# Theory review of spin-polarization phenomena in heavy ion collisions

**8th International Conference on**
**Chirality, Vorticity, and Magnetic Field in Quantum Matter**

West University of Timișoara
Romania

22 July

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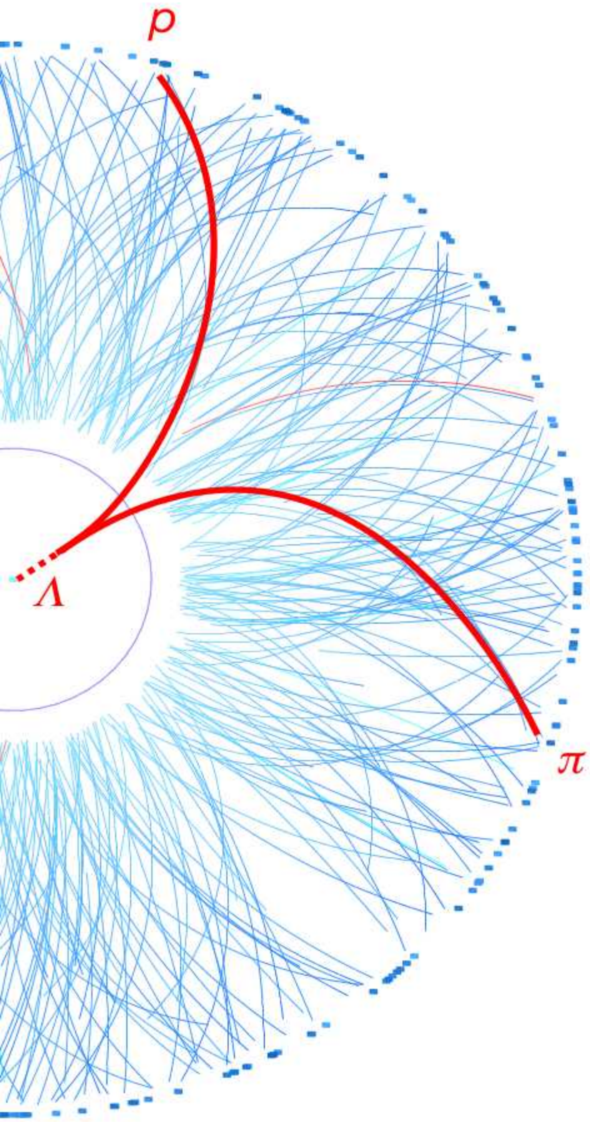
# A personal note




# Outline

- **What do we mean by “spin polarization”?**
- **Λ polarization**
- **Alignment: vector mesons polarization**
- **Open problems (personal view)**

# Relativistic spin operator

In a relativistic framework, the spin of massive particles is defined with the Pauli Lubanski operator:

$$\widehat{S}^{\mu}(p) = -\frac{1}{2m}\epsilon^{\mu\nu\rho\sigma}\widehat{J}_{\nu\rho}p_{\sigma} \qquad p_{\mu}\widehat{S}^{\mu}(p) = 0$$

Pryce formulation:
**I. Cotaescu's talk**
today

For particles at rest

$$\mathfrak{p} = (m, \mathbf{0}) \qquad \widehat{S}(\mathfrak{p}) = (0, \mathbf{J}_x, \mathbf{J}_y, \mathbf{J}_z)$$

Boosting to the frame where the particle's momentum is p

$$\widehat{S}^{\mu}(p) = \sum_{i=1}^{3}\widehat{S}_i(p)n_i^{\mu}(p) \qquad n_i(p)\cdot p = 0$$

$$[\widehat{S}_i(p), \widehat{S}_j(p)] = i\epsilon_{ijk}\widehat{S}_k(p) \qquad \widehat{S}_i(p) = -\widehat{S}(p)\cdot n_i(p)$$

SO(3) algebra

The Hilbert space of one particle states is built using the four momentum and the spin operator

$$\widehat{P}^{\mu}|p,\sigma\rangle = p^{\mu}|p,\sigma\rangle, \qquad \widehat{S}_3(p)|p,\sigma\rangle = \sigma|p,\sigma\rangle$$

The polarization of a pure state is rather uninteresting. We want to study polarization of mixed states: **spin density matrix**.

In quantum field theory, given the statistical operator $\rho$ the definition of the spin density matrix is:

$$\rho^{(S)}_{sr}(p) = \frac{\mathrm{Tr}\left(\widehat{\rho}\,\widehat{a}^{\dagger}_{r}(p)\widehat{a}_{s}(p)\right)}{\sum_l \mathrm{Tr}\left(\widehat{\rho}\,\widehat{a}^{\dagger}_{l}(p)\widehat{a}_{l}(p)\right)} = \frac{N_{rs}(p)}{N_{tot}(p)} \qquad r,s = -S,\ldots,S$$

Notation: the spin density matrix is often denoted $\rho$, like the statistical operator...

The spin density matrix is a (2S+1)x(2S+1) hermitian matrix with unit trace: 4S(S+1) degrees of freedom (d.o.f). There are different effects depending on the spin!

- S = ½, d.o.f=3

Trace constraint

$$\rho^{(S)} = \frac{1}{2}\mathbb{I} + \frac{1}{2}\sum_{i=1}^{3} P_i\sigma_i$$

Pauli matrices (3 d.o.f)

**One polarization vector**

- S=1, d.o.f=8

Trace constraint

$$\rho^{(S)} = \frac{1}{3}\mathbb{I} + \sum_{i=1}^{3} P_i J_i + \sum_{i,j=1}^{3} A_{ij}\Sigma_{ij}$$

Generators of rotations (3 d.o.f)

Symmetric traceless tensor (5 d.o.f)

$$\Sigma_{ij} = \frac{1}{2}(J_i J_j + J_j J_i) - \frac{2}{3}\delta_{ij}\mathbb{I}$$

**One polarization vector and One polarization tensor**

# Spin-vector polarization vs alignment

If all the states are equiprobable, $\rho^{(S)} = \mathbb{I}/S$ , isotropic spin distribution.

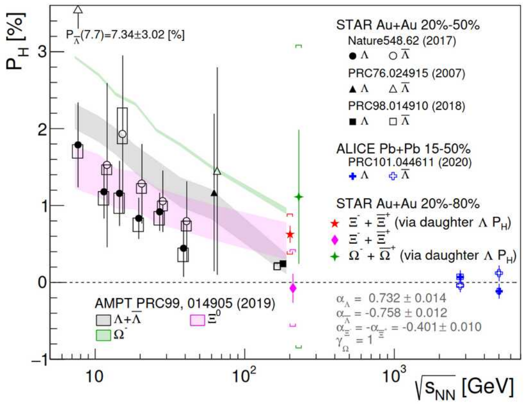
In the rest frame, the spin polarization vector is computed

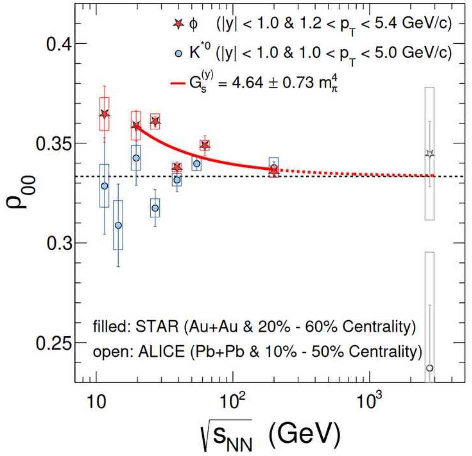
$$P_i = \frac{1}{S}\mathrm{Tr}\left(\rho^{(S)} D^S(\mathrm{J}^i)\right)$$

The alignment of a vector meson on the other hand is related to the rank-2 components of the spin density matrix:

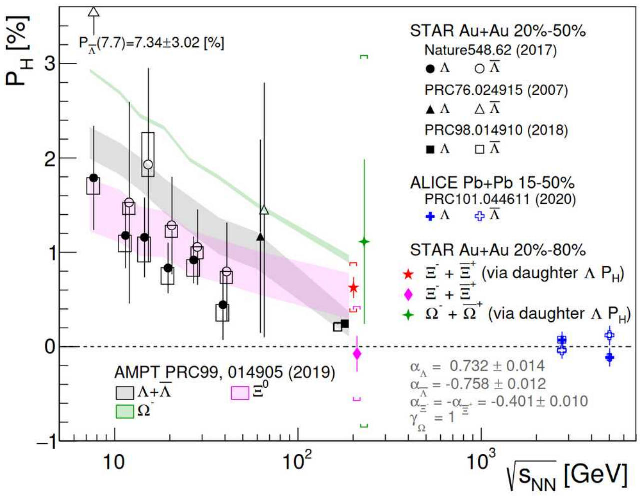
$$A_{33} = \frac{1}{3} - \rho_{00}^{(S)}$$

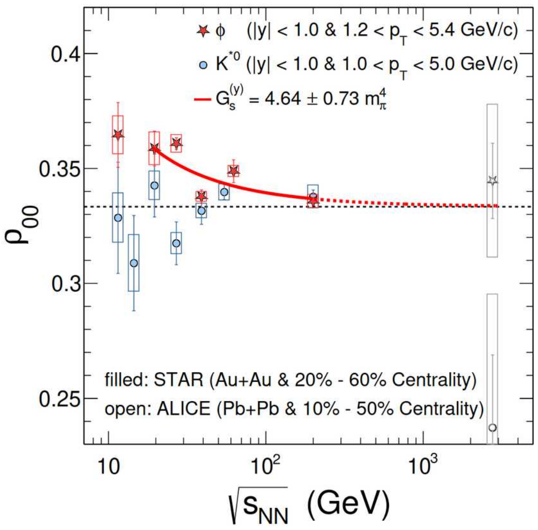
*Phys.Rev.Lett. 126 (2021) 16, 162301*




*STAR, Nature 614 (2023) 7947, 244-248*




In heavy ion collisions **the spin distribution of emitted hadrons is not isotropic.**

**Why?**

➔**Hydrodynamics**

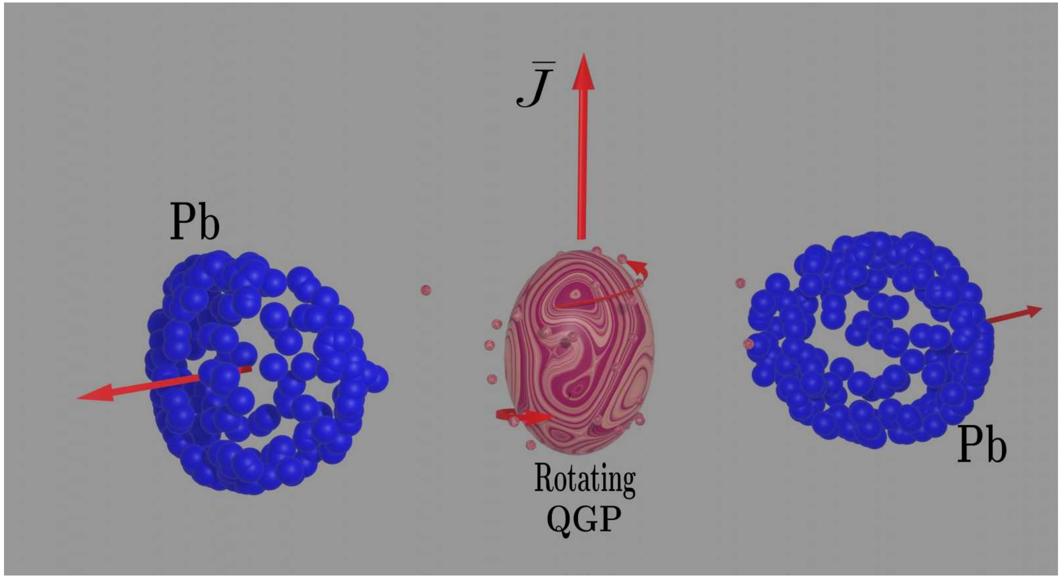
➔**Interactions**

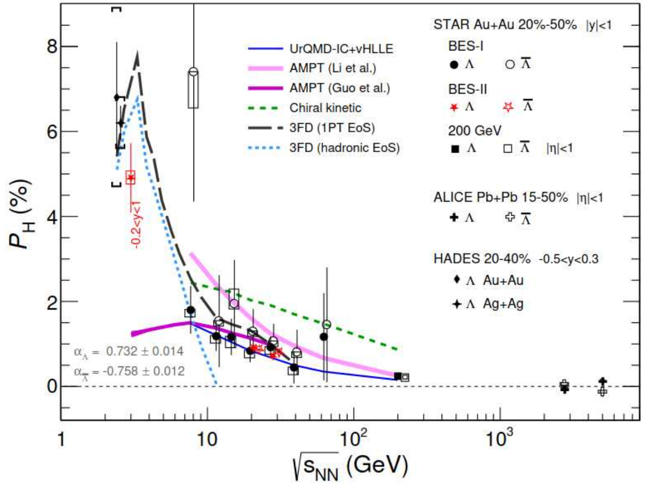
# Λ polarization

Initial **prediction**: spin polarization is caused by angular momentum

*QCD, recombination: Liang, Wang, Phys.Rev.Lett.94, 102301 (2005); Liang, Wang, Phys.Lett.B 629 (2005);*
*Hydrodynamics: Becattini, Piccinini, Rizzo, Phys. Rev. C77, 024906 (2008)*

*Becattini, Buzzegoli, Niida, Pu, Tang, Wang 2402.04540*




Polarization peaks near threshold: **J. Liao's Talk** today

*Numerical studies: Karpenko, Becattini, Eur. Phys. J. C 77, 213 (2017); Li, Pang, Wang, Xia, Phys. Rev. C 96, 054908 (2017); Guo, Liao, Wang, Xing, Zhang, Phys. Rev. C 104, L041902 (2021); Ivanov, Phys. Rev. C 103, L031903 (2021); Sun, Ko, Phys. Rev. C96, 024906….*

## Thermal vorticity-induced polarization

*Becattini, Chandra, Del Zanna, Grossi, Annals Phys. 338 (2013) 32-49; Becattini, Csernai, Wang Phys.Rev.C 88 (2013) 3, 034905; Becattini, Inghirami, Rolando, Beraudo, Del Zanna, Eur. Phys. J. C 75, 406 (2015); Fang, Pang, Wang, Wang Phys.Rev.C 94 (2016) 2, 024904*

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

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

Exact thermal vorticity-induced polarization at global equilibrium has been found: negligible corrections from higher orders in vorticity

Palermo, Becattini, Eur.Phys.J.Plus 138 (2023) 6, 547

$$\theta^\mu = -\frac{1}{2m}\epsilon^{\mu\nu\rho\sigma}\varpi_{\nu\rho} p_\sigma \qquad S^\mu(p) = \frac{1}{2}\,\frac{\theta^\mu}{\sqrt{-\theta^2}}\,\frac{\sinh\left(\frac{\sqrt{-\theta^2}}{2}\right)}{\cosh\left(\frac{\sqrt{-\theta^2}}{2}\right) + e^{-b\cdot p+\zeta}}$$

Vorticity is the only drive of polarization at global equilibrium...

