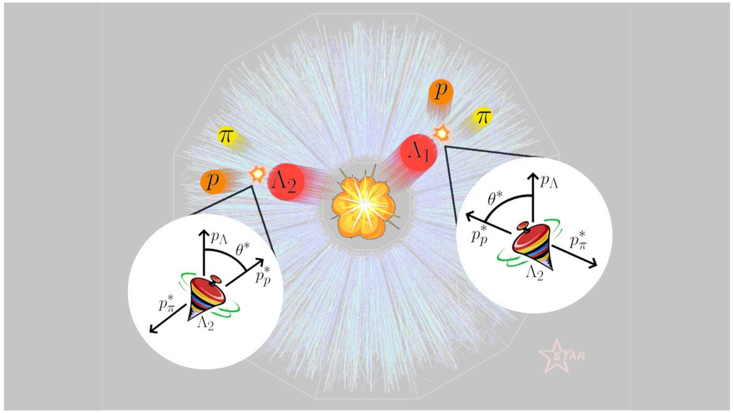
Local equilibrium and Λ-polarization in high-energy heavy-ion collisions

Based on:

F. Becattini, M. Buzzegoli, A.P., *Phys.Lett.B 820 (2021)*
F. Becattini, M. Buzzegoli, A.P. , I. Karpenko, G. Inghirami *Phys.Rev.Lett. 127 (2021)*
A.P., I. Karpenko, F. Becattini, *in preparation*



SQM 2022

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CRC-TR 211 Strong-interaction matter under extreme conditions

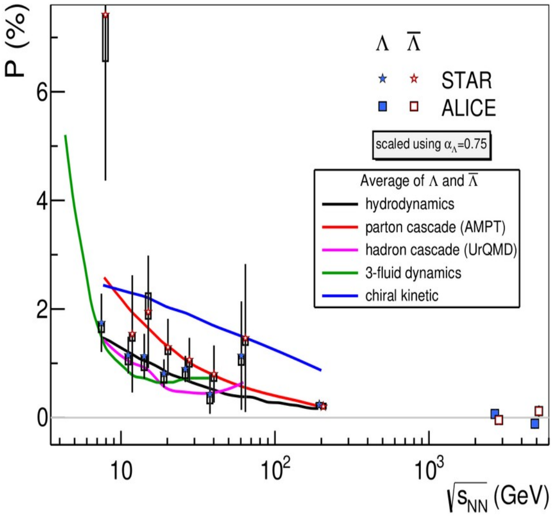
Motivations

Polarization is a probe of the fluidodynamical properties of the Quark-Gluon Plasma (QGP).

$$\beta^\mu = \frac{u^\mu}{T} \qquad \varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right)$$

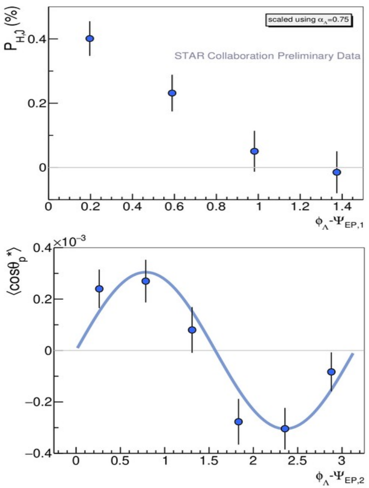
$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int \mathrm{d}\Sigma \cdot p \, n_F (1-n_F) \varpi_{\nu\rho}}{\int \mathrm{d}\Sigma \cdot p \, n_F}$$

F.Becattini, V.Chandra, L.Del Zanna, E.Grossi Annals Phys. 338 (2013)

