Theory review of spin-polarization phenomena in heavy ion collisions

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Chirality, Vorticity, and Magnetic Field in Quantum Matter

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Romania

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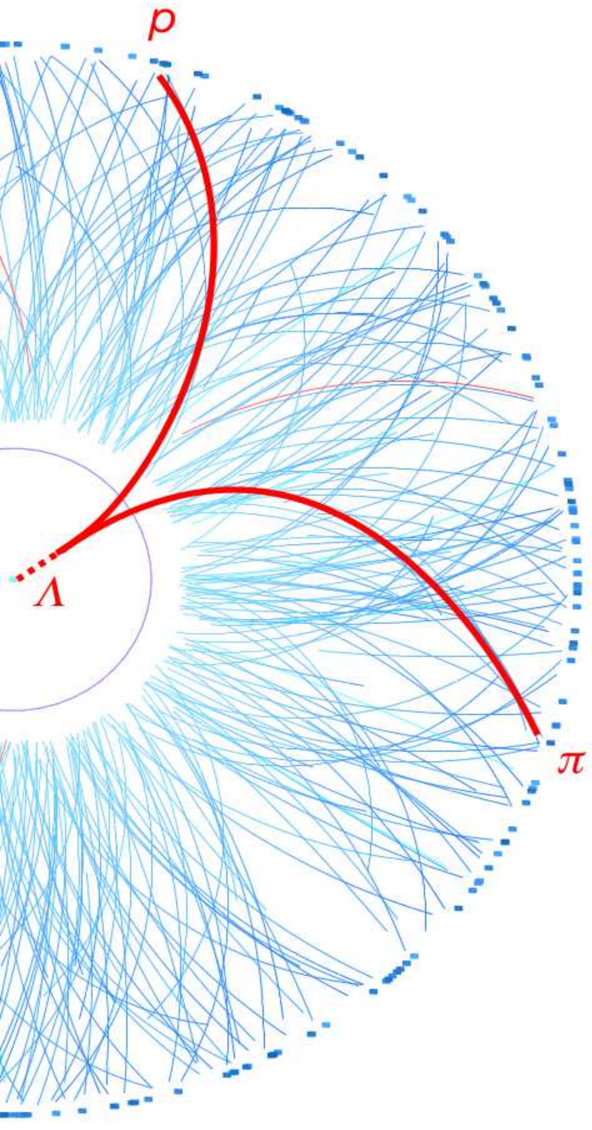
A personal note



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 ρ the definition of the spin density matrix is:

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

Notation: the spin density matrix is often denoted ρ, 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.

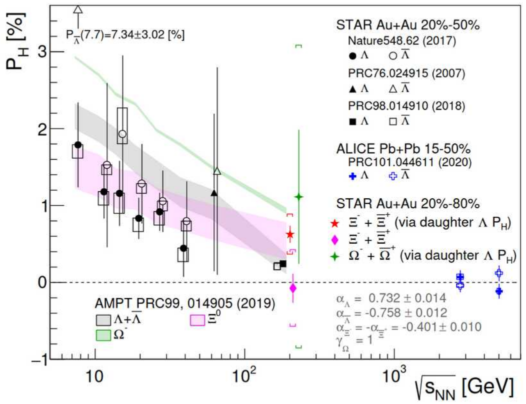
In the rest frame, the spin polarization vector is computed

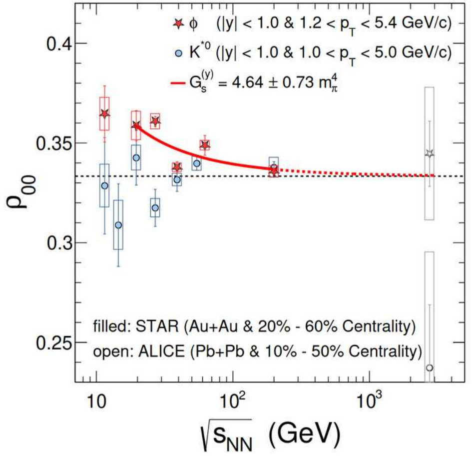
$$P_i = \frac{1}{S}\mathrm{Tr}\left(\rho^{(S)} D^S(\mathrm{J}^i)\right)$$