# … but there are many more sources!

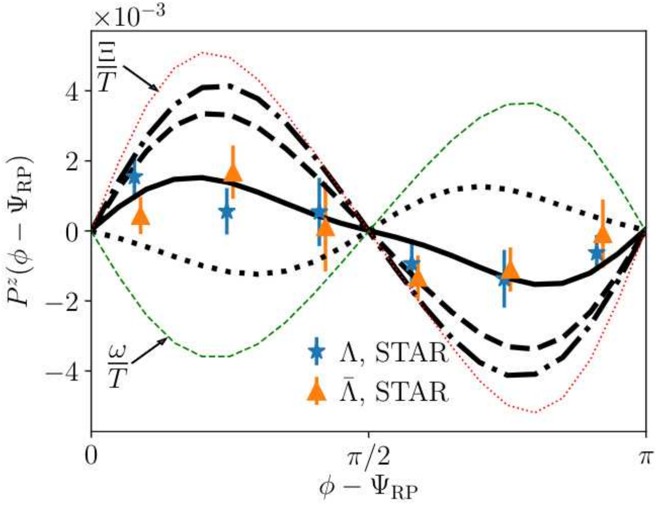
*Liu, Huang, Sci.China Phys.Mech.Astron. 65 (2022) 272011*

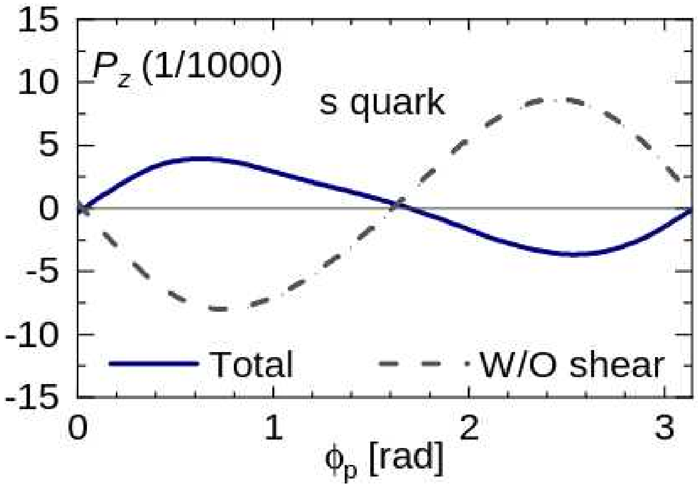
$$S_\mu(p) = -\frac{1}{8m\int d\Sigma\cdot p\, n_F}\int d\Sigma\cdot p\left\{\epsilon_{\mu\nu\rho\sigma}p^\nu\varpi^{\rho\sigma} + 2\epsilon_{\mu\nu\rho\sigma}\frac{p^\rho}{p\cdot n}n^\sigma\left[p_\lambda(\xi^{\nu\lambda}+\Theta^{\nu\lambda}) + \frac{1}{4}\partial^\nu\frac{\mu}{T}\right]\right\}n_F(1-n_F)$$

$$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu) \qquad \Theta_{\mu\nu} = \mathfrak{S}_{\mu\nu} - \varpi_{\mu\nu}$$

- **Thermal shear:** essential for local polarization
  *Becattini, Buzzegoli, Palermo, Phys. Lett. B 820, 136519 (2021); Liu, Yin, JHEP 07, 188 (2021); Becattini, Buzzegoli, Inghirami, Karpenko, Palermo, Phys. Rev. Lett. 127, 272302 (2021); Fu, Liu, Pang, Song, Yin, Phys.Rev.Lett. 127 (2021) 14, 142301, Yi, Pu, Yang, Phys.Rev.C 104 (2021) 6, 064901; Hidaka, Pu, Yang, Phys.Rev.D 97 (2018) 1, 016004*
- **Spin Hall effect:** possibly important in low energies
  *Liu, Yin, Phys. Rev. D 104, 054043 (2021); Ivanov, Soldatov, Pisma Zh.Eksp.Teor.Fiz. 116 (2022); M. Buzzegoli, Nucl. Phys. A 1036, 122674 (2023)*
- $\mathfrak{S}$ is the **spin potential**: **??**
  *Becattini, Florkowski, Speranza, Phys. Lett. B 789, 419 (2019), Speranza, Weickgenannt, Eur. Phys. J. A 57, 155 (2021), Buzzegoli, Phys. Rev. C 105, 044907 (2022)*
- **Dissipative corrections**
- **Interactions**

*Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, Phys.Rev.Lett. 127 (2021) 27, 272302*




*Fu, Liu, Pang, Song, Yin, Phys.Rev.Lett. 127 (2021) 14, 142301*

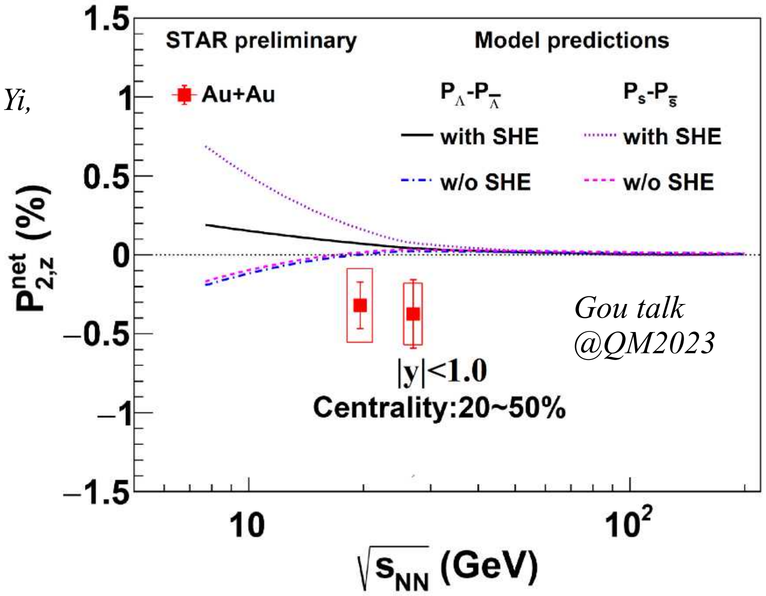
$$S_\mu(p) = -\epsilon_{\mu\nu\rho\sigma}\frac{p^\rho}{p\cdot n}n^\sigma \frac{\int d\Sigma\cdot p\, p_\lambda \xi^{\nu\lambda} n_F(1-n_F)}{4m\int d\Sigma\cdot p\, n_F}$$

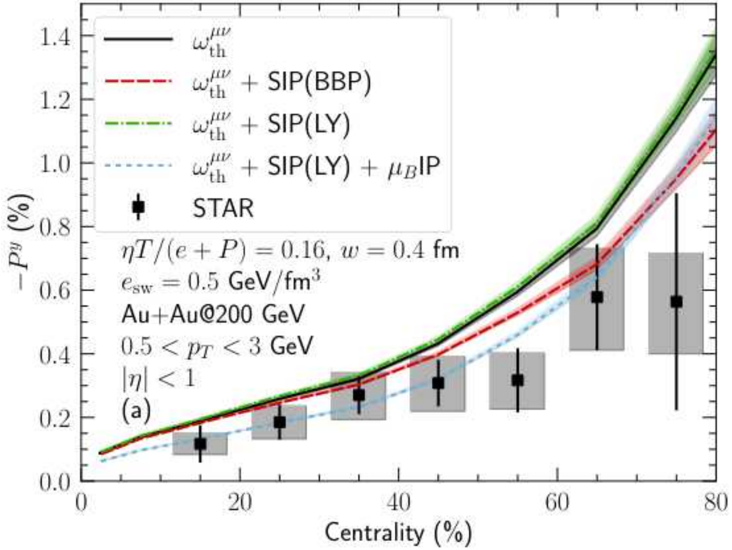
**Thermal shear can explain the local polarization data**, but...

