Shear-Induced Polarization & Spin Hall Effects in heavy-ion collisions

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with S. Liu, L.-G. Pang, H. Song and Y. Yin

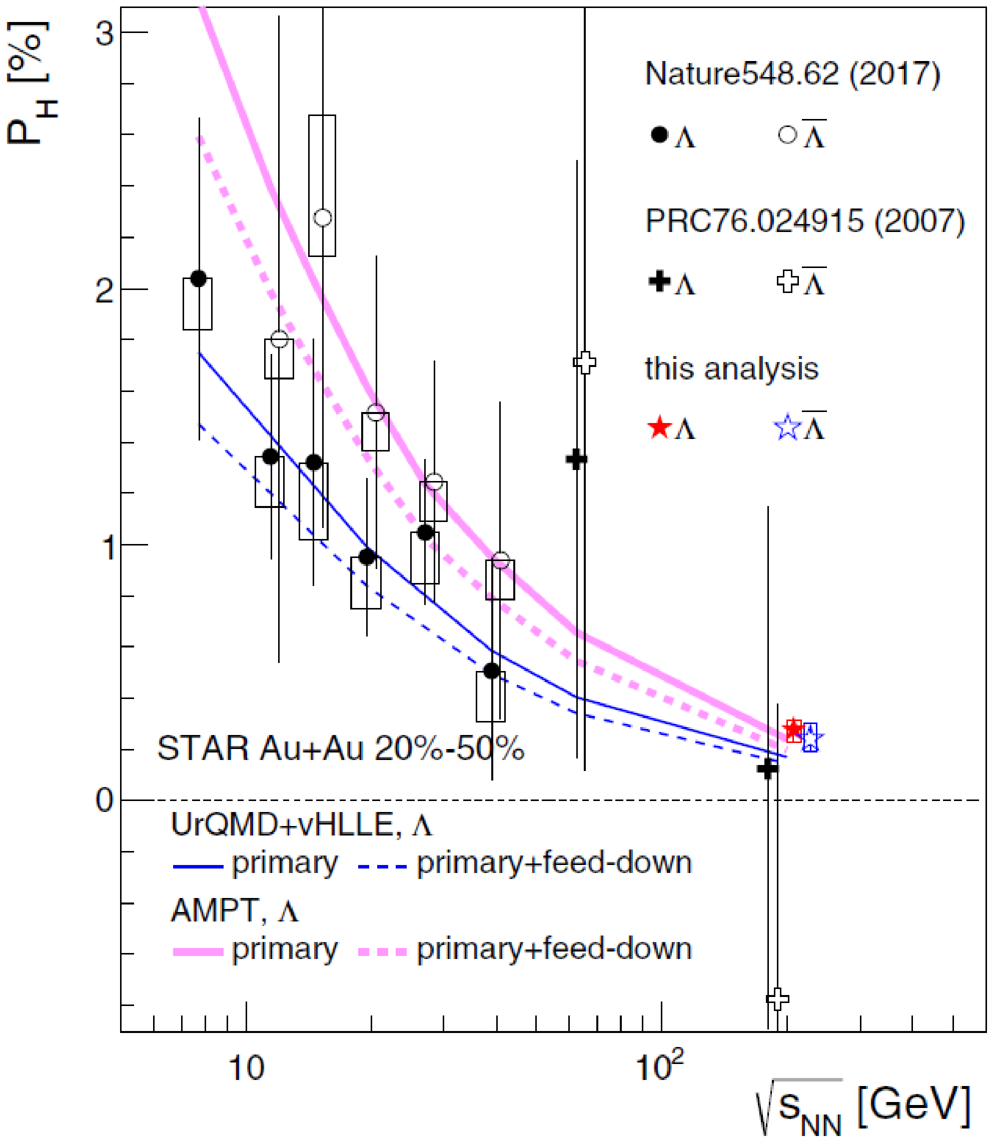
Shear-Induced Polarization: Phys.Rev.Lett. 127 14, 142301(2021)
Spin Hall Effects: arXiv: 2201.12970

北京大學
PEKING UNIVERSITY

QUARK MATTER
KRAKÓW
2022

Global polarization

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



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

- Signals observed at STAR BES energy:

  STAR Collaboration, Nature 548, 62 (2017)

- Data described be the statistic calculation

$$S^{\mu}(p) \leftarrow \varpi_{\nu\rho}(x)$$

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:

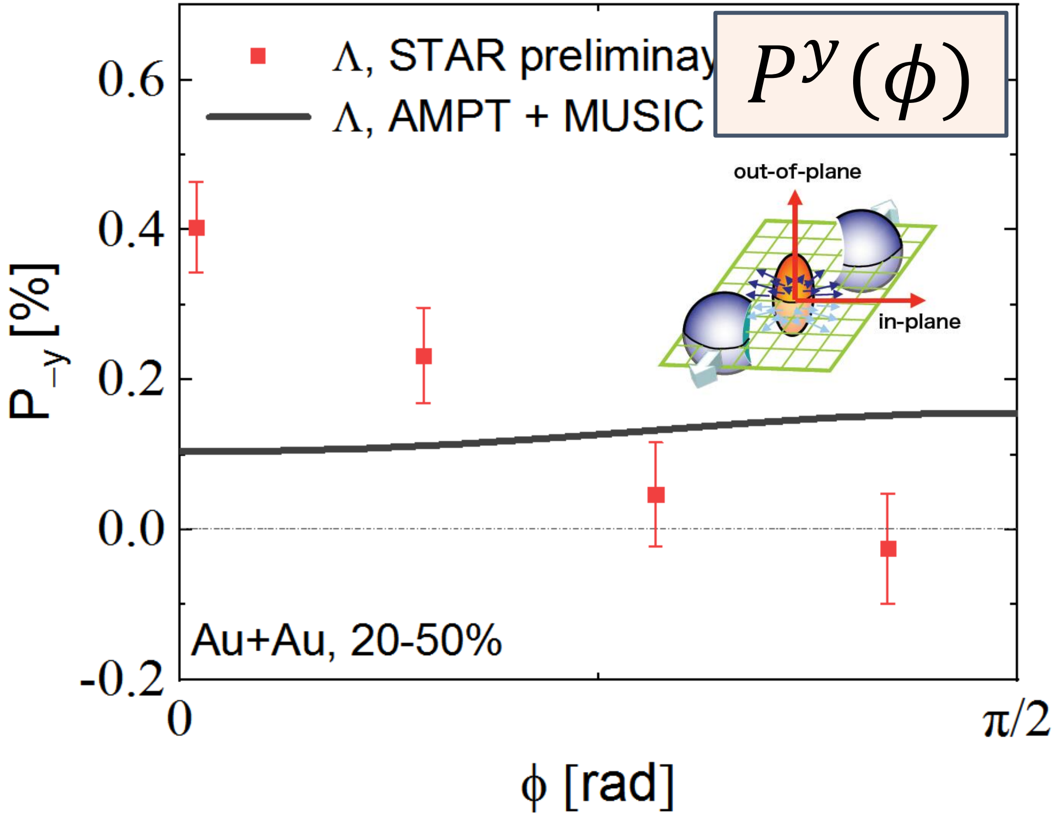
Karpenko, Becattini, EPJC 77 (2017) 4, 213

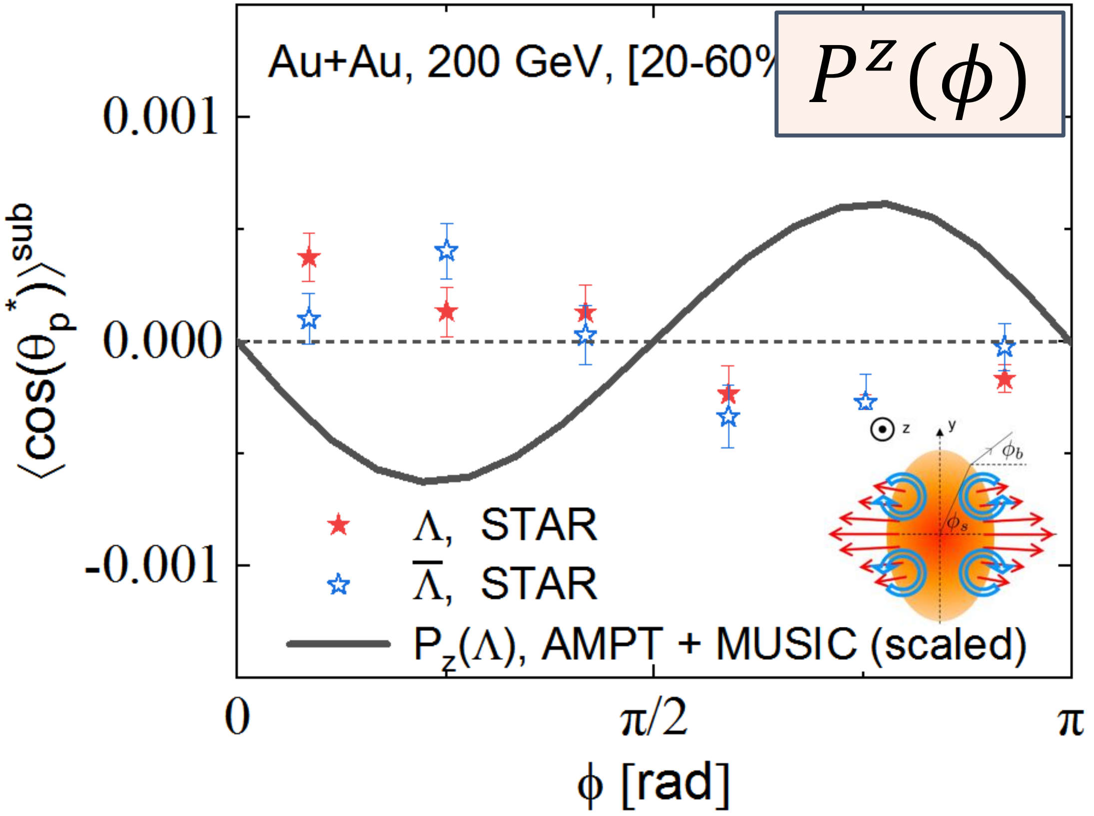
D. Wei, et al., PRC 99 (2019) 014905

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

Becattini, Karpenko, PRL 120 (2018) 012302

- 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

I. Shear Induced Polarization (SIP)

---- toward solving the local polarization puzzle

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

Shear Induced Polarization (SIP)

