Vorticity Effect in Heavy-ion Collisions

Anke Lei

Department of Science, Wuhan University of Technology &
Institute of Particle Physics, Central China Normal University

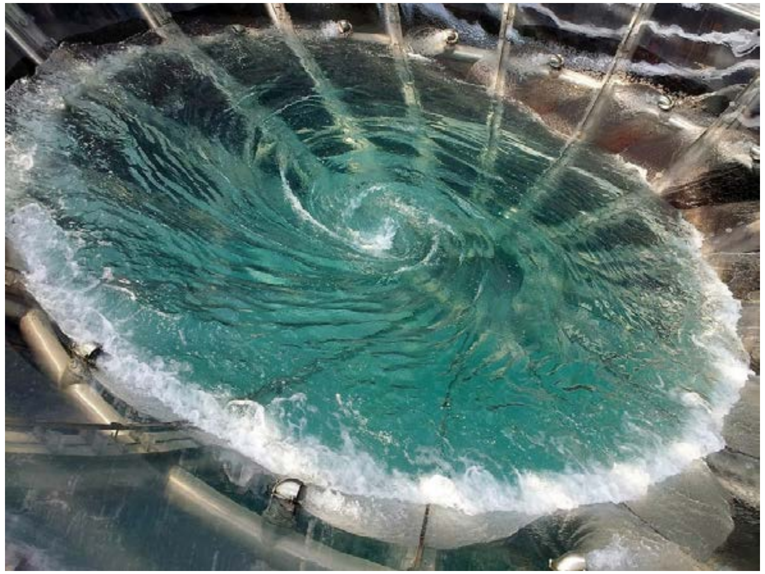
with **D. J. Wang**, **D. M. Zhou**, **B. H. Sa** and **L. P. Csernai**

OUTLINE

1. Introduction
2. Motivation
3. PACIAE model
4. Results
5. Summary

Introduction

Vortex in the nature


Vorticity: $\boldsymbol{\omega} = curl\, \boldsymbol{v} = \nabla \times \boldsymbol{v}$

reflects the local angular velocity of fluid

Introduction

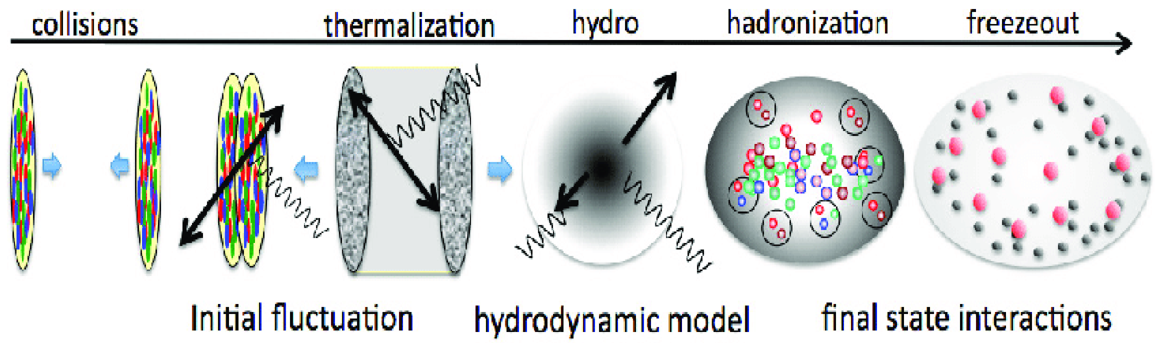


Fig. 1 The evolution of the Heavy-ion Collisions
[S. Suharyo, J. Phys. : Conf. Ser. 856 012002 (2017)]

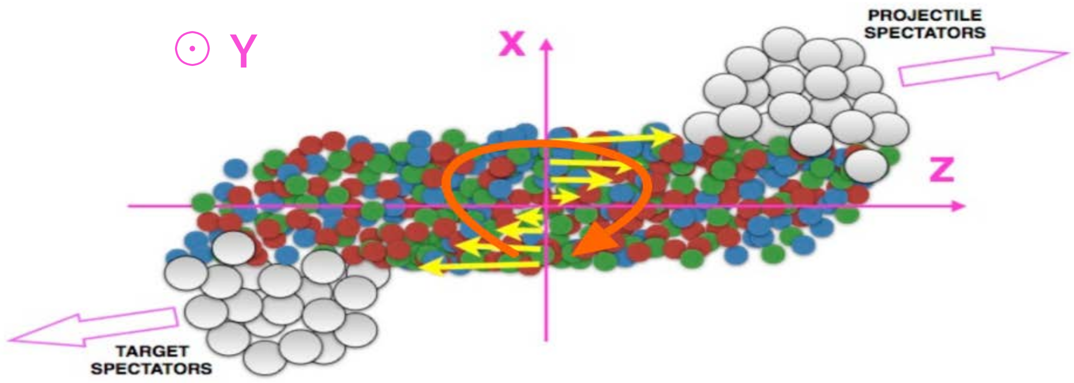


Fig. 2 Longitudinal velocity field and system rotation
[F. Becattini, Phys. Rev. C 95, 054902 (2017)]

non-central collisions → huge initial orbital angular momentum (OAM)

$J_0 \sim 10^5 \hbar$

- rotation / vorticity (-Y)

Introduction

The polarization vector for spin-1/2 particles:
[F. Becattini et al. (2008~2013)]

$$\Pi^{\mu}(x,p) = -\frac{1}{8m}\epsilon^{\mu\nu\sigma\tau}\left(1-n_{F(x,p)}\right)p_{\tau}\varpi_{\rho\sigma}(x)$$

$$\Pi^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\nu\sigma\tau}p_{\tau}\frac{\int d\Sigma_{\lambda}p^{\lambda}n_F(1-n_F)\varpi_{\rho\sigma}}{\int d\Sigma_{\lambda}p^{\lambda}n_F}$$

$\epsilon^{\mu\nu\sigma\tau}$ - Levi-Civita symbol (+1)

p ---- four-momentum

Σ ---- hypersurface of freeze-out

n_F ---- Fermi-Dirac distribution

ϖ ---- thermal vorticity

Recovered:
[R. H. Fang et al. (2016)]

$$S^{\mu}(\mathrm{x,p}) = -\frac{1}{8m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_{\nu}\varpi_{\rho\sigma}(\mathrm{x})$$

$$S^{\mu}(\mathrm{x,p}) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_{\nu}\varpi_{\rho\sigma}(\mathrm{x})$$

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

$$\beta^{\mu} = u^{\mu}/T$$

β ---- inverse temperature 4-vector field

u ---- four velocity of fluid

Introduction

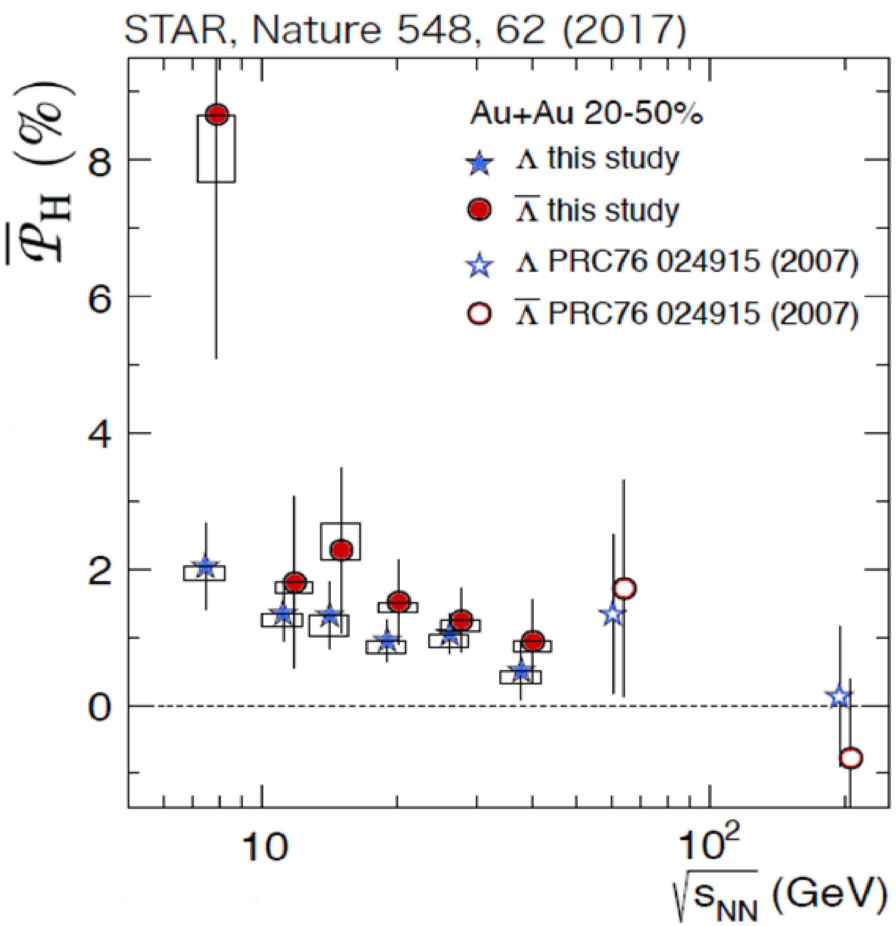


Fig. 3 The global Λ polarization
[STAR, Nature 548,62 (2017)]

The huge initial OAM will be transferred to the hadron polarization via ***spin-vorticity coupling***.

