Spin Polarization of Vector Mesons in Spin Hydro

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USTC - Particle and Nuclear Physics

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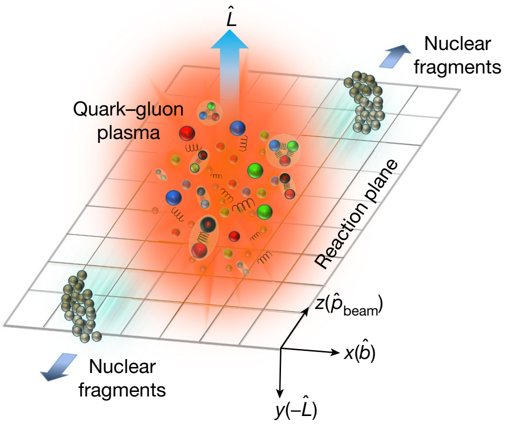
Spin Polarization in HIC



Heavy Ion Collision

B. Mashhoon, Phys. Rev. Lett. 61, 2639 (1988)

spin-orbital coupling $\Rightarrow$ spin-rotation coupling:

$$H_s = -\boldsymbol{s} \cdot \boldsymbol{\omega}$$

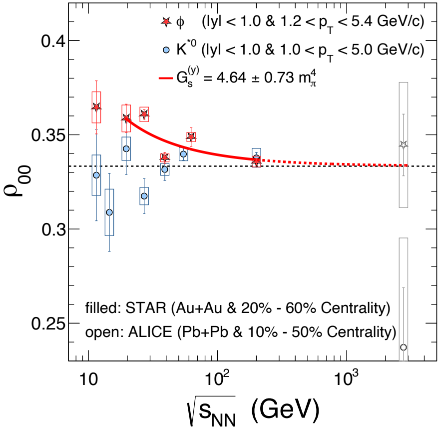
$$\Rightarrow \langle \boldsymbol{s} \rangle = \frac{S(S+1)}{3} \frac{\boldsymbol{\omega}}{T} \sim 10^{-2}$$

Contribution of $u_\mu(x)$, $T(x)$, $\Omega_{\rho\sigma}(x)$

Graph: STAR, Nature 614, 244-248 (2023)

Global Spin Alignment

Global spin alignment



- ϕ meson $\Theta_{00} > 1/3$ and too big

$$\Theta_{00} - \frac{1}{3} \sim - \langle \boldsymbol{s} \rangle^2 \sim -10^{-4}$$

- K^{*0} different from ϕ

Figure: STAR, Nature 614, 244-248 (2023)

Physical Mechanisms

$$\phi \text{ meson: } \delta\Theta_{00} = \Theta_{00} - \frac{1}{3} \approx +c_\Lambda + c_B + c_s + c_F + c_L + \boxed{c_H} + c_\phi + c_g + \cdots$$

Physical mechanism	$\delta\Theta_{00}$
c_Λ: Quark coalescence + vorticity [1]	magnitude $\sim -10^{-4}$
c_B: Quark coalescence + EM-field [1]	magnitude $\sim 10^{-4}$
c_S: Spectrum splitting [2]	unclear
c_F: Quark fragmentation [3]	magnitude $\sim 10^{-5}$
c_L: Local spin alignment [4]	magnitude $\sim -10^{-2}$
c_H: Second-order hydro fields [5]	unclear
c_φ: Vector meson field [6]	> 0, fit to data
c_g: Glasma fields [7]	< 0, magnitude unclear

