Hydrodynamic effects on spin polarization in p+Pb collisions

Cong Yi (易聪)

Central China Normal University

26th International Symposium on Spin Physics (SPIN2025)
September 22-26, 2025, Qingdao, Shandong Province

In collaboration with: Xiang-Yu Wu, Zhu Jie, Shi Pu, Guang-You Qin.

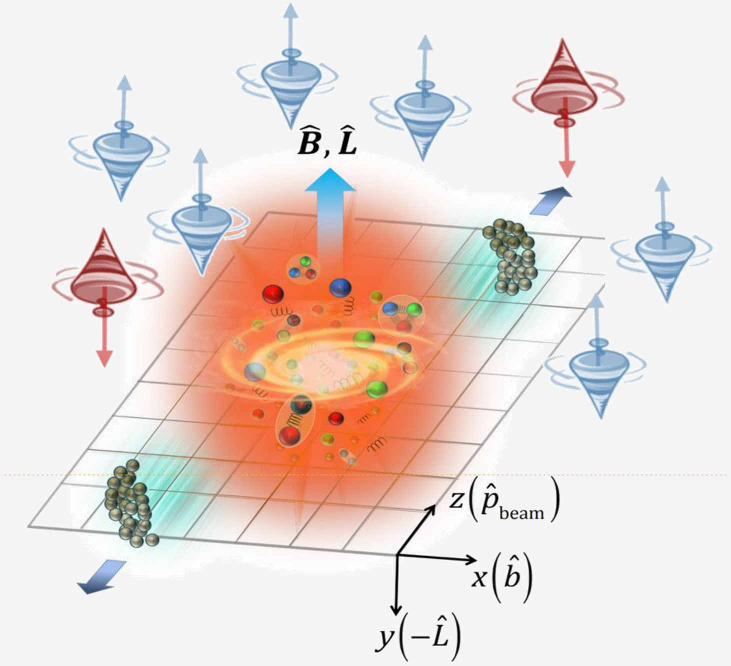
Based on: Phys. Rev. C 111 (2025) 4, 044901

Outline

- **Introduction**
- **Spin polarization at p+Pb collision**
  - **Numerical Setup**
  - **Results**
- **Summary and Outlook**

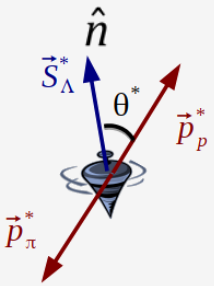
Global Spin Polarization

➢Spin-Orbital Coupling



Hyperons

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



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

STAR, Nature 548, 62 (2017).

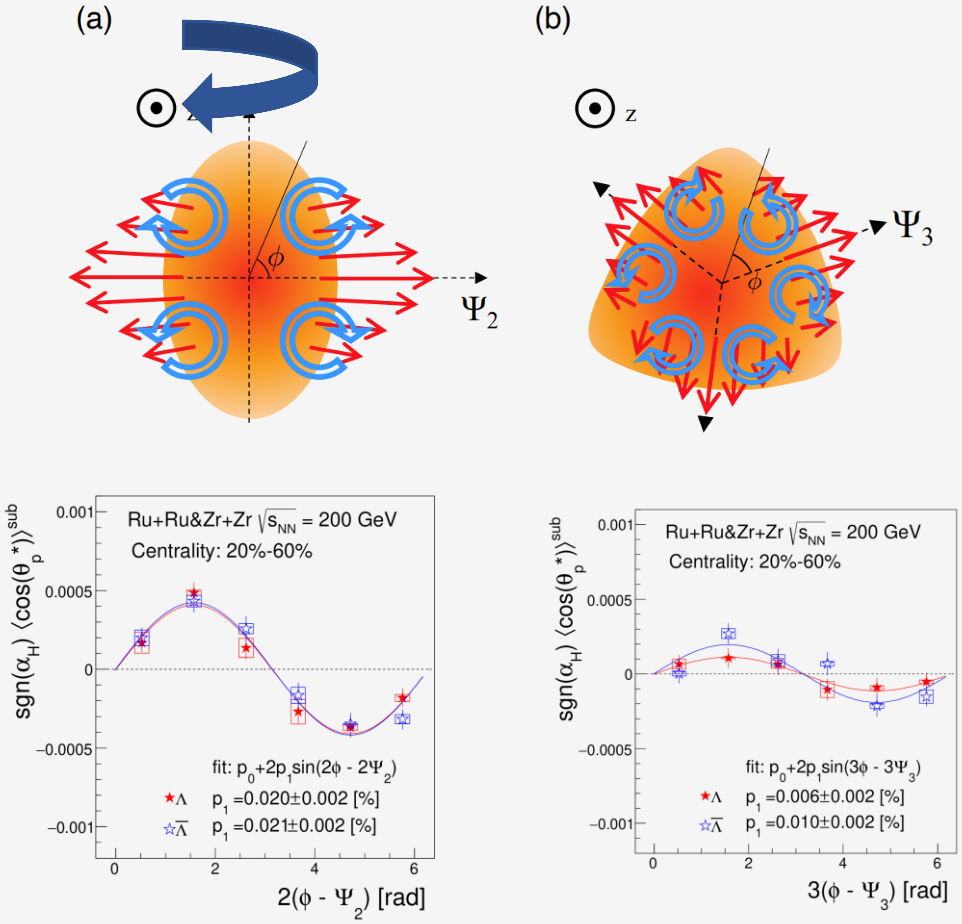
$$\omega = k_B T \left(\overline{P}_{\Lambda'} + \overline{P}_{\bar{\Lambda}'}\right)/\hbar \quad \sim \quad 10^{22} s^{-1}$$

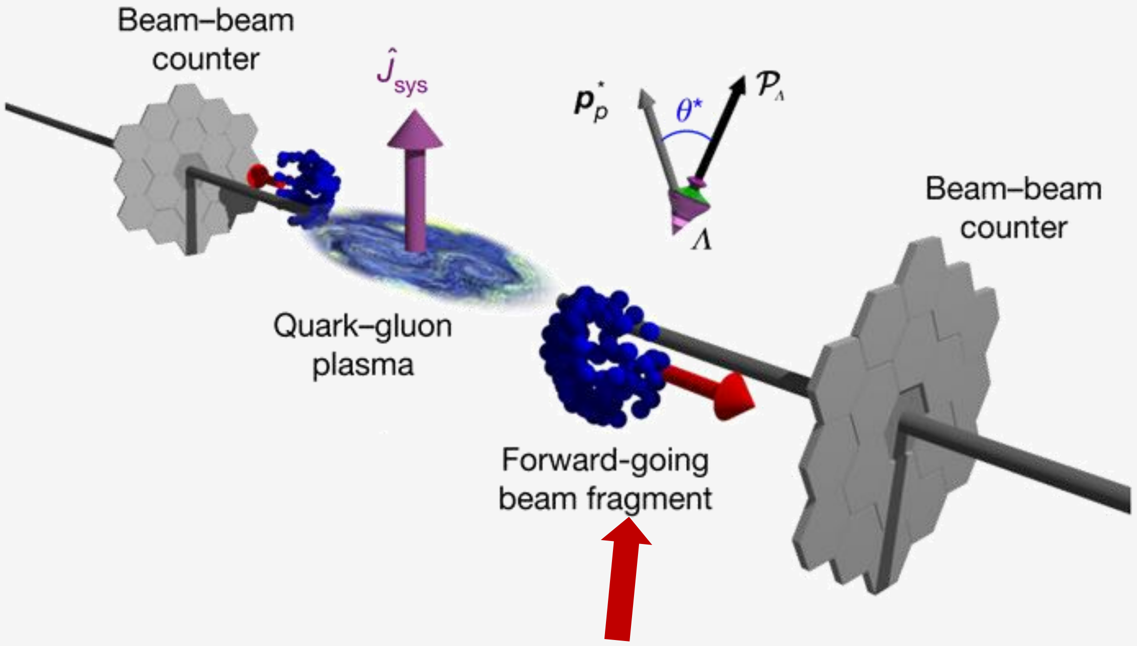
Most vortical fluid !