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

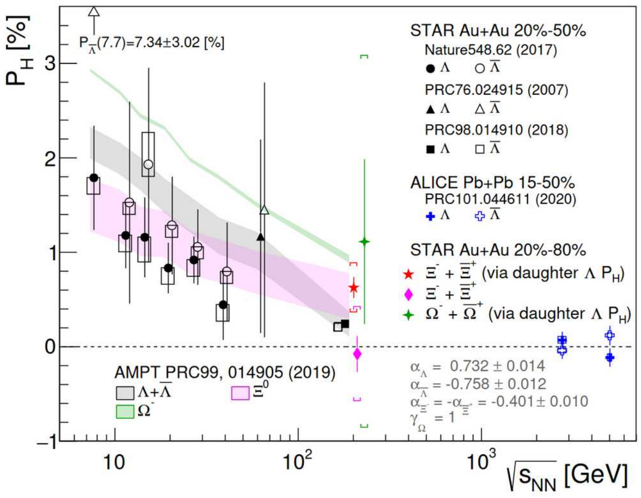
$$A_{33} = \frac{1}{3} - \rho_{00}^{(S)}$$

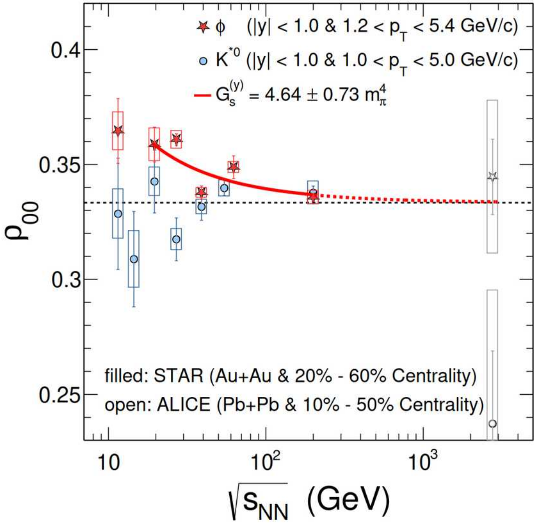
Phys.Rev.Lett. 126 (2021) 16, 162301





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





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

Why?

