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

Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

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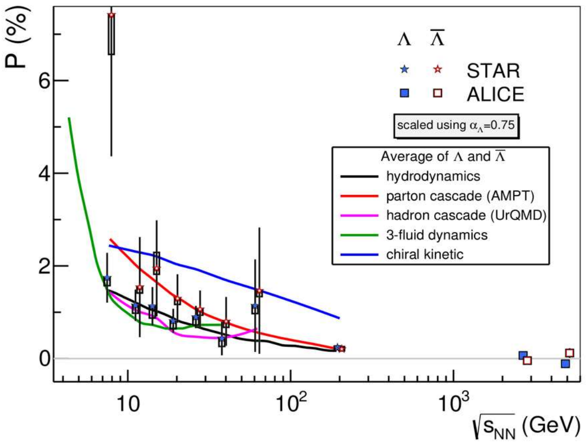
Andrea Palermo

Motivations

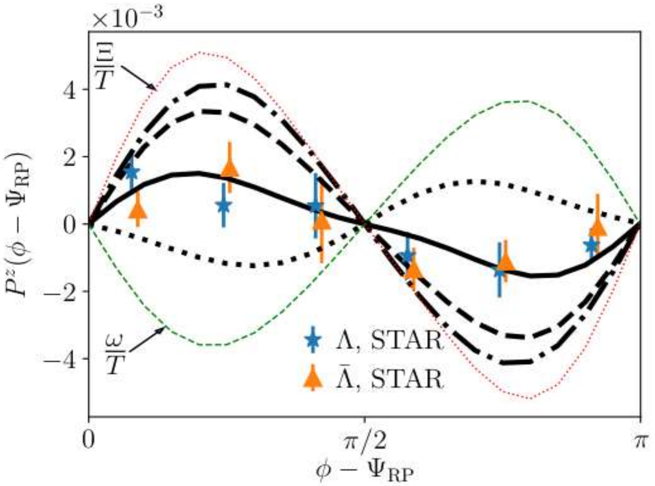
The theoretical understanding of the Λ polarization has improved, and high energy data can be reproduced with isothermal equilibration

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

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



Global polarization



Local polarization

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

Results

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

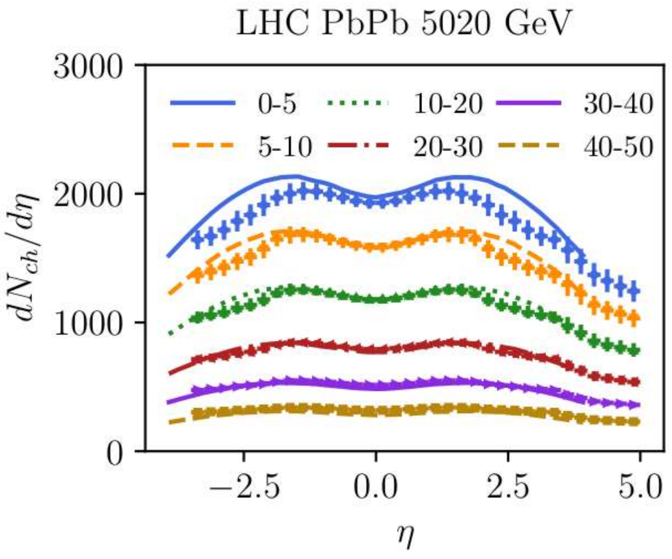
Polarization can be used together with standard bulk observable to study the QGP. Here we study the dependence on:

- **Initial conditions** – Transverse polarization probes the initial momentum flow
- **Viscosity** – Longitudinal polarization is very sensitive to bulk viscosity
- **Feed down** – reduces polarization by 10% at most (not presented here)

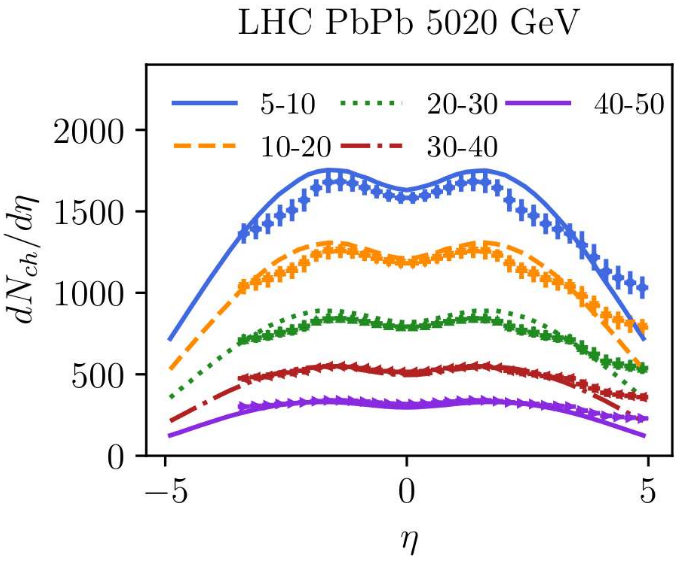
Numerical setup

An average initial state is generated with superMC and GLISSANDO, hydrodynamics is handled with vHLLE and afterburning with SMASH.