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

Axial Wigner function from CKT (Chen, Son, Stephanov, PRL 115 (2015) 2, 021601)

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

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

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

Vorticity — T gradient (spin Nernst effect) — Shear-Induced Polarization

- $\sigma^{\mu\nu}$: shear stress tensor (symmetric)
- No free parameter
- Identical form by linear response theory with arbitrary mass (S. Liu and Y. Yin, JHEP 07 (2021) 188)

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

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

Shear Induced Polarization (SIP)

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

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Vorticity

T gradient (spin Nernst effect)

Shear-Induced Polarization

Total P^μ = [Vorticity] + [T gradient] + [Shear]

Shear Induced Polarization (SIP)

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

Axial Wigner fu

To one-loop order (in charge neutral fluid)

$$\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial_\alpha (\beta u)_\lambda$$

Thermal vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu(\beta u_\mu) - \partial_\mu(\beta u_\nu))$$

Expand $\mathcal{A}^\mu$ to

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

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Vorticity

T gradient
(spin Nernst effect)

Shear-Induced Polarization

Total P^μ = [Vorticity] + [T gradient] + [Shear]

⇨ Total P^μ = [Thermal vorticity] + [Shear]

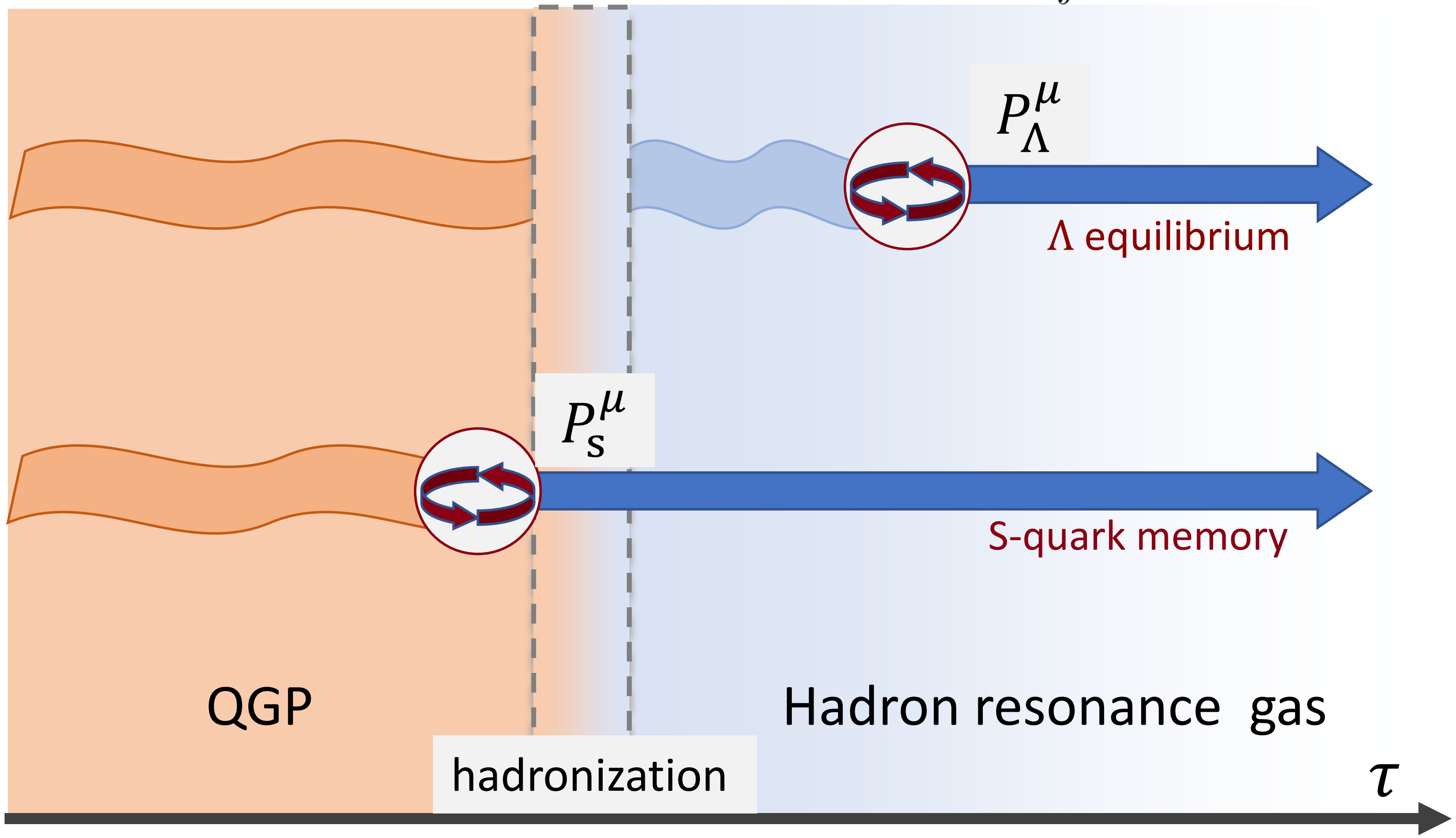
See also: Kumar@Tues. & Buzzegoli@Tues.

The only new effect

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



Hydro evolution

‘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

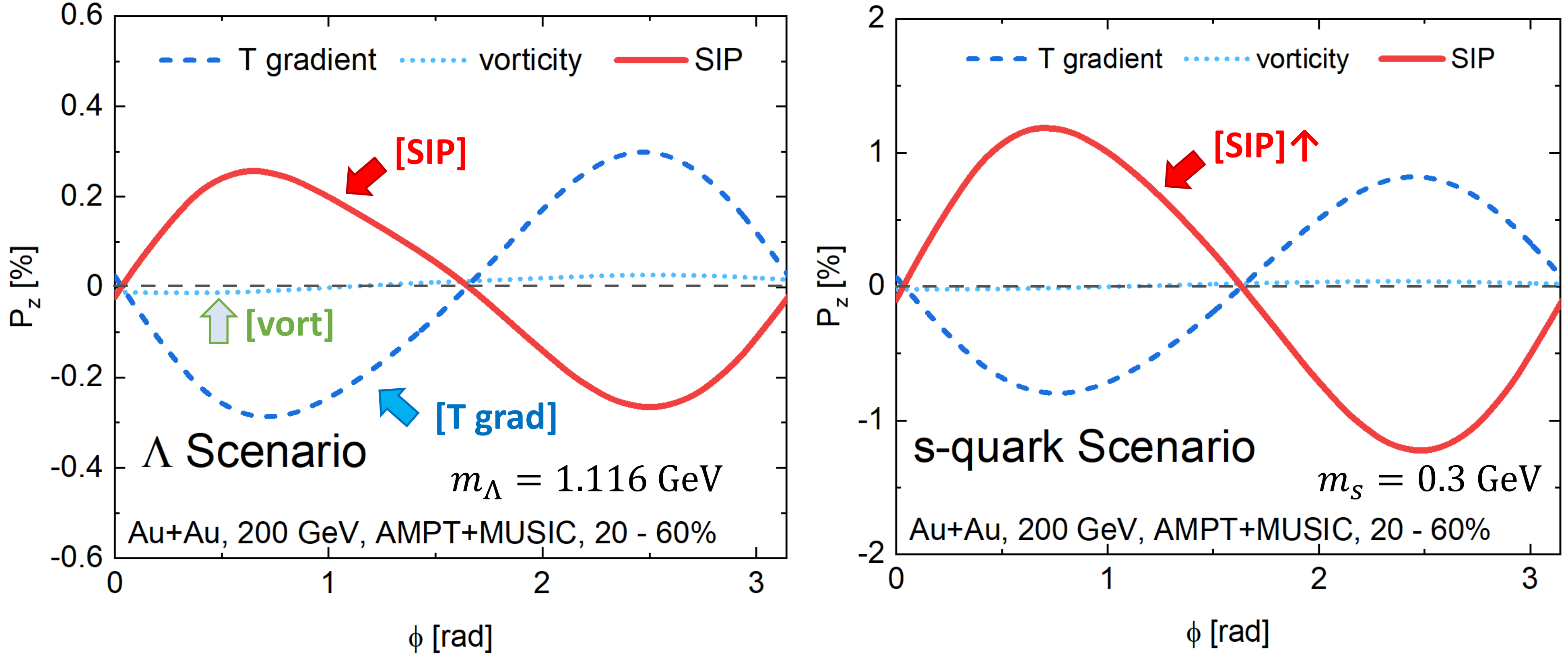
$P^{\mu}_{\Lambda}(p) = P^{\mu}_{s}(p)$

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

Competition of P_z: Grad T vs. SIP

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

Total P^μ = [vorticity] + [T grad] + [SIP]



- [SIP]: " $+\sin(2\phi)$" structure for P_z (same as exp.)
- Total polarization: a competition between [SIP] and [Grad T]

Competition between:

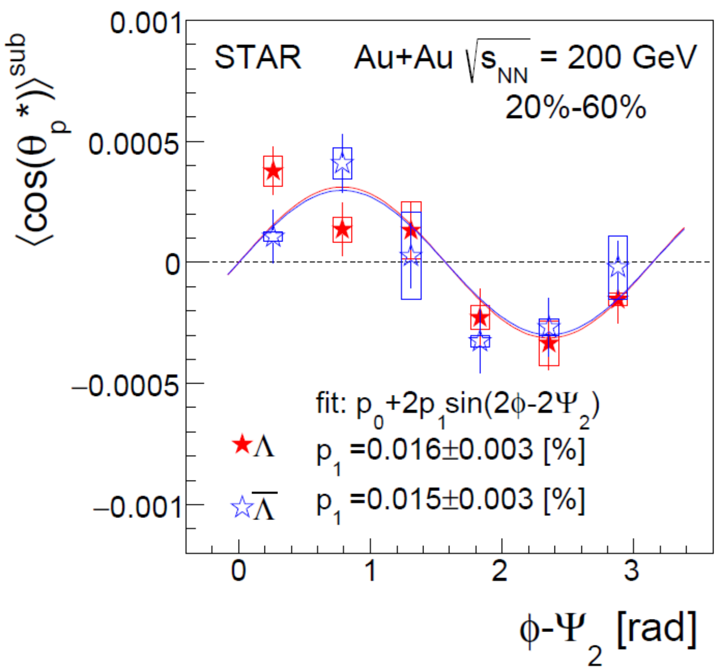
T-grad: $\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha [\beta^{-1}\partial_\lambda \beta]$