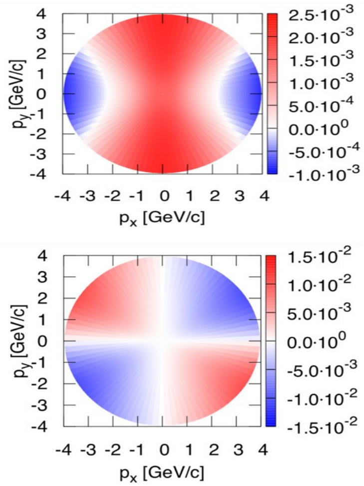


Global polarization

Data



Theory



Local polarization

SIGN PUZZLE

Additional contribution: *the thermal shear* ξ

(S.Liu, Y.Yin, JHEP 07 (2021), F. Becattini, M. Buzzegoli, A.P., Phys.Lett.B 820 (2021))

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

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\hat{t}_\nu \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\xi_{\sigma\rho}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

$\hat{t}^\mu = (1, \mathbf{0})$ in the lab frame.

Non-dissipative, **non-equilibrium** effect!

Restores qualitative agreement with the data

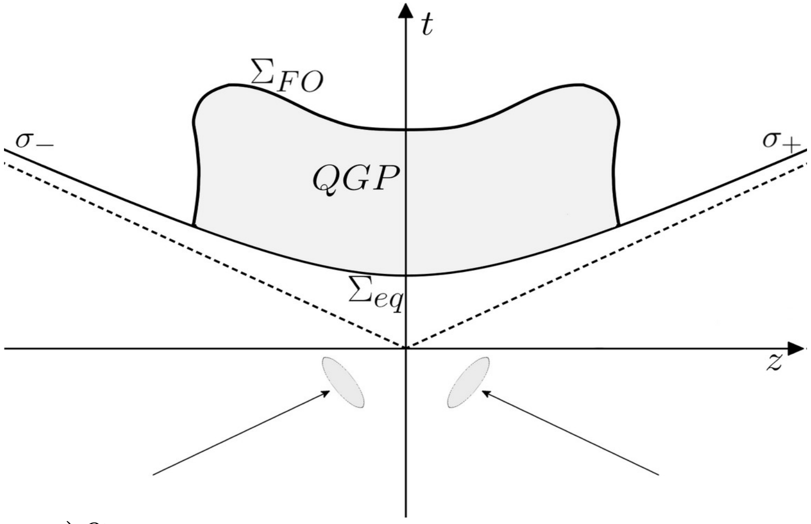
(B.Fu, S.Liu, L.Pang, H.Song, Y.Yin, Phys.Rev.Lett. 127 (2021); F.Becattini, M.Buzzegoli, A.P. , I.Karpenko, G.Inghirami Phys.Rev.Lett. 127 (2021))

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): $\langle \widehat{O} \rangle_\beta = \frac{1}{Z} \mathrm{Tr}\left(e^{-\beta(x)\cdot \widehat{P}} \widehat{O} \right)$

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

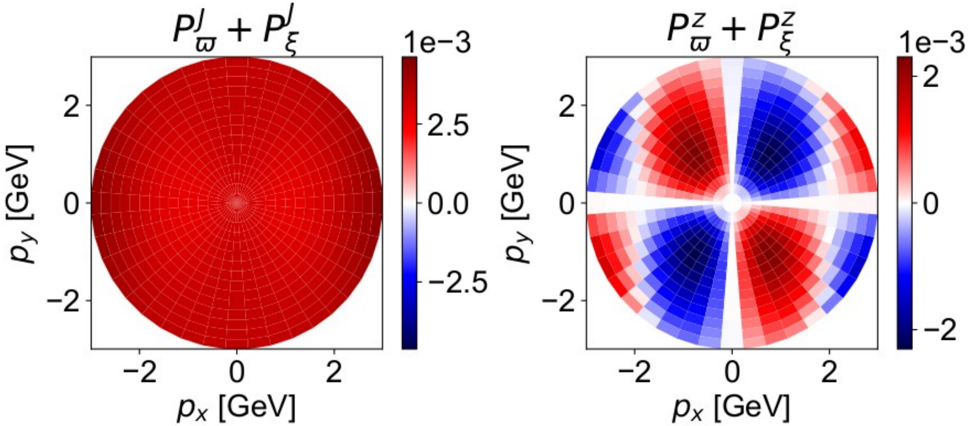
The gradients of the four-temperature contribute to polarization:

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

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

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

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)*

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

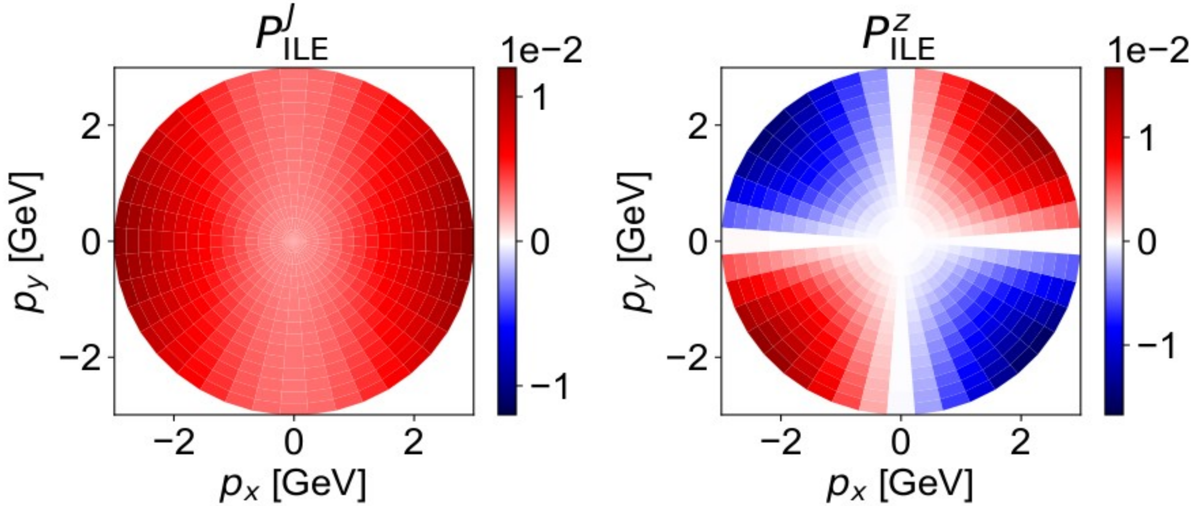
The final formula now depends only on gradients of the four velocity

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

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

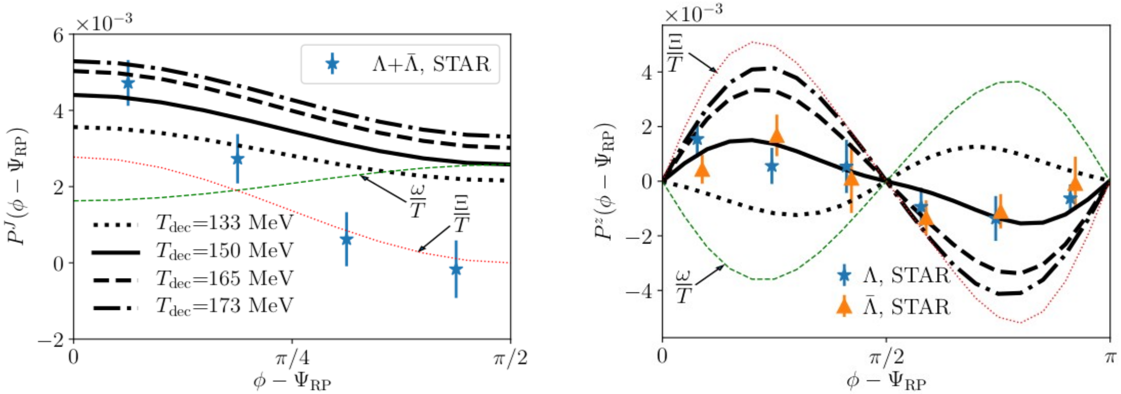
The isothermal decoupling hypersurface restores **agreement with the data.**

Polarization can **probe the decoupling hypersurface.**



Alternative approach, strange-memory scenario: Λ polarization is entirely given by the s-quark (slightly different formula).

