Spin polarization and alignment in heavy ion collisions

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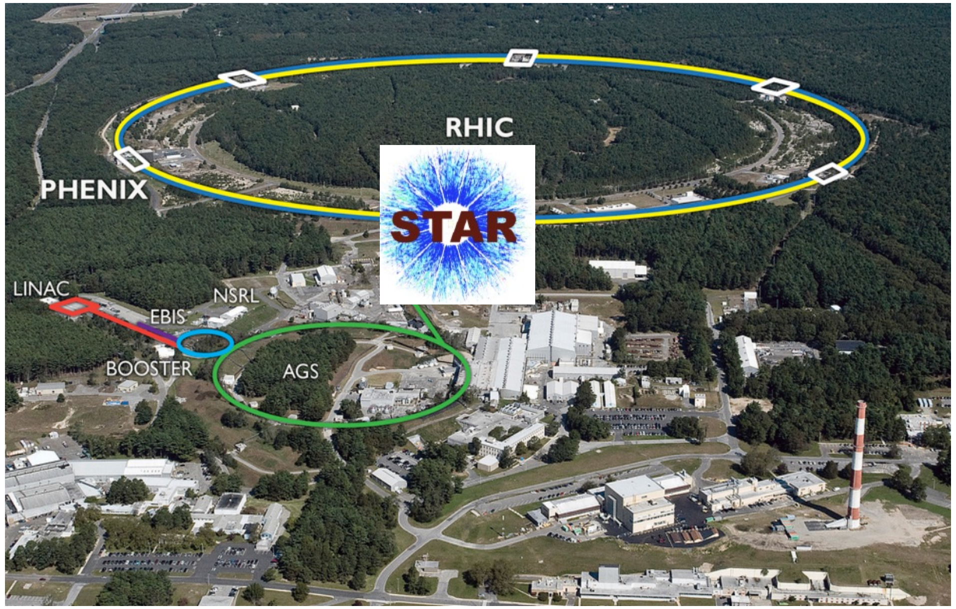
Introduction

Heavy ion collisions

- Currently operating facilities



RHIC@BNL,2000 -

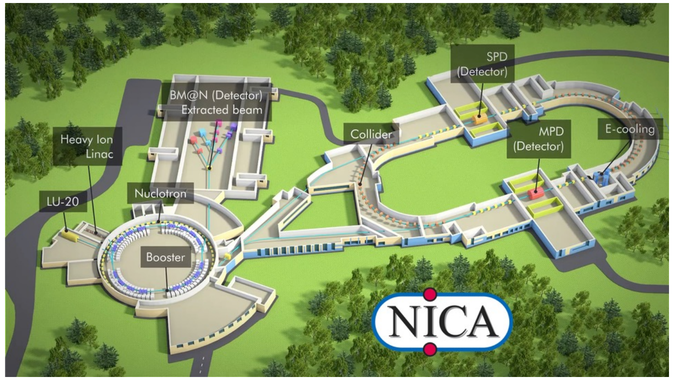
Top energy: Au + Au @ $\sqrt{s} = 200$ GeV

LHC@CERN, 2010 -

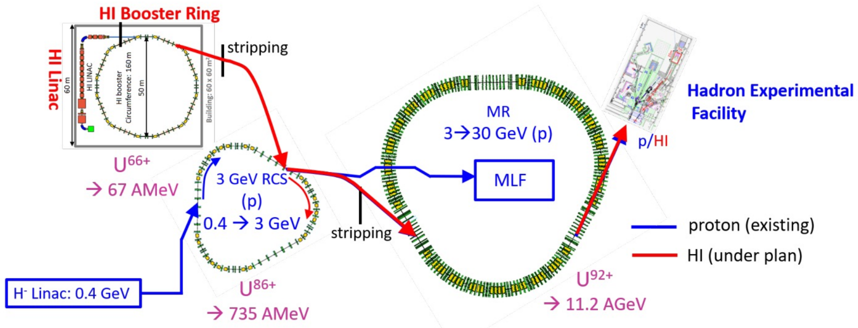
Top energy: Pb + Pb @ $\sqrt{s} = 5.02$ TeV

Heavy ion collisions

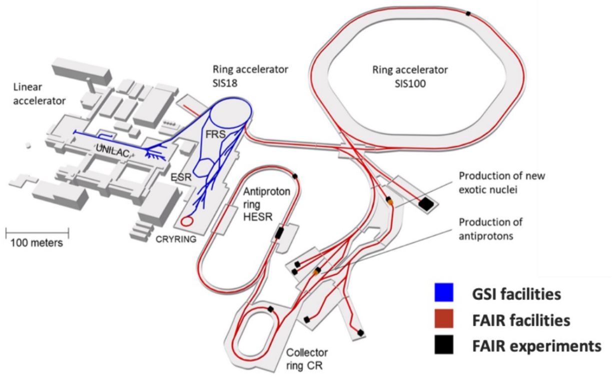
- Future facilities



NICA@Russia

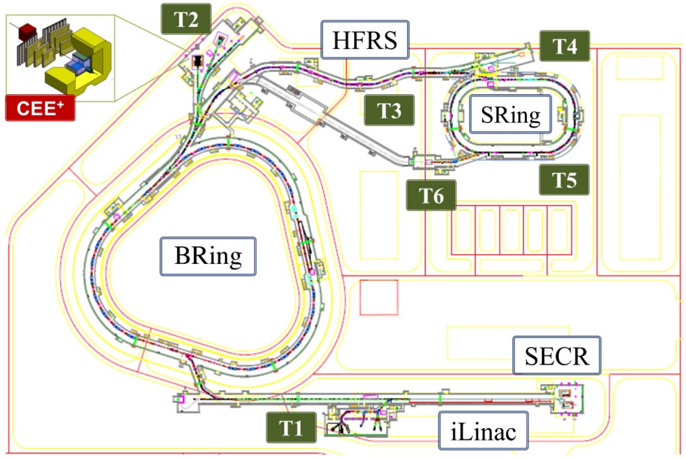


J-PARC@Japan



FAIR@Germany

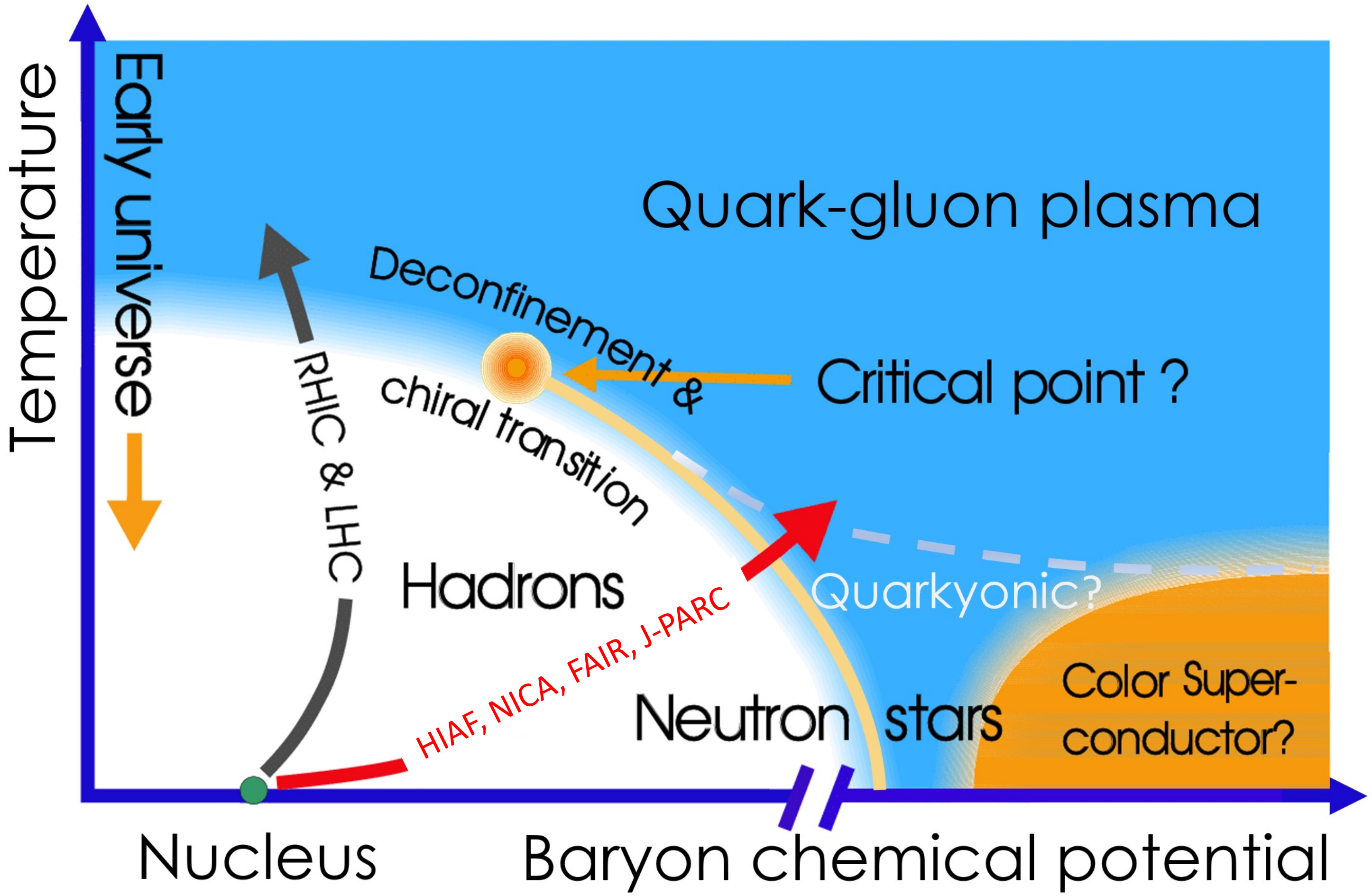
High Intensity heavy-ion Accelerator Facility (HIAF)



HIAF@China

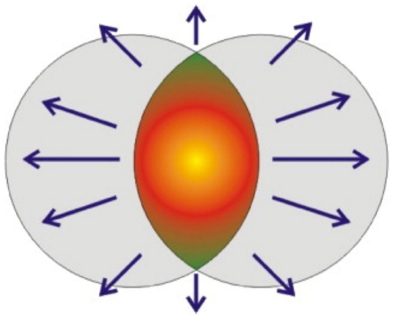
Heavy ion collisions

- Why heavy ion collisions? QCD phase diagram and quark gluon plasma (QGP)

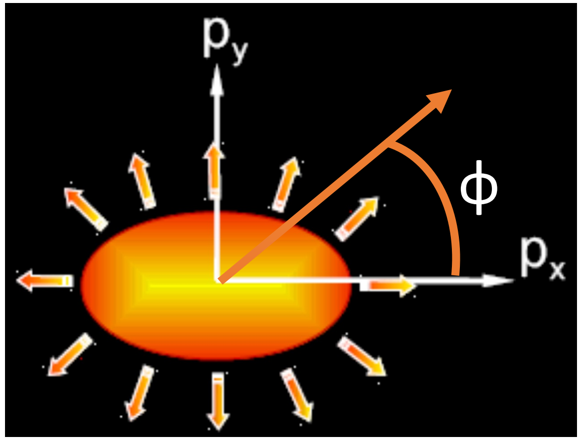


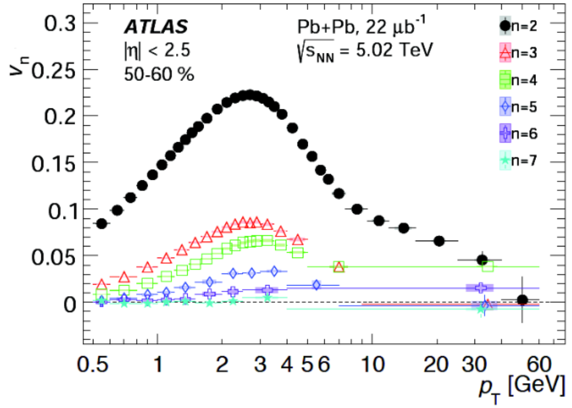
Probes of the quark gluon plasma

- Electric or flavor probes of QGP
- For example: Anisotropy in charged-hadron spectra
  harmonic flow coefficients ➡ equation of state, transport properties