$\omega \sim 10^{-22}\ s^{-1}$

The most vortical fluid observed in the nature!

Motivation

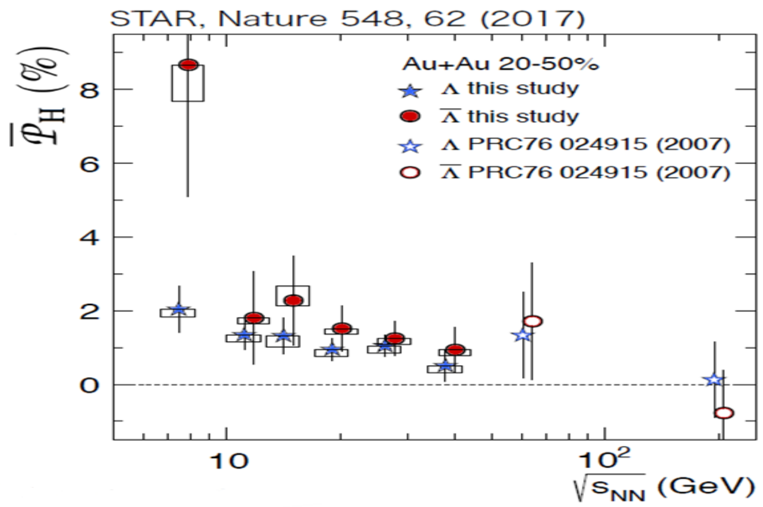


Fig. 4 STAR 2017

[STAR, Nature 548,62(2017)]

The energy dependence of Λ polarization

$\sqrt{S_{NN}} \uparrow$ ------ $P_H \downarrow$

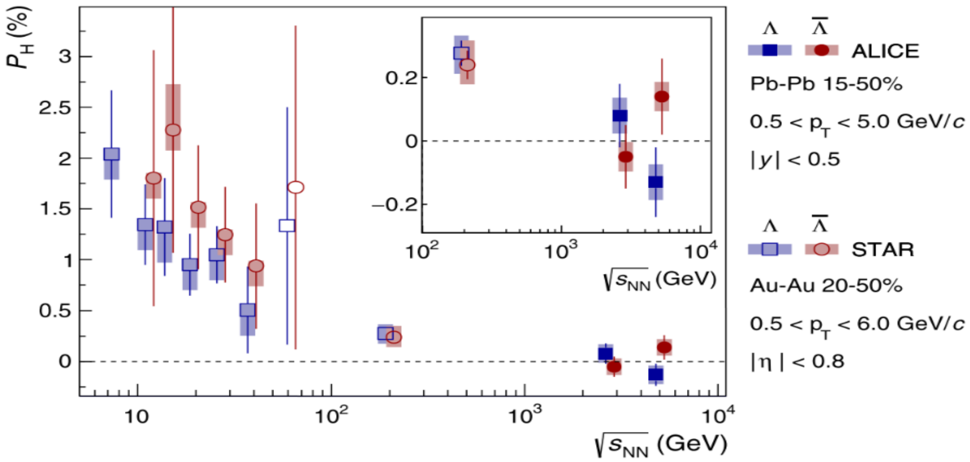


Fig. 5 ALICE 2020

[ALICE, PRC 101, 044611 (2020)]

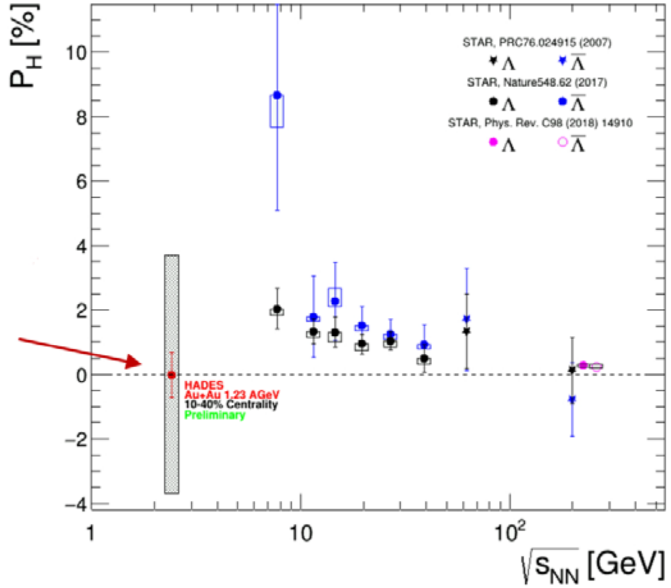


Fig. 6 HADES 2019

[HADES, Frédéric Kornas` talk in Strange Quark Matter 2019]

Motivation

The energy dependence of Λ polarization

$\sqrt{S_{NN}}$ ↑ ------ P_H ↓

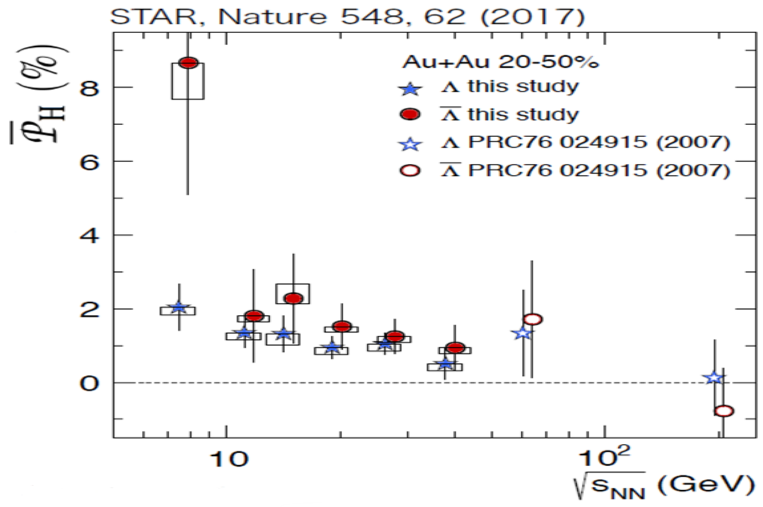
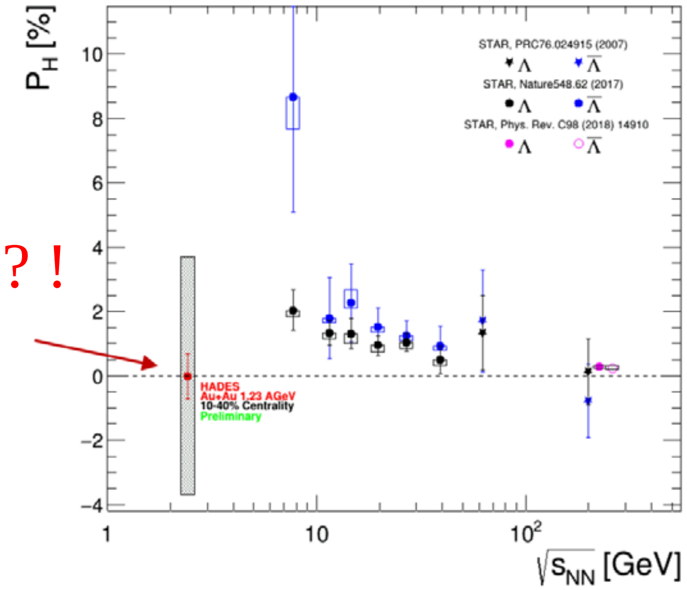


Fig. 4 STAR 2017

[STAR, Nature 548,62(2017)]

P_H ↑, then ↓, non-monotonic trend ? !



