Polarization in heavy ion collisions: a theoretical review

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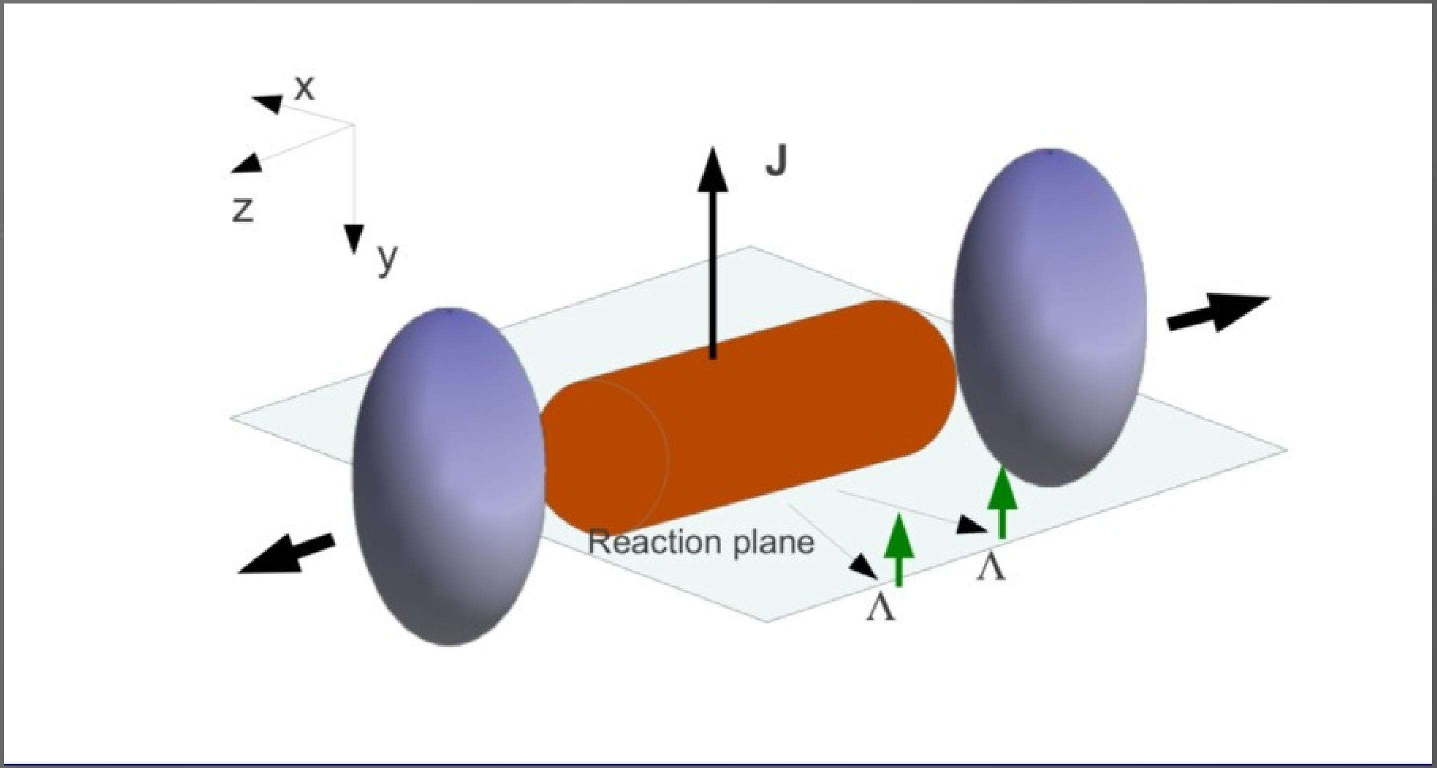
Premise

- Spin physics in heavy ion collisions has developed quickly and intensively in the last two years, especially in the theory sector
- This is not a comprehensive review

Peripheral collisions: large angular momentum

Peripheral collisions ⇨ Angular momentum ⇨ Global polarization w.r.t. reaction plane