B.*Fu, S.Liu, L.Pang, H.Song, Y.Yin, Phys.Rev.Lett. 127 (2021)*



vHLLE: AuAu $\sqrt{s}=200\mathrm{GeV}$, $\eta/s=0.08$, $\zeta/s=0$, Monte Carlo Glauber initial state.

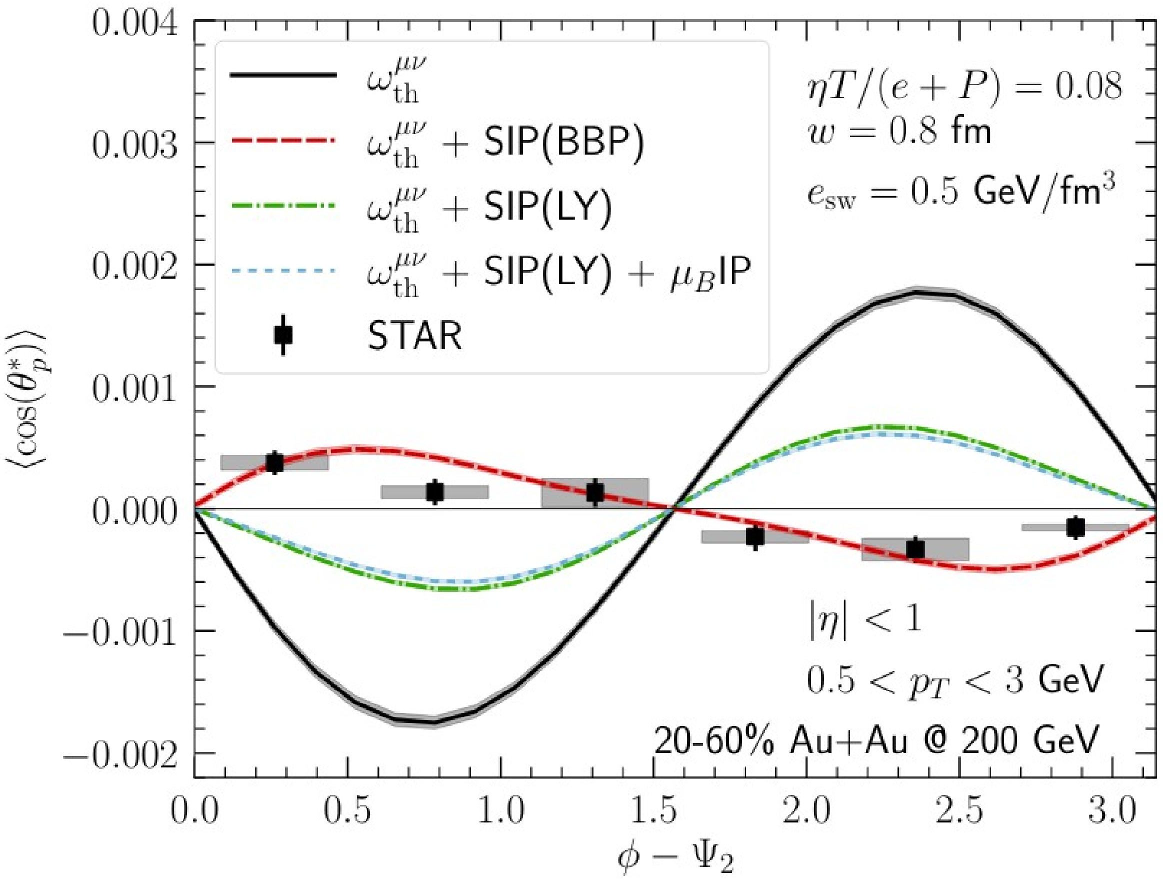
Recent developements

The initial state affects strongly the results.
(*S.Alzhrani, S.Ryu, C.Shen 2203.15718*)

Geometry-based initial state with local energy-momentum conservation.

