Hydrodynamic effects on spin polarization in AA and pA collisions

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Based on: CY, et.al. in preparation
Phys. Rev. C 111 (2025) 4, 044901

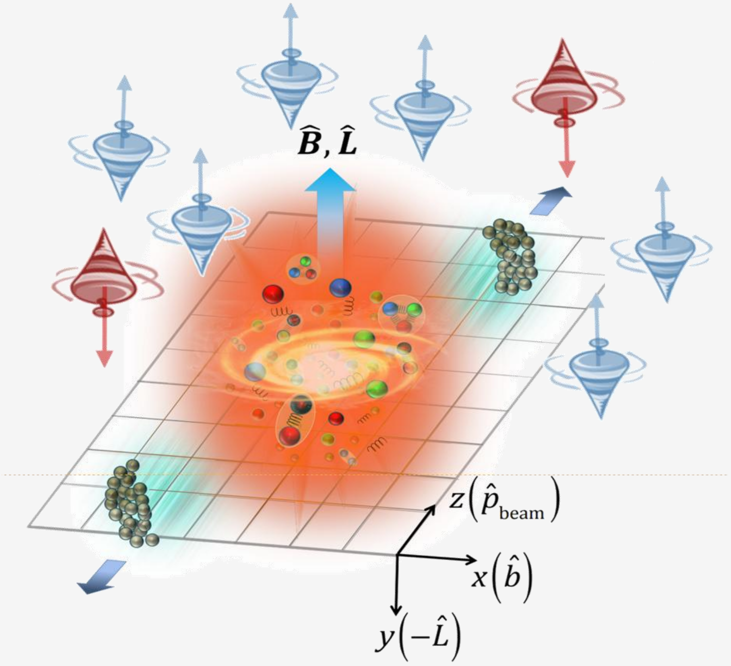
Outline

- **Introduction**
- Global polarization at a few GeV Au+Au collision
- Local Spin polarization at p+Pb collision
- Summary and Outlook

Global Spin Polarization

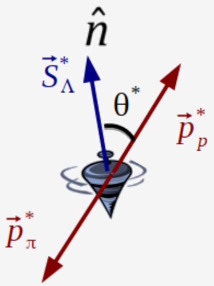
➤Spin-Orbital Coupling

STAR, Nature 548, 62 (2017).



Hyperons

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



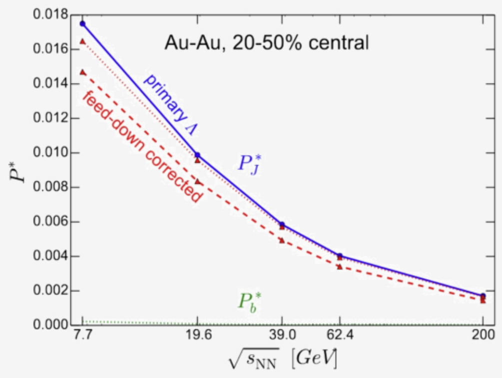
$$\Lambda \to p + \pi^-$$

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

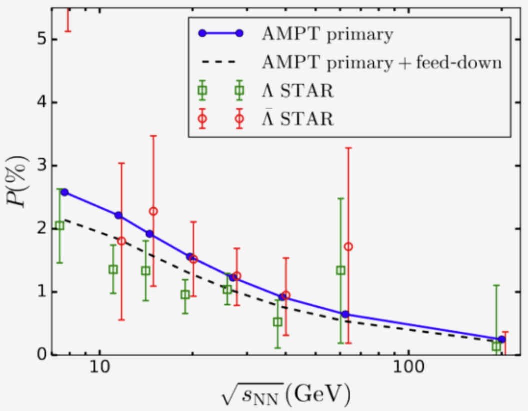
Liang, Wang, PRL. 94, 102301 (2005)
Liang, Wang, PLB 629, 20 (2005)
Becattini, Chandra, Zanna, and Grossi, Annals Phys. (2013).
Becattini and Karpenko, PRL 120, 012302

Most vortical fluid !

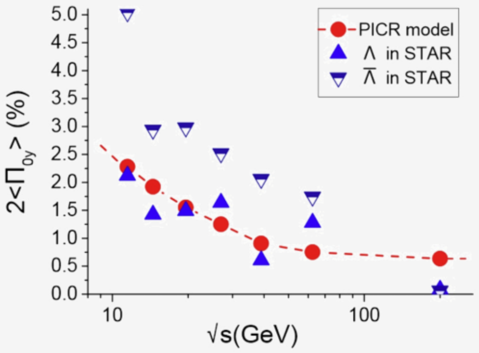
Phenomenological models for global polarization



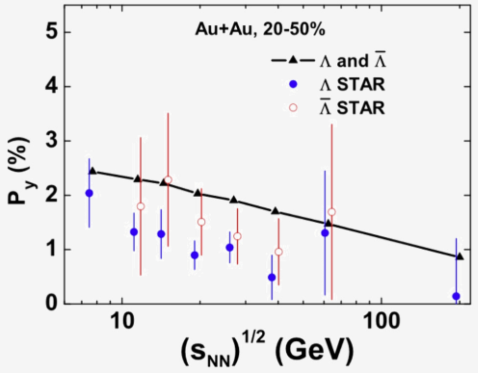
Karpenko, Becattini, EPJC(2017)



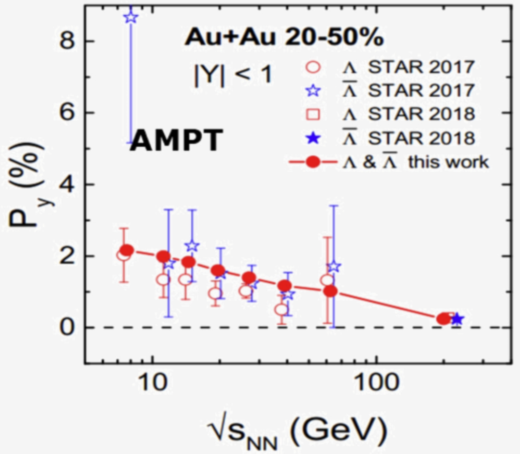
Li,Pang,Wang,Xia PRC(2017)



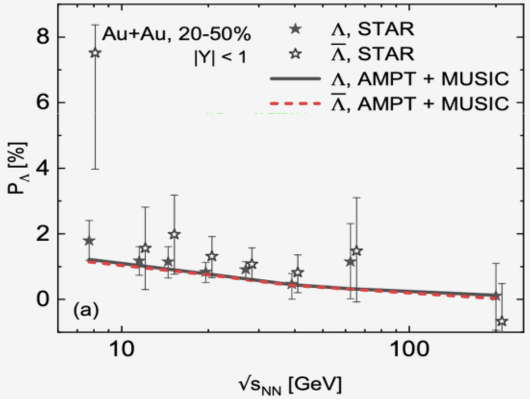
Xie, Wang, Csernai, PRC(2017)



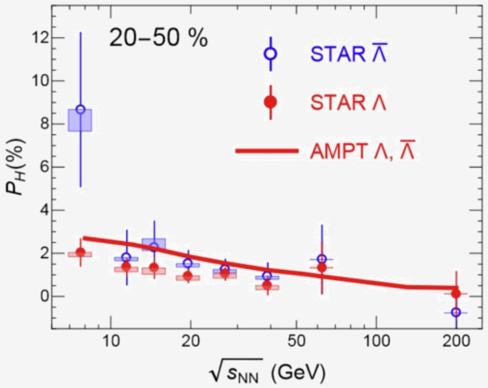
Sun, Ko, PRC(2017)



