Shear Induced Polarization：
——Toward solving the local polarization puzzle

main points

- Shear Induce Polarization (SIP)
- With SIP, $P^{\mu}(\phi)$ of s-quark qualitatively describe the data

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arXiv: 2103.10403

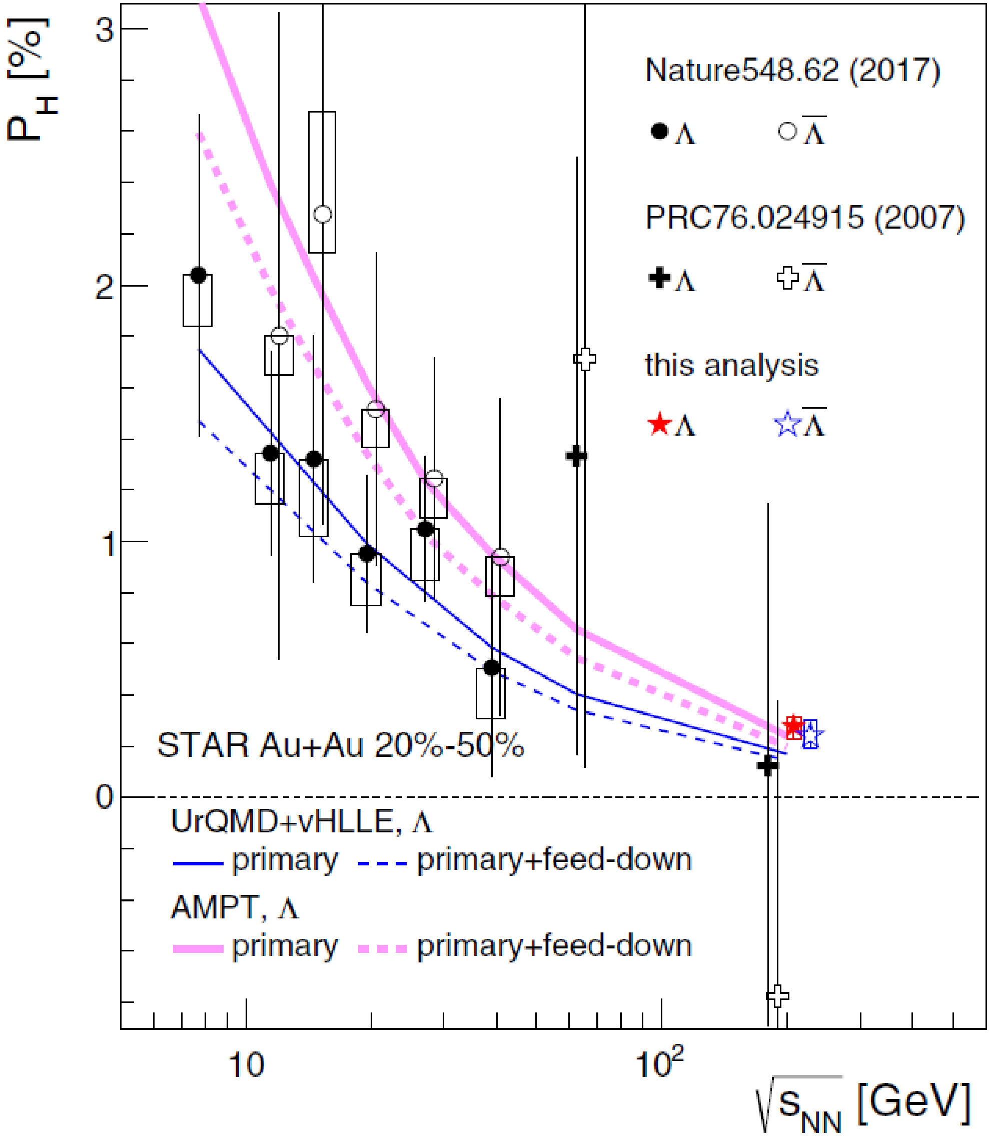
北京大學
PEKING UNIVERSITY

CPOD 2021, 19 March 2021

Introduction

Global polarization

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



- Orbital angular momentum transferred to particle spin
- Signals observed at STAR BES energy:

  STAR Collaboration, Nature 548, 62 (2017)
- Data described be the statistic model

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

Hydrodynamics:

I. Karpenko, F. Becattini, Eur.Phys.J.C 77 (2017) 4, 213

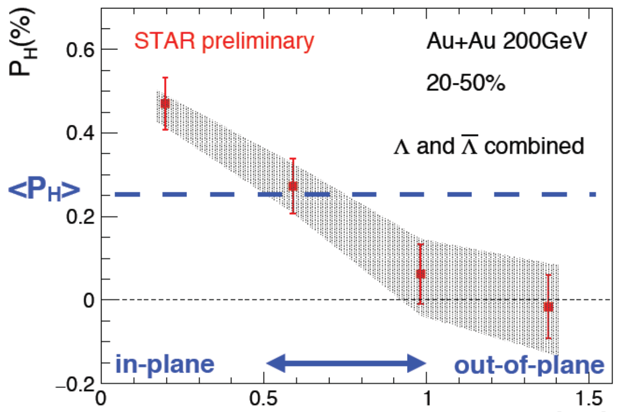
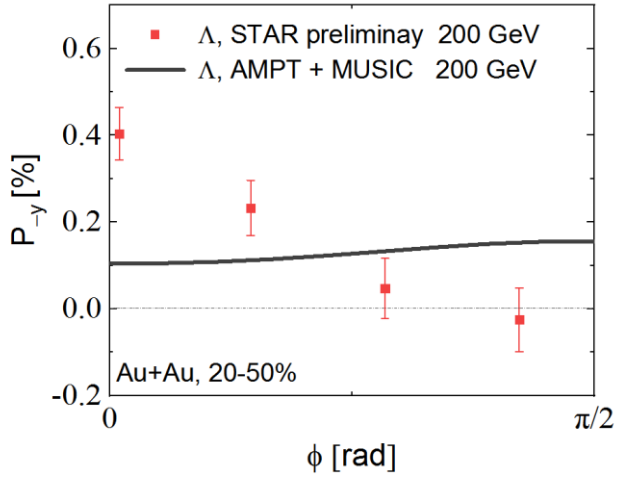
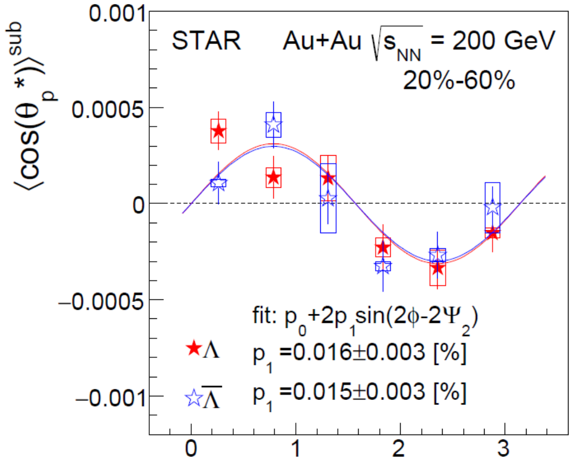
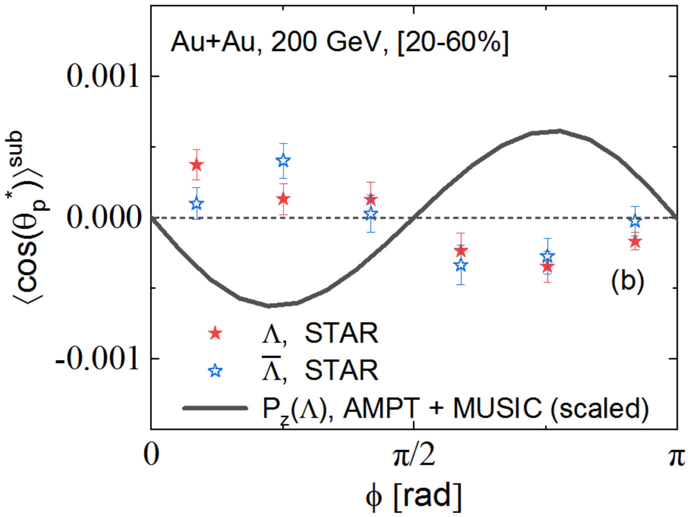
BF, K. Xu, X-G, Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903