Shear: $\epsilon^{\mu\nu\alpha\rho} u_\nu p_\rho \left(\frac{p^\lambda}{\epsilon_0}\right) \partial_{(\alpha} u_{\lambda)}$

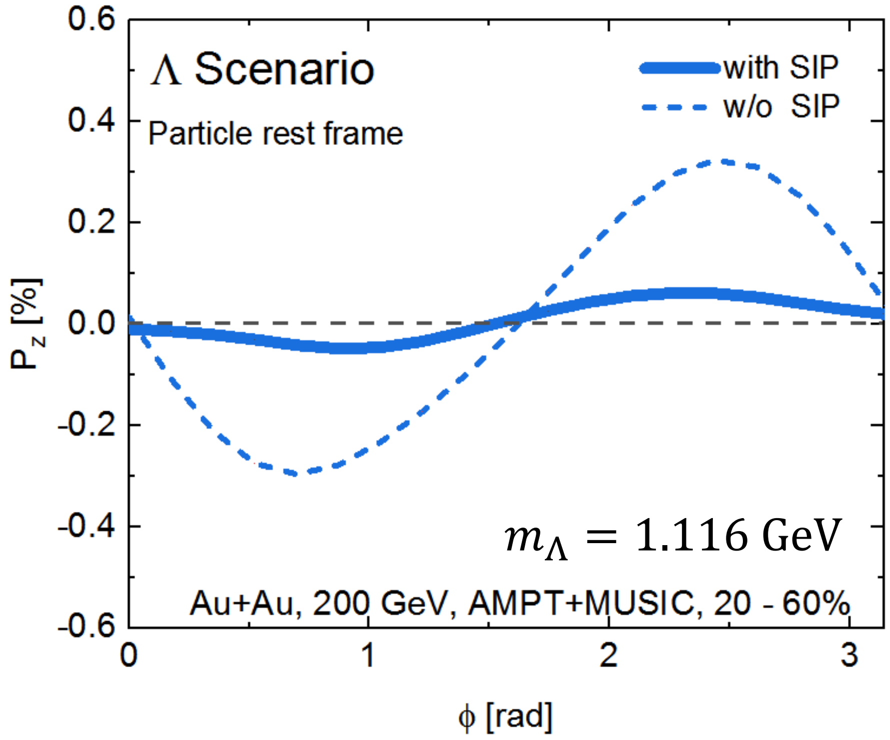
$P_z(\phi)$ with SIP

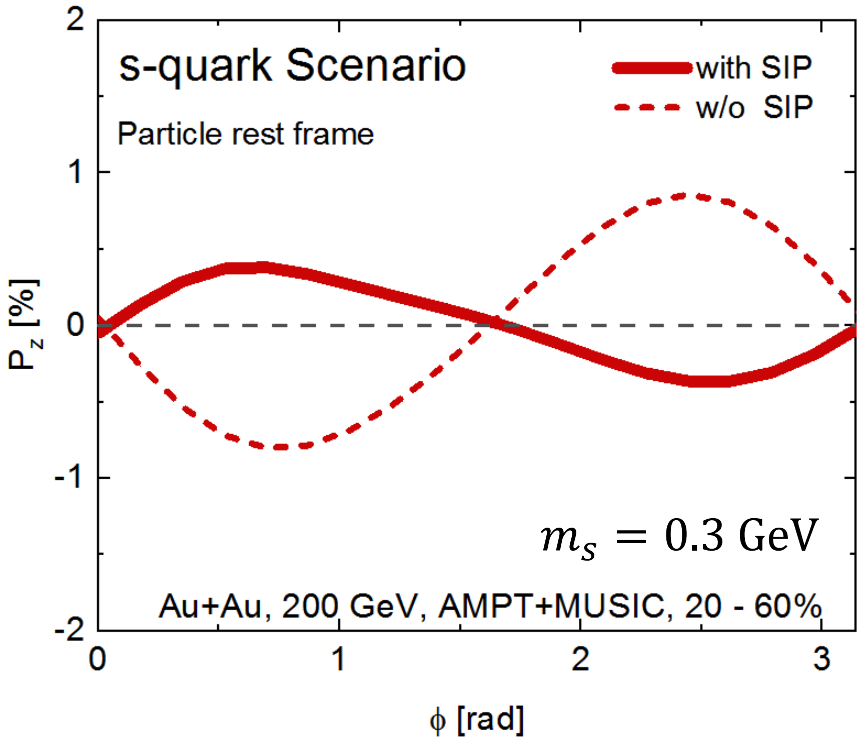
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021)

Total P^μ = [vorticity] + [T grad] + [SIP]
= [thermal vorticity] + [SIP]



STAR, PRL 123 (2019) 132301





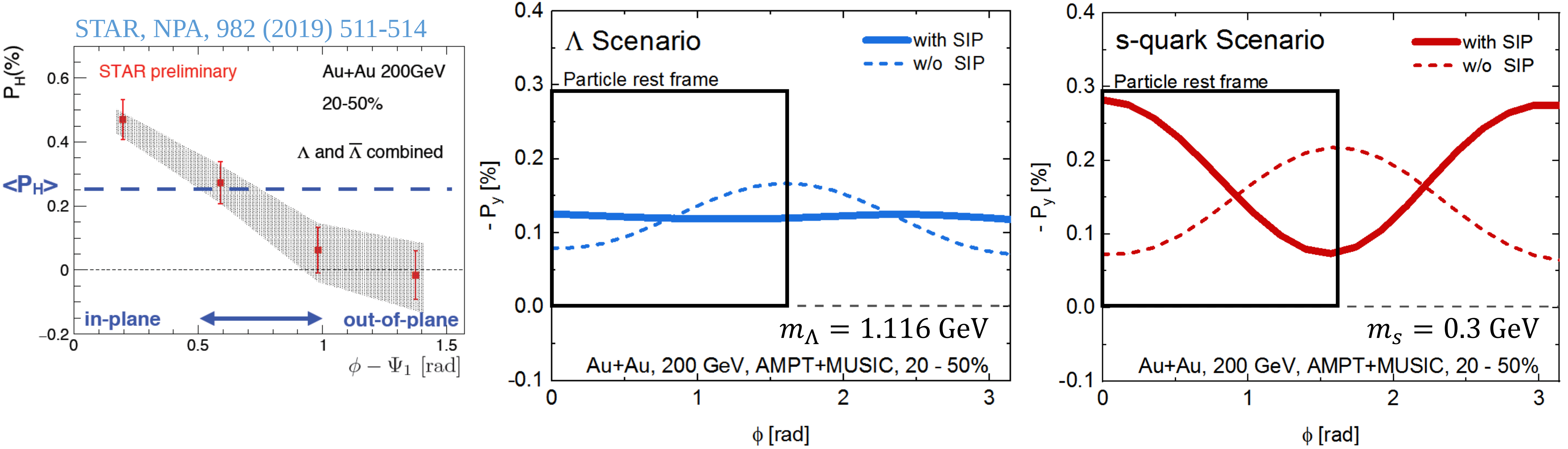
- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

$P_y(\phi)$ with SIP

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

Total P^μ = [vorticity] + [T grad] + [SIP]
= [thermal vorticity] + [SIP]

