Hydrodynamic effects on spin polarization in AA and pA collisions

Cong Yi (易聪)
Central China Normal University

The 9th Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter, July 7-11, 2025
ICTP-SAIFR, São Paulo, Brazil

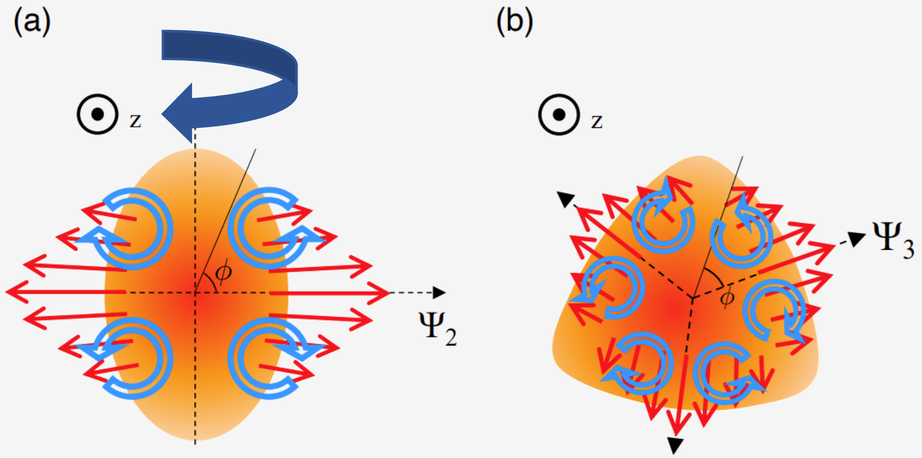
In collaboration with: Xiang-Yu Wu, Shi Pu, Guang-You Qin, Di-Lun Yang, Jian-Hua Gao

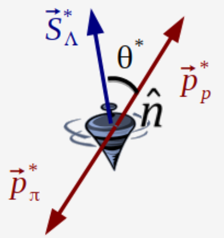
Outline

- **Introduction**
- **Global and local polarization at AA systems**
- **Spin polarization at pA system**
- **Summary**

Spin Polarization

➢Local Vortical Structure



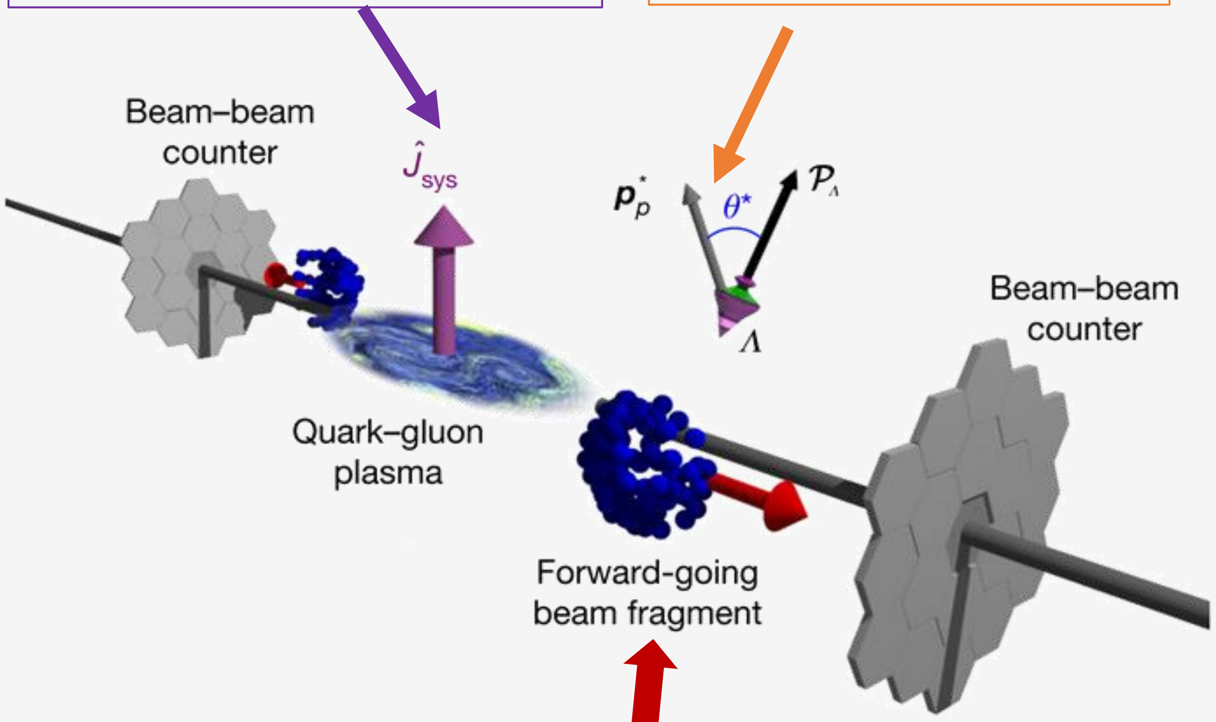


$$\Lambda \rightarrow p + \pi^-$$

STAR, Nature 548, 62 (2017).
STAR, PRL 123, 132301 (2019).
STAR, PRL 131, 202301 (2023)

Orbital Angular momentum
(Out-plane direction)

Helicity polarization
(particle’s momentum)



Beam direction polarization

Polarization induced by different sources

➢Spin polarization at local equilibrium

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

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

Thermal vorticity

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

Shear Induced Polarization (SIP)

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

Fluid Acceleration

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

Spin Hall Effect (SHE)

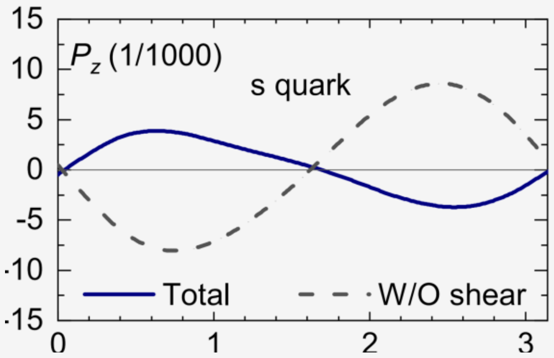
$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = \frac{\hbar}{4m_{\Lambda}N}\int d\Sigma\cdot p f_{V}^{(0)}(1-f_{V}^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}E_{\nu}+\frac{B^{\mu}}{T}\right),$$

EM Field

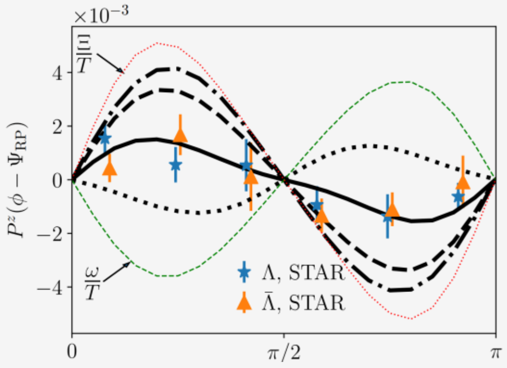
Hidaka, Pu, Yang, PRD 97, 016004 (2018) ; Liu, Yin, PRD 104, 054043 (2021) ; Becattini, Buzzegoli, Palermo, PLB 820, 136519 (2021) ; Liu, Yin, JHEP 07,188 (2021); CY, Pu, Yang, PRC 04, 064901(2021)

Shear induced polarization(SIP)

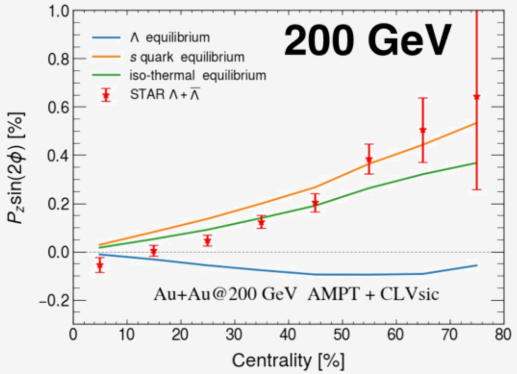
➢ **Hydrodynamic contribution to the local spin polarization**



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.
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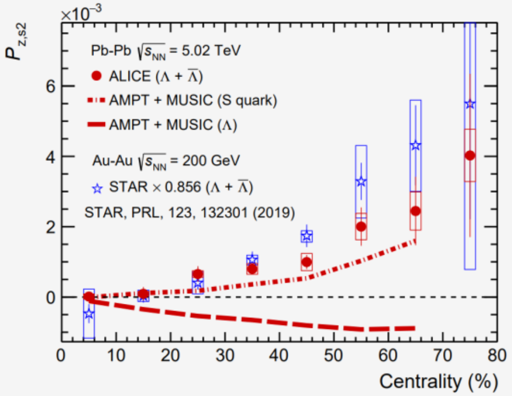
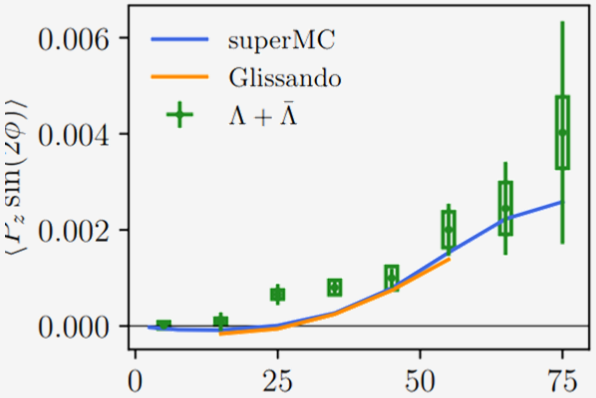


ALICE, PRL 128, 172005(2022)



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

Considering SIP under some assumptions, the theoretical calculations qualitatively/ quantitatively agree with the experimental data at RHIC top energy and 5.02 TeV Pb+Pb collision.

