

Global and local spin polarization in relativistic heavy-ion collisions

Baochi Fu (Peking University)

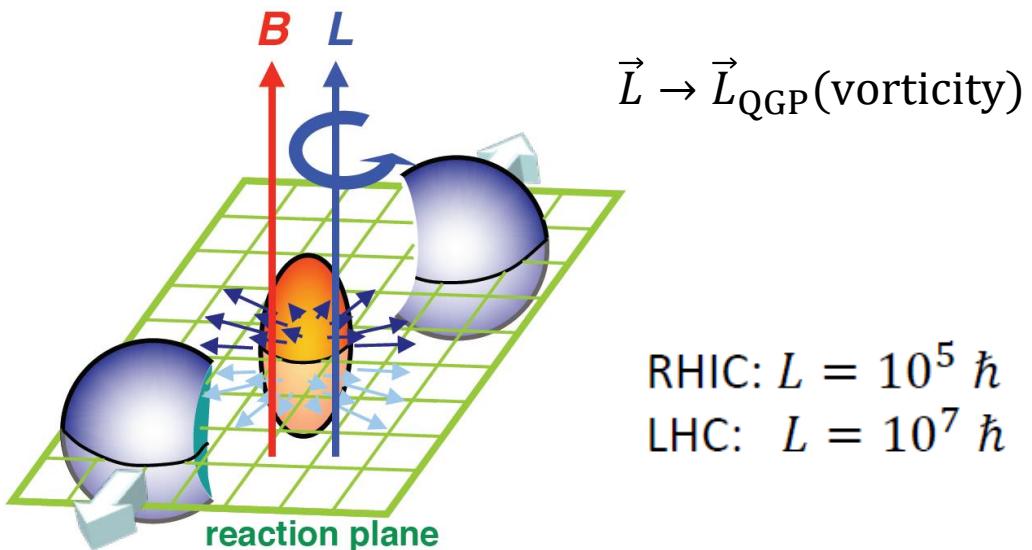


The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions, 2023-07-15

Global spin polarization

Angular momentum

- Large angular momentum and magnetic field in non-central heavy ion collisions
- Inducing vorticity along the out-of-plane direction (soft EoS)



Observable prediction

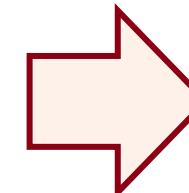
- Orbital angular momentum transferred to spin (spin-orbital coupling)

$$\langle \vec{S}_{\omega}; \text{hadrons} \rangle \parallel \vec{L}_{\text{QGP}}$$

- Global polarization of emitted hadrons

Z. T. Liang, X. N. Wang,
PRL 94 (2005) 102301, PLB 629 (2005) 20-26

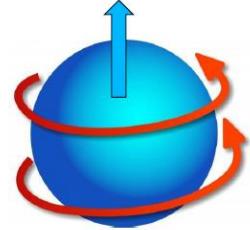
Global quark polarization



- Hyperon polarization
- Meson spin alignment

Spin-Orbital Coupling

- Barnett effect: rotation \rightarrow polarization

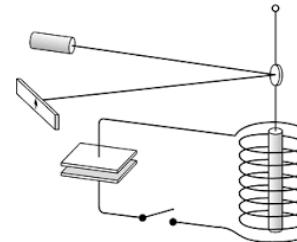


$$\vec{J} \rightarrow \vec{S}$$

Barnett, Phys. Rev. 6 (4) 239, (1915)

Barnett, Rev. Mod. Phys. 7, 129 (1935)

- Einstein-de Haas Effect: polarization \rightarrow rotation



$$\vec{S} \rightarrow \vec{J}$$

Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

Nuclear magnetic resonance

Applied Physics Express

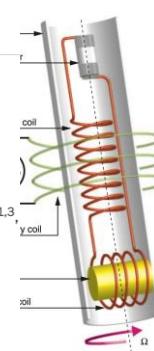
FREE ARTICLE

Observation of Barnett fields in solids by nuclear magnetic resonance

Hiroyuki Chudo^{1,3}, Masao Ono^{1,3}, Kazuya Harii^{1,3}, Mamoru Matsuo^{1,3}, Jun'ichi Ieda^{1,3}, Rie Haruki^{1,3}, Satoru Okayasu^{1,3}, Sadamichi Maekawa^{1,3}, Hiroshi Yasuoka¹ and Eiji Saitoh^{1,2,3,4}

Published 21 May 2014 • © 2014 The Japan Society of Applied Physics

Applied Physics Express, Volume 7, Number 6



Paramagnetic states



M. Ono, et al, Phys. Rev. B, 2015

Condensed matter

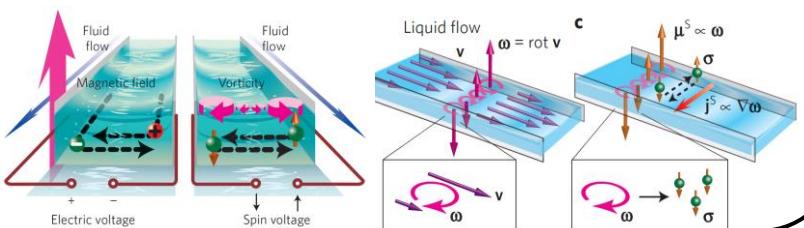
LETTERS

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3526

nature
physics

Spin hydrodynamic generation

R. Takahashi^{1,2,3,4*}, M. Matsuo^{2,4}, M. Ono^{2,4}, K. Harii^{2,4}, H. Chudo^{2,4}, S. Okayasu^{2,4}, J. Ieda^{2,4}, S. Takahashi^{1,4}, S. Maekawa^{2,4} and E. Saitoh^{1,2,3,4*}

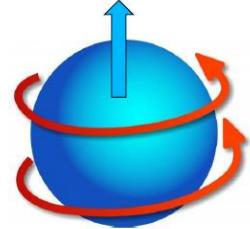


R. Takahashi, Nature Physics, 2016²

H. Chudo, et al, Applied Physics Express, 2015

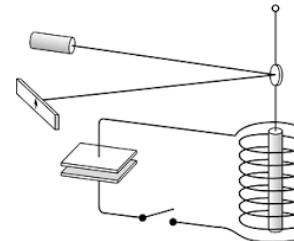
Spin-Orbital Coupling

- Barnett effect: rotation \rightarrow polarization



Barnett, Phys. Rev. 6 (4) 239, (1915)
Barnett, Rev. Mod. Phys. 7, 129 (1935)

- Einstein-de Haas Effect: polarization \rightarrow rotation



$$\vec{s} \rightarrow \vec{J}$$

Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

RHIC and LHC can study such effects at extreme conditions

Nuclear mag

atter

nature
physics

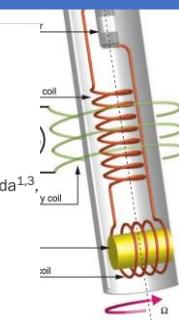
Applied Physics Express

FREE ARTICLE

Observation of Barnett fields in solids by nuclear magnetic resonance

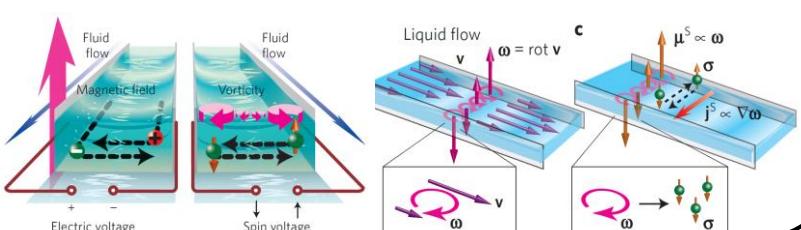
Hiroyuki Chudo^{1,3}, Masao Ono^{1,3}, Kazuya Harii^{1,3}, Mamoru Matsuo^{1,3}, Jun'ichi Ieda^{1,3}, Rie Haruki^{1,3}, Satoru Okayasu^{1,3}, Sadamichi Maekawa^{1,3}, Hiroshi Yasuoka¹ and Eiji Saitoh^{1,2,3,4}

Published 21 May 2014 • © 2014 The Japan Society of Applied Physics
Applied Physics Express, Volume 7, Number 6



Spin hydrodynamic generation

R. Takahashi^{1,2,3,4*}, M. Matsuo^{2,4}, M. Ono^{2,4}, K. Harii^{2,4}, H. Chudo^{2,4}, S. Okayasu^{2,4}, J. Ieda^{2,4}, S. Takahashi^{1,4}, S. Maekawa^{2,4} and E. Saitoh^{1,2,3,4*}



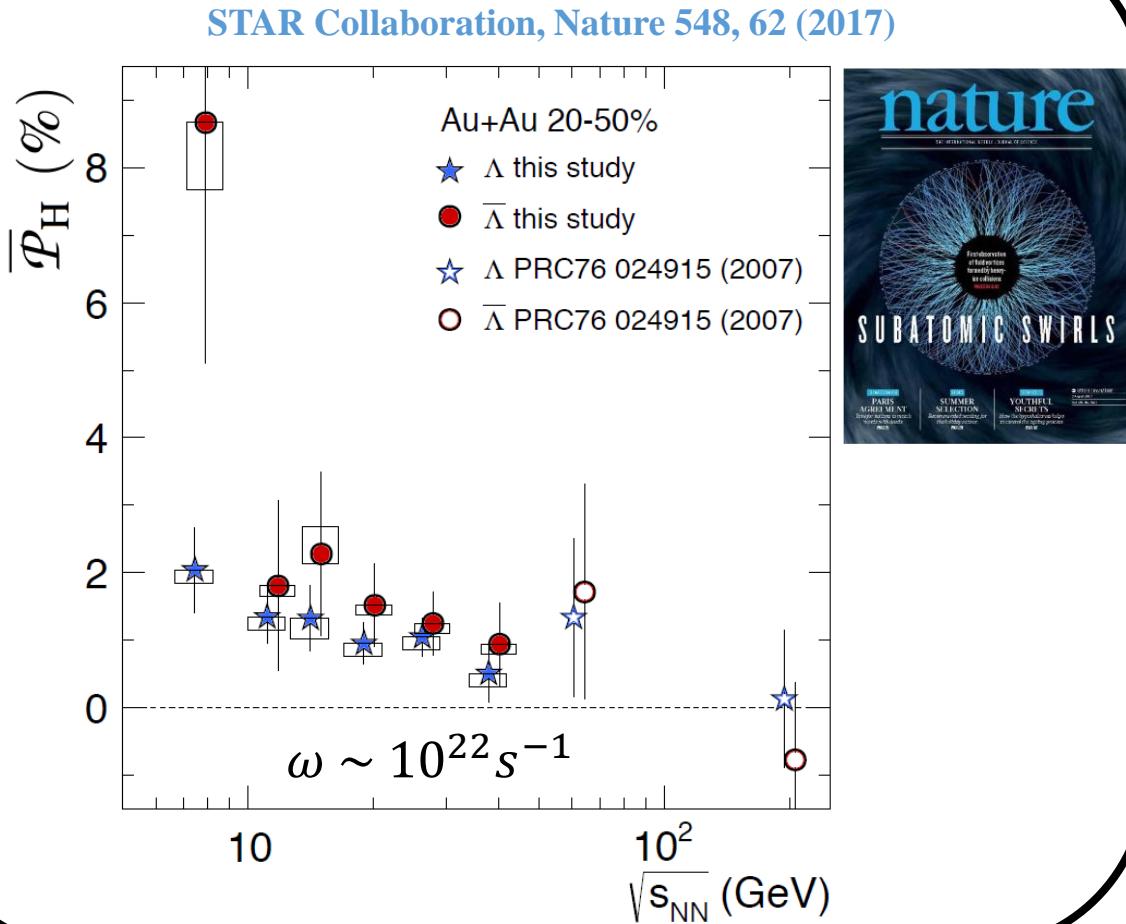
H. Chudo, et al, Applied Physics Express, 2015

M. Ono, et al, Phys. Rev. B, 2015

R. Takahashi, Nature Physics, 2016⁴

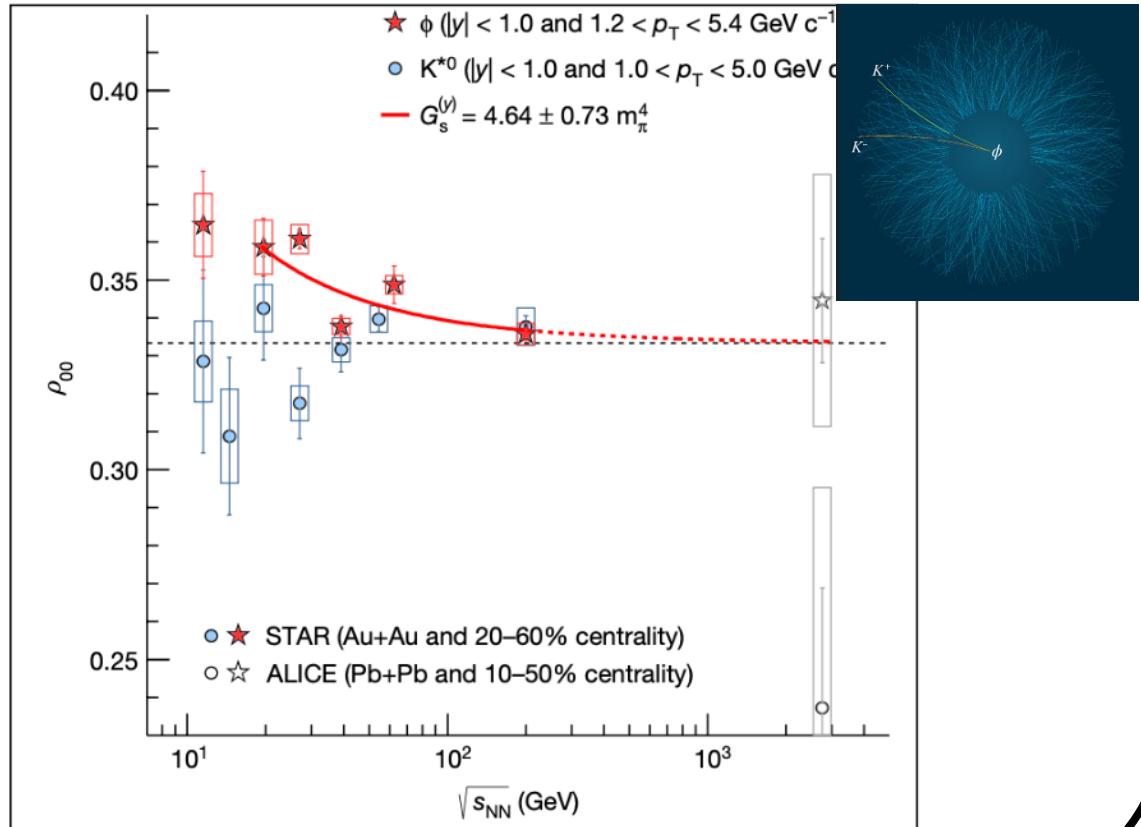
Global polarization measurements

Most vortical fluid!



Meson spin alignment

STAR Collaboration, Nature 614, 224 (2023)



Spin polarization: a new direction to probe the property of QGP

Outline

- **Λ Global Polarization**
- **Λ Local Polarization**
 - Shear-induced polarization
- **Some recent phenomenology progress**
 - Baryonic Spin Hall Effect (SHE)
- **Spin alignment from light front spinor**

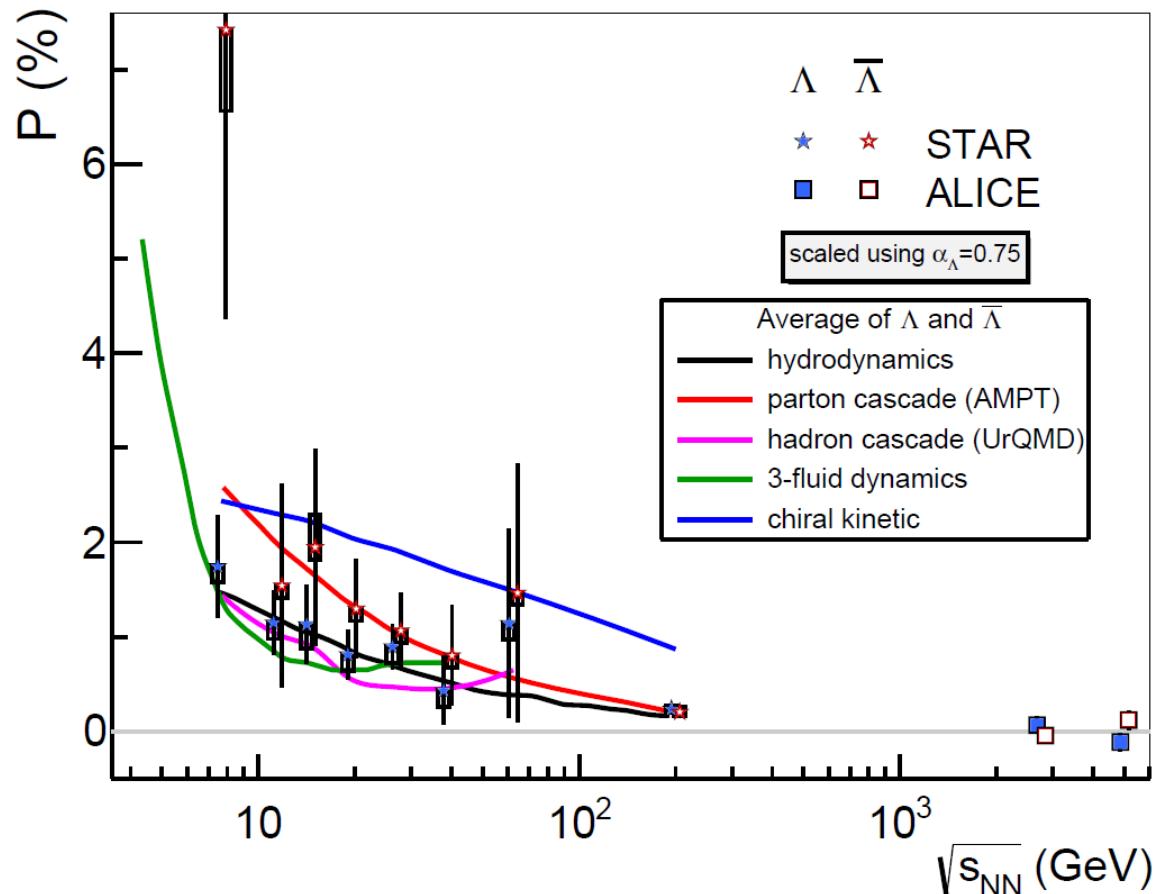
A Global Polarization

Global polarization: thermal vorticity description

Thermal vorticity induced polarization (global eq.)

$$S^\mu(x, p) = -\frac{1}{2m} \frac{S(S+1)}{3} [1 - f(x, p)] \epsilon^{\mu\nu\rho\sigma} p_\sigma \varpi_{\nu\rho}$$

$$\varpi_{\mu\nu} = -\frac{1}{2} (\partial_\mu \beta_\nu - \partial_\nu \beta_\mu) \quad \beta_\mu = u_\mu/T$$



P^μ = [thermal vorticity]

Viscous hydrodynamics:

Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)

Partonic cascade (AMPT):

Li H, Pang L-G, Wang Q, Xia XL. Phys. Rev. C96:054908 (2017)

Hadron cascade (UrQMD):

O. Vitiuk, L. Bravina and E. Zabrodin, Phys.Lett.B 803 (2020) 135298

3-fluid dynamics:

Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)

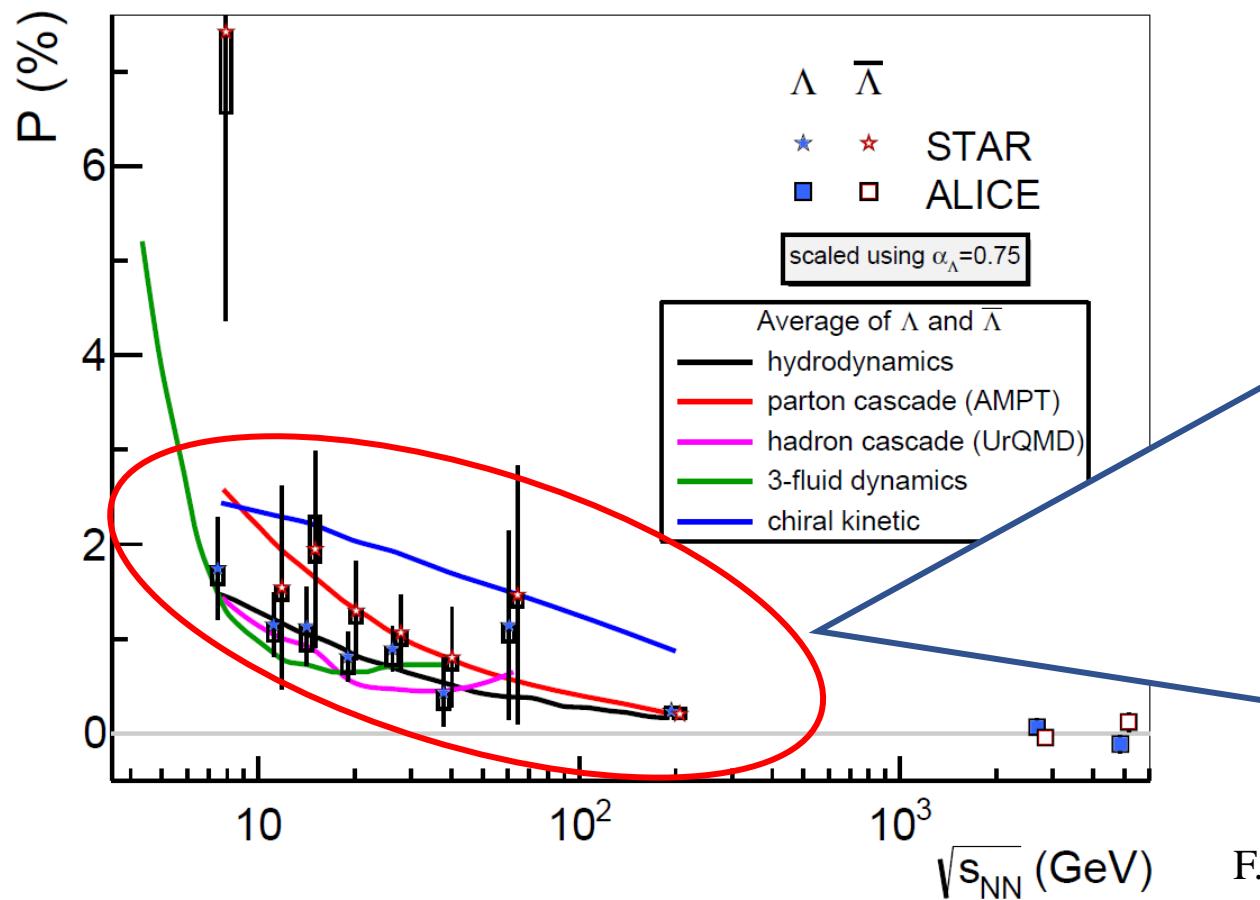
Chiral Kinetic Theory (chiral vorticity):

Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

Global polarization

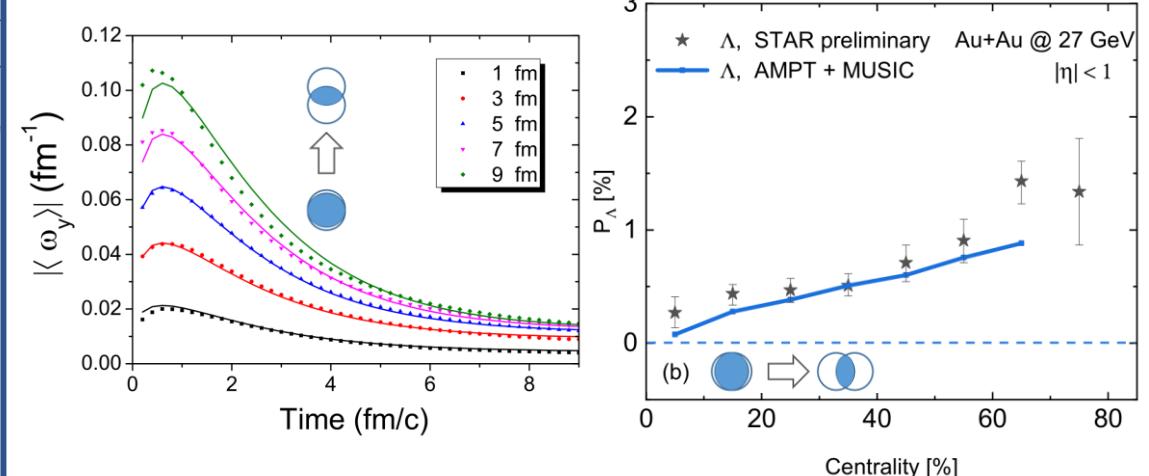
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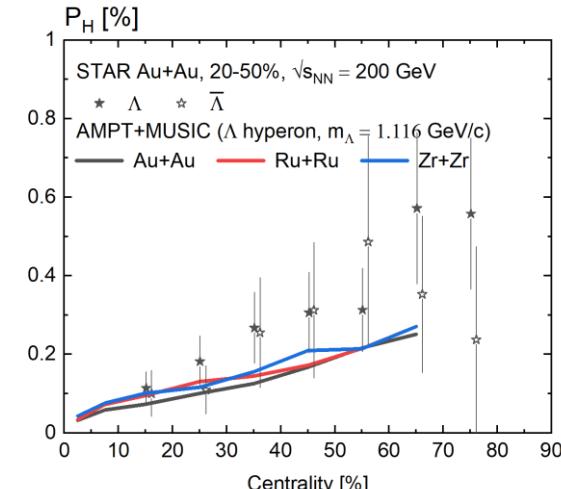


System geometry driven

- Centrality dependence from averaged vorticity (OAM)



- Extend to isobar systems



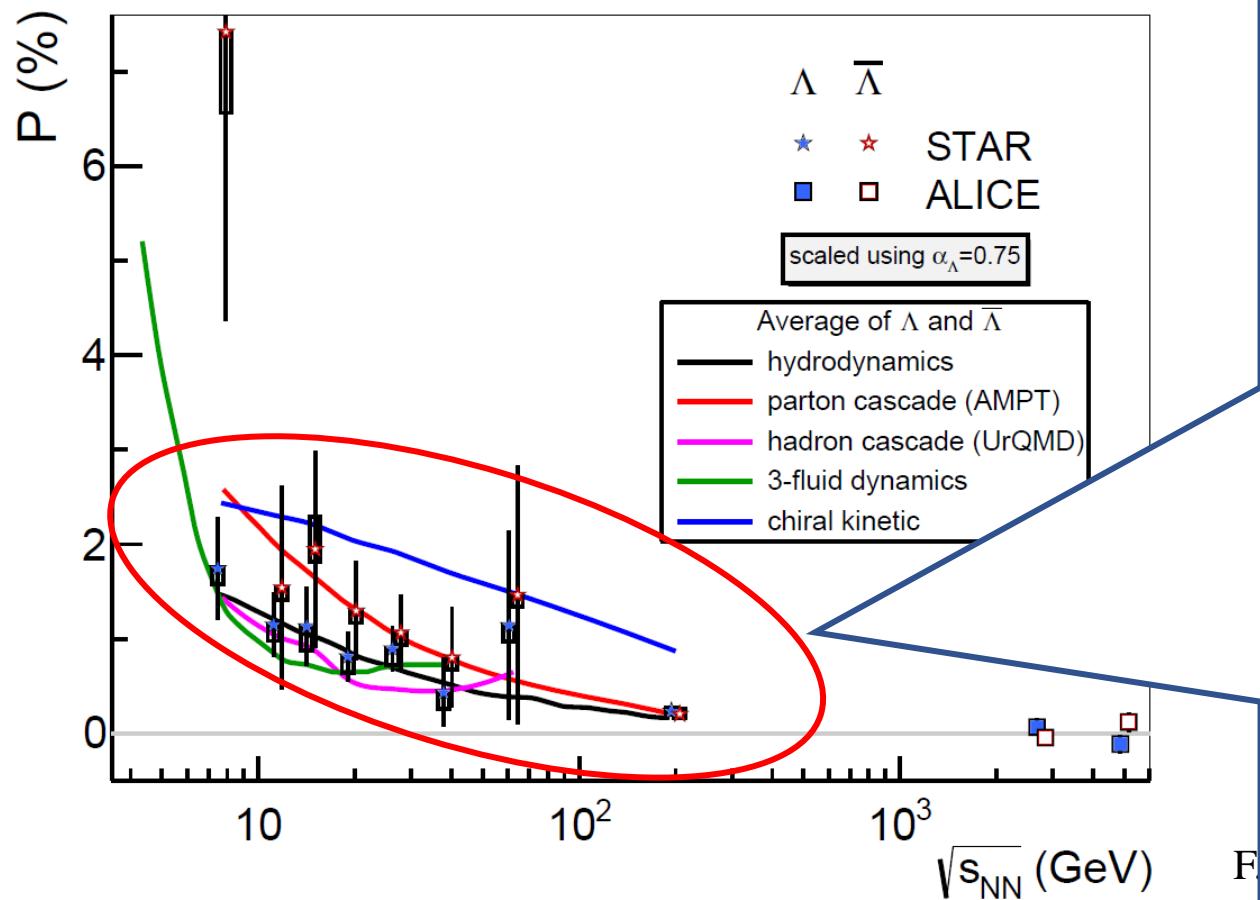
See exp. talk:
X. Gou@Mon.

Y. Jiang, Z. Lin, J. Liao,
PRC 94 (2016) no.4, 044910
BF, K. Xu, X-G, Huang, H. Song,
PRC 103 (2021) 2, 024903

Global polarization

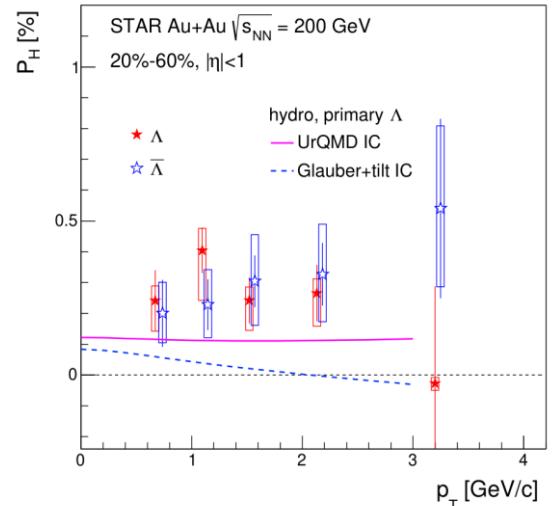
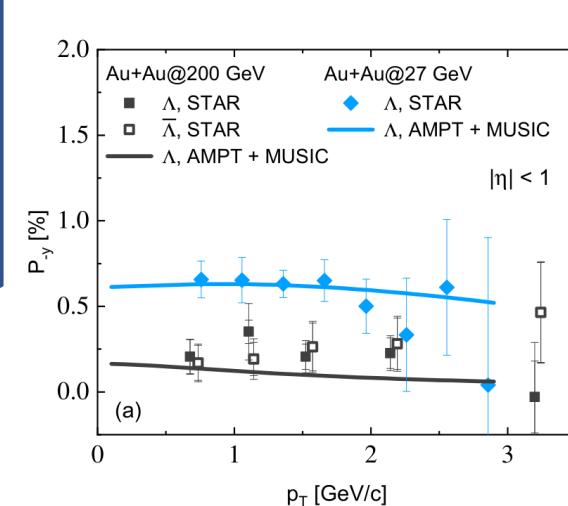
Thermal vorticity induced polarization (global eq.)

$$S^\mu(x, p) = -\frac{1}{2m} \frac{S(S+1)}{3} [1 - f(x, p)]$$



Hydro / Transport describe the data

- Collision energy dependence
- Centrality dependence
- p_T dependence

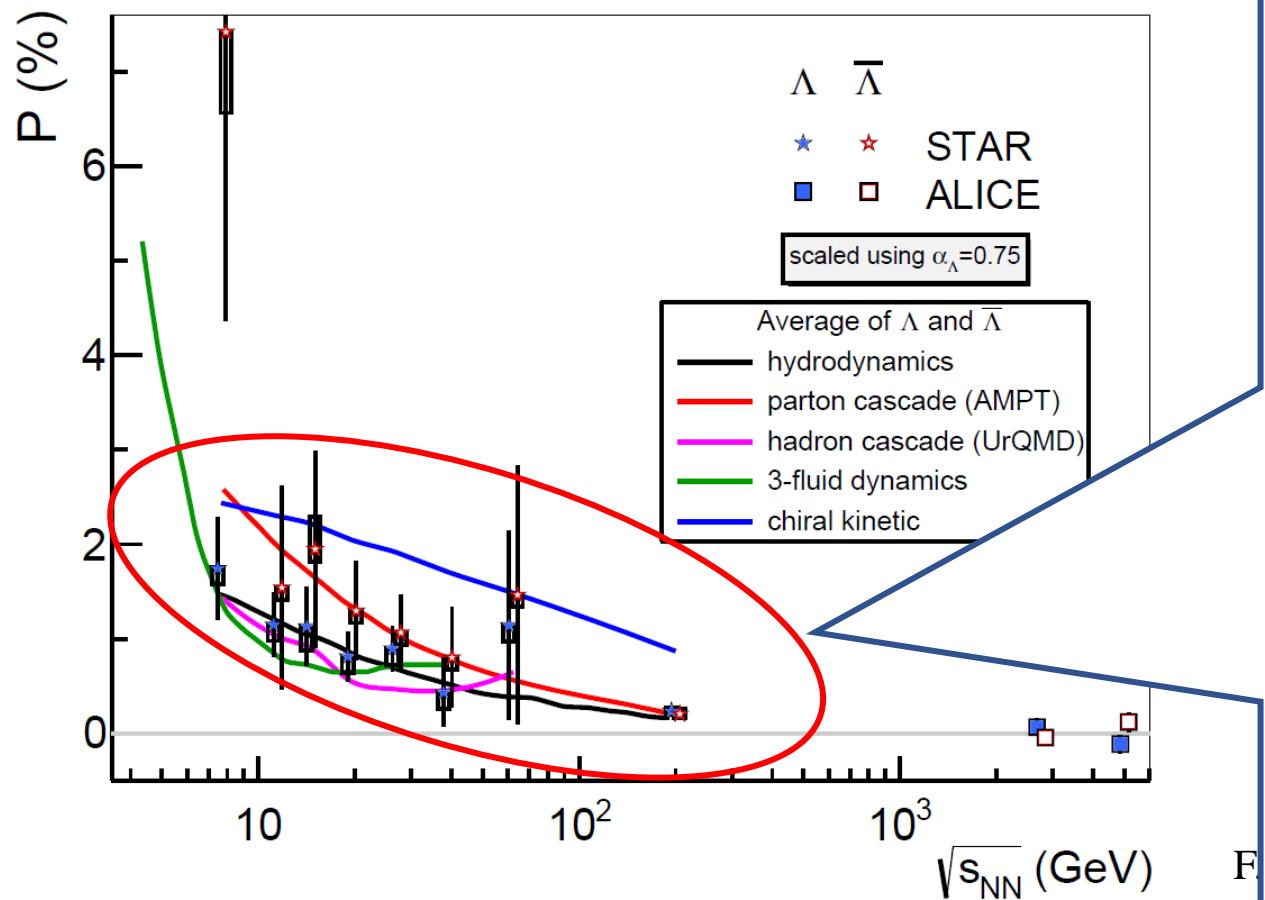


BF, K. Xu, X-G, Huang, H. Song, PRC 103 (2021) 2, 024903
F. Becattini and I. Karpenko PRL 120, 012302 (2018)

Global polarization

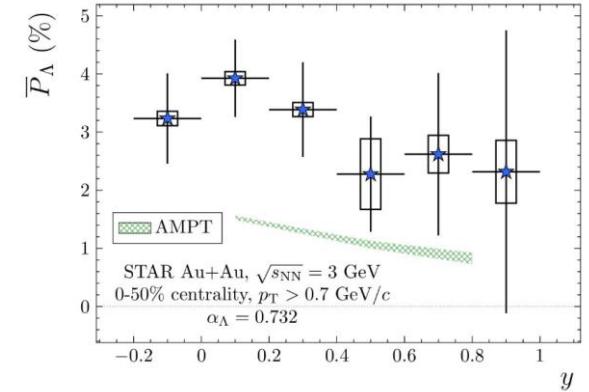
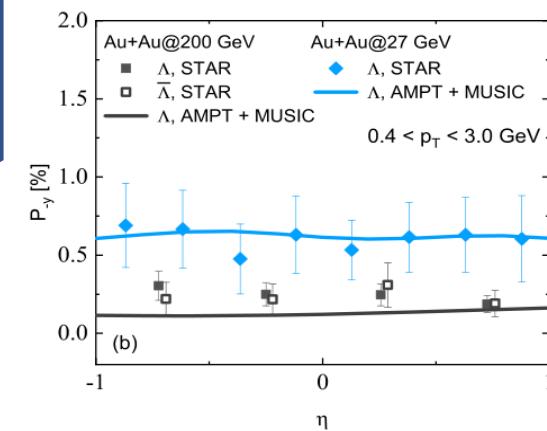
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Hydro / Transport describe the data

- Collision energy dependence
- Centrality dependence
- p_T dependence
- Υ dependence (at mid-rapidity)

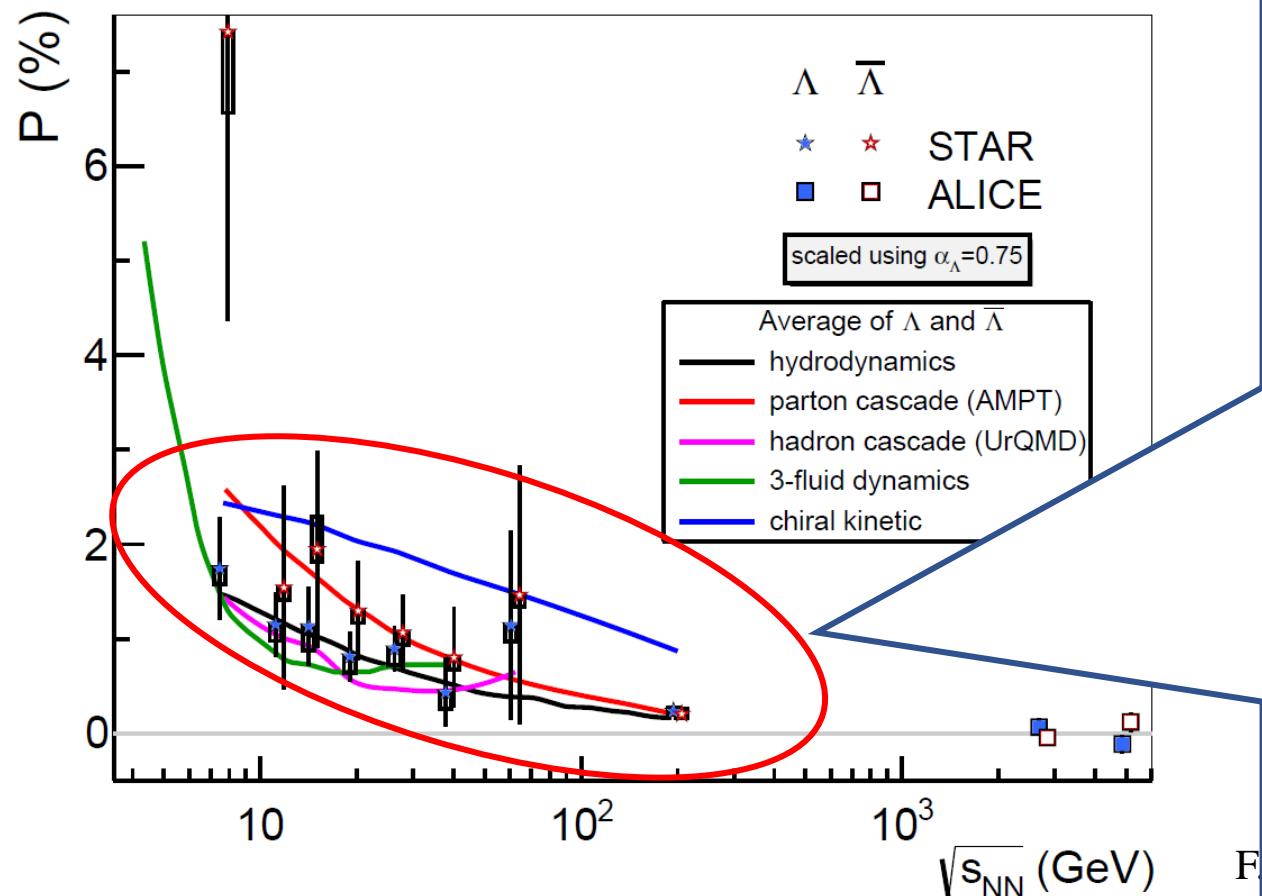


BF, K. Xu, X-G, Huang, H. Song, PRC 103 (2021) 2, 024903
Y. Guo, et al., Phys.Rev.C 104 (2021) 4, L041902

Global polarization

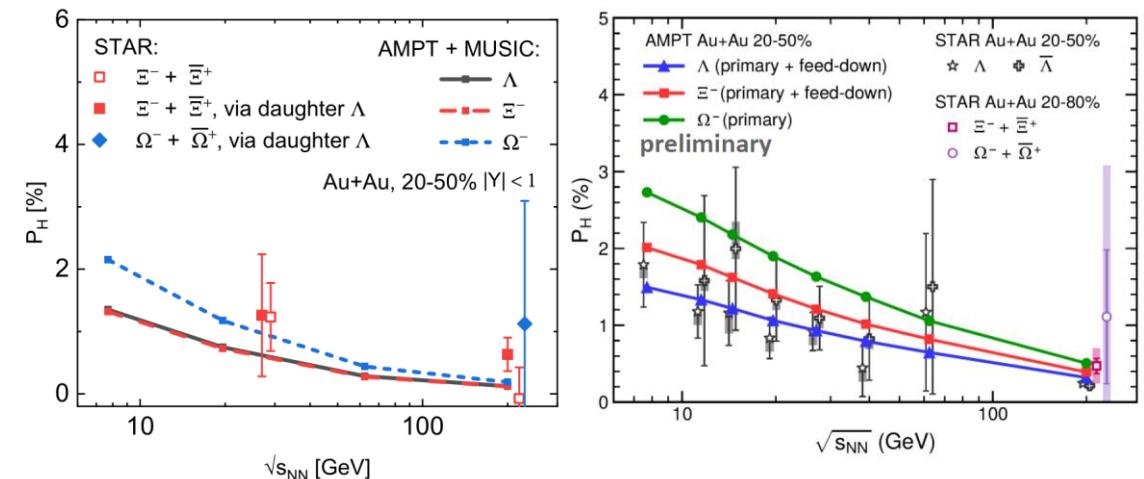
Thermal vorticity induced polarization (global eq.)

$$S^\mu(x, p) = -\frac{1}{2m} \frac{S(S+1)}{3} [1 - f(x, p)]$$



Hydro / Transport describe the data

- Collision energy dependence
- Centrality dependence
- p_T dependence
- Y dependence (at mid-rapidity)
- Global polarization of Ξ^- and Ω^-

