Spin polarization and the baryonic Spin Hall Effect

Baochi Fu (Peking University)

- Spin polarization & Local polarization puzzle
- Shear Induced Polarization (SIP)
- Baryonic Spin Hall Effect (SHE)

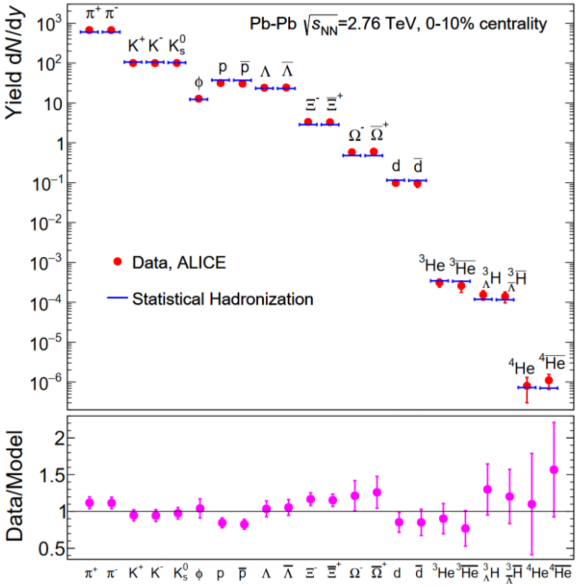
BF, K. Xu, XG. Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903
BF, S. Liu, LG. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021)
BF, LG. Pang, H. Song and Y. Yin, arXiv:2201.12970

Exploring QGP through soft and hard probes
SANU, 29-31 May 2023

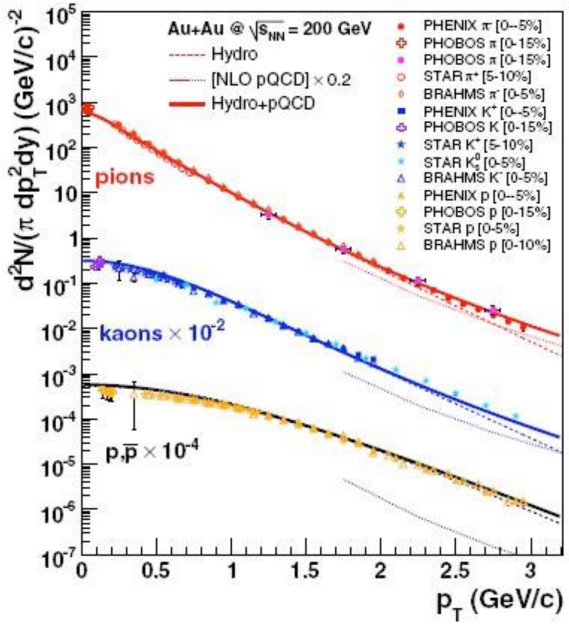
Explore QGP through soft probes

Soft probes with finer details

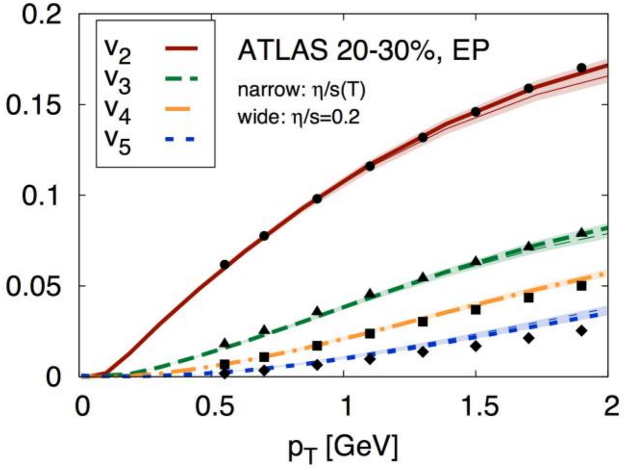
Particle Yields (T & μ_B)



p_T/y Spectra ($\langle u^\mu \rangle$)



Anisotropic Flow ($u^\mu(x)$)

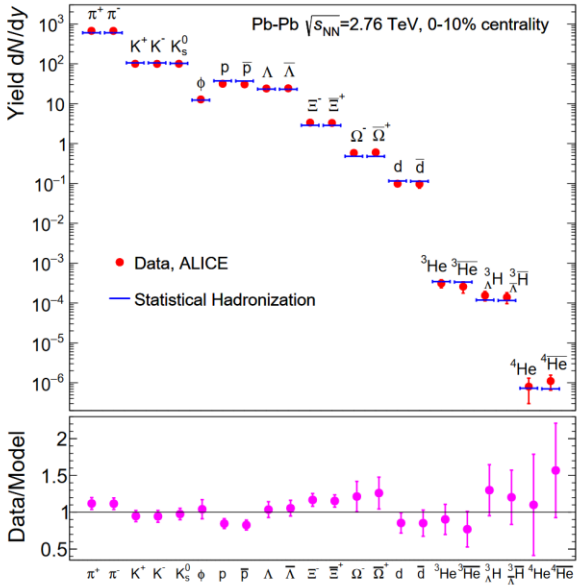


Credit: M. Lisa, X. Huang

Explore QGP through soft probes

Soft probes with finer details

Particle Yields $(\mathrm{T}\ \&\ \mu_B)$



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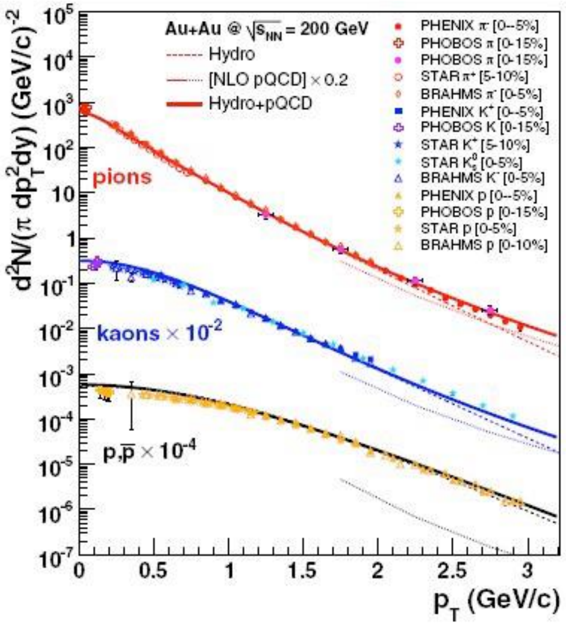

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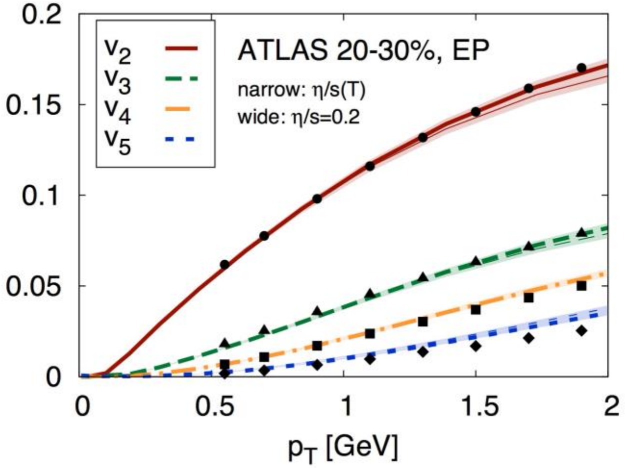
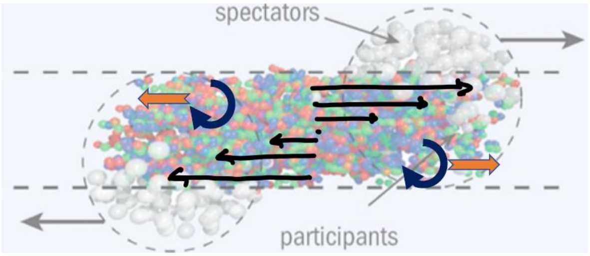


Spin Polarization

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



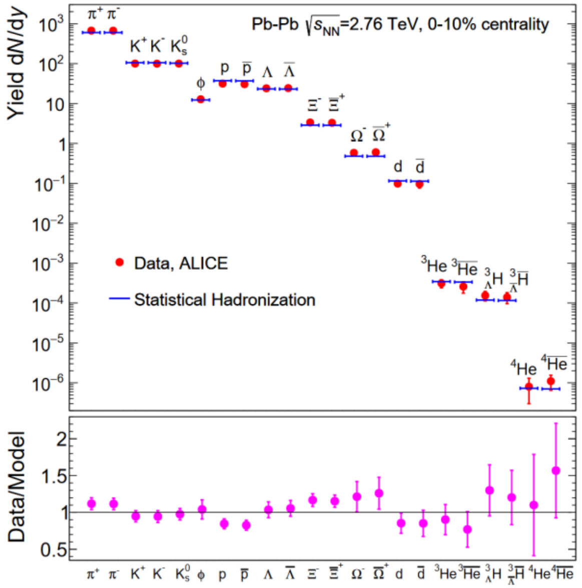
$$\boxed{\boldsymbol{\omega} = \frac{1}{2}\nabla\times\boldsymbol{v}}$$

Credit: M. Lisa, X. Huang

Explore QGP through soft probes

Soft probes with finer details

Particle Yields $(T\ \&\ \mu_B)$



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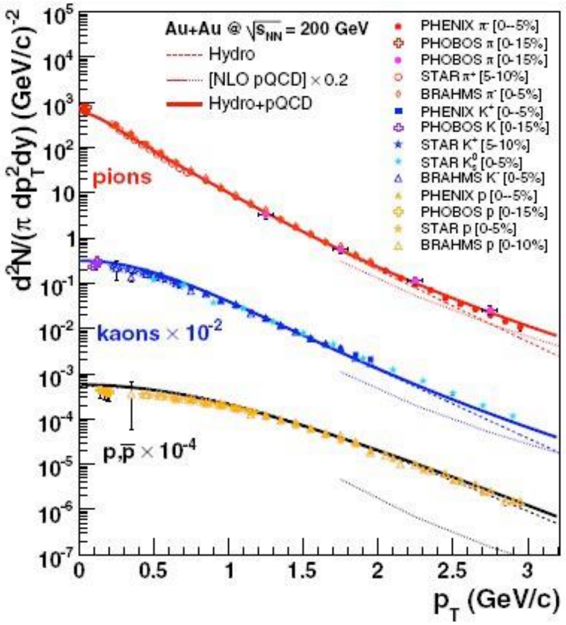

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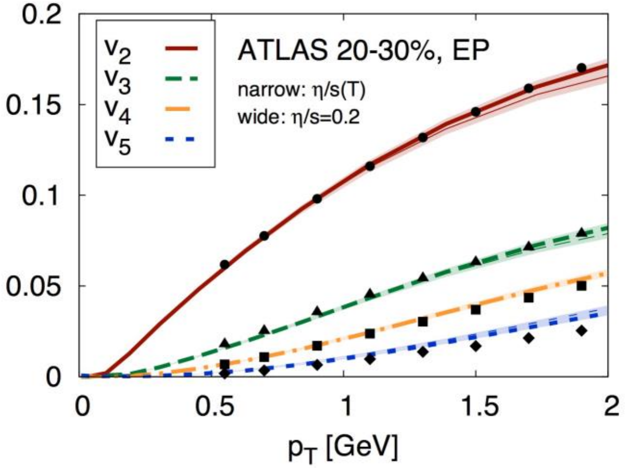

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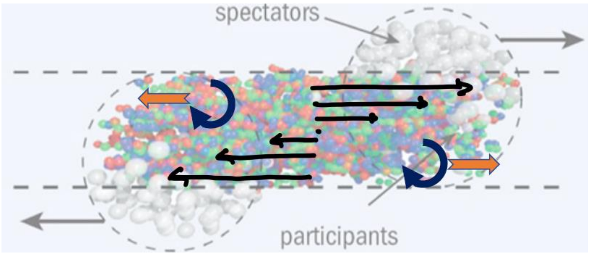
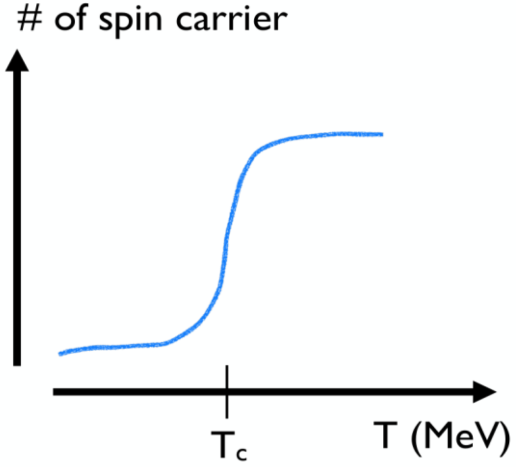


$$\boxed{\boldsymbol{\omega} = \frac{1}{2}\boldsymbol{\nabla}\times\boldsymbol{v}}$$