- Different formulae for different gorups ( n, ξ vs σ...)
- isothermal freeze-out (geometry of decoupling hypersurface)
- Strange memory scenario.

Geometry sources alignment:
**Z. Zhang's talk** today at 12:30

*Fu, Pang, Song, Yi, 2208.00430*




*Alzhrani, Ryu, Shen, Phys.Rev.C 106 (2022) 1, 014905*

$$S_\mu(p) = -\frac{1}{16m\int d\Sigma\cdot p\, n_F}\int d\Sigma\cdot p\,\epsilon_{\mu\nu\rho\sigma}\frac{p^\rho}{p\cdot n}n^\sigma\partial^\nu\frac{\mu}{T}n_F(1-n_F)$$

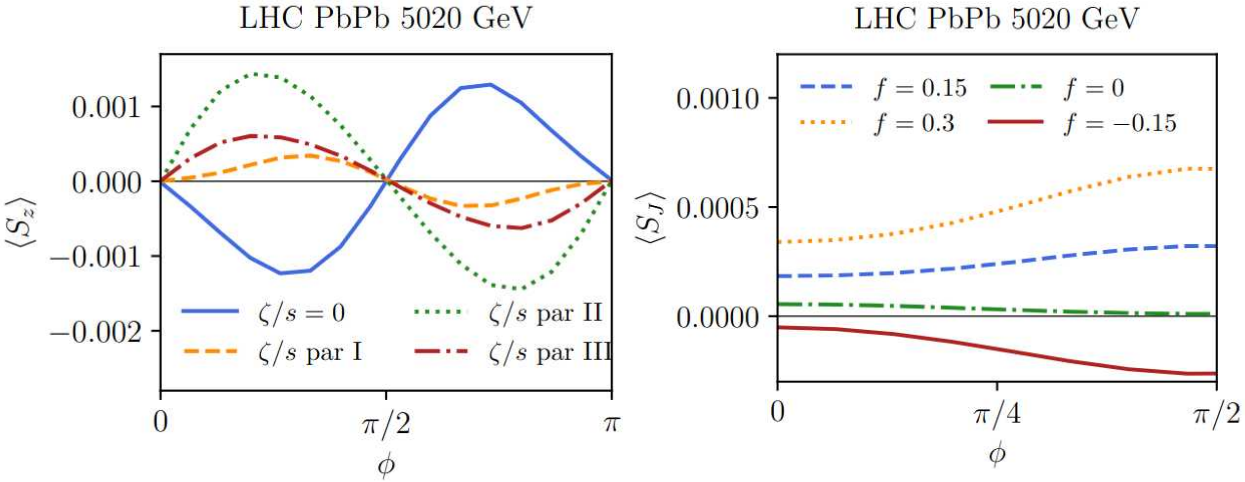
The Spin Hall effect seems to be marginal in high energy heavy ion collisions.

It becomes important in lower energy collisions.

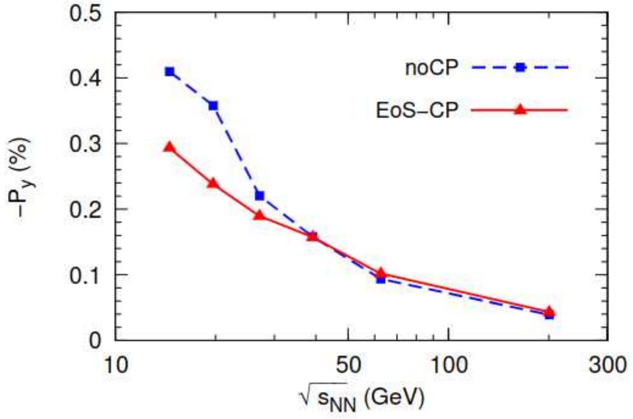
**More numerical work on the spin Hall effect should be done**.

# Spin as a probe of hydrodynamics

*Palermo, Grossi, Karpenko, Becattini, 2404.14295*




*Singh, Alam, Eur. Phys. J. C 83, 585 (2023)*




$$T_0^{\tau\tau} = e \cosh(f\, y_{CM}), \quad T_0^{\tau\eta} = \frac{e}{\tau} \sinh(f\, y_{CM})$$

Polarization is sensitive:

- To bulk viscosity (at high energy) and the initial longitutinal flow
  *Jiang, Wu, Cao, Zhang, Phys. Rev. C 108, 064904 (2023)*
- To the critical point: **S. Singh’s talk** on Friday

# Pseudogauge

Spin hydrodynamics builds upon the ambiguity in the definition of the spin tensor: the pseudogauge symmetry

*Becattini, Florkowski, Speranza, Phys. Lett. B 789, 419 (2019)*

$$P^{\mu} = \int d\Sigma_{\nu} T^{\nu\mu} \qquad\qquad J^{\mu\nu} = \int d\Sigma_{\lambda}\, x^{\mu} T^{\lambda\nu} - x^{\nu} T^{\lambda\mu} + S^{\lambda,\mu\nu}$$

The charges are invariant under redefinitions

$$T'^{\mu\nu} = T^{\mu\nu} + \frac{1}{2}\nabla_{\lambda}\left(\Phi^{\lambda,\mu\nu} - \Phi^{\mu,\lambda\nu} - \Phi^{\nu,\lambda\mu}\right)$$

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

If a spin tensor exists, it can be included in hydrodynamics: **relativistic spin hydrodynamics**

$$\partial_{\lambda} S^{\lambda,\mu\nu} = T^{\nu\mu} - T^{\mu\nu}$$

Popular choices:

- Belinfante: $T^{\mu\nu} = T^{\nu\mu},\ S^{\mu\nu\rho} = 0$ (Florence group)
  *Becattini, Buzzegoli, Palermo, Phys. Lett. B 820, 136519 (2021)...*
- Canonical: $T^{\mu\nu} \neq T^{\nu\mu},\ S^{\mu\nu\rho} \neq 0$
  *Daher, Das, Florkowski, Ryblewski, Phys. Rev. C 108, 024902 (2023); Gallegos, Gursoy, Yarom JHEP 05 (2023) 139; Gallegos, Gursoy, Yarom, SciPost Phys 11, 041 (2021)...*
- de Groot-van Leeuwen-van Weert (GLW): $T^{\mu\nu} = T^{\nu\mu},\ S^{\mu\nu\rho} \neq 0$ (Krakow group)
  *Daher, Florkowski, Ryblewski 2401.07608...*
- Hilgevoord-Wouthuysen (HW): $T^{\mu\nu} = T^{\nu\mu},\ S^{\mu\nu\rho} \neq 0$ (Frankfurt group)
  *Weickgenannt, E. Speranza, X.-l. Sheng, Q. Wang, and D. H. Rischke, Phys. Rev. Lett. 127, 052301 (2021)...*

**No decisive argument to favor a pseudogauge!** Recent developments: canonical pseudogauge?

- SO(3) algebra
  *Dey, Florkowski, Jaiswal, Ryblewski Phys.Lett.B 843 (2023) 137994.*

$$S^i = \frac{1}{2}\epsilon^{ijk}\int d^3x S^{0,ij} \qquad [S^i, S^j] = i\epsilon^{ijk}S^k$$

- Interaction-induced spin tensor: **M. Buzzegoli's talk** on Tuesday
  *Buzzegoli, Palermo, today on the arXiv!*

$$Z|_{\text{NJL+rotation}} \equiv Z|_{\text{LEDO+canonical PG}}$$

The local-equilibrium **density operator depends on the pseudogauge**

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

Even if the spin operator is pseudogauge independent, its mean value is not

*Buzzegoli, Phys. Rev. C 105, 044907 (2022); Liu, Huang, Sci.China Phys.Mech.Astron. 65 (2022) 272011*

$$S^\mu_{GLW,HW}(k) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}k_\tau \frac{\int_\Sigma d\Sigma \cdot k\, n_F\,(1-n_F)\,\mathfrak{S}_{\rho\sigma}}{\int_\Sigma \Sigma \cdot k\, n_F}$$

$$S^\mu_B(k) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}k_\tau \frac{\int_\Sigma d\Sigma \cdot k\, n_F\,(1-n_F)\left[\varpi_{\rho\sigma} + 2\frac{k^\lambda n_\rho}{k\cdot n}\xi_{\lambda\sigma}\right]}{\int_\Sigma d\Sigma \cdot k\, n_F}$$

They are equal only in global equilibrium. In the GLW/HW there is no spin induced polarization in local equilibrium.

