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

main points

- Shear stress tensor contributes to spin polarization (SIP)
- With SIP, $P^{\mu}(\phi)$ of s-quark qualitatively describe the data

Baochi Fu (付宝迟)

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

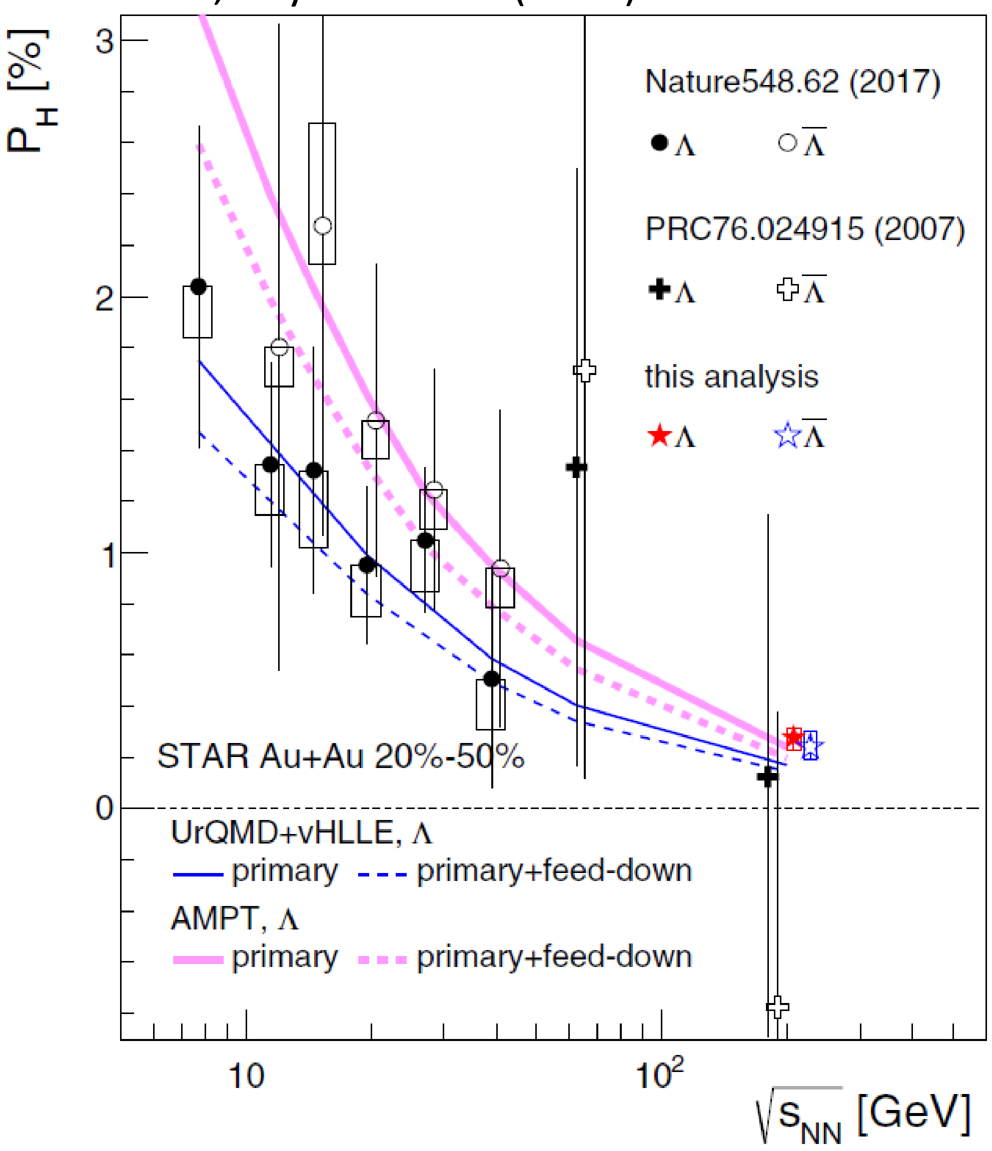
北京大学
PEKING UNIVERSITY

第十三届全国粒子物理学术会议
山东青岛（Online），16 Aug 2021

Introduction

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 by the statistic method

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

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'

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

See also:

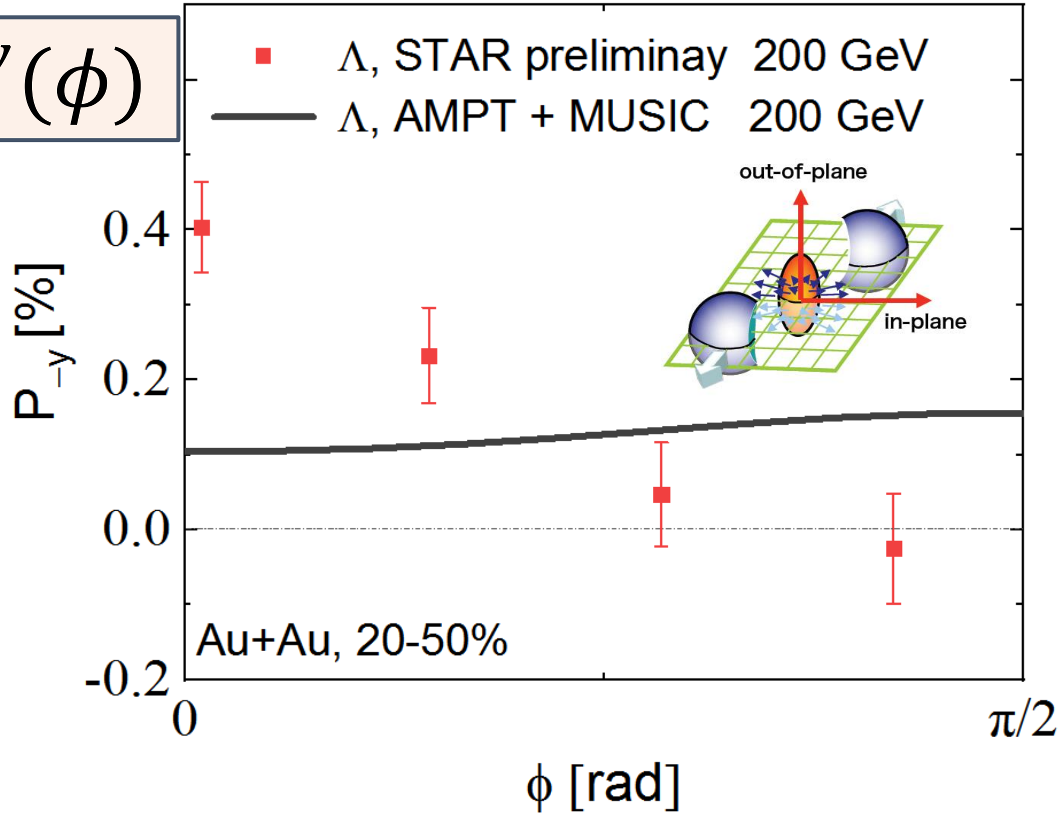
Karpenko, Becattini, EPJC 77 (2017) 4, 213

