Hyperon polarization and its correlation with directed flow in heavy ion collisions

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Based on [arXiv:2307.04257]() and [Phys. Rev. C 107, 034904 (2023)]()

outline

1. Introduction

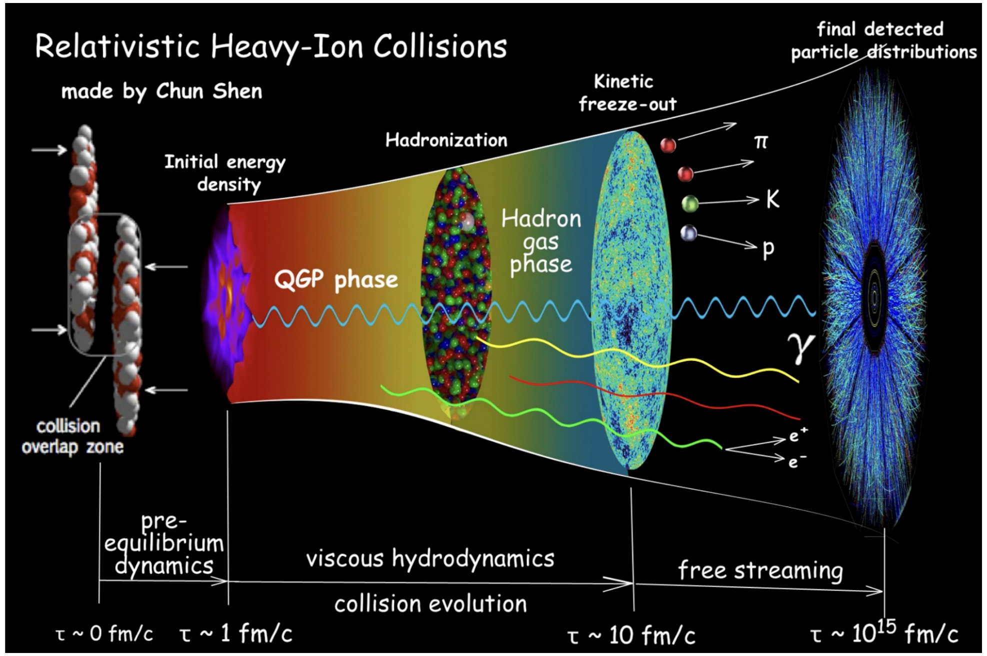
2. Theory framework

- tilted initial condition
- (3+1)-D hydrodynamic CLVisc
- spin polarization

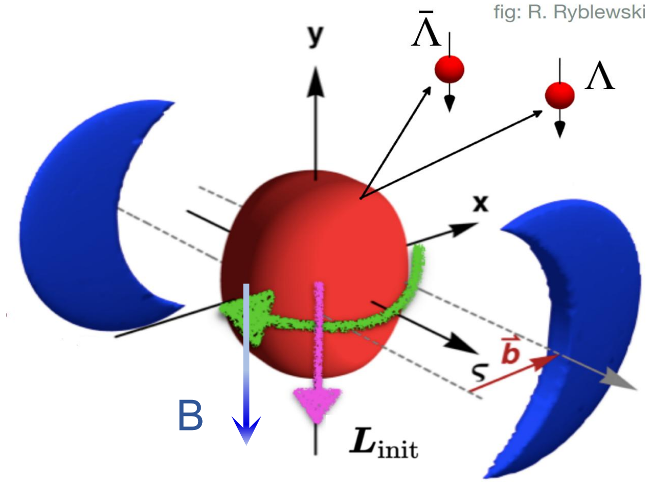
3. Numerical results

4. Summary

Introduction



" Standard Model " of heavy ion collision



...the hottest, least viscous – and most votrical-fluid produced in the laboratory...

Introduction: global polarization

Using screened potential model to calculate the global quark polarization

Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94 (2005) 102301

Λ and $\overline{\Lambda}$ hyperons are “self-analysing”, $\Lambda \rightarrow p + \pi$,
the proton tends to be emitted along the spin direction of the parent hyperons

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{\mathrm{H}}\left|\mathscr{P}_{\mathrm{H}}\right|\cos\theta^*\right)$$

θ^*: the angle between proton momentum

And Λ polarization vector $\mathscr{P}_{\mathrm{H}}$

α_{H}: the decay parameter

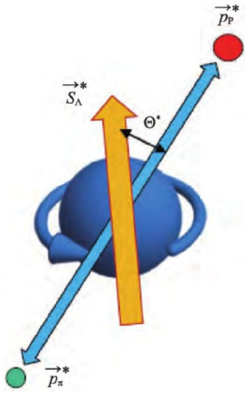
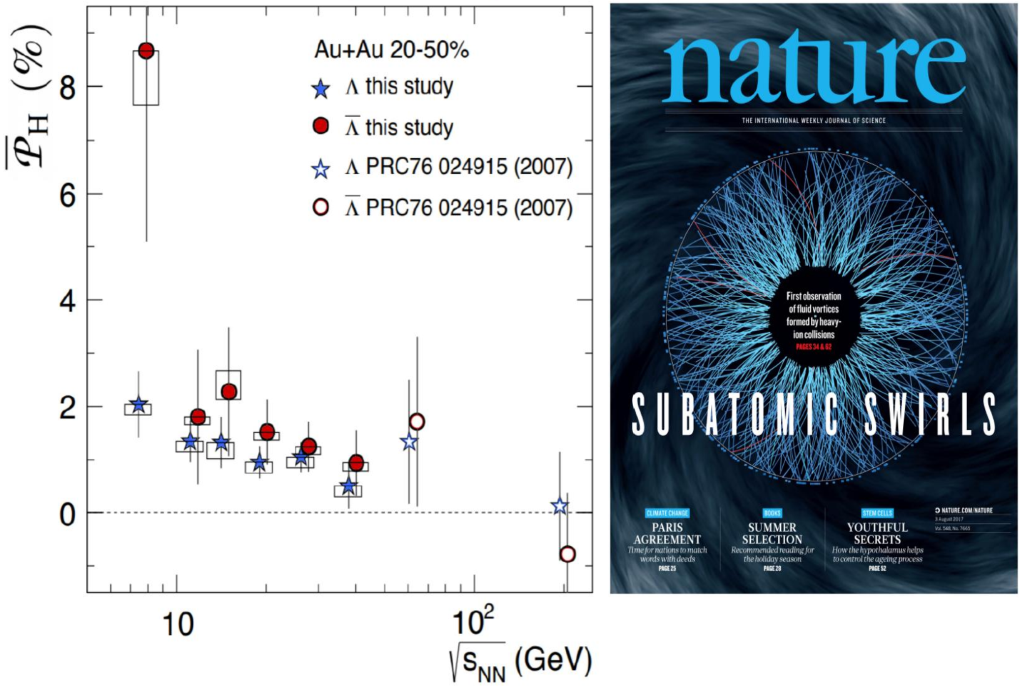