Sensitive probe of

QCD phase transition

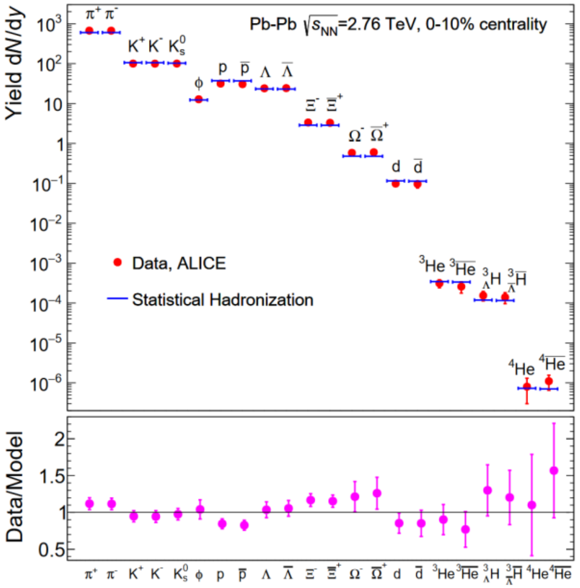


Credit: M. Lisa, X. Huang

Explore QGP through soft probes ← spin polarization

Soft probes with finer details

Particle Yields (T & μ_B)



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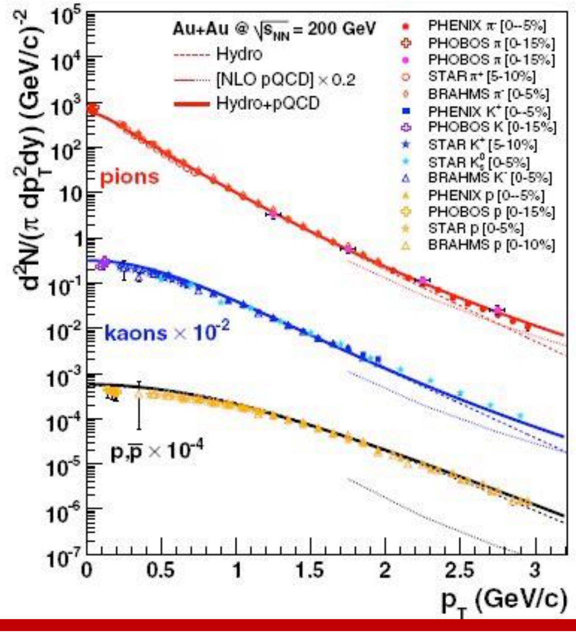

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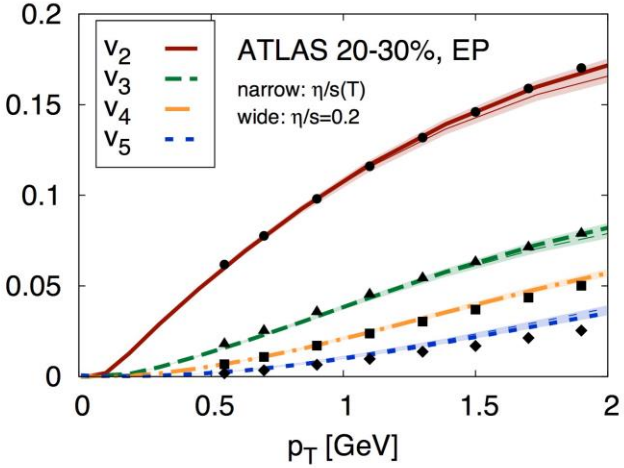

Spin Polarization

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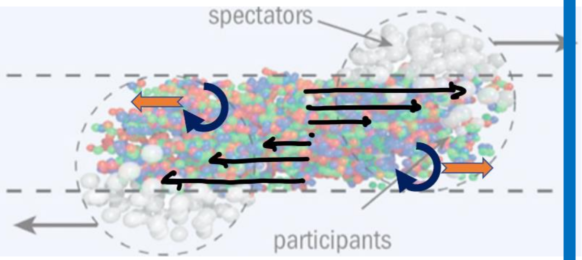

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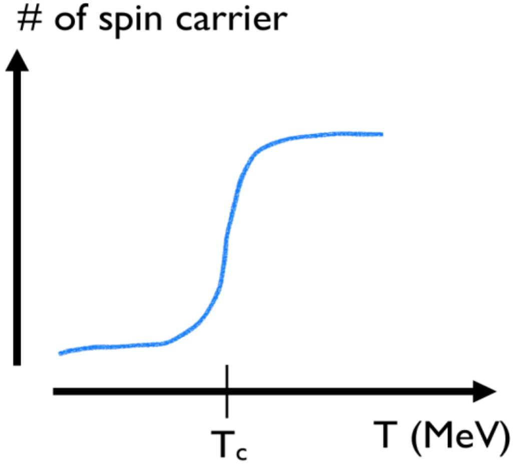


Sensitive probe of QCD phase transition

Exploring QGP through spin observables

Electronics (Flavortronics) Vs. **Spintronics**

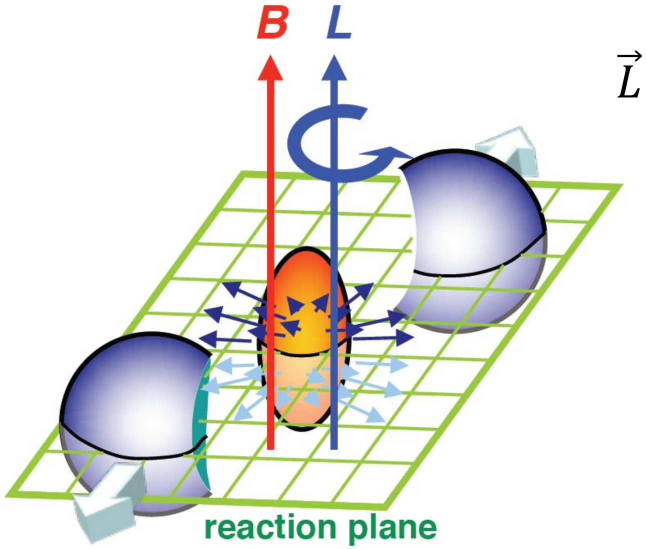
Credit: M. Lisa, X. Huang

Introduction: Spin Polarization

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)



$\vec{L} \rightarrow \vec{L}_{\text{QGP}}(\text{vorticity})$

RHIC: $L = 10^5\ \hbar$
LHC: $L = 10^7\ \hbar$

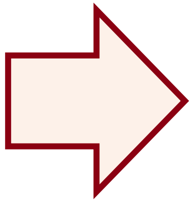
Observable prediction

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

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

- Global polarization of emitted hadrons

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



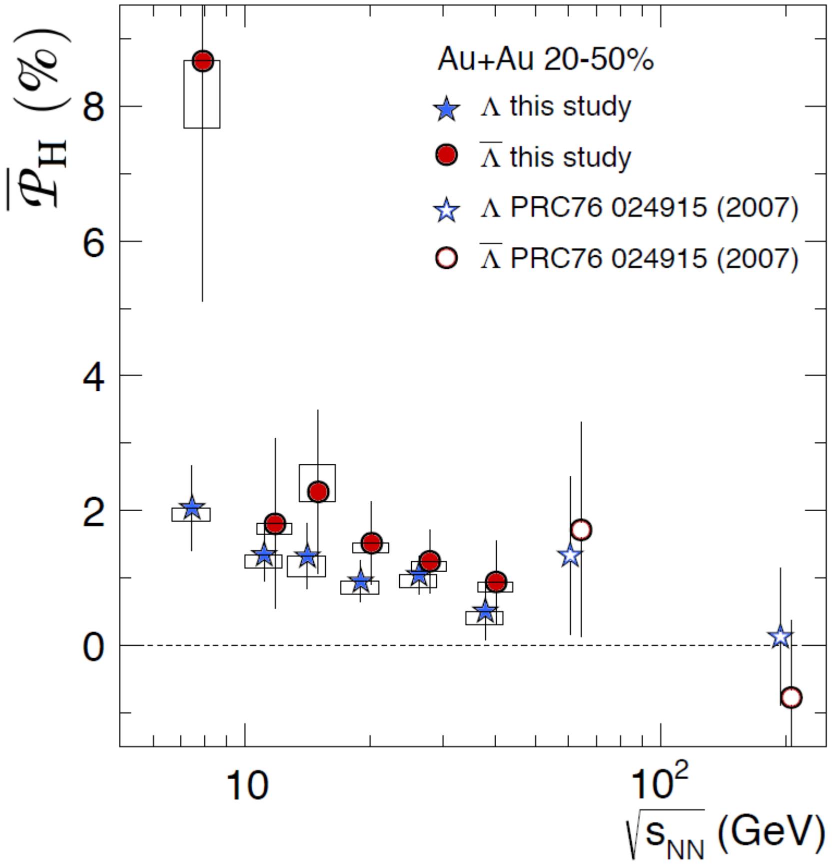
Global quark polarization

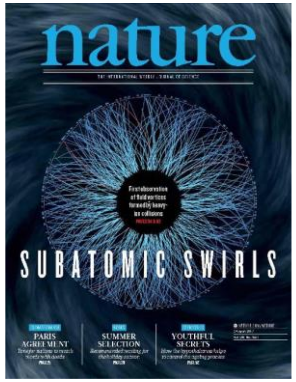
- Hyperon polarization
- Meson spin alignment

Global polarization measurements

Hyperon global polarization

STAR Collaboration, Nature 548, 62 (2017)



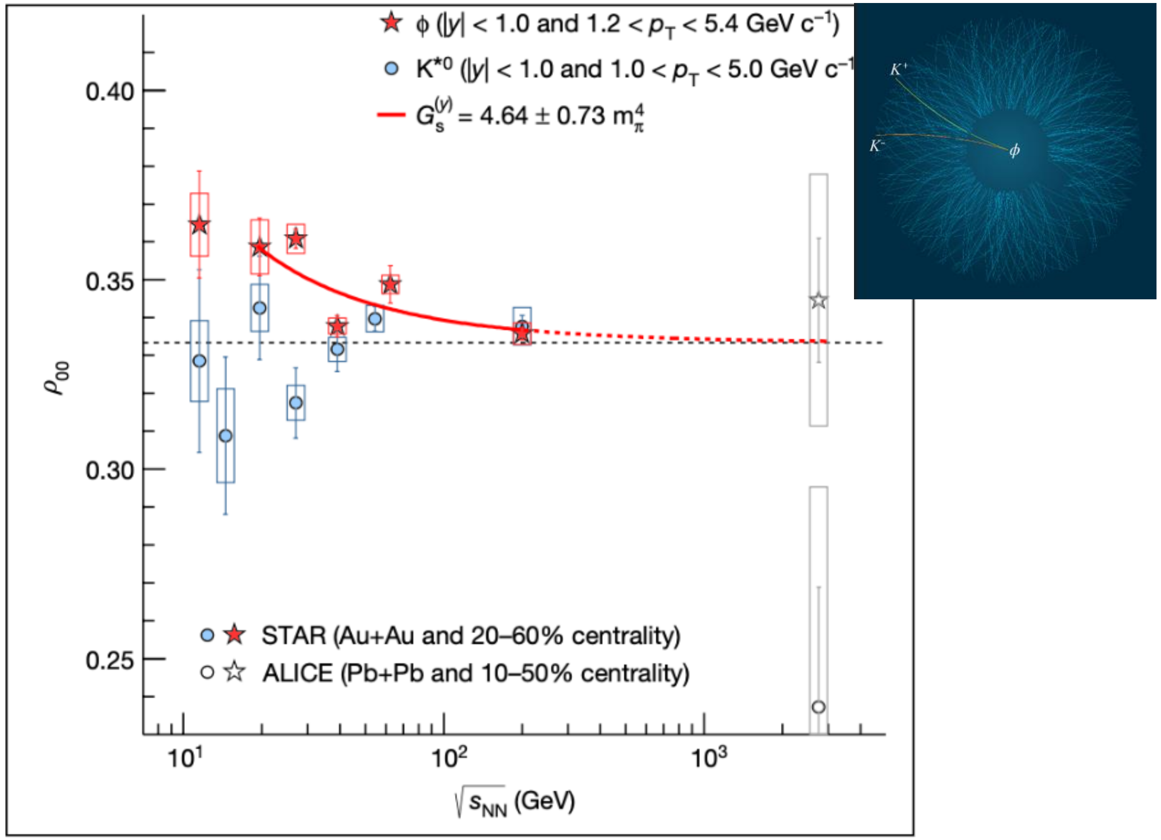


$$\omega = (P_{\Lambda} + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22} s^{-1}$$

Most vortical fluid!

