

Initial conditions and bulk viscosity effects on Λ polarization in high-energy heavy ion collisions

Based on 2404.14295

In collaboration with E. Grossi, I. Karpenko and F. Becattini



Andrea Palermo



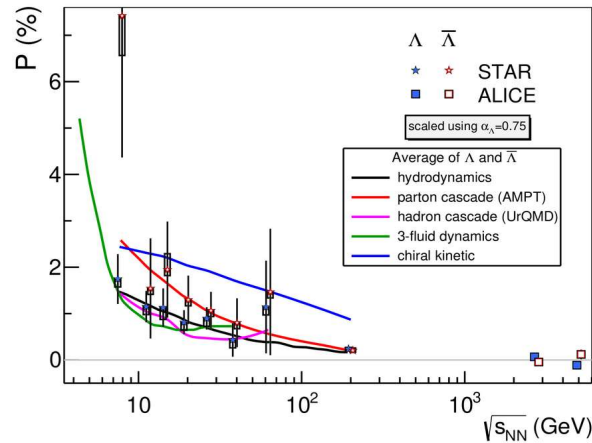
Stony Brook
University

Motivations

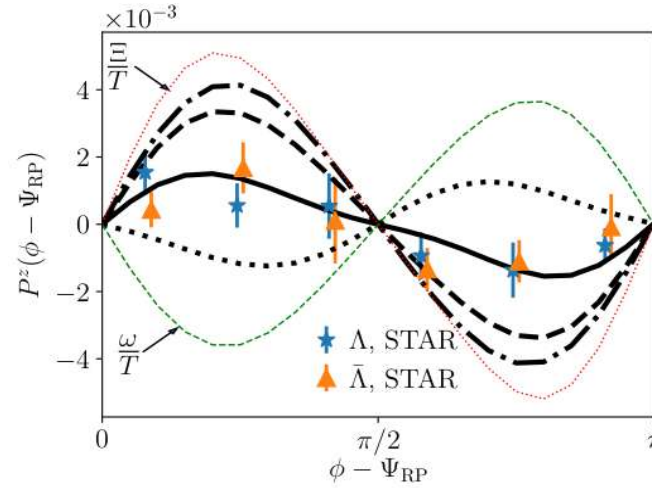
The theoretical understanding of the Λ polarization has improved, and high energy data can be reproduced with isothermal equilibration

$$\beta^\mu = \frac{u^\mu}{T} \quad \omega_{\mu\nu} = \frac{1}{2} (\partial_\nu u_\mu - \partial_\mu u_\nu), \quad \Xi_{\mu\nu} = \frac{1}{2} (\partial_\nu u_\mu + \partial_\mu u_\nu)$$

$$S^\mu(p) = -\frac{S(S+1)}{3} \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma \cdot p n_{FB} (1 + (-1)^{2S} n_{FB}) \left[\omega_{\rho\sigma} + 2 \hat{t}_\rho \frac{p^\lambda}{\epsilon} \Xi_{\lambda\sigma} \right]}{2mT_H \int_\Sigma d\Sigma \cdot p n_{FB}}$$



Global polarization



Local polarization

*F.Becattini, M.Buzzegoli, AP,
I.Karpenko, G.Inghirami
Phys.Rev.Lett.127 (2021)*

Motivations

The leading order of polarization is sensitive to the gradient of the fluid velocity

Polarization can be used together with more standard bulk observable to study the QGP. Here we study the dependence on:

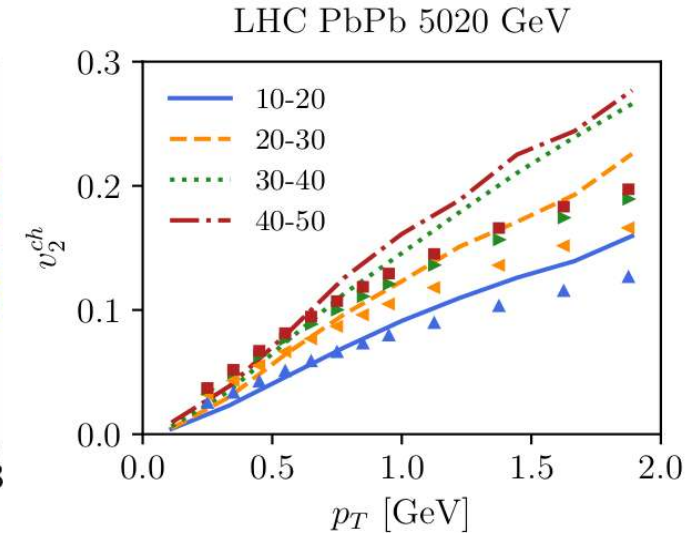
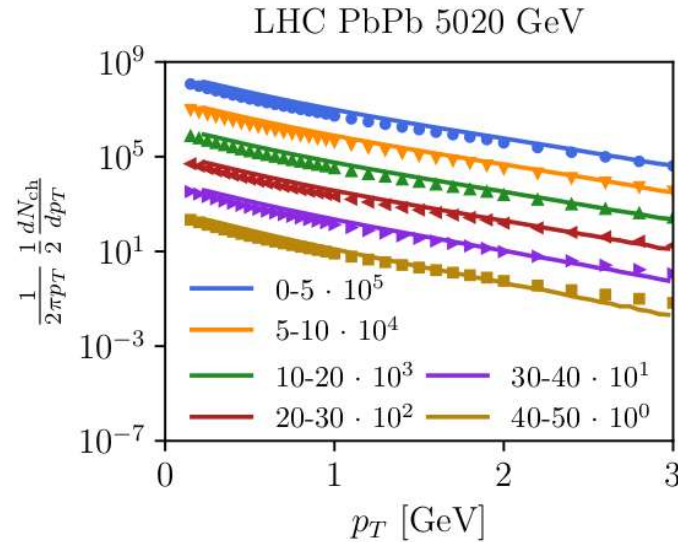
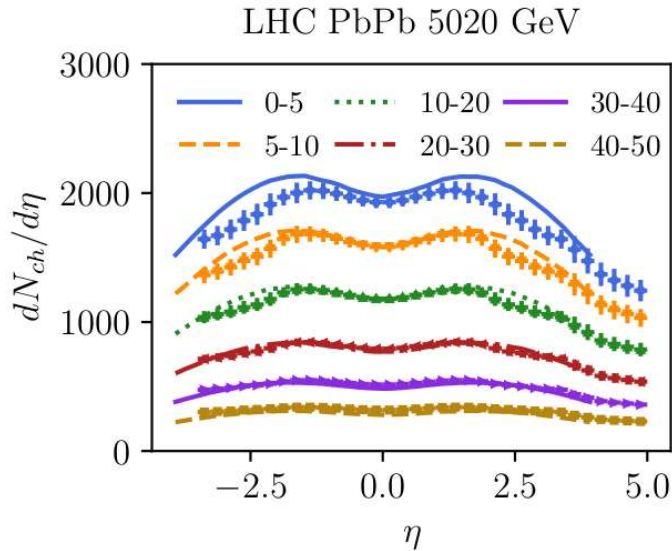
- **Viscosity** – Longitudinal polarization is very sensitive to bulk viscosity
- **Initial flow** – Transverse polarization probes the initial momentum flow

We also study the **effect of feed down** corrections on local polarization including the shear induced polarization.