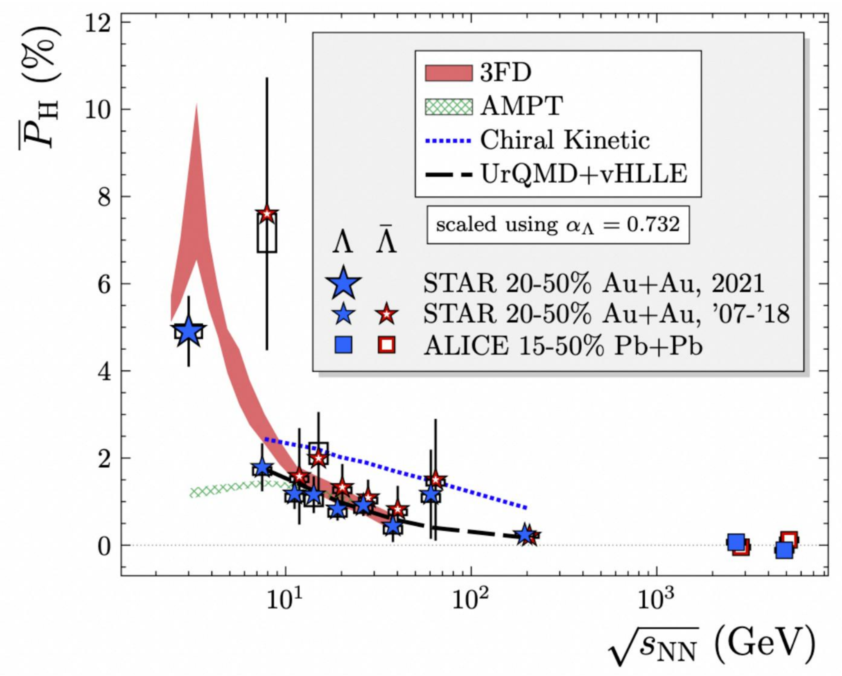
fig: L. Adamczyk et al. (STAR) (2017), Nature 548 (2017) 62-65

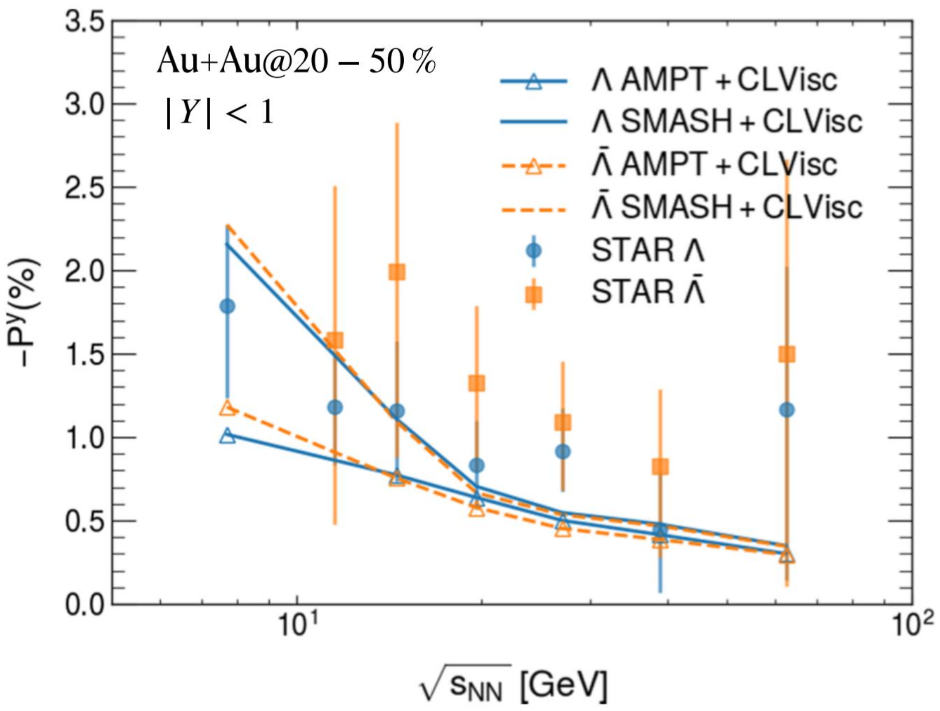


$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 0.6 - 2.7 \times 10^{22}\ \mathrm{s}^{-1}$$

Introduction: global polarization

Fig: CLVisc 2.0, Xiangyu Wu





- Hydrodynamic model and transport model reproduce the global polarization of Λ hyperons above 7.7 GeV
- The global polarization is sensitive to the initial state of the system

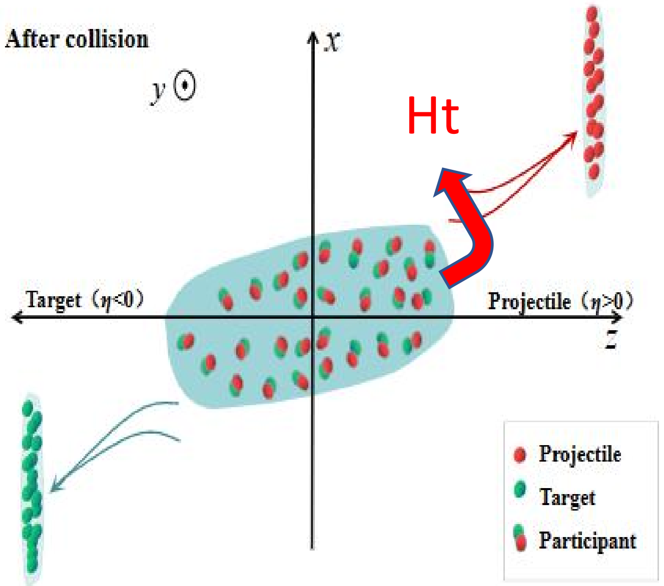
Initial condition: longitudianl tilted geometry of QGP

Jiang, Wu, Cao, Zhang, Phys. Rev. C 107, 034904 (2023)

Based on the results of directed flow, a counter-clockwise tilted of the medium profile is expected *in the reaction plane*

$$W_{\mathrm{N}}(x,y,\eta_{\mathrm{s}}) = T_1(x,y) + T_2(x,y) + \boxed{H_{\mathrm{t}}}[T_1(x,y) - T_2(x,y)]\tan\left(\frac{\eta_{\mathrm{s}}}{\eta_{\mathrm{t}}}\right)$$

A larger value of Ht gives a more tilted fireball in the reaction plane.



