Signature of the baryonic Spin Hall Effects at RHIC BES

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Peking University（北京大学）

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

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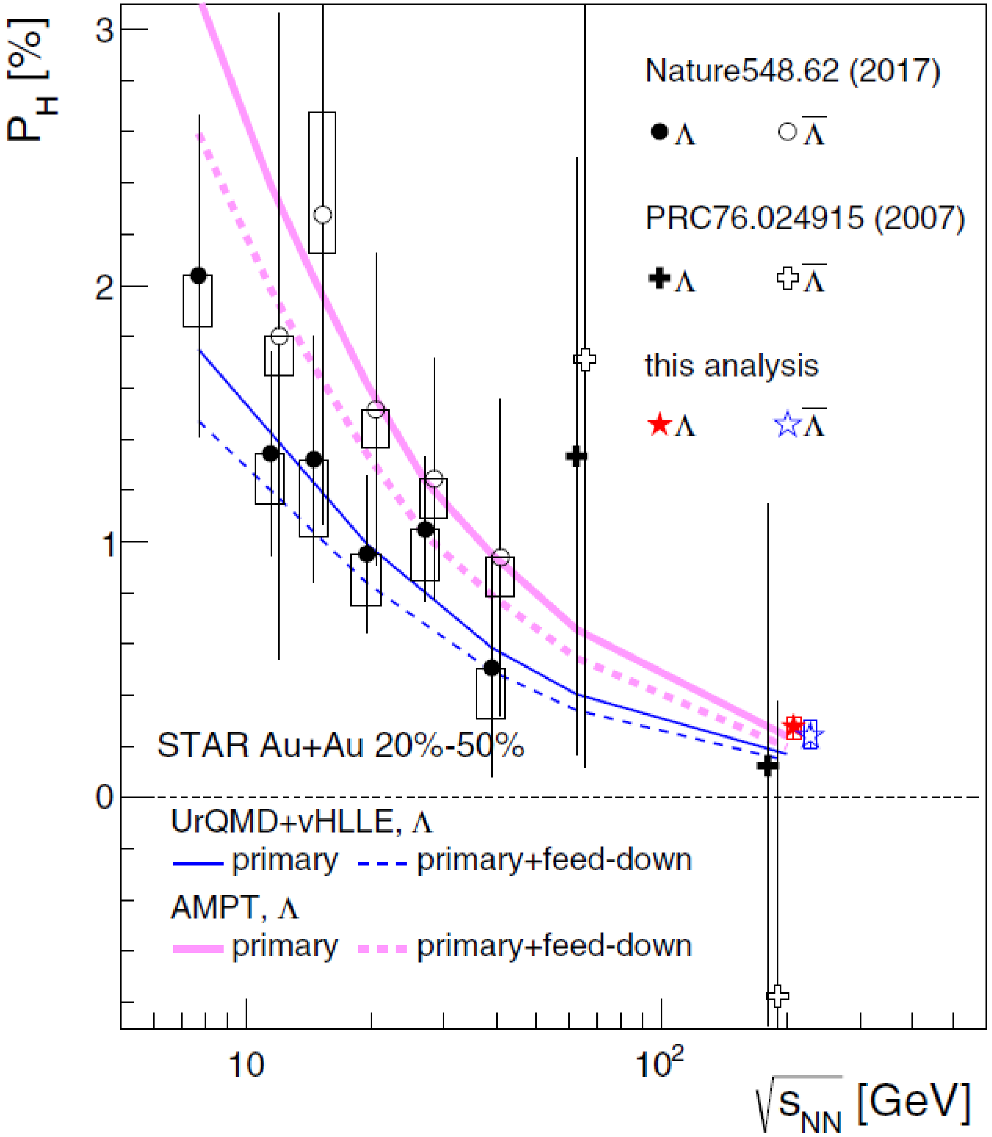
大连，2022-08-11

Global polarization

STAR, Phys.Rev.C 98 (2018) 014910



- **Spin-orbital coupling** in non-central heavy ion collisions

  Z. T. Liang, X. N. Wang, Phys.Rev.Lett. 94 (2005) 102301

- Signals observed at RHIC-BES

  STAR Collaboration, Nature 548, 62 (2017)

- Data described be the statistic calculation

$$P^{\mu}(p) \leftarrow \varpi_{\mu\nu}(x) = \frac{1}{2}(\partial_{\nu}\left(\frac{u_{\mu}}{T}\right) - \partial_{\mu}\left(\frac{u_{\nu}}{T}\right))$$

Hydrodynamics:

I. Karpenko, F. Becattini, Eur.Phys.J.C 77 (2017) 4, 213
BF, K. Xu, X-G, Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903

Transport model:

H. Li, L. Pang, Q. Wang, X. Xia, Phys.Rev. C96 (2017) 054908
D. Wei, W. Deng, X. Huang, Phys.Rev. C99 (2019) 014905

local polarization ‘Sign puzzle’

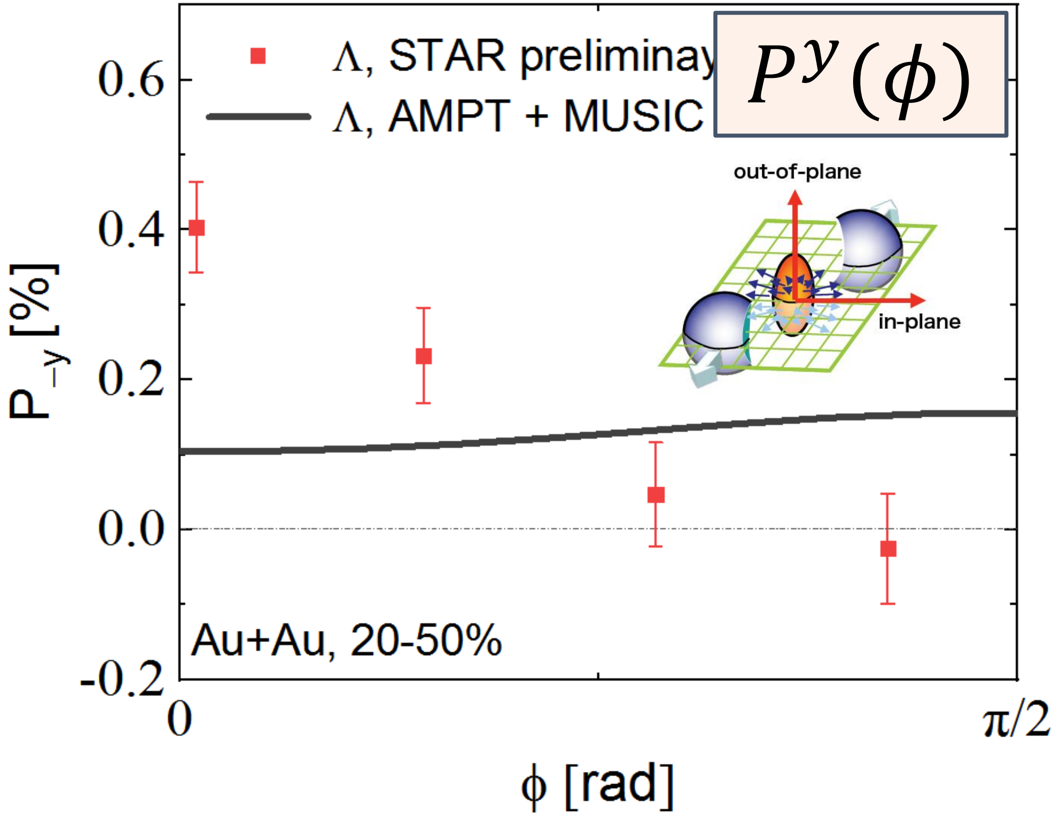
See also:

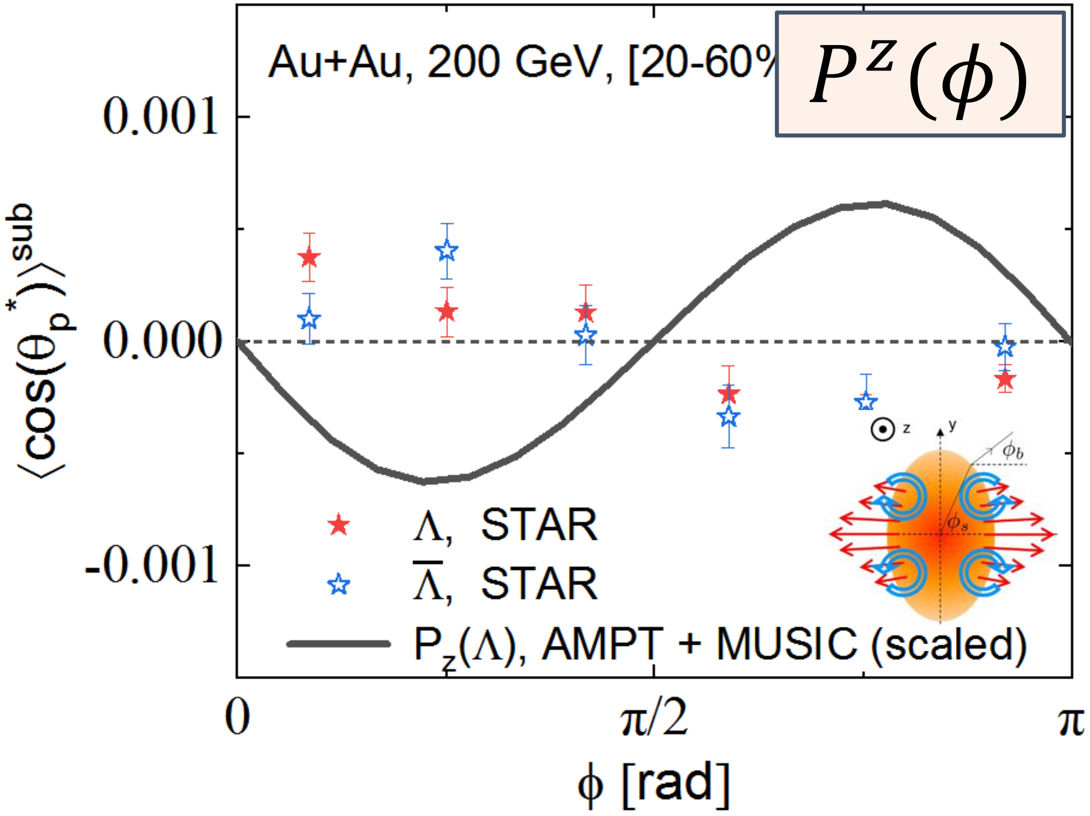
Becattini, Karpenko, PRL 120 (2018) 012302

D. Wei, et al., PRC 99 (2019) 014905

X. Xia, et al., PRC 98 (2018) 024905

- Different trend/sign in $P_y(\phi)$ and $P_z(\phi)$ results
- Long exist in hydrodynamic and transport calculations





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

local polarization: shear effect

See also:
Becattini, et al, PRL 127 27, 272302 (2021)
Yi, et al, PRC 104 6, 064901 (2021)
Alzhrani, et al, arxiv: 2203.15562

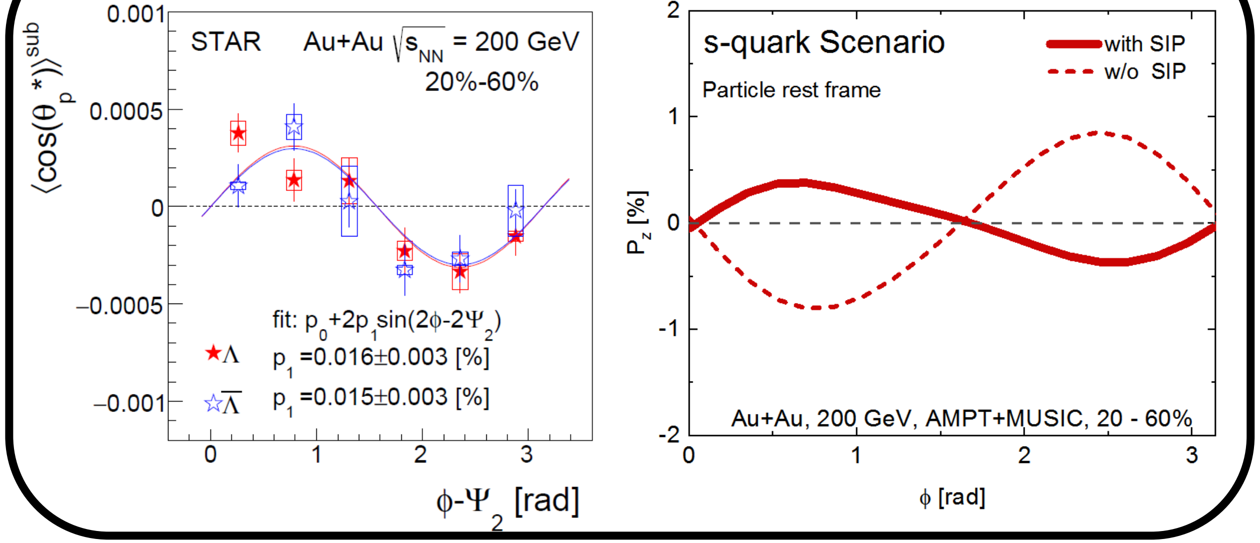
- Shear induced polarization (SIP) S. Liu and Y. Yin, JHEP 07 (2021) 188; Becattini, et al., PLB820 (2021) 136519

Total P^{μ} = [Thermal vorticity] + [SIP]

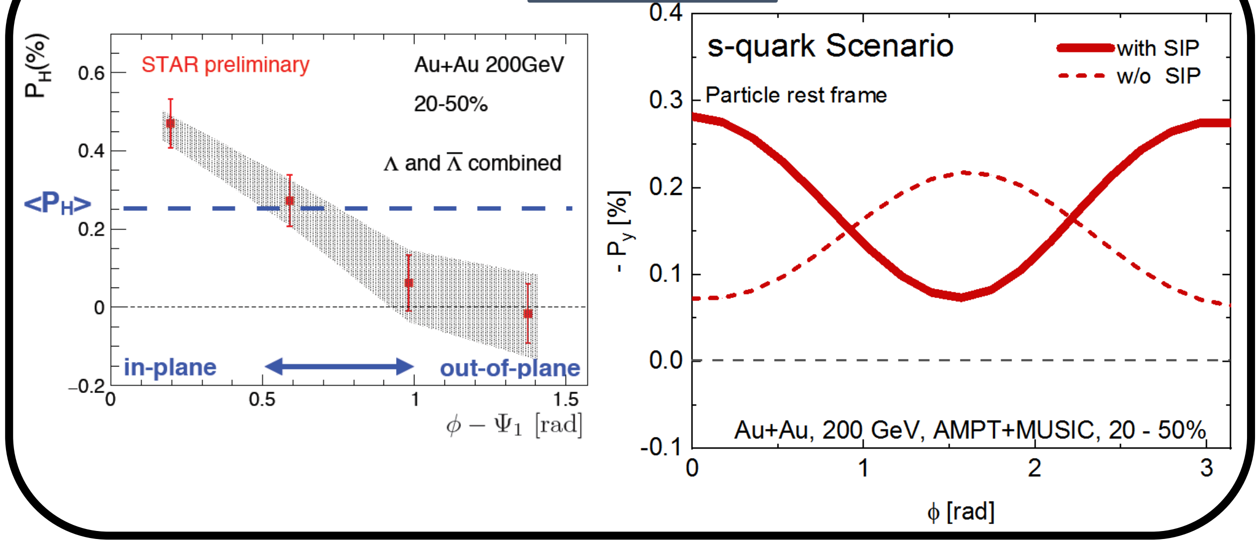
Shear stress tensor: $\sigma^{\mu\nu} \;=\; \frac{1}{2}\left(\partial_{\perp}^{\mu}u^{\nu}+\partial_{\perp}^{\nu}u^{\mu}\right)-\frac{1}{3}\Delta^{\mu\nu}\partial_{\perp}\cdot u$

- Qualitatively describes local polarization with SIP

$P_z(\phi)$



$P_y(\phi)$



BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, PRL 127 14, 142301(2021)

How about with finite μ_B?