Liang, Wang, PRL. 94, 102301 (2005)
Liang, Wang, PLB 629, 20 (2005)
Becattini, Chandra, Zanna, and Grossi, Annals Phys. (2013).
Becattini and Karpenko, PRL 120, 012302

Local Spin Polarization

➤Local Vortical Structure





Beam direction polarization

STAR, PRL 123, 132301 (2019).
STAR, PRL 131, 202301 (2023)

Polarization induced by different sources

➢Spin polarization at local equilibrium

$$\mathcal{S}^{\mu}(\mathbf{p}) = \mathcal{S}^{\mu}_{\rm thermal} + \mathcal{S}^{\mu}_{\rm shear} + \mathcal{S}^{\mu}_{\rm accT} + \mathcal{S}^{\mu}_{\rm chemical} + \mathcal{S}^{\mu}_{\rm EB}$$

$$\mathcal{S}^{\mu}_{\rm thermal}(\mathbf{p}) = \frac{\hbar}{8m_{\Lambda}N}\int d\Sigma^{\sigma}p_{\sigma}f_V^{(0)}(1-f_V^{(0)})\epsilon^{\mu\nu\alpha\beta}p_{\nu}\partial_{\alpha}\frac{u_{\beta}}{T},$$

Thermal vorticity

$$\mathcal{S}^{\mu}_{\rm shear}(\mathbf{p}) = -\frac{\hbar}{4m_{\Lambda}N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}}{(u\cdot p)T}\frac{1}{2}p^{\sigma}[(\partial_{\sigma}u_{\nu}+\partial_{\nu}u_{\sigma})-u_{\sigma}Du_{\nu}]$$

Shear Induced Polarization (SIP)

$$\mathcal{S}^{\mu}_{\rm accT}(\mathbf{p}) = -\frac{\hbar}{8m_{\Lambda}N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{T}\epsilon^{\mu\nu\alpha\beta}p_{\nu}u_{\alpha}(Du_{\beta}-\frac{1}{T}\partial_{\beta}T),$$

Fluid Acceleration

$$\mathcal{S}^{\mu}_{\rm chemical}(\mathbf{p}) = \frac{\hbar}{4m_{\Lambda}N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\partial_{\nu}\frac{\mu}{T},$$

Spin Hall Effect (SHE)

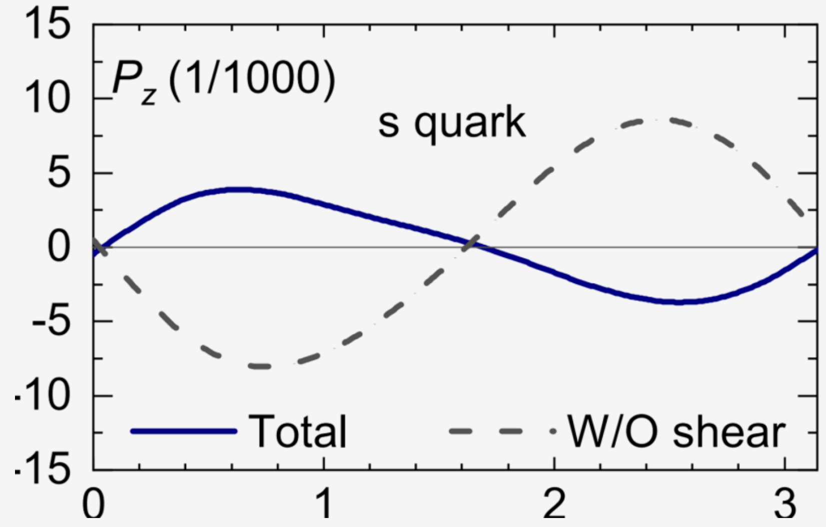
$$\mathcal{S}^{\mu}_{\rm EB}(\mathbf{p}) = \frac{\hbar}{4m_{\Lambda}N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}E_{\nu}+\frac{B^{\mu}}{T}\right),$$

EM Field

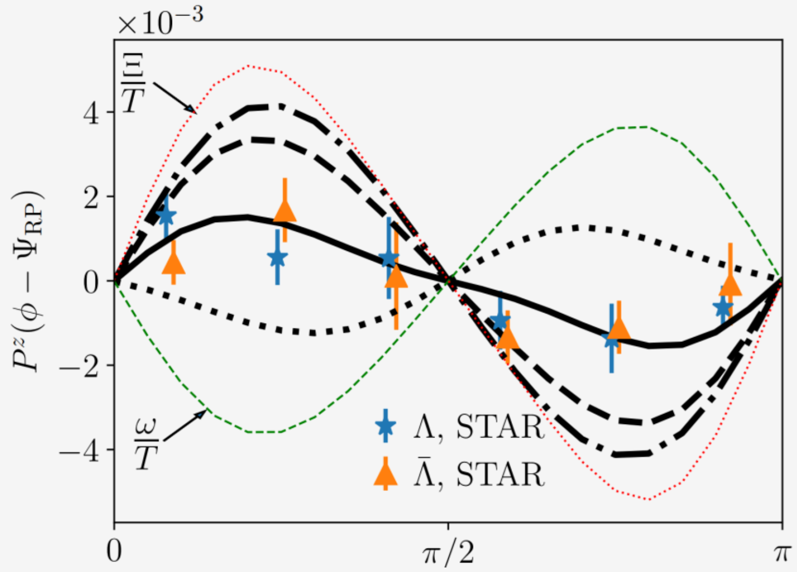
Liu, Yin, PRD 104, 054043 (2021) ; Becattini, Buzzegoli, Palermo, PLB 820, 136519 (2021) ; Liu, Yin, JHEP 07,188 (2021); Hidaka, Pu, Yang, PRD 97, 016004 (2018) ; CY, Pu, Yang, PRC 04, 064901(2021)

Shear induced polarization(SIP)