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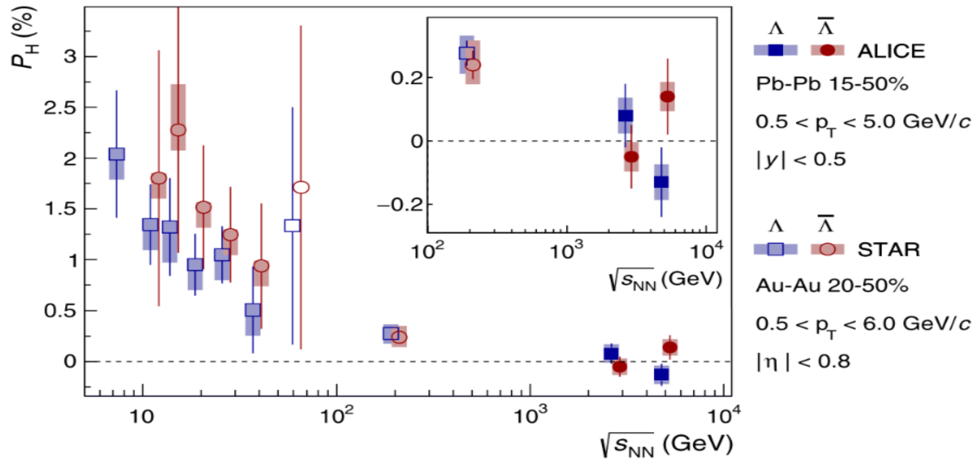

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Motivation

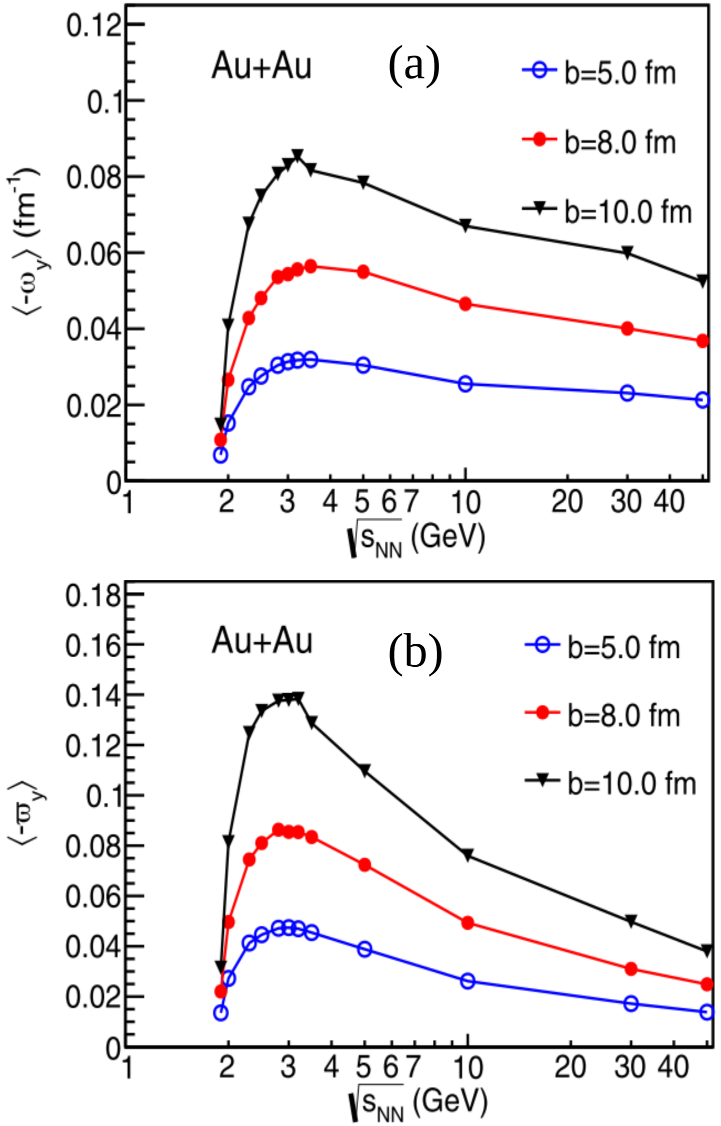


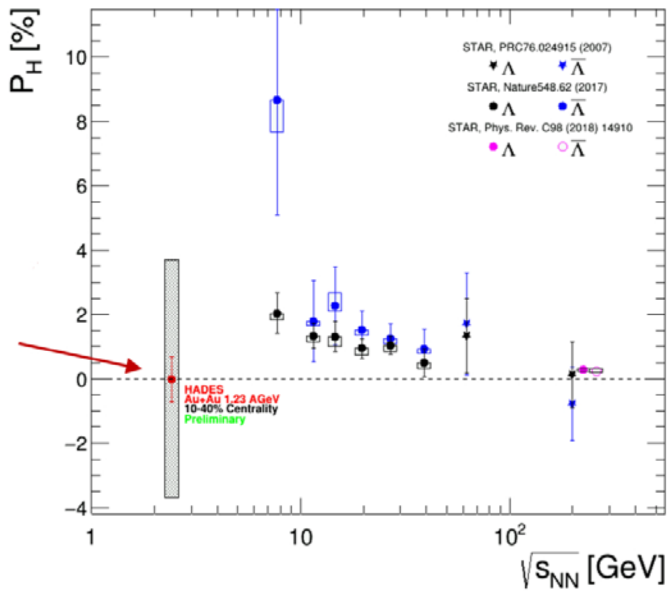
Fig. 7 The initial vorticities in **UrQMD**

[X. G. Deng et al. PRC 101, 064908 (2020)]

The energy dependence of Λ polarization

$\sqrt{S_{NN}}$ ↑ ------ P_H ↓

The initial vorticities show similar non-monotonic trend.



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Motivation

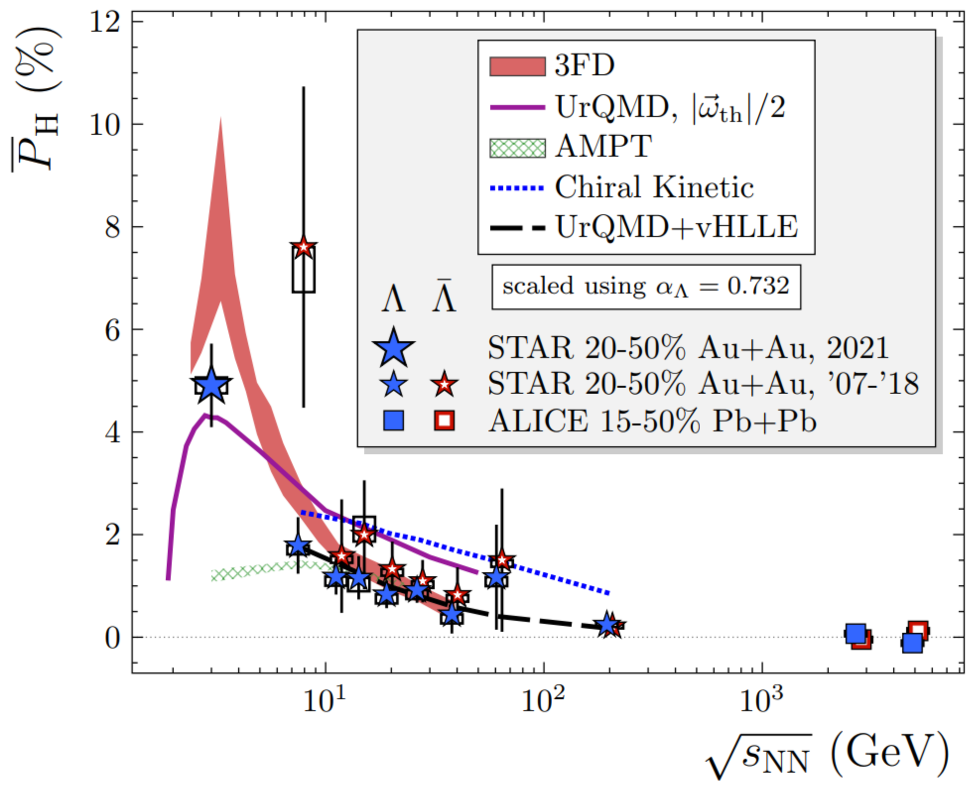


Fig. 8 STAR 2021, fixed target @ 3 GeV
[arXiv:2108.00044]