Meson spin alignment

STAR Collaboration, Nature 614, 224 (2023)



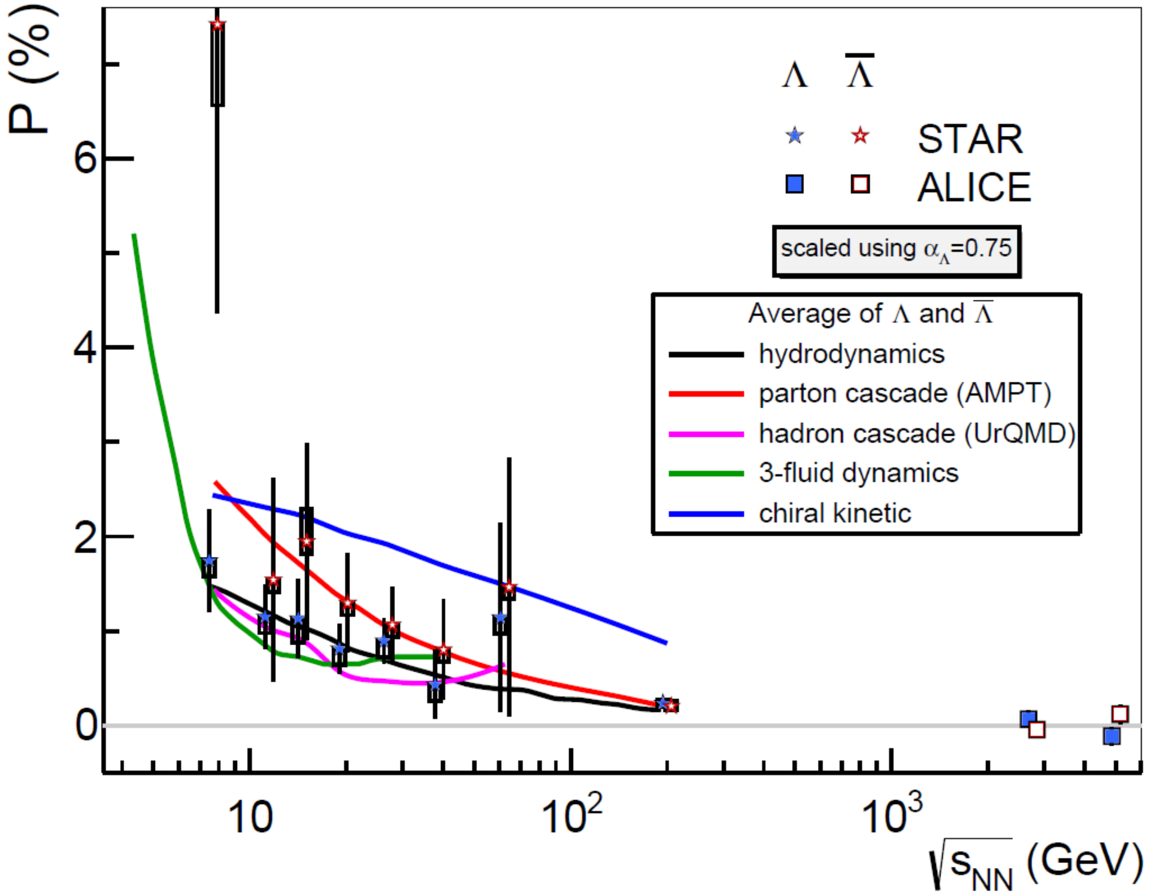
A possible avenue to study strong force field

Hydrodynamics describe global polarization

Thermal vorticity induced polarization (global eq.)

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

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



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

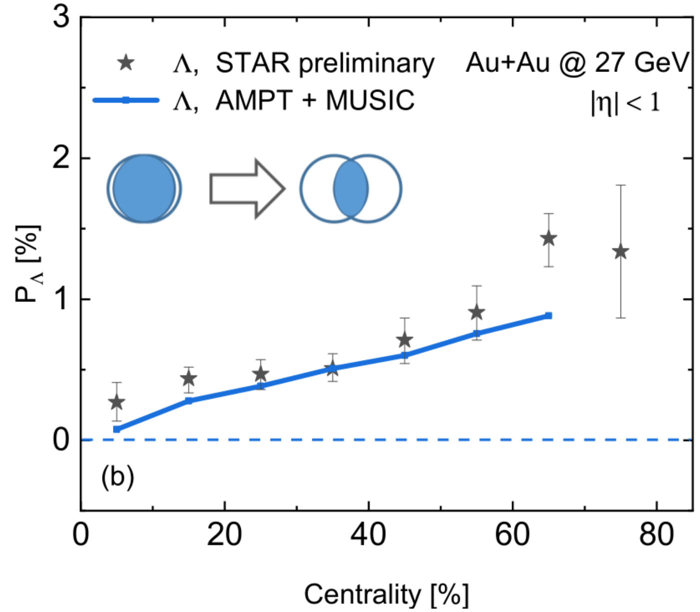
3-fluid dynamics:
Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)

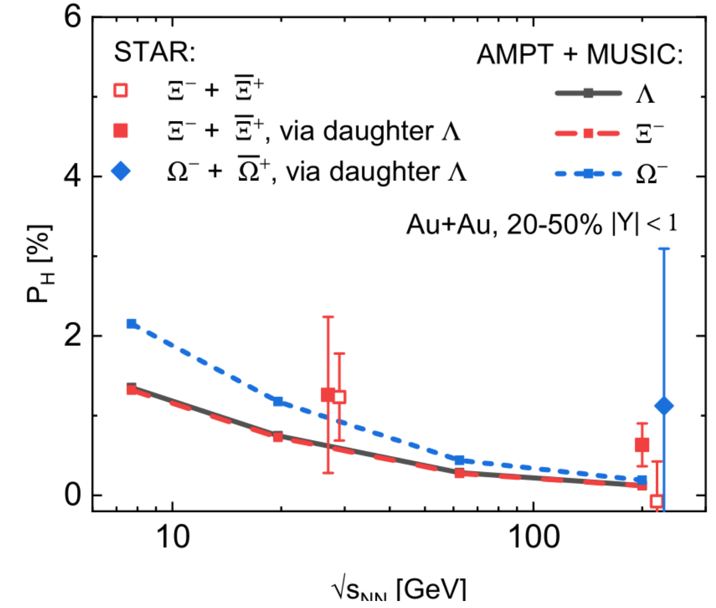
Chiral Kinetic Theory (chiral vorticity):
Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

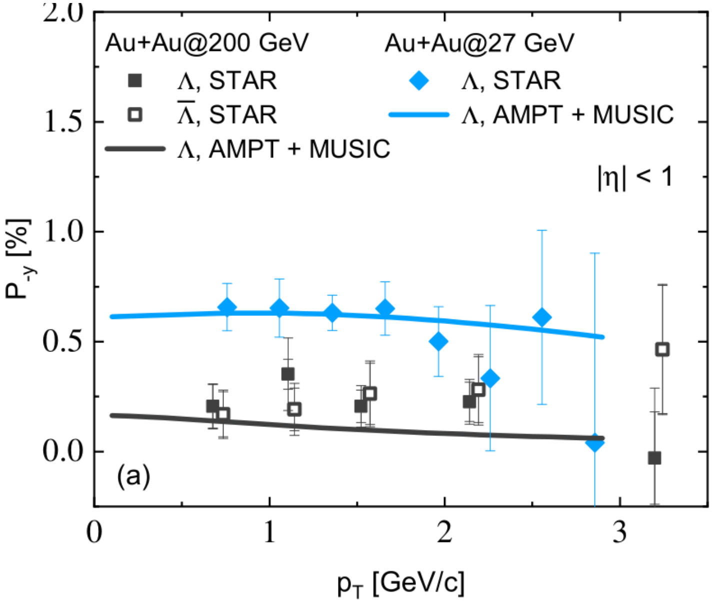
F. Becattini and M. Lisa, Ann.Rev.Nucl.Part.Sci. 70 (2020) 395-423

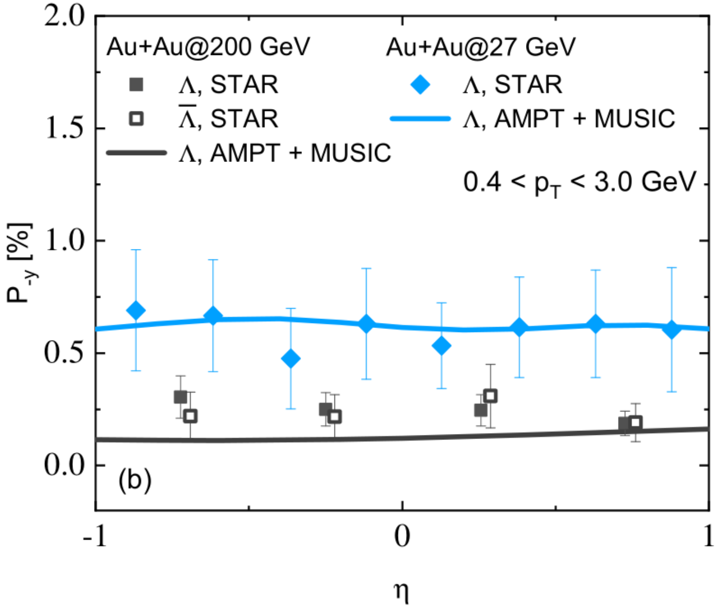
Hydrodynamics describe global polarization

- Centrality dependence
- Transverse momentum dependence
- Pseudo-rapidity dependence
- Ξ^- and Ω^- particles









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

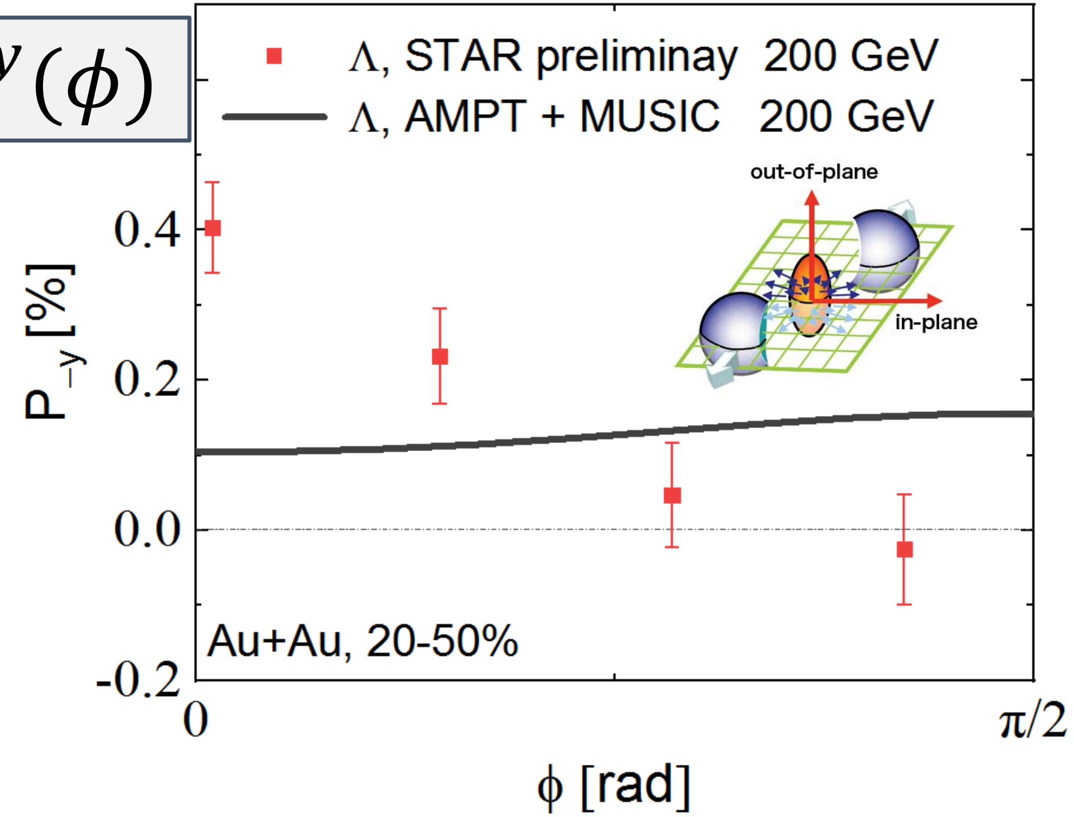
See also:
Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)
Li H, Xia X, Huang X, Huang H, Phys.Lett.B 827 (2022) 136971

local polarization puzzle

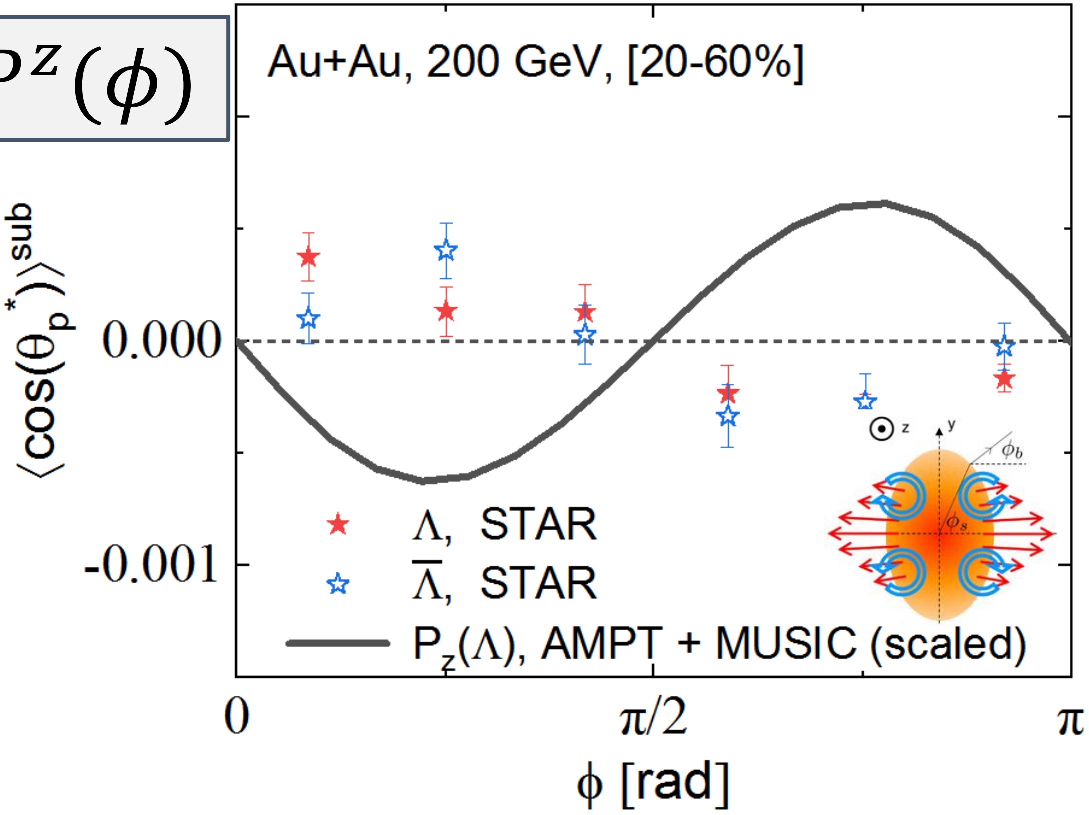
BF, K. Xu, X-G, Huang, H. Song, PRC 103 (2021) 2, 024903