More investigations needed.

Feed down corrections are not taken into account



Feed-down corrections

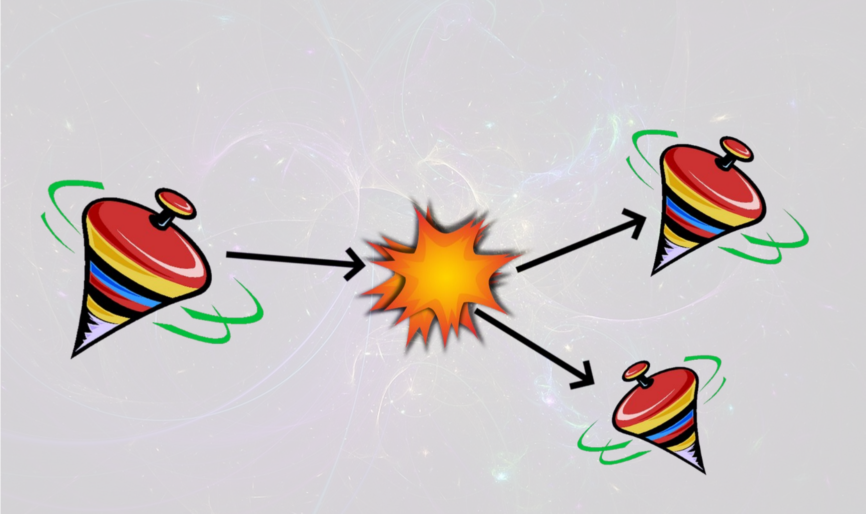
Most Λ particles do not come from the QGP but from decays.

We consider $\Sigma^{*}\rightarrow\Lambda\pi$ and $\Sigma_{0}\rightarrow\Lambda\gamma$.

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

The fractions of Λ produced in a given channel can be extimated from the statistical hadronization model.

$$n_{\Lambda}^{(FO)} \sim 0.243$$
$$n_{\Lambda}^{\Sigma_0} \sim 0.275 \times 60\%$$
$$n_{\Lambda}^{\Sigma^*} \sim 0.359$$

