Global and local spin polarization in heavy-ion collisions

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at HENPIC online seminar, 2021-06-02

Outline

Based on: BF, K. Xu, X.-G. Huang, H. Song, PRC103 (2021) 2, 024903

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

- Introduction
- Polarization from thermal vorticity

  Global polarization

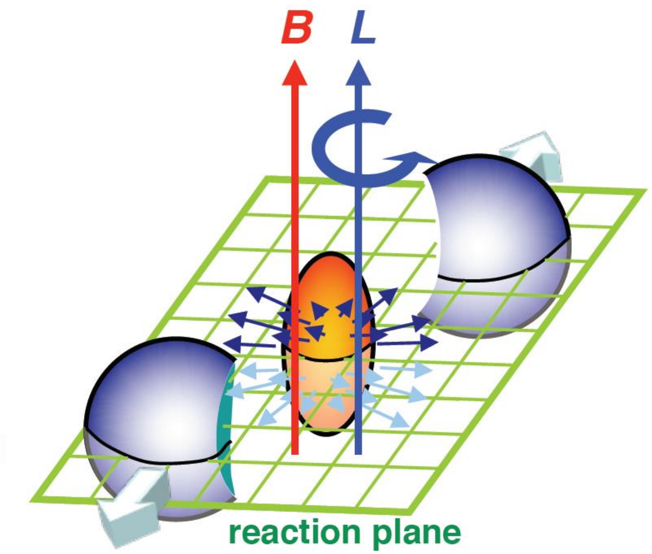
  Local polarization puzzle
- Shear induced polarization

Introduction: spin polarization

Global Angular Momentum & Global Polarization

Orbital Angular Momentum

Large angular momentum and magnetic field in non-central heavy ion collisions



RHIC: $L = 10^5\ \hbar$ @ 200 GeV & 7 fm
LHC: $L = 10^7\ \hbar$ @ 2760 GeV & 7 fm

X. Xia's henpic talk

Early works on polarization

Global polarization of Λ and spin alignment of vector mesons from spin-orbital coupling

Z. T. Liang, X. N. Wang,
Phys.Rev.Lett. 94 (2005) 102301, Phys.Lett.B 629 (2005) 20-26

Secondary particles can be polarized in un-polarized high energy collisions

S. Voloshin nucl-th/0410089

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

Global quark polarization

⇩

Global Λ polarization
(recombination/fragmentation)

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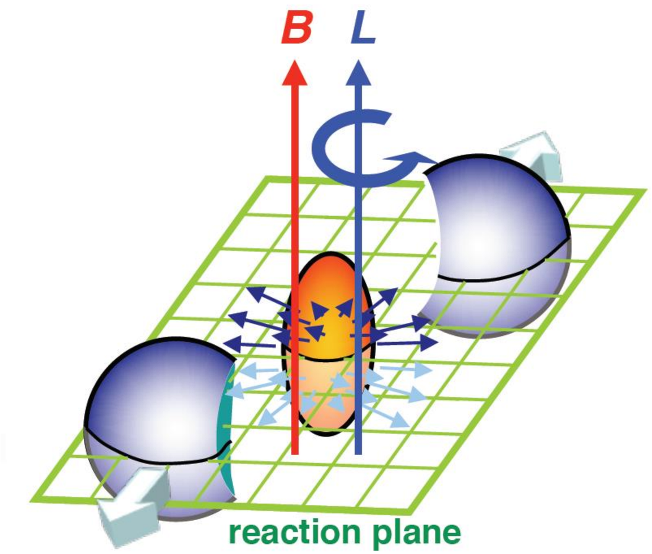

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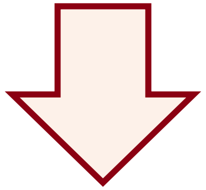


Global Λ polarization
(recombination/fragmentation)

Motivate spin polarization measurements in experiments!

Polarization Measurement

'self-analyzing' of hyperon

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P}_{\rm H} \cdot \mathbf{p}_{\mathbf{p}}^*)$$

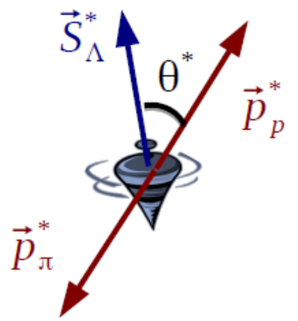
P_H: Λ polarization

p_p^*: proton momentum in the Λ rest frame

α_H: Λ decay parameter

α_Λ=0.642±0.013 → α_Λ=0.732±0.014

P.A. Zyla et al. (PDG), PTEP2020.083C01



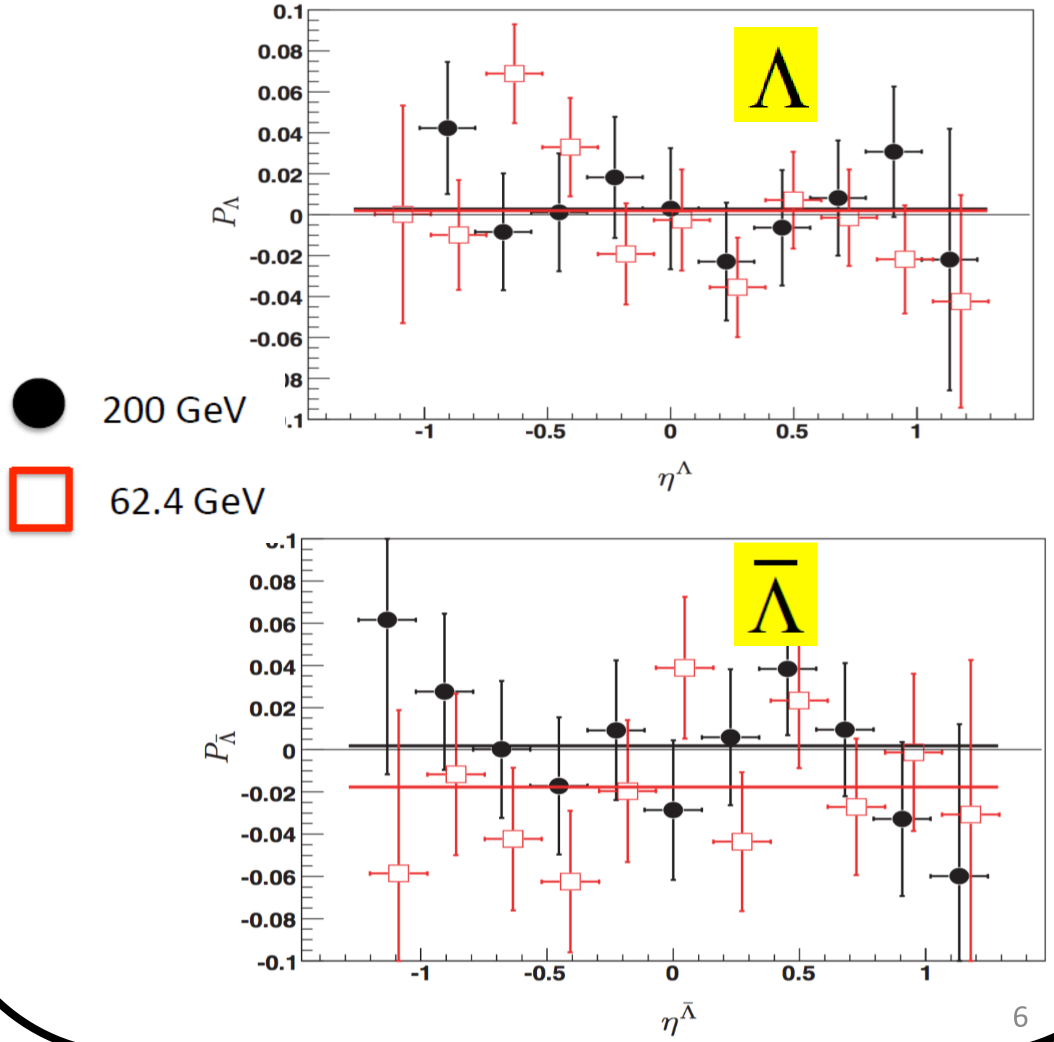
$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ~7.9 cm)

S. Voloshin and T. Niida, PRC 94.021904 (2016)

No signal at high energy

Phys. Rev. C **76**, 024915 (2007)



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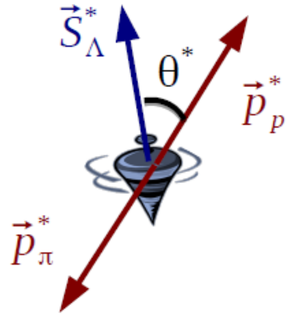


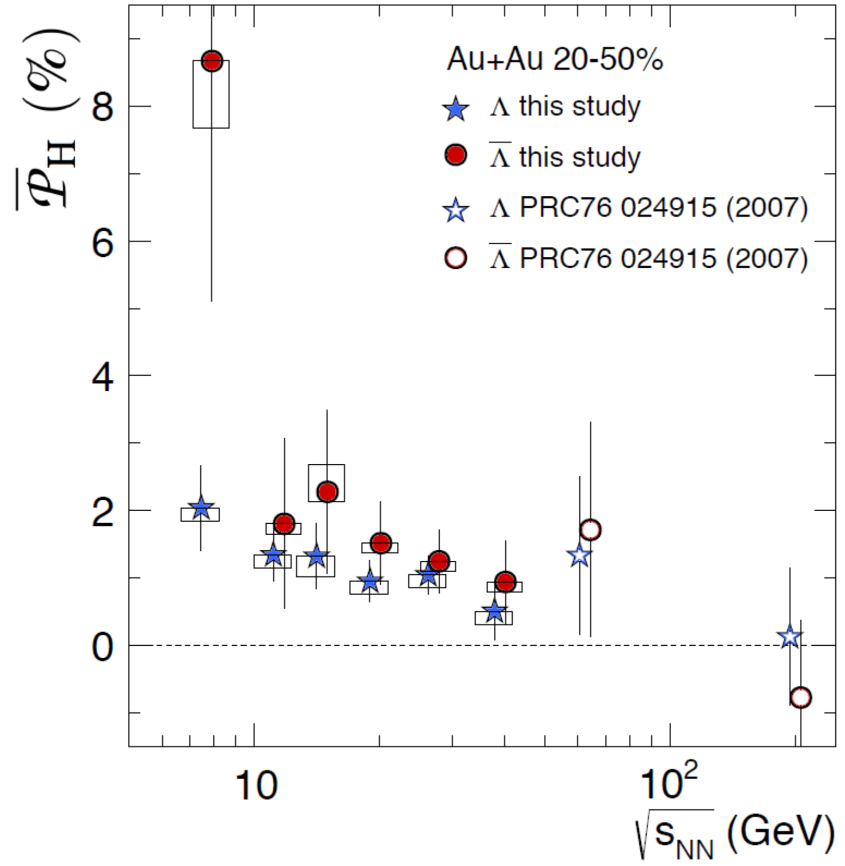
$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ~7.9 cm)

S. Voloshin and T. Niida, PRC 94.021904 (2016)

Most vortical fluid!

STAR Collaboration, Nature 548, 62 (2017)



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

Spin-orbital coupling in Condensed Matter

Gradient of spin voltage → spin current

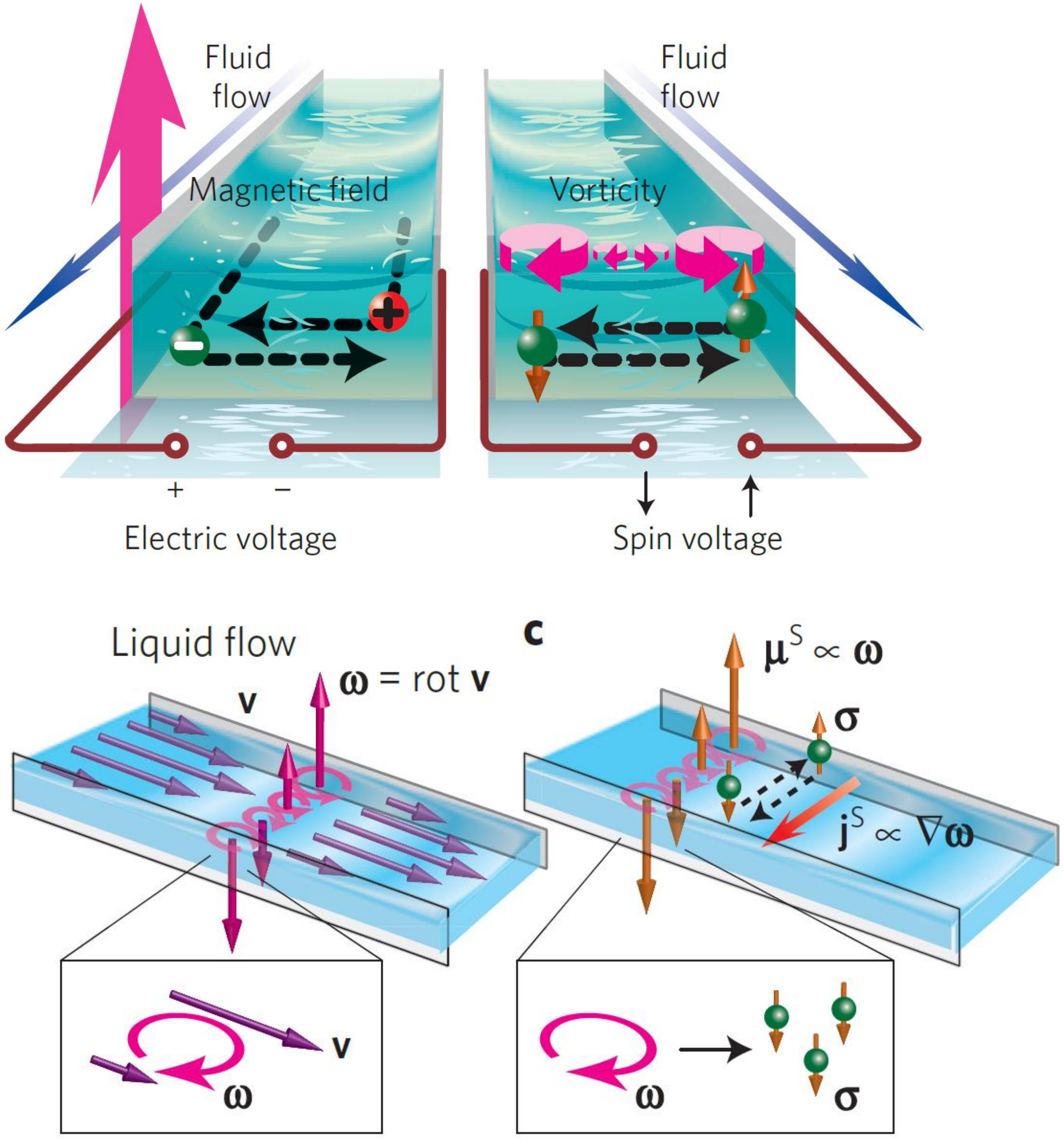
Spin voltage from Electrochemical potential:

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

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

Theoretical frameworks

Theories for spin-vorticity coupling

Early works: Polarization from global orbital angular momentum

Z. T. Liang, X. N. Wang, Phys.Rev.Lett. 94 (2005) 102301,   Voloshin nucl-th/0410089

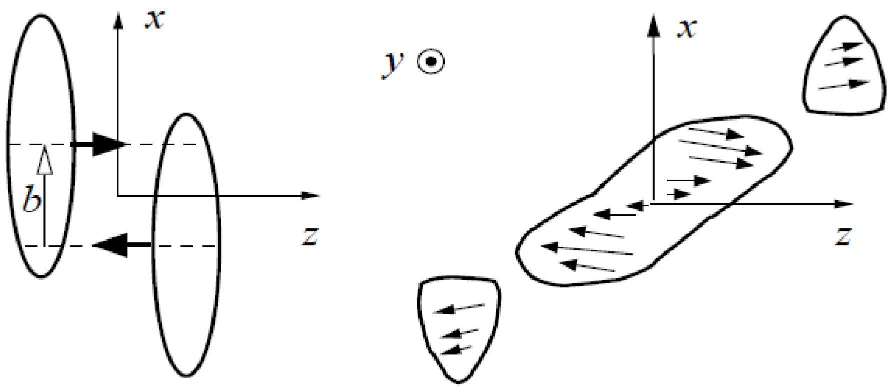
- In non-central heavy-ion collisions, L_y induce global quark polarization

$$P_q = -\pi\mu p/2E(E + m_q).$$

- Quark polarization transfer to final hyperon polarization via recombination (or fragmentation)

$$P_\Lambda = P_s,\ R_\Lambda = 3(1 - P_q^2);$$

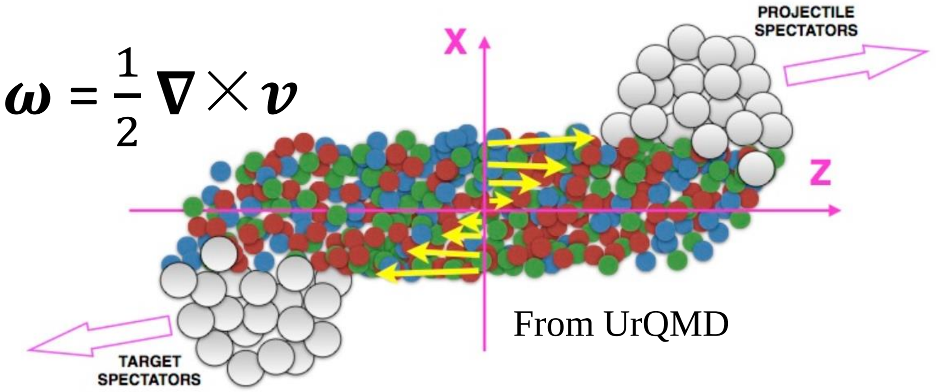
$$\begin{aligned}
P_\Sigma &= (4P_q - P_s - 3P_sP_q^2)/R_\Sigma, & R_\Sigma &= 3 - 4P_qP_s + P_q^2; \\
P_\Xi &= (4P_s - P_q - 3P_qP_s^2)/R_\Xi, & R_\Xi &= 3 - 4P_qP_s + P_s^2; \\
P_\Omega &= 2P_s(5 + P_s^2)/R_\Omega, & R_\Omega &= 6(1 + P_s^2).
\end{aligned}$$



Vorticity from hydro/transport pic

Averaged vorticity $\langle \omega_y \rangle$

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



From UrQMD

$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S} \quad \rightarrow \quad \frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S})/T}$$

Landau & Lifshitz, Statistical Physics

$$\langle \vec{\omega}_{\mathrm{QGP}} \rangle || \vec{L}_{\mathrm{QGP}} \quad \Rightarrow \quad \langle \vec{S}_{\vec{\omega};\,\mathrm{hadrons}} \rangle || \vec{L}_{\mathrm{QGP}}$$

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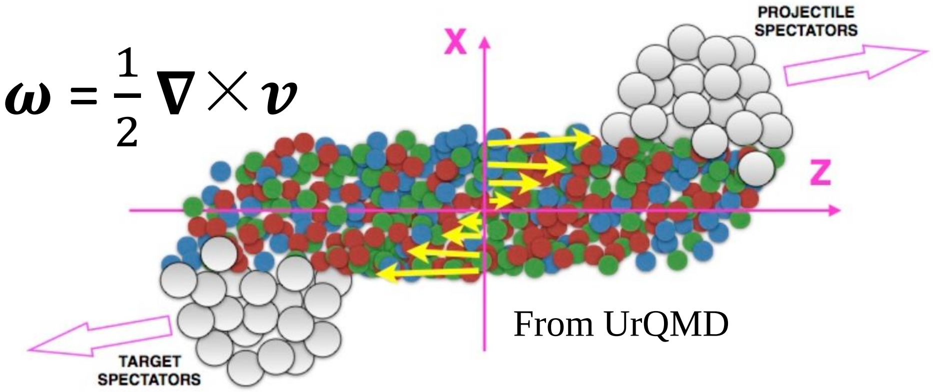

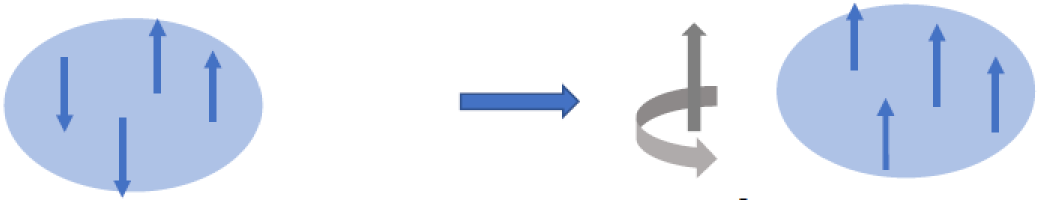

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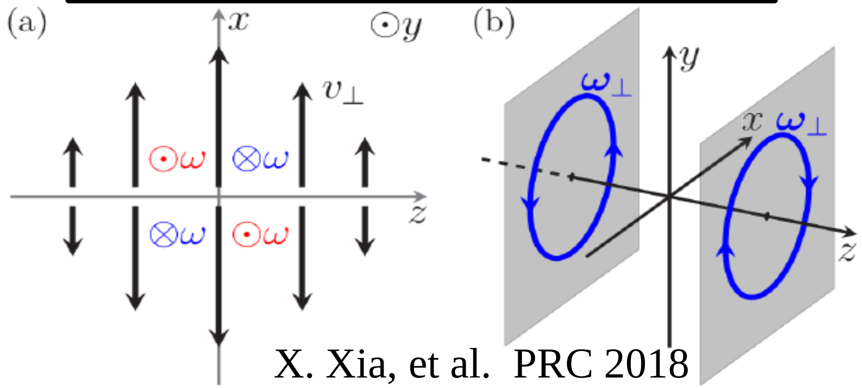
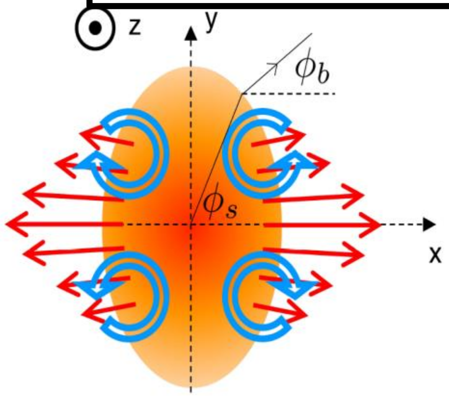
inhomogeneous expansion

Transverse vorticity

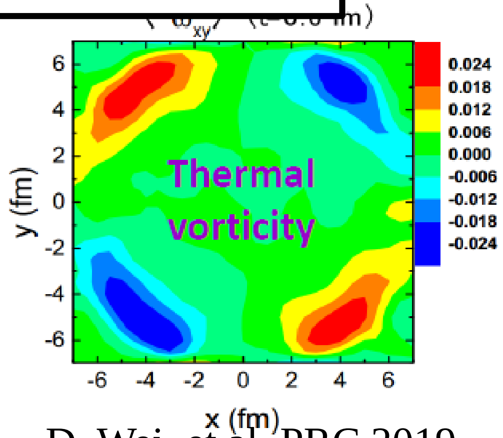


X. Xia, et al. PRC 2018

Longitudinal vorticity



S. Voloshin, SQM 2018



D. Wei, et al, PRC 2019

Thermal vorticity induced polarization

thermal vorticity & Polarization

- Valid at global equilibrium.
- Always extrapolated to local equilibrium.