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 puzzle

	Experiment data		Statistic model
$P^y(\phi)$		$\neq$	
$P^z(\phi)$		$\neq$	

T. Niida, ECT2020

PRL 123 (2019) 132301

BF, Xu, Huang, Song, PRC 103 (2021) 2, 024903

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

Hydrodynamic gradients

Derivatives of the velocity field:

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

Anti-symmetric — vorticity

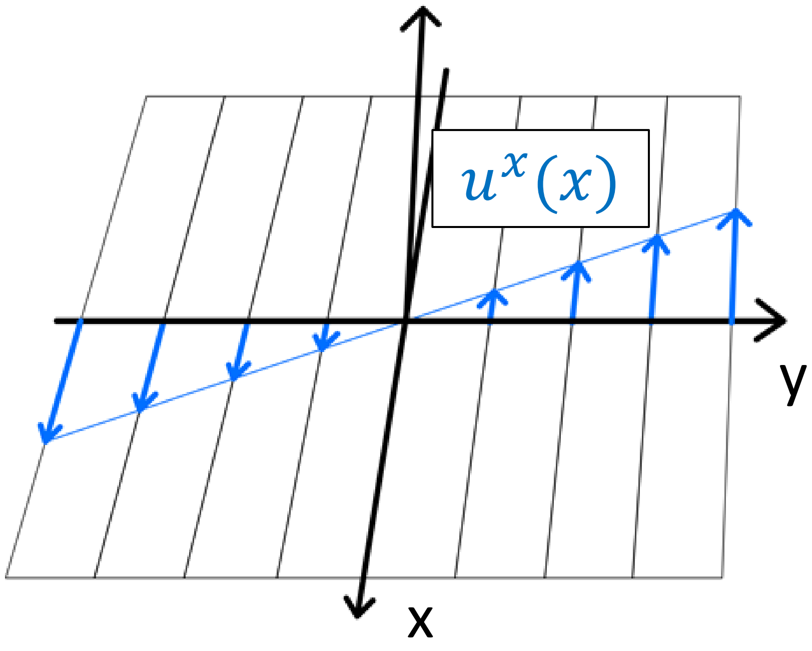
$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\partial_\alpha^\perp u_\beta$$

→ Spin polarization

Symmetric — Shear strength

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

→ ?



Effects of shear strength will be discussed in this talk

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

Shear Induced Polarization (SIP)

Shear Induced Polarization (SIP)

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:

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

Shear Induced Polarization (SIP)

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Shear Induced Polarization

$$\boxed{\mathcal{A}^{\mu}_{\text{SIP}} = -\beta n_0 (1 - n_0) \frac{p_{\perp}^2}{\varepsilon_0} \epsilon^{\mu\nu\alpha\rho} u_{\nu} Q_{\alpha}{}^{\lambda} \sigma_{\rho\lambda}}$$

Sensitive to particle mass

- Can be extended to arbitrary mass (Linear response)
- No free parameter

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

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

S. Liu and Y. Yin, arXiv: 2103.09200

Shear Induced Polarization (SIP)

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

$$\mathcal{A}^\mu = \frac{1}{2}\beta n_0(1-n_0)\left\{\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial^\perp_\alpha u_\lambda + 2\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha\left[\beta^{-1}(\partial_\lambda\beta)\right]\right\} + \mathcal{A}^\mu_{\rm SIP}$$

thermal vorticity SIP

For charge neutral fluid:

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

Shear Induced Polarization [SIP]:

The only new effect additional to thermal vorticity (at 1 loop order)