# Spin hydrodynamics

One uses the spin tensor as an independent degree of freedom.

Assumes the existence of a spin potential $\mathfrak{S}$ (6 d.o.f), which acts as lagrange multiplier for the spin tensor and enters its constitutive equation

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu S^{\mu,\nu\rho} = \hbar(T^{\nu\mu} - T^{\mu\nu}) \qquad \partial_\mu j^\mu = 0$$

Some times it is preferred to work in symmetric pseudogauges (GLW, HW): defines a global conserved tensor. **A matter of choice**

$$\partial_\mu S^{\mu\nu\rho} = 0, \qquad \mathcal{S}^{\mu\nu} = \int d\Sigma_\mu S^{\mu\nu\rho}$$

Non-local collisions spoil spin conservation!

*Weickgenannt, Speranza, Sheng, Wang, Rischke, Phys. Rev. Lett. 127, 052301 (2021)*

Many equations of motion, hard to tackle.

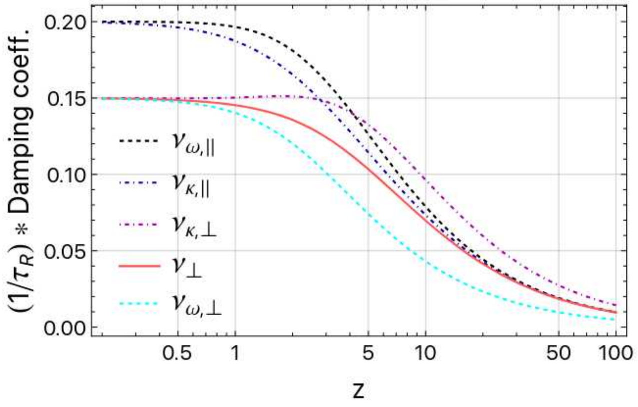
Ideal spin-hydro: **M. Shokri's talk** on Tuesday

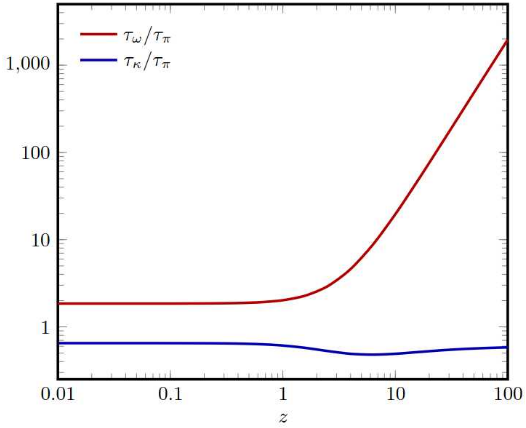
… in a rotating background: **A. Chiarini's poster**

# Spin and dissipation

Some studies of solutions of spin waves damping have been performed

*Ambrus, Ryblewski, Singh, Phys.Rev.D 106 (2022) 1, 014018*



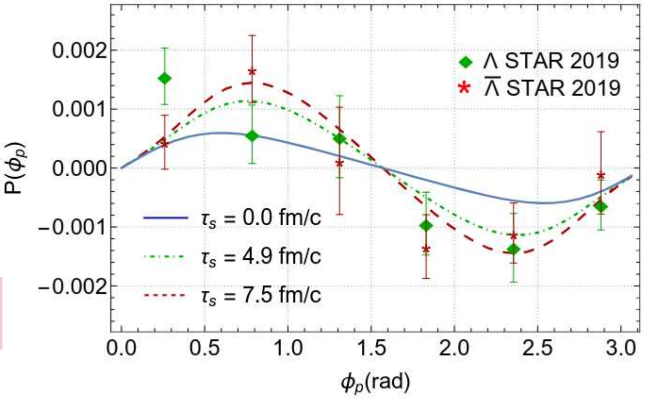




*Wagner, Shokri, Rischke 2405.00533*

Spin modes may live as long as the QGP:
if so, spin hydro is **phenomenologically important!**

Effects of dissipation in spin hydro

In a thermal model: **S. Bhadury's talk** on Friday




*Banerjee, Bhadury, Florkowski, Jaiswal, Ryblewski 2405.05089*

Entropy production rate from quantum relativistic statistical mechanics

*Becattini, Daher, Sheng Phys.Lett.B 850 (2024) 138533*

**A. Daher's talk** on Tuesday

$$\nabla_\mu s^\mu = \left( T_S^{\mu\nu} - T_{S(\mathrm{LE})}^{\mu\nu} \right) \xi_{\mu\nu} - \left( j^\mu - j^\mu_{\mathrm{LE}} \right) \nabla_\mu \zeta + \left( T_A^{\mu\nu} - T_{A(\mathrm{LE})}^{\mu\nu} \right) \left( \Omega_{\mu\nu} - \varpi_{\mu\nu} \right) - \frac{1}{2} \left( S^{\mu\lambda\nu} - S^{\mu\lambda\nu}_{\mathrm{LE}} \right) \nabla_\mu \Omega_{\lambda\nu}$$

Effects of collisions (dissipation?) on polarization: **needs numerical simulation**

*Weickgenannt, Wagner, Speranza, Rischke, Phys.Rev.D 106 (2022) 9, L091901*

$$\Pi^\mu_{\mathrm{NS}}(p) = \int d\Sigma \cdot p \, \frac{f_{0p}}{2\mathcal{N}} \left\{ - \frac{\hbar}{2m} \tilde{\Omega}^{\mu\nu} p_\nu + \left( g^\mu_\nu - \frac{u^\mu p_{\langle\nu\rangle}}{E_p} \right) \times \left[ \mathfrak{e} \chi_{\mathfrak{p}} \left( \tilde{\Omega}^{\nu\rho} - \tilde{\varpi}^{\nu\rho} \right) u_\rho - \chi_{\mathfrak{q}} \mathfrak{d} \beta_0 \sigma_\rho{}^{\langle\alpha} \epsilon^{\beta\rangle\nu\sigma\rho} u_\sigma p_{\langle\alpha} p_{\beta\rangle} \right] \right\}$$

Problem: up to first order in spin potential there is no backreaction on regular hydro.

