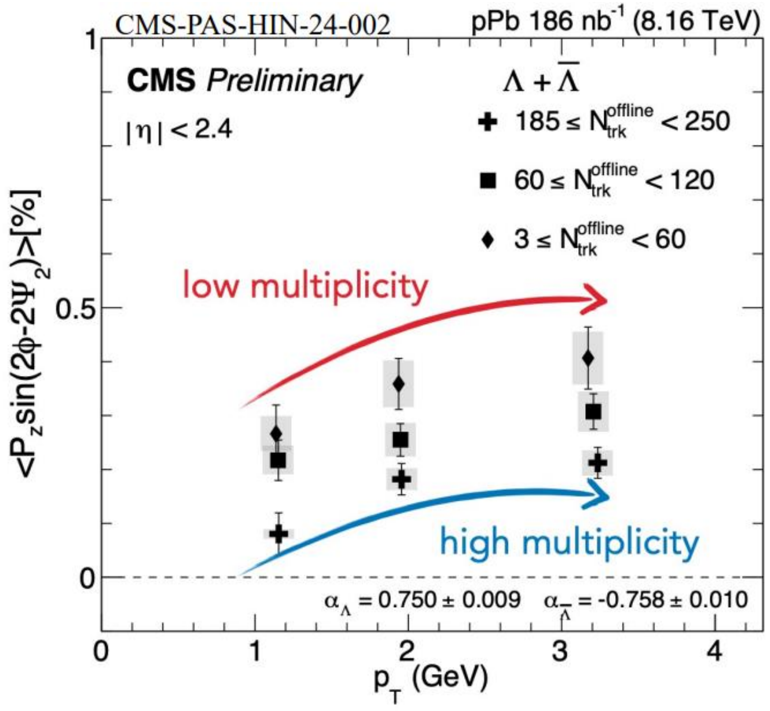
CMS Results

- **Polarization along the beam direction in p+Pb collisions**





Chenyan Li, Talks on SQM 2024

- ➢ **The magnitude of polarization is the same order of magnitude as that in AA collisions**
- ➢ **Its dependence on multiplicity is inconsistent with that of v2**

Setup of simulation

• Initial condition

We implement the parameterized TRENTo-3D model as initial conditions and consider the constituents

$$T_{A/B}(\mathbf{x}_\perp) = \sum_{i=1}^{N_{A/B}} \frac{1}{n_c} \sum_{q=1}^{n_c} \gamma_q \frac{e^{-(\mathbf{x}_\perp - \mathbf{x}_\perp^i - \mathbf{s}_q)^2/2v^2}}{2\pi v^2}$$

$$s(\mathbf{x}_\perp) \propto \left(\frac{T_A^a + T_B^a}{2}\right)^{1/a}$$

IP-Glasma like entropy deposition with a =0.
For the longitudinal direction,

$$s(\mathbf{x}_\perp, \eta_s)|_{\tau=\tau_0} = K s(\mathbf{x}_\perp) g(\mathbf{x}_\perp, y) \frac{dy}{d\eta_s},$$

• CLVisc Framework

The subsequent evolution of the system is simulated by the 3+1D CLVisc hydrodynamics model.
We just focus on the energy-momentum conservation equations with the temperature dependent shear and bulk viscosity

$$\partial_\mu T^{\mu\nu} = 0,$$

$$\tau_\Pi D\Pi + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} + \pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma_\lambda^{\nu\rangle} + \varphi_1 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha}.$$

Spin Polarization Vector

Spin Polarization Vector

We the polarization pseudo-vector including the contribution from thermal vorticity and thermal shear tensor and neglect the spin hall effect:

$$\mathcal{S}^{\mu}(\mathbf{p}) = \mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{th-shear}}(\mathbf{p}),$$

$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} p_\nu \varpi_{\alpha\beta},$$

$$\mathcal{S}^{\mu}_{\text{th-shear}}(\mathbf{p}) = \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{\epsilon^{\mu\nu\alpha\beta} p_\nu n_\beta}{(n \cdot p)} p^\sigma \xi_{\sigma\alpha},$$

thermal vorticity: $$\varpi_{\alpha\beta} = \frac{1}{2}\left[\partial_\alpha\left(\frac{u_\beta}{T}\right) - \partial_\beta\left(\frac{u_\alpha}{T}\right)\right],$$

thermal shear tensor: $$\xi_{\alpha\beta} = \frac{1}{2}\left[\partial_\alpha\left(\frac{u_\beta}{T}\right) + \partial_\beta\left(\frac{u_\alpha}{T}\right)\right]$$

Three different scenarios:

Λ equilibrium :

Λ hyperons reach the local equilibrium at the freeze-out hyper-surface

s quark equilibrium:

The spin of Λ hyperons is carried by the constituent s quark.