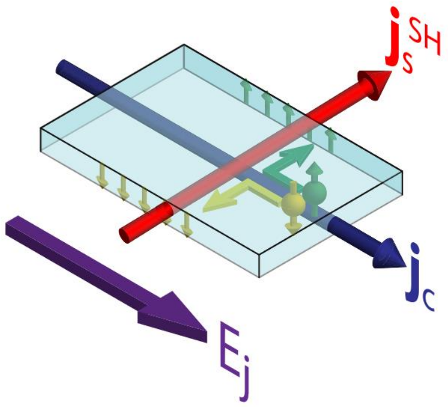
Baryonic Spin Hall Effects (SHE) at RHIC-BES

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

Spin Hall Effects (SHE)

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

- Probes transport properties in quantum materials with theory under **QED**
- Has been observed in semiconductors, metal and insulators at room temperature or below

In hot QCD matter

- With similar form, replacing electric field $\vec{E}$ to baryon chemical potential gradient $\vec{\nabla}\mu_B$

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

Spin Polarization:

- Thermal vorticity
  F. Becattini, et al., Annal Phys. 2013
- Shear-Induced Polarization
  S. Liu and Y. Yin, JHEP 2021, BF, et al., PRL 2021
  F. Becattini, et al., PLB 2021, PRL 2021
- Baryonic Spin Hall Effects (SHE) — In this talk

- Another mechanism for spin generation under **QCD**
- Probes the properties of QCD matter at extremely high temperature ($\sim 10^{12}$K)

Baryonic Spin Hall Effects (SHE)

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

Axial Wigner function $\mathcal{A}^\mu$ expansion with finite chemical potential:

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

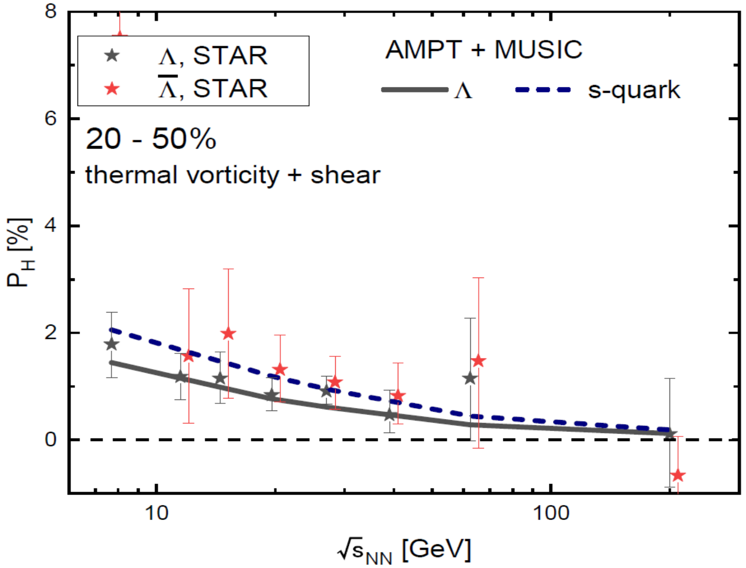
thermal vorticity **shear** **baryonic SHE**

- Spin current generation: search SHE signal in differential observables like $P^\mu(\phi)$
- Induced by μ_B gradient: more important at RHIC-BES or finite rapidity
- Opposite contribution for particles / anti-particles

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

Well calibrated hydrodynamic model: **AMPT + MUSIC**

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

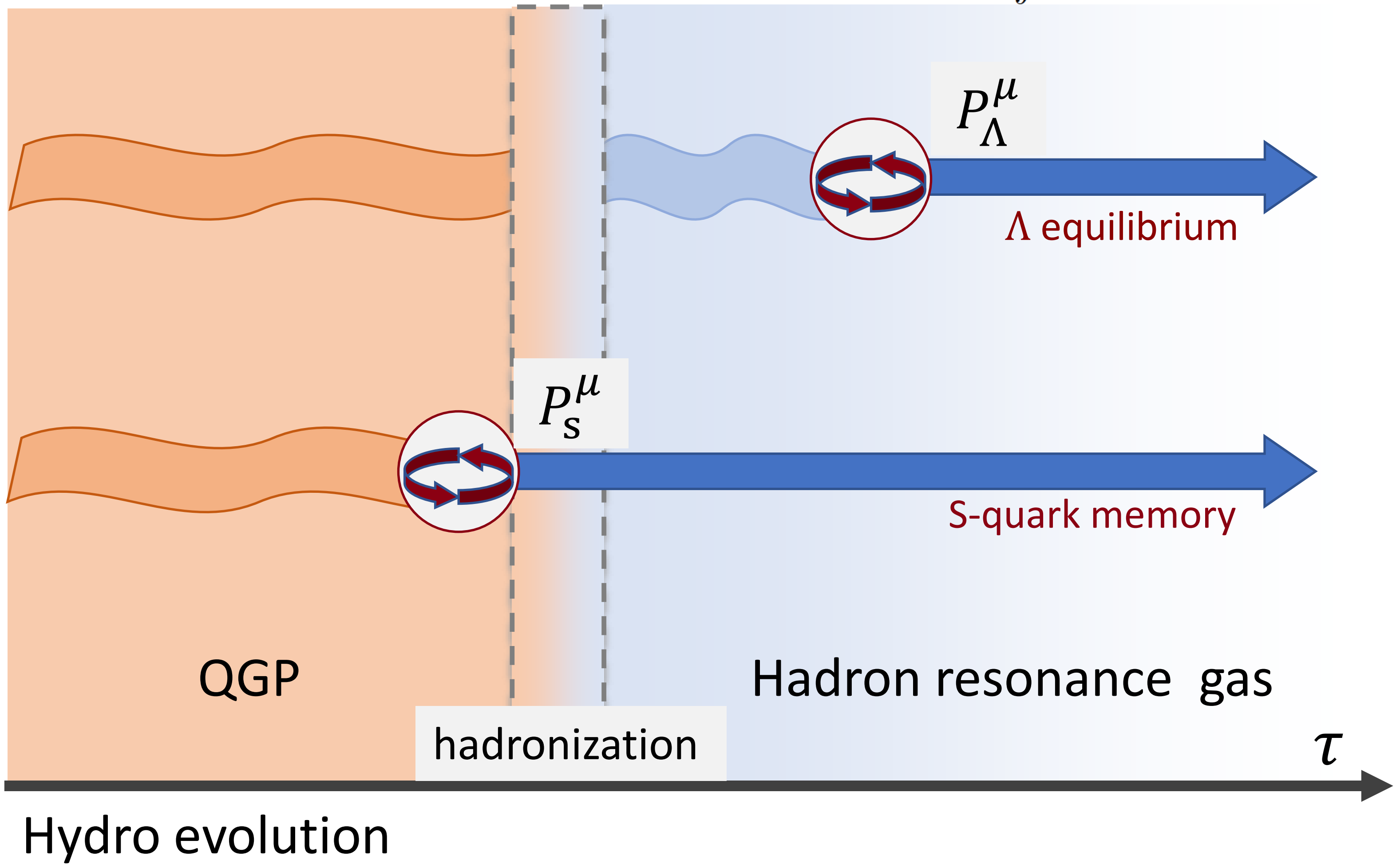


See also: S.Ryu, et al., PRC 104 (2021) 5, 054908 (Global effect)
S. Liu and Y. Yin, PRD 104 (2021) 5, 054043 (B-W model)
X. Wu, et al., PRC 105 (2022) 064909 (baryon diffusion)

‘Λ equilibrium’ vs. ‘S-quark memory’

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

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



‘Λ equilibrium’

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

Polarization of Λ-hyperon

$P^\mu_\Lambda(p)$

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

‘S-quark memory’