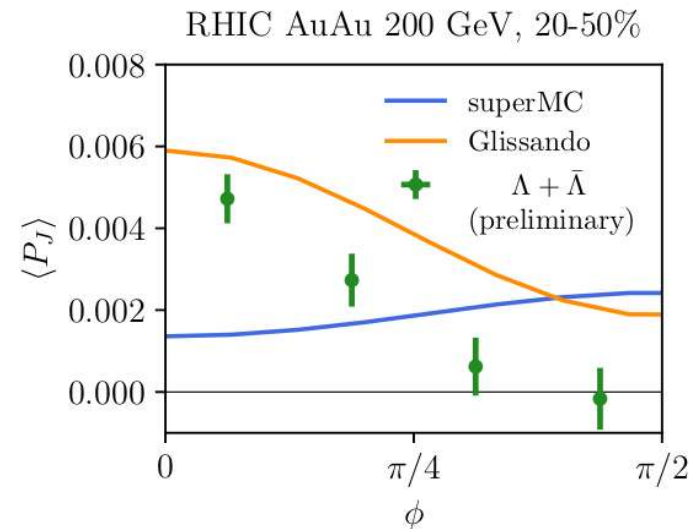
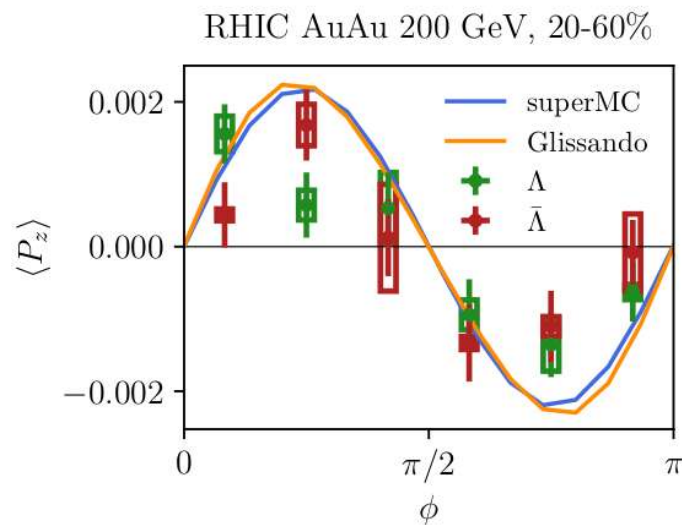
Numerical setup

An average initial state is generated with superMC, hydrodynamics is handled with vHLE and afterburning with SMASH. We also used GLISSANDO initial state.

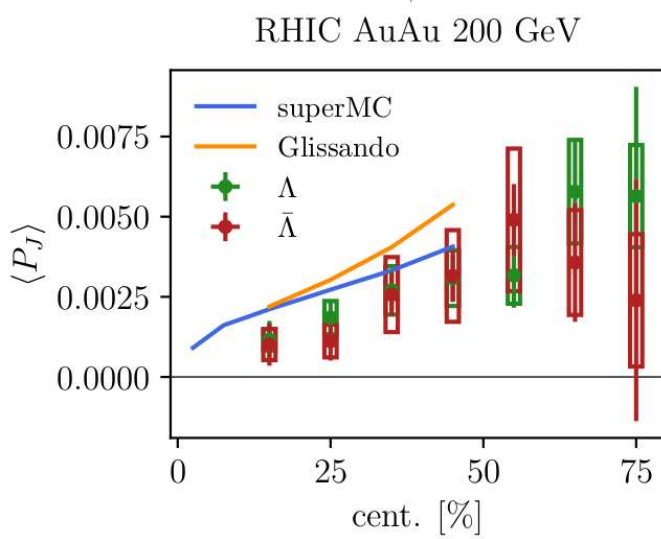
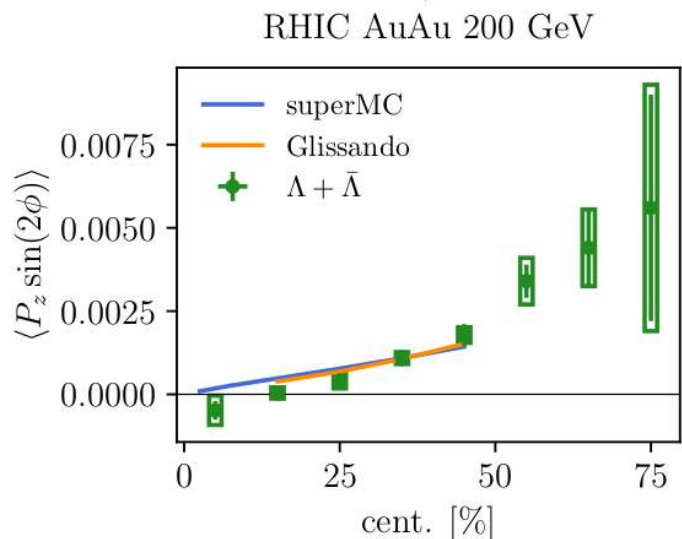
We use a constant η/s and a temperature dependent ζ/s . Decoupling happens at $e_{\text{crit}}=0.4 \text{ GeV/fm}^3$, that is $T \cong 160 \text{ MeV}$