**Overfitting problem**

# Even more sources of polarization!

Magnetic field corrections: **J. Sun's talk** on Thursday

*Buzzegoli Nucl.Phys.A 1036 (2023) 122674; Y. Guo, S. Shi, S. Feng, and J. Liao, Phys. Lett. B 798, 134929 (2019); Singh, Shokri, Tabatabaee Nucl.Phys.A 1035 (2023) 122656...*

$$S^\mu_B(p) = \frac{\int_\Sigma d\Sigma \cdot p\, \beta(x) n_F (1-n_F)(qB^\mu(x) - u^\mu \frac{(qB(x)\cdot p)}{\varepsilon_p})}{4m \int_\Sigma d\Sigma \cdot p\, n_F}$$

Higher order corrections: **F. Becattini's talk** today

*Sheng, Becattini, Huang, Zhang 2407.12130*

$$S^\mu = S^\mu_{(1)}[\varpi, \xi, \mathfrak{S}, \partial(\mu/T)] + S^\mu_{(2)}[\partial\varpi, \partial\xi, \partial\mathfrak{S}, \partial\partial(\mu/T)] + S^\mu_{(2)}[\varpi^2, \xi^2, \mathfrak{S}^2, \partial(\mu/T)^2]$$

Gradients of the effective mass **R. Ryblewski's talk** on Friday

*Bhadury, Das, Florkowski, Gowthama, Ryblewski, Phys.Lett.B 849 (2024) 138464*

$$\partial_\mu S^{\mu,\nu\rho} = \frac{\partial_\mu M(x)}{M(x)} \left(S^{\nu,\rho\alpha} - S^{\rho,\nu\alpha}\right)$$

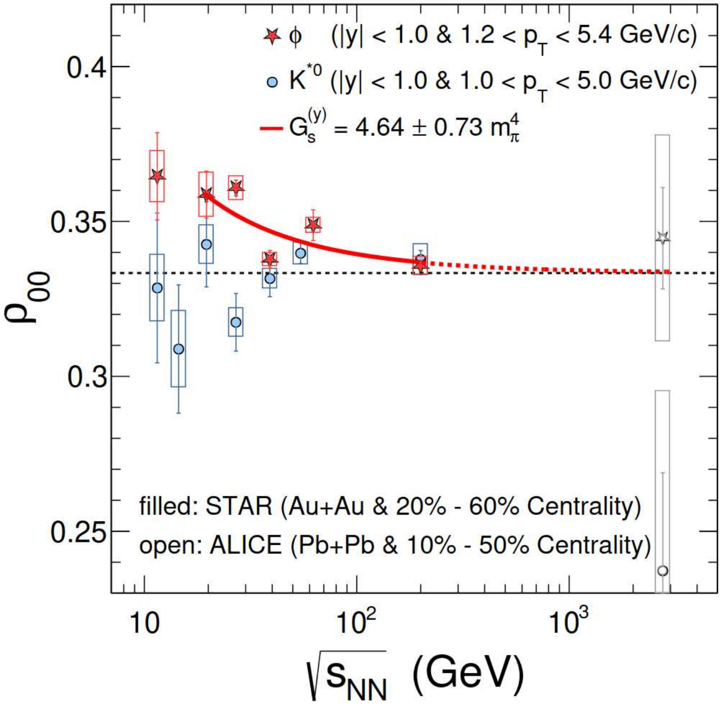
# More references

- More on spin hydrodynamics and dissipative corrections to polarization
  *Biswas, Daher, Das, Florkowski, Ryblewski, Phys.Rev.D 108 (2023) 1, 014024; Weickgenannt, Sheng, Speranza, Wang, Rischke, Phys. Rev. D100, 056018 (2019); Weickgenannt, Phys.Rev.D 108 (2023) 7, 076011; Xie, Wang, Yang, Pu, Phys. Rev. D108 (2023) 9, 094031; Ren,Yang, Wang, Pu 2405.03105; Shi, Gale, Jeon, Phys.Rev.C 103 (2021) 4, 044906; Lin, Tang, 2406.17632; Ayala, Bernal-Lagarica, Jimenez, Maldonado, Medina-Serena, Phys.Rev.D 109 (2024) 7, 074018; Ayala, de la Cruz, Hernández, Salinas, Phys. Rev. D 102, 056019 (2020); Hu, Xu, Phys.Rev.D 107 (2023) 1, 016010...*

- Studies of global polarization at low energy
  *Ayala, Dominguez, Maldonado, Tejeda-Yeomans Phys.Rev.C 105 (2022) 3, 034907; Guo, Liao, Wang, Xing, Zhang, Phys.Rev. C 104, L041902 (2021); Deng, Huang, Ma, Zhang, Phys. Rev. C 101, 064908 (2020); Guo, Liao, Wang, Sci.Rep. 10 (2020) 1, 2196...*

- Reviews
  *Becattini, Buzzegoli, Niida, Pu, Tang, Wang 2407.06480; Becattini, Rept.Prog.Phys. 85 (2022) 12, 122301;Bhadury, Bhatt, Jaiswal, Kumar, Eur.Phys.J.ST 230 (2021) 3, 655-672 ....*

# Spin alignment of vector mesons




Is a **tensor-type polarization**

$$\rho^{(S)} = \frac{1}{3}\mathbb{I} + \sum_{i=1}^{3} P_i J_i + \sum_{i,j=1}^{3} A_{ij}\Sigma_{ij}$$

$$A_{33} = \frac{1}{3} - \rho_{00} \qquad \Sigma_{ij} = \frac{1}{2}(J_i J_j + J_j J_i) - \frac{2}{3}\delta_{ij}\mathbb{I}$$

The spin vector polarization of vector meson exist theoretically, but is undetectable.

Different effects for $\phi$ and $\mathrm{K}^*$ mesons: statistical effect?

**Effects due to vorticity and shear are too small**

# Strong meson field

Approach based on Kadanov-Baym equations and closed-time-path formalism

*Sheng, Oliva, Liang, Wang, Wang, Phys. Rev. D 109, 036004 (2024); Sheng, Oliva, Liang, Wang, Wang, Phys. Rev. Lett. 131, 042304 (2023)*

Kinetic equation for the matrix-valued spin-dependent distribution function for the vector meson

$$p \cdot \partial_x f^V_{m_1 m_2}(x,\vec{p}) = \frac{1}{8}\left[\epsilon^*_\mu(m_1,\vec{p})\epsilon_\nu(m_2,\vec{p})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\vec{p}) - \mathcal{C}_{\text{diss}}(\vec{p}) f^V_{m_1 m_2}(x,\vec{p})\right]$$

The spin density matrix turns out to be proportional on the coalescence kernel:

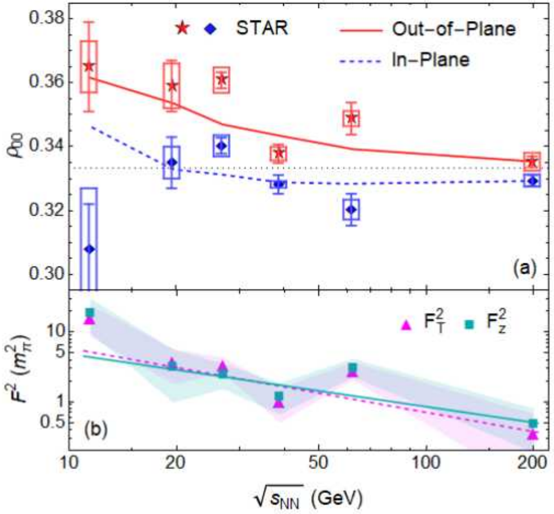
$$\rho^{(S)}_{m_1 m_2}(x,\vec{p}) = \frac{\epsilon^*_\mu(m_1,\vec{p})\epsilon_\nu(m_2,\vec{p})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\vec{p})}{\sum_{m=0,\pm 1}\epsilon^*_\alpha(m,\vec{p})\epsilon_\beta(m,\vec{p})\mathcal{C}^{\alpha\beta}_{\text{coal}}(x,\vec{p})}$$

The coalescence kernel depends on the polarization state and the momentum of quarks

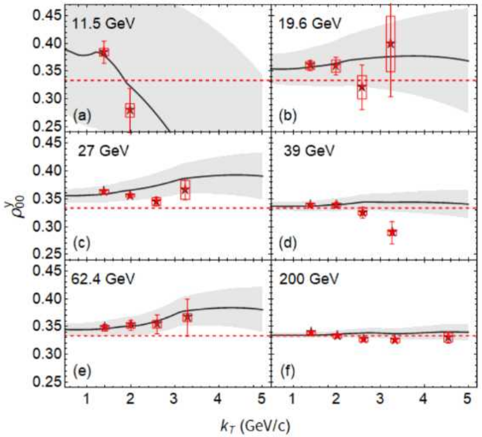
Quarks can be polarized by interactions with an effective vector meson field $\phi$, which in a static fluid induces an alignment of the form