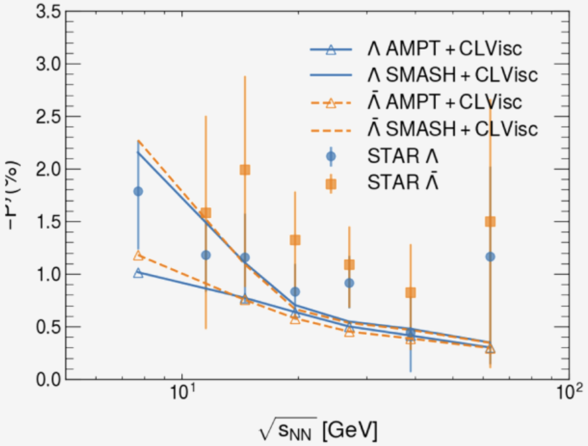
Wei, Deng, Huang, PRC(2019



Fu, Xu, Huang, Song, PRC (2021)

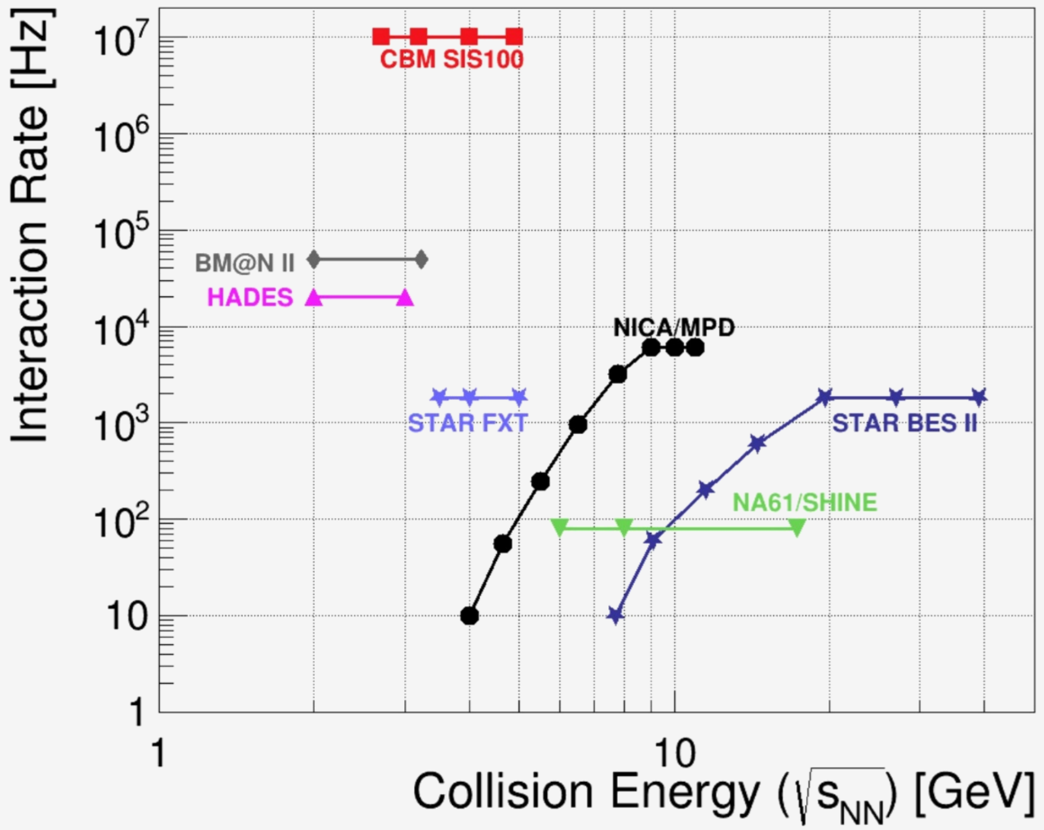


Shi, Li, Liao, PLB(2018)



Wu, CY, Qin, Pu, PRC(2022)

Experimental Facilities

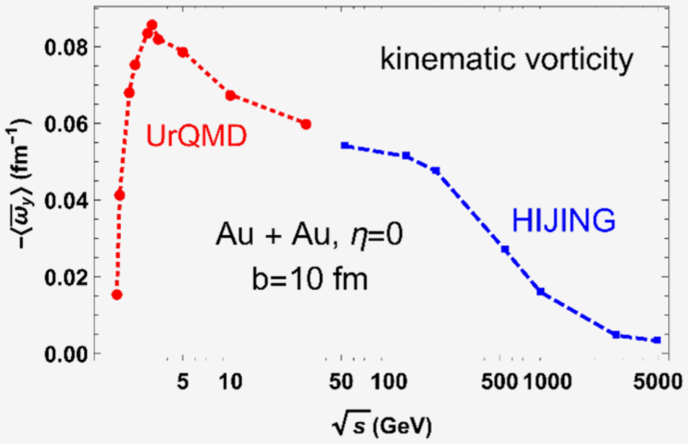


研究机构	加速器	建成时间	离子束 (GeV/u)	束流强度
IMP	HIAF	2025	$^{238}U^{35+}$ 0.8	1.0-2. 0×10^{11} ppp
			$^{238}U^{76+}$ 2.45	0.5-1.0×10^{11} ppp
			p 9.3	5×10^{13}
IMP	HIAF-U	2027 – 2032	$^{238}U^{35+}$ 2.95	2. 0×10^{12} ppp
			$^{238}U^{76+}$ 7.3	1.0×10^{12} ppp
			$^{238}U^{92+}$ 9.1	1.0×10^{12} ppp
			p 25.0	4.0×10^{14}
GSI	FAIR SIS100	2028	$^{238}U^{28+}$ 2.7	5×10^{11} ppp

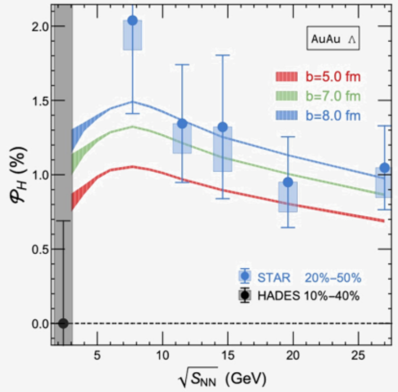
- **These new facilities will offer an opportunity to explore the behavior of global polarization at a few GeV.**