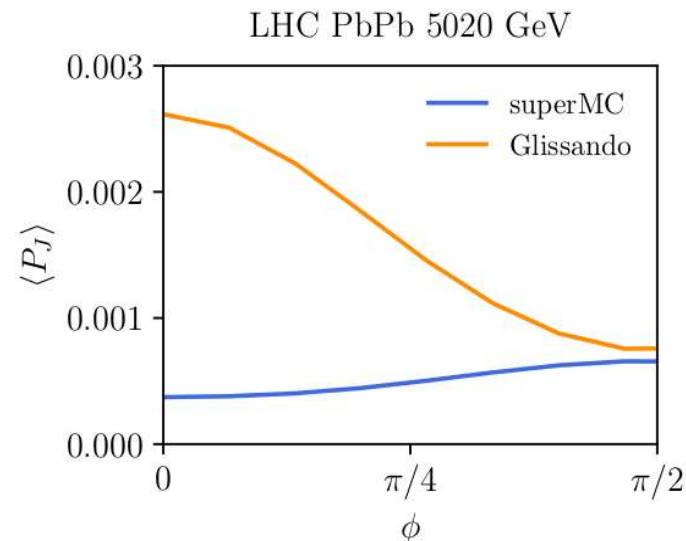
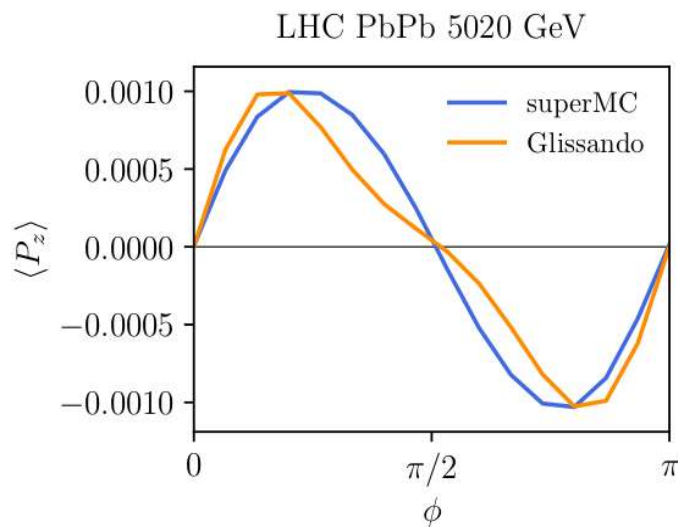
Polarization is computed at freeze-out and it is not accounted for in the afterburning stage.



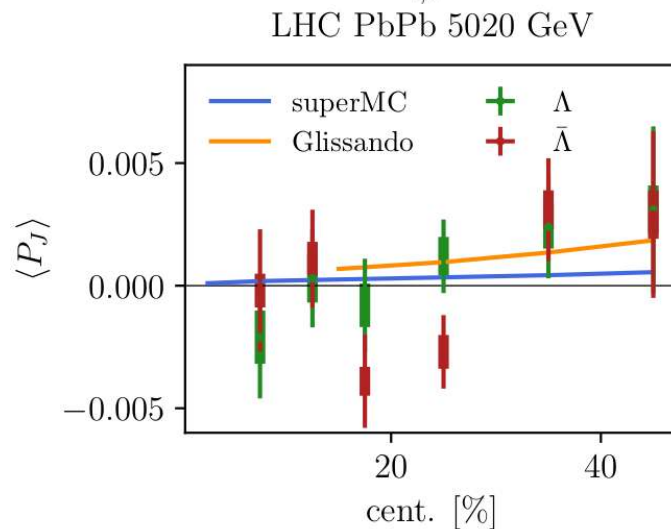
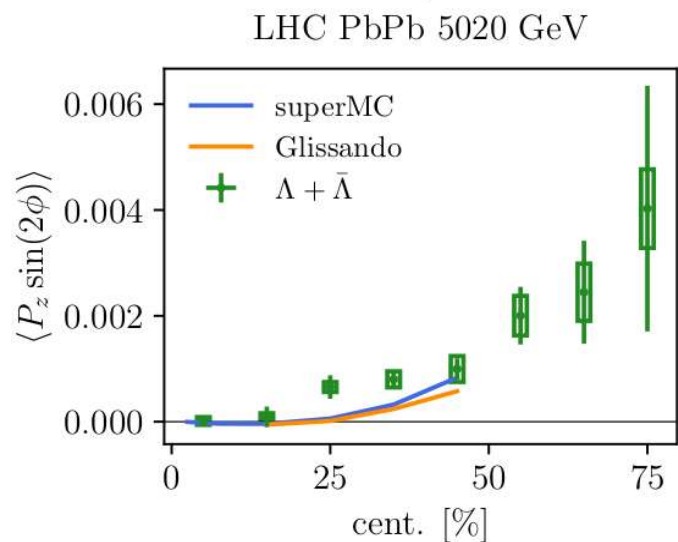
We obtain a good agreement in the longitudinal sector. The two different initial states produce a **significantly different transverse polarization.**



Polarization is computed at freeze-out and it is not accounted for in the afterburning stage.



We obtain a good agreement in the longitudinal sector. The two different initial states produce a **significantly different transverse polarization.**



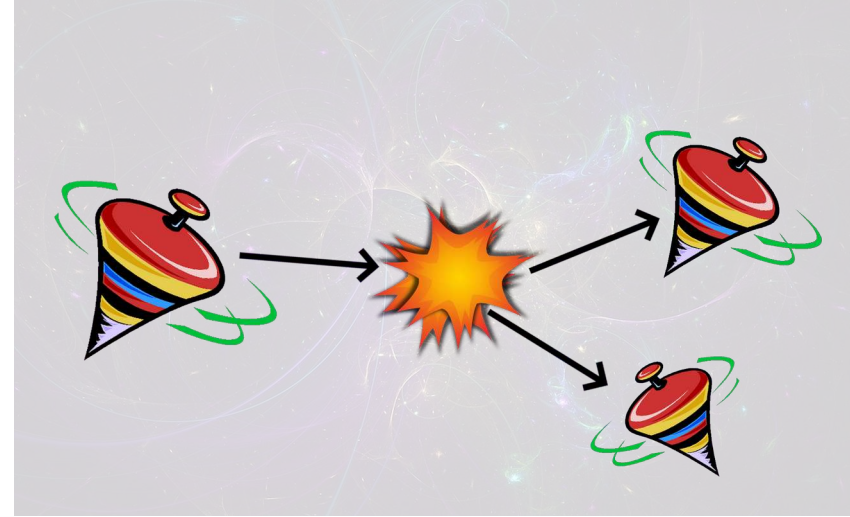
Feed-down corrections

Most Λ particles do not come from the QGP but from decays.

$$\mathbf{S}_*^{(M)}(\mathbf{p}) = \frac{\int d\Omega_* n(\mathbf{P}) F(\mathbf{p}, \Omega_*) \mathbf{S}_{M \rightarrow \Lambda}(\mathbf{P}, \mathbf{p})}{\int d\Omega_* n(\mathbf{P}) F(\mathbf{p}, \Omega_*)}$$

We consider $\Sigma^* \rightarrow \Lambda \pi$ and $\Sigma_0 \rightarrow \Lambda \gamma$.

The total polarization is the sum of the polarizations from each channel, rescaled by the multiplicity.

