Spin polarization: theoretical updates & experimental perspective

-Topical discussion：

Francesco Becattini (Univ. of Florence)

Huichao Song (Peking Univ.)

On-line seminar series III on “RHIC Beam Energy Scan: Theory and Experiment”

Nov 23 2021

Outline

-Introduction

-Shear Induced Polarization (SIP)

-Spin Hall Effects (SHE)

-Comparison between groups & discussion

B. Fu, K. Xu, X-G, Huang, H. Song,
Phys.Rev.C103 2, 024903 (2021).

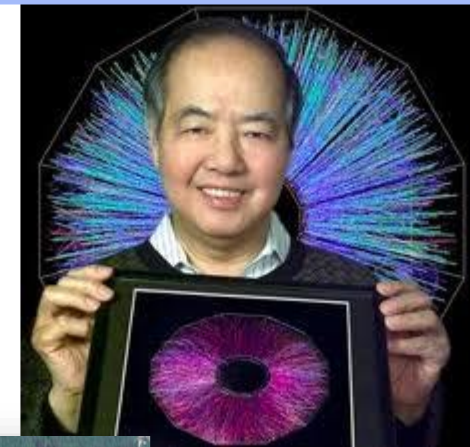
B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin,
Phys.Rev.Lett. 127 14, 142301 (2021).

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

Baochi Fu

Workshop on celebration the 95th birthday of T. D. Lee
& the 35th anniversary of Center for Modern Physics, Beijing

A brief history for relativistic heavy ion collisions



1974: Workshop on “GeV/nucleon collisions of heavy ions”

We should investigate.... phenomena by distributing energy of high nucleon density of a relatively large volume”

---T.D.Lee

1984: SPS starts, (end 2003)

1986: AGS stars, (end 2000)

2000: RHIC starts

2010: LHC starts

Future: FAIR & NICA

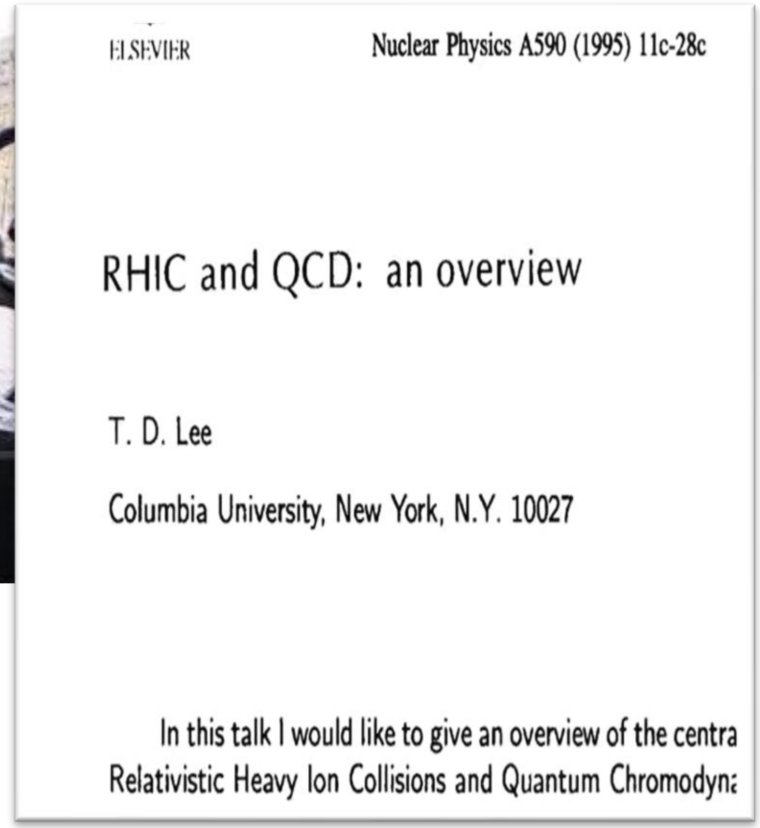
A brief history for relativistic heavy ion collisions

1974: Workshop on “GeV/nucleon collisions of heavy ions”

We should investigate.... phenomena by distributing energy of high nucleon density of a relatively large volume” ---T.D.Lee

核子重如牛，对撞生新态

The nucleons are as heavy as bulls
Collisions create new state of matter



ELSEVIER Nuclear Physics A590 (1995) 11c-28c

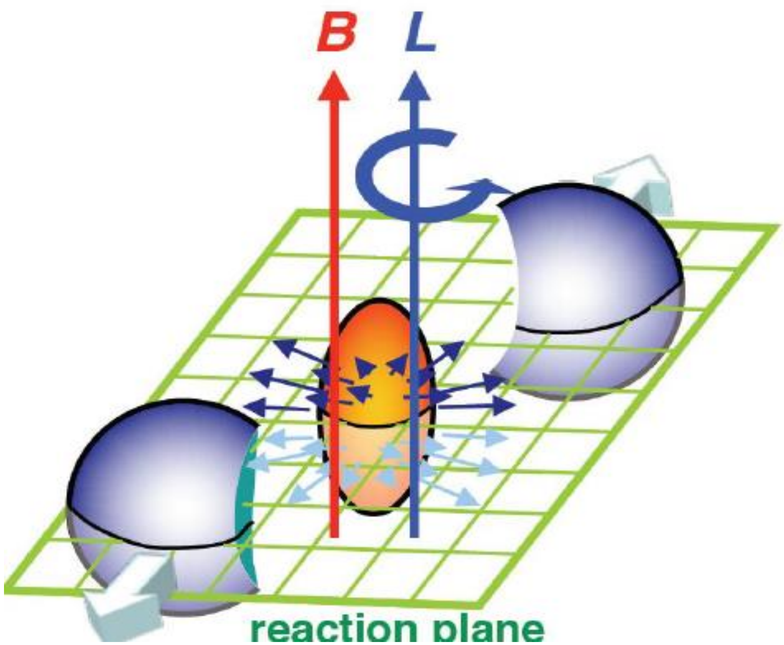
RHIC and QCD: an overview

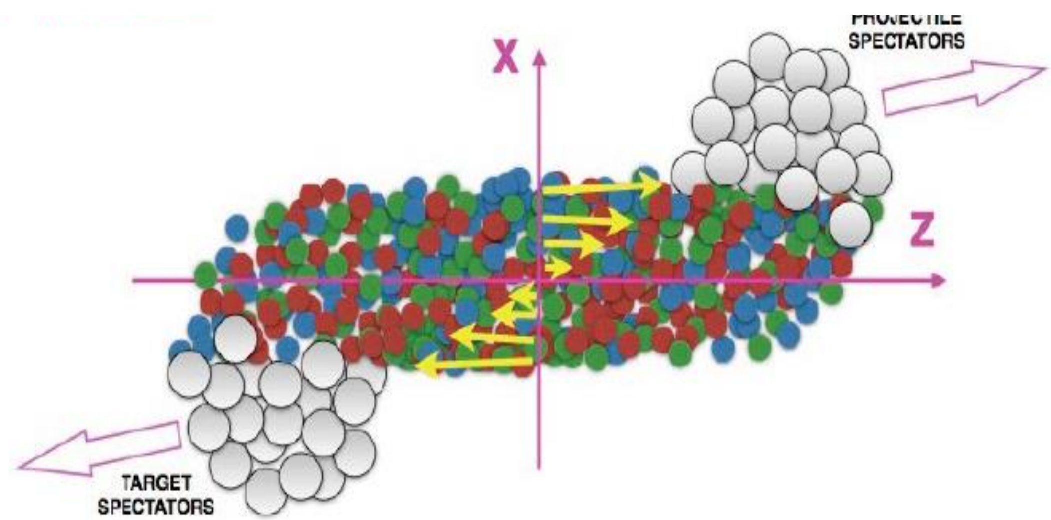
T. D. Lee

Columbia University, New York, N.Y. 10027

In this talk I would like to give an overview of the centra
Relativistic Heavy Ion Collisions and Quantum Chromodyna

A brief history for spin polarization





The earlier but very pioneering work:

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

Motivate the spin polarization measurements in experiments!

Spin-orbital coupling

Global polarization of quarks

Polarization of final hadron (recombination/fragmentation)

Global polarization measurements in heavy ion collisions

'self-analyzing' of hyperon

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

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)$$

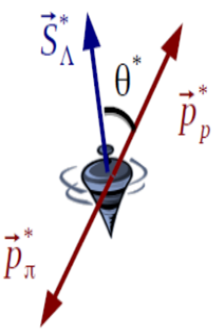
P_H: Λ polarization

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



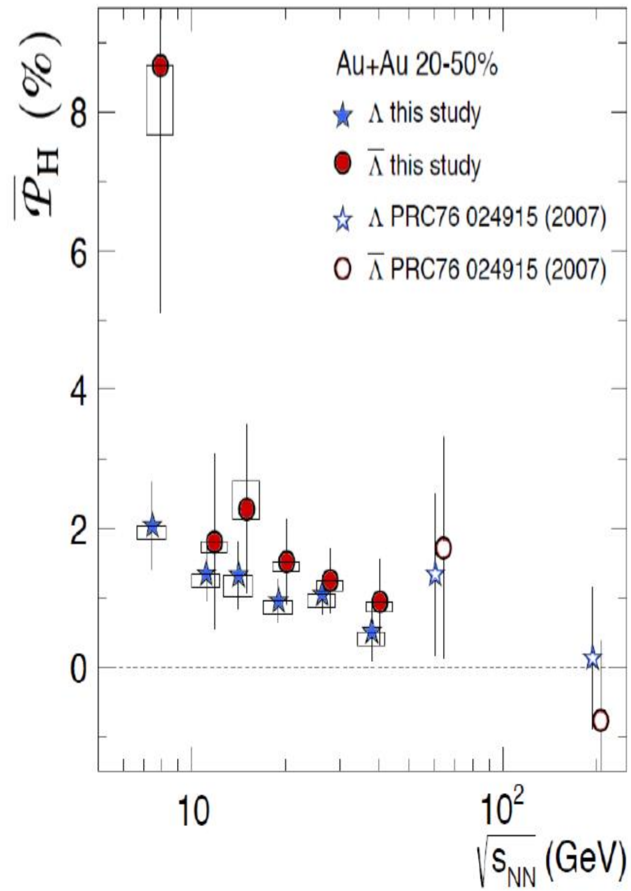
$$\Lambda \to p + \pi^-$$

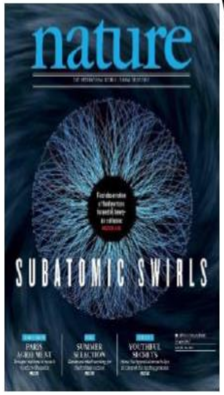
(BR: 63.9%, cτ~7.9 cm)

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 polarization within the statistical approach

Mean spin vector with **thermal vorticity:** F. Becattini,et al, Annals Phys. 338, 32 (2013）

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

obtained with density operator with

$$\widehat{\rho}_{\rm LE} = \frac{1}{Z}\exp[-\beta(x)_\mu\widehat{P}^\mu + \frac{1}{2}(\partial_\mu\beta_\nu(x) - \partial_\nu\beta_\mu(x))\widehat{J}^{\mu\nu}_x + \ldots]$$

thermal vorticity:

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

Spin Polarization within hydrodynamics

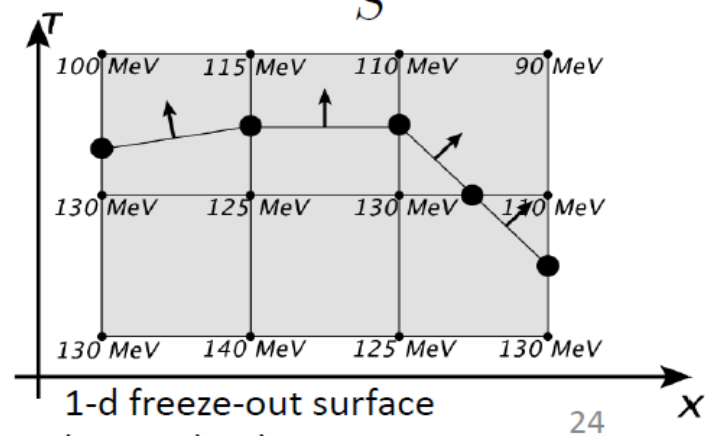
Mean spin vector with **thermal vorticity:** F. Becattini,et al, Annals Phys. 338, 32 (2013)

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

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

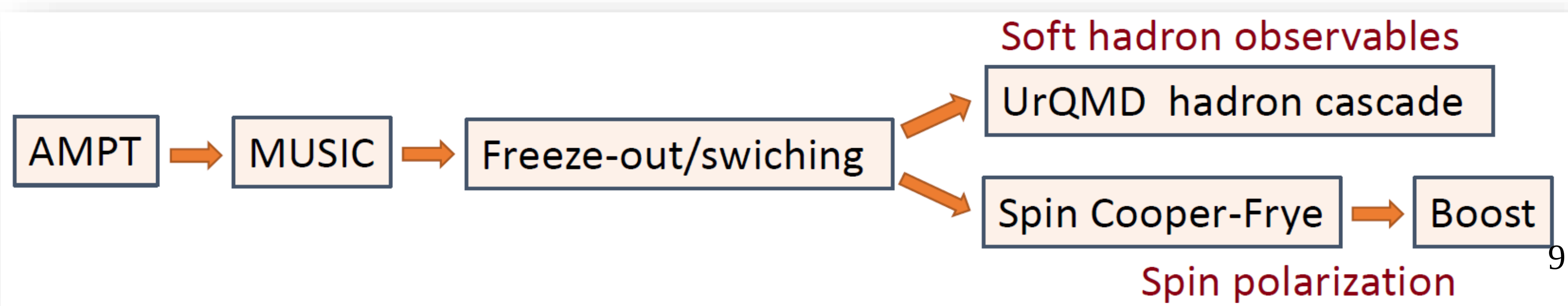
Spin polarization within hydrodynamics (Spin Cooper-Fryer):

$$P^\mu(p) = \frac{\int d\Sigma_\nu p^\nu f(x,p)P^\mu(x,p)}{\int d\Sigma_\nu p^\nu f(x,p)} \qquad P^\mu(x,p) = \frac{1}{S}S^\mu(x,p)$$



Boost to particle rest frame:

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



Spin Polarization within hydrodynamics

Spin vector with thermal vorticity: F. Becattini,et al, Annals Phys. 338, 32 (2013）

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

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

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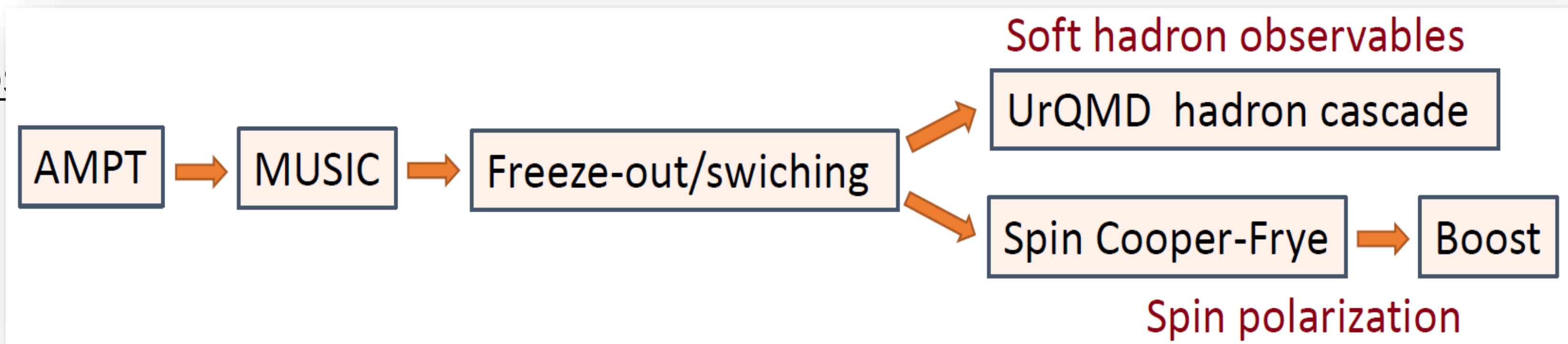
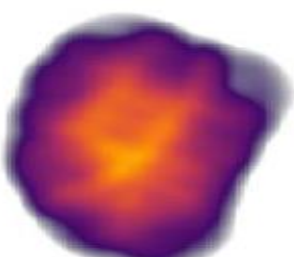
Boo