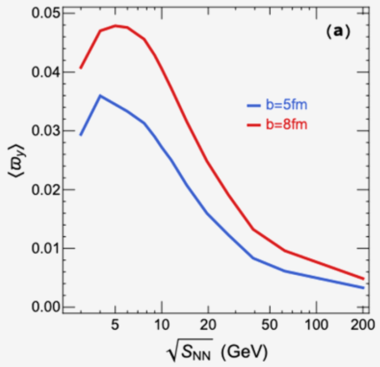
Global Polarization at a few GeV

➢ Theoretical prediction



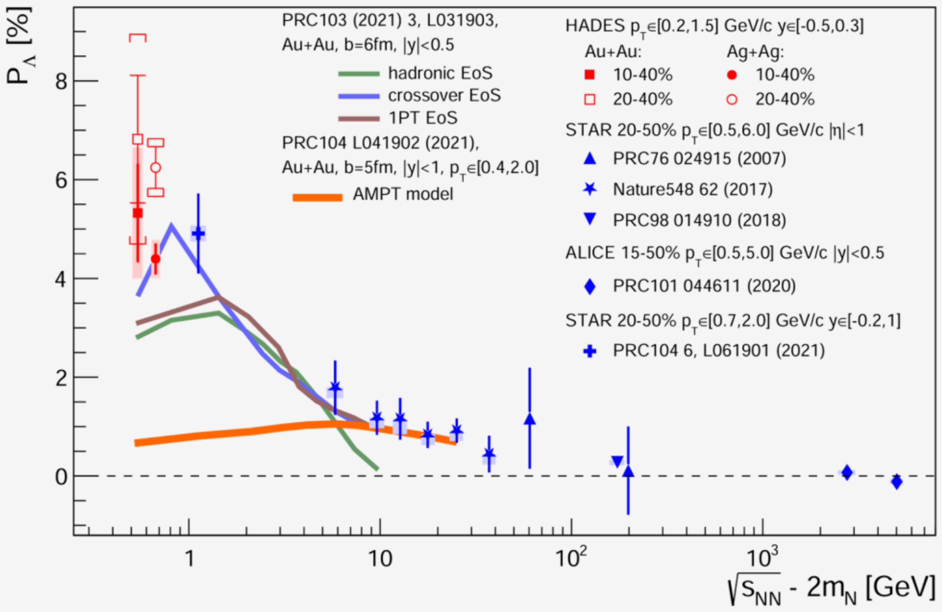
Deng, Huang PRC 2016, PRC 2020





Guo, Liao, et. al, PRC 2021

➢ Experimental results

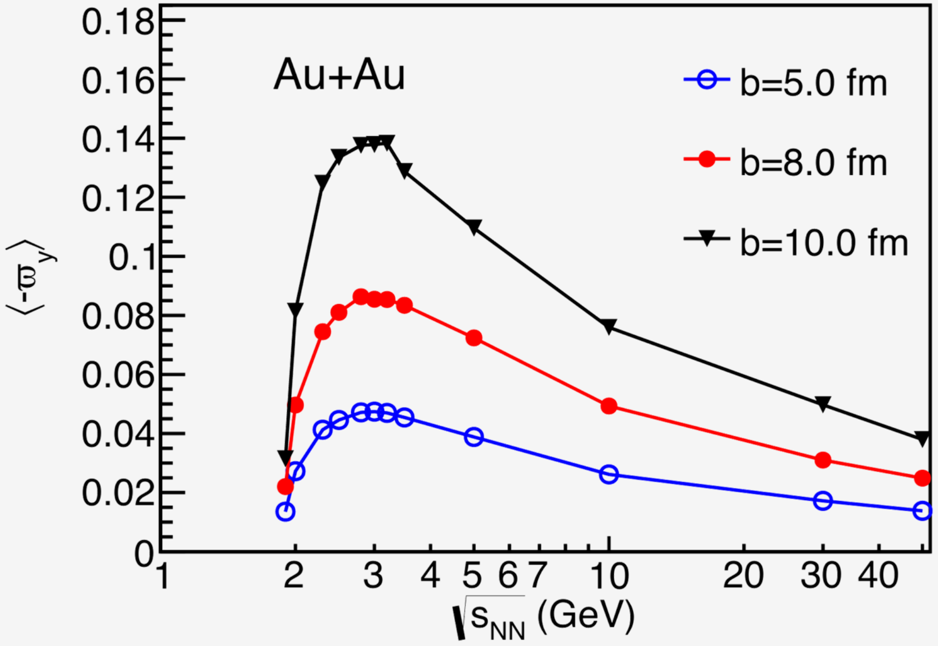


HADES, Phys.Lett.B (2022) 137506

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

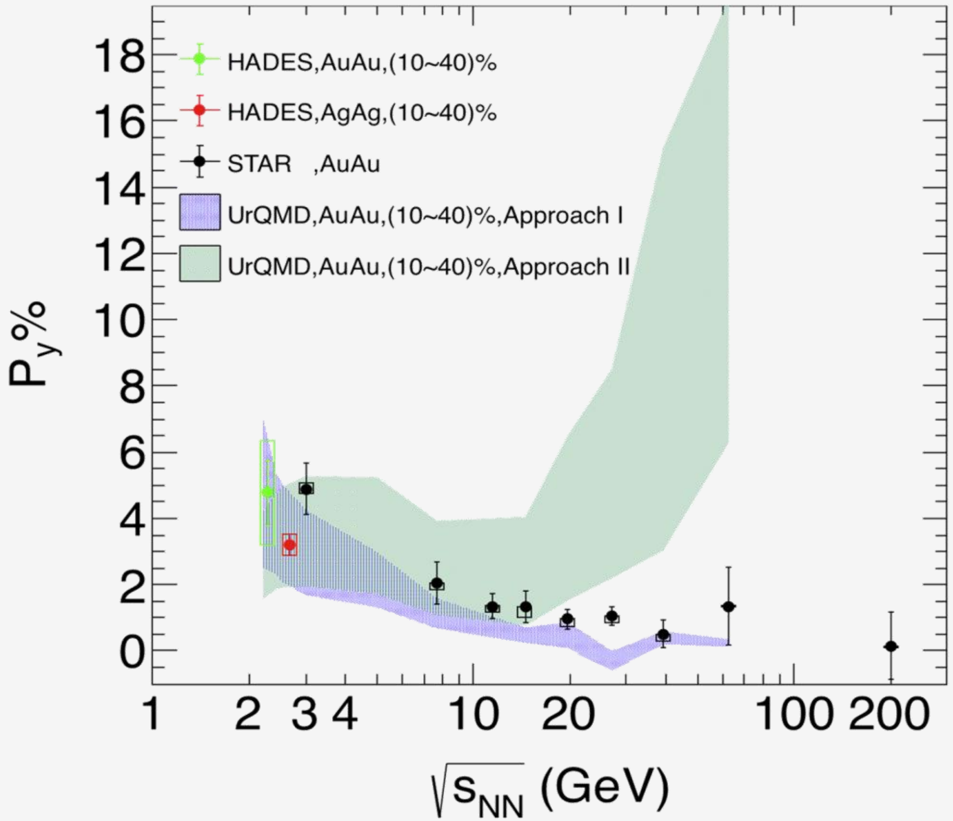
Global Polarization with URQMD

➢ Thermal vorticity



Deng, Huang, Ma, Zhang PRC 101 (2020) 6, 064908
Deng, Huang, Ma, Zhang PLB 835 (2022) 137560

➢ Polarization



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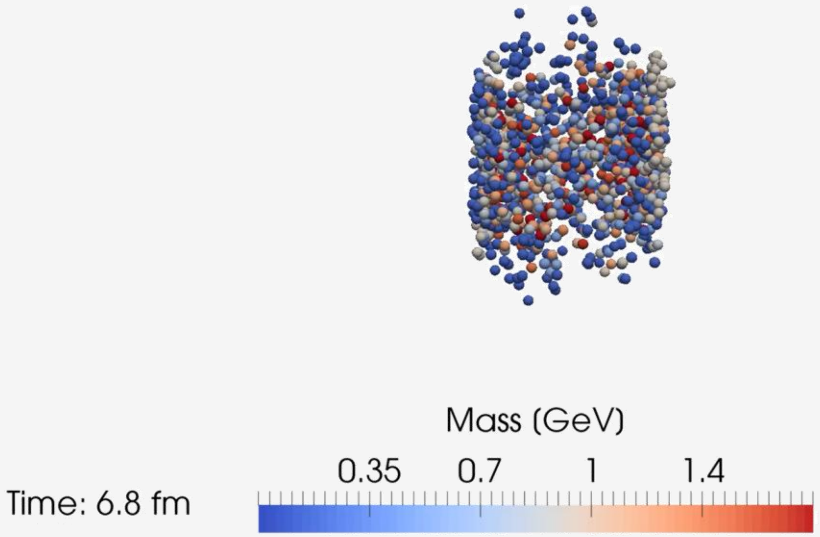
SMASH Model



SMASH, Phys. Rev. C 94 (2016) 5, 054905

➢ SMASH

➢ It solves the relativistic Boltzmann equation effectively.