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

F. Becattini, et al. Annals Phys. 338 32 (2013)

Thermal vorticity:

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

$$\beta_\mu = u_\mu/T$$

See also: R. Fang, L. Pang, Q. Wang, X. Wang, PRC 2016

Y. Liu, K. Mameda, X. Huang, CPC 2020

'Spin Cooper-Frye' formula

- Integration on freeze-out hyper surface

$$S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p)\langle S(x,p)\rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}$$

- Boost to particle rest frame

$$\boldsymbol{S}^* = \boldsymbol{S} - \frac{\boldsymbol{p}\cdot\boldsymbol{S}}{E(E+m)}\boldsymbol{p}$$

- Normalized spin polarization

$$P^\mu(p) = \frac{1}{S}S^\mu(p)$$

Numerical simulation

thermal vorticity & Polarization

- Valid at global equilibrium.
- Always extrapolated to local equilibrium.

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

'Spin Cooper-Frye' formula

- Integration on freeze-out hyper surface

$$S^{\mu}(p) = \frac{\int d\Sigma_{\lambda}p^{\lambda}f(x,p)\langle S(x,p)\rangle}{\int d\Sigma_{\lambda}p^{\lambda}f(x,p)}$$

- Boost to particle rest frame

- Most of the calculations on market are built as:

1) hydrodynamic calculations

Hydrodynamic evolution → Freeze-out → Formula from above

2) Microscopic(transport,cascade) model calculations

Parton/hadron cascade → Coarse-graining → Formula from above

Hydrodynamic/transport models

Hydrodynamic models

PICR: Y.L. Xie, D.J. Wang, L.P. Csernai, Phys.Rev.C 95 (2017) 3, 031901, Eur.Phys.J.C 80 (2020) 1, 39

ECHO-QGP: F. Becattini, G. Inghirami, et al., Eur.Phys.J.C 75 (2015) 9, 406

AMPT + CLVisc: L.-G Pang, H. Elfner, Q. Wang and X.-N. Wang , Phys.Rev.Lett. 117 (2016) 192301

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

UrQMD/Glauber + vHLLE: Iu. Karpenko, F. Becattini , Eur.Phys.J.C 77 (2017) 4, 213, Phys.Rev.Lett. 120 (2018) 012302

3FD (3-fluid dynamics): Yu. Ivanov, A. Soldatov, Phys. Rev. C 97, 024908 (2018)

Transport models

AMPT: Y. Jiang, J. Liao, Z. Lin, Phys.Rev.C 94 (2016) 4, 044910

D. Wei, W. Deng and X-G. Huang, Phys.Rev. C99 (2019) 014905

H. Li, L. Pang, Q. Wang and X. Xia, Phys.Rev. C96 (2017) 054908

UrQMD: O. Vitiuk, L. Bravina and E. Zabrodin, Phys.Lett.B 803 (2020) 135298

X-G. Deng, X-G. Huang, Y-G. Ma and S. Zhang, Phys.Rev.C 101 (2020) 6, 064908

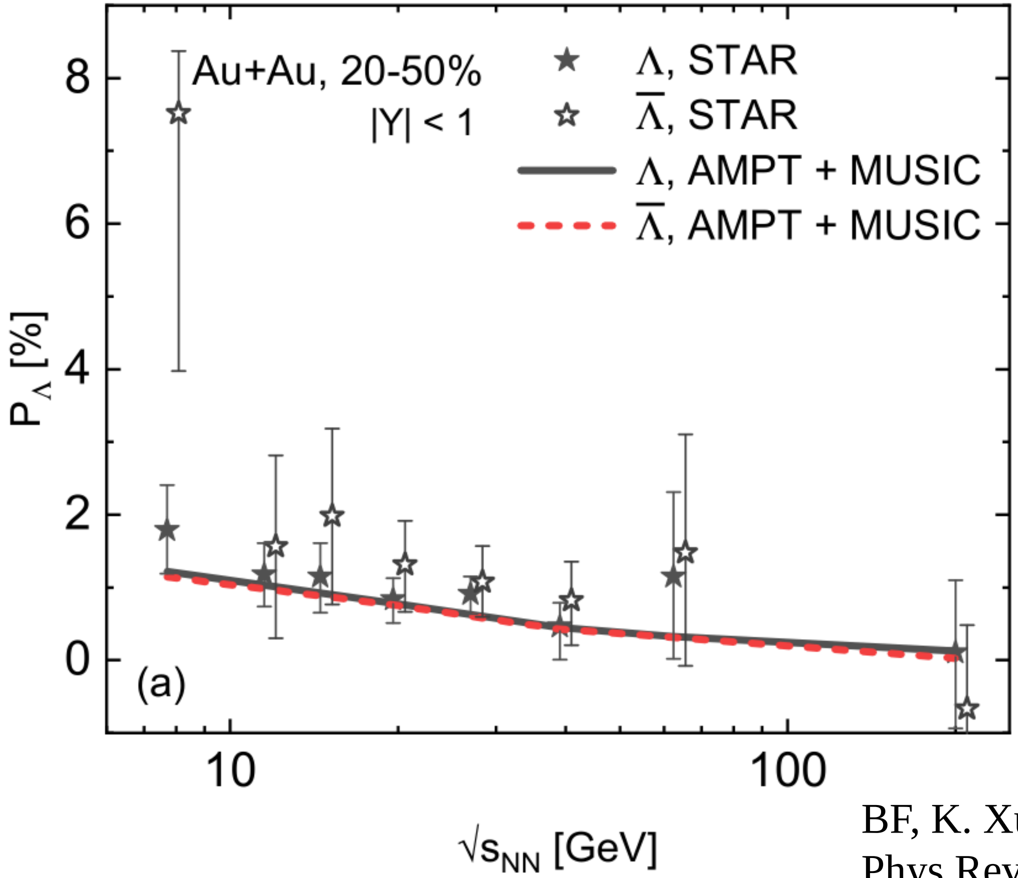
...

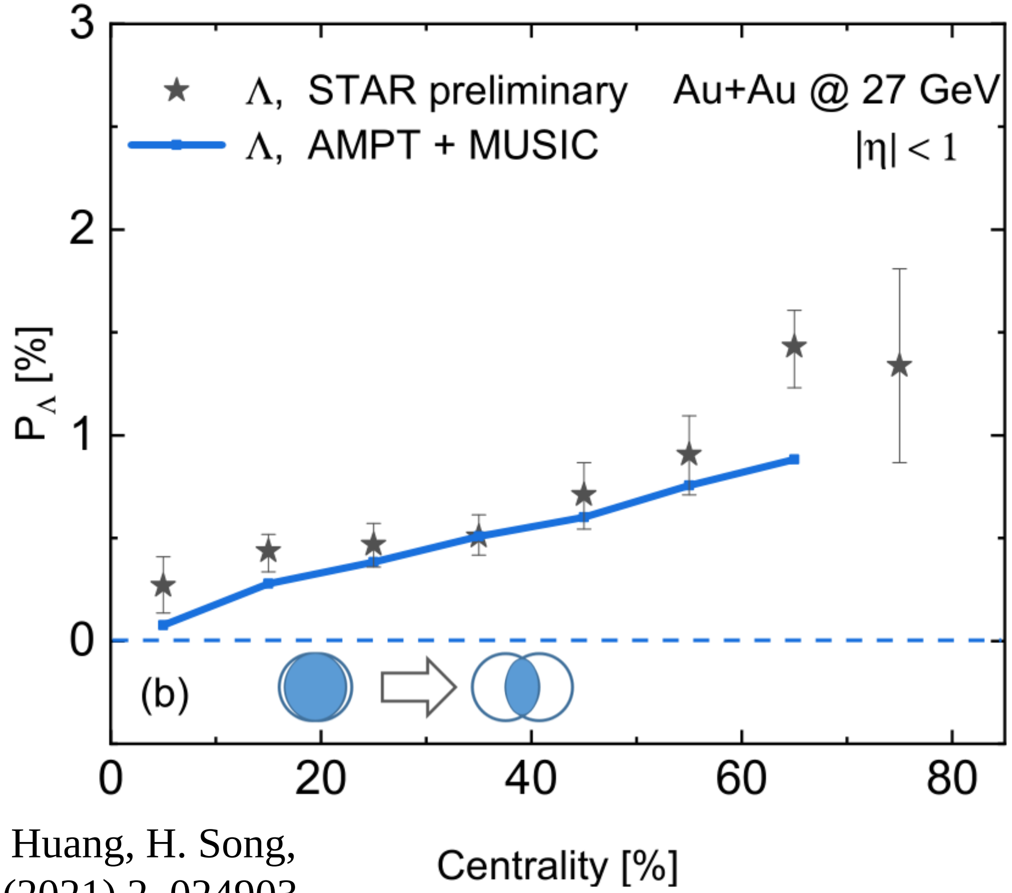
Global polarization

Global polarization

$$P^{\mu} = \langle P^{\mu}(p) \rangle = \frac{\int \frac{d^3p}{E} \int d\Sigma_\nu p^\nu f(x,p) P^\mu(x,p)}{\int \frac{d^3p}{E} \int d\Sigma_\nu p^\nu f(x,p)}$$

- Decrease with the collision energy
- $\Lambda - \bar{\Lambda}$ difference negligible

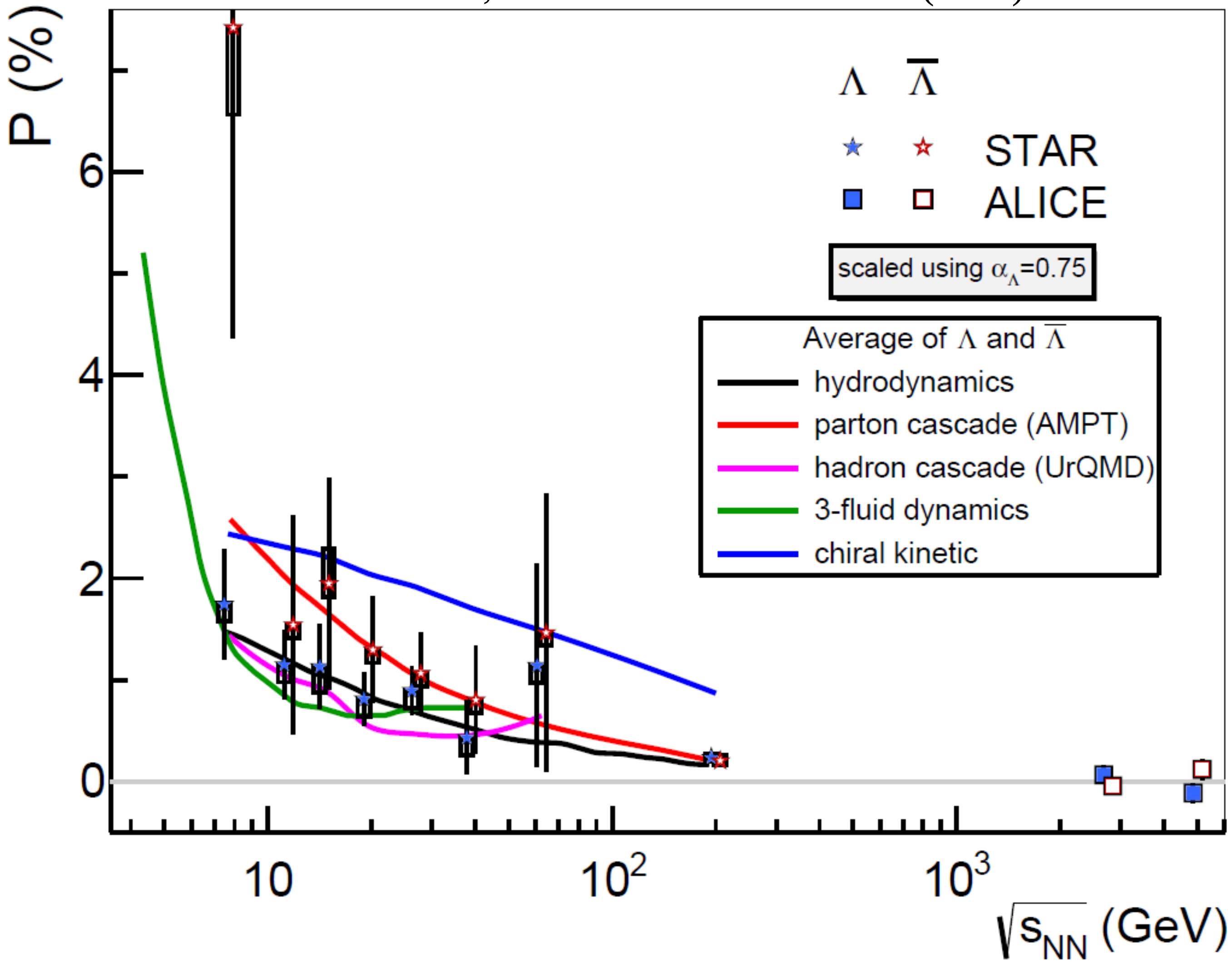




BF, K. Xu, X-G, Huang, H. Song,
Phys.Rev.C 103 (2021) 2, 024903

Global polarization

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



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:
Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

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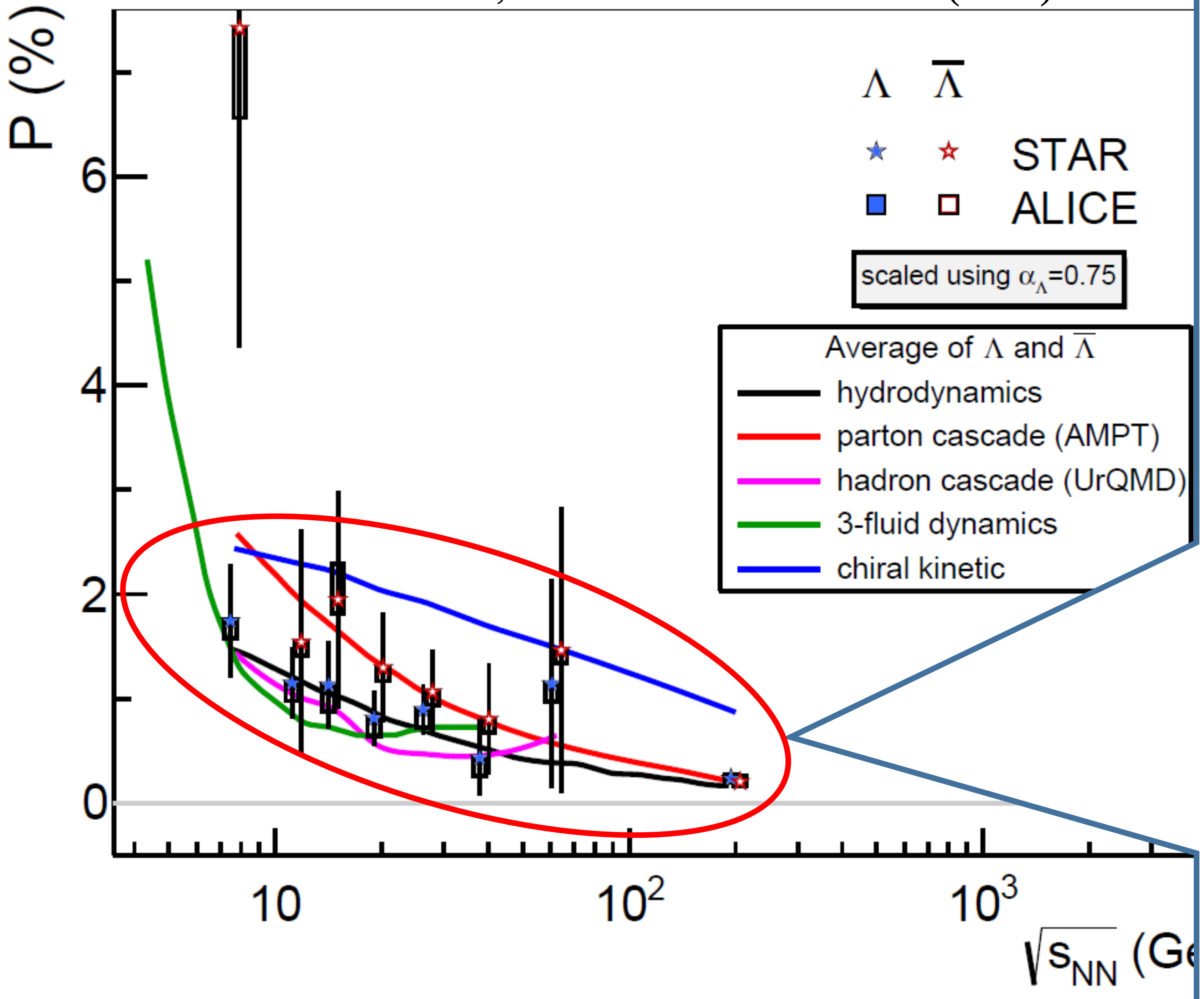
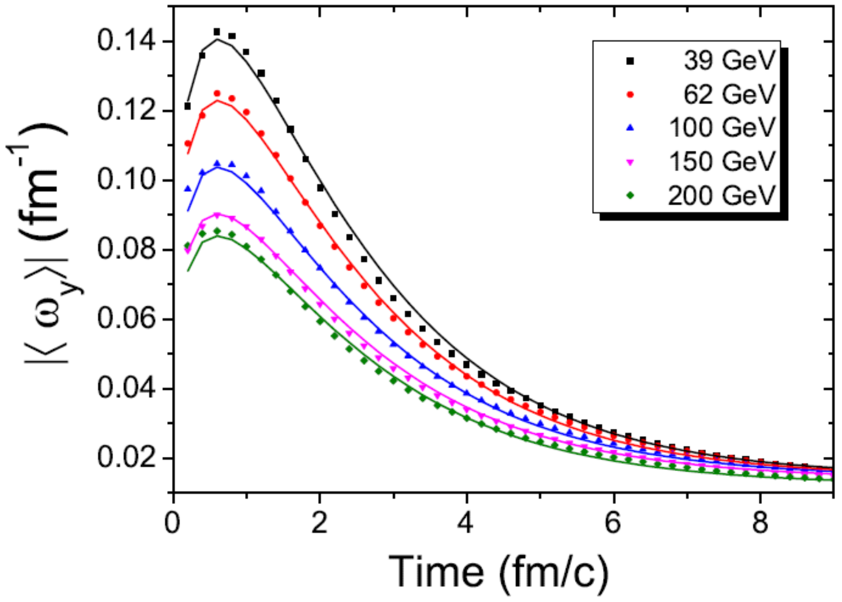


Collision energy dependence

- More transparent and symmetric in the mid-rapidity region in higher energies
  H. Li, et al, PRC 96 (2017) 054908
- Longer evolution time will dilute the vorticity effect
  Iu. Karpenko and F. Becattini , EPJC 77 (2017) 4, 213
- The inertia moment increase



Y. Jiang and Z. Lin, Phys.Rev. C94 (2016) no.4, 044910

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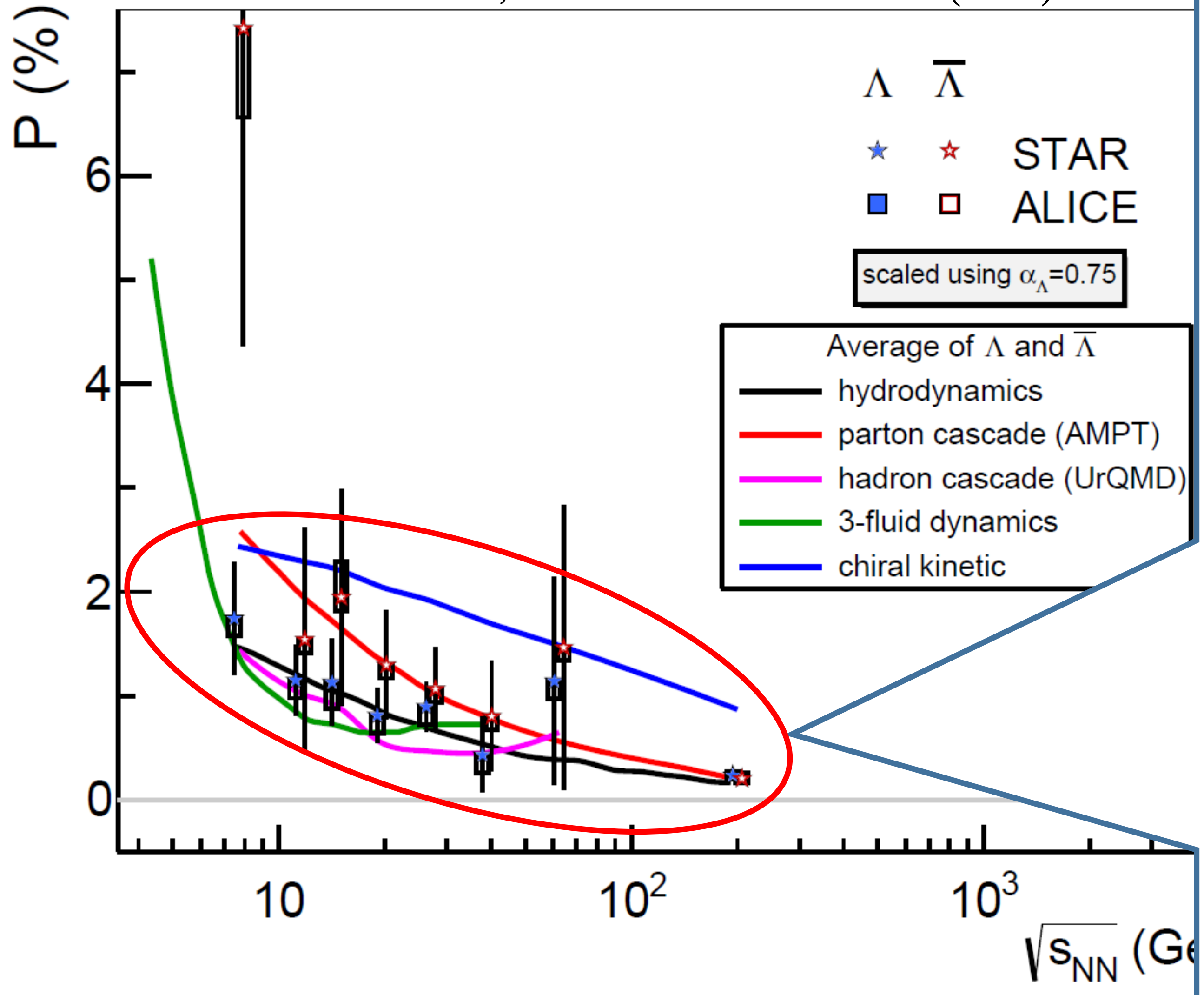
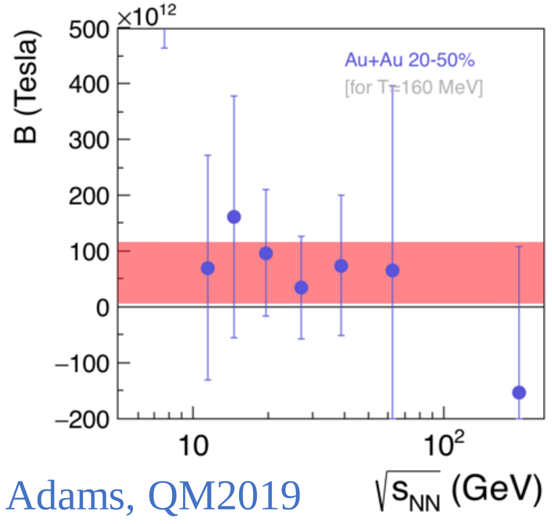
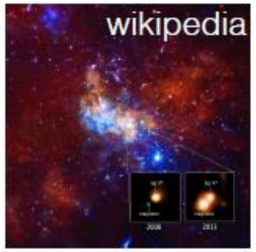