S. Liu and Y. Yin, arXiv: 2103.09200

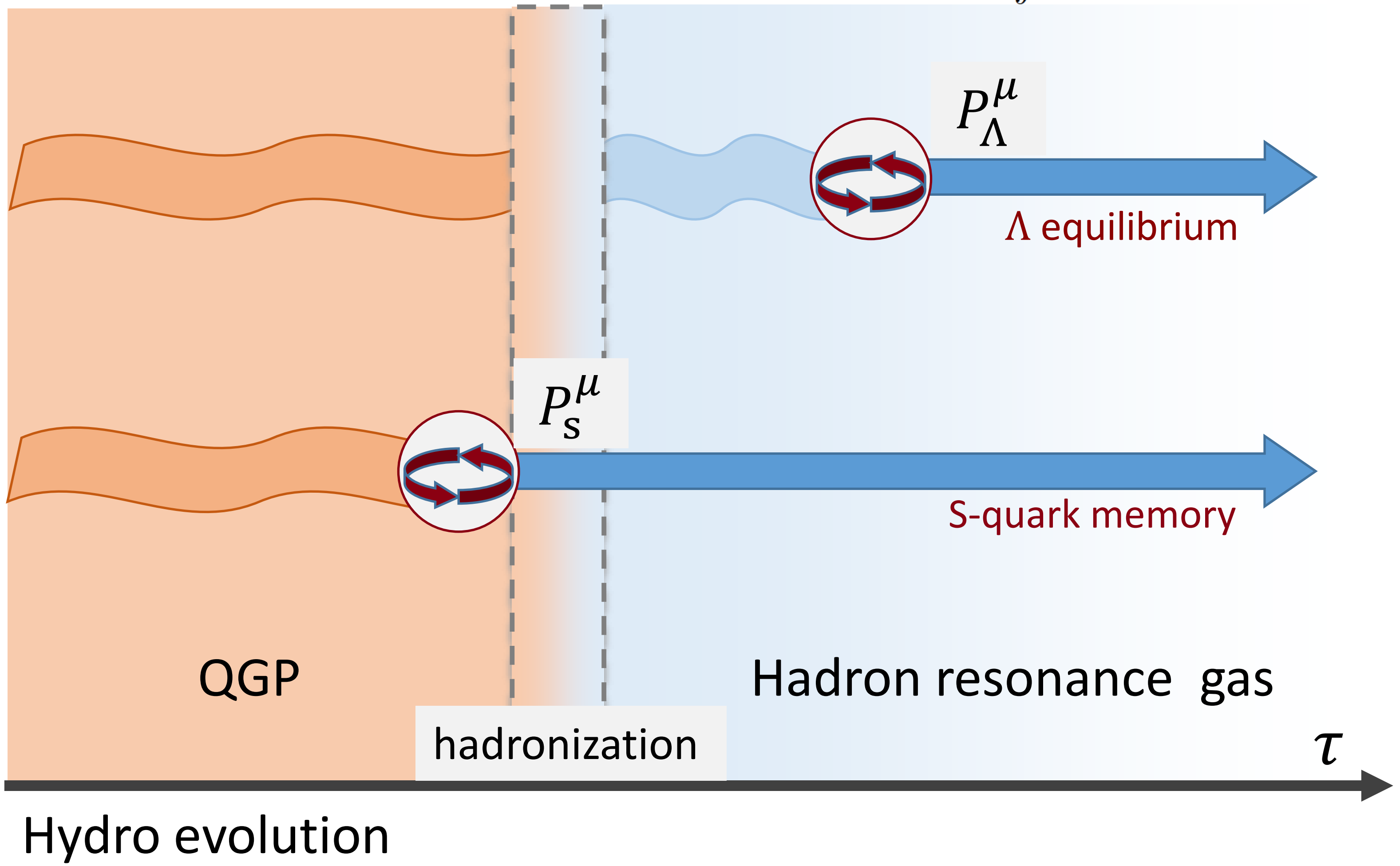
2 Scenarios for Λ polarization

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

‘Λ equilibrium’ vs. ‘S-quark memory’

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

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

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

Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301
Quark model: $P_{\Lambda} \sim P_{s}$