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

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

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)

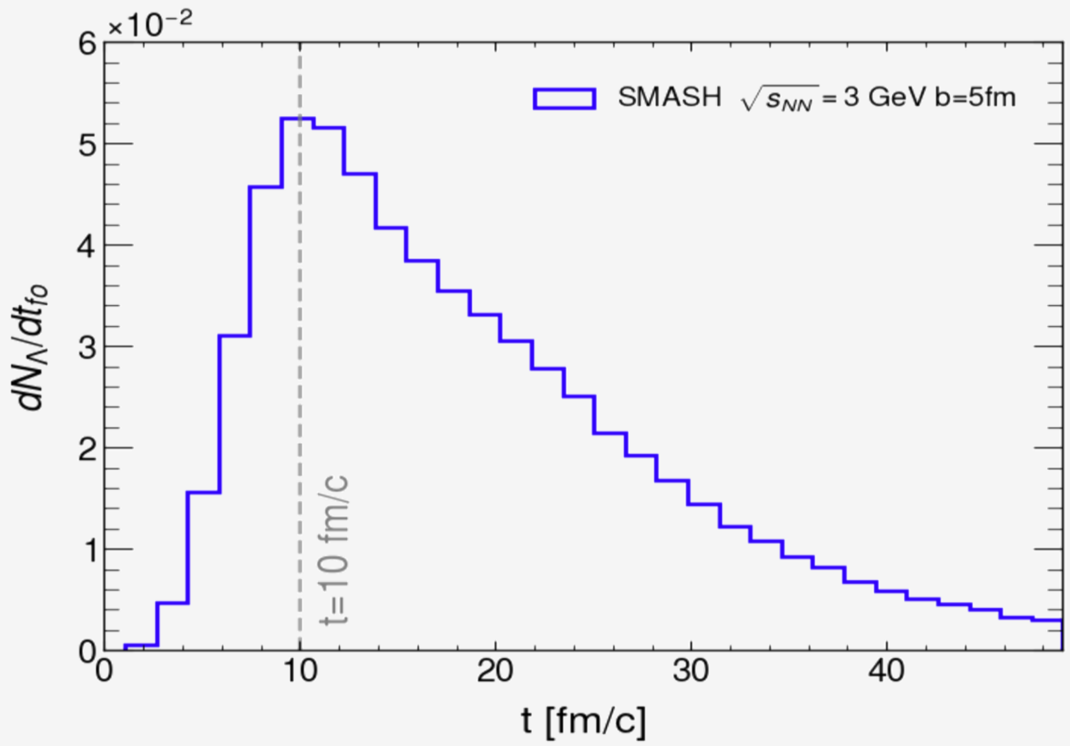
$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = \frac{\hbar}{4m_{\Lambda}N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_{\alpha}u_{\beta}E_{\nu}+\frac{B^{\mu}}{T}\right),$$

EM Field

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)

Thermalization Assumption

➢ Freeze-out time distribution



- Last interaction time mostly around t = 10fm/c
- We assume most of the lambda hyperons reach the local equilibrium at freeze-out
- Then we can calculate the spin polarization at lower energy by the modified Cooper-Frye formula

Thermal Vorticity

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

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

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

➢ Baryon density

$$J_B^\mu = \frac{1}{N_e \Delta V}\sum_i Q_i \frac{p_i^\mu}{E_i}$$

$$N_B = J_B^\mu u_\mu$$

➢ Global Polarization

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

Equation of State

➢ Hadron Resonance Gas

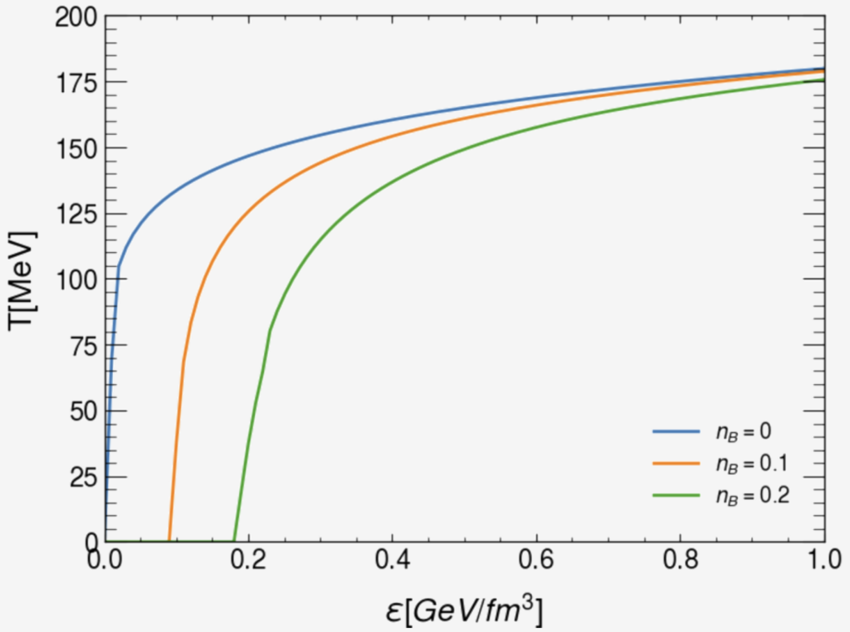
Grand canonical partition function

$$\ln Z_i^{id.gas} = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln\left[1 \pm \exp\left(-\left(E_i - \mu_i\right)/T\right)\right]$$

$$\begin{aligned} n_i &= \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \ \mathrm{d}p}{\exp\left[\left(E_i - \mu_i\right)/T\right] \pm 1} \\ \varepsilon_i &= \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \ \mathrm{d}p}{\exp\left[\left(E_i - \mu_i\right)/T\right] \pm 1} E_i \\ \mu_i &= b_i \mu_B + s_i \mu_S + q_i \mu_Q \end{aligned}$$

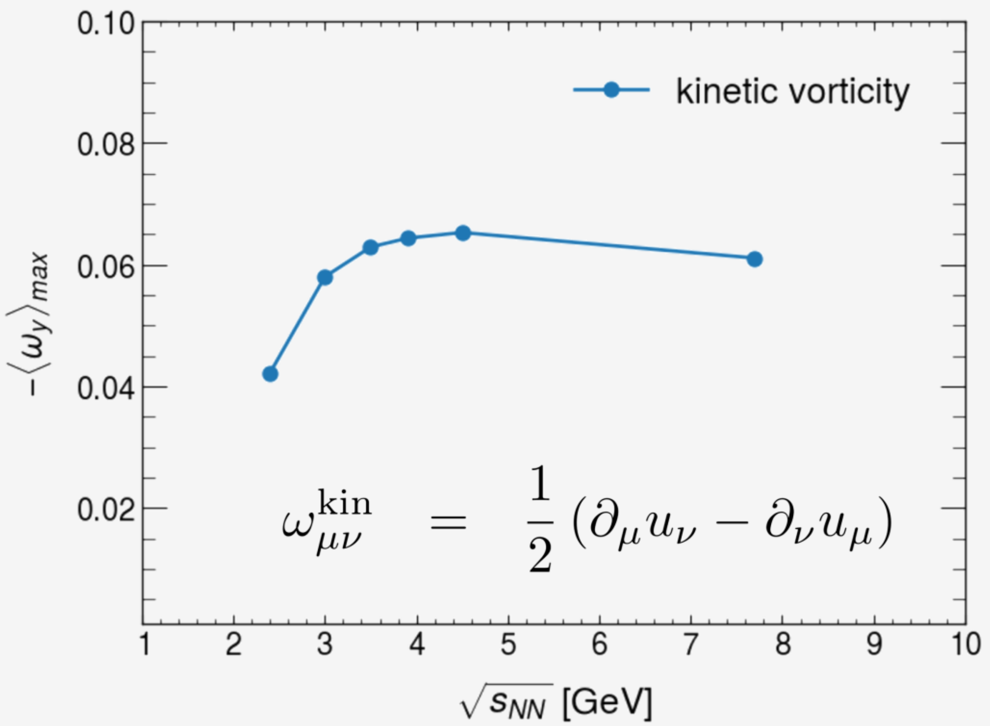
As the net baryon density increases, the extracted temperature at a given energy density will decrease.