Questions

$$
\begin{aligned}
\mathcal{J}^{\mu}_{\text{thermal}} &= a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_{\nu}\boxed{\partial_{\alpha}\frac{u_{\beta}}{T}},\\
\mathcal{J}^{\mu}_{\text{shear}} &= -a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}p^{\sigma}\boxed{\partial_{<\sigma}u_{\nu>}}\\
\mathcal{J}^{\mu}_{\text{accT}} &= -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_{\nu}u_{\alpha}\left(\boxed{Du_{\beta}-\frac{1}{T}\partial_{\beta}T}\right).\\
\mathcal{J}^{\mu}_{\text{chemical}} &= a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\boxed{\partial_{\nu}\frac{\mu}{T}}\\
\mathcal{J}^{\mu}_{\text{EB}} &= a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}\boxed{E_{\nu}},
\end{aligned}
$$

Shear induced polarization

Fluid acceleration

Spin Hall Effect

- **These hydrodynamic effects on spin polarization have been well studied by many works at high energy large collision systems.**
- **How about hydrodynamic contributions to spin polarization at lower energies and p+Pb collisions?**

Outline

- ➢Introduction
- ➢**Global and local polarization at AA systems**
- ➢Spin polarization at pA system
- ➢ Summary

Setup of simulation

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

Solve the Energy-momentum conservation and net baryon current:

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

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

RHIC-BES

Equation of motion for dissipative currents:

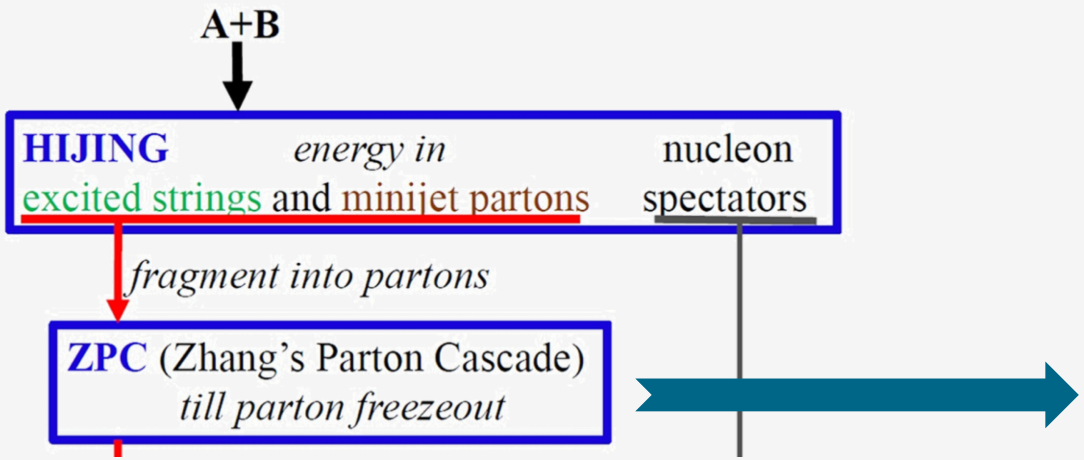
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha\langle}\sigma^{\mu\nu\rangle}_\alpha + \frac{9}{70}\frac{4}{e+P}\pi^{\langle\mu}_\alpha \pi^{\nu\rangle\alpha}$$

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

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

Initial Condition

➢ AMPT initial condition (Patron level)



$$\tau = \tau_0$$

➢ SMASH initial condition (Hadron level)

It solves the relativistic Boltzmann equation effectively.

$$p^\mu \partial_\mu f + m F^\mu \partial_{p_\mu}(f) = C[f]$$

The collision kernel includes elastic collisions, resonance formation and decays, string fragmentation for all mesons and baryons up to mass 2.35 GeV.

Gaussian smearing

➢ Initial $T^{\mu\nu}$ and J^{μ} at τ_0

At the initial proper time τ_0 , the initial energy momentum tensor and the initial baryon current can be constructed at Melin coordinate via the local space-time formations of partons and hadrons,

$$\begin{aligned} T^{\mu\nu}(\tau_0, x, y, \eta_s) &= K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} G(\tau_0, x, y, \eta_s), \\ J^{\mu}(\tau_0, x, y, \eta_s) &= \sum_i Q_i \frac{p_i^\mu}{p_i^\tau} G(\tau_0, x, y, \eta_s), \end{aligned}$$

where G denotes the Gaussian smearing:

$$G\left(\tau_0, x, y, \eta_s\right) = \frac{1}{\mathcal{N}} \exp\left[-\frac{\left(x - x_i\right)^2 + \left(y - y_i\right)^2}{2\sigma_r^2} - \frac{\left(\eta_s - \eta_{si}\right)^2}{2\sigma_{\eta_s}^2}\right]$$

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,

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

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

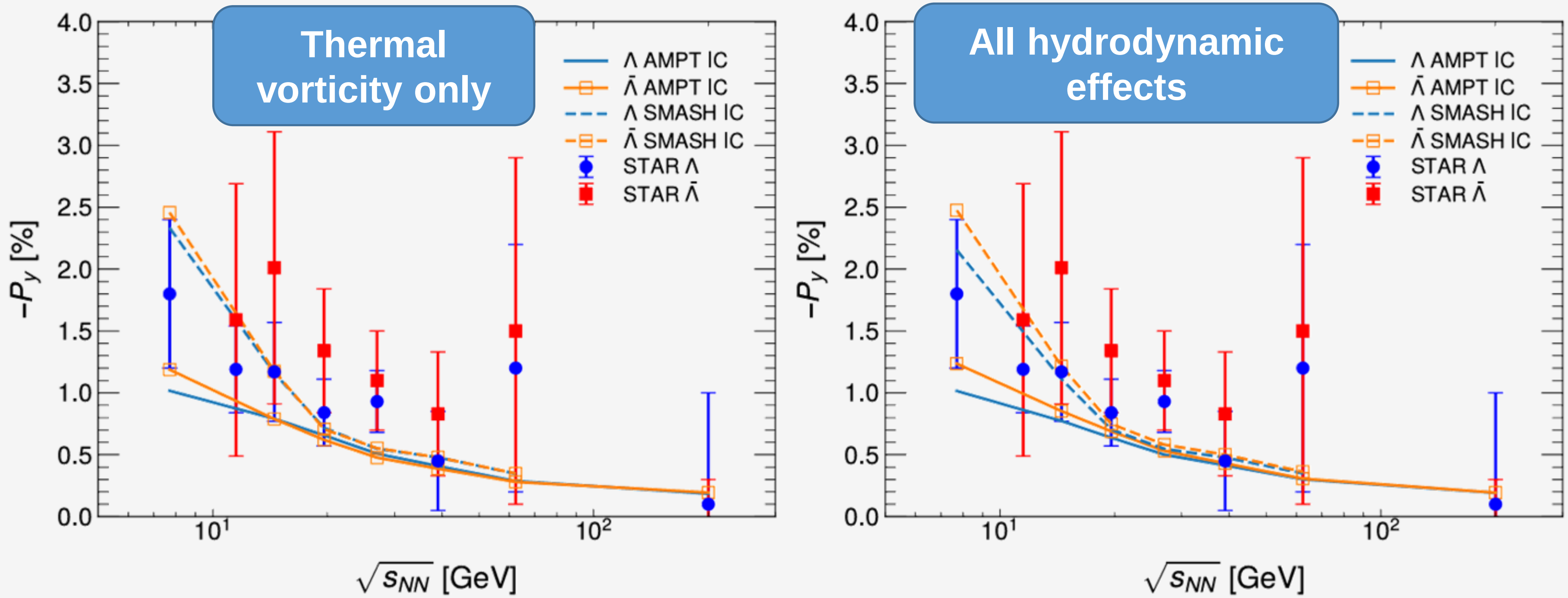
Finally, the local and global polarization is given by the averaging over momentum and rapidity.

$$\langle \vec{P}(\phi_p) \rangle = \frac{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T [\Phi(\mathbf{p}) \vec{P}^{*}(\mathbf{p})]}{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\min}}^{p_{T\max}} p_T dp_T \Phi(\mathbf{p})} \qquad \Phi(\mathbf{p}) \ = \int d\Sigma^{\mu} p_{\mu} f_{eq}$$

Global Polarization

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

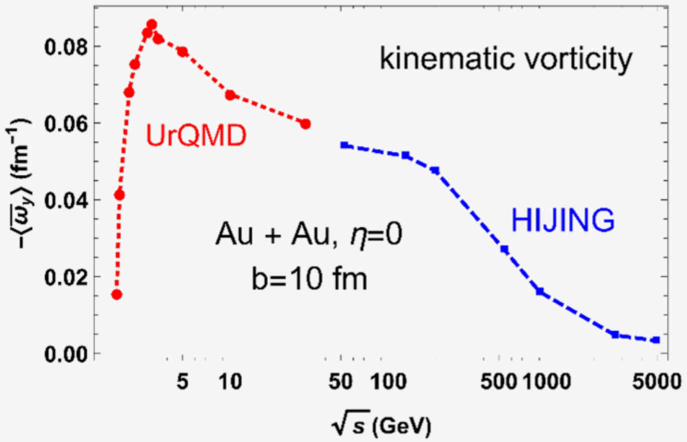
Wu, CY, Qin, and Pu, PRC 105 6, 064909 (2022)



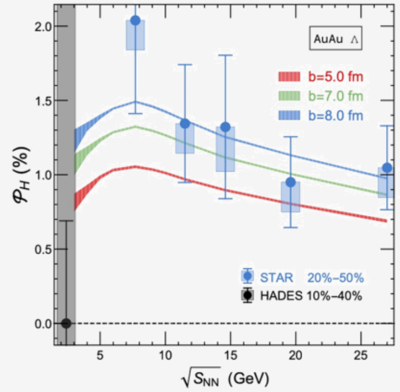
Whether the global polarization will continue to increase as the collision energy decreases further.