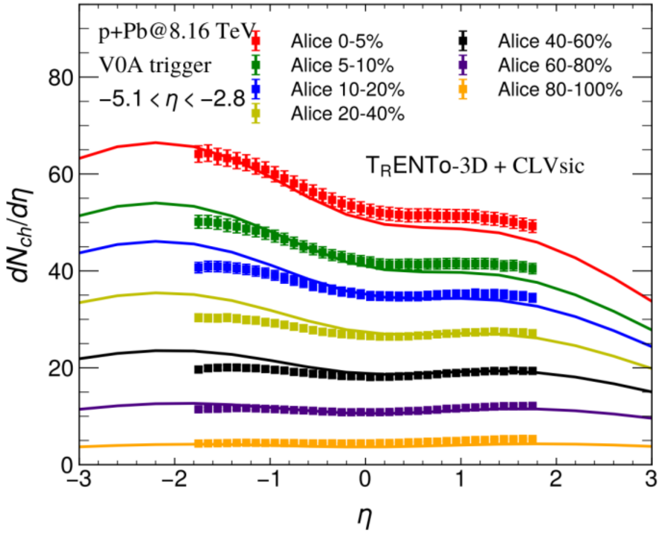
Iso-thermal equilibrium:

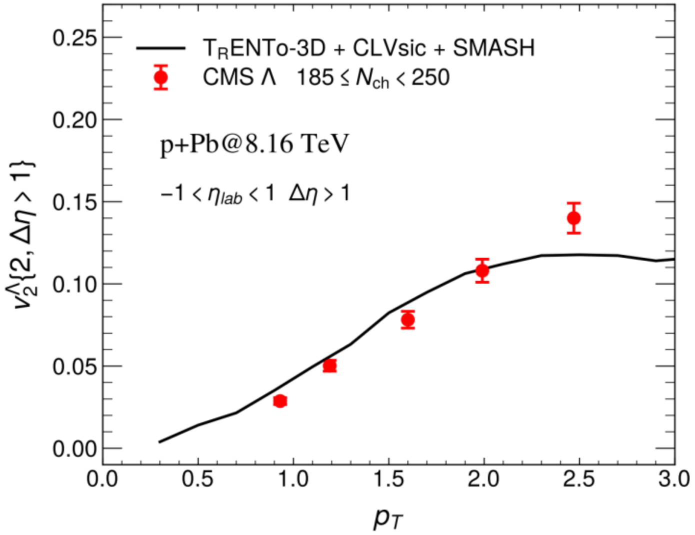
Neglect all the temperature gradient

$$\varpi_{\alpha\beta} \to (\partial_\alpha u_\beta - \partial_\beta u_\alpha)/(2T)$$

$$\xi_{\alpha\beta} \to (\partial_\sigma u_\alpha + \partial_\alpha u_\sigma)/(2T)$$