⊙ z direction





$$\frac{dN_{\mathrm{ch}}}{d\phi} \propto 1 + 2v_1 \cos\left(\phi - \Psi_1\right) + 2v_2 \cos\left[2(\phi - \Psi_2)\right] + \cdots$$

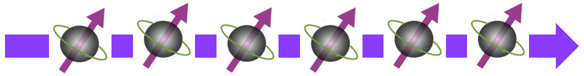
- These are the “electronics (flavortronics)” of QGP

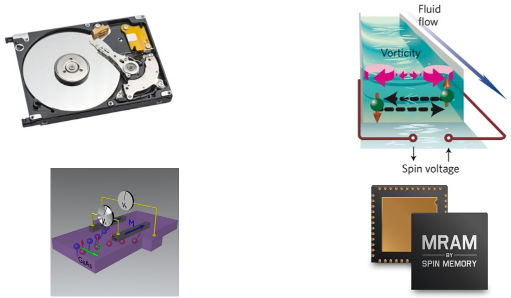
Probes of the quark gluon plasma

- Electronics vs. spintronics in condensed matter physics

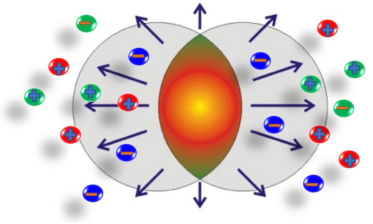
Electronics

Spintronics

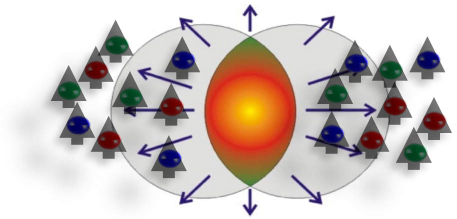




- "Electronics" vs. "spintronics" in heavy-ion collisions?
  - Charged hadrons multiplicity N_{ch}
  - Harmonic flows of charges $v_1, v_2, \ldots$
  - … …



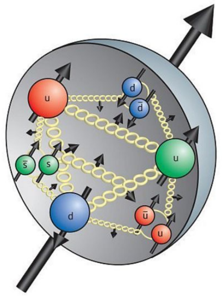
  - Hyperon spin polarization $P_{y,x,z}$
  - Harmonic flows of spin $f_{2;x,y,z}, \ldots$
  - … …

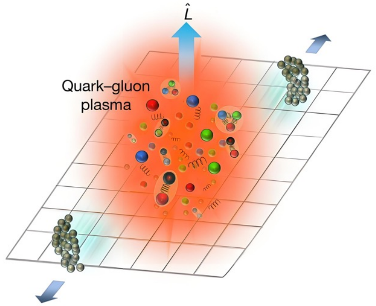


Early theoretical proposal

- Angular momentum (AM) distribution in strong-interaction systems

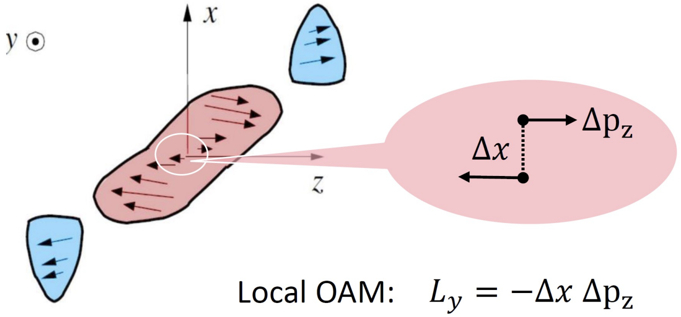
Proton
AM=1/2 fixed





Heavy ion collisions
AM varying

- Hyperon spin polarization and vector meson spin alignment (Liang and Wang 2004)



Local OAM: $L_y = -\Delta x \, \Delta p_z$

(Figure by J. H. Gao)

$$P_q = -\frac{\pi \mu p}{2E(E+m)}$$

$$\rho_{00}^{V(\mathrm{rec})} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}}$$

Spin polarization and spin density matrix

- Spin state of particle ensemble can be described by the spin density matrix
  - Spin-1/2 particle (3 parameters: vector polarization)

$$\rho_{1/2} = \frac{1}{2} + \frac{1}{2}\boldsymbol{P}_{1/2} \cdot \boldsymbol{\sigma}$$

  - Spin-1 particle (8 parameters: 3 for vector and 5 for tensor polarizations)

$$\rho_1 = \frac{1}{3} + \frac{1}{2}\boldsymbol{P}_1 \cdot \boldsymbol{S} + \sum_{m=-2}^{2} (-1)^m T_{2,-m} S_{2,m}$$

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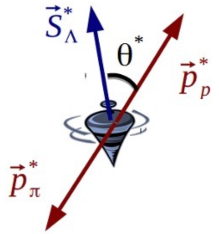
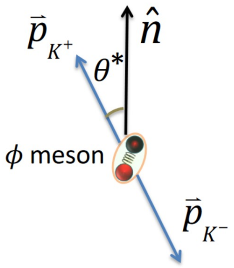


$\Lambda \rightarrow p + \pi^-$

$$\frac{1}{N}\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha \boldsymbol{P}_{1/2} \cdot \hat{\mathbf{p}}^*\right)$$

  - Spin-1 particle (8 parameters: 3 for vector and 5 for tensor polarizations)

$$\rho_1 = \frac{1}{3} + \frac{1}{2}\boldsymbol{P}_1 \cdot \boldsymbol{S} + \sum_{m=-2}^{2} (-1)^m T_{2,-m} S_{2,m}$$

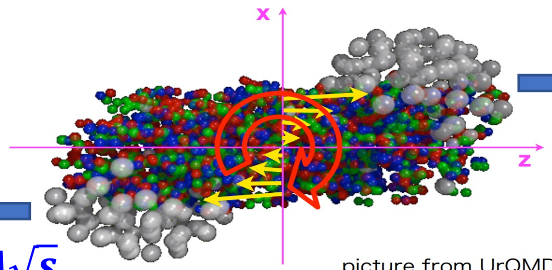


$\phi \rightarrow K^+ + K^-$

$$\frac{1}{N}\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 - \sqrt{\frac{24\pi}{5}} \sum_{m=-2}^{2} (-1)^m T_{2,-m} Y_{2,-m}(\theta^*, \phi^*)\right)$$

From angular momentum to fluid vorticity

- Stirring the quark gluon plasma:



picture from UrQMD

$P_z \sim \frac{A\sqrt{s}}{2}$

$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

(RHIC Au+Au 200 GeV, b=10 fm)

$$\boldsymbol{J} = \int d^3x\, \boldsymbol{I}(\boldsymbol{x}) \boldsymbol{\omega}(\boldsymbol{x})$$

$$\boldsymbol{\omega} = \frac{1}{2} \nabla \times \boldsymbol{v}$$

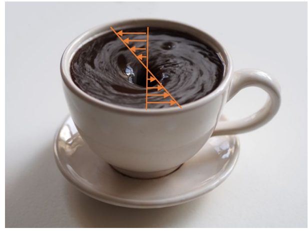
(Angular velocity of fluid cell)

- Understanding spin polarization in terms of vorticity (local rotation)

Angular momentum

$H_{\text{Spin-rotation}} = -S \cdot \Omega$

Rotation field



(at thermal equilibrium)

$$\frac{dN_s}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S})/T}$$

$$\mathrm{P} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\omega}{2T}$$

Spin as a probe of quark gluon plasma

- What spin can probe?

Angular momentum

$$H_{\text{Spin-rotation}} = -S \cdot \Omega$$

Rotation field

Vortical structure of the QGP medium

Spin as a probe of quark gluon plasma

- What spin can probe?

Angular momentum

$$H_{\text{Spin-rotation}} = -S \cdot \Omega$$

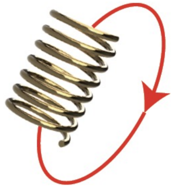
Rotation field

Vortical structure of the QGP medium

Magnetic moment

$$H_{\text{Zeeman}} = -\gamma \boldsymbol{S} \cdot \boldsymbol{B}$$

Magnetic field



Magnetic field,
color magnetic field,
magnetic component of strong field, … …

Spin orbit coupling

$$H_{\text{SOC-E}} = -\lambda \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{E})$$

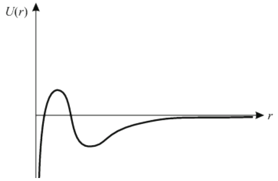
Electric field

Electric field,
color electric field,
electric component of strong field, … …

Spin orbit coupling

$$H_{\text{SOC-U}} = -\eta \boldsymbol{S} \cdot (\boldsymbol{p} \times \nabla U)$$

Other forces



Gradient of temperature, density, or other forces

Spin as a probe of quark gluon plasma

- What spin can probe?

Angular momentum

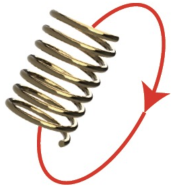
$$H_{\text{Spin-rotation}} = -S\cdot\Omega$$

Rotation field

Magnetic moment

$$H_{\text{Zeeman}} = -\gamma \boldsymbol{S}\cdot\boldsymbol{B}$$

Magnetic field



Spin orbit coupling

$$H_{\text{SOC-E}} = -\lambda \boldsymbol{S}\cdot(\boldsymbol{p}\times\boldsymbol{E})$$

Electric field

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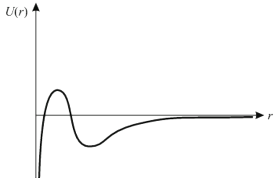
$$H_{\text{SOC-U}} = -\eta \boldsymbol{S}\cdot(\boldsymbol{p}\times\boldsymbol{\nabla} U)$$

Other forces



Vortical structure of the QGP medium

Magnetic field, color magnetic field, magnetic component of strong field, … …

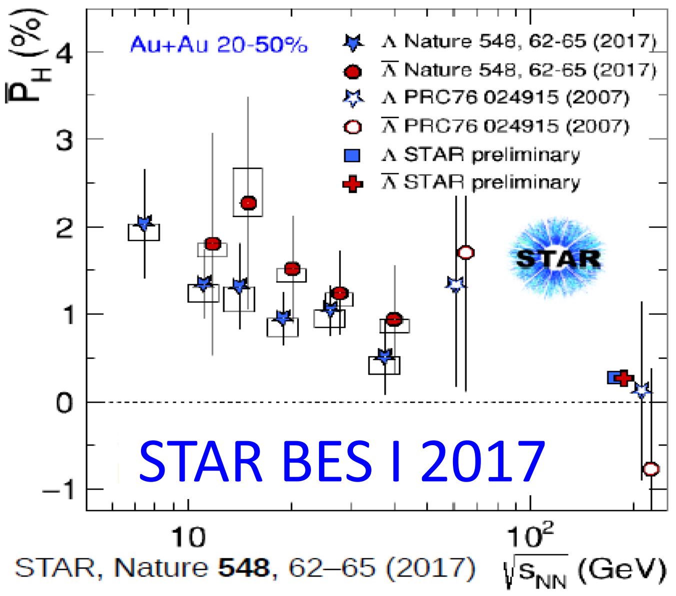
Electric field, color electric field, electric component of strong field, … …