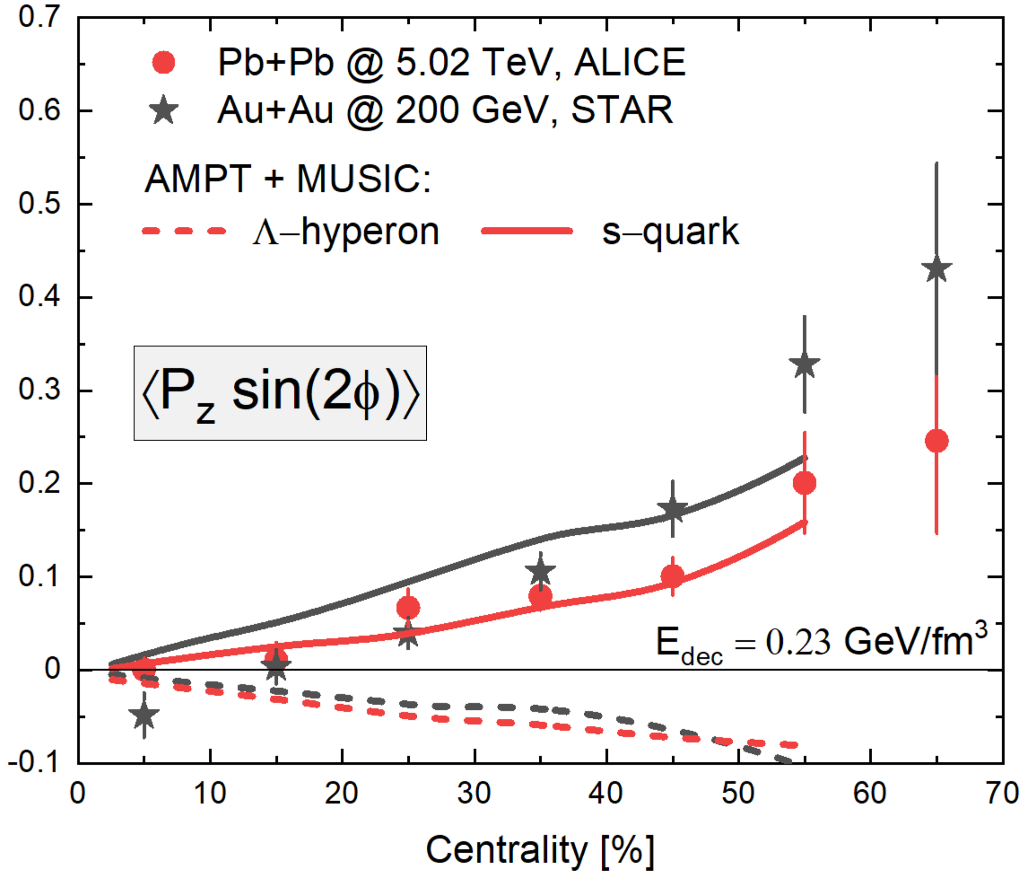
STAR, NPA, 982 (2019) 511-514

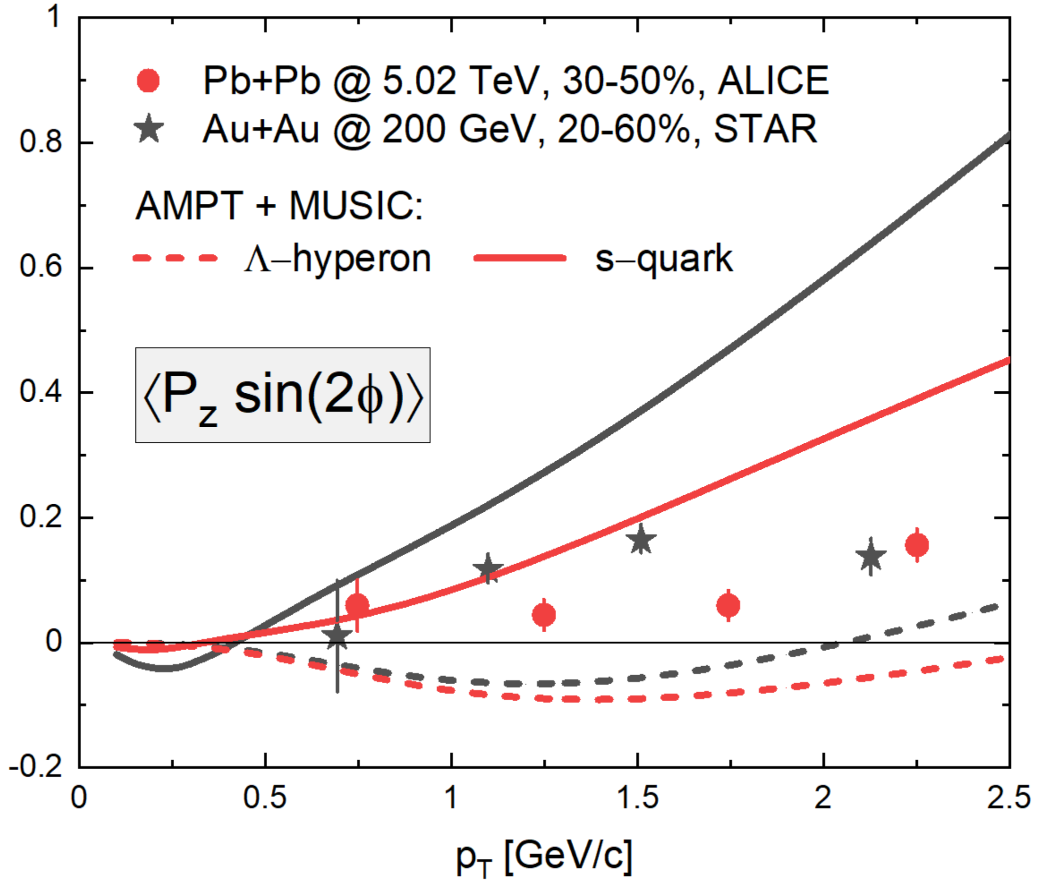


- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

From RHIC to LHC

Same hydrodynamic model: AMPT + MUSIC
(LHC parameter from EPJC 77 (2017) 9, 645)



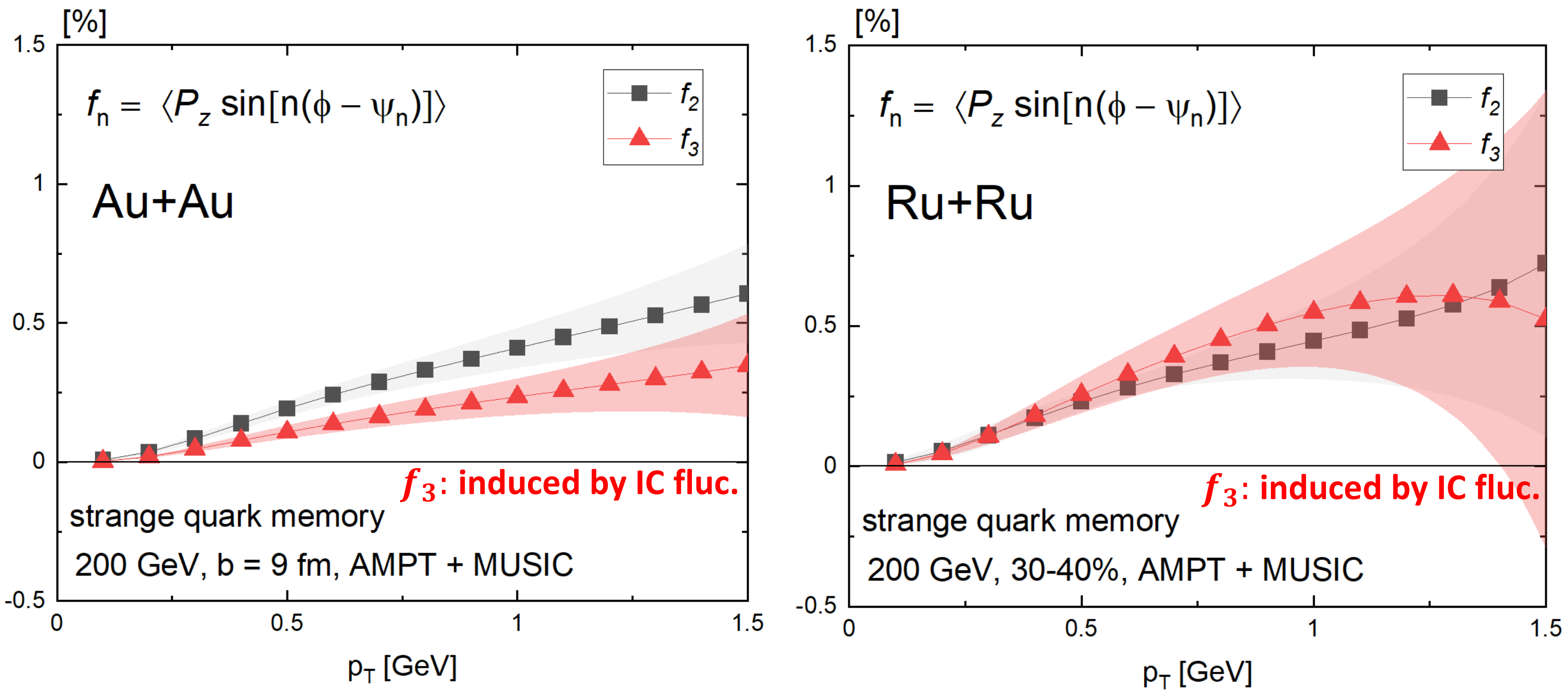


- "Strange Memory" scenario qualitatively describes the centrality & p_T dependence
- More precise model needed to quantitative description

BF & H. Song, in preparation

The 3[rd] order Fourier coefficient of P_z

Event-by-event AMPT + MUSIC



$$f_n = \langle P_z \sin[n(\phi - \Psi_n)]\rangle = \frac{\int p_T dp_T d\phi dy \ \int p \cdot d\sigma \, \mathcal{A}^\mu(x,p) \sin[n(\phi - \Psi_n)]}{\int p_T dp_T d\phi dy \, 2m \int p \cdot d\sigma \, f(x,p)}$$

- Non-zero f_3 is comparable to f_2 in both Au+Au and Ru+Ru systems
- Spin polarization also probes the initial state fluctuations

BF & H. Song, in preparation

II. Spin Hall Effects (SHE) at RHIC-BES

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

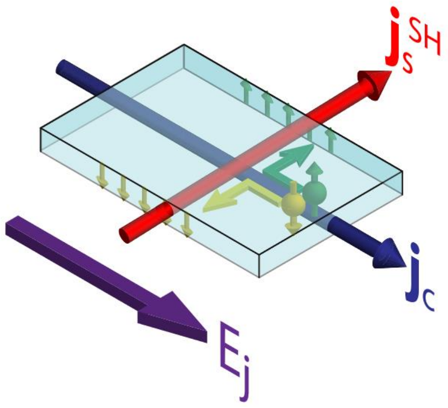
How about with finite μ_B?

$$\mathcal{A}^\mu(x,p) = \beta f_0(x,p)(1-f_0(x,p))\varepsilon^{\mu\nu\alpha\rho} \times \Big(\underbrace{\frac{1}{2}p_\nu \partial^\perp_\alpha u_\rho}_{\text{vorticity}} - \underbrace{\frac{1}{T}u_\nu p_\alpha \partial_\rho T}_{\text{T-gradient}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0} u_\nu Q^\lambda_\alpha \sigma_{\rho\lambda}}_{\text{SIP}} - \underbrace{\frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho (\beta\mu_B)}_{\text{SHE}} \Big),$$

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
- 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)

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:

$$\mathcal{A}^\mu(x,p) = \beta f_0(x,p)(1-f_0(x,p))\varepsilon^{\mu\nu\alpha\rho} \times \Big(\underbrace{\frac{1}{2} p_\nu \partial^\perp_\alpha u_\rho}_{\text{vorticity}} - \underbrace{\frac{1}{T} u_\nu p_\alpha \partial_\rho T}_{\text{T-gradient}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0} u_\nu Q^\lambda_\alpha \sigma_{\rho\lambda}}_{\text{SIP}} \underbrace{- \frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho (\beta \mu_B)}_{\text{SHE}} \Big),$$