Multiplicity and v2 of Λ

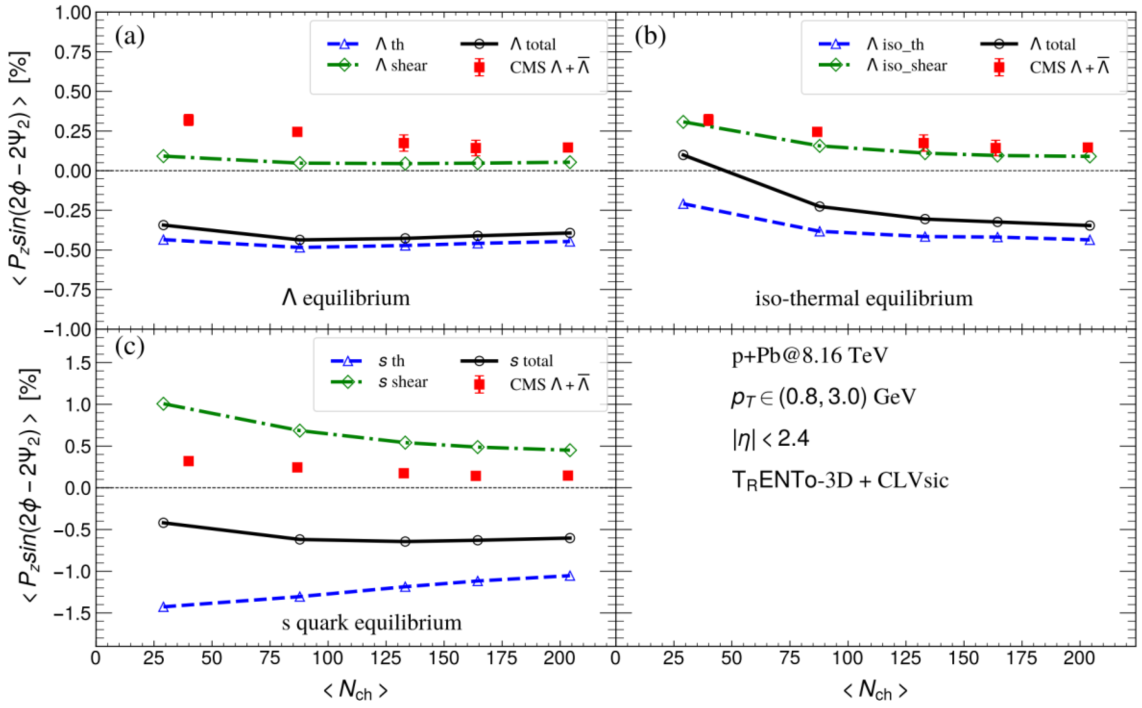




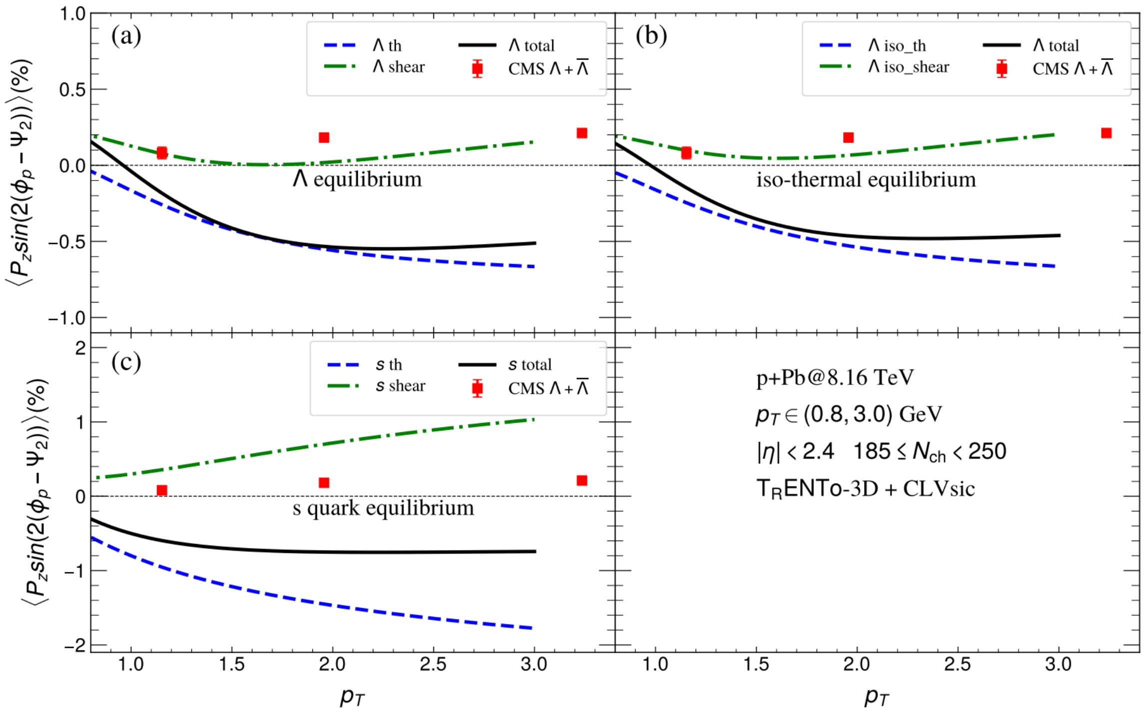
Multiplicity intervals	$\langle N_{ch} \rangle_{exp}$	$\langle N_{ch} \rangle_{CLVisc}$
[185,250)	203.3	204.2
[150,185)	163.6	164.5
[120,150)	132.7	133.57
[60,120)	86.7	87.7
[3,60)	40	29.3

