Spin Alignment as a Dissipative Structure In Heavy-ion Collisions

PRC.109.064916, arXiv:2206.11890, …

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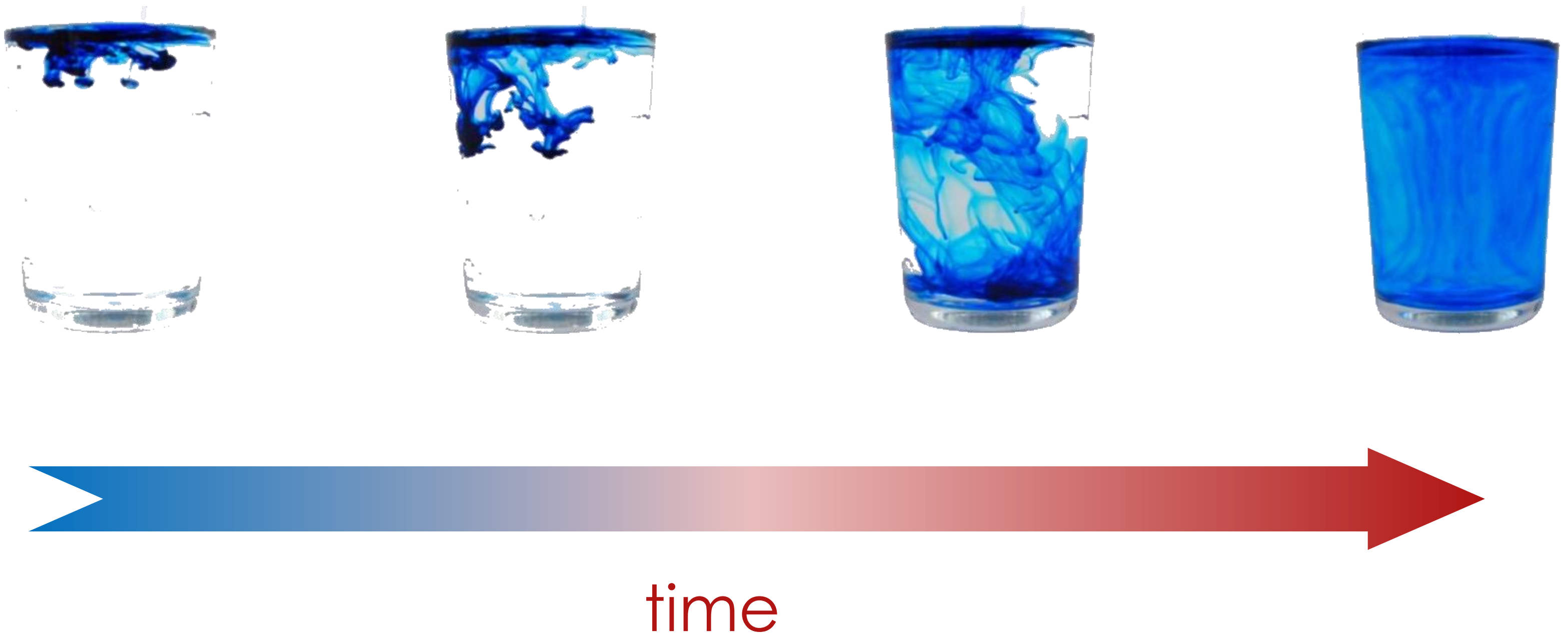
兰州大学
LANZHOU UNIVERSITY

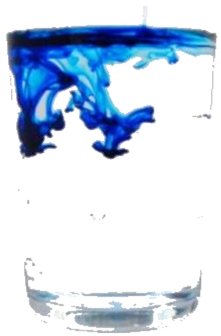
- **Dissipative Structure**
- Spin Alignment as Dissipative Structure
- Shear Induced Tensor Polarization (SITP)
- Diffusion Induced Tensor Polarization (DITP)
- Summary & Outlook

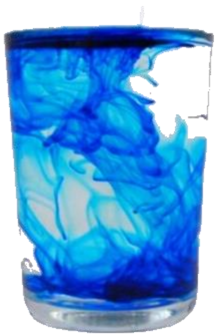
Dissipation



Dissipative Structures

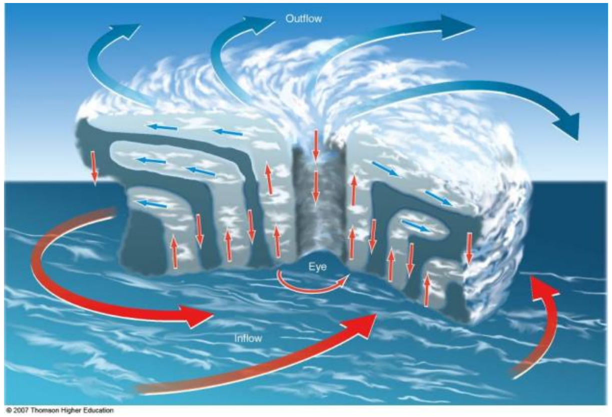
Local Equilibrium





Off Equilibrium

Global Equilibrium



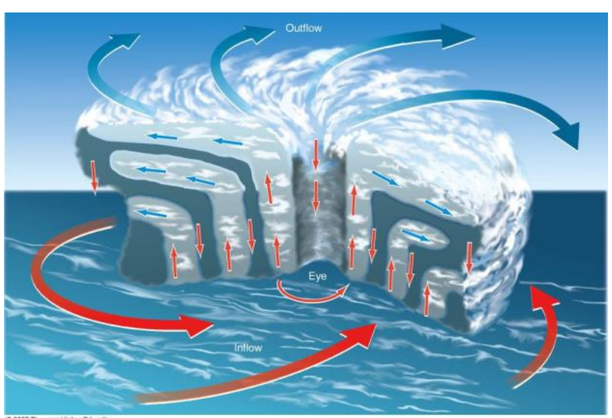
Hurricane

Karman's Vortices

B-Z Reaction

Dissipative Structures

Entropy Flow in **Open** System Or **Freeze-Out**



Hurricane

Karman's Vortices

B-Z Reaction

- Dissipative Structure
- **Spin Alignment as Dissipative Structure**
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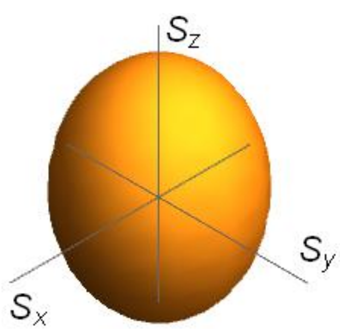
Spin Alignment (Gen. Intro.)

Negatively Polarizaed

+1 +1 -1 +1 +1 -1 -1 -1 -1 -1 +1 +1 -1

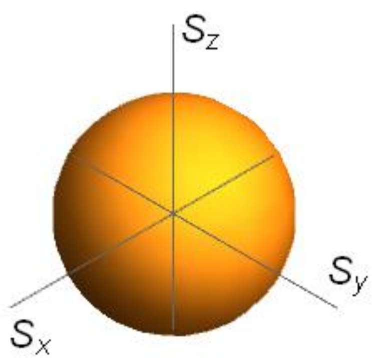
$\overline{S_x^2} \sim \overline{S_y^2} < \overline{S_z^2}$



Unpolarizaed

0 +1 -1 +1 +1 0 -1 -1 0 0 -1 +1

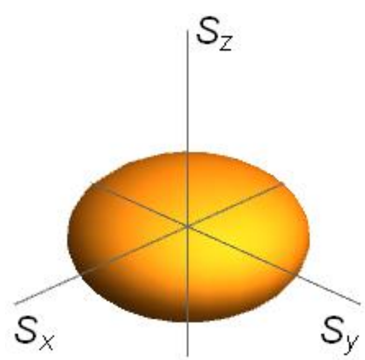
$\overline{S_x^2} = \overline{S_y^2} = \overline{S_z^2}$



Positively Polarizaed

0 0 0 0 0 0 0 0 0 0 0 0

$\overline{S_x^2} \sim \overline{S_y^2} > \overline{S_z^2}$



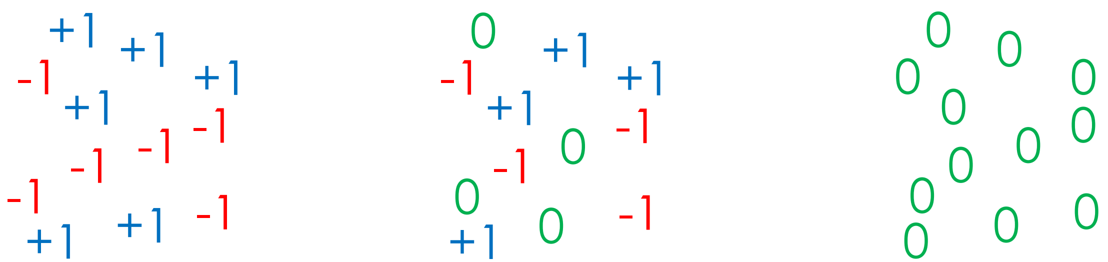
- **Picture**
- Observable
- Experimental Measurement
- Mechanism

Tensor Polarization:

Anisotropy of Spin Fluctuation

Spin Alignment (Gen. Intro.)