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

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

Spin Cooper-Frye type formula:

- "Λ equilibrium" scenario
- "Strange memory" scenario

Same hydrodynamic model: AMPT + MUSIC

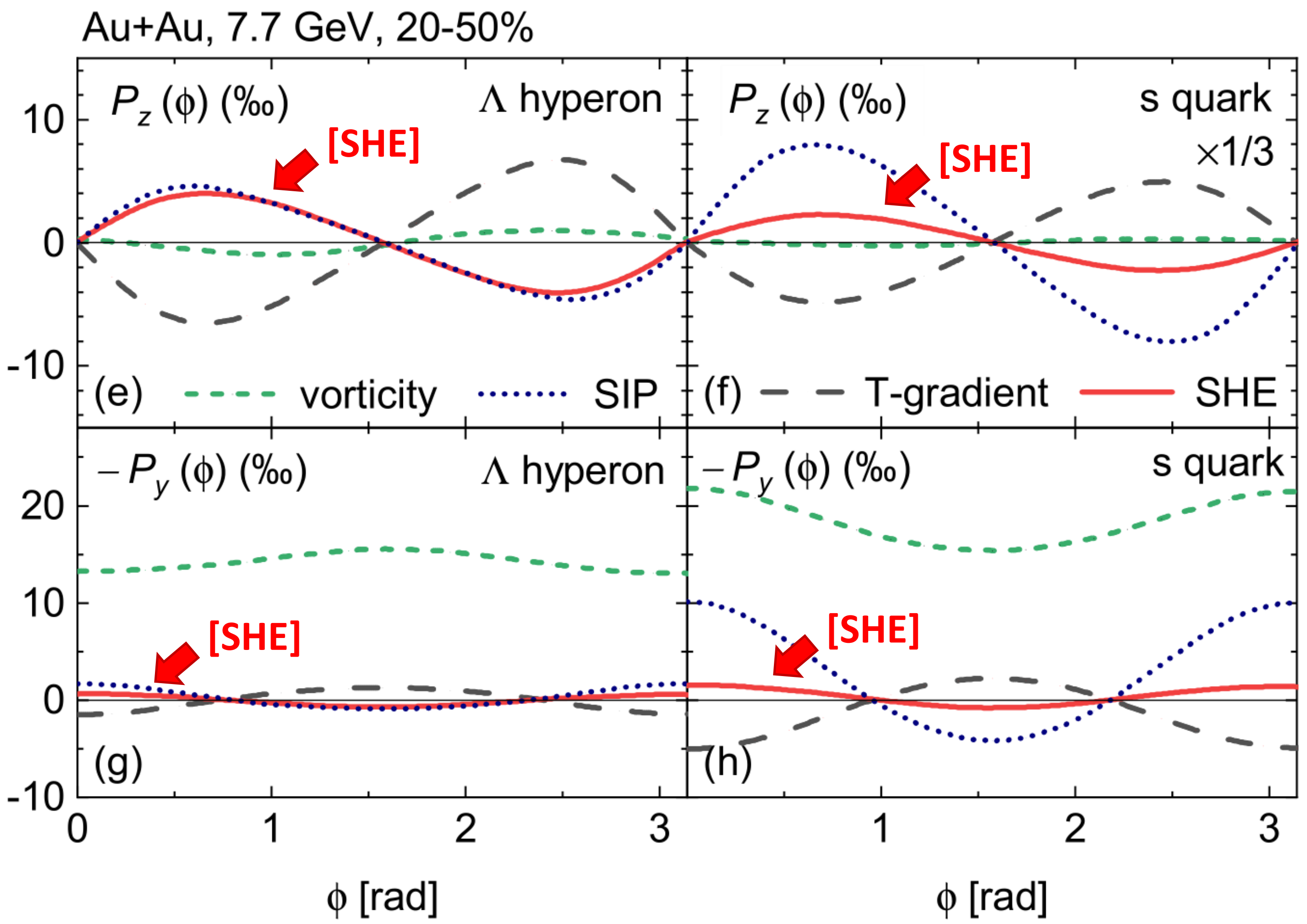
BF, K. Xu, X-G, Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903

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)

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] $\vec{P}_{\mathrm{SHE}} \propto \pm\, \vec{p} \times \vec{\nabla}\mu_B$



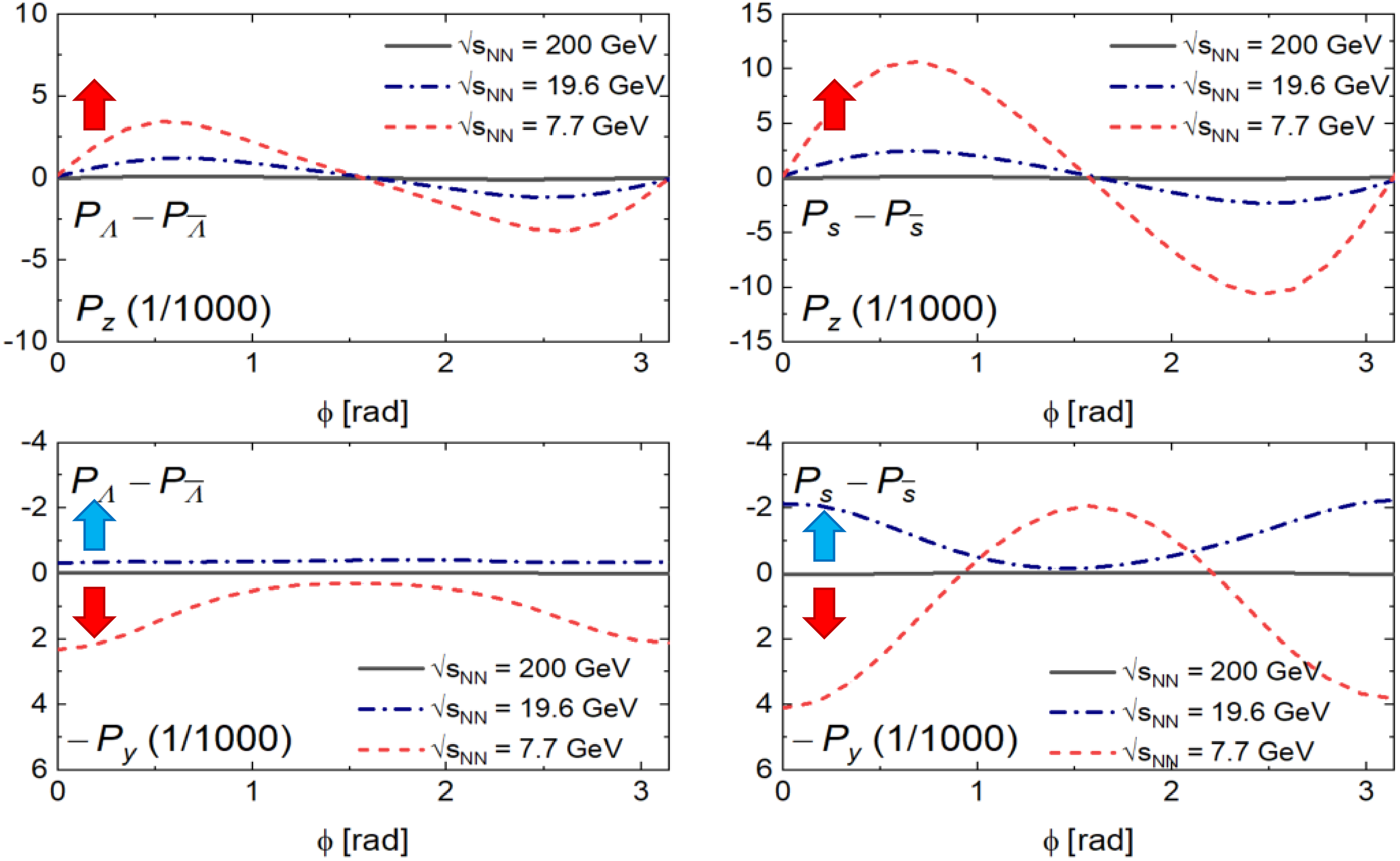
- SHE: “$\sin(2\phi)$” on P_z & “$\cos(2\phi)$” on P_y
- The magnitude of SHE is comparable to other effects
- Opposite SHE for particles and anti-particles

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

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

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

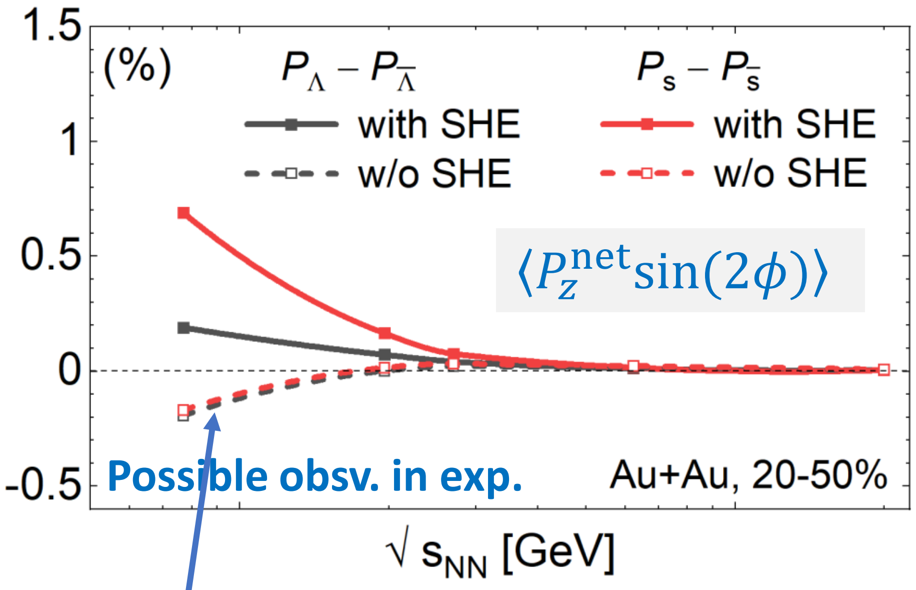
$P_s^{\text{net}} \equiv P_s(\phi) - P_{\bar{s}}(\phi)$