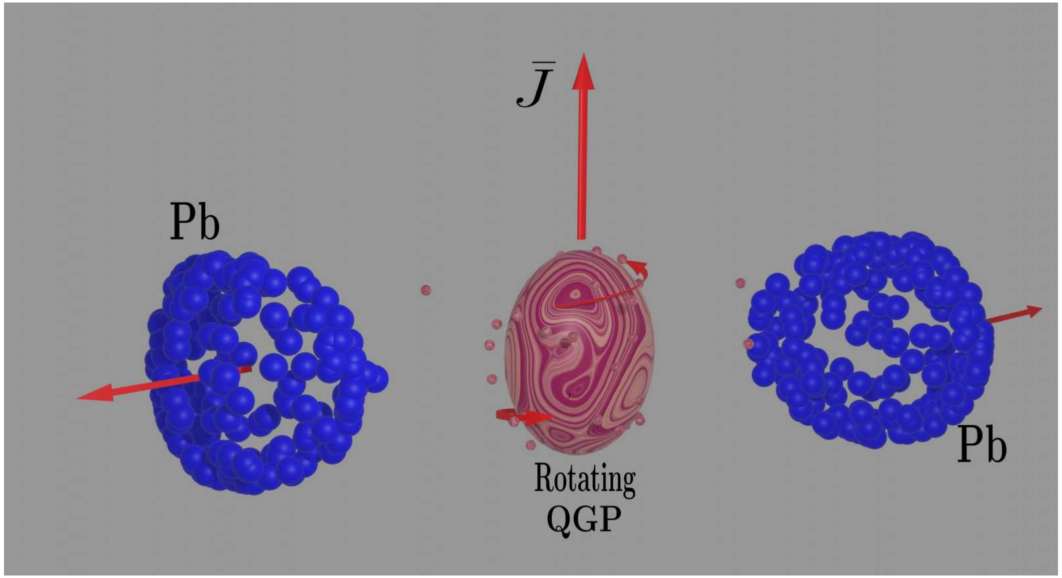
➔Hydrodynamics

➔Interactions

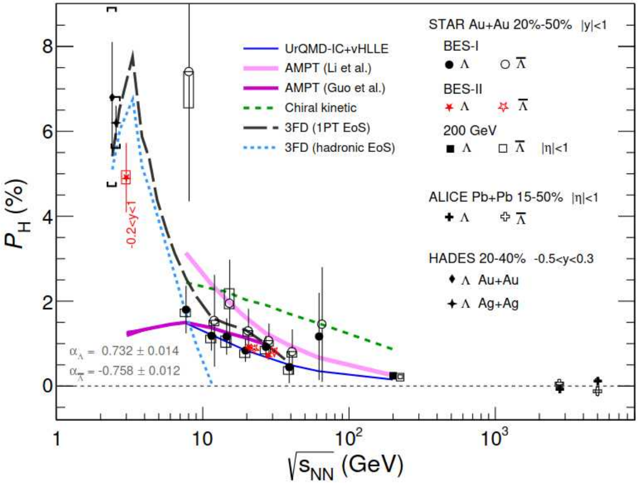
Λ polarization

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



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….

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

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!

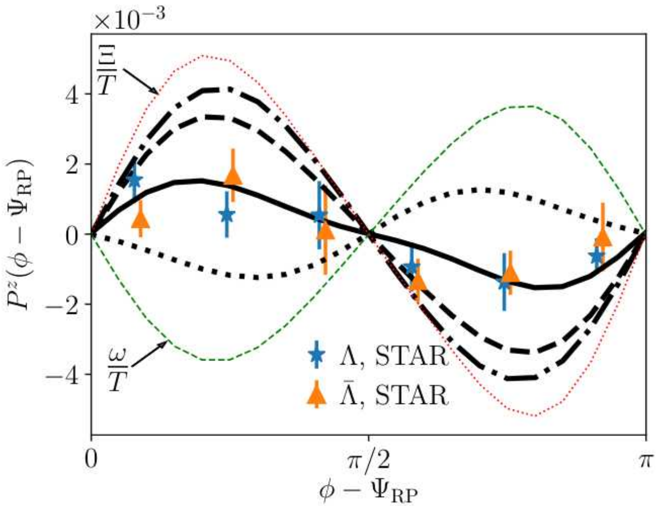
Liu, Huang, Sci.China Phys.Mech.Astron. 65 (2022) 272011

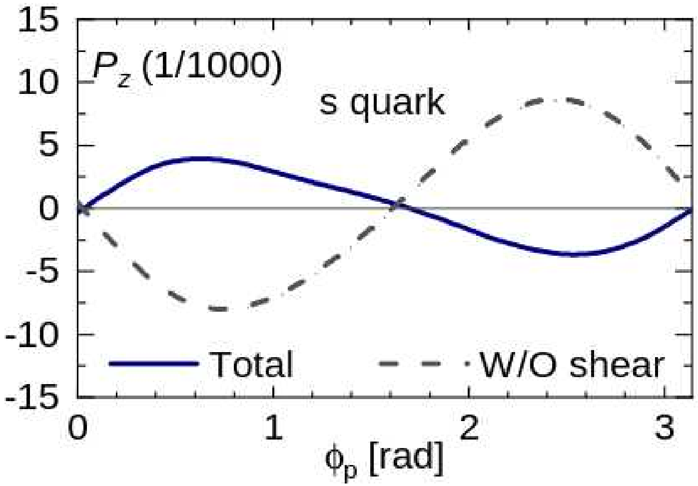
$$S_\mu(p) = -\frac{1}{8m \int d\Sigma \cdot p\, n_F} \int d\Sigma \cdot p \left\{ \epsilon_{\mu\nu\rho\sigma} p^\nu \varpi^{\rho\sigma} + 2\epsilon_{\mu\nu\rho\sigma} \frac{p^\rho}{p \cdot n} n^\sigma \left[p_\lambda (\xi^{\nu\lambda} + \Theta^{\nu\lambda}) + \frac{1}{4} \partial^\nu \frac{\mu}{T} \right]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