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

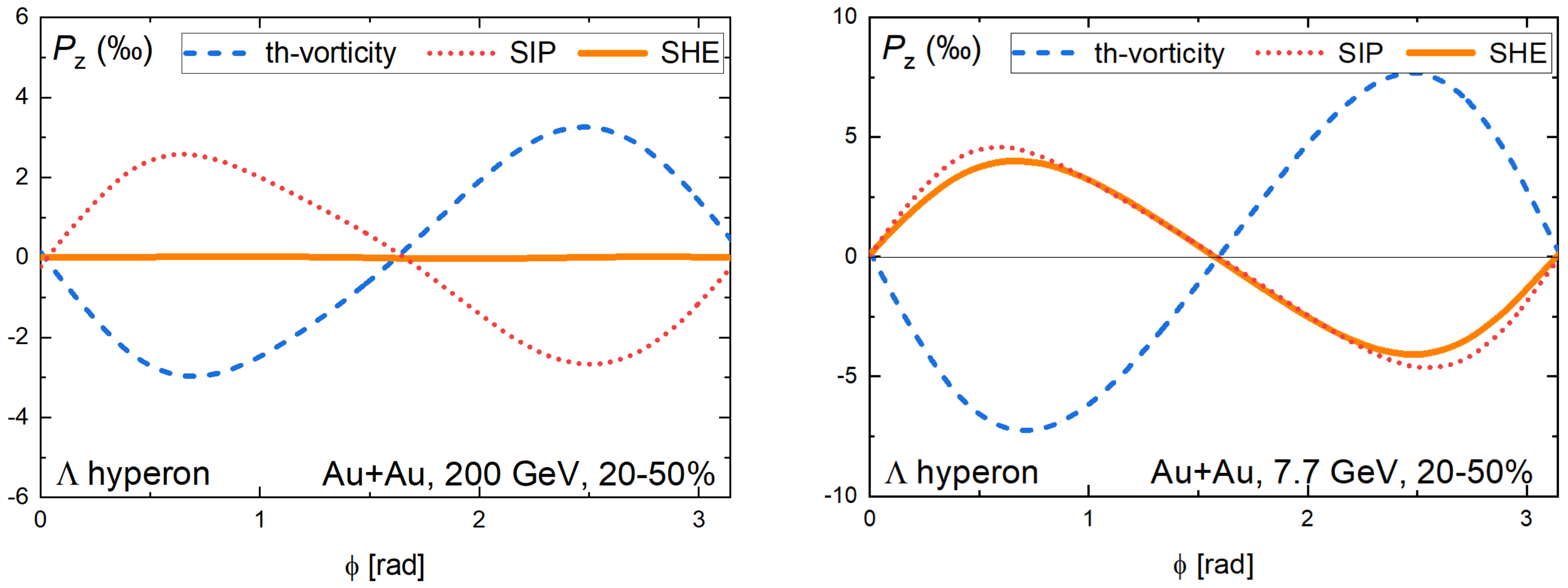
Polarization of S-quark

$P^\mu_\Lambda(p) = P^\mu_s(p)$

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

Individual contributions to $P_z(\phi)$ and $P_y(\phi)$

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



- Similar thermal vorticity and shear effects
- Sizeable Spin Hall Effects may induce separation between baryons and anti-baryons

Individual contributions to $P_z(\phi)$ and $P_y(\phi)$

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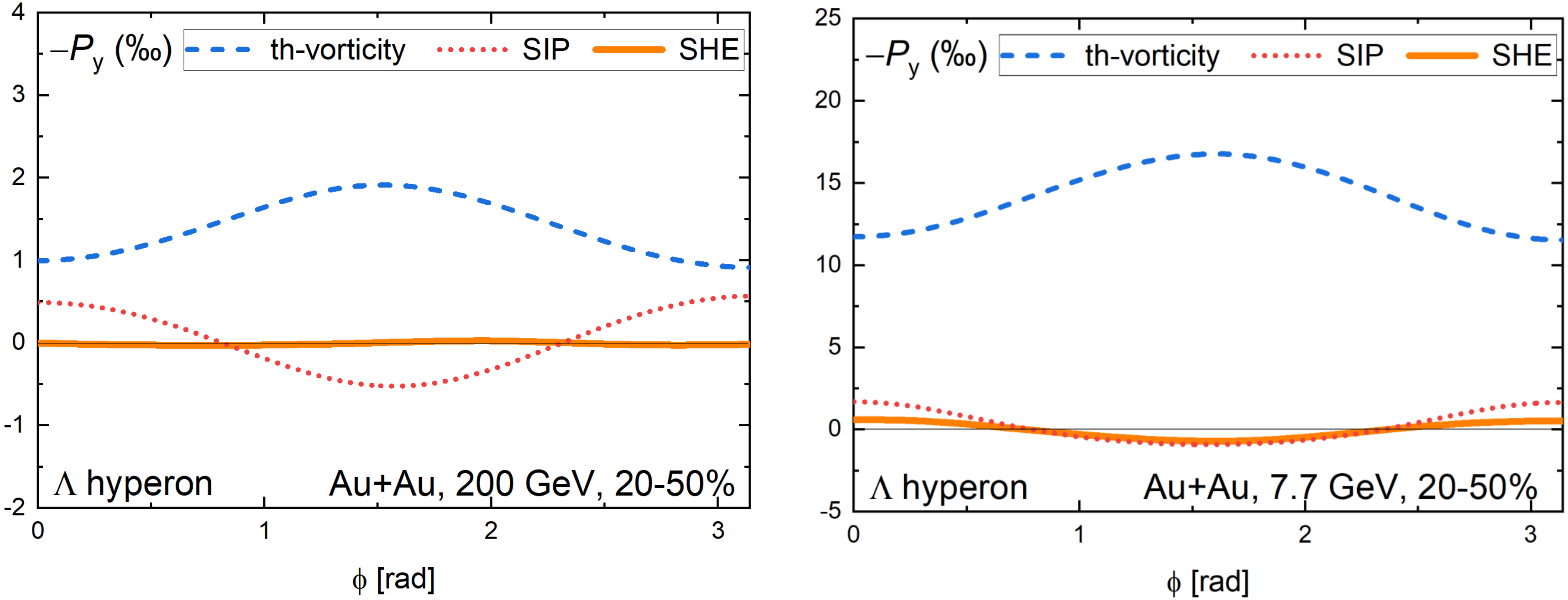
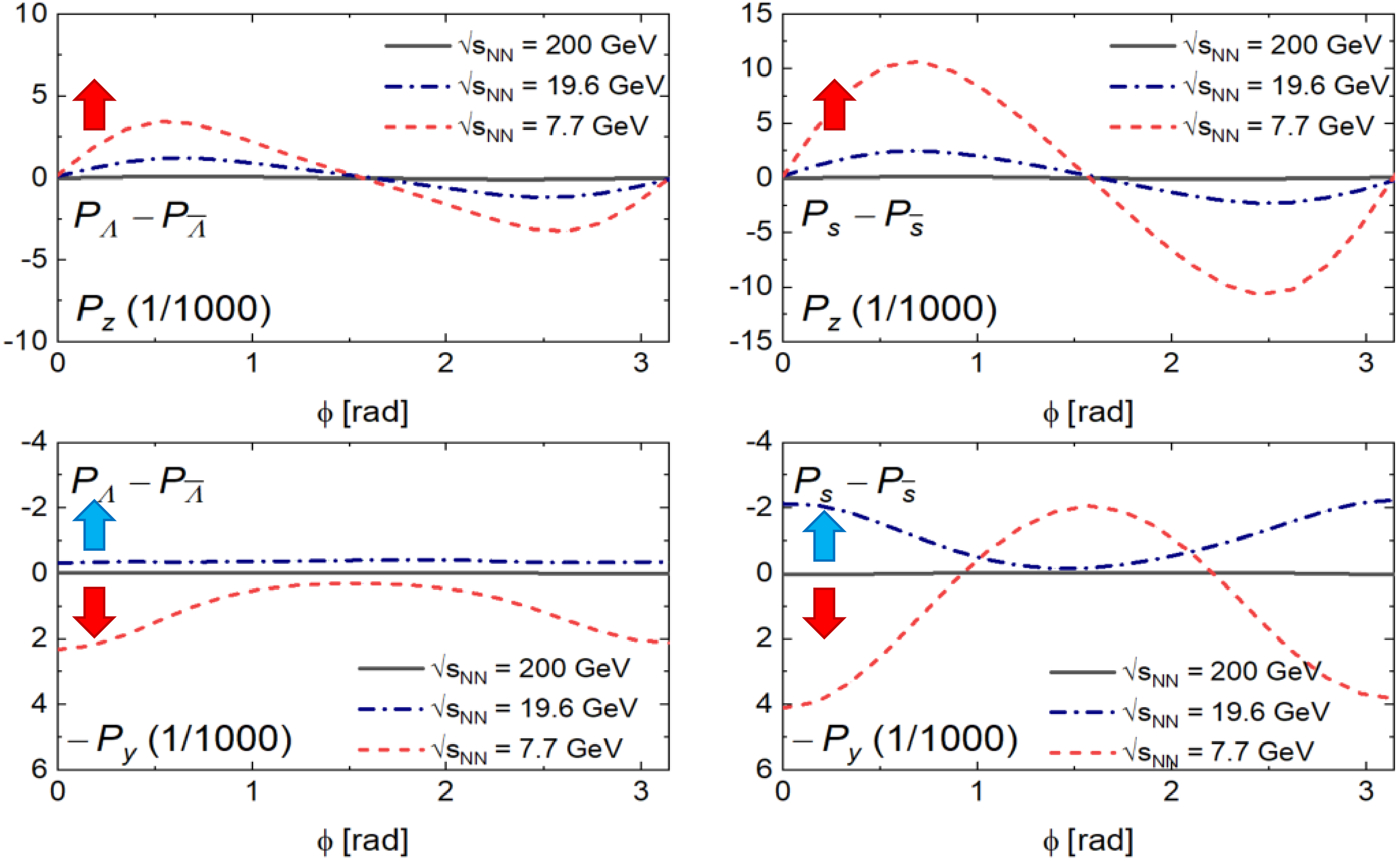