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

$P^y(\phi)$



$P^z(\phi)$



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’ …

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 Csernai, ECT talk 2020, Csernai, Kapusta, Welle, PRC 2019)
- …

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

Shear-Induced Polarization

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

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

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 $\boldsymbol{\mathcal{A}^\mu}$ to 1st order gradient of the fields:

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

Thermal vorticity

Shear-Induced Polarization

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)

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

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

- 'Spin Cooper-Frye' Formula

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

- 'Λ equilibrium': $\tau_{\text{spin},\Lambda} \to 0, \quad P_\Lambda$
- 'Strange memory': $\tau_{\text{spin},\Lambda} \to \infty, \quad P_\Lambda = P_s$

$P^\mu(\phi)$ with shear-induced polarization

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

P^μ = [thermal vorticity] + [Shear]

- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

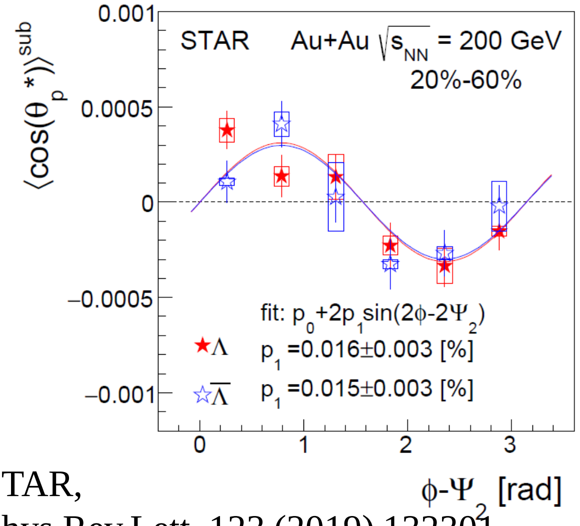
- See also:

Hydrodynamics(vhlle with iso-thermal)
F. Becattini, et al., Phys.Rev.Lett. 127 (2021) 27, 272302

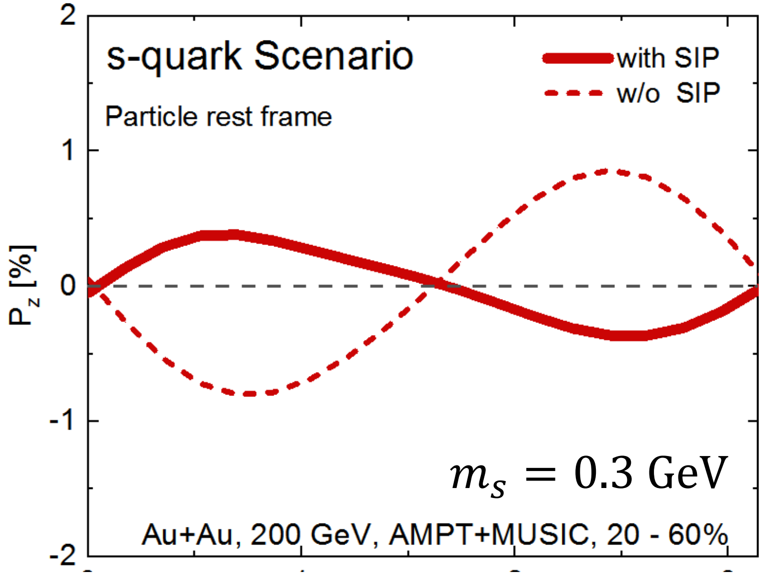
Hydrodynamics(CLVisc)
C. Yi, et al., Phys.Rev.C 104 (2021) 6, 064901

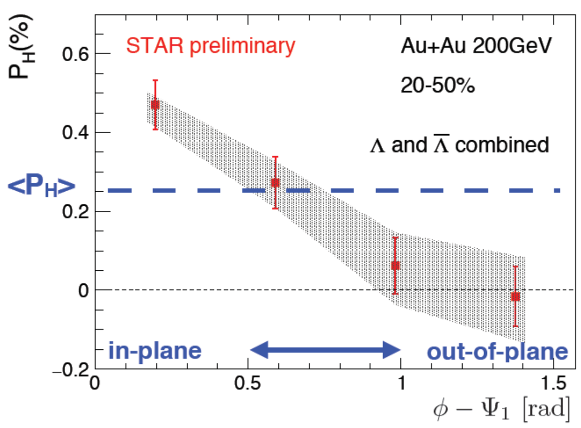
UrQMD
Y. Sun, et al, Phys.Rev.C 105 (2022) 3, 034911

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

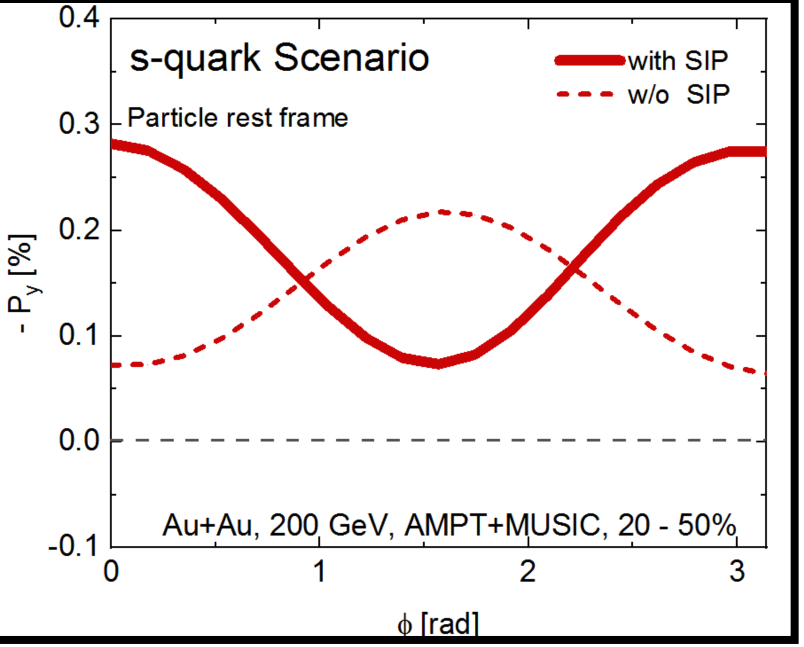


STAR,
Phys.Rev.Lett. 123 (2019) 132301





STAR,
NPA, 982 (2019) 511-514

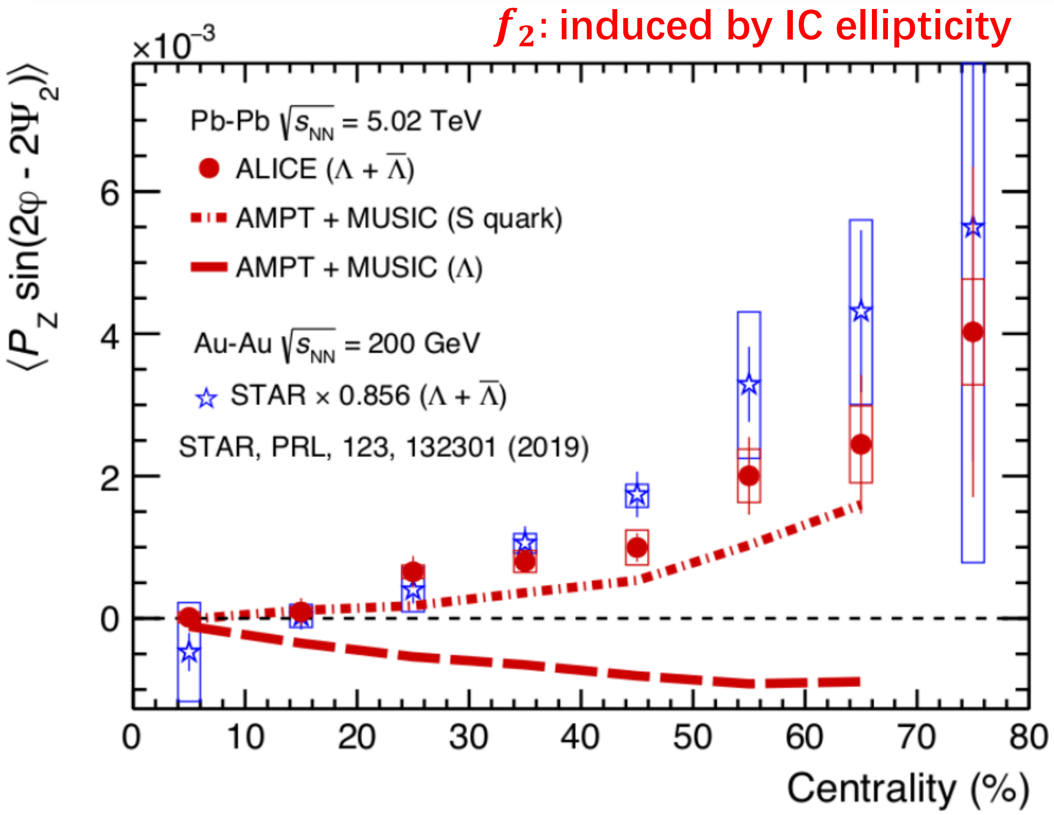


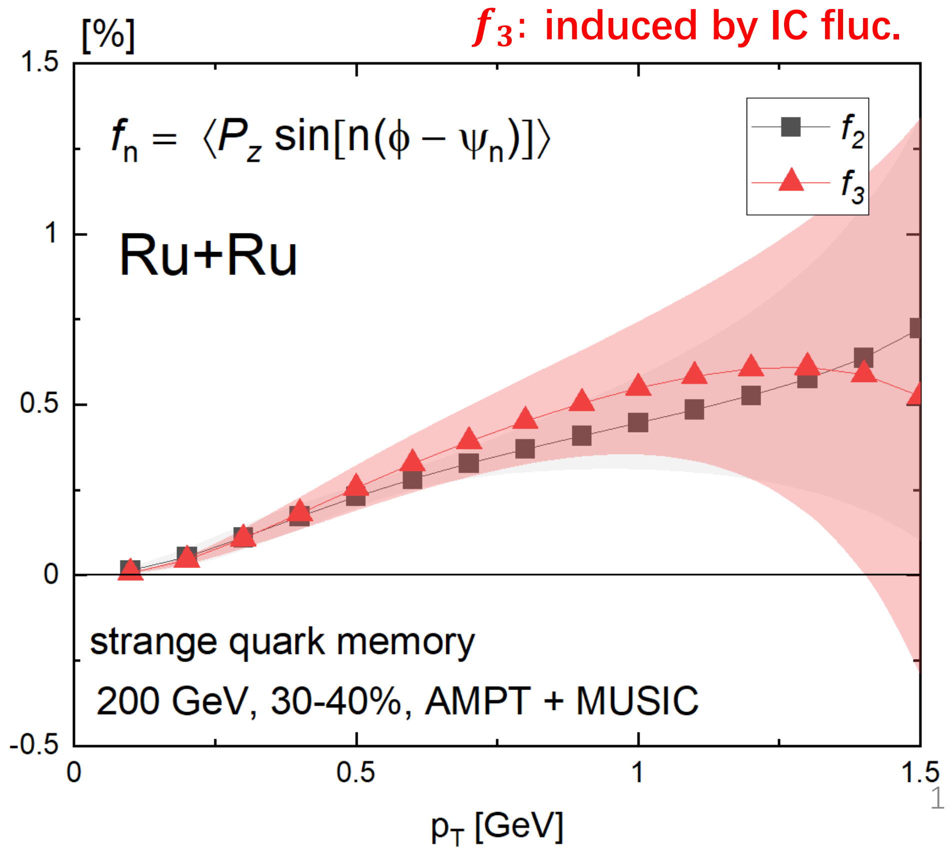
Toward quantitative description

- “Strange Memory” scenario qualitatively describes the 2nd Fourier coefficient f_2 in both RHIC and LHC
- Non-zero f_3 probes the initial state fluctuations in event-by-event simulation

ALICE: A journey through QCD, arXiv: 2211.04384

BF, Y. Wang, H. Song, in preparation





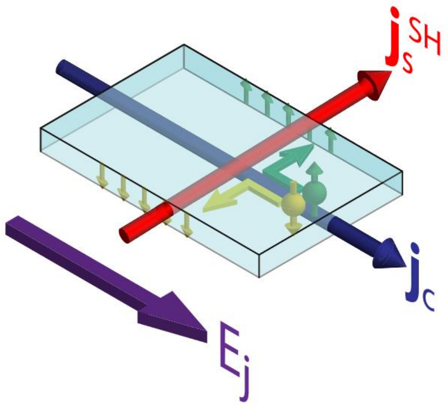
How about with finite μ_B?