- **Current parameters can have a good description of the multiplicity of charged particles and elliptic flow for Λ hyperons**

Multiplicity (centrality) dependence



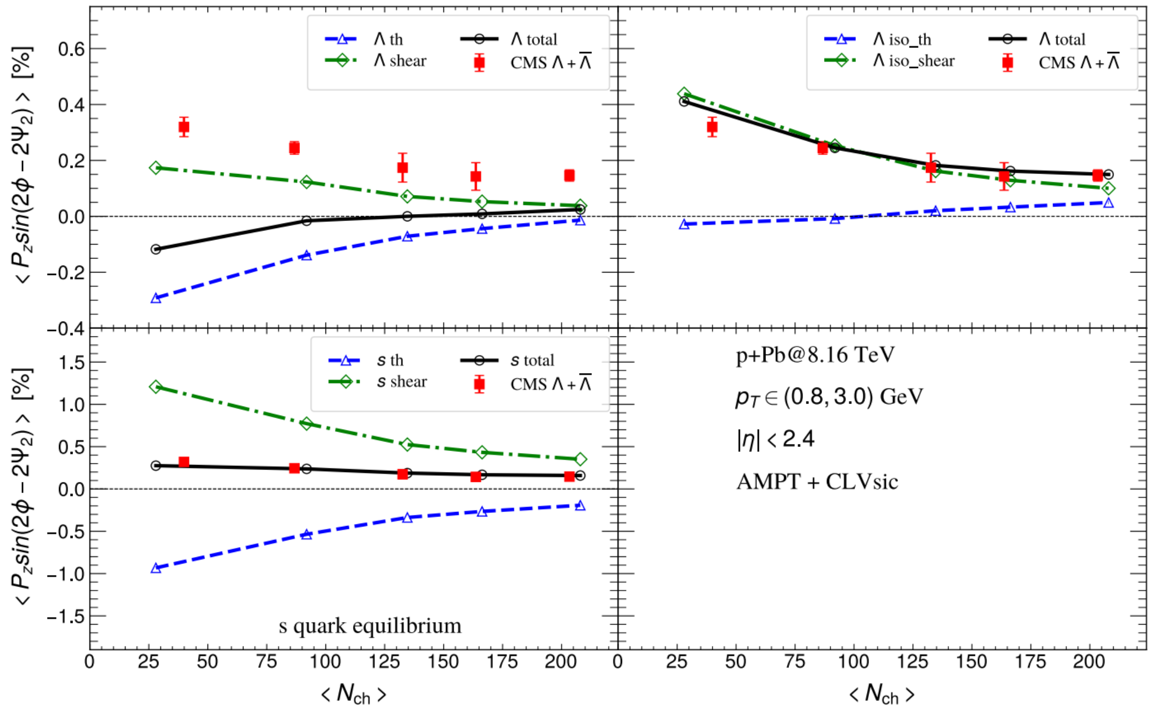
Multiplicity dependence

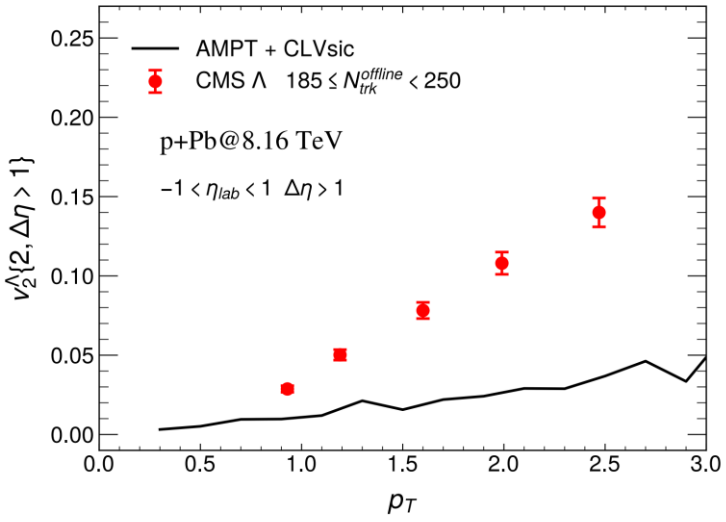


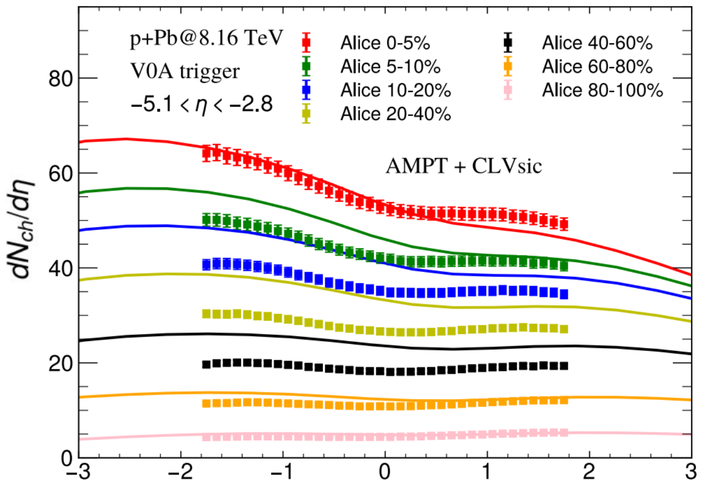
p_T dependence

- **Shear induced polarization always gives a positive contribution**
- **Polarization induced by the thermal vorticity is negative**
- **The results in the three scenarios are inconsistent with the data from the LHC-CMS experiments.**