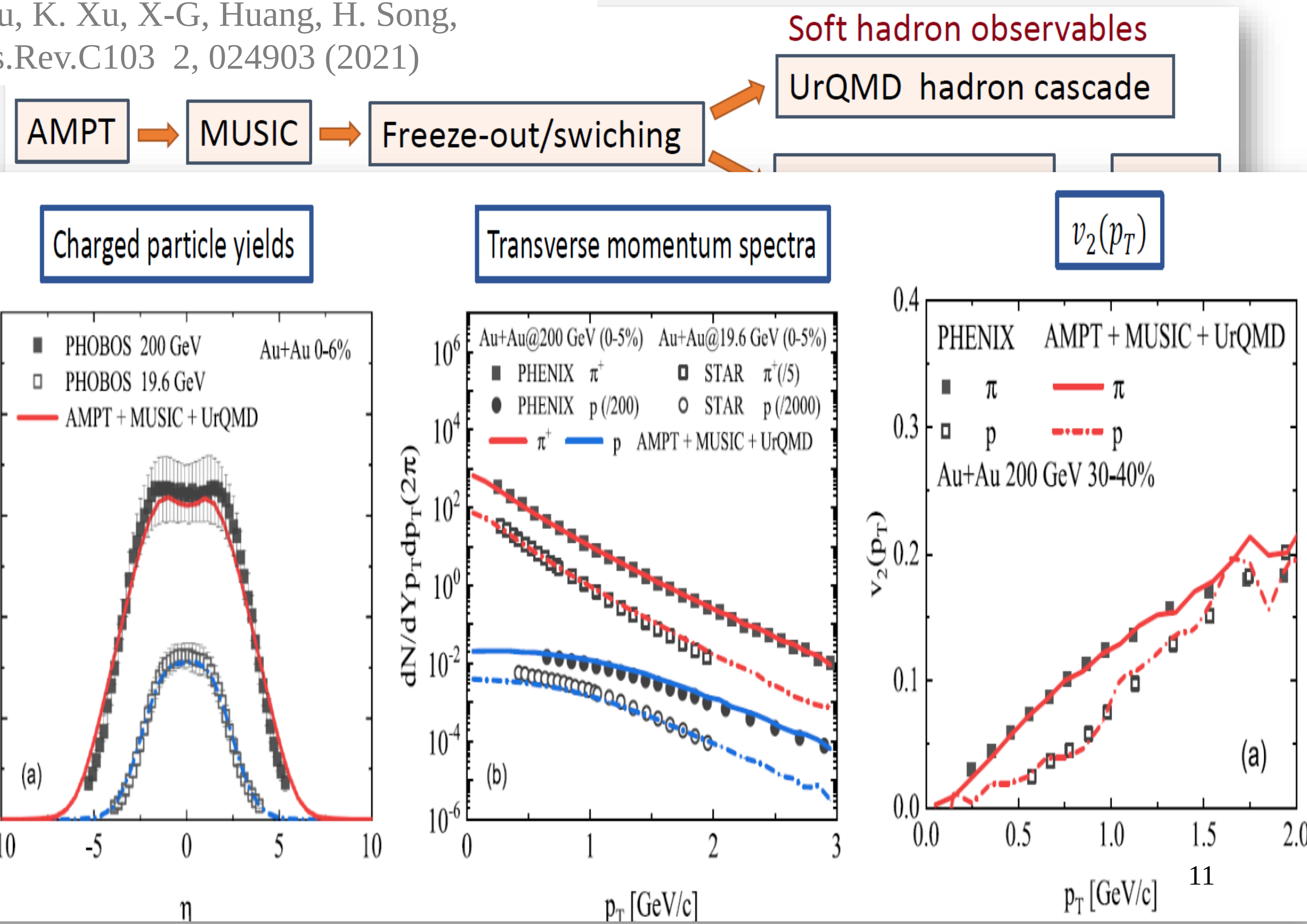


velocity fields: $u_\mu(x)$ → Collective flow

velocity gradients (vorticity) $\partial_\mu u_\nu(x)$ → Spin polarization

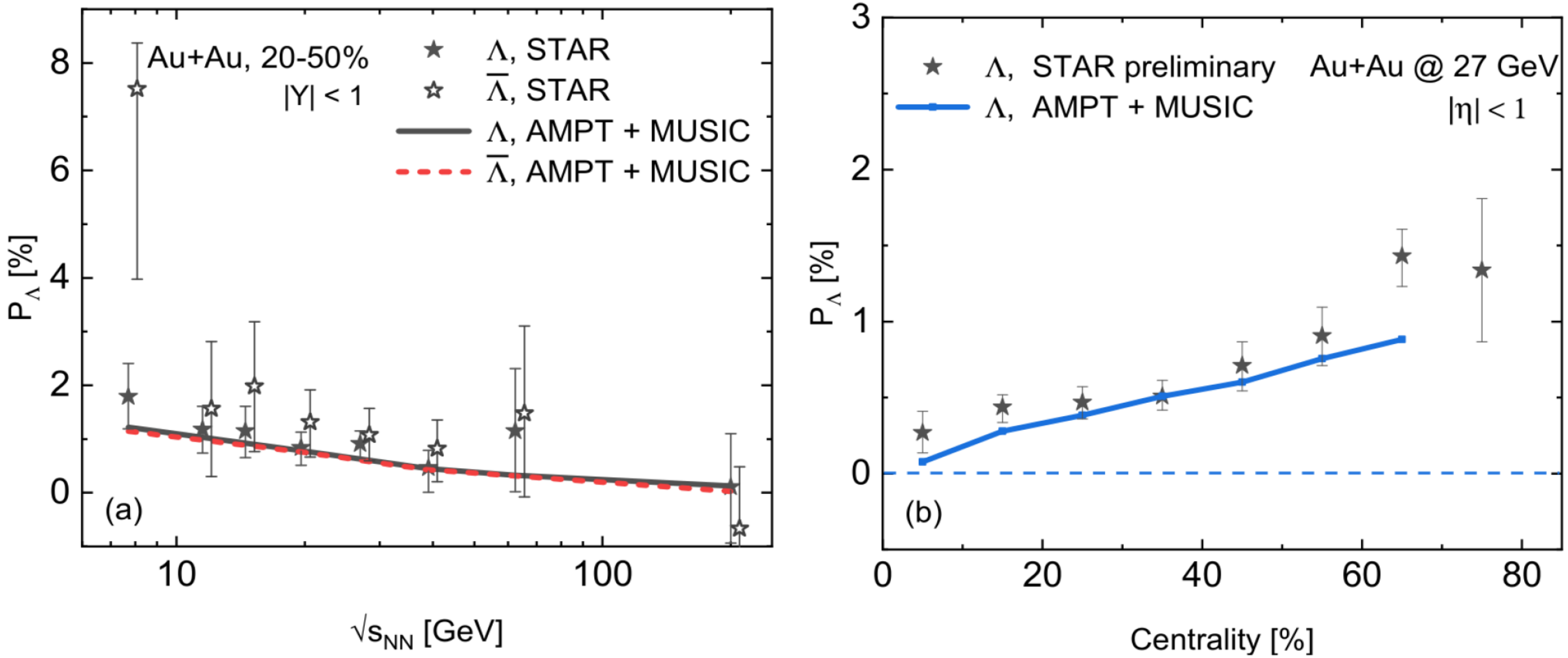
Calibrated hydro for polarization study

B. Fu, K. Xu, X-G, Huang, H. Song,
Phys.Rev.C103 2, 024903 (2021)



Global Λ Polarization with thermal vorticity

B. Fu, K. Xu, X-G, Huang, H. Song, Phys.Rev.C103 2, 024903 (2021)



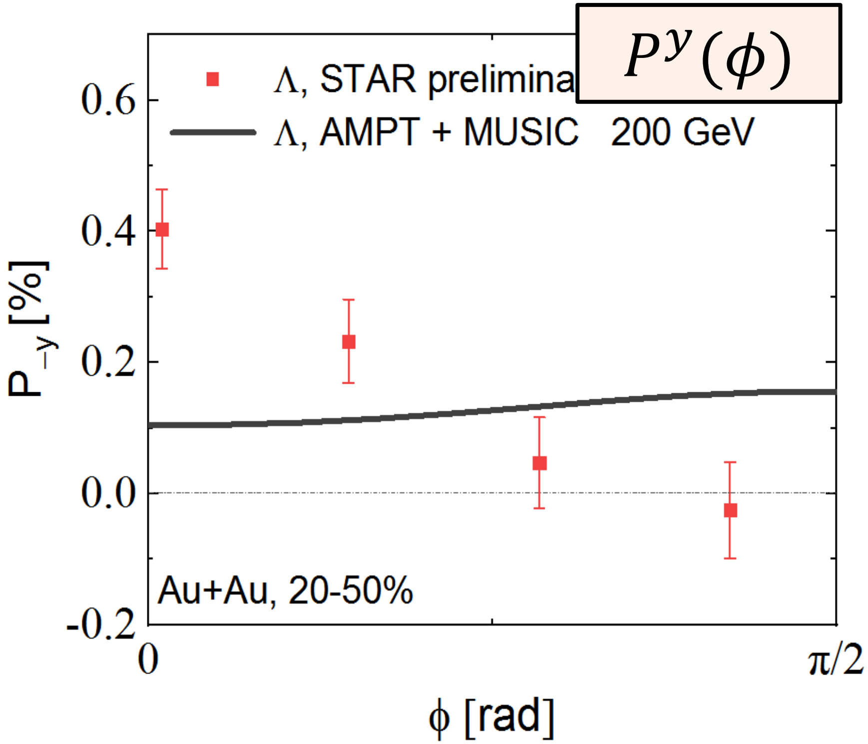
$$P^\mu = \langle P^\mu(p) \rangle = \frac{\int \frac{d^3p}{E} \int d\Sigma_\nu p^\nu f(x,p) P^\mu(x,p)}{\int \frac{d^3p}{E} \int d\Sigma_\nu p^\nu f(x,p)}$$

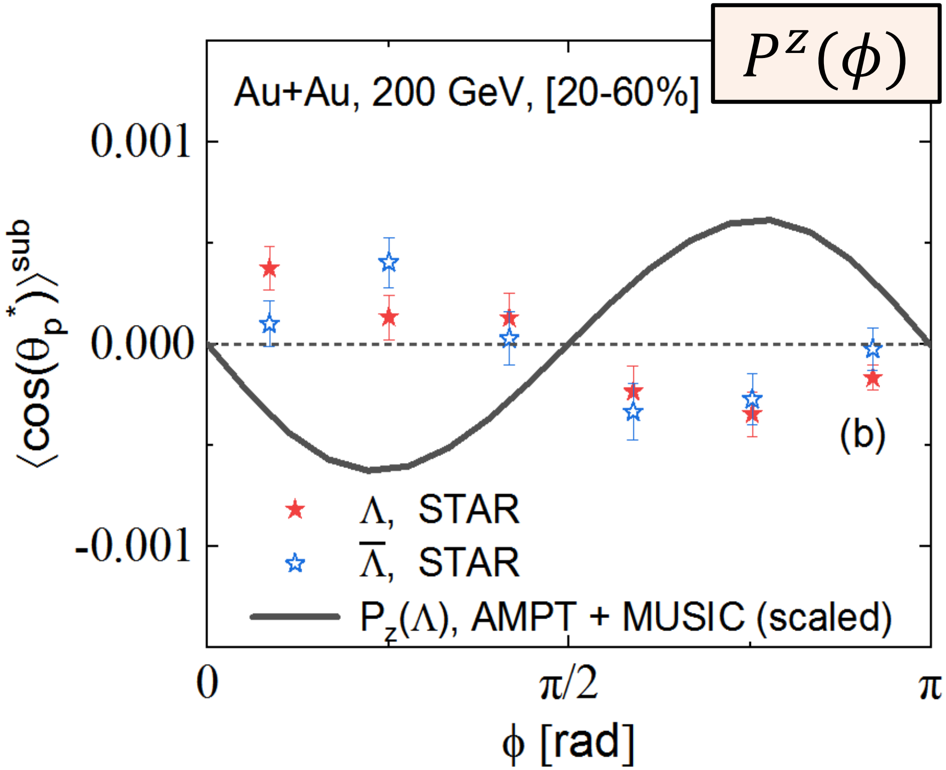
-Decrease with the collision energy; increase with centrality;

-Roughly describe the data within error bars

Local Λ Polarization puzzle with thermal vorticity

B. Fu, K. Xu, X-G, Huang, H. Song, Phys.Rev.C103 2, 024903 (2021)





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

-Local Λ Polarization 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

Efforts to Solve the Local Polarization Puzzle

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

[no obvious effects]

Other spin chemical potential (Wu, Pang, Huang, Wang, PRR 2019) **[extra assumption]**

Polarization from projected thermal vorticity (Florkowski, Kumar, Ryblewski, Mazeliauskas, PRC 2019) **[extra assumption]**

Side-jump in CKT (Liu, Ko, Sun, PRL 2019) **[massless limit/ extra assumption]**

Spin as a dynamical d.o.f: **[under development]**

- 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)

… … … …

Shear induced polarization
& the Local polarization puzzle

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

Re-evaluate mean spin vector

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

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

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

Hydrodynamic gradients

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

Anti-symmetric: vorticity

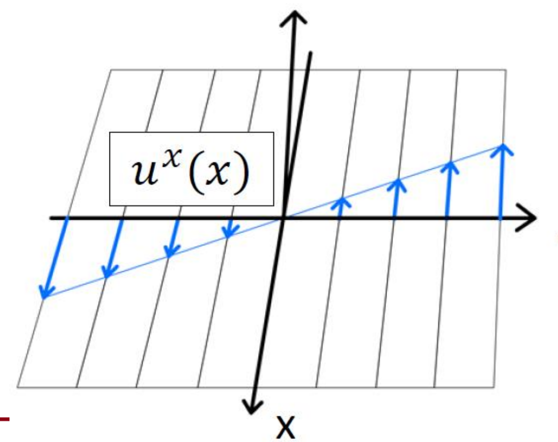
$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\partial^\perp_\alpha u_\beta$$

→ Traditional mean spin vector

Symmetric: shear stress

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

→ ?



[Strain induced polarization]
In crystal physics:

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

Shear Induced Polarization

B. Fu, S. Liu, L. -G. 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 $\mathcal{A}^\mu$ to 1st order gradient of the fields:

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

Vorticity — T gradient — Shear（SIP）

-Identical form by linear response theory with arbitrary mass

S.Y.F.Liu and Y.Yin, JHEP07, 188 (2021).

-No free parameter

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

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

-Different mass sensitivity of each term

Shear Induced Polarization

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

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

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Vorticity — T gradient — Shear (SIP)

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

using ideal hydro eqn:

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

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

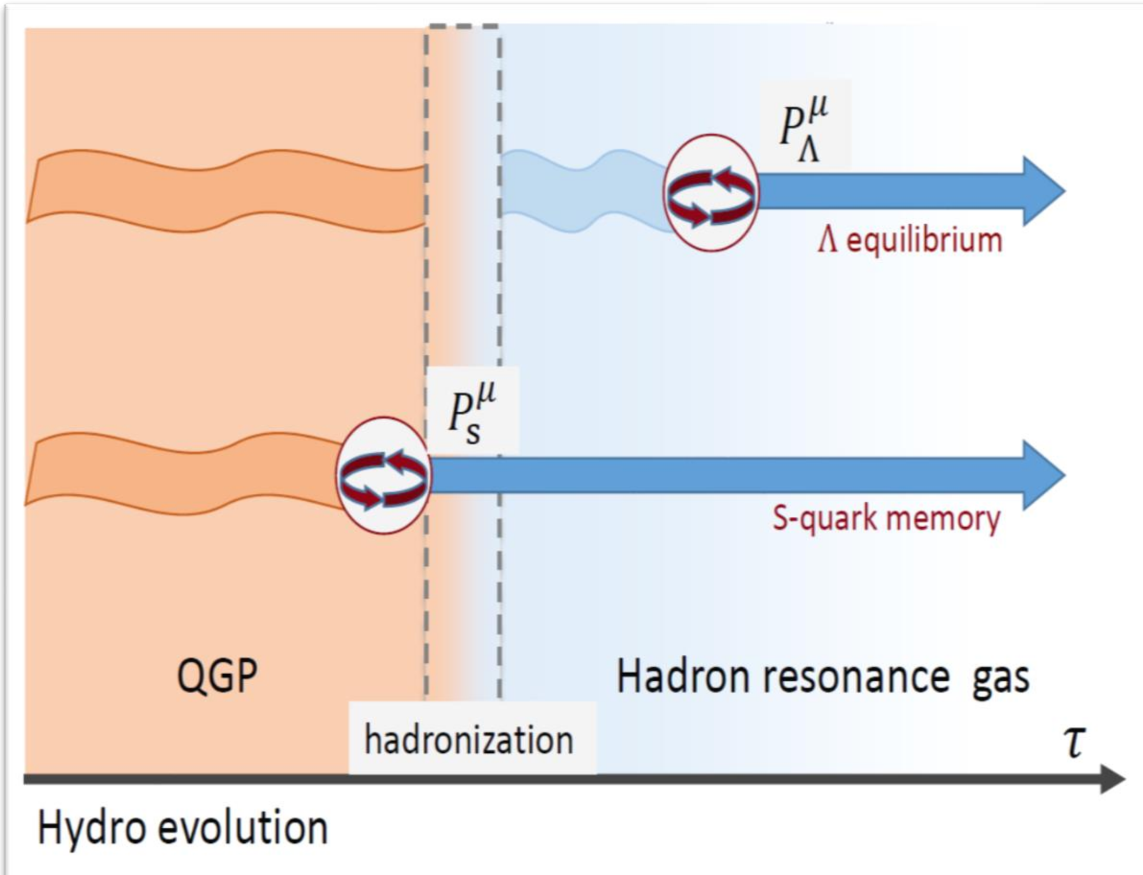
Total P^μ = [Vorticity] + [T gradient] + [Shear]

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

The only new effect

'Λ equilibrium' vs. 'S-quark memory'

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



'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

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

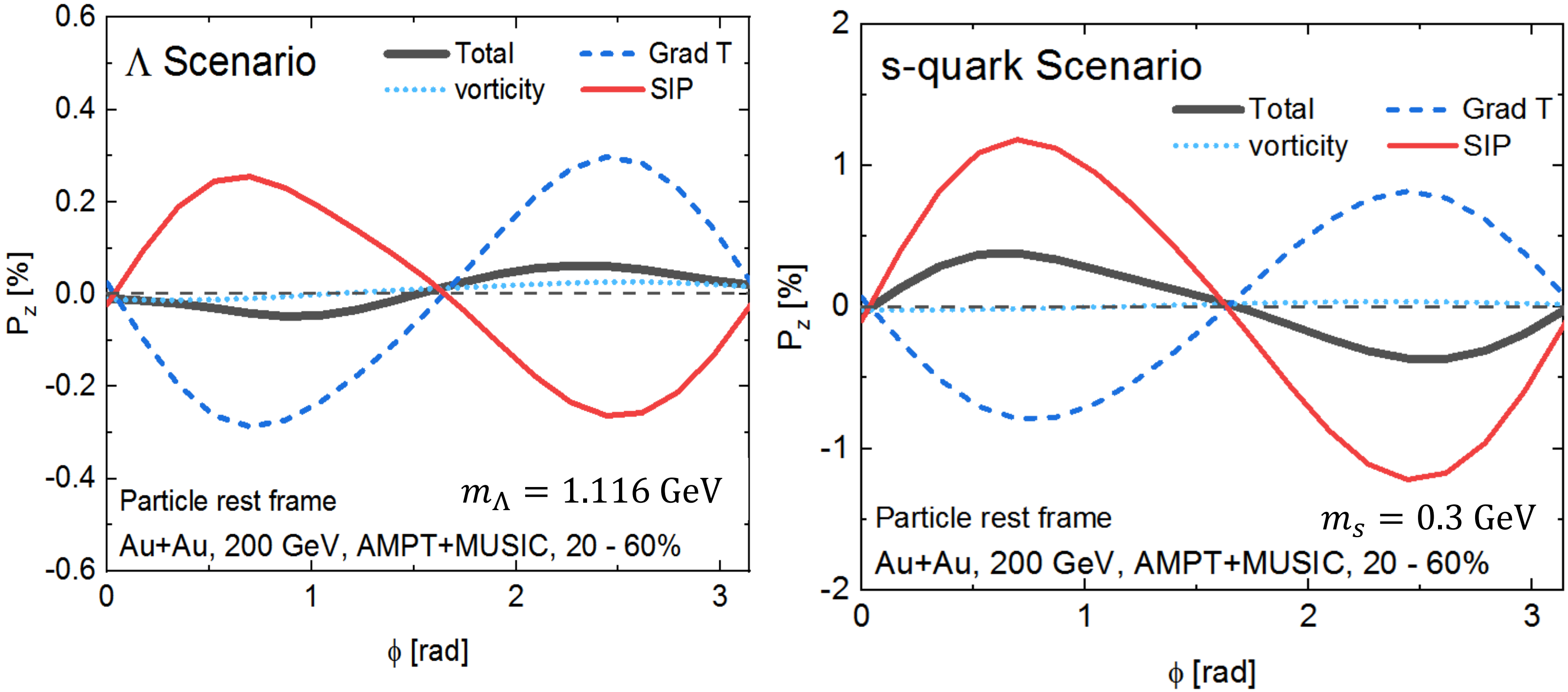
Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301