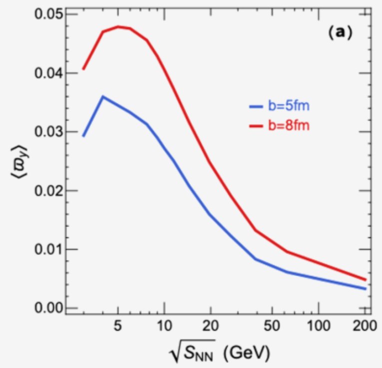
Global Polarization at a few GeV

➢ Theoretical prediction



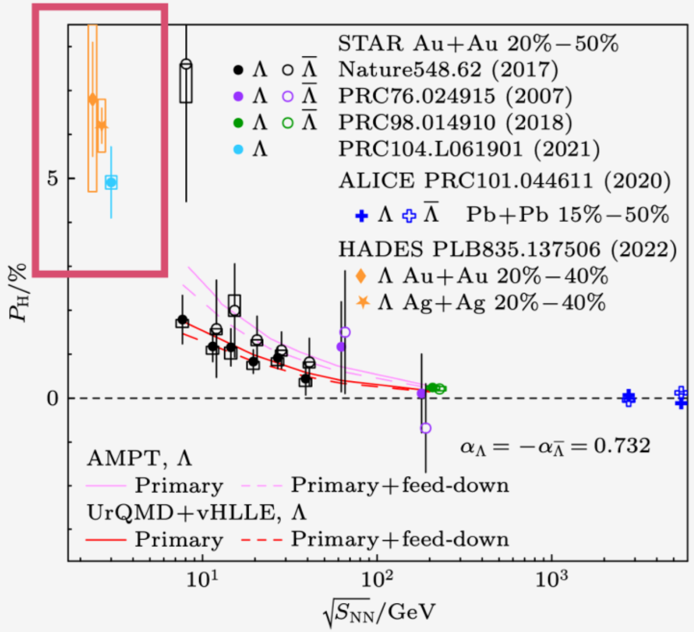
Deng, Huang PRC 2016, PRC 2020





Guo, Liao, et. al, PRC 2021

➢ Experimental results



Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)

- ➢ **Will the polarization of Λ keep rising with decreasing energy?**
- ➢ **If not, how large will the turning energy be.**

Global Polarization at a few GeV

At such low collision energies, hydrodynamic models may no longer be applicable.

- **Flow velocity**

$$T^{\mu\nu}(\tau, x, y, \eta_s) = \frac{1}{\Delta V}\left\langle \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} \right\rangle,$$

$$T^{\mu}{}_{\nu} u^{\nu} = \varepsilon u^{\mu}$$

- **Thermal Vorticity**

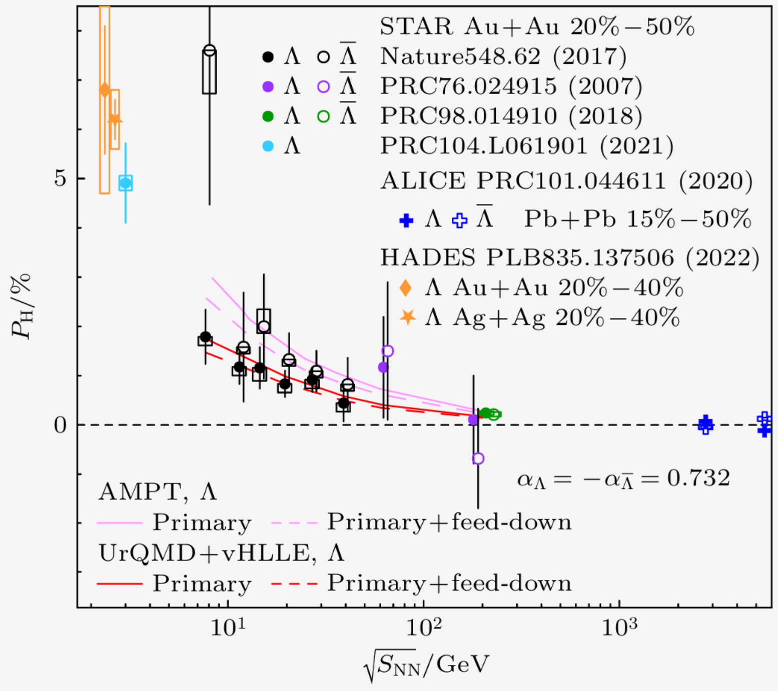
$$\boldsymbol{\varpi}_{\mathrm{T}} = (\varpi_{tx}, \varpi_{ty}, \varpi_{tz}) = \frac{1}{2}(\nabla\beta_t + \partial_t \boldsymbol{\beta}),$$

$$\boldsymbol{\varpi}_{\mathrm{S}} = (\varpi_{yz}, \varpi_{zx}, \varpi_{xy}) = \frac{1}{2}\nabla \times \boldsymbol{\beta}.$$

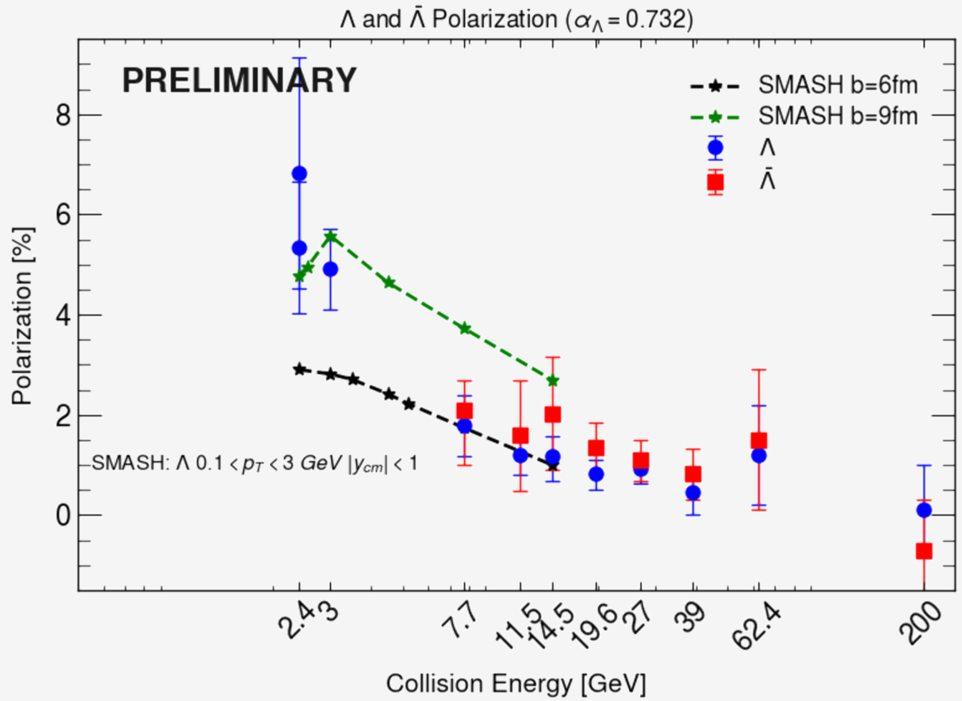
- **Global Polarization**

$$\mathbf{P}_{\mathrm{H}} = \frac{S+1}{3}\left[\frac{E}{m}\boldsymbol{\varpi}_{\mathrm{S}}(x) + \frac{\mathbf{p}}{m} \times \boldsymbol{\varpi}_{\mathrm{T}}(x) - \frac{\mathbf{p}\cdot\boldsymbol{\varpi}_{\mathrm{S}}(x)}{m(E+m)}\mathbf{p}\right].$$

Global Polarization at a few GeV



Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



CY, et.al. (in preparation)

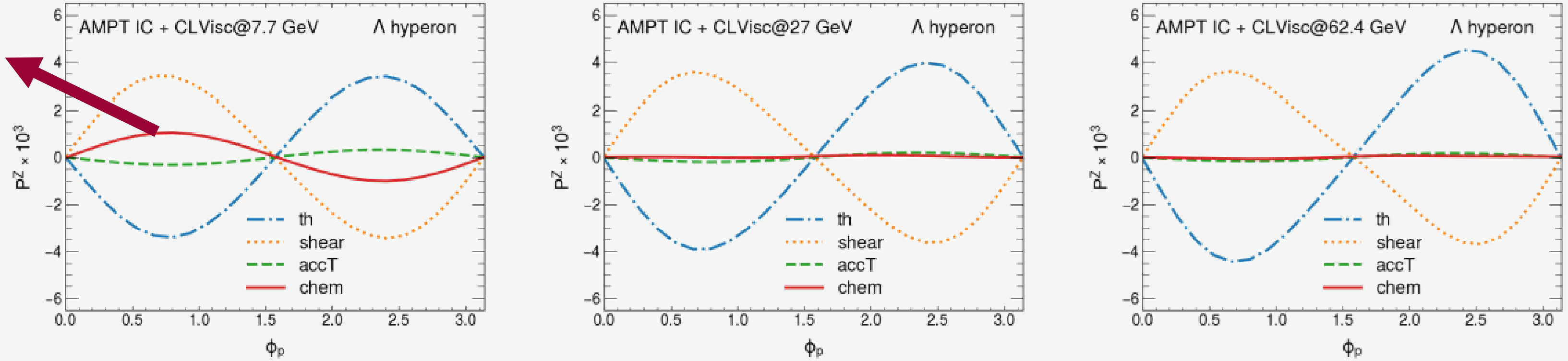
➢ **The turning energy depends on the impact parameter**