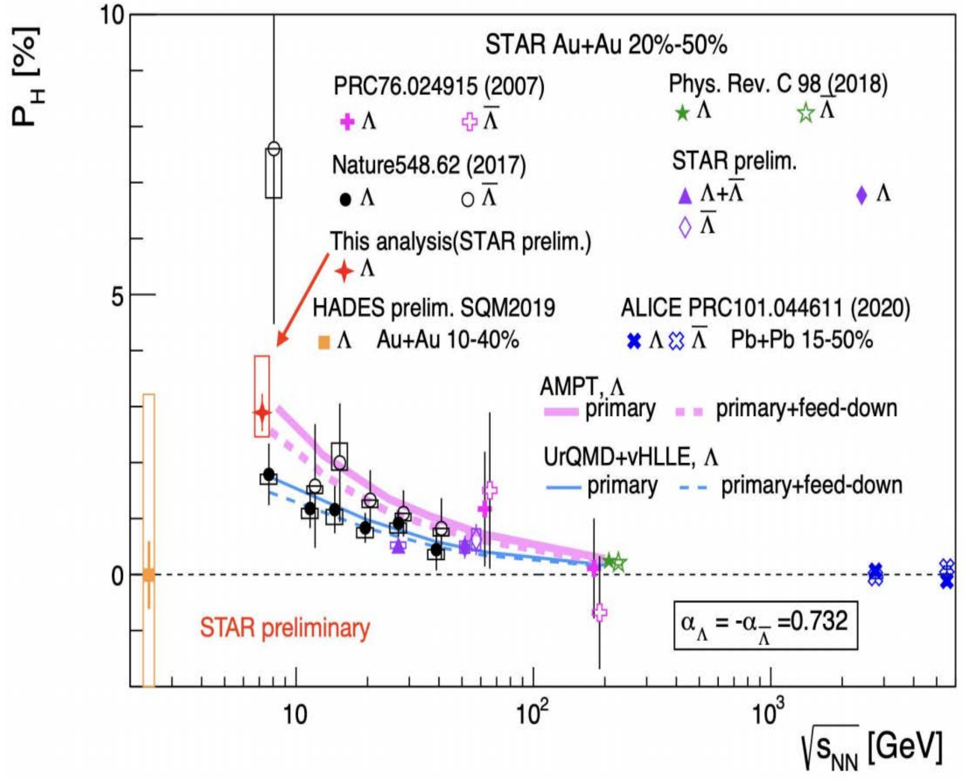


Fig. 9 STAR 2021, fixed target @ 7.2 GeV
[arXiv:2108.10012]

Very new results from STAR

Motivation

The "*spin puzzle*" of
the longitudinal Λ polarization

On the transverse momentum plane
(azimuthal angle) :

Experiment: (+, -, +, +)

Theoretical predictions: (-, +, -, +)

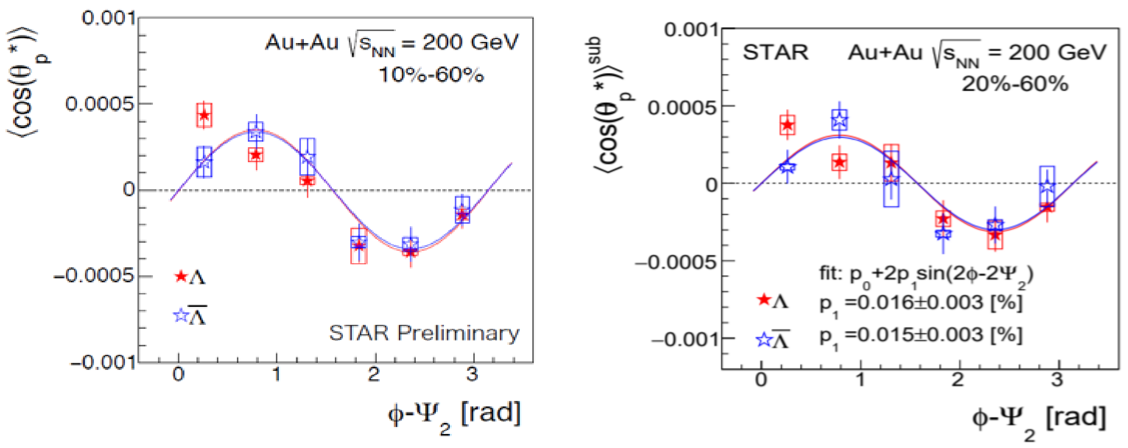


Fig. 10 STAR 2018, 2019 the longitudinal Λ polarization

[STAR, NPA 2019, PRL 2019]

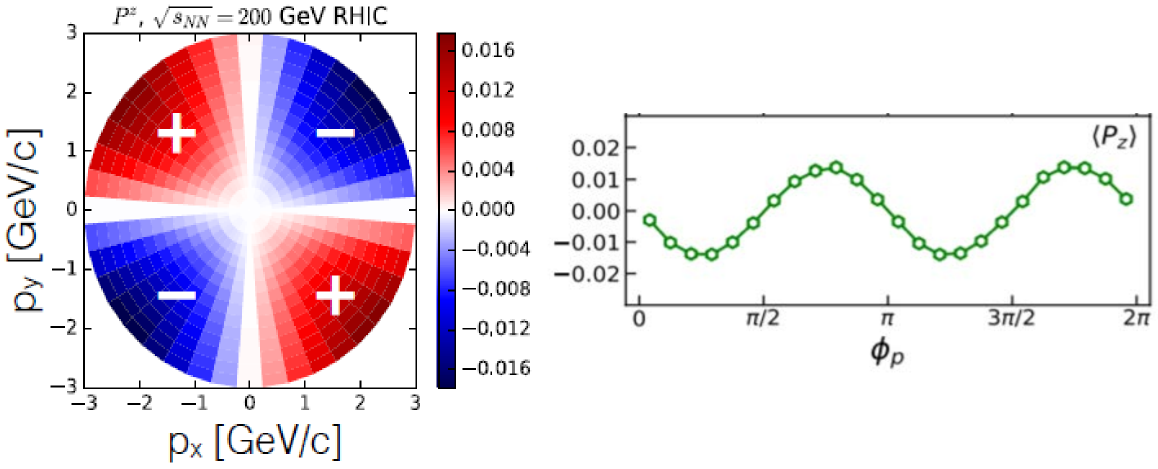


Fig. 11 Left: prediction from ECHO-QGP
Right: prediction from AMPT

[F. Becattini et al. PRL 2018] [X. Liang et al. PRC 2018]

Motivation

- Non-relativistic vorticity

$$\omega^{NR}_{ij} = -\frac{1}{2}(\partial_i v_j - \partial_j v_i)$$

- Kinematic vorticity:

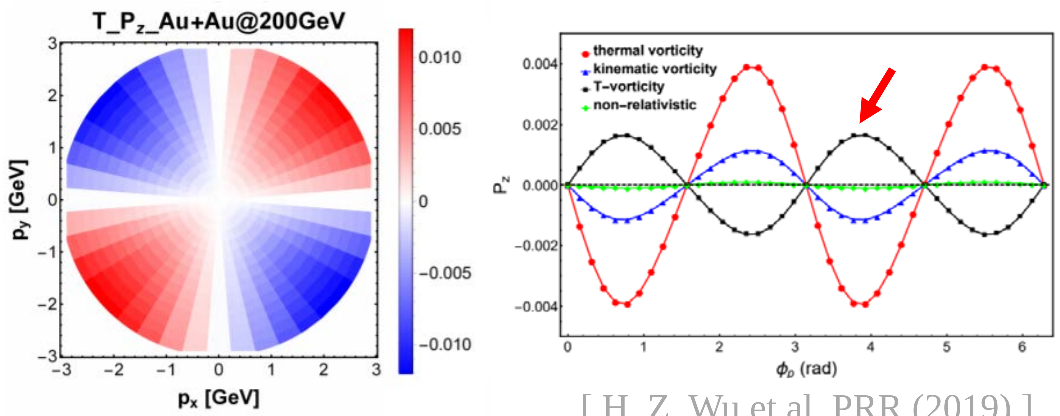
$$\omega^{K}_{\mu\nu} = -\frac{1}{2}(\partial_\mu u_\nu - \partial_\nu u_\mu)$$

- Thermal vorticity:

$$\omega^{th}_{\mu\nu} = -\frac{1}{2}[\partial_\mu (u_\nu / T) - \partial_\nu (u_\mu / T)]$$

- Temperature vorticity:

$$\omega^{T}_{\mu\nu} = -\frac{1}{2}[\partial_\mu (T u_\nu) - \partial_\nu (T u_\mu)]$$



[H. Z. Wu et al, PRR (2019)]

Fig. 12 Longitudinal polarization based on T-vorticity and other three types of vorticities