Spin polarization on the freeze-out surface

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

$P_z(\phi)$: competition between T-gradient and shear (SIP) effects

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



Total P^μ = Vorticity + T gradient + Shear (SIP) = **Thermal vorticity** + **Shear effects**

-[Vorticity] ~ 0

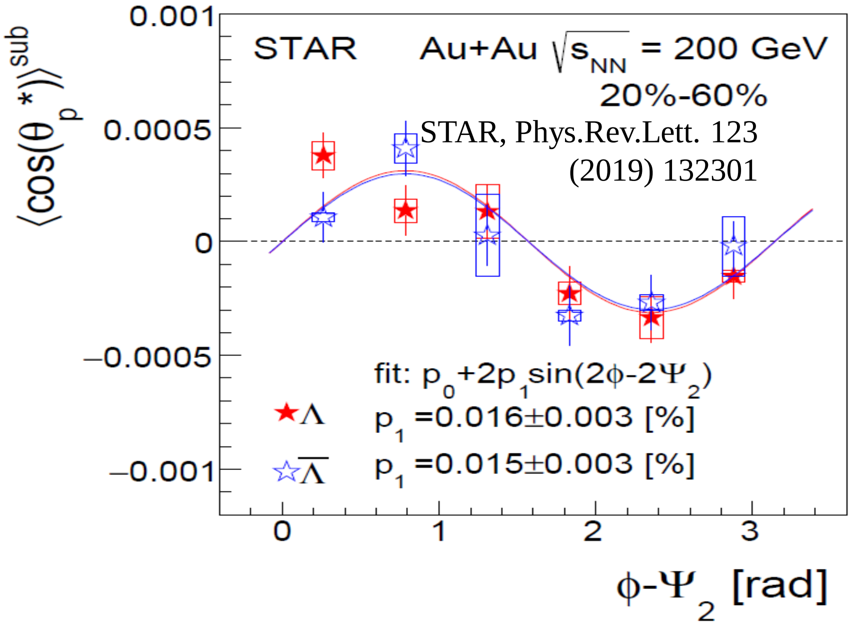
-[SIP] and [T Grad] show similar magnitude but opposite sign

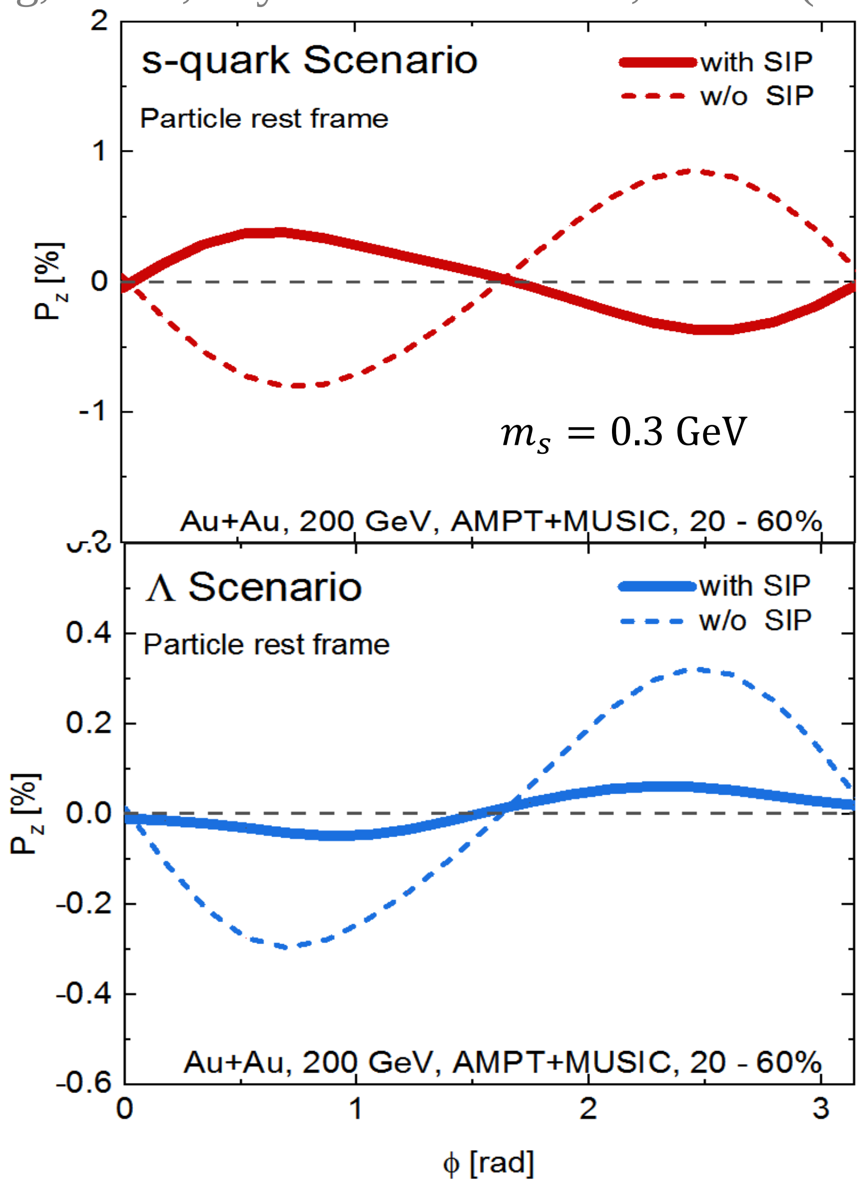
❖ Competition between

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

Compare with exp data: $P_z(\phi)$ with & without SIP

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



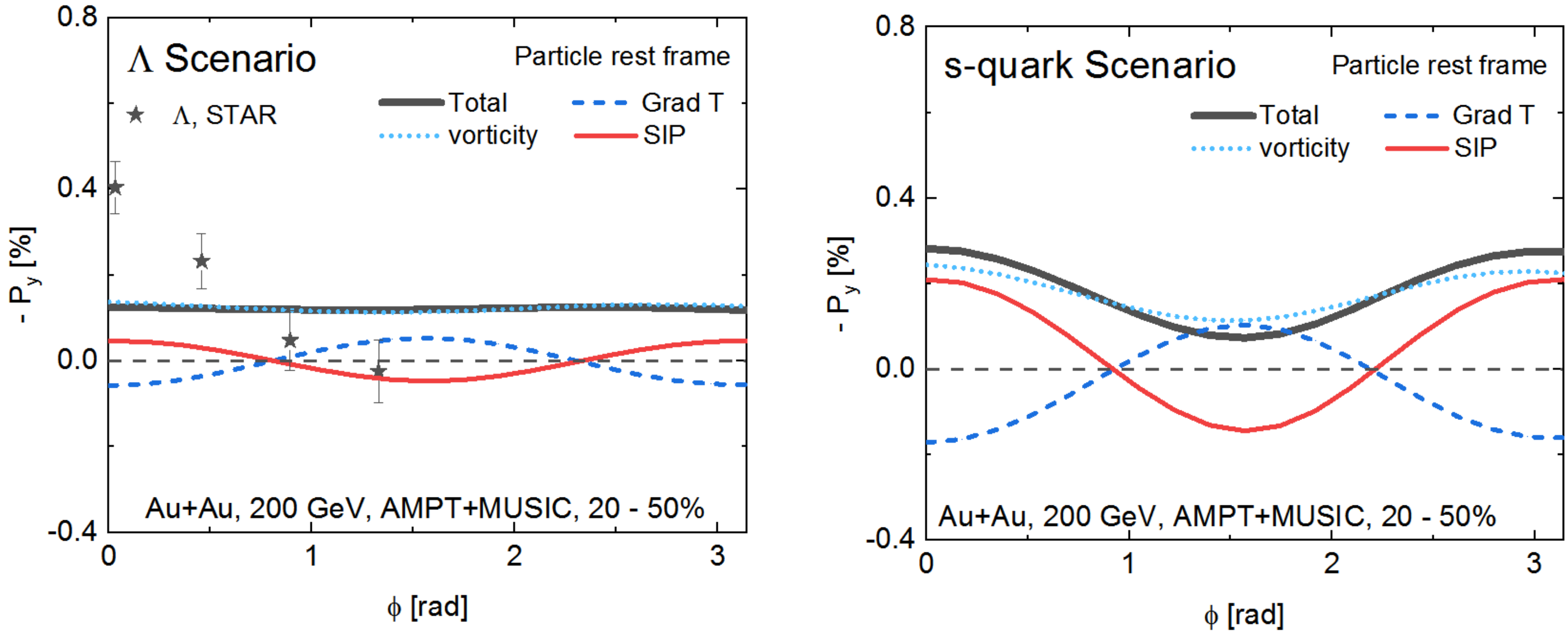


Total P^μ
=**Thermal vorticity** + **Shear effects**

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

$P_y(\phi)$: competition between T-gradient and shear (SIP) effects

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



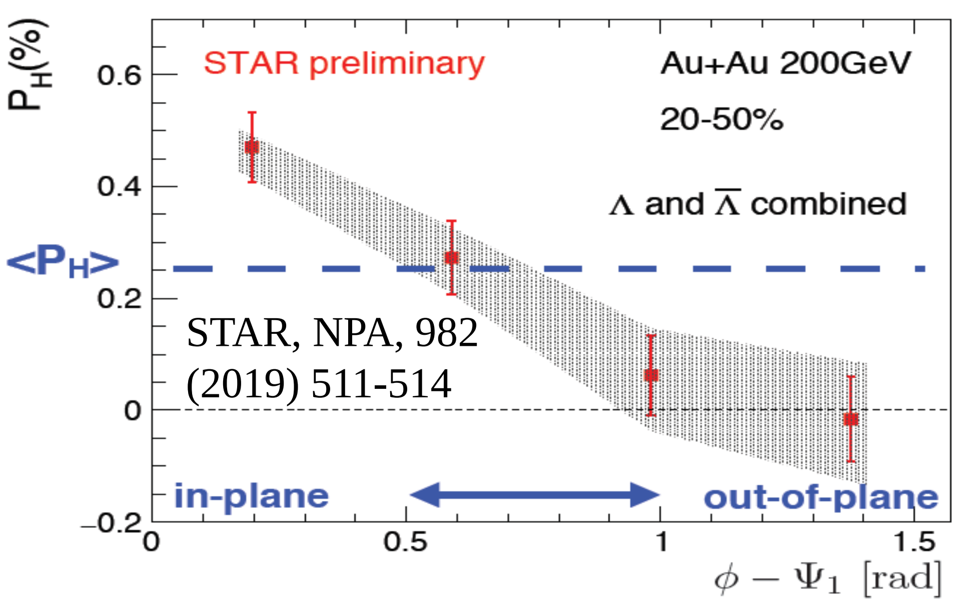
Total P^{μ} = Vorticity + T gradient + Shear (SIP) =**Thermal vorticity** + **Shear effects**

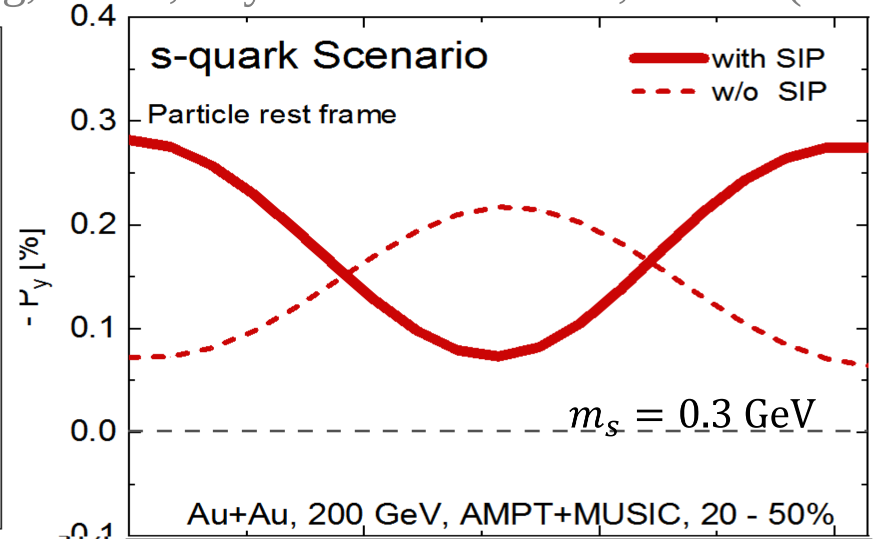
-[Vorticity]: dominant, contribute most to the global polarization

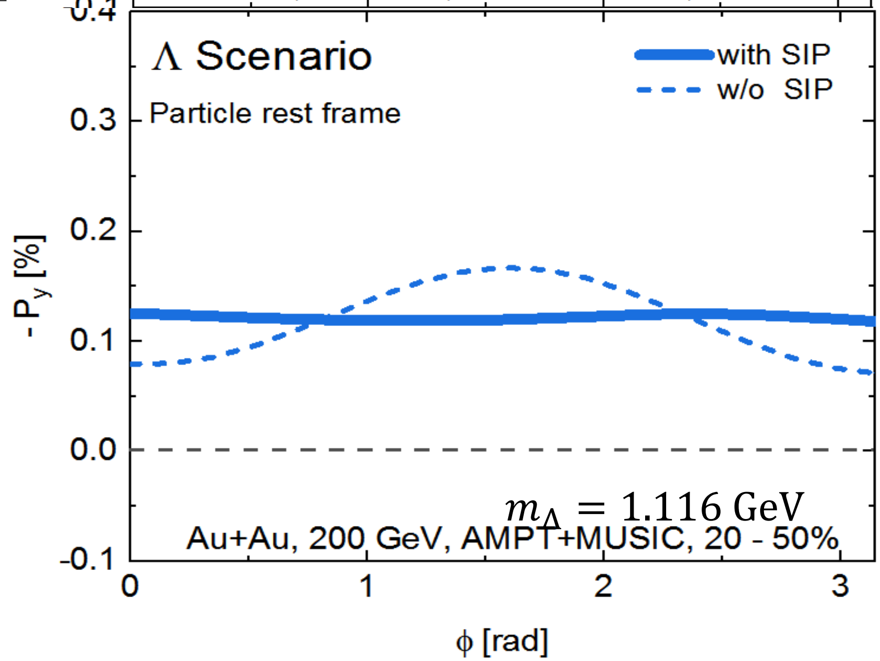
-[SIP] and [T Grad] show similar magnitude but opposite sign

Compare with exp data: $P_y(\phi)$ with & without SIP

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







Total P^μ
=**Thermal vorticity** + **Shear effects**

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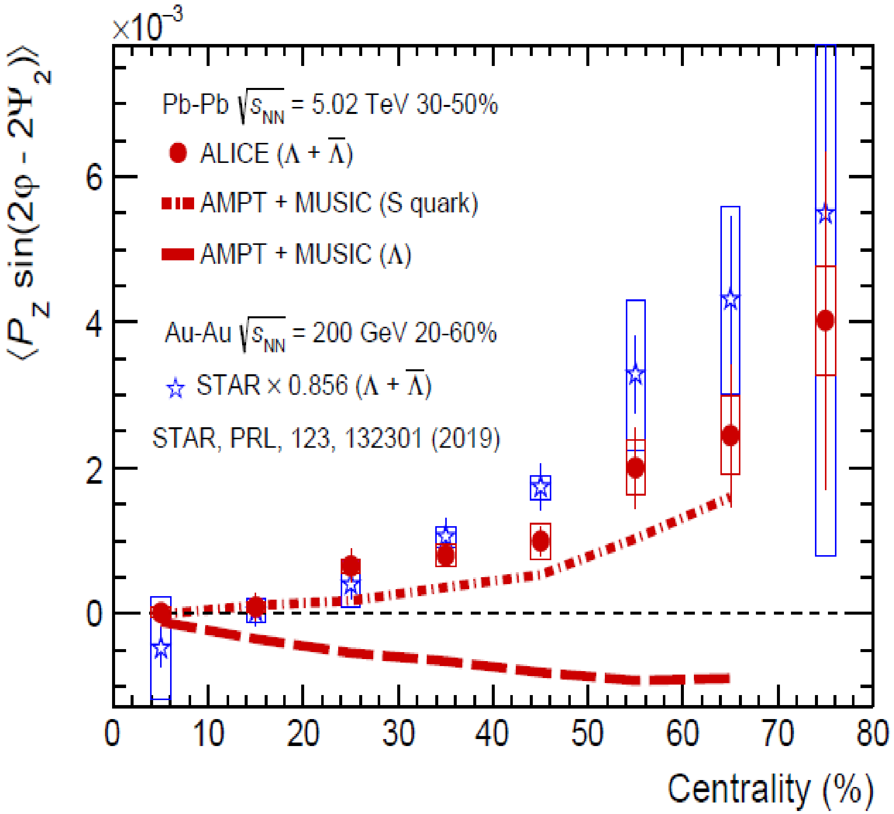
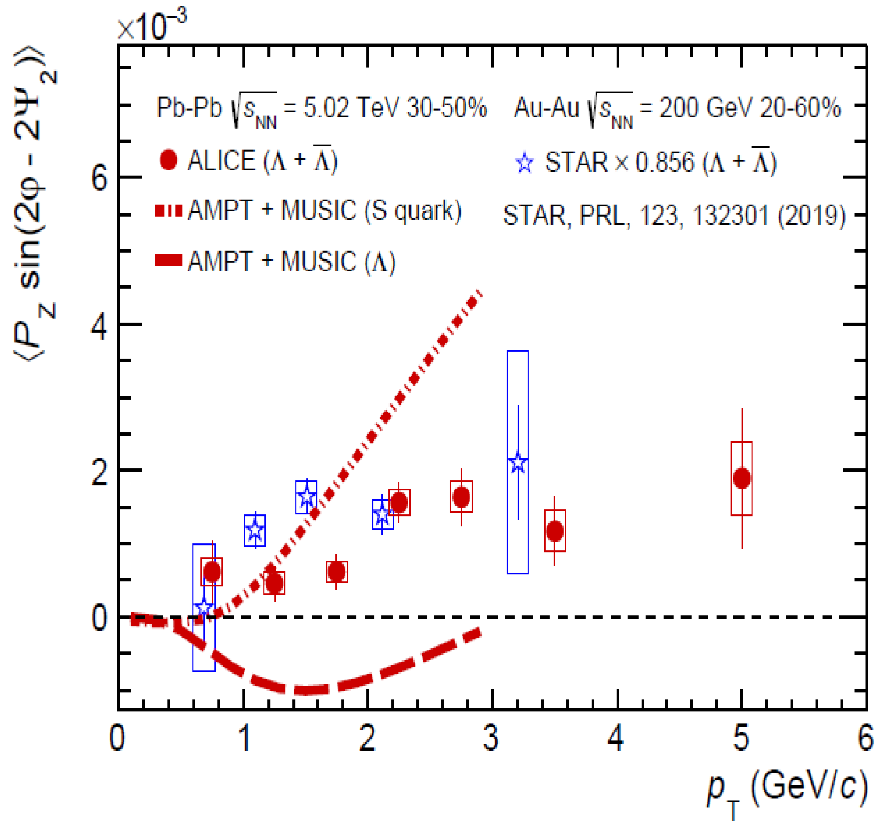
The 2nd order Fourier sine coefficients of P_z