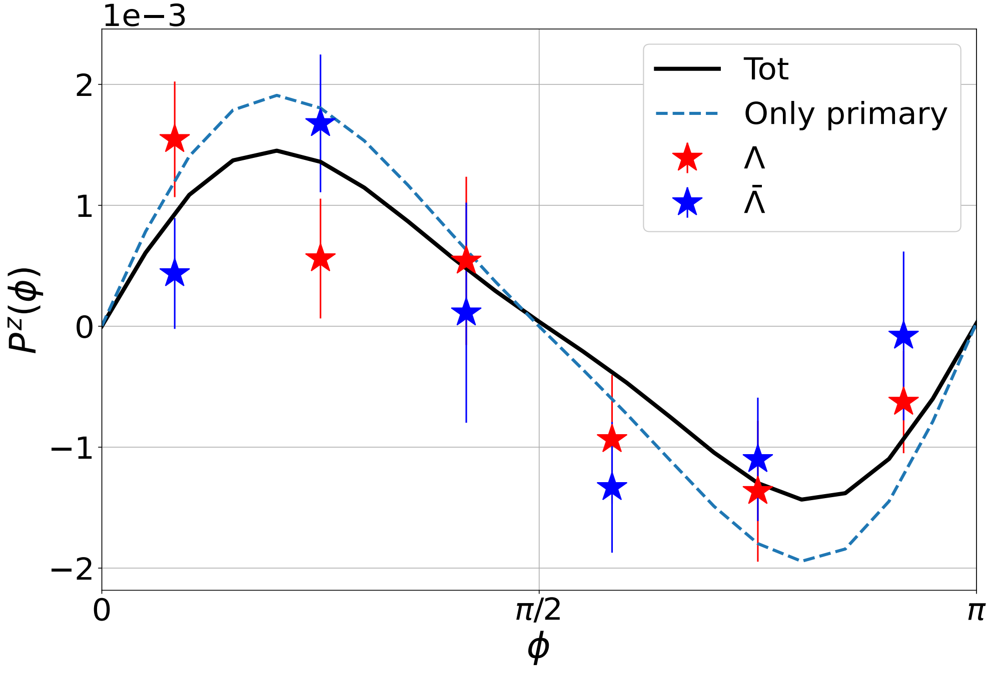


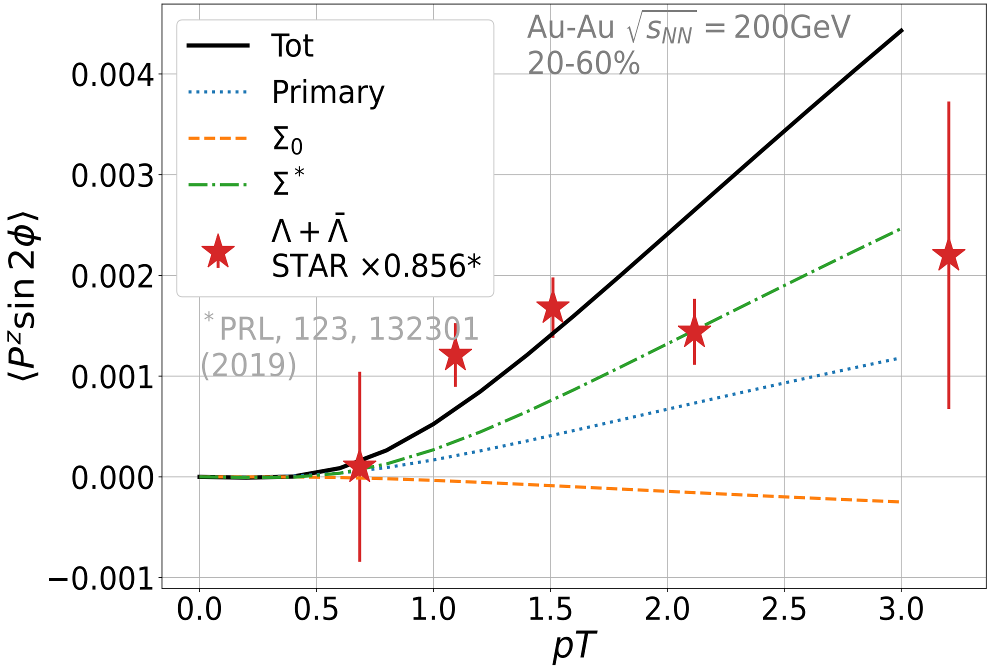
X.Xia, H.Li, X.Huang, X.Huang Phys.Rev.C 100 (2019); F.Becattini, G.Cao, E.Speranza Eur.Phys.J.C 79 (2019)

