Hydrodynamic contributions to spin polarization in Au+Au and p+Pb collisions

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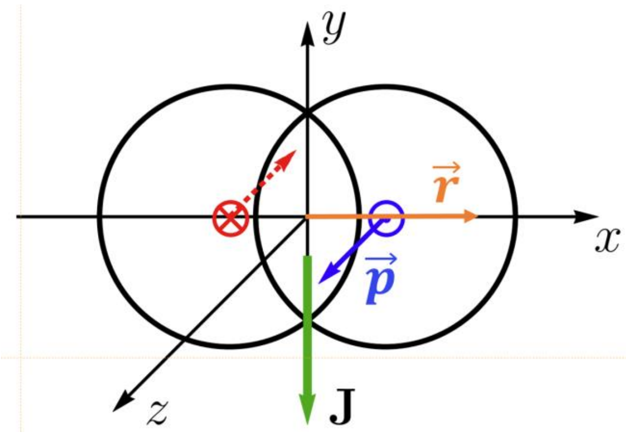
Based on
- CY , X.Y. Wu, J. Zhu, S. Pu, G.Y. Qin, 2408.04296
- CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, Phys.Rev.C 109 (2024) 1, L011901
- X.Y. Wu, CY , G.Y. Qin, S. Pu, Phys.Rev.C 105 (2022) 6, 064909
- In preparation.

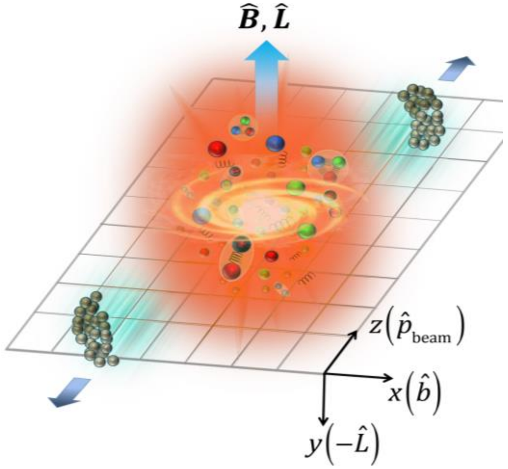
Outline

- Introduction
- Spin polarization of Λ hyperons in Au+Au collisions
- Spin polarization of Λ hyperons in p+Pb collisions
- Summary

Orbital Angular Momentum (OAM)

- **Non-central heavy ion collision**





b=7fm

$$|J_y| = |\mathbf{r} \times \mathbf{p}|$$
$$\approx \frac{b}{2} A \sqrt{s_{NN}}$$

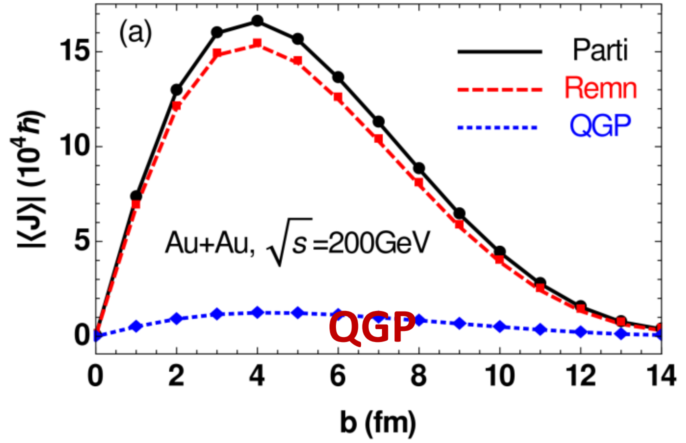
- RHIC: Au+Au@200GeV:

$$J_y \sim 7 \times 10^5 \hbar$$

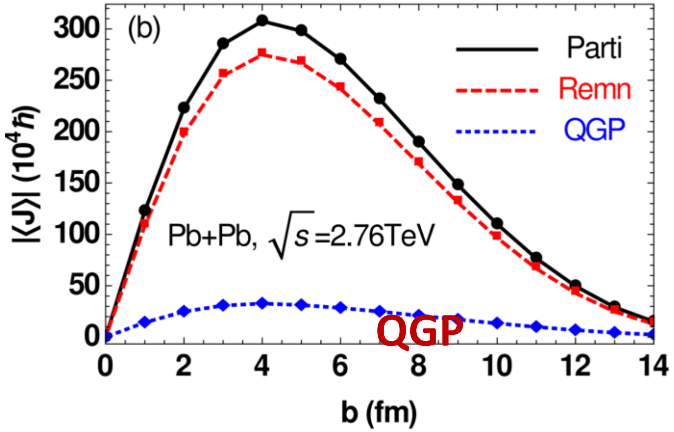
- LHC: Pb+Pb@2760GeV:

$$J_y \sim 10^7 \hbar$$

\>>  $\frac{1}{2}\hbar$

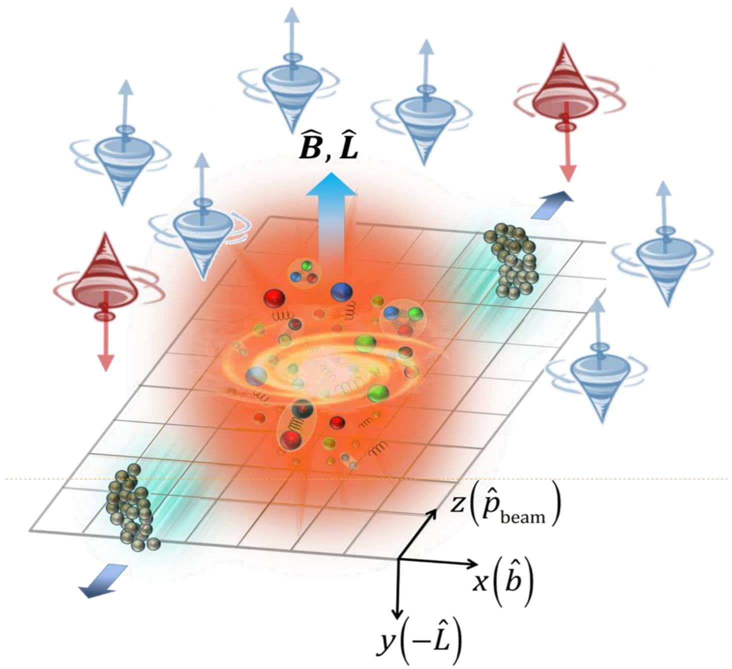


W.-T. Deng and X.-G. Huang, Phys. Rev. C 93, 064907.
H. Li, L.-G. Pang, Q. Wang, and X.-L. Xia, Phys. Rev. C 96, 054908.