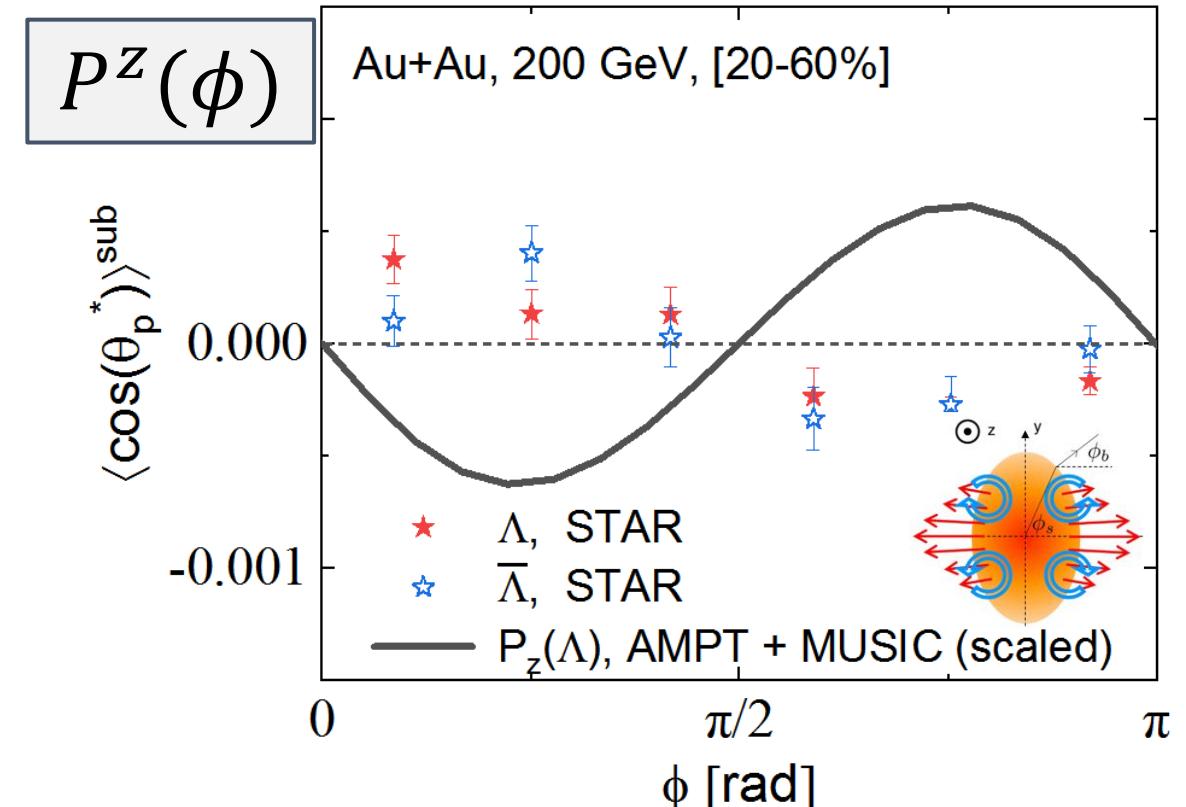
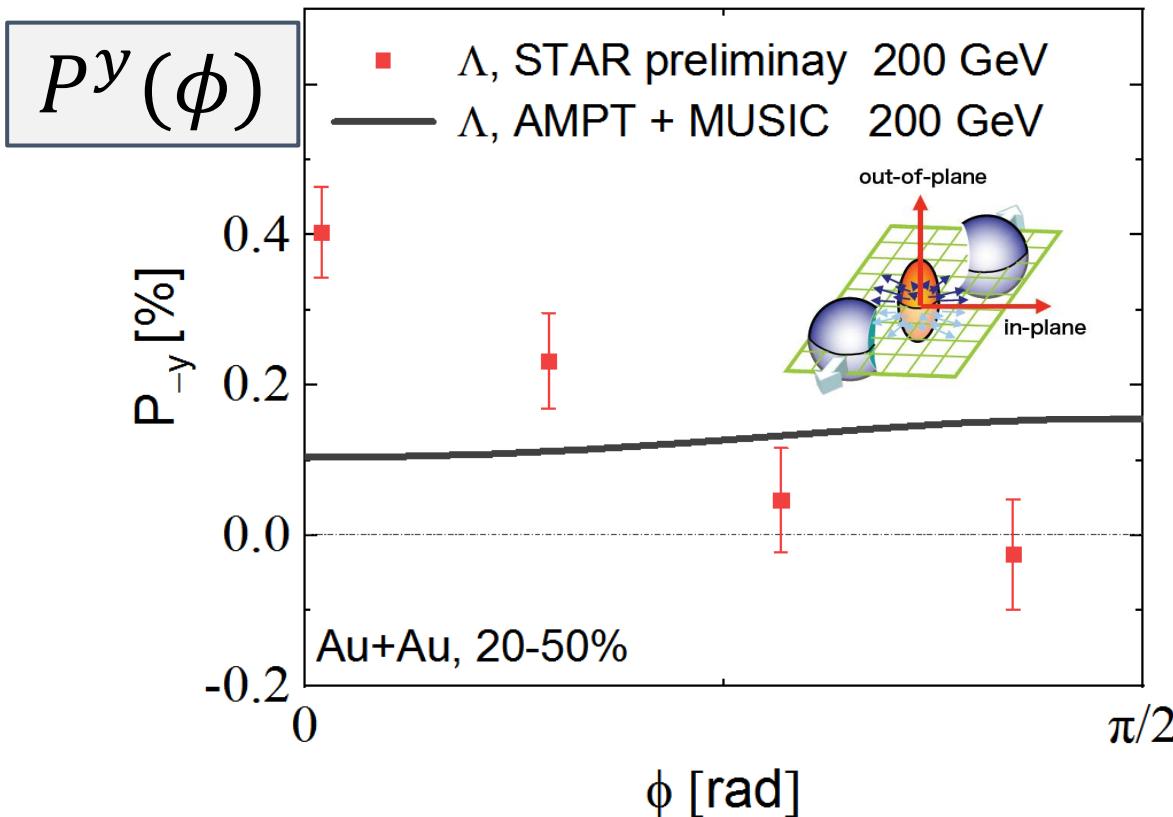


Λ Local Polarization puzzle

local polarization puzzle

BF, K. Xu, X-G, Huang, H. Song, PRC 103 (2021) 2, 024903

Opposite trend/sign in $P_y(\phi)$ and $P_z(\phi)$ results



Long exist in hydrodynamic and transport calculations, see also:

Karpenko and Becattini EPJC 17' PRL 18', X. Xia, PRC 18', D. Wei, et al PRC 19', X. Wu, et al PRR 19' ...

Shear Induced Polarization

BF, S. Liu, LG. Pang, H. Song, Y. Yin,
Phys.Rev.Lett. 127 14, 142301(2021)

- Axial Wigner function from CKT

$$\mathcal{A}^\mu = \sum_\lambda \left(\lambda p^\mu f_\lambda + \frac{1}{2} \frac{\epsilon^{\mu\nu\alpha\rho} p_\nu u_\alpha \partial_\rho f_\lambda}{p \cdot u} \right)$$

Chen, Son, Stephanov, PRL 115 (2015) 2, 021601

- Expand \mathcal{A}^μ to 1st order gradient of the fields:

$$\mathcal{A}^\mu = \frac{1}{2} \beta n_0 (1 - n_0) \left\{ \boxed{\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial_\alpha^\perp u_\lambda + 2\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha [\beta^{-1}(\partial_\lambda \beta)]} - \boxed{2 \frac{p_\perp^2}{\varepsilon_0} \epsilon^{\mu\nu\alpha\rho} u_\nu Q_\alpha^\lambda \sigma_{\rho\lambda}} \right\}$$

Thermal vorticity

Shear-Induced Polarization

- No free parameter
- Identical form by linear response theory with **arbitrary mass**

$$Q^{\mu\nu} = -p_\perp^\mu p_\perp^\nu / p_\perp^2 + \Delta^{\mu\nu}/3$$

$$\sigma^{\mu\nu} = \frac{1}{2} (\partial_\perp^\mu u^\nu + \partial_\perp^\nu u^\mu) - \frac{1}{3} \Delta^{\mu\nu} \partial_\perp \cdot u$$

See also:

- Linear response theory (S. Liu and Y. Yin, JHEP 07 (2021) 188)
- Thermal field theory (F. Becattini, et al., Phys.Lett.B 820 (2021) 136519)

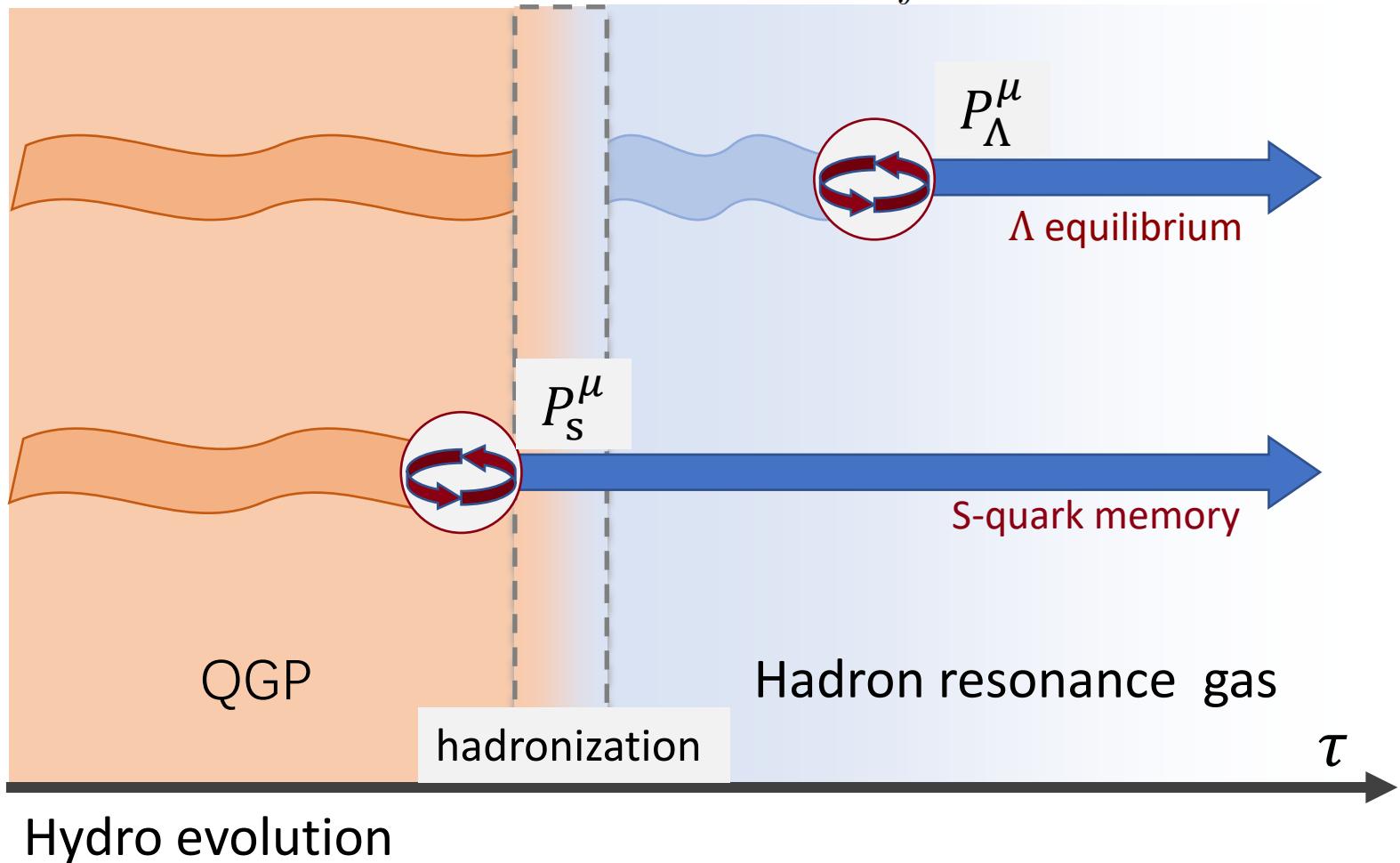
c.f. Becattini@Sat.

‘ Λ equilibrium’ vs. ‘S-quark memory’

BF, S. Liu, LG. Pang, H. Song, Y. Yin,
Phys.Rev.Lett. 127 14, 142301(2021)

Spin Cooper-Frye: $P^\mu(p) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x, p; m)}{2m \int d\Sigma^\alpha p_\alpha n(\beta \varepsilon_0)}$

$P^\mu = [\text{thermal vorticity}] + [\text{Shear}]$



‘ Λ equilibrium’

$$\tau_{\text{spin}, \Lambda} \rightarrow 0$$

Polarization of Λ -hyperon

$$P_\Lambda^\mu(p)$$

F. Becattini (2013)
and later hydrodynamic(transport) calculations

‘S-quark memory’

$$\tau_{\text{spin}, \Lambda} \rightarrow \infty$$

Polarization of S-quark

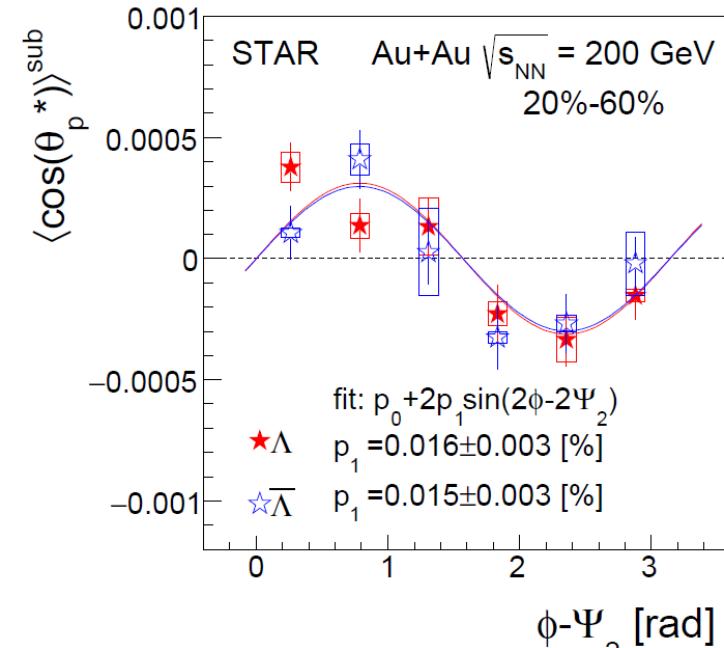
$$P_\Lambda^\mu(p) = P_s^\mu(p)$$

Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301

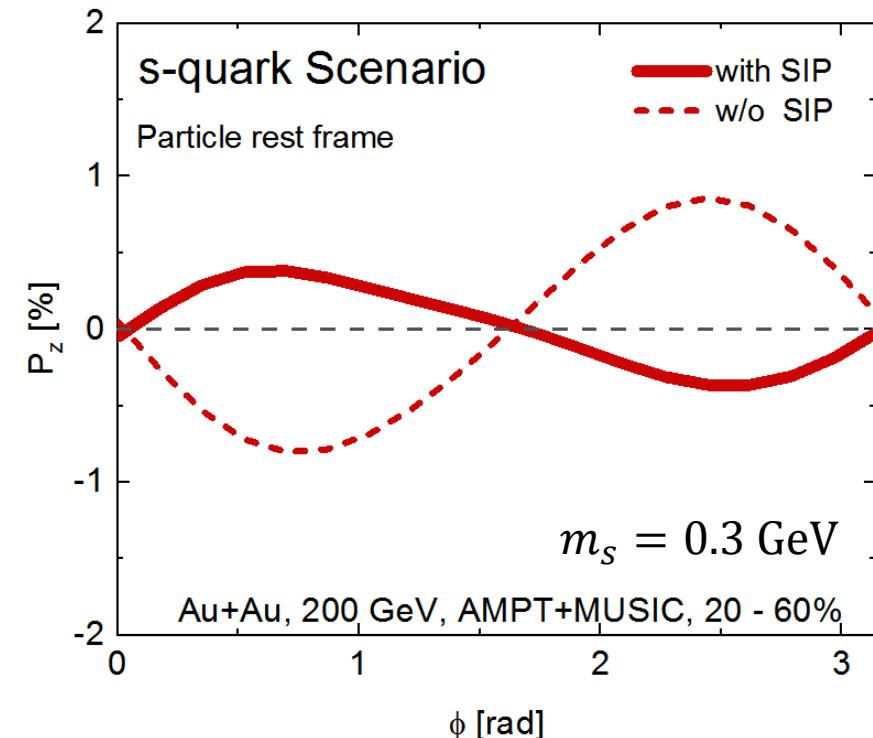
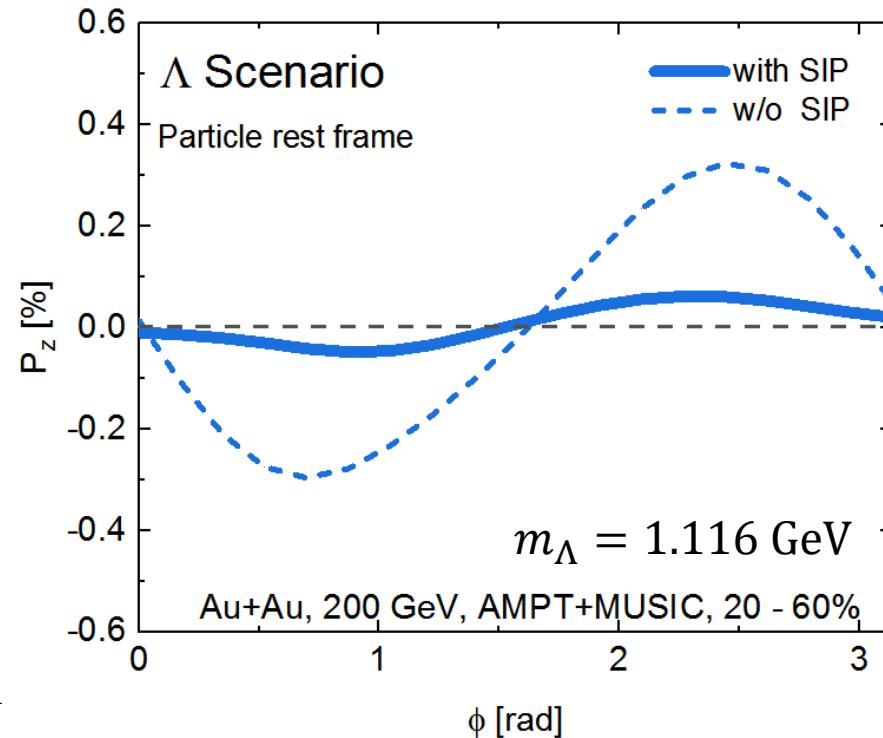
$P_z(\phi)$ with shear-induced polarization

BF, S. Liu, LG. Pang, H. Song, Y. Yin,
Phys.Rev.Lett. 127 14, 142301(2021)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}]$$



STAR, Phys.Rev.Lett. 123 (2019) 132301

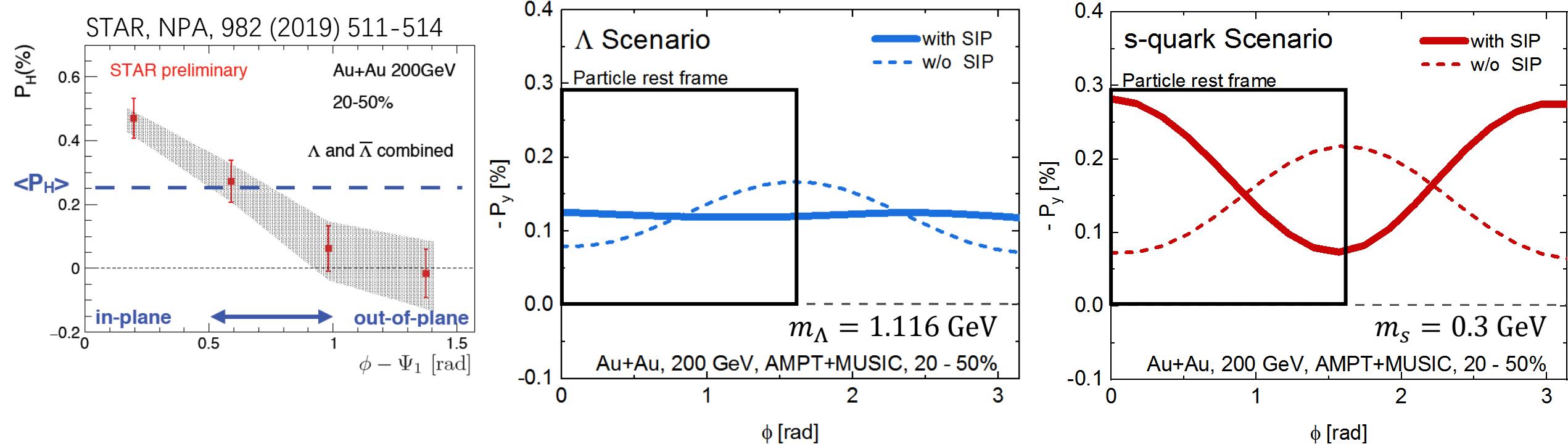


- In the scenario of ‘S-quark memory’, the total P^μ with SIP qualitatively agrees with the data
- Similar local polarization results from thermal shear: Becattini@Sat.
- Toward solving the “local polarization puzzle”

$P_y(\phi)$ with shear-induced polarization

BF, S. Liu, LG. Pang, H. Song, Y. Yin,
Phys.Rev.Lett. 127 14, 142301(2021)