$$\begin{aligned} n_B &= \sum_i n_i b_i \\ n_Q &= \sum_i n_i q_i \\ n_S &= \sum_i n_i s_i \\ n_Q &= 0.4 n_B, \quad n_S = 0 \end{aligned}$$

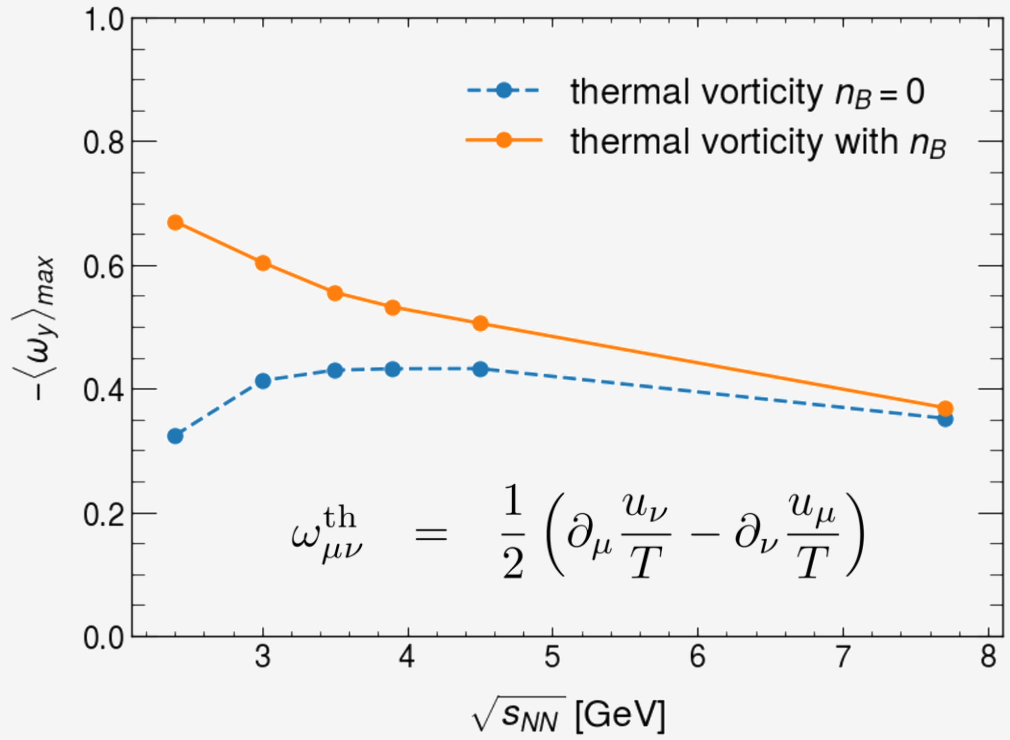


Vorticity Vs collision energy

➢ Kinetic vorticity



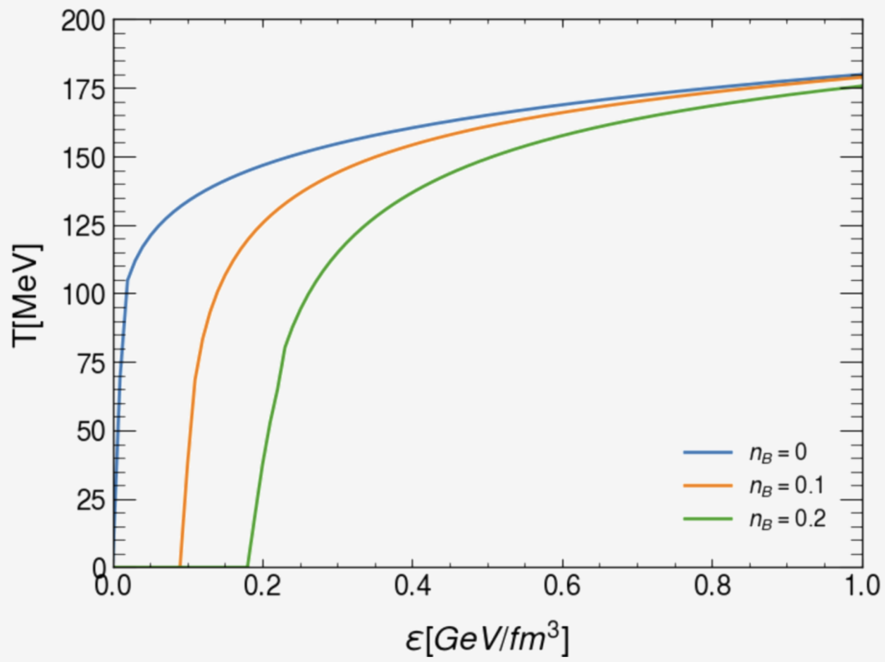
➢ Thermal vorticity



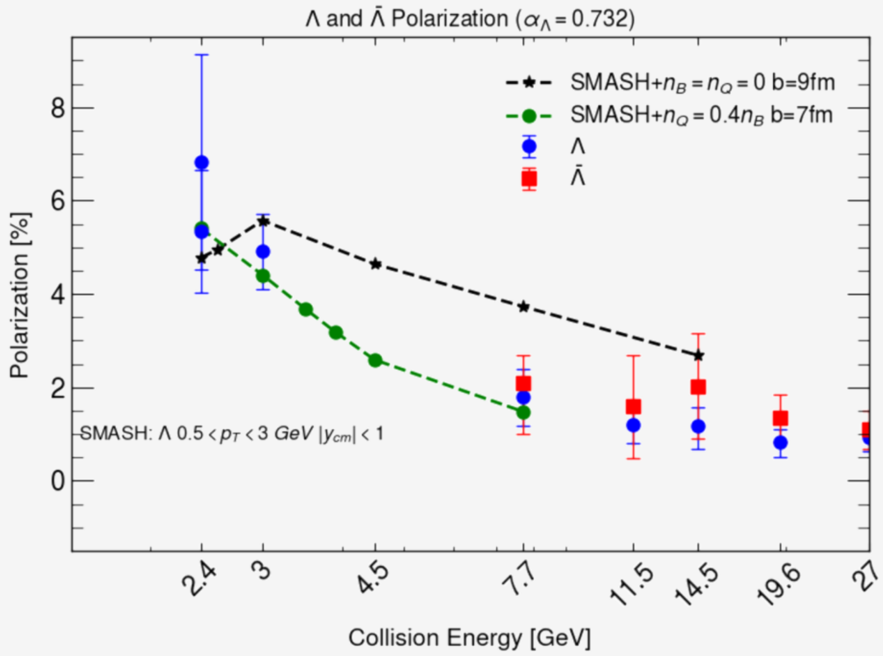
- **Kinetic vorticity peaks and then decreases as collision energy falls to a few GeV**
- **Including net baryon density leads to stronger thermal vorticity without a decrease at the energy is larger than 2.4 GeV ,unlike results that ignore baryon density**