- Similar thermal vorticity and shear effects
- Sizeable Spin Hall Effects may induce separation between baryons and anti-baryons

Net spin polarization: $P^{\rm net}(\phi)$

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

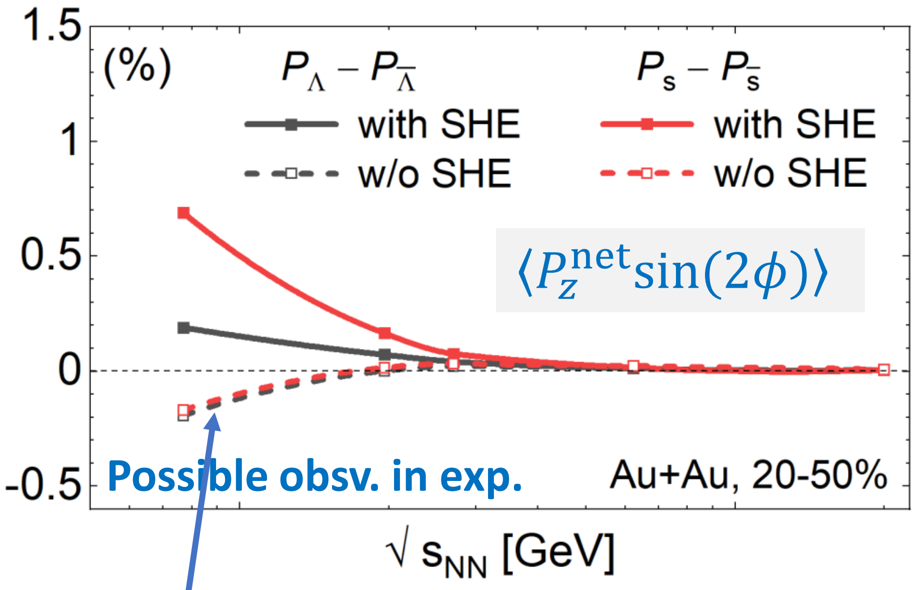
$P_\Lambda^{\rm net} \equiv P_\Lambda(\phi) - P_{\bar{\Lambda}}(\phi)$ $\quad$ $P_s^{\rm net} \equiv P_s(\phi) - P_{\bar{s}}(\phi)$



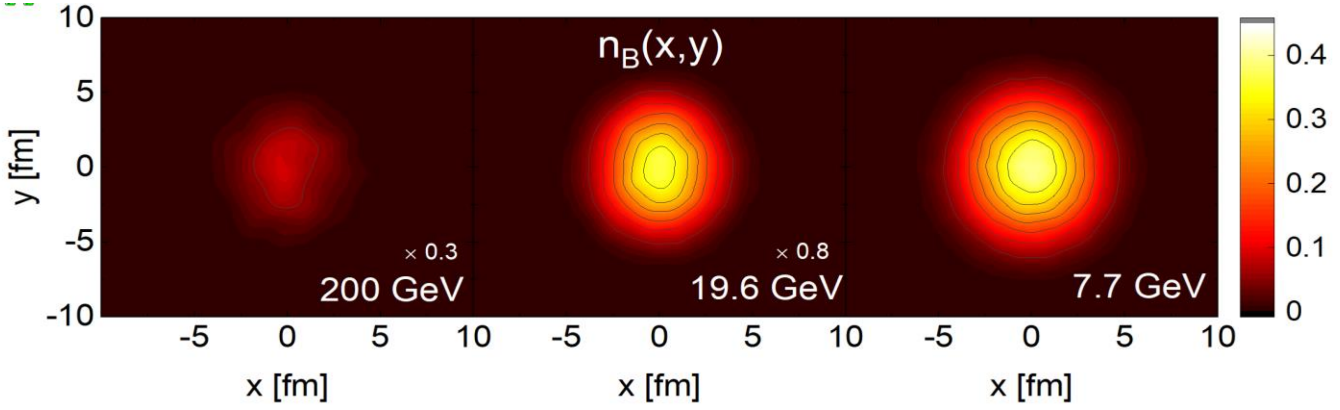
- The ‘net’ spin polarization used to extract SHE signals
- Net $P_z(\phi)$: increase with decreasing collision energy
- Net $P_y(\phi)$: non-monotonic behavior from SHE

The 2nd order Fourier coeff. of $P_z^{\mathrm{net}}(\phi)$ & $P_y^{\mathrm{net}}(\phi)$

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



- Monotonic increasing

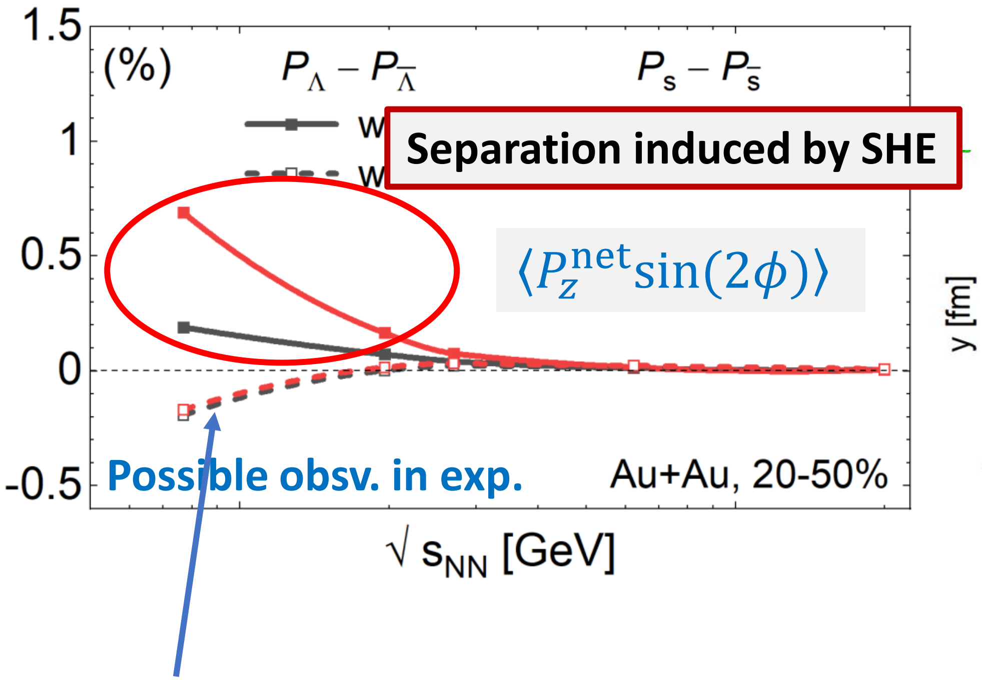


From the distribution function

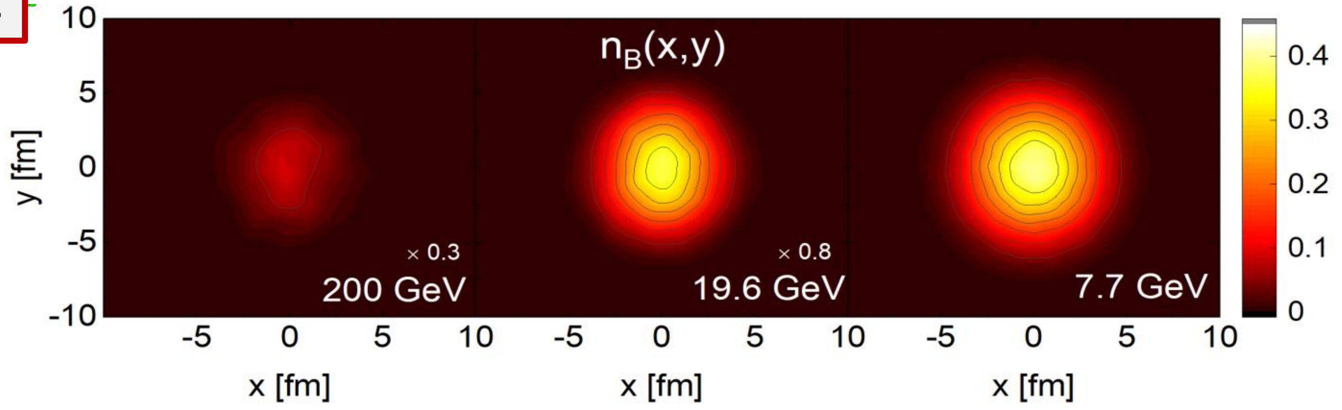
$$f(x,p) = \left(e^{(\epsilon_0 - q_B \mu_B)\beta} + 1\right)^{-1}$$