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

- **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

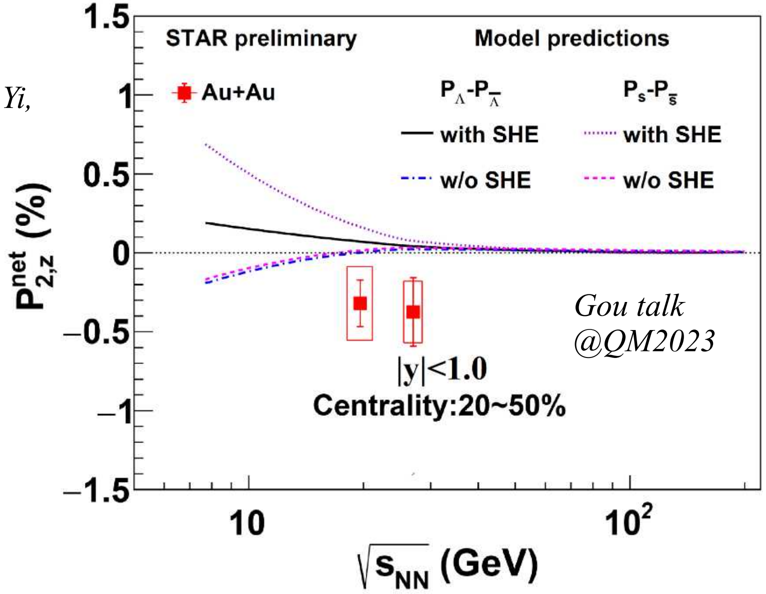
$$S_\mu(p) = -\epsilon_{\mu\nu\rho\sigma}\frac{p^\rho}{p\cdot n}n^\sigma\frac{\int d\Sigma\cdot p\, p_\lambda \xi^{\nu\lambda} n_F(1-n_F)}{4m\int d\Sigma\cdot p\, n_F}$$

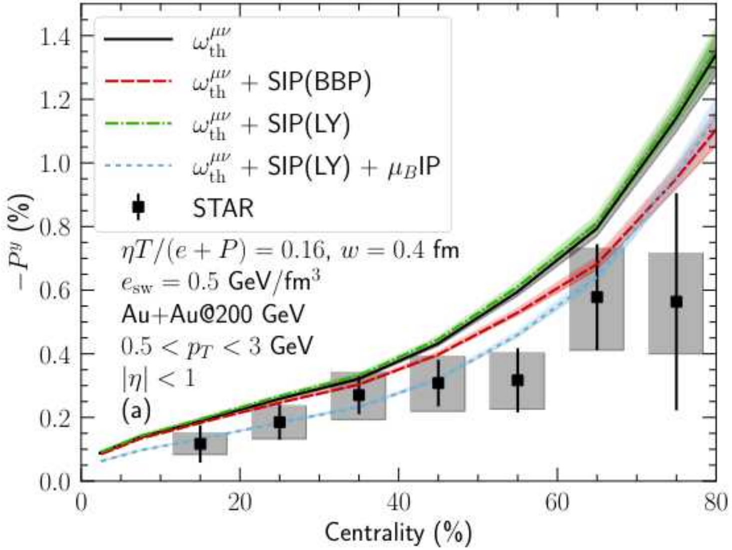
Thermal shear can explain the local polarization data, but...

- 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

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

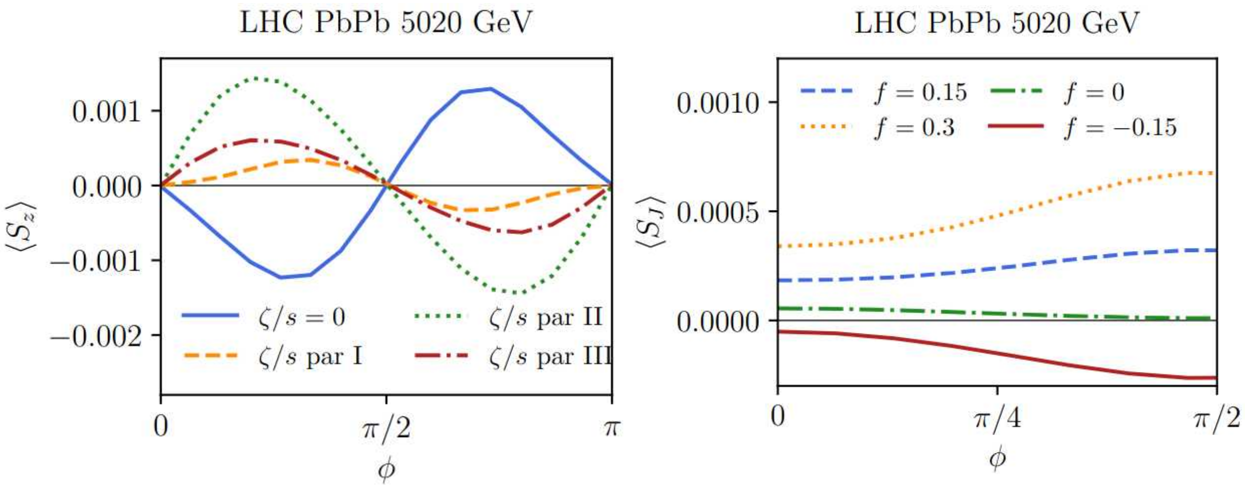
The Spin Hall effect seems to be marginal in high energy heavy ion collisions.