We use a constant η/s and a temperature dependent ζ/s. Decoupling happens at $e_{crit}=0.4$ GeV/fm^3, that is $T\cong160$ MeV



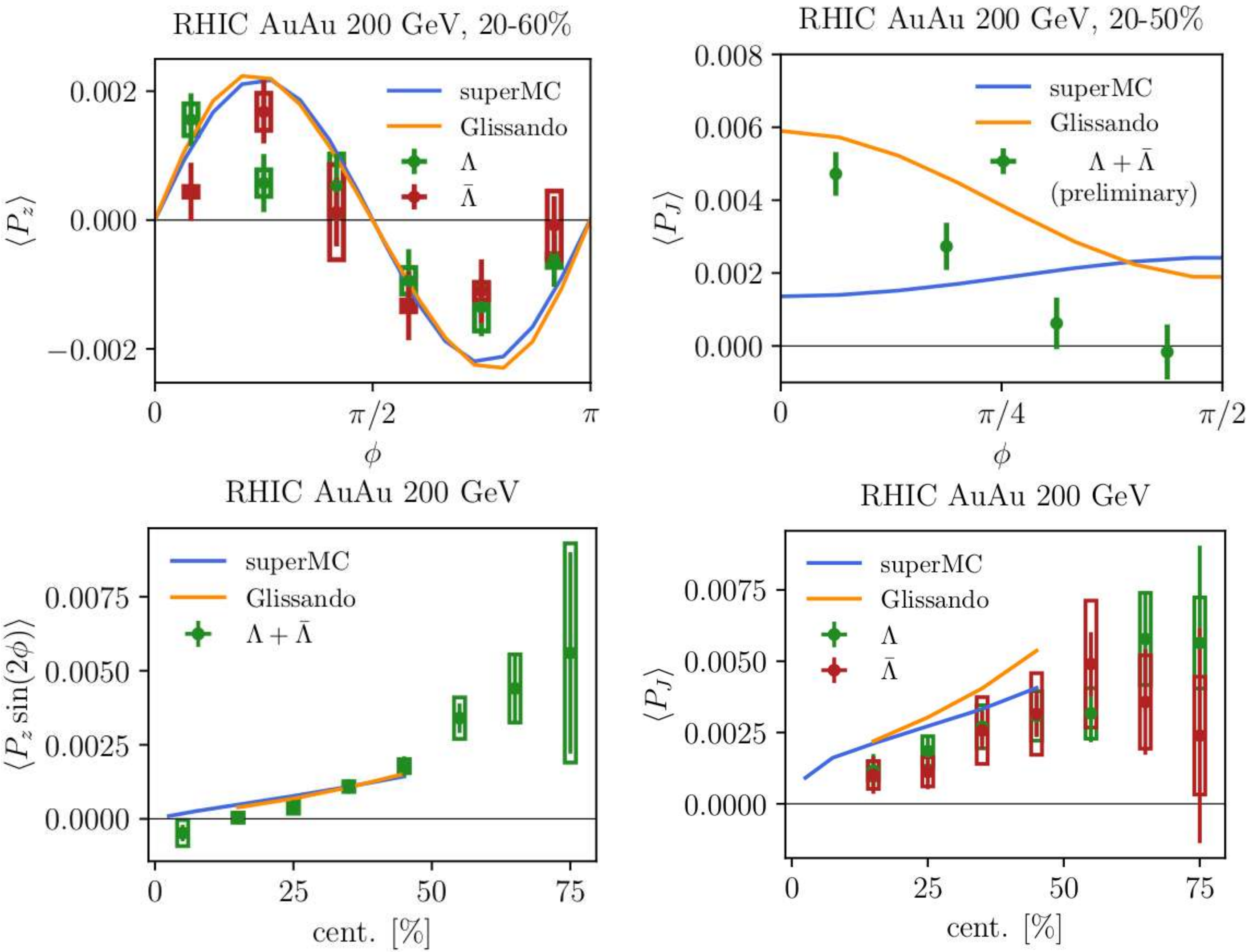
SuperMC



GLISSANDO

We obtain a good agreement in the longitudinal sector.

The two different initial states produce a **significantly different transverse polarization.**