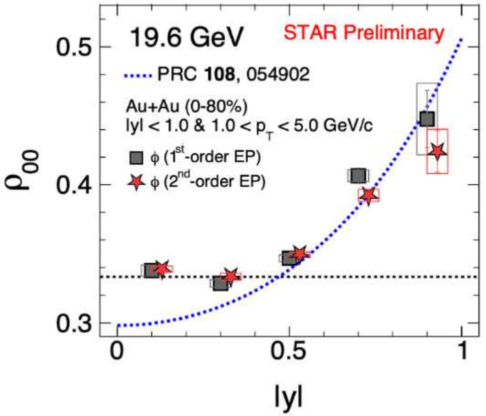
$$\langle \rho_{00}^{(S)\,\phi}(x,\vec{p})\rangle \approx \frac{1}{3} - \frac{4g_\phi^2}{3M_\phi^4 T_{\rm h}^2}\sum_{i=1,2,3} I_{B,i}(\vec{p})\langle(\vec{B}_i^\phi)^2\rangle - \frac{4g_\phi^2}{3M_\phi^4 T_{\rm h}^2}\sum_{i=1,2,3} I_{E,i}(\vec{p})\langle(\vec{E}_i^\phi)^2\rangle$$

Alignment induced by fluctuations of the strong field. Fitted from data.




**Predictions**




**Problem:** other effects of this field? Overfitting?

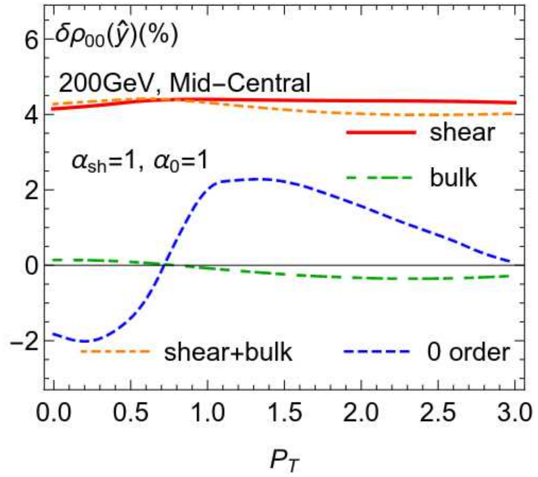
*Sheng, Oliva, Liang,Wang, Wan Phys.Rev.Lett. 131 (2023) 4, 042304*

*Sheng, Pu, Wang Phys.Rev.C 108 (2023) 5, 054902*

$\Lambda$ correlations: **X.N. Wang's talk** on Wednesday

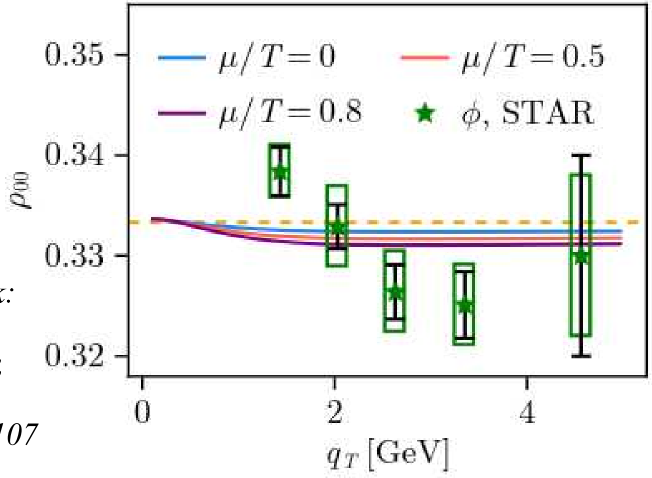
# In medium spectral functions

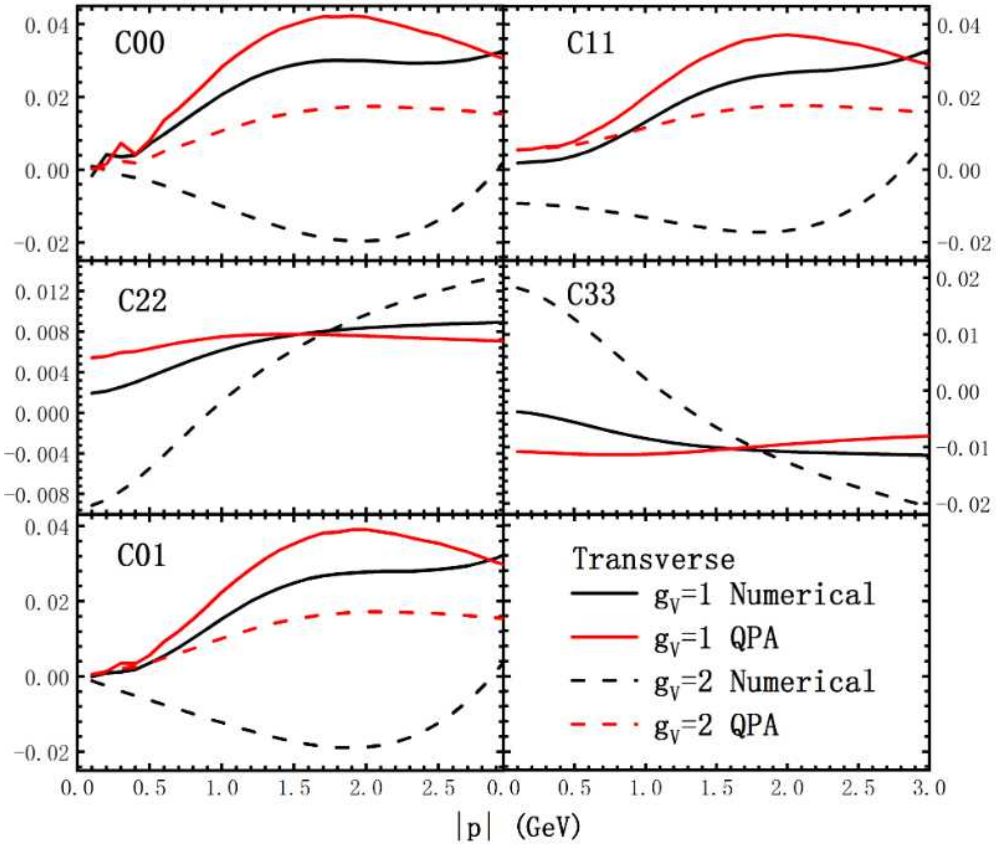
*Li, Liu, 2206.11890*




*Grossi, Palermo, Zahed 2407.10524*

*Related work: Park, Sako, Aoki, Gubler, Huong Lee, Phys.Rev.D 107 (2023) 7, 074033*




*Dong, Yin, Sheng, Yang, Wang, Phys.Rev.D 109 (2024) 5, 056025*

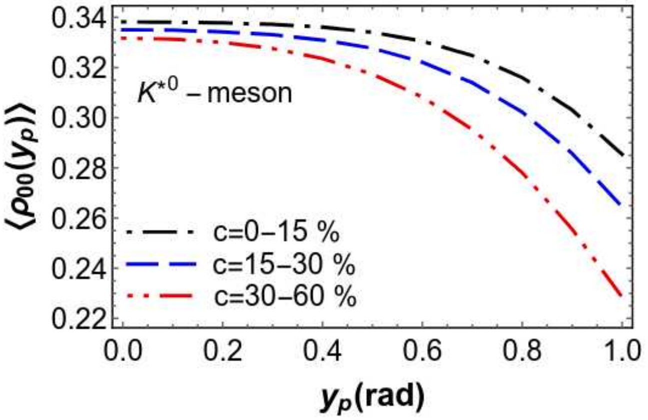
# Standard and spin hydrodynamics

No contribution to alignment at first order in gradients in local equilibrium.