SIP results in hydrodynamics

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

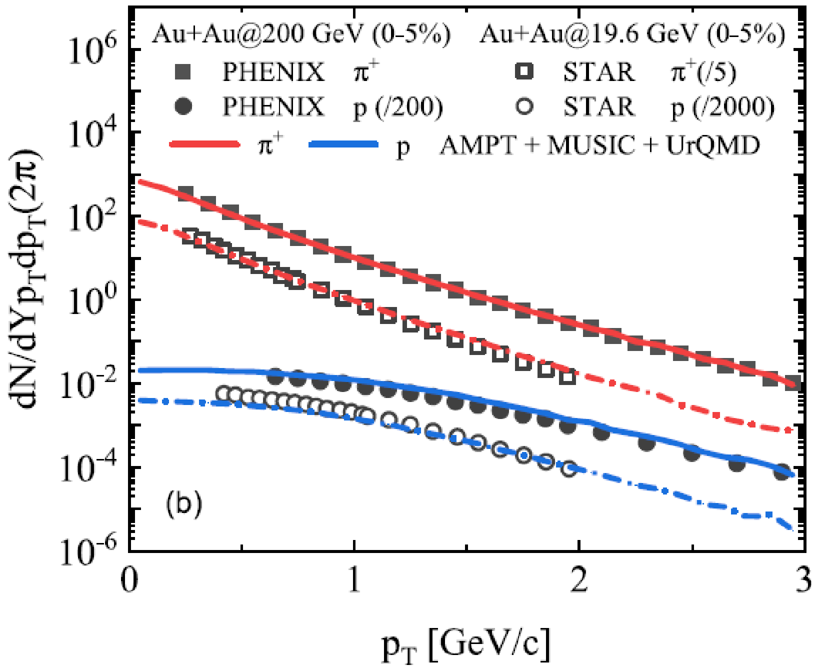
Well calibrated hydrodynamic model

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

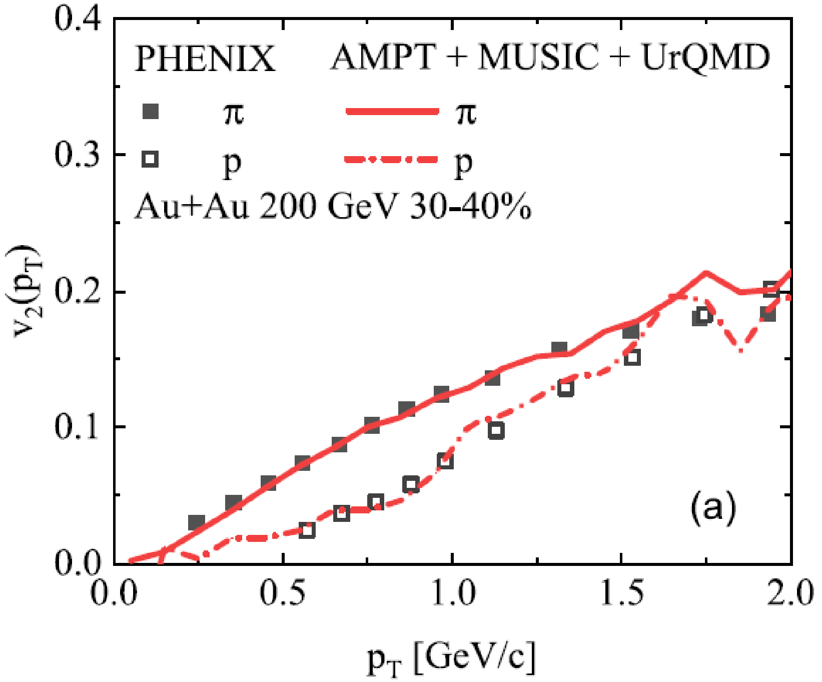
AMPT → MUSIC → iSS → UrQMD

Parameters are tuned to reproduce the soft hadron observables

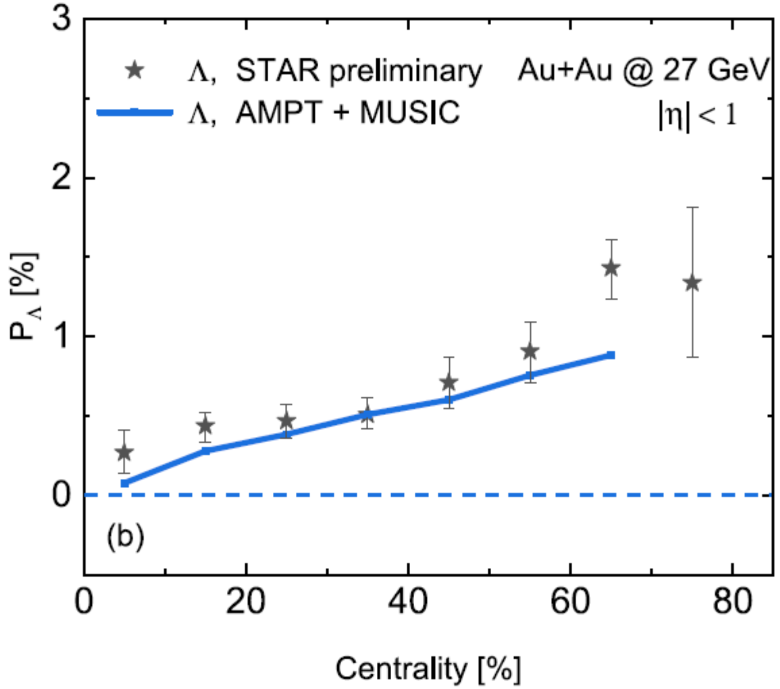
Transverse momentum spectra



$v_2(p_T)$



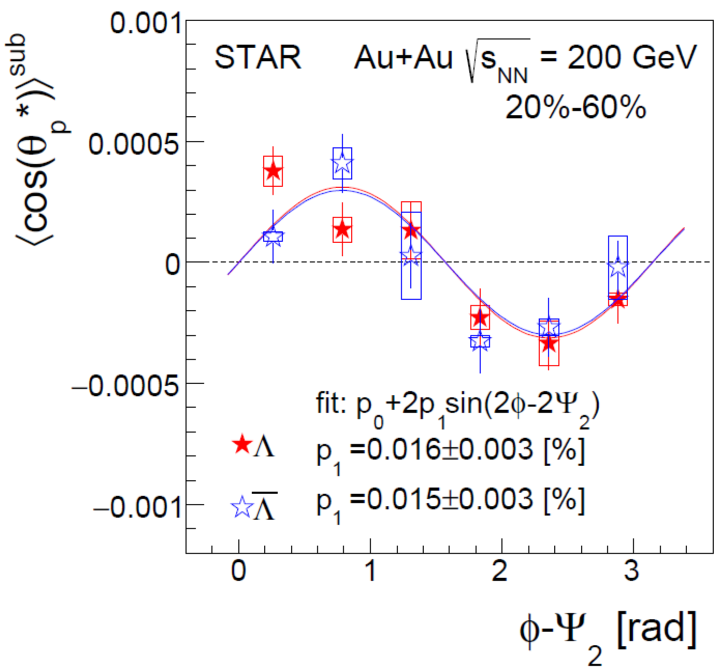
Global Polarization from thermal vorticity



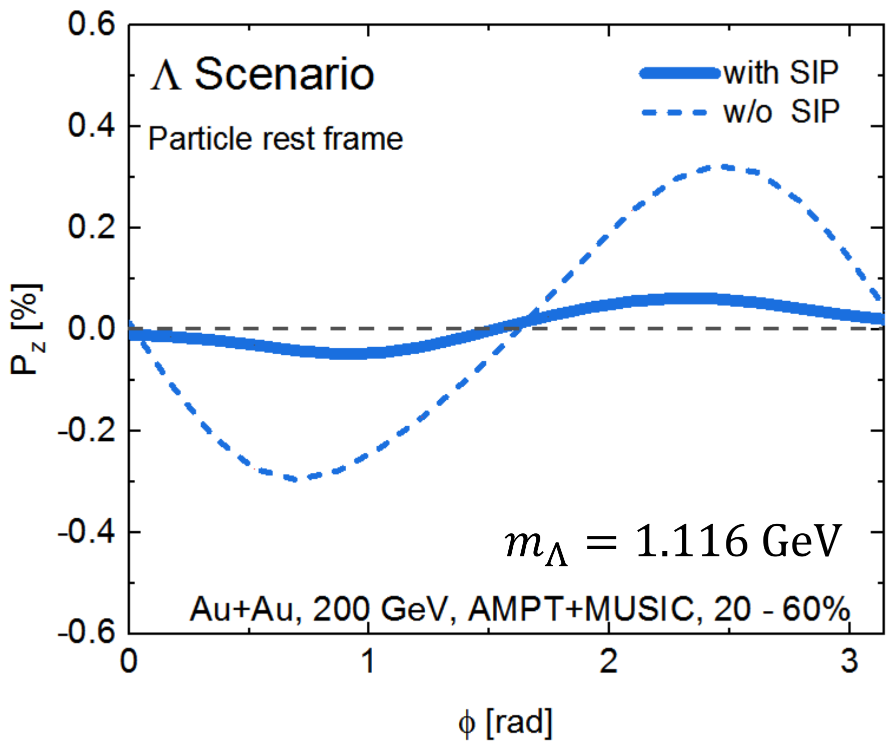
$P^z(\phi)$ with SIP

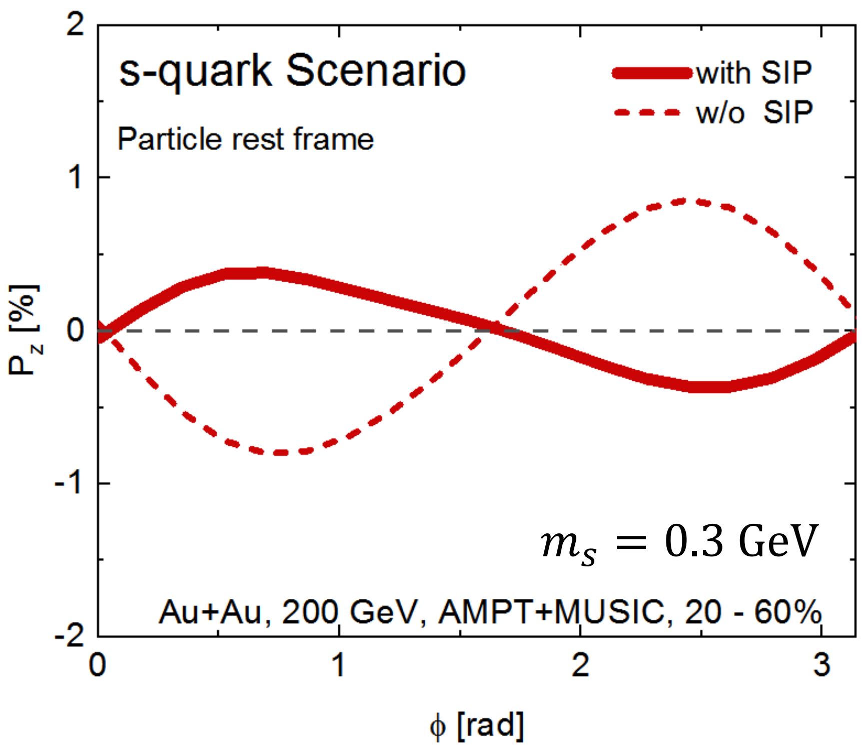
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