The total weight function: $$W(x,y,\eta_s) = \frac{(1-\alpha)W_{\mathrm{N}}(x,y,\eta_s) + \alpha n_{\mathrm{BC}}(x,y)}{[(1-\alpha)W_{\mathrm{N}}(0,0,0) + \alpha n_{\mathrm{BC}}(0,0)]|_{\mathbf{b}=0}}$$

The initial energy density $$\varepsilon_0(x,y,\eta_s) = K \cdot W(x,y,\eta_s) \cdot H(\eta_s)$$

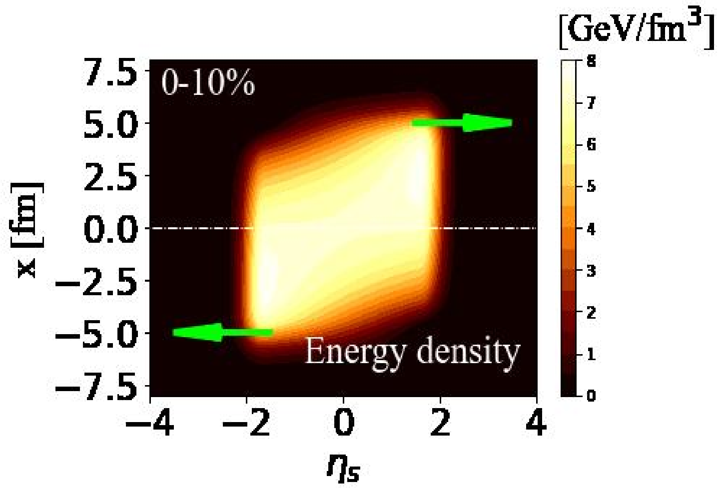
The initial local baryon density: $$n(x,y,\eta_s) = \frac{1}{N} W(x,y,\eta_s) H(\eta_s) H_B(\eta_s)$$

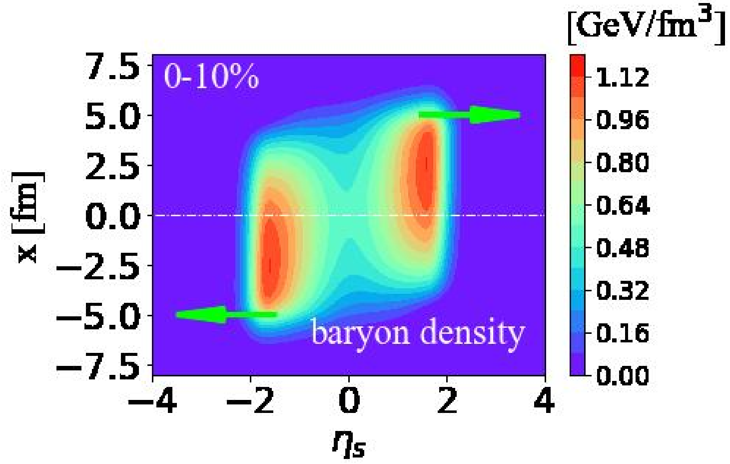
Initial condition: initial fluid velocity field

Ryu, Jupic, Shen, Phys. Rev. C 104 (2021) 5, 054908

At the initial proper time τ_0, the initial energy-momentum tensor components are:

$$\begin{cases} T^{\tau\eta_s} = \frac{1}{\tau_0}\varepsilon_0(x,y,\eta_s)\sinh(y_L) \\ T^{\tau\tau} = \varepsilon_0(x,y,\eta_s)\cosh(y_L) \\ y_L \equiv \boxed{f_v} y_{CM} \\ y_{CM} = \mathrm{arctanh}\left[\frac{T_1 - T_2}{T_1 + T_2}\tanh(y_{beam})\right] \end{cases}$$





This $f_v \in [0,1]$ parameter allows one to vary the magnitude of the longitudinal flow velocity gradient.

The transverse expansion is ignored: $T^{\tau x} = T^{\tau y} = 0$ at $\tau = \tau_0$.

Au+Au @ 27 GeV

Hydrodynamic evolution: (3+1)-D CLVisc

Wu, Qin, Pang, Wang, Phys. Rev. C 105 (2022) 3, 034909

Energy-momentum conservation and net baryon current conservation:

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

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

Equation of motion of dissipative current:

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

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

The shear viscosity: $\eta = C_\eta \dfrac{e+p}{T}$

The baryon diffusion: $\kappa_B = \dfrac{C_B}{T} n \left(\dfrac{1}{3}\cot\left(\dfrac{\mu_B}{T}\right) - \dfrac{nT}{e+P}\right)$

Equation of state: NEOS-BQS

Spin polarization

Yi, Pu, Yang, Phys. Rev. C 104 (2021) 6, 064901

The polarization pseudo vector for spin $\frac{1}{2}$ particles

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

axial charge current density

fermions number density

For massless fermions, S(p) can be decomposed into different sources

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

Spin polarization

Yi, Pu, Yang, Phys. Rev. C 104 (2021) 6, 064901

$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \epsilon^{\mu\nu\alpha\beta} p_{\nu} \partial_{\alpha} \frac{u_{\beta}}{T}$$

Thermal vorticity

$$\mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\beta}}{(u\cdot p)T} p^{\rho} (\partial_{\rho} u_{\alpha} + \partial_{\alpha} u_{\rho} - u_{\rho} D u_{\alpha})$$

Shear viscous tensor

$$\mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) = -\int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\alpha}}{T} \left(D u_{\beta} - \frac{\partial_{\beta} T}{T} \right)$$

Fluid acceleration

$$\mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) = 2 \int d\Sigma^{\sigma} F_{\sigma} \frac{1}{(u\cdot p)} \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \partial_{\nu} \frac{\mu}{T}$$

Gradient of chemical potential

$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = 2 \int d\Sigma^{\sigma} F_{\sigma} \left[\frac{\epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} E_{\nu}}{(u\cdot p)T} + \frac{B^{\mu}}{T} \right]$$

Electromagnetic Fields

Here,

$$F^{\mu} = \frac{\hbar}{8 m_{\Lambda} \Phi(\mathbf{p})} p^{\mu} f_{\text{eq}} (1 - f_{\text{eq}})$$

$$\Phi(\mathbf{p}) = \int d\Sigma^{\mu} p_{\mu} f_{\text{eq}}.$$

Spin polarization

Wu, Yi, Qin, Pu, Phys.Rev.C 105 (2022) 6, 064909

The polarization vector of Λ and $\overline{\Lambda}$ hyperons in its rest frame can be constructed as

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

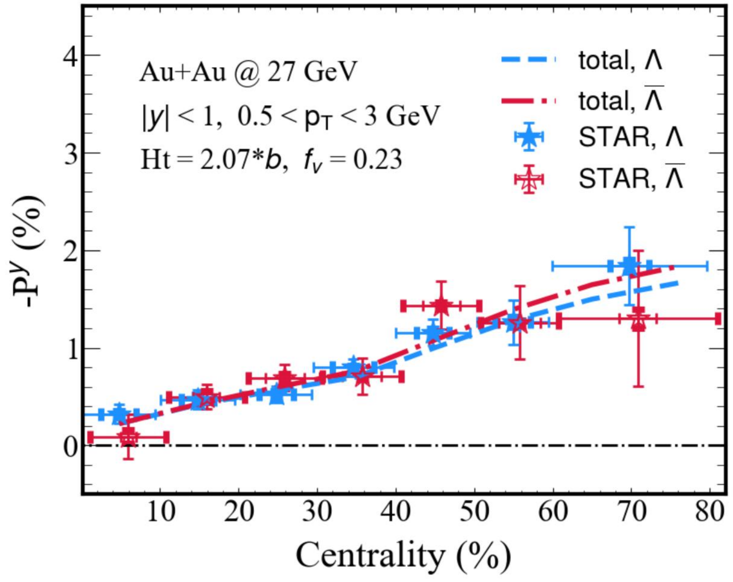
Here, $s = \frac{1}{2}$ is the spin of the particle.