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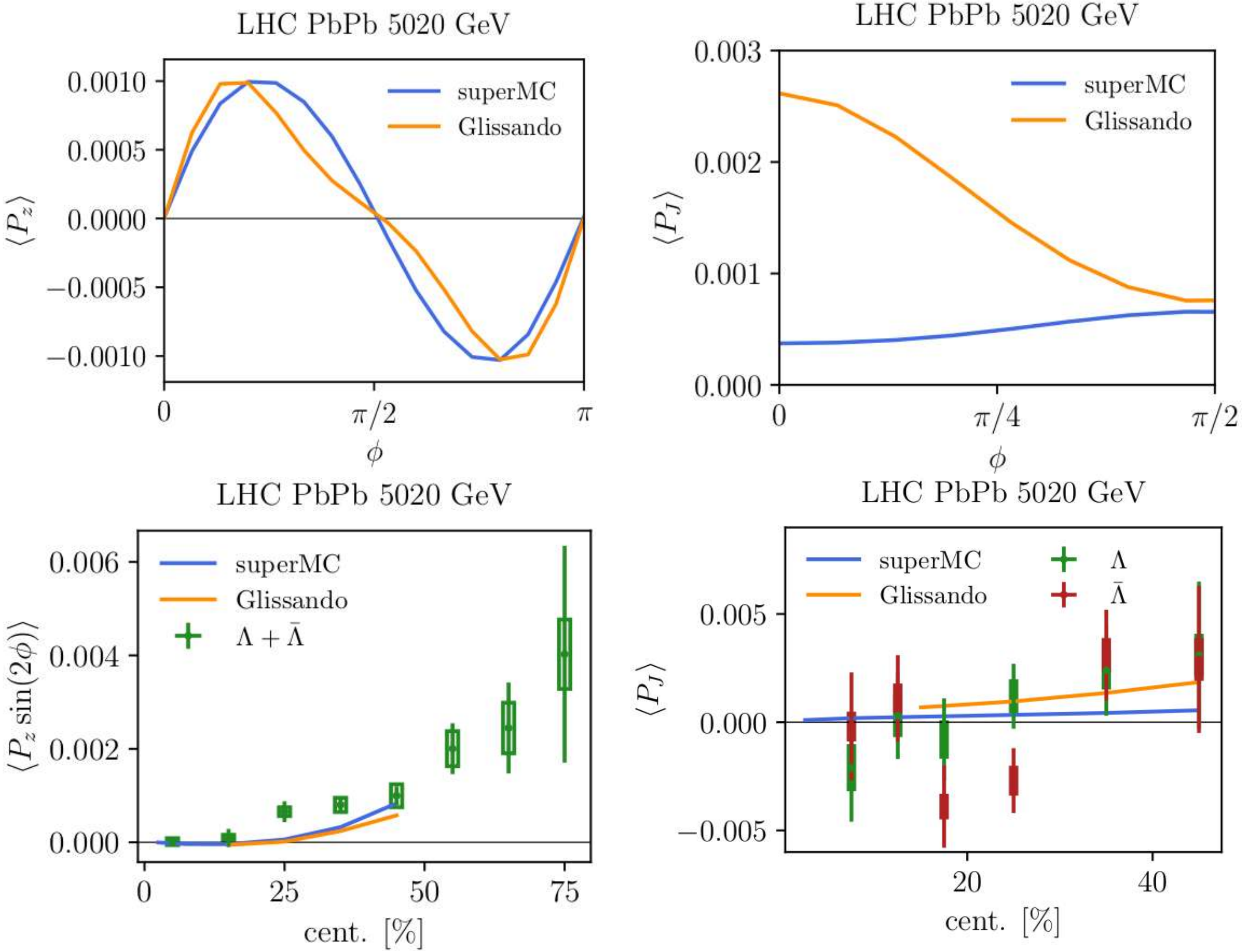
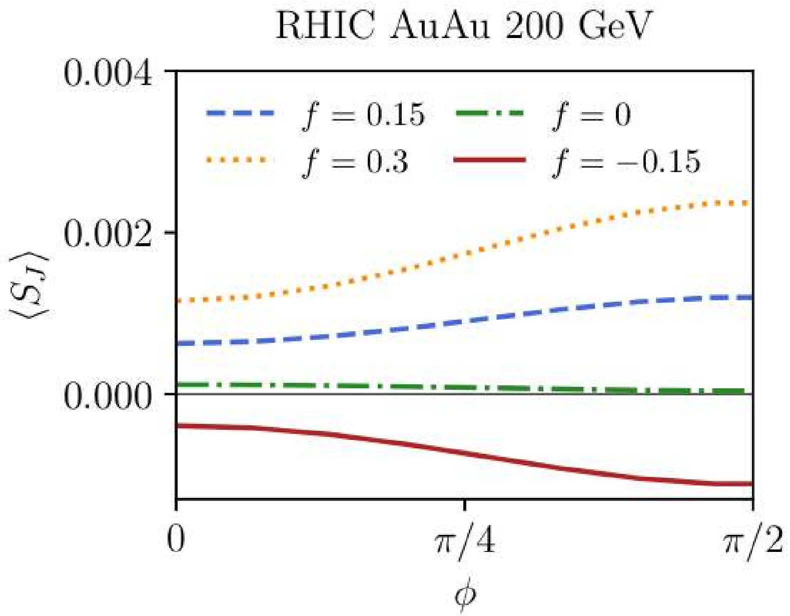


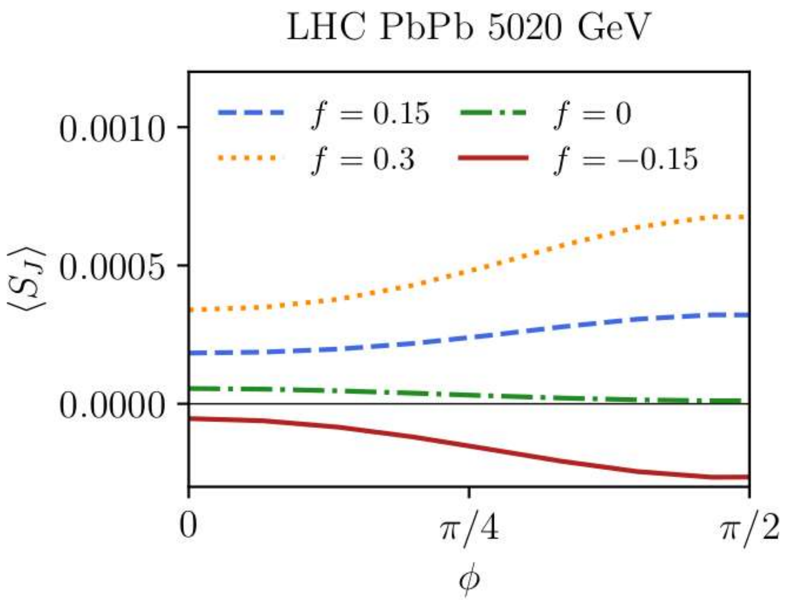
Initial longitudinal flow

The initial energy momentum tensor (superMC initial state):