[1]. Liang, Wang, PLB 629, 20 (2005);
Yang *et al.*PRC 97, 034917 (2018);
Xia *et al.*PLB 817, 136325 (2021);
Becattini *et al.*PRC 88, 034905 (2013).
[2]. Liu, Li, arXiv: 2206.11890;
Sheng *et al.*, Eur.Phys.J.C 84, 299 (2024);
Wei, Huang, Chin.Phys.C 47,104015 (2023).
[3]. Liang, Wang PLB 629, 20 (2005);
[4]. Xia *et al.*PLB 817, 136325 (2021);
Gao, PRD 104, 076016 (2021).
[5]. Kumar, Yang, Gubler, PRD 109, 054038(2024);
Gao, Yang, Chin.Phys.C 48, 053114 (2024);
ZZ, Huang, Becattini, Sheng, 2024.
[6]. Sheng *et al.*, PRD 101, 096005 (2020);
Sheng *et al.*, PRD 102, 056013 (2020);
Sheng *et al.*, PRL 131, 042304 (2023).
[7]. Muller, Yang, PRD 105, L011901 (2022);
Kumar *et al.*, Phy. Rev. D108, 016020 (2023).

Spin Density Matrix

- Free Lagrangian for neutral vector bosons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$$

- Mode decomposition

$$\widehat{A}^\mu(x) = \sum_{s=1}^{3}\int \frac{d^3\boldsymbol{k}}{(2\pi)^3}\frac{1}{2E_{\boldsymbol{k}}}\left[\widehat{a}^s_{\boldsymbol{k}}\epsilon^\mu_s(k)e^{-ik\cdot x} + \widehat{a}^{s\dagger}_{\boldsymbol{k}}\epsilon^\mu_s(k)e^{ik\cdot x}\right],$$

- Spin density matrix:

$$\boxed{\Theta_{rs}(k) \equiv \frac{\mathrm{Tr}\left(\widehat{\rho}\,\widehat{a}^{s\dagger}_{\boldsymbol{k}}\widehat{a}^{r}_{\boldsymbol{k}}\right)}{\sum_r \mathrm{Tr}\left(\widehat{\rho}\,\widehat{a}^{r\dagger}_{\boldsymbol{k}}\widehat{a}^{r}_{\boldsymbol{k}}\right)}}$$

- Dependence on mode decomposition

$$\widehat{a}^{r\dagger\prime}_{\boldsymbol{k}} = \sum_s D^1(R)_{sr}\widehat{a}^{s\dagger}_{\boldsymbol{k}}$$

$$\Theta'(k)_{tu} = \sum_{rs} D^1(R^{-1})_{tr}\Theta(k)_{rs}D^1(R)_{su}$$

with R belongs to the little group $SO(3)$

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

Spin Polarization

- Spin polarization vector and tensor:

polarization vector

$$\Theta(k) = \frac{1}{3} I + \frac{1}{2} \sum_i \mathfrak{S}^i(k)\, s^i + \sum_{ij} \mathfrak{T}^{ij}(k)\, \Sigma^{ij}$$

polarization tensor

$$\Sigma^{ij} = s^{(i} s^{j)} - s^2 \delta^i/3, \quad \mathfrak{S}^i(k) = \mathrm{tr}\{\Theta(k) s^i\}, \quad \mathfrak{T}^{ij}(k) = \mathrm{tr}\{\Theta(k)\Sigma^{ij}\}$$

- Covariant polarization vector and tensor:

$$\mathcal{S}^\mu(k) = \sum_i \mathfrak{S}^i(k) \epsilon_i^\mu(k),$$

$$\mathcal{T}^{\mu\nu}(k) = \sum_{ij} \mathfrak{T}^{ij}(k) \epsilon_i^\mu(k) \epsilon_j^\nu(k)$$

$$\delta\Theta_{00}(k) = -\epsilon_\mu^0(k)\epsilon_\nu^0(k)\mathcal{T}^{\mu\nu}(k)$$

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

E. Leader, *Spin in Particle Physics, Cambridge University Press (2023)*

- They are the expectation values of

$$\widehat{\mathcal{S}}^\mu \equiv -\frac{1}{m} \widehat{W}^\mu = -\frac{1}{2m} \epsilon^{\mu\nu\rho\sigma} \widehat{J}_{\nu\rho} \widehat{P}_\sigma\,, \qquad \widehat{\mathcal{T}}^{\mu\nu} \equiv \widehat{\mathcal{S}}^{(\mu} \widehat{\mathcal{S}}^{\nu)} + \frac{2}{3}\left(\eta^{\mu\nu} - \frac{1}{m^2} \widehat{P}^\mu \widehat{P}^\nu\right)$$