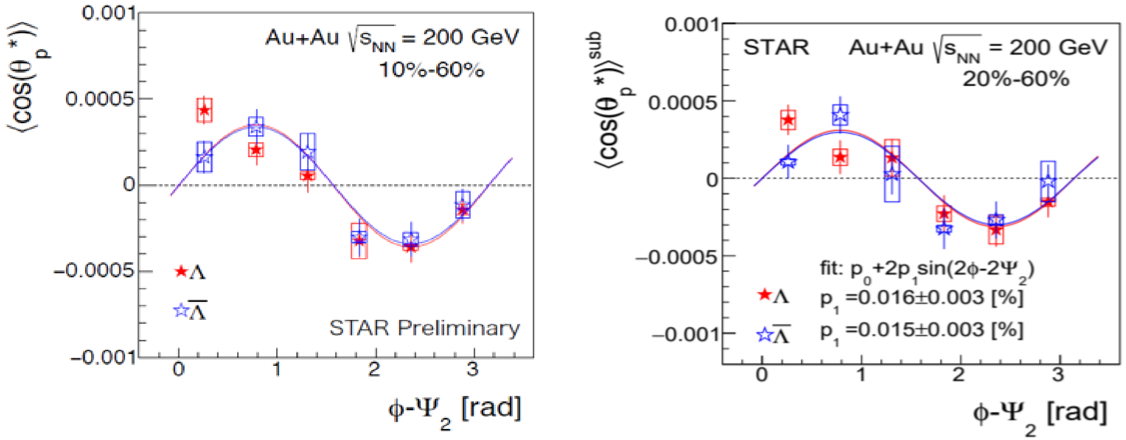
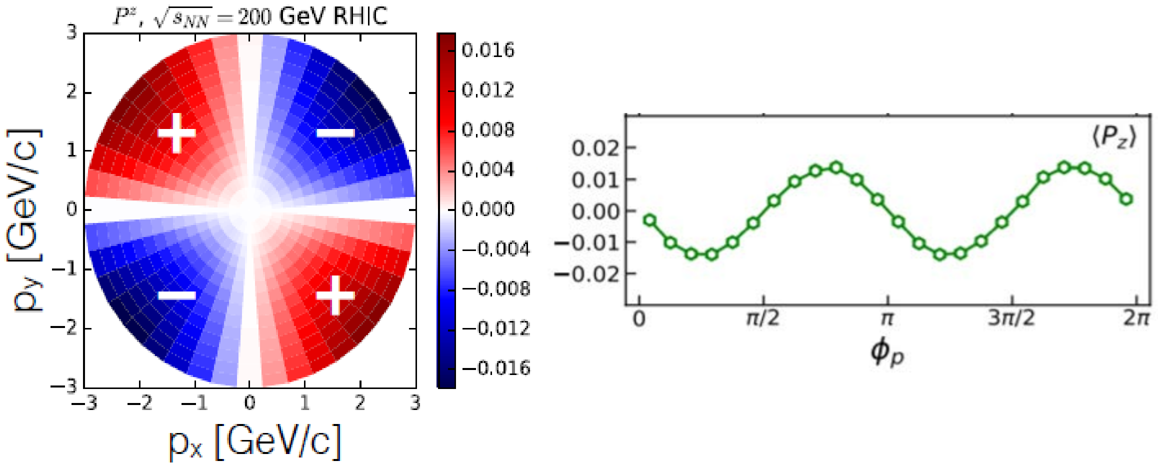


Fig. 10 STAR 2018, 2019 the longitudinal Λ polarization

[STAR, NPA 2019, PRL 2019]



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Motivation

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

- Temperature vorticity:

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

Behaviors of four types of vorticities?

Non-monotonic trend in other models?

PACIAE model

PACIAE: a microscopic parton and hadron transport model (based on PYTHIA)

parton initialization

parton rescatterring

hadronization

hadron rescatterring

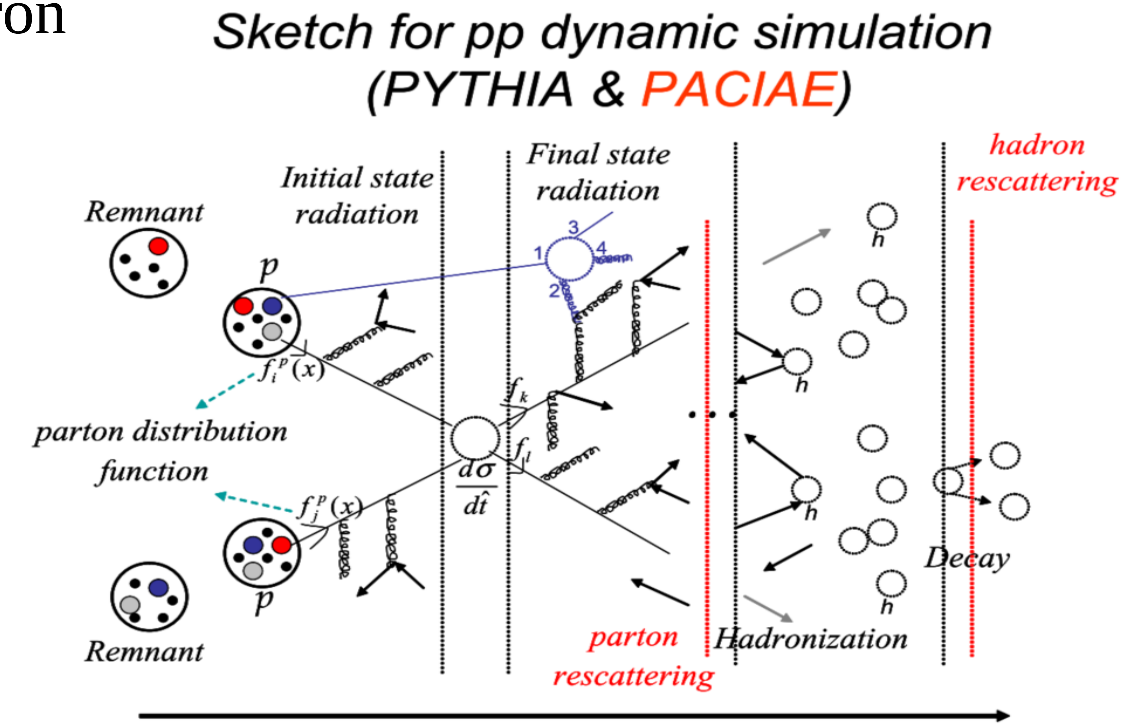

Fig. 13 Sketch of PYTHIA and PACIAE

π, K, p, n, ρ(ω), Δ, Λ, Σ, Ξ, Ω,J/Ψ

PACIAE model: fluidization

- Coarse-graining: the partons are divided into cell

$$\vec{P}_{cell} = \frac{1}{\Delta x \Delta y \Delta z} \langle \Sigma_i \vec{P}_i \rangle$$

$$\epsilon_{cell} = \frac{1}{\Delta x \Delta y \Delta z} \langle \Sigma_i E_i \rangle$$

$$\vec{v}_{cell} = \vec{P}_{cell} / \epsilon_{cell}$$

[Y. Jiang, et al., Phys. Rev. C 94, 044901 (2016)]

- Temperature : B-E & F-D distribution for partons

$$\epsilon_{cell} = \pi^2 (16 + 10.5 N_f) T_{cell}^4 / 30$$

N_f – the number of quark flavors (3; *u*, *d*, *s*)

[Z. W. Lin, Physical Review C, 2014, 90: 014904]

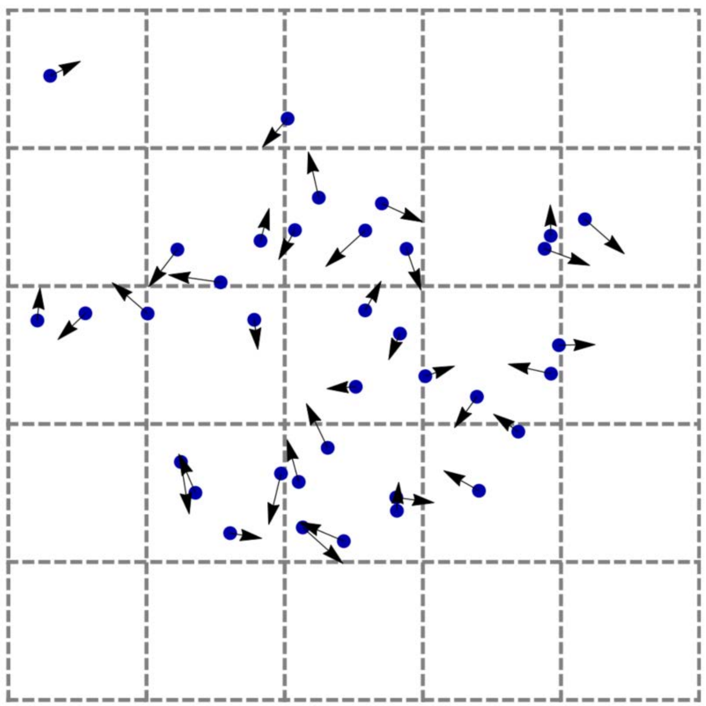

Fig. 14 The cell division in the transport model

[Y. Jiang, et al., Phys. Rev. C 94, 044901 (2016)]

- Another method: smearing function

[Phys. Rev. C 93, 064907 (2016)]