Local Polarization at RHIC-BES

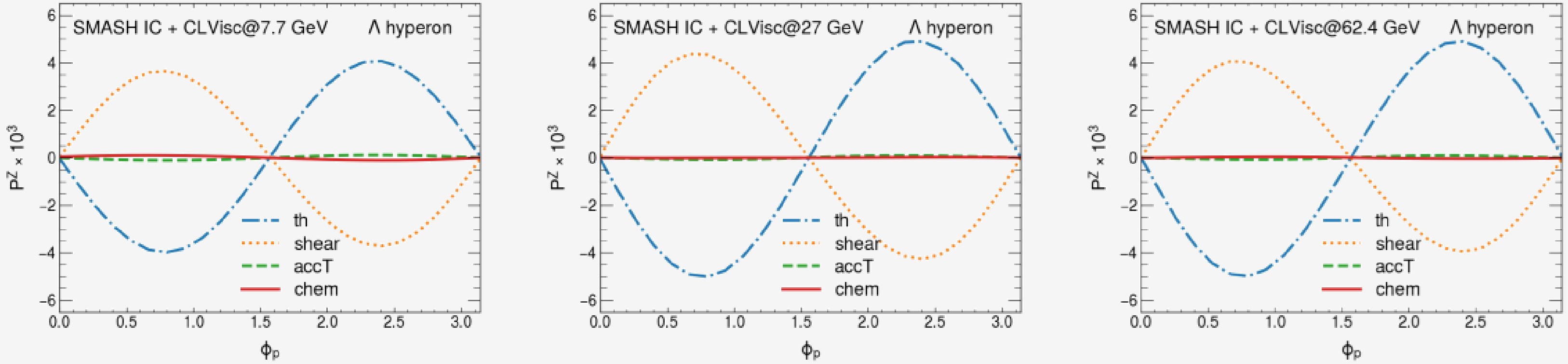
7.7 GeV | 27 GeV | 62.4 GeV

Chemical Gradient

AMPT initial condition



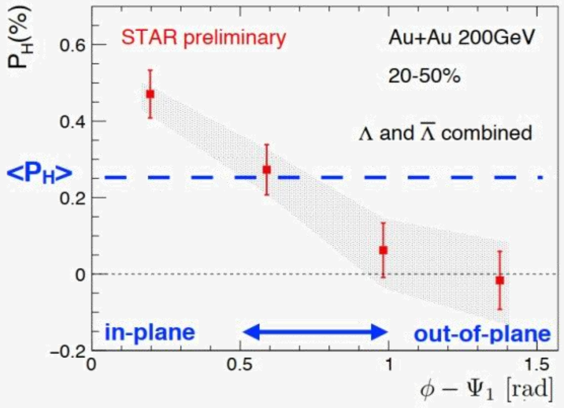
SMASH initial condition



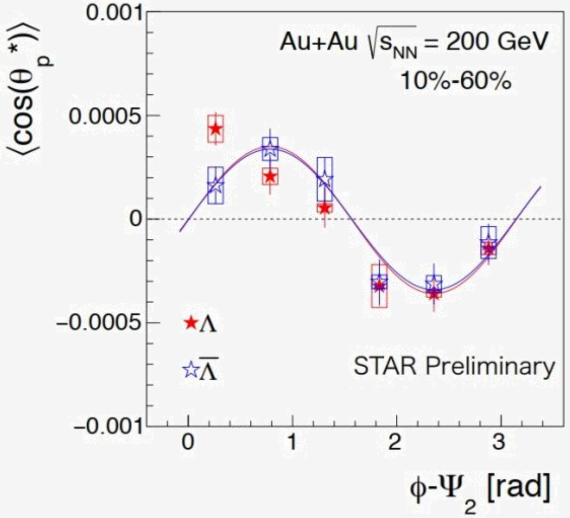
X.Y. Wu, CY, G.Y. Qin, S. Pu Phys. Rev. C 105, 064909

- **The longitudinal polarization induced by baryonic chemical gradient depends on initial conditions strongly**

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

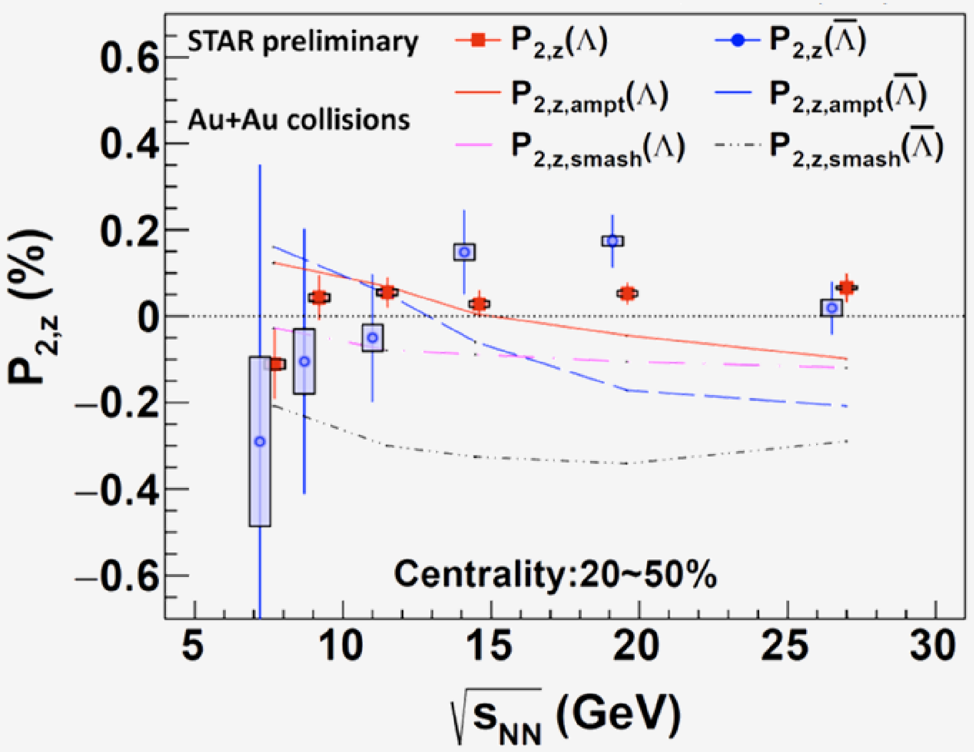


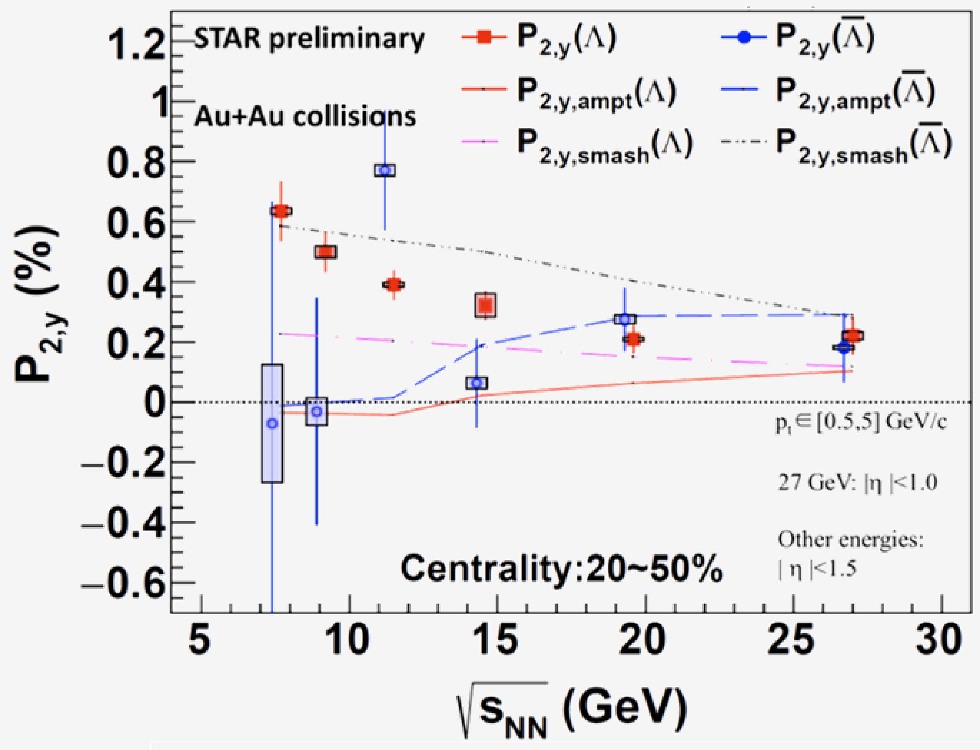
$$P_{2,y} \equiv \langle P_y \cos[2(\phi_\Lambda - \Psi_2)] \rangle$$