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



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





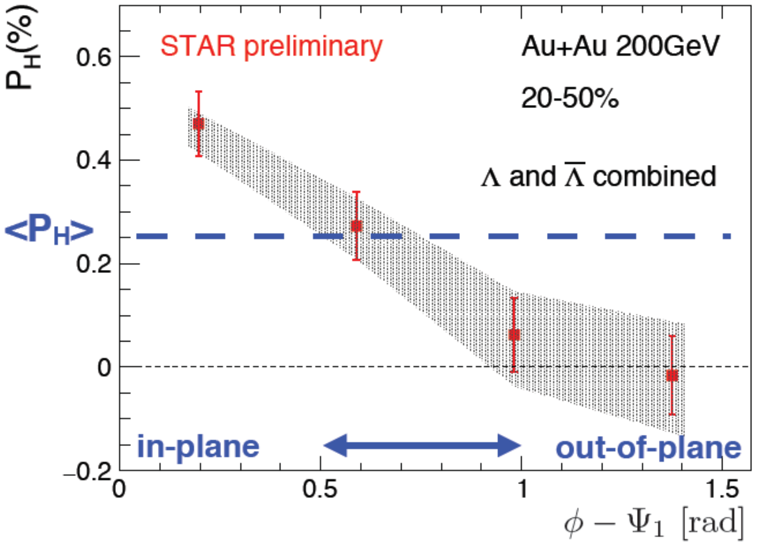
- In the scenario of ‘S-quark memory’, the total P^μ with SIP qualitatively agrees with data

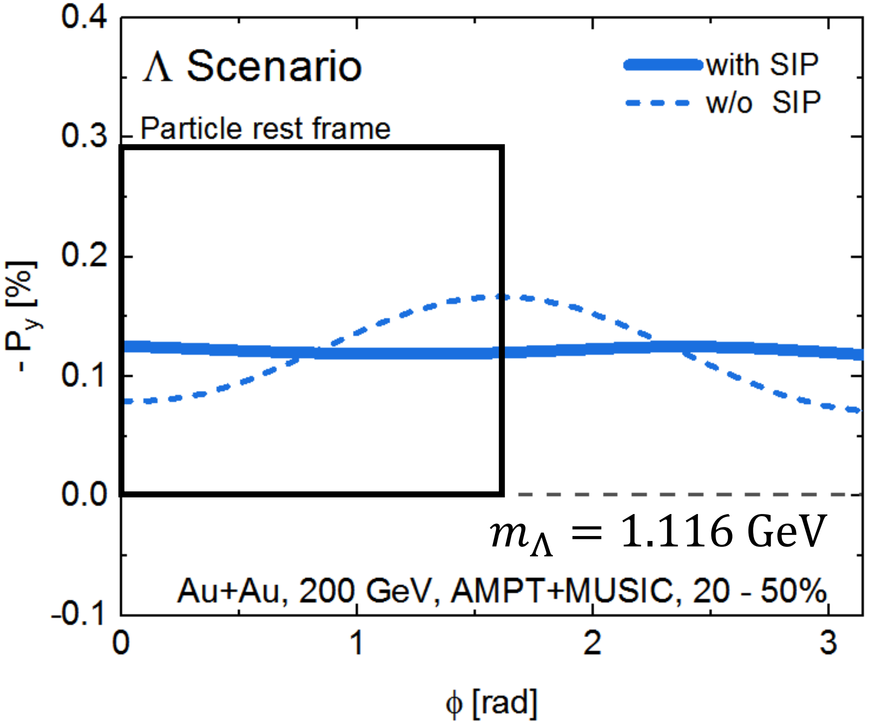
$P^y(\phi)$ with SIP

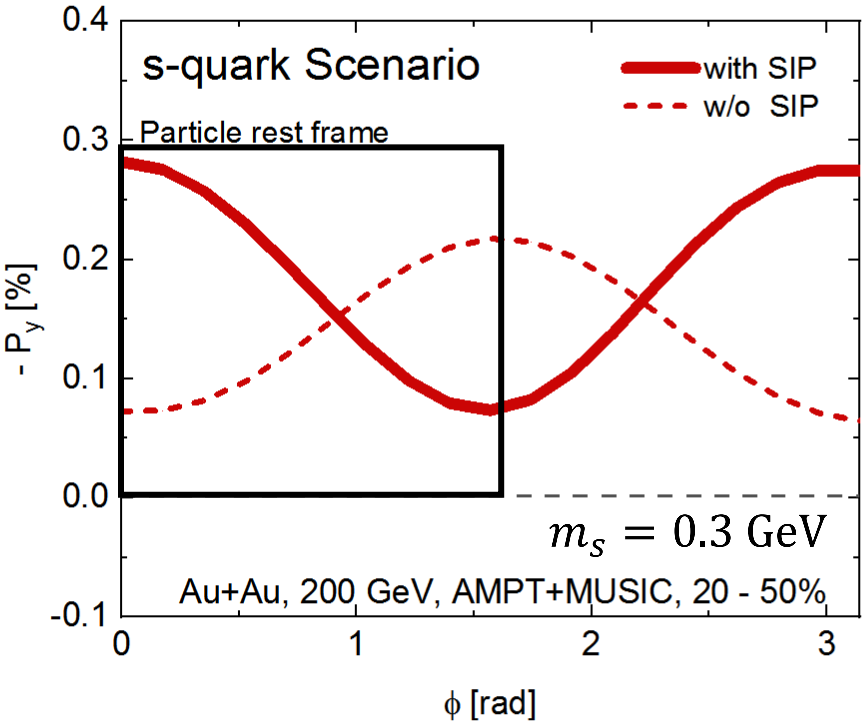
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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