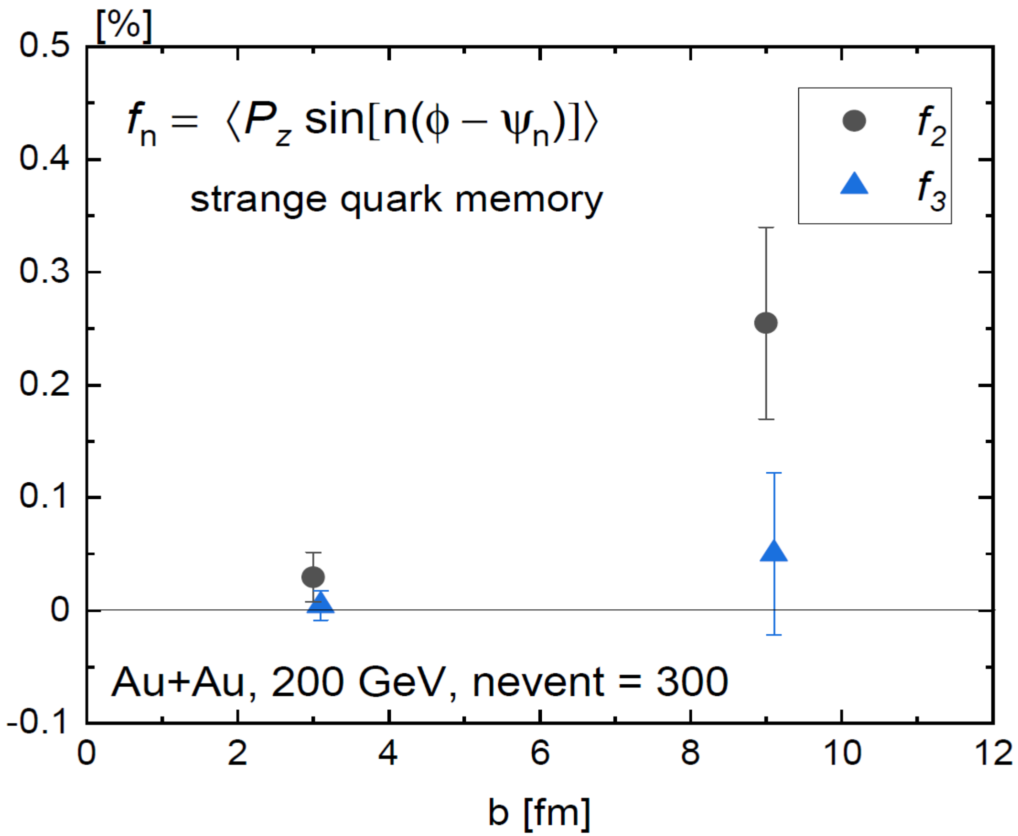


-For the 2nd order Fourier since coefficients of P_Z(centrality dependence & p_T dependence), Model calculations with shear (SIP) effects qualitatively agrees with data with the scenario of 'S-quark memory',

Figs are from [ALICE], arXiv:2107.11183 [nucl-ex]

AMPT+MUSIC results are from B.Fu & H.Song (private comm.), paper in preparation.

Prediction of the 3rd order Fourier coefficients of P_z



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

-Model calculations with shear (SIP) effects in 'S-quark memory scenario using event-by-event AMPT+MUSIC

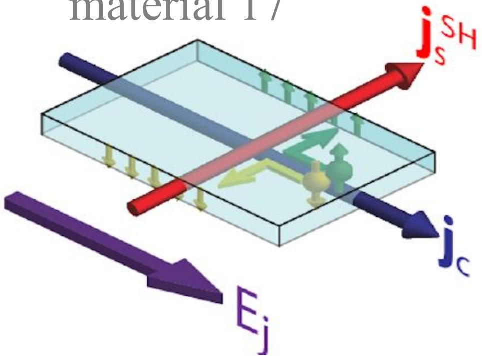
Spin Hall effects at RHIC BES

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

Spin Hall Effects (SHE)

SHE in condense matter $\vec{s} \propto \vec{v} \times \vec{E}$

Meyer et al, Nature material 17'



-induced by electric filed; theory behind **QED**

-A hot research area in spintronics

-observed in various materials (semi-conductors, metals, insulators); not exceeding room temperature

J. Sinova Rev. Mod. Phys. **87**, 1213 (2015)

Spin Hall Effects (SHE)

SHE in condense matter $\vec{s} \propto \vec{v} \times \vec{E}$

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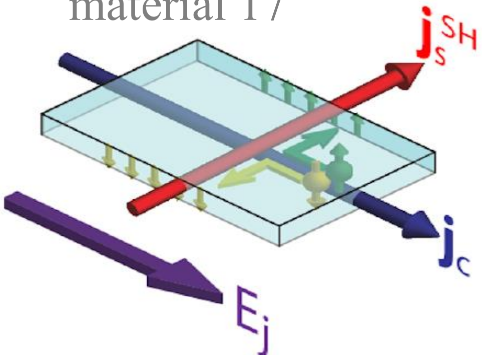


J. Sinova Rev. Mod. Phys. **87**, 1213 (2015)

SHE for hot **QCD** matter $\vec{P}_{\pm} \propto \pm \hat{p} \times \nabla \mu_B$

-induced by baryon density gradient; theory behind **QCD**

-Another Mechanism for spin polarization

Spin polarization:

- Thermal vorticity — F. Becattini,et al, Annals Phys(2013） & may hydro & Transport papers
- Shear induced polarization — Fu, et al PRL2021. Liu & Yin JHEP2021; Becattini, et al PLB2021, 2103.14621 & others
- Spin Hall effects(SHE) have not been fully explored

Spin Hall Effects in Heavy Ion Collisions

Can we observe and explore SHE in heavy ion collisions ?

SHE for hot **QCD** matter $\vec{P}_{\pm} \propto \pm \hat{p} \times \nabla \mu_B$

- -Induced by baryon density gradient ⟶ RHIC –BES & forward rapidity
- -Sign dependence on baryon charge ⟶ Net Lambda Polarization
- -Momentum dependence ⟶ Local polarization

(For global polarization, see arXiv:2106.08125)

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

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

-Λ, + $\bar{\Lambda}$
-s, + $\bar{s}$

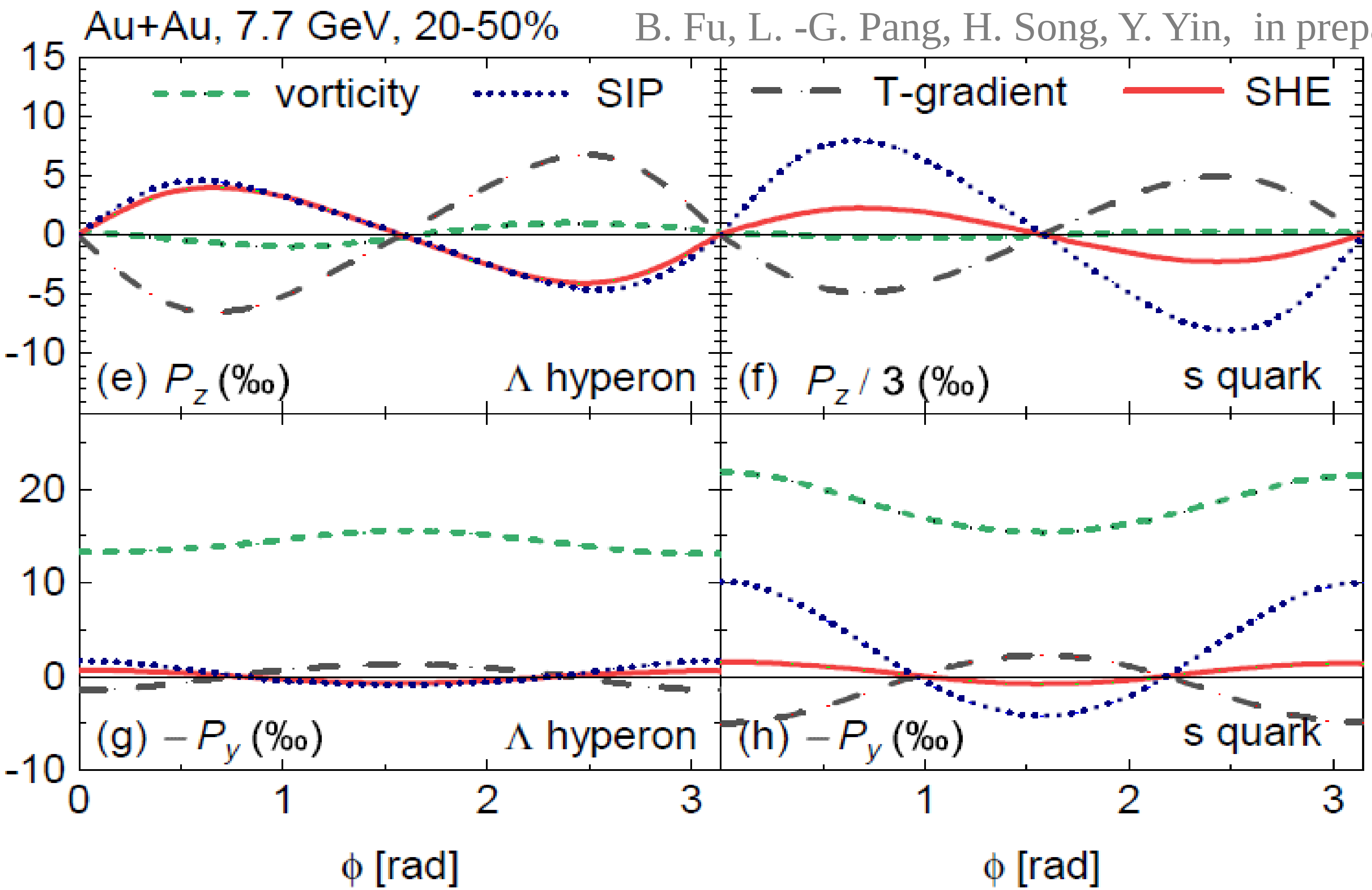
Spin Cooper-Fryer:

$$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x,\boldsymbol{p};m)}{2m \int d\Sigma^\alpha p_\alpha f_0(x,p)},$$

S. Y. F.Liu and Y. Yin, JHEP07, 188 (2021); *Phys.Rev.D* 104 5, 054043(2021);
B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

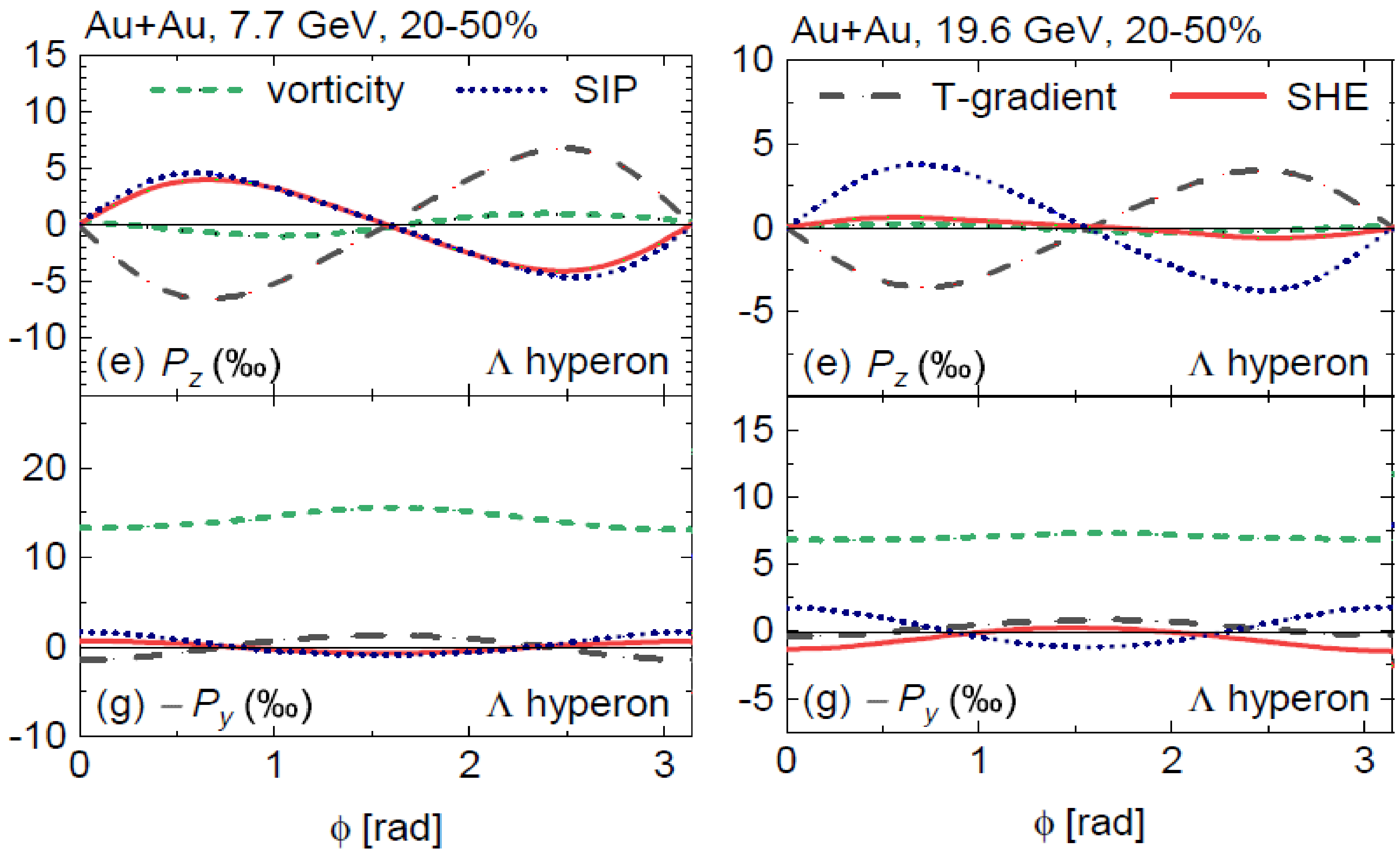
Competition between different effects

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.