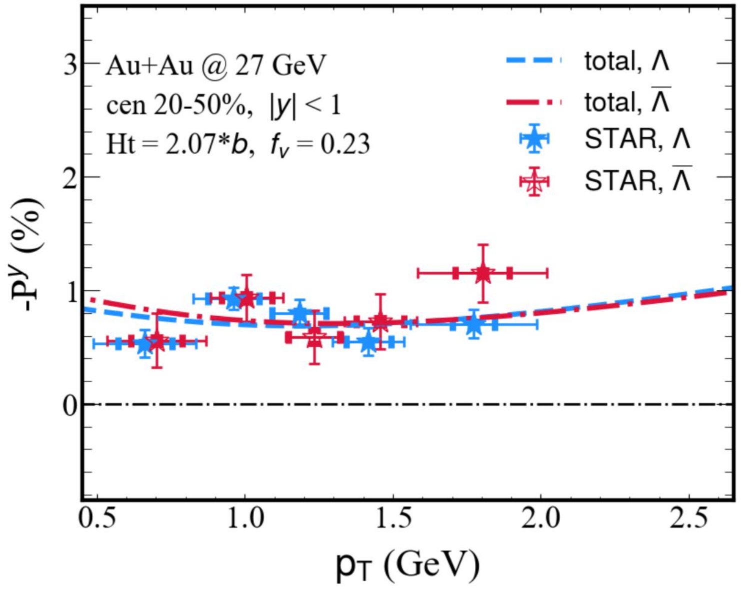
Finally, the local polarization is given by averaging over the momentum and rapidity:

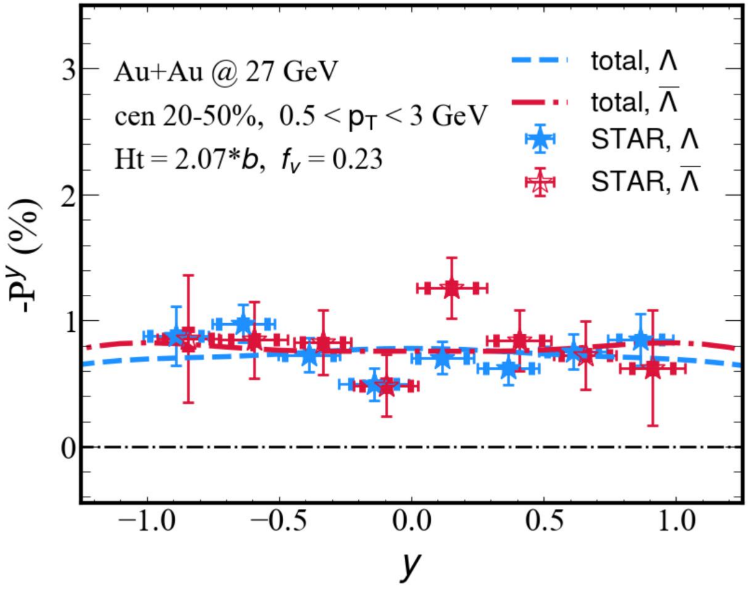
$$\langle \vec{P}(\phi_p) \rangle = \frac{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{\mathrm{T}\min}}^{p_{\mathrm{T}\max}} p_{\mathrm{T}} dp_{\mathrm{T}} [\Phi(\mathbf{p}) \vec{P}^*(\mathbf{p})]}{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{\mathrm{T}\min}}^{p_{\mathrm{T}\max}} p_{\mathrm{T}} dp_{\mathrm{T}} \Phi(\mathbf{p})}$$

Global polarization @ 27 GeV

STAR, arXiv: 2305.08705

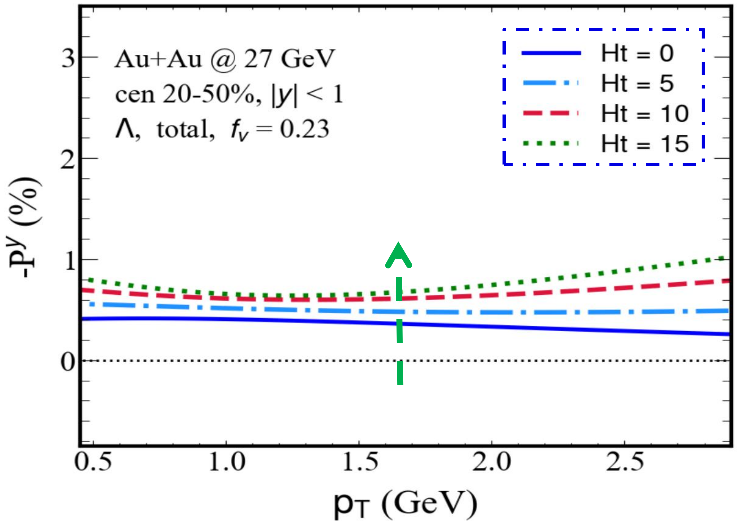


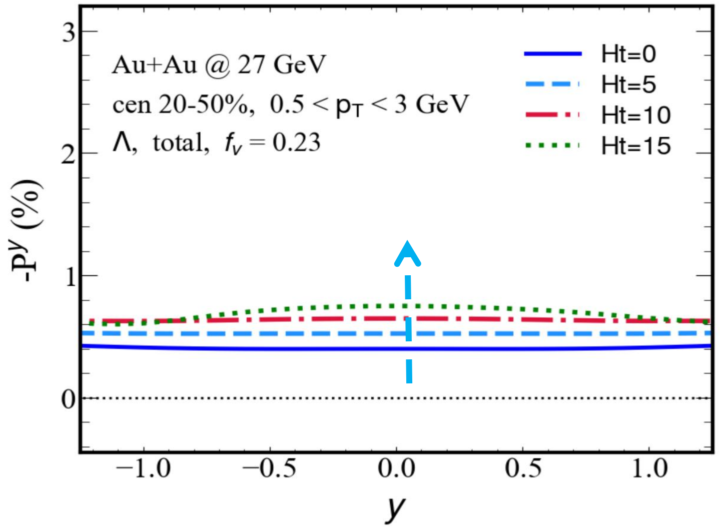




- Modified optical Glauber model coupled with CLVisc reproduce the STAR data.
- Total = thermal + shear + accT + Chemical