Negatively Polarizaed | Unpolarizaed | Positively Polarizaed

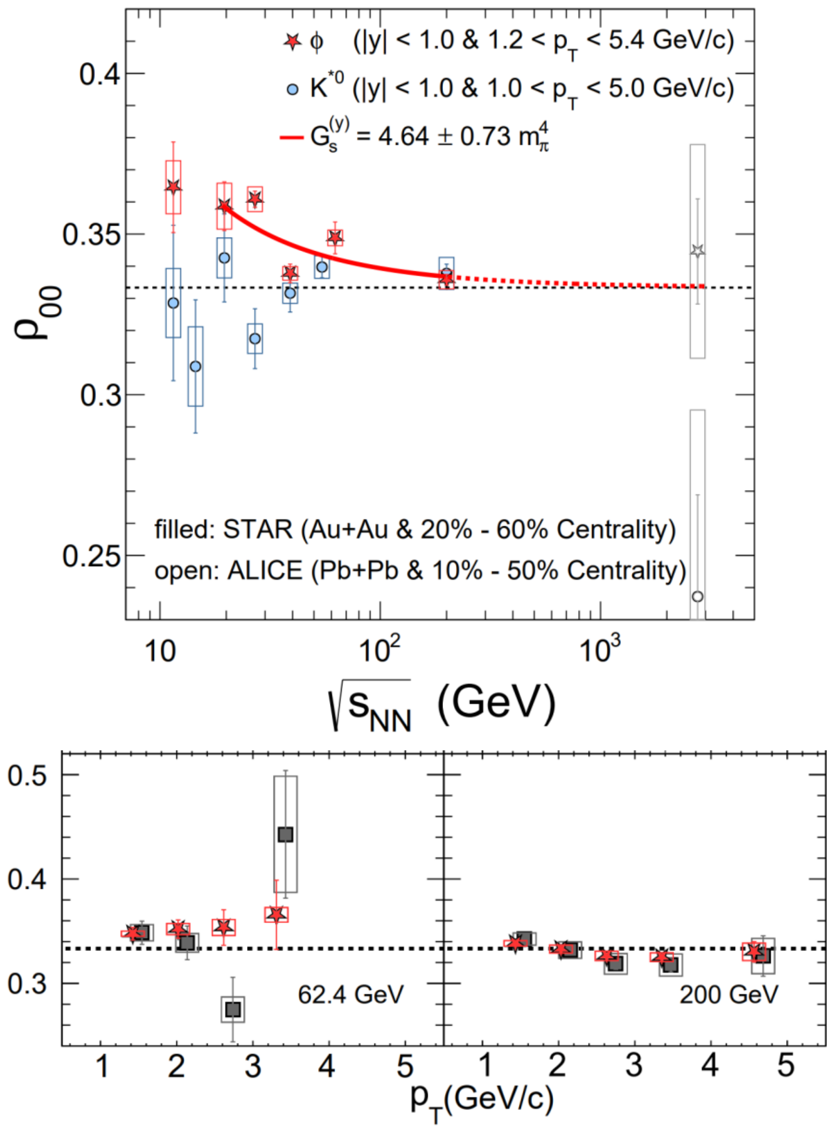


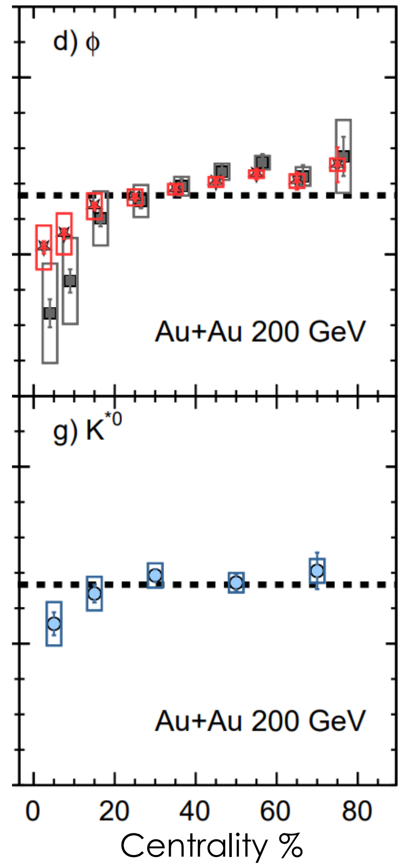
- Picture
- **Observable**
- Experimental Measurement
- Mechanism

$$\delta\rho_{00} \equiv \rho_{00} - \frac{1}{3}$$

Chance for Occupying $|0\rangle$

Spin Alignment (Gen. Intro.)

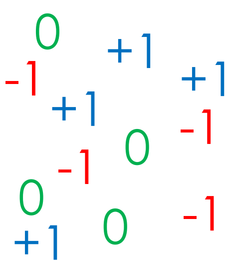




- Picture
- Observable
- **Experimental Measurement**
- Mechanism

Nature volume 614, 244 (2023)

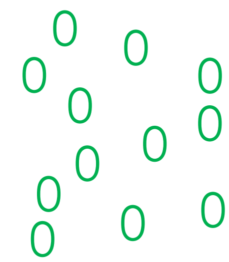
Spin Alignment (Gen. Intro.)



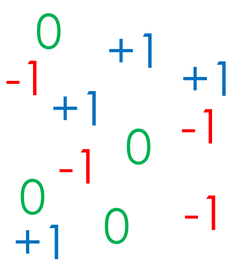
Polarization of $Q, \bar{Q}$
(Z. Liang & X.Wang, PLB 629, 20 (2005))

Vorticity
(F. Becattini, et al., PRC 77, 024906 (2008))

Fluctuating Strong Forces or Gluon Fields
(X. Sheng, et al., PRL 131, 042304 (2023); A. Kumar, et al., PRD 108, 016020 (2023))

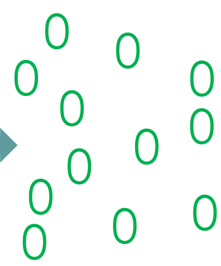


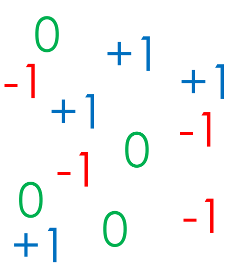
- Picture
- Observable
- Experimental Measurement
- **Mechanism**