-SHE(μ_B gradient effects): comparable to T-gradient and Shear (SIP) effects

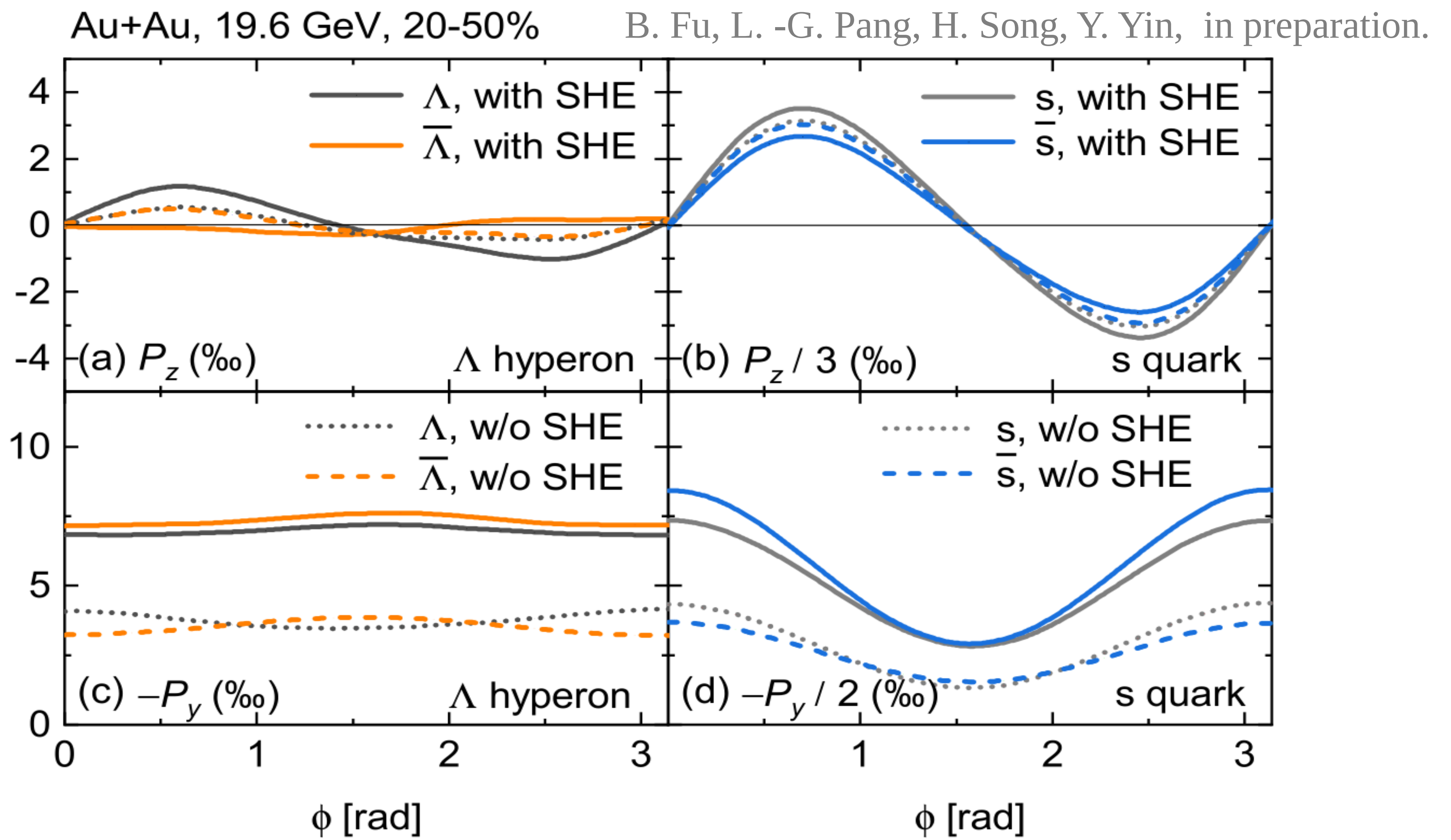
Competition between different effects



-SHE(μ_B gradient effects): comparable to T-gradient and Shear (SIP) effects

depends on collision energy

$P_z(\phi)$ and $P_y(\phi)$ without / with SHE

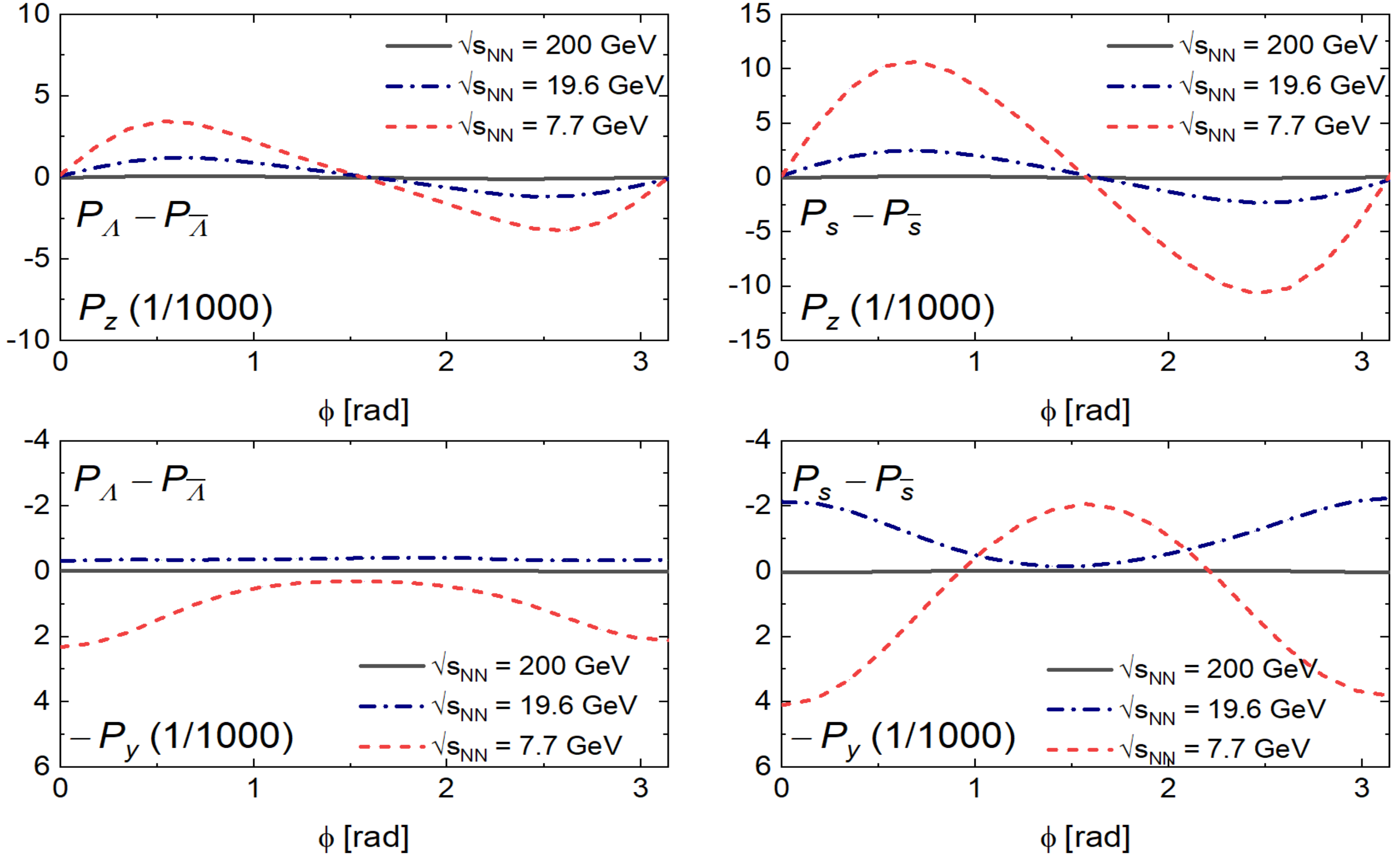


-SHE: different sign for baryon and anti-baryon

leading to separation between local polarization of Λ & $\bar{\Lambda}$ (s & $\bar{s}$)

$P_z(\phi)$ and $P_y(\phi)$ for net Λ and net s

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

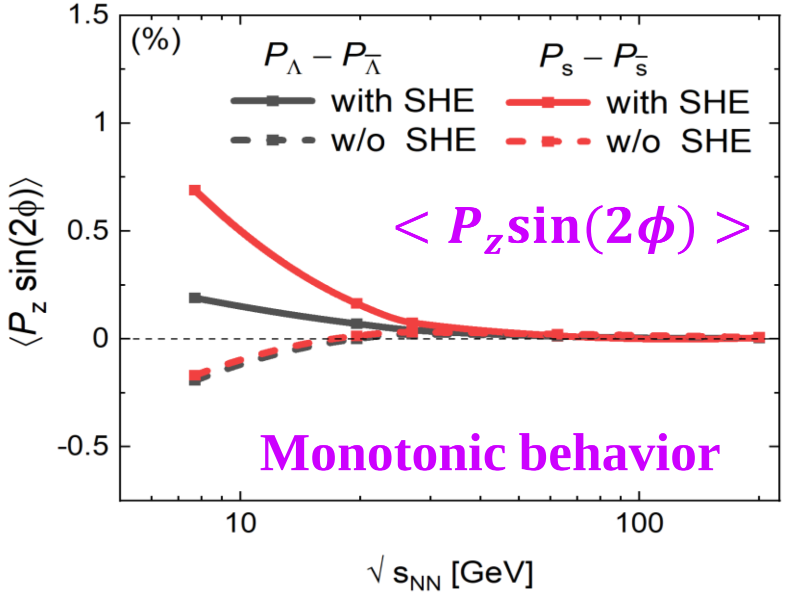


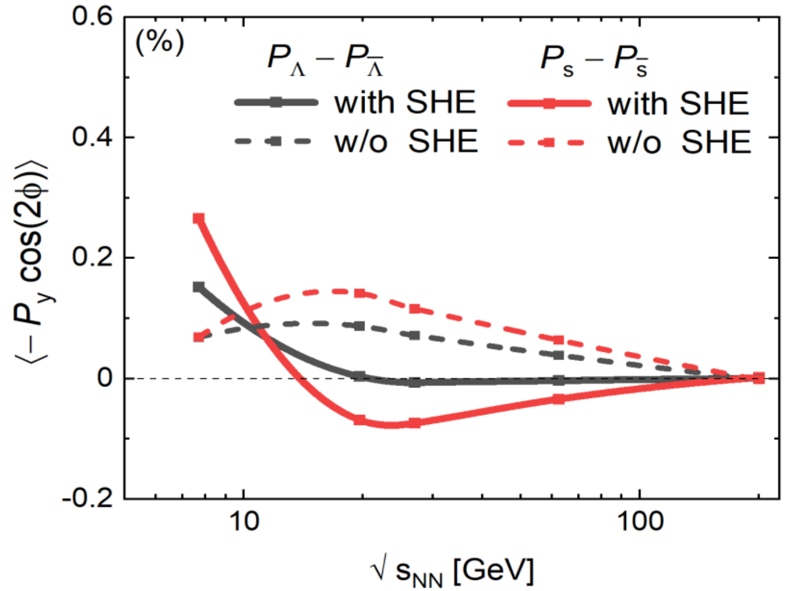
- $P_z(\Phi)$: larger SHE effects at lower collision energy

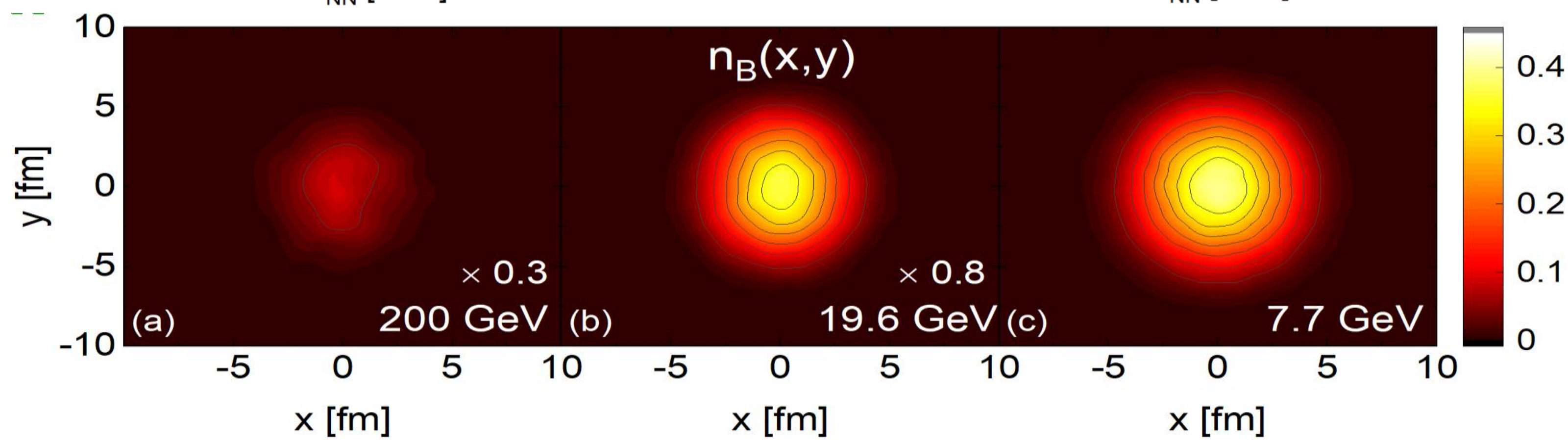
-$P_y(\Phi)$: different Φ dependent behavior at 7.7 & 19.6 GeV due to SHE

2^{nd} order Fourier coeff. of P_z and P_y

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.





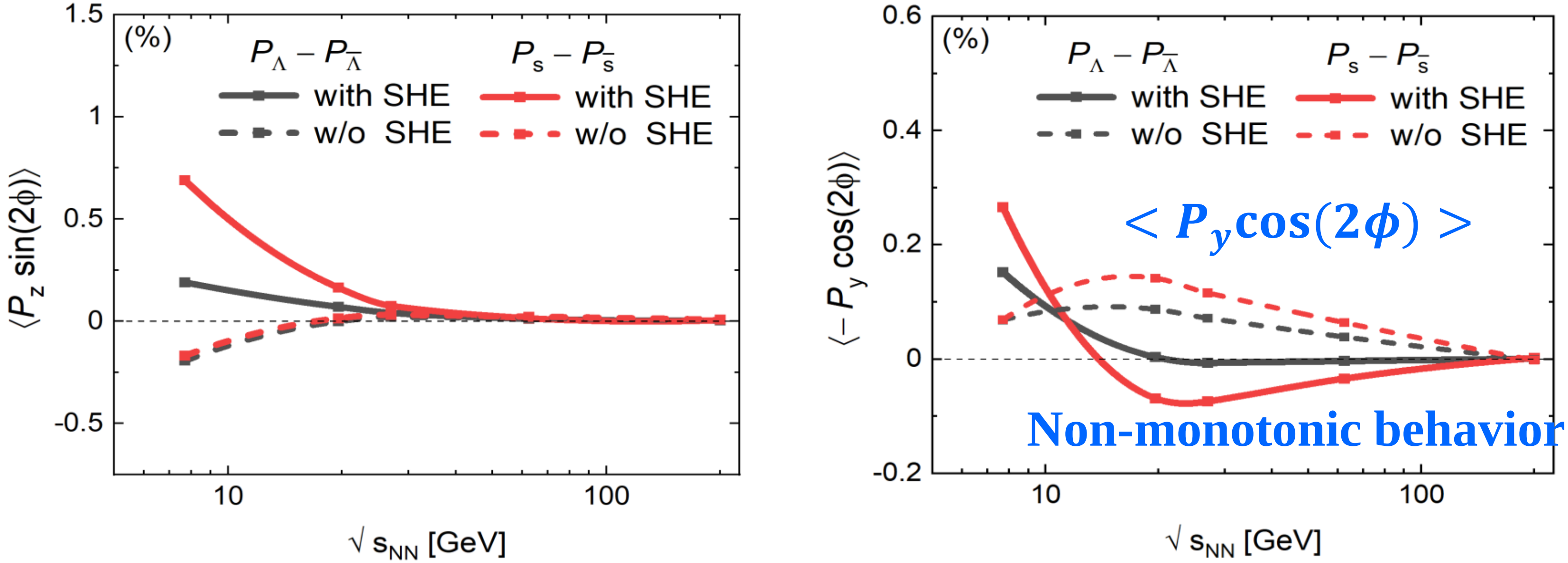


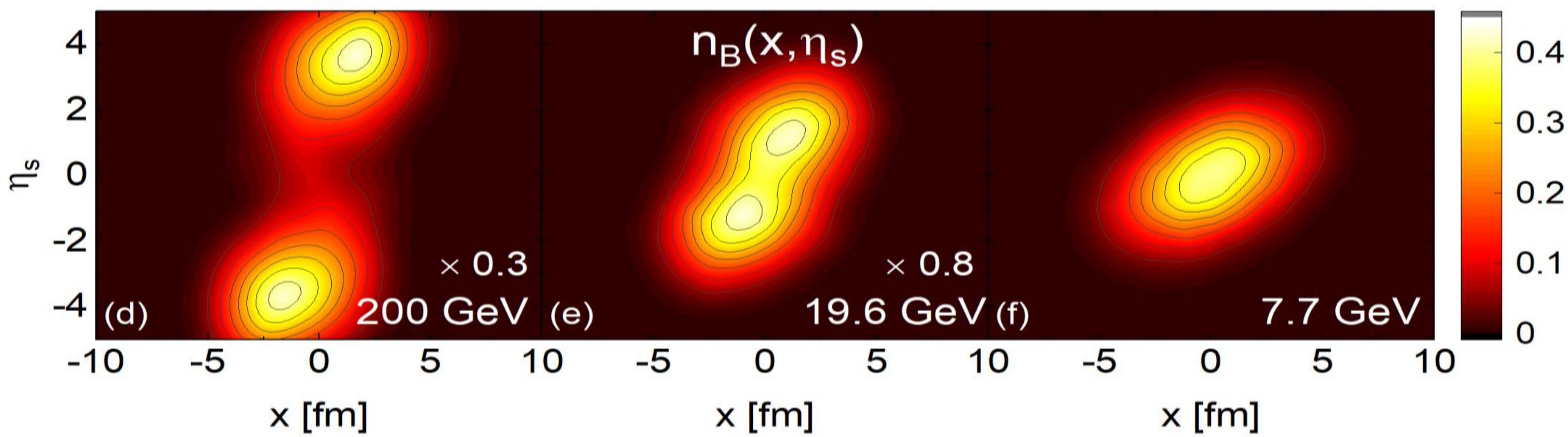
-With and without SHE: different sign for $< P_z \sin(2\phi) >$

A signal to search the SHE at RHIC-BES

2^{nd} order Fourier coeff. of P_z and P_y

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.





-With and without SHE: different sign for $< P_y \cos(2\phi) >$

Another signal to search the SHE at RHIC-BES

Comparison between Groups

Theoretical Formula with shear induced polarization

S. Y. F.Liu and Y. Yin, JHEP07, 188 (2021).

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

F.Becattini, M.Buzzegoli and A.Palermo, Phys. Lett. B 820, 136519 (2021).

F.Becattini, M.Buzzegoli, A.Palermo, G.Inghirami and I.Karpenko, arXiv:2103.14621.

Numerical Simulations & local lambada Polarization Puzzle

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

F.Becattini, M.Buzzegoli, A.Palermo, G.Inghirami and I.Karpenko, arXiv:2103.14621

Other related recent progress:

C. Yi, S. Pu and D. L. Yang, arXiv:2106.00238 [hep-ph].

Y. C. Liu and X. G. Huang, arXiv:2109.15301 [nucl-th].

Comparison between the theoretical formula

Our group: S.Y.F.Liu & Y.Yin, JHEP (2021); B. Fu, et al PRL (2021)

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

Vorticity T gradient Shear (SIP)

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

S^{μ} = Vorticity + T gradient + Shear (SIP)

=**Thermal vorticity** + **Shear effects**

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Becattini group: F.Becattini, et al, PLB(2021).