Gradient of temperature, density, or other forces

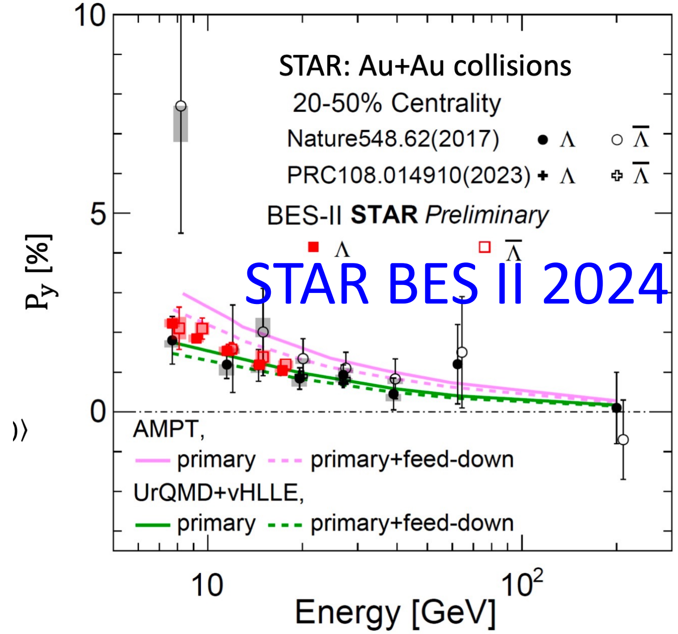
Many features of the partonic medium can be extracted from hadron spin polarization measurements

Hyperon spin polarization

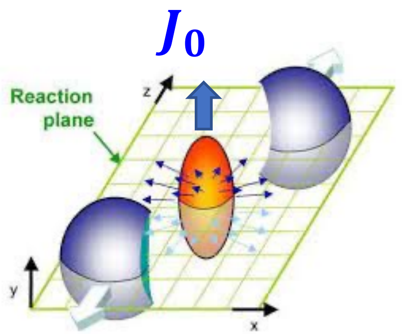
Global spin polarization: Experiments



2024 Update

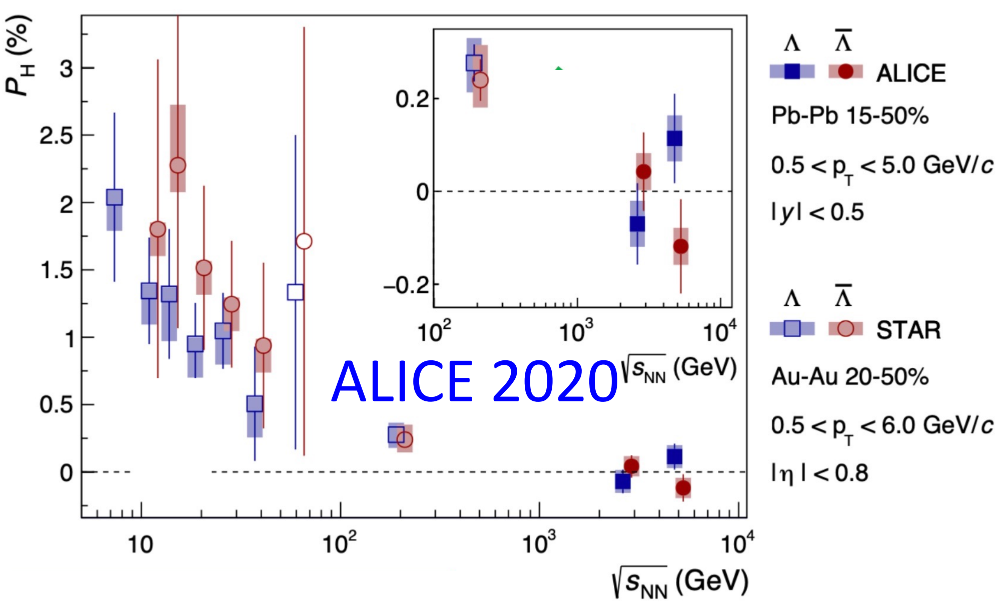


- Along global angular momentum direction
- Decreasing at higher energies
- Λ and $\bar{\Lambda}$ consistent within error bar

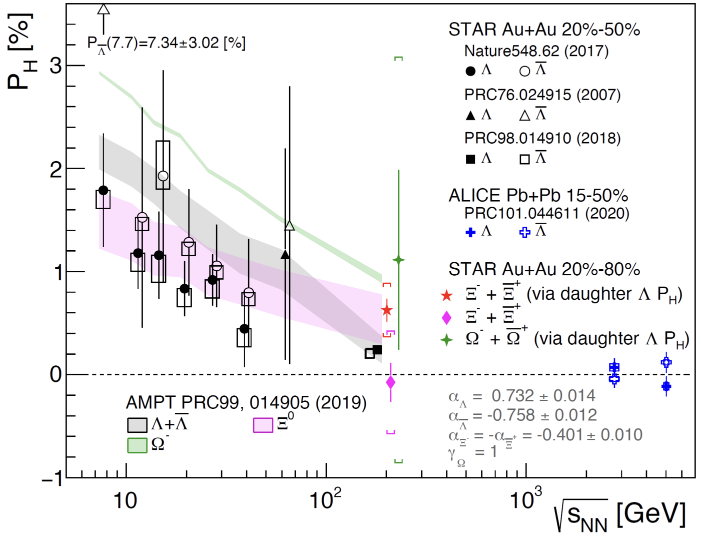


Global spin polarization: Experiments

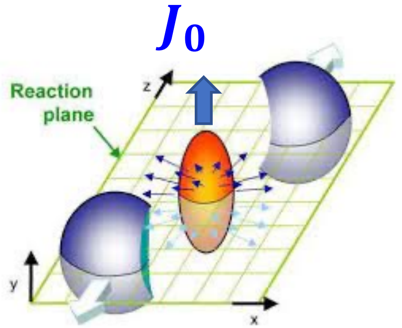
ALICE, Phys. Rev. C 101 (2020) 044611



STAR, PRL126, 162301 (2021) STAR BES I 2021

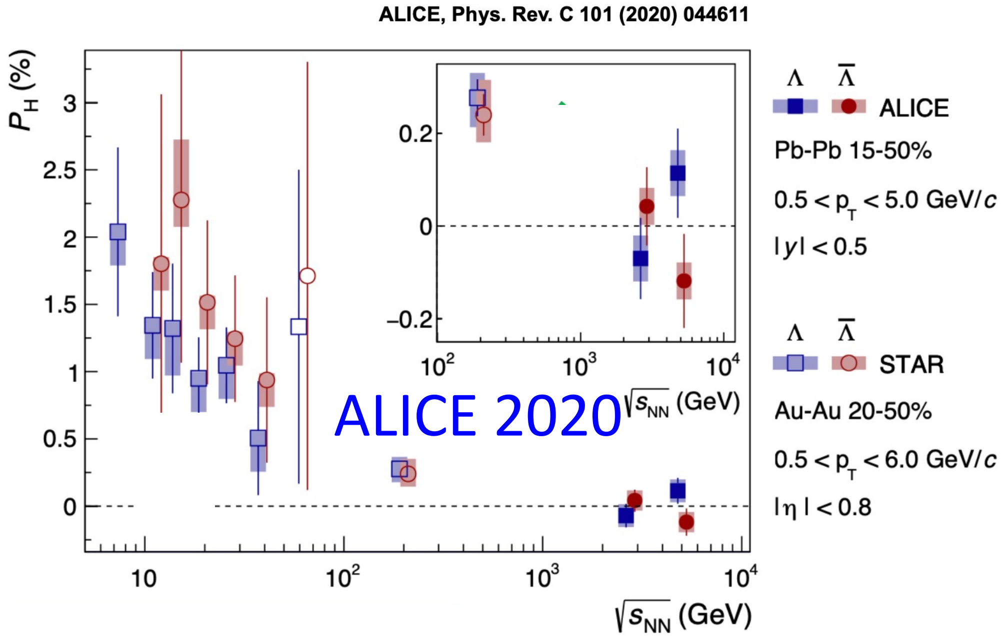


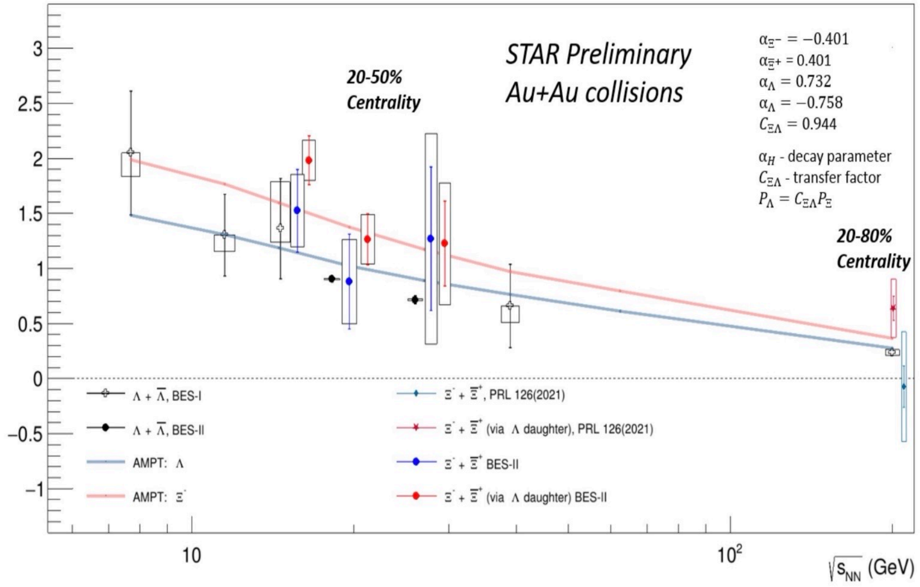
- Along global angular momentum direction
- Decreasing at higher energies
- Λ and $\bar{\Lambda}$ consistent within error bar
- Consistent with zero at LHC energies
- Ξ polarization is stronger than Λ



Global spin polarization: Experiments

STAR BES II 2024





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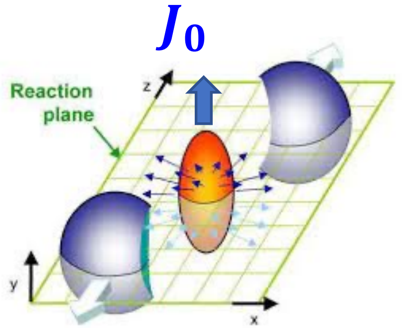


Global spin polarization: Theory

- Global polarization is (mainly) due to global angular momentum (AM)
- Vorticity: a bridge connecting initial AM and final global polarization

An estimate for static spin: $\boldsymbol{P} = \frac{\langle \boldsymbol{s} \rangle}{s} = \frac{1}{sZ}\mathrm{Tr}\left(\boldsymbol{s}e^{-\beta H + \beta \boldsymbol{s}\cdot\boldsymbol{\omega}}\right) \approx \frac{s+1}{3}\frac{\boldsymbol{\omega}}{T}$

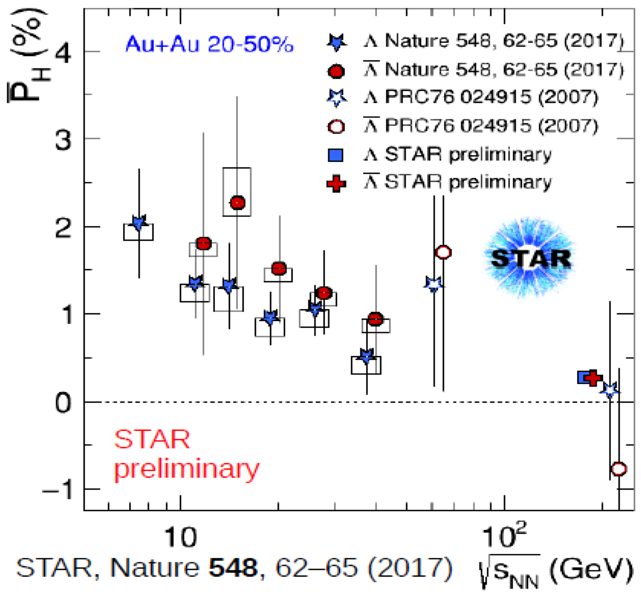
Covariant extension for spin-1/2: (Becattini etal 2013, Fang-Pang-Wang-Wang 2016, Liu-Mameda-Huang 2020)

$$P^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_{\nu}\frac{\int d\Sigma_{\lambda}p^{\lambda}f'(x,p)\varpi_{\rho\sigma}(x)}{\int d\Sigma_{\lambda}p^{\lambda}f(x,p)} + O(\varpi^{2})$$