Pauli-Lubanski vector

Wigner function

- Future time-like (particle) Wigner function: $W^{\mu\nu}(x,k) = \mathrm{Tr}\left\{\hat{\rho}\,\widehat{W}^{\mu\nu}(x,k)\right\}$

$$\widehat{W}^{\mu\nu}(x,k) \equiv \frac{1}{2\pi}\int d^4s\, e^{ik\cdot s}\hat{A}^{\nu}(x-\frac{s}{2})\hat{A}^{\mu}(x+\frac{s}{2})\theta(k^2)\theta(k^0)$$

- With $\epsilon_r^{\mu}(k)\epsilon_s^{\nu}(k)\int_{\Sigma} d\Sigma\cdot k\,\widehat{W}_{\mu\nu}(x,k) = \frac{1}{2}\delta(k^2-m^2)\theta(k^0)\hat{a}^{s\dagger}_{\boldsymbol{k}}\hat{a}^{r}_{\boldsymbol{k}}\,,$

  Spin density matrix

$$\Theta_{rs}(k) = \frac{\epsilon_r^{\mu}\epsilon_s^{\nu}\int_{\Sigma} d\Sigma\cdot k\,W_{\mu\nu}(x,k)}{\int_{\Sigma} d\Sigma\cdot k\,f(x,k)}$$

  Scalar distribution $f(x,k) = -\underbrace{\Delta^{\mu\nu}_{(k)}}_{\text{projection }\perp\text{ to }k}W_{\mu\nu}(x,k)$

Polarization vector and tensor in phase space

- Decomposition of Wigner function

$$\underbrace{W_\perp^{\mu\nu}(x,k)}_{\text{projected Wigner function}} = \overbrace{f(x,k)}^{\text{scalar distribution}} \left\{ -\frac{1}{3}\Delta^{\mu\nu}_{(k)} + \frac{i}{2m}\epsilon^{\mu\nu\rho\sigma} k_\rho \overbrace{\mathcal{S}_\sigma(x,k)}^{\text{pseudo vector}} - \underbrace{\mathcal{T}^{\mu\nu}(x,k)}_{\text{tensor}} \right\}$$

$$W_\perp^{\mu\nu} = \Delta^{\mu\alpha}_{(k)}\Delta^{\nu\beta}_{(k)} W_{\alpha\beta}$$

- Spin polarization vector and tensor in phase space

$$\mathcal{S}^\mu(x,k) = -i\frac{\epsilon^{\mu\nu\alpha\beta}k_\nu W_{\alpha\beta}(x,k)}{m f(x,k)}, \qquad \mathcal{T}^{\mu\nu}(x,k) = -\frac{\overbrace{W^{\langle\mu\nu\rangle}}^{\text{traceless and symmetric part of } W_\perp^{\mu\nu}}(x,k)}{f(x,k)}$$

- Average over the hypersurface

$$\mathcal{S}^\mu(k) = \frac{\int_\Sigma d\Sigma\cdot k\,\mathcal{S}^\mu(x,k) f(x,k)}{\int_\Sigma d\Sigma\cdot k\, f(x,k)}, \qquad \mathcal{T}^{\mu\nu}(k) = \frac{\int_\Sigma d\Sigma\cdot k\,\mathcal{T}^{\mu\nu}(x,k) f(x,k)}{\int_\Sigma d\Sigma\cdot k\, f(x,k)}$$