Medium Modification on Spectral Properties

Viscous Damping: $\partial(\beta u)$

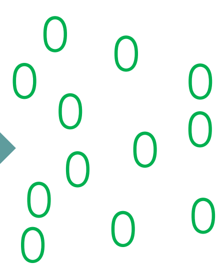


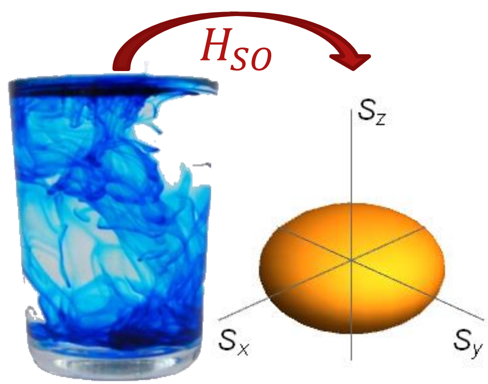


Medium Modification on Spectral Properties

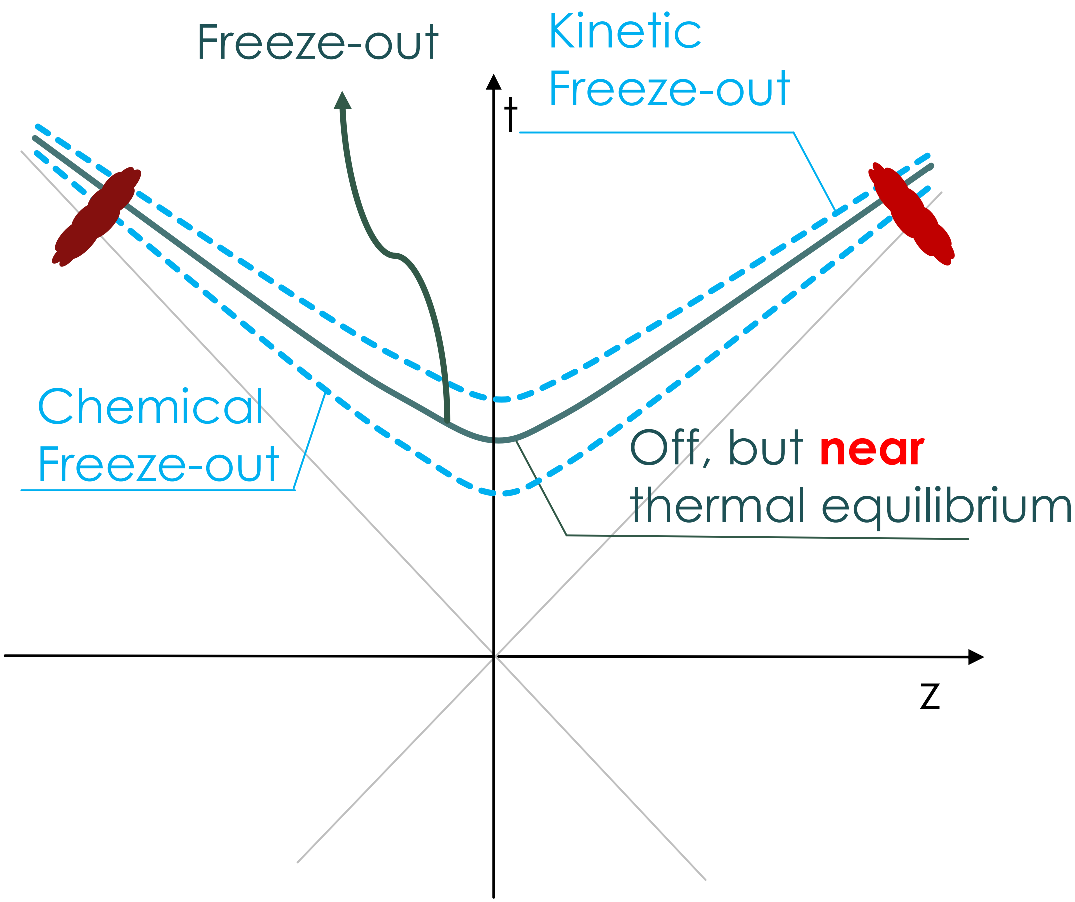
Diffusion: $\partial(\beta \mu_S)$

K^* ✔ ϕ ×

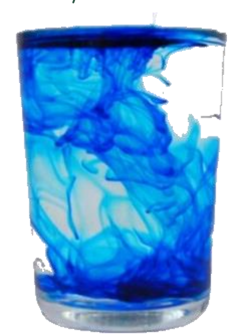




Framework & Assumption



Diffusion coeffients evaluated **near** equilibirum



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Linear Response

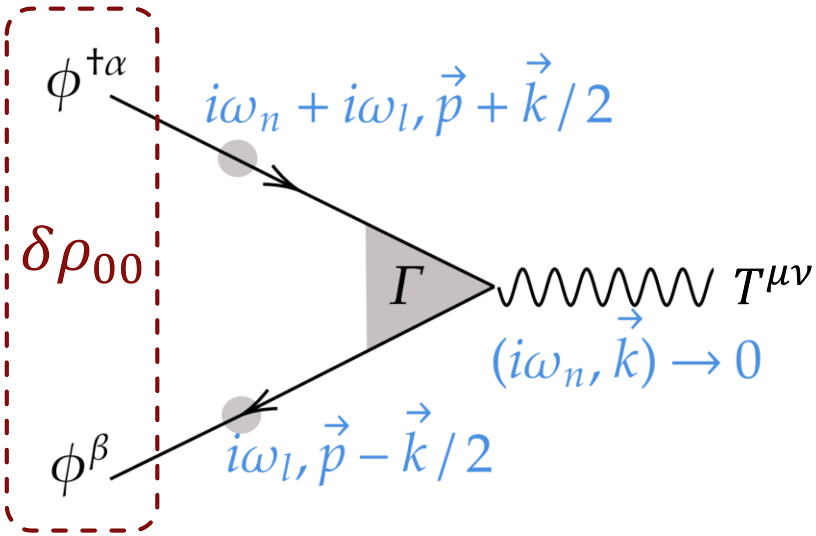
$$\delta\rho_{00} = \lim_{k^0\to 0} \frac{\tilde{\varrho}_T^{\mu\nu}(k^0, \vec{k}=0)}{2k^0} \frac{\partial_\mu(\beta u_\nu)}{\bar{\beta}}$$

Driven by Flow and Thermal Gradients

In Equilibrium

$$\tilde{\varrho}_T^{\mu\nu} \equiv \int d^4x\ e^{ik\cdot x}\left[\delta\rho_{00}\left(x'+\frac{x}{2}\right), T^{\mu\nu}\left(x'-\frac{x}{2}\right)\right]$$

(Belinfante) Stress-Energy Tensor



D. N. Zubarev, Nonequilibrium statistical thermodynamics

Linear Response

$tr\rho = 1$

Projectors and Polarizors

$$\delta\rho_{00}(\vec{p}) = \mathcal{N}^{-1}\left[\epsilon^0_{\langle\alpha}\epsilon^0_{\beta\rangle} - \alpha_0\tilde{\Delta}_{\alpha\beta}\right]\int d^3\vec{X}\, W^{\alpha\beta}_{(1)}$$

Bose Distribution

$$W^{\alpha\beta}_{(1)} = -E_p\int\frac{dp^0}{2\pi}\sum_{a,b=T}^{L}\mathcal{A}_a(p)\mathcal{A}_b(p)\,\Delta_a^{\beta\rho}(p)\Delta_b^{\sigma\alpha}(p)Re\left\{\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(p;p)\right\}\frac{\partial n}{\partial p^0}\frac{\partial_\mu(\beta u_\nu)}{\bar{\beta}}$$

Assumption:

- There is no pole on p^0 in
  $\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(i\omega_n + p^0, \vec{p}; p^0, \vec{p})$
- Time reversesal symmetry on $\tilde{\Gamma}$
  $\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(p;q) = \tilde{\Gamma}^{\mu\nu}_{\sigma\rho}(q;p)$
- $\lim_{q\to 0}\partial_{q^0}\tilde{\Gamma}(p+q;p)$ is real
- Or, $\mathcal{A}$ is analytic on the upper-half complex plane, and real on the real axis.

Linear Response

$$\delta\rho_{00}(\vec{p}) = \mathcal{N}^{-1}\left[\epsilon^0_{\langle\alpha}\epsilon^0_{\beta\rangle} - \alpha_0\widetilde{\Delta}_{\alpha\beta}\right]\int d^3\vec{X}\, W^{\alpha\beta}_{(1)}$$

$$W^{\alpha\beta}_{(1)} = -E_p\int\frac{dp^0}{2\pi}\sum_{a,b=T}^{L}\mathcal{A}_a(p)\mathcal{A}_b(p)\,\Delta^{\beta\rho}_a(p)\Delta^{\sigma\alpha}_b(p)Re\left\{\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(p;p)\right\}\frac{\partial n}{\partial p^0}\frac{\partial_\mu(\beta u_\nu)}{\bar{\beta}}$$

$$\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(p,p) = -p^{(\nu}\partial_{p_{\mu)}}\tilde{S}^{-1}_{\rho\sigma}(p) + g^{\nu\mu}\tilde{S}^{-1}_{\rho\sigma}(p) - g^{(\mu\alpha}\tilde{S}^{-1}_{\rho\alpha}(p)\delta^{\nu)}_{\sigma} - g^{(\mu\beta}\tilde{S}^{-1}_{\beta\sigma}(p)\delta^{\nu)}_{\rho}$$