The $\Lambda - \bar{\Lambda}$ splitting

Might from magnetic field, but with large uncertainties



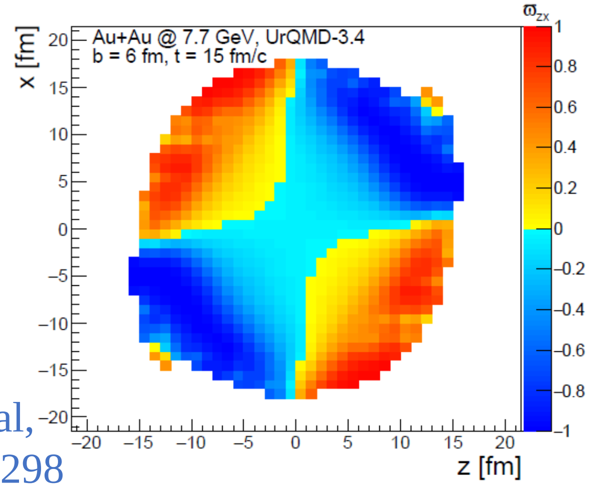
Joseph Adams, QM2019



magnetar

$B \sim 10^{11}$ T

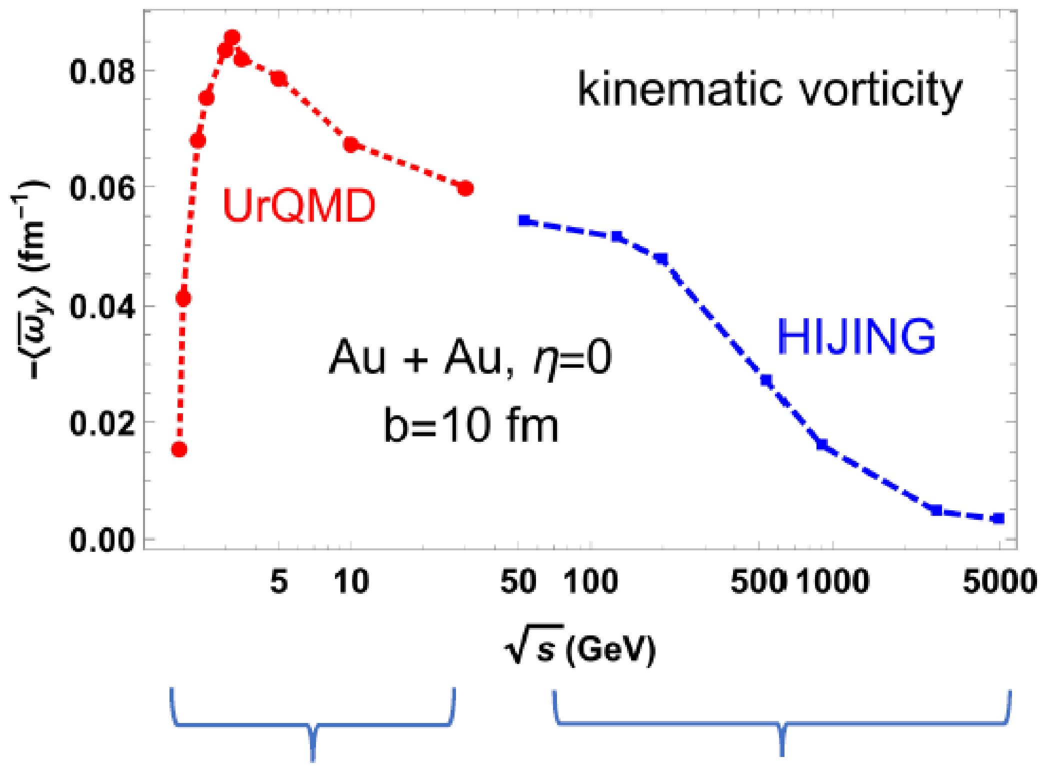
Also might from the different space-time distribution



O. Vitiuk, et al,
PLB 803,135298

Global polarization at lower energies

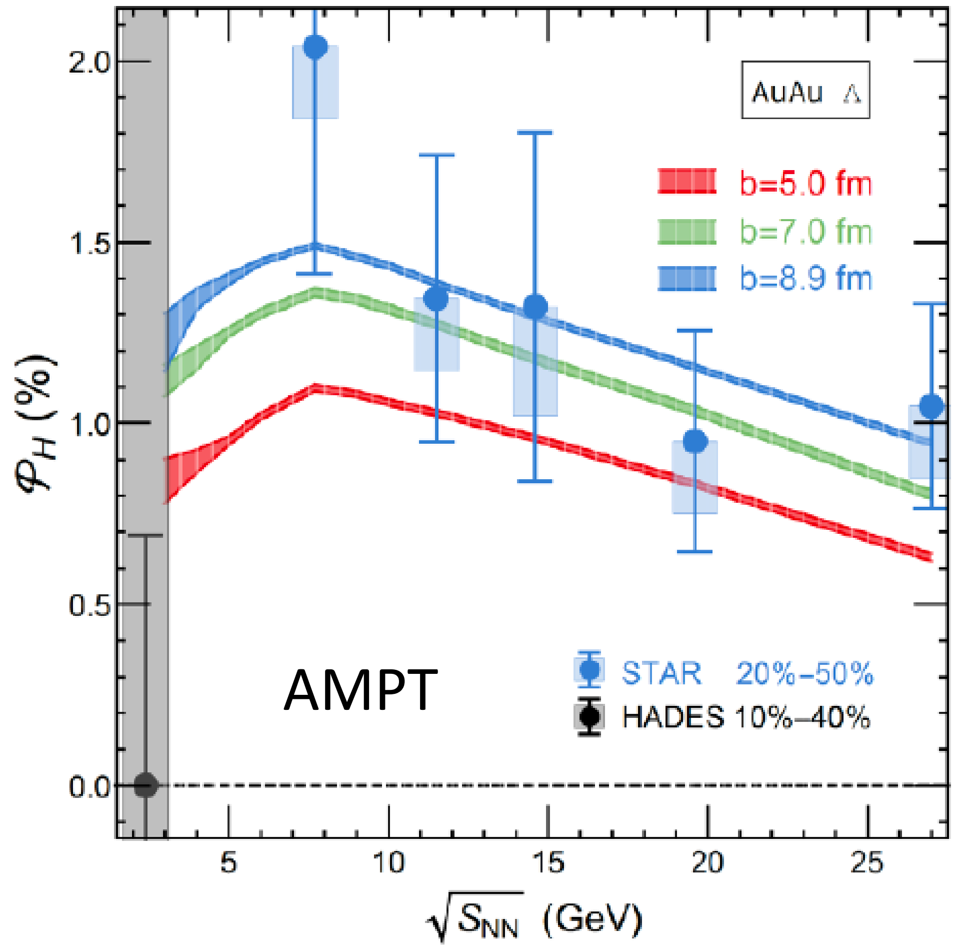
- Transport model predicts a maximum of vorticity around 3-7 GeV
- Need an out of equilibrium theory to calculate



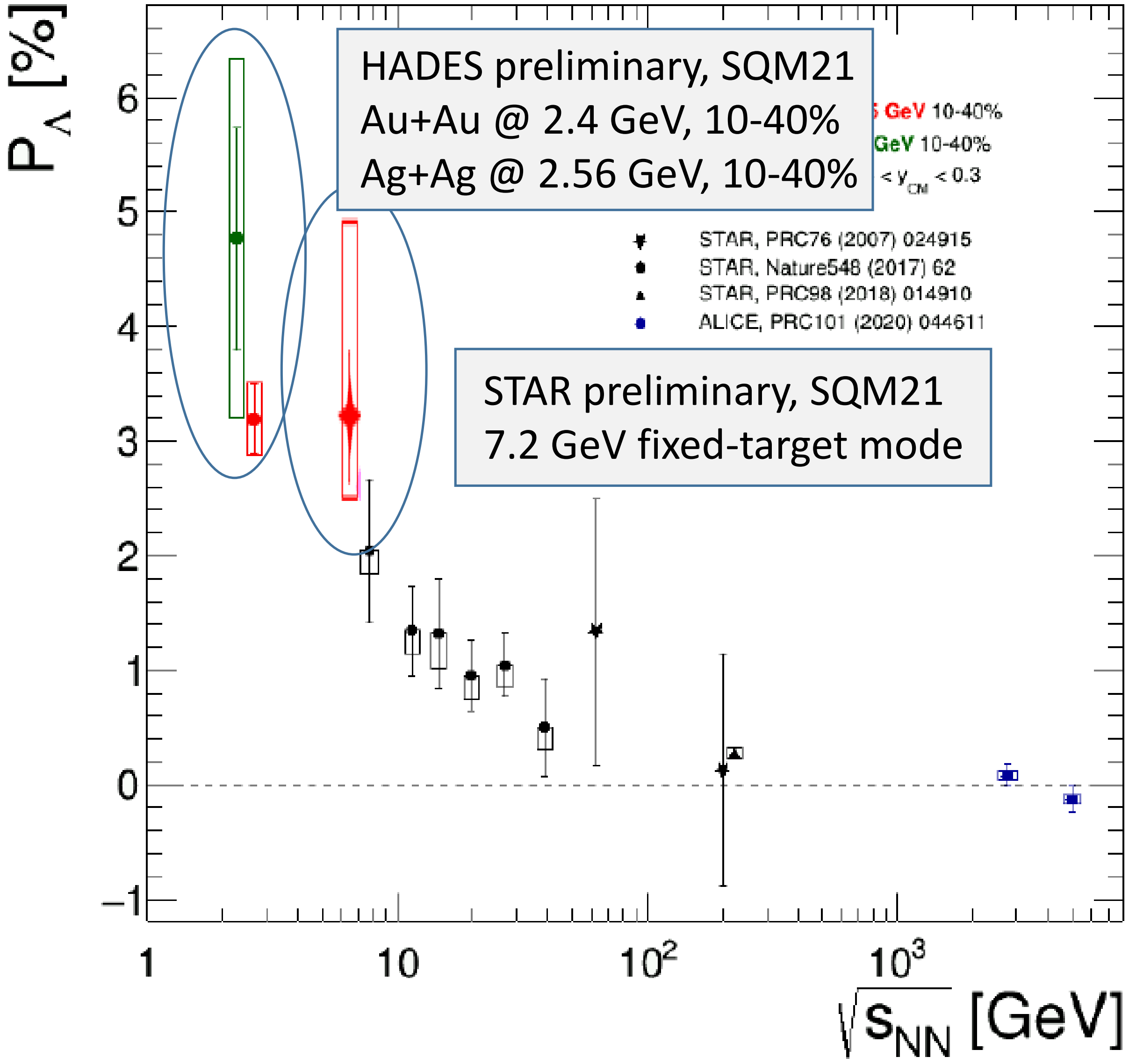
Deng, Huang, Ma and Zhang, Phys.Rev.C 101 (2020) 6, 064908

W. Deng and X-G. Huang, Phys.Rev.C 93 (2016) 6, 064907

Y. Guo, et al., arXiv: 2105.13481



Global polarization at lower energies



- P_H still shows increasing trend down to 2.4 GeV
- Will it 'turns-off' at lower energies?

HADES

(1) Au+Au 2012:

- $\sqrt{s_{NN}} = 2.4\ GeV$
- $7 \cdot 10^9$ **events**

(2) Ag+Ag 2019:

- $\sqrt{s_{NN}} = 2.55\ GeV$
- $14 \cdot 10^9$ **events**

STAR

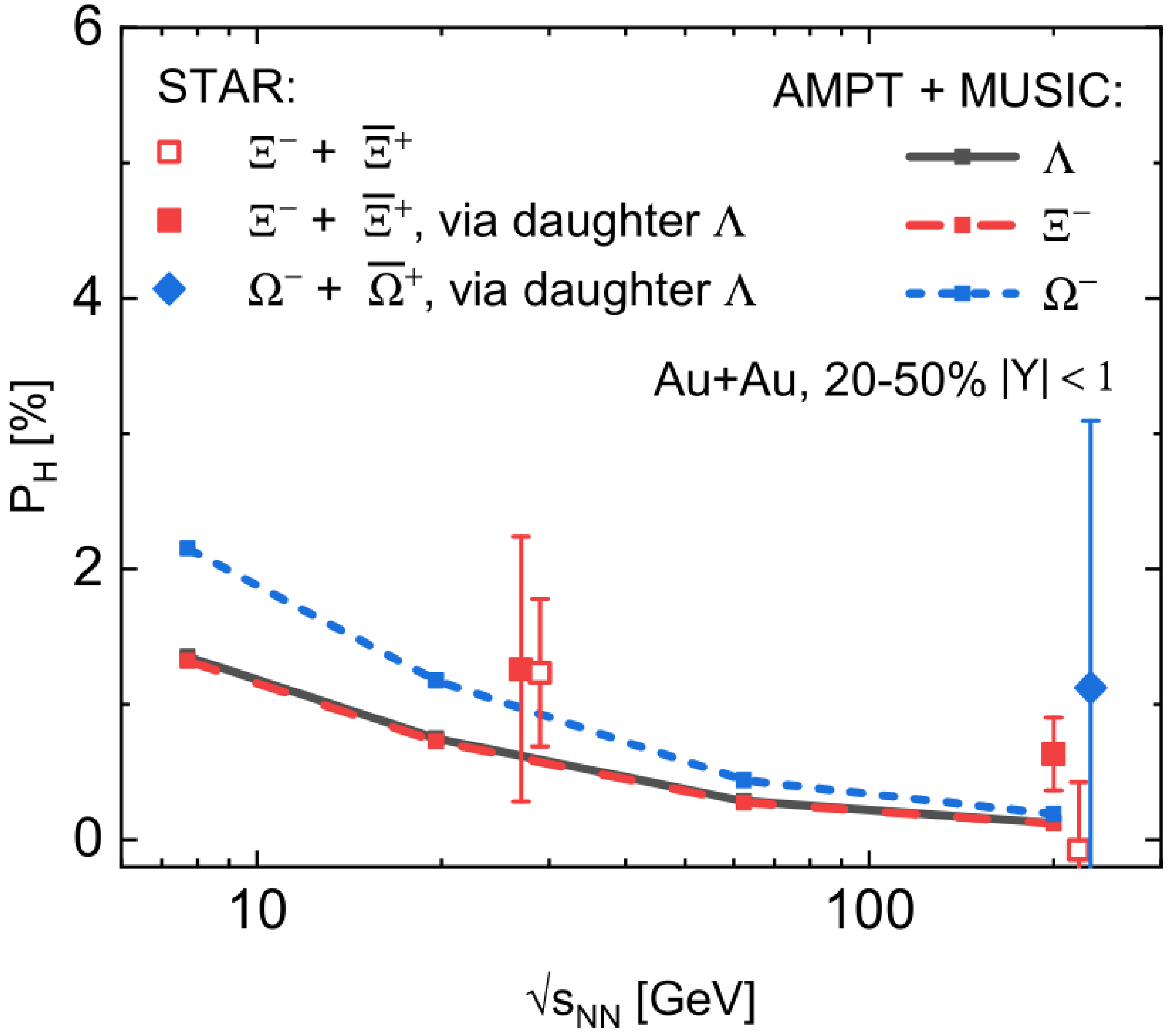
More data will come from BES-II+FXT

FXT (GeV): 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 5.2, 6.2, 7.7

Collider (GeV): 7.7, 9.1, 11.5, 14.5, 17.3, 19.6

Global Ξ^- and Ω^- polarization

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



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

Spin ratio:

$$S_{\Omega^-} : S_{\Xi^-} : S_{\Lambda} = 3 : 1 : 1$$

Mass ratio:

$$m_{\Omega^-} : m_{\Xi^-} : m_{\Lambda} = 1.5 : 1.2 : 1$$

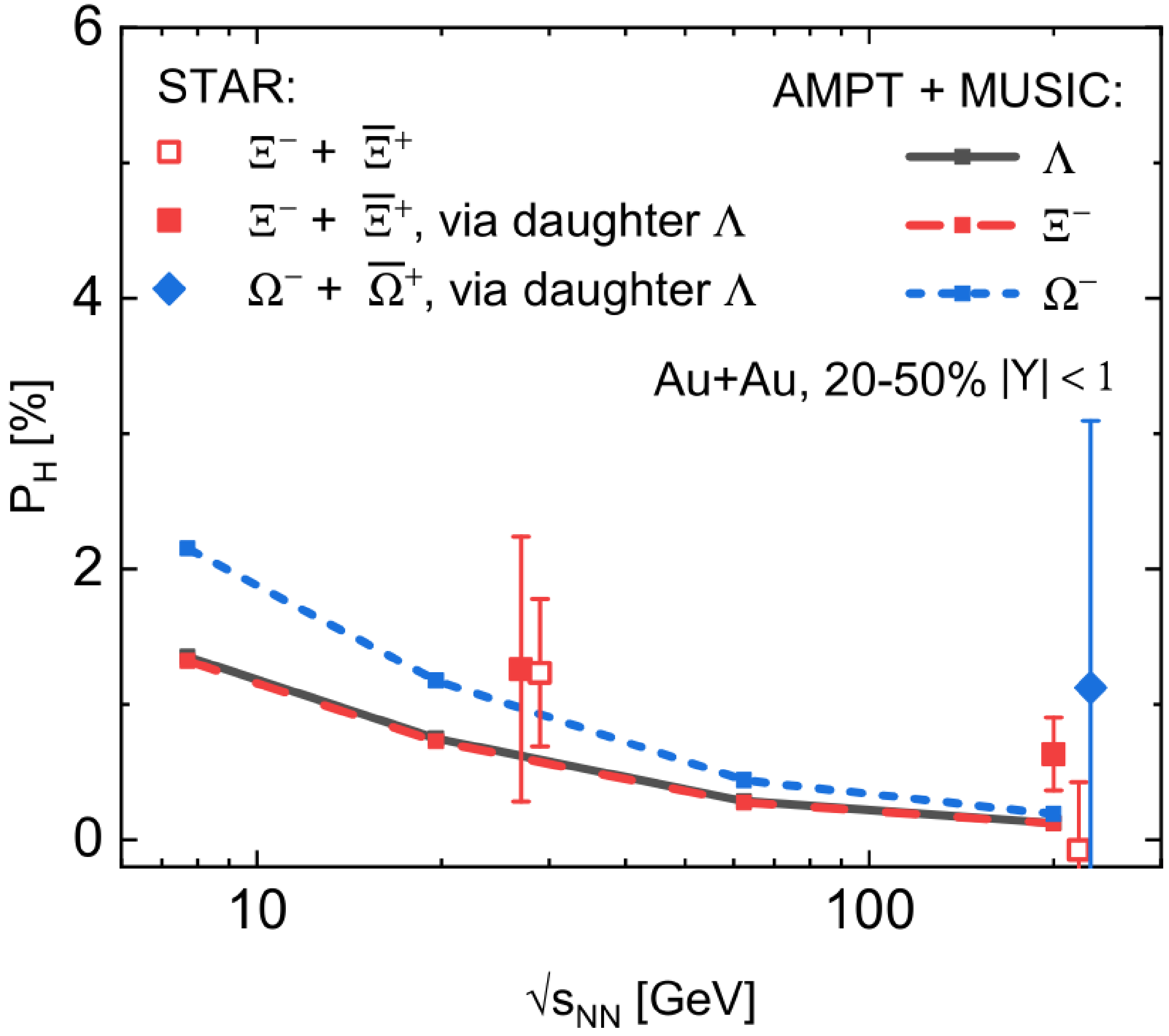
Magnetic moments ratio:

$$|M_{\Omega^-}| : |M_{\Xi^-}| : |M_{\Lambda}| \approx 3 : 1 : 1$$

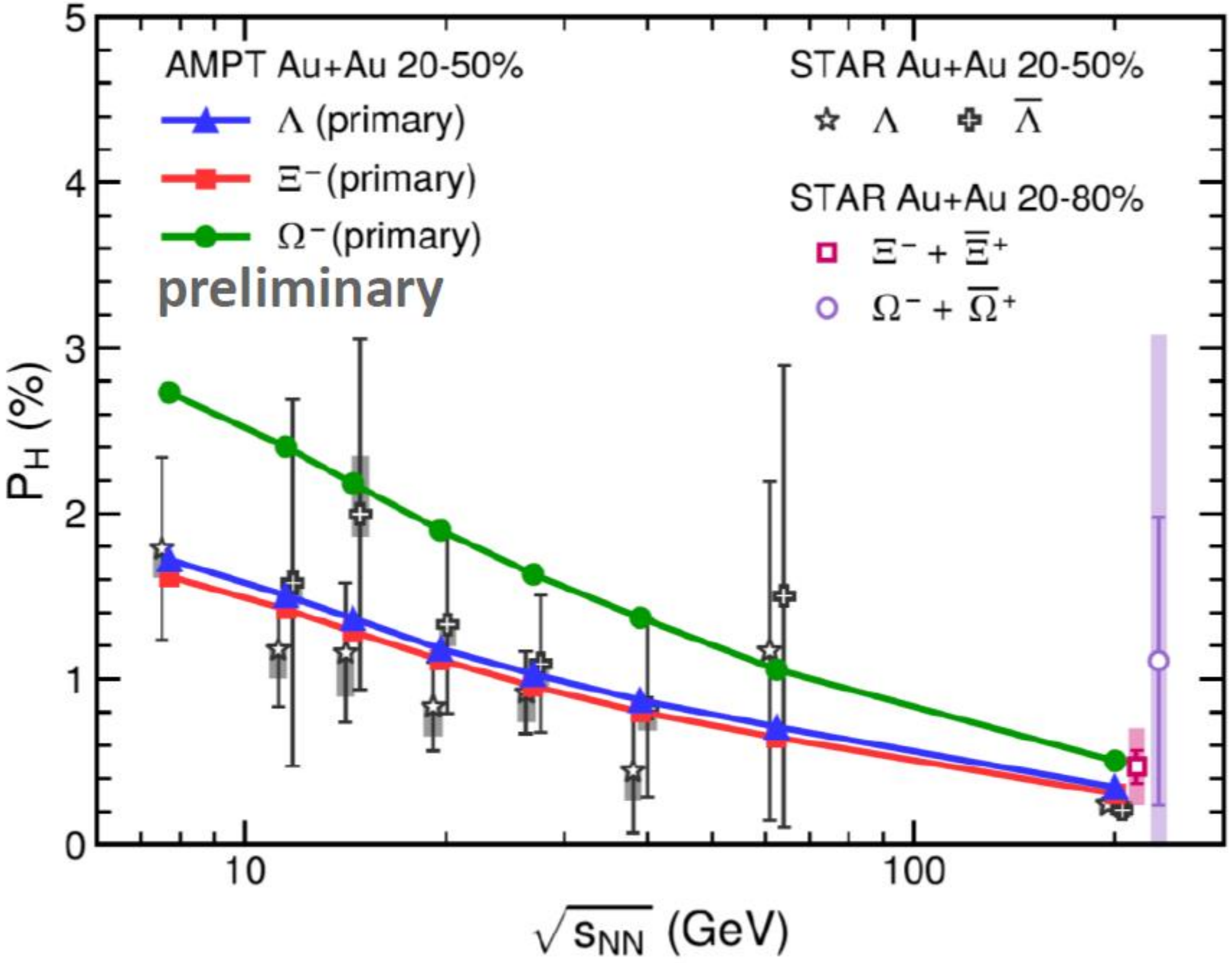
- Baseline for future feed-down and magnetic field study