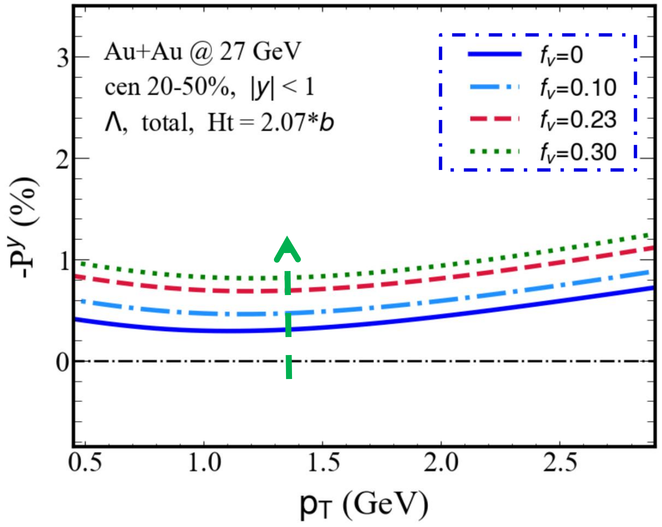
Global polarization (effects of the tilted geometry)

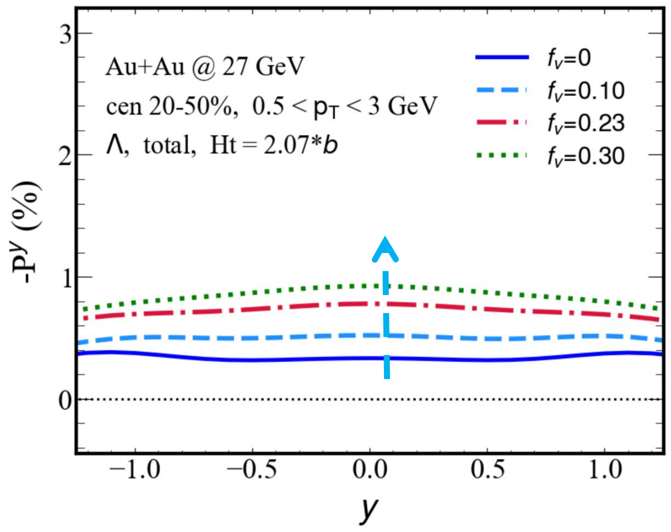




- The magnitude of P^y is amplified with increasing Ht from 0 to 15.
- A non-monotonic behavior of polarization with respect to p_T appears when Ht is large.

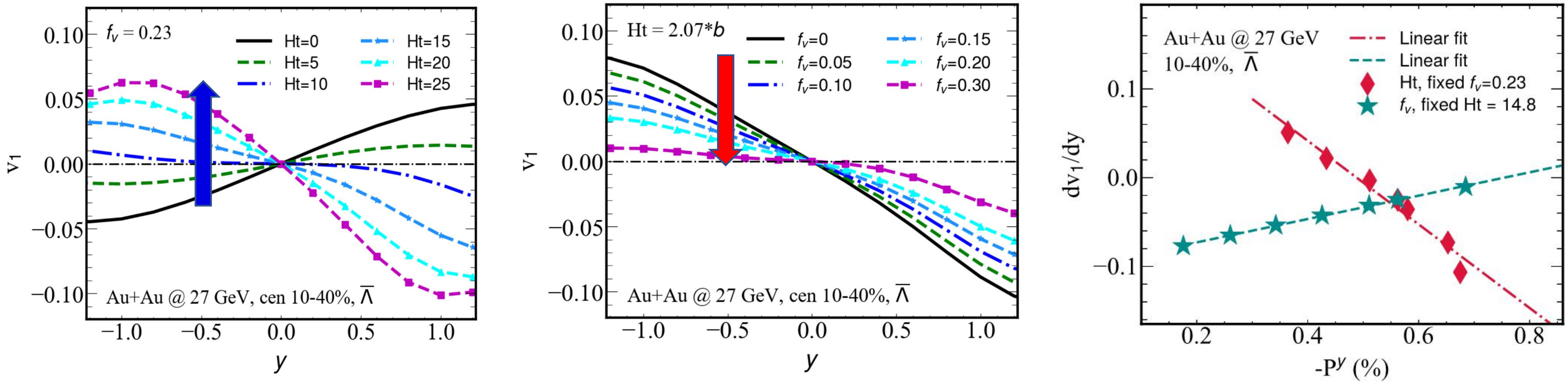
Global polarization (effects of longitudinal flow)





- The stronger longitudinal velocity gradient (or larger f_v) leads to a larger magnitude of the global vorticity and therefore the global polarization of hyperons.

Correlation between the global polarization and the directed flow



- When f_v is fixed, increasing Ht increases $-P^y$ but decreases dv_1/dy , resulting in an anti-correlation.
- When Ht is fixed, increasing f_v increases dv_1/dy and $-P^y$, resulting in a positive correlation.

Summary

- We discuss the effects of tilted geometry and initial longitudinal flow of the QGP on the hyperons polarization.
- We propose a possible correlation between hyperon polarization and directed flow.

Thank you

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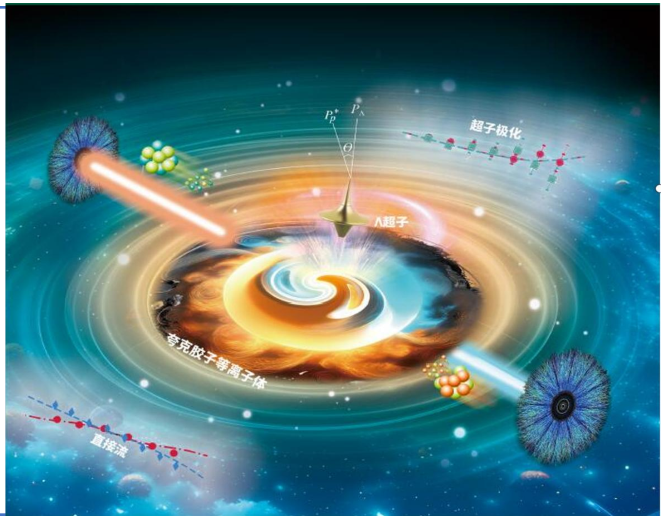
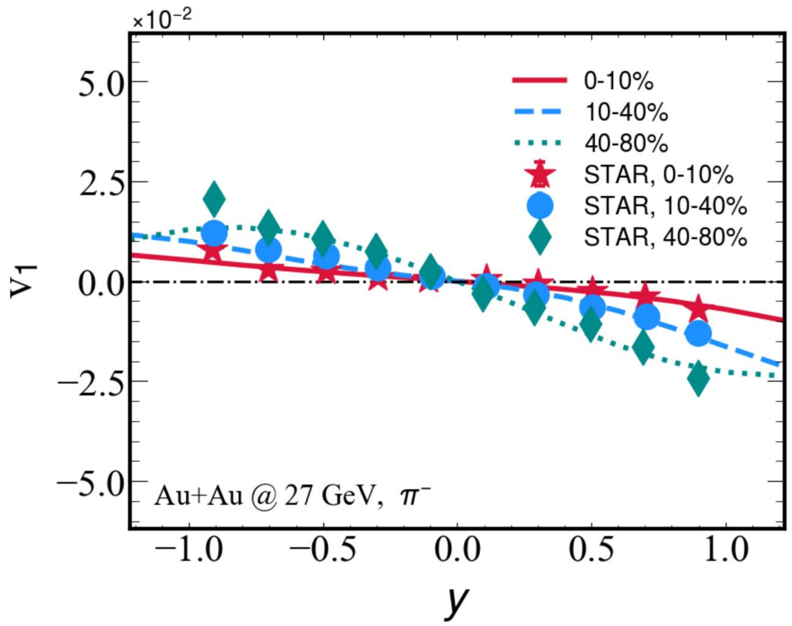