Feed-down corrections: 200 GeV

Including decays reduces the signal of about $\sim 20\%$

The data are well reproduced for $\mathrm{T_{dec}} \sim 160\ \mathrm{MeV}$

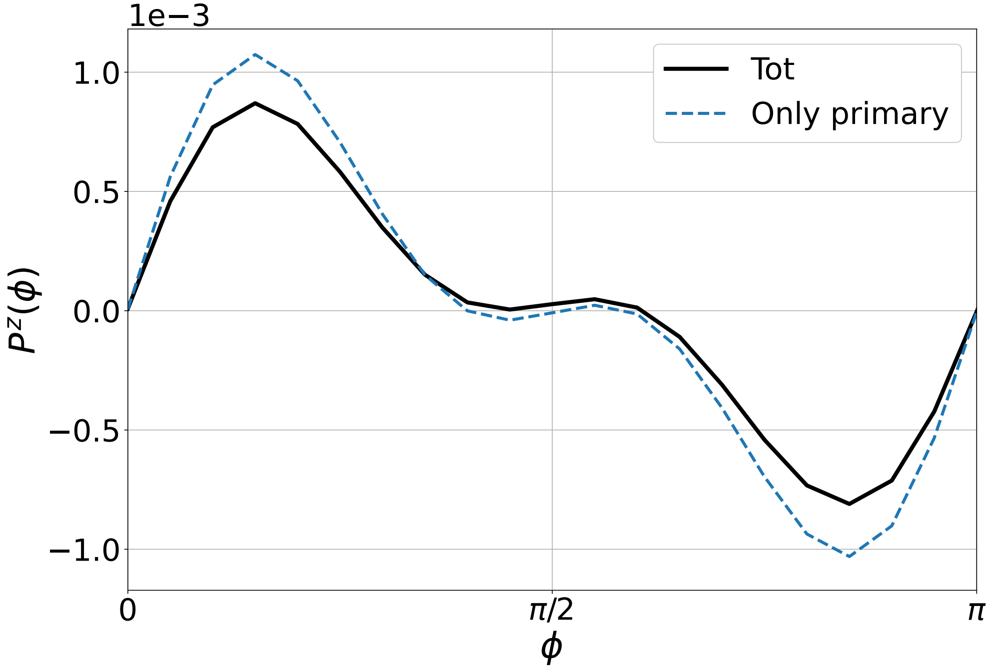


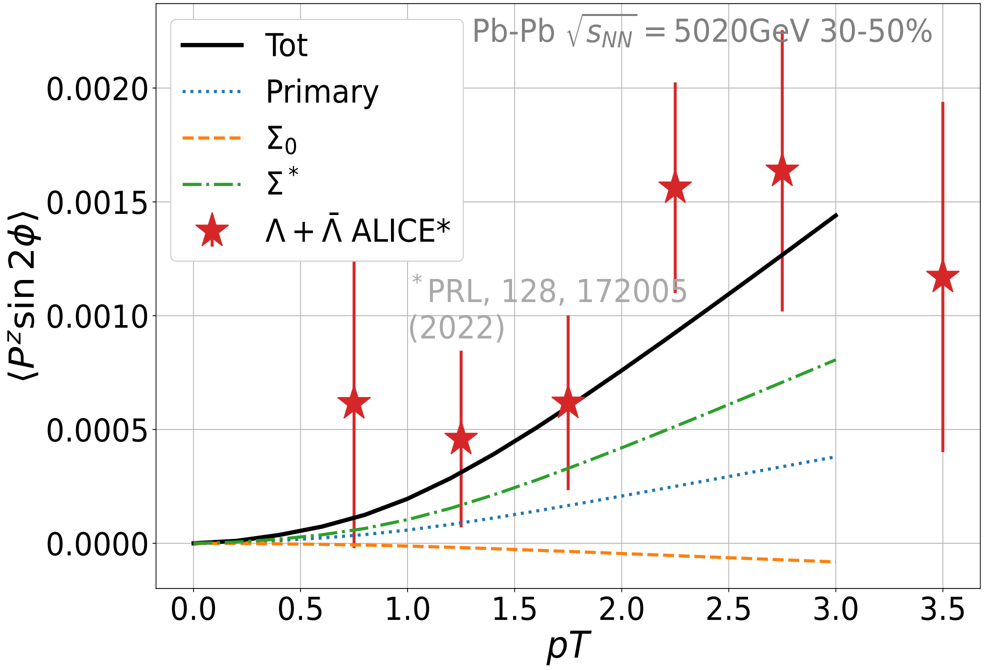


A.P., I.Karpenko, F.Becattini, (in preparation).