The 2nd order Fourier coeff. of $P_z^{\mathrm{net}}(\phi)$ & $P_y^{\mathrm{net}}(\phi)$

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



- Monotonic increasing



From the distribution function

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

The 2nd order Fourier coeff. of $P_z^{\rm net}(\phi)$ & $P_y^{\rm net}(\phi)$

BF, L.-G. Pang, H. Song, Y. Yin
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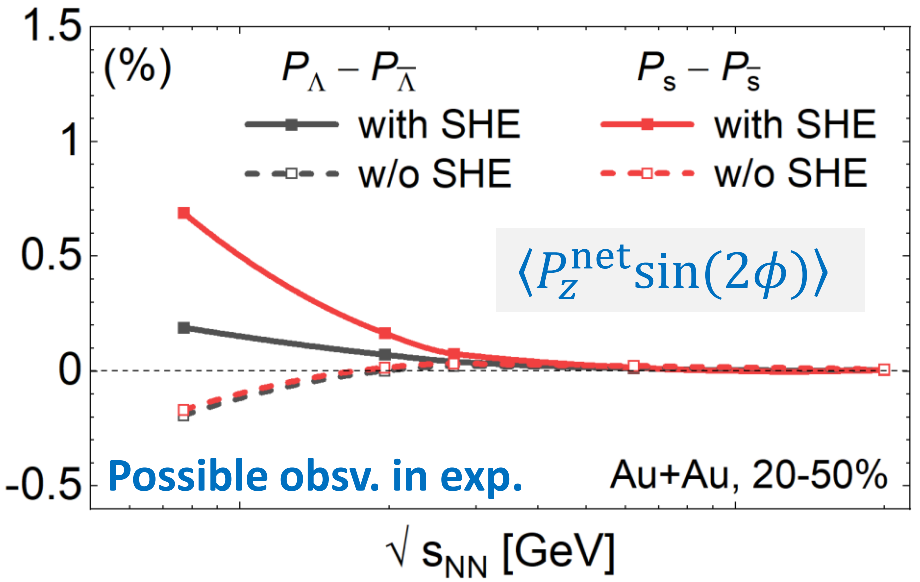
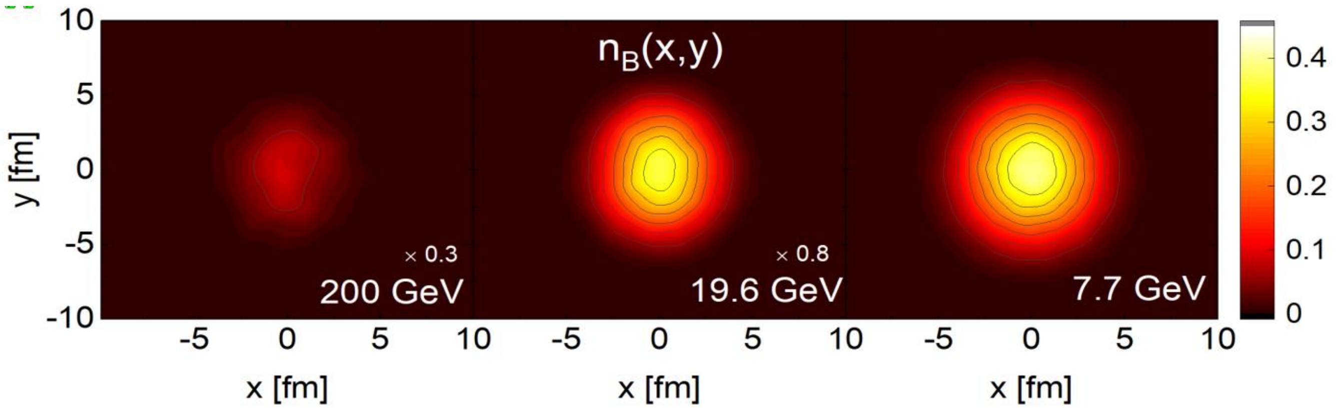
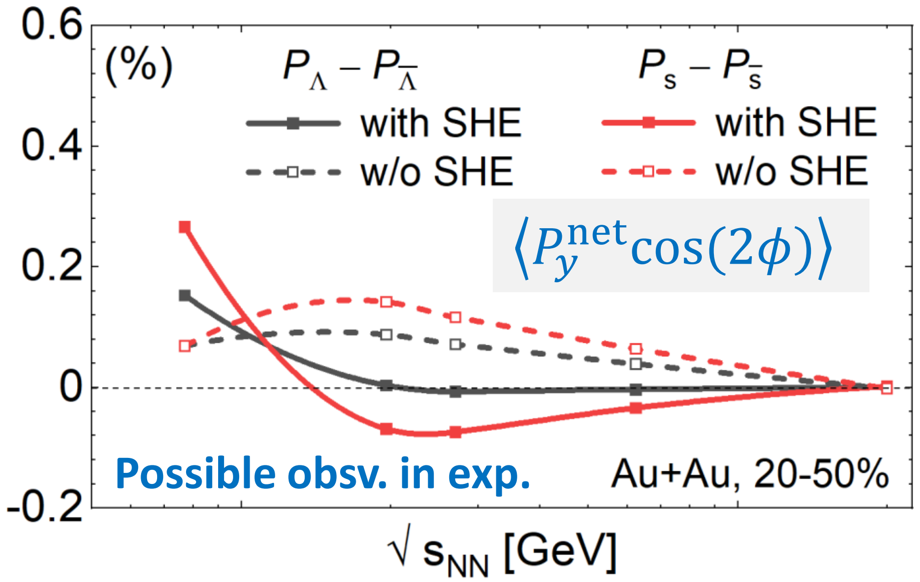
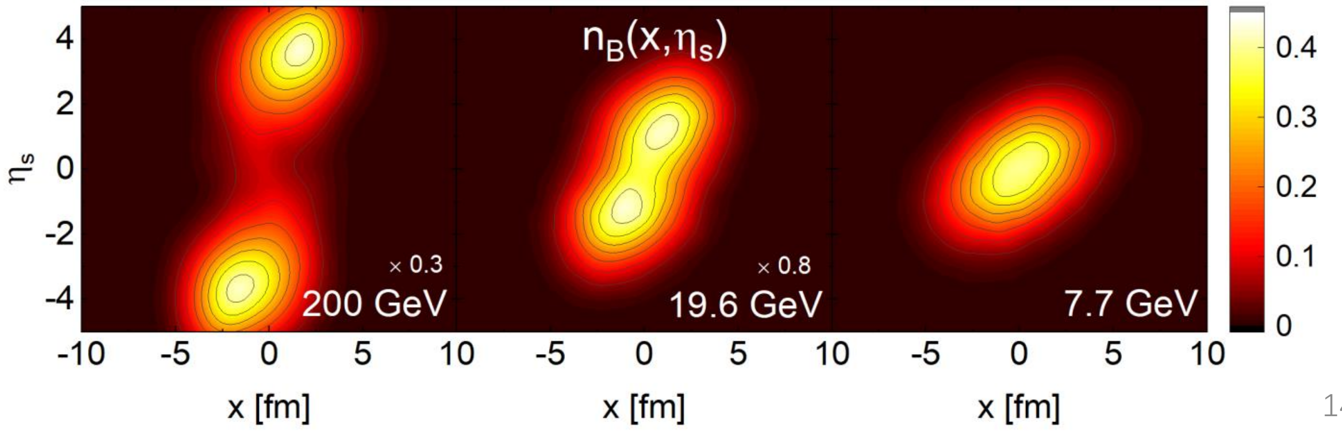