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

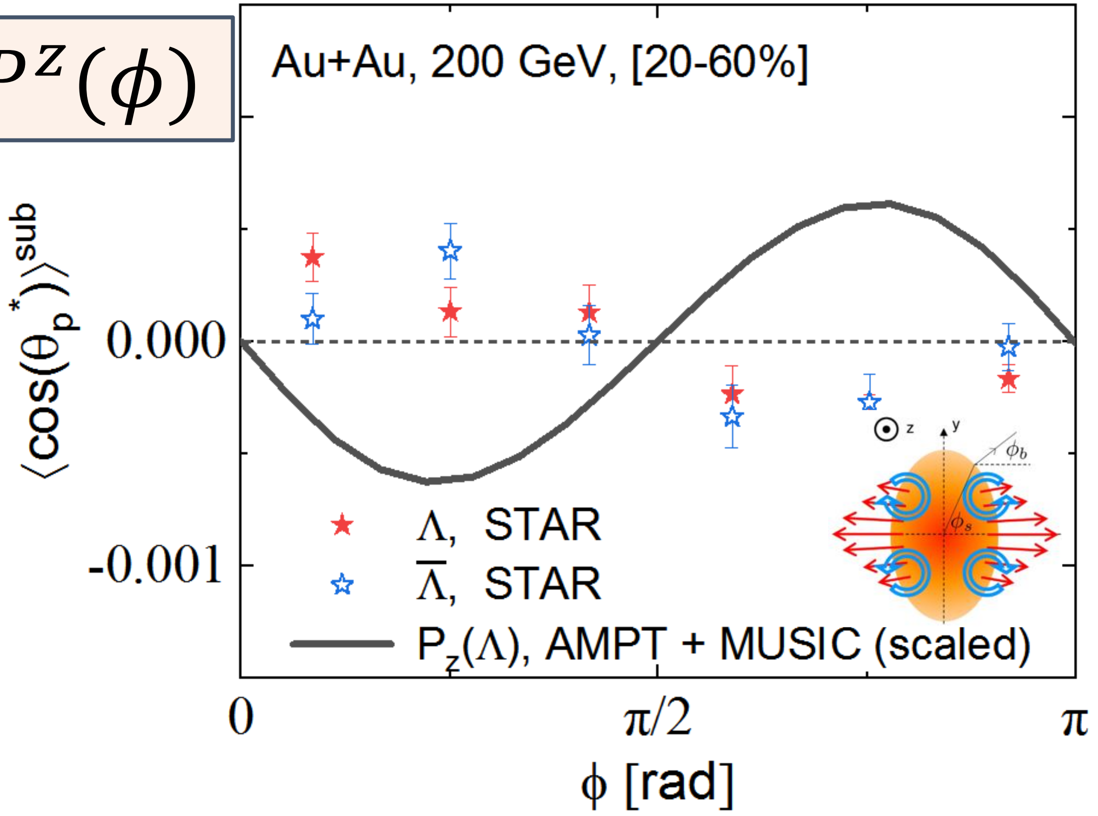
X. Xia, et al., PRC 98 (2018) 024905

Becattini, Karpenko, PRL 120 (2018) 012302

$P^y(\phi)$



$P^z(\phi)$

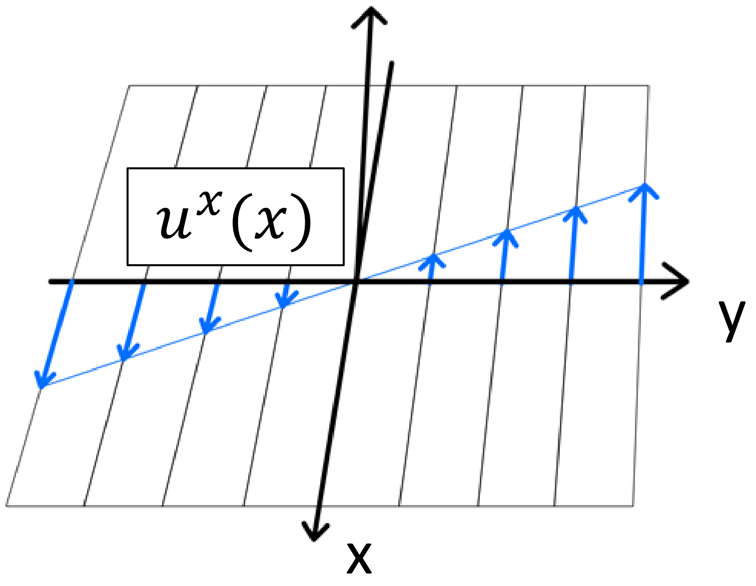


BF, K. Xu, X-G, Huang, H. Song, Phys.Rev.C 103 (2021) 2, 024903

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 ✓

(heavy ion, condensed matter ...)

Symmetric: shear stress

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

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

Shear Induced Polarization (SIP)

Shear Induced Polarization (SIP)

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

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:

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

Vorticity

T gradient (spin Nernst effect)

Shear strength

- No free parameter
- Identical form by linear response theory with arbitrary mass (S. Liu and Y. Yin, JHEP 07 (2021) 188)
- Different mass sensitivity of each term

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

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

Shear Induced Polarization (SIP)

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

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Vorticity — T gradient (spin Nernst effect) — Shear strength

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

Shear Induced Polarization (SIP)

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

Axial Wigner fu

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

To one-loop order (in charge neutral fluid)

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

Thermal vorticity

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

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

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Vorticity — T gradient (spin Nernst effect) — Shear strength

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

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

The only new effect

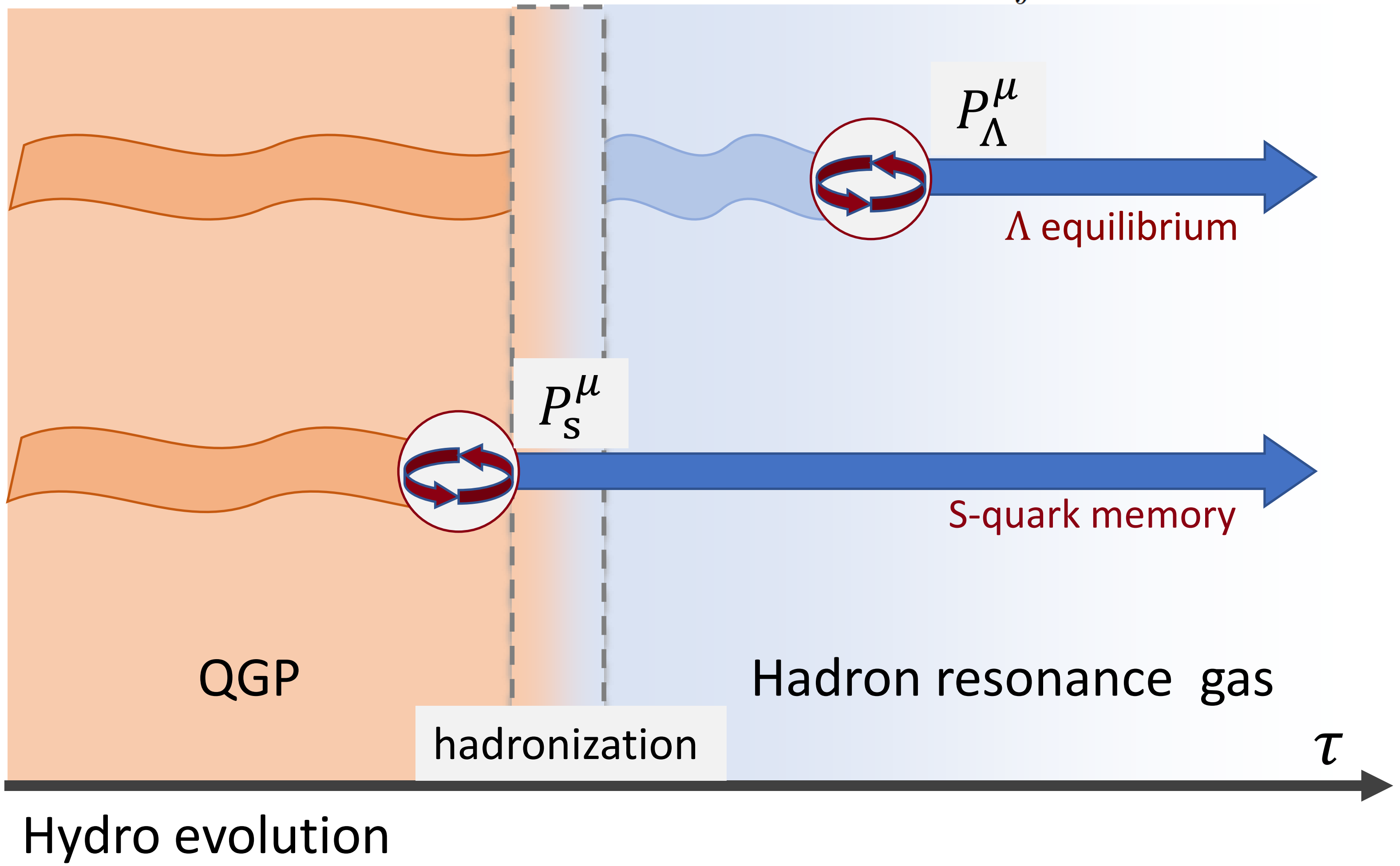
Similar result obtained independently by
Becattini, Buzzegoli, Palermo, arXiv: 2103.10917

2 Scenarios for Λ polarization

‘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

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

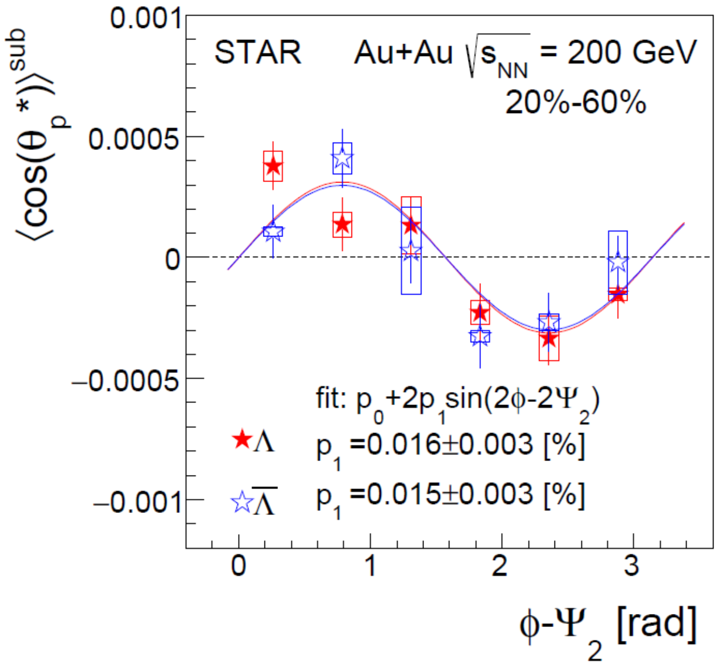
Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301