Test for AMPT initial conditions

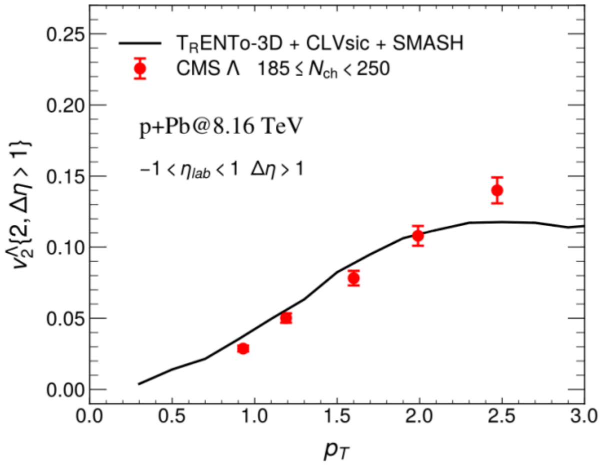


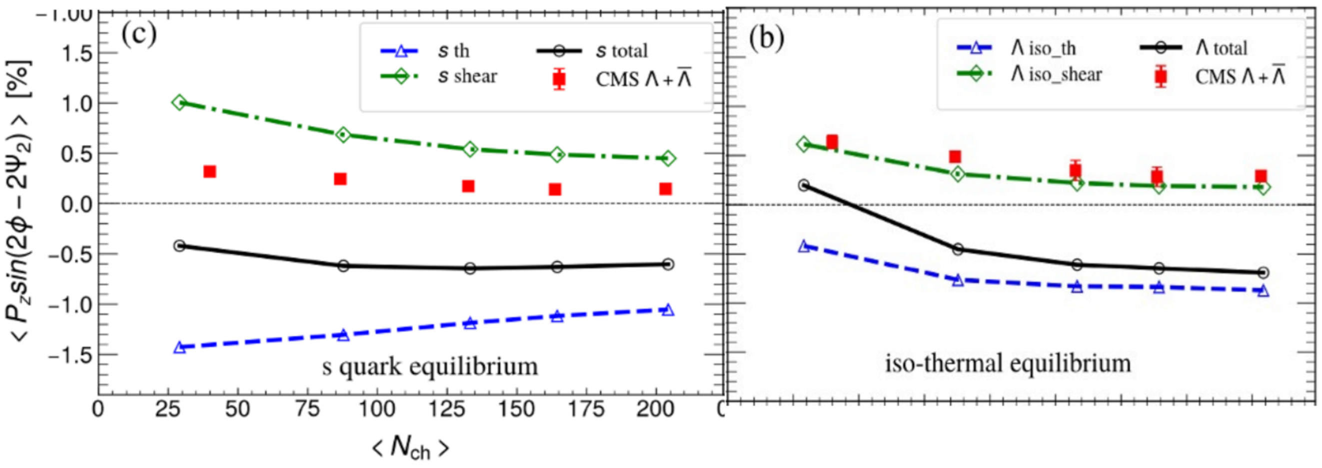




- **The parameters can describe spin polarization at the s quark equilibrium and iso-thermal equilibrium can not fit the multiplicity of charged particles and v2 of Λ.**

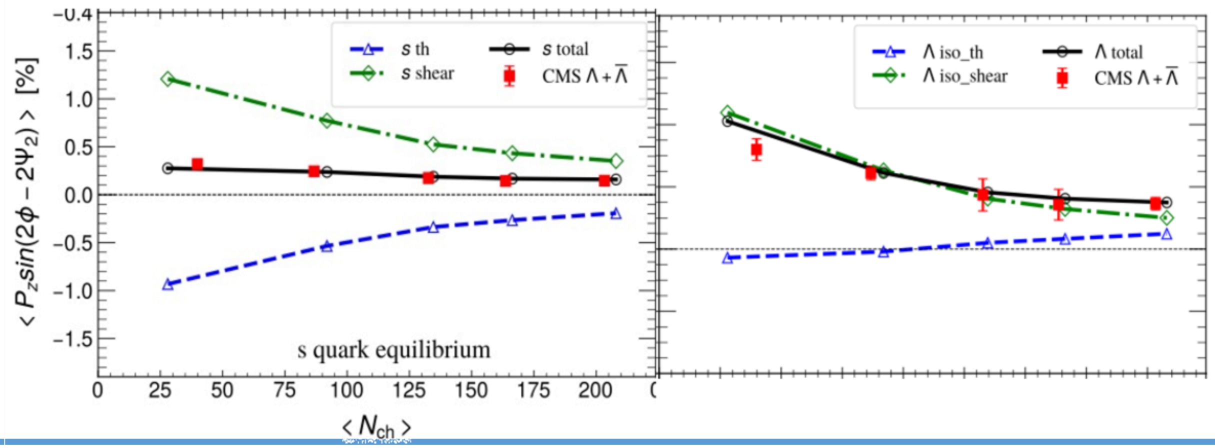
Different initial conditions

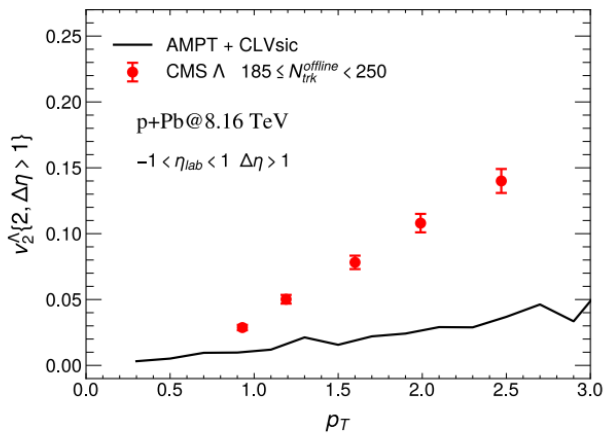




The P2z of Λ hyperons is not only induced by the v2 in the p+Pb collisions.

New effects need to be considered in the polarization at p+Pb collisions.





Summary

- **Spin Polarization in Au+Au collision**
  - The influence of these new effects on the global polarization is small.
  - Shear induced polarization is significant for local spin polarization.
  - The spin hall effect plays an important role in the low energy collisions.

- **Spin Polarization in p+Pb collision**
  - Shear induced polarization always gives a positive contribution.
  - Polarization induced by the thermal vorticity is negative.
  - The results from hydrodynamics are inconsistent with the data from CMS.
  - New effects need to be considered in the polarization at p+Pb collisions

Thanks for your time !