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



Fu, et al. PRL 127, 142301

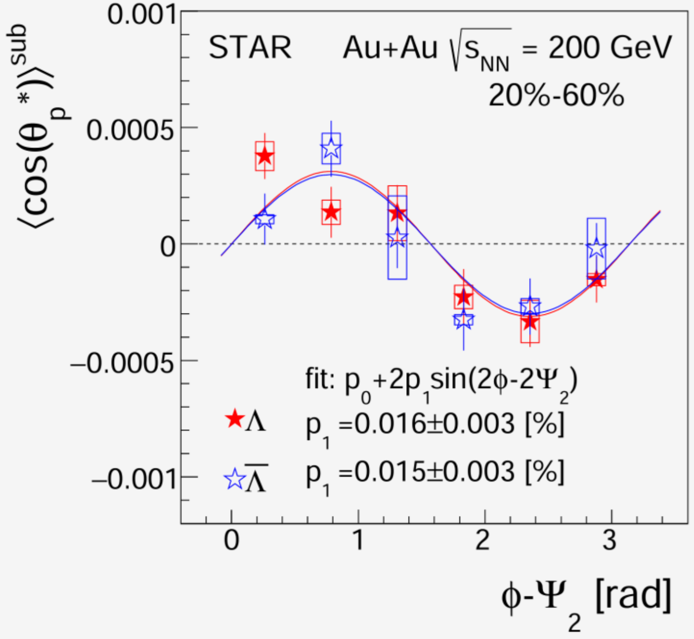


Becattini et al, PRL 127, 272302

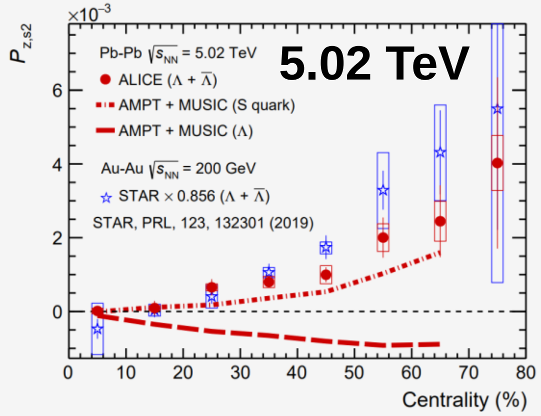
Also see: CY, Pu, Yang, PRC 104, 064901.
Ryu, Jupic, Shen, PRC 104, 054908
Wu, CY, Qin,Pu, PRC 105 6, 064909
Fu, Pang, Song, Yin, (2022), 2201.12970.
……

Considering SIP under some assumptions, the theoretical calculations qualitatively/ quantitatively agree with the experimental data at 200GeV Au+Au collision.

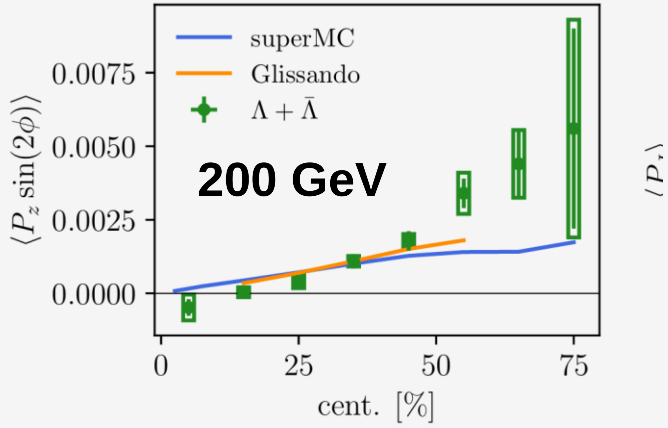
$P_{2,z}$ across collision energy



STAR, PRL 123, 132301 (2019).

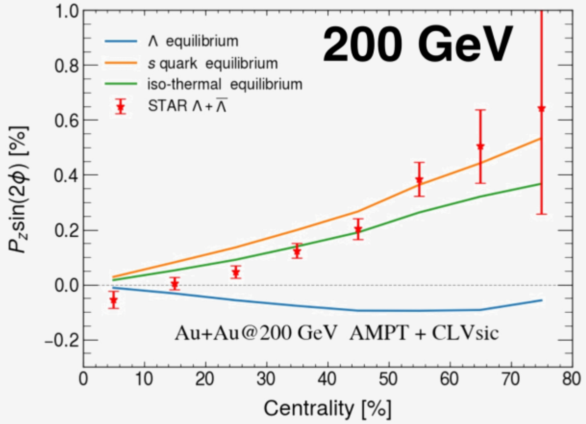


ALICE, PRL 128, 172005(2022)

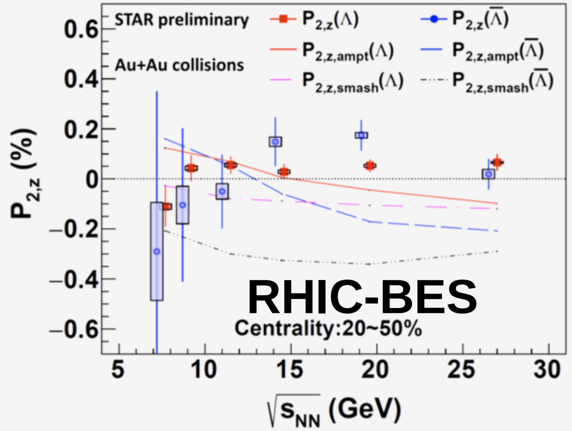


Palermo, et al. EPJC 84 9, 920 (2024)

$$P_{2,z} \equiv \langle P_z \sin\left[2(\phi-\Psi_2)\right]\rangle$$



arXiv: 2509.00377



PRC 105 6, 064909 (2022)

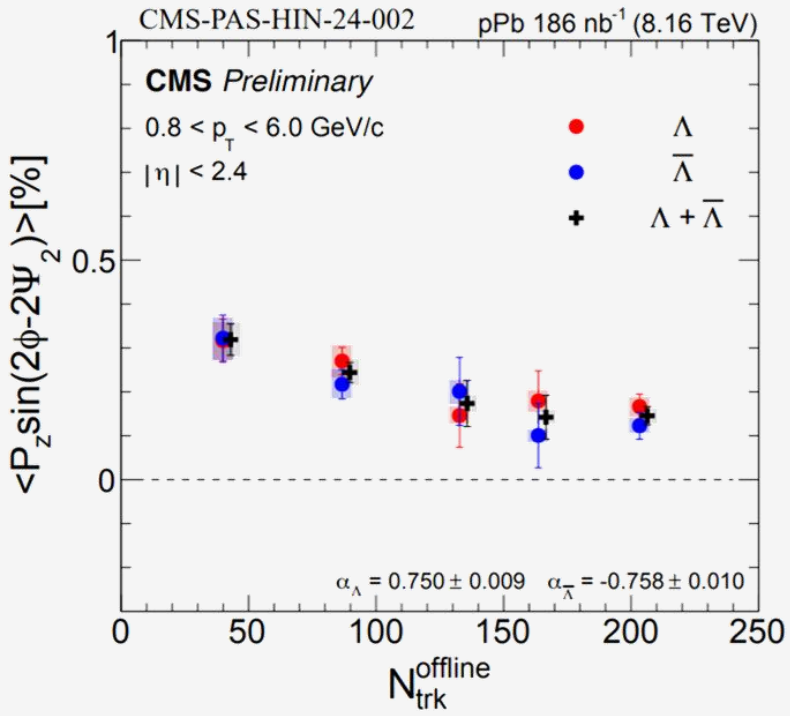
- **How about hydrodynamic contributions to spin polarization at p+Pb collisions?**