Global Ξ^- and Ω^- polarization

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



AMPT, Hui Li, SQM2021



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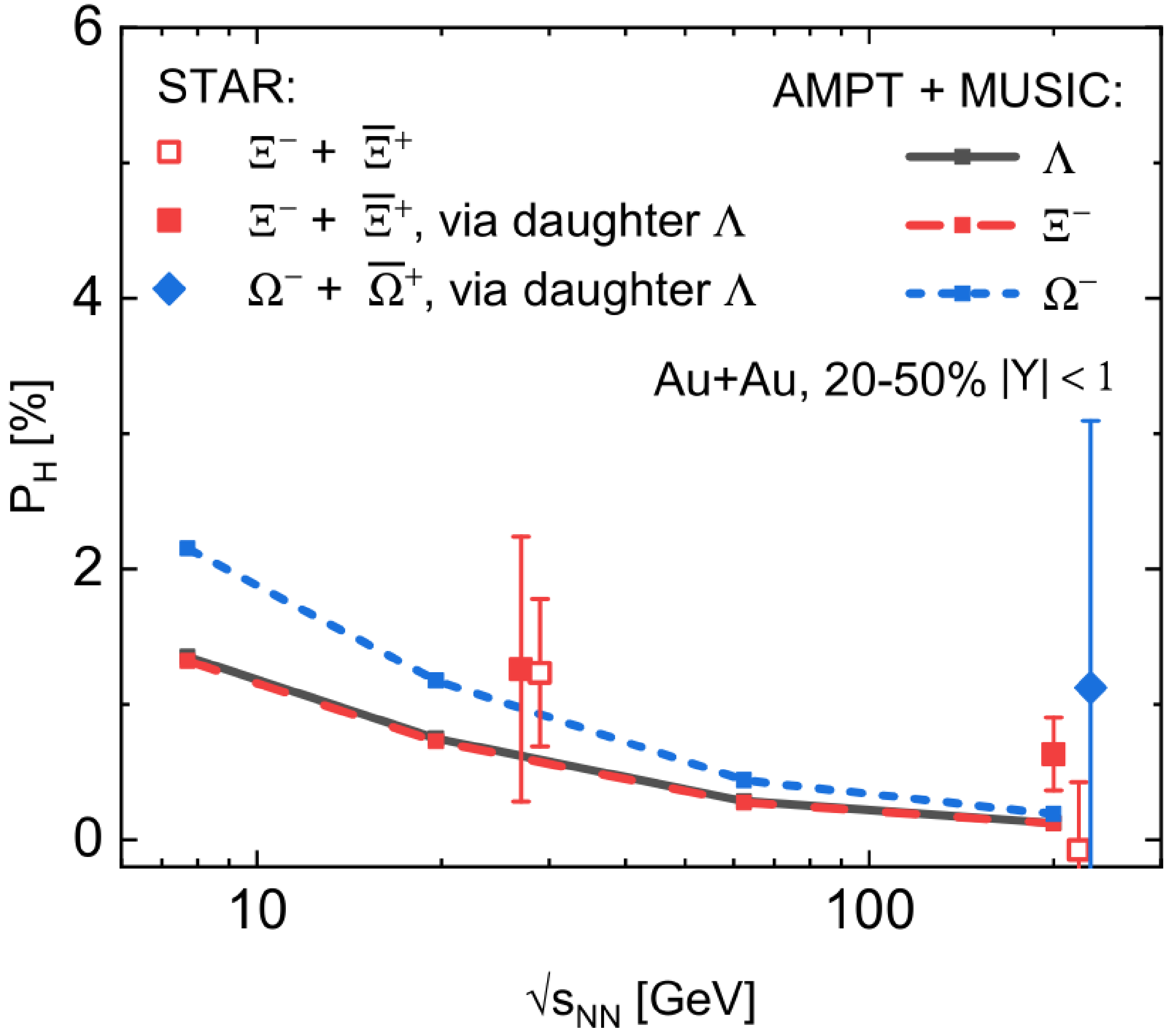

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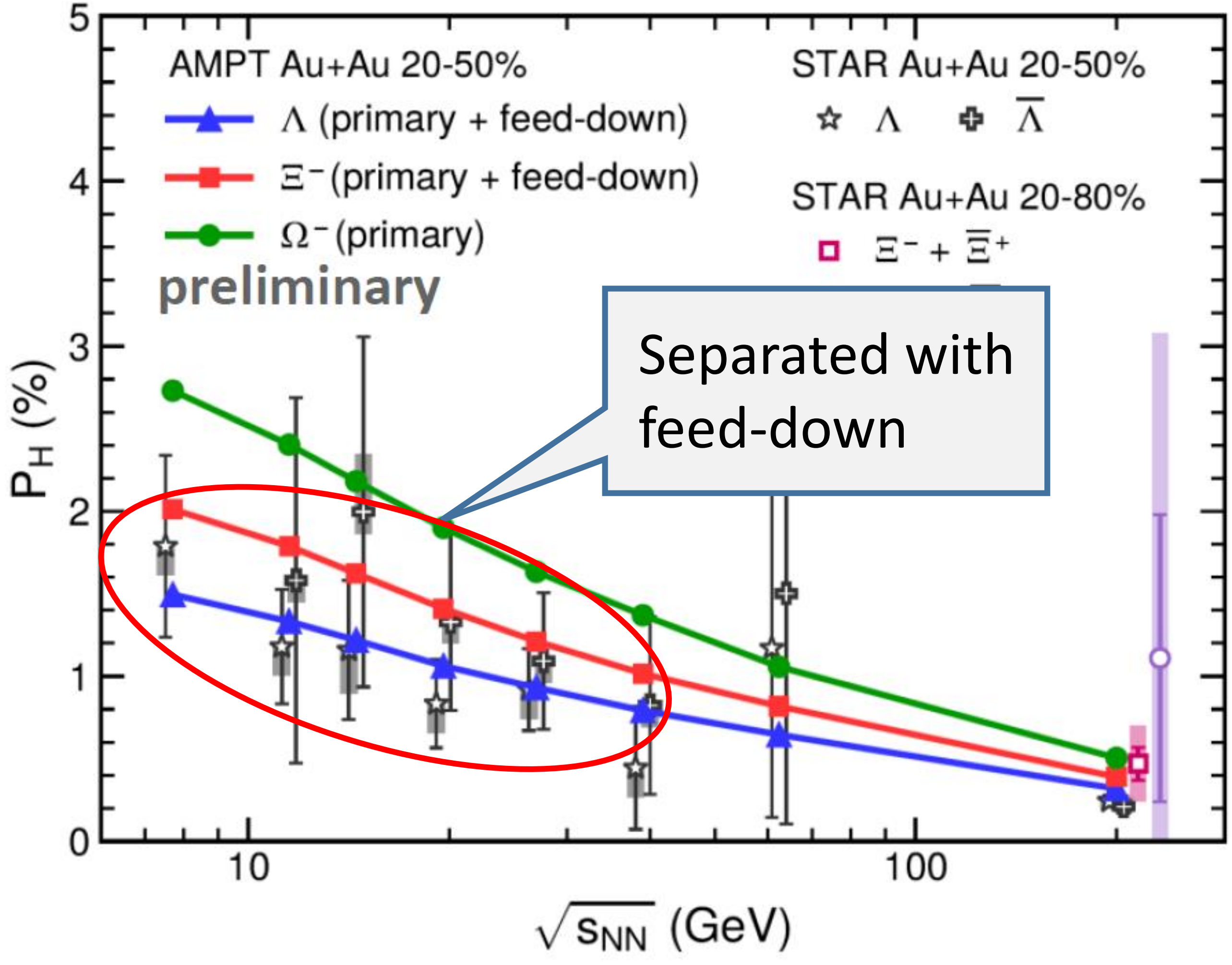
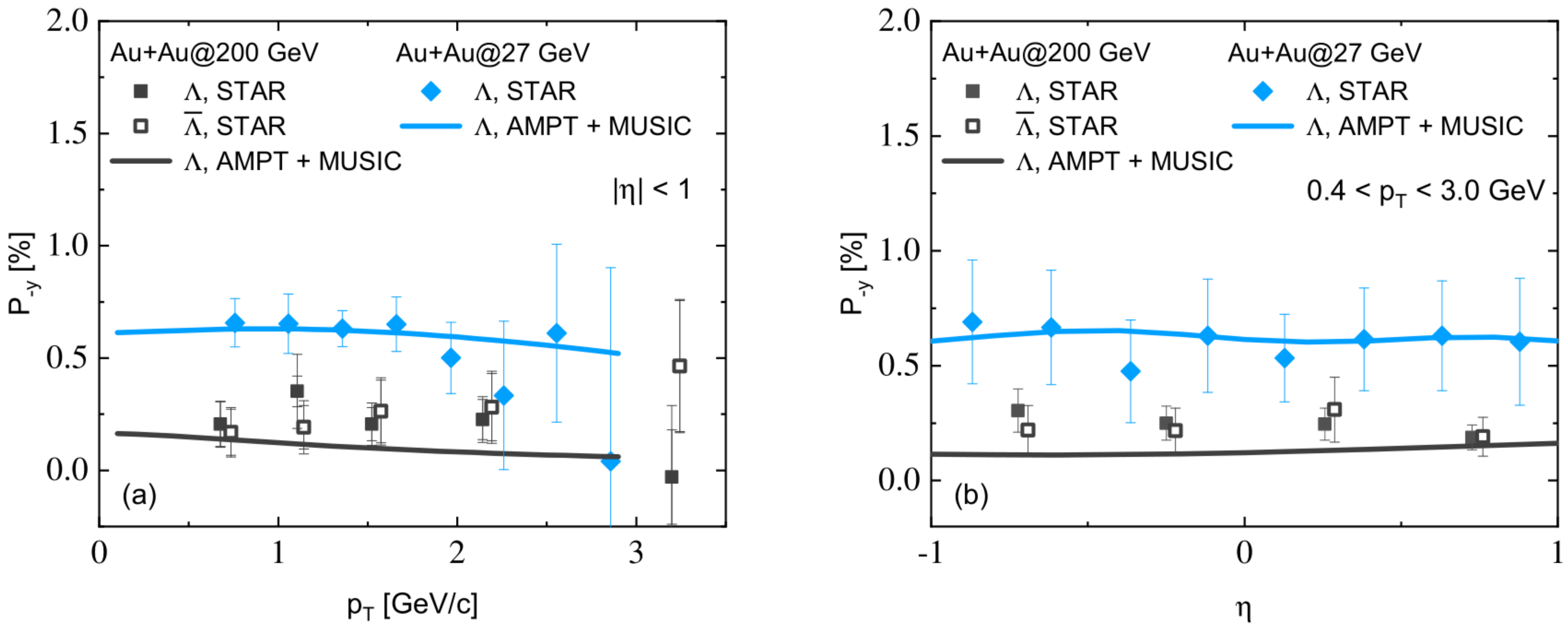


Local polarization puzzle

local polarization: p_T and η dependence

- $P_y(p_T)$ and $P_y(\eta)$ Describes data within error bars



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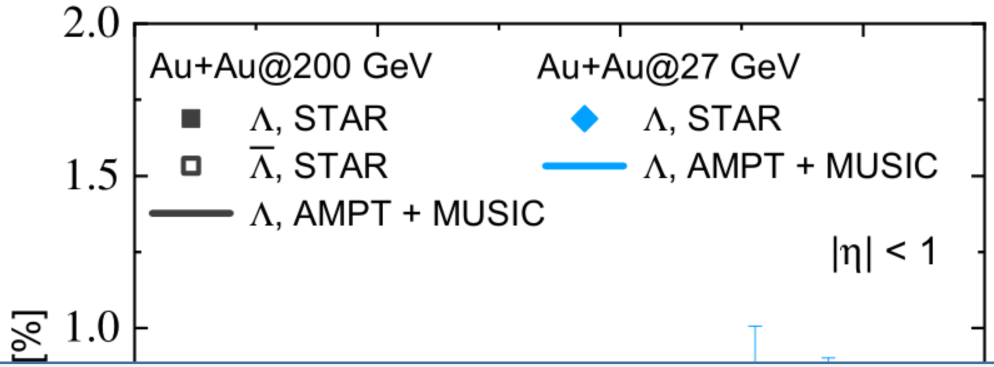
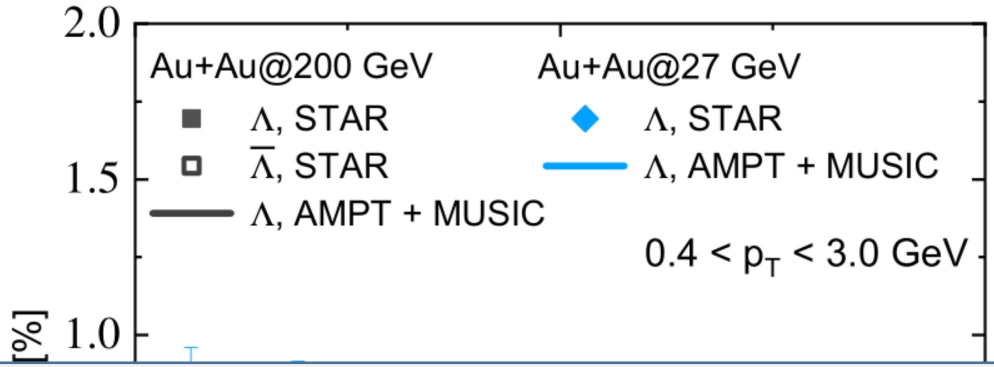
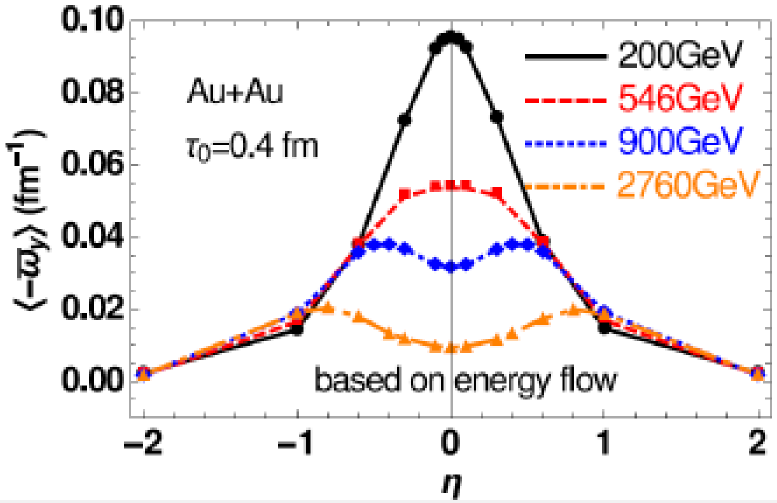


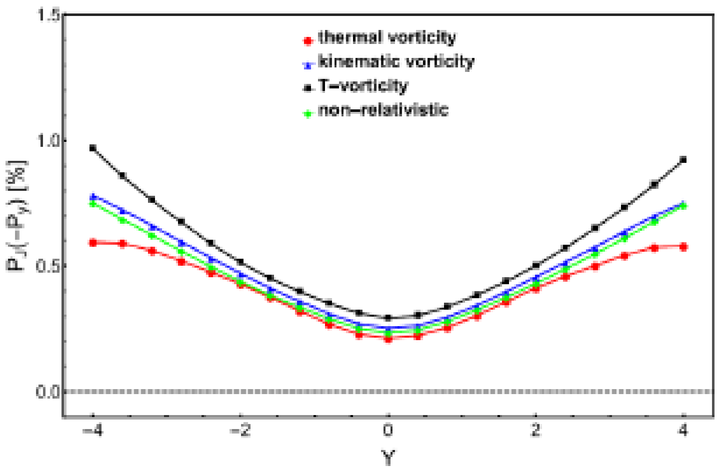


- how about large rapidity?

Initial vorticity by HIJING



Final polarization by hydro



HIJING:
W-T. Deng and X-G. Huang
PRC 93 (2016) 6, 064907

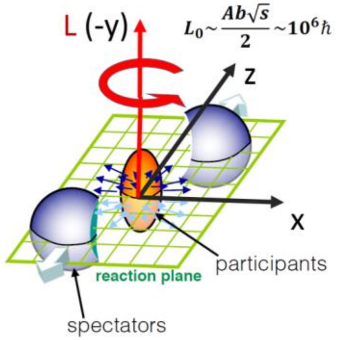
Hydro:
H-Z. Wu, L-G. Pang, X-G. Huang and Q. Wang
PRR 1 (2019) 033058

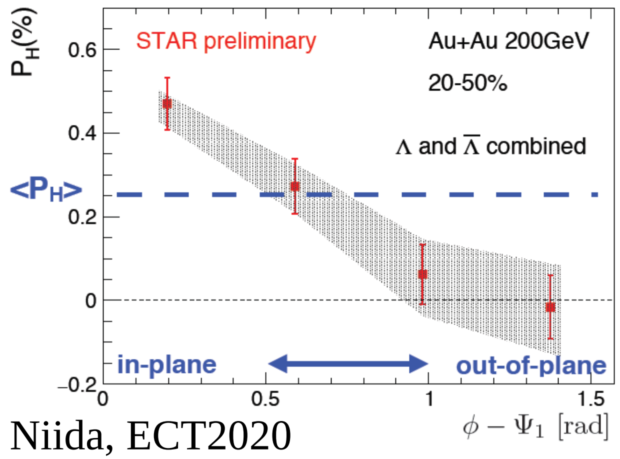
local polarization: ϕ dependence

Experiment data

Hydrodynamics

$P^y(\phi)$





T. Niida, ECT2020

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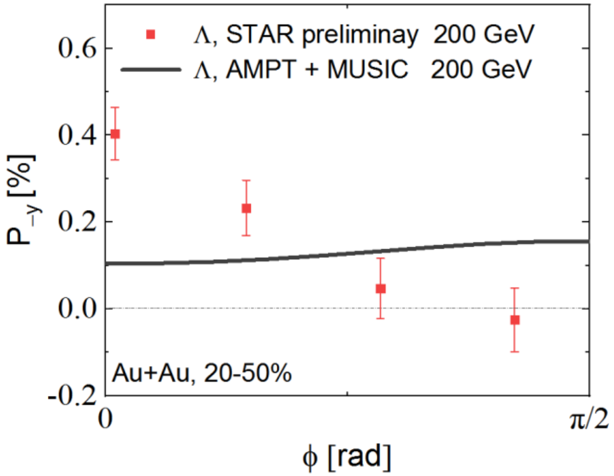


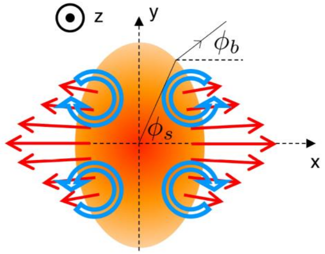
BF, Xu, Huang, Song, PRC103 (2021) 2, 024903

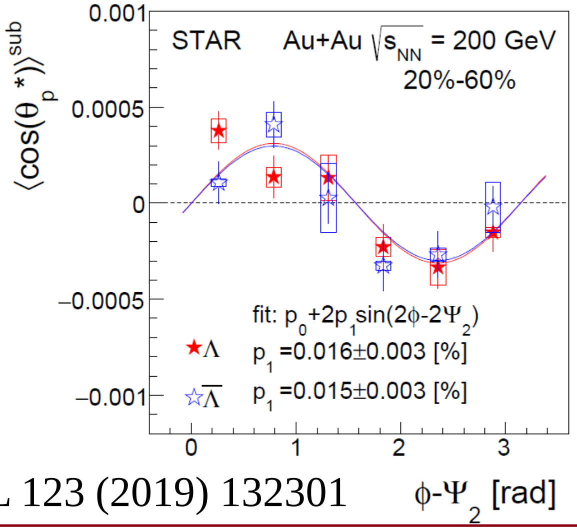
See also:

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

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

$P^z(\phi)$





PRL 123 (2019) 132301

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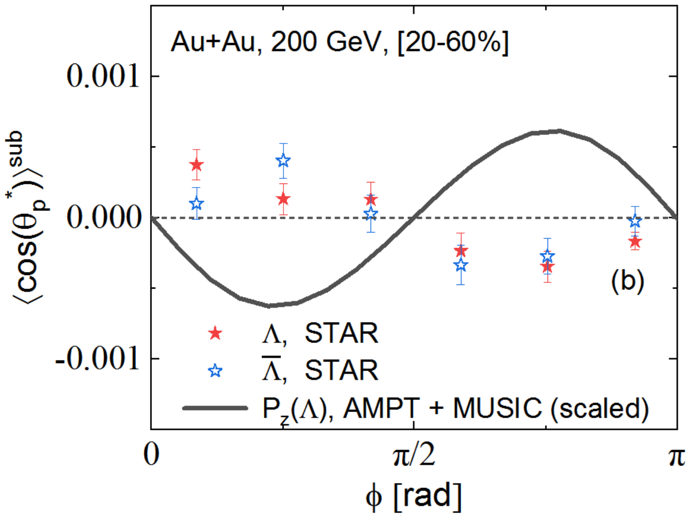


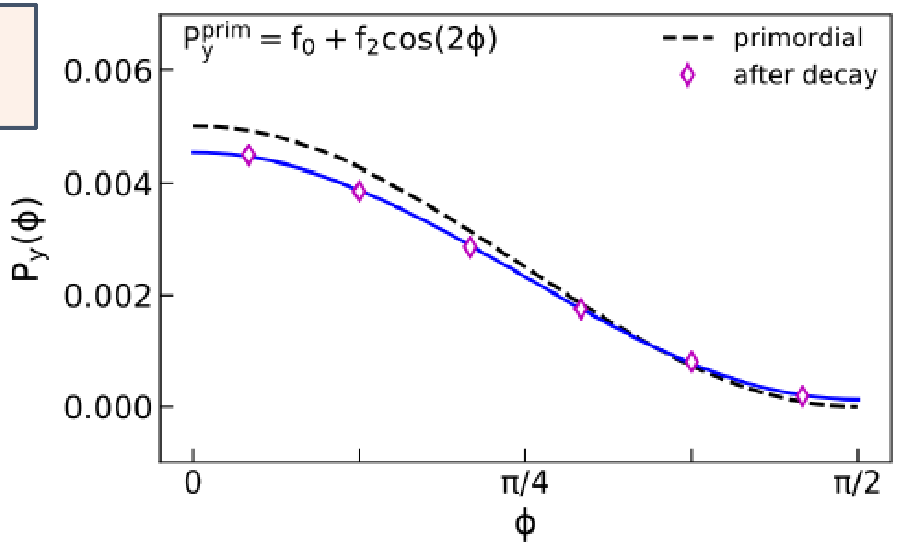
X. Xia, et al., PRC 98 (2018) 024905

Becattini, Karpenko, PRL 120 (2018) 012302

Efforts to resolve the 'sign puzzle'

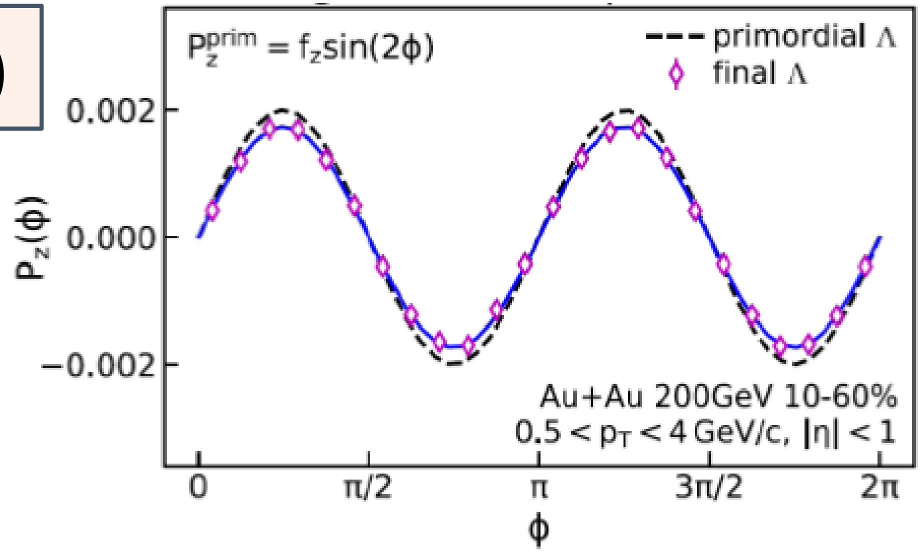
- Feed-down effects (Xia, Li, Huang, Huang, PRC 2019, Becattini, Cao, Speranza, EPJC 2019)