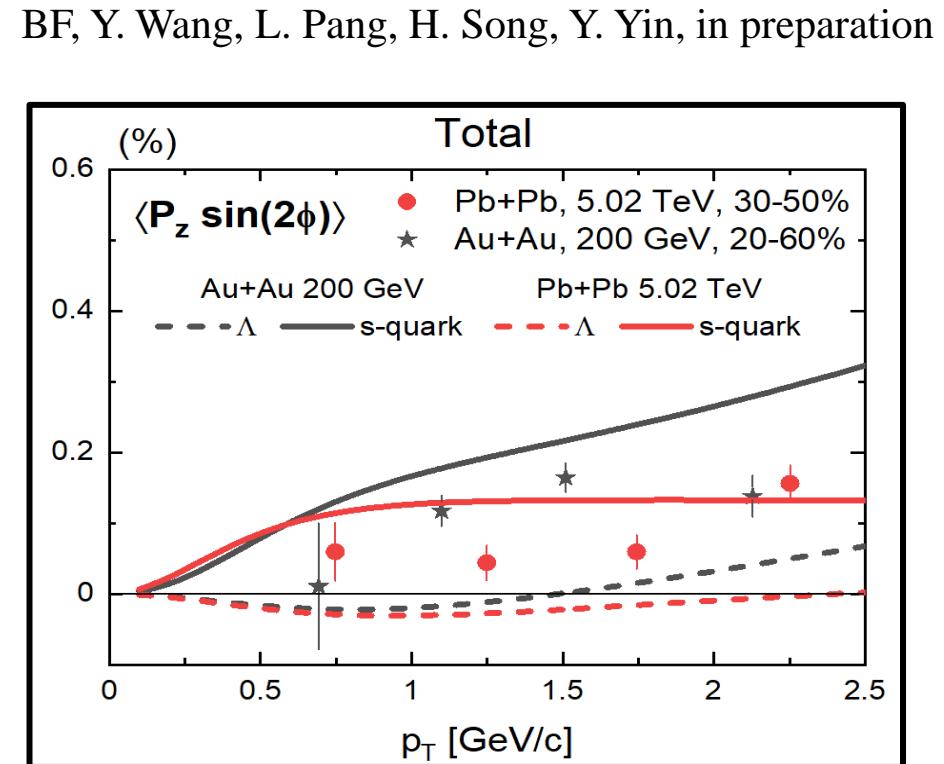
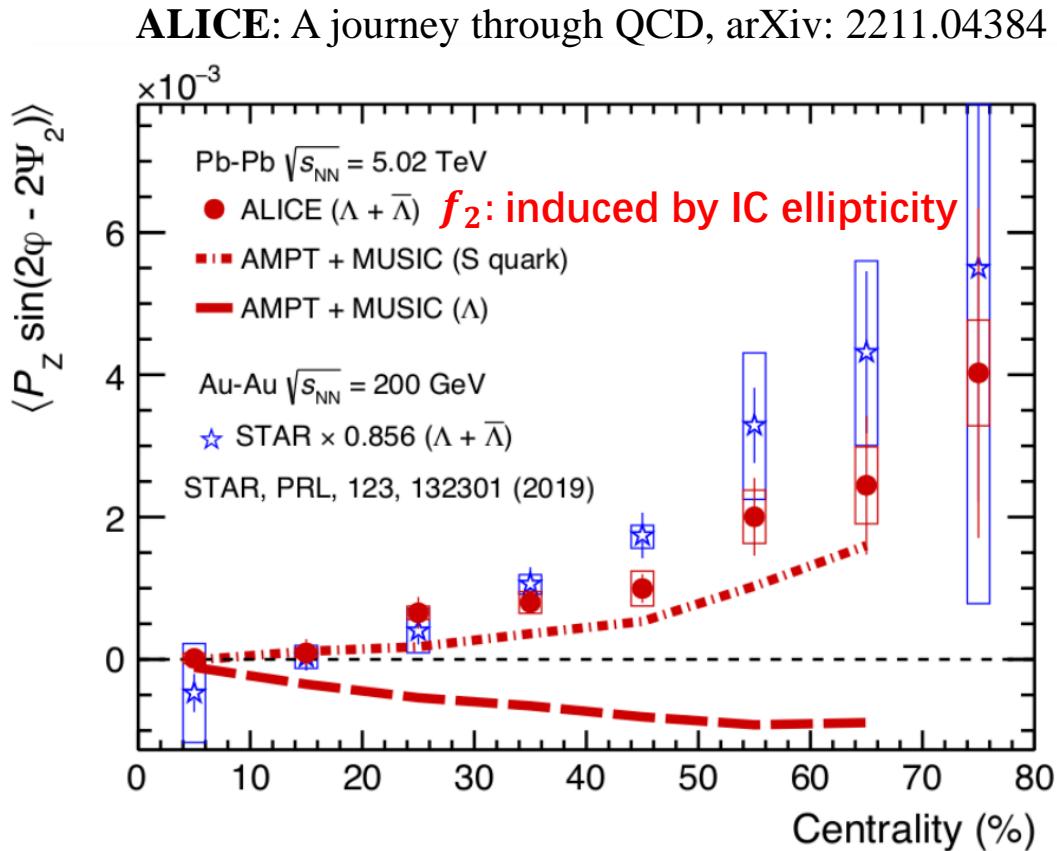
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- In the scenario of ‘S-quark memory’, the total P^μ with SIP qualitatively agrees with the data
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- Toward solving the “local polarization puzzle”

Toward quantitative description

- “Strange Memory” scenario qualitatively describes the 2nd Fourier coefficient f_2 in both RHIC and LHC
- A more precise description needs spin-coalescence and hadronic transport



This **shear-induced polarization** has been confirmed by different hydrodynamic / transport calculations

Hydrodynamics(vhlle)

F. Becattini, et al., Phys.Rev.Lett. 127 (2021) 27, 272302

Hydrodynamics(CLVisc)

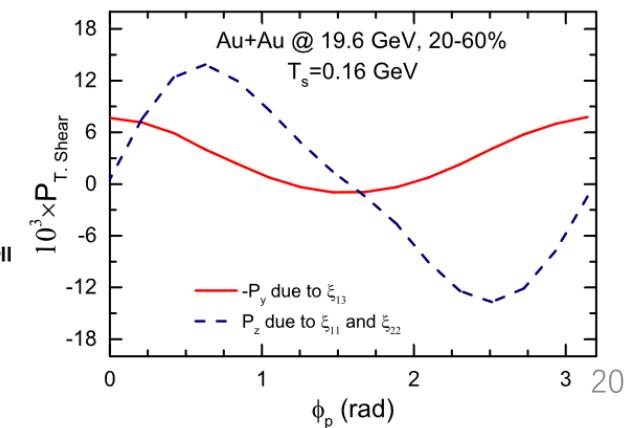
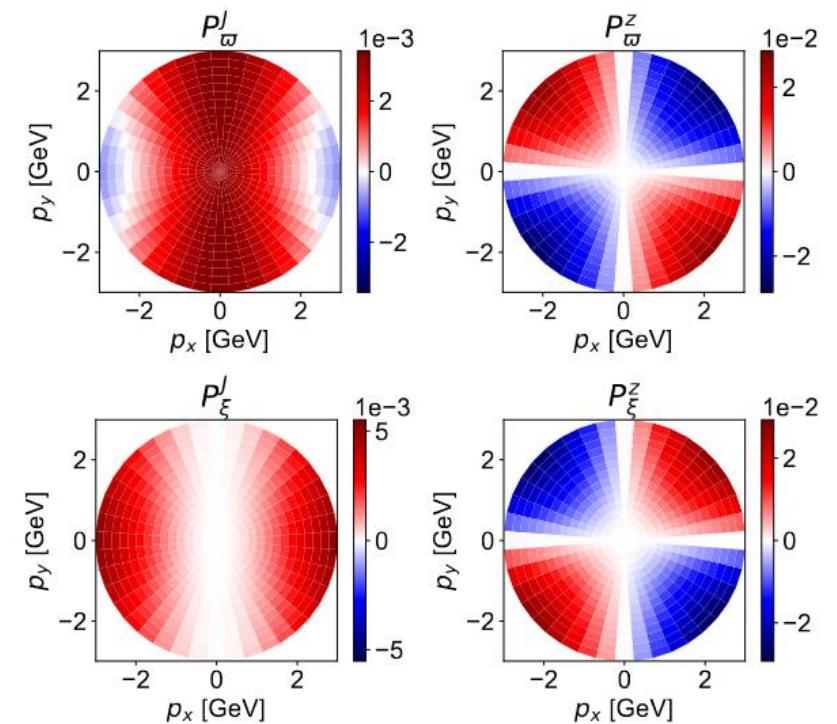
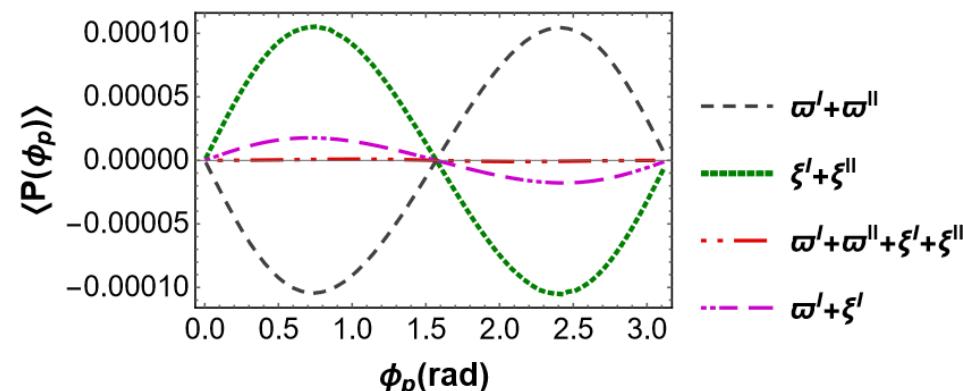
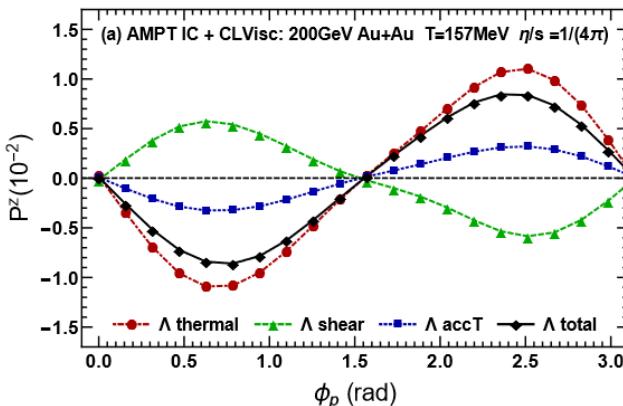
C. Yi, et al., Phys.Rev.C 104 (2021) 6, 064901

UrQMD

Y. Sun, et al, Phys.Rev.C 105 (2022) 3, 034911

Blast-Wave

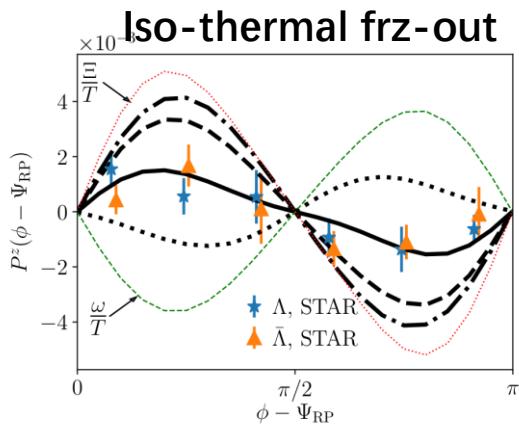
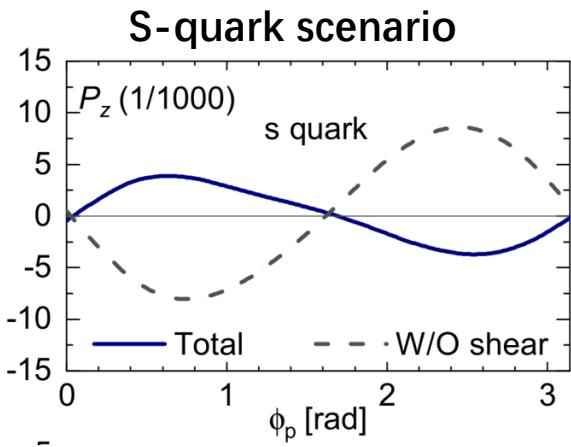
W. Florkowski, et al., Phys.Rev.C 105 (2022) 6, 064901



A brief summary of local polarization

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}]$$

- Shear effect shows a sizeable contribution with the sign same as experimental measurements
- Correct sign by including the shear effect in ‘iso-thermal frz’ / ‘s-quark scenario’

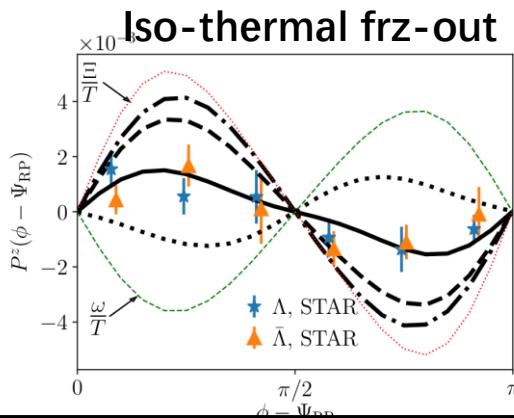
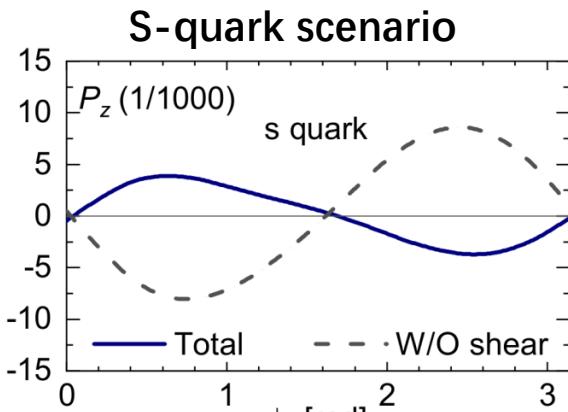


BF, S. Liu, LG. Pang, H. Song, Y. Yin, PRL 127 (2021)14, 142301
F. Becattini, et al., PRL 127 (2021)27, 272302

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BF, S. Liu, LG. Pang, H. Song, Y. Yin, PRL 127 (2021)14, 142301
F. Becattini, et al., PRL 127 (2021)27, 272302

1. What is the exact form of the shear effect?

kinetic theory:

$$-\beta n_0(1 - n_0) \frac{1}{\varepsilon_0} \epsilon^{\mu\nu\alpha\rho} u_\nu p_\rho p^\lambda \partial_{(\alpha}^\perp u_{\lambda)}$$

S. Liu and Y. Yin, JHEP 07 (2021) 188

statistical method: replace by \hat{t}_ν

F. Becattini, et al., Phys.Lett.B 820 (2021) 136519

2. To quantitative description: spin hadronization

Some recent phenomenology progress

From ‘electronic’ to ‘spintronic’

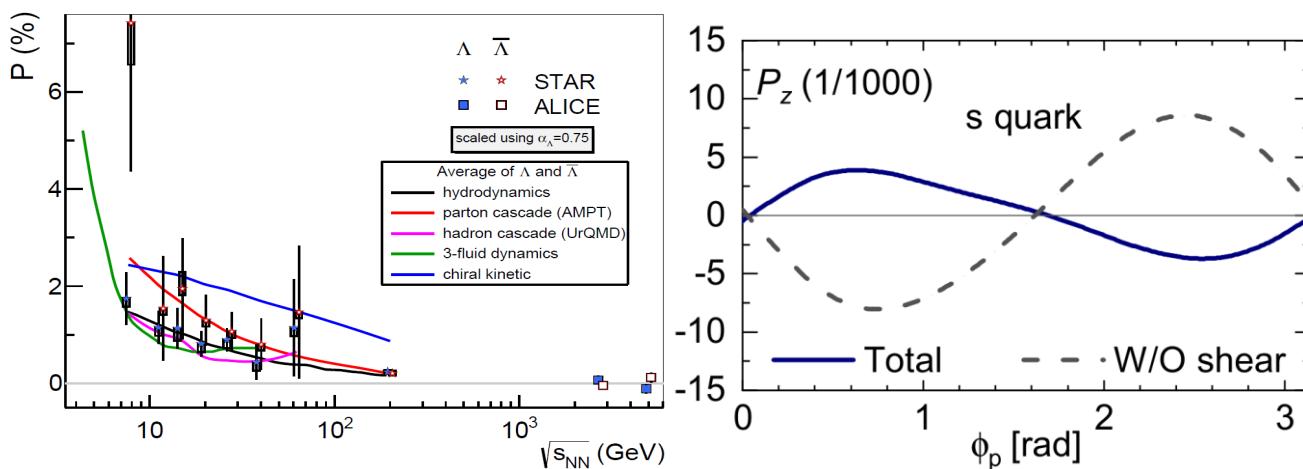
6. SUMMARY AND OUTLOOK

F. Becattini and M. Lisa,
Ann.Rev.Nucl.Part.Sci. 70 (2020) 395-423

Polarization has opened an exciting new direction in relativistic heavy ion physics; one of the increasingly rare truly new developments in this rather mature field. Its measurement has definitely proved that a new degree of freedom other than momentum is now available to probe the QGP formation and dynamics. In the hydrodynamic model, unlike particle momentum, polarization is primarily sensitive to the gradients of the hydro-thermal fields,

What can we learn from the ‘spintronic’ observables?

- Spin probes the fluid gradients with finest scale



$$P^\mu = [\text{thermal vorticity}] + [\text{shear}]$$

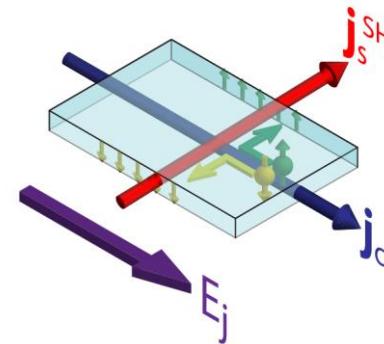
Reflects fluid gradients of $u^\mu(x)$ and $T(x)$

Probing the μ_B gradients – baryonic Spin Hall Effects

In condensed-matter

- Transverse spin current induced by spin-orbital coupling under external electric field

$$\vec{s} \propto \vec{p} \times \vec{E}$$



S. Meyer, et al., Nature Materials, 2017

J. Sinova, et al., Rev. Mod. Phys. 2015

In hot QCD matter

- Replacing electric field \vec{E} to baryon chemical potential gradient $\vec{\nabla}\mu_B$

$$\vec{P}_+ \propto \pm \vec{p} \times \vec{\nabla} \mu_B$$

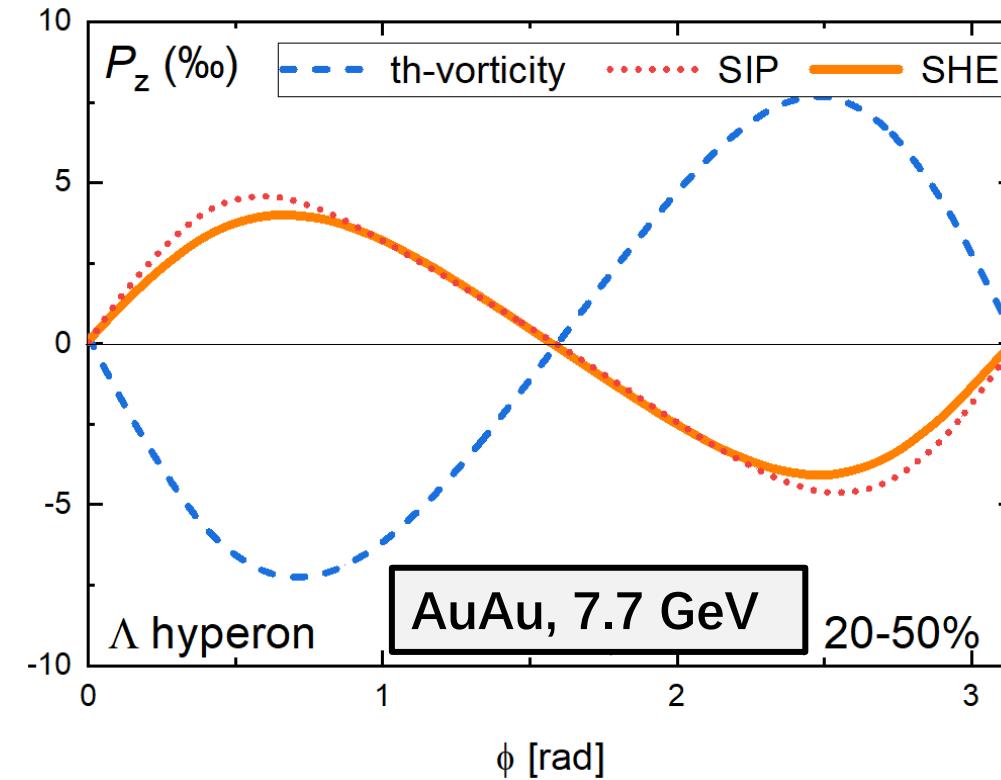
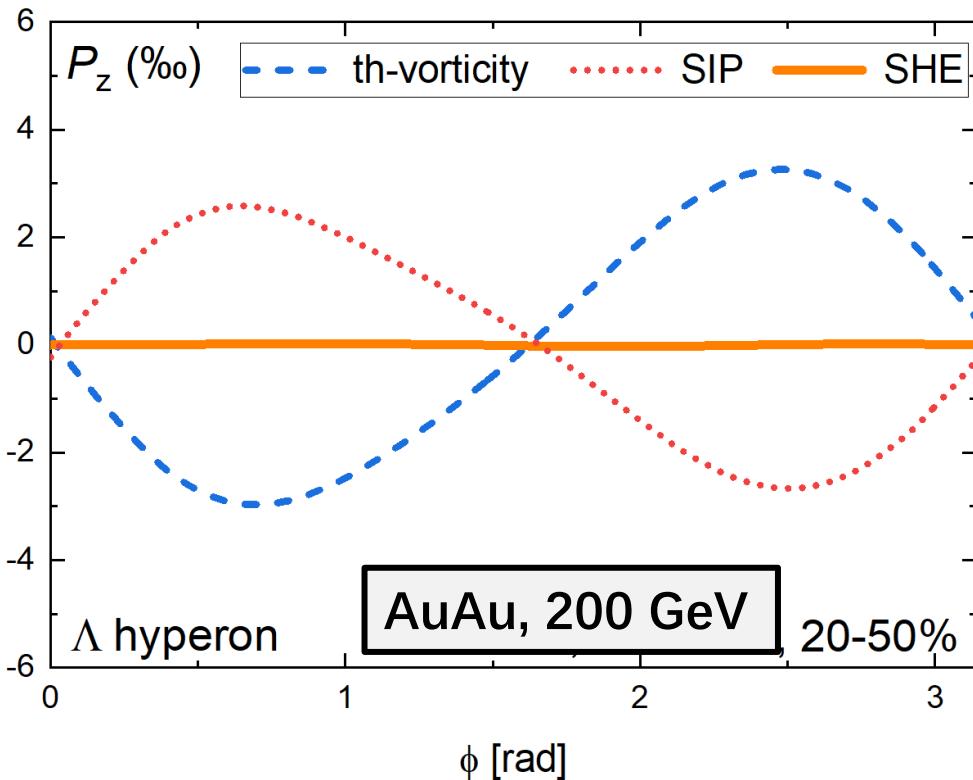
Axial Wigner function \mathcal{A}^μ expansion with finite chemical potential: S. Liu and Y. Yin, PRD 104, 054043 (2021)