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

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





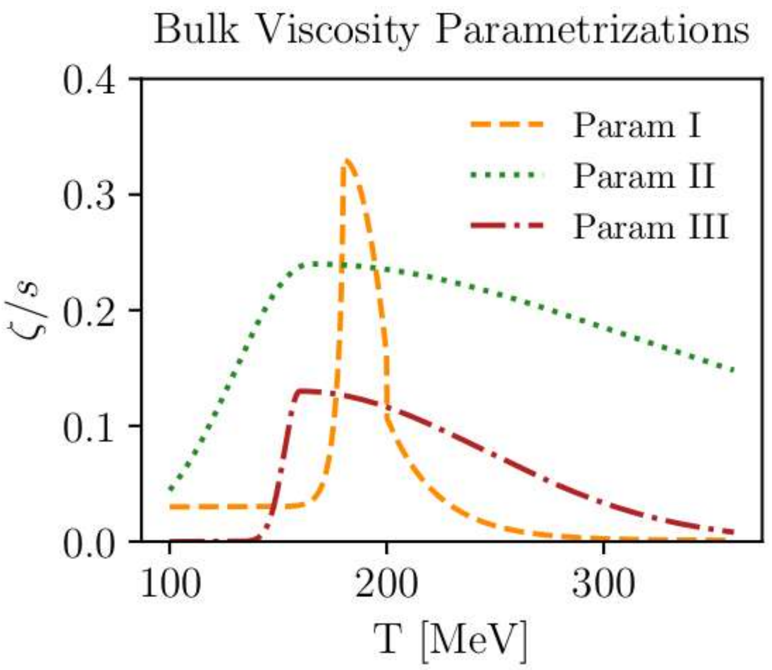
Viscosity

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

Param I: S.Ryu, J-F.Paquet, C.Shen, G.Denicol, 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

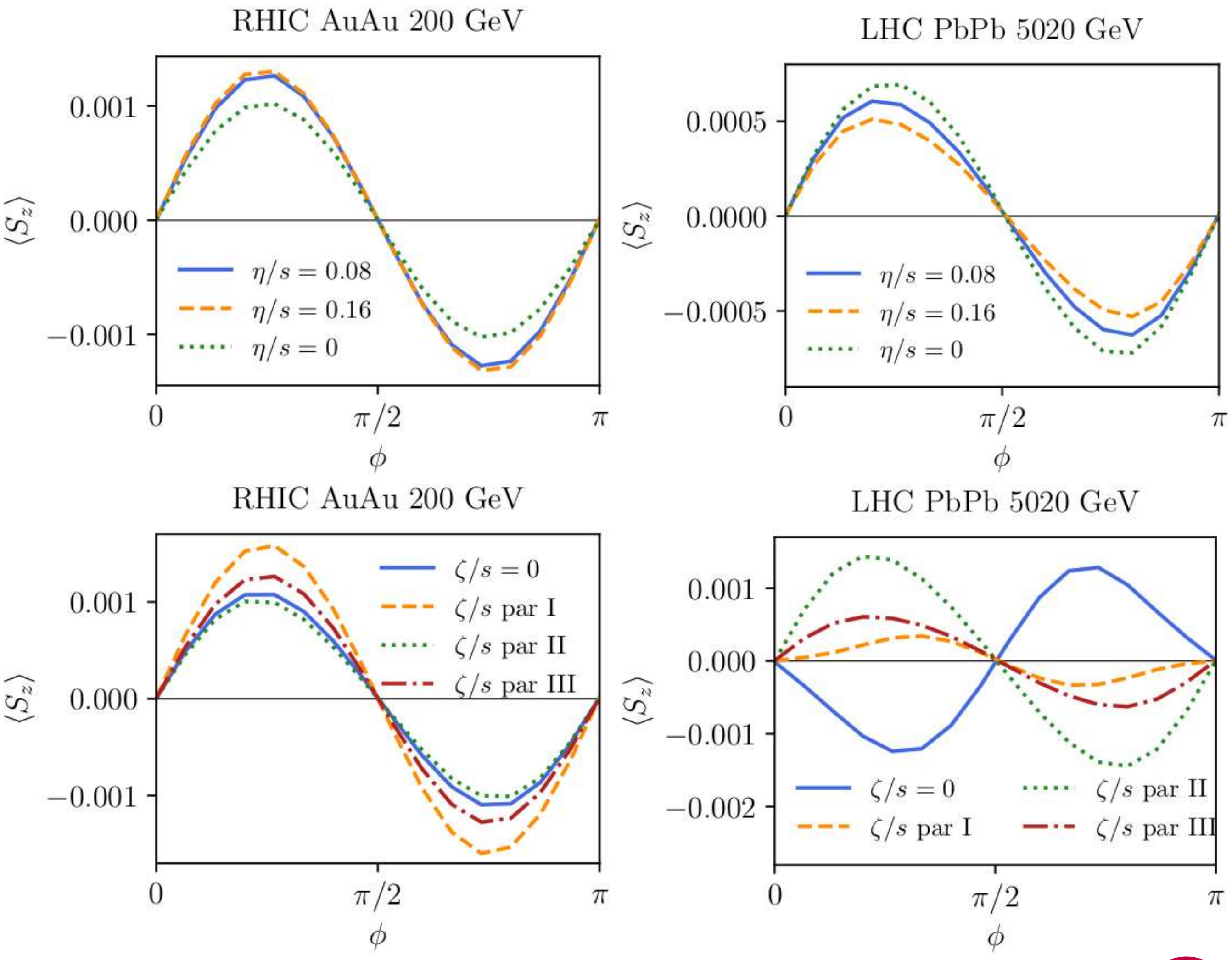
Param III: B.Schenke, C.Shen, P.Tribedy Phys.Rev.C 102 (2020) 4, 044905