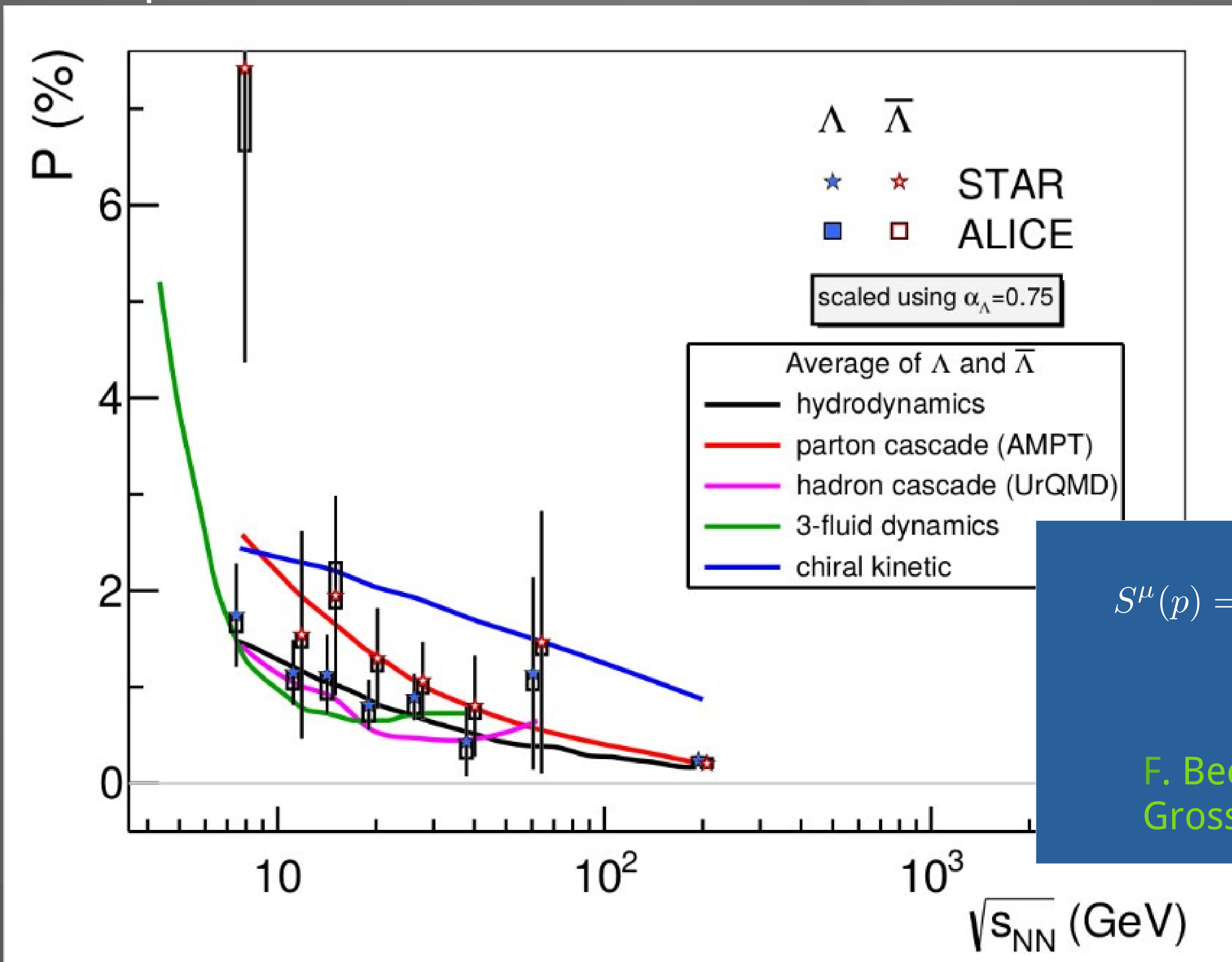


- Polarization estimated at quark level by spin-orbit coupling
  Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94 (2005) 102301
- By local thermodynamic equilibrium of the spin degrees of freedom
  F. Becattini, F. Piccinini, Ann. Phys. 323 (2008) 2452; F. Becattini, F. Piccinini, J. Rizzo, Phys. Rev. C 77 (2008) 024906

Spin $\propto$(thermal) vorticity

Agreement between hydrodynamic predictions and the data

Global polarization



Different models of the collision, same formula for polarization

$$S^\mu(p) = \frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\partial_\rho \beta_\sigma}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

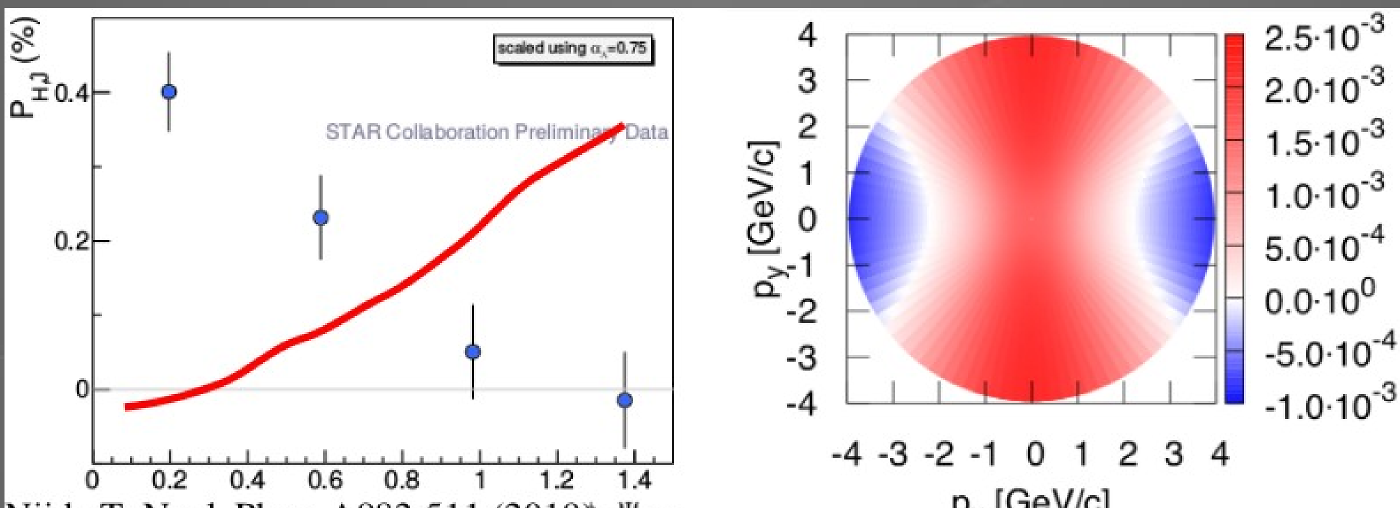
$$n_F = \left(\mathrm{e}^{\beta\cdot p - \zeta} + 1\right)^{-1}$$

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338:32 (2013)

F. Becattini, M. Lisa, Polarization and vorticity in the QGP, Ann. Rev. Part, Nucl. Sc. 70, 395 (2020)

Puzzles: momentum dependence of polarization

a strong motivation for theoretical investigation!



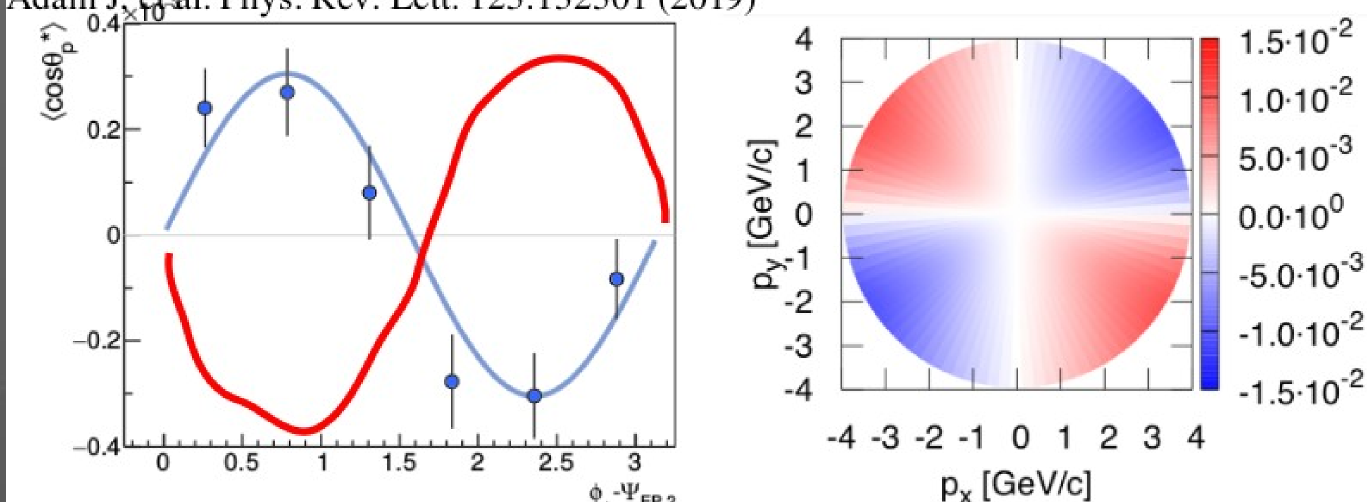
Niida T. Nucl. Phys. A982:511 (2019)

Au + Au, 20 - 60 %

$\sqrt{s_{NN}} = 200$ GeV

Theory prediction

Adam J. et al. Phys. Rev. Lett. 123:132301 (2019)



Not the effect of decays:

X. L. Xia, H. Li, X.G. Huang and H. Z. Huang, Phys. Rev. C 100 (2019), 014913

F. Becattini, G. Cao and E. Speranza, Eur. Phys. J. C 79 (2019) 741

Polarization of fermions in a relativistic fluid: basic theory tools

The covariant Wigner function of the free Dirac field:
(of the effective hadronic fields):

$$W(x,k)_{AB} = \frac{1}{(2\pi)^4} \int \mathrm{d}^4 y \, \mathrm{e}^{-ik\cdot y} \langle : \bar{\Psi}_B(x+y/2) \Psi_A(x-y/2) : \rangle$$

where:

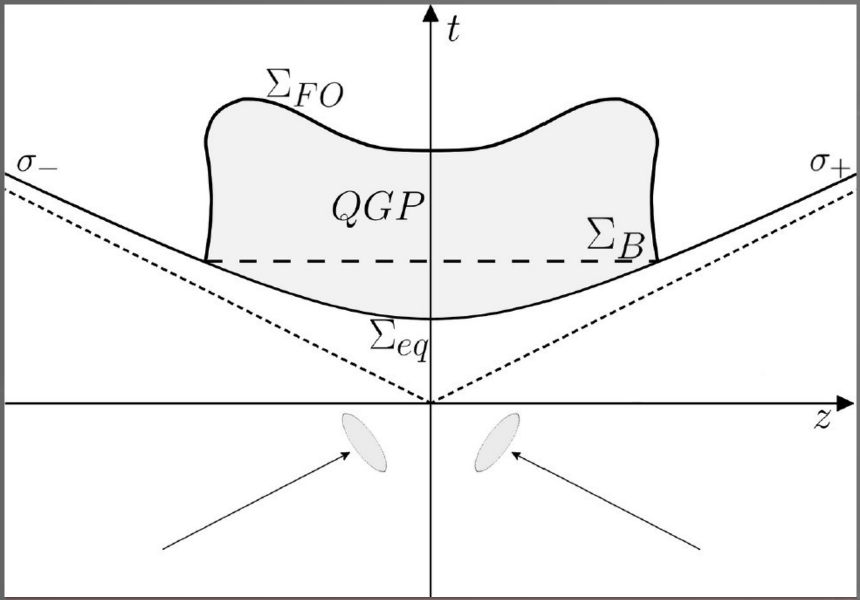
$$\langle \widehat{X} \rangle = \mathrm{tr}\left(\widehat{\rho}\, \widehat{X} \right)$$

It allows to calculate the mean spin vector:

$$S^\mu(p) = \frac{1}{2} \frac{\int \mathrm{d}\Sigma \cdot p \, \mathrm{tr}_4 \left[\gamma^\mu \gamma^5 W_+(x,p) \right]}{\int \mathrm{d}\Sigma \cdot p \, \mathrm{tr}_4 W_+(x,p)}$$

F. Becattini, Lect. Notes Phys. 987 (2021) 15-52.

Density operator - Zubarev theory



D.N. Zubarev, et al, Theor. Math. Phys. 1979, 40, 821
C.G. van-Weert, Ann. Phys. 1982, 140, 133
F. Becattini, MB, E. Grossi, Particles 2 (2019)
MB, Lect. Notes Phys. 987 (2021) 53-93.

General covariant Local thermodynamic Equilibrium density operator:

$$\widehat{\rho} = \frac{1}{Z} \exp\left[-\int_{\Sigma_{eq}} \mathrm{d}\Sigma_\mu \left(\widehat{T}^{\mu\nu} \beta_\nu - \zeta \, \widehat{j}^\mu \right) \right]$$

$$\beta^\nu = \frac{u^\nu}{T}, \quad \zeta = \frac{\mu}{T}$$

The operator is obtained by maximizing the entropy:

$$S = -\mathrm{tr}\left(\widehat{\rho} \log \widehat{\rho} \right)$$

with the constraints of fixed energy-momentum density

With the Gauss theorem:

$$\widehat{\rho} = \frac{1}{Z} \exp\left[-\int_{\Sigma_{FO}} \mathrm{d}\Sigma_\mu \left(\widehat{T}^{\mu\nu} \beta_\nu - \zeta \, \widehat{j}^\mu \right) + \underbrace{\int_\Theta \mathrm{d}\Theta \left(\widehat{T}^{\mu\nu} \nabla_\mu \beta_\nu - \widehat{j}^\mu \nabla_\mu \zeta \right)}_{\text{Dissipative}} \right]$$

Local thermodynamic equilibrium

Non-dissipative ⇒ $$\widehat{\rho}_{\rm LE} = \frac{1}{Z}\exp\left[-\int_{\Sigma_{FO}} {\rm d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta\,\widehat{j}^\mu\right)\right]$$

Hydrodynamic approximation (β and ζ are slowly varying fields)

$$\widehat{\rho}_{LE} \simeq \frac{1}{Z}\exp\Big[-\beta_\nu(x)\widehat{P}^\nu + \zeta(x)\widehat{Q} + \frac{1}{2}\varpi_{\mu\nu}(x)\widehat{J}^{\mu\nu}_x - \frac{1}{2}\xi_{\mu\nu}(x)\widehat{Q}^{\mu\nu}_x + \partial_\lambda\zeta(x)\int {\rm d}\Sigma_\mu (y-x)^\lambda \widehat{j}^\mu(y) + \cdots\Big]$$

$$\widehat{J}^{\mu\nu}_x = \int {\rm d}\Sigma_\lambda \left[(y-x)^\mu \widehat{T}^{\lambda\nu}(y) - (y-x)^\nu \widehat{T}^{\lambda\mu}(y)\right] \qquad \widehat{Q}^{\mu\nu}_x = \int {\rm d}\Sigma_\lambda \left[(y-x)^\mu \widehat{T}^{\lambda\nu}(y) + (y-x)^\nu \widehat{T}^{\lambda\mu}(y)\right]$$

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

Thermal vorticity

Adimensional in natural units

Equilibrium

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

Thermal shear

Adimensional in natural units

Non-equilibrium

Gradient of chemical potential $\partial_\lambda\zeta$

Non-equilibrium

At global equilibrium the thermal shear vanishes because of the Killing equation

Spin polarization at local thermal equilibrium

Linear response theory ⇒ $S^\mu(p) = S^\mu_\varpi + S^\mu_\xi + S^\mu_{\partial\zeta} + \cdots$

Vorticity:

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

Shear:

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

F. Becattini, MB, A. Palermo, Phys. Lett. B 820 (2021) 136519

Same (not precisely the same) formula obtained by Liu and Yin with a different method:
S. Liu, Y. Yin, JHEP 07 (2021) 188

Chem. Potential:
(Spin Hall effect)