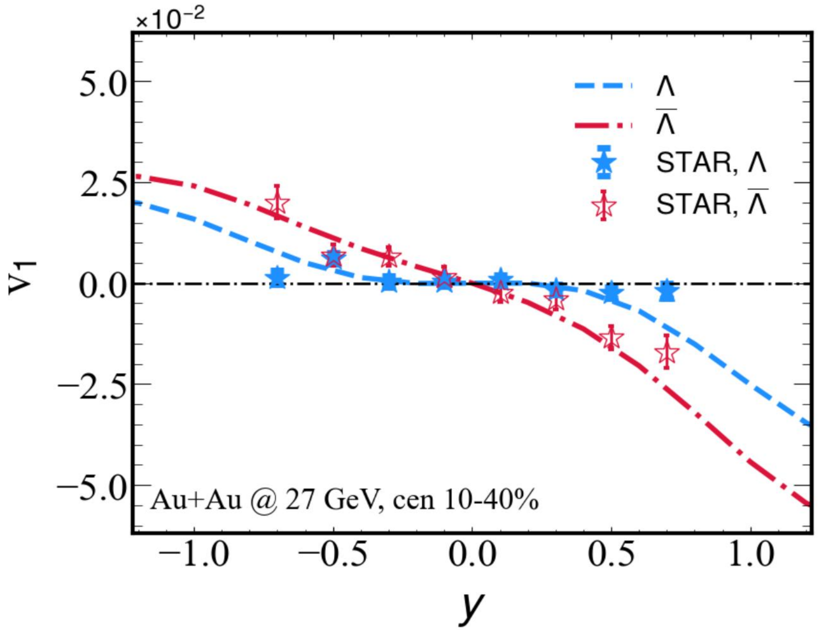
Backup

directed flow v_1

$$v_1 = \langle p_x / p_T \rangle$$

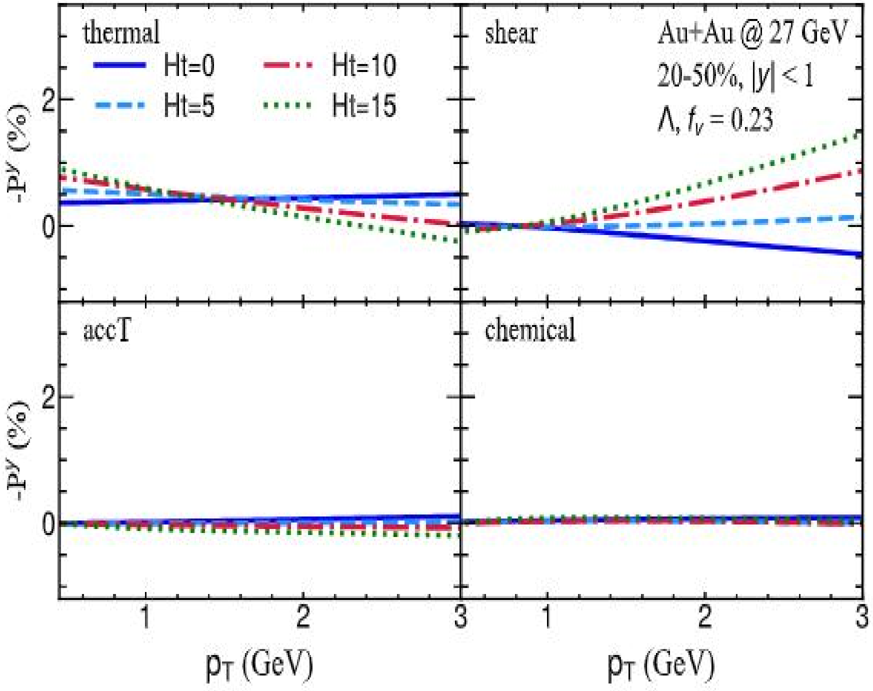
Jiang, Wu, Cao, Zhang, Phys. Rev. C 107, 034904 (2023)