Baryonic Spin Hall Effects (SHE) at RHIC-BES

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
- In this talk: Baryonic Spin Hall Effects (SHE)

- 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)

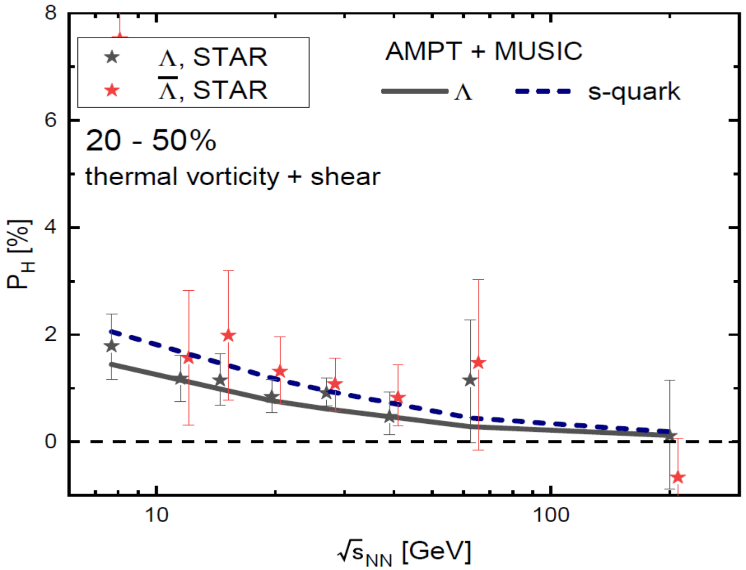
Axial Wigner function $\mathcal{A}^\mu$ expansion with finite chemical potential: S. Liu and Y. Yin, PRD 104, 054043 (2021)

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

- Spin current generation: search SHE signal in differential observables like $P^\mu(\phi)$ $\vec{P}_\pm \propto \pm\vec{p}\times\vec{\nabla}\mu_B$
- Induced by μ_B gradient: more important at RHIC-BES or finite rapidity
- Opposite contribution for particles / anti-particles

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

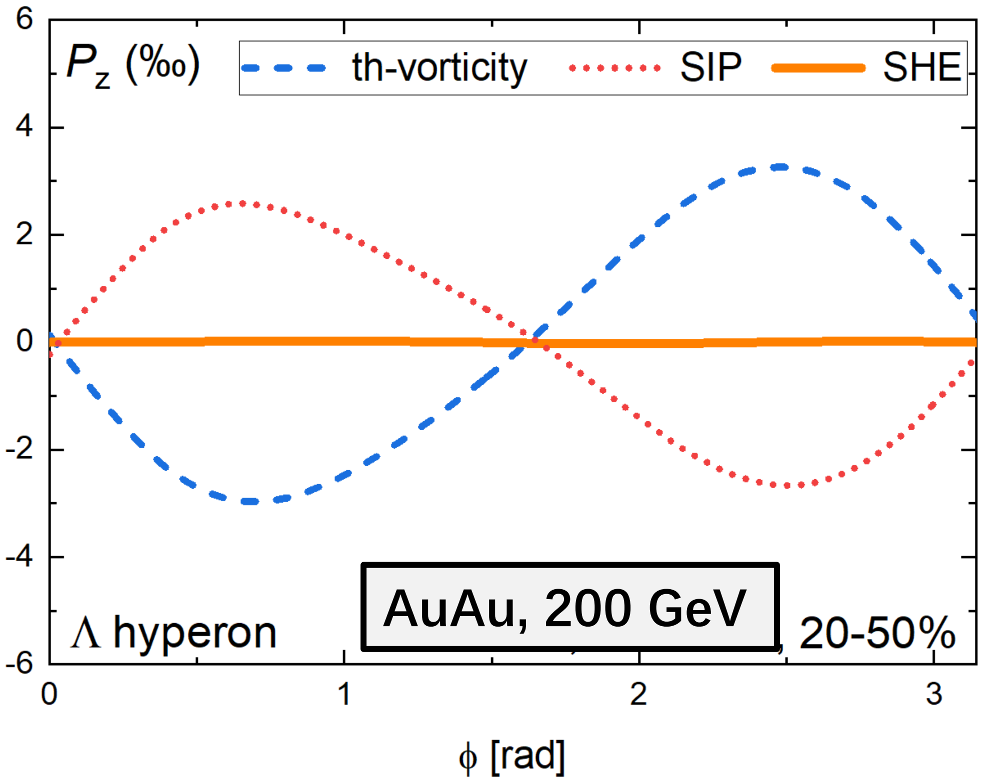
BF, K. Xu, X-G, Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903

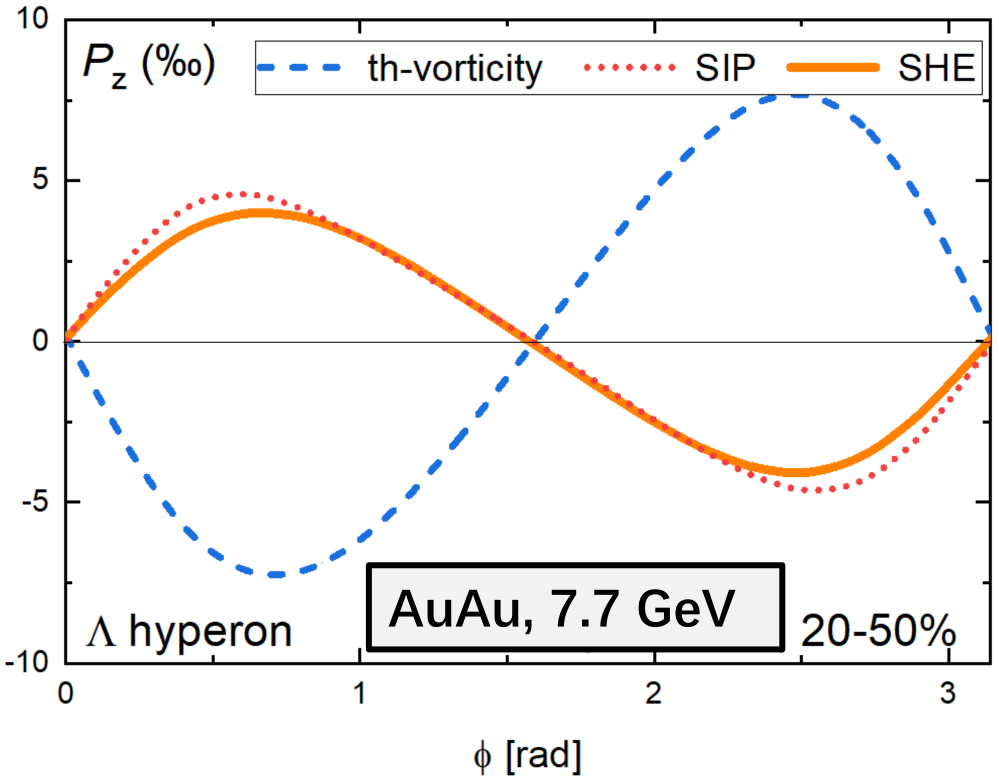


See also: S.Ryu, et al., PRC 104 (2021) 5, 054908 (Global effect)
S. Liu and Y. Yin, PRD 104 (2021) 5, 054043 (B-W model)
X. Wu, et al., PRC 105 (2022) 064909 (baryon diffusion)

Spin Hall Effects in $P_z(\phi)$

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



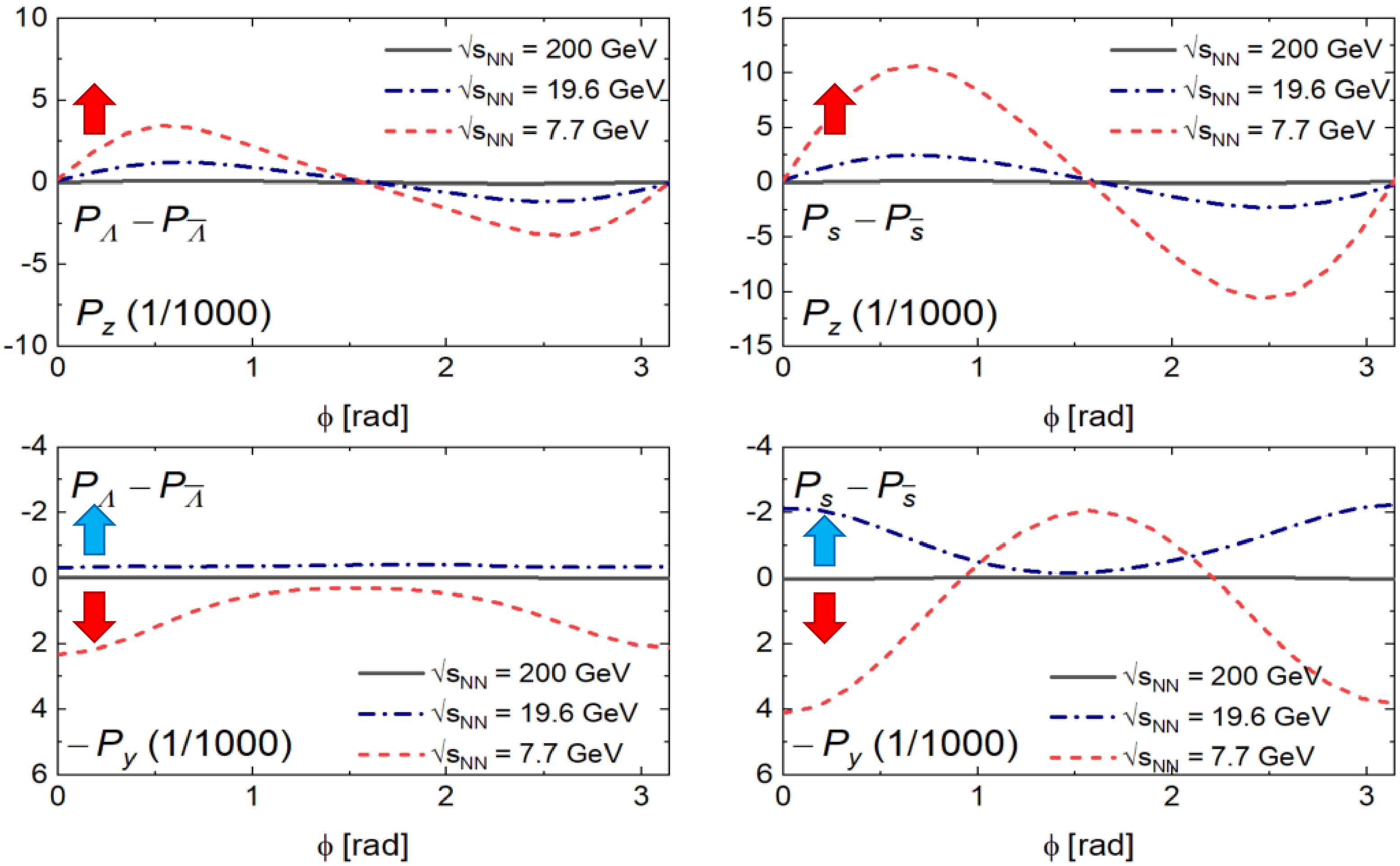


- Similar thermal vorticity and shear effects
- Sizeable Spin Hall Effects at 7.7 GeV with its magnitude comparable with other effects
- **Polarization separation:** Opposite contribution for particles / anti-particles

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

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

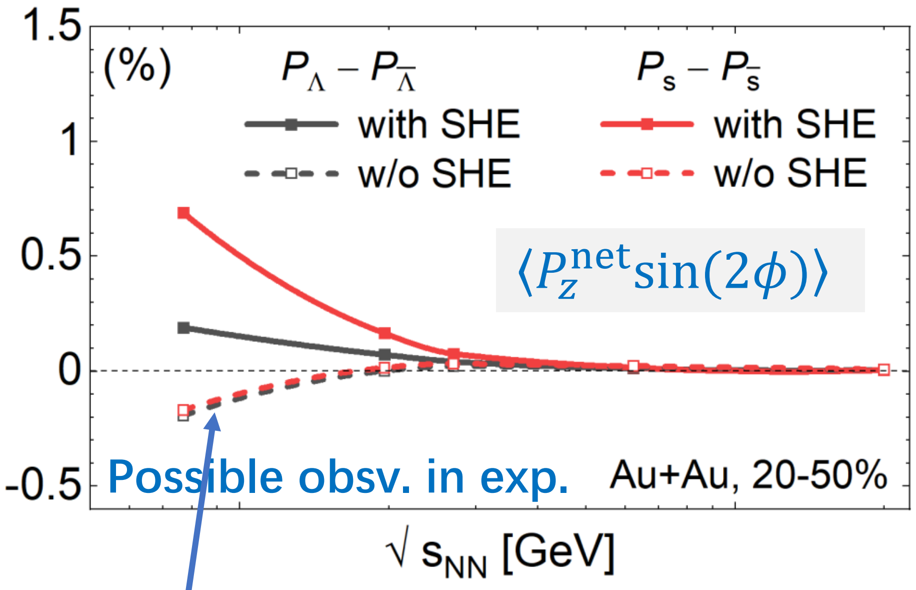
$$P_{\Lambda}^{\text{net}} \equiv P_{\Lambda}(\phi) - P_{\overline{\Lambda}}(\phi) \qquad P_{s}^{\text{net}} \equiv P_{s}(\phi) - P_{\bar{s}}(\phi)$$



- 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

The 2nd order Fourier coeff.