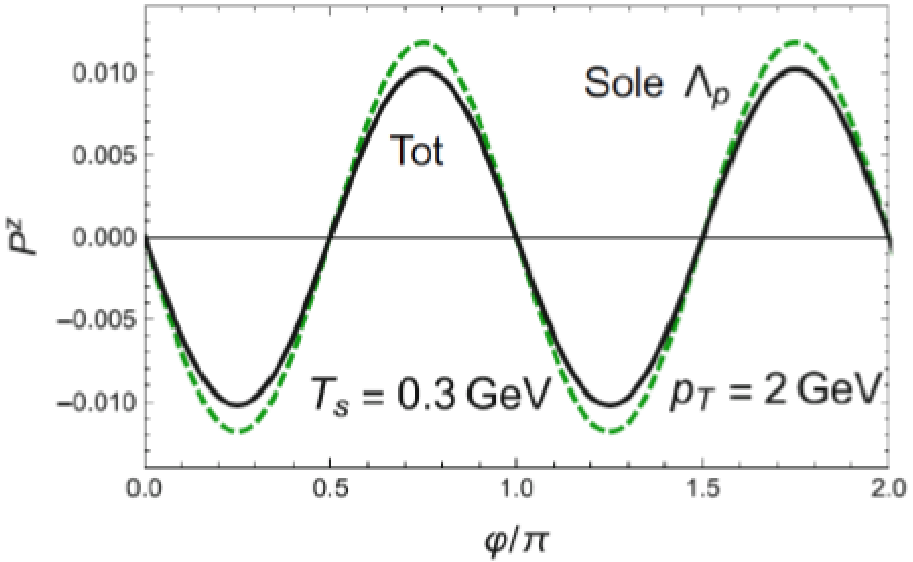
$P^y(\phi)$



- About 80% of final Λ from decays
- Feed-down effect suppress ~10 − 20% primordial spin polarization

$P^z(\phi)$

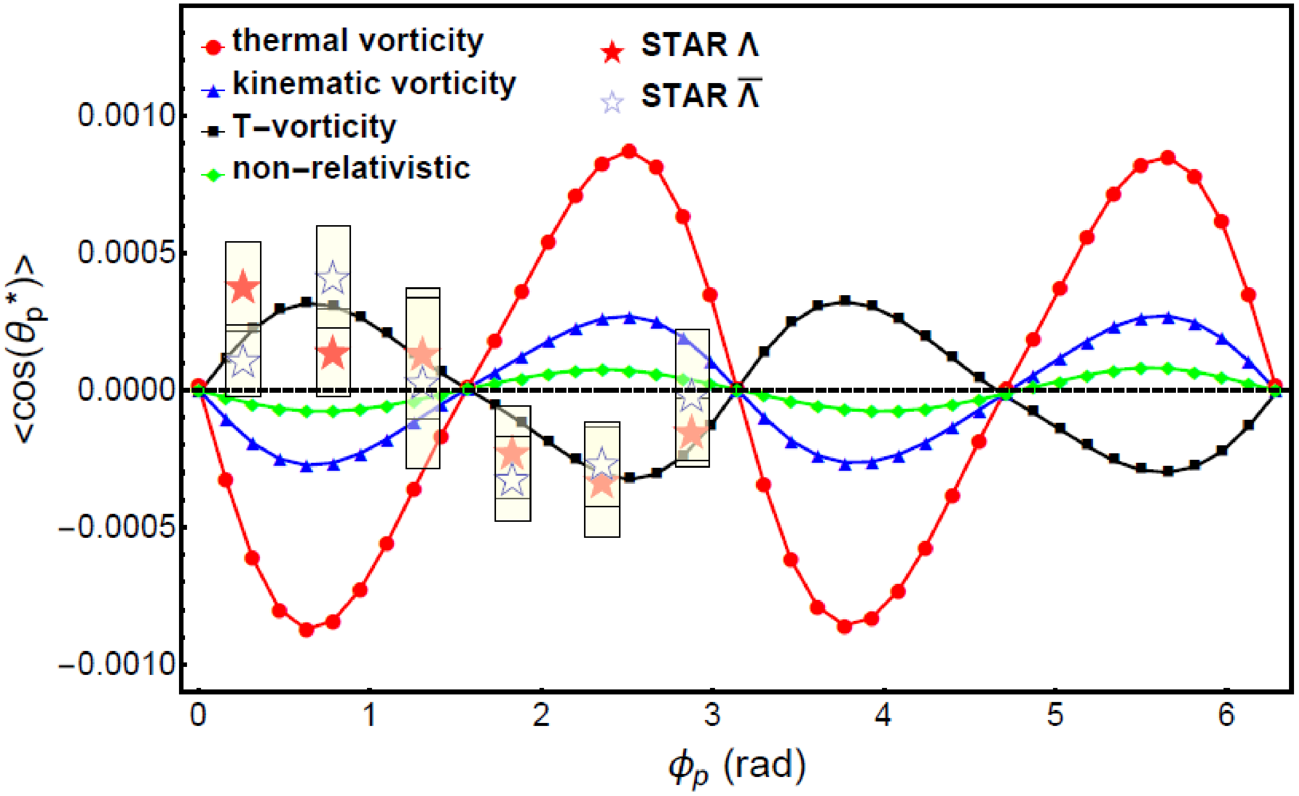




Efforts to resolve the 'sign puzzle'

- Feed-down effects (Xia, Li, Huang, Huang, PRC 2019, Becattini, Cao, Speranza, EPJC 2019)
- Other spin chemical potential (Wu, Pang, Huang, Wang, PRR 2019)

AMPT IS (includes angular momentum) + 3D viscous hydro (CLVisc



Red Line: thermal vorticity

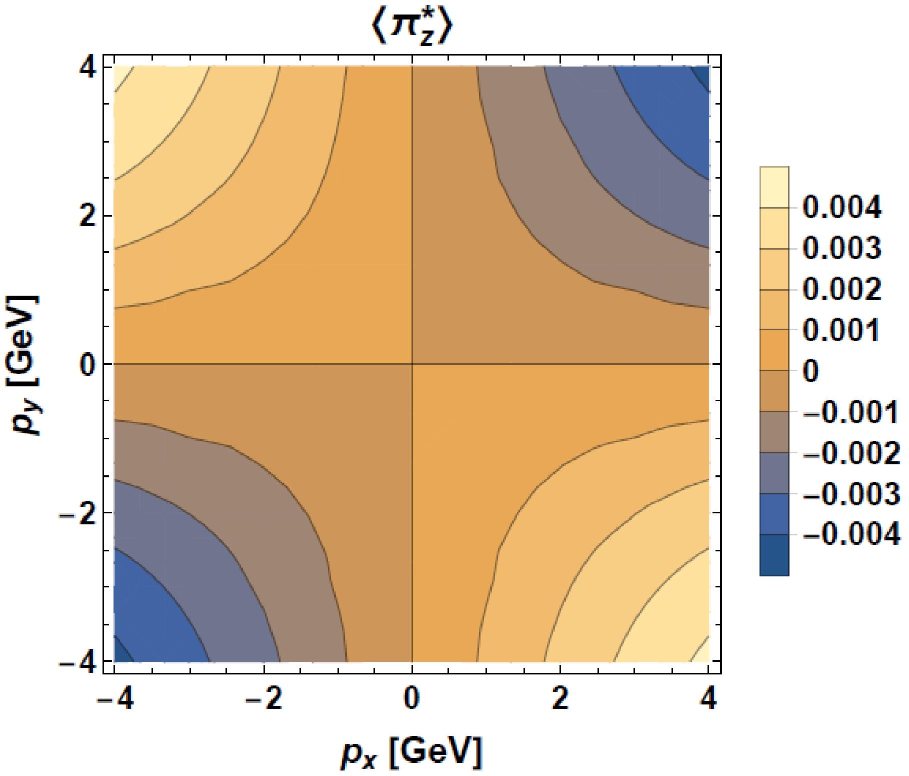
$$\omega_{\mu\nu}^{(th)} = -\frac{1}{2}(\,\partial_\mu(u_\nu/T) - \partial_\nu(u_\mu/T))$$

Black Line: T-vorticity

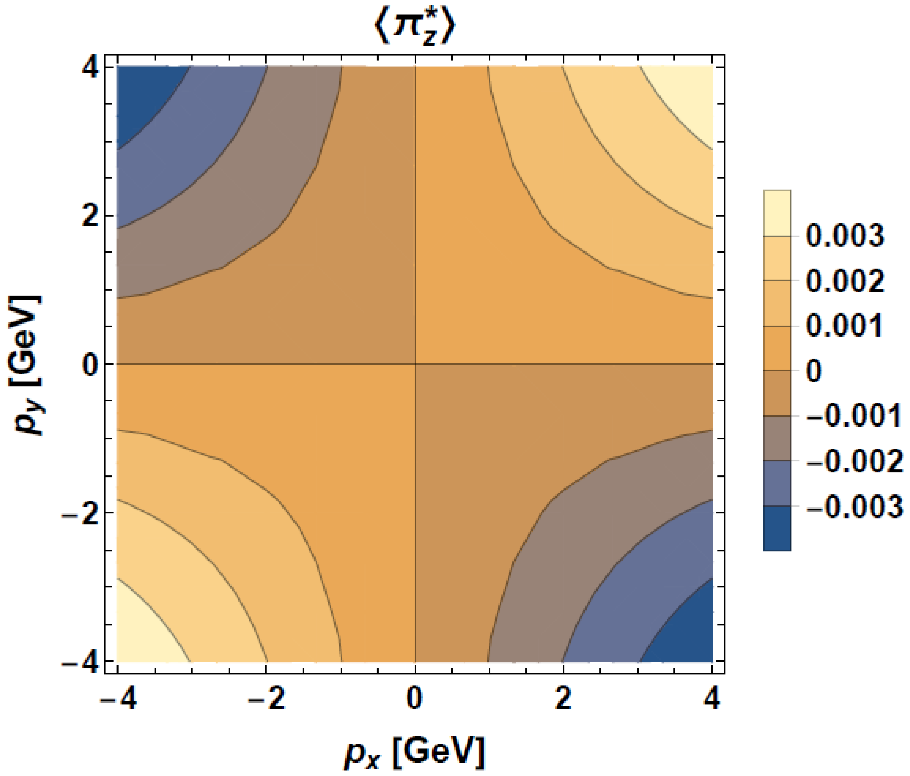
$$\omega_{\mu\nu}^{(T)} = -\frac{1}{2}(\,\partial_\mu(u_\nu T) - \partial_\nu(u_\mu T))$$

Efforts to resolve the ‘sign 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)



Standard thermal vorticity:
$\varpi^{\mu\nu} = -\frac{1}{2}\left(\partial^\mu \beta^\nu - \partial^\nu \beta^\mu\right)$



Projected thermal vorticity: $\varpi^{\mu\nu}_{\text{proj}} = \varpi_{\alpha\beta}\Delta^\mu_\alpha \Delta^\nu_\beta$

Efforts to resolve the 'sign 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)
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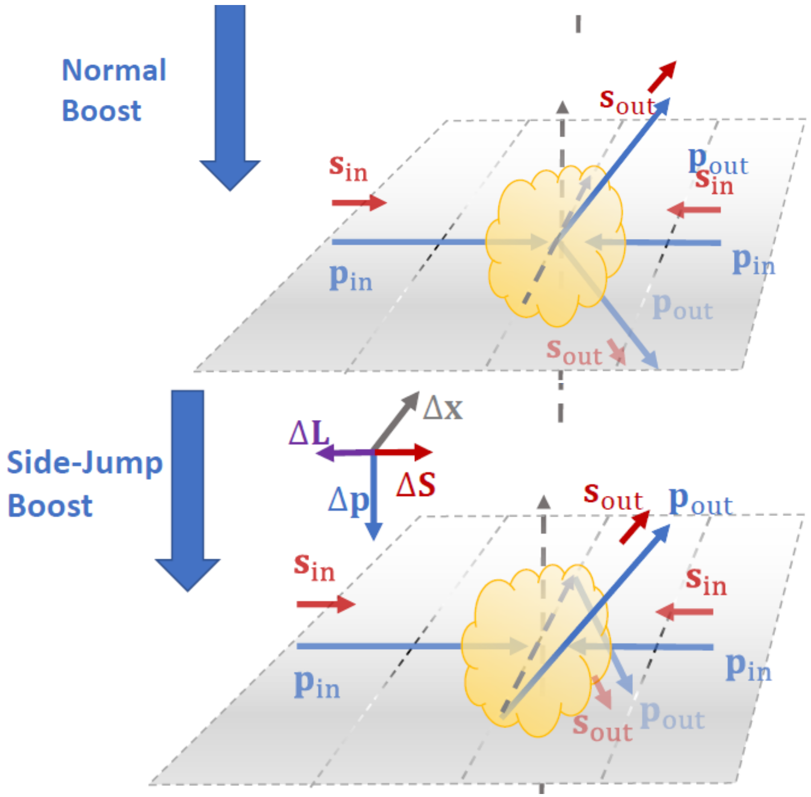
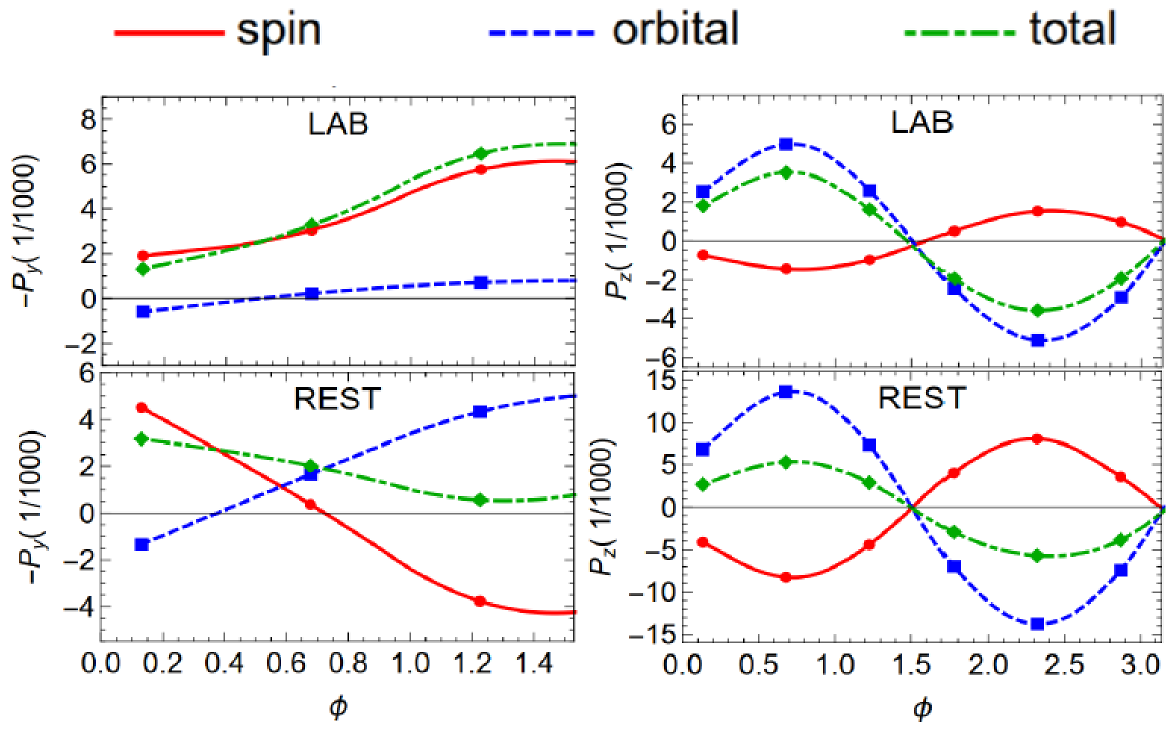
- Side-jump in CKT (Liu, Ko, Sun, PRL 2019)





Efforts to resolve the 'sign 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

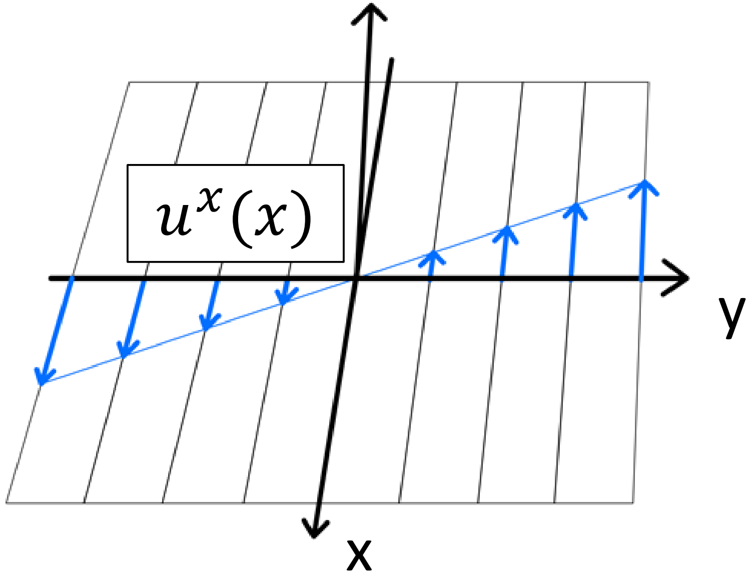
Shear Induced Polarization (SIP)

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

Hydrodynamic gradients

Derivatives of the velocity field:

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



Anti-symmetric: vorticity

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

(Thermal) vorticity induced polarization

In condensed matter physics:

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

In heavy ion collision:

F. Becattini (2013) and later works

Symmetric: shear stress

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

Shear Induced polarization: ?

[Strain induced polarization]

In crystal physics:

S. Crooker and D. Smith, PRL (2005) 94, 236601

T. Kissikov, et al., Nature Comm. (2018) 9, 1058

Shear effects in heavy ion collisions will be discussed in this talk

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:

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

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

- Identical form by linear response theory with arbitrary mass (S. Liu and Y. Yin, arXiv: 2103.09200)
- No free parameter
- Different mass sensitivity of each term

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

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

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

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

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

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

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

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

Vorticity

T gradient (spin Nernst effect)

Shear strength

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

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

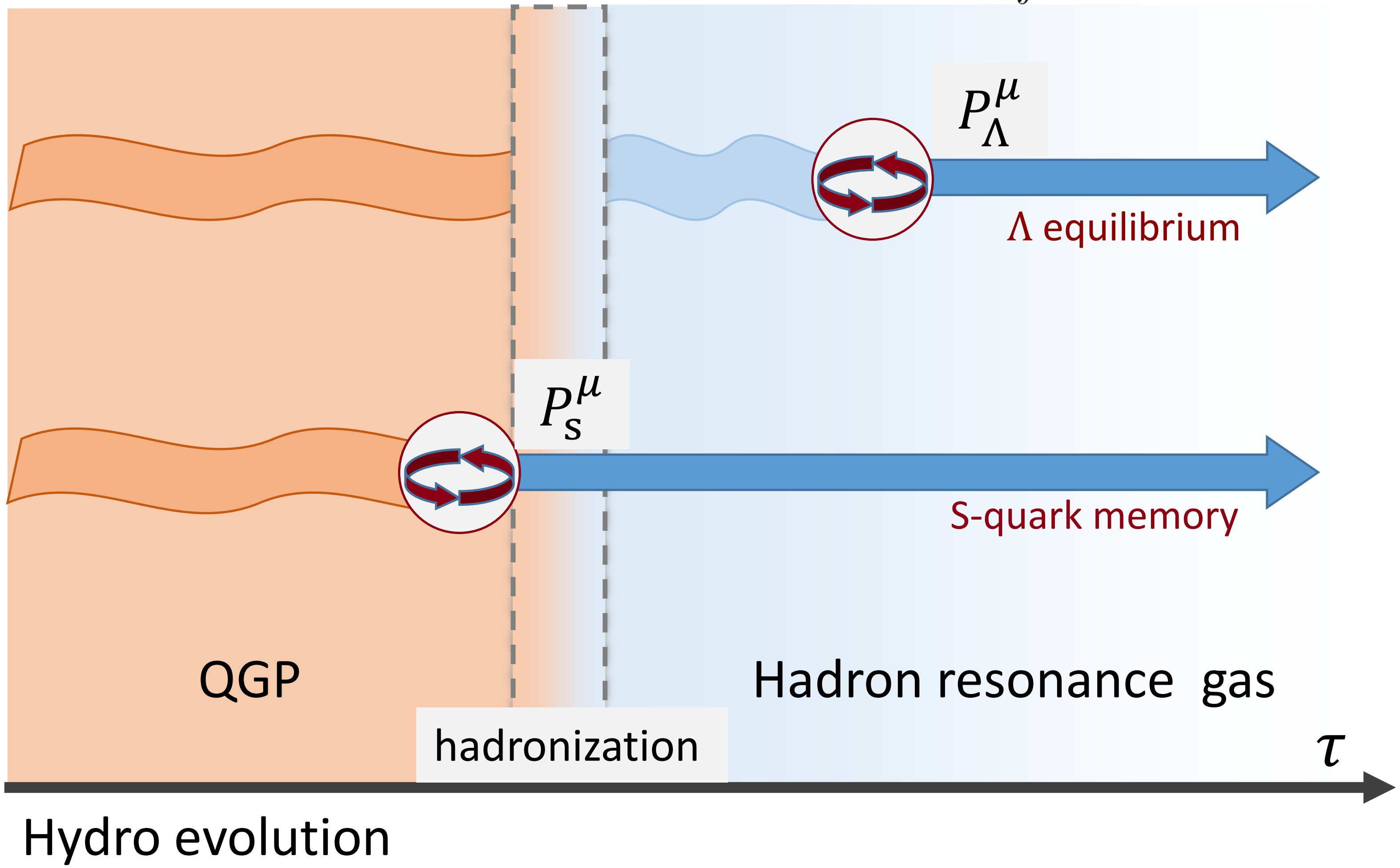
The only new effect

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

‘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’

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

Polarization of Λ-hyperon

$P^\mu_\Lambda(p)$

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

‘S-quark memory’