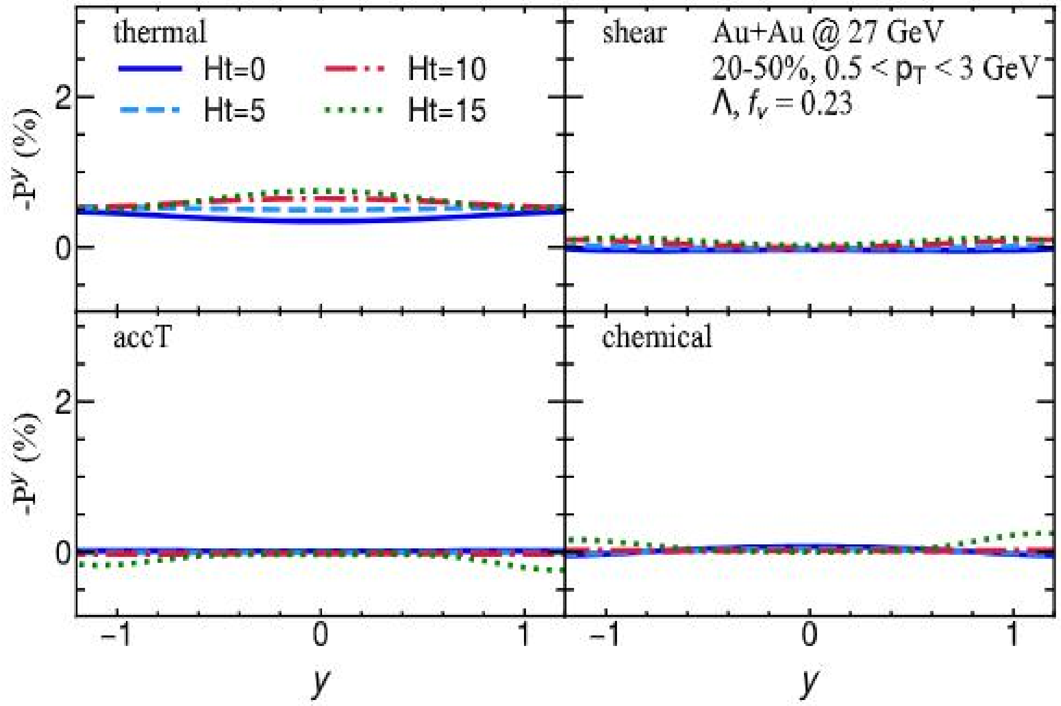




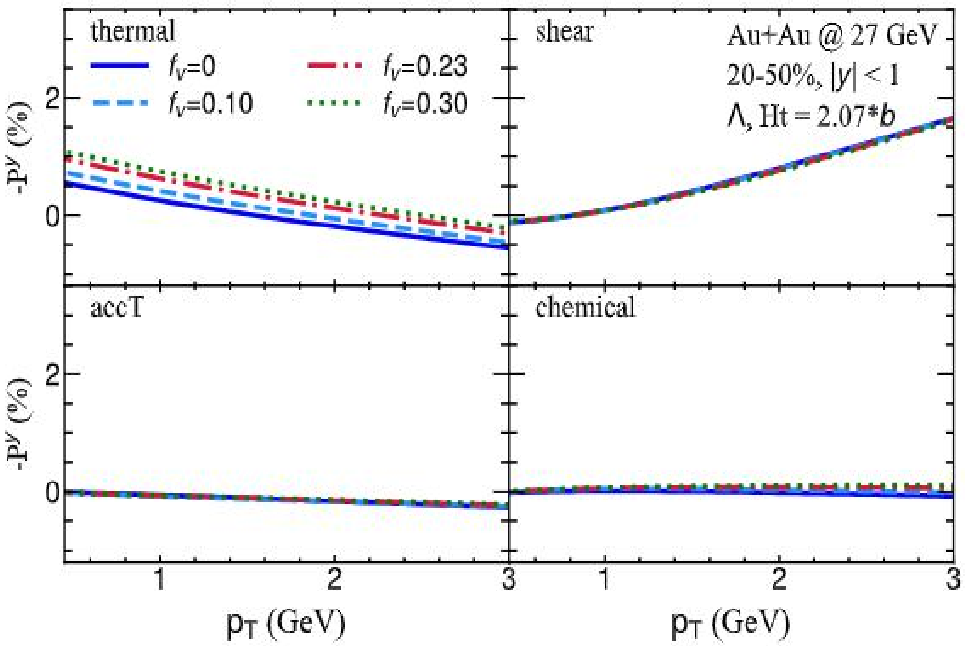
- v_1 is sensitive to the QGP volume, size, asymmetry shape and velocity field in transverse plane.
- Longiduianl shape and size of the QGP can be reconstructed from v_1 data!

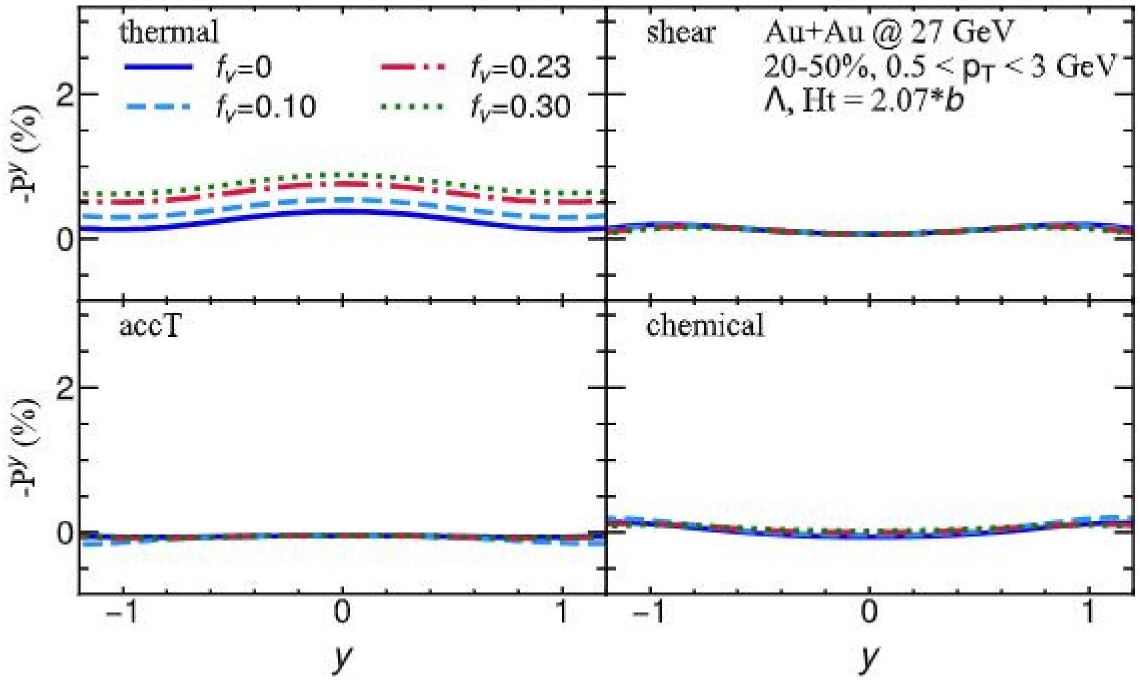
Global polarization (different tilted fireball)



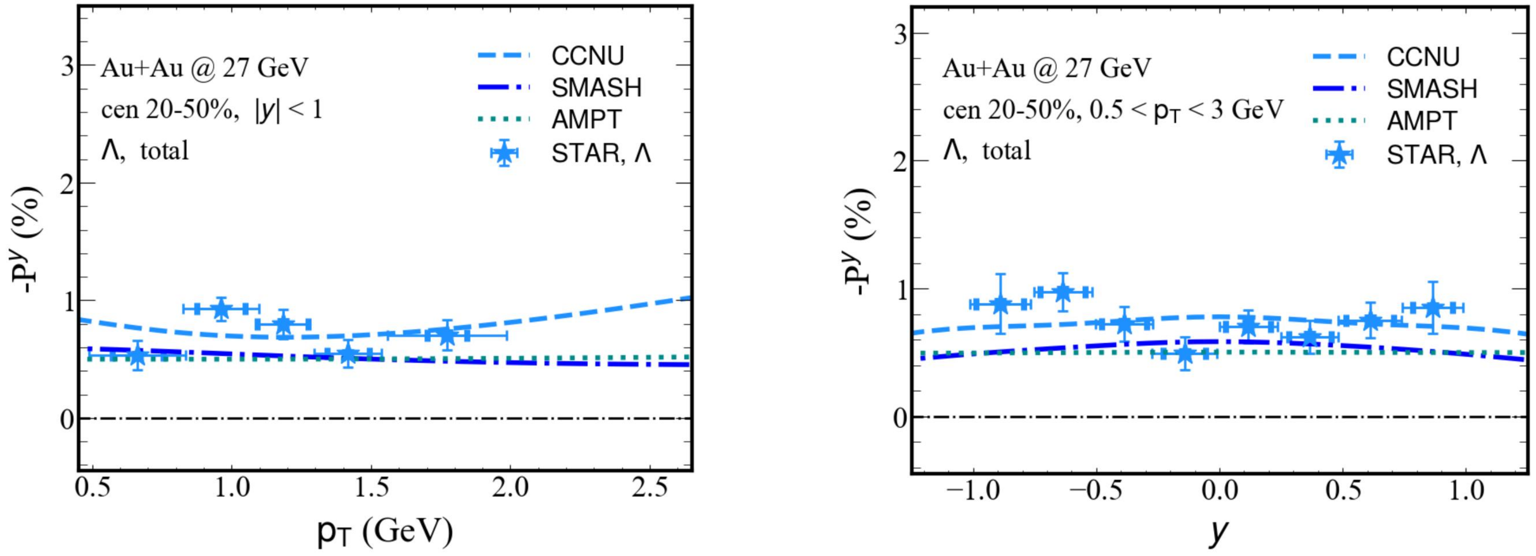


Global polarization (different velocity field)