PACIAE model: fluidization

- Generalized coarse-graining:

  add ϵ_{cell} and $\vec{P}_{cell}$ of each nearest side and corner cells into the central one, then do average

$$\bar{P}_{cell} = \frac{1}{27} \sum_{icell} \vec{P}_{icell}$$

$$\bar{\epsilon}_{cell} = \frac{1}{27} \sum_{icell} \epsilon_{icell}$$

$$\vec{v}_{cell} = \bar{P}_{cell} / \bar{\epsilon}_{cell}$$

- Temperature : B-E & F-D distribution for partons

$$\bar{\epsilon}_{cell} = \pi^2 (16 + 10.5 N_f) T_{cell}^4 / 30$$

N_f – the number of quark flavors (3; u, d, s)

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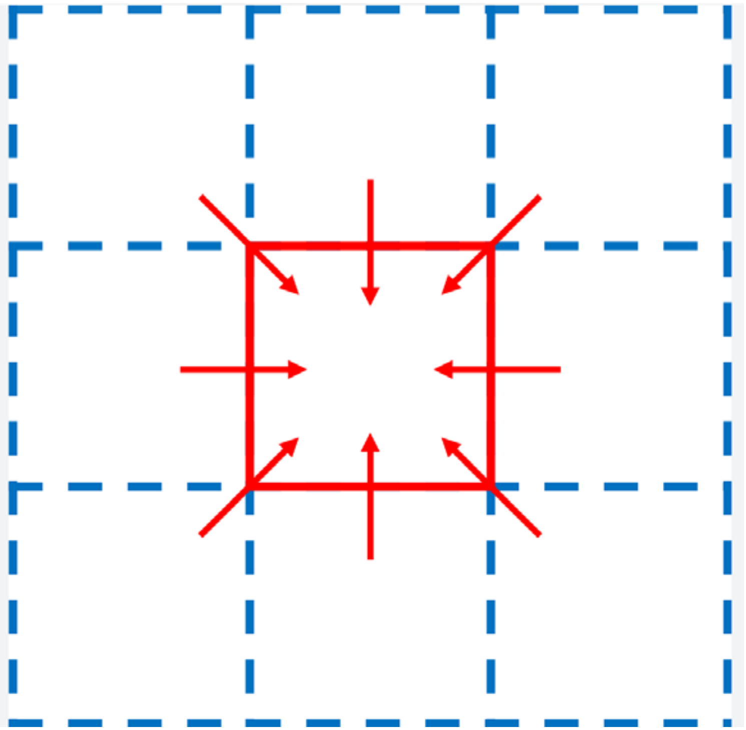


Fig. 15 The generalized coarse-graining

- Another method: smearing function

  [Phys. Rev. C 93, 064907 (2016)]