SIP results in hydrodynamics

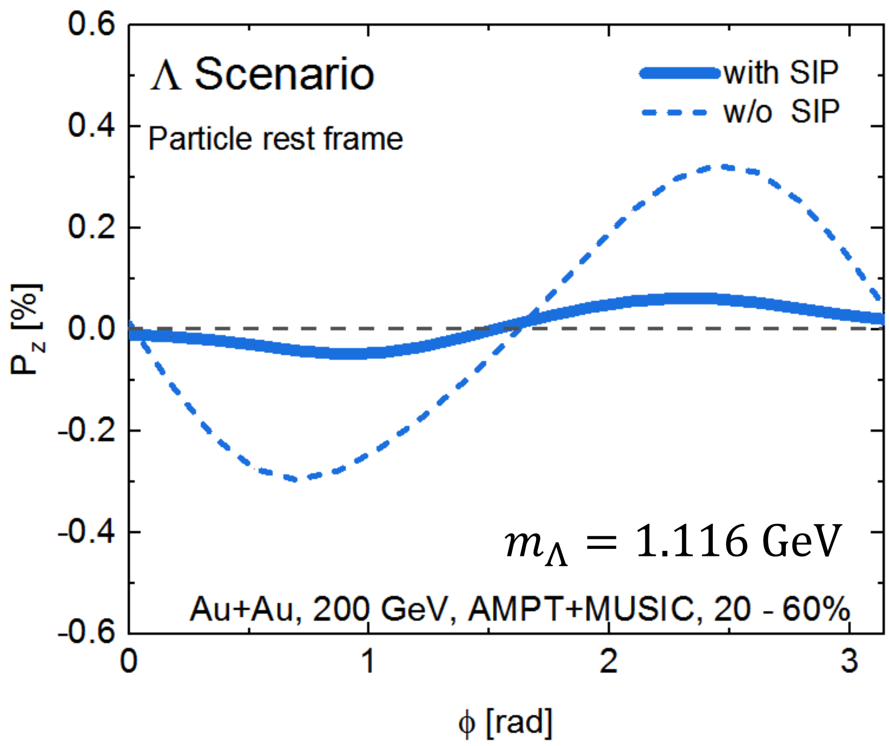
$P_z(\phi)$ with SIP

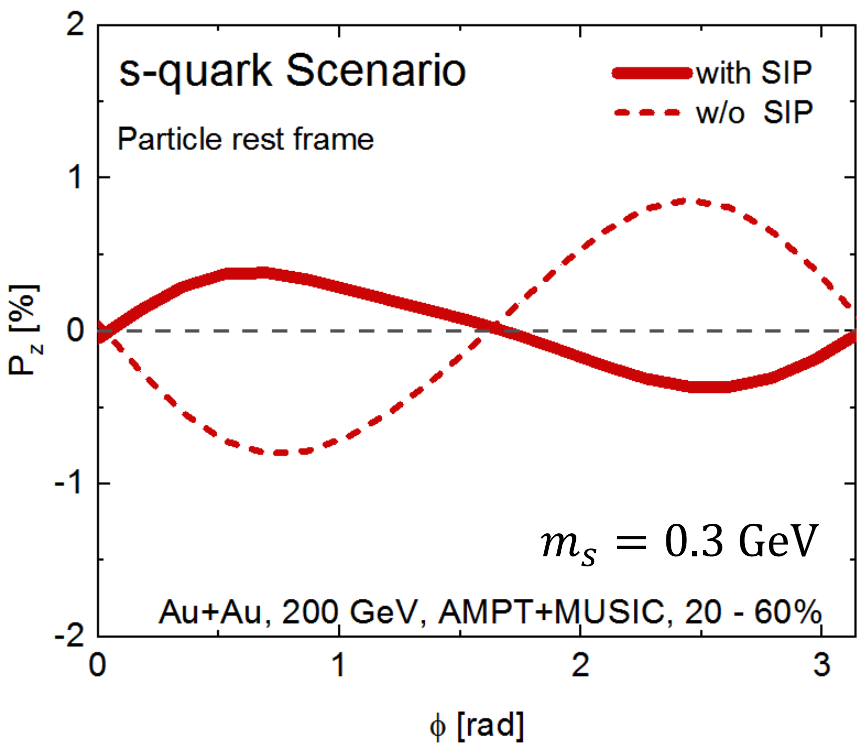
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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



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





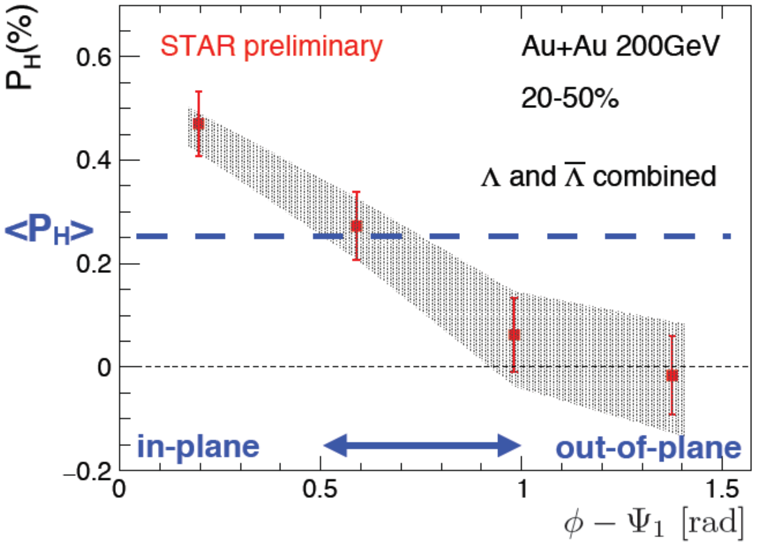
- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