- Valid at global equilibrium in lab frame. $f(x,p)$ is Fermi-Dirac distribution
- Thermal vorticity $\varpi_{\rho\sigma} = \left(\frac{1}{2}\right)\left(\partial_{\sigma}\beta_{\rho} - \partial_{\rho}\beta_{\sigma}\right), \beta_{\mu} = u_{\mu}/T$
- Spin polarization is enslaved to thermal vorticity, not dynamical
- When magnetic field is present: $\boldsymbol{\omega} \Rightarrow \boldsymbol{\omega} + s^{-1}\mu_H \boldsymbol{B}$ and $\varpi^{\perp}_{\rho\sigma} \Rightarrow \varpi^{\perp}_{\rho\sigma} - 2\beta\mu_H F^{\perp}_{\rho\sigma}$

Global spin polarization: Theory

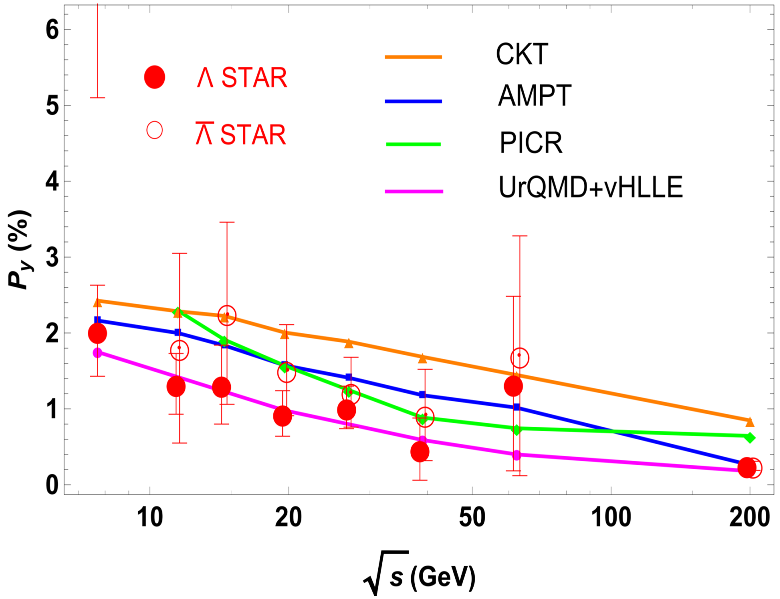
Experiment = Theory based on thermal vorticity



STAR, Nature **548**, 62–65 (2017)

$$\langle \omega \rangle = \langle T(P_\Lambda + P_{\bar{\Lambda}}) \rangle_{\sqrt{s}=7-200\mathrm{GeV}}$$
$$\approx (9 \pm 1) \times 10^{21} \mathrm{s}^{-1}$$

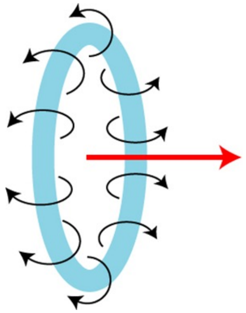
"The most vortical fluid"

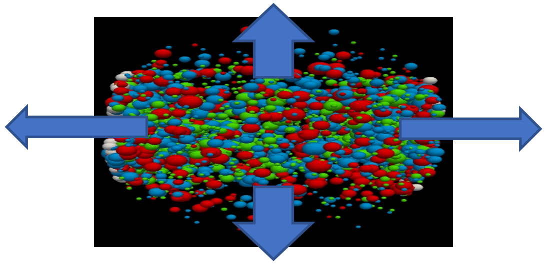


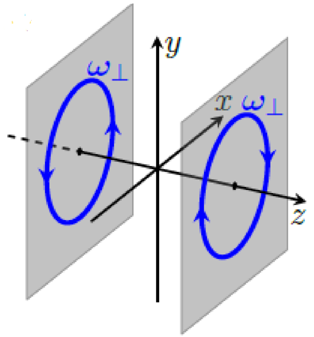
(Li-Pang-Wang-Xia 2017; Sun-Ko 2017; Wei-Deng-Huang 2019; Xie-Wang-Csernai 2017; Karpenko-Becattini 2016)

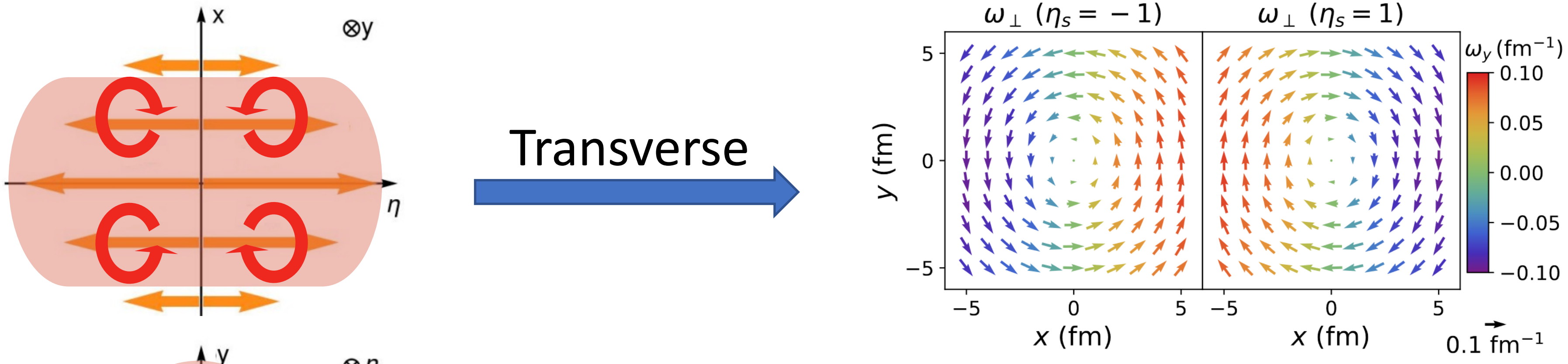
(See also: Sun-Ko etal 2019; Xie-Wang-Csernai etal 2018-2021; Ivanov etal 2017-2019; Liao etal 2018-2021; Deng-Huang-Ma 2021; Fu etal 2021; Pu etal 2022; ……)

Vorticity by inhomogeneous expansion

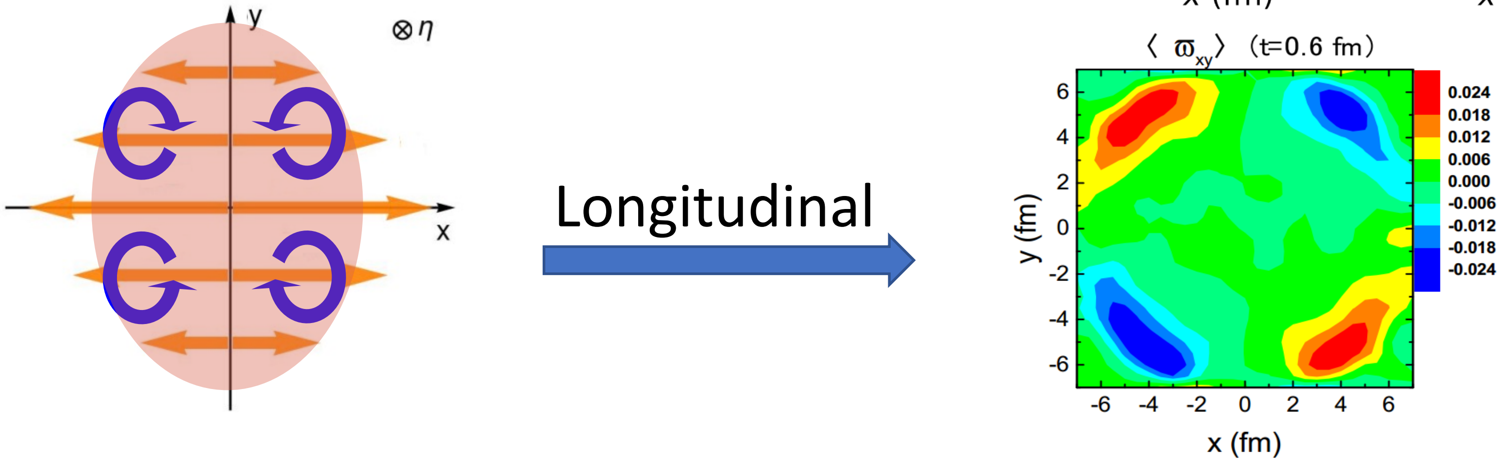








(Xia-Li-Wang 2017)



(Wei-Deng-Huang 2019)

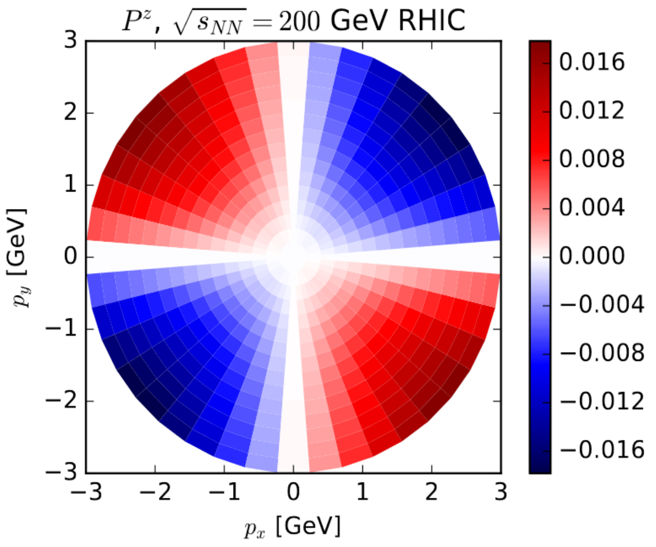
(See also: Karpenko-Becattini 2017; Csernai etal 2014; Teryaev-Usubov 2015; Ivanov-Soldatov 2018; Fu etal 2020; Lei etal 2021; … …)

Local spin polarization

- Spin harmonic flows: $$\frac{dP_{y,z}}{d\phi} = \frac{1}{2\pi}[P_{y,z} + 2f_{2y,z}\sin(2\phi) + 2g_{2y,z}\cos(2\phi) + \cdots]$$

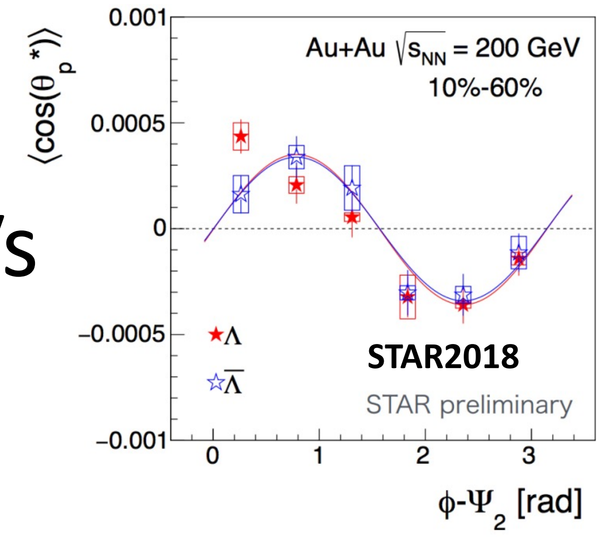
1) longitudinal polarization vs ϕ

(Becattini-Karpenko 2018)