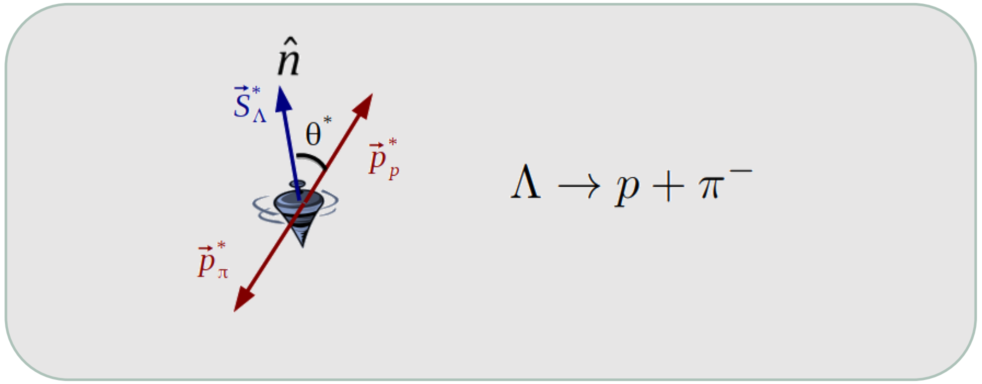
Spin-Orbital Coupling

- ## Spin-Orbital Coupling



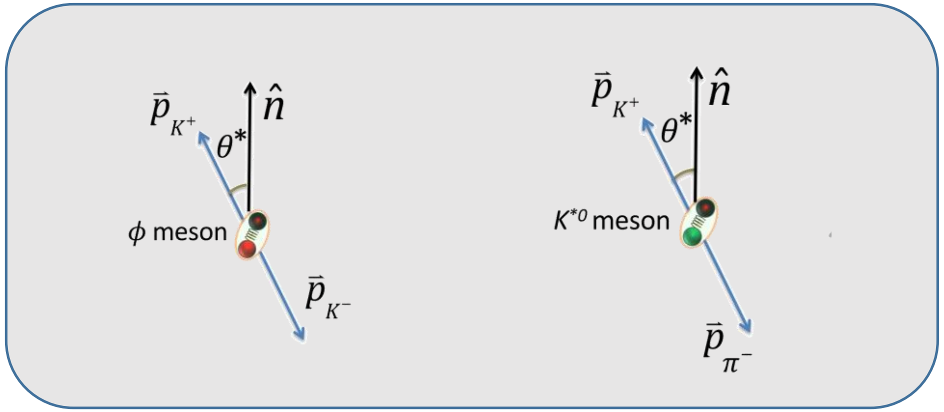
Hyperons

Spin Polarization $S = \frac{1}{2}$



Vector meson

Spin Alignment: S=1



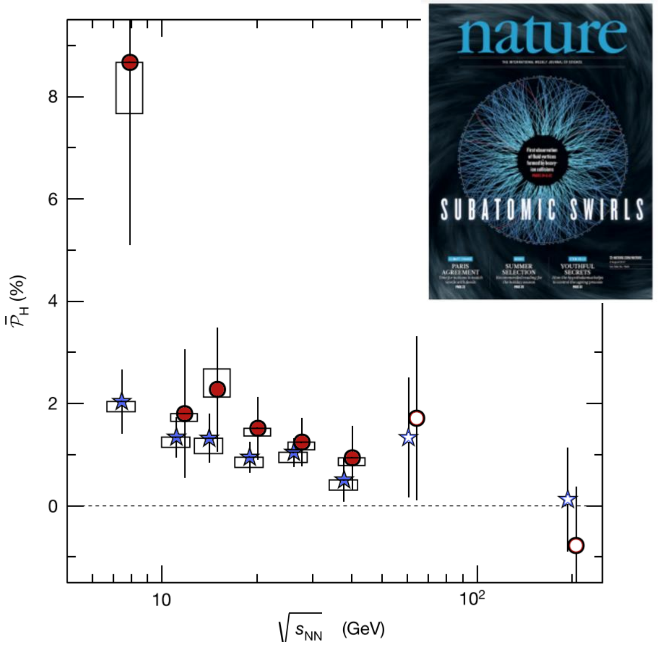
Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005)
Z.-T. Liang and X.-N. Wang, Phys. Lett. B 629, 20 (2005)

Global Polarization

- **Global Spin Polarization of Λ Hyperons**

Experiments

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

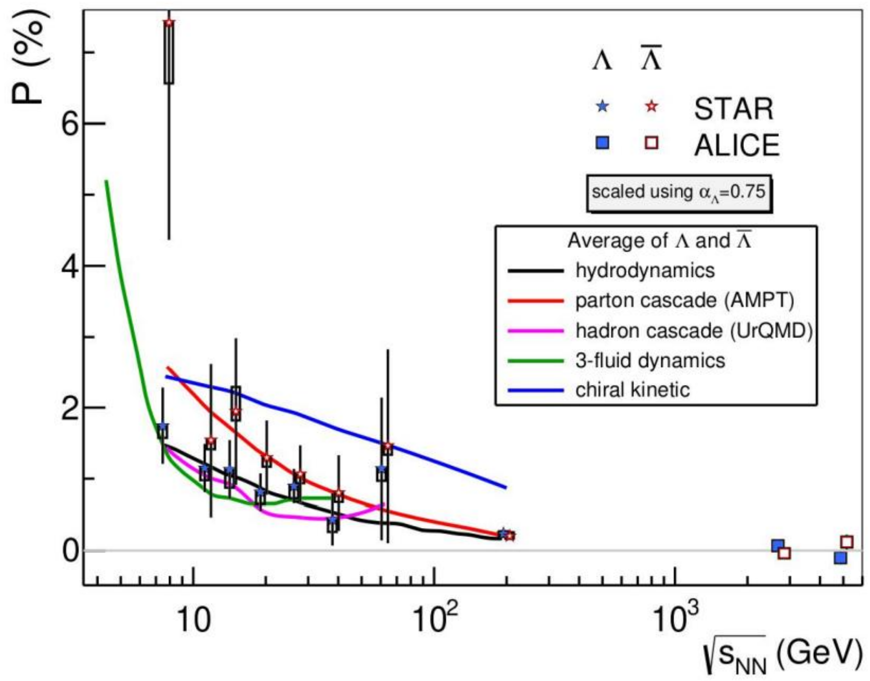


$$\omega = k_B T\left(\overline{P}_{\Lambda'} + \overline{P}_{\bar{\Lambda}'}\right)/\hbar \quad \sim \quad 10^{22}s^{-1}$$

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).

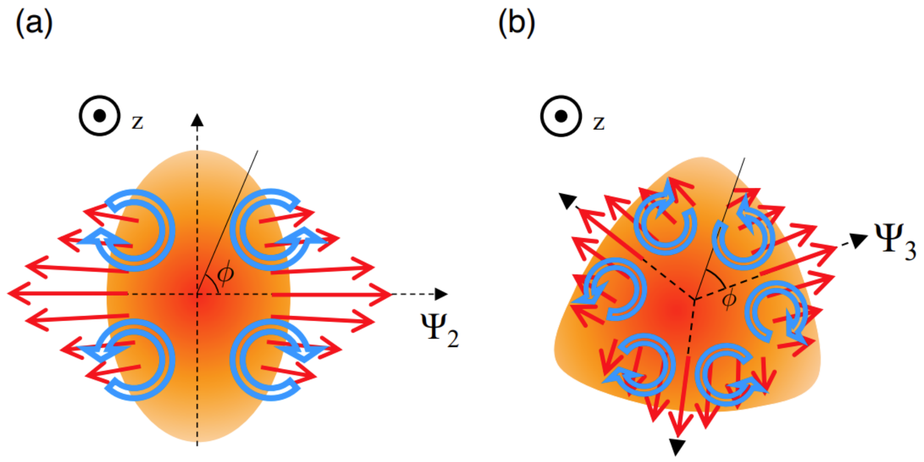
Theory

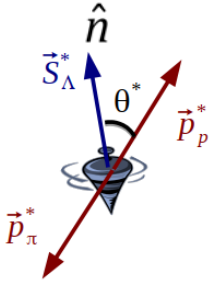


I. Karpenko and F. Becattini, Eur. Phys. J. C 77, 213 (2017).
H. Li, L.-G. Pang, Q. Wang, and X.-L. Xia, Phys. Rev. C 96, 054908 (2017).
Y. Xie, D. Wang, and L. P. Csernai, Phys. Rev. C 95, 031901(R) (2017).
Y. Sun and C. M. Ko, Phys. Rev. C 96, 024906 (2017)
S. Shi, K. Li, and J. Liao, Phys. Lett. B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