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



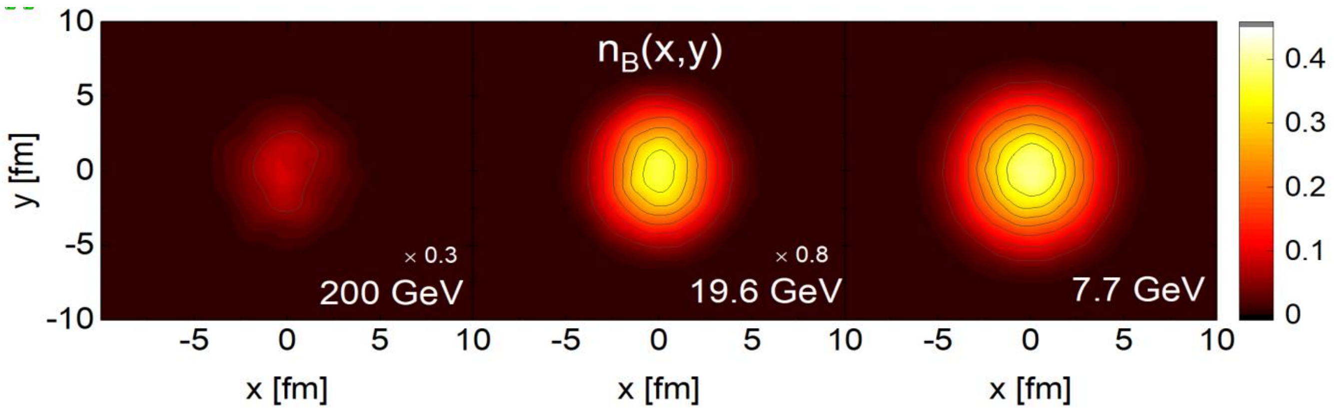
$\langle P_z^{\mathrm{net}} \sin(2\phi) \rangle$

Possible obsv. in exp.

From the distribution function

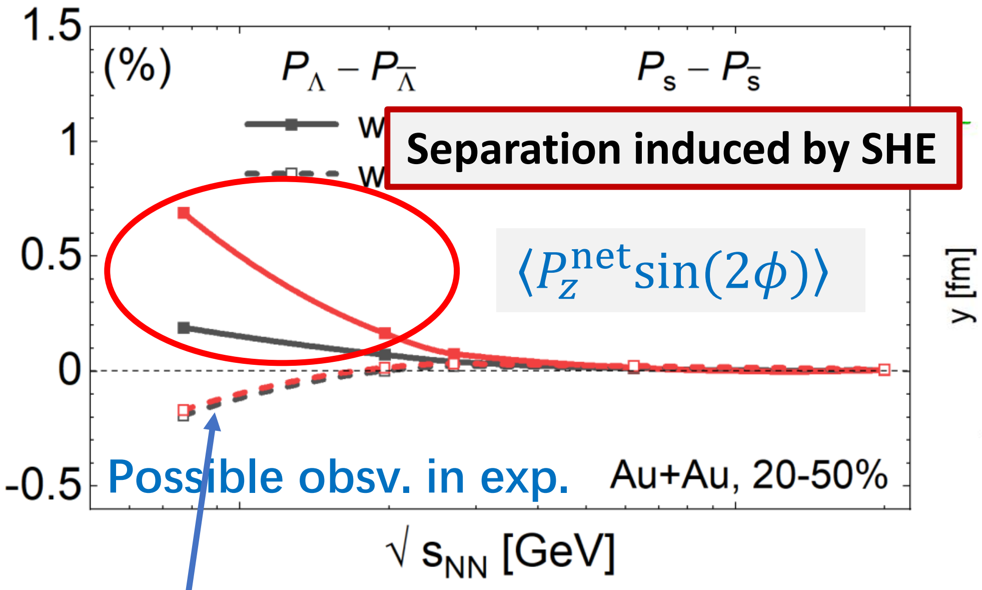
$f(x,p) = \left(e^{(\epsilon_0 - q_B \mu_B)\beta} + 1\right)^{-1}$

- Monotonic increasing



The 2nd order Fourier coeff.

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

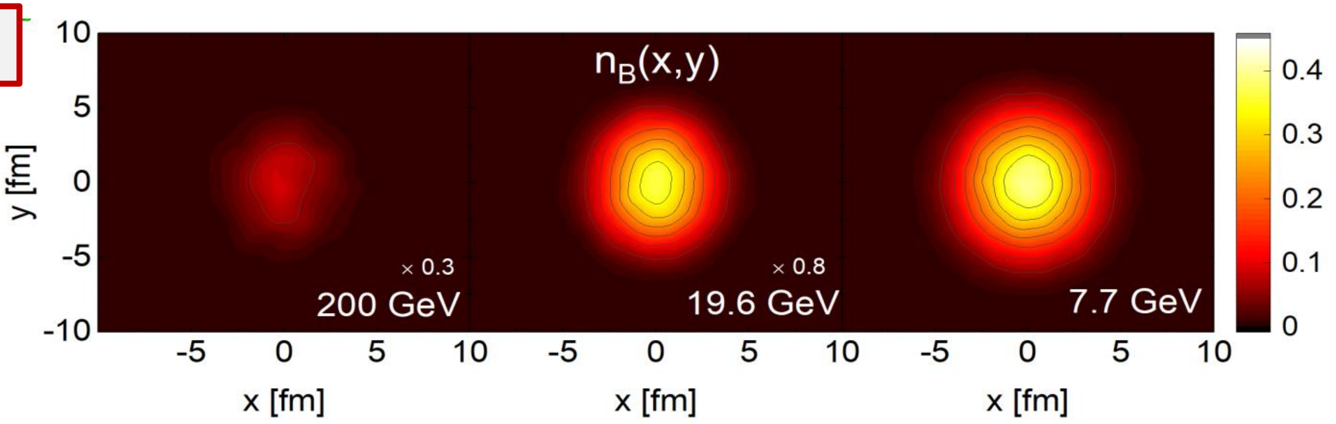


Separation induced by SHE

$\langle P_z^{\text{net}} \sin(2\phi) \rangle$

Possible obsv. in exp.

- Monotonic increasing

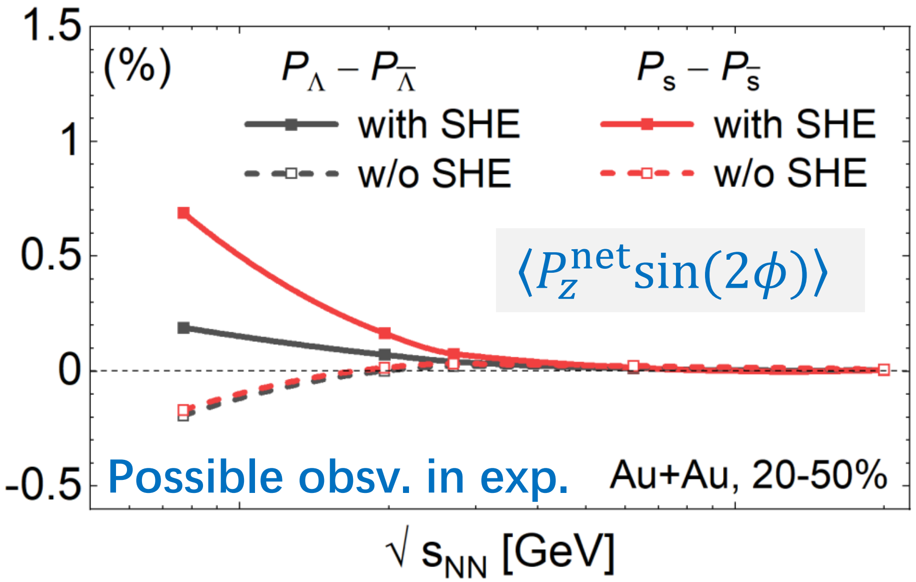


From the distribution function

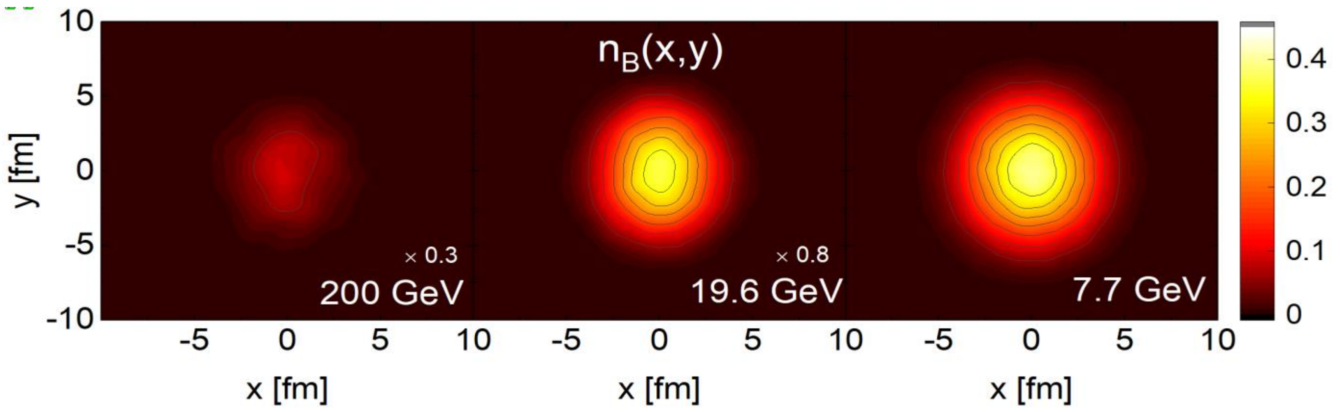
$$f(x,p) = \left(e^{(\epsilon_0 - q_B \mu_B)\beta} + 1\right)^{-1}$$

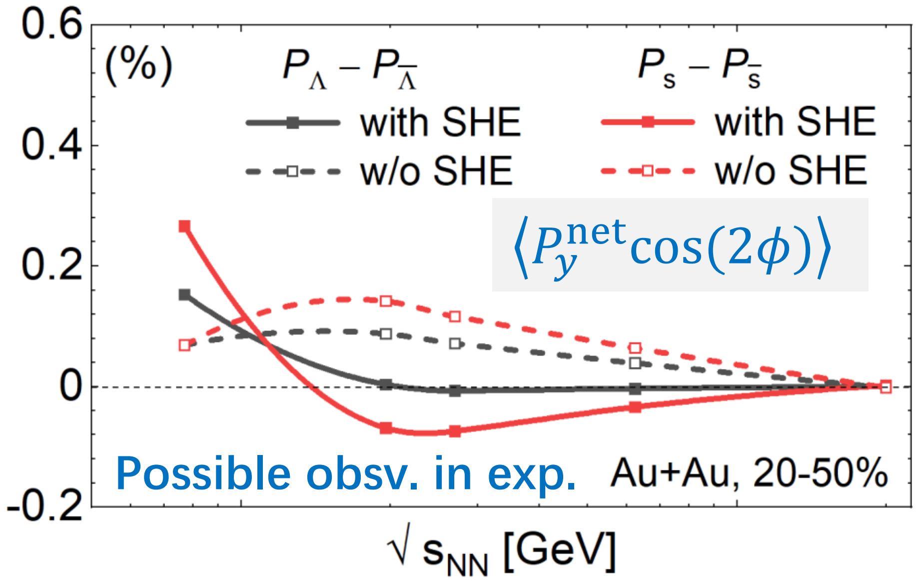
The 2nd order Fourier coeff.

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

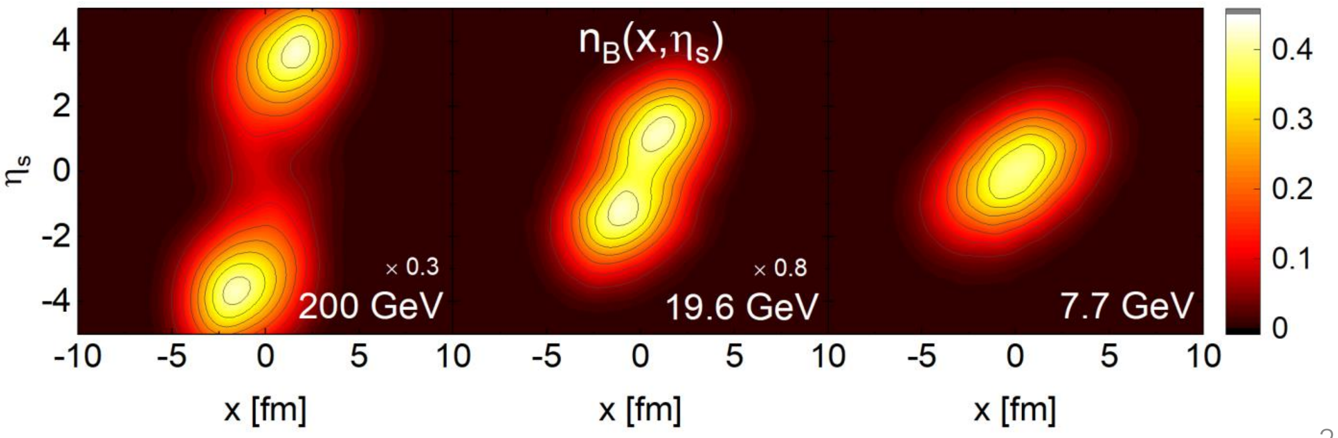


- Monotonic increasing



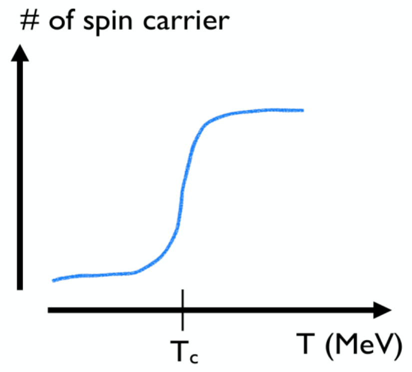


- Non-monotonic behavior



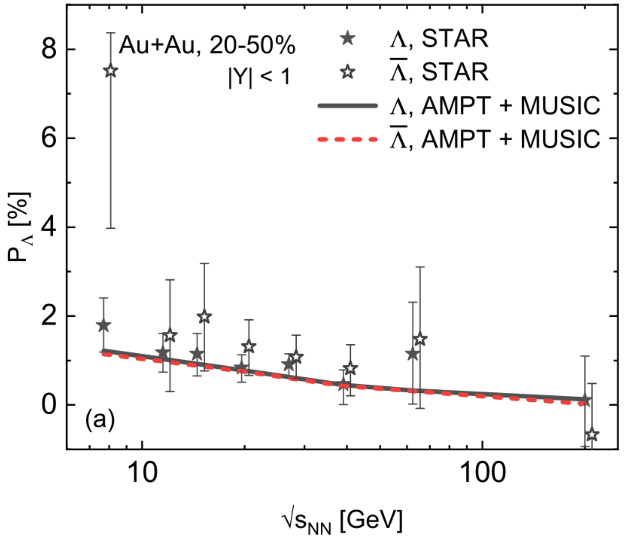
Summary

- Spin polarization reflects gradient information on surface
- Sensitive probe for EoS (CEP, 1st PT), initial n_B profile, transport properties …