It becomes important in lower energy collisions.

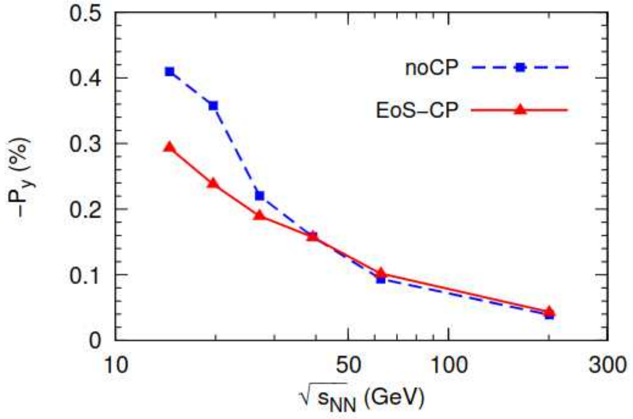
More numerical work on the spin Hall effect should be done.

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! 2407.14345

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

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

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

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.

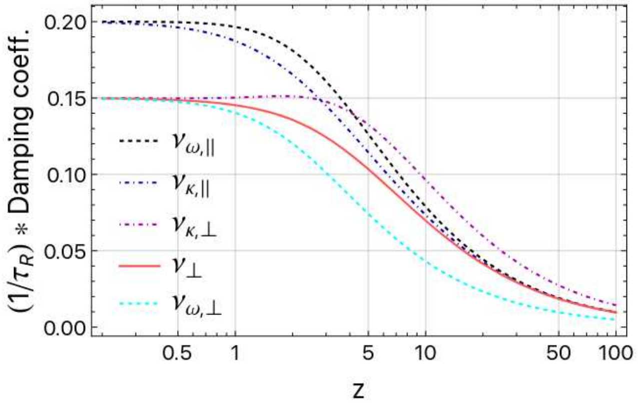
Ideal spin-hydro: **M. Shokri's talk** on Tuesday

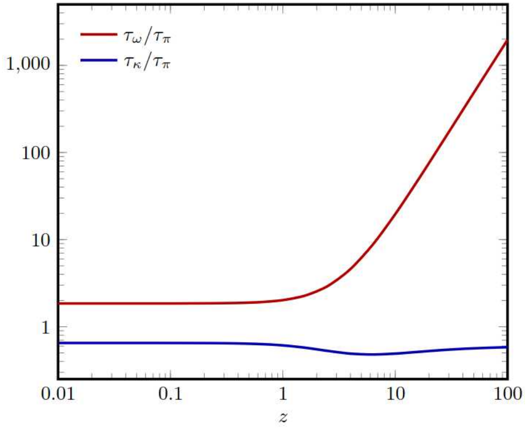
… in a rotating background: **A. Chiarini's poster**