Local Polarization

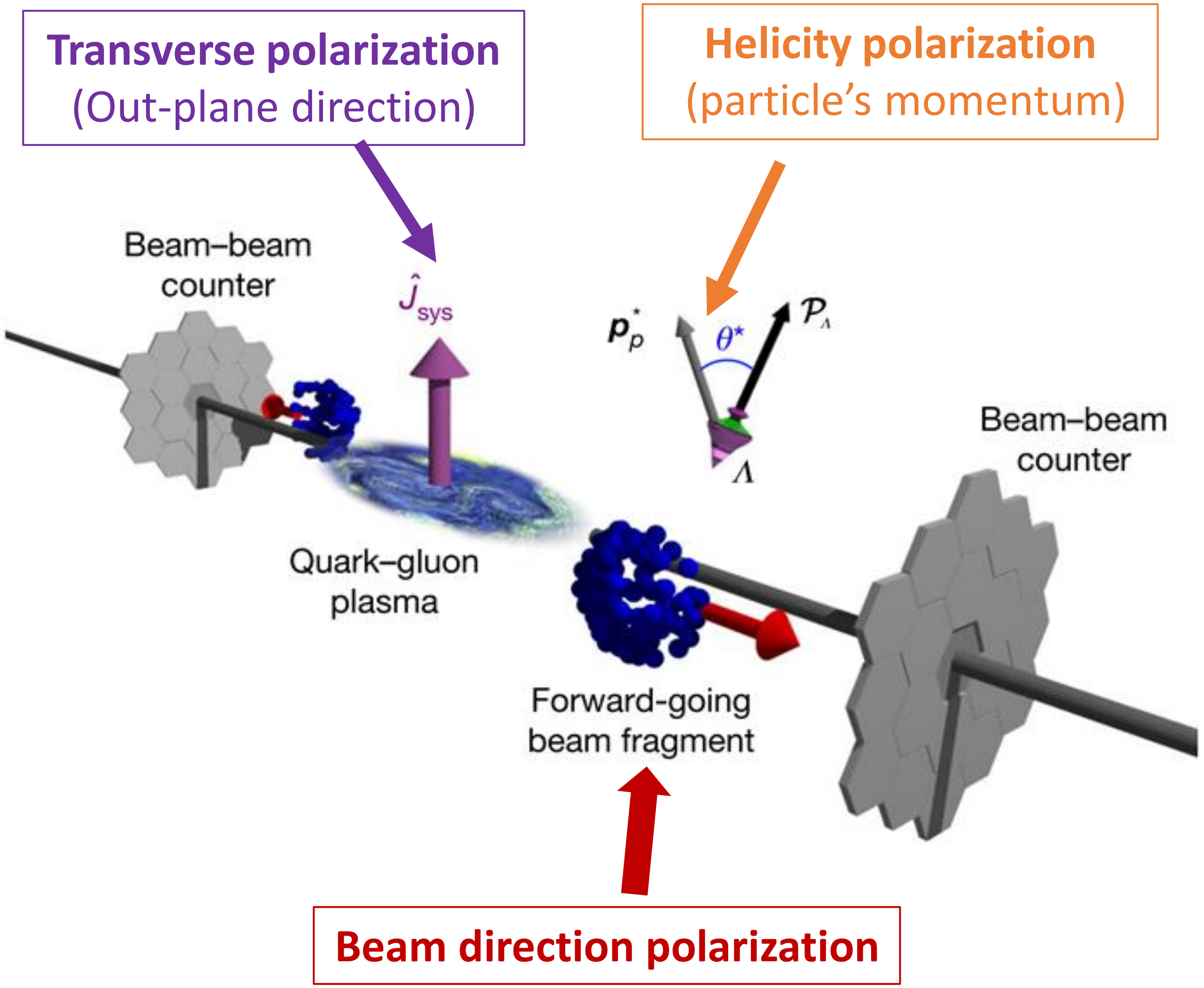
- **Local Vortical Structure**





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

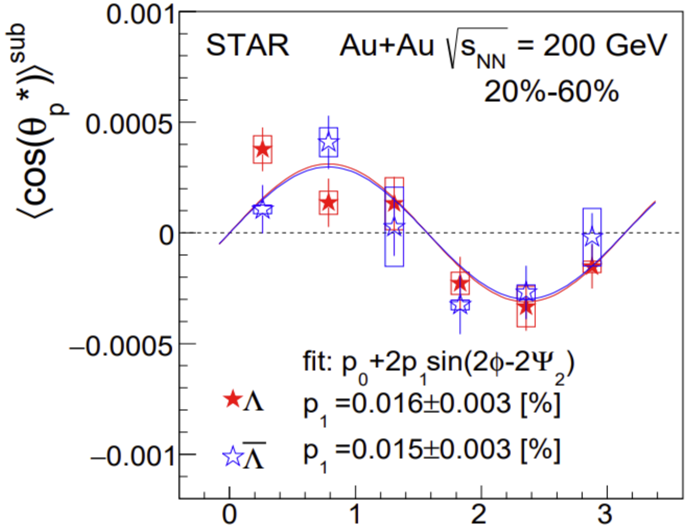
STAR, L. Adamczyk et al., Nature (London) 548, 62.
STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301.



“Sign” Problem& shear induced polarization

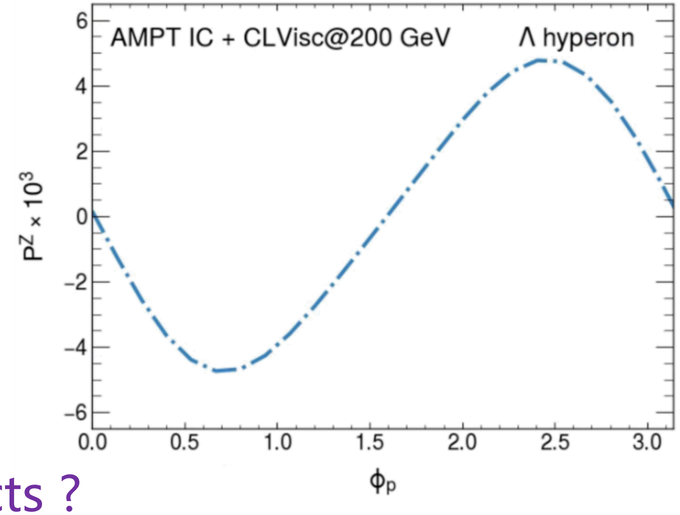
STAR, J. Adam et al., Phys. Rev. Lett. 123, 132301

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

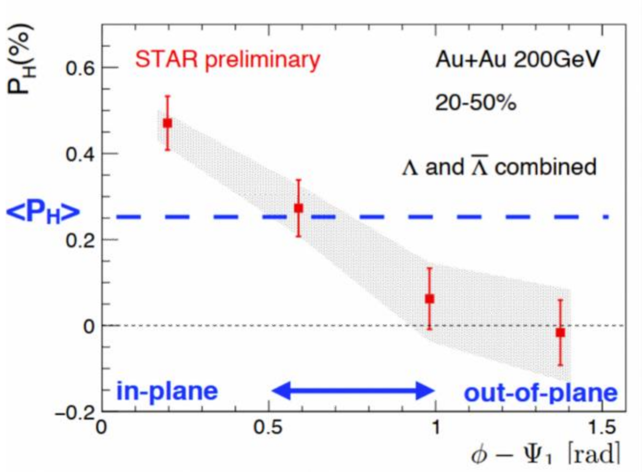


Beam direction Polarization

Opposite Sign!

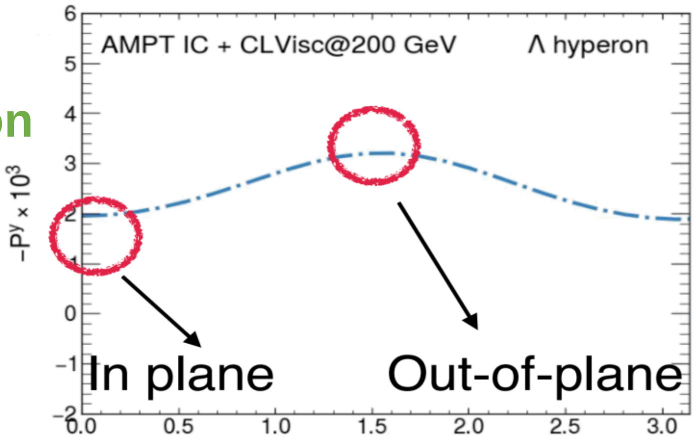


Out of global equilibrium effects ?



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

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

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

Thermal vorticity

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

Shear viscous tensor
Shear Induced Polarization(SIP)

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

Fluid acceleration

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

Gradient of chemical potential
Spin Hall Effect (SHE)

New effects!

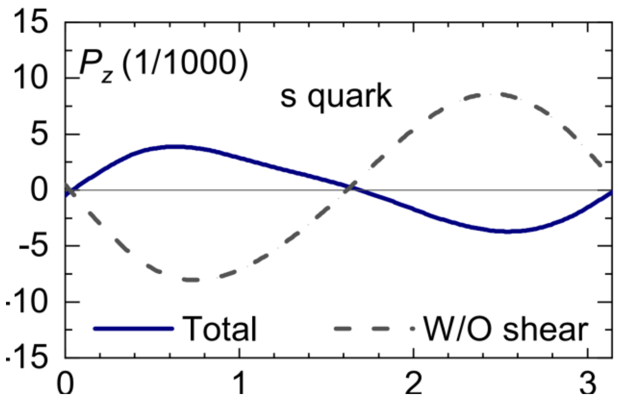
$$\mathcal{J}^\mu_{\text{EB}} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta E_\nu,$$

Electromagnetic fields

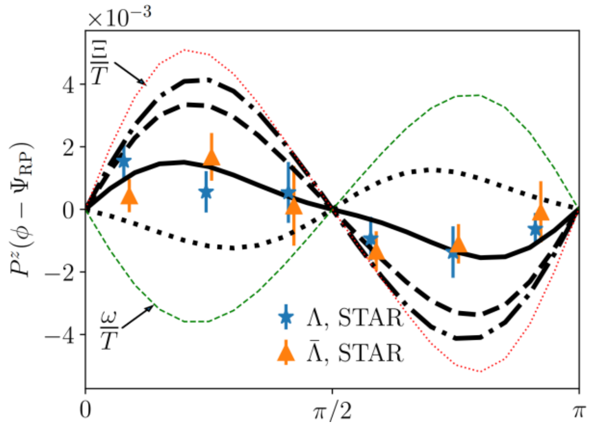
Y. Hidaka, S. Pu, and D.-L. Yang, Phys. Rev. D97, 016004 (2018)
S. Y. F. Liu, Y. Yin, PRD 104, 054043 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519
S. Y. F. Liu, Y. Yin, JHEP 07 (2021) 188.

Hydrodynamic Effect

- **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.
……

Considering shear induced Polarization under some assumption, the theoretical calculations agree qualitatively/quantitatively with the experimental data.

Has the "sign" problem been solved ?