Global Polarization at a few GeV

➢Equation of State



➢-Py Vs collision energy

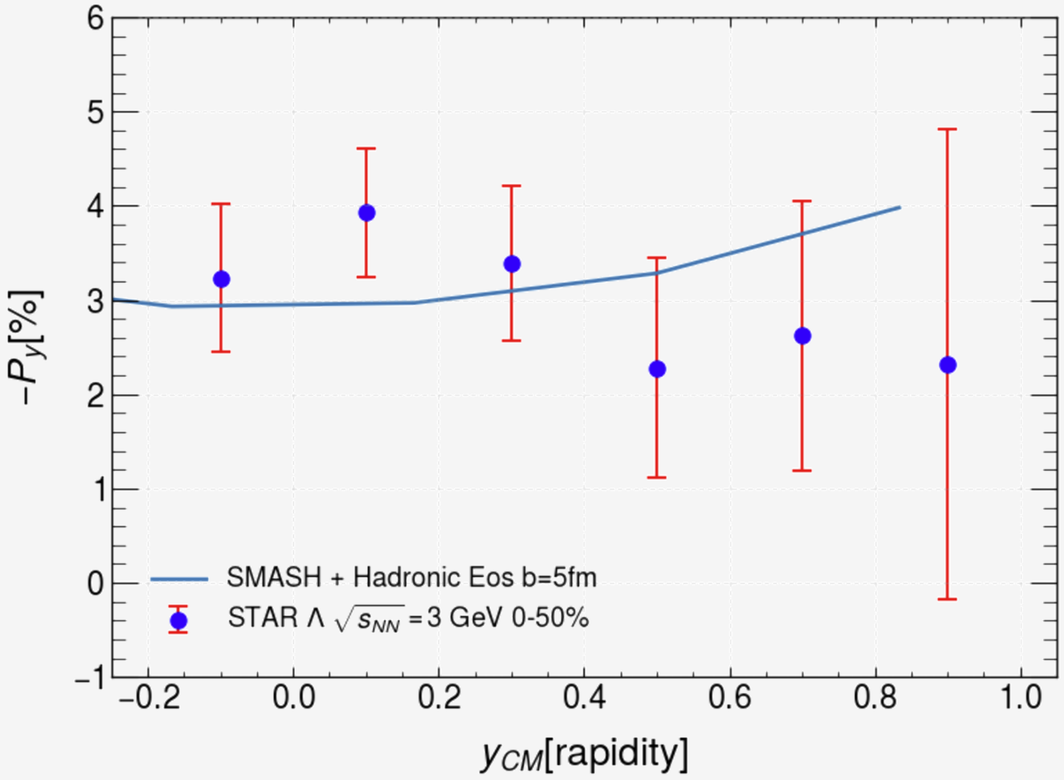


CY, et.al. (in preparation)

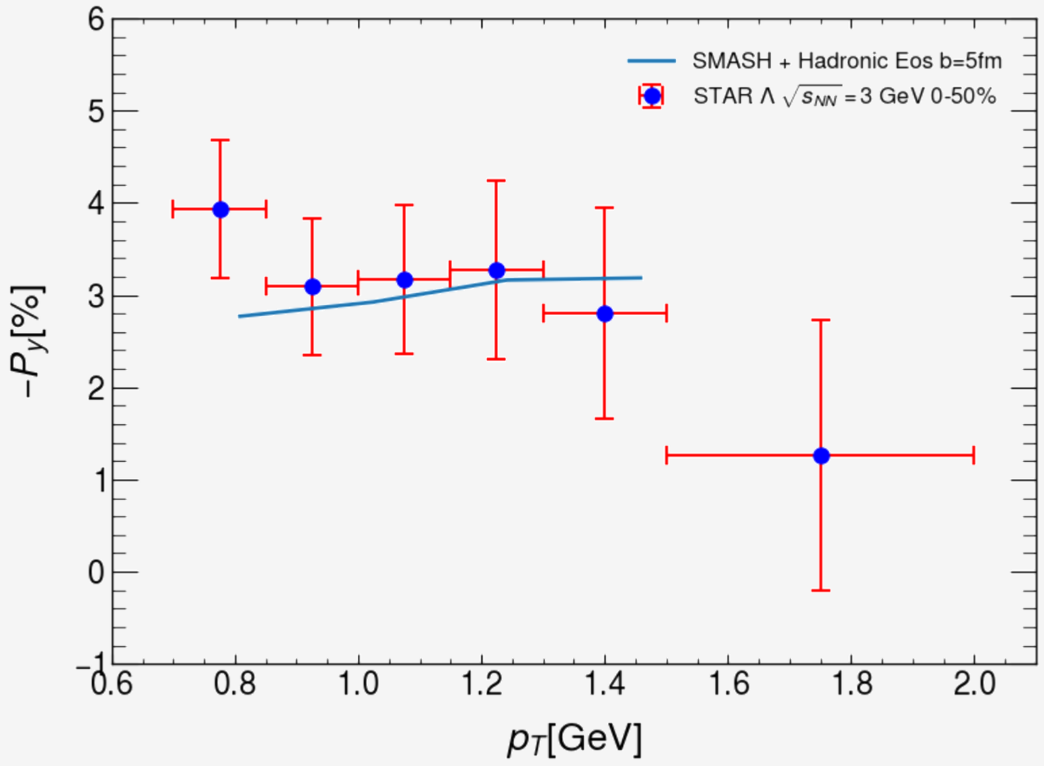
➢ **The behavior of spin polarization at low energies is sensitive to the baryonic density**

Global Polarization at 3 GeV

➢Rapidity dependence



➢pT dependence



- **Our results also have a good description of Global spin polarization at 3 GeV**