STAR, NPA, 982 (2019) 511-514





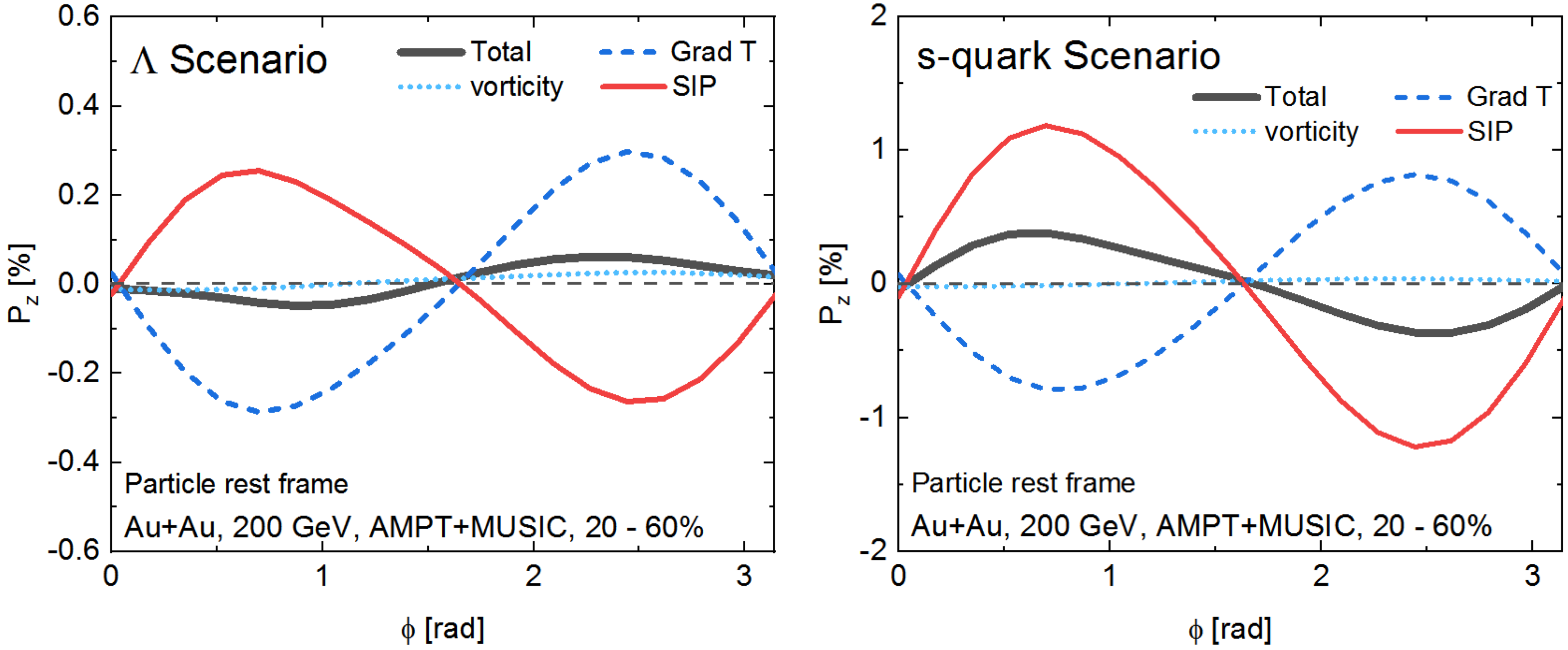


- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

Competition of P^z: Grad T vs. SIP

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

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

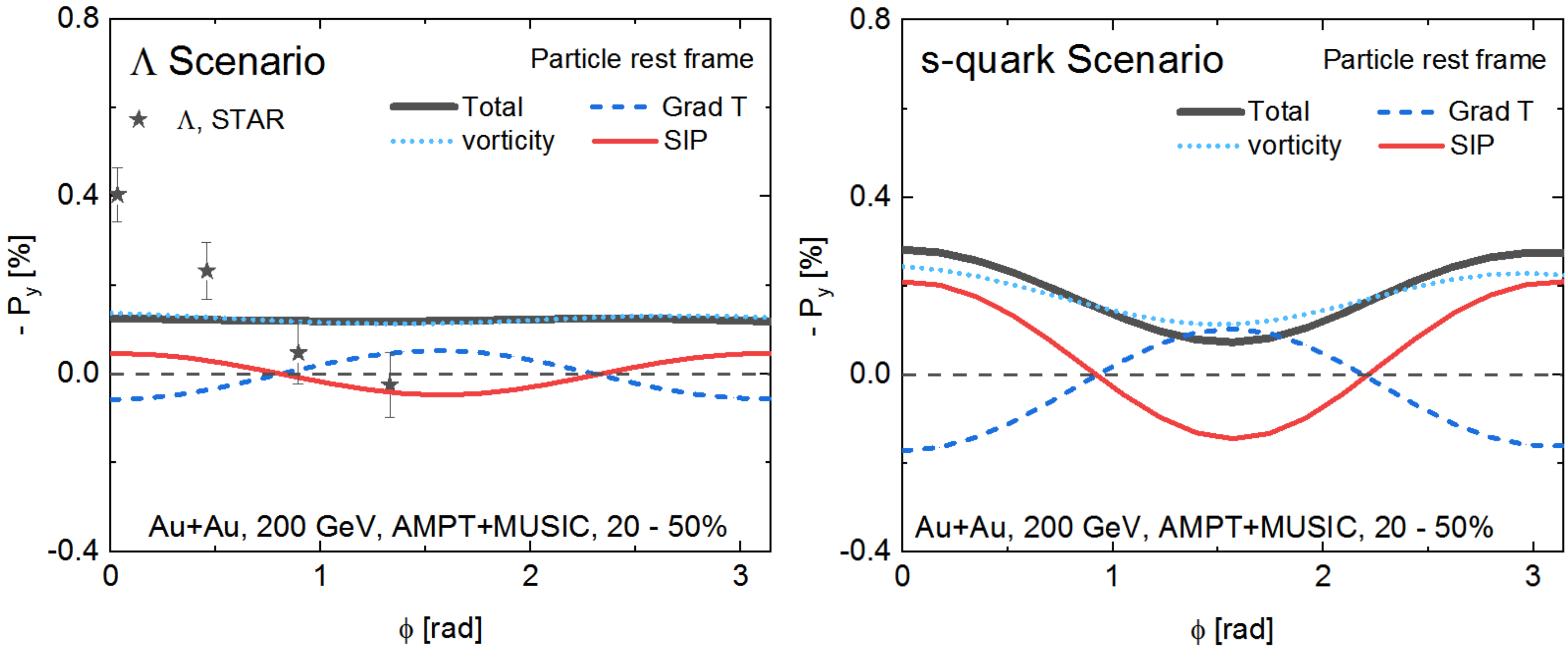


- [vorticity] ~ 0
- [SIP] and [Grad T] show similar magnitude but opposite sign

Competition of P^y: Grad T vs. SIP

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

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



- [vorticity] dominates the global polarization
- [SIP] and [Grad T] show similar magnitude but opposite sign