Outline

- Introduction
- Spin polarization of Λ hyperons in Au+Au collisions
- Spin polarization of Λ hyperons in p+Pb collisions
- Summary

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:

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

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

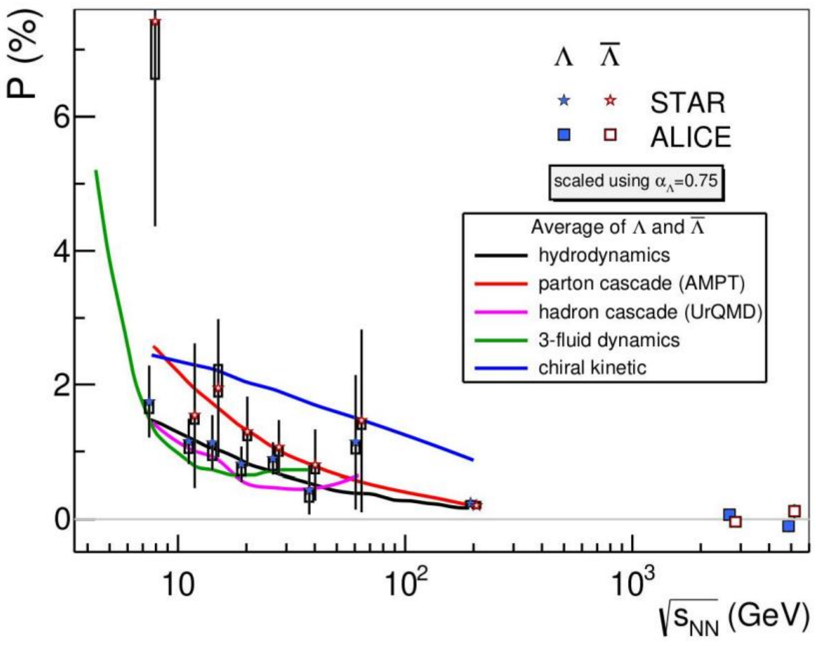
- **Setup**

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

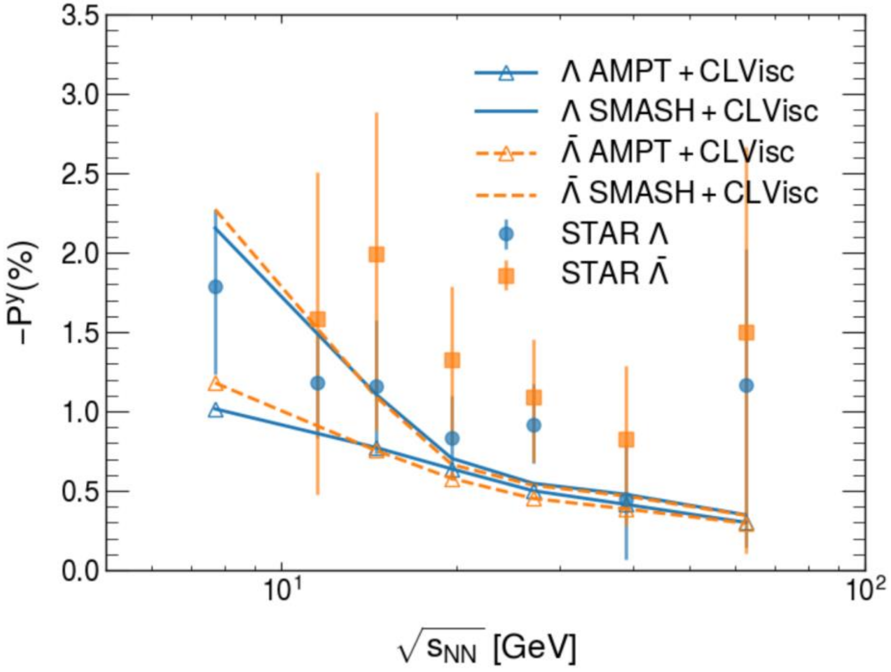
L. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C 86, 024911
X.-Y. Wu, G.-Y. Qin, L.-G. Pang, and X.-N. Wang, Phys. Rev. C 105, 034909

Global Polarization

Thermal vorticity only



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



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.**

Local Polarization

- **RHIC Beam Energy Scan**

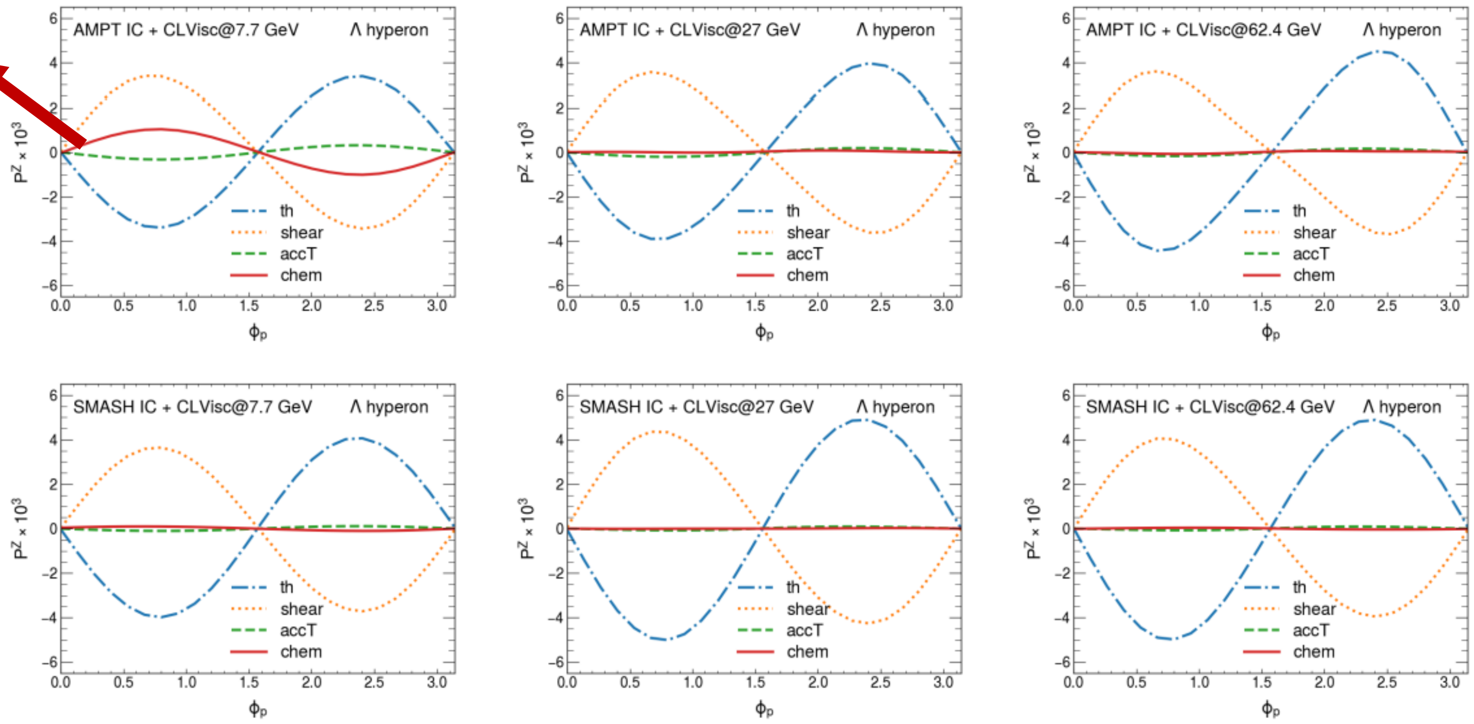
$$\mathcal{J}_5^\mu = \mathcal{J}_{\rm thermal}^\mu + \mathcal{J}_{\rm shear}^\mu + \mathcal{J}_{\rm accT}^\mu + \mathcal{J}_{\rm chemical}^\mu$$

7.7 GeV **27 GeV** **62.4 GeV**

Chemical Gradient

AMPT

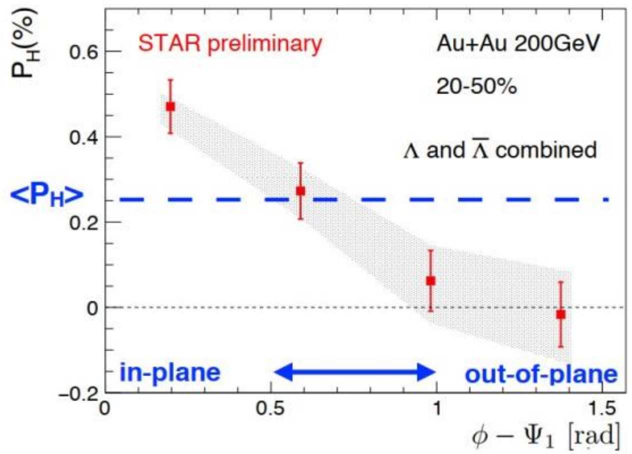
SMASH



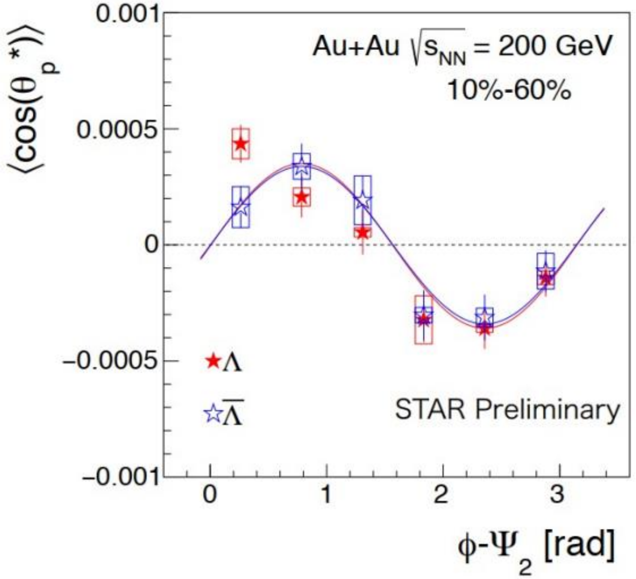
X.Y. Wu, CY, G.Y. Qin, S. Pu Phys. Rev. C 105, 064909