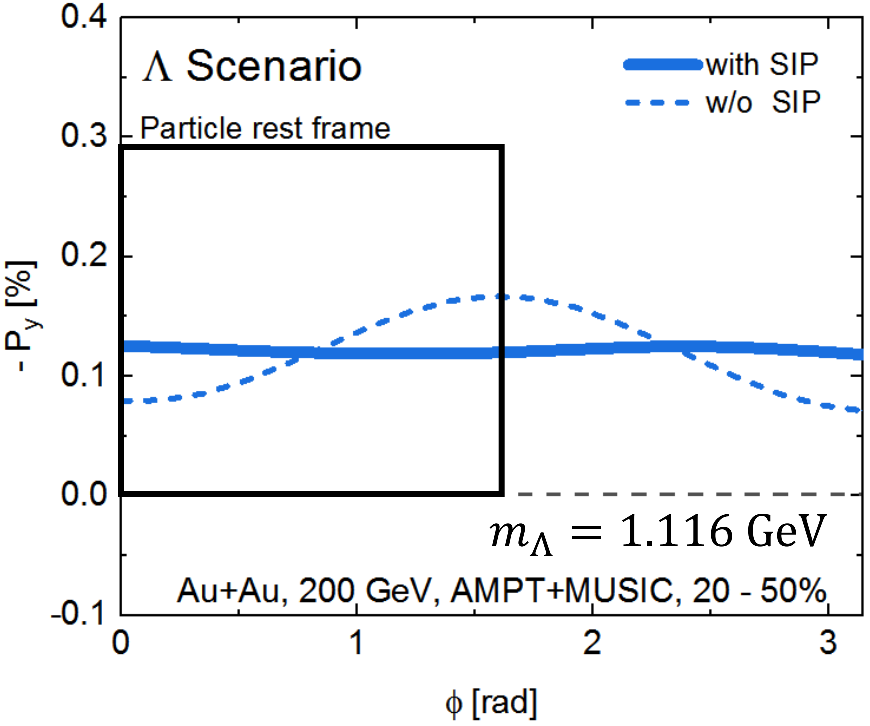
$P_y(\phi)$ with SIP

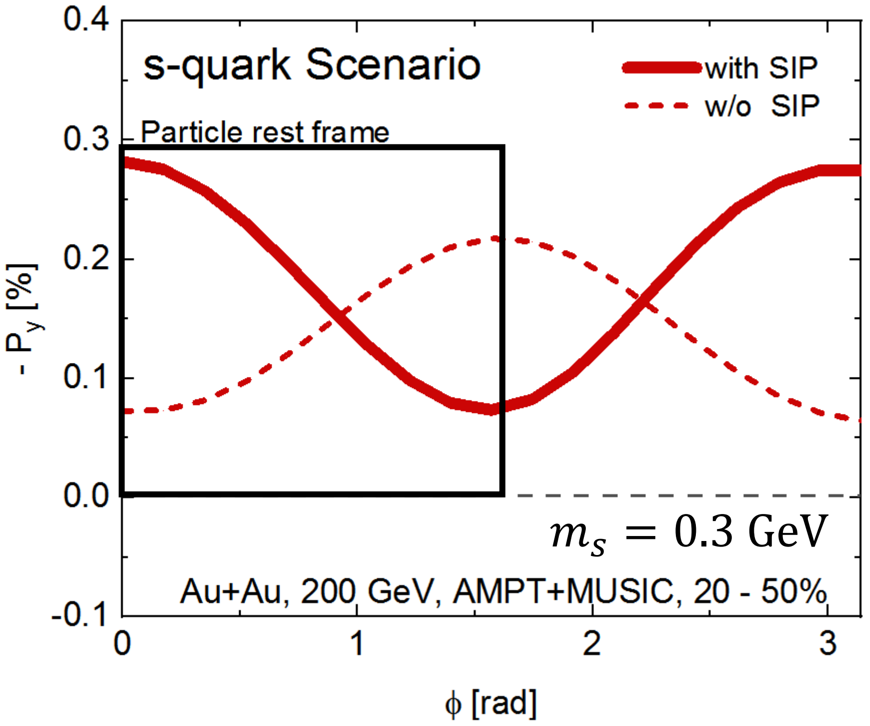
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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

STAR, NPA, 982 (2019) 511-514







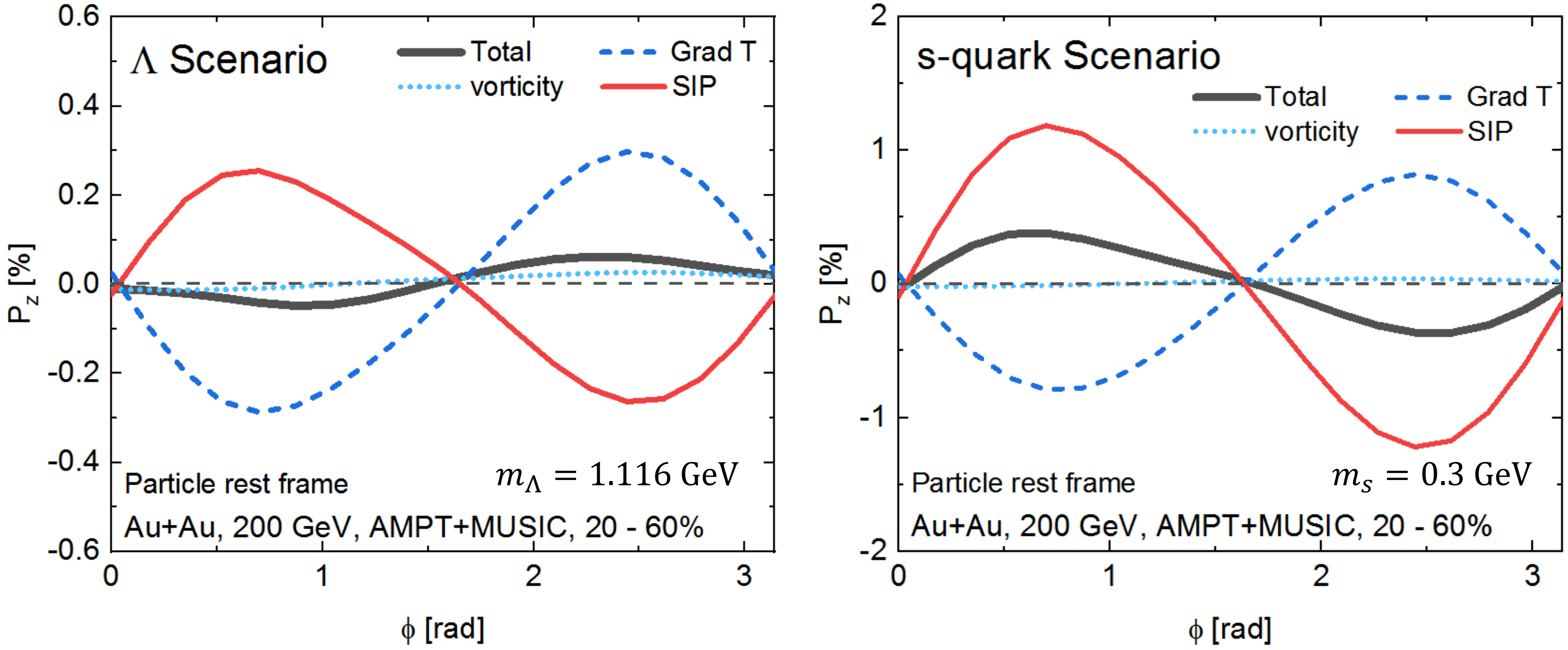
- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

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]



- Total polarization: a competition between [SIP] and [Grad T]

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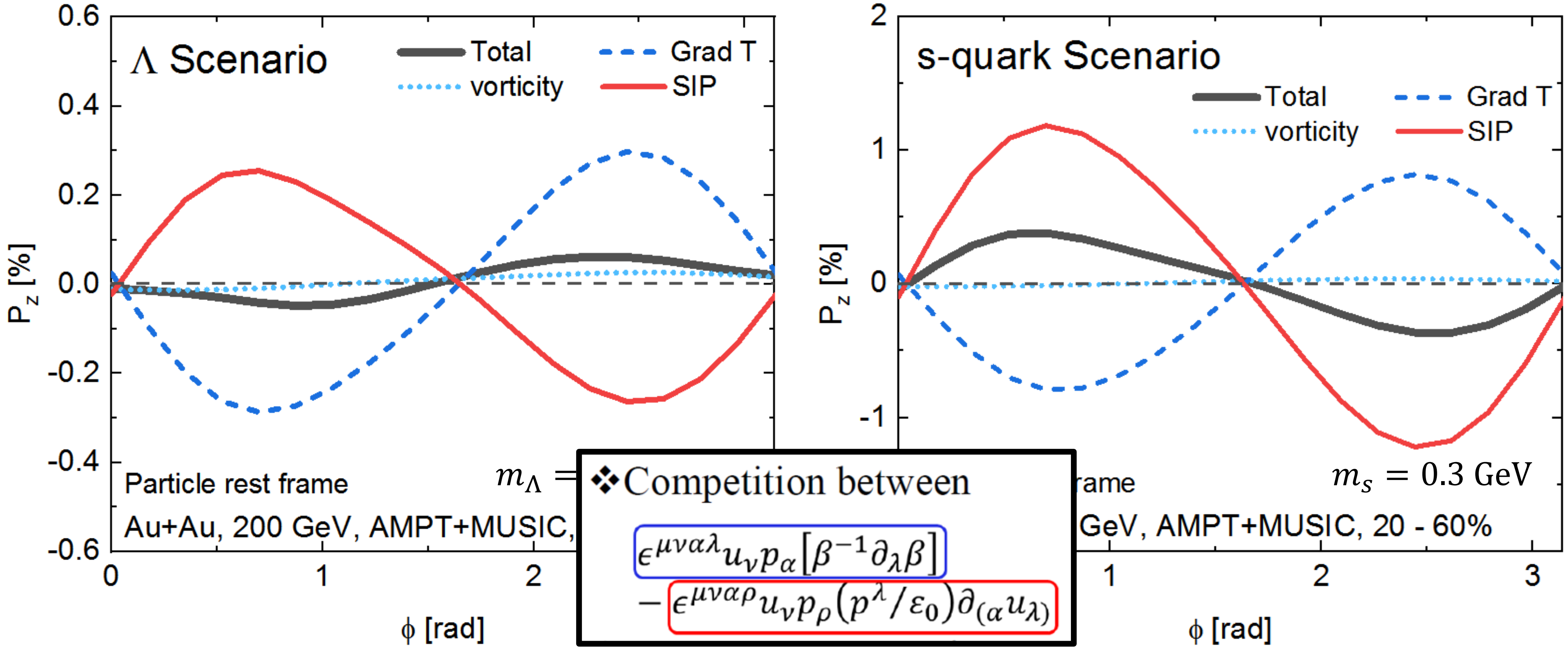
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