$S^\mu = S^\mu_\varpi + S^\mu_\xi$ =**Thermal vorticity** $\varpi_{\mu\nu}$ + **Thermal shear** $\xi_{\mu\nu}$ **effects**

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

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

Comparison between the theoretical formula

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

Vorticity — T gradient — Shear (SIP)

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

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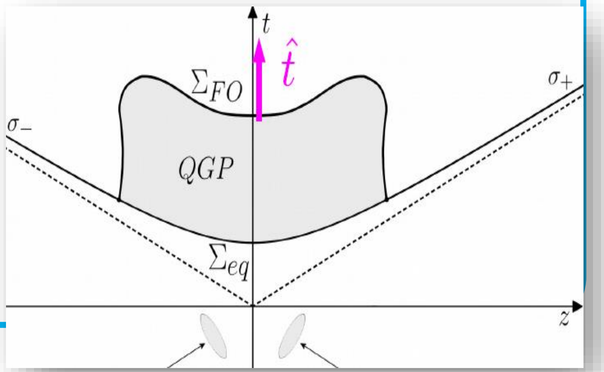


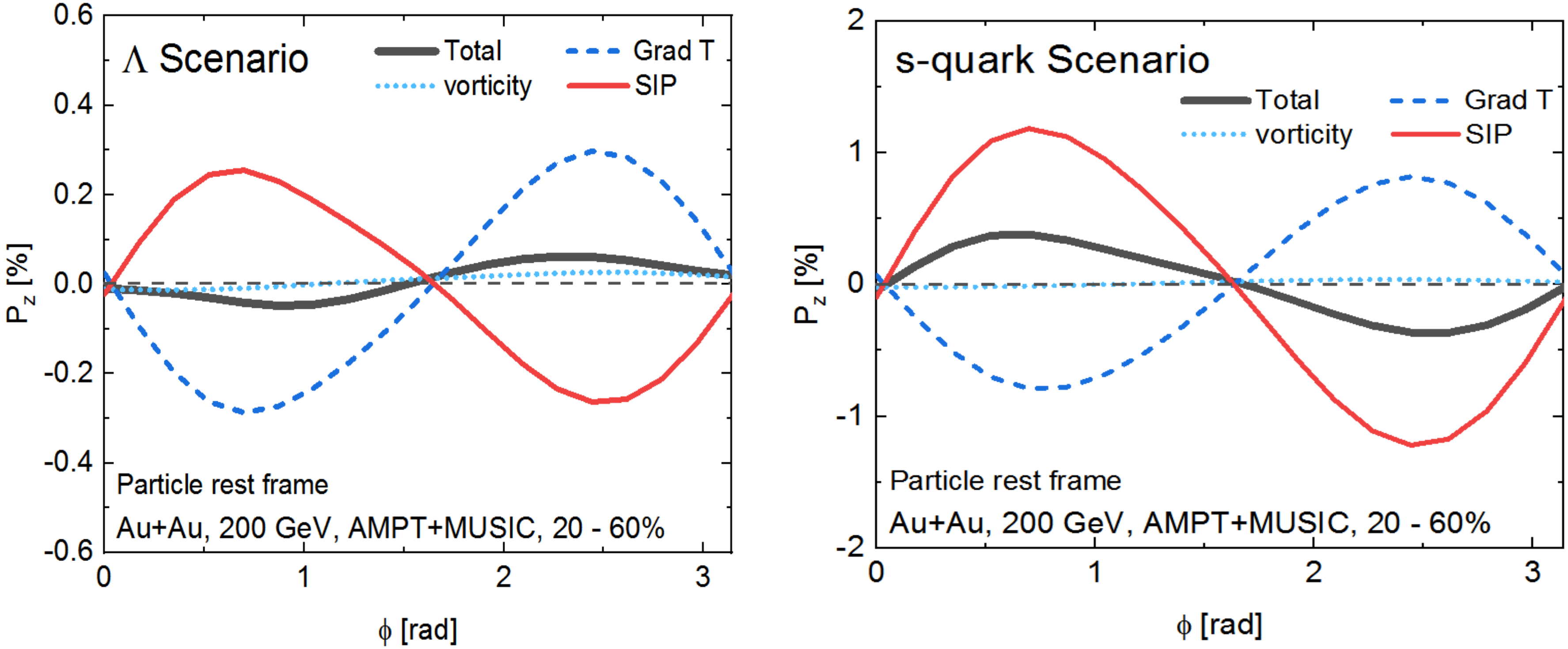
-If we change $\hat{t}_\nu \to u_\nu$ in Becattini's eqn S^μ =Thermal vorticity + Shear effects
similar but not exactly the same formula

Numerical Simulations: (our group)

Theoretical formula: S.Y.F.Liu & Y.Yin, JHEP (2021); B. Fu, et al PRL (2021)

S^{μ} = Vorticity + T gradient + Shear (SIP)=**Thermal vorticity** + **Shear effects**

Numerical Simulations: B. Fu, et al PRL (2021)



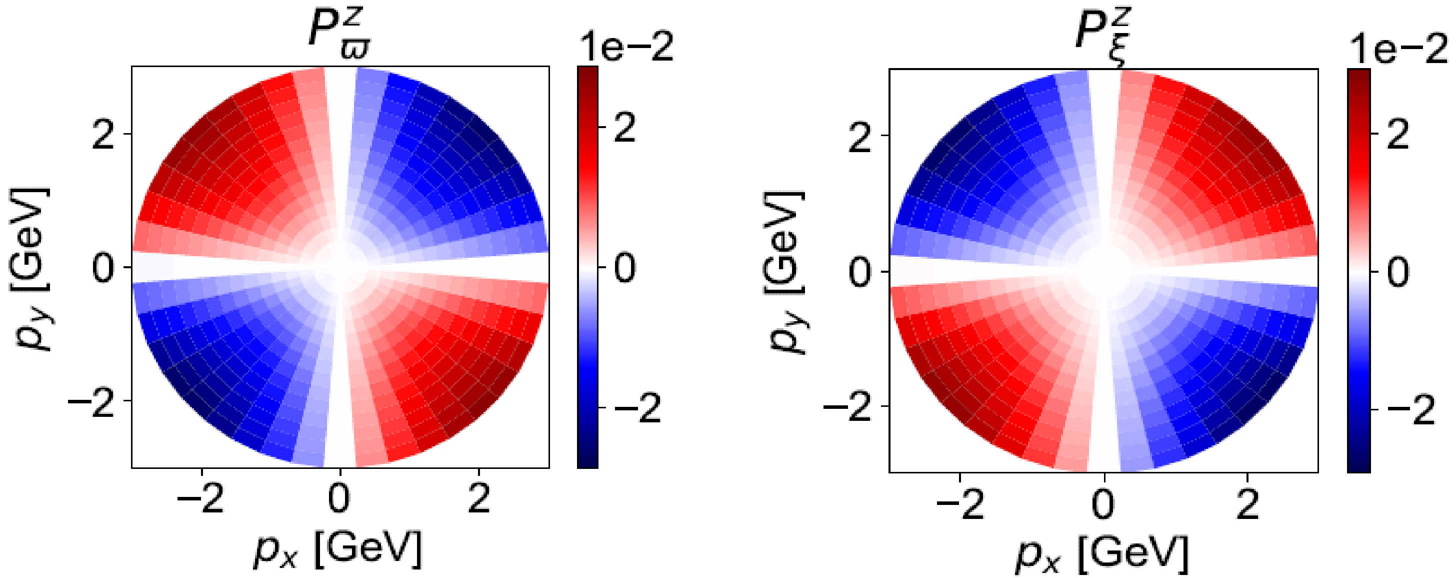
-**Shear** (**SIP**) and **T gradient** terms: comparable magnitude; opposite sign.

Numerical Simulations(Part I): (Becattini group)

Theoretical formula: F.Becattini, et al, PLB(2021).

$S^{\mu} = S^{\mu}_{\varpi} + S^{\mu}_{\xi}$ =Thermal vorticity $\varpi_{\mu\nu}$ + Thermal shear $\xi_{\mu\nu}$ effects

Numerical Simulations: F.Becattini,et al arXiv:2103.14621 **(numer. simul. Part I)**



-**Thermal shear** and **thermal vorticity** terms: similar magnitude; opposite sign.

-Agreement between two groups: **shear** terms are important.

Numerical Simulation (Part-II): (Becattini group)

Theoretical formula: F.Becattini, et al, PLB(2021).

$S^\mu = S^\mu_\varpi + S^\mu_\xi$ =Thermal vorticity $\varpi_{\mu\nu}$ + Thermal shear $\xi_{\mu\nu}$ effects

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

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z}\exp[-\beta_\mu(x)\widehat{P}^\mu - \frac{1}{2}(\partial_\mu\beta_\nu(x) - \partial_\nu\beta_\mu(x))\widehat{J}^{\mu\nu}_x - \frac{1}{2}(\partial_\mu\beta_\nu(x) + \partial_\nu\beta_\mu(x))\widehat{Q}^{\mu\nu}_x + \ldots]$$

Numerical Simulation (Part-II): (Becattini group)

Theoretical formula: F.Becattini, et al, PLB(2021).

$S^{\mu} = S^{\mu}_{\varpi} + S^{\mu}_{\xi}$ =Thermal vorticity $\varpi_{\mu\nu}$ + Thermal shear $\xi_{\mu\nu}$ effects

β_{ν}(y)= β_{ν}(x)+ $\partial_{\lambda}\beta_{\nu}(x)(y-x)^{\lambda}$+ … ...

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z}\exp[-\beta_{\mu}(x)\widehat{P}^{\mu} - \frac{1}{2}(\partial_{\mu}\beta_{\nu}(x) - \partial_{\nu}\beta_{\mu}(x))\widehat{J}^{\mu\nu}_{x} - \frac{1}{2}(\partial_{\mu}\beta_{\nu}(x) + \partial_{\nu}\beta_{\mu}(x))\widehat{Q}^{\mu\nu}_{x} + \ldots]$$

Revised formula for numerical simulations: F.Becattini,et al

Isothermal frz: $\widehat{\rho}_{\rm LE} = \frac{1}{Z}\exp\left[-\int_{\Sigma_{FO}} {\rm d}\Sigma_{\mu}\, \widehat{T}^{\mu\nu}\beta_{\nu}\right] = \frac{1}{Z}\exp\left[-\frac{1}{T}\int_{\Sigma_{FO}} {\rm d}\Sigma_{\mu}\, \widehat{T}^{\mu\nu}u_{\nu}\right]$

u_{ν}(y)= u_{ν}(x)+ $\partial_{\lambda}u_{\nu}(x)(y-x)^{\lambda}$+ … ...

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z}\exp[-\beta_{\mu}(x)\widehat{P}^{\mu} - \frac{1}{2T}(\partial_{\mu}u_{\nu}(x) - \partial_{\nu}u_{\mu}(x))\widehat{J}^{\mu\nu}_{x} - \frac{1}{2T}(\partial_{\mu}u_{\nu}(x) + \partial_{\nu}u_{\mu}(x))\widehat{Q}^{\mu\nu}_{x} + \ldots]$$

Isothermal freeze-out ⟶ **T-gradient is negligible**

Thermal vorticity & shear $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu})\,.\ \xi_{\mu\nu} = \frac{1}{2}(\partial_{\mu}\beta_{\nu} + \partial_{\nu}\beta_{\mu})$ PLB(2021)

⟶ kinetic vorticity & shear $\omega_{\rho\sigma} = \frac{1}{2}(\partial_{\sigma}u_{\rho} - \partial_{\rho}u_{\sigma})$ $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_{\sigma}u_{\rho} + \partial_{\rho}u_{\sigma})$

arXiv:2103.14621

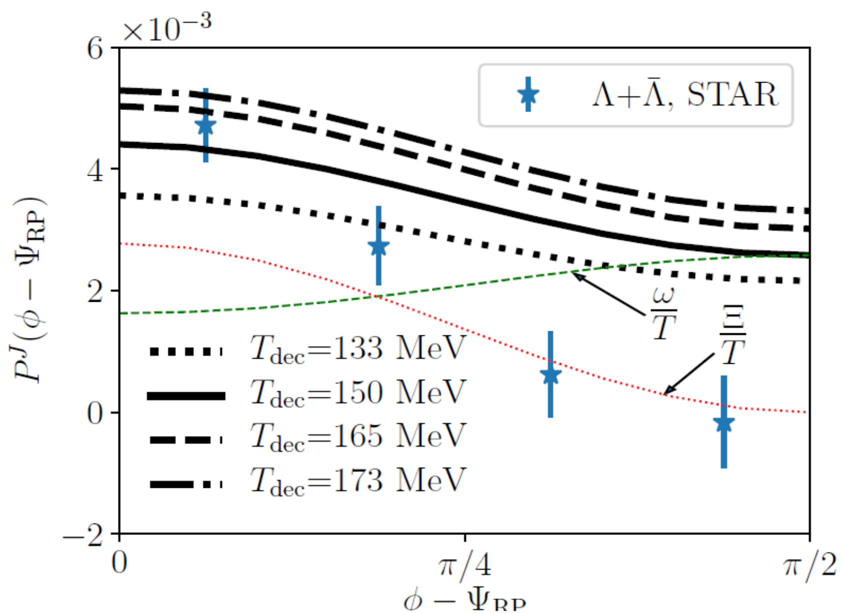
Numerical Simulation (Part-II): (Becattini group)

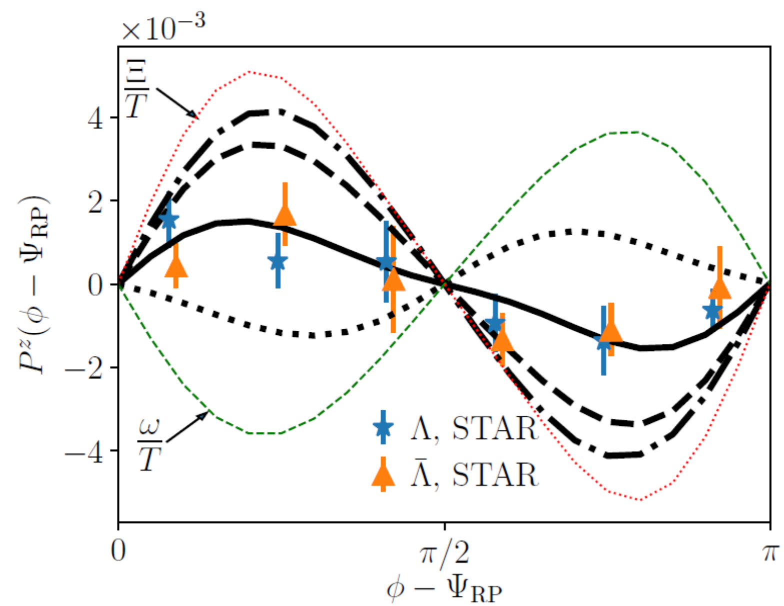
Revised formula: F.Becattini,et al arXiv:2103.14621

$S^{\mu}_{ILE} = S^{\mu}_{\omega} + S^{\mu}_{\Xi}$ =Kinetic vorticity $\omega_{\mu\nu}$ + Kinetic shear $\Xi_{\mu\nu}$ effects

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

Numerical Simulations: F.Becattini,et al arXiv:2103.14621 **(numer. simul. Part II)**





- **Kinetic shear + Kinetic vorticity** can roughly fit the data with tuning Tdec .

(1) Our group JHEP(2021); PRL(2021)

S^μ = Vorticity + T gradient + Shear (SIP)=**Thermal vorticity** + **Shear effects**

(2) Becattini Group PLB(2021)

$S^\mu = S^\mu_\varpi + S^\mu_\xi$ =**Thermal vorticity** $\varpi_{\mu\nu}$ + **Thermal shear** $\xi_{\mu\nu}$ **effects**

Comments: (1) (2) has similar but not exactly the same form $(\hat{t}_\nu \rightarrow u_\nu)$

(3) Becattini Group arXiv:2103.14621 (numerical simul part-II)

$S^\mu_{ILE} = S^\mu_\omega + S^\mu_\Xi$ =**Kinetic vorticity** $\omega_{\mu\nu}$ + **Kinetic shear** $\Xi_{\mu\nu}$ **effects**

Comments: isothermal freeze-out, changing **thermal** vorticity to **kinetic** vorticity, etc

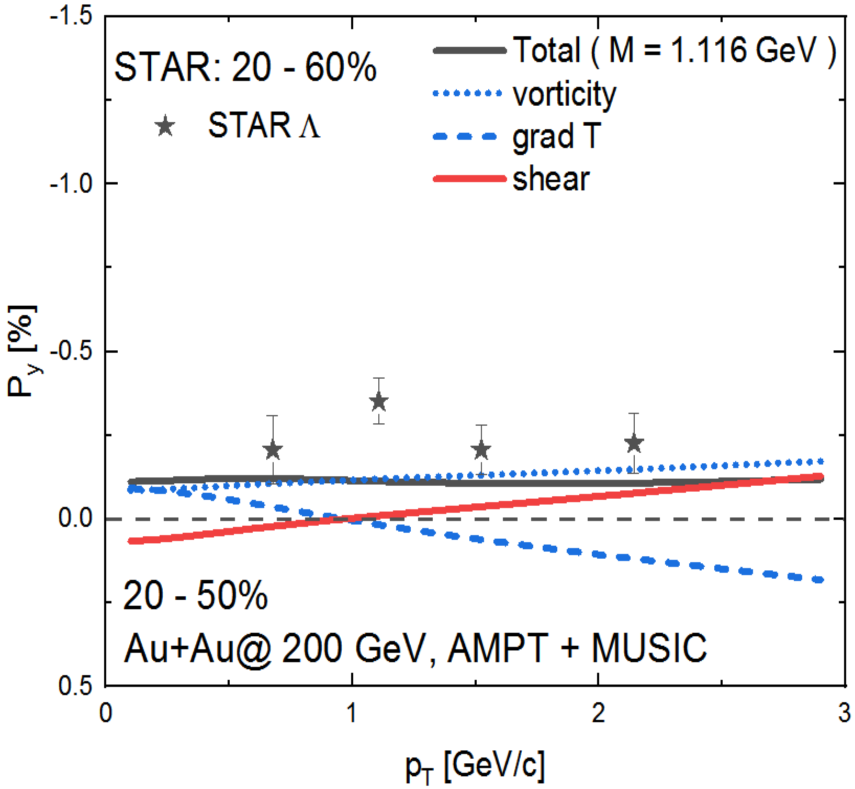
Questions:

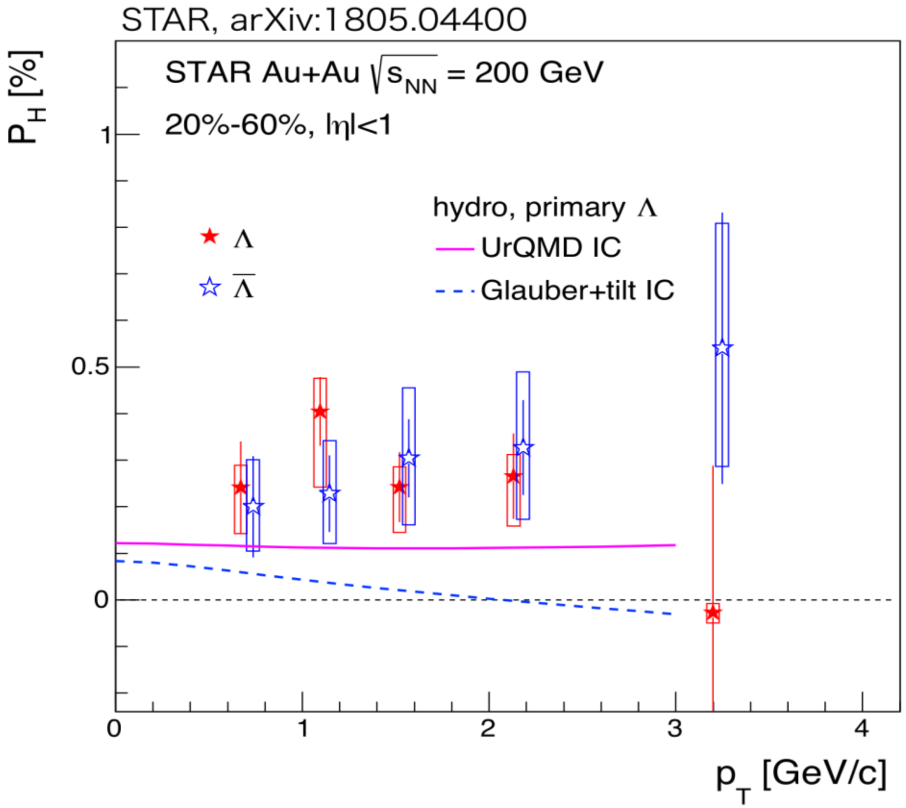
-What is the proper formula for spin polarization with the shear term?