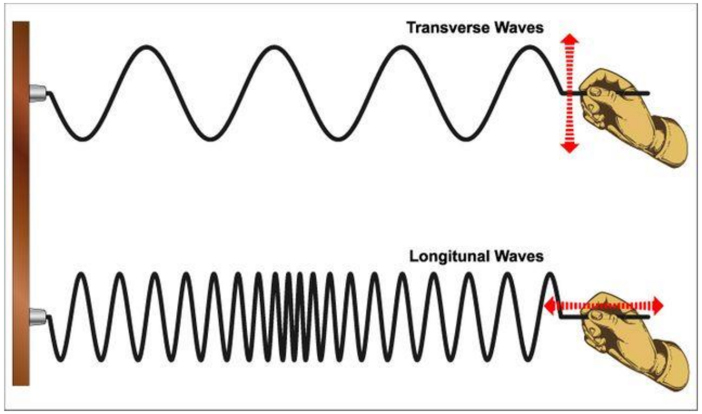
Inspired by B. S. DeWitt, Phys. Rev. 162, 1239 (1967)

- Non-perturbative expression under certain assumptions
- Meson-medium interactions are encoded in the spectral function $\mathcal{A}$ and Propagator $\tilde{S}$

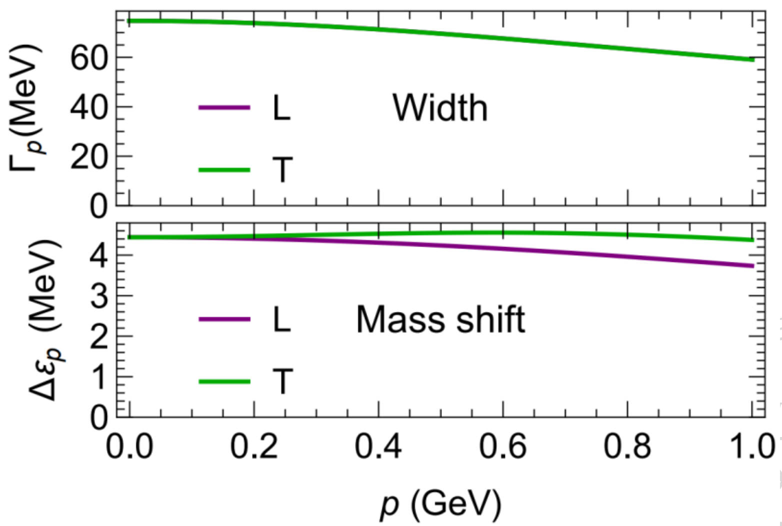
SITP

$$\delta\rho_{00}(\vec{p}) = -\left[\epsilon^0_{\langle\alpha}\epsilon^0_{\beta\rangle} - \alpha_0\widetilde{\Delta}_{\alpha\beta}\right]$$

$$\times\int\frac{d^3\vec{X}}{\mathcal{N}}T\partial_\mu(\beta u_\nu)E_p\int\frac{d\varepsilon}{2\pi}\frac{\partial n}{\partial\varepsilon}\left\{\begin{array}{c} -Re(\Pi_T-\Pi_L)\mathcal{A}_L\mathcal{A}_T p^{(\nu}\frac{\varepsilon}{\kappa^2}\left(1-\frac{\varepsilon\Omega}{\varsigma}\right)u^{(\alpha}\widetilde{\Delta}_T^{\beta)\mu)} \\ +\sum_{a=L}^{T}\mathcal{A}_a^2\left[\begin{array}{c}2p^\mu p^\nu\left(1+\partial_\varsigma Re\Pi_a\right)+u^\mu p^\nu\partial_\varepsilon Re\Pi_a \\ -g^{\mu\nu}\left(\bar{p}^2-M^2+Re\Pi_a\right)\end{array}\right]\Delta_a^{\alpha\beta} \\ -\sum_{a,b}\mathcal{A}_a\mathcal{A}_b\,2\Delta_a^{\mu(\beta}\Delta_b^{\nu\alpha)}\left(\bar{p}^2-M^2+Re\Pi_a\right)\end{array}\right\}$$



Caused by splitting of spectral properties between the L & T modes



W. Dong, et al., PRD 109, 056025 (2024)

$$\Delta_L - \widetilde{\Delta_L} \sim \mathcal{O}\left(\frac{\Omega}{M}\sqrt{\frac{T}{M}}\right)$$

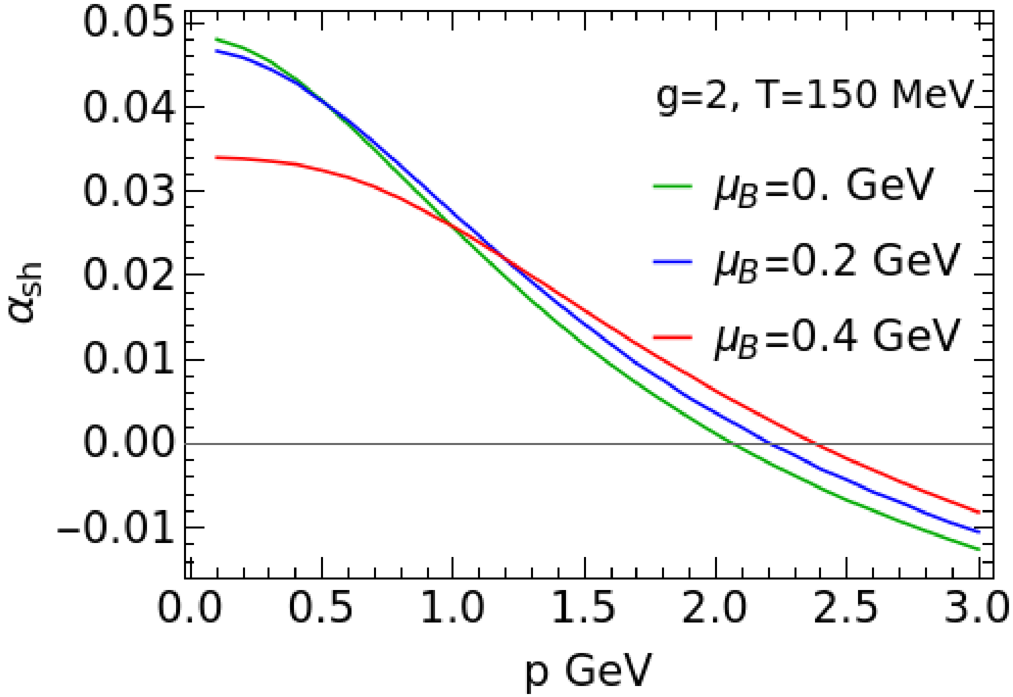
$$-\sum_{a,b} \mathcal{A}_a \mathcal{A}_b \, 2\Delta_a^{\mu(\beta}\Delta_b^{\nu\alpha)}\left(\bar{p}^2 - M^2 + Re\Pi_a\right)$$

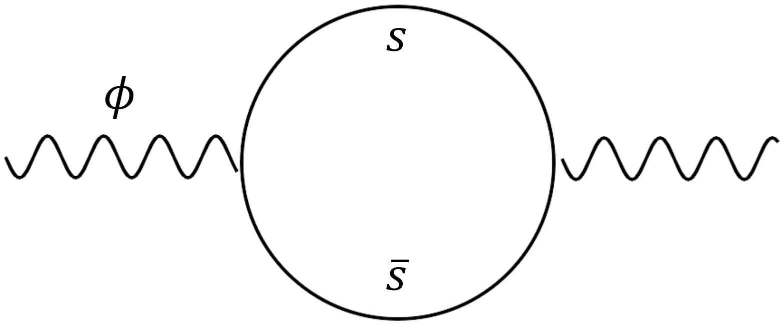
After neglecting L, T splitting & difference between Δ & $\widetilde{\Delta}$

$$\delta\rho_{00}^{SITP} = \alpha_{sh}\partial_\mu(\beta u_\nu)\epsilon^{\langle\mu}\epsilon^{\nu\rangle}$$

$$\alpha_{sh} \equiv \mathcal{N}_0^{-1} T E_p \int \frac{d\varepsilon}{\pi}\frac{\partial n}{\partial \varepsilon}\mathcal{A}^2\left(\bar{p}^2 - M^2 + Re\bar{\Pi}\right)$$ Off-Shell