Sensitivity to frame

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

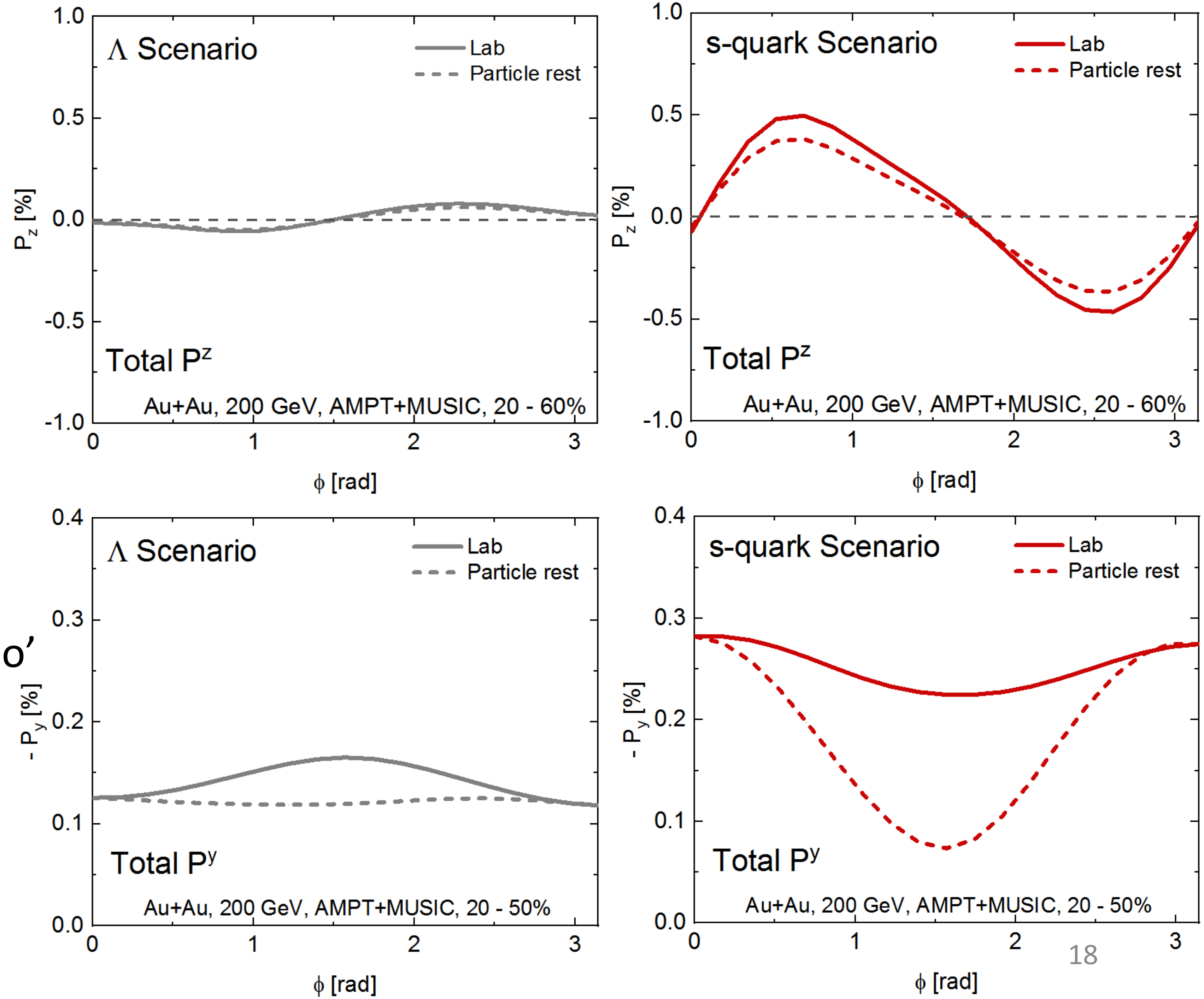
- $P^z(\phi)$

not sensitive to frame

- $P^y(\phi)$

sensitive to frame,

especially in 'S-quark scenario'



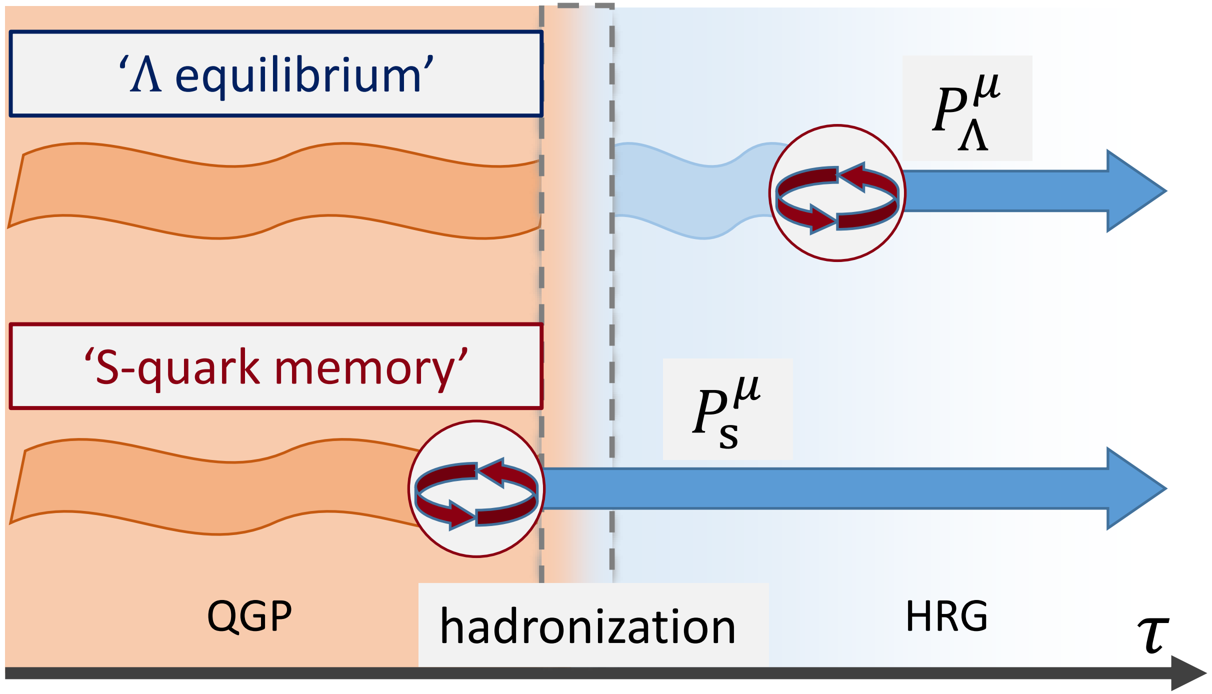
Summary

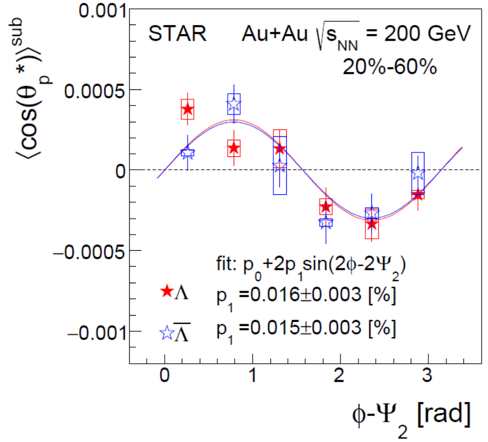
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

Shear strength contributes to spin polarization

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

Both SIP and the memory of strange quarks are required to agree with data qualitatively





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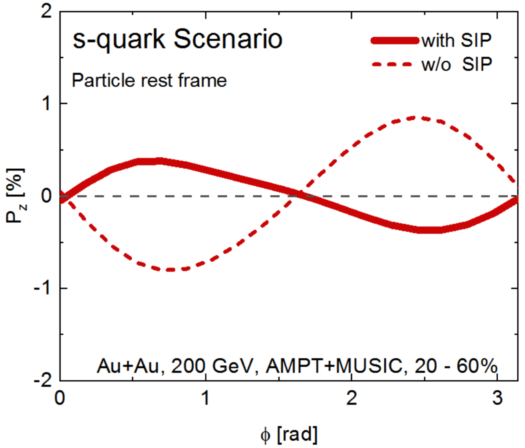