Outline

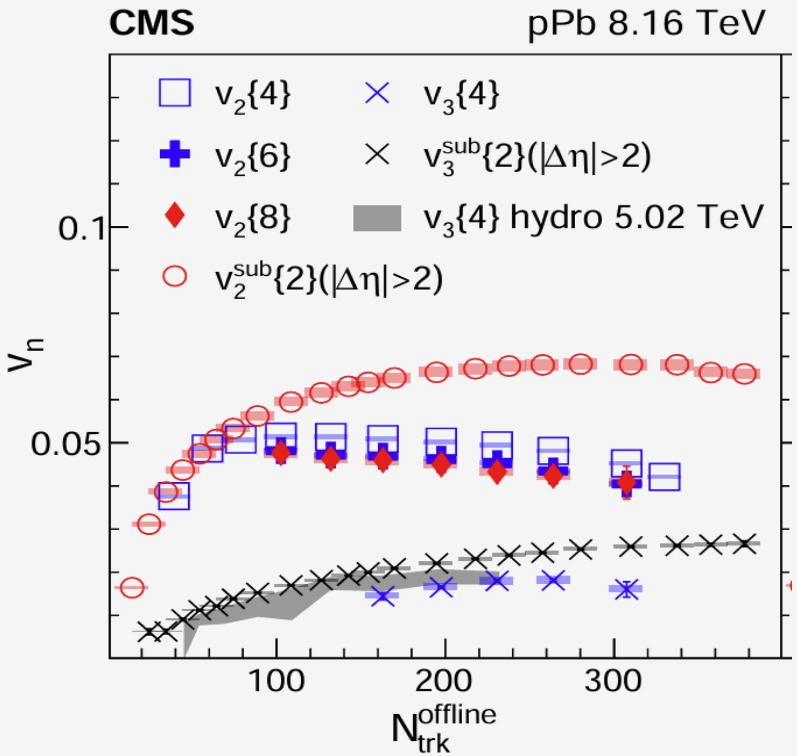
- Introduction
- **Spin polarization at p+Pb collision**
  - **Numerical Setup**
  - **Results**
- Summary and Outlook

CMS Measurements

➢ Polarization along the beam direction in p+Pb collisions



CMS, arXiv:2502.07898 (2025)



CMS,PRC,101, 014912 (2020)

- ➢ **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

W. Ke, J. S. Moreland, J. E. Bernhard, and S. A. Bass, PRC 96, 044912 (2017),

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 Framework

➢ CLVisc Framework

Pang, Wang, and Wang, PRC 86, 024911 .
Wu, Qin, Pang, and Wang, PRC 105, 034909.

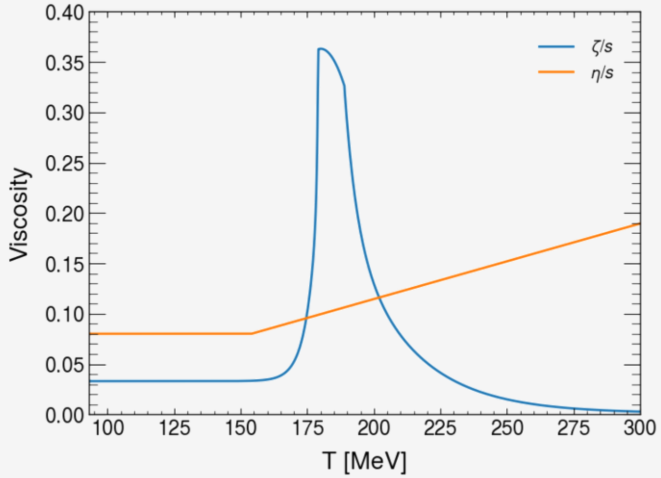
The subsequent evolution of the system is simulated by the 3+1D CLVisc hydrodynamics model.

We just focus on the energy-momentum conservation equations

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

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

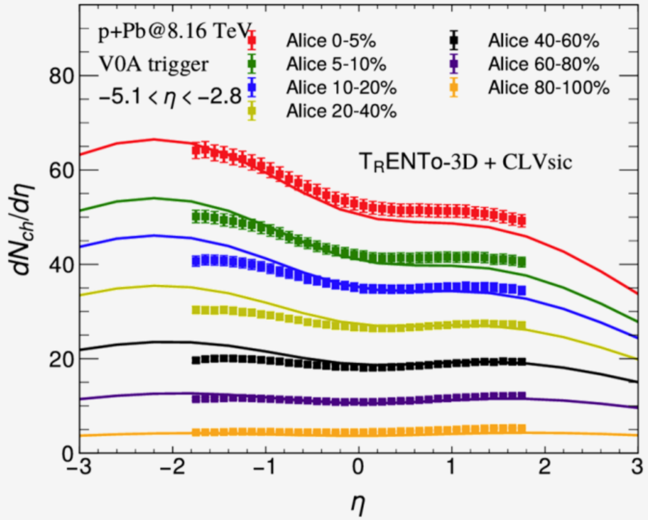
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} + \pi^{\mu\nu} = \eta_v\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}_{\lambda} + \varphi_1\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}.$$

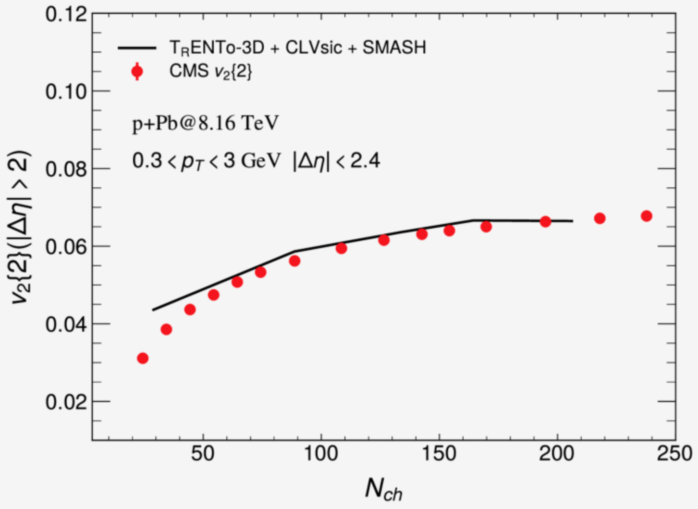


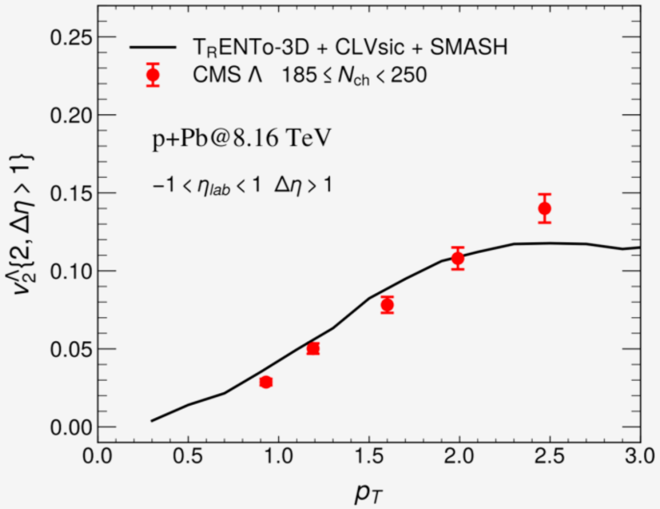
We use the temperature dependent shear and bulk viscosity given by Bayesian parameter estimation in Phys. Rev. C 94, 024907 (2016) .
The equations of state is given by the HotQCD collaboration and freeze-out temperature T_f = 154 MeV.