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:

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

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

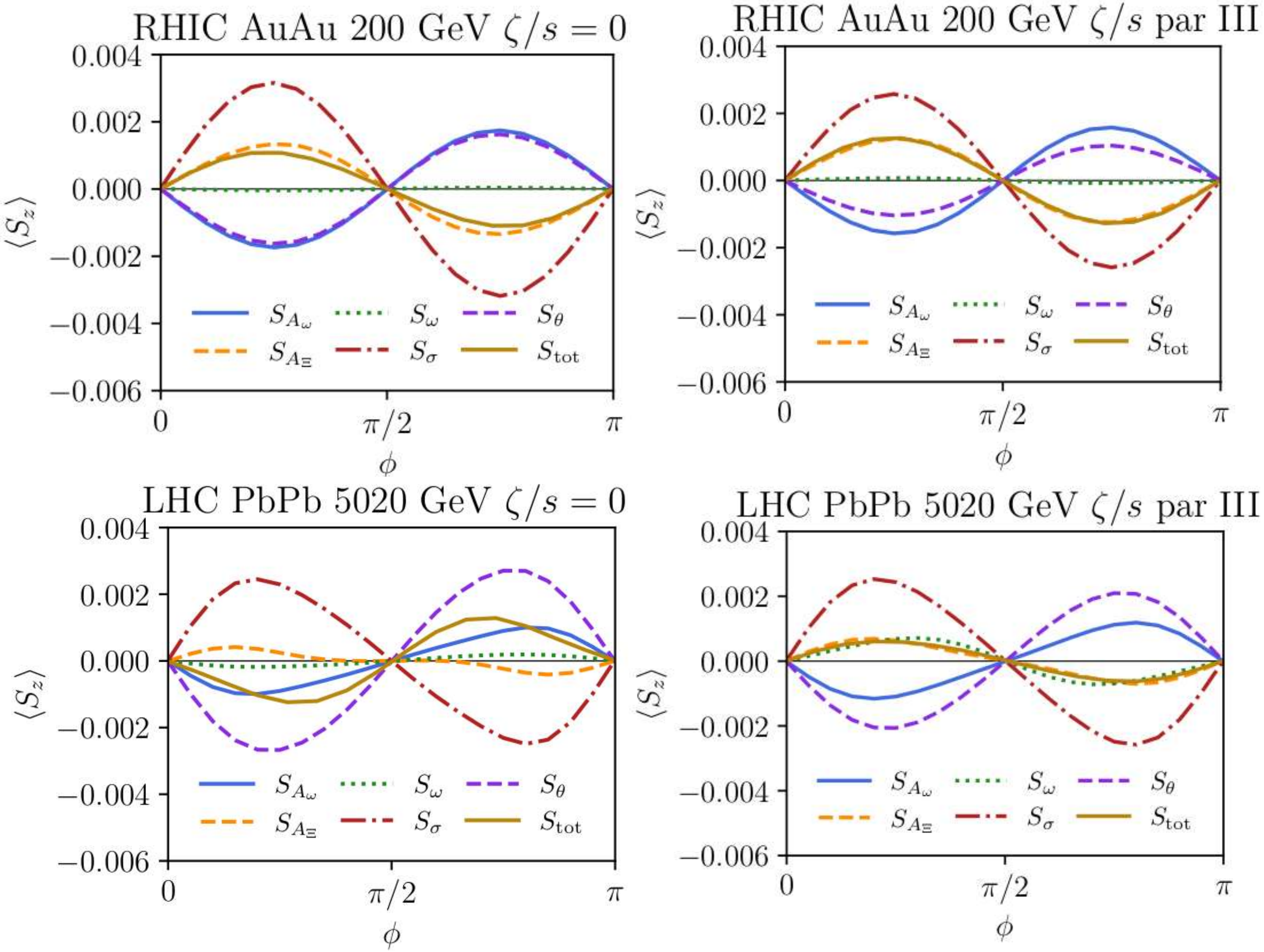
$$S^\mu_{A_\omega} = -\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\; A_\nu u_\rho}{8mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}, \qquad S^\mu_\omega = \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\; [\omega^\mu u\cdot p - u^\nu \omega\cdot p]}{4mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_\sigma = -\epsilon^{\mu\rho\sigma\tau}\hat{t}_\rho p_\tau \frac{p^\lambda}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\sigma_{\lambda\sigma}}{4mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}, \qquad S^\mu_\theta = -\epsilon^{\mu\rho\sigma\tau}\hat{t}_\rho p_\tau \frac{p^\lambda}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\theta\Delta_{\lambda\sigma}}{12mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_{A_\Xi} = -\epsilon^{\mu\rho\sigma\tau}\hat{t}_\rho \frac{p_\tau}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\, [u_\sigma A\cdot p + A_\sigma u\cdot p]}{8mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}.$$

For √s=200 GeV the most affected components are S_θ and S_σ, but the variations compensate.