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

Polarization of S-quark

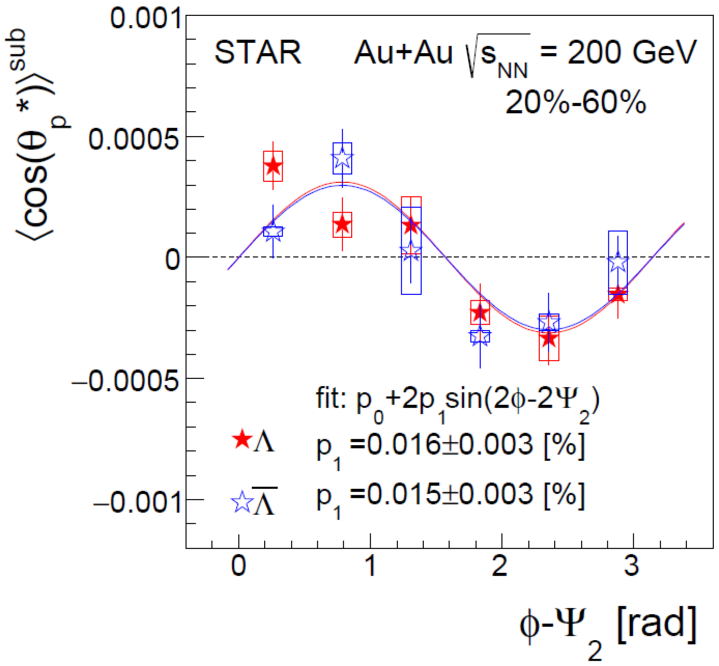
$P^\mu_s(p)$

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

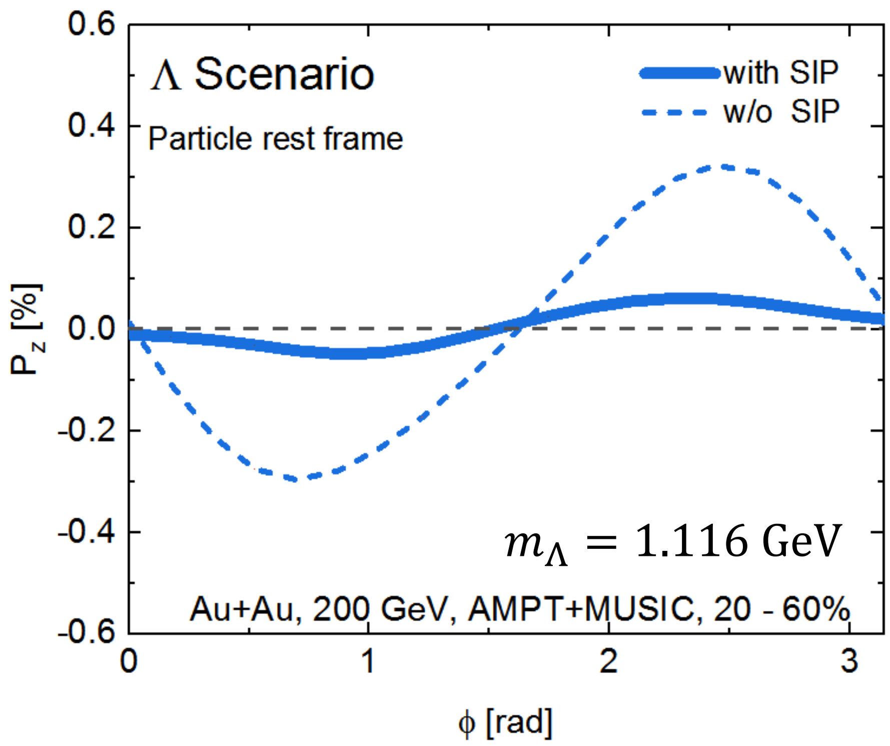
$P_z(\phi)$ with SIP

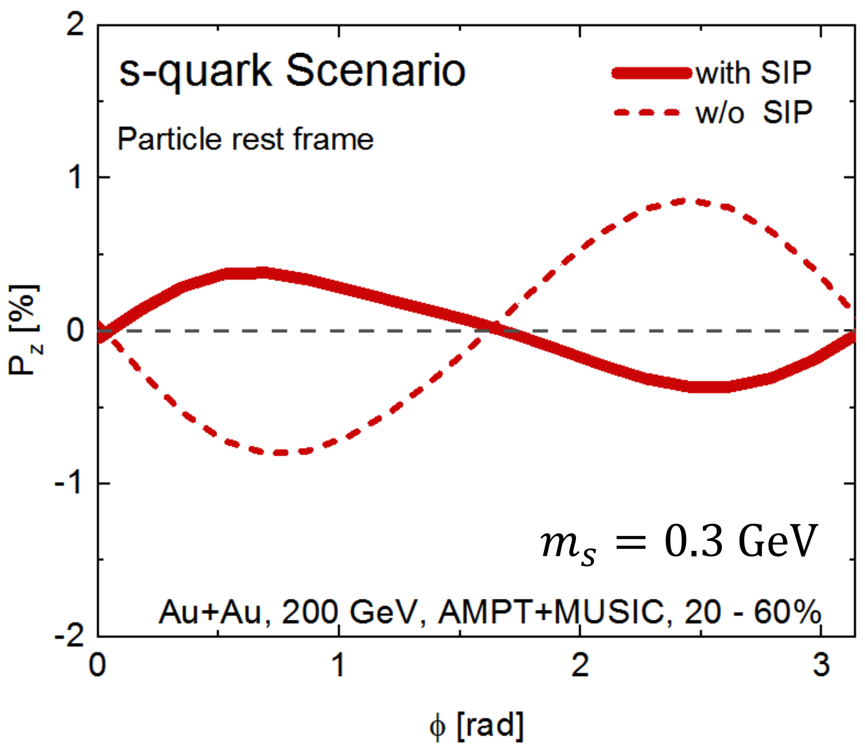
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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



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





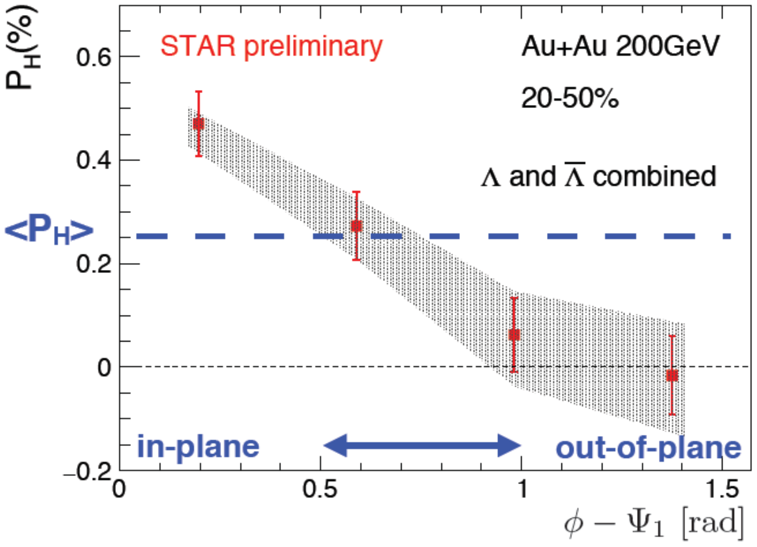
- In the scenario of ‘S-quark memory’, the total P^{μ} with SIP qualitatively agrees with data

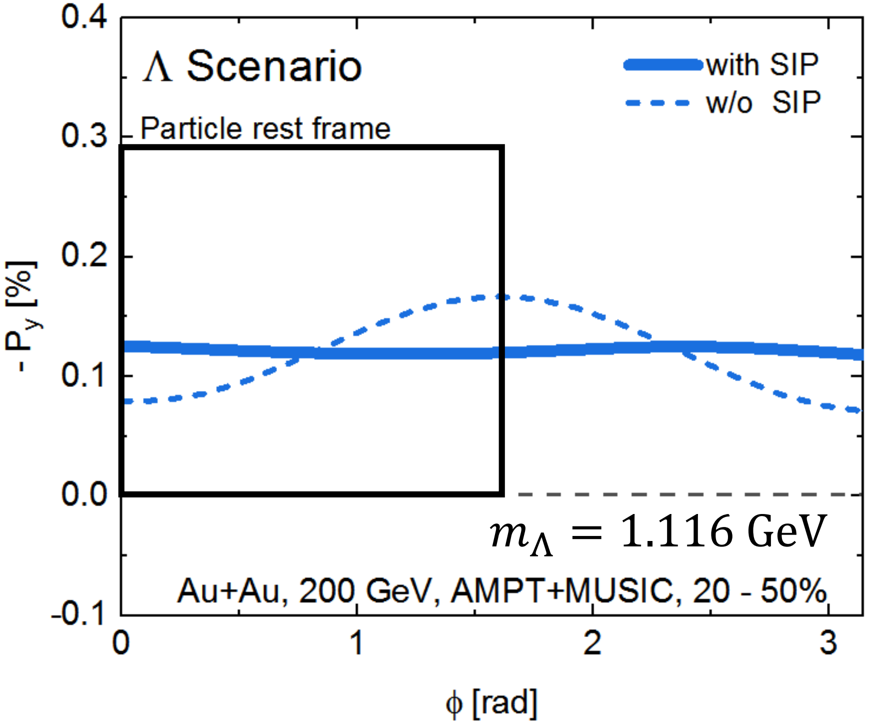
$P_y(\phi)$ with SIP

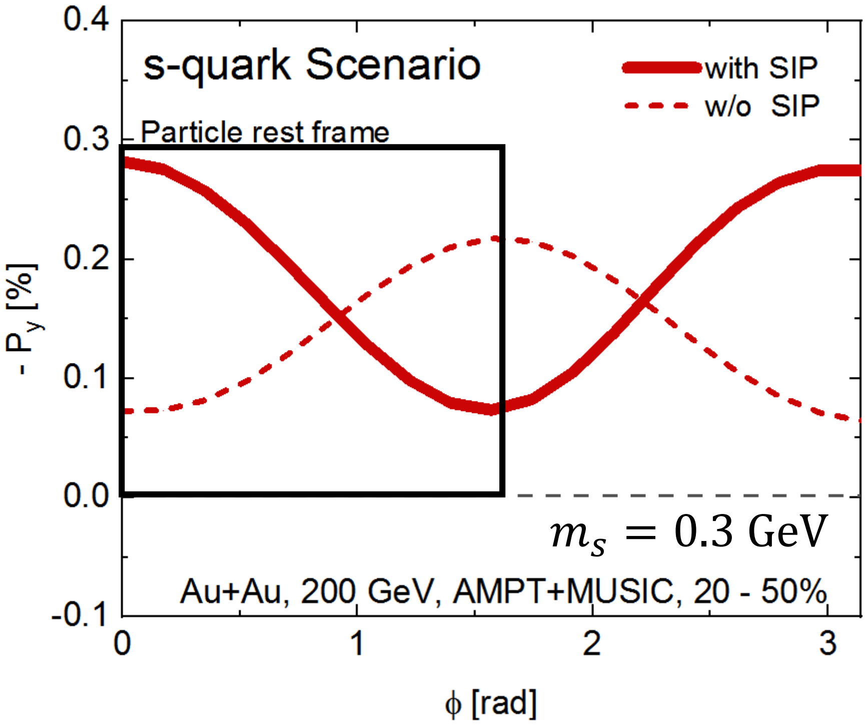
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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

STAR, NPA, 982 (2019) 511-514





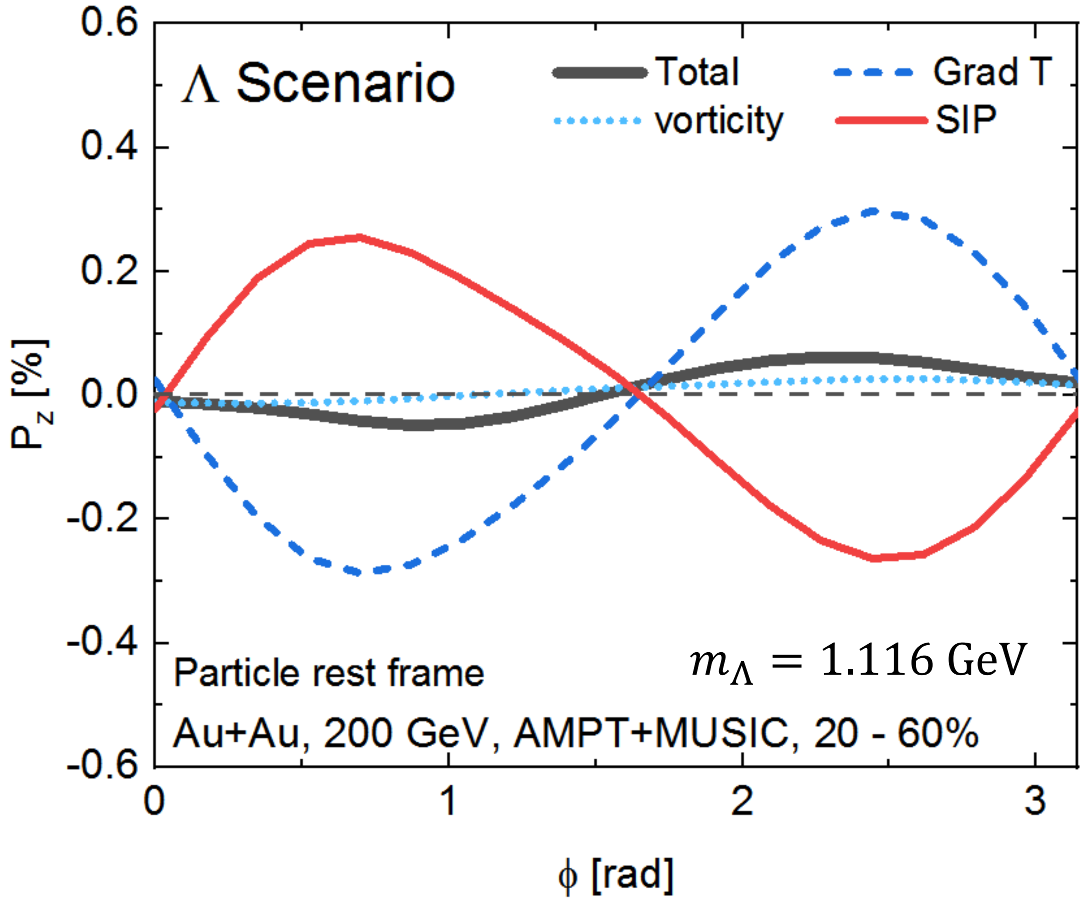


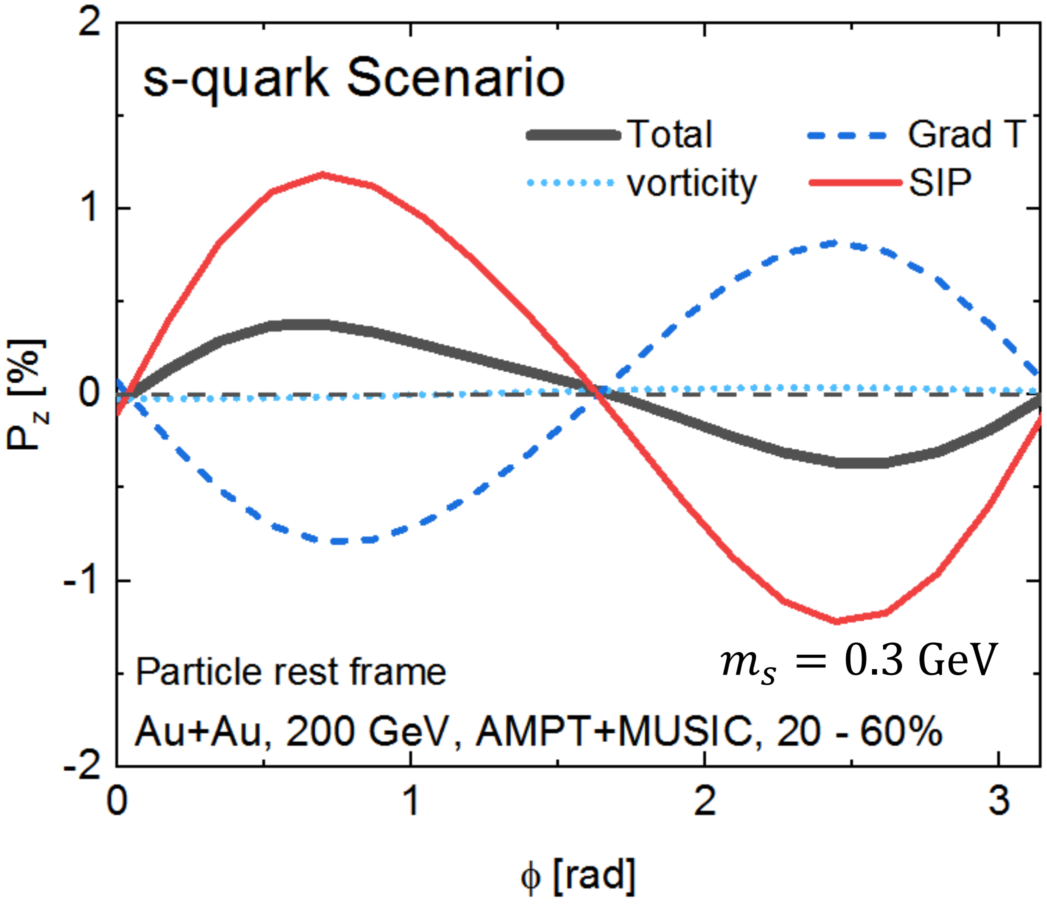
- In the scenario of 'S-quark memory', the total P^μ with SIP qualitatively agrees with data

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] + [shear] = [vorticity] + [Grad T] + [shear]



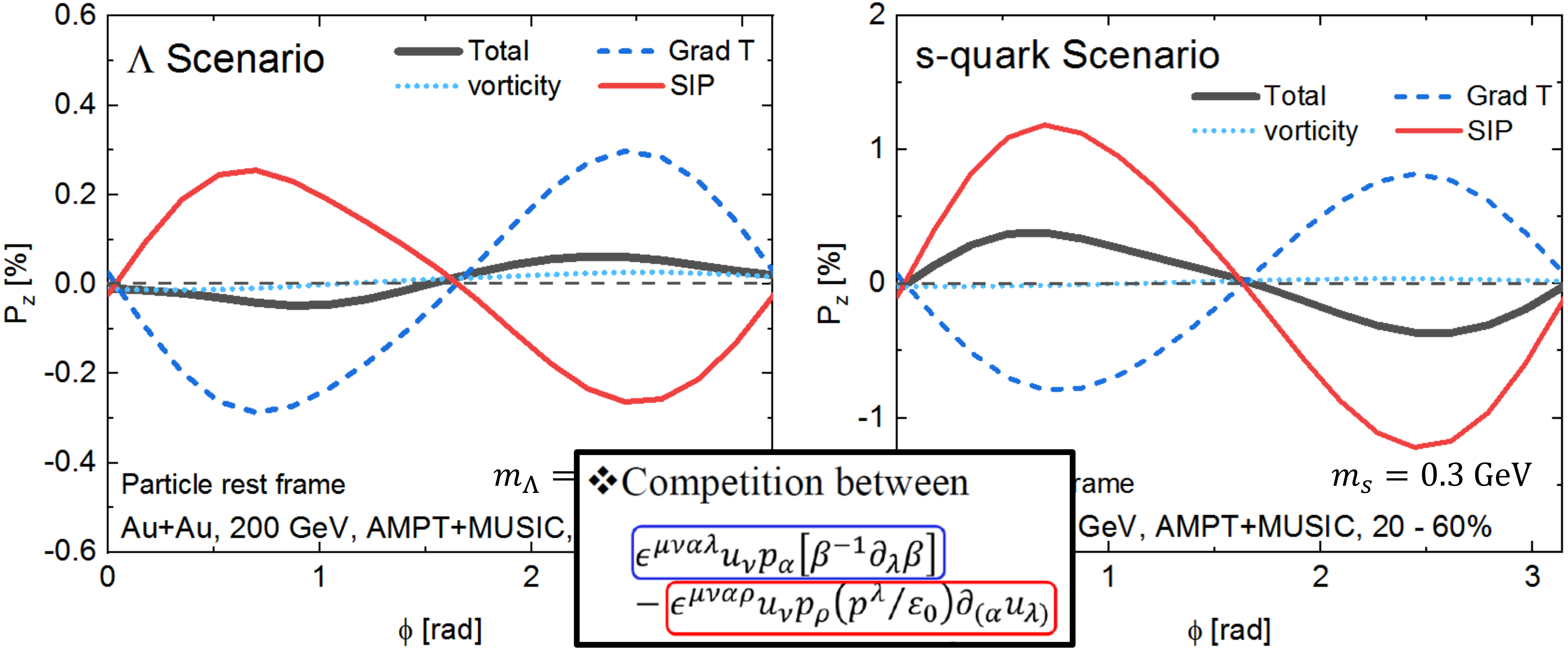


- [vorticity] ~ 0
- [SIP] and [Grad T] show similar magnitude but opposite sign

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] + [shear] = [vorticity] + [Grad T] + [shear]



❖Competition between

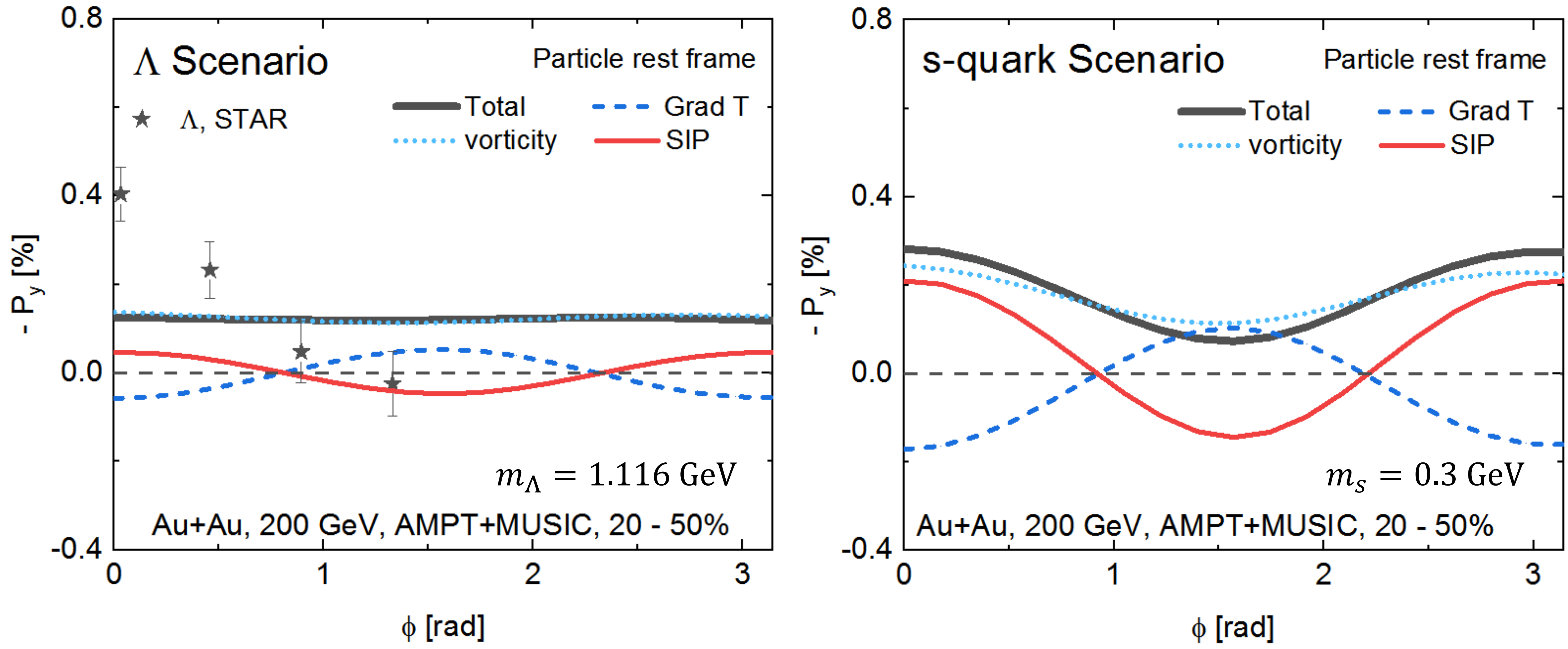
$$\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha[\beta^{-1}\partial_\lambda\beta]$$
$$-\epsilon^{\mu\nu\alpha\rho}u_\nu p_\rho(p^\lambda/\varepsilon_0)\partial_{(\alpha}u_{\lambda)}$$