➢ **The longitudinal polarization contributed by chemical gradient depends on initial conditions strongly**

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

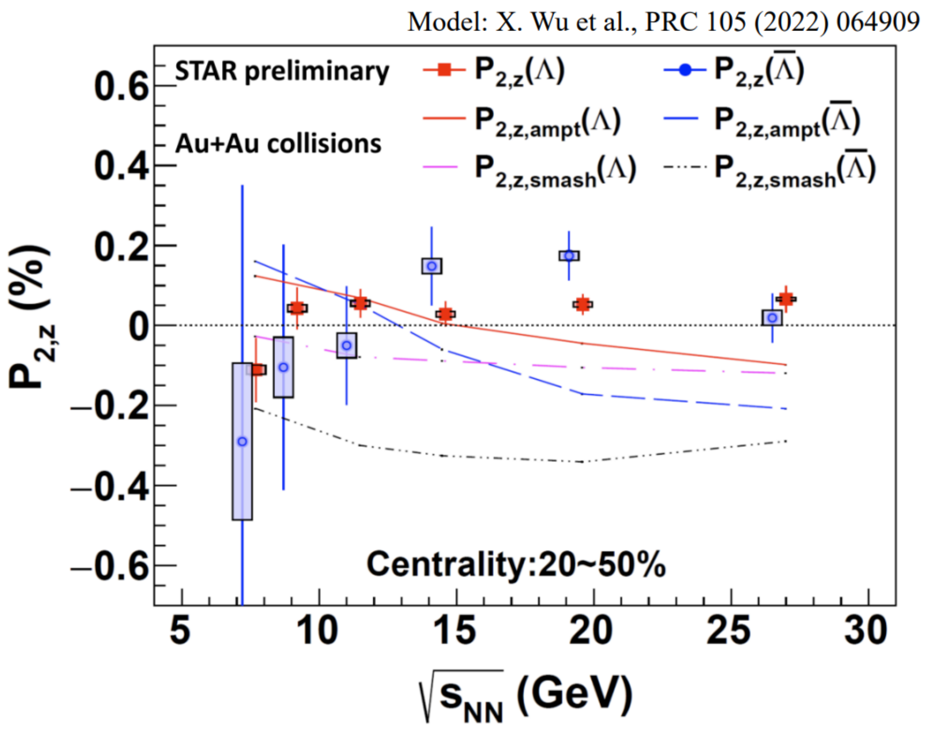


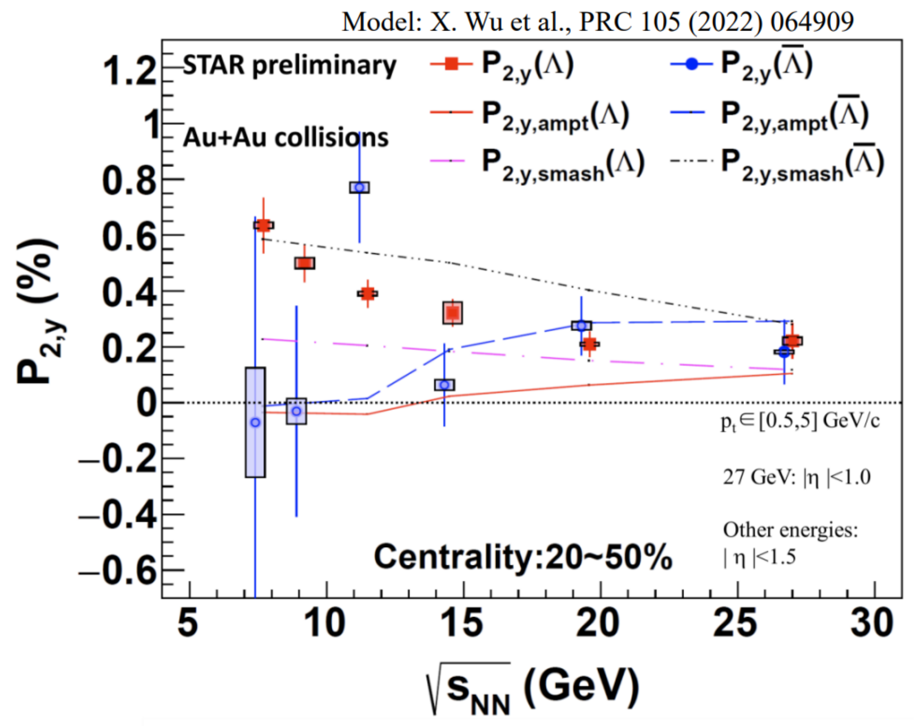
$$P_{2,y} \equiv \langle P_y \cos[2(\phi_\Lambda - \Psi_2)]\rangle$$



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

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



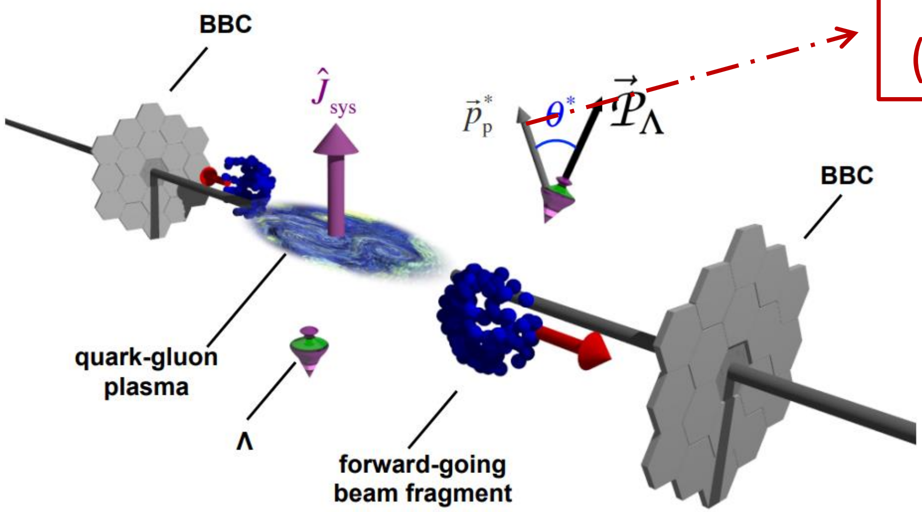


Qiang Hu, Talks on SQM 2024

- 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

Local Helicity polarization

Helicity polarization is the projection of the spin polarization vector in the direction of momentum.



Helicity polarization
(particle's momentum)

The original idea for helicity polarization is proposed to probe the initial chiral chemical potential.

$$S^h = \widehat{\mathbf{p}} \cdot \mathcal{S}(\mathbf{p}) \qquad\qquad S^h = S^h_{\text{hydro}} + S^h_\chi$$

F. Becattini, M. Buzzegoli, A. Palermo, and G. Prokhorov, Phys. Lett. B 826, 136909
J.-H. Gao, Phys. Rev. D 104, 076016

Hydrodynamic helicity polarization

Helicity polarization induced by thermal vorticity, shear viscous tensor, fluid acceleration and spin hall effect

CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

$$\begin{aligned}
S^h_{\rm thermal}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma p_0 \epsilon^{0ijk} \widehat{p}_i \partial_j \left(\frac{u_k}{T}\right), \\
S^h_{\rm shear}(\mathbf{p}) &= -\int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0}{(u\cdot p)T}(p^\sigma \pi_{\sigma j} u_k), \\
S^h_{\rm accT}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{\epsilon^{0ijk}\widehat{p}^i p_0 u_j}{T}\left[(u\cdot\partial)u_k + \frac{\partial_k T}{T}\right], \\
S^h_{\rm chemical}(\mathbf{p}) &= -2\int d\Sigma^\sigma F_\sigma \frac{p_0 \epsilon^{0ijk}\widehat{p}_i}{(u\cdot p)} \partial_j \left(\frac{\mu}{T}\right) u_k, \qquad (4)
\end{aligned}$$