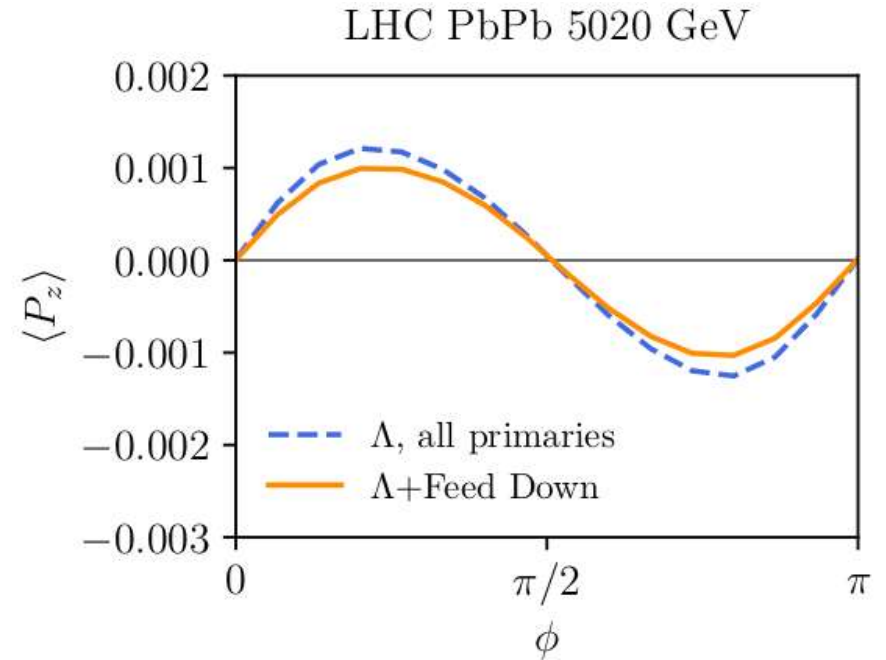
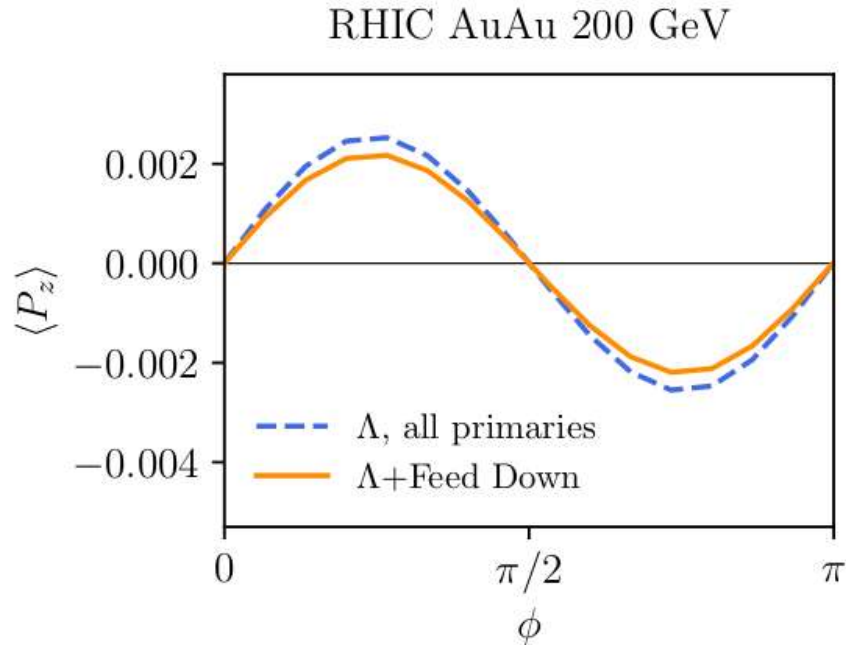


$$\mathbf{S}_{\Lambda, tot}(p) = \frac{n_{\Lambda}^{(FO)} \mathbf{S}_{\Lambda}^{(FO)}(p) + n_{\Lambda}^{(\Sigma^*)} \mathbf{S}^{(\Sigma^*)}(p) + n_{\Lambda}^{(\Sigma_0)} \mathbf{S}^{(\Sigma_0)}(p)}{n_{\Lambda}^{(FO)} + n_{\Lambda}^{(\Sigma^*)} + n_{\Lambda}^{(\Sigma_0)}}$$

Feed-down corrections

Including decays reduces longitudinal polarization by about 10%.

Transverse polarization is reduced only by 3%.



Viscosity

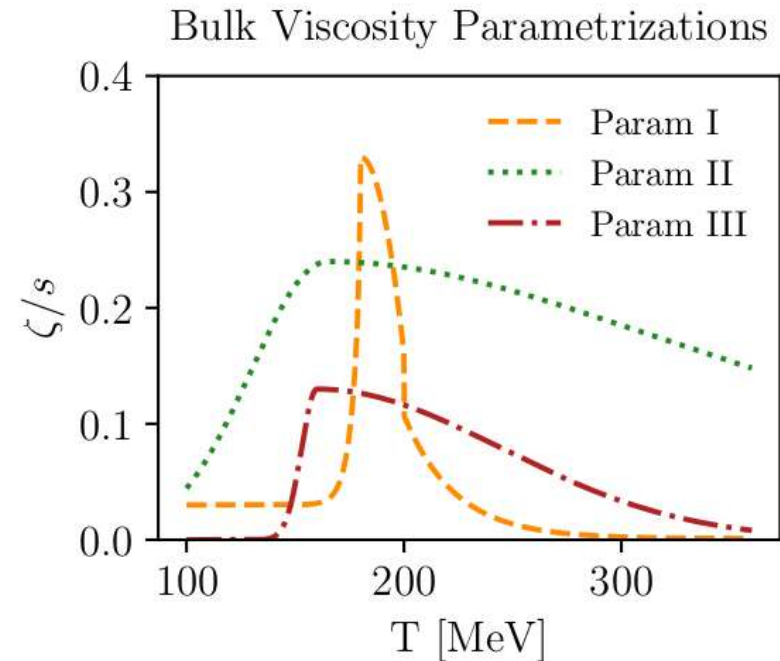
The shear viscosity dependence of polarization has been studied to some extent (e.g. S.Alzhrani, S.Ryu, C.Shen Phys.Rev.C 106 (2022), 014905)

We study for the first time the dependence of polarization on bulk viscosity

Param I: S.Ryu, J-F.Paquet, C.Shen, G.Denicola, B.Schenke, S.Jeon, C.Gale, Phys.Rev.C 97 (2018) 3, 034910