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

Competition of P_y: Grad T vs. SIP

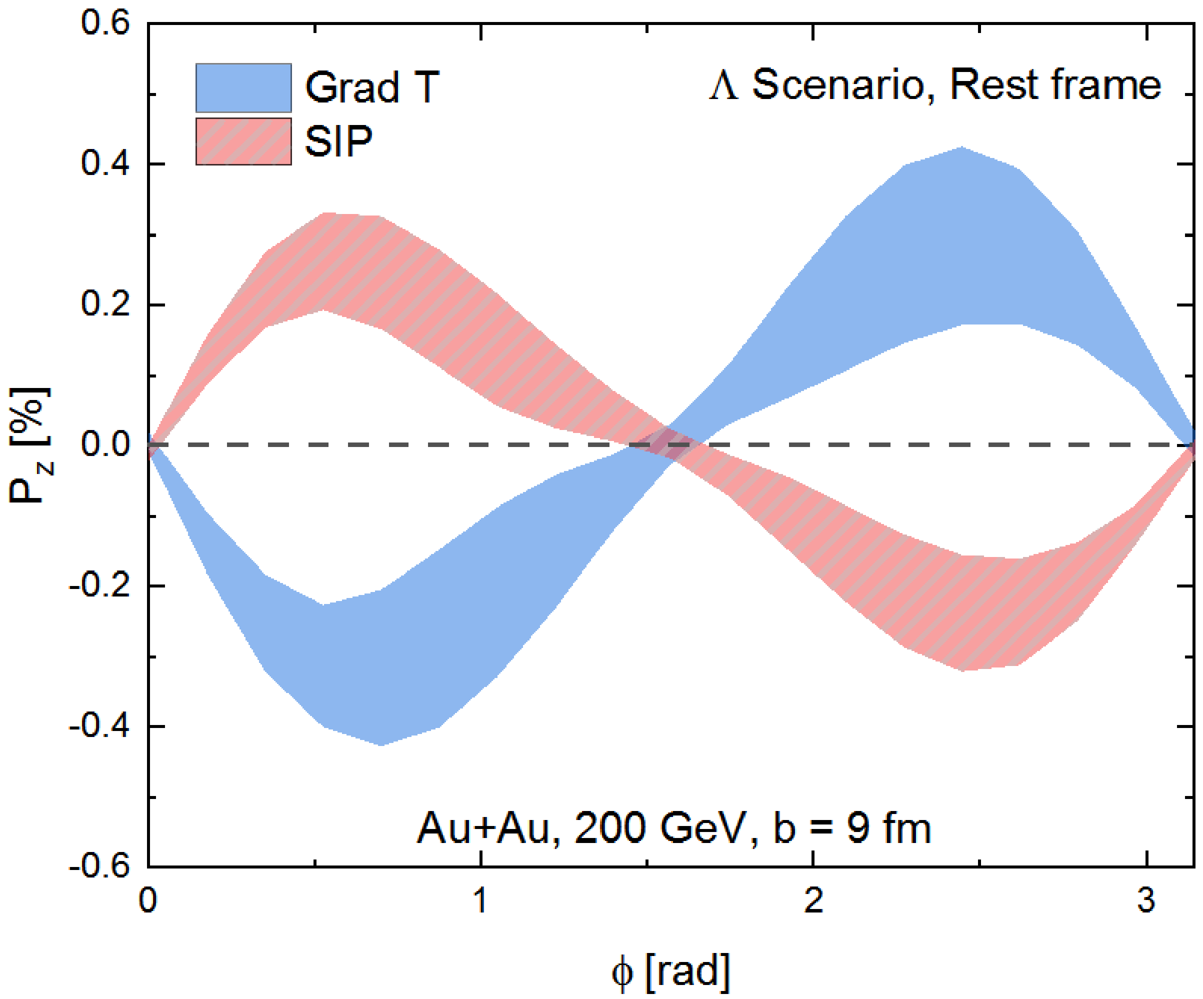
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

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



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

Robustness of the competition



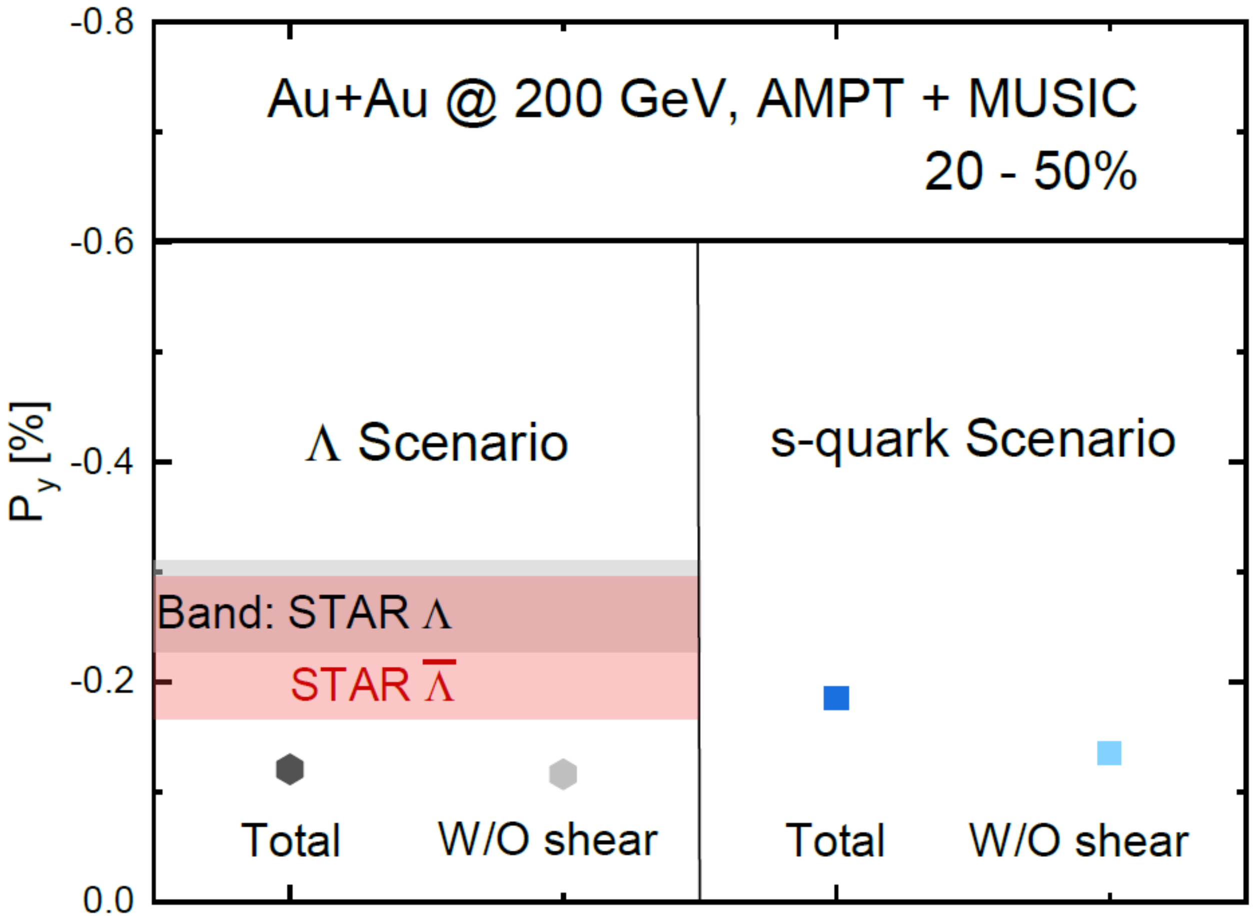
Band: possible flexibility of [Grad T] and [SIP]

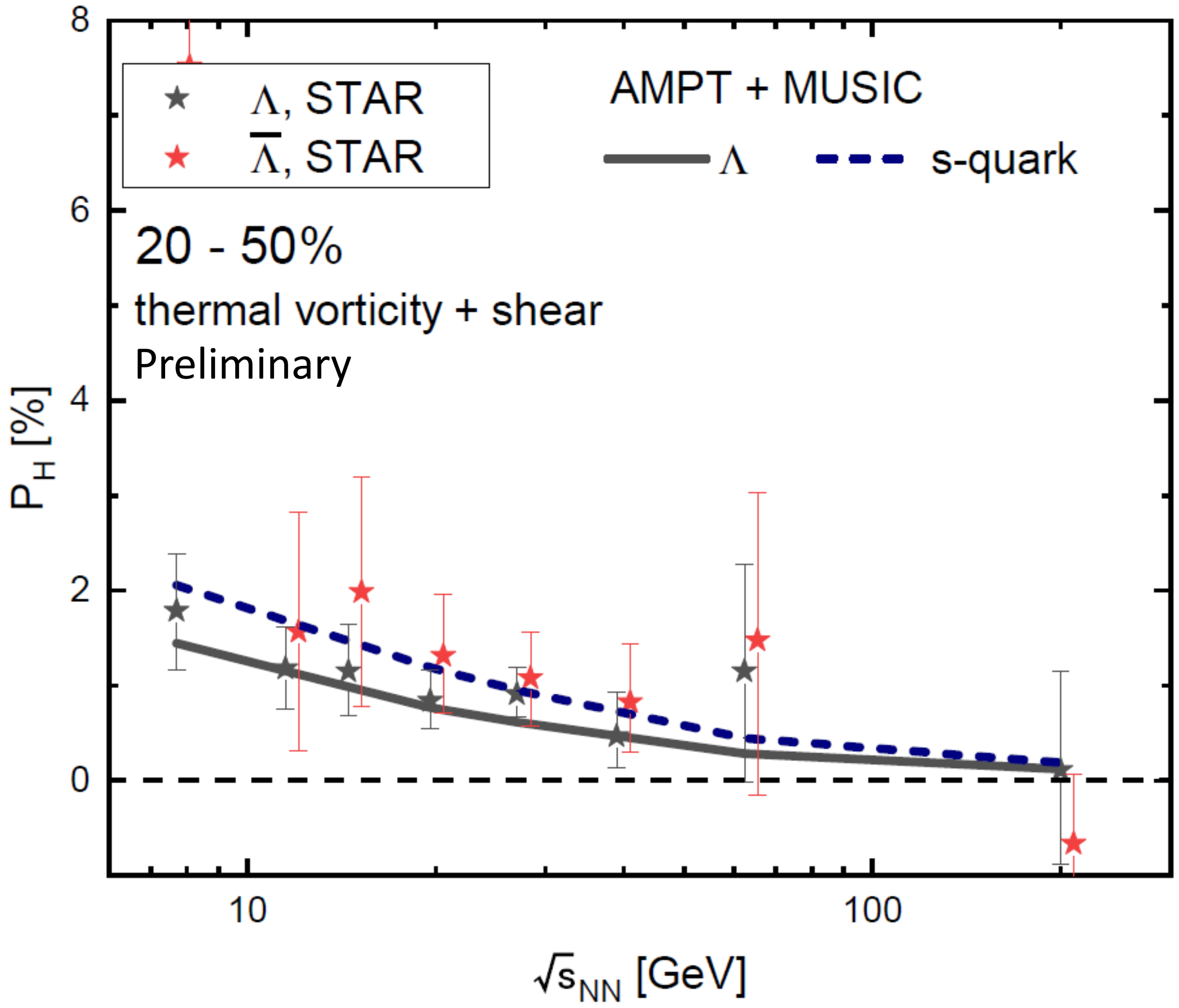
- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: $\zeta/s(T)$ → off
- Freeze-out temperature:

  167 MeV → 157 MeV

Global polarization with shear effect

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





Sensitivity to frame

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

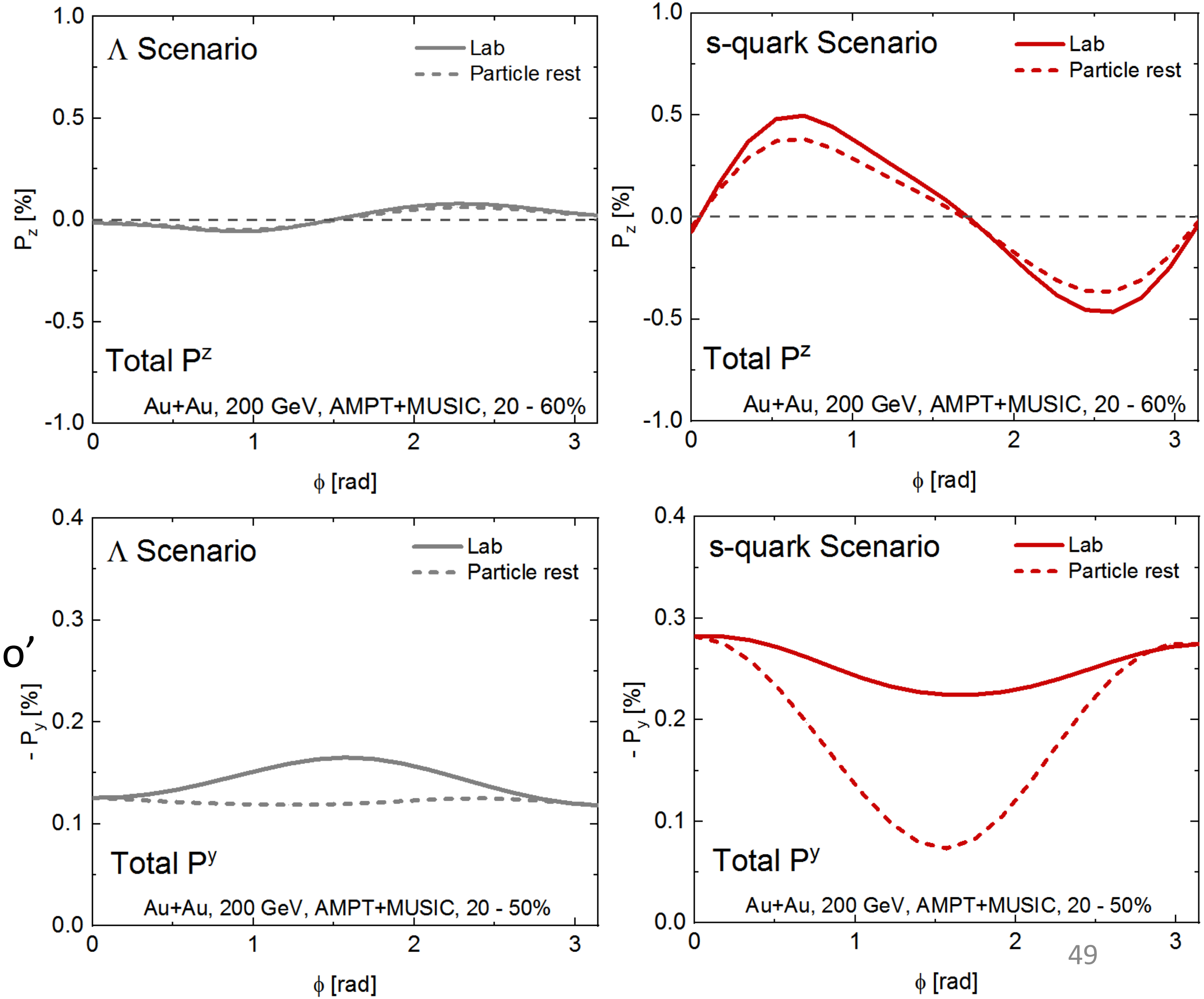
- $P^z(\phi)$

not sensitive to frame

- $P^y(\phi)$

sensitive to frame,

especially in 'S-quark scenario'



A brief comparison with F. Becattini's work

F. Becattini, et al. arXiv: 2103.10917, arXiv: 2103.14621

1) The definition of (thermal) shear formula
2) T-gradient effect on freeze-out surface

Comparison with the results from F. Becattini

Spin polarization F. Becattini, et al. arXiv: 2103.10917, arXiv: 2103.14621

$$S^\mu = S^\mu_\varpi + S^\mu_\xi$$

Thermal vorticity effect:

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F} \qquad \varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right)$$

Thermal shear effect:

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\hat{t}_\nu \xi_{\sigma\rho}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F} \qquad \xi_{\mu\nu} = \frac{1}{2}(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu)$$

Polarization formula used in our work:

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

[Thermal vorticity] [Shear effect]

Comparison with the results from F. Becattini

Spin polarization F. Becattini, et al. arXiv: 2103.10917, arXiv: 2103.14621

$$S^\mu = S^\mu_\varpi + S^\mu_\xi$$

Thermal vorticity effect:

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F} \qquad \varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu\right)$$

Thermal shear effect:

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\hat{t}_\nu \xi_{\sigma\rho}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F} \qquad \xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu)$$

Polarization formula used in our work:

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

[Thermal vorticity] [Shear effect]

1) Different choice of $\hat{t}_\nu$ or u_ν

Comparison with the results from F. Becattini

Spin polarization F. Becattini, et al. arXiv: 2103.10917, arXiv: 2103.14621

$$S^\mu = S^\mu_\varpi + S^\mu_\xi$$

Thermal vorticity effect:

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

Thermal shear effect:

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F(1-n_F)\hat{t}_\nu \xi_{\sigma\rho}}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}$$

Polarization formula used in our work:

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

[Thermal vorticity] [Shear effect]

If we change $\hat{t}_\nu \rightarrow u_\nu$ in Becattini's definition:

- **Identical** definition of total polarization

  P^μ = [thermal vorticity] + [shear]

- Using the equation of motion:

  $$(u\cdot\partial)u_\mu = -\beta^{-1}\partial^\perp_\mu \beta$$

  the [thermal vorticity] and [shear] definition are identical individually

Same (not precisely the same) formula

* From F. Becattini's HENPIC talk

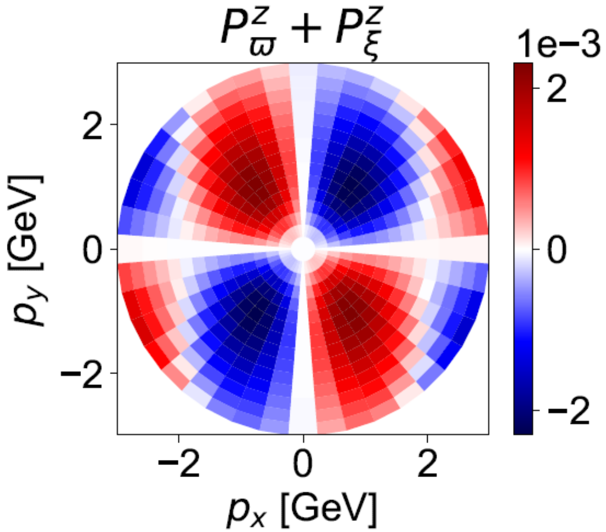
1) Different choice of $\hat{t}_\nu$ or u_ν

Comparison with the results from F. Becattini

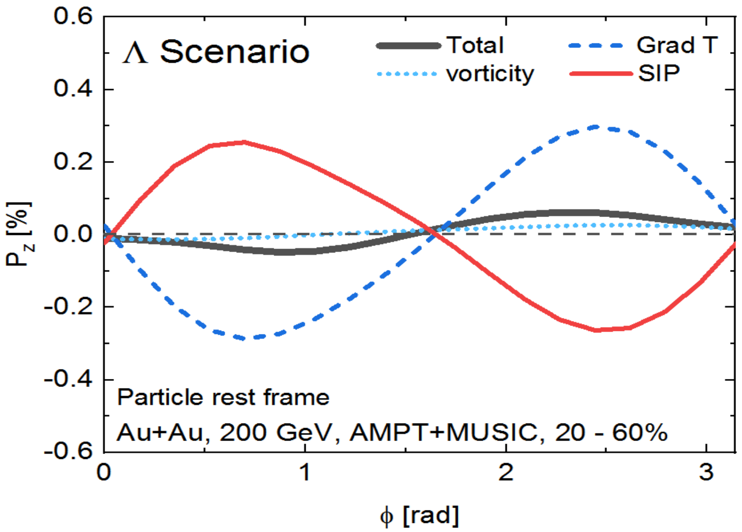
2) T-gradient effect

- Simply use P^{μ} = [thermal vorticity] + [shear] for Λ hyperon can't reproduce the sign

F. Becattini, et al. arXiv: 2103.14621



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



Comparison with the results from F. Becattini

2) T-gradient effect

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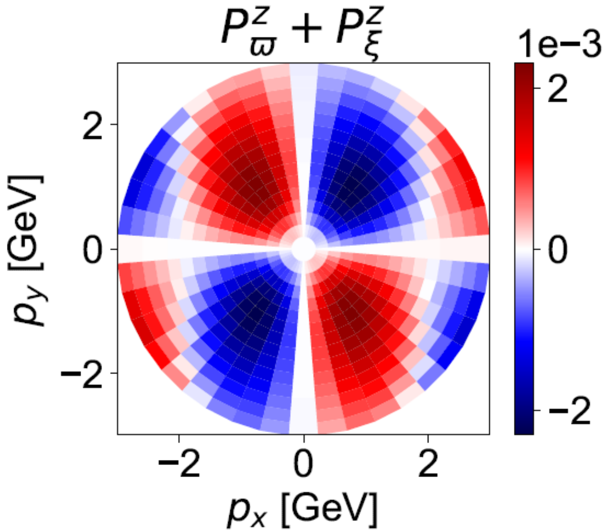
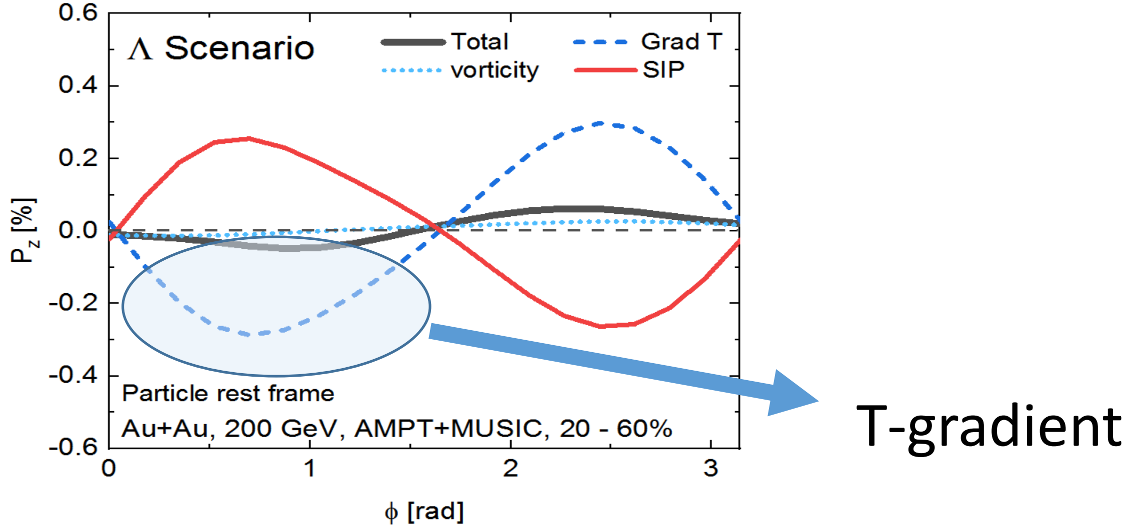


BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403



- They assume the T-gradient is negligible (isothermal freeze-out)

[thermal vorticity] $\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right).$ ⇒ $\omega_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho - \partial_\rho u_\sigma\right)$ [kinetic vorticity]

[thermal shear] $\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu\right)$ ⇒ $\Xi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho + \partial_\rho u_\sigma\right)$ [kinetic shear]

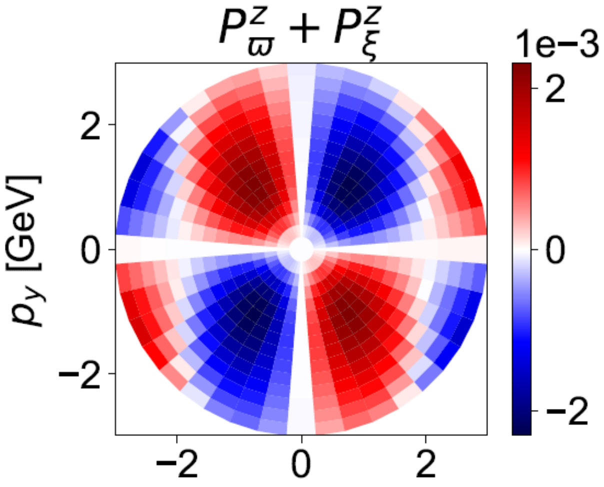
F. Becattini, et al. arXiv: 2103.14621

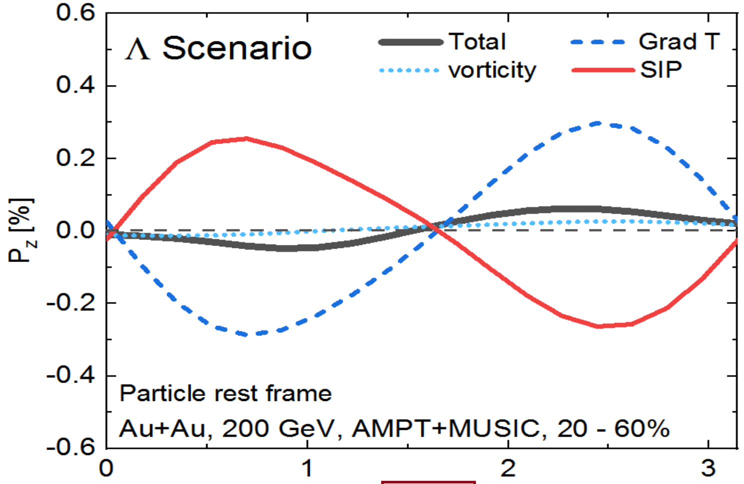
Comparison with the results from F. Becattini