-Can we identify T-gradient & shear effects from exp observable?

Comparison between T-grad and shear effects

-Can we identify T-gradient & shear effects from exp observable? Not so easy.



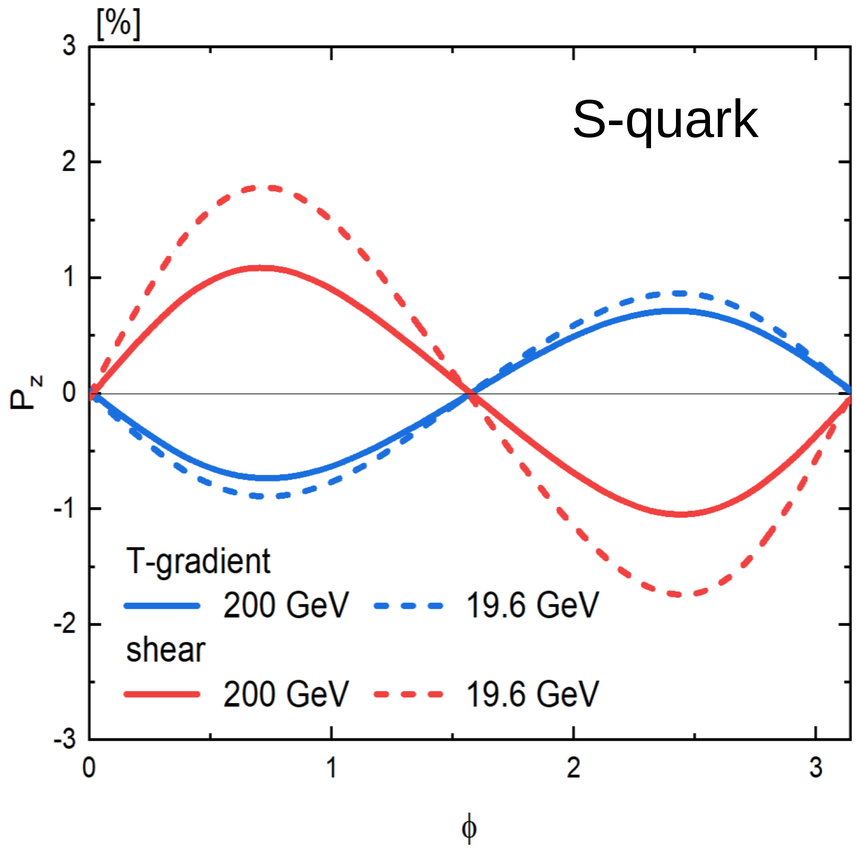


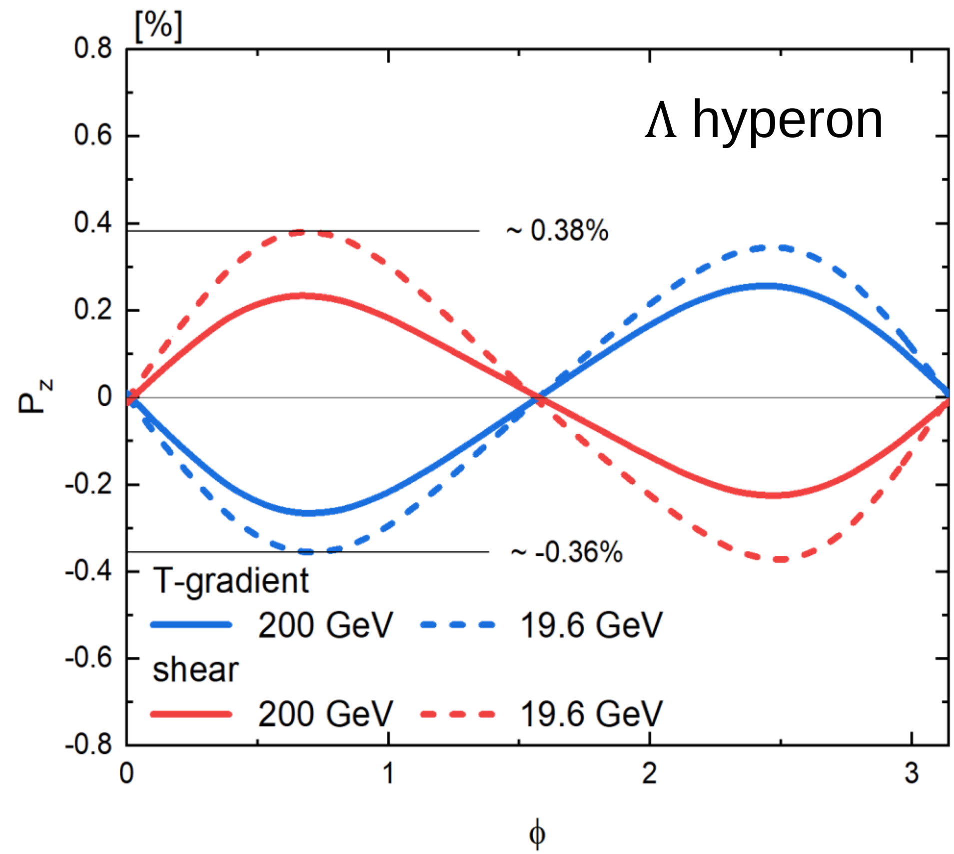
- P_y (p_T): different p_T dependence for T-grad and shear (SIP) terms

  Large uncertainties from initial condition model

Comparison between T-grad and shear effects

-Can we identify T-gradient & shear effects from exp observable? Not so easy.



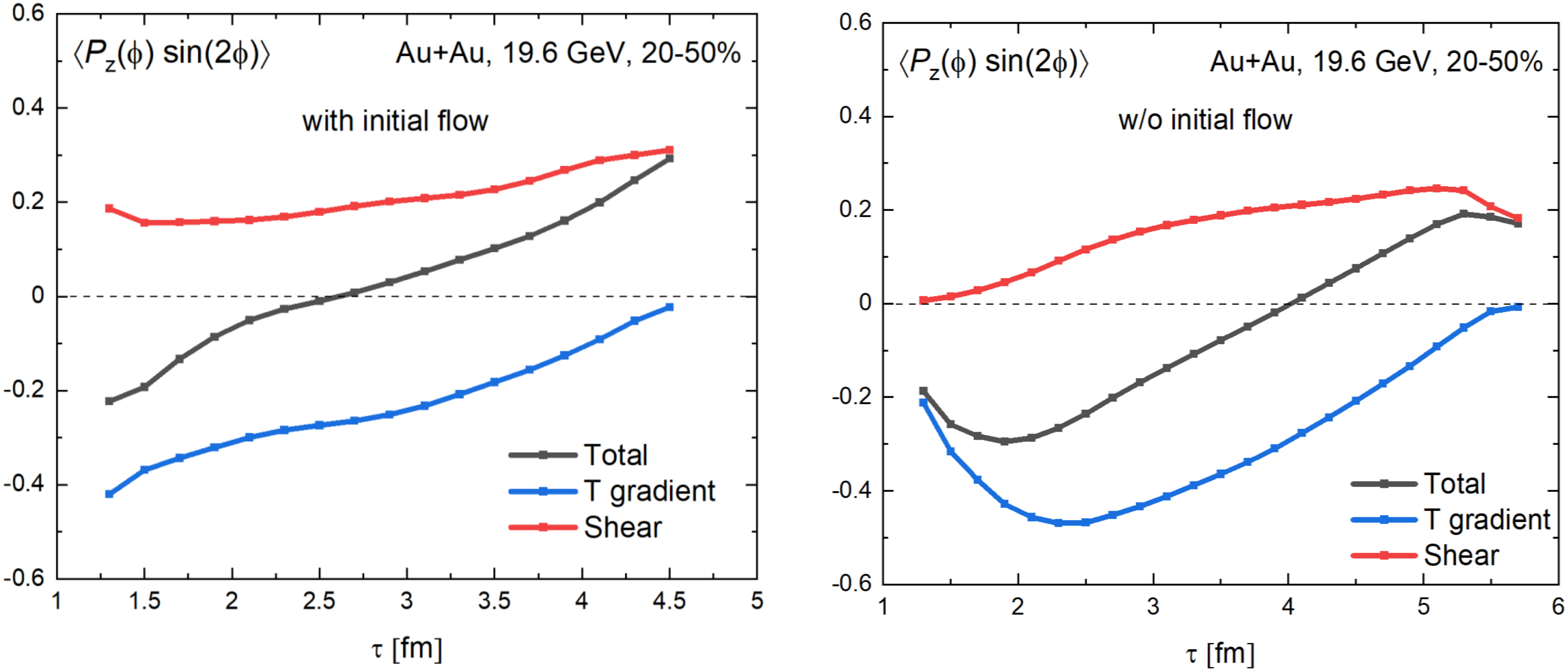


$P_z(\phi)$: energy dependence for T-gradient and shear (SIP) term

also depend on S-quark memory scenario or Λ equilibrium scenario

Comparison between T-grad and shear effects

-Can we identify T-gradient & shear effects from exp observable? Not so easy.



-T-gradient effects are developed at early stage of the evolution for different initial conditions

-Maybe we should find observables sensitive to time evolution of the system

(1) Our group JHEP(2021); PRL(2021)

S^{μ} = Vorticity + T gradient + Shear (SIP)=**Thermal vorticity + Shear effects**

(2) Becattini Group PLB(2021)

$S^{\mu} = S^{\mu}_{\varpi} + S^{\mu}_{\xi}$ =**Thermal vorticity** $\varpi_{\mu\nu}$ **+ Thermal shear** $\xi_{\mu\nu}$ **effects**

<u>**Comments:**</u> (1) (2) has similar but not exactly the same form $(\hat{t}_{\nu} \rightarrow u_{\nu})$

~~**(3) Becattini Group** arXiv:2103.14621 (numerical simul part-II)~~

~~$S^{\mu}_{ILE} = S^{\mu}_{\omega} + S^{\mu}_{\Xi}$ =**Kinetic vorticity** $\omega_{\mu\nu}$ **+ Kinetic shear** $\Xi_{\mu\nu}$ **effects**~~

~~<u>**Comments:**</u> isothermal freeze-out, changing **thermal** vorticity to **kinetic** vorticity, etc~~

-Focus on the two formula (1) (2) **(personal opinion)**

-without additional assumptions on constant T isothermal freezeout

-can be applied to RHIC-BES energies

What is the proper formula for spin polarization with shear term?

(1) **Our group** JHEP(2021); PRL(2021)

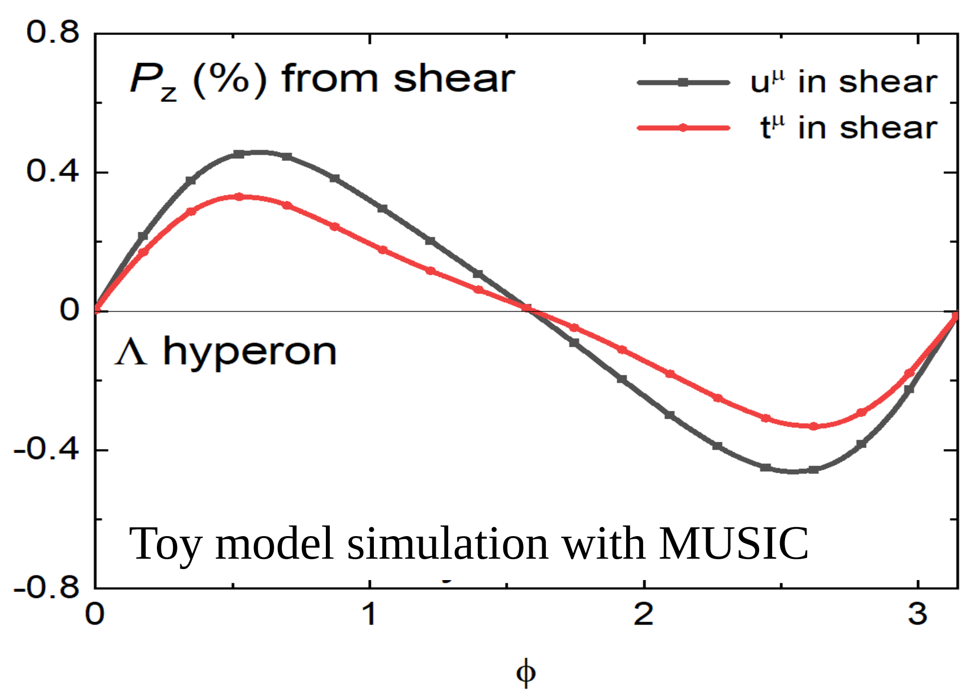
S^μ = Vorticity + T gradient + Shear (SIP)=**Thermal vorticity** + **Shear effects**

(2) **Becattini Group** PLB(2021)

$S^\mu = S^\mu_\varpi + S^\mu_\xi$ =**Thermal vorticity** $\varpi_{\mu\nu}$ + **Thermal shear** $\xi_{\mu\nu}$ **effects**

-(1) (2) has similar but not exactly the same form ($u_\nu \leftrightarrow \hat{t}_\nu$) obtain the same shear term)

-$u_\nu \leftrightarrow \hat{t}_\nu$ in the shear term lead to ~20% difference for $P_z(\Phi)$



Uncertainties for spin polarization

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S^μ = Vorticity + T gradient + Shear (SIP)=**Thermal vorticity** + **Shear effects**

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

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$S^\mu = S^\mu_\varpi + S^\mu_\xi$ =**Thermal vorticity** $\varpi_{\mu\nu}$ + **Thermal shear** $\xi_{\mu\nu}$ **effects**

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

$$\xi_{\mu\nu} = \frac{1}{2}(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu)$$

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

$$\int_{\Sigma_B} d\Sigma_\lambda(y)(y-x)^\kappa e^{i(p-p')(x-y)} = \int_{\Sigma_B} d^3y\, \hat{t}_\lambda(y-x)^\kappa e^{i(p-p')(x-y)}$$

$y\cdot t$ is constant in Σ_B by definition.

Spin Cooper-Frye (used by many groups)

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

F. Becattini,et al, Annals Phys. 338, 32 (2013） R.-h. Fang, L.-g. Pang, Q. Wang, and X.-n. Wang, Phys.Rev. C94, 024904 (2016) and many dynamical calculations.