- **Kinetic vorticity**

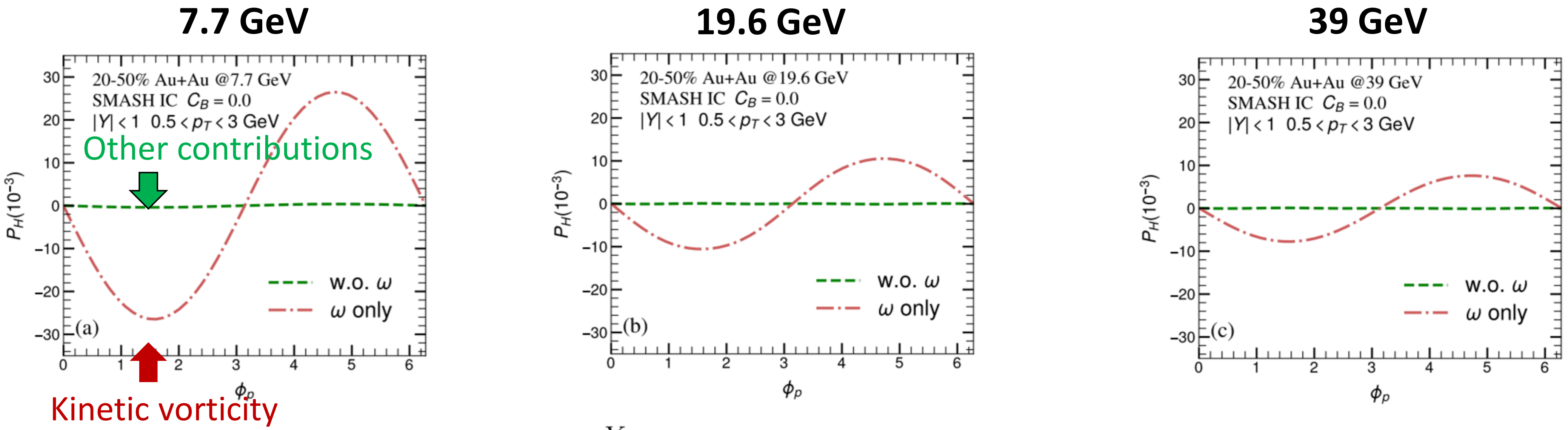
$$\begin{aligned}
S^h_{\nabla T}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T^2} \widehat{\mathbf{p}} \cdot (\mathbf{u}\times\nabla T), \\
S^h_{\omega}(\mathbf{p}) &= \int d\Sigma^\sigma F_\sigma \frac{p_0}{T} \widehat{\mathbf{p}} \cdot \boldsymbol{\omega},
\end{aligned}$$

Kinetic vorticity

$\boldsymbol{\omega} \rightarrow \nabla \times \mathbf{u}$

Numerical results

• Helicity polarization across RHIC-BES energies



$$P_H(\phi_p) = \frac{2\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [\Phi(\mathbf{p}) S^h_{\text{hydro}}]}{\int_{Y_{\min}}^{Y_{\max}} dY \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \Phi(\mathbf{p})}$$

- ➢ **Helicity polarization induced by kinetic vorticity dominates at BES energies**
- ➢ **Helicity polarization induced by other contributions are almost vanishing**
- ➢ **A possible way to probe the fine vorticity structure of the QGP by measuring helicity polarization.**

CY , X.Y. Wu, D.-L. Yang, J.H. Gao, S. Pu, G.Y. Qin, 2304.08777.

Outline

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- **Spin polarization of Λ hyperons in p+Pb collisions**
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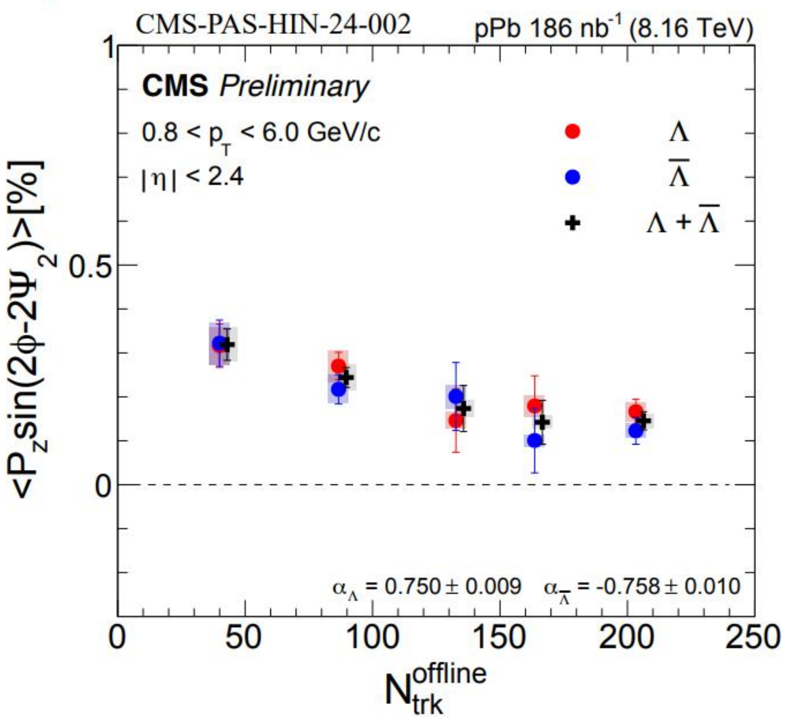
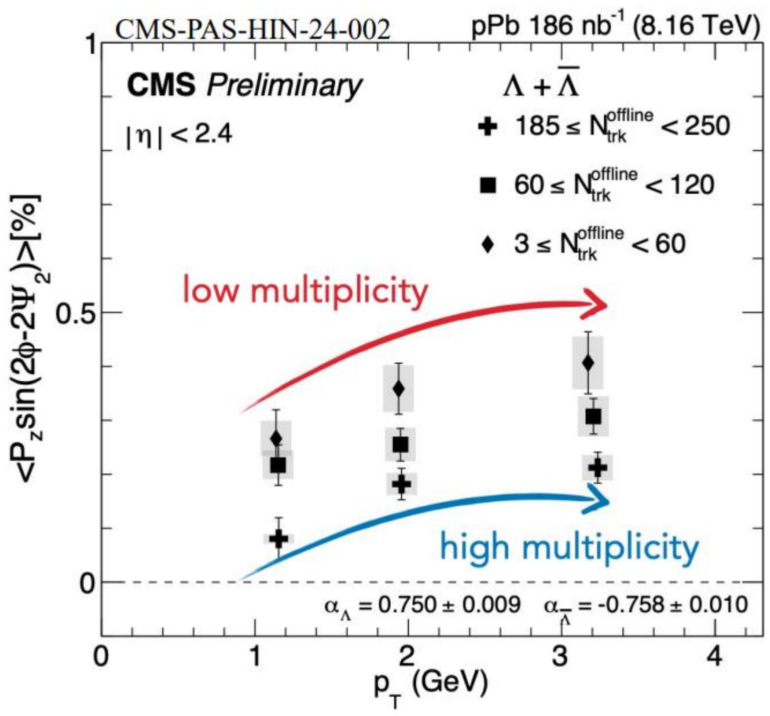
CMS Results

- **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**

Initial condition

- **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,

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

We construct the function from of g by parameterizing its cumulant generating function.

CLVisc hydrodynamics model

- **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

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

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

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

We use the temperature dependent shear and bulk viscosity given by Bayesian parameter estimation in Phys. Rev. C 94, 024907 (2016) .
The equations of state are provided by the HotQCD collaboration and freeze-out temperature T_f = 154 MeV.

Spin Polarization Vector

We follow the modified Cooper-Frye formula to compute the polarization pseudo-vector including the contribution from thermal vorticity and thermal shear tensor and neglect the spin hall effect:

$$\begin{aligned}
\mathcal{S}^\mu(\mathbf{p}) &= \mathcal{S}^\mu_{\text{thermal}}(\mathbf{p}) + \mathcal{S}^\mu_{\text{th-shear}}(\mathbf{p}), \\
\mathcal{S}^\mu_{\text{thermal}}(\mathbf{p}) &= \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} p_\nu \varpi_{\alpha\beta}, \\
\mathcal{S}^\mu_{\text{th-shear}}(\mathbf{p}) &= \hbar \int d\Sigma \cdot \mathcal{N}_p \frac{\epsilon^{\mu\nu\alpha\beta} p_\nu n_\beta}{(n \cdot p)} p^\sigma \xi_{\sigma\alpha},
\end{aligned}$$

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

Different scenarios

We consider three different scenarios:

- **Λ equilibrium :**
  It is assumed that Λ hyperons reach the local (thermal) equilibrium at the freeze-out hyper-surface