Density Operator

- True density operator should be a constant

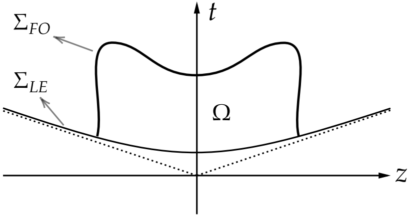
$$\hat{\rho}_{\text{true}} = \frac{1}{Z} \exp\left\{ - \int_{\Sigma_{\text{LE}}} d\Sigma\, t_\mu \left(\overbrace{\hat{T}^{\mu\nu}}^{\text{stress tensor}} \underbrace{\beta_\nu}_{\text{thermal current } u_\nu/T \sim \mathcal{O}(1)} - \frac{1}{2} \overbrace{\hat{S}^{\mu\rho\sigma}}^{\text{spin tensor}} \underbrace{\Omega_{\rho\sigma}}_{\text{spin potential} \sim \mathcal{O}(\partial)} \right) \right\}$$

Canonical currents: $T^{\mu\nu} = -F^{\mu\rho}\partial^\nu A_\rho - g^{\mu\nu}\mathcal{L}$, $S^{\mu\rho\sigma} = -F^{\mu\rho}A^\sigma + F^{\mu\sigma}A^\rho$

Zubarev, Prozorkevich, Smolyanskii, Theo. and Math. Phys. 40, 821 (1979)

van Weert, Ann. of Phys. 140, 133 (1982)

Becattini, Buzzegoli, Grossi, Particles 2, 197 (2019)



- Connect with the freeze-out

$$\hat{\rho}_{\text{true}} = \frac{1}{Z} \exp\left\{ \underbrace{- \int_{\Sigma_{\text{FO}}} d\Sigma\, t_\mu \left(\hat{T}^{\mu\nu}\beta_\nu - \frac{1}{2}\hat{S}^{\mu\rho\sigma}\Omega_{\rho\sigma} \right)}_{\text{local equilibrium}} \underbrace{+ \int_\Omega d\Omega \left[\hat{T}^{\mu\nu}(\partial_\mu \beta_\nu + \Omega_{\mu\nu}) - \frac{1}{2}\hat{S}^{\mu\rho\sigma}\partial_\mu \Omega_{\rho\sigma} \right]}_{\text{dissipation}} \right\}$$

Cumulant Expansion

- Density operator $\widehat{\rho}_{\text{LE}} = \dfrac{1}{Z_{\text{LE}}} \exp\left\{\widehat{A} + \widehat{B}\right\}$, with $Z_{\text{LE}} = \text{Tr}\left(e^{\widehat{A}+\widehat{B}}\right)$

  "Gaussian" term $\widehat{A}(x) = -\beta_\nu(x)\widehat{P}^\nu = -\beta_\nu(x)\int_\Sigma d\Sigma_\mu(y)\widehat{T}^{\mu\nu}(y)$

  "Perturbative" terms $\widehat{B}(x) = -\int_\Sigma d\Sigma_\mu(y)\left[\widehat{T}^{\mu\nu}(y)(\beta_\nu(y) - \beta_\nu(x)) - \dfrac{1}{2}\widehat{S}^{\mu,\rho\sigma}(y)\Omega_{\rho\sigma}(y)\right]$

- Cumulant expansion: $e^{\widehat{A}+\widehat{B}} = e^{\widehat{A}}\sum_{n=0}^{\infty}\widehat{B}_n$, with $\widehat{B}_n \sim (\widehat{B})^n \sim \mathcal{O}(\partial^n)$

$$O(x) \equiv \text{Tr}\left(\widehat{\rho}_{\text{LE}}\widehat{O}(x)\right) = \frac{1}{Z_{\text{LE}}}\text{Tr}\left(e^{\widehat{A}(x)+\widehat{B}(x)}\widehat{O}(x)\right)$$

$$= \boxed{\sum_n \left\langle \widehat{B}_n\widehat{O}(x)\right\rangle_0 \Big/ \sum_n \left\langle \widehat{B}_n\right\rangle_0} = \boxed{\sum_n \left\langle \widehat{B}_n\widehat{O}(x)\right\rangle_{0,c}}$$

with $\langle\cdots\rangle_0 = \text{Tr}\left(e^{\widehat{A}}\cdots\right)\Big/\text{Tr}\left(e^{\widehat{A}}\right)$ the expectation value under the Gaussian-type distribution.