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



Conclusions

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

- Transverse polarization is **very sensitive** to the initial longitudinal flow

- **Bulk viscosity** has a strong impact on longitudinal polarization at 5.02 TeV

Polarization can be used to **constrain initial conditions and transport coefficients.**

THANK YOU FOR THE ATTENTION!

Back up

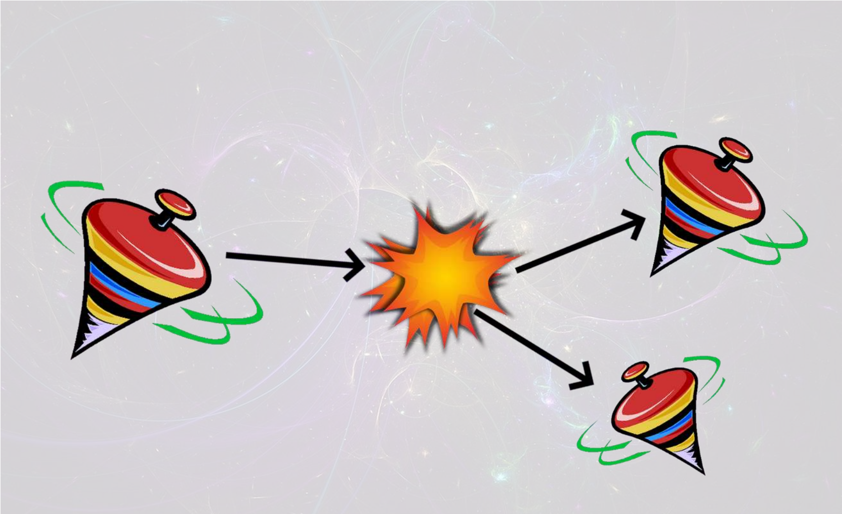
Feed-down corrections

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

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

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

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



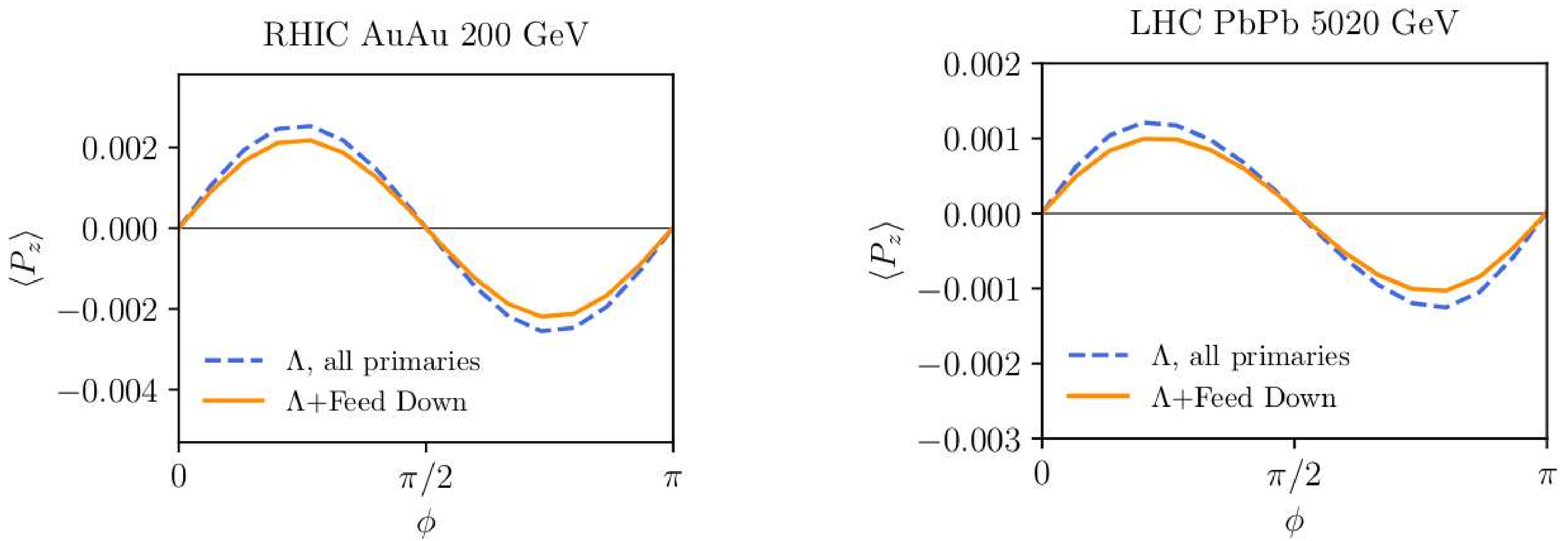
$$\boldsymbol{S}_{\Lambda,tot}(p) = \frac{n_\Lambda^{(FO)} \boldsymbol{S}_\Lambda^{(FO)}(p) + n_\Lambda^{(\Sigma^*)} \boldsymbol{S}^{(\Sigma^*)}(p) + n_\Lambda^{(\Sigma_0)} \boldsymbol{S}^{(\Sigma_0)}(p)}{n_\Lambda^{(FO)} + n_\Lambda^{(\Sigma^*)} + n_\Lambda^{(\Sigma_0)}}$$