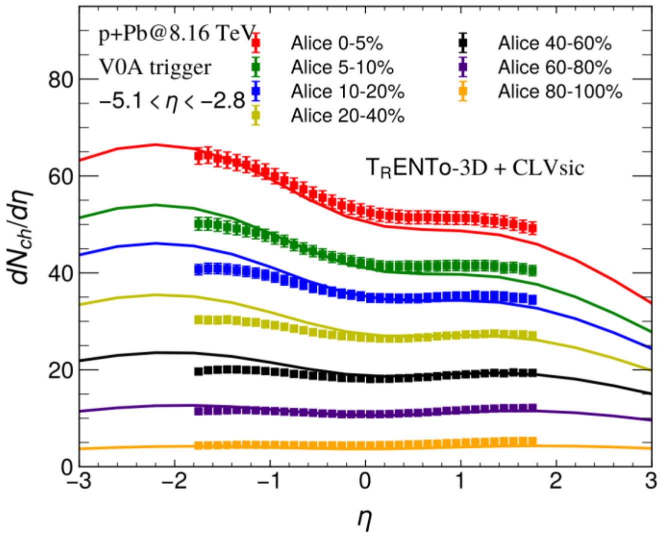
- **s quark equilibrium:**
  The spin of Λ hyperons is assumed to be carried by the constituent s quark. We take the s quark' s mass instead of Λ' s mass in the simulation

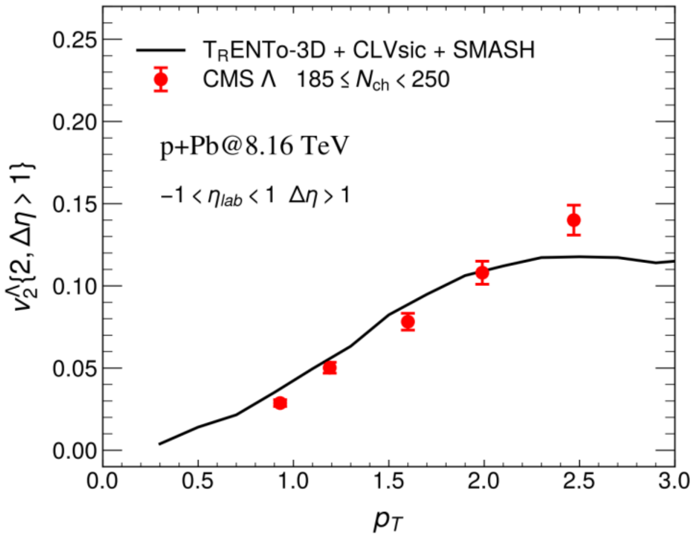
- **Iso-thermal equilibrium:**
  The temperature of the system at the freeze-out hyper-surface is assumed to be constant. The time unit vector is taken as fluid velocity for simplicity.

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

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

Multiplicity and v2 of Λ

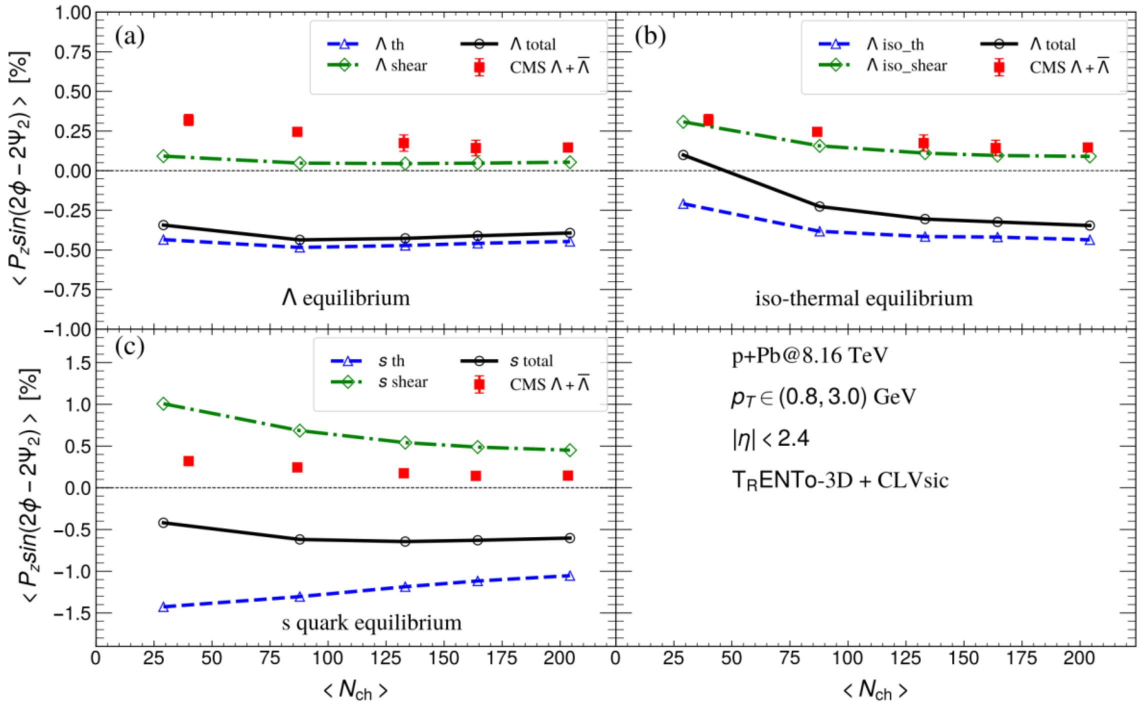


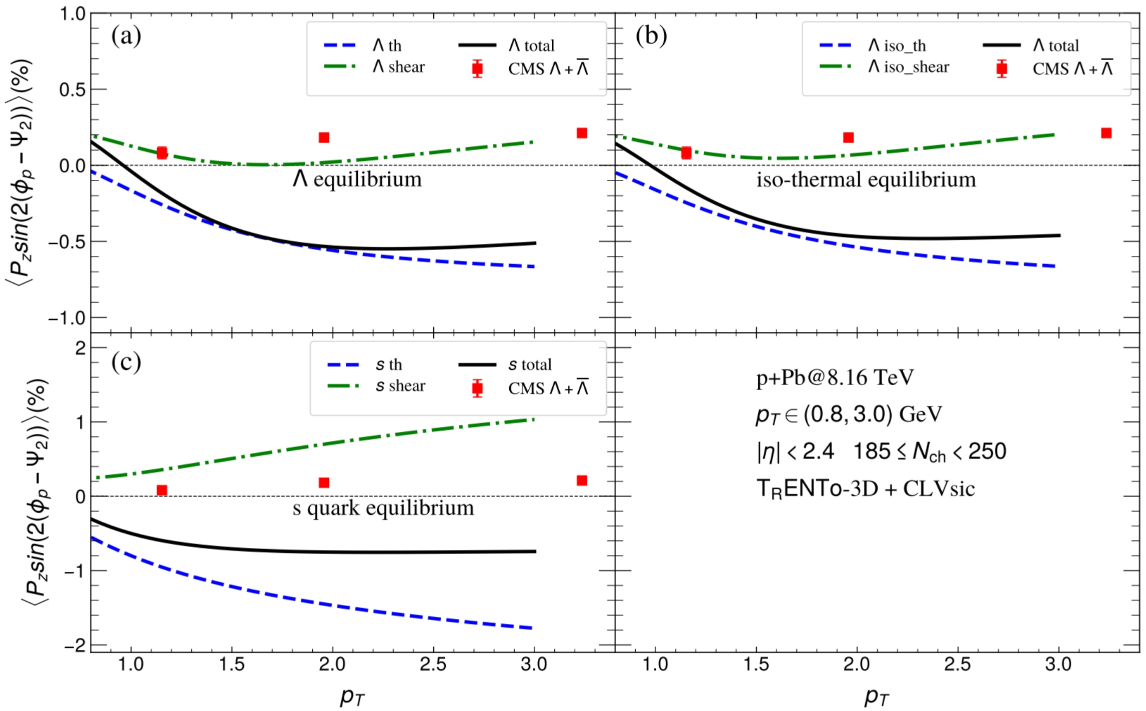


Multiplicity intervals	$\langle N_{ch} \rangle_{exp}$	$\langle N_{ch} \rangle_{CLVisc}$
[185,250)	203.3	204.2
[150,185)	163.6	164.5
[120,150)	132.7	133.57
[60,120)	86.7	87.7
[3,60)	40	29.3