Zeroth-Order Result

- Cumulant expansion at 0th order: $W^{(0)}_{\mu\nu}(x,k) = \mathrm{Tr}\left\{\widehat{\rho}_0\, \widehat{W}_{\mu\nu}(x,k)\right\}$

- “Free" distribution: $\widehat{\rho}_0 = \frac{1}{Z_0}\exp\left\{-\beta(x)\cdot\widehat{P}\right\}$

$$W^{(0)}_{\mu\nu}(x,k) = -\delta(k^2-m^2)\theta(k^0)\Delta^{(k)}_{\mu\nu}\, n_B(\beta(x)\cdot k)$$

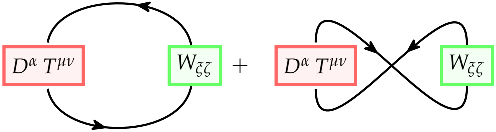
- $f(x,k) = 3\delta(k^2-m^2)\theta(k^0)n_B(\beta(x)\cdot k)\,,\quad \mathcal{S}^{\mu}(x,k)=0\,,\quad \mathcal{T}^{\mu\nu}(x,k)=0$

First-Order Gradient Expansion

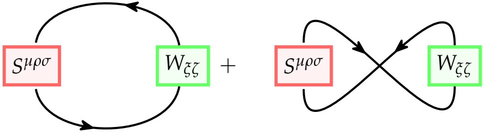
Cumulant expansion: $W^{(1)}_{\mu\nu}(x,k) = \left\langle \widehat{B}_1 \widehat{W}_{\mu\nu}(x,k) \right\rangle_{0,c} = \left\langle \widehat{B}_1 \widehat{W}_{\mu\nu}(x,k) \right\rangle_0 - \left\langle \widehat{B}_1 \right\rangle_0 \left\langle \widehat{W}_{\mu\nu}(x,k) \right\rangle_0$

$$\widehat{B}_1 = -n_\mu \partial_\alpha \beta_\nu(x) \int_0^1 d\lambda \int_P d^3\boldsymbol{y}\, (y-x)^\alpha \widehat{T}^{\mu\nu}(y - i\lambda\beta(x)) + \frac{1}{2} n_\mu \Omega_{\rho\sigma}(x) \int_0^1 d\lambda \int_P d^3\boldsymbol{y}\, \widehat{S}^{\mu\rho\sigma}(y - i\lambda\beta(x))$$

$$\int_0^1 d\lambda \int_P d^3\boldsymbol{y}\, (y-x)^\alpha \left\langle \widehat{T}^{\mu\nu}(y - i\lambda\beta(x)) \widehat{W}_{\xi\zeta}(x,k) \right\rangle_{0,c} =$$



$$\int_0^1 d\lambda \int_P d^3\boldsymbol{y}\, \left\langle \widehat{S}^{\mu\rho\sigma}(y - i\lambda\beta(x)) \widehat{W}_{\xi\zeta}(x,k) \right\rangle_{0,c} =$$



First-Order Result

- Recall that: $W^{(1)}_{\mu\nu}(x,k) = -n_\xi \partial_\alpha \beta_\lambda(x) \int_0^1 d\lambda \int_P d^3\boldsymbol{y}(y-x)^\alpha \left\langle \widehat{T}^{\xi\lambda}(y - i\lambda\beta(x))\widehat{W}_{\mu\nu}(x,k) \right\rangle_{0,c}$ + spin potential contribution