Param II: B.Schenke, C.Shen, P.Tribedy, Phys.Rev.C 99 (2019) 4, 044908

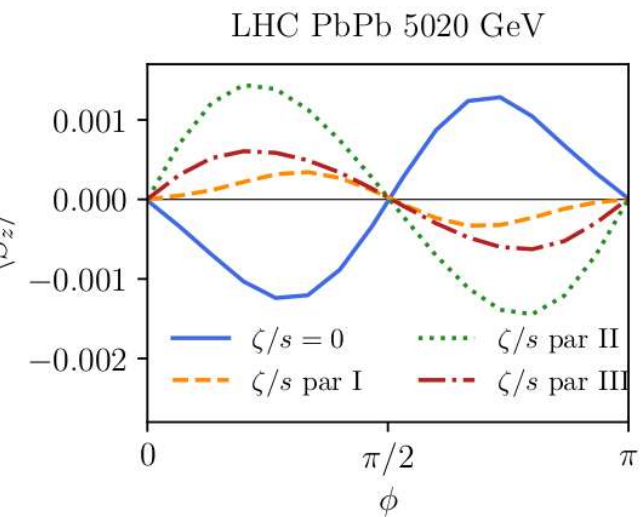
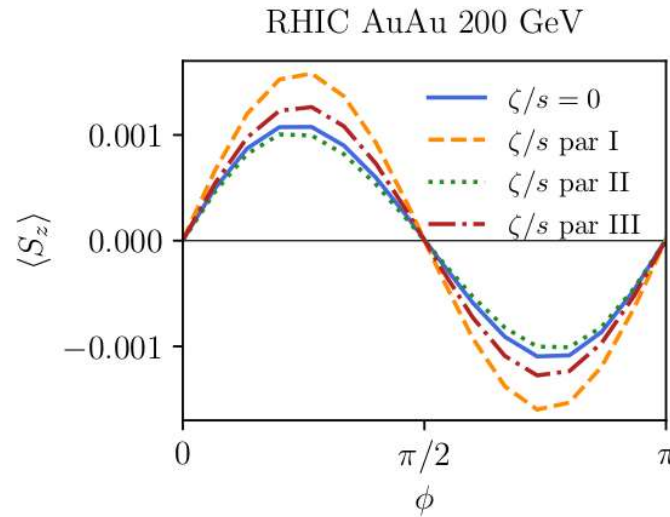
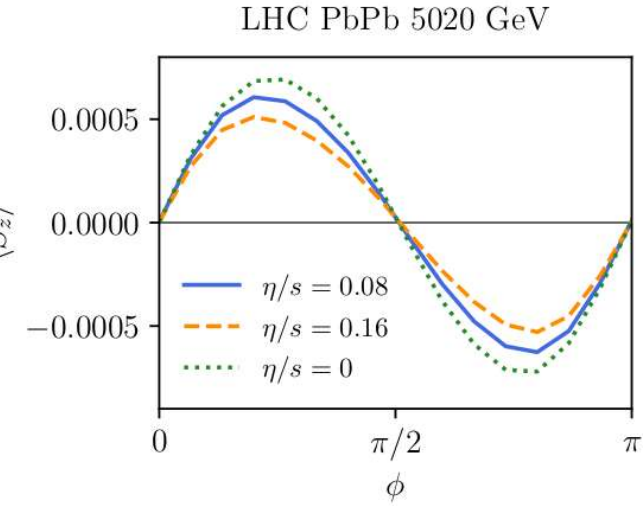
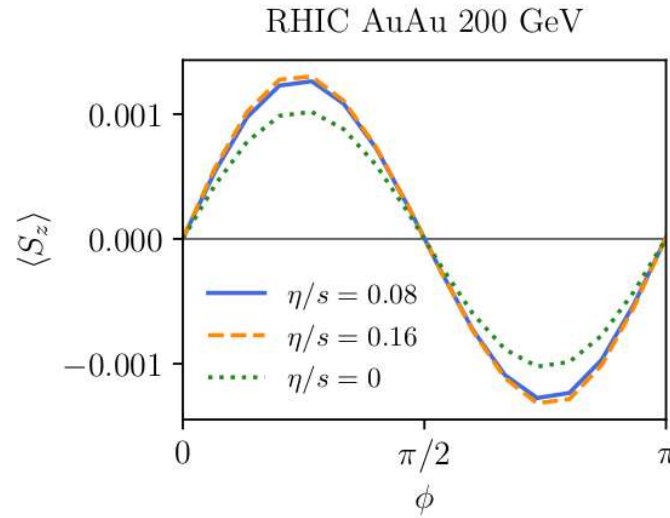
Param III: B.Schenke, C.Shen, P.Tribedy Phys.Rev.C 102 (2020) 4, 044905



The shear viscosity has a minor effect on longitudinal and transverse polarization.

Bulk viscosity has a significant effect, which becomes more important in higher energy collisions.

Bulk viscosity **can change the sign of longitudinal polarization!** Transverse polarization is also affected, but to minor extent.



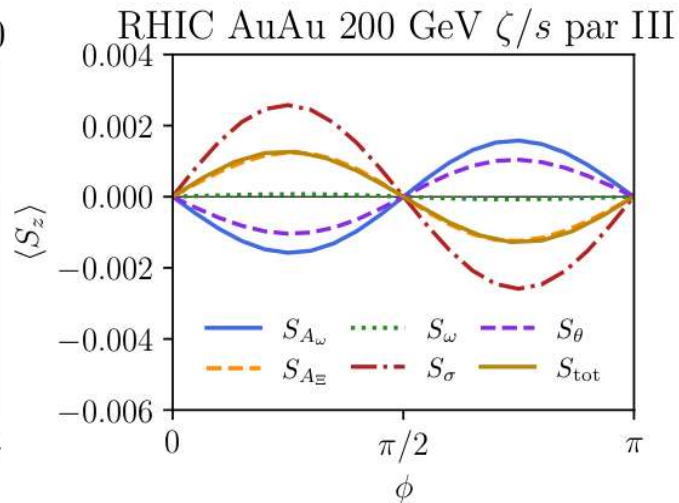
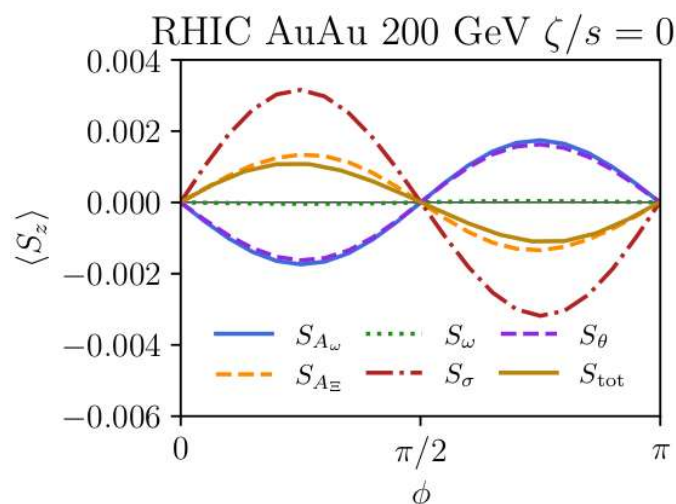
We can study how fluid components vary by decomposing the kinematic vorticity and shear:

$$\omega_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} \omega^\rho u^\sigma + \frac{1}{2} (A_\mu u_\nu - A_\nu u_\mu), \quad \Xi_{\mu\nu} = \frac{1}{2} (A_\mu u_\nu + A_\nu u_\mu) + \sigma_{\mu\nu} + \frac{1}{3} \theta \Delta_{\mu\nu}$$