$f_{2z}^{\text{ther}} < 0$

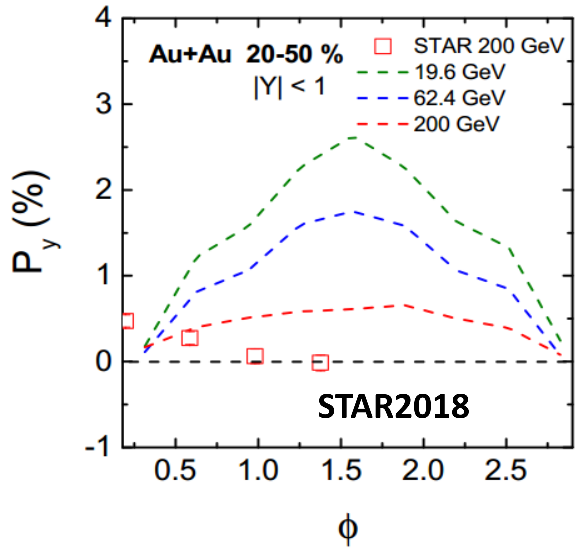
Vs



$f_{2z}^{\text{exp}} > 0$

2) Transverse polarization vs ϕ

(Wei-Deng-Huang 2019)

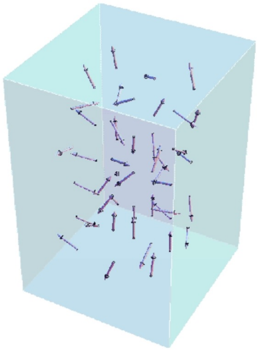


$g_{2y}^{\text{ther}} < 0, \quad g_{2y}^{\text{exp}} > 0$

Failure of global equilibrium ansatz in describing local spin polarization

Spin at local equilibrium

- A local Gibbs state for spin-1/2 fermions* (Zubarev etal 1979, Van Weert 1982, Becattini etal 2013)



Canonical stress tensor — Canonical spin tensor

$$\hat{\rho}_{\rm LG} = \frac{1}{Z_{\rm LG}} \exp\left\{ - \int_{\Xi} d\Xi_\mu(y) \left[\hat{\Theta}^{\mu\nu}(y)\beta_\nu(y) - \frac{1}{2}\hat{\Sigma}^{\mu\rho\sigma}(y)\mu_{\rho\sigma}(y) \right] \right\}$$

Thermal flow vector — Spin potential

- A spin Cooper-Frye formula (Liu-Huang 2021; Buzzegoli 2021)

$$\bar{S}_\mu(p) = \bar{S}_{5\mu}(p) - \frac{1}{8\int d\Xi\cdot p\ n_F}\int d\Xi\cdot p\frac{n_F(1-n_F)}{E_p}\left\{\epsilon_{\mu\nu\alpha\beta}p^\nu\mu^{\alpha\beta} + 2\frac{\varepsilon_{\mu\nu\rho\sigma}p^\rho n^\sigma}{p\cdot n}\left[p_\lambda(\xi^{\nu\lambda} + \Delta\mu^{\nu\lambda}) + \partial^\nu\alpha\right]\right\}$$

$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu)$: Thermal shear tensor $\alpha = -\beta\mu$: Baryon chemical potential

$\Delta\mu_{\rho\sigma} = \mu_{\rho\sigma} - \varpi_{\rho\sigma}$ with $\varpi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma\beta_\rho - \partial_\rho\beta_\sigma)$ thermal vorticity tensor

$\bar{S}_5^\mu$ is the polarization induced by finite chirality

* Obtained by maximizing Von Neumann entropy under local constraints of stress and angular momentum tensors:

$s = -{\rm Tr}\,(\hat{\rho}\ln\hat{\rho})$ with $n_\mu {\rm Tr}(\hat{\rho}\,\hat{\Theta}^{\mu\nu}) = n_\mu\Theta^{\mu\nu}$ and $n_\mu {\rm Tr}(\hat{\rho}\,\hat{\Sigma}^{\mu\rho\sigma}) = n_\mu\Sigma^{\mu\rho\sigma}$

Thermal shear contribution

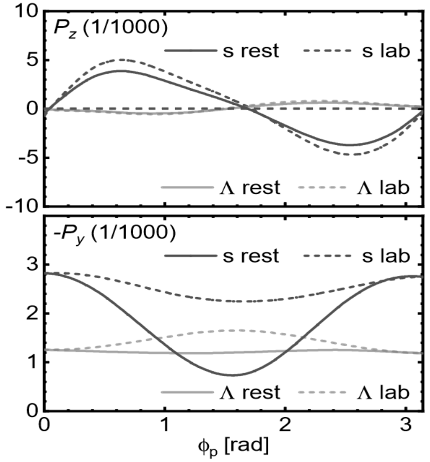
- Recall

$$S^\mu(x,p) = -\frac{1}{E_p}\left[\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}p_\nu\mu_{\alpha\beta} + \frac{1}{2p\cdot n}\epsilon^{\mu\nu\alpha\beta}\left(\xi_{\nu\lambda}+\Delta\mu_{\nu\lambda}\right)n_\beta p_\alpha p^\lambda\right]n_F(1-n_F) + O(\mu^2_{\rho\sigma},\partial^2)$$

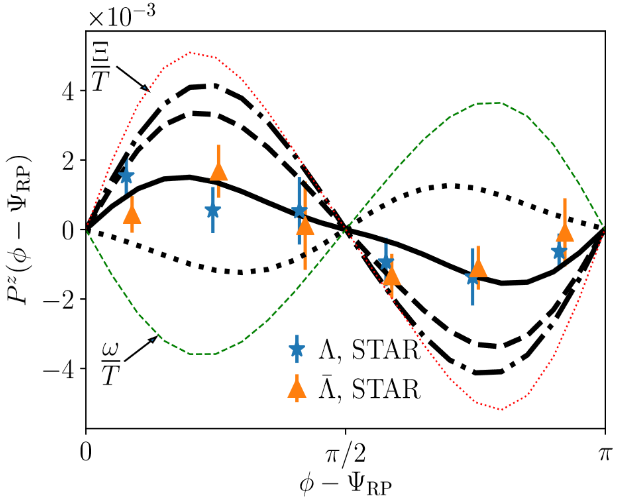
- Relax the global equilibrium condition (1) (Becattini-Buzzegoli-Palermo 2021, Liu-Yin 2021)

$$\partial_\mu\beta_\nu + \partial_\nu\beta_\mu \neq 0 \qquad \mu_{\rho\sigma} = \varpi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma\beta_\rho - \partial_\rho\beta_\sigma\right)$$

(Fu-Liu-Song-Yin 2021)



(Becattini-Buzzegoli-Palermo-Inghirami-Karpenko 2021)



(See also Hidaka-Pu-Yang 2018; Yi-Pu-Yang 2021; Florkowski-Kumar-Mazeliauskas-Ryblewski 2021; Sun-Zhang-Ko-Zhao 2021; Alzhrani-Ryu-Shen 2022; Lin-Wang 2022; Jiang-Wu-Cao-Zhang 2023; … …)

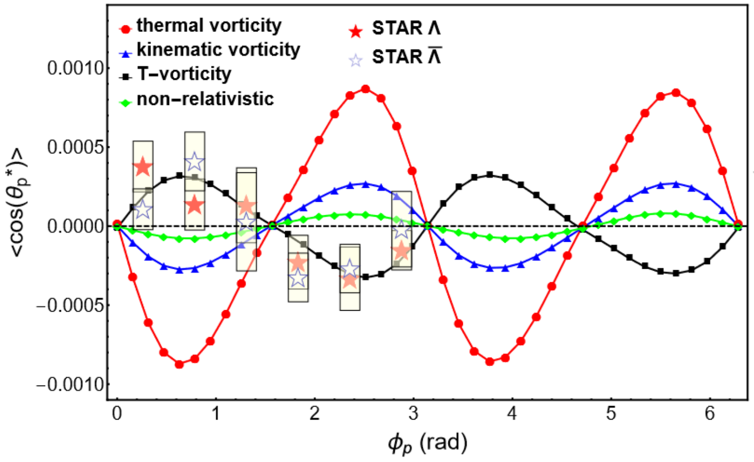
Temperature vorticity as spin potential

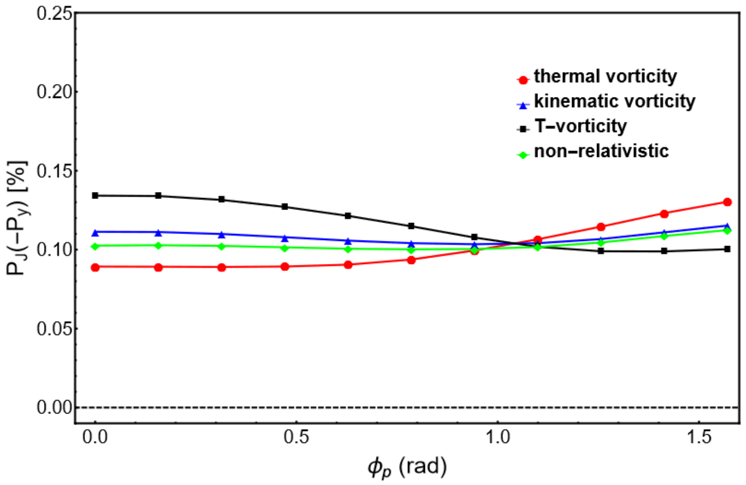
- Recall

$$S^{\mu}(x,p) = -\frac{1}{E_p}\left[\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}p_\nu \mu_{\alpha\beta} + \frac{1}{2p\cdot n}\epsilon^{\mu\nu\alpha\beta}\left(\xi_{\nu\lambda}+\Delta\mu_{\nu\lambda}\right)n_\beta p_\alpha p^\lambda\right] n_F(1-n_F) + O(\mu_{\rho\sigma}^2, \partial^2)$$

- Relax the global equilibrium condition (2) (Wu-Pang-Huang-Wang 2019)

$$\partial_\mu \beta_\nu + \partial_\nu \beta_\mu = 0 \qquad \mu_{\rho\sigma} = \frac{1}{2T^2}\left[\partial_\sigma(Tu_\rho) - \partial_\rho(Tu_\sigma)\right]$$





(See also Florkowski-Kumar-Ryblewski-Mazeliauskas 2019)

Discussion 1: Pseudo-gauge ambiguity

- The pseudo-gauge ambiguity

Conservation laws
$$\partial_\mu \hat{\Theta}^{\mu\nu} = 0, \quad \partial_\mu \hat{J}^{\mu\rho\sigma} = \hat{\Theta}^{\rho\sigma} - \hat{\Theta}^{\sigma\rho} + \partial_\mu \hat{\Sigma}^{\mu\rho\sigma}$$

Conserved charges
$$\hat{P}^\nu = \int d\Xi_\mu \hat{\Theta}^{\mu\nu}, \quad \hat{J}^{\rho\sigma} = \int d\Xi_\mu \hat{J}^{\mu\rho\sigma}$$

Unchanged by pseudo-gauge transformation
$$\hat{\Theta}'^{\mu\nu} = \hat{\Theta}^{\mu\nu} + \frac{1}{2}\partial_\lambda(\hat{\Phi}^{\lambda\mu\nu} - \hat{\Phi}^{\mu\lambda\nu} - \hat{\Phi}^{\nu\lambda\mu})$$
$$\hat{\Sigma}'^{\mu\rho\sigma} = \hat{\Sigma}^{\mu\rho\sigma} - \hat{\Phi}^{\mu\rho\sigma}$$