Summary

-Shear induced polarization (SIP)

SIP is important to solve the local polarization puzzle

-Spin Hall Effects (SHE)

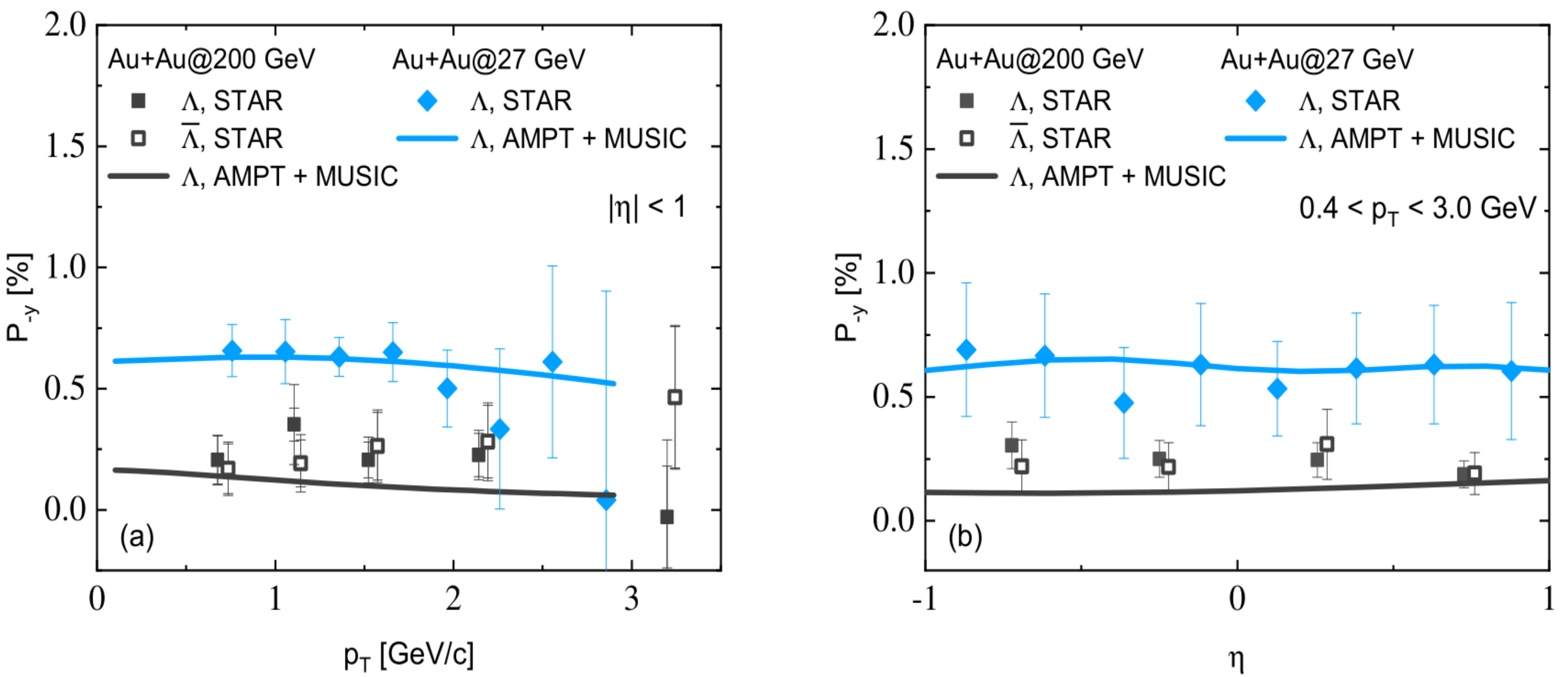
One can search the SHE at RHIC-BES with the collision energy dependent $< P_z \sin(2\phi) >$ and $< P_y \cos(2\phi) >$

-Comparison between groups

It is important & urgent to reach agreement on formulism of spin polarization with the shear effects for numerical implementations

Back-Ups

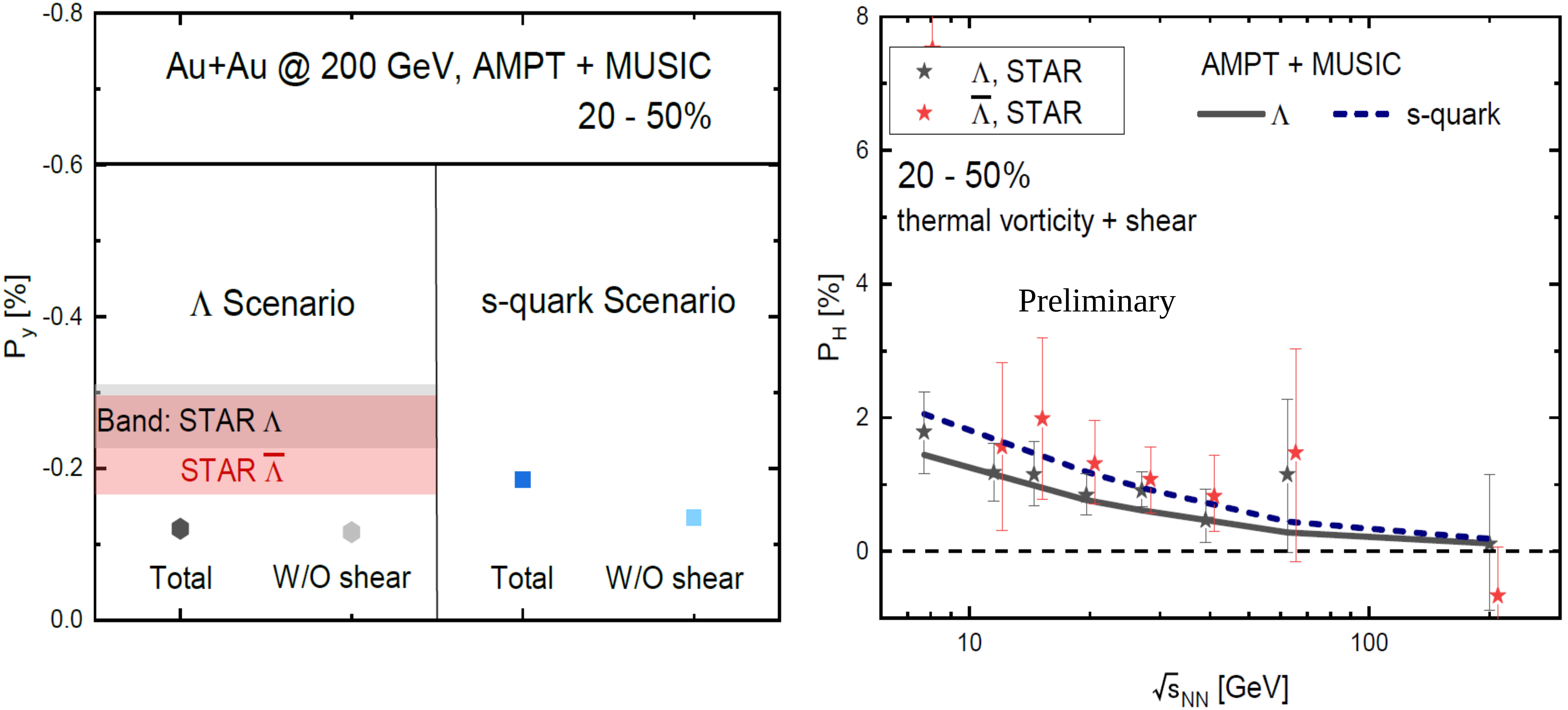
local polarization: p_T and η dependence



Total P^{μ} = [thermal vorticity]

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

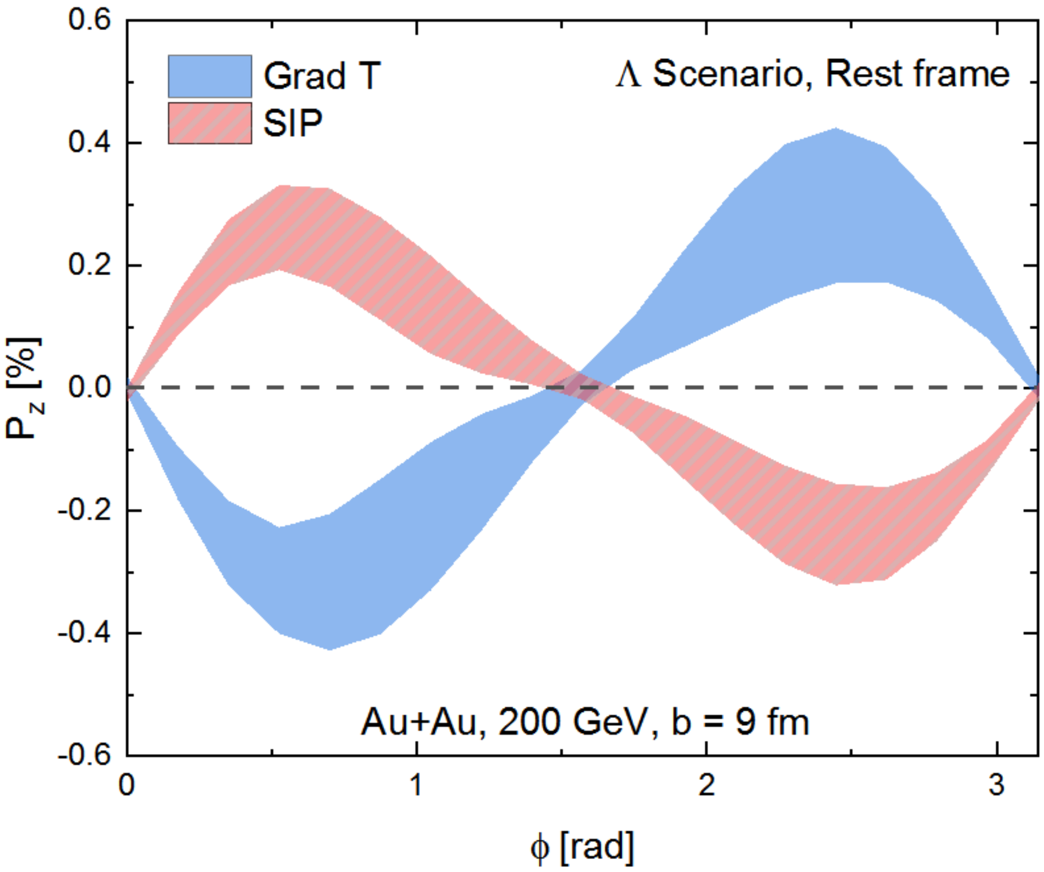
Global polarization with shear effect



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

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

Robustness of the competition



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

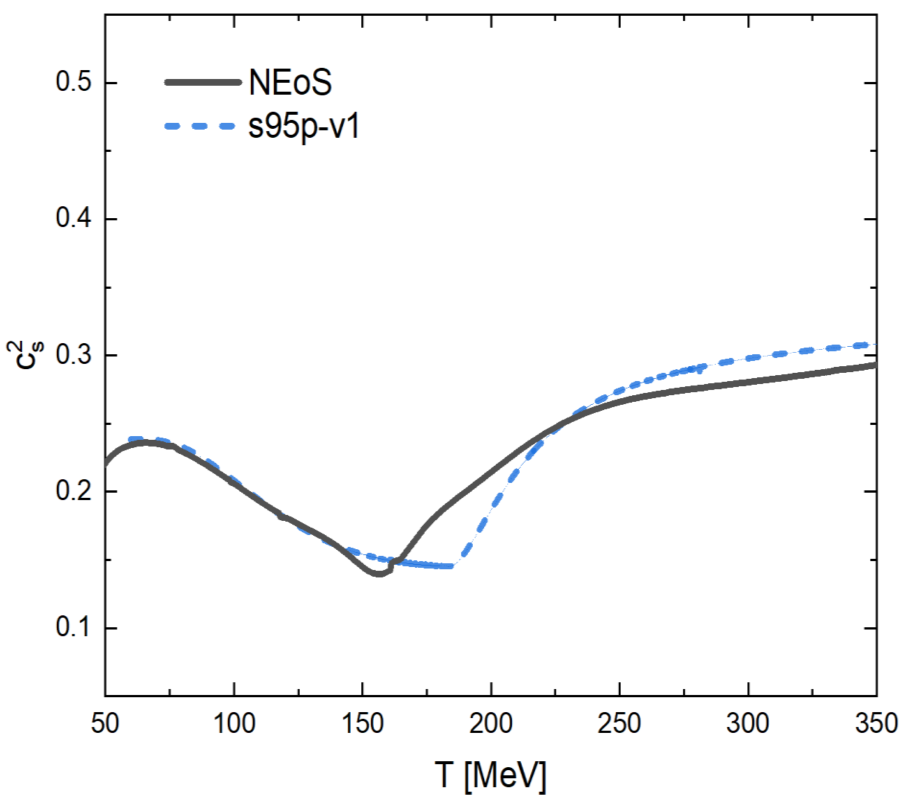
- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: $\zeta/s(T)$ → off
- Freeze-out temperature:

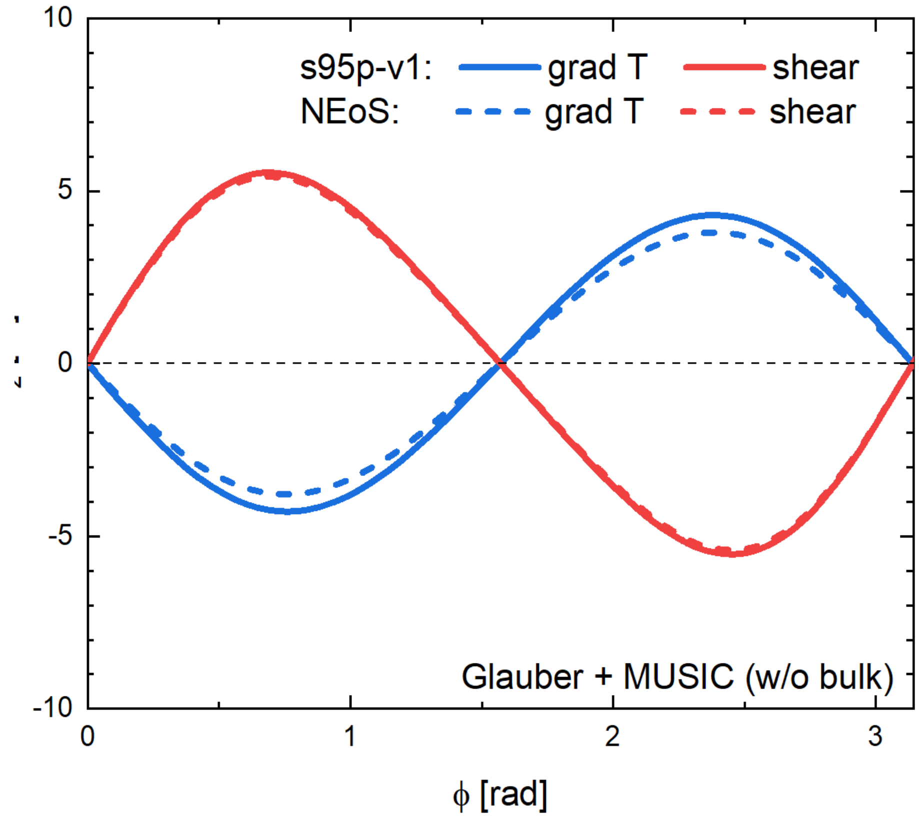
  167 MeV → 157 MeV

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

Dependence on EoS

s95p-v1 Vs. NEoS





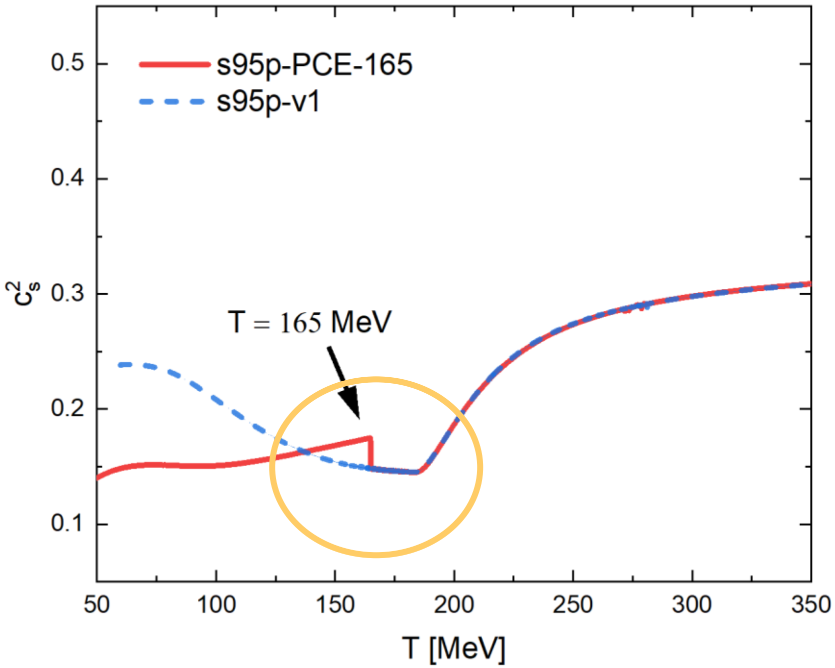
NEoS:

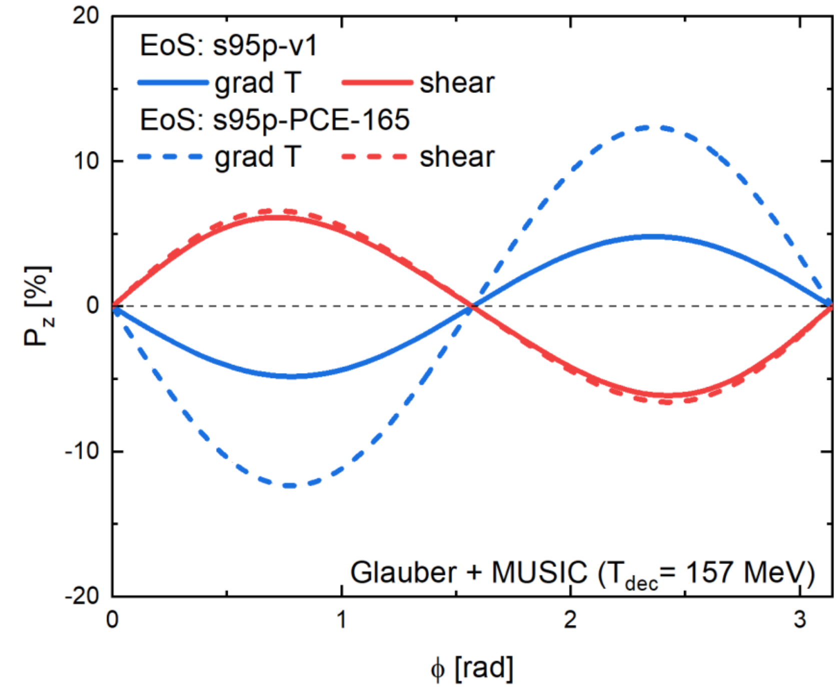
A. Monnai, B. Schenke, C. Shen, *Phys.Rev.C* 100 (2019) 2, 024907

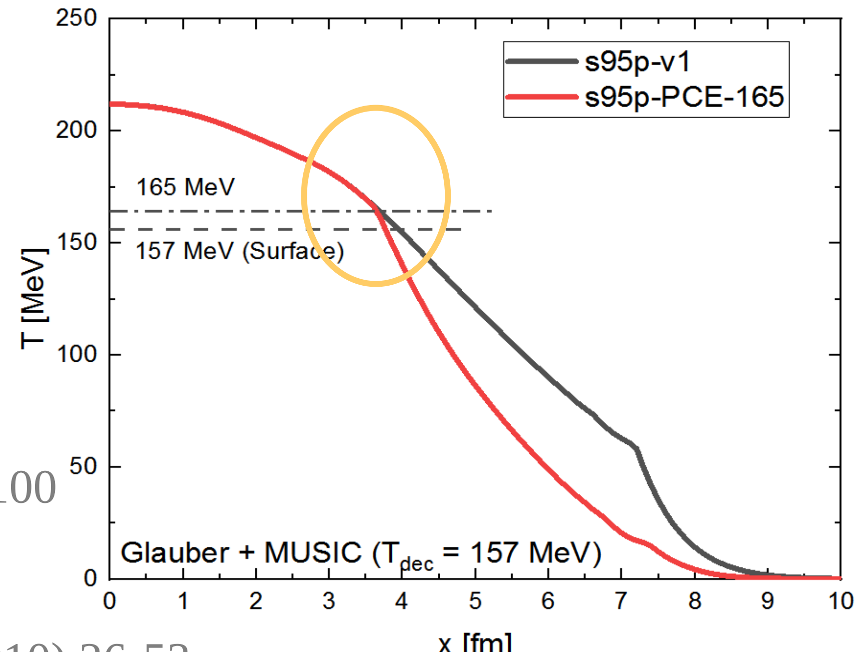
S95p-v1:

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

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