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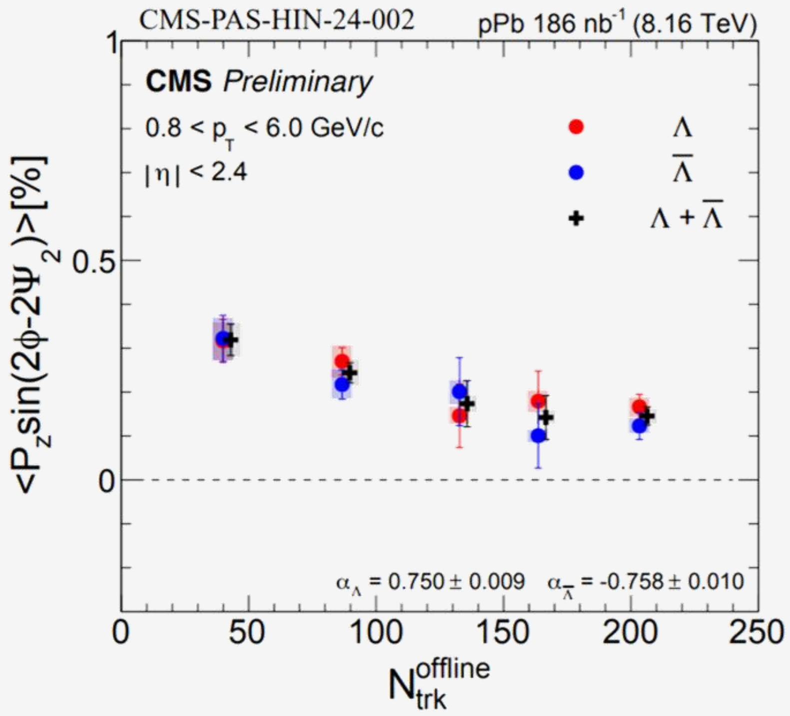
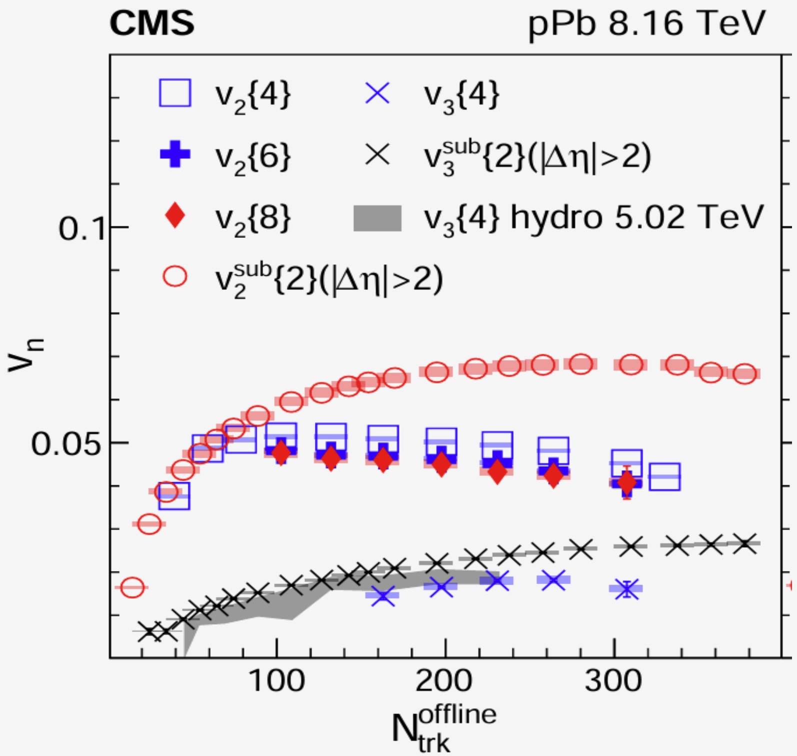
CMS Measurements

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



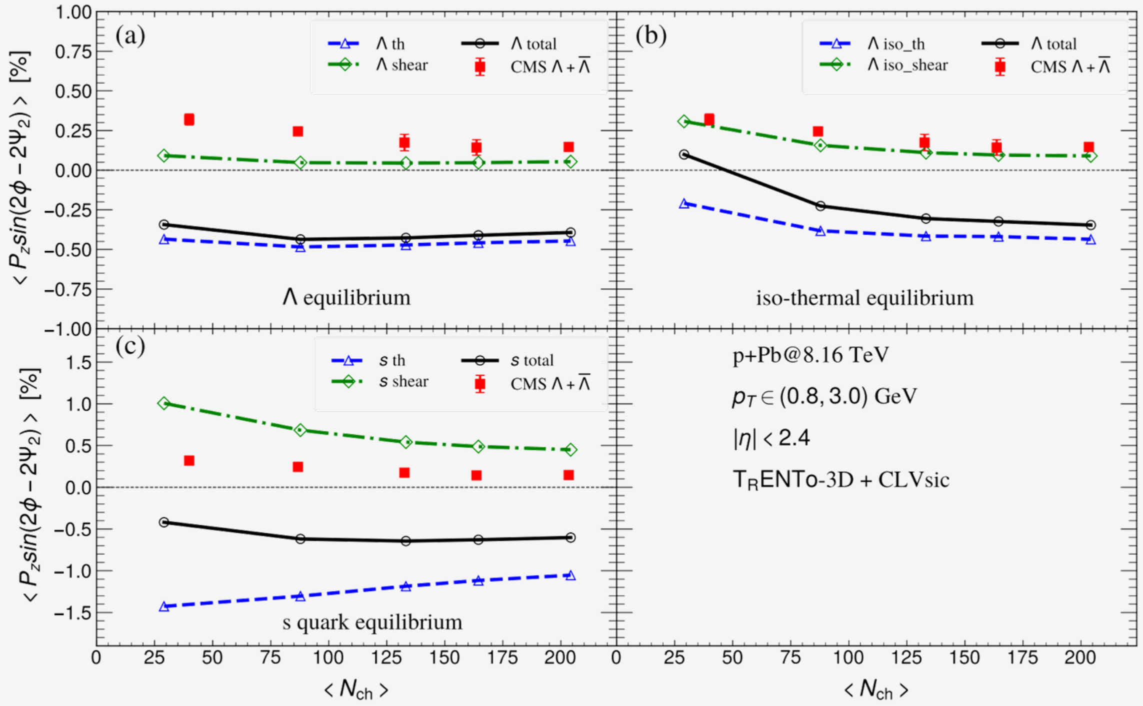
CMS, Phys.Rev.Lett. 135 (2025) 13, 132301



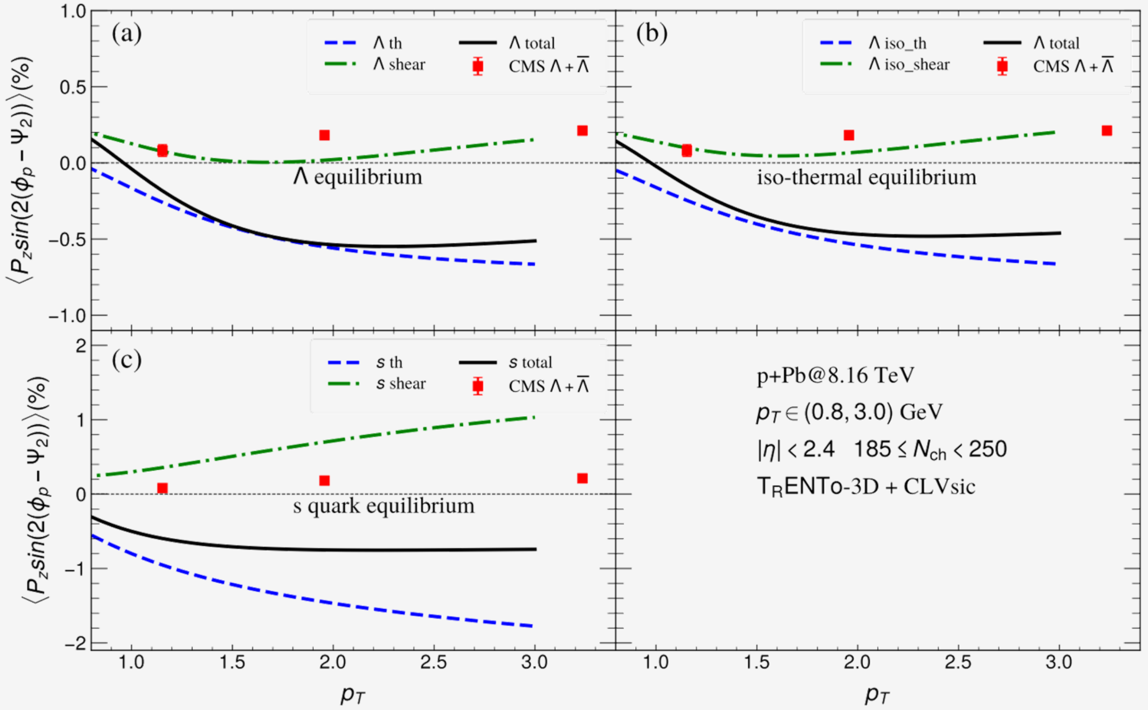
CMS,PRC,101, 014912 (2020)