X.Xia, H.Li, X.Huang, X.Huang Phys.Rev.C 100 (2019); F.Becattini, G.Cao, E.Speranza Eur.Phys.J.C 79 (2019)

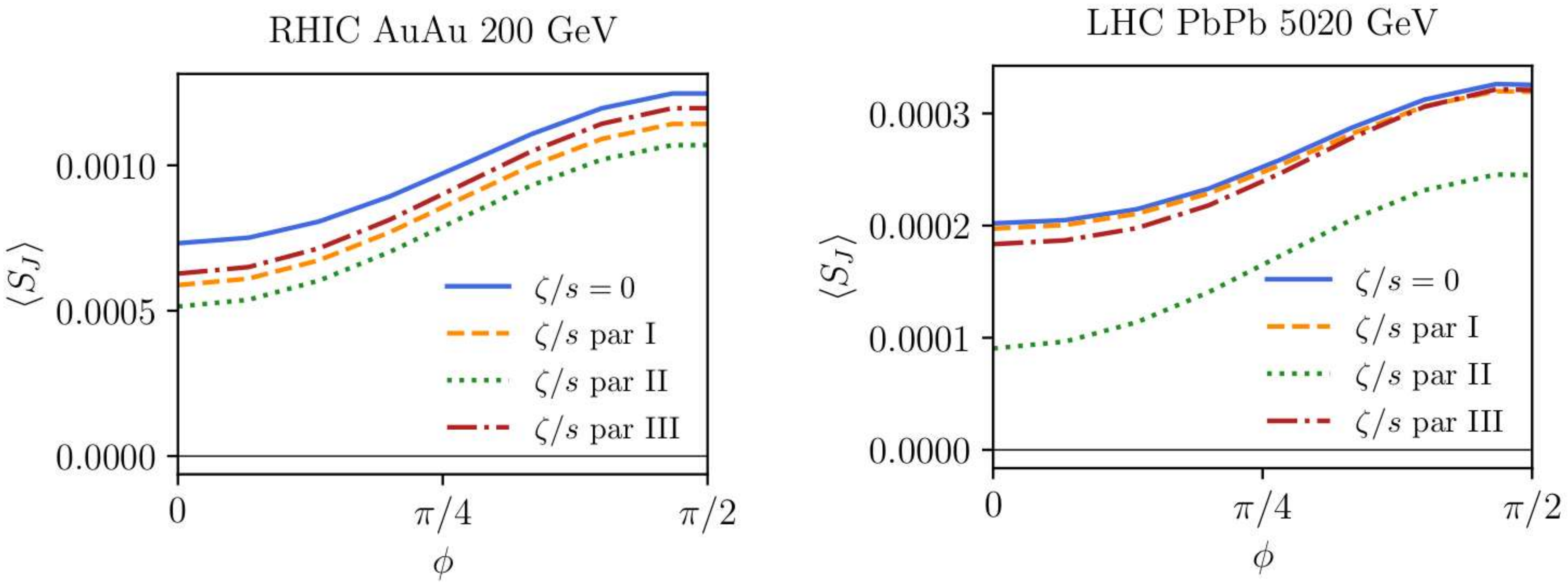
Feed-down corrections

Including decays reduces longitudinal polarization by about 10%.

Transverse polarization is reduced only by 3%.



Bulk viscosity and transverse polarization



Spin-shear coupling

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

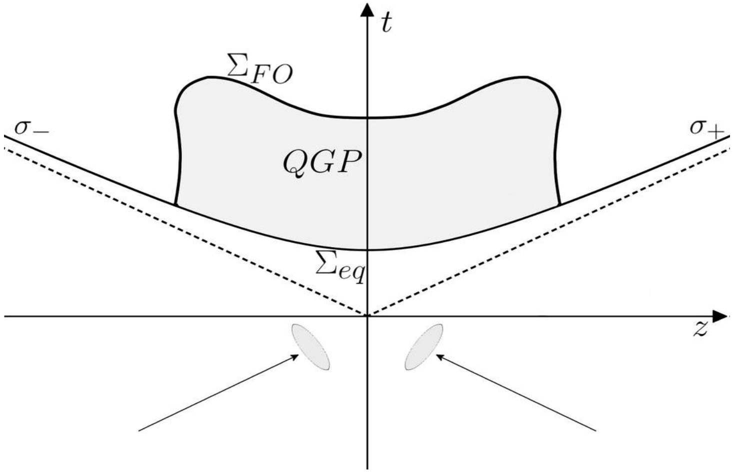
$$\widehat{J}^{\tau\nu}_x = \int \mathrm{d}\Sigma_\mu [\widehat{T}^{\mu\tau}(x-y)^\nu - \widehat{T}^{\mu\nu}(x-y)^\tau] = \int \mathrm{d}\Sigma_\mu \widehat{J}^{\mu,\tau\nu}$$

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

The Q operator depends on the hypersurface!