$$\mathcal{A}^\mu(x, p) = \beta f_0(x, p)(1 - f_0(x, p))\varepsilon^{\mu\nu\alpha\rho} \times \left(\frac{1}{2}p_\nu\partial_\alpha^\perp u_\rho - \frac{1}{T}u_\nu p_\alpha\partial_\rho T \right) - \frac{p_\perp^2}{\varepsilon_0}u_\nu Q_\alpha^\lambda\sigma_{\rho\lambda} - \frac{q_B}{\varepsilon_0\beta}u_\nu p_\alpha\partial_\rho(\beta\mu_B),$$

thermal vorticity
shear
baryonic SHE

Baryonic Spin Hall Effects in $P_z(\phi)$

BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970



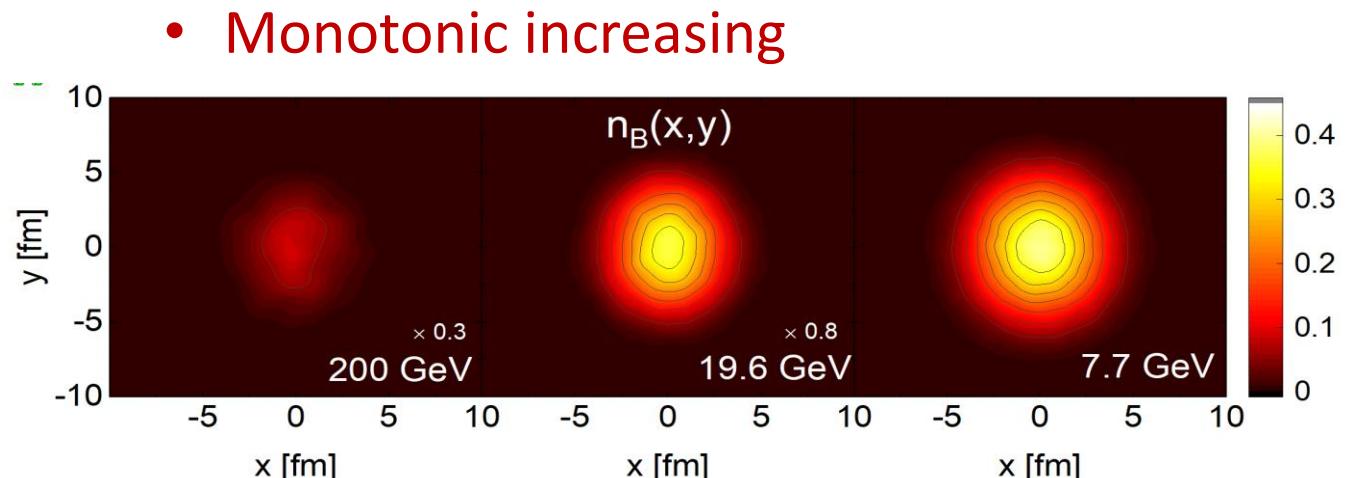
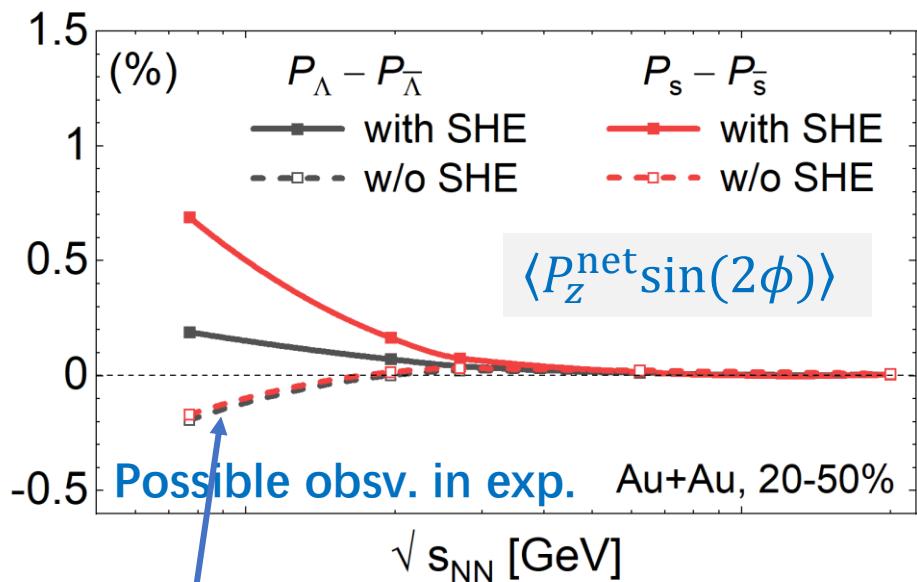
- Sizeable Spin Hall Effects at 7.7 GeV with its magnitude comparable with other effects
- **Polarization separation:** Opposite contribution for particles / anti-particles

$$\frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho (\beta \mu_B)$$

See also: S.Ryu, et al., PRC 104 (2021) 5, 054908 (Global effect)
S. Liu and Y. Yin, PRD 104 (2021) 5, 054043 (B-W model)
X. Wu, et al., PRC 105 (2022) 064909 (baryon diffusion)

The 2nd order Fourier coeff.

BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970

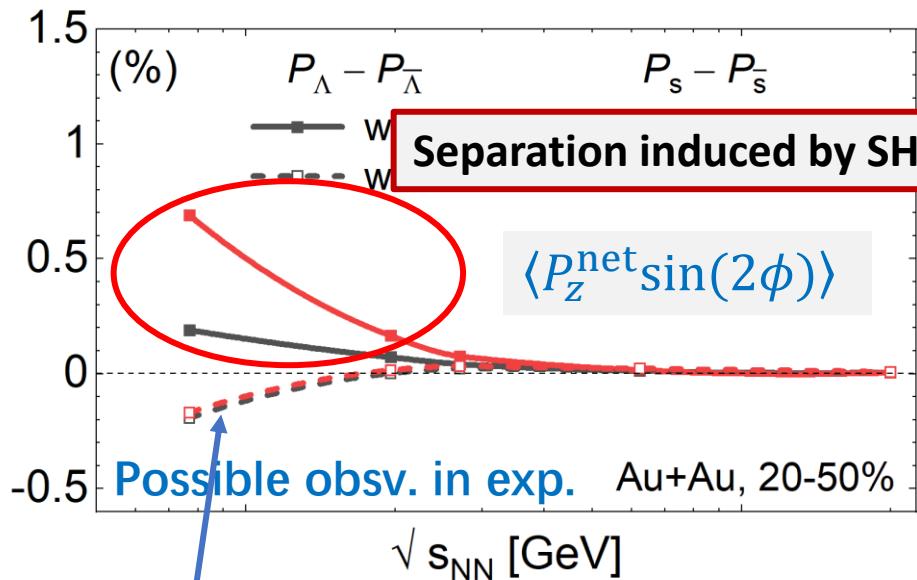


From the distribution function

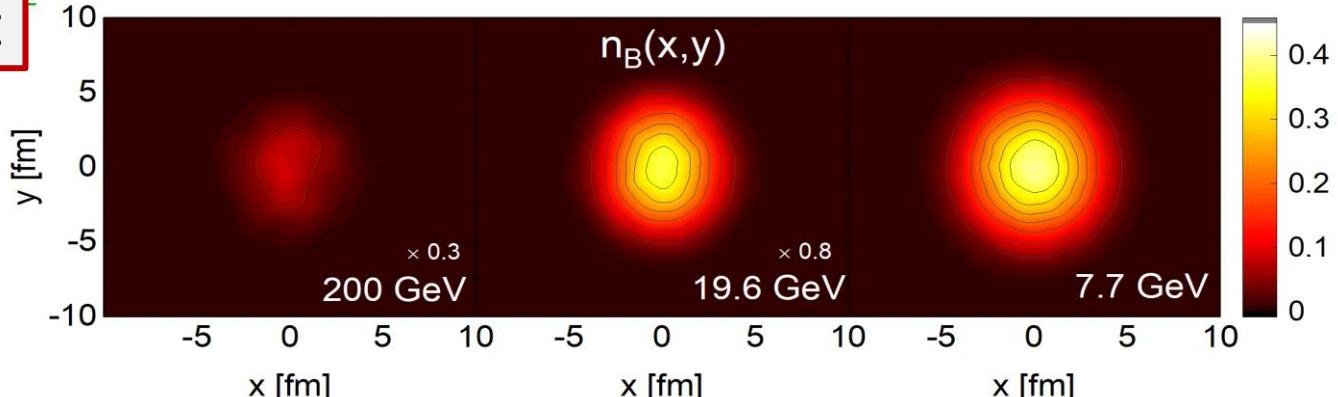
$$f(x, p) = (e^{(\epsilon_0 - q_B \mu_B) \beta} + 1)^{-1}$$

The 2nd order Fourier coeff.

BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970



- Monotonic increasing

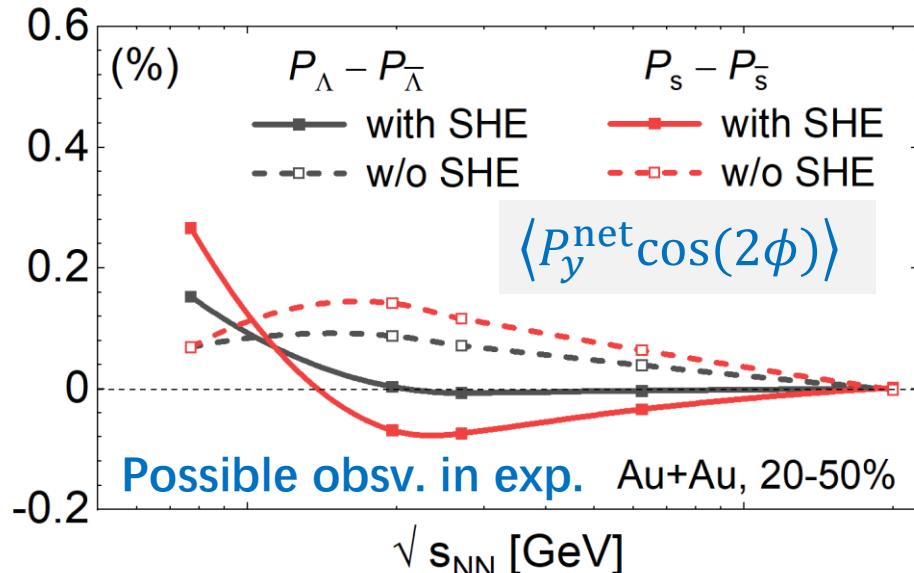
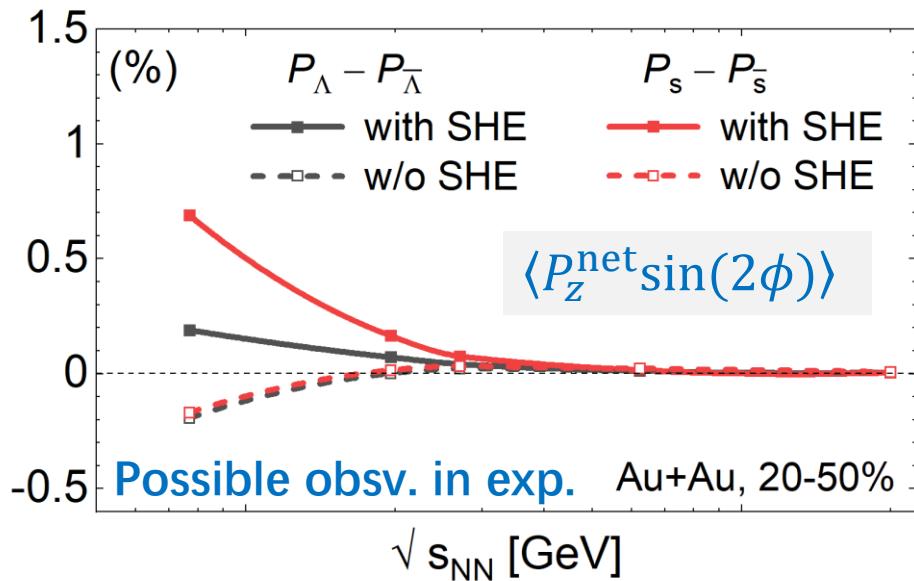


From the distribution function

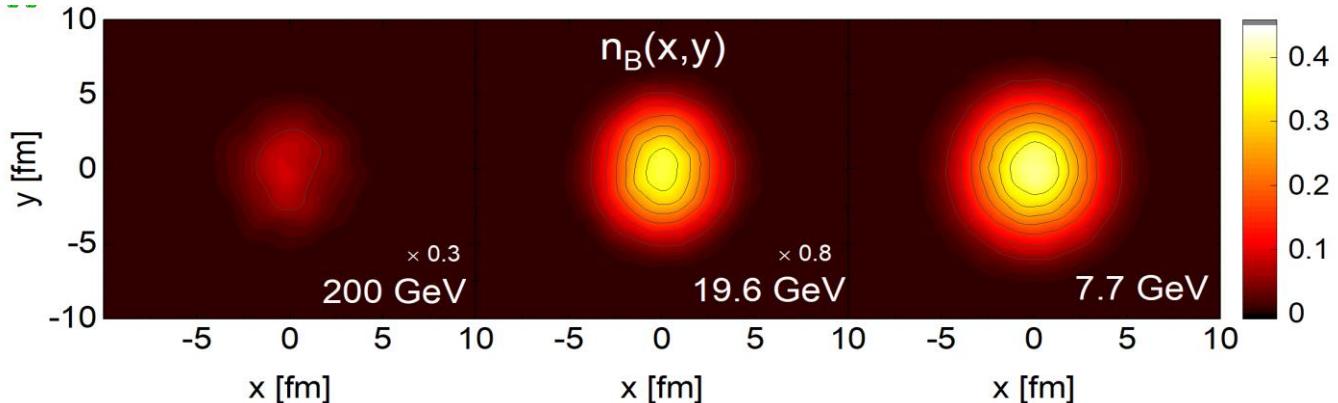
$$f(x,p) = (e^{(\epsilon_0 - q_B \mu_B)\beta} + 1)^{-1}$$

The 2nd order Fourier coeff.

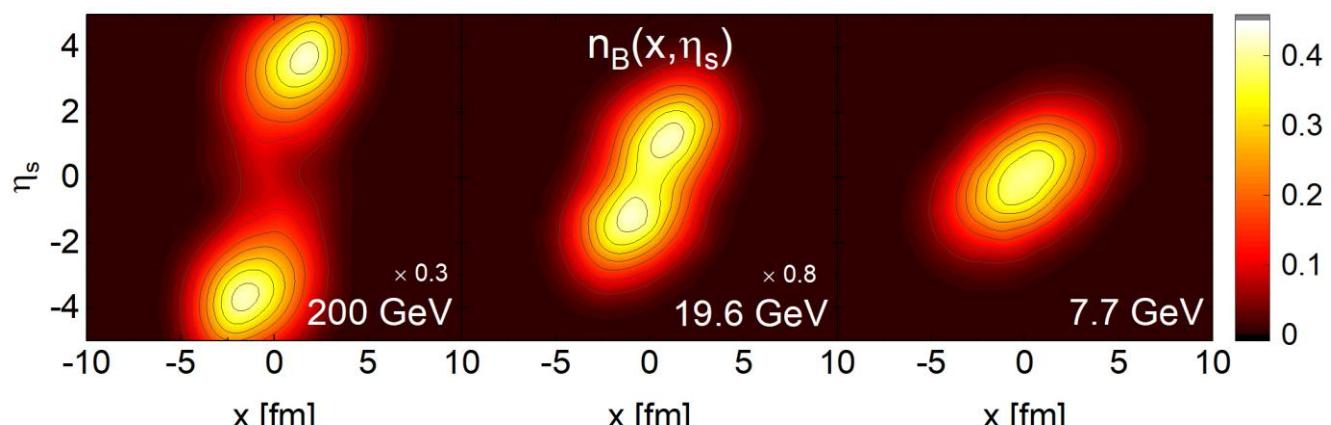
BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970



- Monotonic increasing

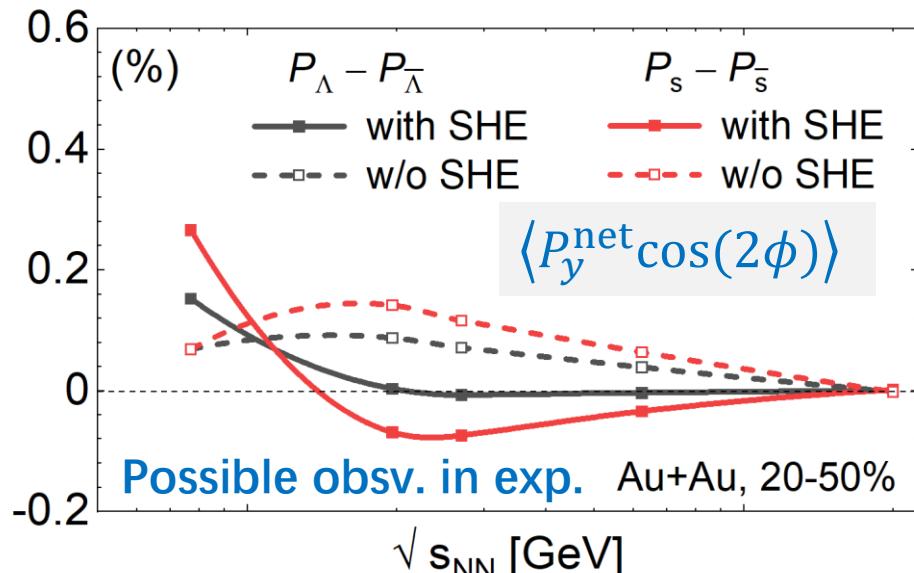
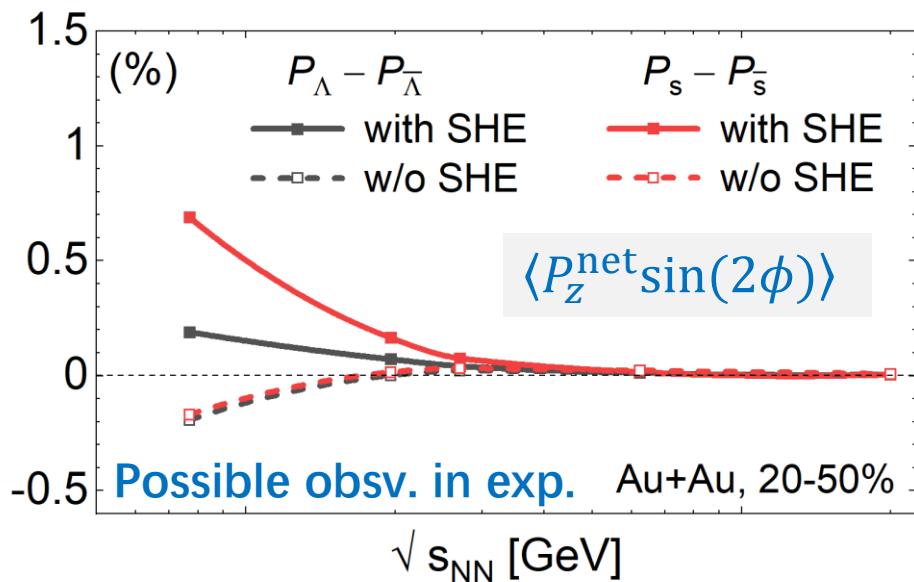


- Non-monotonic behavior

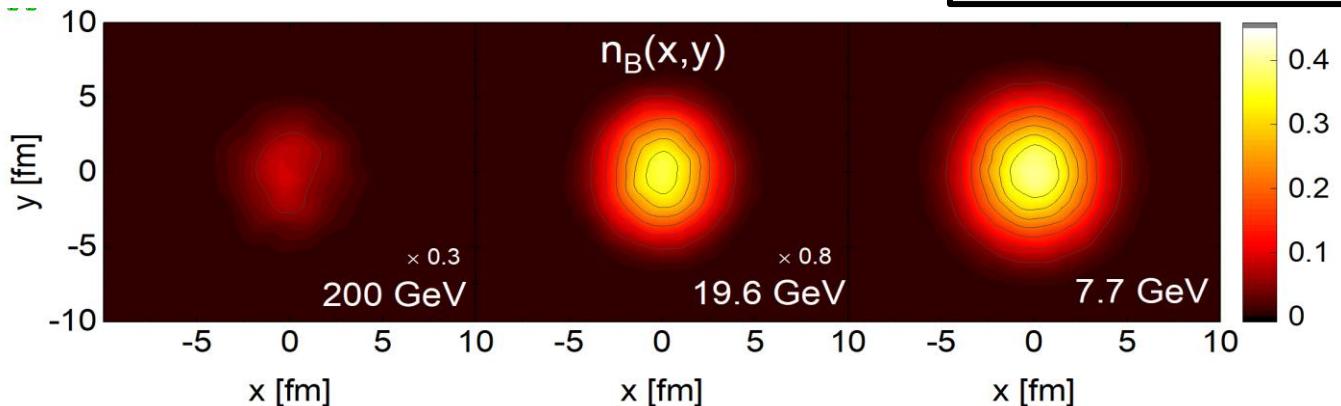


The 2nd order Fourier coeff.

BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970

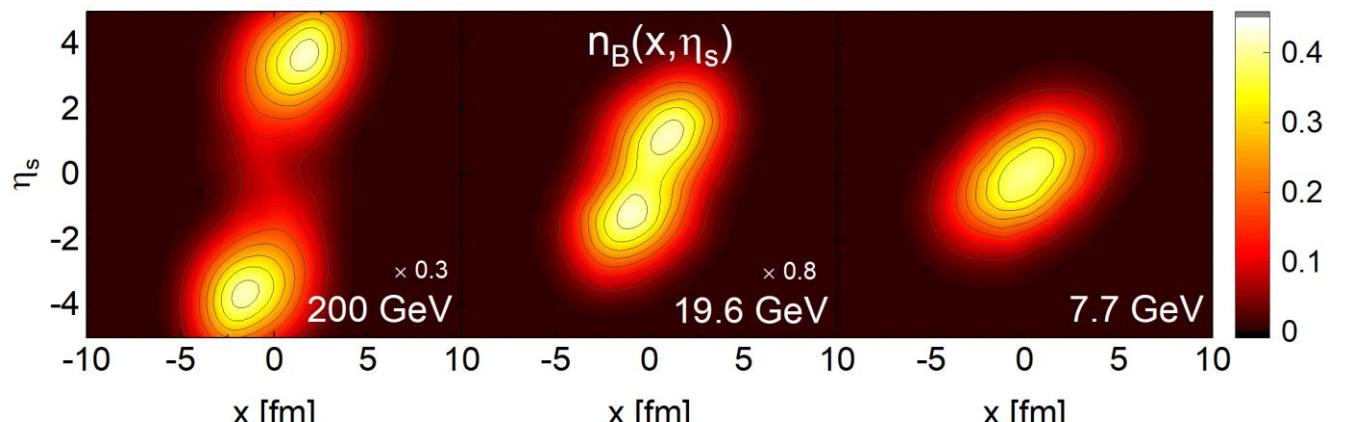


- Monotonic increasing



Experimental talk
Qiang Hu@Tues

- Non-monotonic behavior



Probing the QGP dynamics by spin polarization

(1) Probing the μ_B gradients (baryonic SHE)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

(2) Probing the direct flow and initial conditions

Probing the QGP dynamics by spin polarization

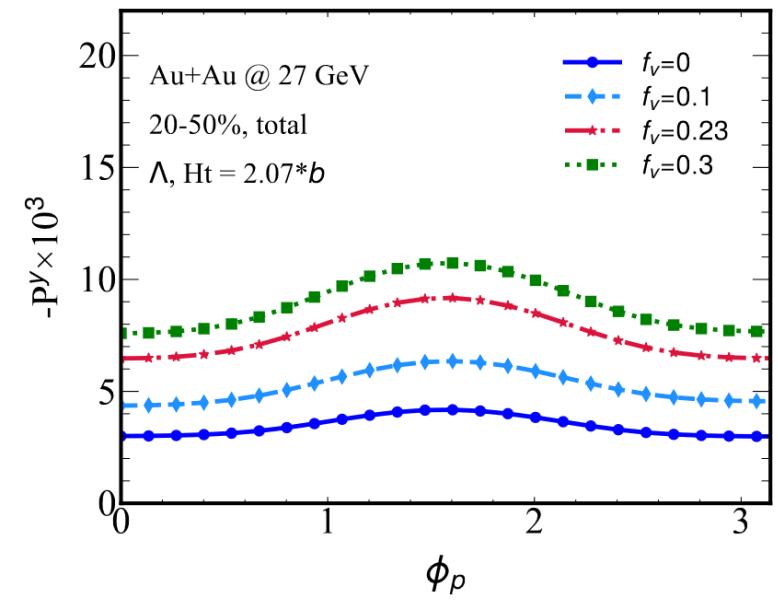
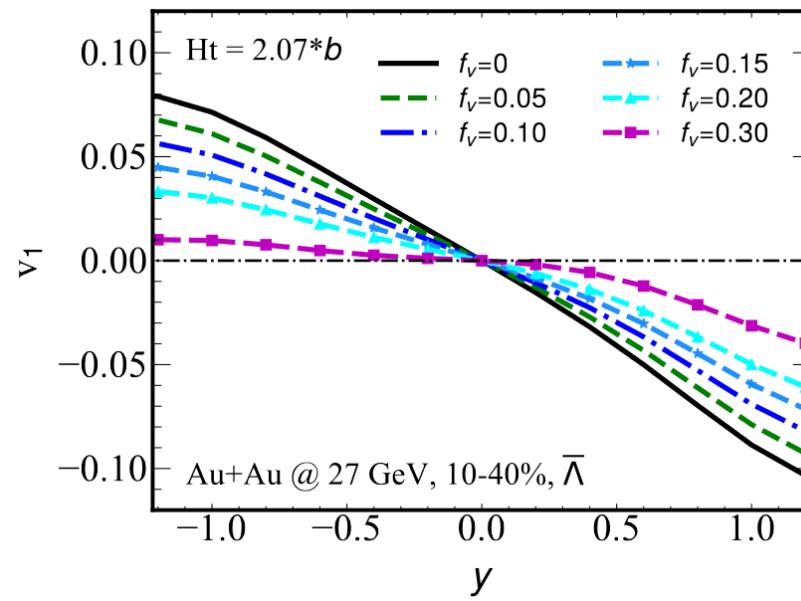
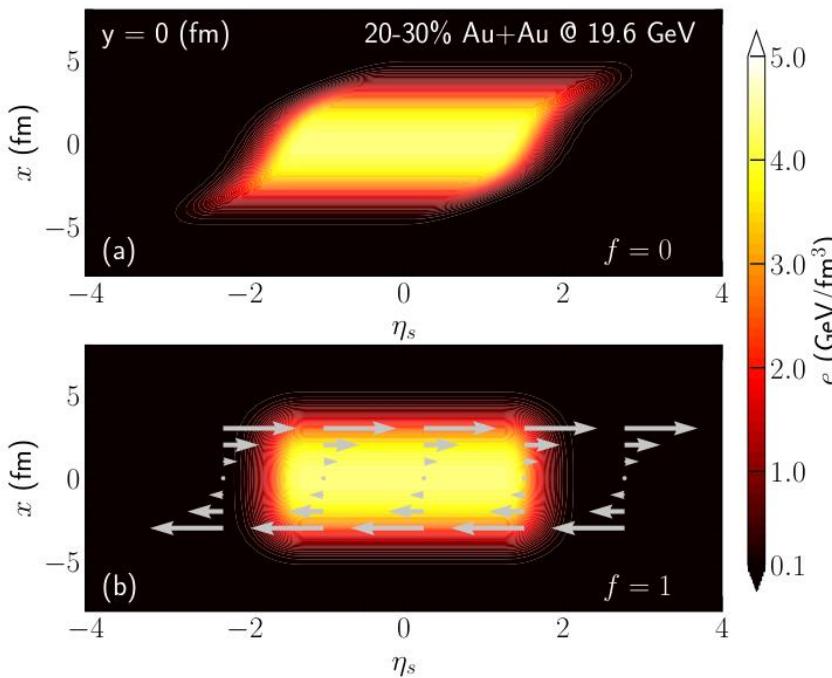
(1) Probing the μ_B gradients (baryonic SHE)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

Global spin polarization is closely related to the longitudinal flow and v_1

Z. Jiang's talk @Tues

(2) Probing the direct flow and initial conditions



S.Ryu, et al., PRC 104 (2021) 5, 054908
Z. Jiang, et al., arXiv: 2307.04257

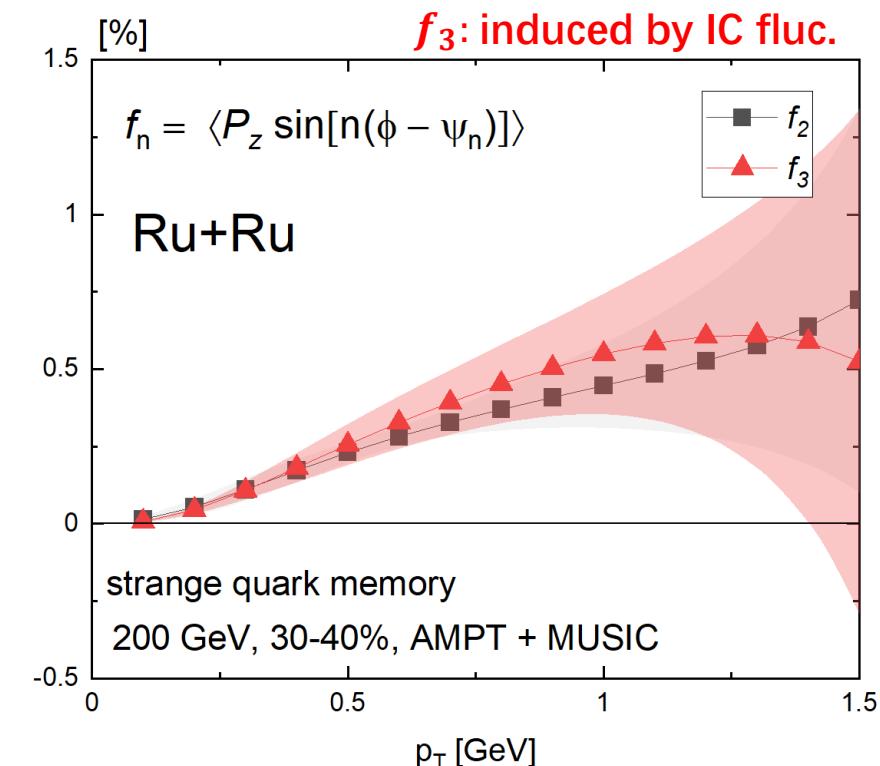
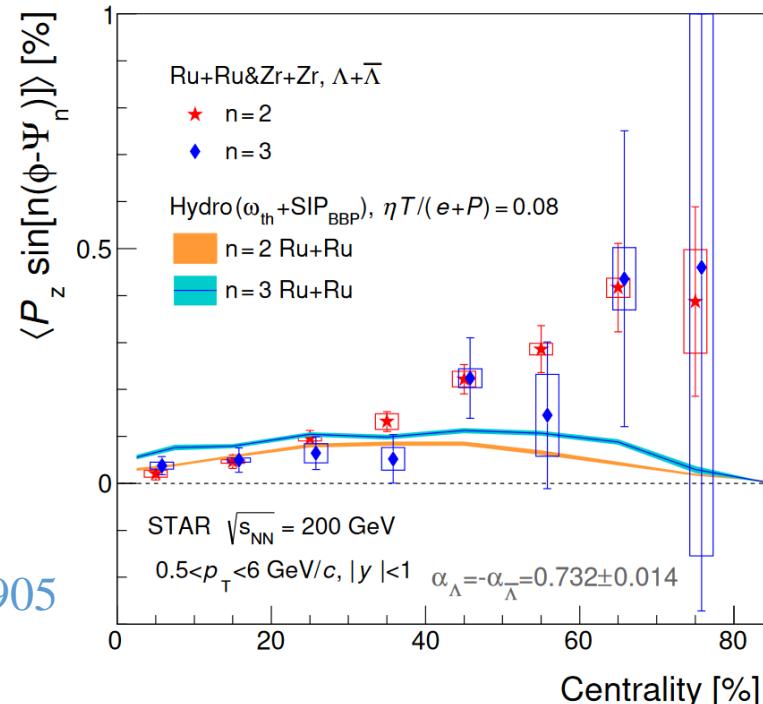
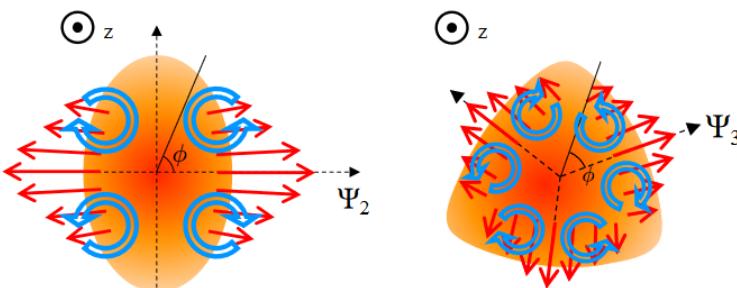
Probing the QGP dynamics by spin polarization

(1) Probing the μ_B gradients (baryonic SHE)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

Probe Event-by-event fluctuation

(2) Probing the direct flow and initial conditions



Probing the QGP dynamics by spin polarization

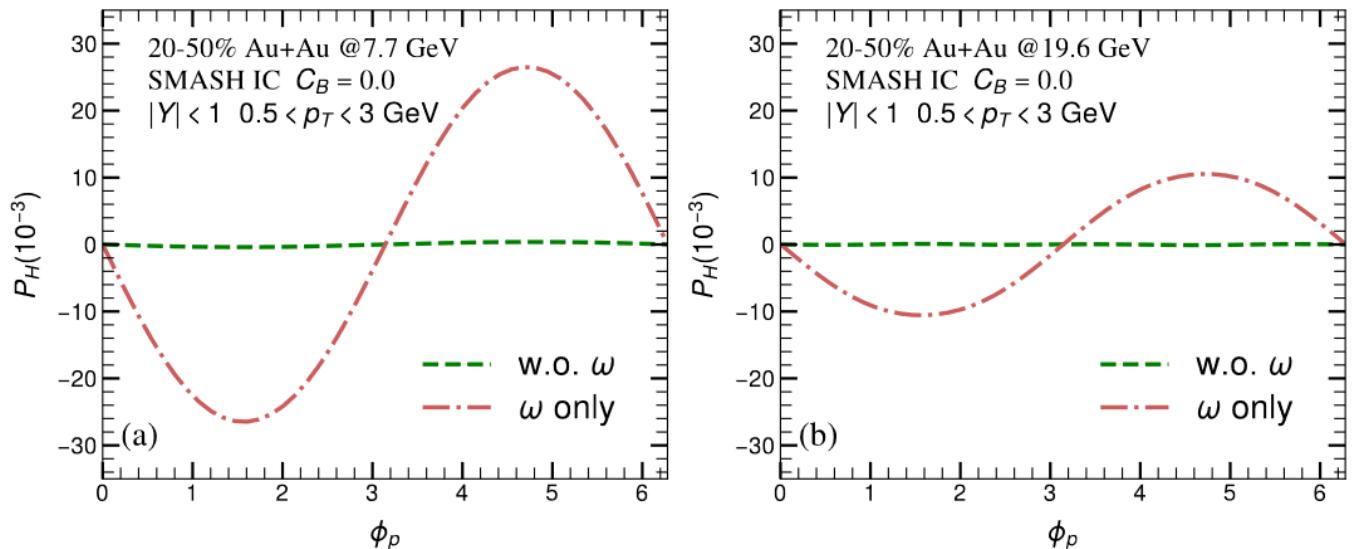
(1) Probing the μ_B gradients (baryonic SHE)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

- P_H : projection to momentum direction
- A possible signal to probe the fine structure of local kinetic vorticity at low energies

C. Yi's talk @Wed.

(3) Helicity polarization



Probing the QGP dynamics by spin polarization

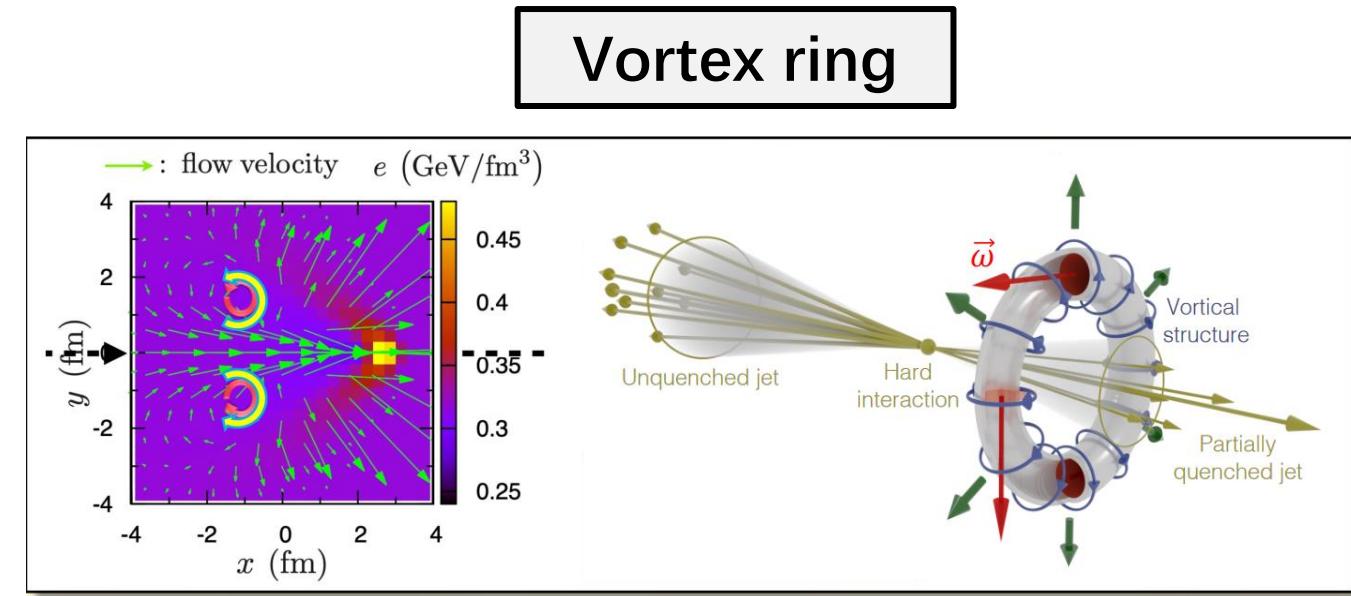
(1) Probing the μ_B gradients (baryonic SHE)

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

(2) Probing the direct flow and initial conditions

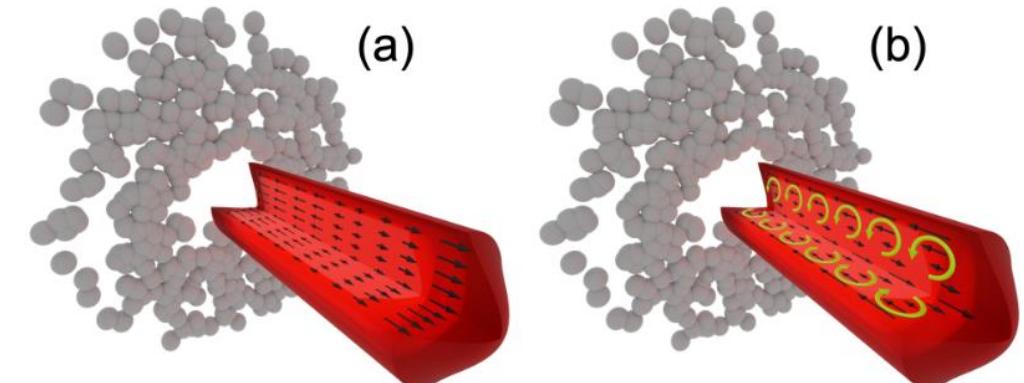
(3) Helicity polarization

(4) Fine structure from Jet-induced polarization



W. Serenone, et al., Phys. Lett. B 820 (2021) 136500

- Jet-medium interaction
- The fluid nature in small systems

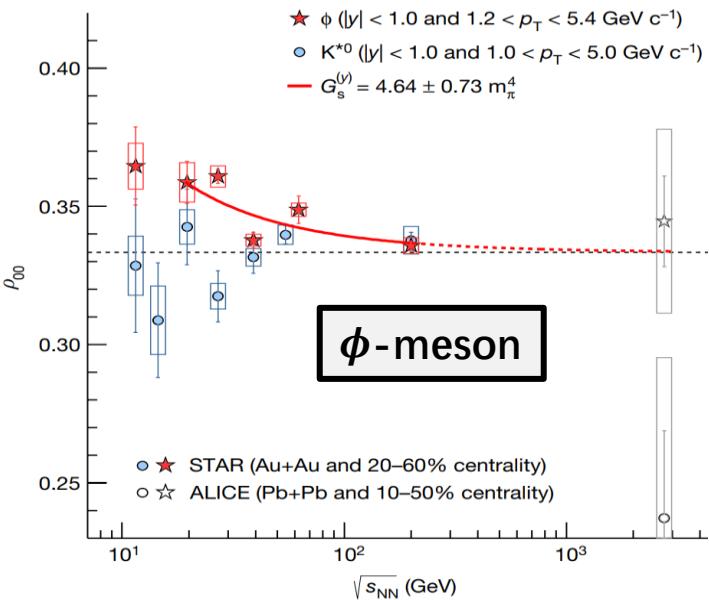


M. Lisa, et al., Phys. Rev. C104, 011901 (2021)

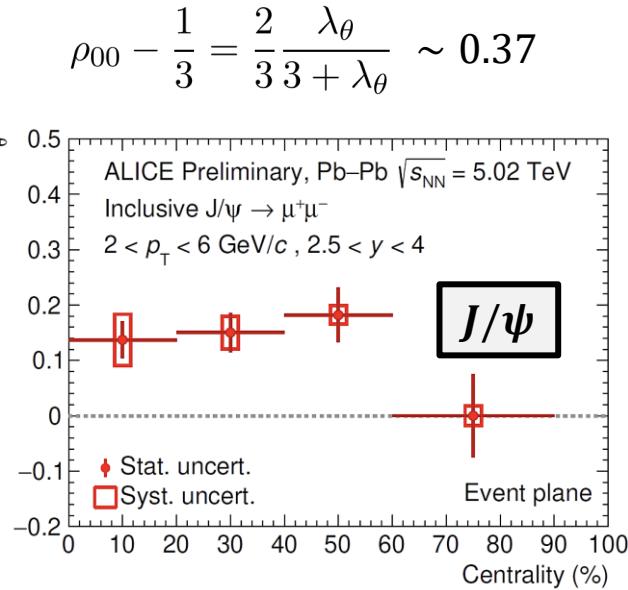
Spin alignment from light front quarks

Spin alignment of vector mesons

- $\rho_{00} \neq 1/3$ indicates non-zero spin alignment.