$$W^{(1)}_{\perp,\mu\nu}(x,k) = -i\delta(k^2-m^2)\theta(k^0)n_B(1+n_B)\Delta^{(k)}_{\mu\rho}\Delta^{(k)}_{\nu\sigma}\left[\overbrace{\varpi^{\rho\sigma}}^{\text{thermal vorticity}} - \Xi_\alpha{}^{[\rho}\left(\overbrace{\xi^{\sigma]\alpha}}^{\text{thermal shear}} + \underbrace{\delta\Omega^{\sigma]\alpha}}_{\text{net spin potential: } \Omega-\varpi}\right)\right]$$

with: $\Xi^{\mu\nu} = \eta^{\mu\nu} - \hat{k}^\mu n^\nu\,, \quad \hat{k}^\mu \equiv k^\mu/(n\cdot k)\,, \quad \varpi_{\rho\sigma} = \partial_{[\sigma}\beta_{\rho]} \sim \omega/T\,, \quad \xi_{\rho\sigma} = \partial_{(\sigma}\beta_{\rho)}$

- Spin polarization vector

$$\mathcal{S}^\mu(x,k) = -\frac{1+n_B}{3m}\epsilon^{\mu\nu\rho\sigma}k_\nu\left(\varpi_{\rho\sigma} + n_\rho\xi_{\sigma\lambda}k^\lambda/E_{\boldsymbol{k}} - \Xi_\alpha{}^\rho\delta\Omega^{\sigma\alpha}\right)$$

- Space-time reversal odd: $\boxed{W^{(1)}_{\mu\nu} = -W^{(1)}_{\nu\mu} \;\Rightarrow\; \mathcal{T}^{\mu\nu} = 0 + \mathcal{O}(\partial^2)}$

Second-Order Gradient Expansion

- Based on the cumulant expansion:

$$
\begin{aligned}
\widehat{\mathcal{B}}_2 \equiv & \int_0^1 d\lambda_1 \int_0^{\lambda_1} d\lambda_2 \int_{\Sigma_{\mathrm{FO}}} d\Sigma_{\mu_1}(y_1) d\Sigma_{\mu_2}(y_2) \\
& \times \Big[\partial_{\alpha_1}\beta_{\nu_1}(x)\partial_{\alpha_2}\beta_{\nu_2}(x)(y_1-x)^{\alpha_1}(y_2-x)^{\alpha_2}\widehat{T}^{\mu_1\nu_1}(y_1^{(\beta)})\widehat{T}^{\mu_2\nu_2}(y_2^{(\beta)}) \\
& - \frac{1}{2}\partial_{\alpha_1}\beta_{\nu_1}(x)\Omega_{\rho_2\sigma_2}(x)(y_1-x)^{\alpha_1}\widehat{T}^{\mu_1\nu_1}(y_1^{(\beta)})\widehat{S}^{\mu_2,\rho_2\sigma_2}(y_2^{(\beta)}) \\
& - \frac{1}{2}\Omega_{\rho_1\sigma_1}(x)\partial_{\alpha_2}\beta_{\nu_2}(x)(y_2-x)^{\alpha_2}\widehat{S}^{\mu_1,\rho_1\sigma_1}(y_1^{(\beta)})\widehat{T}^{\mu_2\nu_2}(y_2^{(\beta)}) \\
& + \frac{1}{4}\Omega_{\rho_1\sigma_1}(x)\Omega_{\rho_2\sigma_2}(x)\widehat{S}^{\mu_1,\rho_1\sigma_1}(y_1^{(\beta)})\widehat{S}^{\mu_2,\rho_2\sigma_2}(y_2^{(\beta)}) \Big] \\
& + \int_0^1 d\lambda_1 \int_{\Sigma_{\mathrm{FO}}} d\Sigma_{\mu_1}(y_1) \Big[-\partial_{\alpha_1}\partial_{\alpha_2}\beta_{\nu_1}(x)\frac{1}{2}(y_1-x)^{\alpha_1}(y-x)^{\alpha_2}\widehat{T}^{\mu_1\nu_1}(y_1^{(\beta)}) \\
& + \frac{1}{2}\partial_{\alpha_1}\Omega_{\rho_1\sigma_1}(x)(y_1-x)^{\alpha_1}\widehat{S}^{\mu_1,\rho_1\sigma_1}(y_1^{(\beta)}) \Big]
\end{aligned}
$$