Feed-down corrections: 5.02 TeV

The feed down has a similar importance as at 200 GeV. To reproduce the data it is necessary to include the **bulk viscosity**.





Conclusion and outlook

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

- Additional contribution to spin polarization: **thermal shear spin coupling**
- **Isothermal freeze-out** fits the experimental data for a decoupling temperature $\mathrm{T_{dec}=160\ MeV}$
- Feed-down corrections contribute up to **20-25%** to the signal
- **Bulk viscosity** is needed to reproduce the experimental data at 5.02 TeV

→ Investigate initial state dependence

→ Impact of bulk viscosity

THANK YOU FOR THE ATTENTION!

Back up

Shear coupling

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

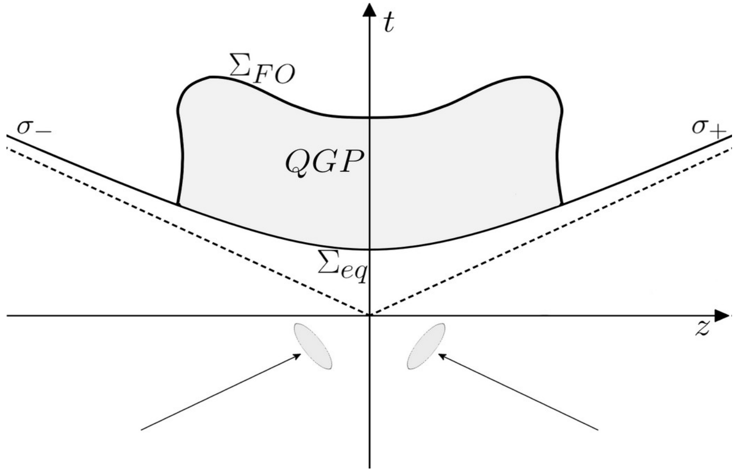
$$\widehat{J}^{\tau\nu}_x = \int \mathrm{d}\Sigma_\mu [\widehat{T}^{\mu\tau}(x-y)^\nu - \widehat{T}^{\mu\nu}(x-y)^\tau] = \int \mathrm{d}\Sigma_\mu \widehat{J}^{\mu,\tau\nu}$$

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

The Q operator depends on the hypersurface!

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

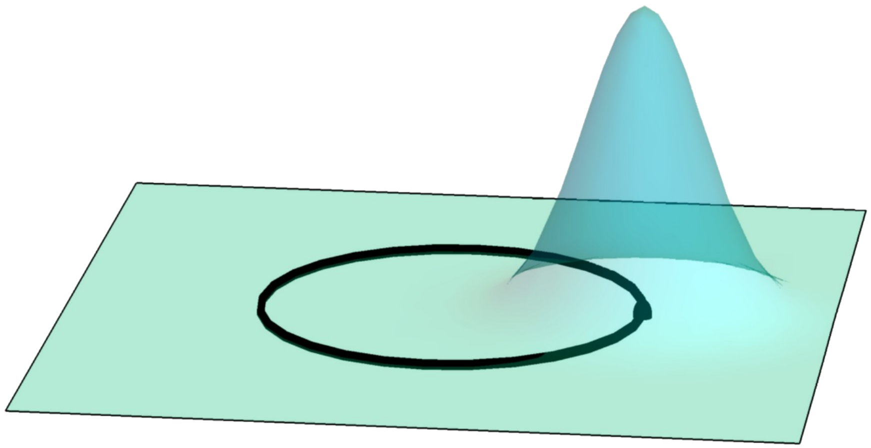
$$\partial_\mu \widehat{J}^{\mu,\nu\rho} = 0 \qquad \partial_\mu \widehat{Q}^{\mu,\nu\rho} \neq 0$$



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.