Fitting Multiplicity and v2

➢Bulk properties







Multiplicity intervals	$\langle N_{\rm ch}\rangle_{\rm exp}$	$\langle N_{\rm ch}\rangle_{\rm CLVisc}$
[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

- **CLVisc with Trento-3D initial condition can have a good description of the multiplicity of charged particles and elliptic flow for Λ hyperons**

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:

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

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

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

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

Spin Polarization

In the experiment, the polarization of Λ are measured in their own rest frames. Therefore, we express the polarization pseudo vector in the rest frame of Λ, by taking the Lorenz transformation,

$$\vec{P}^*(\mathbf{p}) = \vec{P}(\mathbf{p}) - \frac{\vec{P}(\mathbf{p})\cdot\vec{p}}{p^0(p^0+m)}\vec{p}, \qquad P^\mu(\mathbf{p}) \equiv \frac{1}{s}\mathcal{S}^\mu(\mathbf{p}),$$

P2z as a function of p_T and multiplicity are given by

$$P_{2,z}(p_T) = \frac{\int d\eta \int d\phi [\Phi P^{*z} \sin 2(\phi - \Psi_2)]}{\int d\eta \int d\phi \Phi}$$

$$P_{2,z} = \frac{\int p_T dp_T \int d\eta \int d\phi [\Phi P^{*z} \sin 2(\phi - \Psi_2)]}{\int p_T dp_T \int d\eta \int d\phi \Phi}$$

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:** Fu, et al. PRL 127, 142301

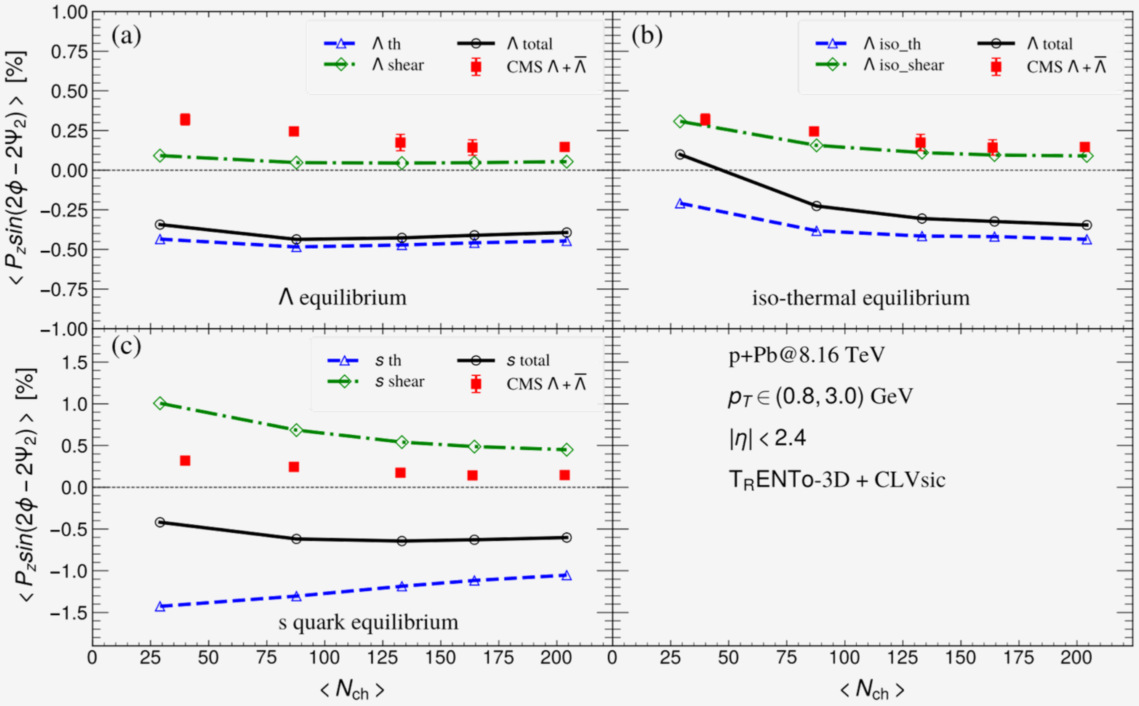
  The spin of Λ hyperons is assumed to be carried by the constituent s quark. We take the s quark's mass instead of Λ's mass in the simulation

- **Iso-thermal equilibrium:** Becattini et al, PRL 127, 272302

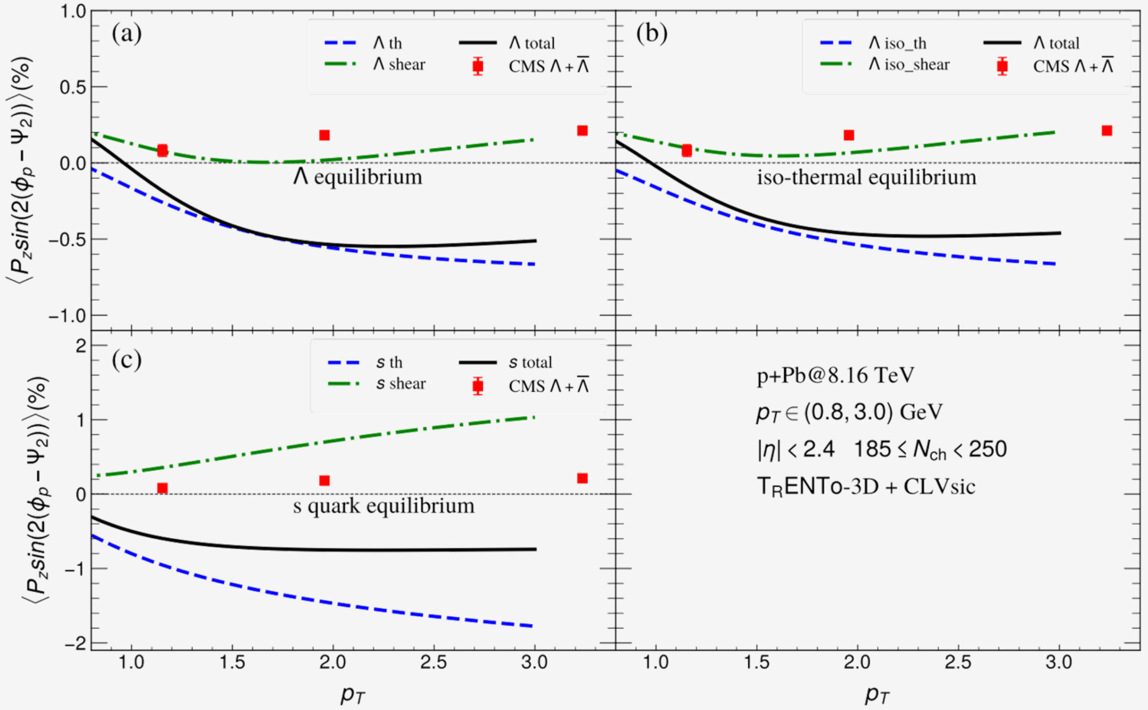
  The temperature of the system at the freeze-out hyper-surface is assumed to be constant. The time unit vector is taken as fluid velocity for simplicity.