- Wigner function induced by second-order hydro fields:

$$
W^{(2)}_{\mu\nu}(x,k) = \left\langle \widehat{\mathcal{B}}_2 \widehat{W}_{\mu\nu}(x,k) \right\rangle_{0,c}
$$

Result: Spin Alignment

- PT even: $W^{(2)}_{\mu\nu}(x,k) = W^{(2)}_{\nu\mu}(x,k)$
- Spin alignment induced by various hydro fields

$$\delta\Theta_{00}\big|_{\varpi^2}(x,k) = -\frac{1}{6}(1+n_B)(1+2n_B)\left[\epsilon_0^\mu\epsilon_0^\nu + \frac{1}{3}\Delta^{\mu\nu}_{(k)}\right]\left[\Delta^{\rho\sigma}_{(k)} + \frac{1}{2m^2}k^\rho k^\sigma\right]\boxed{\varpi_{\rho\mu}\varpi_{\sigma\nu}}$$

$$\delta\Theta_{00}\big|_{\partial\varpi}(x,k) = (1+n_B)\left[\epsilon_\mu^0\epsilon_\nu^0 + \frac{1}{3}\Delta^{(k)}_{\mu\nu}\right]\frac{1}{6E_{\boldsymbol{k}}}n^{[\rho}\boxed{\partial^{\mu]}\varpi_{\rho\sigma}}\left(2\eta^{\sigma\nu} - \hat{k}^\sigma n^\nu\right)$$

$$\begin{aligned}\delta\Theta_{00}\big|_{\partial\xi}(x,k) = (1+n_B)\left[\epsilon_\mu^0\epsilon_\nu^0 + \frac{1}{3}\Delta^{(k)}_{\mu\nu}\right]\frac{1}{6E_k}\boxed{\partial_\alpha\xi_{\rho\sigma}}\Big[&(2n^\rho + \gamma_k^2\hat{k}^\rho)\eta^{\alpha\mu}\eta^{\sigma\nu} \\ &+ (\eta^{\rho(\sigma}\hat{k}^{\alpha)} + \gamma_k^2\hat{k}^\alpha\hat{k}^\rho\hat{k}^\sigma)n^\mu n^\nu - (\eta^{\rho(\alpha} + n^\rho\hat{k}^{(\alpha} + \gamma_k^2\hat{k}^\rho\hat{k}^{(\alpha})\eta^{\sigma)\mu}n^\nu\Big].\end{aligned}$$

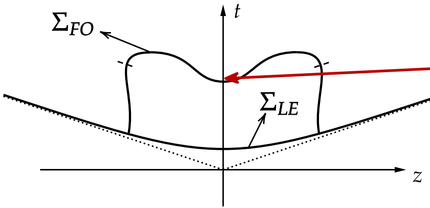
$$\delta\Theta_{00}\big|_{\partial\delta\Omega}(x,k) = (1+n_B)\left[\epsilon_\mu^0\epsilon_\nu^0 + \frac{1}{3}\Delta^{(k)}_{\mu\nu}\right]\frac{1}{6E_k}\boxed{\partial_\alpha\delta\Omega_\rho{}^\nu}\left(\hat{k}^\alpha n^\rho n^\mu - \gamma_k^2\,\hat{k}^\rho\eta^{\mu\alpha} - \Delta^{\alpha\rho}_{(k)}n^\mu\right).$$