- Monotonic increasing





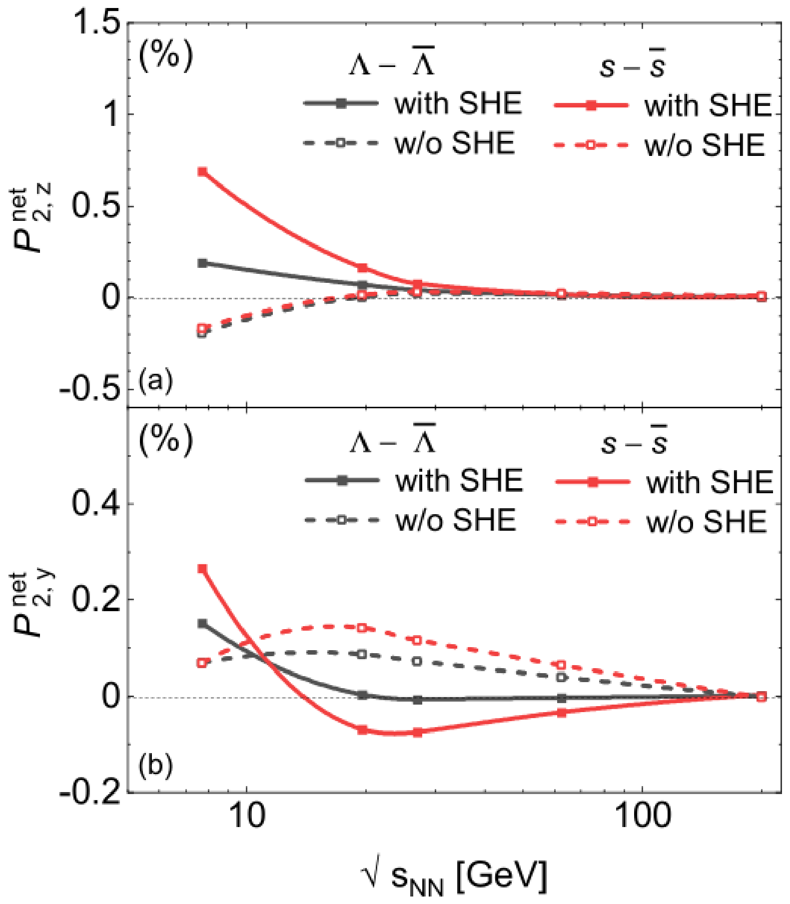
- Non-monotonic behavior



Summary

Total P^{μ} = [thermal vorticity] + [SIP] + [SHE]

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



- Particle – Anti-particle **separation**
- Relevant for RHIC-BES and RHIC/LHC forward rapidity
- Possibly observed by 2nd Fourier coefficients and be used to constrain initial condition / EoS

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

Back up

Individual contributions to $P_z(\phi)$ and $P_y(\phi)$

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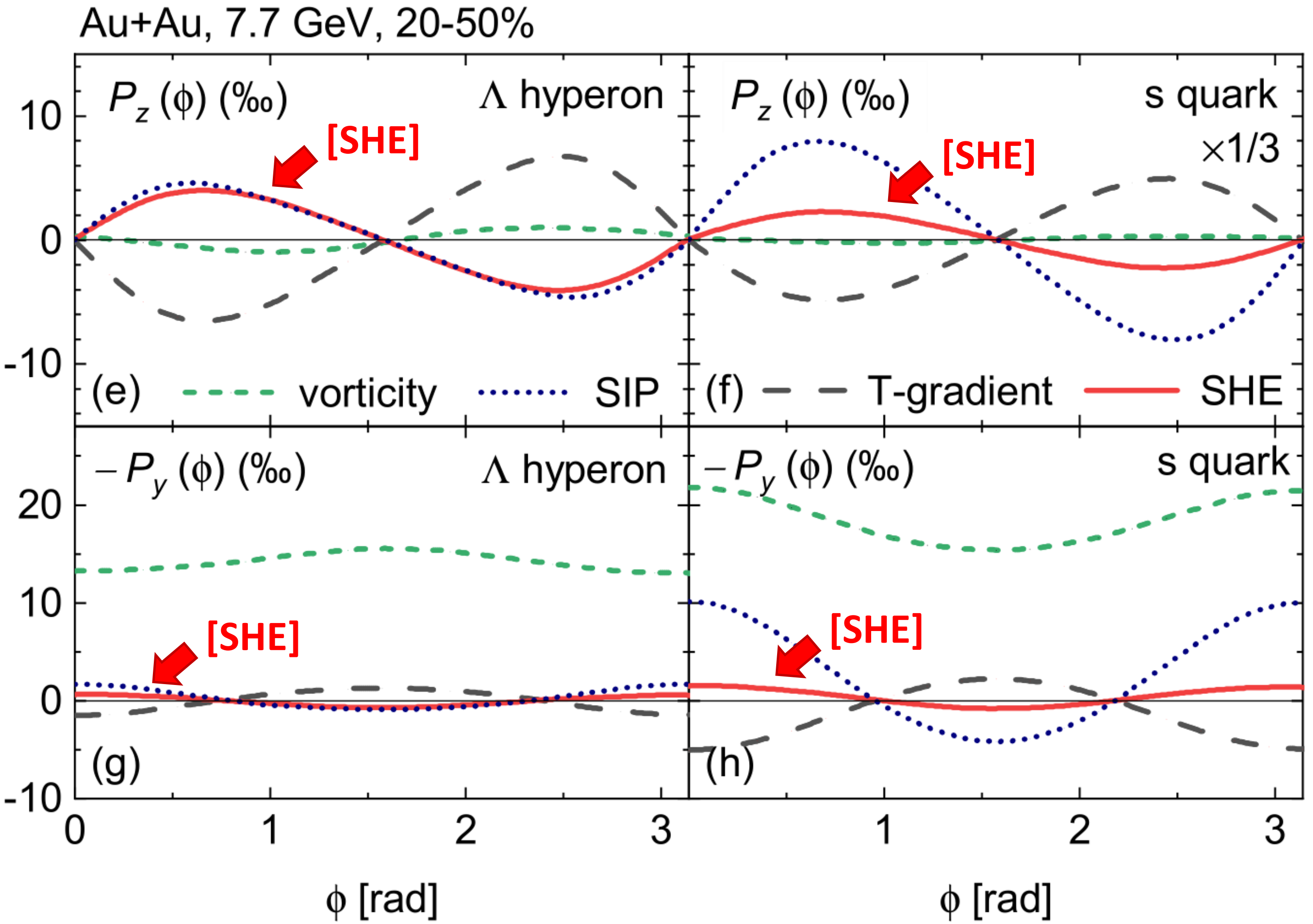
Total P^{μ} = [vorticity] + [T grad] + [SIP] + [SHE] $\vec{P}_{\mathrm{SHE}} \propto \pm \vec{p} \times \vec{\nabla} \mu_B$