Phenomonology (p_T)





$$\partial_\mu(\beta u_\nu) \sim \frac{\beta}{\tau} \sim \mathcal{O}(0.1)$$

at the end of partonic phase

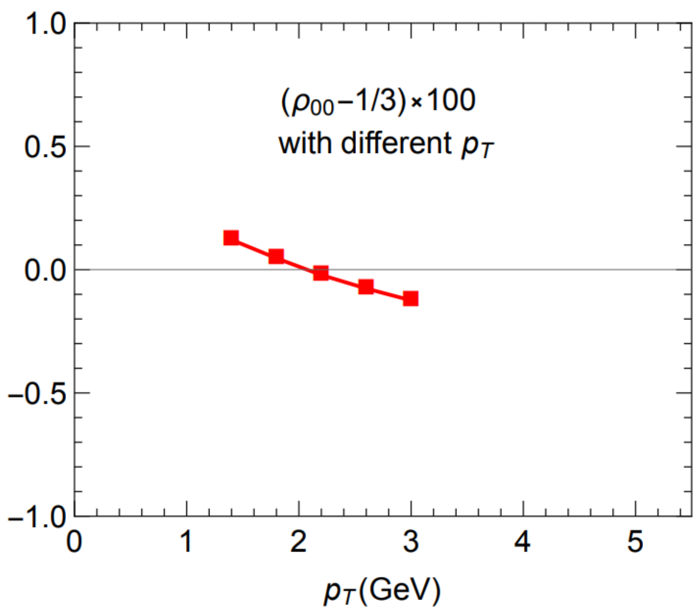
After neglecting L, T splitting & difference between Δ & $\widetilde{\Delta}$

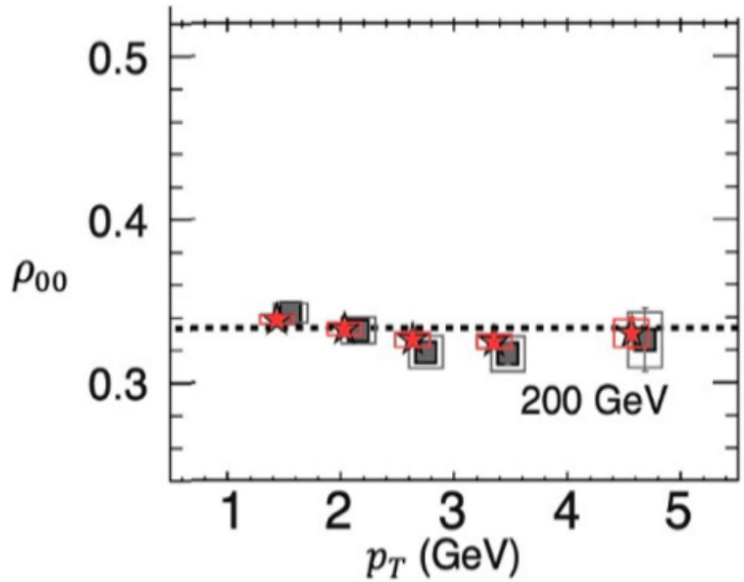
$$\delta\rho_{00}^{SITP} = \alpha_{sh}\partial_\mu(\beta u_\nu)\epsilon^{\langle\mu}\epsilon^{\nu\rangle}$$

$$\alpha_{sh} \equiv \mathcal{N}_0^{-1} T E_p \int \frac{d\varepsilon}{\pi}\frac{\partial n}{\partial \varepsilon}\mathcal{A}^2\left(\bar{p}^2 - M^2 + Re\overline{\Pi}\right)$$ Off-Shell

Phenomonology (p_T)

Au + Au @ 200 GeV (Using CLVisc)





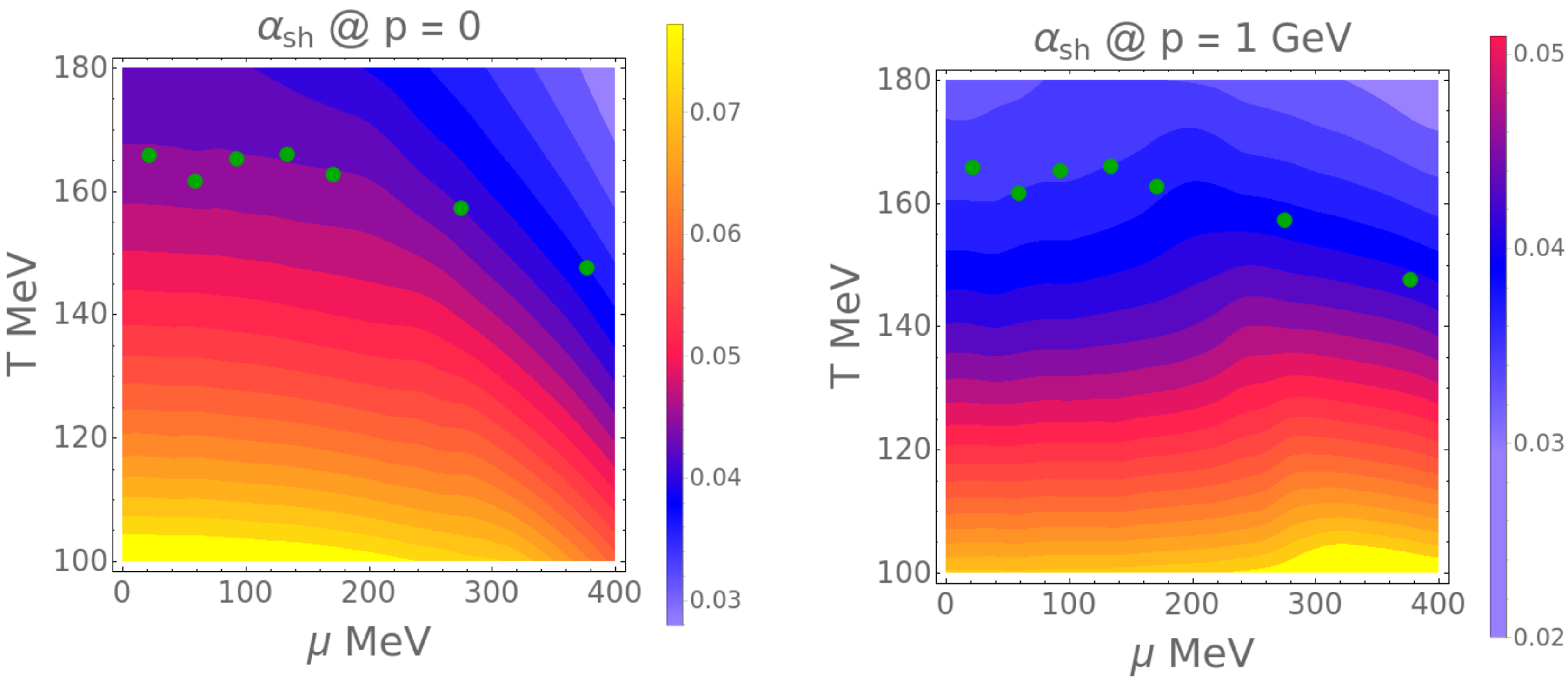
After neglecting L, T splitting & difference between Δ & $\tilde{\Delta}$

$$\delta\rho_{00}^{SITP} = \alpha_{sh}\partial_\mu(\beta u_\nu)\epsilon^{\langle\mu}\epsilon^{\nu\rangle}$$

$$\alpha_{sh} \equiv \mathcal{N}_0^{-1} T E_p \int \frac{d\varepsilon}{\pi}\frac{\partial n}{\partial \varepsilon}\mathcal{A}^2(\bar{p}^2 - M^2 + Re\overline{\Pi})$$ Off-Shell

Phenomonology ($\sqrt{s_{NN}}$)

Dots for Chemical Freeze-Out from: STAR, PRC 96, 044904 (2017)