2) T-gradient effect

F. Becattini, et al.
arXiv: 2103.14621

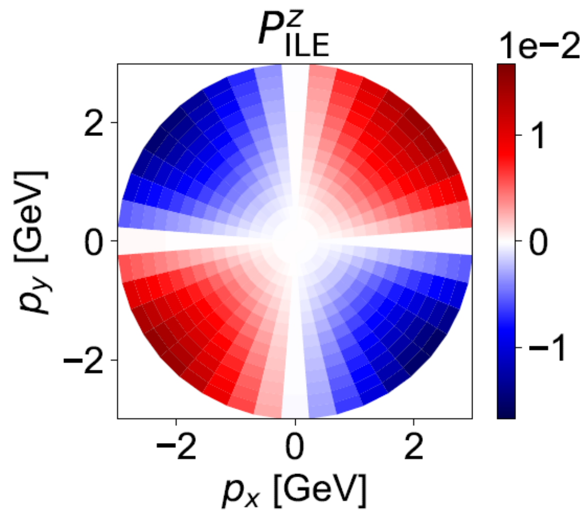
BF, S. Liu, L. -G. Pang, H. Song, Y. Yin,
arXiv: 2103.10403

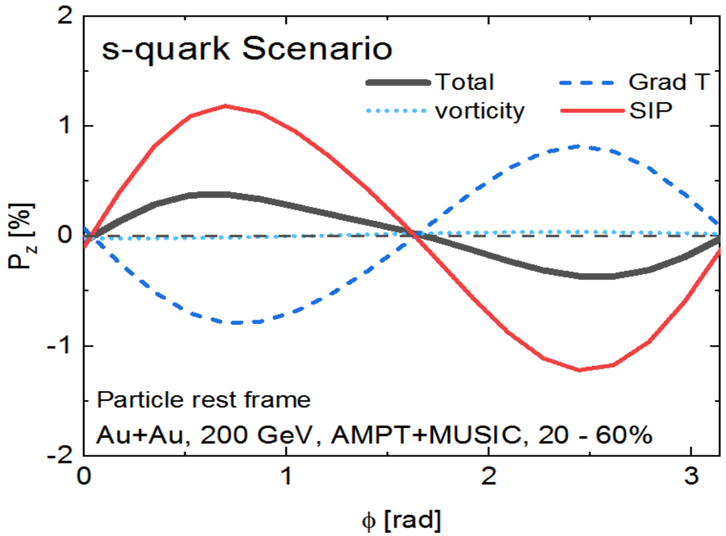




T-gradient excluded

T-gradient included
Using s-quark scenario



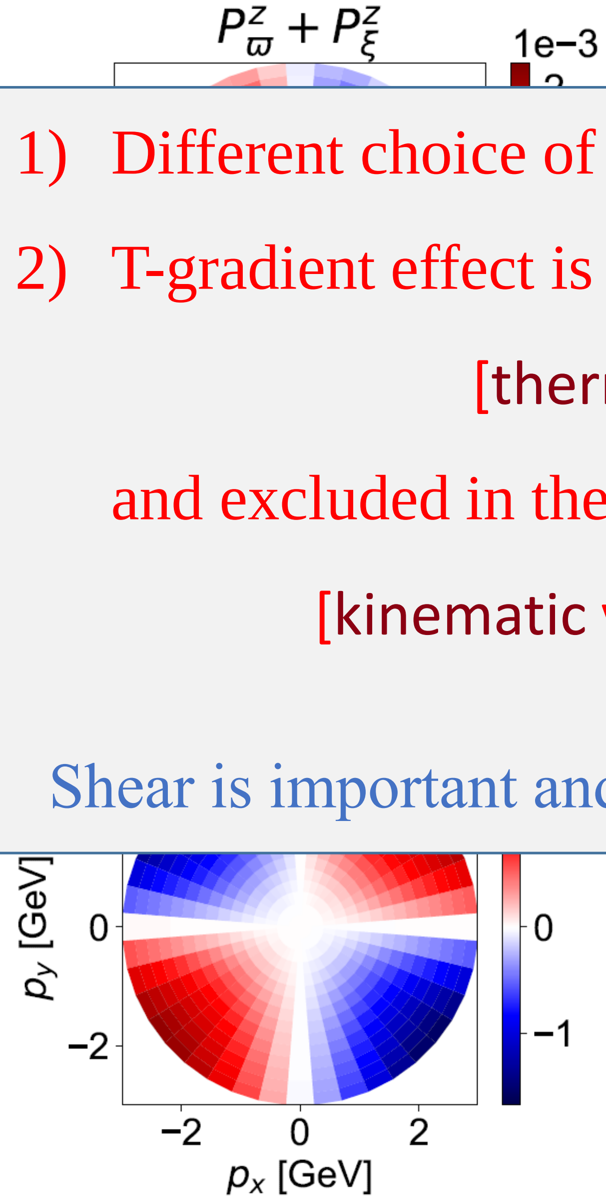


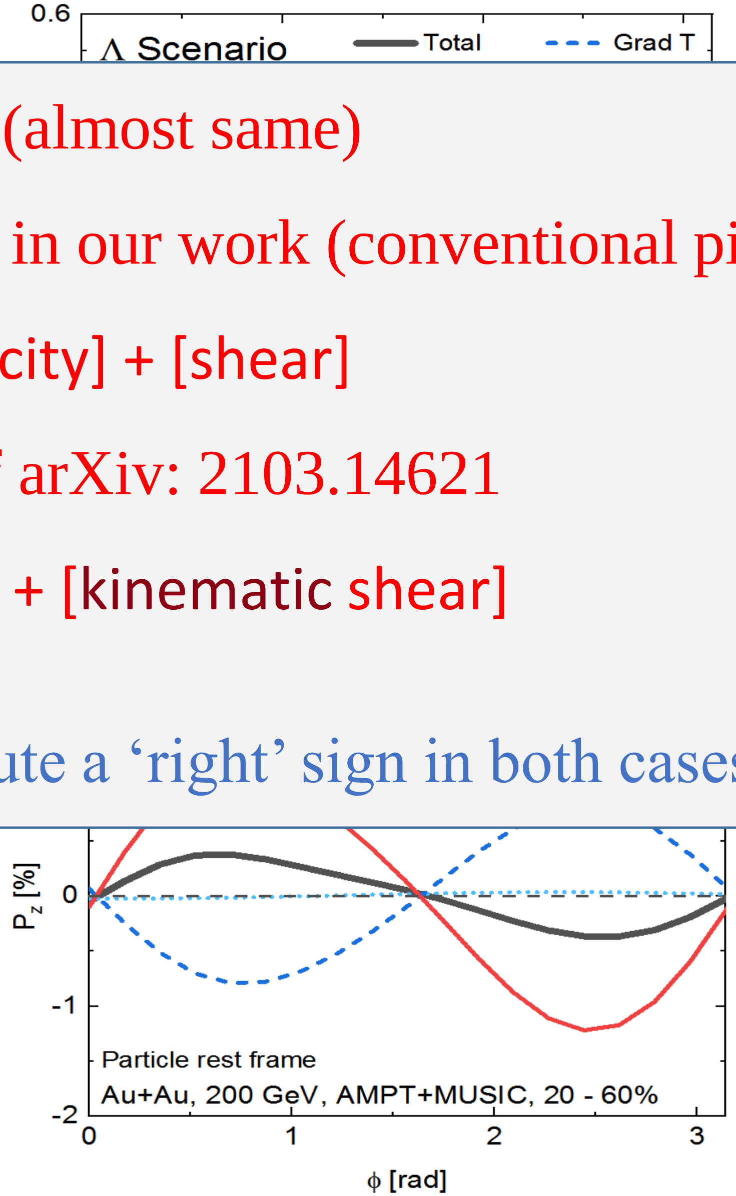
Comparison with the results from F. Becattini

2) T-gradient effect

F. Becattini, et al.
arXiv: 2103.14621

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





1) Different choice of $\hat{t}_\nu$ or u_ν (almost same)

2) T-gradient effect is included in our work (conventional pic.)

[thermal vorticity] + [shear]

and excluded in the result of arXiv: 2103.14621

[kinematic vorticity] + [kinematic shear]

Shear is important and contribute a ‘right’ sign in both cases!

T-gradient ex

ent included
-quark scenario

Summary & Outlook

- Spin polarization opens a new door to study the properties of QCD matter
- Conventional thermal vorticity describes the global polarization but fails at local polarization
- New discovered shear effect always provides ‘same sign’ like experimental data
- ‘Strange memory’ scenario might provide insights on the hadronization mechanism

- To quantitative calculation: spin hadronization / hadronic evolution
- Higher order observables like v_3 in collective flow
- Will it helps to understand the spin alignment puzzle?

Back up

Comparison with the results from F. Becattini

The isothermal freeze-out picture (F. Becattini, et al. arXiv: 2103.10917, arXiv: 2103.14621)

- Taylor expansion of the density operator (take T outside in isothermal assumption)

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z_{\rm LE}} \exp\left[-\beta_\nu(x)\widehat{P}^\nu - \partial_\lambda\beta_\nu(x)\int_\Sigma \mathrm{d}\Sigma_\mu(y)(y-x)^\lambda \widehat{T}^{\mu\nu}(y)\right]$$

$$\Rightarrow$$

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z_{\rm LE}} \exp\left[-\beta_\nu(x)\widehat{P}^\nu + - \frac{1}{T}\partial_\lambda u_\nu(x)\int_\Sigma \mathrm{d}\Sigma_\mu(y)(y-x)^\lambda \widehat{T}^{\mu\nu}(y)\right]$$

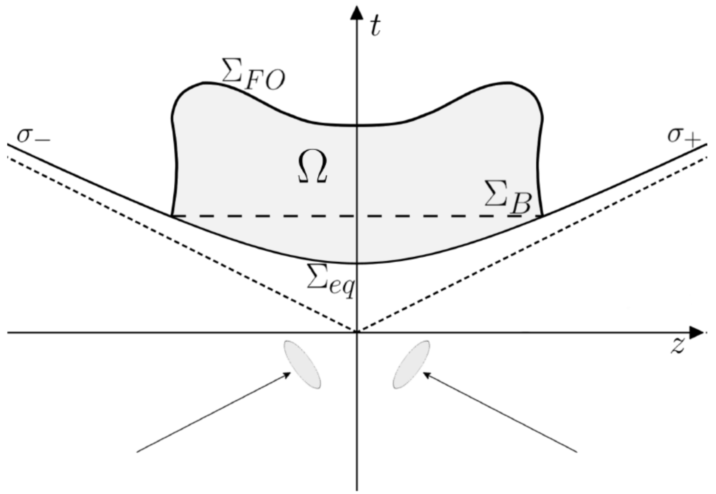
$$\beta_\nu(y) \simeq \beta_\nu(x) + \partial_\lambda\beta_\nu(x)(y-x)^\lambda$$

- Is it self-consist with the definition of equal-time surface?

$$\widehat{W}^+_{ab}(x,k) = \theta(k^0)\theta(k^2)\frac{1}{(2\pi)^4}\int \mathrm{d}^4 s\, \mathrm{e}^{-ik\cdot s} : \overline{\Psi}_b(x+s/2)\Psi_a(x-s/2) :$$

$$\langle \widehat{W}^+_{ab}(x,k)\rangle_{\rm LE} \simeq \langle \widehat{W}^+_{ab}(x,k)\rangle_{\beta(x)} + \Delta W^+_{ab}(x,k),$$

$$\Delta W^+_{ab}(x,k) = -\int_0^1 \mathrm{d}z \int_\Sigma \mathrm{d}\Sigma_\lambda(y)\Delta\beta_\rho(x,y)\langle \widehat{W}^+_{ab}(x,k)\widehat{T}^{\lambda\rho}(y+iz\beta(x))\rangle_{c,\beta(x)}$$



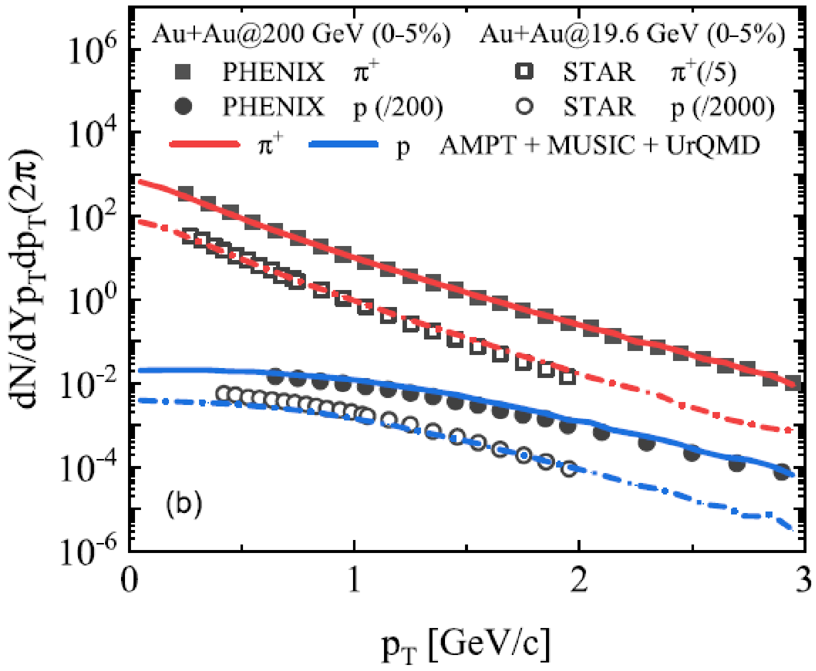
Well calibrated hydrodynamic model

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

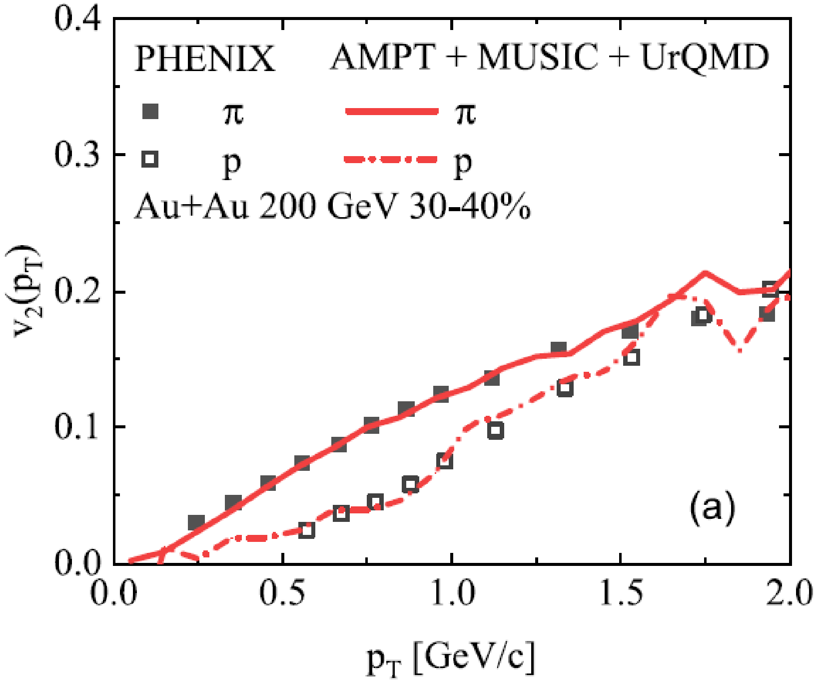
AMPT → MUSIC → iSS → UrQMD

Parameters are tuned to reproduce the soft hadron observables

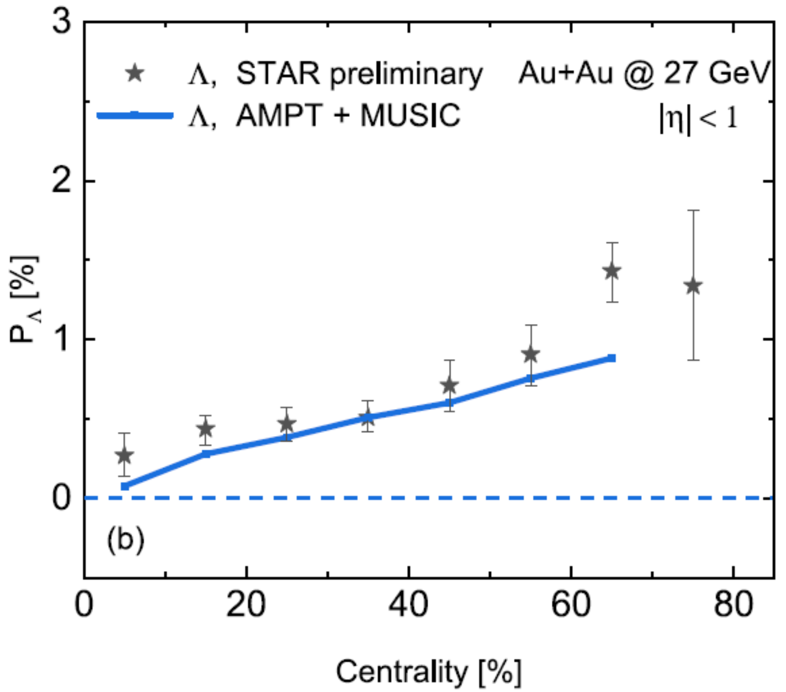
Transverse momentum spectra



$v_2(p_T)$



Global Polarization from thermal vorticity



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:

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

[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)

Comparison with the results from F. Becattini

The isothermal freeze-out picture (F. Becattini, et al. arXiv: 2103.14621)

$$S^{\mu}_{\rm ILE}(p) = -\,\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma \cdot p\, n_F(1-n_F)\left[\omega_{\rho\sigma} + 2\,\hat{t}_\rho \frac{p^\lambda}{\varepsilon}\Xi_{\lambda\sigma}\right]}{8mT_{\rm dec}\int_\Sigma d\Sigma \cdot p\, n_F}$$

$$\omega_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho - \partial_\rho u_\sigma\right) \qquad \Xi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho + \partial_\rho u_\sigma\right)$$

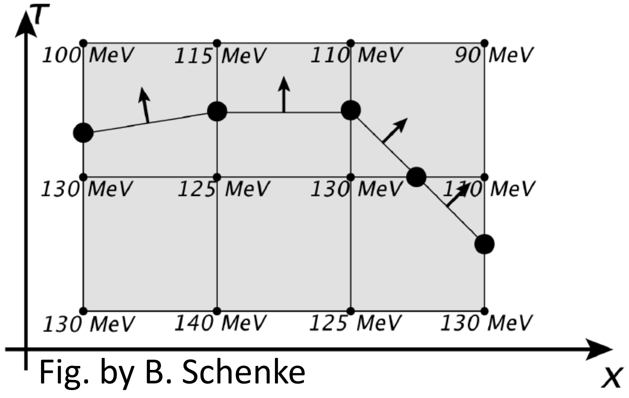
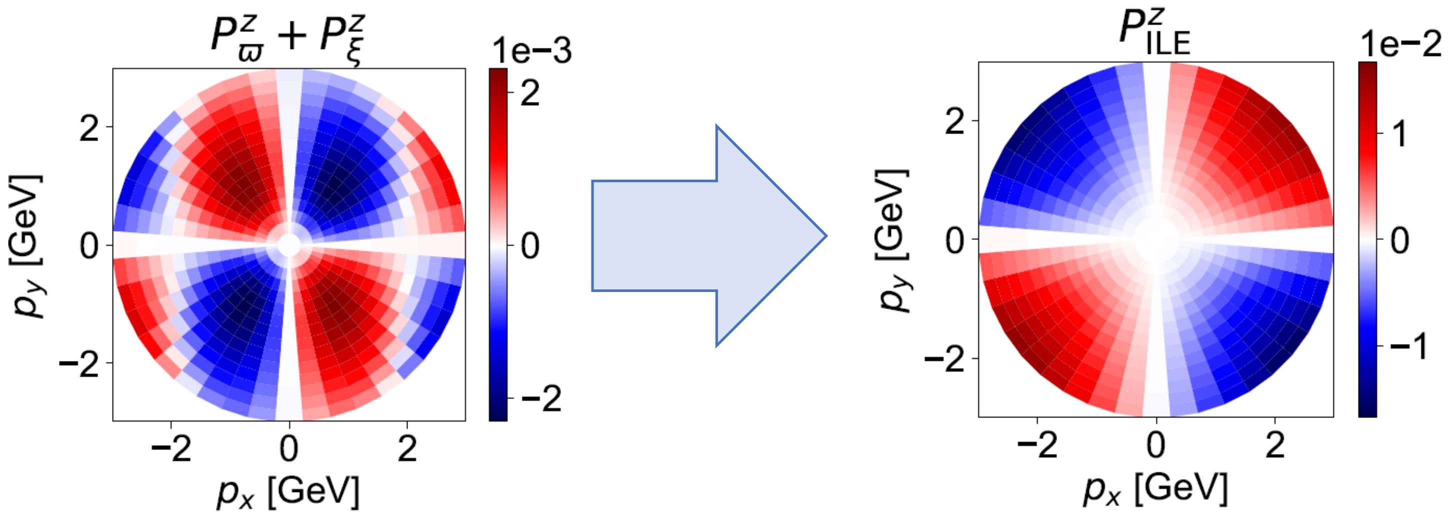
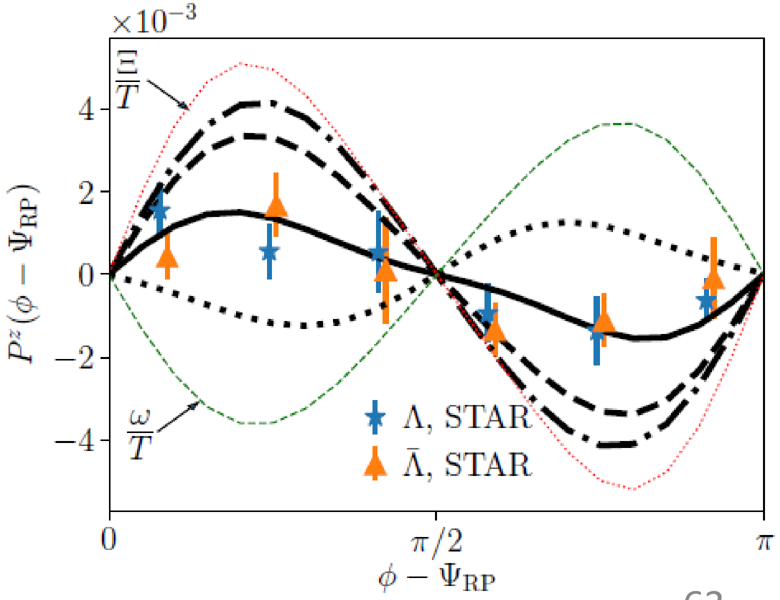


Fig. by B. Schenke

- With the T-gradient removed, the thermal vorticity (shear) is replaced by kinematic vorticity (shear)





1) T-gradient on the freeze-out surface