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

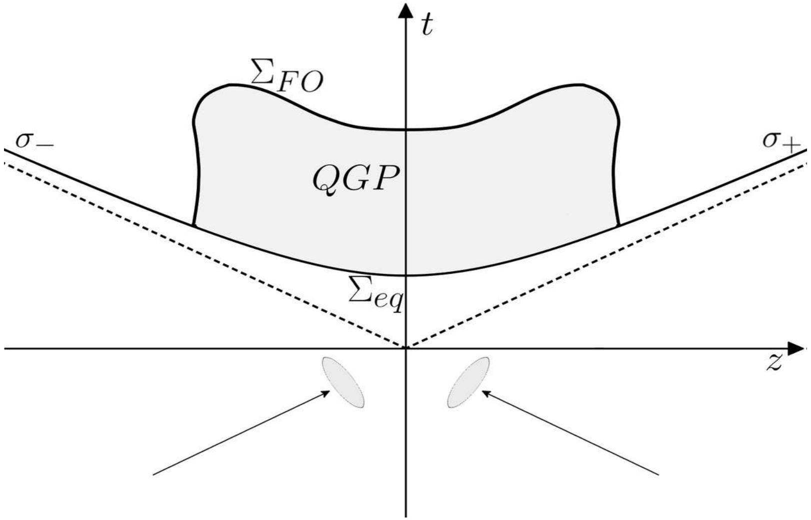
$$\partial_\mu \widehat{J}^{\mu,\nu\rho} = 0 \qquad \partial_\mu \widehat{Q}^{\mu,\nu\rho} \neq 0$$



Theory: local-equilibrium density operator

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

Hydrodynamic approximation: gradients are small.
Linear response theory



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

$$\widehat{\rho}_{LE} \simeq \frac{1}{Z_\beta} e^{-\beta(x)\cdot\widehat{P}} + \frac{1}{Z_\beta} \partial_\alpha \beta_\nu \int \mathrm{d}\Sigma_\mu \int_0^1 \mathrm{d}z\, e^{-(1+z)\beta(x)\cdot\widehat{P}} \widehat{T}^{\mu\nu} e^{z\beta(x)\cdot\widehat{P}} (y-x)^\alpha$$

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

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

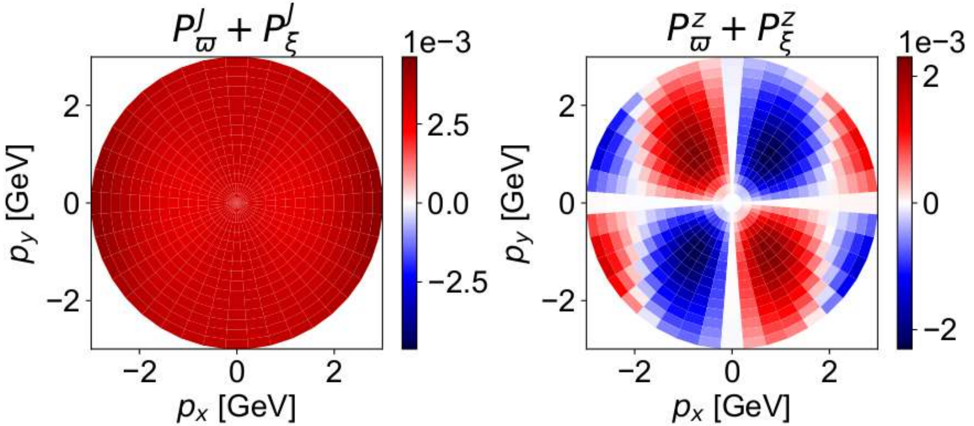
The gradients of the four-temperature contribute to polarization:

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

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

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

Vector $\hat{t}^\mu = (1, \mathbf{0})$ 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)*

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

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

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

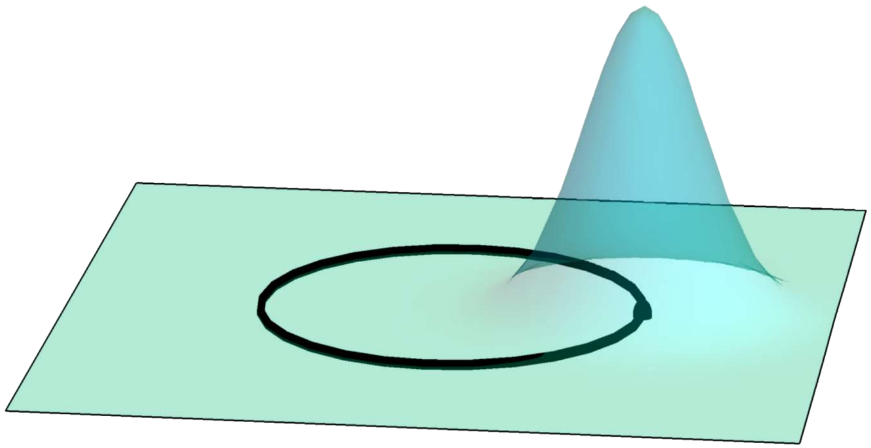
$$S^\mu_{ILE}(p) = -\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F)\left[\omega_{\rho\sigma} + 2\,\hat{t}_\rho \frac{p^\lambda}{\varepsilon}\Xi_{\lambda\sigma}\right]}{8 m T_{\rm dec}\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

Isothermal freeze-out

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

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

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



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

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

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