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

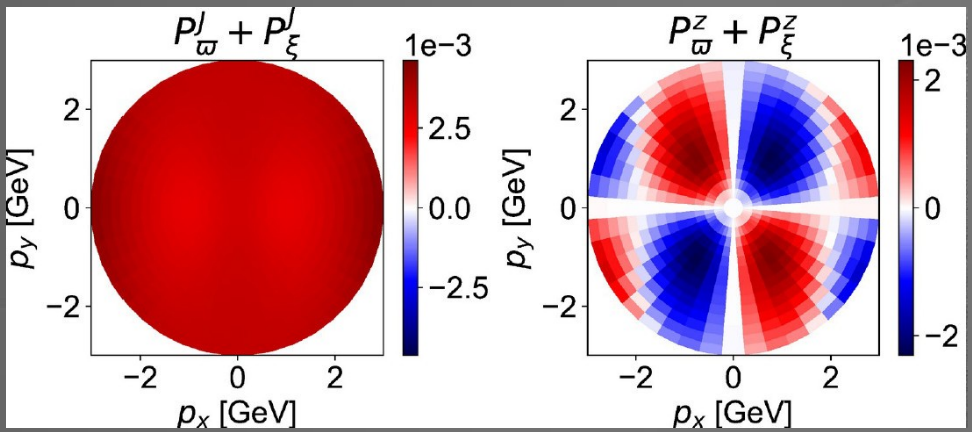
Shuai Y. F. Liu, and Yi Yin PRD 104, 054043 (2021)
B. Fu, L. Pang, H. Song and Y. Yin, 2201.12970

These additional local equilibrium terms have been confirmed in more analyses:

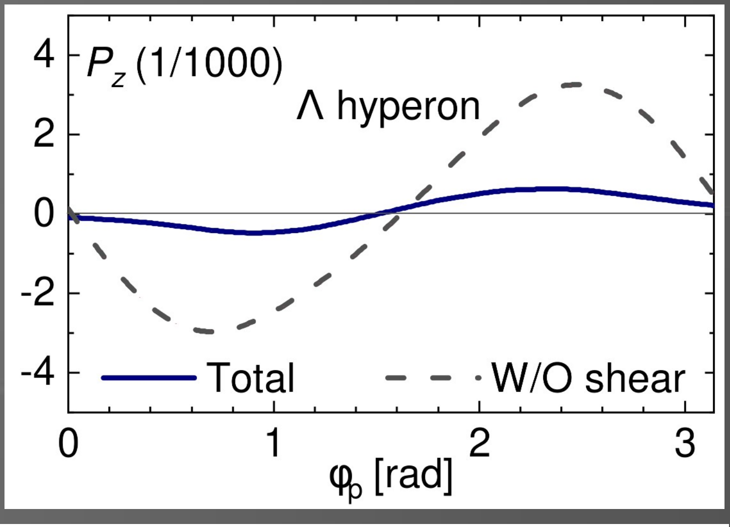
C. Yi, S. Pu, D. L. Yang, PRC 104, 064901 (2021)
Y. C. Liu, X. G. Huang, Sci. China-Phys. Mech. Astron. 65, 272011 (2022)

Local polarization
Shear-Spin coupling

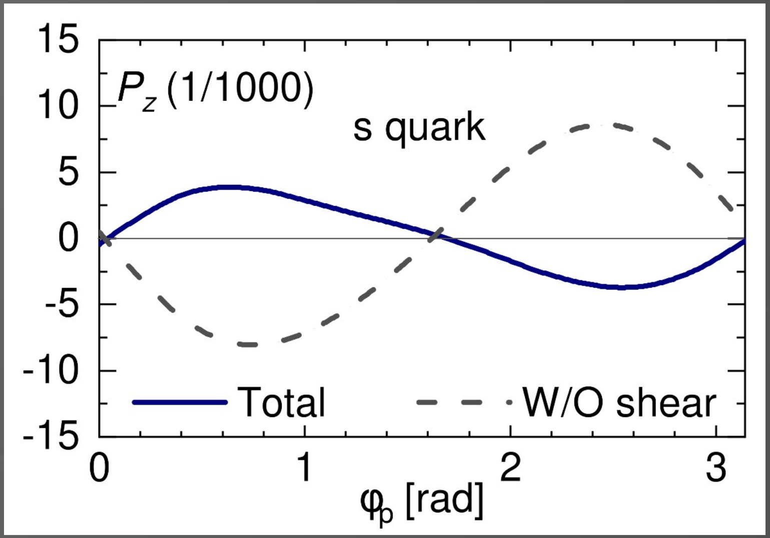
The shear-induced polarization is **not sufficient** to restore the agreement between data and model



F. Becattini, MB, A. Palermo, G. Inghirami and I. Karpenko, PRL 127 (2021) 27, 272302



Qualitative agreement found in the "strange memory" scenario



B. Fu, S. Liu, L. Pang, H. Song and Y. Yin, PRL 127 (2021) 14, 142301

Solution of the puzzle

Isothermal local equilibium (ILE)

At high energy, Σ_{FO} expected to be T_{FO}= constant! ⇒ Improved approximation

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

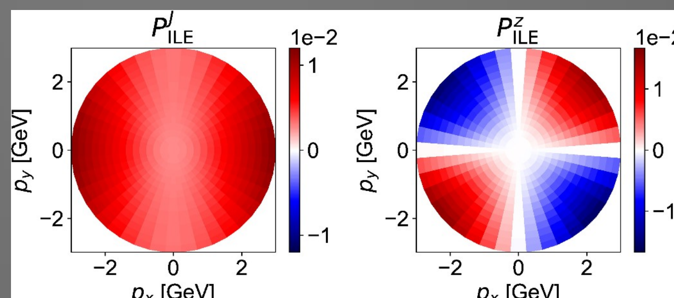
Kinematic vorticity

$$\omega_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho - \partial_\rho u_\sigma\right)$$

Kinematic shear

$$\Xi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho + \partial_\rho u_\sigma\right)$$

Quantitative agreement:



See A. Palermo's talk for feed-down and Pb+Pb at 5 TeV

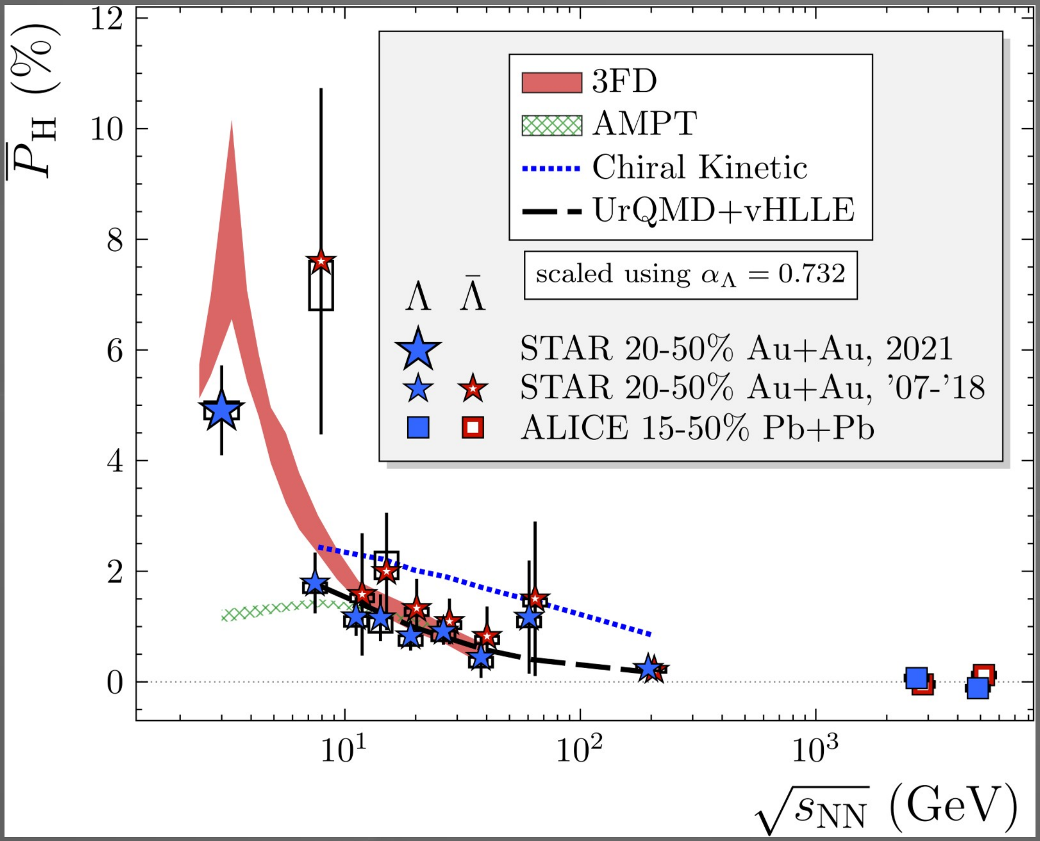
F. Becattini, MB, A. Palermo, G. Inghirami and I. Karpenko, PRL 127 (2021) 27, 272302

Recent analysis of shear induced polarization:
C. Yi, S. Pu, D. L. Yang, PRC 104, 064901 (2021);
Y. Sun, Z. Zhang, C. M. Ko and W. Zhao, PRC 105 (2022) 3, 034911;
S. Ryu, V. Jupic, C. Shen, PRC 104 (2021);
S. Alzhrani, S. Ryu, C. Shen, 2203.15718;
X.-Y. Wu, C. Yi, G.-Y. Qin, S. Pu, 2204.02218;

- Global polarization is not significantly affected by thermal shear
- The gradient of (μ/T) does not affect local polarization at high energy
- Sensitivity to initial conditions
- Isothermal equlibrium should be implemented at high energies

See also O. Lomicky's poster

Spin polarization at low energies



Polarization at very low energy
Ivanov, Toneev, Soldatov, PRC 100 (2019) 1, 014908;
Ivanov, Soldatov, PRC 105 (2022) 3, 034915,
Deng, Huang, Ma, Zhang, PRC 101 (2020) 6, 064908;
Deng, Huang, Ma, 2109.09956;
Guo, Liao, Wang, Xing, Zhang, PRC 104 (2021) 4, L041902;
See also J. Liao's talk and O. Vitiuk's poster

Role of chemical potential:
Liu, and Yin PRD 104, 054043 (2021);
Fu, Pang, Song, Yin, 2201.12970;
See also Q. Hu's poster

Role of the Magnetic field:
Guo, Shi, Feng and J. Liao, Phys. Lett. B 798(2019), 134929

M. S. Abdallah et al [STAR], PRC 104 (2021) no.6, L061901

Effect of shear induced polarization?

We need to include all first order contributions to spin polarization.

Pseudo-gauge dependence

The LTE operator is noninvariant under a pseudogauge transformation!
ONLY at global equilibrium it is

$$\widehat{T}^{\mu\nu}_{\Phi} = \widehat{T}^{\mu\nu}_{B} + \frac{1}{2}\nabla_{\lambda}\left(\widehat{\Phi}^{\lambda,\mu\nu} - \widehat{\Phi}^{\mu,\lambda\nu} - \widehat{\Phi}^{\nu,\lambda\mu}\right),$$

$$\widehat{\mathcal{S}}^{\lambda,\mu\nu}_{\Phi} = -\widehat{\Phi}^{\lambda,\mu\nu} + \nabla_{\rho}\widehat{Z}^{\mu\nu,\lambda\rho}$$

$$\widehat{\rho}^{\Phi}_{\rm LTE} = \frac{1}{\mathcal{Z}}\exp\left\{-\int {\rm d}\Sigma_{\mu}\left[\widehat{T}^{\mu\nu}_{B}\beta_{\nu} - \frac{1}{2}\left(\varpi_{\lambda\nu} - \Omega_{\lambda\nu}\right)\widehat{\Phi}^{\mu,\lambda\nu} - \xi_{\lambda\nu}\widehat{\Phi}^{\lambda,\mu\nu} - \frac{1}{2}\Omega_{\lambda\nu}\nabla_{\rho}Z^{\lambda\nu,\mu\rho} - \widehat{j}^{\mu}\zeta\right]\right\}$$

F. Becattini, W. Florkowski, and E. Speranza, Phys. Lett. B 789, 419 (2019)

If the spin tensor is nonzero (non-Belinfante) angular momentum constraints must be additionally implemented with spin potential: $\Omega_{\lambda\nu}$
Confirmed in the analysis by K. Fukushima, Shi Pu, Phys. Lett. B 817 (2021) 136346

Hydrodynamic with a spin tensor

W. Florkowski, A. Kumar, R. Ryblewski, Prog. Part. Nucl. Phys. 108 (2019) 103709;
M. Hongo, X. G. Huang, M. Kaminski, M. Stephanov, H.U. Yee, JHEP 11 (2021), 150 and 2201.12390;
K. Hattori et al, Phys.Lett.B 795 (2019) 100; S. Bhadury et al, Eur.Phys.J.ST 230 (2021) 3, 655;
D. She et al, 2105.04060; S. Bhadury et al., Phys.Rev.D 103 (2021) 1, 014030; Z. Cao et al, 2205.0805

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F. Becattini, W. Florkowski, and E. Speranza, Phys. Lett. B 789, 419 (2019)

If the spin tensor is nonzero (non-Belinfante) angular momentum constraints must be additionally implemented with spin potential: $\Omega_{\lambda\nu}$

Spin polarization predictions are pseudo-gauge dependent MB, PRC 105, 044907 (2022)