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

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

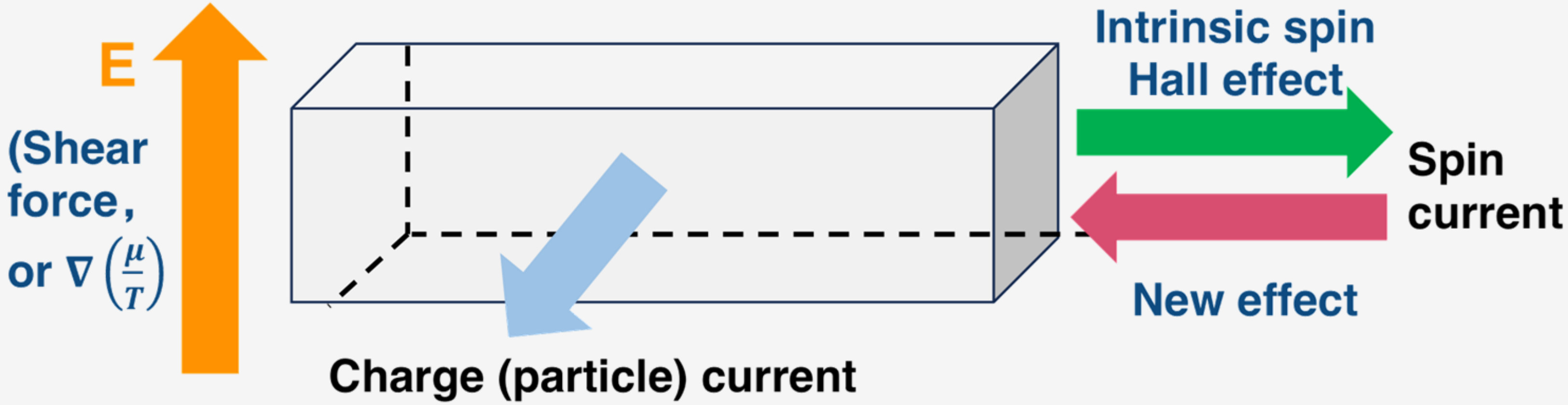




Prediction: Wu, CY, Qin, Pu PRC 105, 064909 (2022)

- **The current mode can not describe the experiment data at RHIC-BES**
- **Dose it imply there are some new effects we have not considered ?**

Anomalous (spin) Hall effects



By replacing the electric field with shear force or gradient of baryon chemical potential, our results align consistently with findings in condensed matter physics. Valet, Raimondi, PRB Lett. (2024)

$$\delta\mathcal{P}^{\mu}_{(\mathrm{I}),\mathrm{shear}} = -\frac{\hbar^2}{4N}\int_{\Sigma}\frac{\mathrm{d}\Sigma\cdot p}{E_{\mathbf{p}}}\beta_0 g_2(E_{\mathbf{p}})\epsilon^{\mu\nu\rho\sigma}p_\rho u_\sigma \sigma_{\nu\alpha}p^{\alpha},$$

$$\delta\mathcal{P}^{\mu}_{(\mathrm{I}),\mathrm{chem}} = -\frac{\hbar^2}{4N}\int_{\Sigma}\frac{\mathrm{d}\Sigma\cdot p}{E_{\mathbf{p}}}\beta_0 g_1(E_{\mathbf{p}})\epsilon^{\mu\nu\rho\sigma}p_\rho u_\sigma \nabla_\nu \alpha_0.$$

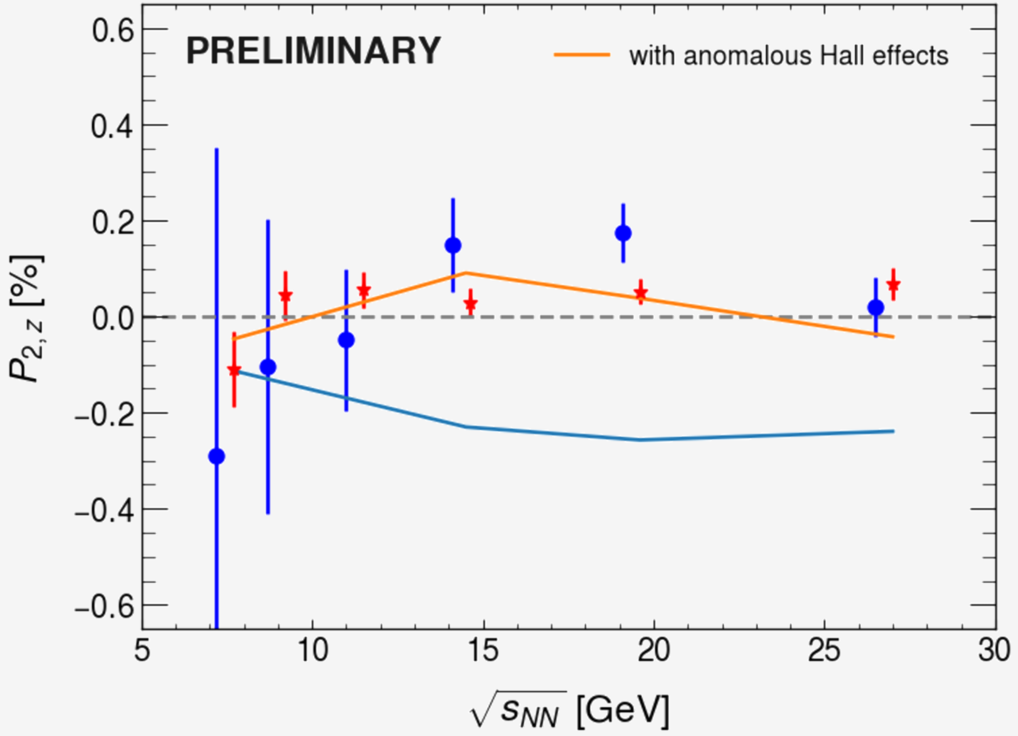
g1 and g2 **come from scatterings but do NOT depend on coupling constant explicitly.** They correspond to anomalous (spin) Hall effects in condensed matter.

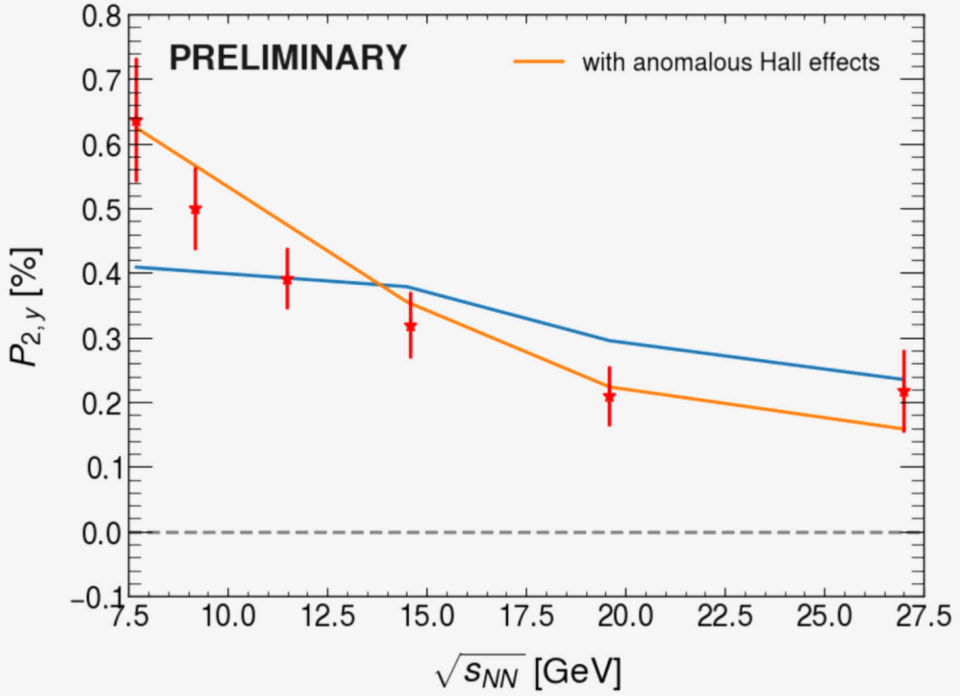
Fang, SP, PRD (2024) for QED type scattering in Hard-Thermal-Loop approximation.

Can we observe the anomalous (spin) Hall effect in HIC?