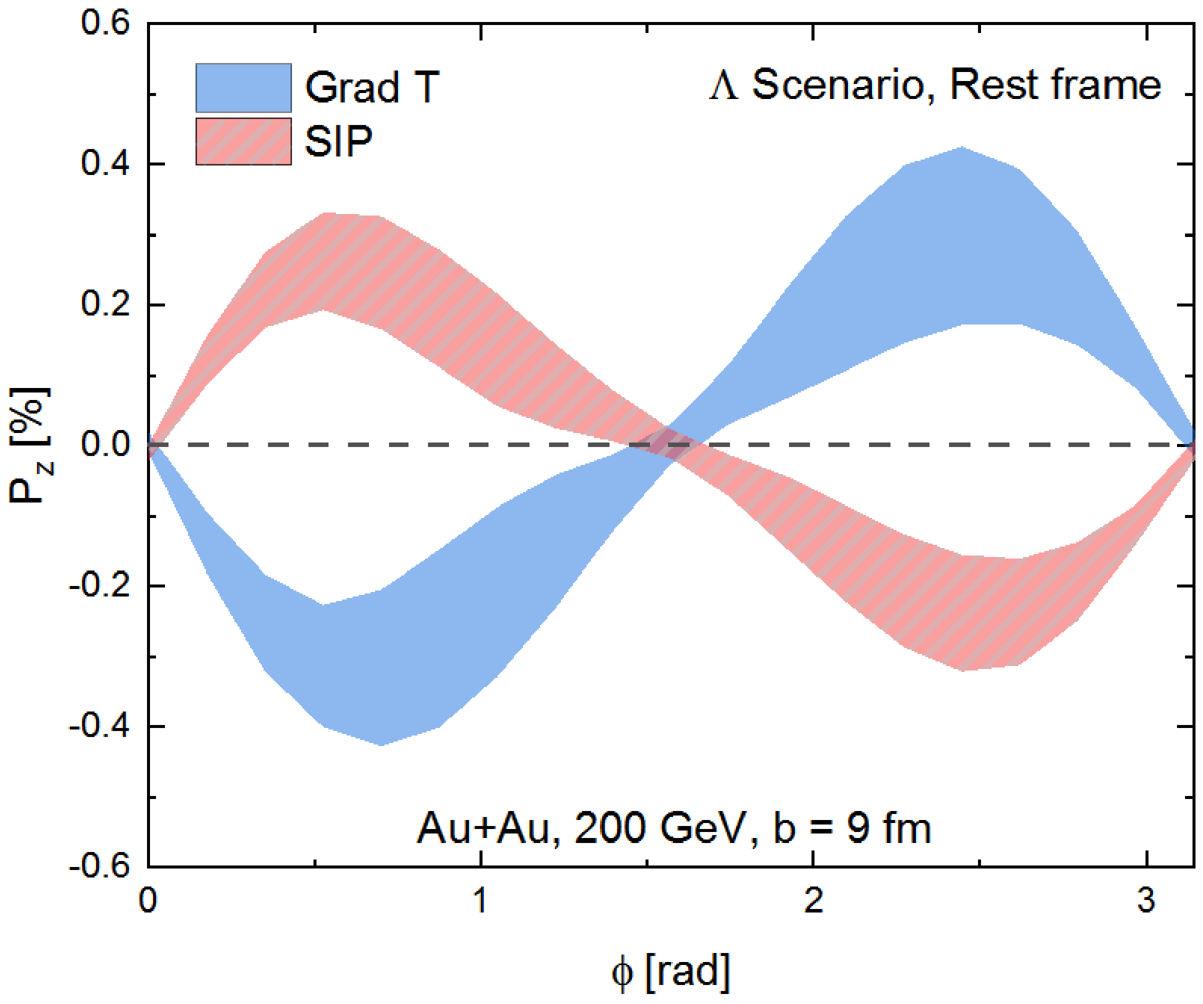


❖Competition between

$$\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha \left[\beta^{-1}\partial_\lambda \beta\right] - \epsilon^{\mu\nu\alpha\rho} u_\nu p_\rho \left(p^\lambda/\varepsilon_0\right)\partial_{(\alpha} u_{\lambda)}$$

- Total polarization: a competition between [SIP] and [Grad T]

Robustness of the competition



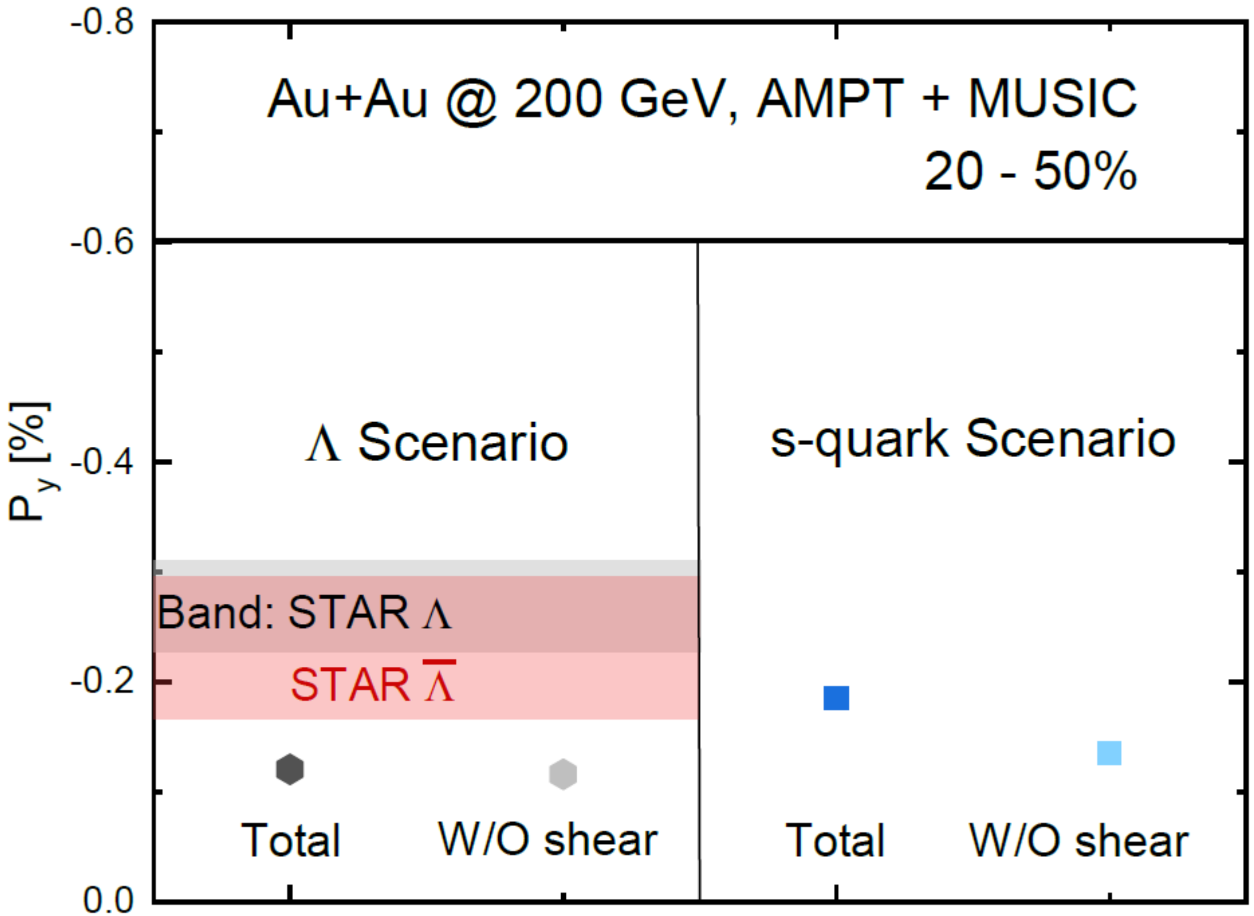
Band: possible flexibility of [Grad T] and [SIP]