- Canonical spin potential induced polarization

$$S^\mu_\Omega(k) = \frac{\epsilon^{\lambda\rho\sigma\tau}\hat{t}_\lambda(k^\mu k_\tau - \eta^\mu_\tau m^2)}{8m\varepsilon_k}\frac{\int_\Sigma {\rm d}\Sigma(x)\cdot k\, n_F\left(1-n_F\right)\left(\varpi_{\rho\sigma} - \Omega_{\rho\sigma}\right)}{\int_\Sigma {\rm d}\Sigma\cdot k\, n_F}$$

- de Groot–van Leeuwen–van Weert (GLW) and Hilgevoord-Wouthuysen (HW) shear induced polarization $S^\mu_\xi(k) = 0$

Role of pseudo-gauge transformations
F. Becattini, W. Florkowski, and E. Speranza, Phys. Lett. B 789, 419 (2019)
E. Speranza and N. Weickgenannt, Eur. Phys. J. A 57, 155 (2021)
K. Fukushima and S. Pu, Phys. Lett. B 817, 136346 (2021)
A. Das, W. Florkowski, R. Ryblewski and R. Singh, Phys. Rev. D 103, L091502 (2021)
S. Li, M. A. Stephanov and H. U. Yee, Phys. Rev. Lett. 127, 082302 (2021)
N. Weickgenannt, D. Wagner and E. Speranza, 2204.01797

Pseudo-gauge dependence
Relativistic kinetic theory with spin

Trying to solve the dynamical Wigner equation for interacting fermions without the introduction of the density operator

$$\left[\gamma\cdot\left(p+\mathrm{i}\frac{\hbar}{2}\partial\right)-m\right]W_{\alpha\beta}=\hbar\,\mathcal{C}_{\alpha\beta}$$

Equilibrium problem

Equilibrium form of the Wigner function is an *ansatz* and for consistency it depends on the chosen pseudo-gauge.

- Wigner-function formalism, recent developments
  N. Weickgenannt, X.-L. Sheng, E. Speranza, Q. Wang, and D. H. Rischke, PRD100, 056018 (2019)
  J.-H. Gao and Z.-T. Liang, PRD100, 056021(2019)
  K. Hattori, Y. Hidaka, and D.-L. Yang, PRD100, 096011 (2019)
  Y.-C. Liu, K. Mameda, and X.-G. Huang, Chin.Phys.C 44 (2020) 9, 094101
  N. Weickgenannt, E. Speranza, X.-l. Sheng, Q. Wang, and D.H. Rischke, PRL127 (2021) 5, 052301
  X.L. Sheng, N. Weickgenannt, E. Speranza, D. H. Rischke , Q. Wang PRD104 (2021) 1, 016022

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Equilibrium form of the Wigner function is an *ansatz* and for consistency it depends on the chosen pseudo-gauge.

The exact form of the equilibrium solution for free fermions at all orders has been recently derived:

A. Palermo, MB, F. Becattini, JHEP 10 (2021) 077, F. Becattini, MB, A. Palermo, JHEP 02 (2021) 101

$$W(x,k)=\frac{1}{(2\pi)^3}\int\frac{\mathrm{d}^3\mathrm{p}}{2\varepsilon}\sum_{n=1}^{\infty}(-1)^{n+1}\mathrm{e}^{-n\widetilde{\beta}_n\cdot p}\times$$
$$\left[S(\Lambda)^n(m+\not{p})\delta^4\left(k-\frac{\Lambda^n p+p}{2}\right)+(m-\not{p})S(\Lambda)^{-n}\delta^4\left(k+\frac{\Lambda^n p+p}{2}\right)\right]$$

Spin and dissipative corrections

$$\widehat{\rho} = \frac{1}{Z}\exp\left[-\int_{\Sigma_{FO}} \mathrm{d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta\,\widehat{j}^\mu\right) + \underbrace{\int_\Theta \mathrm{d}\Theta\left(\widehat{T}^{\mu\nu}\nabla_\mu\beta_\nu - \widehat{j}^\mu\nabla_\mu\zeta\right)}_{\text{Dissipative}}\right]$$

For massless field: S. Shi, C. Gale, S. Jeon, Phys. Rev. C 103 (2021) 4, 044906

$$\begin{aligned} S^\mu(p) = \frac{1}{2m_H}&\left\{\left[\int_\Sigma f_{V,0}\right] + \int_\Sigma f_{V,0}(1-f_{V,0})(\lambda_\nu \nu^\alpha p_\alpha + \lambda_\pi \pi^{\alpha\beta}p_\alpha p_\beta)\right\}^{-1} \\ &\times\left\{\left[-\frac{\hbar}{4}\epsilon^{\mu\nu\rho\sigma}\int_\Sigma p_\nu \varpi_{\rho\sigma} f_{V,0}(1-f_{V,0})\right] + \int_\Sigma p^\mu f_{V,0}(1-f_{V,0})\frac{\mu_A}{T}\right. \\ &\left. + \int_\Sigma p^\mu f_{V,0}(1-f_{V,0})\left(\frac{\lambda_\nu}{2}\nu_A^\alpha p_\alpha + \frac{\lambda_\nu^+ - \lambda_\nu^-}{2}\nu^\alpha p_\alpha + \frac{\lambda_\pi^+ - \lambda_\pi^-}{2}\pi^{\alpha\beta}p_\alpha p_\beta\right)\right\} + \mathcal{O}(\hbar^2) \end{aligned}$$

For massive field (in HW pseudo-gauge): N. Weickgenannt, D. Wagner, E. Speranza and D. Rischke, 2203.04766.

$$\begin{aligned} \Pi^\mu(p) = &\frac{1}{2\mathcal{N}}\left(g^\mu{}_\nu - \frac{p^\mu p_\nu}{p^2}\right)\int d\Sigma_\lambda p^\lambda f_{0p}\left\{-\frac{\hbar}{2m}\tilde{\Omega}^{\nu\rho}\left(E_p u_\rho + p_{\langle\rho\rangle}\right) + \chi_{\mathfrak{p}}\mathfrak{p}^{\langle\nu\rangle} - 6\chi_{\mathfrak{n}}\mathfrak{q}^{\rho\nu}{}_\rho + \mathfrak{x}_{\mathfrak{n}}u^\nu\mathfrak{z}^\lambda{}_\lambda\right. \\ &\left. + \left[\chi_{\mathfrak{z}}\mathfrak{z}^{\nu\alpha} + \left(\mathfrak{x}_{\mathfrak{q}}\mathfrak{q}^{\lambda\alpha}{}_\lambda + \mathfrak{x}_{\mathfrak{p}}\mathfrak{p}^{\langle\alpha\rangle}\right)u^\nu\right]p_{\langle\alpha\rangle} + \left(\chi_{\mathfrak{q}}\mathfrak{q}^{\langle\nu\rangle\alpha\beta} + \mathfrak{x}_{\mathfrak{z}}u^\nu\mathfrak{z}^{\langle\alpha\beta\rangle}\right)p_{\langle\alpha}p_{\beta\rangle}\right\} \end{aligned}$$

Relaxation time of spin:

Yoshimasa Hidaka, Shi Pu, Di-Lun Yang, Phys.Rev.D 97 (2018) 1, 016004;
M. Hongo, X.G. Huang, M. Kaminski, M. Stephanov, H.U. Yee, JHEP 11 (2021), 150 and 2201.12390;

New transport coefficients related to spin

Rich Phenomenology

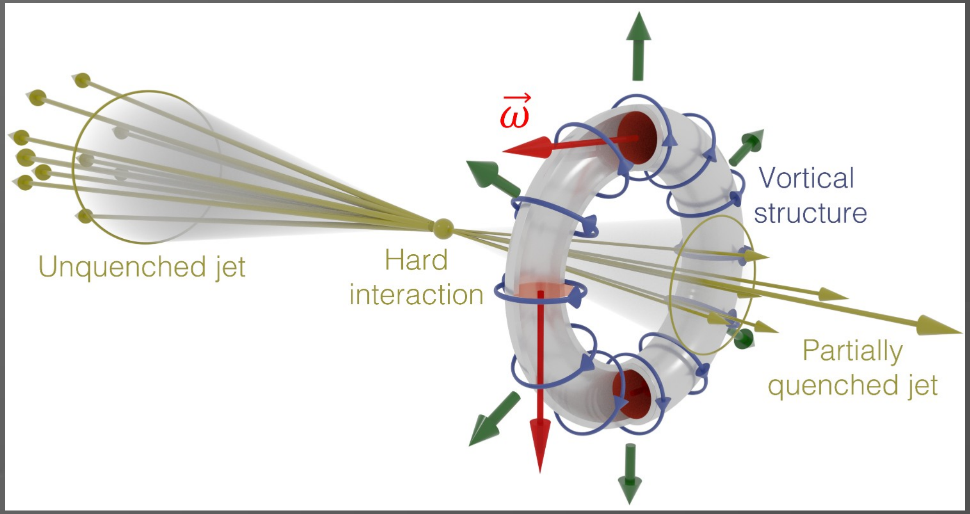
- Use of Λ polarization and spin-spin correlation to study vorticity structure and properties of the QGP

L. Pang, H. Petersen, Q. Wang, and X.-N. Wang, PRL 117,192301 (2016);
X. L. Xia, H. Li, Z. B. Tang and Q. Wang, PRC 98, 024905 (2018);
S. Ryu, V. Jupic, C. Shen, PRC 104 (2021) 054908;

- Use of Λ polarization to detect vortices induced by the jet energy loss

W. Serenone, J. Barbon, D. Chinellato, M. Lisa, C. Shen, J. Takahashi, G. Torrieri, Phys.Lett.B 820 (2021) 136500

Sensitive to shear-viscosity



Spin polarization as a probe

- Spin as a tool to reveal local parity violation without the mediation of the EM field

$$S^\mu(p) = S^\mu_{\text{hydro}}(p) + \frac{g_h}{2} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p \, \zeta_A n_F \, (1 - n_F)}{\int_\Sigma \mathrm{d}\Sigma \cdot p \, n_F} \frac{\varepsilon p^\mu - m^2 \hat{t}^\mu}{m\varepsilon}$$

F. Du, L. E. Finch and J. Sandweiss, Phys. Rev. C 78(2008), 044908
F. Becattini, MB, A. Palermo, G. Prokhorov, Phys. Lett. B 822 (2021) 136706s
J. H. Gao, Phys. Rev. D 104 (2021) 7, 076016

- Radiative corrections to spin-rotation coupling are caused by the breaking of the Einstein equivalence principle at finite temperature

$$\vec{S} \sim g_\Omega \, \vec{\omega} \quad g_\Omega = 1 - \frac{N_c^2 - 1}{2} \frac{1}{6} \frac{g^2 T^2}{m^2}, \, T \ll m$$

MB, D. Kharzeev, Phys. Rev. D 103 (2021) 11, 116005

- Use spin polarization to reveal the presence of the QCD critical point

S. K. Singh and J. e. Alam, arXiv:2110.15604

Summary and Outlook

- Make predictions with all first order non-dissipative contributions to spin polarization
- Relevance of dissipative effects?
- What is the role of pseudo-gauge transformations?
- Spin as a tool to investigate fundamental physics in the QGP and beyond

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Thank you!

Backup

Decomposition of thermal shear

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

A is the acceleration field
ω is the rotation field

$$\sigma_{\mu\nu} = \frac{1}{2}(\nabla_\mu u_\nu + \nabla_\nu u_\mu) - \frac{1}{3}\Delta_{\mu\nu}\theta$$