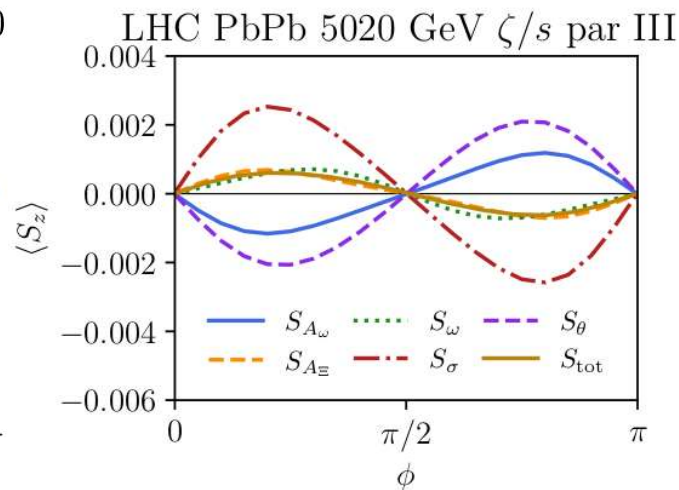
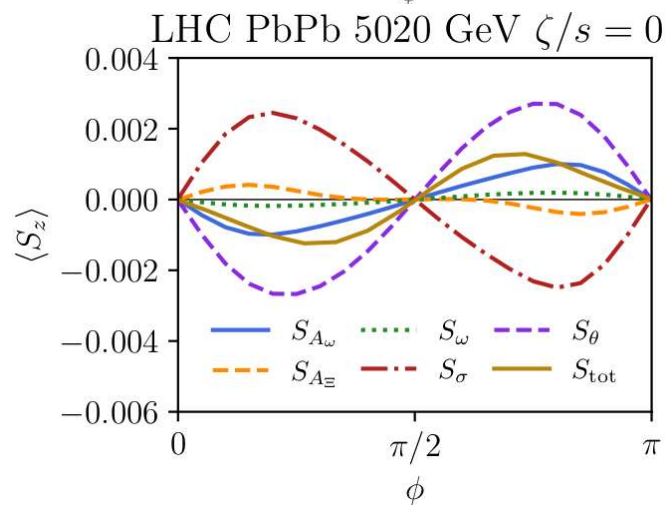
And we can identify the components of polarization coming from rotation, acceleration, shear and expansion:

$$\begin{aligned} S_{A_\omega}^\mu &= -\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) A_\nu u_\rho}{8mT_H \int_\Sigma d\Sigma \cdot p n_F}, & S_\omega^\mu &= \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) [\omega^\mu u \cdot p - u^\nu \omega \cdot p]}{4mT_H \int_\Sigma d\Sigma \cdot p n_F}, \\ S_\sigma^\mu &= -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho p_\tau \frac{p^\lambda \int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \sigma_{\lambda\sigma}}{4mT_H \int_\Sigma d\Sigma \cdot p n_F}, & S_\theta^\mu &= -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho p_\tau \frac{p^\lambda \int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \theta \Delta_{\lambda\sigma}}{12mT_H \int_\Sigma d\Sigma \cdot p n_F}, \\ S_{A_\Xi}^\mu &= -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho \frac{p_\tau \int_\Sigma d\Sigma \cdot p n_F (1 - n_F) [u_\sigma A \cdot p + A_\sigma u \cdot p]}{8mT_H \int_\Sigma d\Sigma \cdot p n_F}. \end{aligned}$$

For $\sqrt{s}=200$ GeV the most affected components are S_θ and S_σ , but the variations compensate.



For $\sqrt{s}=5020$ GeV also $S_{A\Xi}$ and S_ω change significantly.

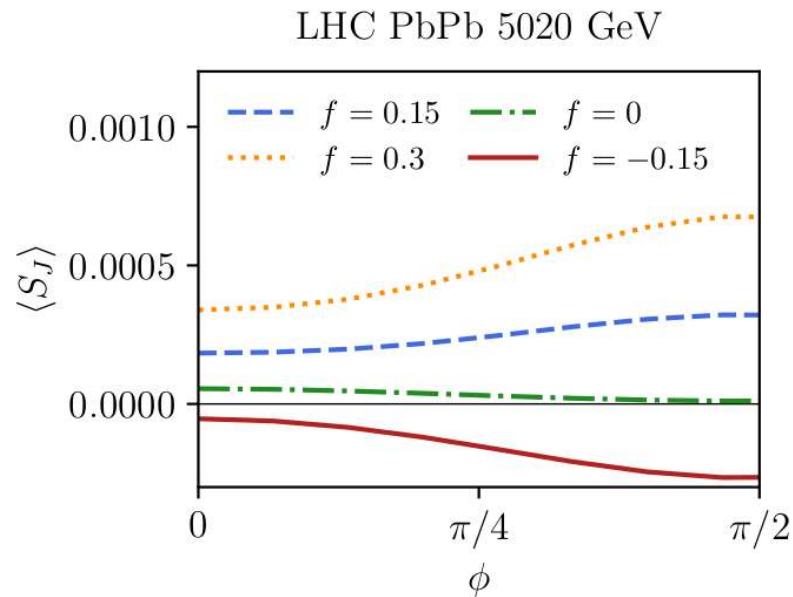
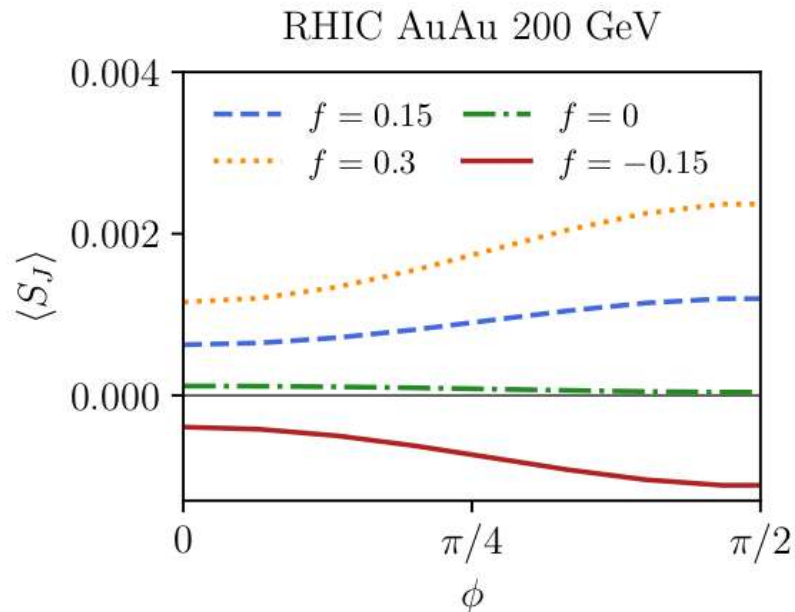