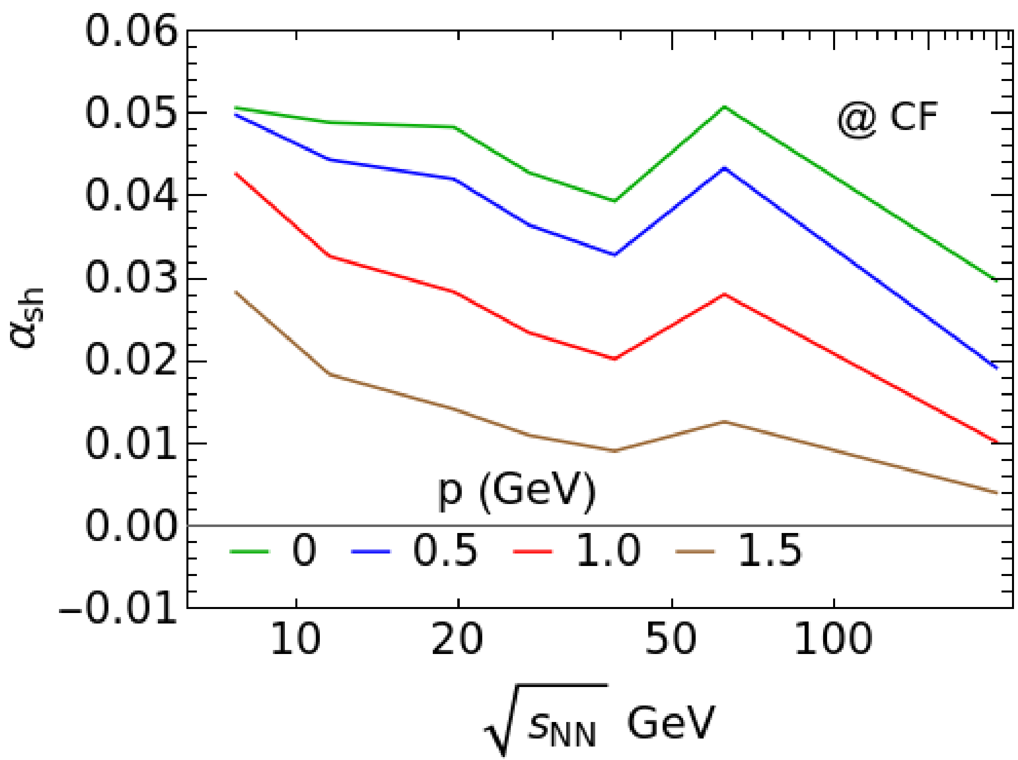


After neglecting L, T splitting & difference between Δ & $\widetilde{\Delta}$

$$\boldsymbol{\delta\rho_{00}^{SITP} = \alpha_{sh}\partial_{\mu}(\beta u_{\nu})\epsilon^{\langle\mu}\epsilon^{\nu\rangle}}$$

$$\alpha_{sh} \equiv \mathcal{N}_0^{-1} T E_p \int \frac{d\varepsilon}{\pi}\frac{\partial n}{\partial \varepsilon}\mathcal{A}^2\left(\bar{p}^2 - M^2 + Re\overline{\Pi}\right)$$ Off-Shell

Phenomonology ($\sqrt{s_{NN}}$)



? $\partial_\mu(\beta u_\nu)$ at lower $\sqrt{s_{NN}}$

After neglecting L, T splitting & difference between Δ & $\tilde{\Delta}$

$$\boldsymbol{\delta\rho_{00}^{SITP} = \alpha_{sh}\partial_\mu(\beta u_\nu)\epsilon^{\langle\mu}\epsilon^{\nu\rangle}}$$

$$\alpha_{sh} \equiv \mathcal{N}_0^{-1} T E_p \int \frac{d\varepsilon}{\pi}\frac{\partial n}{\partial \varepsilon}\mathcal{A}^2\left(\bar{p}^2 - M^2 + Re\overline{\Pi}\right)$$ Off-Shell

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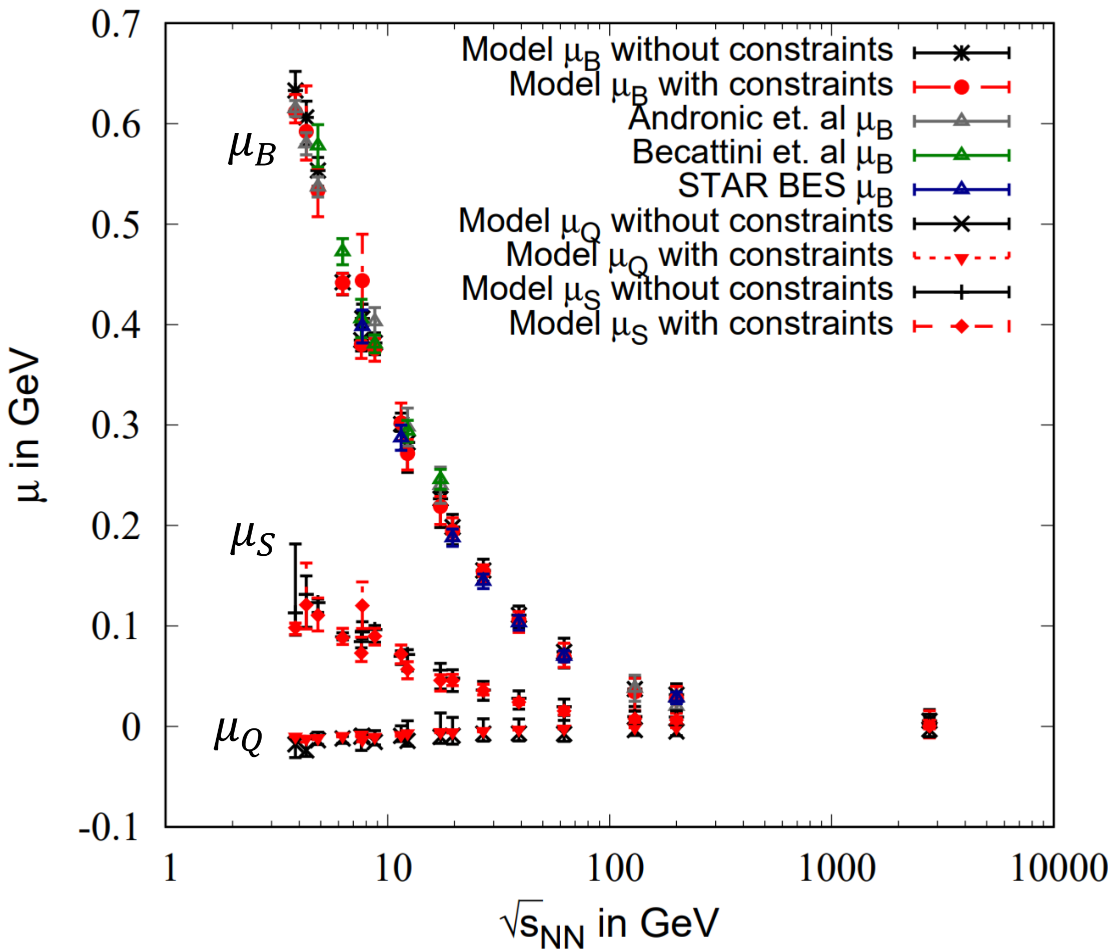
Strange-Baryon Correspondence



In Partonic Phase:

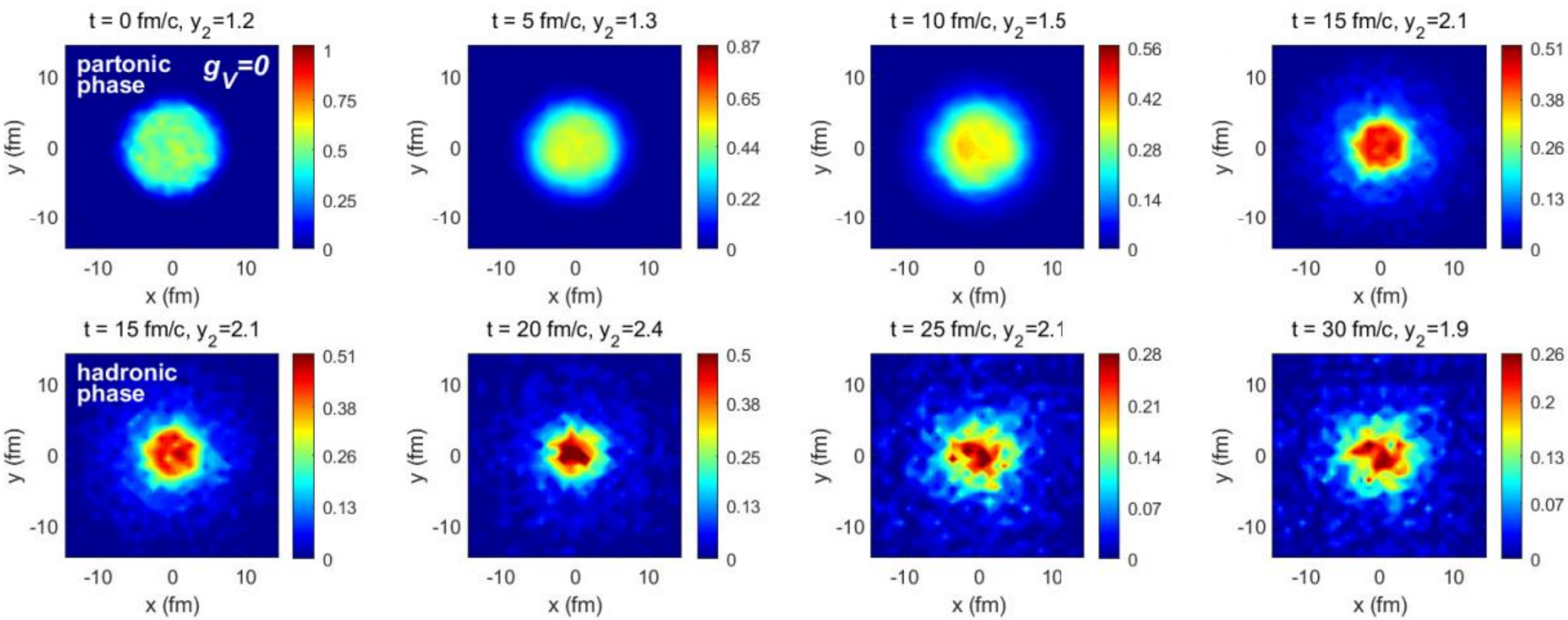
$$N_s \propto \exp\left(\frac{\frac{1}{3}\mu_B - \mu_S}{T}\right)$$

$$N_{\bar{s}} \propto \exp\left(\frac{-\frac{1}{3}\mu_B + \mu_S}{T}\right)$$

$$N_s = N_{\bar{s}} \Rightarrow \boldsymbol{\mu_S = \frac{1}{3}\mu_B}$$

S. Bhattacharyya, et al., PRD 101, 054002 (2020)

Strange-Baryon Correspondence



K. Sun, et al., EPJA 57 (2021) 11, 313

Strange-Baryon Correspondence: $\partial(\beta\mu_S) \to \mu_S'(\mu_B)\partial(\beta\boldsymbol{\mu_B})$

Enhanced During a 1st – order phase transition

A new probe of 1st – order phase transition?

Linear Response

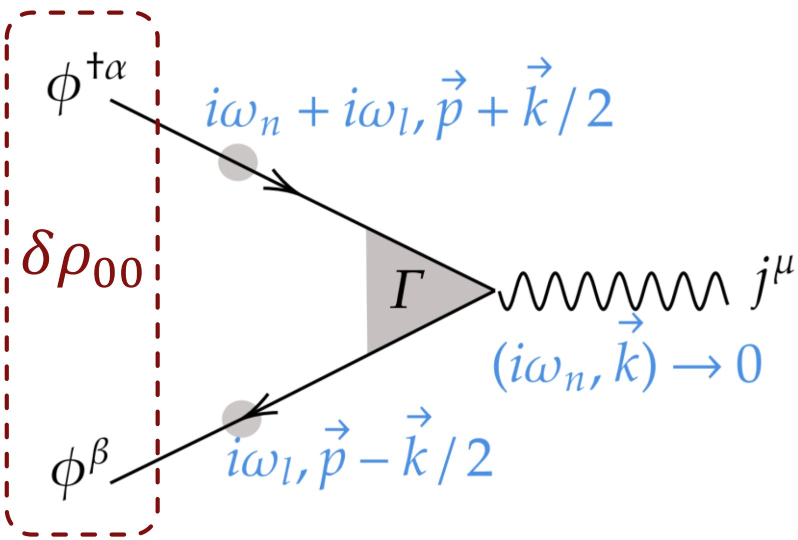
$$\delta\rho_{00} = \lim_{k^0 \to 0} \frac{\tilde{\varrho}_J^{\mu}(k^0, \vec{k} = 0)}{2k^0} \frac{\partial_\mu(\beta\mu_S)}{\bar{\beta}}$$

Driven by S Charge Density and Thermal Gradients

In Equilibrium

$$\tilde{\varrho}_J^{\mu} \equiv \int d^4x\ e^{ik\cdot x} \left[\delta\rho_{00}\left(x' + \frac{x}{2}\right), j^{\mu}\left(x' - \frac{x}{2}\right)\right]$$

(Belinfante) Stress-Energy Tensor



D. N. Zubarev, Nonequilibrium statistical thermodynamics

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Bose Distribution

$$W^{\alpha\beta}_{(1)} = E_p \int \frac{dp^0}{2\pi} \sum_{a,b=T}^{L} \mathcal{A}_a(p)\mathcal{A}_b(p)\, \Delta_a^{\beta\rho}(p)\Delta_b^{\sigma\alpha}(p) Re\left\{\tilde{\boldsymbol{\Gamma}}^{\boldsymbol{\mu}}_{\boldsymbol{\rho\sigma}}(\boldsymbol{p};\boldsymbol{p})\right\} \frac{\partial n}{\partial p^0} \frac{\boldsymbol{\partial_\mu(\beta\mu_S)}}{\boldsymbol{\bar{\beta}}}$$

$$\tilde{\Gamma}^{\mu}_{\rho\sigma}(p,p) = q\partial_{\bar{p}_\mu}\tilde{S}^{-1}_{\rho\sigma}(p)$$

Assumption:

- There is no pole on p^0 in
  $$\tilde{\Gamma}^{\mu}_{\rho\sigma}(i\omega_n + p^0, \vec{p}; p^0, \vec{p})$$
- Time reversesal symmetry on $\tilde{\Gamma}$
  $$\tilde{\Gamma}^{\mu}_{\rho\sigma}(p;q) = \tilde{\Gamma}^{\mu}_{\sigma\rho}(q;p)$$
- $\lim_{q\to 0} \partial_{q^0}\tilde{\Gamma}(p+q;p)$ is real
- Or, $\mathcal{A}$ is analytic on the upper-half complex plane, and real on the real axis.

DITP (General Form)

Sensitive to p Orientation

$$\delta\rho_{00}^{DITP} = \int \frac{d^3\vec{X}}{\mathcal{N}}\left[\left(\vartheta_{sp.}^{p}\frac{\tilde{p}^{\mu}}{m} + \vartheta_{sp.}^{u}u^{\mu}\right)\epsilon_{\langle\alpha}\epsilon_{\beta\rangle}\widetilde{\Delta}_L^{\alpha\beta} + \vartheta_{\Delta}\epsilon_{\alpha}\epsilon_{\beta}u^{(\alpha}\widetilde{\Delta}_T^{\beta)\mu} - \boldsymbol{\alpha_0}\left(\vartheta_{tt.}^{p}\frac{\tilde{p}^{\mu}}{m} + \vartheta_{tt.}^{u}u^{\mu}\right)\right]\frac{\partial_\mu(\beta\mu_S)}{T}$$

$$\vartheta_{sp.}^{p}=\vartheta_L^p - \vartheta_T^p; \quad \vartheta_{sp.}^{u}=\vartheta_L^u - \vartheta_T^u; \quad \vartheta_{tt.}^{p}=\vartheta_L^p + 2\vartheta_T^p; \quad \vartheta_{tt.}^{u}=\vartheta_L^u + 2\vartheta_T^u$$

$$\vartheta_L^p = -q\!\!\!\!\;\; mT^2E_p\int\frac{dp^0}{\pi}\left(1+\partial_{p^2}\mathrm{Re}\Pi_\mathrm{L}\right)\mathcal{A}_L^2(p)\left(1+\frac{\Omega^2\vec{p}^2}{p^2m^2}\right)\frac{\partial n}{\partial p^0}$$

$$\vartheta_L^u = -qT^2E_p\int\frac{dp^0}{\pi}\left(\Omega+\Omega\partial_{p^2}\mathrm{Re}\Pi_\mathrm{L}+\frac{1}{2}\partial_{p^0}\mathrm{Re}\Pi_\mathrm{L}\right)\mathcal{A}_L^2(p)\left(1+\frac{\Omega^2\vec{p}^2}{p^2m^2}\right)\frac{\partial n}{\partial p^0}$$

$$\vartheta_T^p = -qmT^2E_p\int\frac{dp^0}{\pi}\left(1+\partial_{p^2}\mathrm{Re}\Pi_\mathrm{T}\right)\mathcal{A}_T^2(p)\frac{\partial n}{\partial p^0}$$

$$\vartheta_T^u = -qT^2E_p\int\frac{dp^0}{\pi}\left(\Omega+\Omega\partial_{p^2}\mathrm{Re}\Pi_\mathrm{T}+\frac{1}{2}\partial_{p^0}\mathrm{Re}\Pi_\mathrm{T}\right)\mathcal{A}_T^2(p)\frac{\partial n}{\partial p^0}$$

$$\vartheta_\Delta = qT^2E_p\int\frac{dp^0}{\pi}\mathcal{A}_L(p)\mathcal{A}_T(p)\left(1-\frac{p^0}{p^2}\Omega\right)\frac{p^0Re(\Pi_T-\Pi_L)}{\vec{p}^2}\frac{\partial n}{\partial p^0}$$