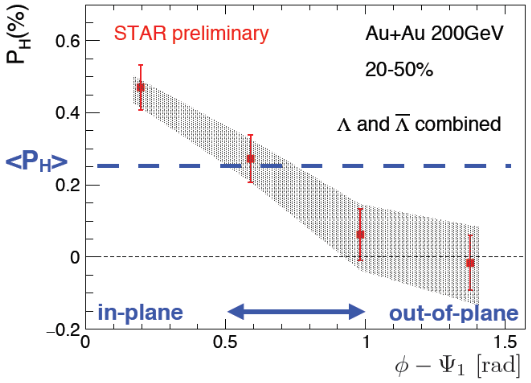

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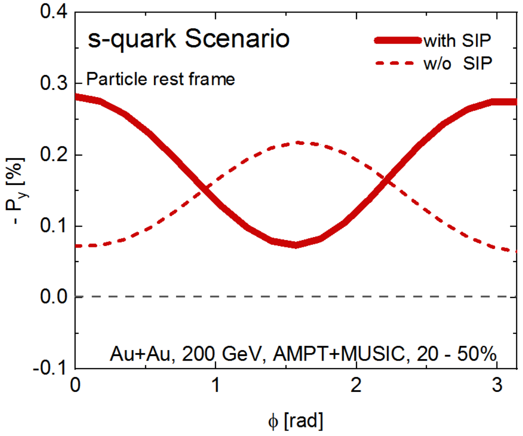
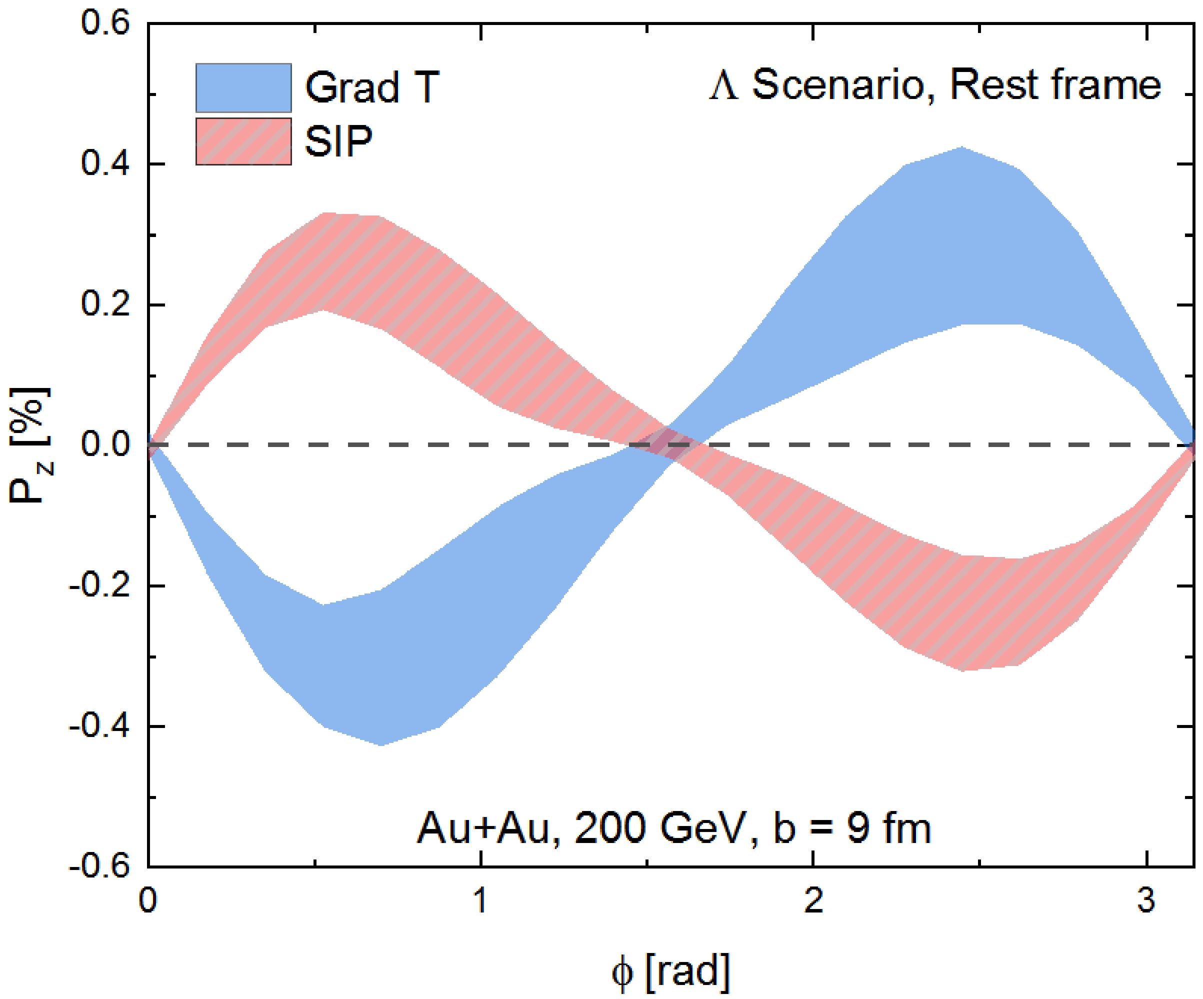


Back up

Robustness of the competition



Band: possible flexibility of [Grad T] and [SIP]

- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: $\zeta/s(T)$ → off
- Freeze-out temperature:

  167 MeV → 157 MeV

Shear Induce Polarization (SIP)

The formula can be rewritten in a more friendly way:

$$S^\mu(x,p) = \mathcal{A}^\mu/4m = \beta n_{\rm FD}(1-n_{\rm FD})\left[-(p\cdot\omega^\mu)u^\mu + \varepsilon_u\omega^\mu + \varepsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha(\partial_{\perp,\lambda}\log\beta) - \varepsilon^{\mu\nu\alpha\lambda}\frac{u_\nu}{\varepsilon_u}Q_\alpha^{\ \rho}Q_{\lambda\rho}\right]$$

[vorticity] [Grad T] [SIP]

The standard formula from thermal vorticity:

$$S^\mu(x,p) = -\frac{1}{8m}(1-f)\{\frac{1}{T}(2(p\cdot u)\omega^\mu - 2(p\cdot\omega)u^\mu) + \epsilon^{\mu\nu\rho\sigma}p_\nu\partial_\rho(1/T)\,u_\sigma + \frac{1}{T}\epsilon^{\mu\nu\rho\sigma}p_\nu u_\rho D u_\sigma\}$$

[vorticity] [Grad T /2] [Acceleration /2]

If the fluid is ideal and uncharged:

[Acceleration] = [Grad T] ⇒

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

= [thermal vorticity] + [SIP]

I. Karpenko, F. Becattini, Nucl.Phys.A 982 (2019) 519-522)