Initial longitudinal flow

The initial energy momentum tensor (superMC initial state):

$$T^{\tau\tau} = \rho \cosh(f y_{CM}), \quad T^{\tau\eta} = \frac{\rho}{\tau} \sinh(f y_{CM})$$

Transverse polarization depends strongly on the initial longitudinal momentum flow
(similar study Z.Jiang, X.Wu, S.Cao, B.Zhang Phys.Rev.C 108 (2023) 6, 064904)



Conclusions

Polarization is a paramount probe of the quark-gluon plasma.

- **Isothermal freeze-out** agrees with the experimental data for a decoupling temperature $T_{\text{dec}}=160$ MeV
- Feed-down corrections contribute up to **10%** to the signal
- **Bulk viscosity** is needed to reproduce the experimental data at 5.02 TeV
- Transverse polarization is **very sensitive** to the initial longitudinal flow

THANK YOU FOR THE ATTENTION!

Back up

Shear coupling

$$\hat{\rho}_{LE} \simeq \frac{1}{Z} \exp \left(-\beta(x) \cdot \hat{P} + \varpi_{\tau\nu} \hat{J}_x^{\tau\nu} - \xi_{\tau\nu} \hat{Q}_x^{\tau\nu} \right)$$

$$\hat{J}_x^{\tau\nu} = \int d\Sigma_\mu [\hat{T}^{\mu\tau}(x-y)^\nu - \hat{T}^{\mu\nu}(x-y)^\tau] = \int d\Sigma_\mu \hat{J}^{\mu,\tau\nu}$$

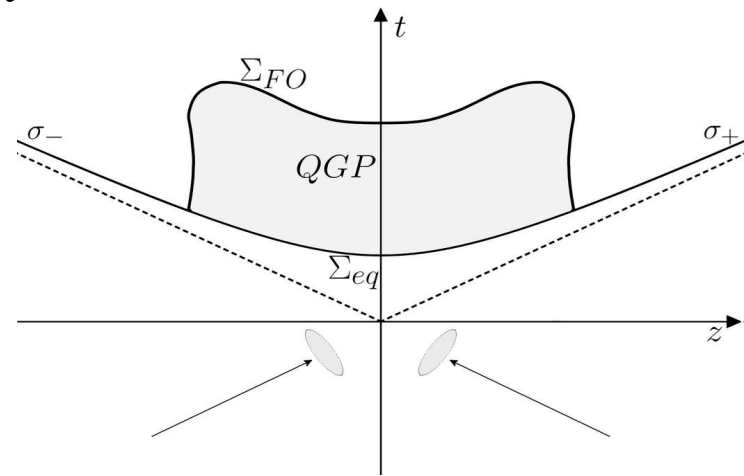
$$\hat{Q}_x^{\tau\nu} = \int d\Sigma_\mu [\hat{T}^{\mu\tau}(x-y)^\nu + \hat{T}^{\mu\nu}(x-y)^\tau] = \int d\Sigma_\mu \hat{Q}^{\mu,\tau\nu}$$

The Q operator depends on the hypersurface!

$$\int_{\Sigma_D} d\Sigma n_\mu v^\mu = \int_{\Sigma_B} d^3x t_\mu v^\mu + \int_{\Omega} d\Omega \partial_\mu v^\mu$$

$$\partial_\mu \hat{J}^{\mu,\nu\rho} = 0$$

$$\partial_\mu \hat{Q}^{\mu,\nu\rho} \neq 0$$



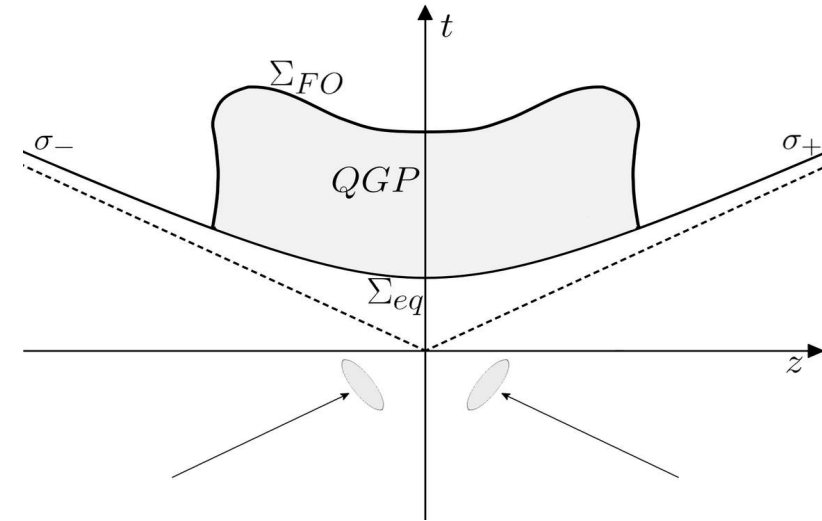
Theory: local-equilibrium density operator

Ideal fluid at local equilibrium $\beta^\mu = \frac{u^\mu}{T}$ $\hat{\rho}_{LE} = \frac{1}{Z_{LE}} \exp \left[- \int_{\Sigma_{FO}} d\Sigma_\mu \hat{T}^{\mu\nu} \beta_\nu \right]$

Hydrodynamic approximation: gradients are small.
Linear response theory

$$\hat{\rho}_{LE} \simeq \frac{1}{Z} \exp \left[-\beta(x) \cdot \hat{P} + \partial_\nu \beta_\mu(x) \int d\Sigma_\alpha(y) \hat{T}^{\alpha\mu} (y-x)^\nu \right]$$

$$\begin{aligned} \hat{\rho}_{LE} \simeq & \frac{1}{Z_\beta} e^{-\beta(x) \cdot \hat{P}} \\ & + \frac{1}{Z_\beta} \partial_\alpha \beta_\nu \int d\Sigma_\mu \int_0^1 dz e^{-(1+z)\beta(x) \cdot \hat{P}} \hat{T}^{\mu\nu} e^{z\beta(x) \cdot \hat{P}} (y-x)^\alpha \end{aligned}$$