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

Multiplicity (centrality) dependence



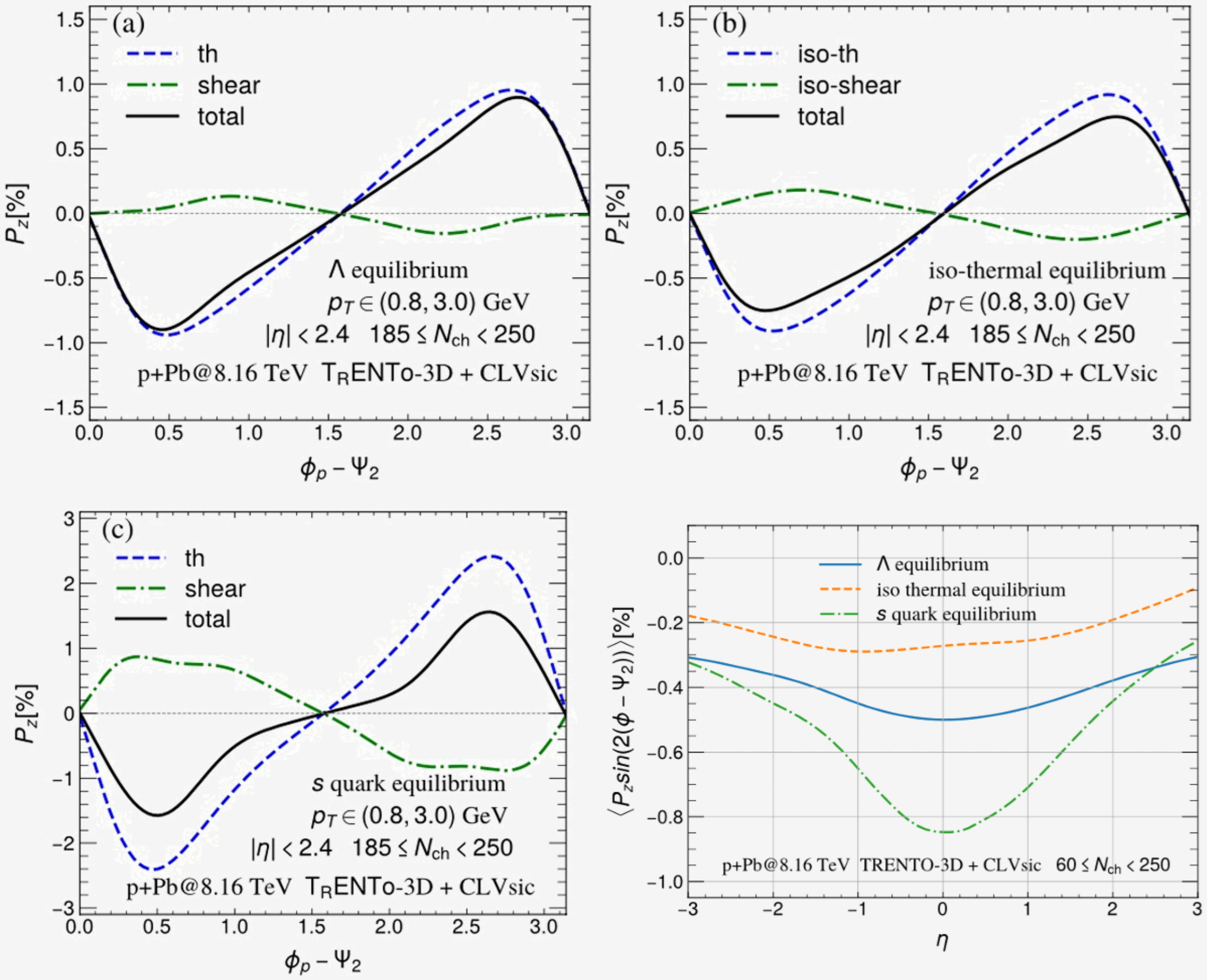
Multiplicity dependence



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.**

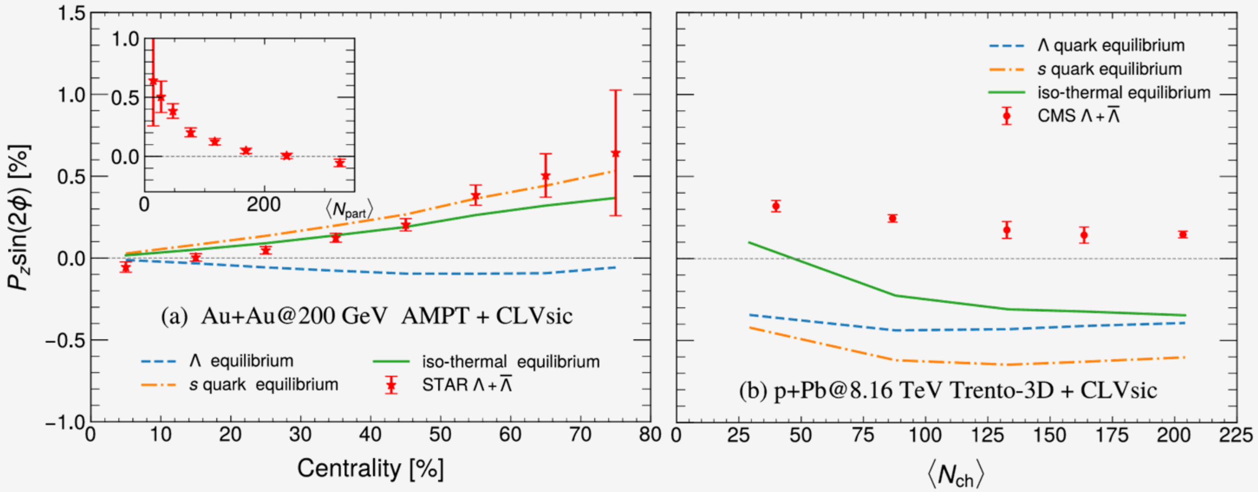
Azimuthal angle and pseudo-rapidity dependence



- The local spin polarization along the beam direction shows a significant deviation from sin(2φ) , mainly due to enhanced event-by-event fluctuations in small systems.

- $P_{2z}(\eta)$ is not symmetric under the transformation $\eta \rightarrow -\eta$, reflecting the initial-state asymmetry between the proton and the lead nucleus.