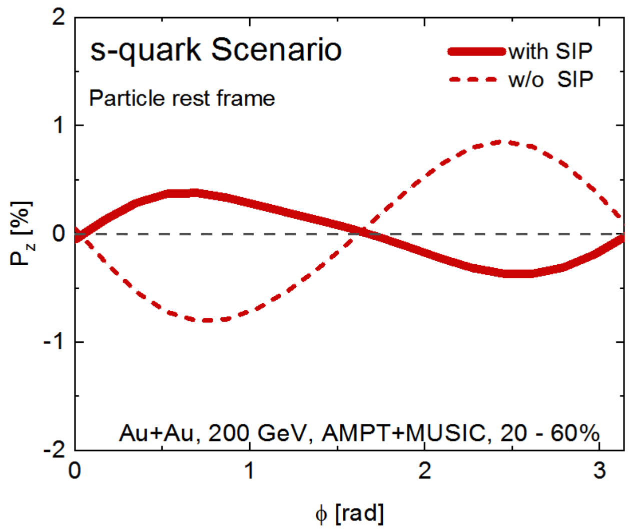


$$P^{\mu} = [\text{thermal vorticity}] + [\text{Shear}] + [\text{SHE}]$$

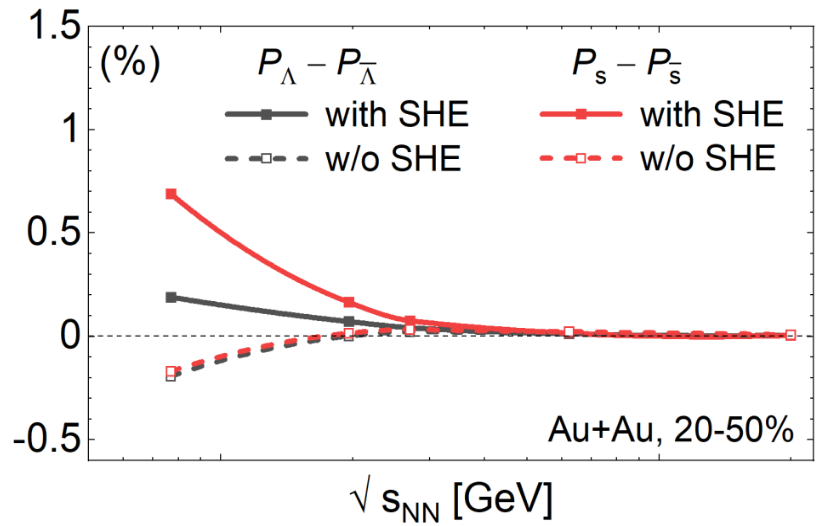
Global polarization



Essential for $P_z(\phi)$ puzzle



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

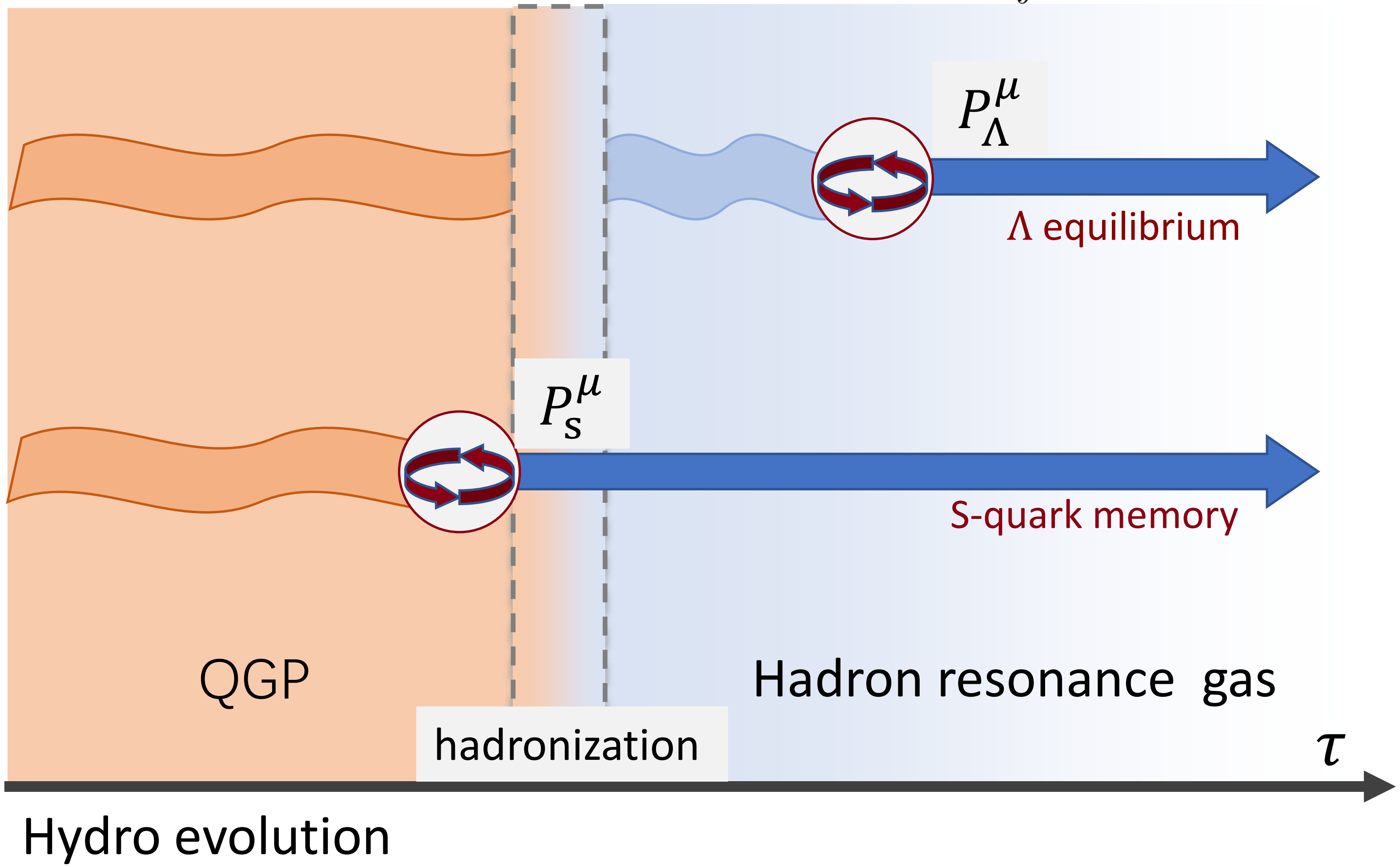


Thanks!

‘Λ equilibrium’ vs. ‘S-quark memory’

(2) Shear-Induced Polarization (SIP)
BF, S. Liu, LG. 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

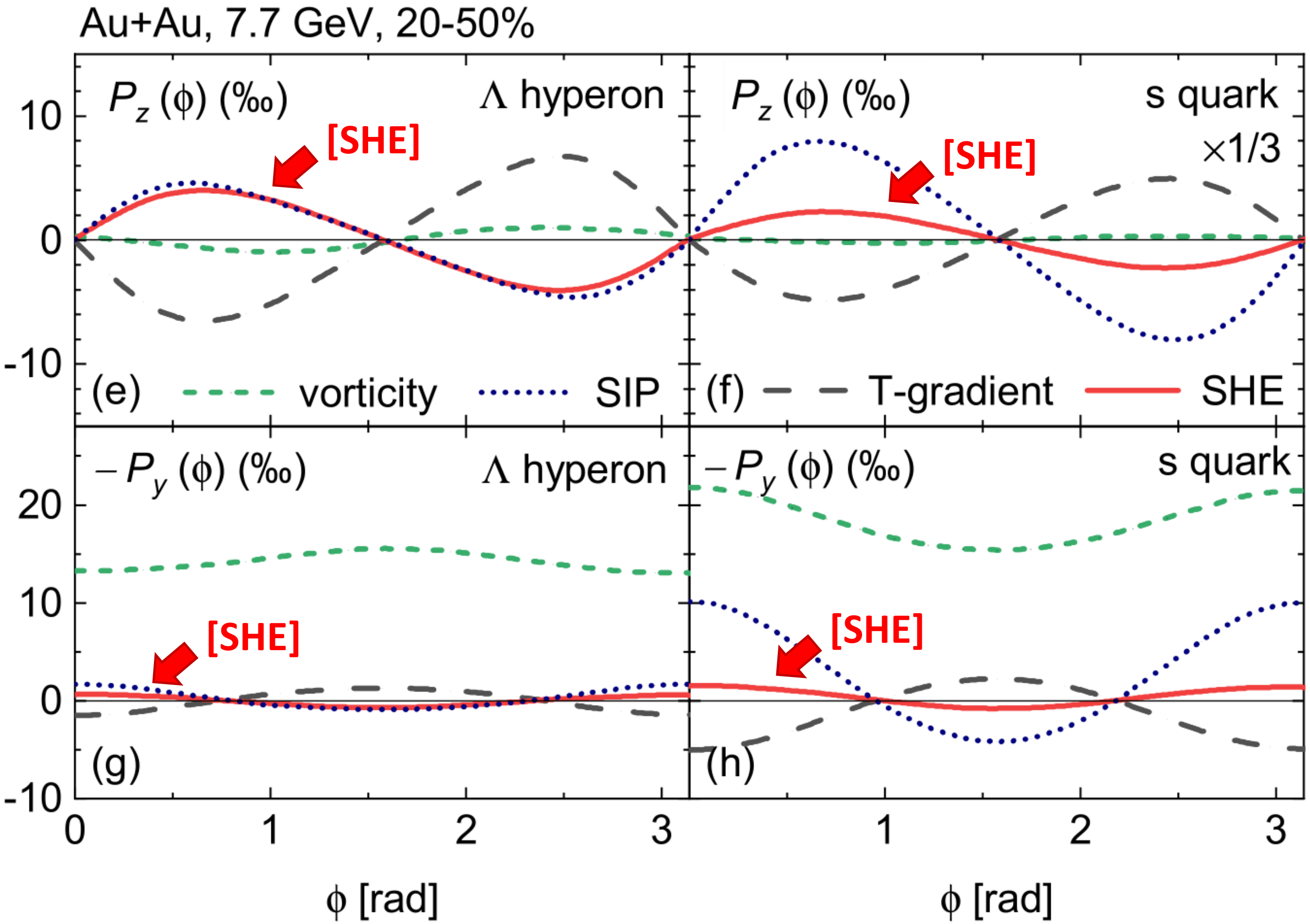
$P^\mu_\Lambda(p) = P^\mu_s(p)$

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

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

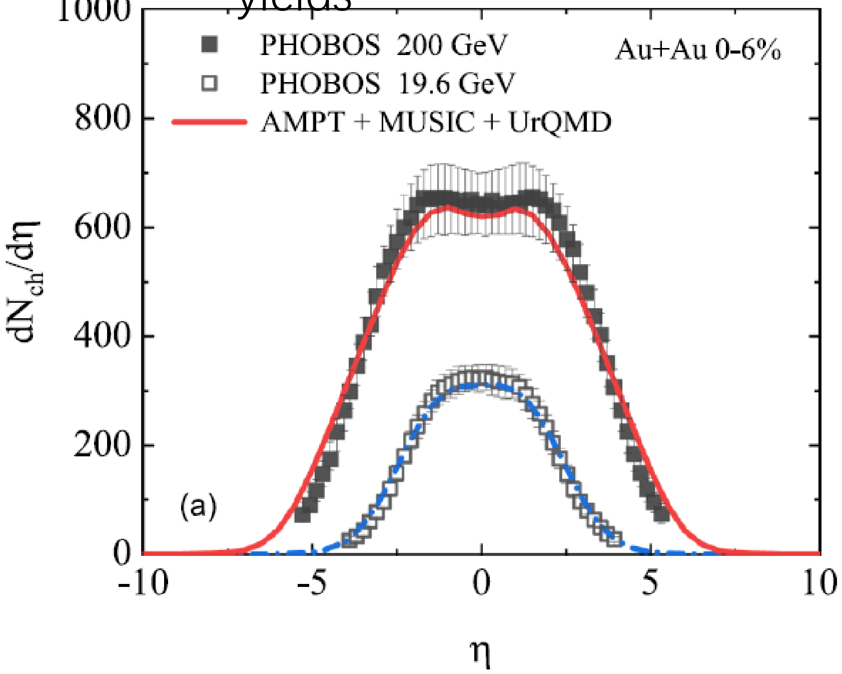
Well calibrated hydrodynamic model

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

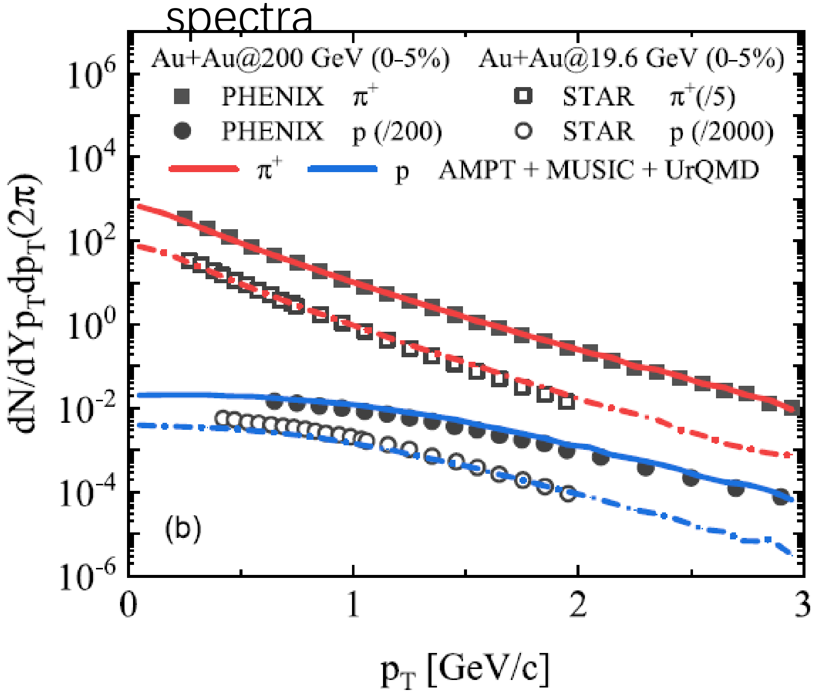
AMPT → MUSIC → Freeze-out surface → iSS → UrQMD