Anomalous (spin) Hall effects

$$P^{\mu} \quad = \quad P^{\mu}_{th} + P^{\mu}_{accT} + (1+g_2)P^{\mu}_{SIP} + (1+g_1)P^{\mu}_{SHE}$$





CY, et.al. (in preparation)

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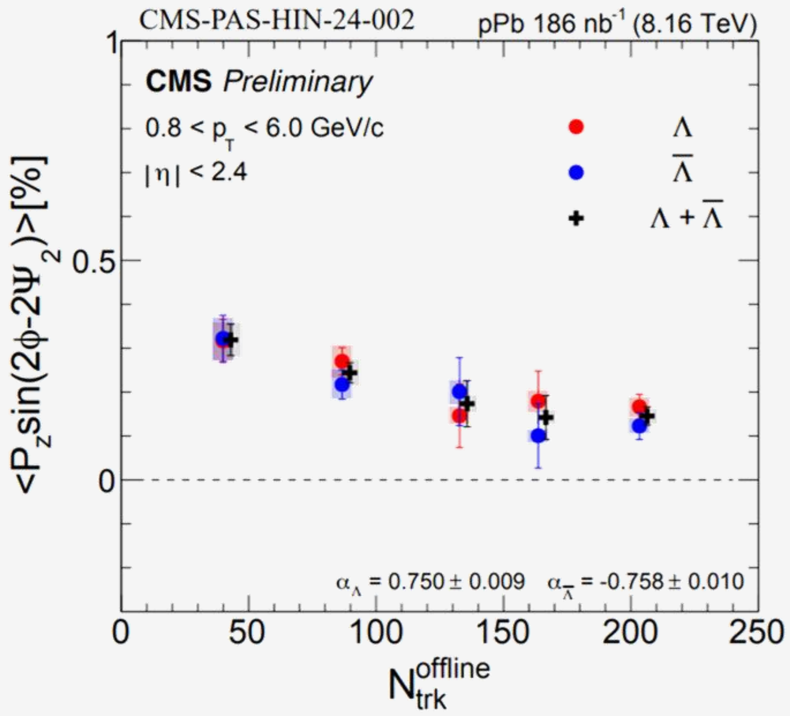
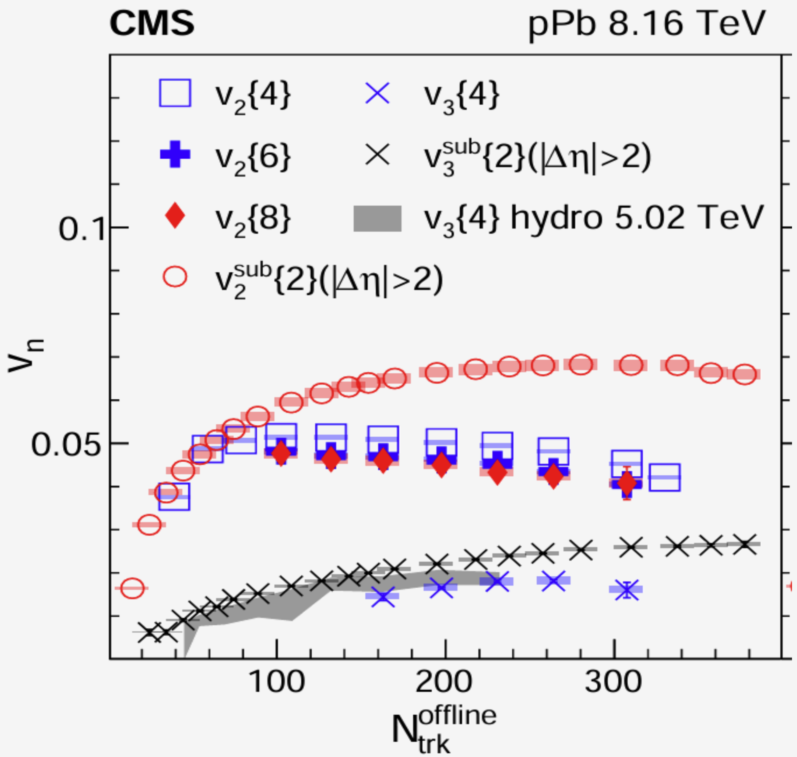
CMS Measurements

- **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

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.

Bulk Viscosity

➢ 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

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

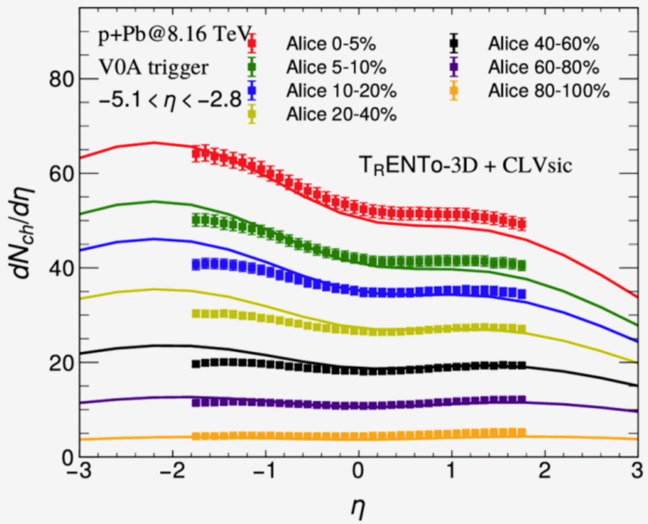
$$\tau_\Pi D\Pi + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

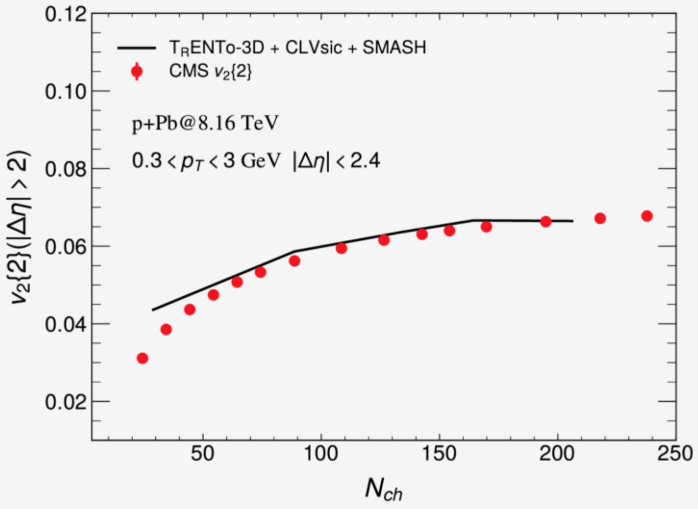
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} + \pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}_{\lambda} + \varphi_1 \pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}.$$

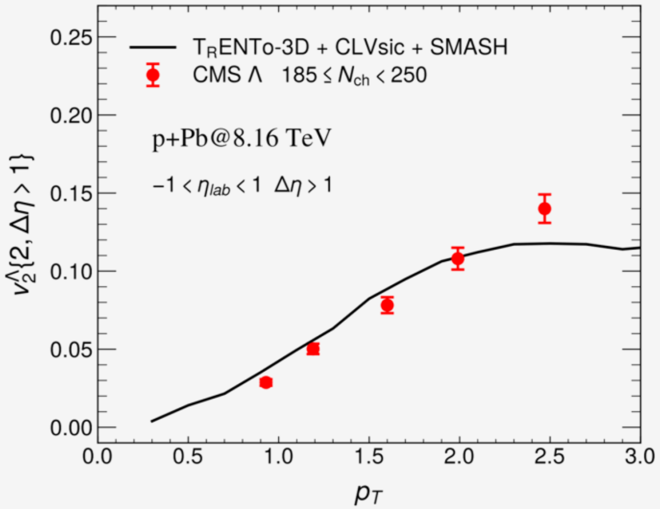
We use the temperature dependent shear and bulk viscosity given by Bayesian parameter estimation in Phys. Rev. C 94, 024907 (2016) .
The equations of state are provided by the HotQCD collaboration and freeze-out temperature T_f = 154 MeV.

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

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:**

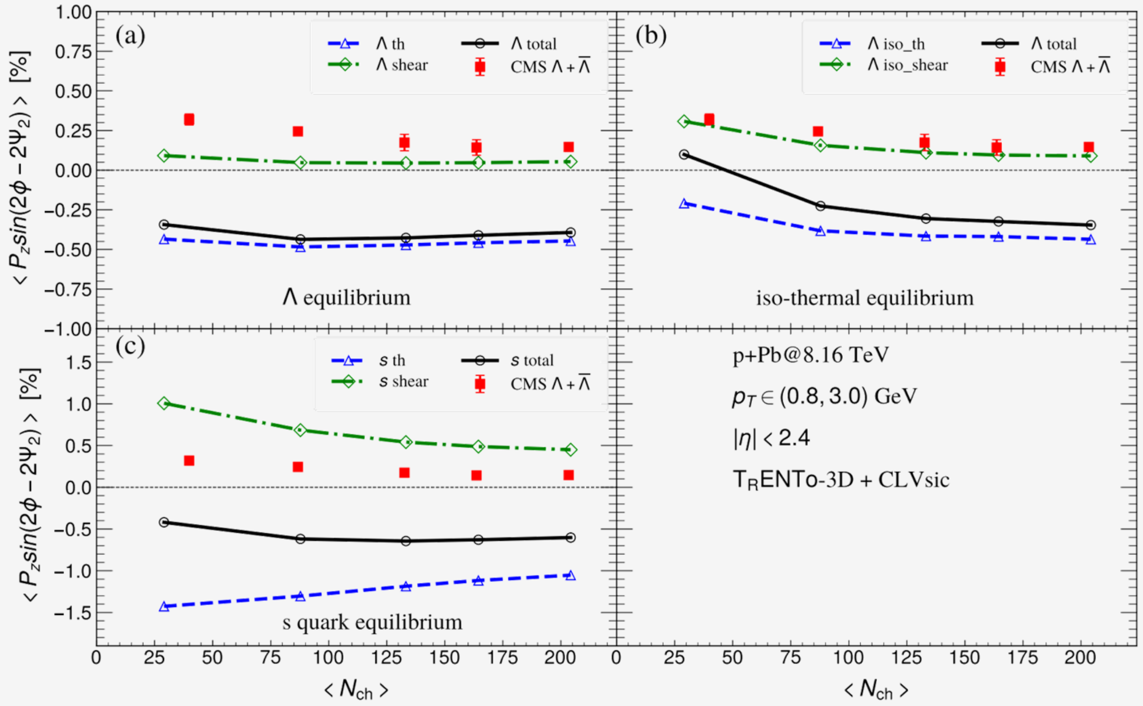
  The spin of Λ hyperons is assumed to be carried by the constituent s quark. We take the s quark's mass instead of Λ's mass in the simulation