- The local equilibrium density operator is, however, changed

$$\hat{\rho}_{\rm LG} = \frac{1}{Z_{\rm LG}} \exp\left\{-\int d\Xi_\mu \left[\hat{\Theta}^{\mu\nu}\beta_\nu - \frac{1}{2}\hat{\Sigma}^{\mu\rho\sigma}\mu_{\rho\sigma}\right]\right\}$$
$$\to \hat{\rho}'_{\rm LG} = \frac{1}{Z'_{\rm LG}} \exp\left\{-\int d\Xi_\mu \left[\hat{\Theta}^{\mu\nu}\beta_\nu - \frac{1}{2}\hat{\Sigma}^{\mu\rho\sigma}\mu_{\rho\sigma} - \frac{1}{2}(\varpi_{\lambda\nu} - \mu_{\lambda\nu})\Phi^{\mu\lambda\nu} - \xi_{\lambda\nu}\Phi^{\lambda\mu\nu}\right]\right\}$$

(Becattini-Florkowski-Speranza 2019)

Discussion 1: Pseudo-gauge ambiguity

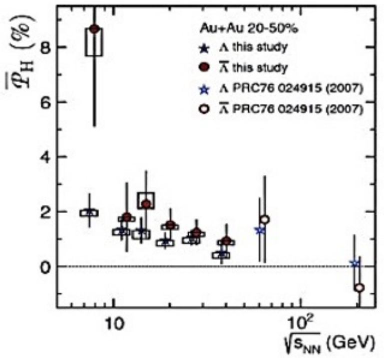
- The spin Cooper-Frye formula is thus pseudo-gauge dependent
- It is possible to eliminate thermal vorticity and shear terms completely

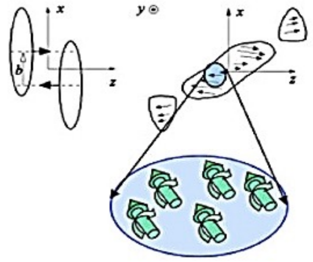
(Liu-Huang 2021; Buzzegoli 2021)

$$\bar{S}_\mu(p) = -\frac{1}{8\int d\Xi\cdot p\ \ n_F}\int d\Xi\cdot p\frac{n_F(1-n_F)}{E_p}\ \epsilon_{\mu\nu\alpha\beta}p^\nu\mu^{\alpha\beta}$$

- Thus the connection between measured spin polarization and its “sources” is ambiguous (more observables are needed)

$\bar{S}^\mu(p)$ $\quad\nLeftrightarrow\quad$ $T(x), u^\alpha(x), \mu(x), \mu_{\alpha\beta}(x)$





Discussion 2: Second-order contribution

- In practice, the gradient of thermodynamic quantities may not be tiny in the "most vortical fluid", and thus second-order contribution is practically important

$$S^{(2)\mu} = S^{(2)\mu}_{\text{lin}} + S^{(2)\mu}_{\text{quad}}$$

(Non-dissipative contribution)

$$\begin{aligned} S^{(2)\mu}_{\text{lin}}(p) = & \frac{1}{4m(p^0)^2 N} \int \mathrm{d}\Sigma \cdot p_+ \, n_F(x,p)\,[1-n_F(x,p)]\,(y^0_\Sigma(0) - x^0) \\ & \times \hat{t}_\alpha p_\rho \left[\epsilon^{\mu\sigma\alpha\rho} p^\lambda p^\nu \partial_\sigma \xi_{\nu\lambda} + \left(\frac{1}{2} p^\alpha \epsilon^{\mu\nu\lambda\rho} - \epsilon^{\mu\alpha\lambda\rho} p^\nu \right) p^\sigma \partial_\sigma \varpi_{\nu\lambda} \right. \\ & \left. - \epsilon^{\mu\sigma\alpha\rho} p^\lambda \partial_\sigma \partial_\lambda \zeta + \frac{1}{2} \epsilon^{\alpha\nu\lambda\sigma} \partial^\rho (\Omega_{\nu\lambda} - \varpi_{\nu\lambda})(p^\mu p_\sigma - m^2 g^\mu_\sigma) \right] . \end{aligned}$$

$$\begin{aligned} S^{(2)\mu}_{\text{quad}}(p) = & \frac{1}{2\int d\Sigma \cdot p_+ \mathrm{tr}\left[W^{(0)}(x,p)\right]} \int d\Sigma \cdot p_+ \frac{[1-2n_F(x,p)]\mathrm{tr}\left[\gamma^\mu\gamma^5 W^{(1)}(x,p)\right] \mathrm{tr}\left[W^{(1)}(x,p)\right]}{[1-n_F(x,p)]\mathrm{tr}\left[W^{(0)}(x,p)\right]} \\ & - \frac{1}{2} \left\{ \frac{\int d\Sigma \cdot p_+ \mathrm{tr}\left[\gamma^\mu\gamma^5 W^{(1)}(x,p)\right]}{\int d\Sigma \cdot p_+ \mathrm{tr}\left[W^{(0)}(x,p)\right]} \right\} \left\{ \frac{\int d\Sigma \cdot p_+ \mathrm{tr}\left[W^{(1)}(x,p)\right]}{\int d\Sigma \cdot p_+ \mathrm{tr}\left[W^{(0)}(x,p)\right]} \right\} \end{aligned}$$

(Sheng-Becattini-Huang-Zhang 2024)

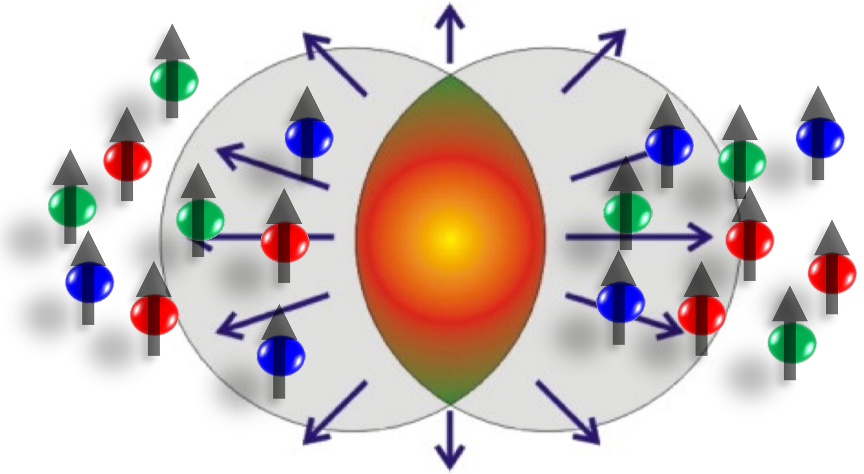
- The numerical simulation are needed to quantify its importance.

Discussion 3: Dynamics of spin polarization

- Give spin potential or spin polarization dynamics

  - **Spin hydrodynamics:** **Fluid velocity, temperature, and spin density evolve together**
  - **Spin kinetic theory:** **Particle and spin phase-space distribution functions evolve together**

- A lot of theoretical progress since 2019

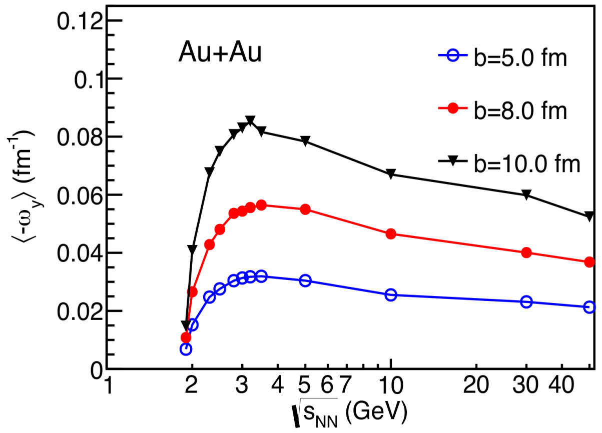


Reviews:
Hidaka-Pu-Wang-Yang 2022;
Hattori-Hongo-Huang 2022;
Huang 2024;
Becattini-Buzzegoli-Niida etal 2024

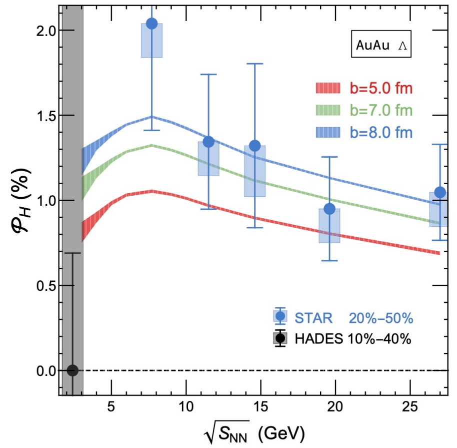
Numerical simulation are strongly needed.

Discussion 4: Very low energies

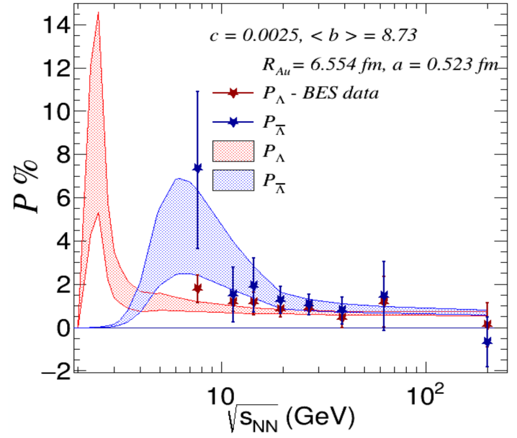
- Vorticity and global spin polarization expected to be vanishing near collision threshold



(Deng-Huang-Ma-Zhang 2020)



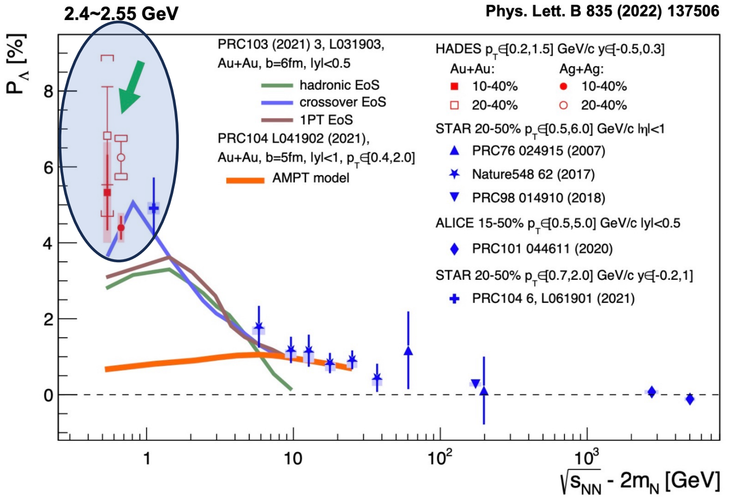
(Guo etal 2021)



(Ayala etal 2022)