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

Multiplicity (centrality) dependence



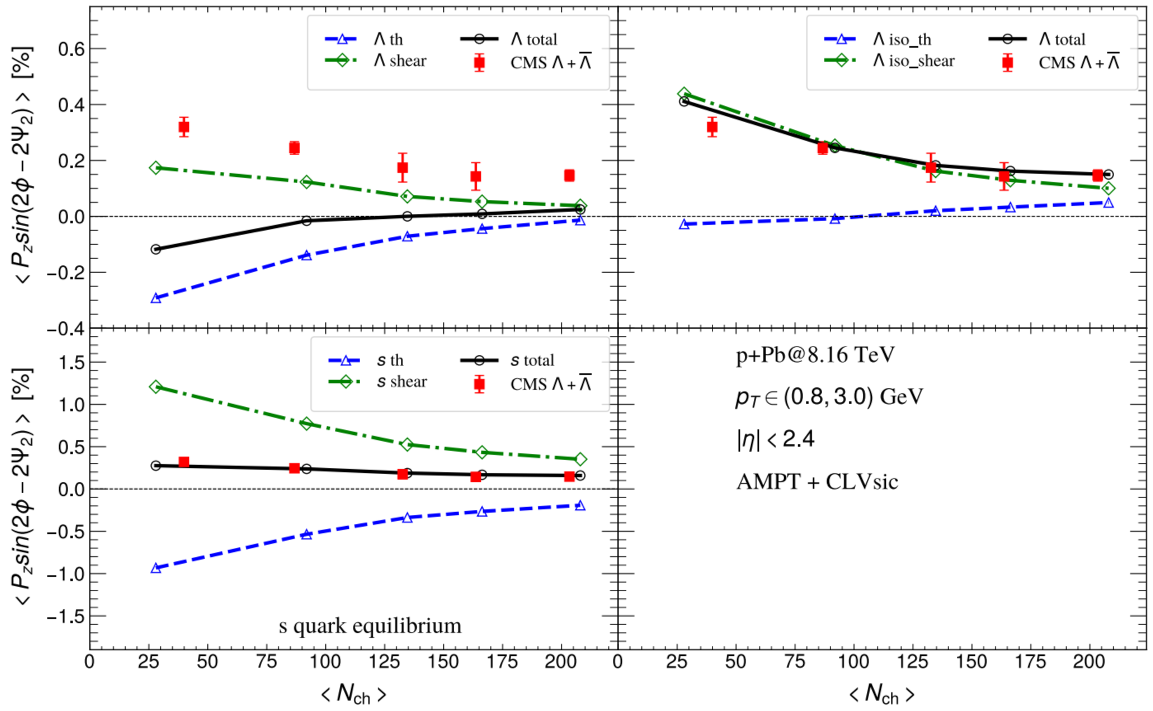


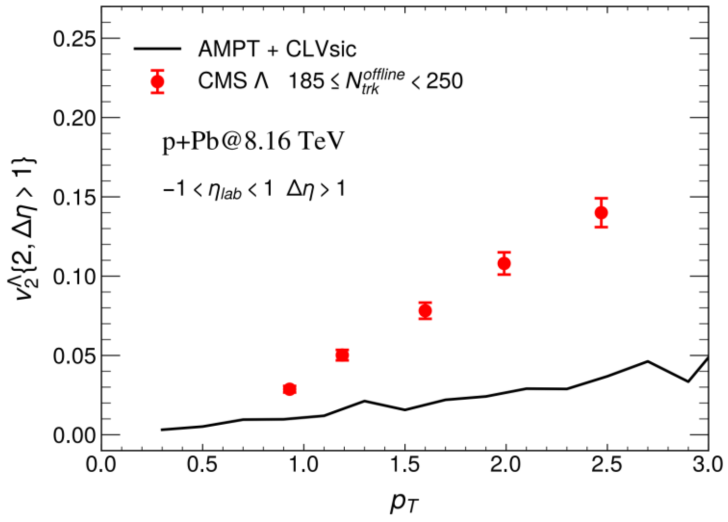
Multiplicity dependence

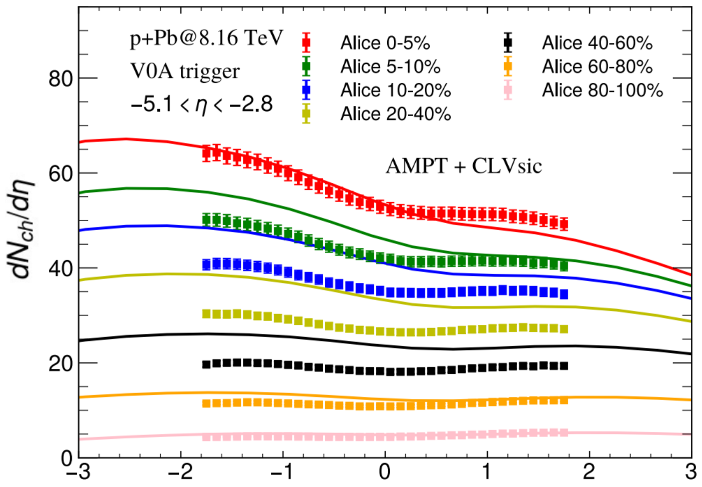
p_T dependence

- **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

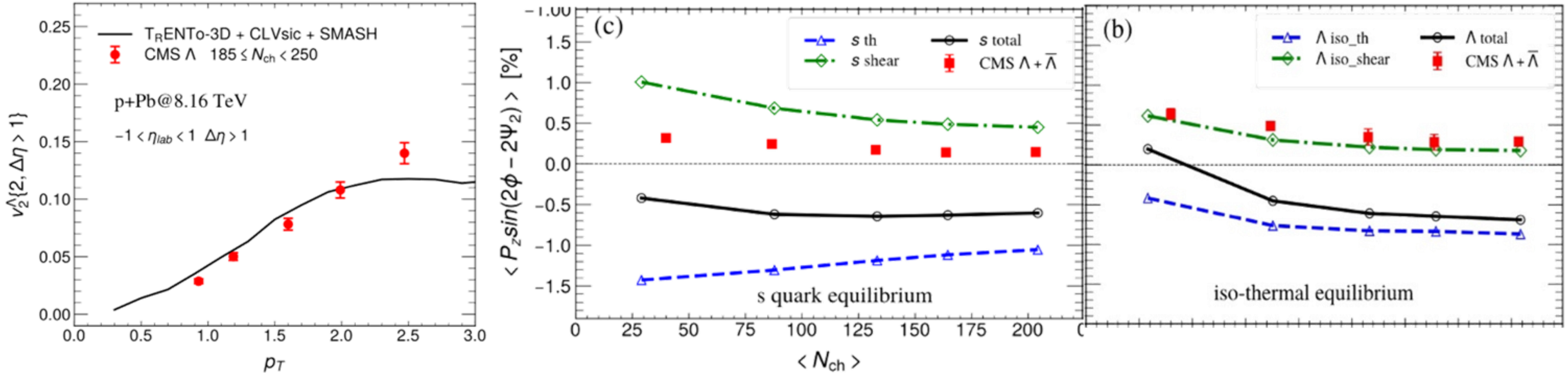






- **The parameters can describe spin polarization at the s quark equilibrium and iso-thermal equilibrium can not fit the multiplicity of charged particles and v2 of Λ.**

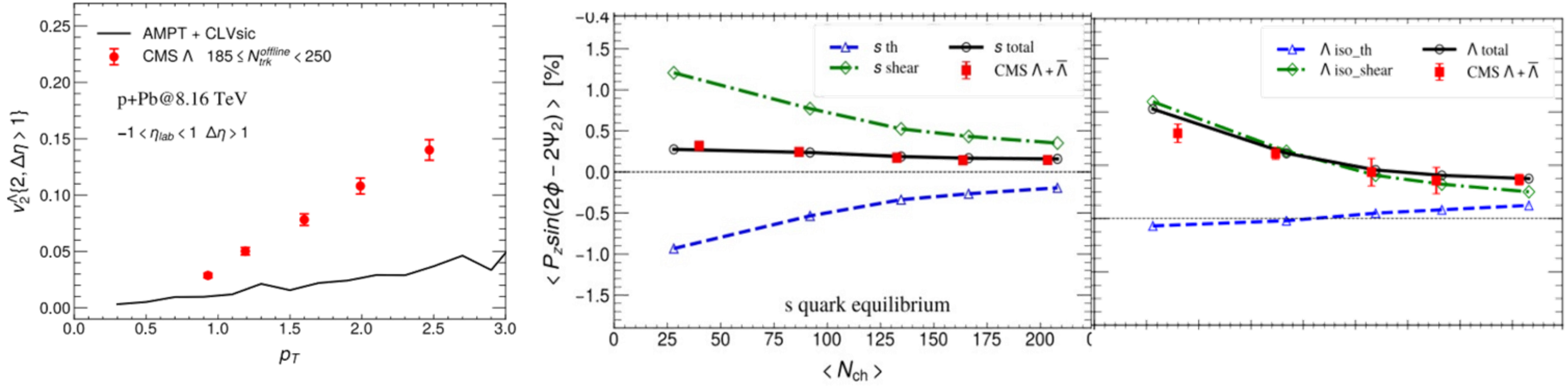
Different initial conditions



Smaller v2 gives a larger polarization along beam direction ?

Smaller v2, larger shear induced polarization, smaller thermal vorticial induced polarization

Non-flow effects play a crucial role in the polarization at pPb collisions.



Summary

- **Spin Polarization in Au+Au collision**
  - The influence of these new effects on the global polarization is small.
  - Shear induced polarization always give a positive contribution.
  - The spin hall effect plays an important role in the low energy collisions
  - Helicity polarization is mainly contributed by the kinetic vorticity at low energy collisions.
  - Helicity polarization is a possible way to probe the fine vortical structure of QGP.

- **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.
  - Non-flow effects play a crucial role in the polarization at pPb collisions

Thanks for your time !