- **Iso-thermal equilibrium:**

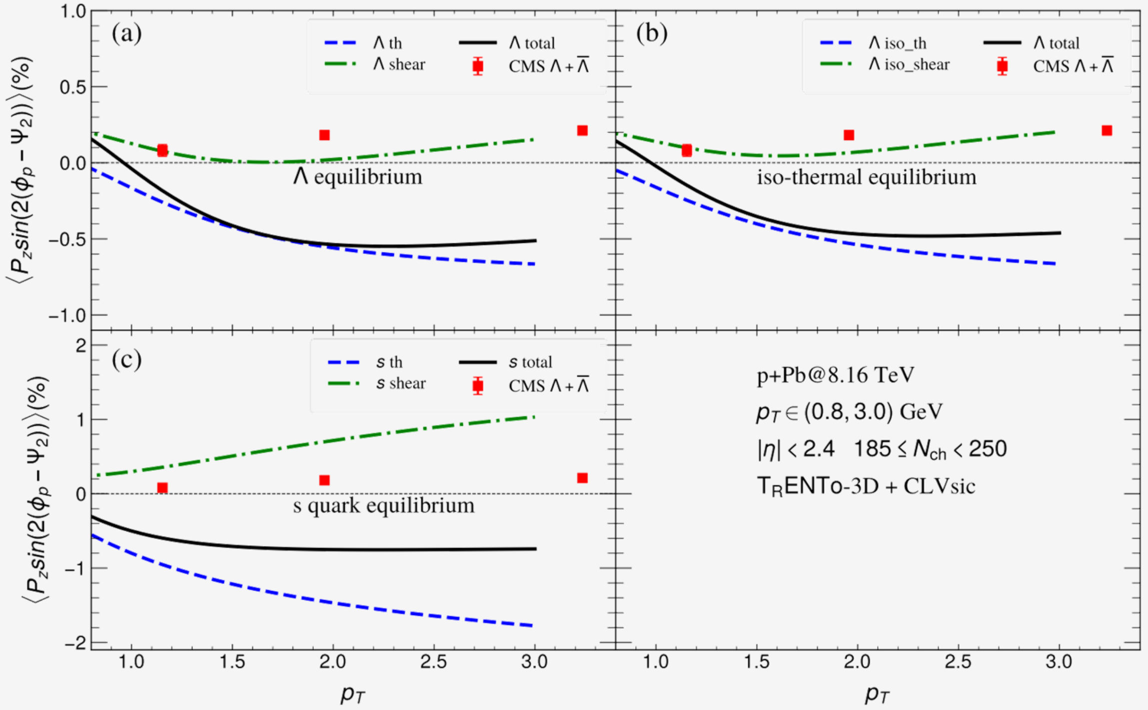
  The temperature of the system at the freeze-out hyper-surface is assumed to be constant. The time unit vector is taken as fluid velocity for simplicity.