Caused by L/T splitting → small

To Global Spin Alignment

In a **static** medium

The polarizer ϵ_0 can be expressed explicitly in the MRF as

$$\epsilon_0 = \frac{1}{m}\begin{pmatrix} E_p & \mathbf{p} \\ \mathbf{p} & m\mathbb{I} + (E_p - m)\hat{\mathbf{p}}\hat{\mathbf{p}} \end{pmatrix}\begin{pmatrix} 0 \\ \hat{\mathbf{z}} \end{pmatrix}, \qquad (21)$$

where $\hat{\mathbf{p}} \equiv \mathbf{p}/|\mathbf{p}|$, and $\hat{\mathbf{z}}$ is the spin quantization axis in the particle rest frame (PRF). Hence, in the MRF,

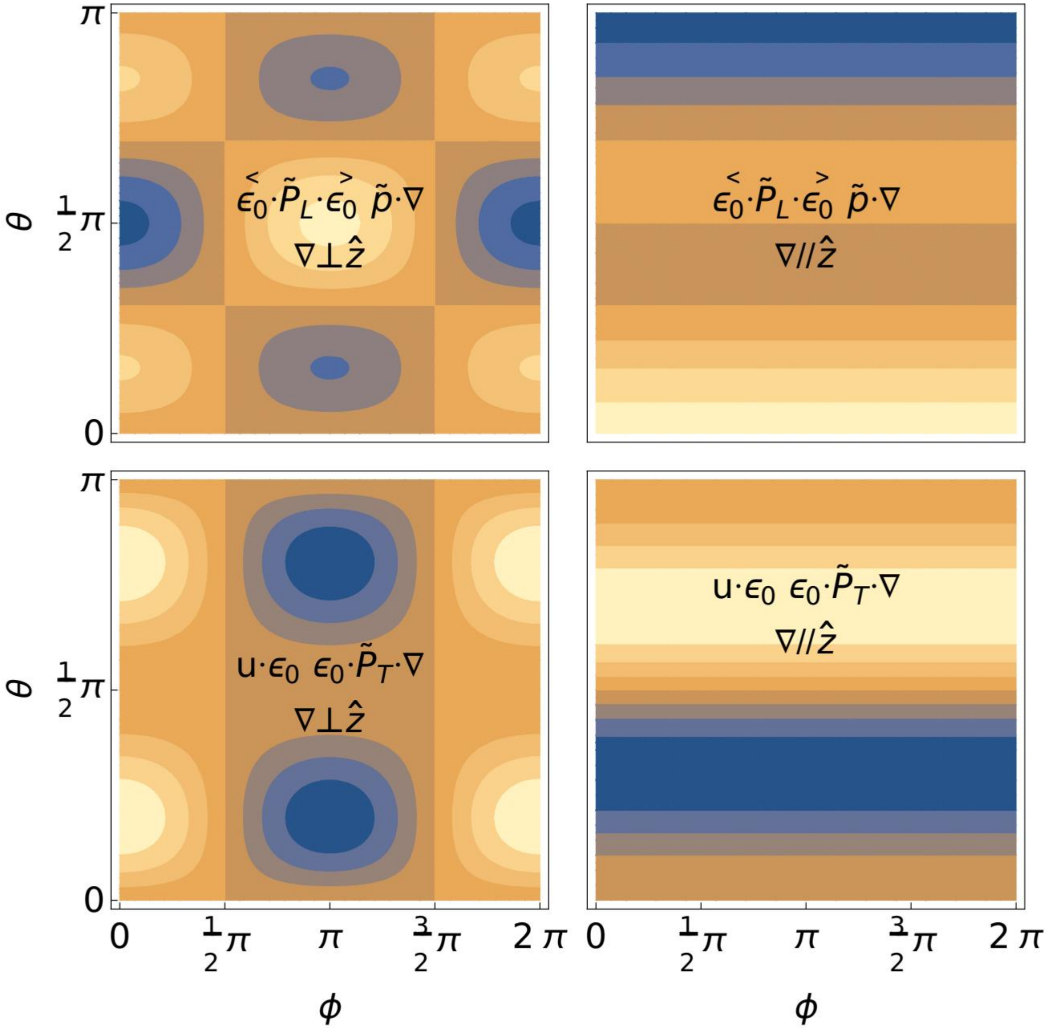
$$\begin{aligned} \epsilon^0_{\langle\alpha}\epsilon^0_{\beta\rangle}\tilde{P}_L^{\alpha\beta}\tilde{p}\cdot\partial &= \left[\frac{(\mathbf{p}\cdot\hat{\mathbf{z}})^2}{\mathbf{p}^2} - \frac{1}{3}\right](E_p\partial_t + \mathbf{p}\cdot\nabla), \\ \epsilon^0_{\langle\alpha}\epsilon^0_{\beta\rangle}\tilde{P}_L^{\alpha\beta}u\cdot\partial &= \left[\frac{(\mathbf{p}\cdot\hat{\mathbf{z}})^2}{\mathbf{p}^2} - \frac{1}{3}\right]\partial_t, \qquad (22) \\ \epsilon^0_{\alpha}\epsilon^0_{\beta}u^{(\alpha}\tilde{P}_T^{\beta)\mu}\partial_\mu &= -\frac{(\mathbf{p}\cdot\hat{\mathbf{z}})}{m}[\hat{\mathbf{p}}\times(\hat{\mathbf{z}}\times\hat{\mathbf{p}})]\cdot\nabla. \end{aligned}$$

Tensor structures related to the p-orientation

All vanish after the integration over p-orientation → **Local Polarization Only**

Orientational Distribution

In a **static** medium



- Dissipative Structure
- Spin Alignment as Dissipative Structure
- Shear Induced Tensor Polarization (SITP)
- Diffusion Induced Tensor Polarization (DITP)
- **Summary & Outlook**

Summary

- Discovery of SITP & DITP, with a magnitude proportional to $\partial(\beta u)$ & $\partial(\beta \mu_S)$
- Both SITP & DITP are dissipative → Spin alignment as a dissipative structure in spin space.
- The transport coefficients are evaluated non-perturbatively, under certain assumptions, by employing the Ward-Takahashi identity.
- Coefficients are sensitive to the medium modification to the spectral functions → SITP & DITP employed as novel probe of in-medium spectral property.
- Off-Shell Effect → SITP; L & T Splitting → SITP & DITP
- SITP → Global & Local Spin Alignment; DITP → Local Spin Alignment in static medium.
- SITP is promising for describing the pT dependencies.
- Once the “local”spin alignments are measured, the DITP effect might be a novel probe of the QCD first order phase transition

Outlook

Validity of Assumption:

- There is no pole on p^0 in $\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(i\omega_n + p^0, \vec{p}; p^0, \vec{p})$ ✘
- Time reversesal symmetry on $\tilde{\Gamma}$ $\tilde{\Gamma}^{\mu\nu}_{\rho\sigma}(p;q) = \tilde{\Gamma}^{\mu\nu}_{\sigma\rho}(q;p)$ ✓
- $\lim_{q\to 0} \partial_{q^0}\tilde{\Gamma}(p+q;p)$ is real ?
- Or, $\mathcal{A}$ is analytic on the upper-half complex plane, and real on the real axis. ✘

- Evaluate the transport coefficients of SITP & DITP with the mesonic spectral functions obtained using FRG.
- Hydro-gradients at freeze-out at various collisional energies obtained using iEBE-MUSIC simulation.
- Look into the freeze-out condition phenomenologically.