$$\theta = \nabla \cdot u$$

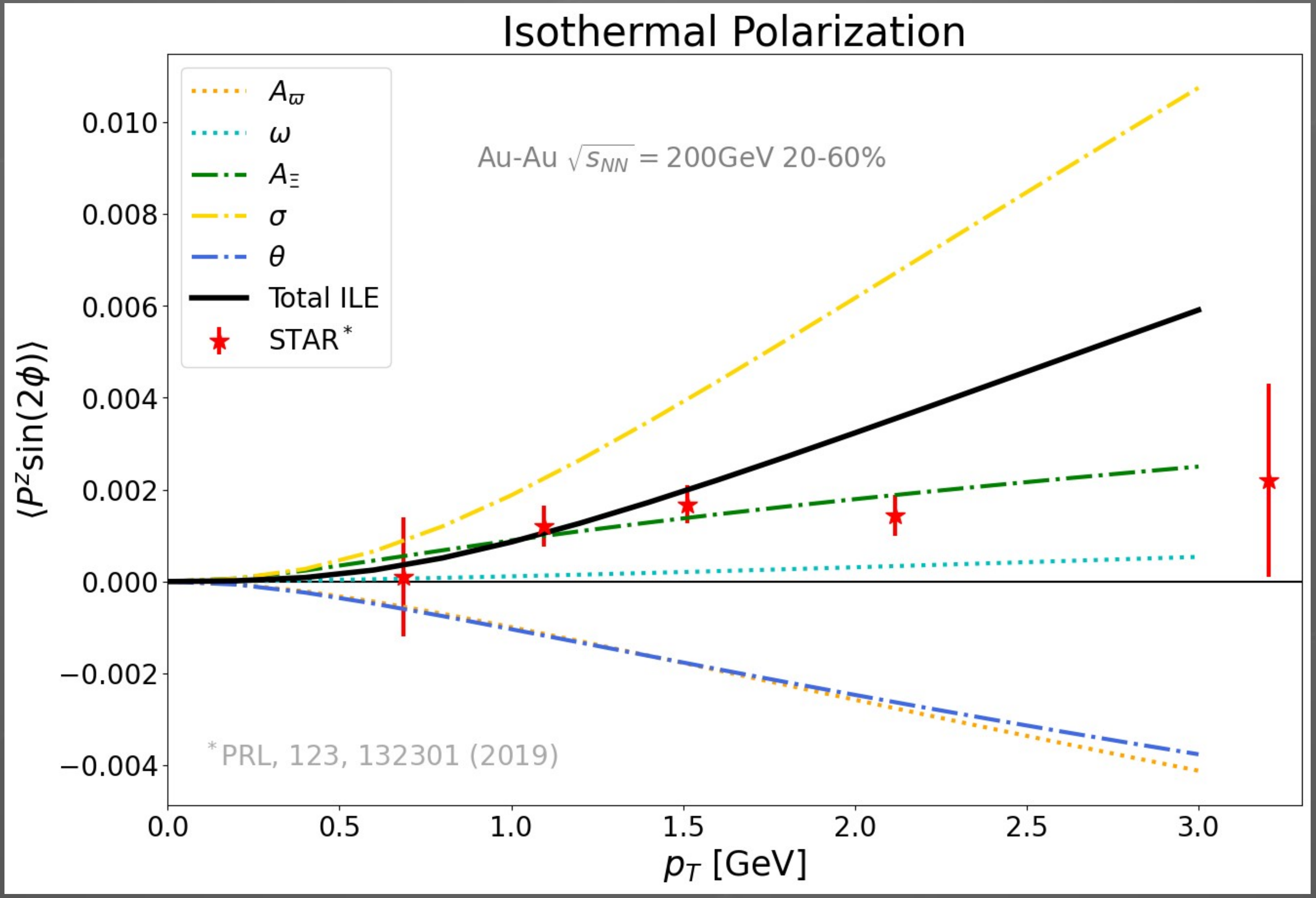
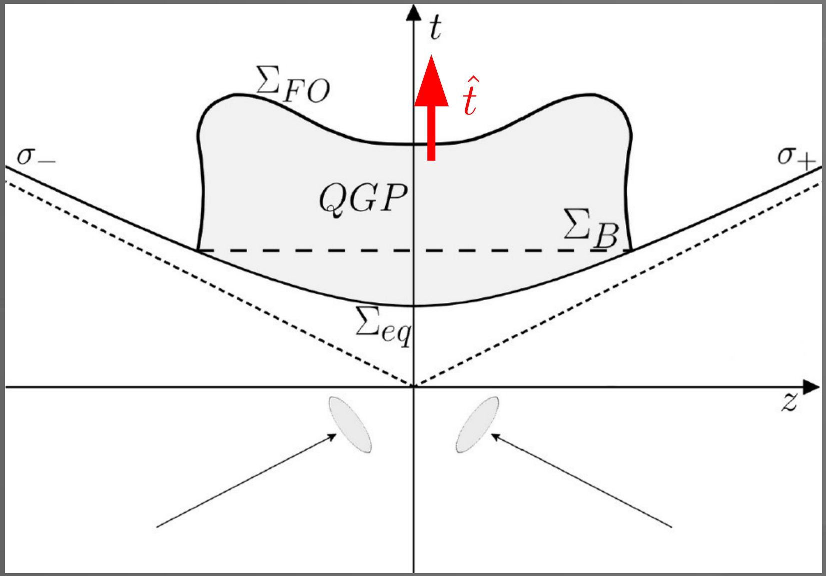


Figure by A. Palermo

Comparison of the two formulas for shear induced polarization



$$\mathcal{A}^{\mu}_{\mathrm{LY}} = -\varepsilon^{\mu\rho\sigma\tau}\frac{1}{(u\cdot p)}u_\rho \xi_{\sigma\lambda} p_\perp^\lambda p_\tau$$

$$p_\perp^\lambda = p^\lambda - (u\cdot p)u^\lambda$$

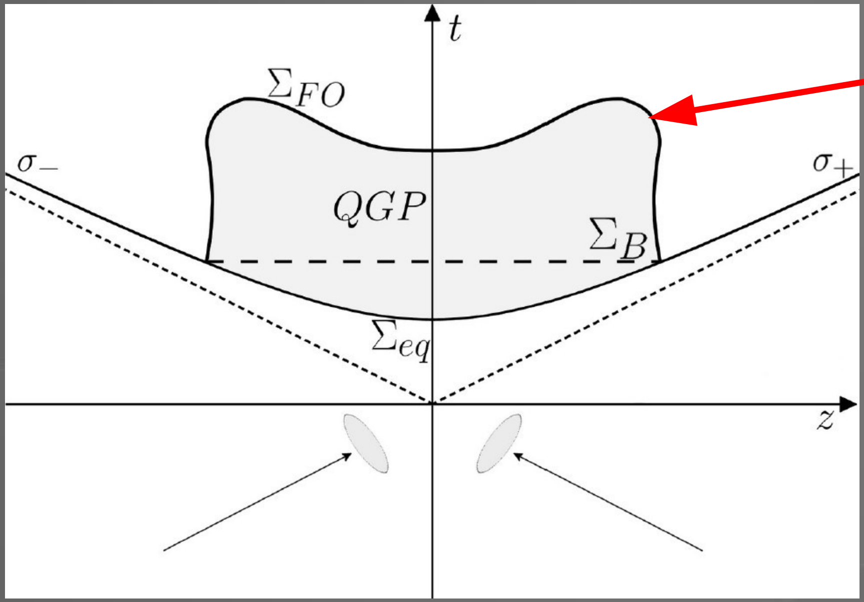
$$\mathcal{A}^{\mu}_{\mathrm{BBP}} = -\varepsilon^{\mu\rho\sigma\tau}\frac{1}{(\hat{t}\cdot p)}\hat{t}_\rho \xi_{\sigma\lambda} p^\lambda p_\tau$$

$$\mathcal{A}^{\mu}_{\mathrm{LY}} - \mathcal{A}^{\mu}_{\mathrm{BBP}}[\hat{t}\to u] = -\varepsilon^{\mu\rho\sigma\tau} u_\rho \xi_{\sigma\lambda} u^\lambda p_\tau$$

S. Alzhrani, S. Ryu, C. Shen, 2203.15718

Isothermal local equilibrium

The most appropriate setting for relativistic heavy ion collisions at very high energy!



At high energy, Σ_{FO} expected to be T= constant!

$$\beta^\mu = (1/T) u^\mu$$

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

Only NOW u can be expanded!

$$u_\nu(y) \simeq u_\nu(x) + \partial_\lambda u_\nu(x)(y-x)^\lambda + \cdots$$

$$\widehat{\rho}_{LE} \simeq \frac{1}{Z} \exp\left[-\beta_\nu(x)\widehat{P}^\nu - \frac{1}{2T}(\partial_\mu u_\nu(x) - \partial_\nu u_\mu(x))\widehat{J}^{\mu\nu}_x - \frac{1}{2T}(\partial_\mu u_\nu(x) + \partial_\nu u_\mu(x))\widehat{Q}^{\mu\nu}_x + \cdots \right]$$