Spin and dissipation

Some studies of solutions of spin waves damping have been performed

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



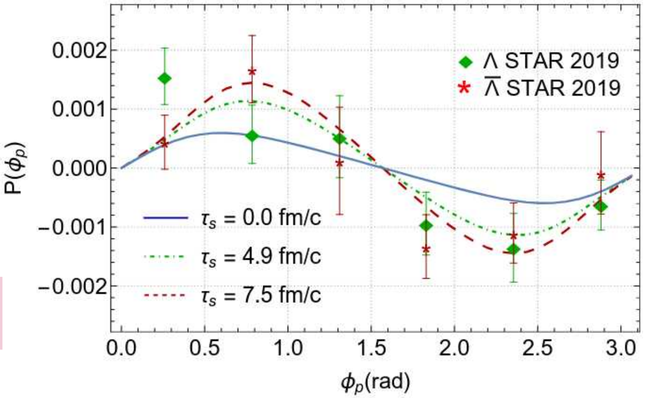


Wagner, Shokri, Rischke 2405.00533

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

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

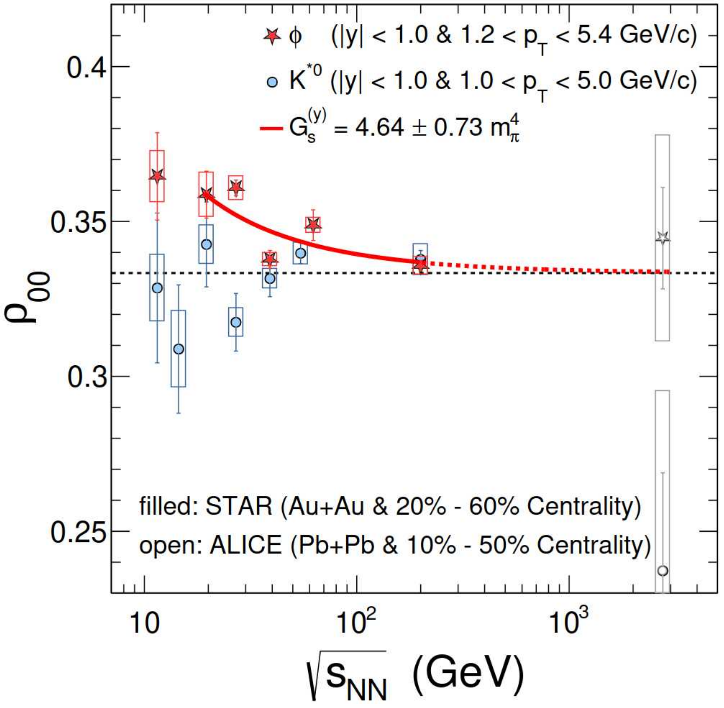
More references

- 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 ϕ and 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:

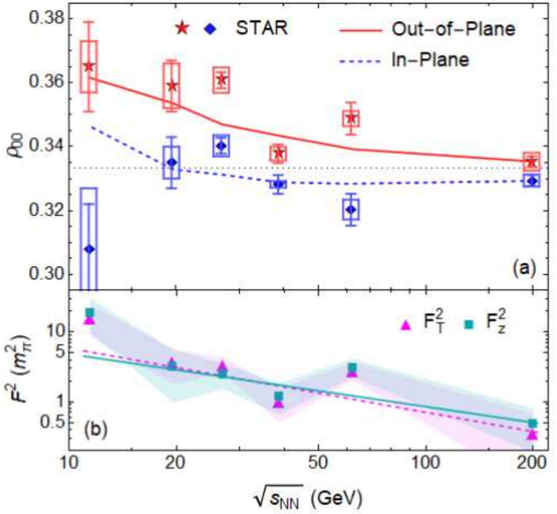
$$\rho^{(S)}_{m_1 m_2}(x, \vec{p}) = \frac{\epsilon^*_\mu(m_1, \vec{p})\epsilon_\nu(m_2, \vec{p})\mathcal{C}^{\mu\nu}_{\text{coal}}(x, \vec{p})}{\sum_{m=0,\pm1} \epsilon^*_\alpha(m, \vec{p})\epsilon_\beta(m, \vec{p})\mathcal{C}^{\alpha\beta}_{\text{coal}}(x, \vec{p})}$$

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

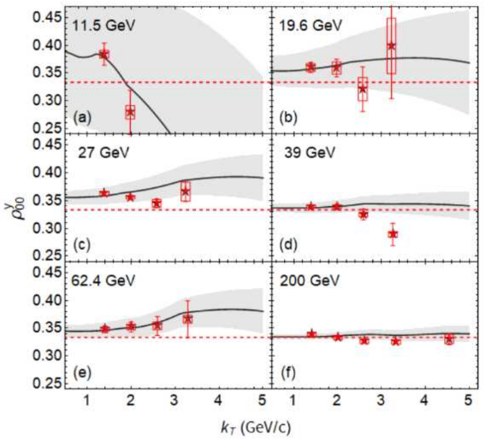
Quarks can be polarized by interactions with an effective vector meson field ϕ, which in a static fluid induces an alignment of the form