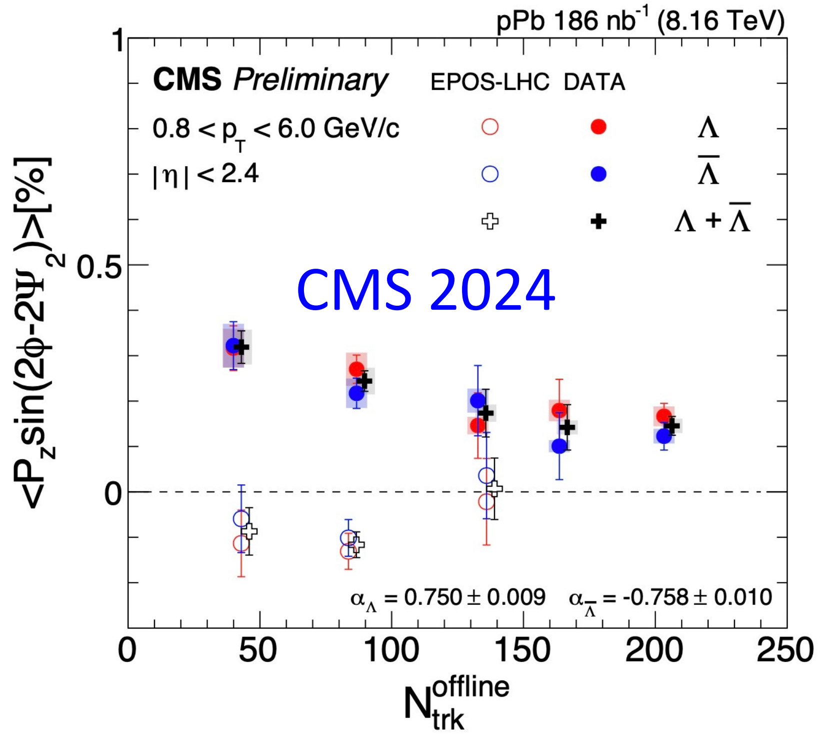
- Not seen in data by STAR@RHIC 2021, HADES@GSI 2021 down to 2.4 GeV

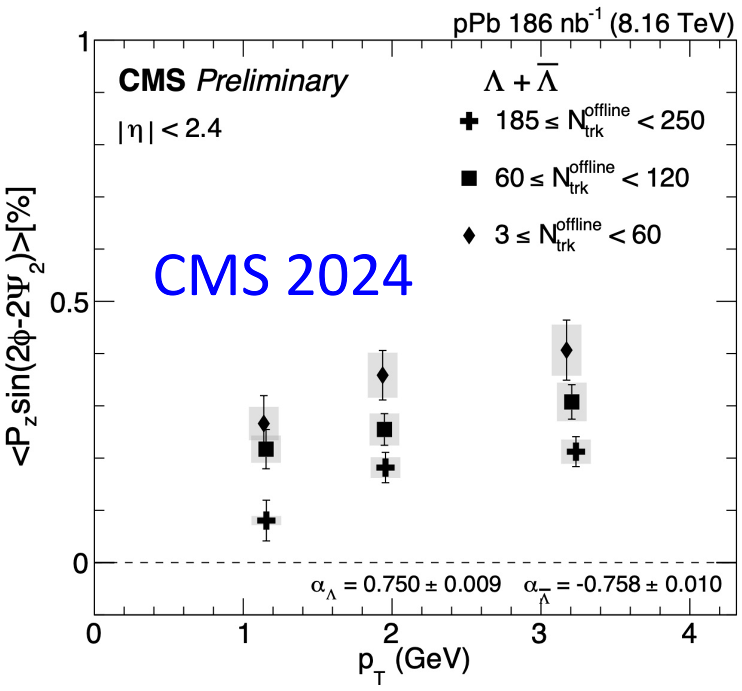
Experiments not see peak till 2.X GeV



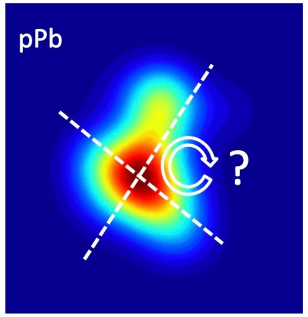
- Very Surprising.
- Further studies @ FAIR, NICA, HIAF, J-PARC?

Discussion 5: small system





- Similar magnitude and trend with AA
- Hydrodynamic collectivity? Seems No
- Gluonic initial condition?
- Polarizing Fragmentation Functions?



Vector meson spin alignment

Global spin alignment

- Recall that the spin density matrix of a spin-1 particle (e.g. ϕ meson):

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

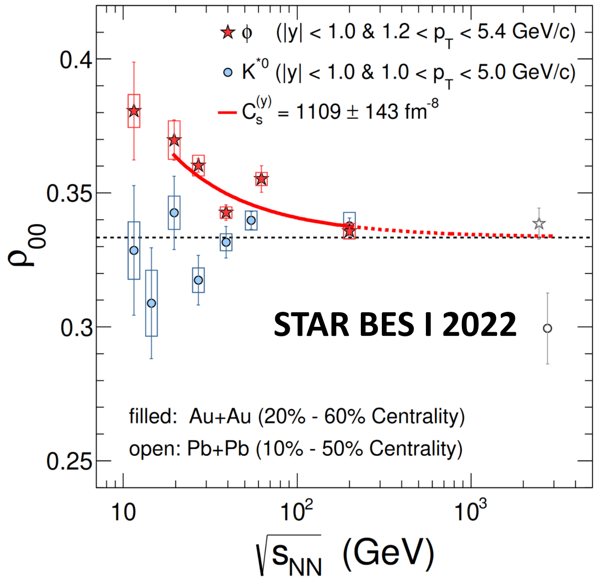
- In recombination process $q + \bar{q} \rightarrow \phi$ (Liang-Wang 2004)

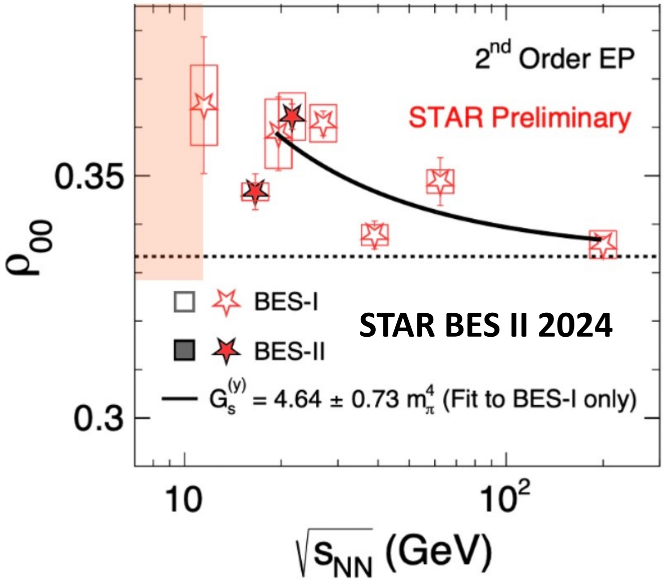
$$\rho_{00} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}$$

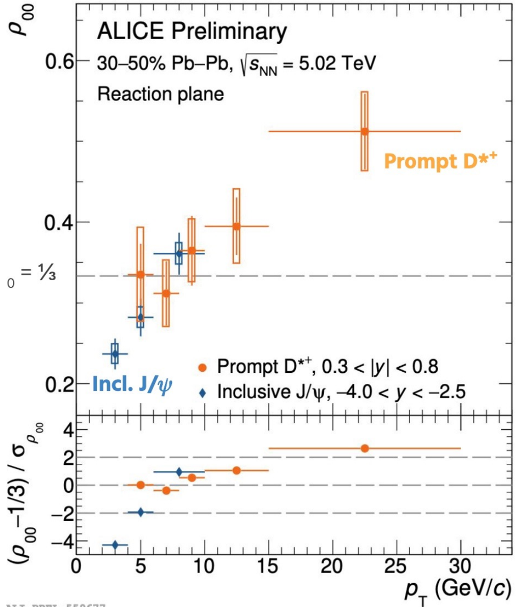
- The results of Λ global polarization suggest $P_q \approx P_{\bar{q}} \sim O(10^{-2})$

➡ Expectation: spin alignment parameter $\rho_{00} - \frac{1}{3} \sim O(10^{-4})$

Global spin alignment







ALICE 2023

- Spin quantization is along global angular momentum direction
- ϕ decreasing at higher energies, similar with Λ global polarization
- Non-monotonic at tens of GeV. Critical phenomenon?
- Puzzle: ϕ-meson $\boldsymbol{\rho_{00}} > 1/3$ and big
- Puzzle: K^{*0} spin alignment consistent with zero
- Puzzle: Low-pt J/ψ $\boldsymbol{\rho_{00}} < 1/3$ and significant

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).

Discussion 1: Possible mesonic ϕ field

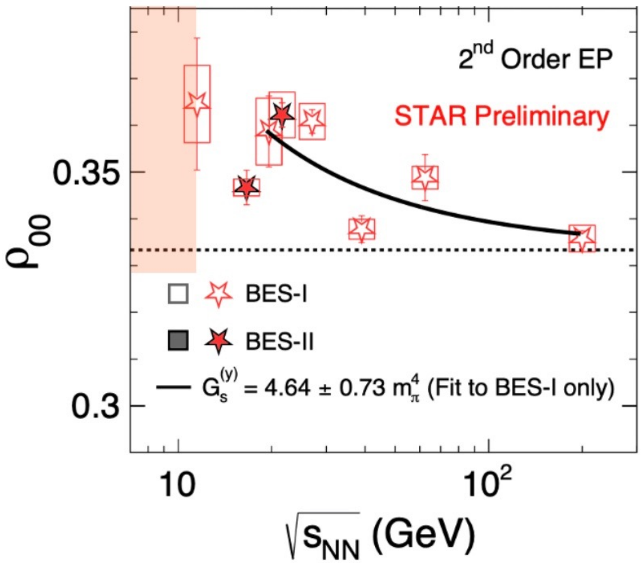
- Quark polarization fluctuation and ϕ spin alignment

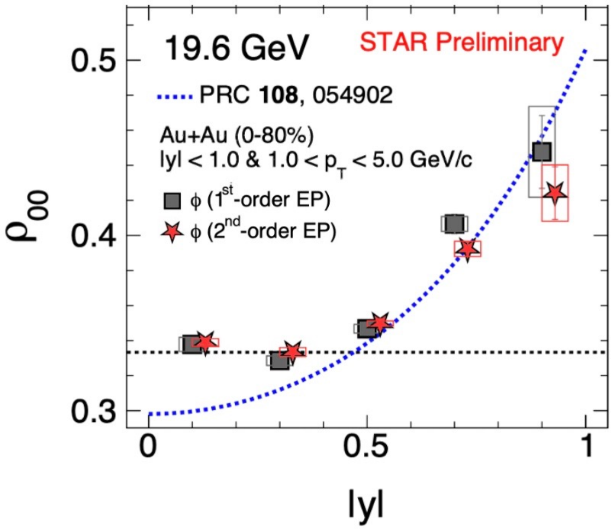
$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle \quad \Rightarrow \quad \rho_{00} = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle} \approx \frac{1}{3} - \frac{4}{9} \langle P_q P_{\bar{q}} \rangle$$

- If a ϕ field exists, s and $\bar{s}$ feel a "strangeness" vector field, just like EM field

$$\rho_{00}(x, \mathbf{k}) \approx \frac{1}{3} - \frac{4 g_\phi^2}{m_\phi^2 T_\mathrm{h}^2} C_1 \left[\frac{1}{3} \mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\epsilon_0 \cdot \mathbf{B}'_\phi)^2 \right] - \frac{4 g_\phi^2}{m_\phi^2 T_\mathrm{h}^2} C_2 \left[\frac{1}{3} \mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\epsilon_0 \cdot \mathbf{E}'_\phi)^2 \right]$$

- Suitably choosing these strangeness field fluctuation can well explain data





(Sheng et. al., 2020, 2022, 2023)

- Does such mesonic field exist?
- Need other independent observables to check
- Spin correlation?