PACIAE model: fluidization

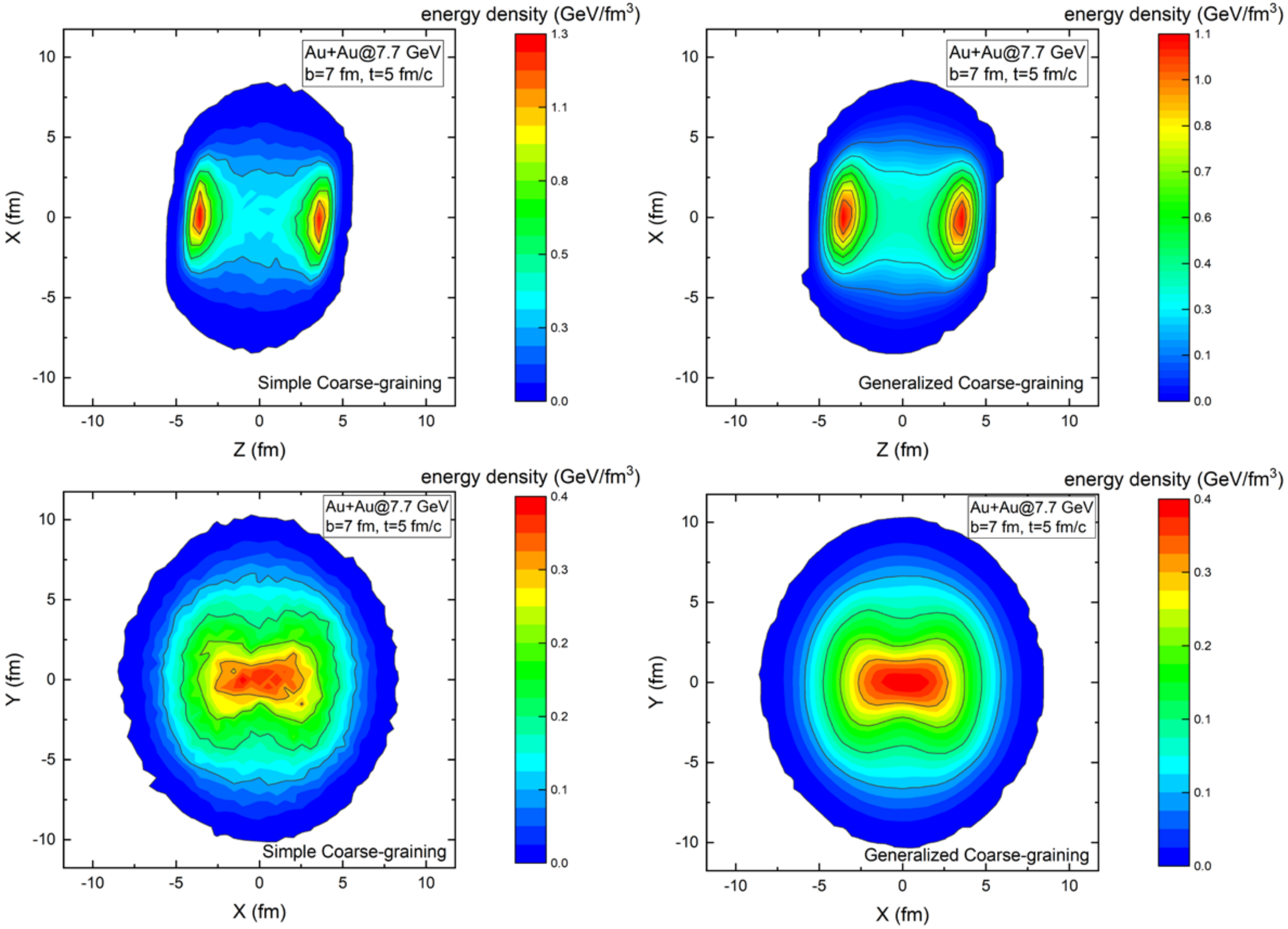


Fig. 16 The energy density distribution in PACIAE

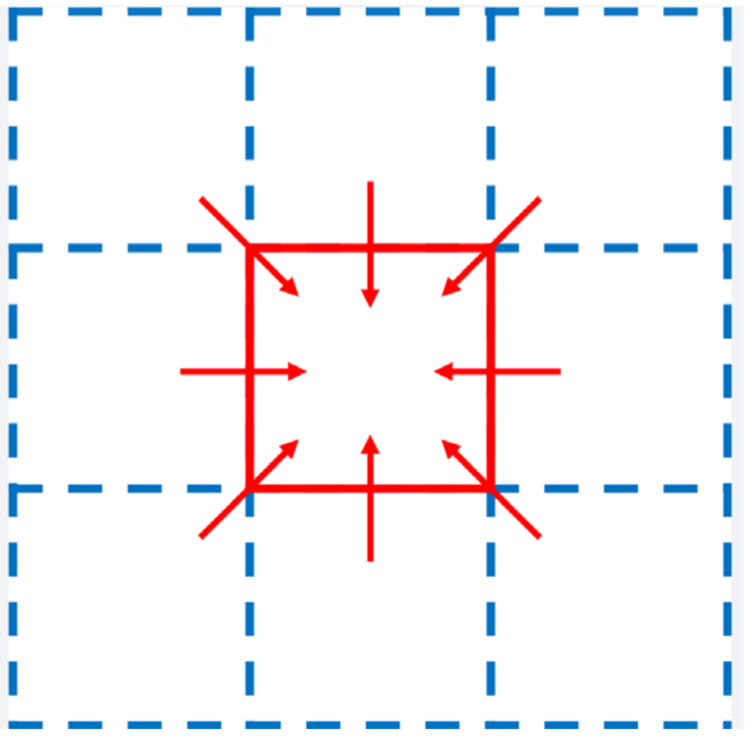


Fig. 15 The generalized coarse-graining

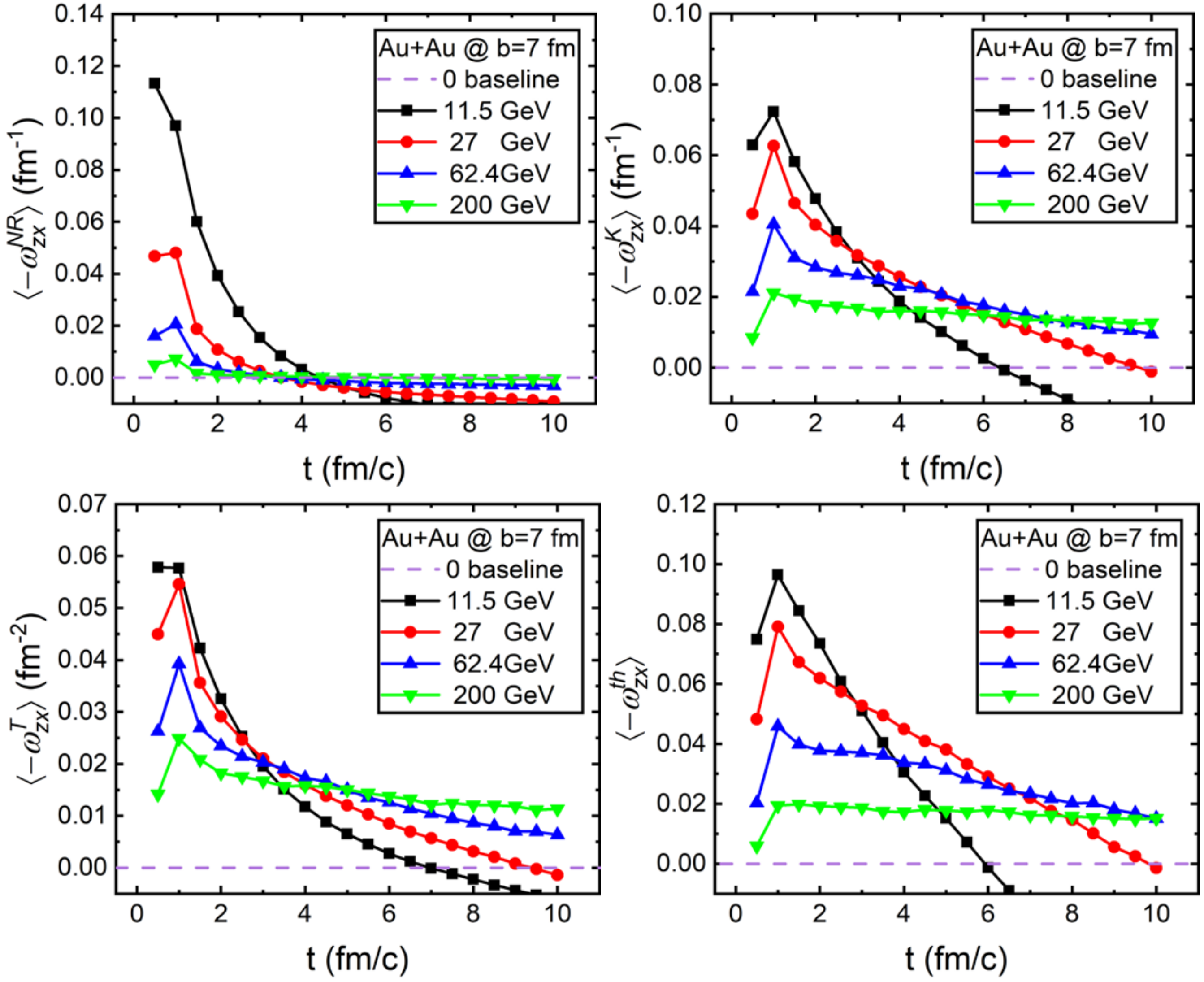
- Another method: smearing function

[Phys. Rev. C 93, 064907 (2016)]

Results: time and energy dependence

The energy-density-weighted average vorticity:

$$\langle -\omega_{zx}\rangle \equiv \langle -\omega_Y\rangle = \frac{\sum_i \bar{\epsilon}_i\,\omega_i}{\sum_i \bar{\epsilon}_i}$$



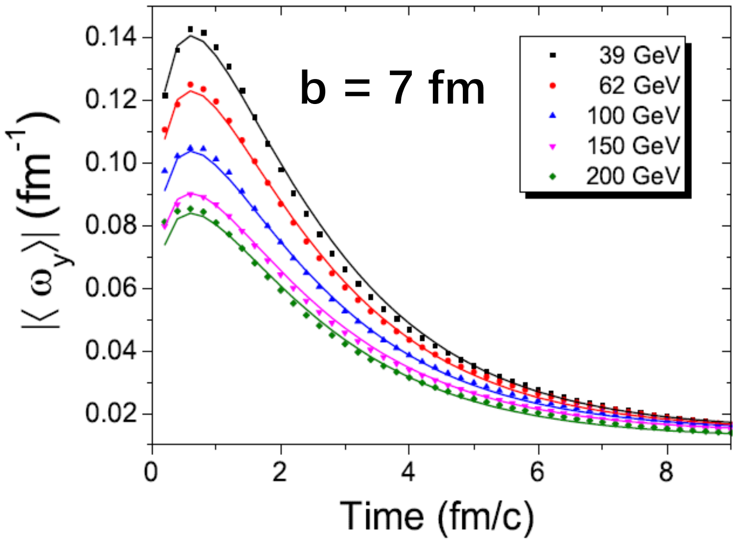


Fig. 17 Results of K-vorticity from **AMPT**

[Y. Jiang, et al., Phys. Rev. C 94, 044901 (2016)]

Fig. 18 Results from **PACIAE**

Results: centrality dependence

The energy-density-weighted average vorticity:

$$\langle -\omega_{zx}\rangle \equiv \langle -\omega_{Y}\rangle = \frac{\sum_i \overline{\epsilon_i}\,\omega_i}{\sum_i \overline{\epsilon_i}}$$

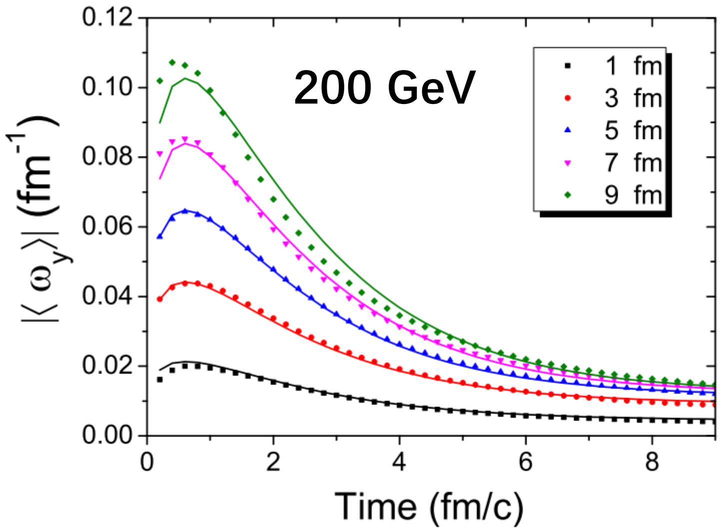


Fig. 19 Results of K-vorticity from **AMPT**

[Y. Jiang, et al., Phys. Rev. C 94, 044901 (2016)]