- **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**

Multiplicity (centrality) dependence



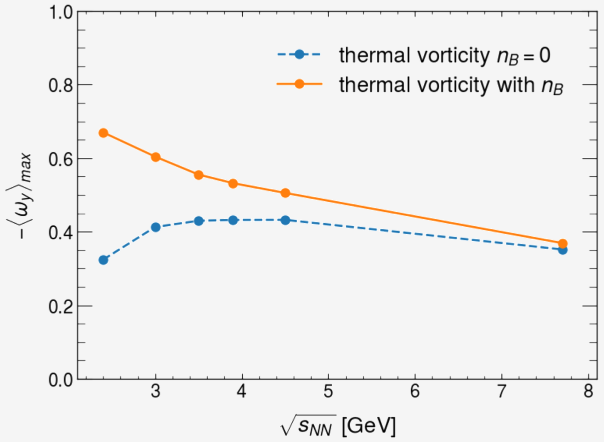
Multiplicity dependence

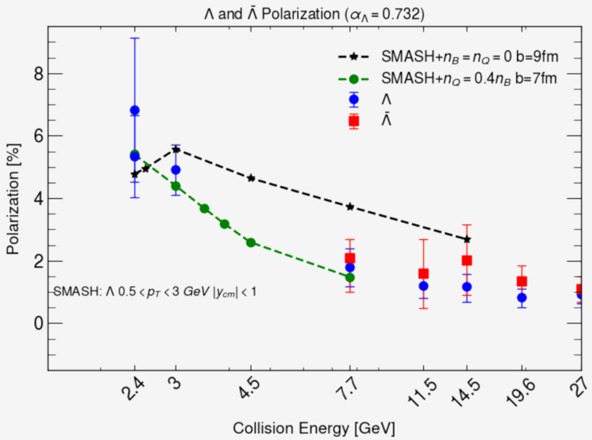


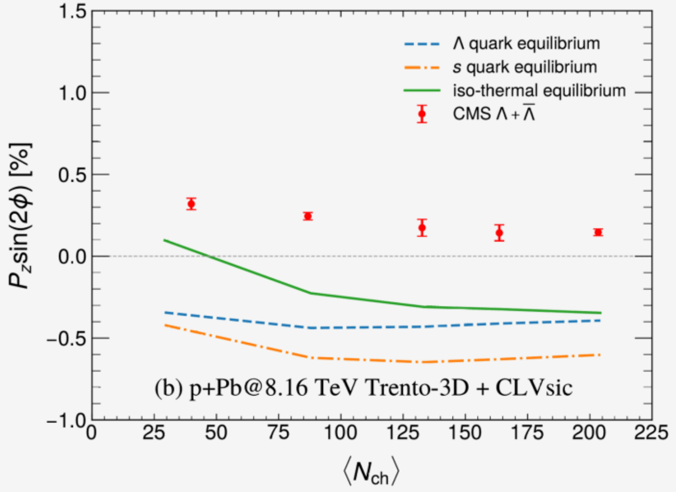
p_T dependence

- ➢ **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.**

Summary and Outlook







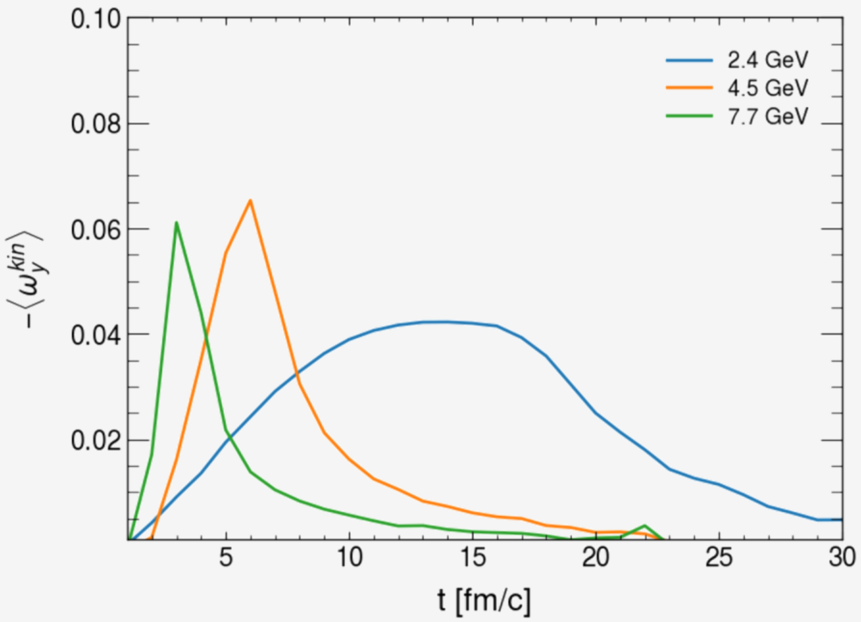
- The kinematic vorticity will peak at low energies.
- When finite net baryon density is included, both the thermal vorticity and the global spin polarization increase as the collision energy decreases down to 2.4 GeV.
- The behavior of global polarization at low energies is sensitive to the temperature extracted from the equation of state.
- The results from hydrodynamics are inconsistent with the data from CMS.

Thanks for your attention!

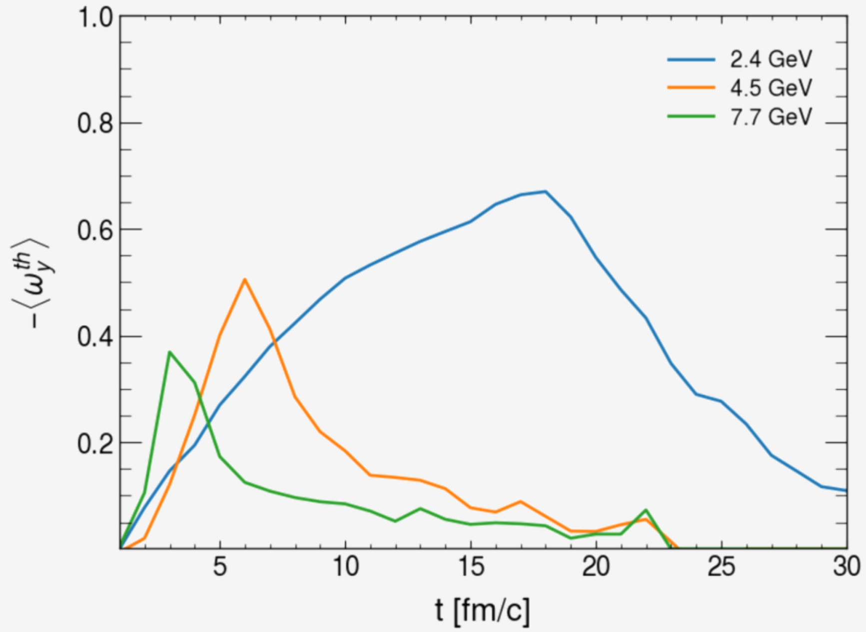
Back Up

Evolution of Vorticity

- **Kinetic Vorticity**



- **Thermal Vorticity**



- ➢ **Higher collision energies lead to faster vorticity deposition and decay.**
- ➢ **Kinetic vorticity: Peak value shows a non-monotonic dependence on decreasing collision energy.**
- ➢ **Thermal vorticity: For energies > 2.4 GeV, the peak value increases as collision energy decreases.**

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