Parameters are tuned to reproduce the soft hadron observables

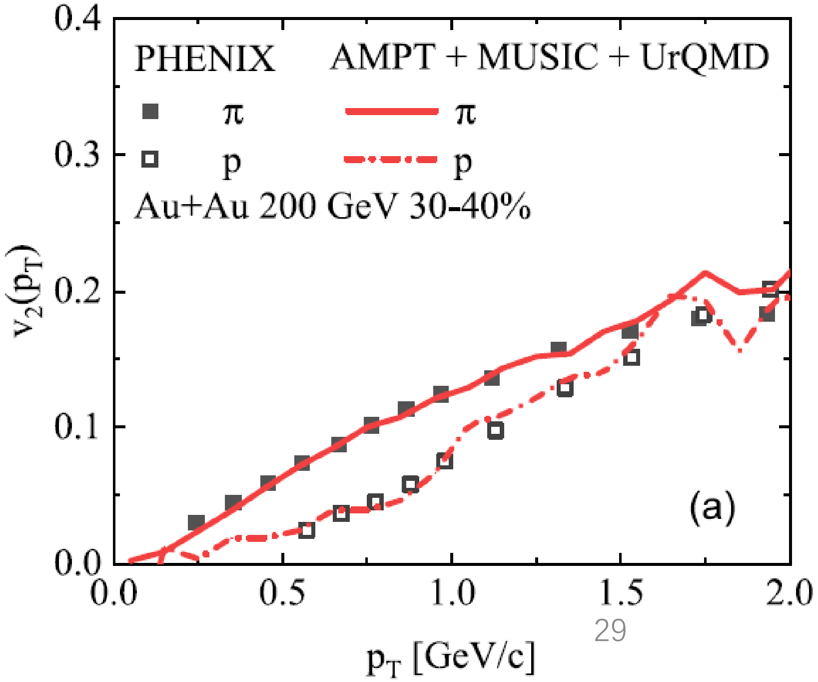
Charged particle yields



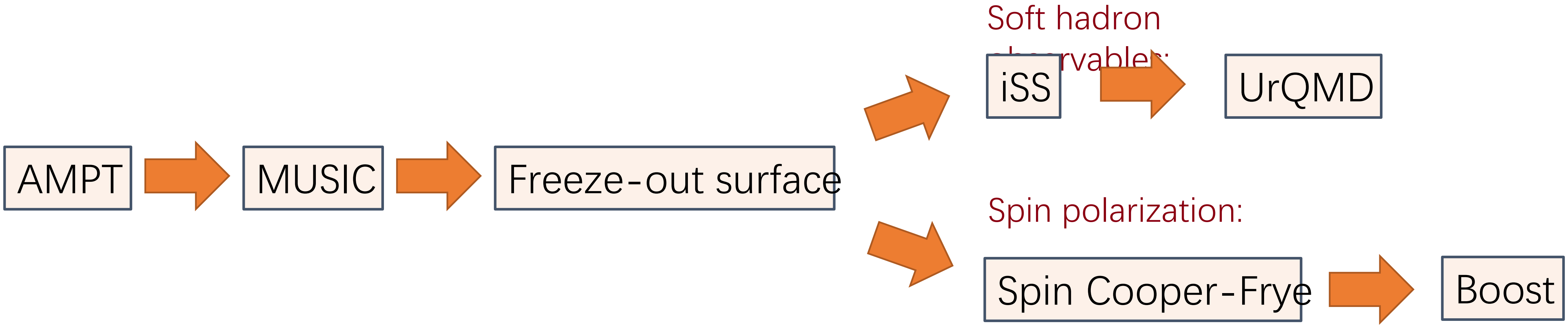
Transverse momentum spectra



$v_2(p_T)$



From thermal vorticity to polarization



Soft hadron observables:

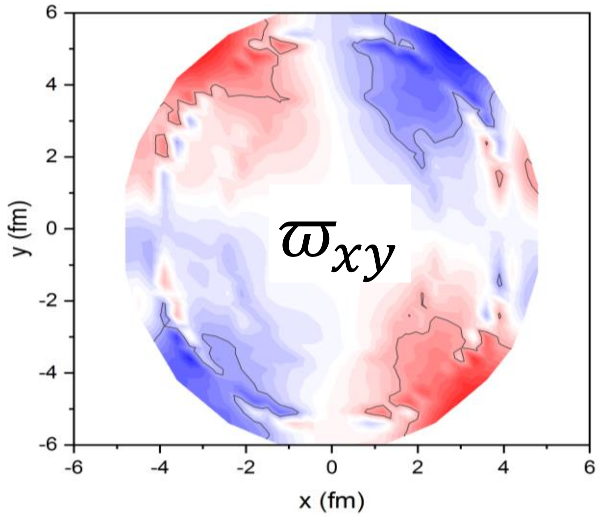
AMPT → MUSIC → Freeze-out surface

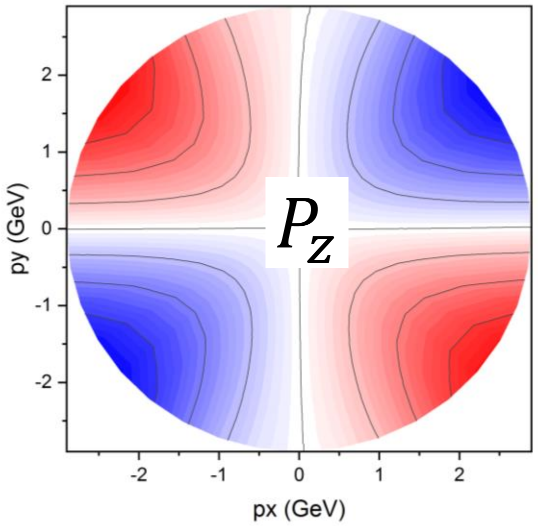
iSS → UrQMD

Spin polarization:

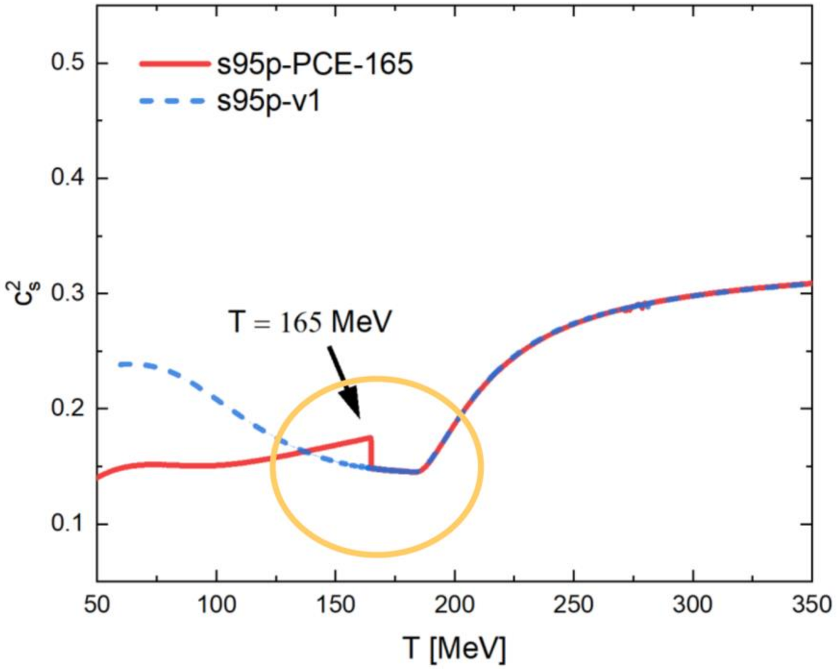
Spin Cooper-Frye → Boost

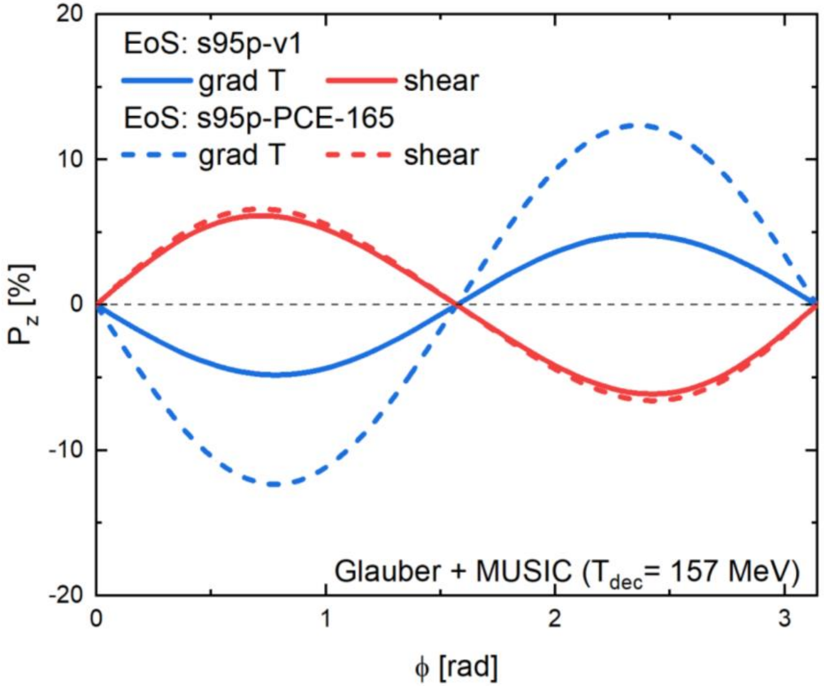
A mapping: $\varpi_{\mu\nu}(x) \rightarrow P^{\mu}(p)$

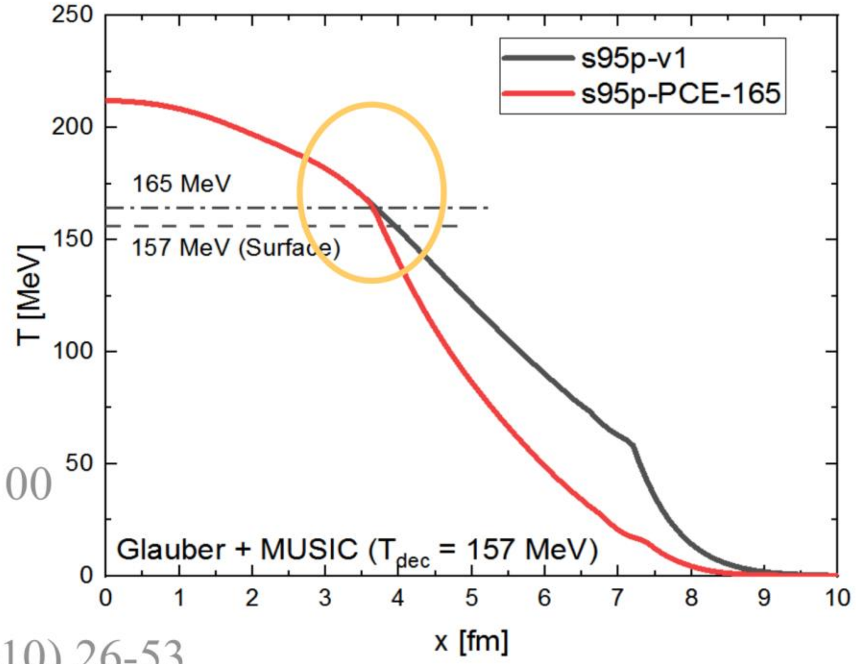




Dependence on EoS







-Do not use EoS-s95p-PCE widely used in hydro calculations !

NEoS:

A. Monnai, B. Schenke, C. Shen, *Phys.Rev.C* 100
B. (2019) 2, 024907

S95p-v1:

P. Huovinen, P. Petreczky, *Nucl.Phys.A* 837 (2010) 26-53