Summary and Outlook

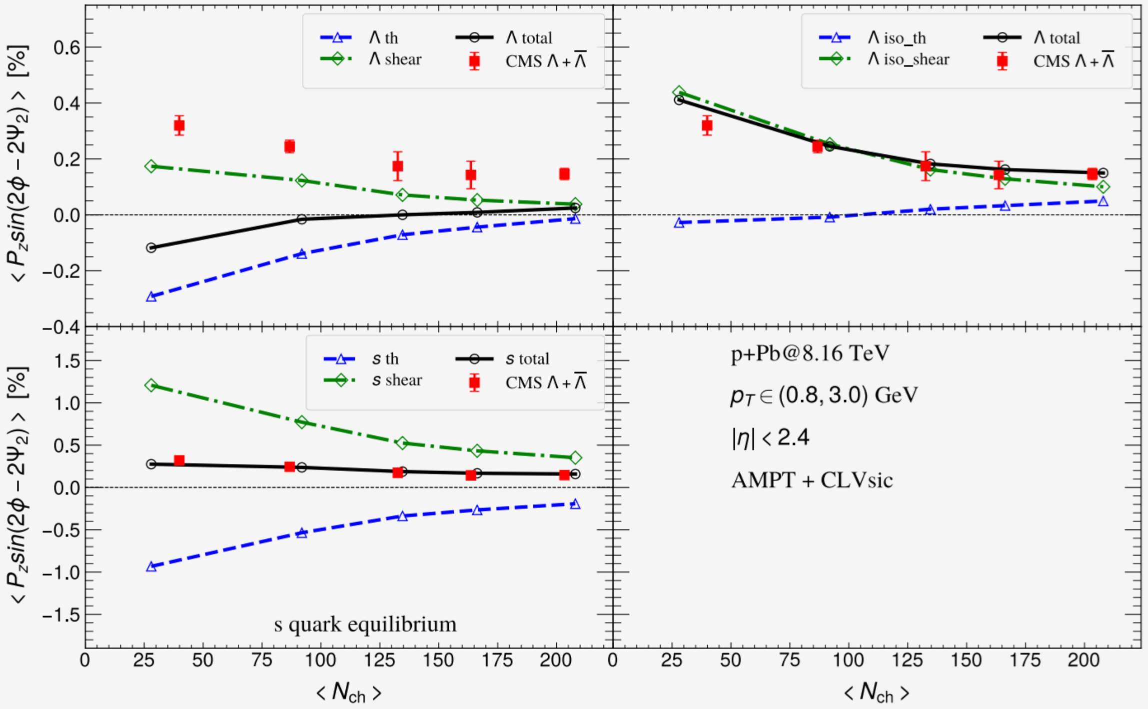


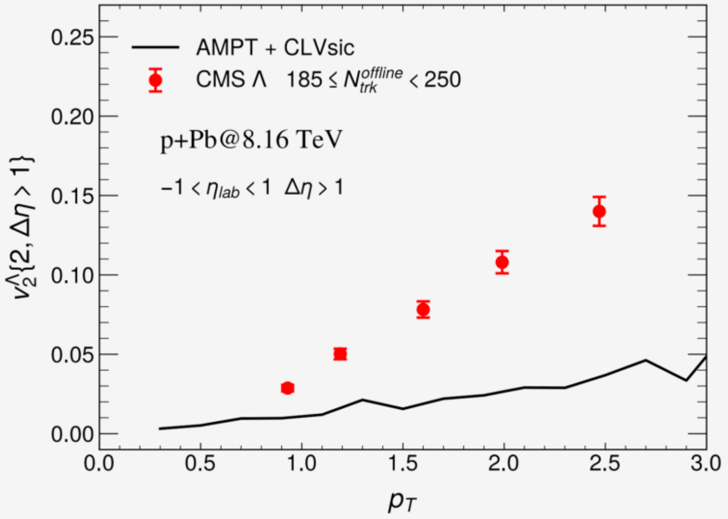
- Shear induced polarization always gives a positive contribution.
- Polarization induced by the thermal vorticity is negative.
- The results from hydrodynamics are inconsistent with the data from CMS.
- New effects need to be considered for the polarization at pPb collisions in the future work.
- We will explore the correlation between v2 and P2z across collision system and energy.

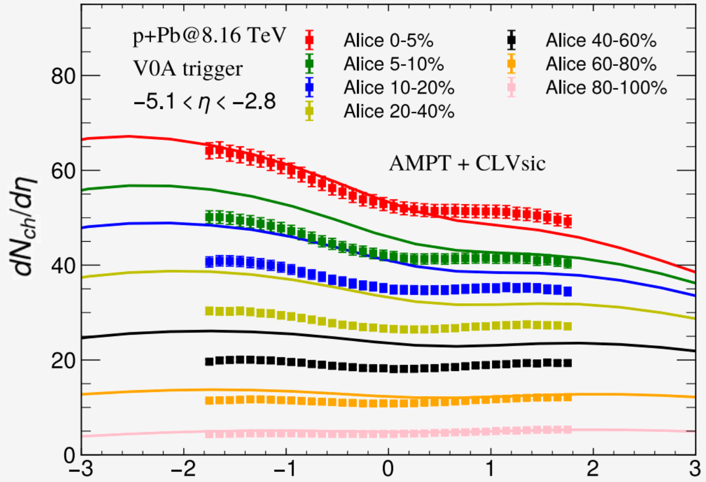
Thanks for your time !

Back Up

Test for AMPT initial conditions

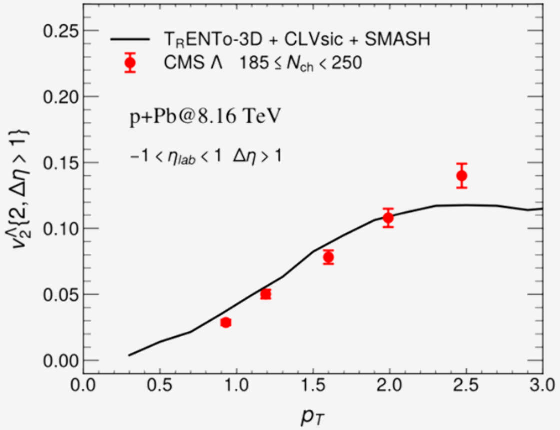


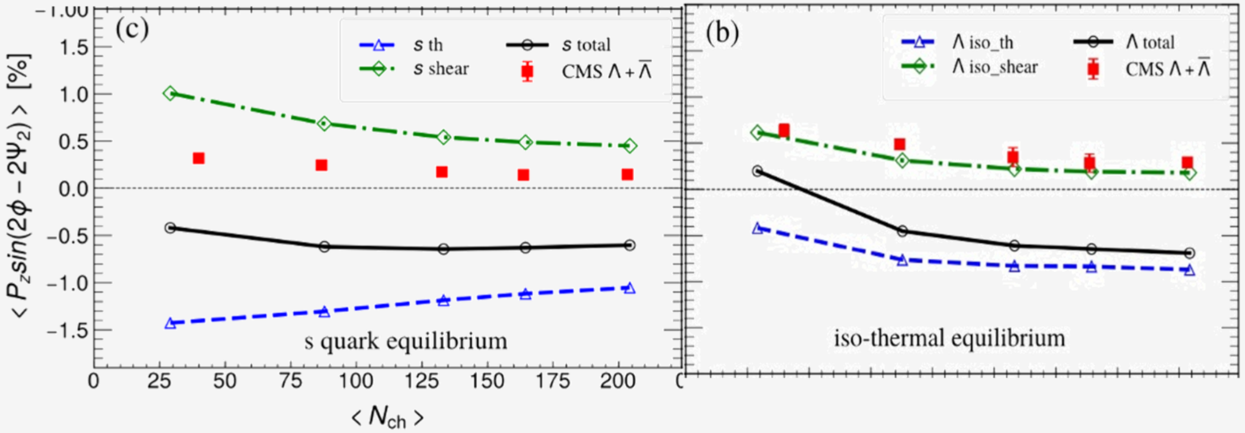




- **The parameters can describe spin polarization at the s quark equilibrium and iso-thermal equilibrium can not fit the multiplicity of charged particles and v2 of Λ.**