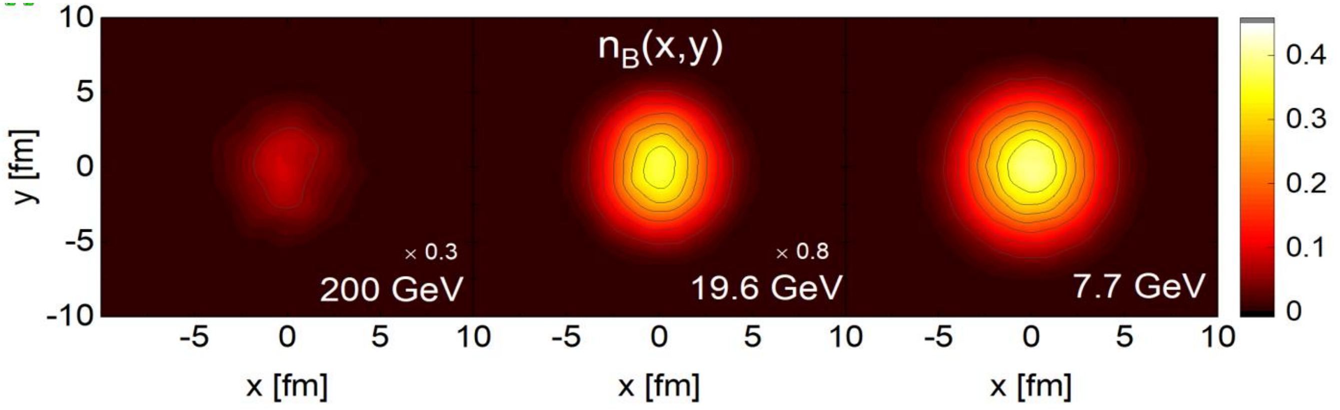
- The 'net' spin polarization used to extract SHE signals
- Net $P_z(\phi)$: increase with decreasing collision energy
- Net $P_y(\phi)$: non-monotonic behavior from SHE

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

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
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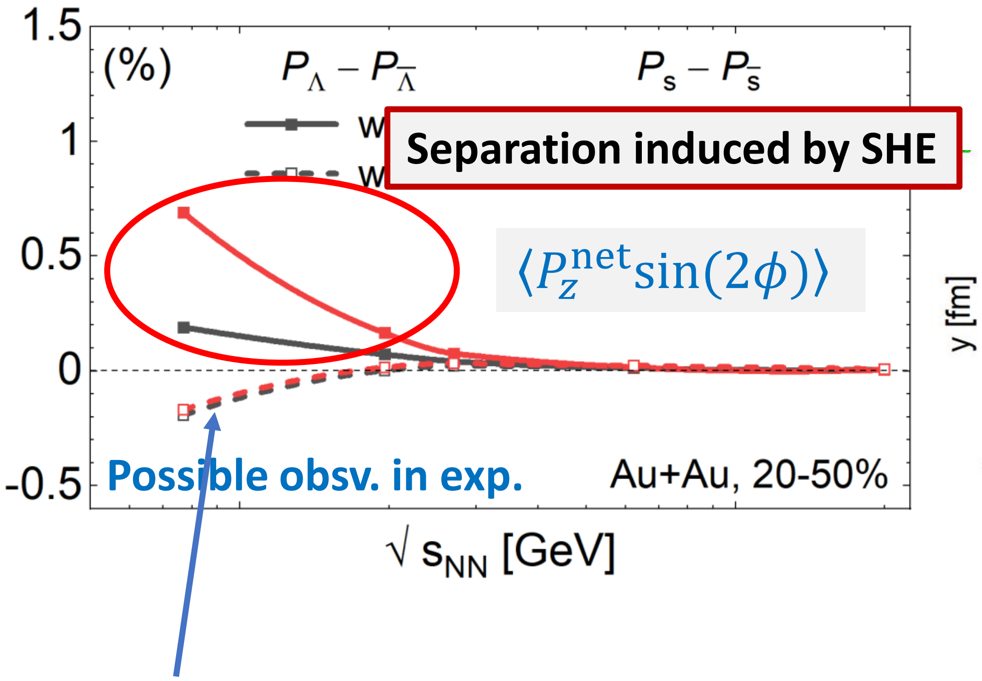

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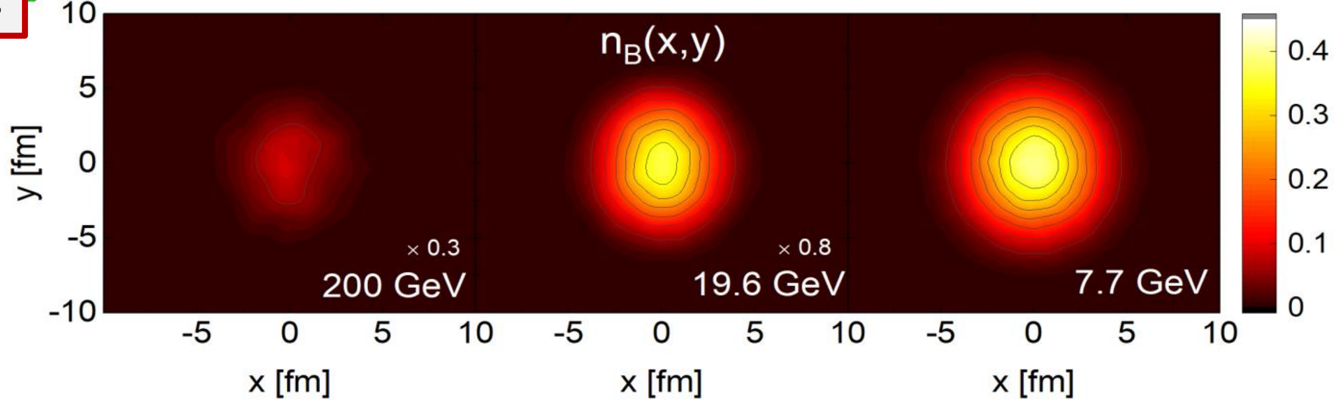

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BF, L.-G. Pang, H. Song, Y. Yin
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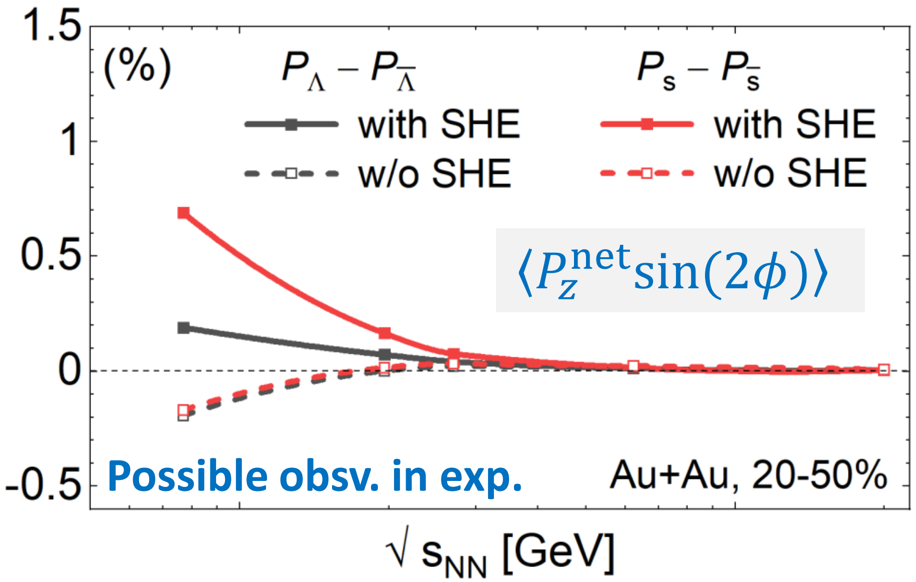
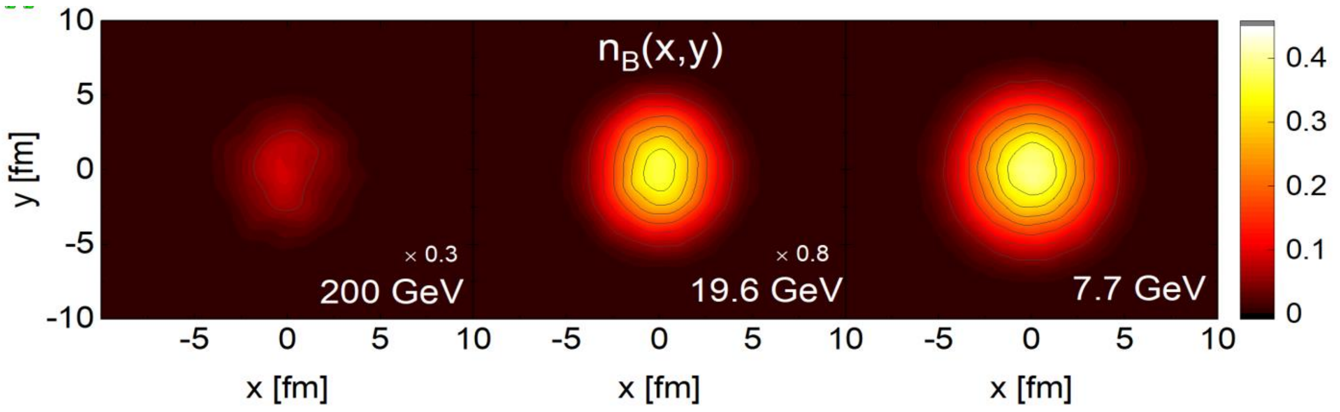
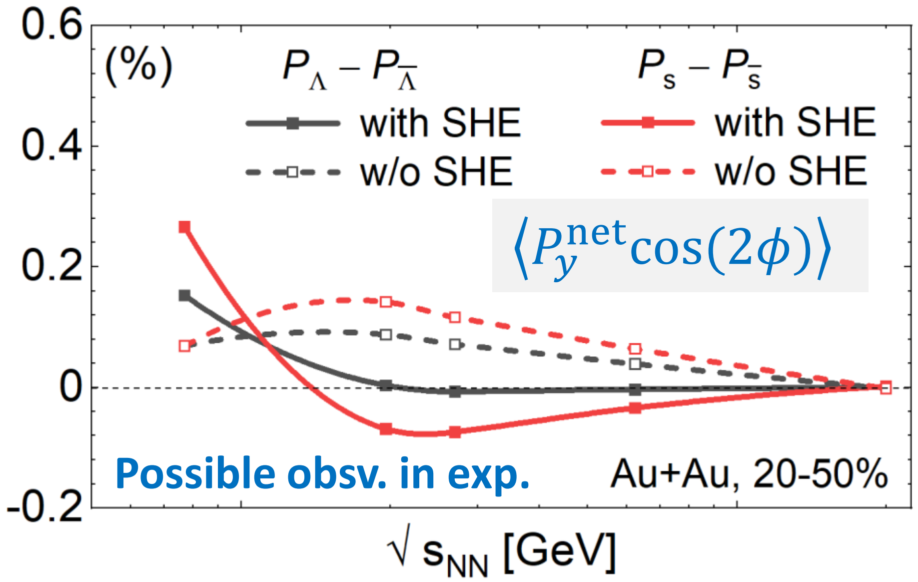
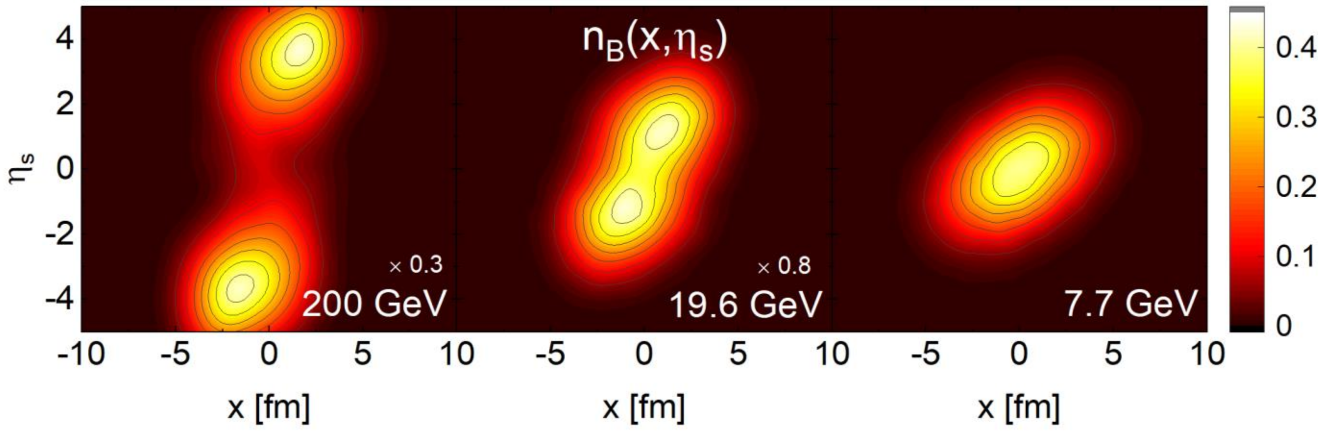