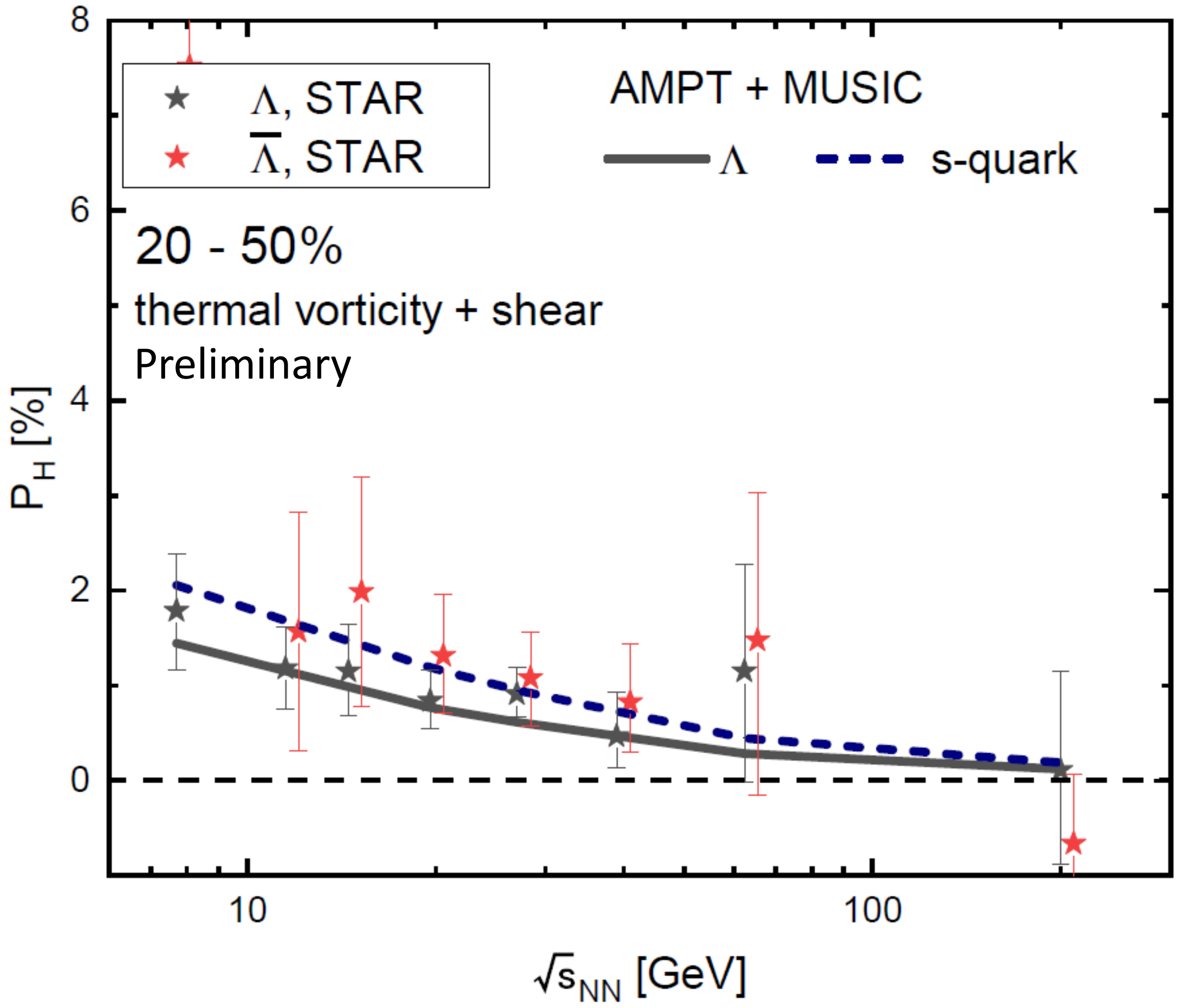
- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: $\zeta/s(T)$ → off
- Freeze-out temperature:

  167 MeV → 157 MeV

Global polarization with shear effect

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



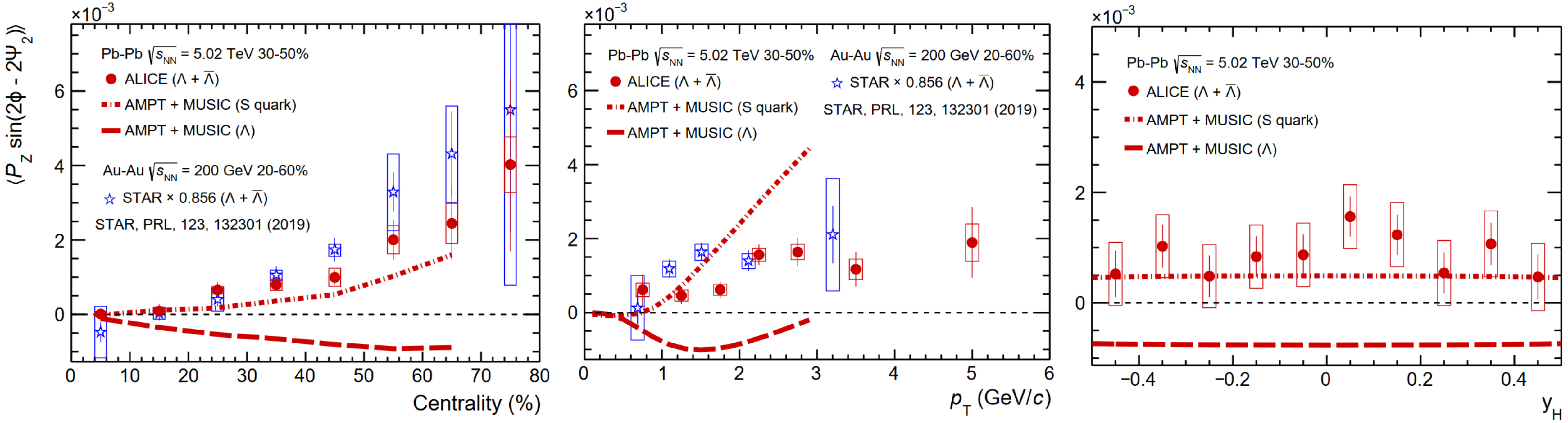


Local polarization at LHC energies

ALICE, arXiv:2107.11183

Same hydrodynamic model: AMPT + MUSIC
(parameter from Zhao, Xu and Song, EPJC 77 (2017) 9, 645)