STAR, Nature 614, 244 (2023)



ALICE, arXiv:2204.10171

- recombination $q + \bar{q} \rightarrow \phi$ with vorticity dominance $P_q = P_{\bar{q}} \sim P_y$

$$\rho^V = \rho^q \otimes \rho^{\bar{q}}$$

$$\rho_{00} = \frac{1 - P_y^2}{3 + P_y^2} \approx \frac{1}{3} - \frac{4}{9} P_y^2$$

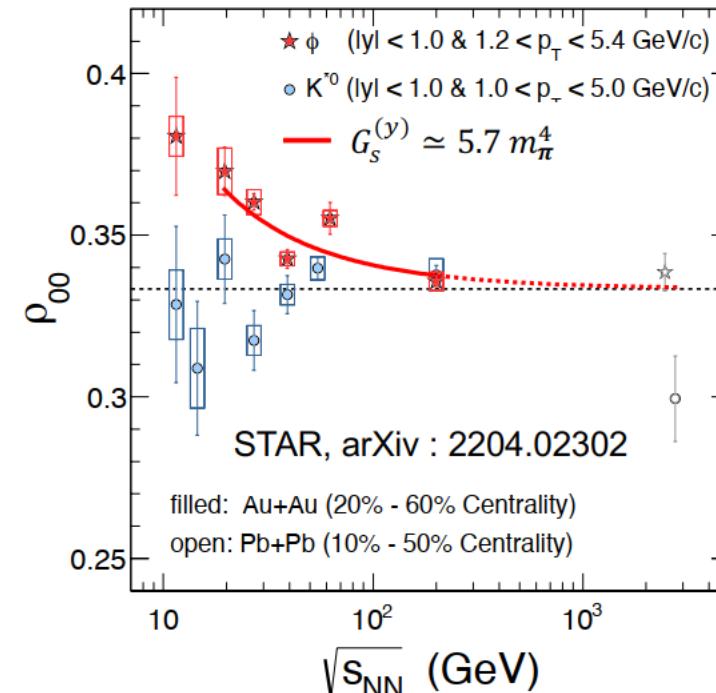
Negative, $\sim 10^5$

- Large spin alignment cannot be explained by immediate quark spin recombination

Can We Explain the Large ρ_{00} of ϕ -meson ?

| Physics Mechanisms | (ρ_{00}) |
|---|--|
| c_A : Quark coalescence vorticity & magnetic field ^[1] | < 1/3 (Negative $\sim 10^{-5}$) |
| c_ϵ : E-comp. of Vorticity tensor ^[1] | < 1/3 (Negative $\sim 10^{-4}$) |
| c_E : Electric field ^[2] | > 1/3 (Positive $\sim 10^{-5}$) |
| c_F : Fragmentation ^[3] | > or, < 1/3 ($\sim 10^{-5}$) |
| c_L : Local spin alignments ^[4] | < 1/3 |
| c_A : Turbulent color field ^[5] | < 1/3 |
| c_ϕ : Vector meson strong force field ^[6] | > 1/3 (Can accommodate large positive signal) |

$$\rho_{00}(\phi) = \frac{1}{3} + C_A + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi$$



$$C_\phi = \frac{G_s^{(y)}}{27m_s^2 T_{eff}^2}, \quad G_s^{(y)} = g_\phi^2 \left[3\langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

Model with vector meson strong force field can accommodate the large signal.

[6]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Sheng et., al., Phys. Rev. D 102, 056013 (2020)

Can We Explain the Large ρ_{00} of ϕ -meson ?

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$$\rho_{00}(\phi) = \frac{1}{3} + C_A + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi$$

[quark spin] + [interaction] \rightarrow [meson spin]

- The interaction (orbital angular momentum) is essential to understand meson spin

Can We Explain the Large ρ_{00} of ϕ -meson ?

| Physics Mechanisms | (ρ_{00}) |
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| c_A : Quark coalescence vorticity & magnetic field ^[1] | < 1/3 (Negative $\sim 10^{-5}$) |
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$$\rho_{00}(\phi) = \frac{1}{3} + C_A + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi$$

[quark spin] + [interaction] \rightarrow [meson spin]

- The interaction (orbital angular momentum) is essential to understand meson spin
 - Interaction is not included in instant Dirac spinors
- $$u^\sigma(p) = \frac{(\not{p} + m)}{\sqrt{2m(m + p_0)}} \begin{bmatrix} \chi^\sigma \\ \xi^\sigma \end{bmatrix} \quad \vec{S} \quad \not{v}$$
- $$\vec{L} + \vec{S} \times$$
- “spin crisis” of proton
 - Applying the light front framework to contain the interaction term in the leading order of the spinor (from hadron physics)
- BF, F. Gao, Y. Liu and H. Song, arXiv: 2307.XXXX

S. J. Brodsky, et al., Phys. Rev. D 69, 076001 (2004)
 S. J. Brodsky, et al., Nucl. Phys. B 593, 311 (2001)

Spin alignment from light front spinor

- The light front spinor with Lorentz trans. in Dirac representation

$$u^{LF,\sigma}(p) = \frac{1}{\sqrt{2p^+}} \left[\begin{array}{c} p_0 + m + \vec{\sigma} \cdot \vec{p} \sigma^3 \\ (p_0 - m) \sigma^3 + \vec{\sigma} \cdot \vec{p} \end{array} \right] \chi^\sigma$$

$p^+ = p_0 + p_z$ with $p_0 = \sqrt{\vec{p}^2 + m^2}$

χ^σ : two component spinor in quark rest frame

The main difference is the $\vec{\sigma} \cdot \vec{p} \sigma^3$, which naturally satisfy the angular condition ($\vec{L} + \vec{S}$ conservation in Lorentz boost)

- Then, we can define the unpolarized spin density matrix in rest frame and transform it into light front

$$\rho_{00}(p^+, p'^+, p_\perp) = \frac{(g^2 + p_\perp^2)^2 + p_\perp^2(p^+ - p'^+)^2}{3(g^2 + p_\perp^2)^2 - 4g^2 p_\perp^2 + 2p_\perp^2(p^+ - p'^+)^2}$$

$$g^2 = (p^+ + m)(p'^+ + m')$$

The ρ_{00} is always larger than 1/3. To illustrate, we consider the equal quark and anti-quark: $p^+ = p'^+$

$$\rho_{00}(p^+, p_\perp) = \frac{(g^2 + p_\perp^2)^2}{3(g^2 + p_\perp^2)^2 - 4g^2 p_\perp^2} > 1/3$$

The instant spinor

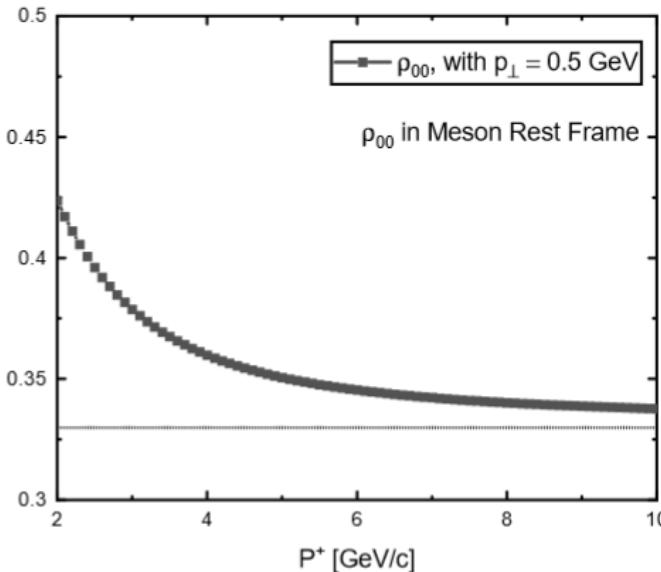
$$u^\sigma(p) = \frac{(\not{p} + m)}{\sqrt{2m(m + p_0)}} \left[\begin{array}{c} \chi^\sigma \\ \xi^\sigma \end{array} \right]$$

Estimations for the spin alignment

$$\rho_{00}(p^+, p'^+, p_\perp) = \frac{(g^2 + p_\perp^2)^2 + p_\perp^2(p^+ - p'^+)^2}{3(g^2 + p_\perp^2)^2 - 4g^2 p_\perp^2 + 2p_\perp^2(p^+ - p'^+)^2}$$

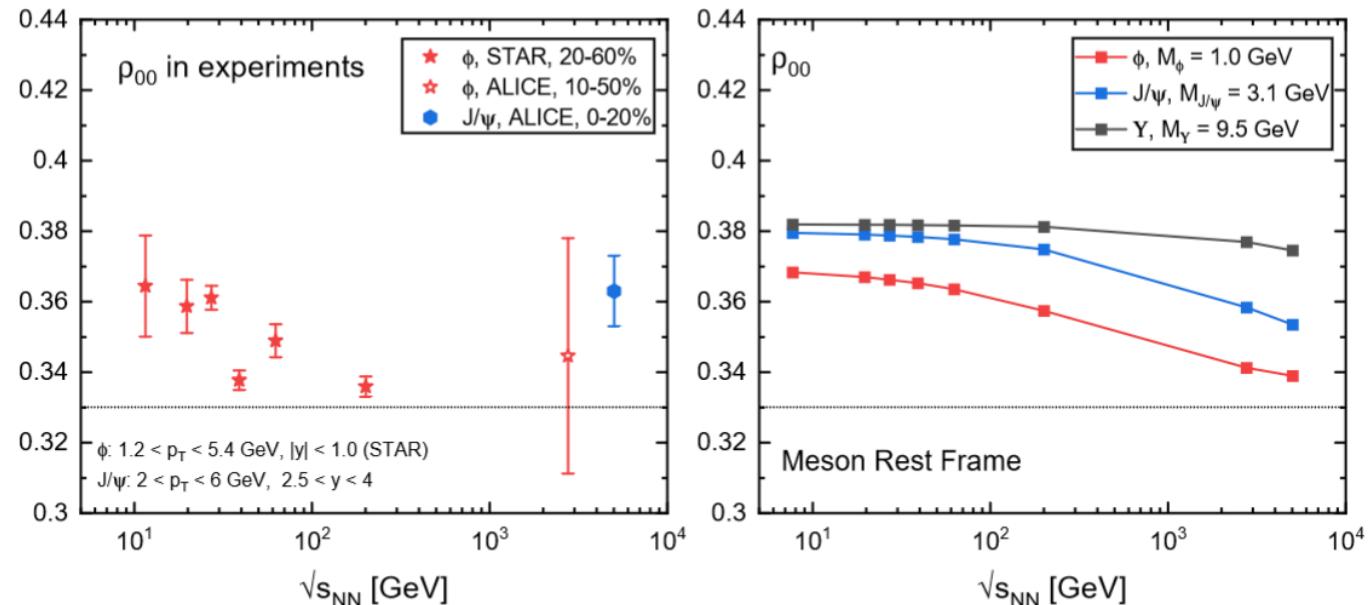
- A simple estimation in symmetric case**

Assuming $p^+ = p'^+$ and neglecting the mass of quark and hadron



- Estimate by light front wave function in vacuum**
- Temperature effect included in the modified energy scale (mass)**

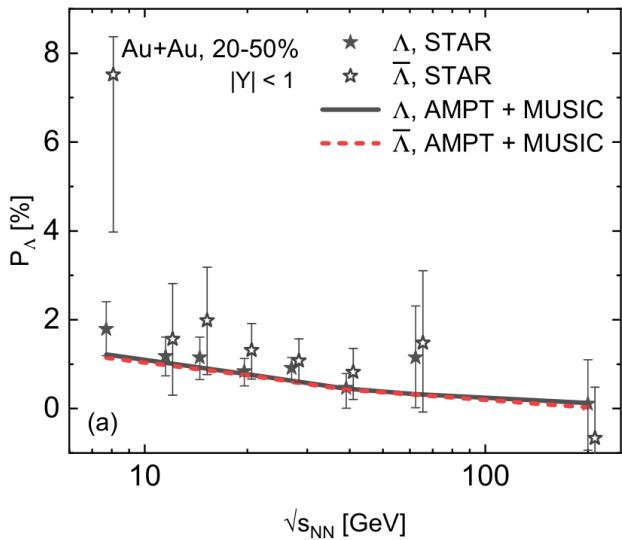
$$P^+ = \sqrt{M^2 + \mu^2 + (2\pi T_{\text{eff}})^2}$$



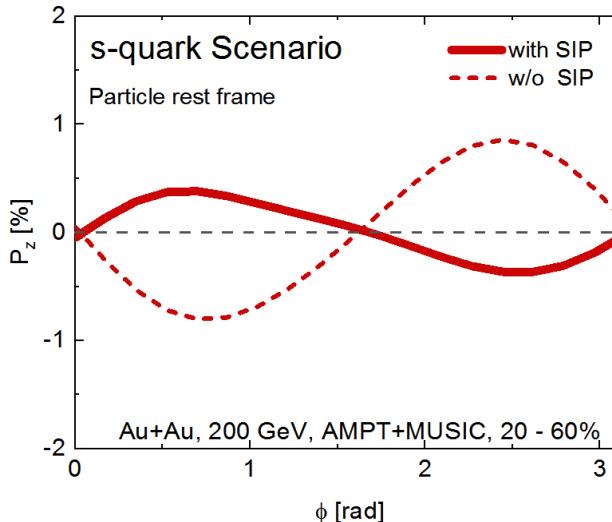
Summary

$$P^\mu = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

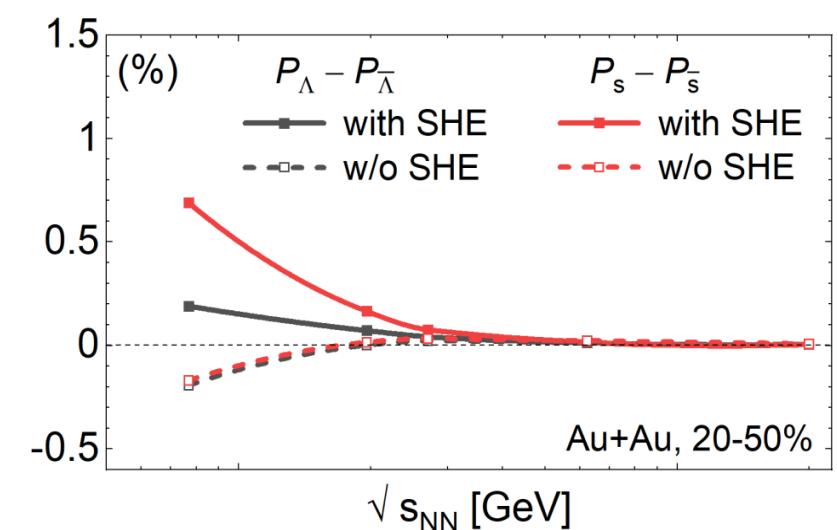
Global polarization



Essential for $P_z(\phi)$ puzzle



Spin generation by $\vec{\nabla} \mu_B$



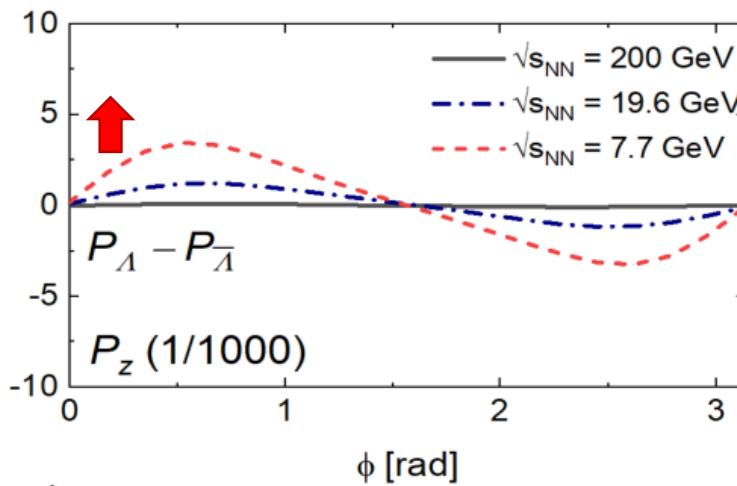
- Spin polarization probes the formation and evolution of QGP
- Spin alignment puzzle: might be understand by light front spinors

Thanks!

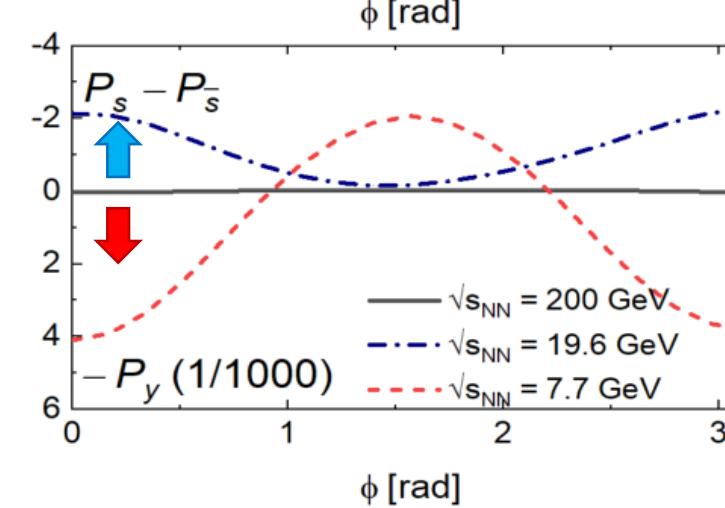
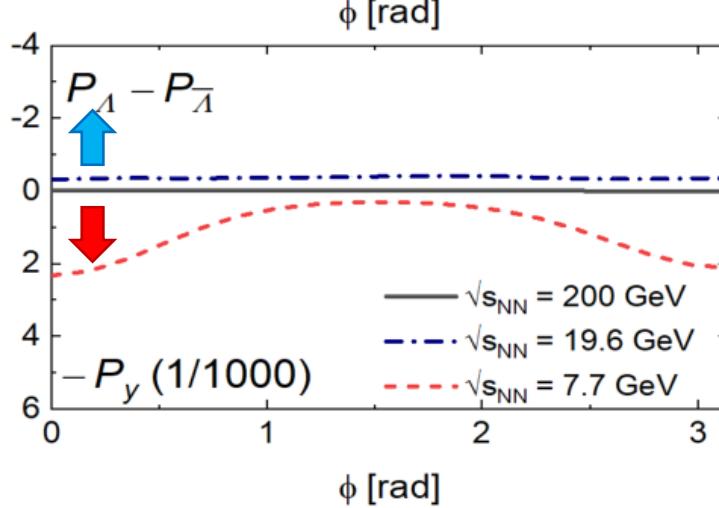
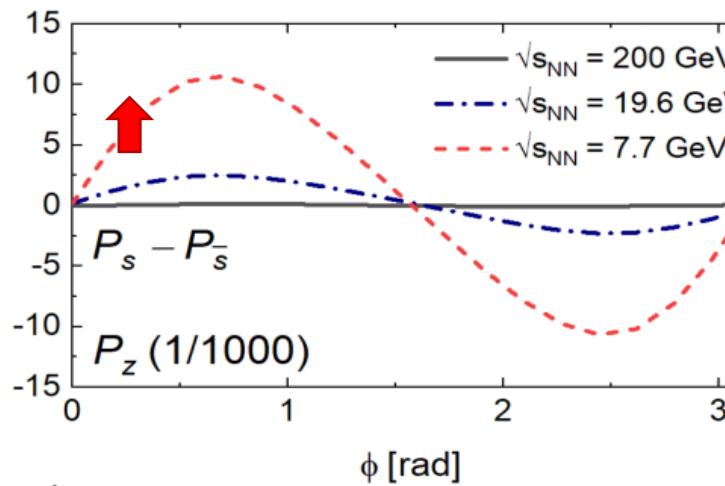
Net spin polarization: $P_{\text{net}}(\phi)$

BF, L.-G. Pang, H. Song and Y. Yin,
arXiv: 2201.12970

$$P_{\Lambda}^{\text{net}} \equiv P_{\Lambda}(\phi) - P_{\bar{\Lambda}}(\phi)$$



$$P_s^{\text{net}} \equiv P_s(\phi) - P_{\bar{s}}(\phi)$$



- The ‘net’ spin polarization used to extract SHE signals
- Net $P_z(\phi)$: increase with decreasing collision energy
- Net $P_y(\phi)$: non-monotonic behavior from SHE

Hydrodynamic gradients

Derivatives of the velocity field:

$$\partial_\mu u_\nu(x)$$

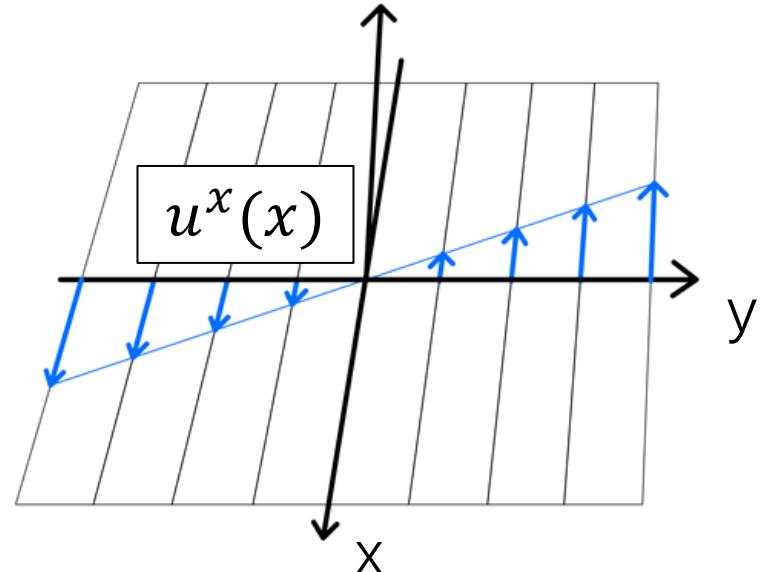
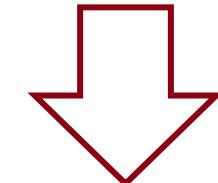
Anti-symmetric: vorticity

$$\omega^\mu = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} u_\nu \partial_\alpha^\perp u_\beta$$

(Thermal) vorticity
induced polarization

Symmetric: shear stress

$$\sigma^{\mu\nu} = \frac{1}{2} (\partial_\perp^\mu u^\nu + \partial_\perp^\nu u^\mu) - \frac{1}{3} \Delta^{\mu\nu} \partial_\perp \cdot u$$



Shear Induced polarization

Also contribute to
local polarization

In condensed matter physics:

R. Takahashi, et al., Nature Physics (2016) 12, 52-56

In heavy ion collision:

F. Becattini (2013) and later works

[Strain induced polarization]

In crystal physics:

S. Crooker and D. Smith, PRL (2005) 94, 236601

T. Kissikov, et al., Nature Comm. (2018) 9, 1058

Efforts to resolve the ‘local polarization puzzle’

- Feed-down effects (Xia, Li, Huang, Huang, PRC 2019, Becattini, Cao, Speranza, EPJC 2019)
- Other spin chemical potential (Wu, Pang, Huang, Wang, PRR 2019)
- Polarization from projected thermal vorticity (Florkowski, Kumar, Ryblewski, Mazeliauskas, PRC 2019)
- Side-jump in CKT (Liu, Ko, Sun, PRL 2019)
- Spin as a dynamical d.o.f:
 - spin hydrodynamics (Florkowski, et al., PRC2017, Hattori, et al., PLB 2019, Shi, et al, PRC 2021, ...)
 - spin kinetic theory (Gao and Liang, PRD 2019, Weickgenannt ,et al PRD 2019, Hattori, et al PRD 2019, Wang, et al, PRD 2019, Liu, et al, CPC 2020, Hattori, et al, PRD 2019, ...)
- Final hadronic interactions (Xie and Csnerai, ECT talk 2020, Csnerai, Kapusta, Welle, PRC 2019)
- ...