Corrections to the spin operator (Pauli-Lubanski vector): $\langle \hat{O} \rangle_\beta = \frac{1}{Z} \text{Tr} \left(e^{-\beta(x) \cdot \hat{P}} \hat{O} \right)$

$$\langle \hat{S}^\mu(p) \rangle_{LE} = \langle \hat{S}^\mu(p) \rangle_\beta + \partial_\nu \beta_\mu(x) \int d\Sigma_\alpha(y) (y - x)^\nu \langle \hat{S}^\mu(p) \hat{T}^{\alpha\nu}(y) \rangle_\beta$$

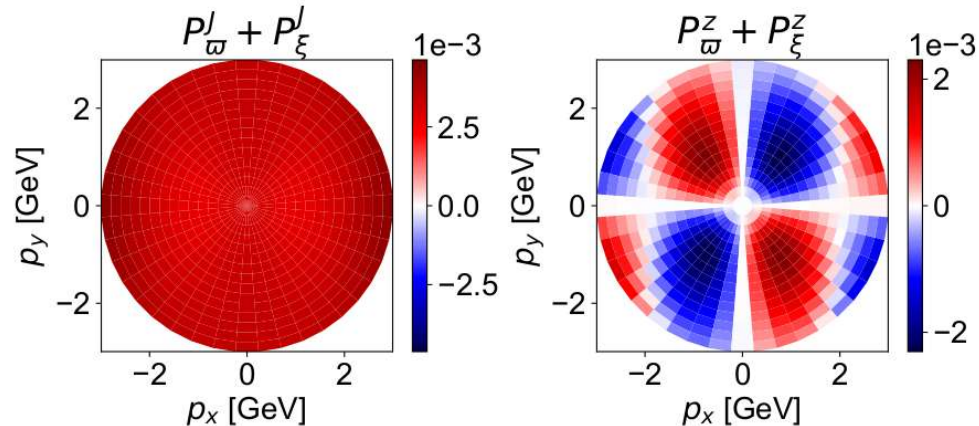
The gradients of the four-temperature contribute to polarization:

$$S^\mu(p) = -\frac{1}{8m} \epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int d\Sigma \cdot p n_F (1 - n_F) [\varpi_{\nu\rho} + 2\hat{t}_\nu \xi_{\lambda\rho} \frac{p^\lambda}{\varepsilon}]}{\int d\Sigma \cdot p n_F}$$

$$\varpi_{\mu\nu} = -\frac{1}{2} (\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

$$\xi_{\mu\nu} = \frac{1}{2} (\partial_\mu \beta_\nu + \partial_\nu \beta_\mu)$$

Vector $\hat{t}^\mu = (1, 0)$ in lab frame.
Origin: the thermal-shear couples to a
non-conserved operator!



Isothermal freeze-out

In **high-energy** heavy-ion collisions, the best approximation for the local density operator at high energy involves an isothermal decoupling hypersurface.

F.Becattini, M.Buzzegoli, A.P. , I.Karpenko, G.Inghirami Phys.Rev.Lett. 127 (2021)

$$\hat{\rho}_{LE} = \frac{1}{Z_{LE}} \exp \left[- \int_{\Sigma_{FO}} d\Sigma_{\mu} \hat{T}^{\mu\nu} \beta_{\nu} \right] = \frac{1}{Z_{LE}} \exp \left[- \frac{1}{T_{\text{dec}}} \int_{\Sigma_{FO}} d\Sigma_{\mu} \hat{T}^{\mu\nu} u_{\nu} \right]$$

The final formula now depends only on gradients of the four velocity

$$\omega_{\mu\nu} = -\frac{1}{2} (\partial_{\mu} u_{\nu} - \partial_{\nu} u_{\mu}) \quad \Xi_{\mu\nu} = \frac{1}{2} (\partial_{\mu} u_{\nu} + \partial_{\nu} u_{\mu})$$

$$S_{ILE}^{\mu}(p) = -\epsilon^{\mu\rho\sigma\tau} p_{\tau} \frac{\int_{\Sigma} d\Sigma \cdot p n_F (1 - n_F) \left[\omega_{\rho\sigma} + 2 \hat{t}_{\rho} \frac{p^{\lambda}}{\varepsilon} \Xi_{\lambda\sigma} \right]}{8mT_{\text{dec}} \int_{\Sigma} d\Sigma \cdot p n_F}$$

Isothermal freeze-out

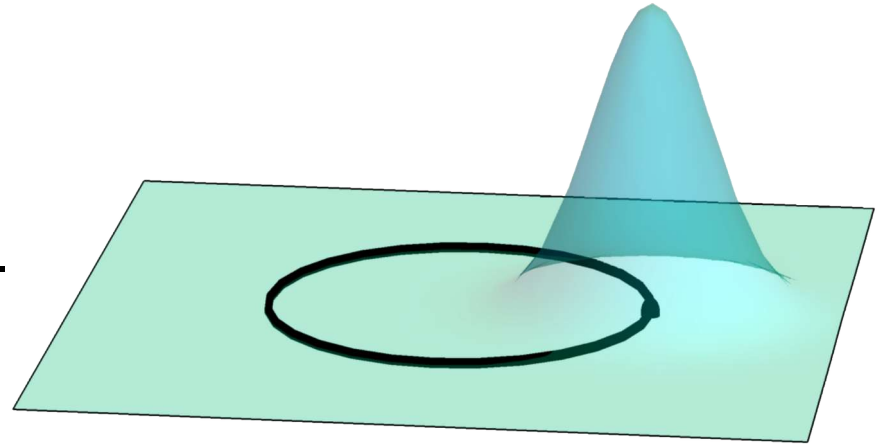
It's only a matter of choosing the best approximation. Suppose you have to approximate:

$$I = \int_{x^2+y^2=r^2} d\gamma e^{-f(x^2+y^2)} G(x, y)$$

$G(x, y)$ is peaked at some point on the circle.

1) Taking “T” out: $I \sim e^{-f(r^2)} \int_{\Gamma} d\gamma G(x, y)$

2) Expanding “ β ” : $I \sim e^{-f(r^2)} \int_{\Gamma} d\gamma e^{-\nabla f|_{(x_0, y_0)} \cdot (x - x_0)} G(x, y)$



The first method is exact, the second one introduces unwanted corrections since the gradients are non vanishing.