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

Multiplicity (centrality) dependence



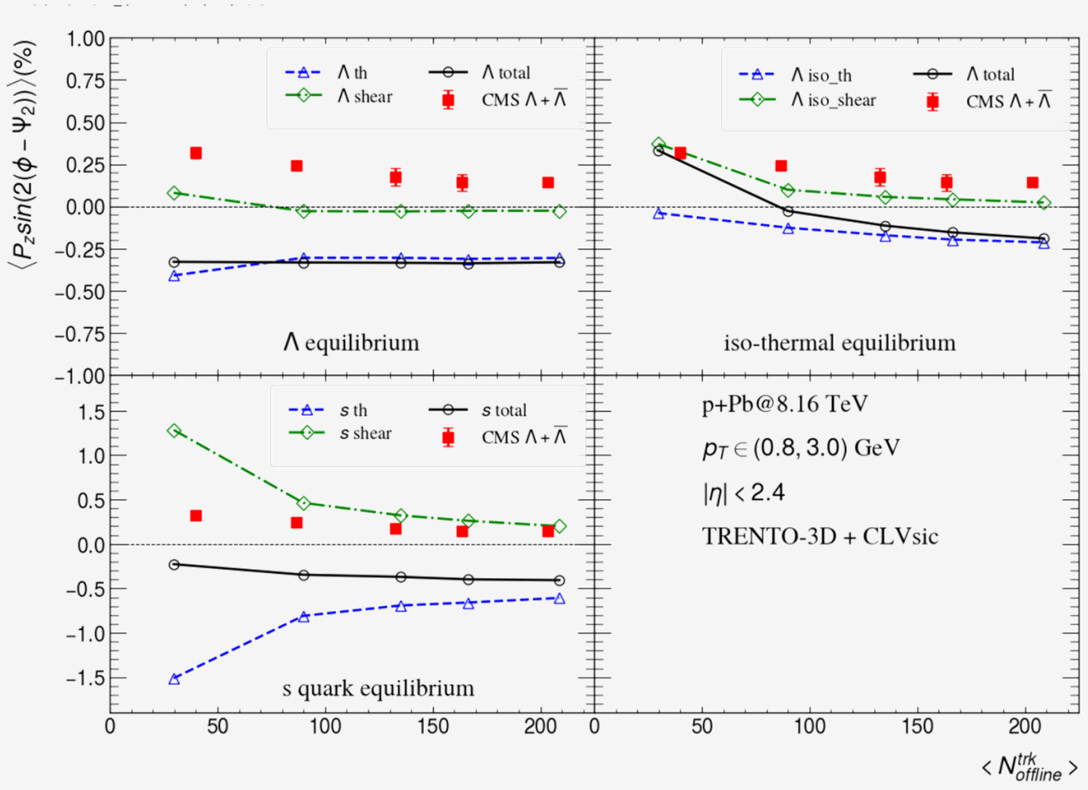
Multiplicity dependence

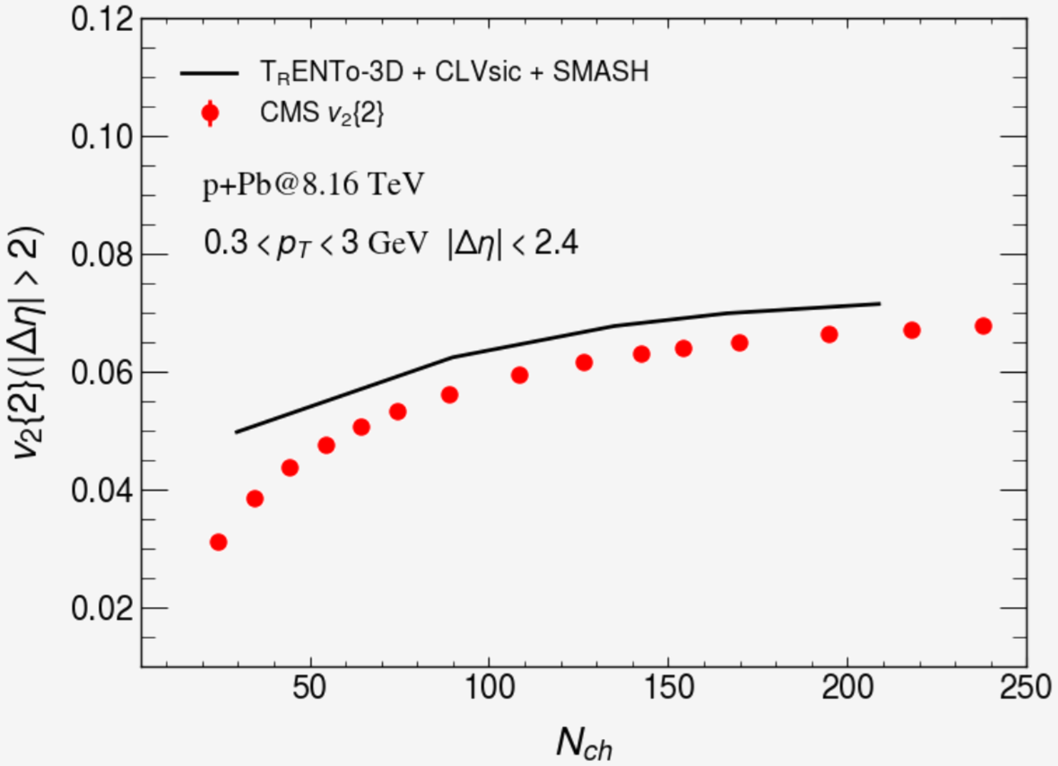


p_T dependence

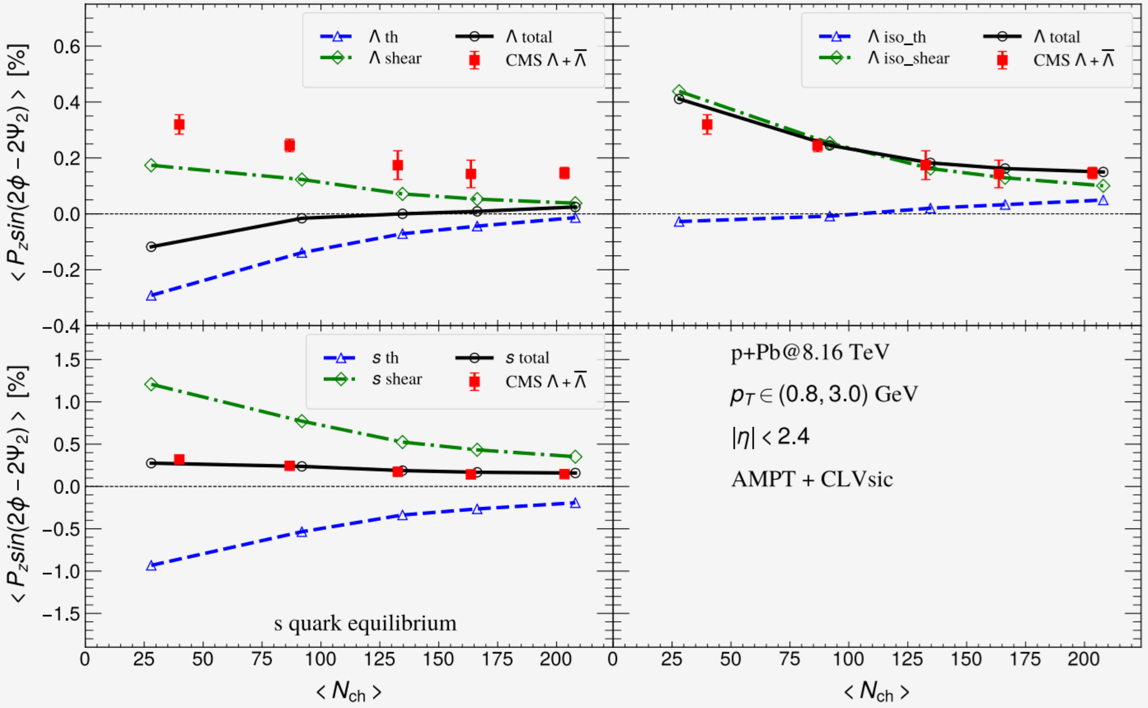
- ➢ **Shear induced polarization always gives a positive contribution**
- ➢ **Polarization induced by the thermal vorticity is negative**
- ➢ **The results in the three scenarios are inconsistent with the data from the LHC-CMS experiments.**

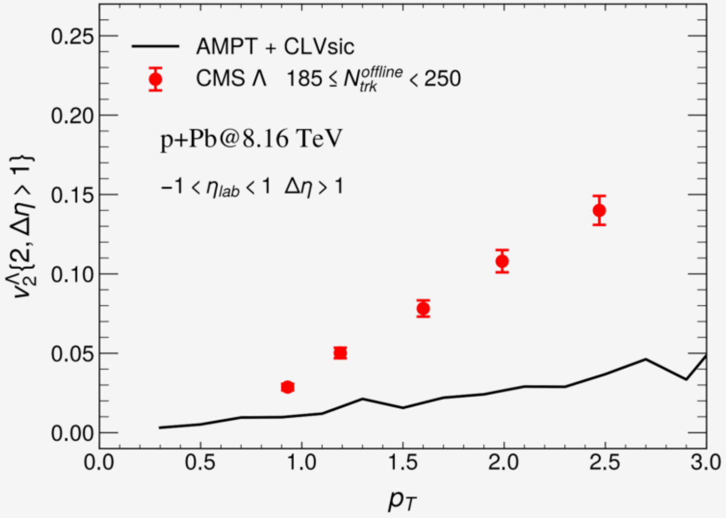
Without bulk viscosity

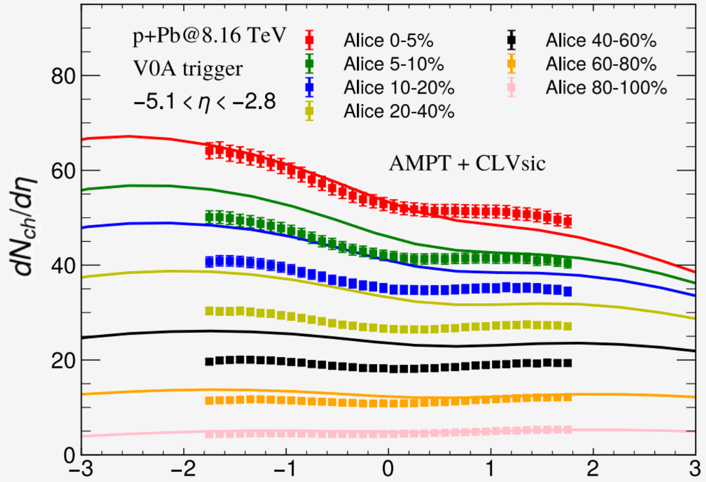




Test for AMPT initial conditions

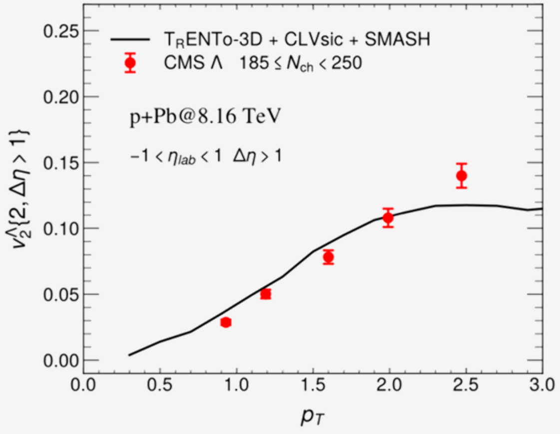


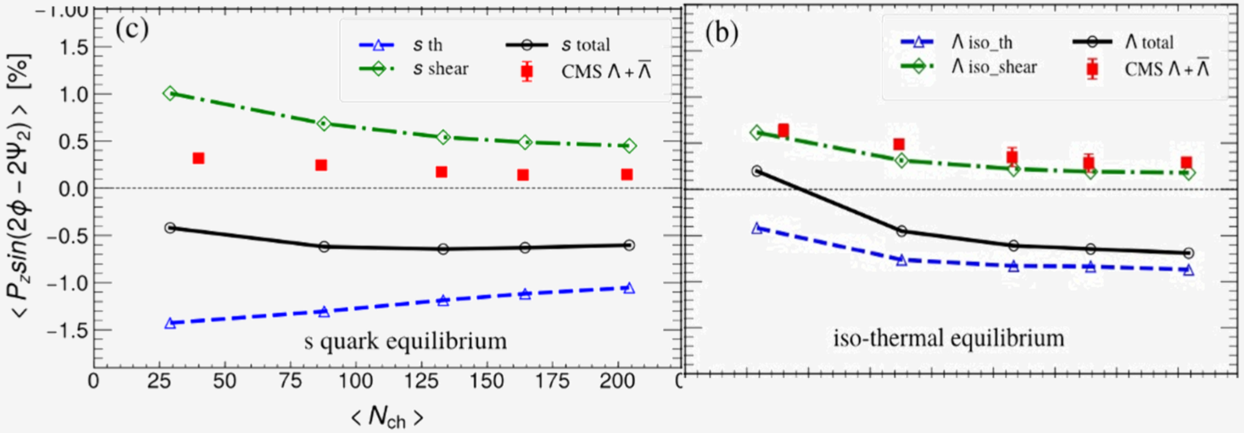




- ➢ **The parameters can describe spin polarization at the s quark equilibrium and iso-thermal equilibrium can not fit the multiplicity of charged particles and v2 of Λ.**

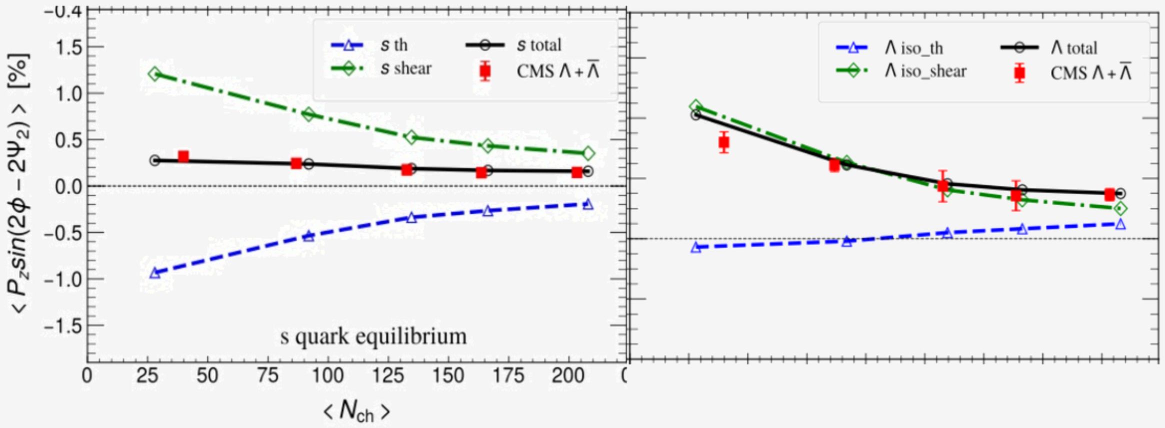
Different initial conditions

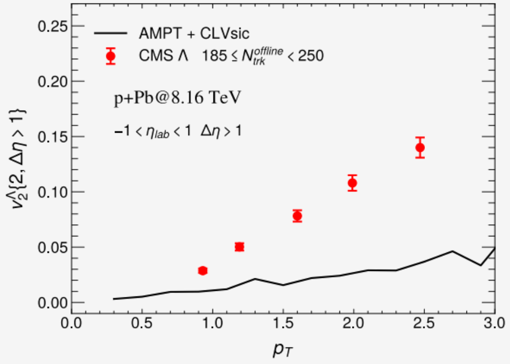




The P2z of Λ hyperons is not only induced by the v2 in the p+Pb collisions.

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





Outline

- Introduction
- Global and local polarization at AA systems
- Spin polarization at pA system
- **Summary**

Summary

➢ Spin Polarization in Au+Au collision

- ➢ The influence of these new effects on the global polarization is small.
- ➢ The turning energy for global polarization depends on the impact parameter.
- ➢ The (anomalous) 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 pPb collisions.

Thanks for your time !