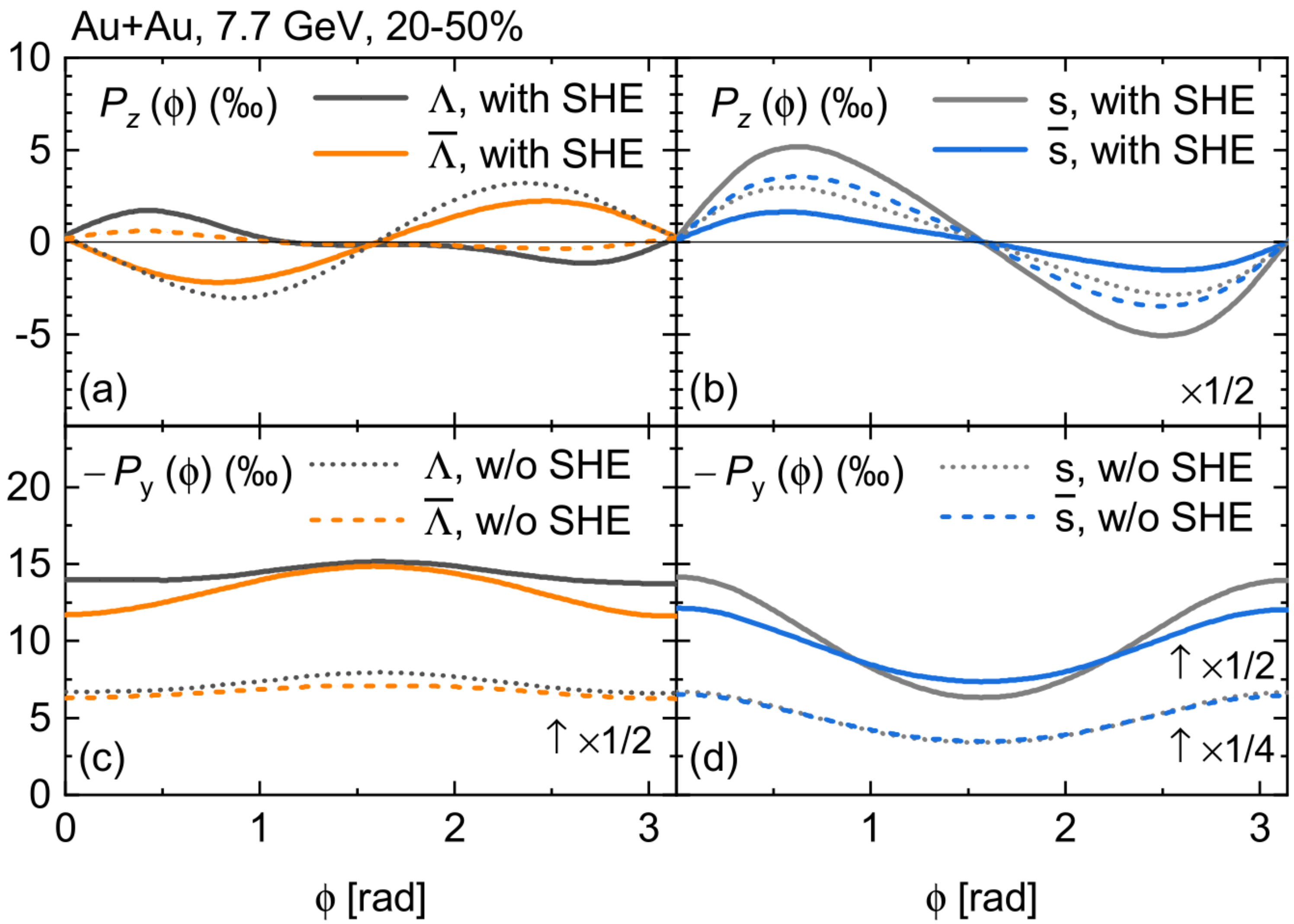


- SHE: "$\sin(2\phi)$" on P_z & "$\cos(2\phi)$" on P_y
- The magnitude of SHE is comparable to other effects
- Opposite SHE for particles and anti-particles

Total $P_z(\phi)$ and $P_y(\phi)$ with SHE

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

Total P^{μ} = [vorticity] + [Grad T] + [SIP] + [SHE] $\vec{P}_{\rm SHE} \propto \pm \vec{p} \times \vec{\nabla}\mu_B$



- Separation between particles and anti-particles by SHE
- Different local polarization w/o SHE:
  - Change the space-time of emitted particles
  - Pauli blocking

  O. Vitiuk, et al., PLB 2020

  R-H. Fang, et al., PRC 2016
- Scenario independent

Baryonic Spin Hall effect (SHE)

Poster-(Bulk,14/06)
Qiang Hu (STAR)

Condensed matter

$$s \propto \pm p \times E$$

Heavy Ion Collisions

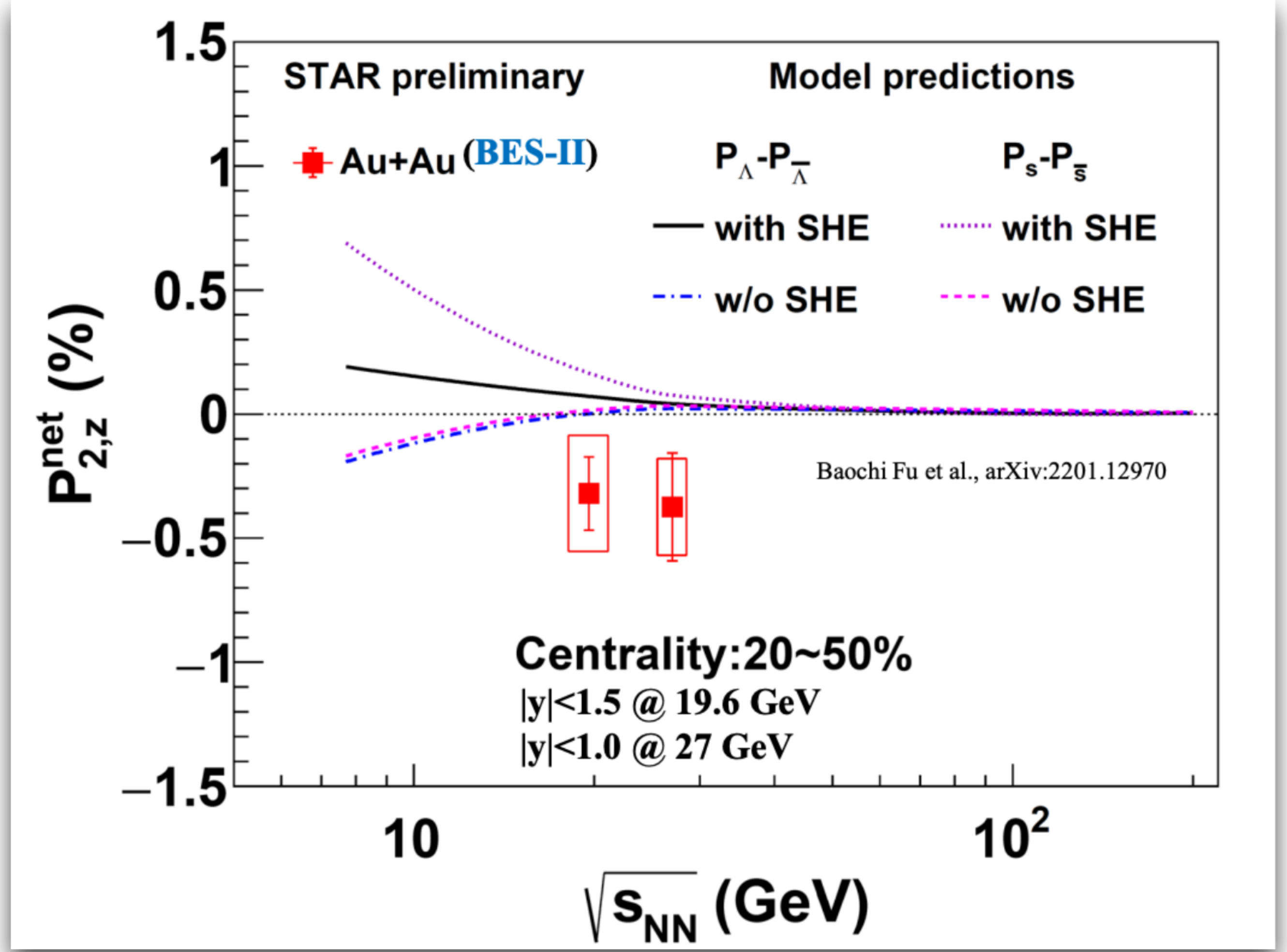
$$s \propto \pm p \times \nabla \mu_B$$

Predicted Spin Hall type effect driven by gradient of baryonic density ($\nabla \mu_B$)

Can be accessed by splitting in local polarization of Λ and $\overline{\Lambda}$: $P_z^{\Lambda} - P_z^{\overline{\Lambda}}$

Fu et., al., arXiv: 2201.12970

Polarization ~ vorticity $\oplus$ ∇T $\oplus$ Shear $\oplus$ $\nabla \mu_B$



- $P_z^{\Lambda} - P_z^{\overline{\Lambda}}$ ~< 0 : No indication of baryonic SHE yet
- Measurement at lower energies?