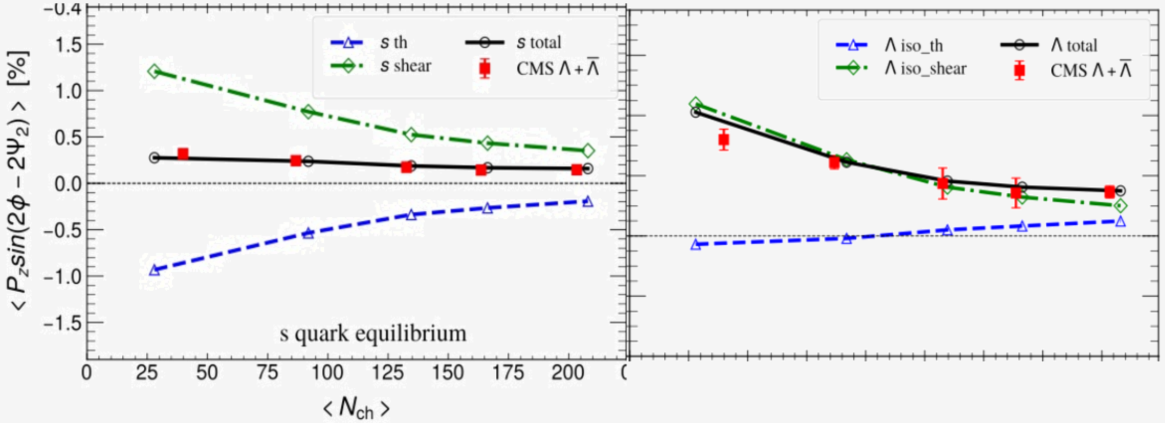
Different initial conditions

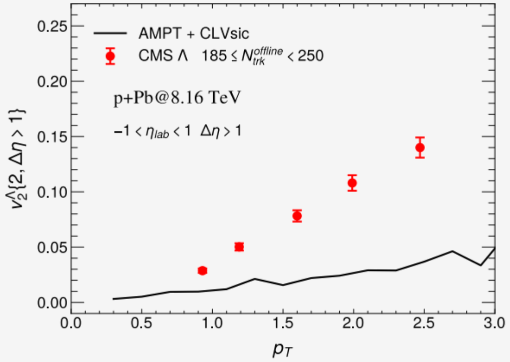




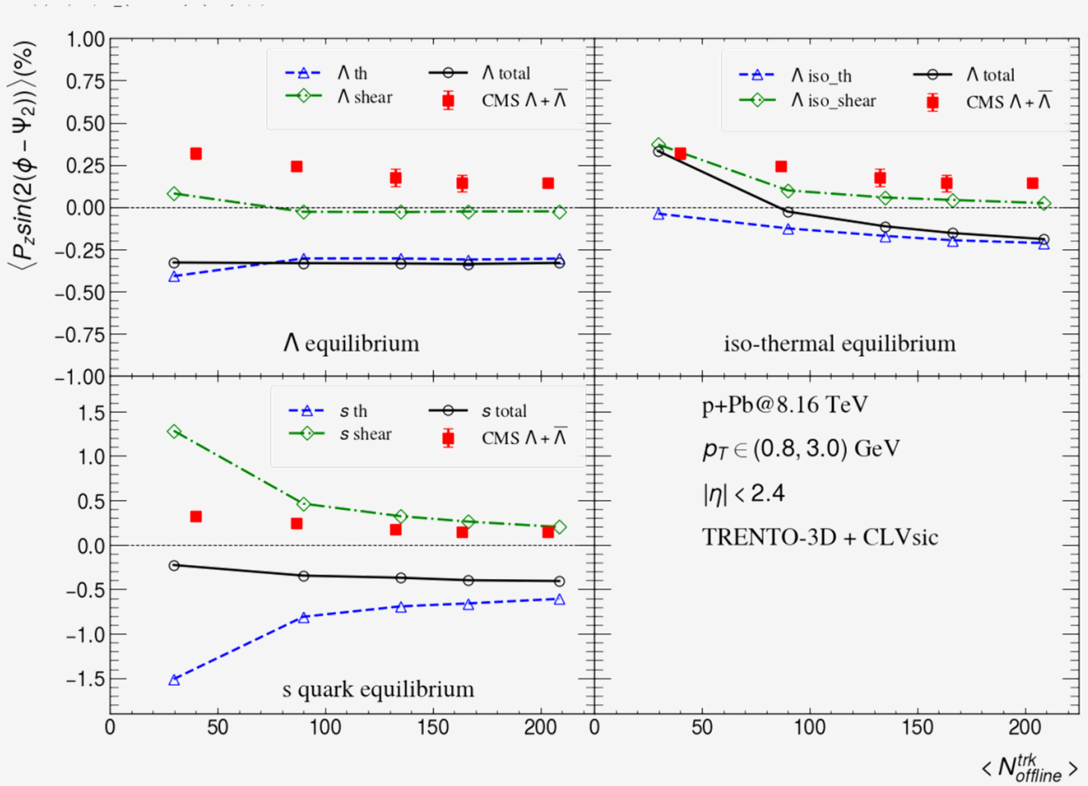
The P2z of **Λ** hyperons is not only induced by the v2 in the p+Pb collisions.

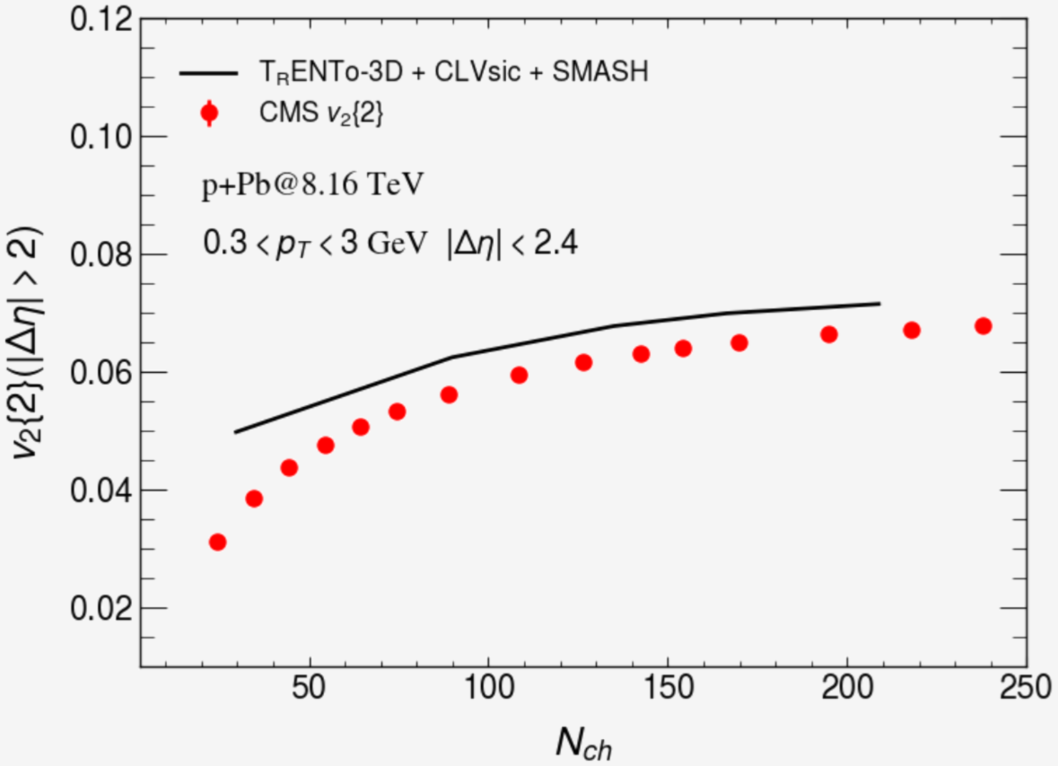
New effects need to be considered in the polarization at p+Pb collisions.





Without bulk viscosity





Event Plane

The event plane is constructed by the flow vector

$$Q_{n,x} = \sum_i \omega_i \cos(n\phi_i)$$

$$Q_{n,y} = \sum_i \omega_i \sin(n\phi_i)$$

$$\Psi_n = \frac{1}{n} \arctan\left(\frac{Q_{n,y}}{Q_{n,x}}\right)$$

$$0.3 < p_T < 3 \text{ GeV}$$

$$|\eta| < 2.4$$