Centrality dependence | p_T dependence | rapidity dependence



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

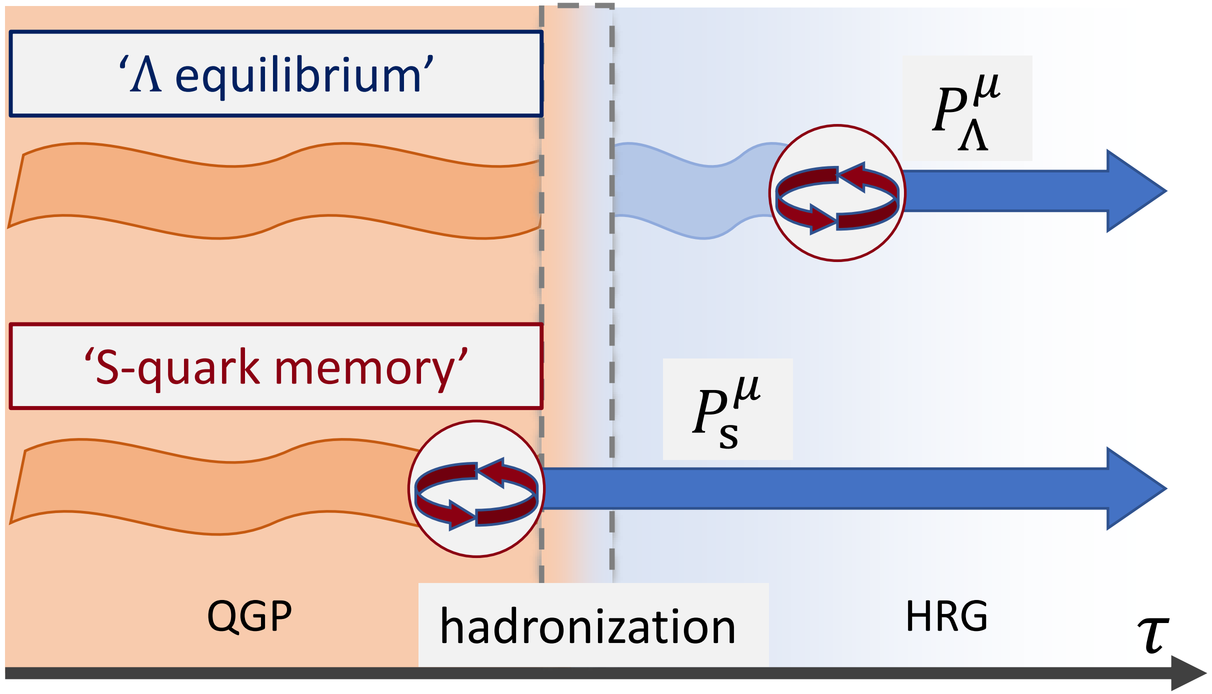
Summary

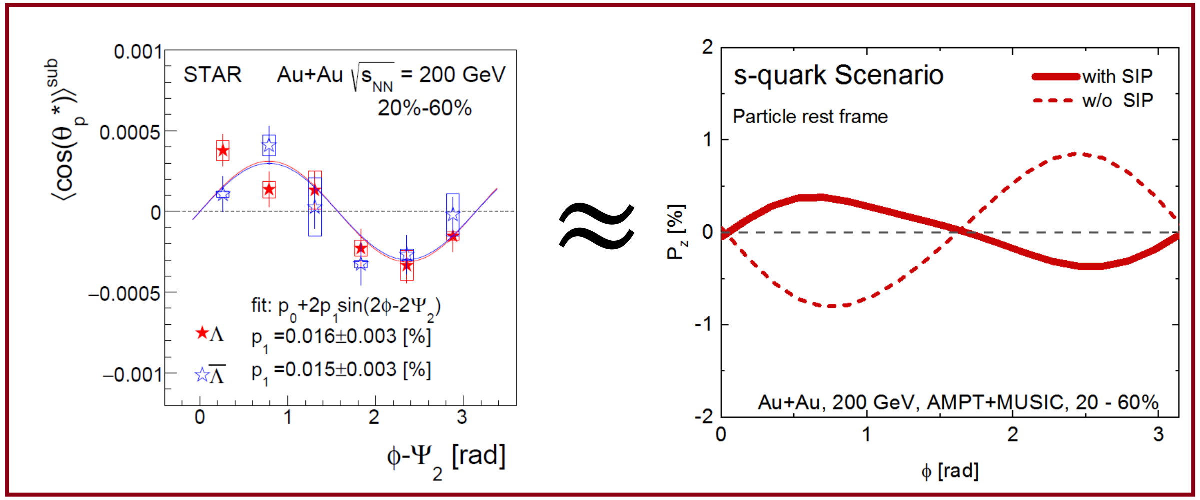
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

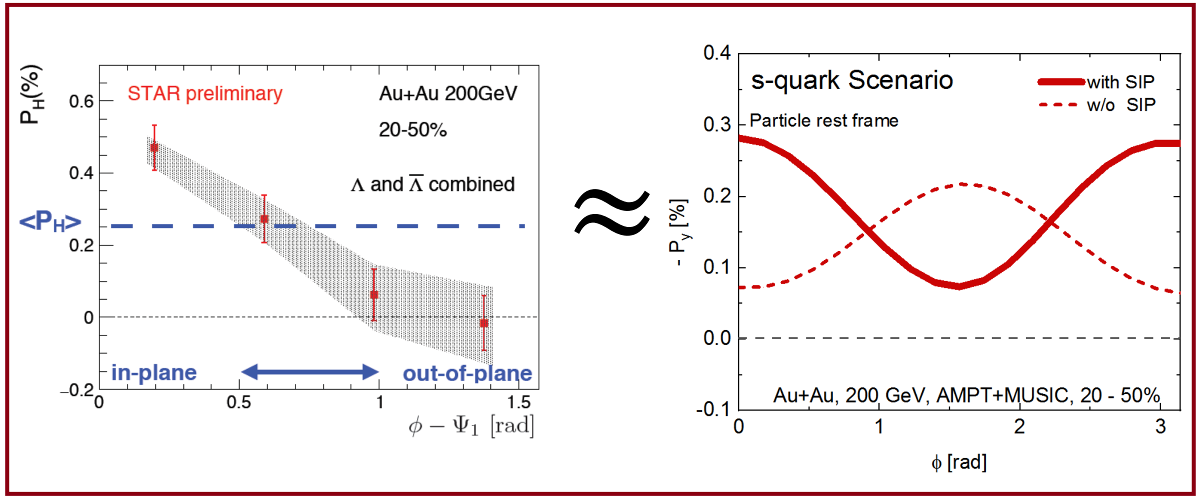
Shear strength contributes to spin polarization

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

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







backup

Spin-orbital coupling in Condensed Matter

Gradient of spin voltage → spin current

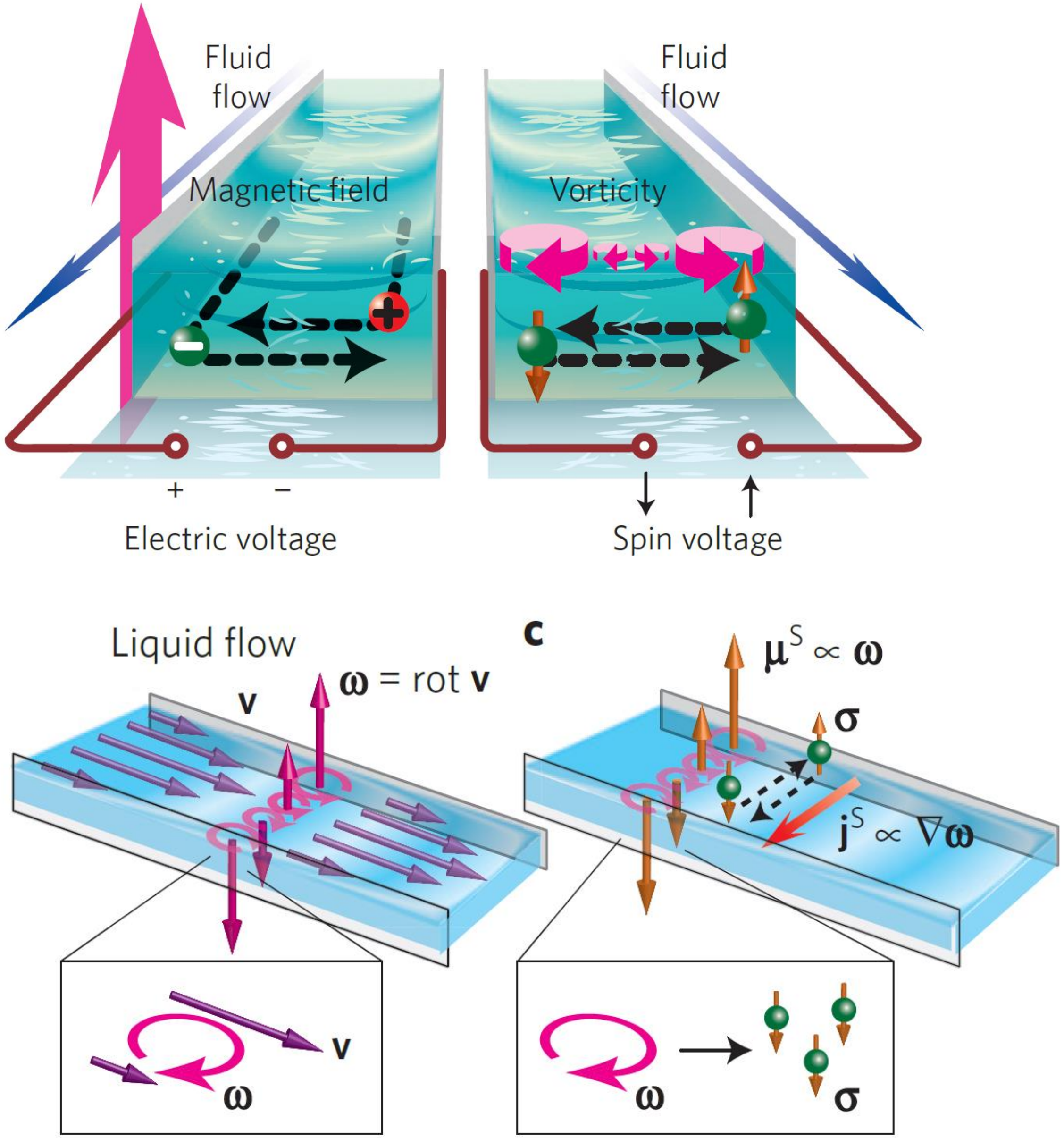
Spin voltage from Electrochemical potential:

$$\mu^S \equiv \mu_\uparrow - \mu_\downarrow$$

Diffusion equation:

$$\nabla^2 \boldsymbol{\mu}^S = \frac{1}{\lambda^2}\boldsymbol{\mu}^S - \frac{4e^2}{\sigma_0 \hbar}\xi \boldsymbol{\omega}$$

The spin current is detected by inverse spin Hall effect (ISHE)