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

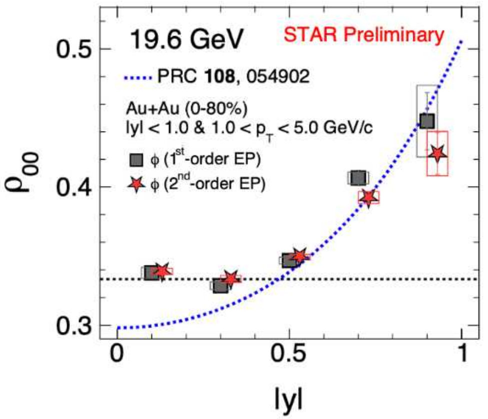
Alignment induced by fluctuations of the strong field. Fitted from data.



Predictions



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



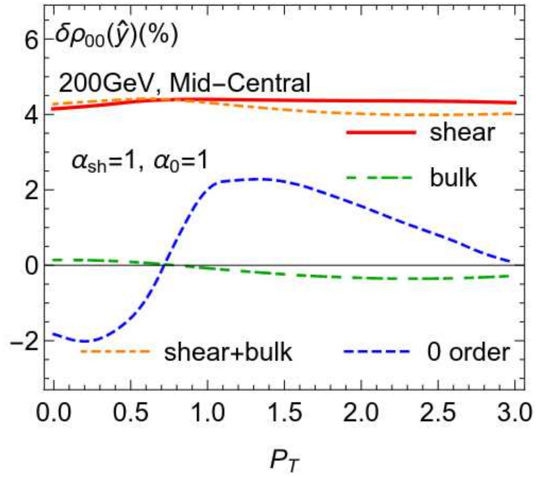
Sheng, Pu, Wang Phys.Rev.C 108 (2023) 5, 054902

Problem: other effects of this field? Overfitting?