- Monotonic increasing





- Non-monotonic behavior



Summary

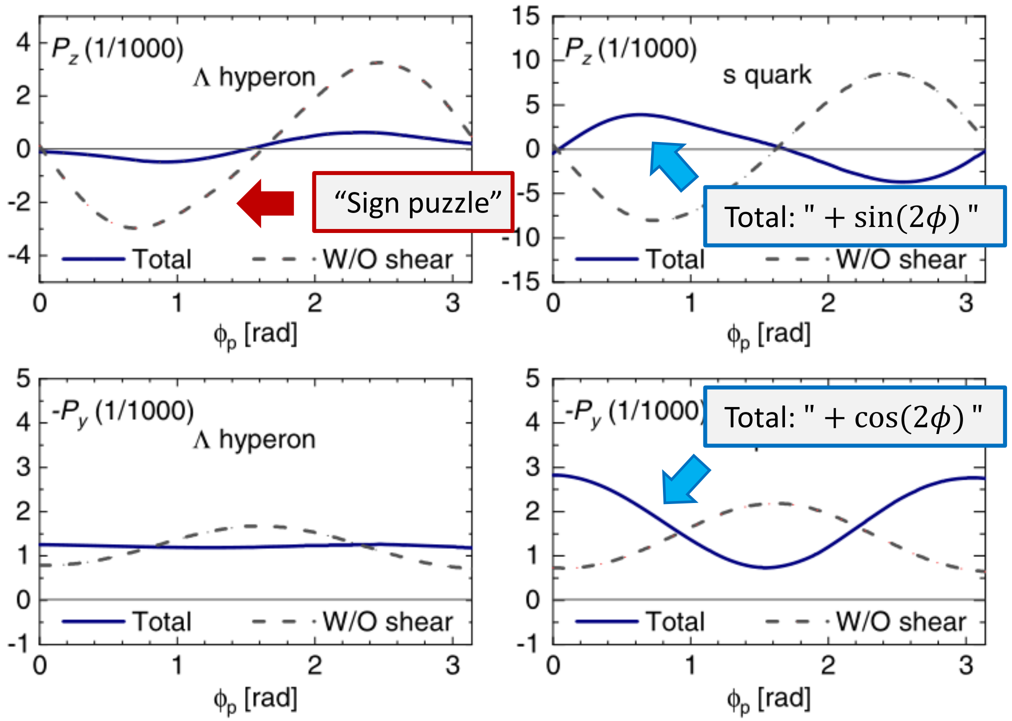
Shear-Induced Polarization: Phys.Rev.Lett. 127 14, 142301(2021)
Spin Hall Effects: arXiv: 2201.12970

$$\text{Total } P^{\mu} = [\text{vorticity}] + [\text{Grad T}] + [\text{SIP}] + [\text{SHE}]$$

Shear-Induced Polarization

“Strange memory” + **Shear-Induced Polarization**

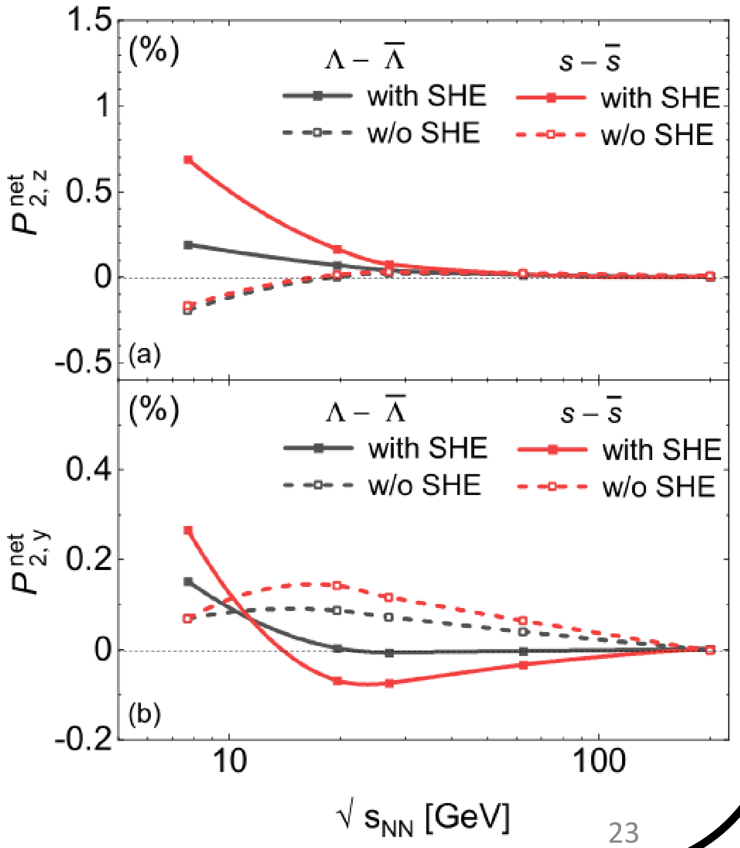
Describes $P_z(\phi)$ and $P_y(\phi)$ qualitatively at **top RHIC** and **LHC**



Spin Hall Effects

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

- Particle – Anti-particle **separation**
- Relevant for RHIC-BES and RHIC/LHC forward rapidity
- Scenario independent

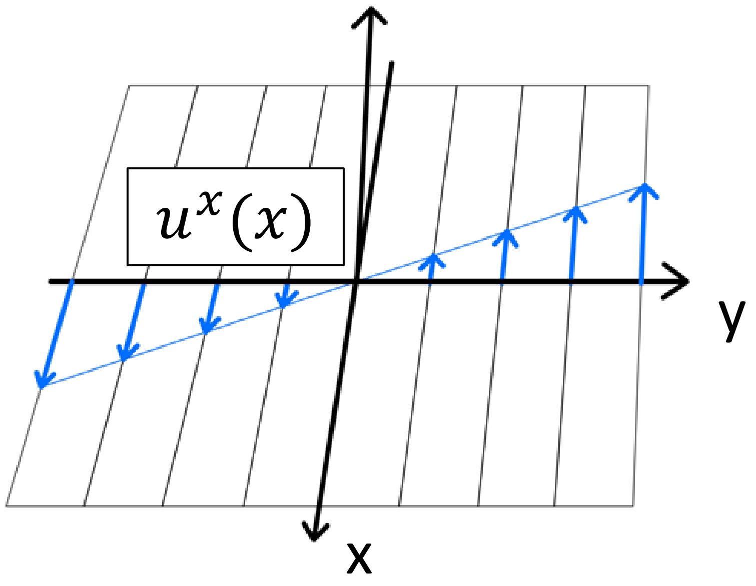


Back up

Hydrodynamic gradients

Derivatives of the velocity field:

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



Anti-symmetric: vorticity

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

Symmetric: shear stress

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

✓ In heavy-ion, condensed matter …

Spin polarization

?

will be discussed in this talk

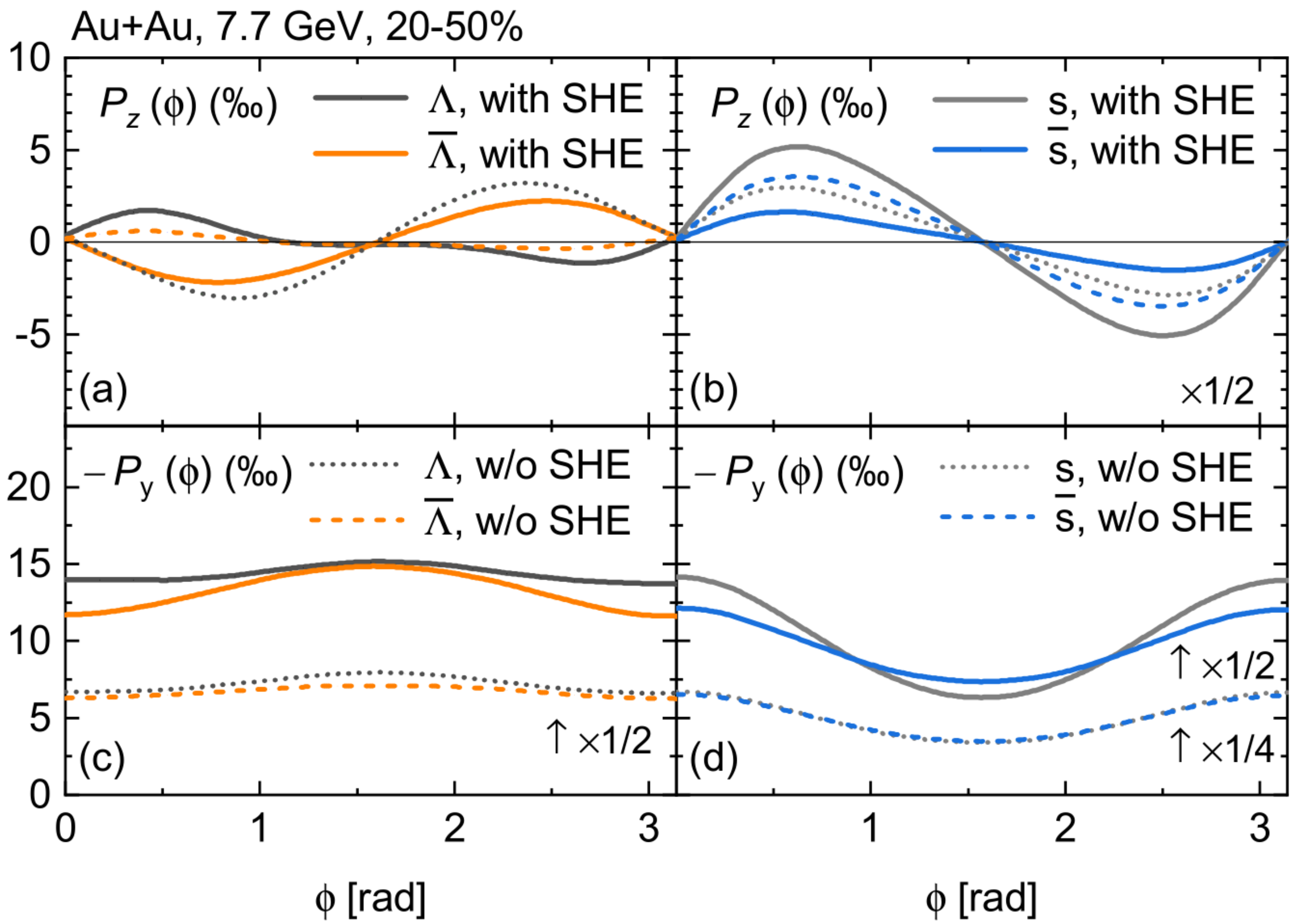
[Strain induced polarization]
In crystal physics:

Crooker and Smith, PRL (2005) 94, 236601
Kissikov, et al., Nature Comm. (2018) 9, 1058

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] $\qquad \vec{P}_{\mathrm{SHE}} \propto \pm \vec{p} \times \vec{\nabla}\mu_B$

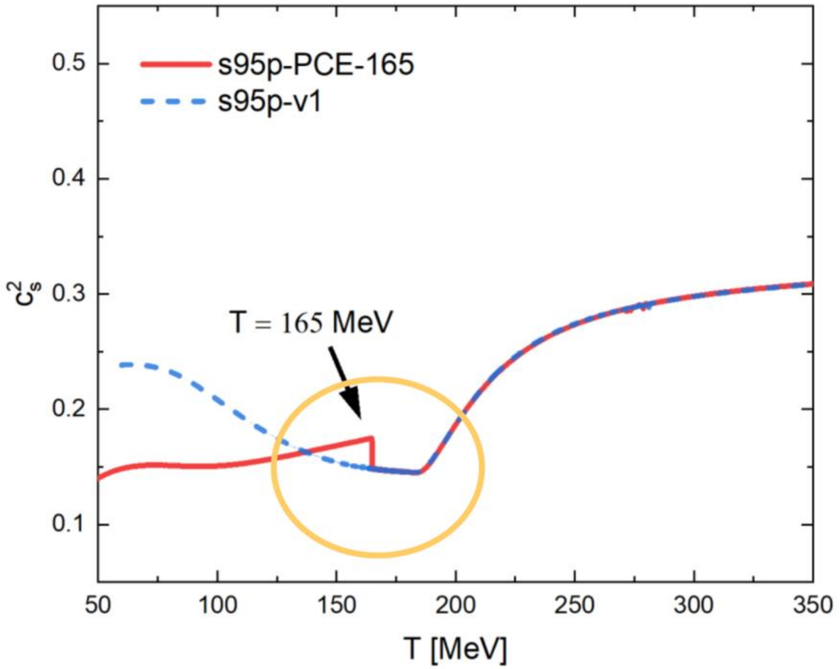


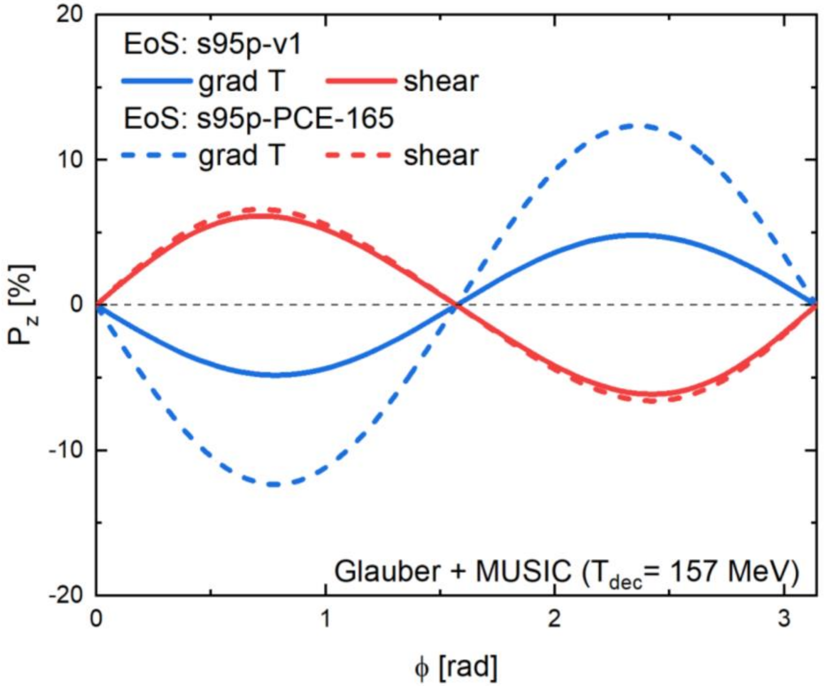
- Separation between particles and anti-particles by SHE
- Different local polarization w/o SHE:
  - Change the space-time of emitted particles
  - Pauli blocking

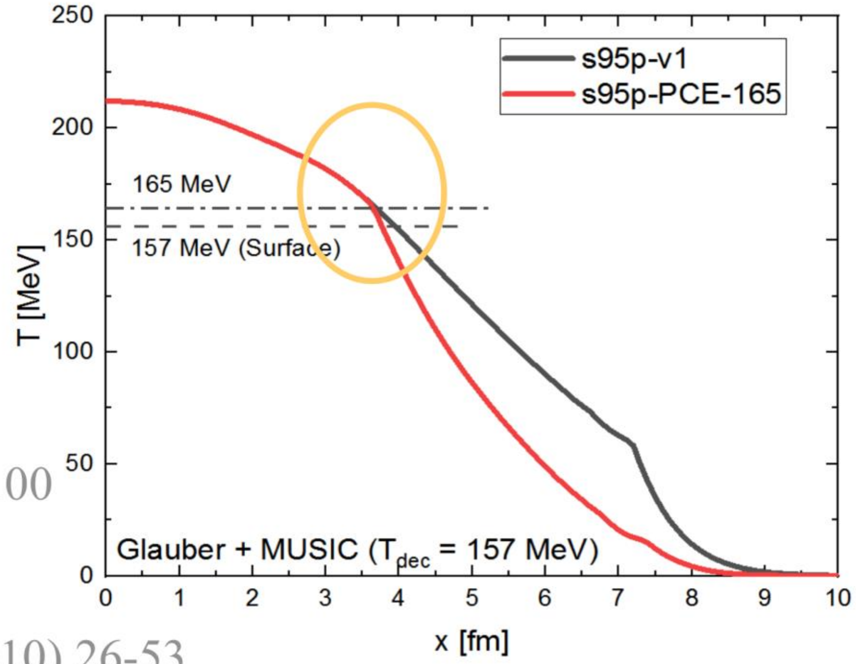
  O. Vitiuk, et al., PLB 2020

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

Dependence on EoS







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

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