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

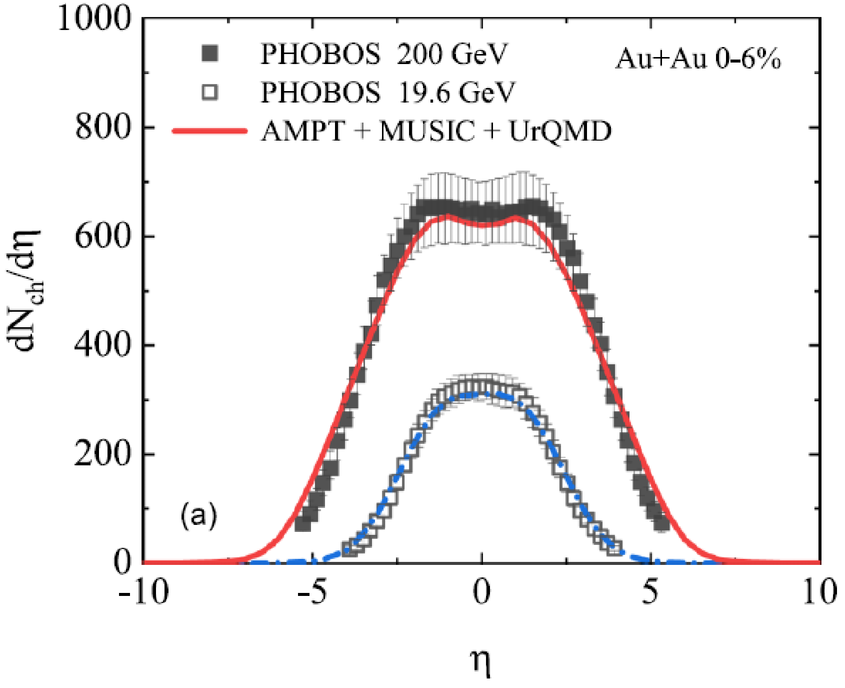
Well calibrated hydrodynamic model

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

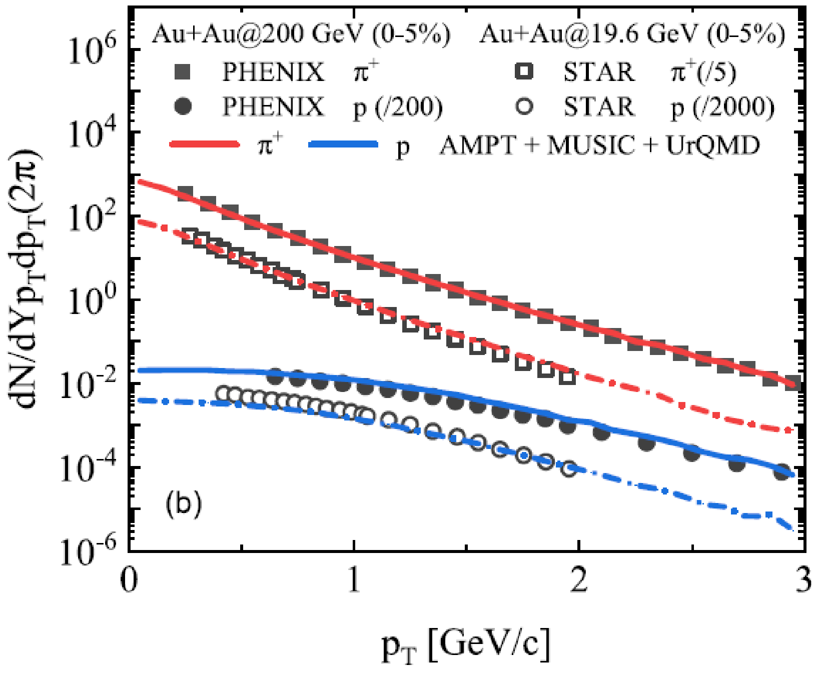
AMPT → MUSIC → Freeze-out surface → iSS → UrQMD

Parameters are tuned to reproduce the soft hadron observables

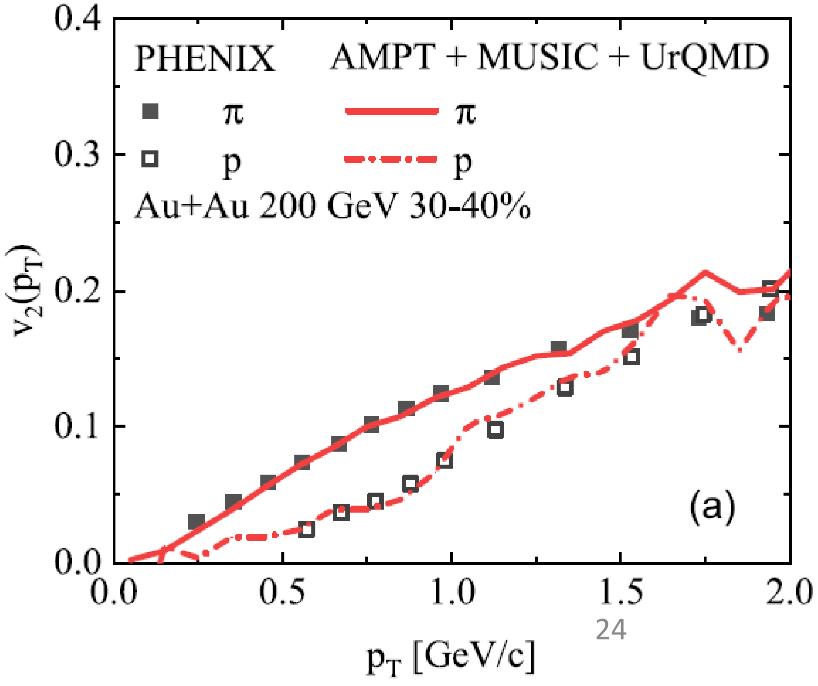
Charged particle yields



Transverse momentum spectra



$v_2(p_T)$



Competition of P_y: Grad T vs. SIP

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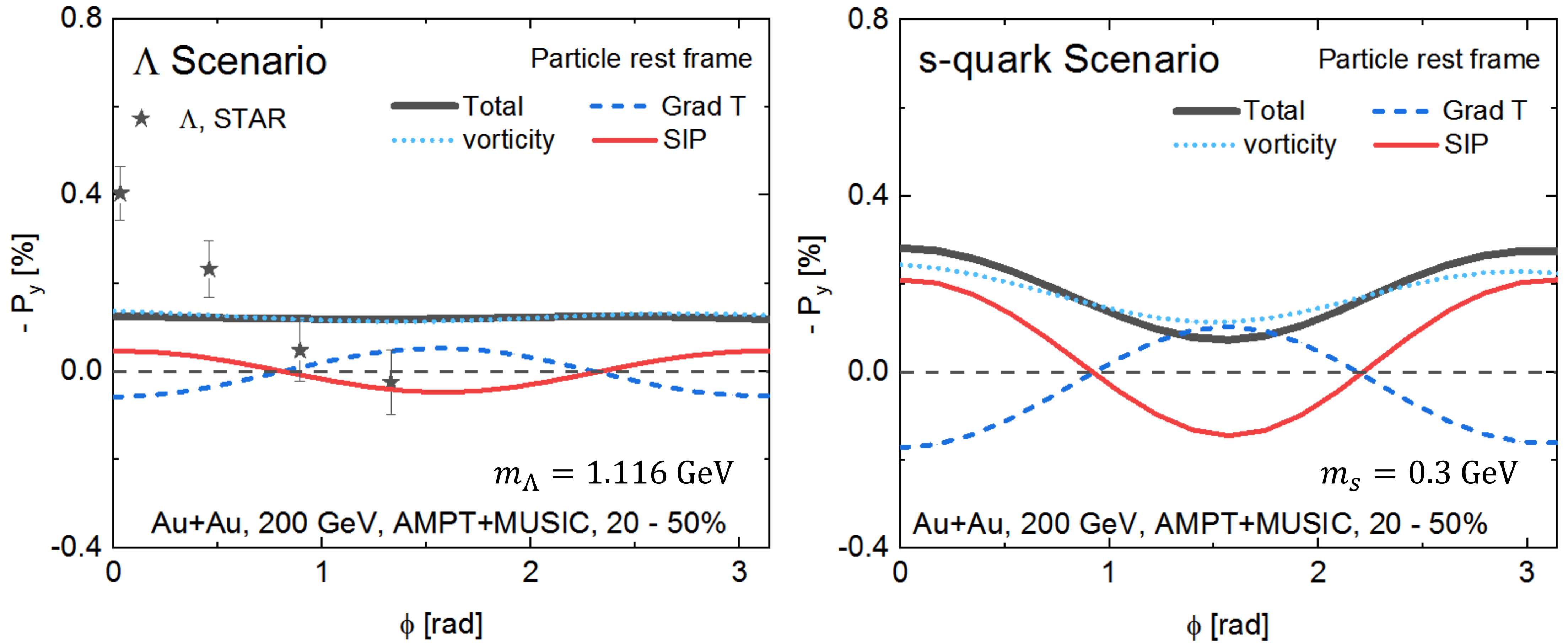

- [vorticity] dominates the global polarization
- [SIP] and [Grad T] show similar magnitude but opposite sign

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’