Still open questions and more precise understanding needed about spin and its dynamics

Global polarization measurements

'self-analyzing' of hyperon

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)$$

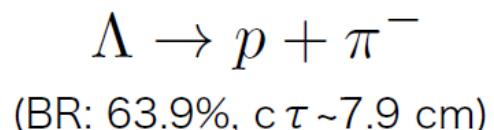
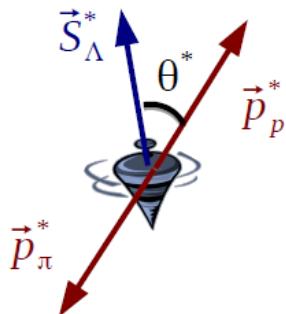
\mathbf{P}_H : Λ polarization

\mathbf{p}_p^* : proton momentum in the Λ rest frame

α_H : Λ decay parameter

$$\alpha_\Lambda = 0.642 \pm 0.013 \rightarrow \alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$

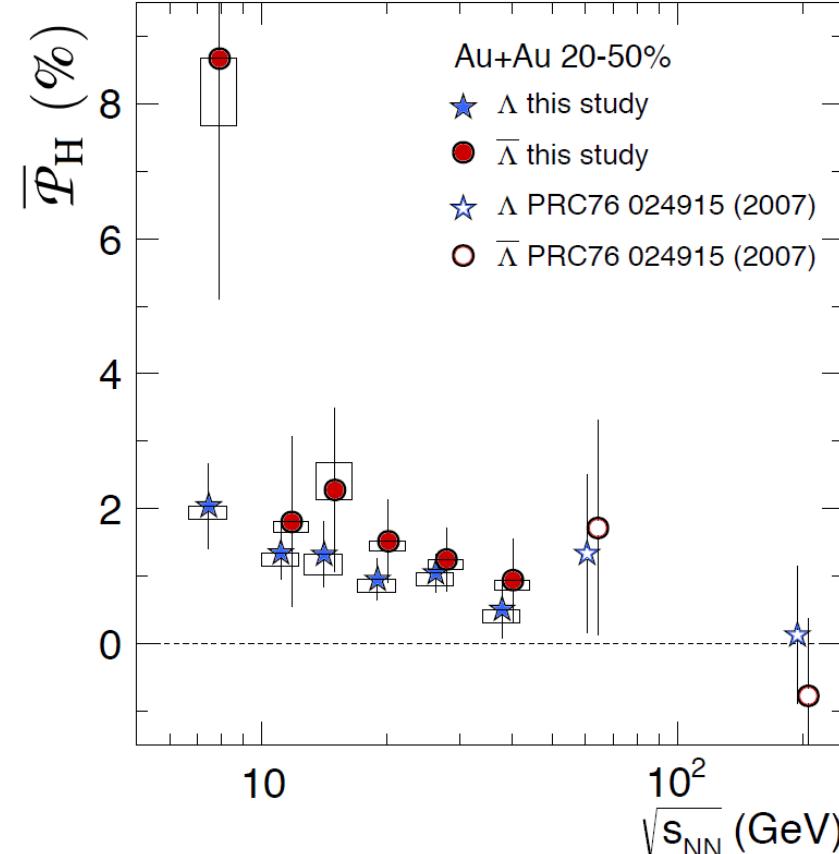
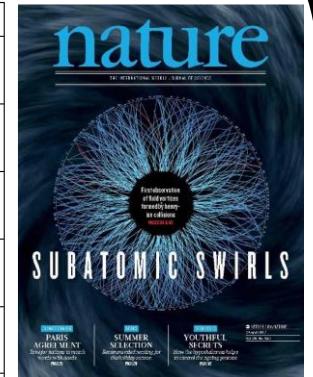
P.A. Zyla et al. (PDG), PTEP2020.083C01



S. Voloshin and T. Niida, PRC 94.021904 (2016)

Most vortical fluid!

STAR Collaboration, Nature 548, 62 (2017)



$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22} s^{-1}$$

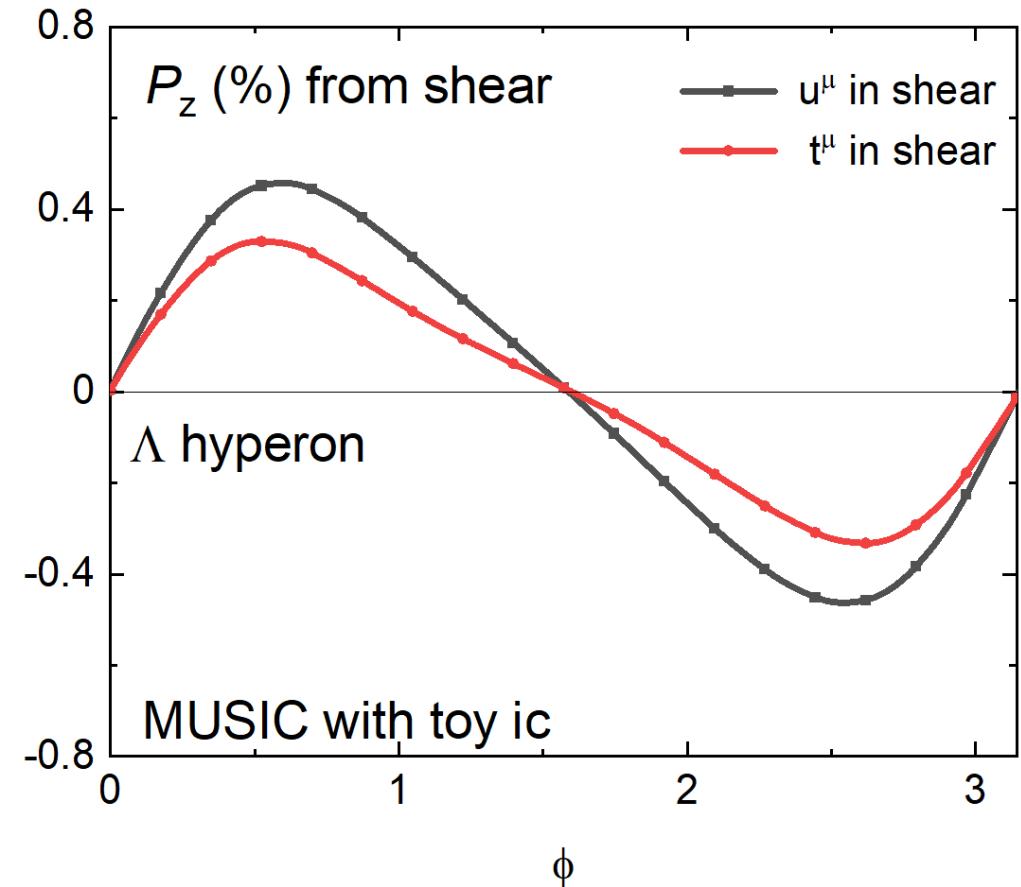
APPENDIX I: Formula check

- The u^μ formula is used in our calculation (default)
- Note: In the t^μ calculation (red line), other terms are not changed (like the perp term)

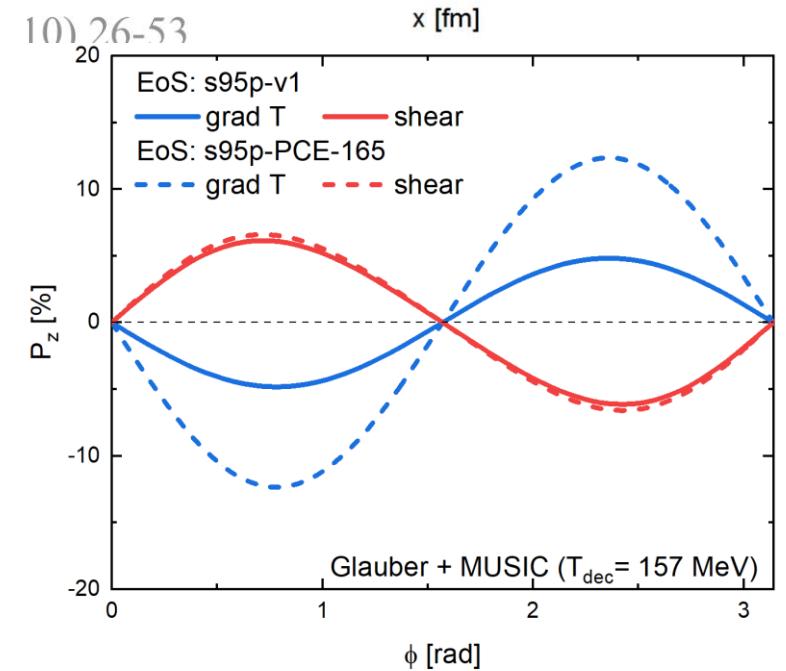
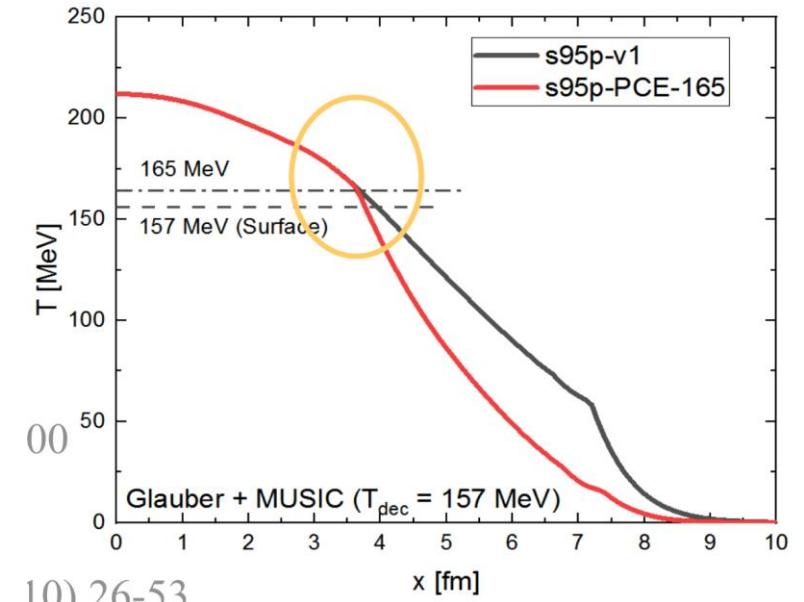
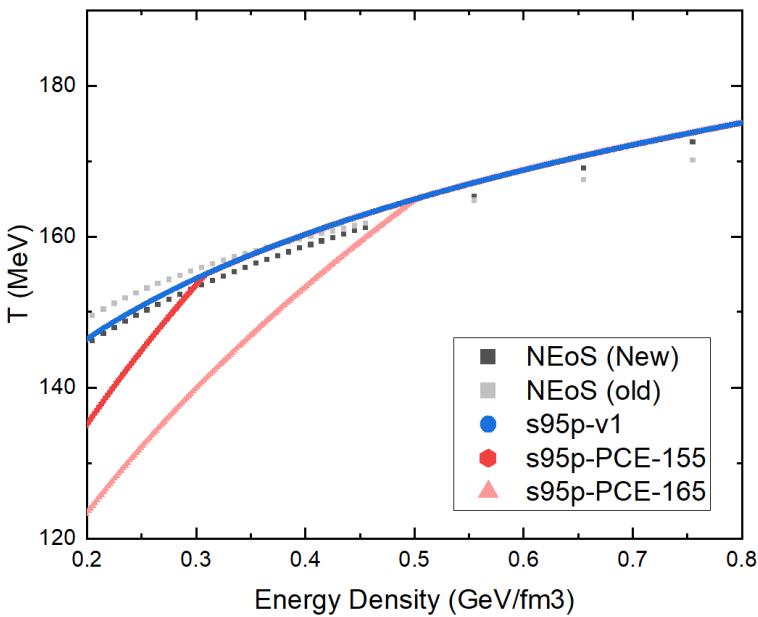
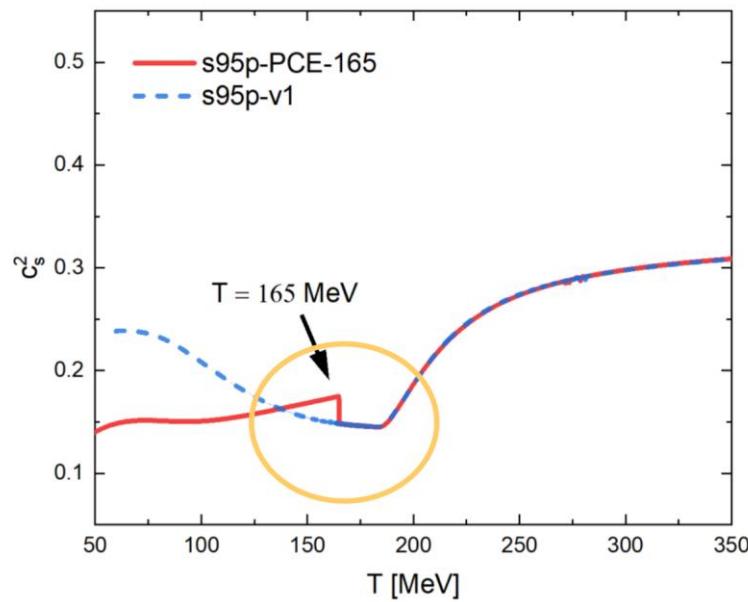
$$\mathcal{A}^\mu(x, p) = \beta f_0(x, p)(1 - f_0(x, p))\varepsilon^{\mu\nu\alpha\rho}$$

$$\times \left(\underbrace{\frac{1}{2}p_\nu \partial_\alpha^\perp u_\rho}_{\text{vorticity}} + \underbrace{\frac{1}{\beta}u_\nu p_\alpha \partial_\rho \beta}_{\text{T-gradient}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0} u_\nu Q_\alpha^\lambda \sigma_{\rho\lambda}}_{\text{SIP}} \right)$$

Replaced by $\hat{t}_\nu = (1, 0, 0, 0)$

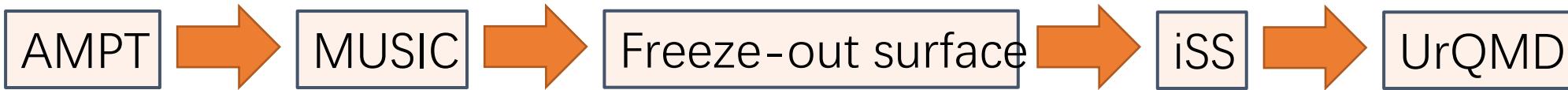


APPENDIX II: EoS-PCE

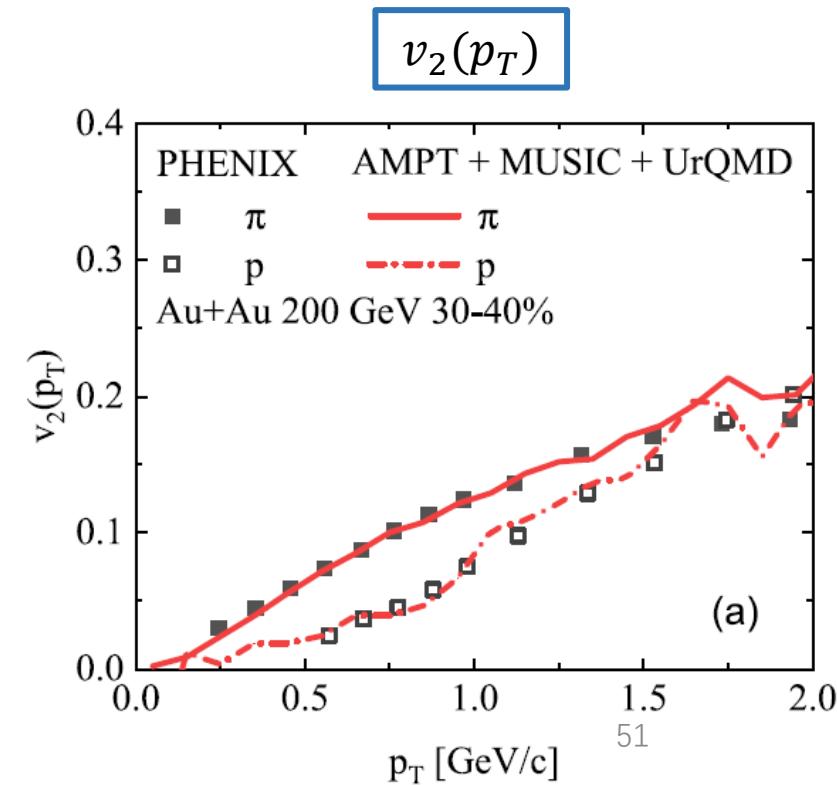
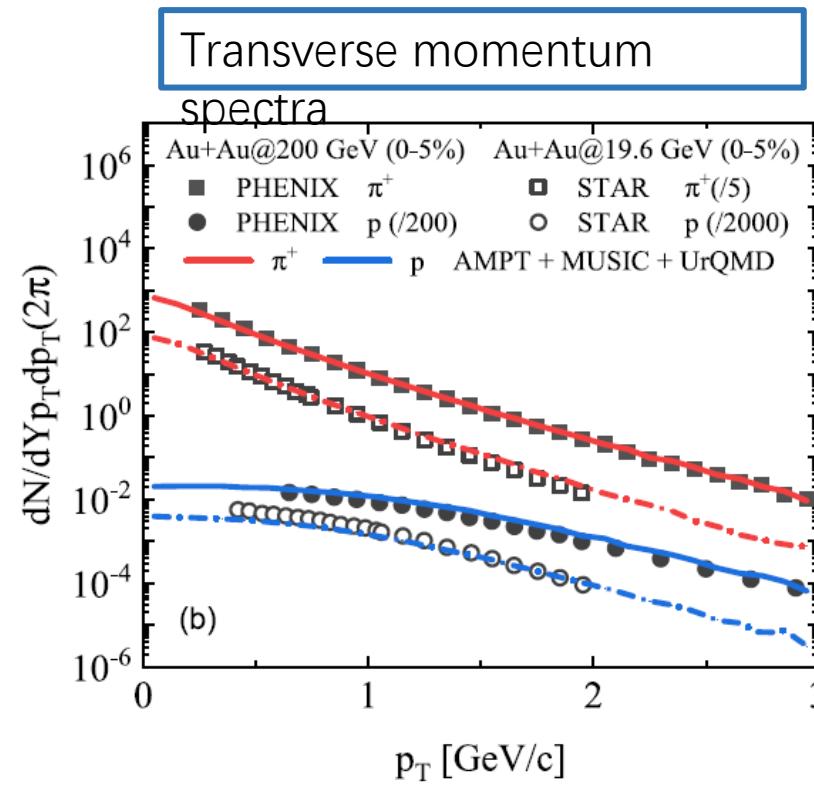
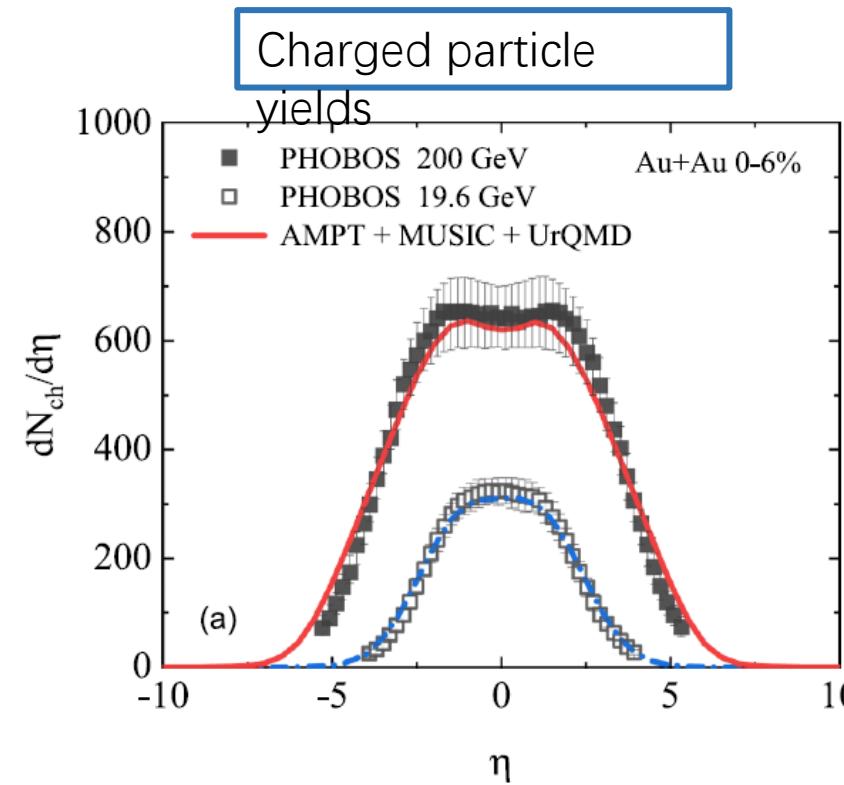


Well calibrated hydrodynamic model

BF, K. Xu, X-G, Huang, H. Song,
Phys.Rev.C 103 (2021) 2, 024903



Parameters are tuned to reproduce the soft hadron observables



Global polarization with shear effect

$$\text{Total } P^\mu = [\text{thermal vorticity}] + [\text{Shear}]$$