(Lv etal 2024)

Discussion 2: Hydrodynamic benchmark

- The spin alignment is a T-even and P-even phenomenon

➡ The leading-order contributions: $(\partial\beta)(\partial\beta),\ (\partial\beta)\mu,\ \mu\mu,\ \partial\partial\beta,\ \partial\mu$

$$\partial_\mu \beta_\nu = \text{Thermal vorticity} + \text{Thermal shear}, \quad \mu_{\rho\sigma} - \text{Spin potential}$$

- The full results at local equilibrium are now known:

$$\rho_{00} \approx \rho_{00}^{(2)}|_T + \rho_{00}^{(2)}|_S + \rho_{00}^{(2)}|_{TT} + \rho_{00}^{(2)}|_{TS} + \rho_{00}^{(2)}|_{ST} + \rho_{00}^{(2)}|_{SS}$$

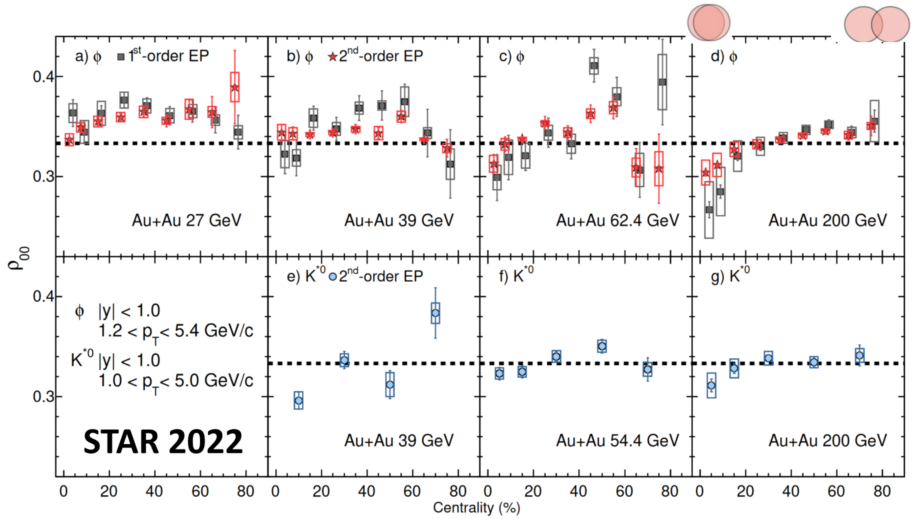
For example:

$$\rho_{00}^{(2)}|_S(x,k) = \frac{1}{3}\delta(k^2-m^2)\theta(k^0)(1+n_B)\epsilon_r^{\gamma_3 *}(k)\epsilon_s^{\gamma_0}(k)\frac{1}{2E_k}[\partial^\perp_{\alpha_1}\Omega_{\rho_1\sigma_1}](x)$$
$$\times \frac{1}{2}\left[\hat{k}^{\alpha_1}\hat{n}^{\rho_1}\eta^{\sigma_1}_{(\gamma_0}\hat{n}_{\gamma_3)} - \left(\eta^{\alpha_1\rho_1} - \frac{k^{\alpha_1}k^{\rho_1}}{m^2}\right)\eta^{\sigma_1}_{(\gamma_0}\hat{n}_{\gamma_3)} - \gamma_k{}^2\hat{k}^{\rho_1}\eta^{\sigma_1}_{(\gamma_0}\eta^{\alpha_1}_{\gamma_3)}\right]$$

(Zhang-Huang-Becattini-Sheng, 2024)

Discussion 3: Local spin alignment

- Centrality dependence

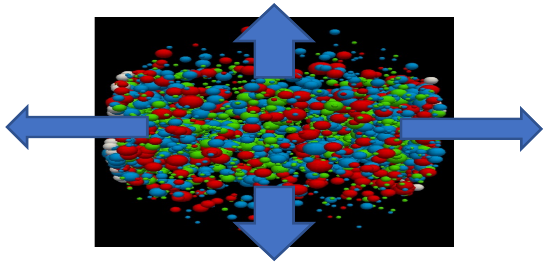


Central: $\rho_{00} < \frac{1}{3}$

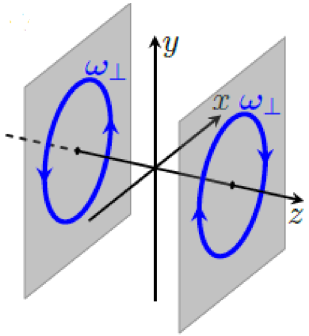
Noncentral: $\rho_{00} > \frac{1}{3}$

More significant at higher energies

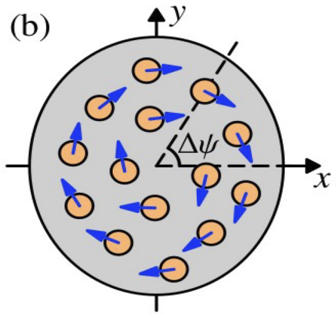
- Local spin alignment



Central collisions



$$\mathbf{P}^{q,\bar{q}} = (P_x^{q,\bar{q}}, P_y^{q,\bar{q}}, P_z^{q,\bar{q}})$$



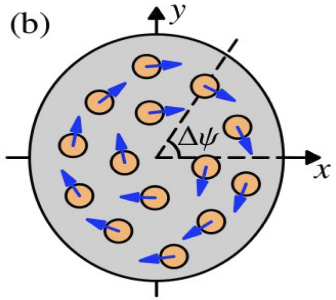
Quark spin density matrix:

$$\rho^{q,\bar{q}} = \frac{1}{2}\begin{pmatrix} 1 + P_y^{q,\bar{q}} & P_z^{q,\bar{q}} - iP_x^{q,\bar{q}} \\ P_z^{q,\bar{q}} + iP_x^{q,\bar{q}} & 1 - P_y^{q,\bar{q}} \end{pmatrix}$$

More significant at higher energies

Discussion 3: Local spin alignment

- Vector meson spin density matrix element



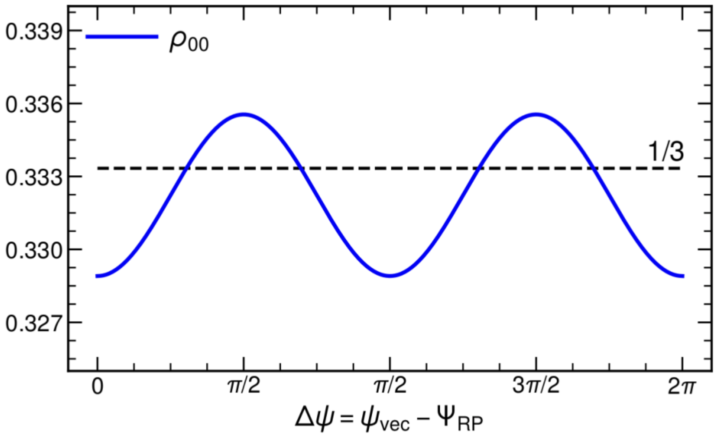
$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$
$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$
$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$

$$\Rightarrow \quad \rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}} \approx \frac{1}{3} - \frac{F_\perp^2}{9} - \frac{F_\perp^2}{3}\cos(2\Delta\psi)$$

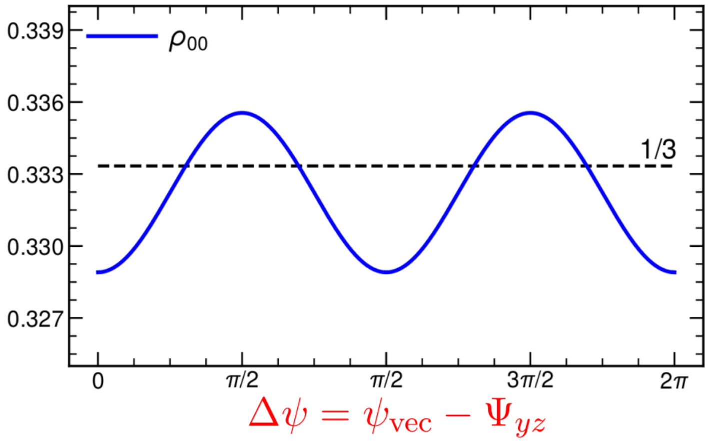
(Xia-Li-Huang-Huang 2020)

- More experimental verification of this scenario is needed

1) Measure azimuthal angle dependence



2) Measure ρ_{00} w.r.t other plane, e.g., yz plane

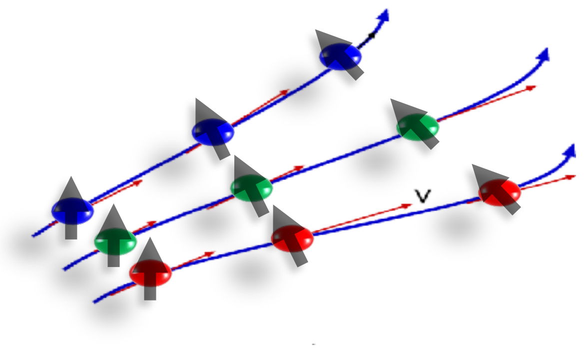


Local spin alignment unchanged, but global one may change significantly

Summary

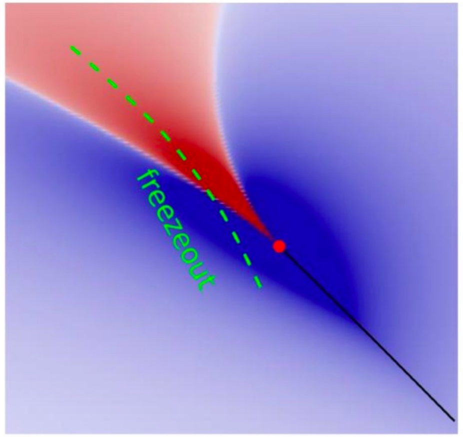
Summary

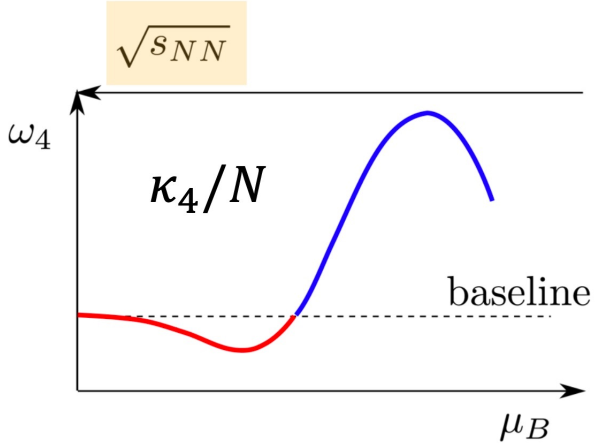
- The spin polarization and alignment phenomena opens new arena for QGP study.
- Global spin polarization of hyperons is understood.
- Local spin polarization of Lambda is not understood (but big progress recently).
- Spin alignment of vector meson is not understood.



Discussion 4: spin fluctuation and criticality

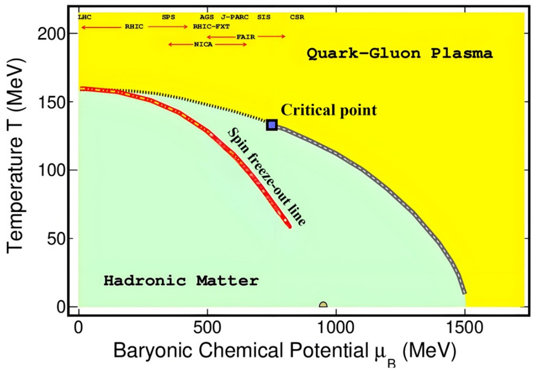
- QCD phase diagram and critical point





Kurtosis of conserved charges

- Critical spin fluctuation and phi spin alignment



(Chen-Fu-Huang-Ma 2024)

$$\langle P_q P_{\bar{q}} \rangle_c = \frac{4(\langle S_q S_{\bar{q}} \rangle - \langle S_q \rangle \langle S_{\bar{q}} \rangle)}{\langle N_q N_{\bar{q}} \rangle - \langle N_q \rangle \langle N_{\bar{q}} \rangle}$$