**At second order**

*Kumar, Yang, Gubler Phys.Rev.D 109 (2024) 5, 054038*

$$\rho_{00}^{(S)}(q) = \frac{1}{3} - \frac{\hbar^2}{12M^2} \frac{\int d\Sigma_X \cdot q\,(2(\partial^y)^2 - (\partial^x)^2 - (\partial^z)^2) f_V(q,X)}{\int d\Sigma_X \cdot q\, f_V(q,X)}$$




Spin alignment induced by the shear stress

*Wagner, Weickgenannt, Speranza, Phys.Rev.Res. 5 (2023) 1, 013187*

$$\rho_{00}^{(S)}(k) = \frac{1}{3} - \frac{4}{15} \frac{\int d\Sigma_\alpha k^\alpha \xi\, \beta_0 f_0 \mathcal{H}_1^{(2,0)} \epsilon_\alpha^{(0)} \epsilon_\beta^{(0)} K^{\alpha\beta}_{\mu\nu} \Xi^{\mu\nu}_{\rho\sigma} \pi^{\rho\sigma}}{\int d\Sigma_\alpha k^\alpha f_0 \left(1 - 3\mathcal{H}_0^{(0,0)} \Pi/m^2 + \mathcal{H}_0^{(0,2)} \pi^{\mu\nu} k_{\langle\mu} k_{\nu\rangle}\right)}$$

Magnitude of the effect unknown. **Needs numerical evaluation**

Can hydro explain the different behavior between K* and $\phi$?

# More sources of alignment

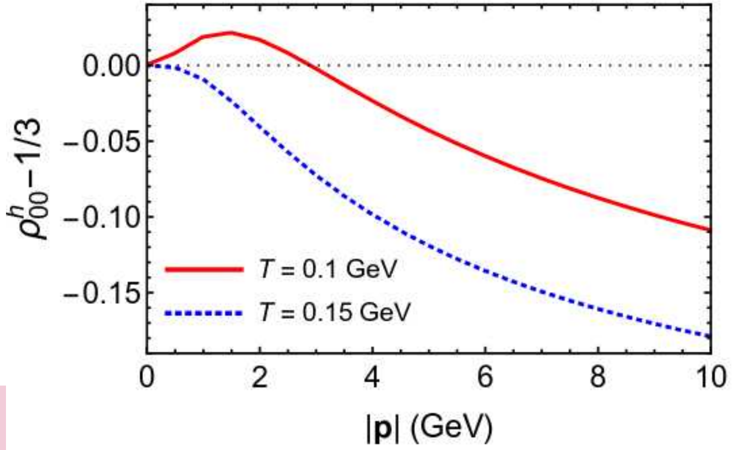
**Alignment from quark correlations: Q. Wang's talk today**

*Lv,Yu, Liang, Wang, Wang Phys.Rev.D 109 (2024) 11, 114003*

$$\rho_{00}^{(S)} = \frac{1}{C_v}(1 + c_{xx}^{q\bar{q}} + c_{yy}^{q\bar{q}} - c_{zz}^{q\bar{q}} + P_x^q P_x^{\bar{q}} + P_y^q P_y^{\bar{q}} - P_z^q P_z^{\bar{q}})$$

Alignment from holography: **X.L. Sheng's talk** on Wednesday

*Sheng, Zhao, Li, Becattini, Hou 2403.07522, Zhao, Sheng, Li, Hou 2403.07468; Zhao, Sheng, Li, Hou 2403.07468*




Non equilibrium effects: **G. Torrieri's talk** on Friday

*Gonçalves, Torrieri Phys.Rev.C 105 (2022) 3, 034913, De Moura,Gonçalves, Torrieri Phys.Rev.D 108 (2023) 3, 034032*

# And more

## Global spin alignment

$$\phi\text{−meson } \rho_{00} \approx \frac{1}{3} + C_\Lambda + C_B + C_S + C_F + C_L + C_H + C_\varphi + C_g$$

| Physics Mechanisms | $\rho_{00}$ |
|---|---|
| $c_\Lambda$: Quark coalescence + vorticity[1] | < 1/3 , magnitude ~ $10^{-4}$ |
| $c_B$: Quark coalescence + EM-field[1] | > 1/3, magnitude ~ $10^{-4}$ |
| $c_S$: Medium induced vector meson spectrum spliting[2] | > or < 1/3, magnitude unclear |
| $c_F$: Quark fragmentation[3] | > 1/3, magnitude ~ $10^{-5}$ |
| $c_L$: Local spin alignment[4] | < 1/3, magnitude ~ $10^{-2}$ |
| $c_H$: Second order hydro fields [5] | > or <1/3, magnitude unclear |
| $c_\varphi$: Vector meson field[6] | > 1/3, magnitude can fit to data |
| $c_g$: Fluctuating glasma fields[7] | <1/3, magnitude unclear |


[1]. Liang et. al., Phys. Lett. B 629, (2005);
Yang et. al., Phys. Rev. C 97, 034917 (2018);
Xia et. al., Phys. Lett. B 817, 136325 (2021);
Beccattini et. al., Phys. Rev. C 88, 034905 (2013).
[2]. Liu and Li, arxiv:2206.11890;
Sheng et. al., Eur.Phys.J.C84, 299 (2024);
Wei and Huang, Chin.Phys.C47, 104105 (2023);
[3]. Liang et. al., Phys. Lett. B 629, (2005).
[4]. Xia et. al., Phys. Lett. B 817, 136325 (2021);
Gao, Phys. Rev. D 104, 076016 (2021).
[5]. Kumar, Yang, Gubler, Phys.Rev.D109, 054038(2024);
Gao and Yang, Chin.Phys.C48, 053114 (2024);
Zhang, Huang, Becattini, Sheng, 2024.
[6]. Sheng et. al., Phys. Rev. D 101, 096005 (2020);
Phys. Rev. D 102, 056013 (2020);
Phys Rev. Lett. 131, 042304 (2023).
[7]. Muller and Yang, Phys. Rev. D 105, L011901 (2022);
Kumar et.al.,, Phy. Rev. D108, 016020 (2023).


From X.G. Huang slides, SQM2024

Open quantum system approach
*Yang, Yao 2405.20280*

$\rho$ meson alignment in a bath of pions
*Yin, Dong, Pang, Pu, Wang, 2402.03672*

Reviews
*Chen, Liang, Ma, Sheng, Wang 2407.06480;*
*Becattini, Buzzegoli, Niida, Pu, Tang, Wang 2407.06480*

# Summary

Vector polariation:

- Global polarization: dominated by **thermal vorticity**
- Local polarization: **many more contributions**, thermal shear, spin-hall effect...
- Sensitivity to **details of the simulations**: transport, initial state...

Alignment:

- is likely induced by **interactions**
- Fluctuating intermediate field predicts transverse momentum and rapidity dependence of alignment

# Open questions

Vector polarization:

- Theoretical unceirtainties on the **pseudogauge** to use

- Polarization at low energy?
- Spin hydro: How to **initialize the spin potential?**
- Furthermore: polarization in small systems? **C. Li's talk** on Wednesday

➔ **Need for numerical tests!**

Alignment:

- Is there an **independent way to detect the effective $\phi$ field's fluctuations**?
- Can **other mechanisms** explain the magnitude of the signal?

# Thank you for your attention!