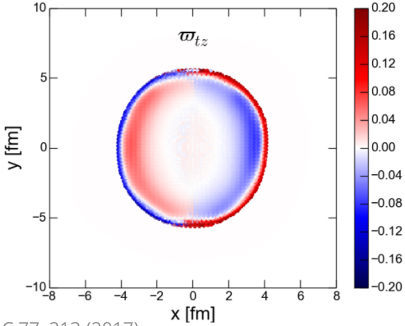
$$\cdots$$

Approximation

$$\delta\Theta_{00}\big|_{\partial\varpi}(x,k) = (1+n_B)\left[\epsilon^0_\mu\epsilon^0_\nu + \frac{1}{3}\Delta^{(k)}_{\mu\nu}\right]\frac{n^{[\rho}\,\partial^{\mu]}\varpi_{\rho\sigma}}{6E_{\boldsymbol{k}}}\left(2\eta^{\sigma\nu} - \hat{k}^\sigma n^\nu\right)\,.$$

- $\partial_x\varpi_{tz} \sim 0.3\,\mathrm{fm}^{-1}$, $\partial_x\varpi_{tz}/E_{\boldsymbol{k}} \sim 0.05$





I. Karpenko, F. Becattini, Eur. Phys. J. C 77, 213 (2017)

Pseudo-Gauge Dependence

- Pseudo-gauge dependence of density operator

F. Becattini, W. Florkowski, E. Speranza, PLB 789, 419 (2019)

$$\widehat{\rho}_{\text{Belinfante}} = \frac{1}{Z_{\text{LE}}^{(\text{B})}} \exp\left\{ -\int_{\Sigma} d\Sigma_\mu \widehat{T}_B^{\mu\nu} \beta_\nu \right\}$$

$$\widehat{\rho}_{\text{Canonical}} = \frac{1}{Z_{\text{LE}}^{(\text{C})}} \exp\left\{ -\int_{\Sigma} d\Sigma_\mu \left[\widehat{T}_B^{\mu\nu} \beta_\nu - \frac{1}{2} \widehat{S}_C^{\mu\rho\sigma} \delta\Omega_{\rho\sigma} + \boxed{\widehat{S}_C^{\lambda\mu\nu} \xi_{\lambda\nu}} \right] \right\}$$

Vector meson: $\widehat{S}^{\mu\rho\sigma} = -F^{\mu\rho} A^\sigma + F^{\mu\sigma} A^\rho$, extra term from thermal shear

- *e.g.*, vector meson's spin polarization vector

$$\mathcal{S}^\mu_{\text{Belinfante}}(x,k) = -\frac{1+n_B}{3m} \epsilon^{\mu\nu\rho\sigma} k_\nu \left(\varpi_{\rho\sigma} + \boxed{2 n_\rho \xi_{\sigma\lambda} k^\lambda / E_{\boldsymbol{k}}} \right)$$

$$\mathcal{S}^\mu_{\text{Canonical}}(x,k) = -\frac{1+n_B}{3m} \epsilon^{\mu\nu\rho\sigma} k_\nu \left(\varpi_{\rho\sigma} + \boxed{n_\rho \xi_{\sigma\lambda} k^\lambda / E_{\boldsymbol{k}}} - \Xi_\alpha{}^\rho \delta\Omega^{\sigma\alpha} \right)$$

with $\delta\Omega \to 0$ still $S^\mu_C \neq S^\mu_B$

- Extra contribution of thermal shear

Conclusion and Outlook

- Flat freezeout hypersurface $\Rightarrow$ tensor polarization $\propto \mathcal{O}(\partial^2)$

$$\delta\Theta_{00}\big|_{\partial\varpi}(x,k) = (1+n_B)\left[\epsilon^0_\mu\epsilon^0_\nu + \frac{1}{3}\Delta^{(k)}_{\mu\nu}\right]\frac{1}{6E_{\boldsymbol{k}}} n^{[\rho}\partial^{\mu]}\varpi_{\rho\sigma}\left(2\eta^{\sigma\nu} - \hat{k}^\sigma n^\nu\right)$$

- Pseudo-gauge dependence

Thank you!

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