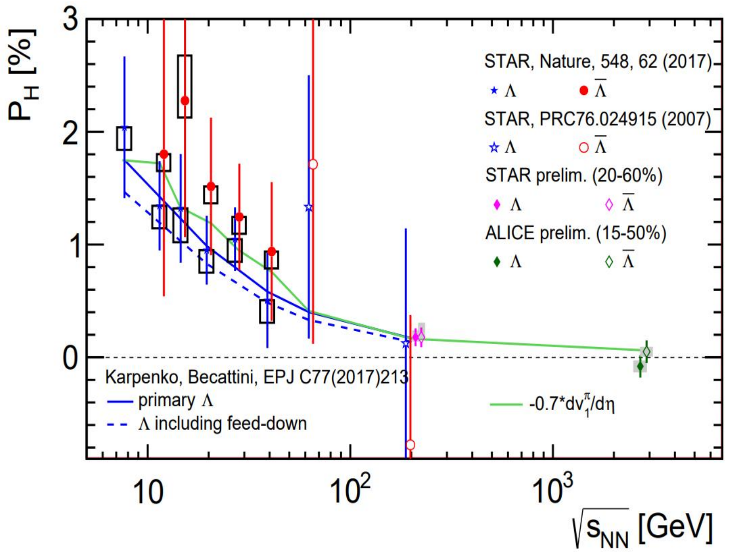
Global polarization (different initial conditions)

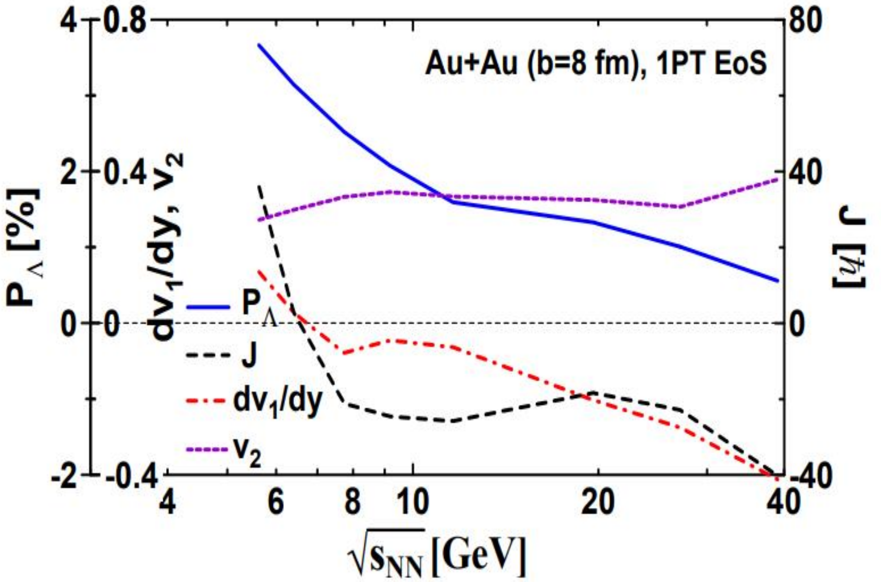


- The tilted initial condition (CCNU) generates a larger $-P^y$ than the SMASH and AMPT models in both transverse momentum and rapidity distribution
- All three initial conditions are capable of describing the STAR measurement data

Possible correlation of global polarization and directed flow

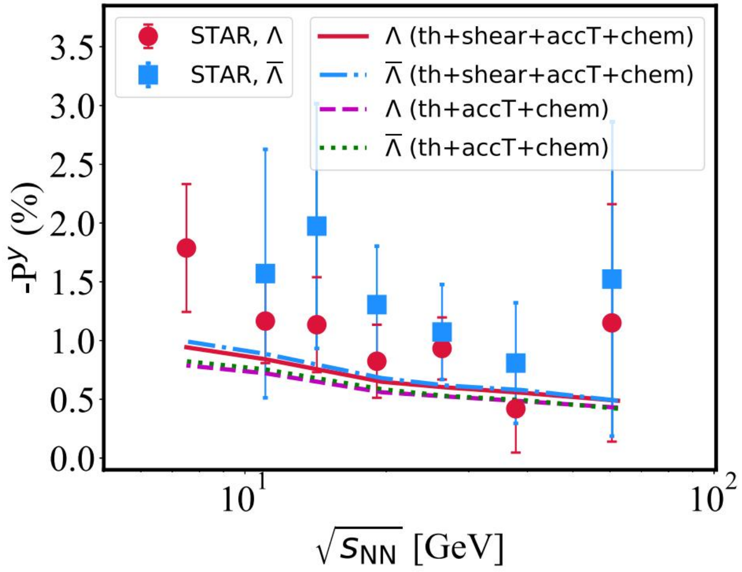
Sergei A. Voloshin EPJ Web Conf. 171 (2018) 07002 Yu. B. Ivanov Phys. Rev. C 102 (2020) 2, 024916

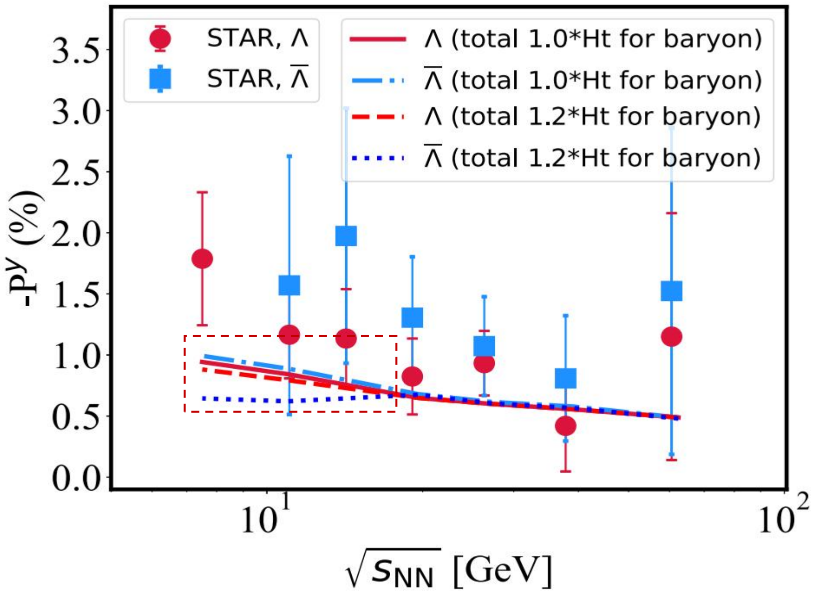




- Can we use the available data on v_1 slope for an estimate of the global polarization at different collisions?

Global polarization





The modified optical Glauber model initial condition is able to reproduce the global polarization

- tilted fireball H_t
- initial velocity field f_v
- local baryon density distribution