Λ correlations: **X.N. Wang's talk** on Wednesday

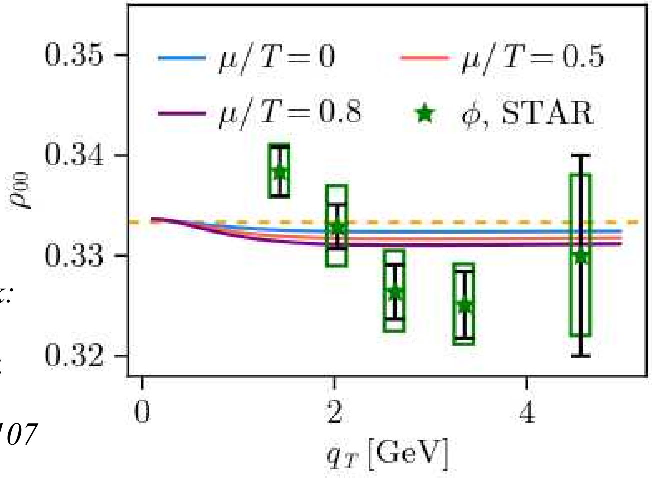
In medium spectral functions

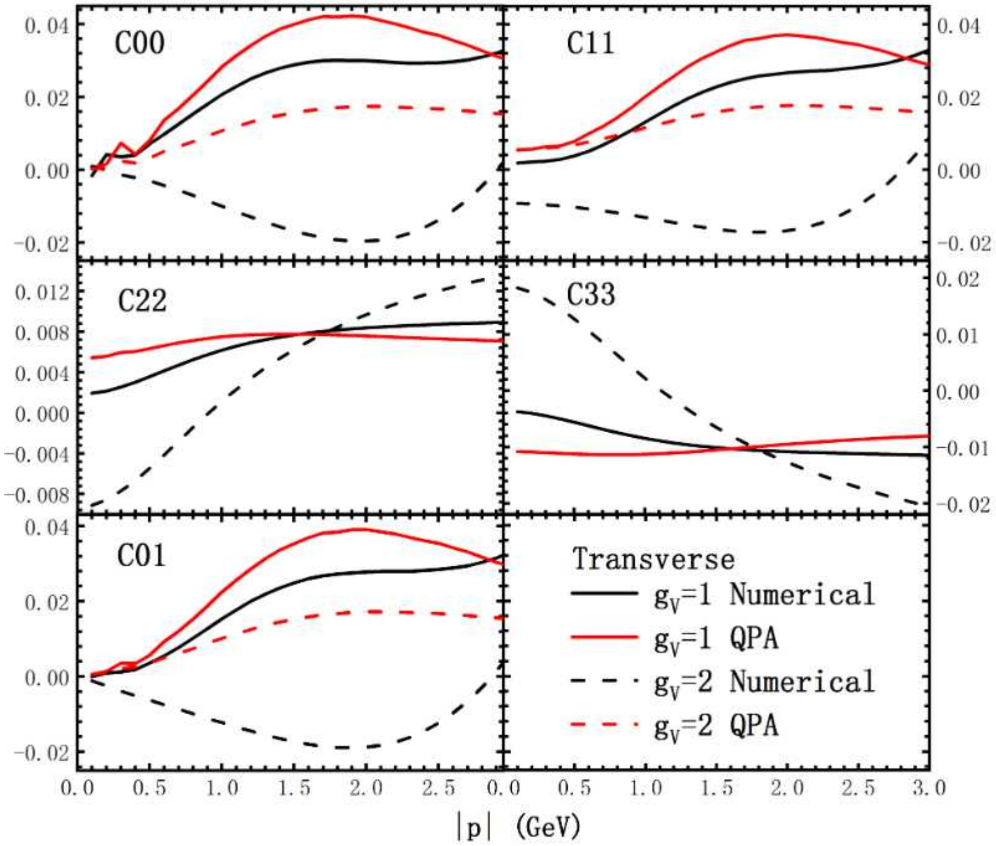
Li, Liu, 2206.11890



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

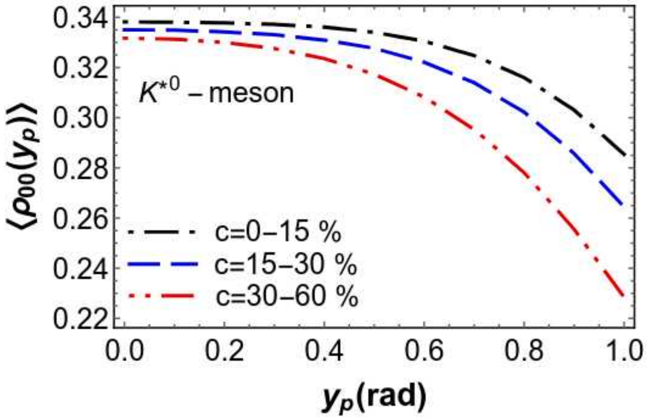
Standard and spin hydrodynamics

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 ϕ?

More sources of alignment

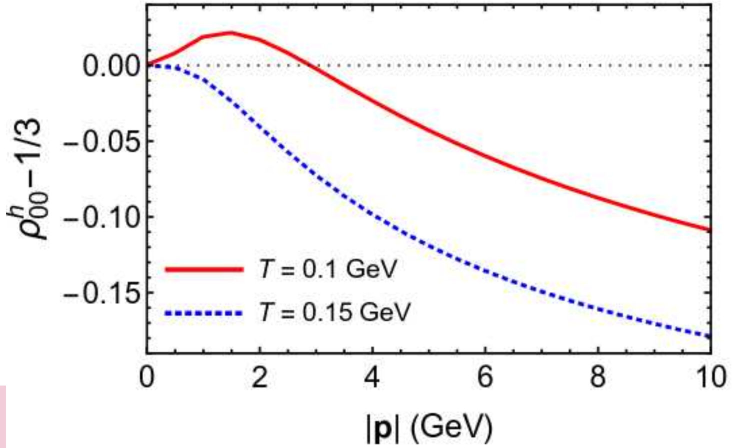
Alignment from quark correlations: **Q. Wang's talk** today

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	ρ_{00}
c_Λ: 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_φ: 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

ρ 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 ϕ field's fluctuations**?
- Can **other mechanisms** explain the magnitude of the signal?

Thank you for your attention!