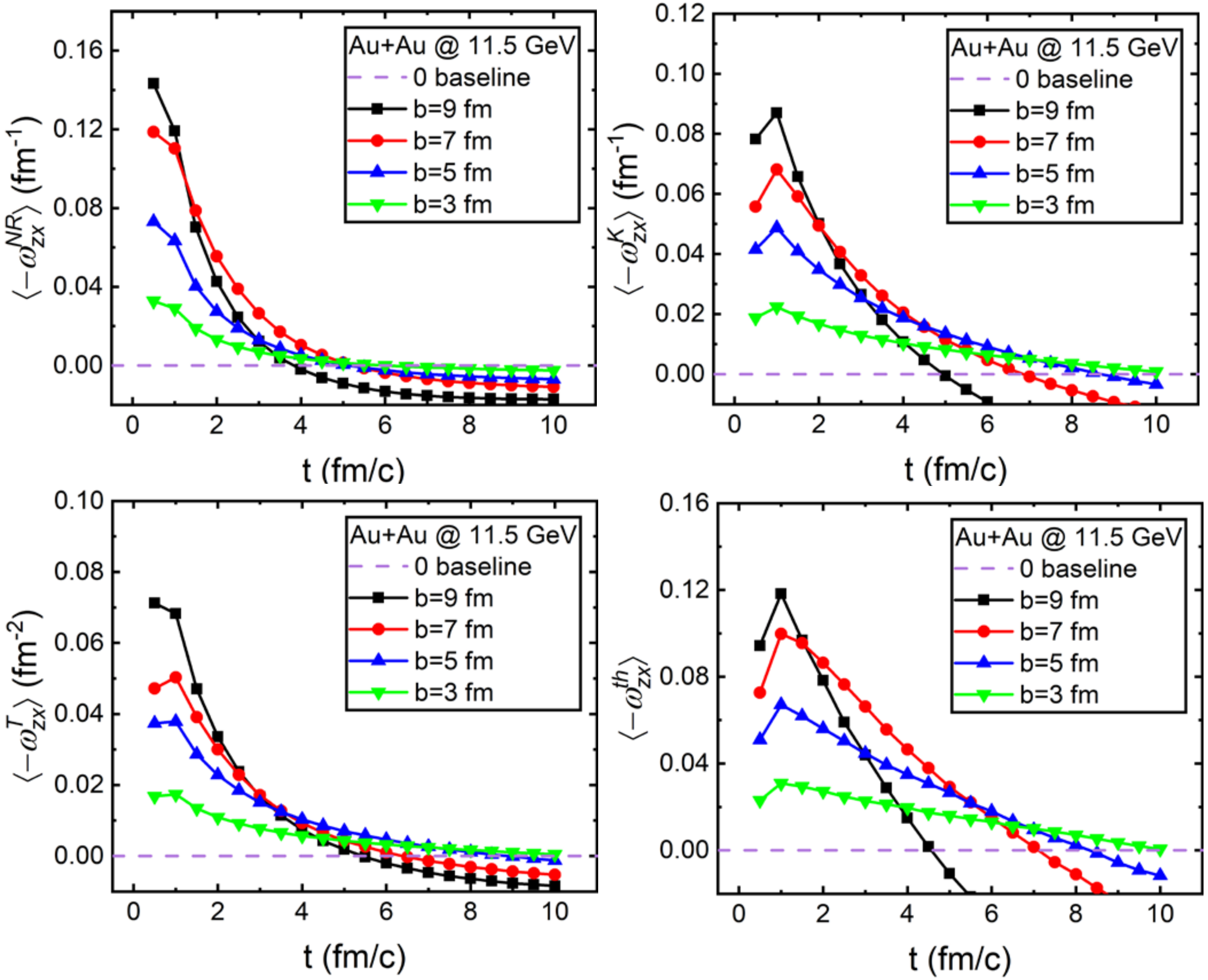


Fig. 20 Results from **PACIAE**

Results: spatial distribution

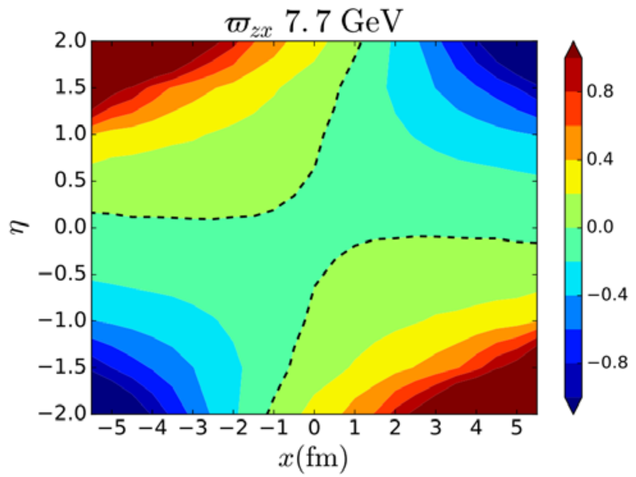


Fig. 21 Thermal vorticity from **AMPT**

[H. Li, et al. , Phys. Rev. C96, 054908 (2017)]

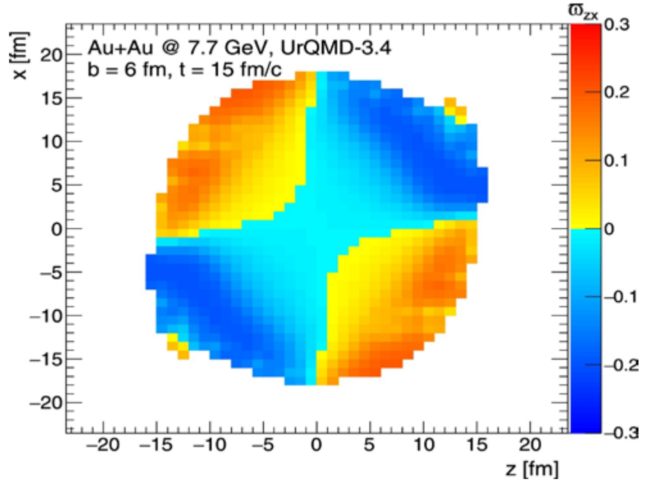


Fig. 22 Thermal vorticity from **UrQMD**

[O. Vitiuk, et al. , Phys. Lett.B 803, 135298 (2020)]

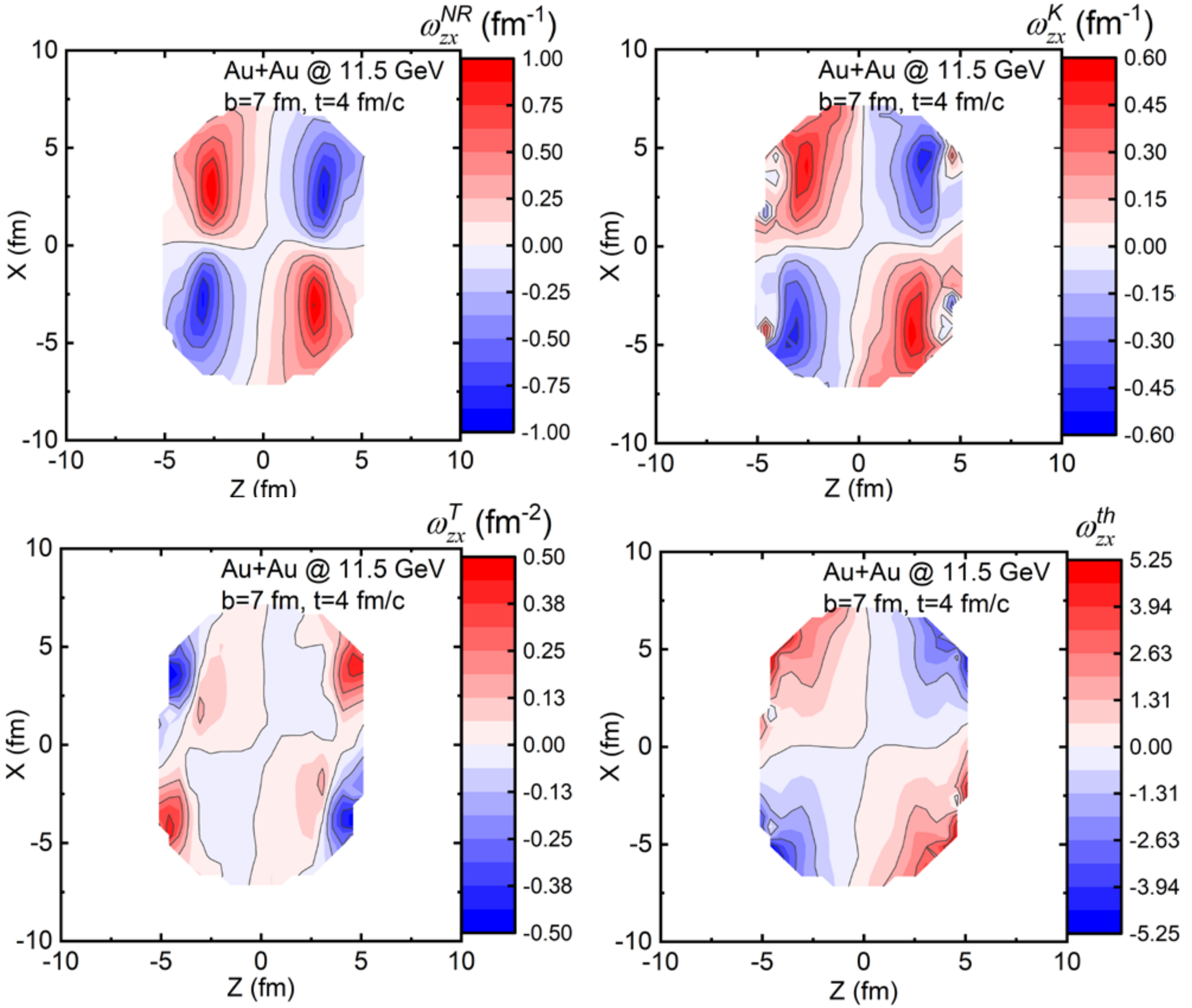


Fig. 23 Results from **PACIAE**

Results: initial vorticity

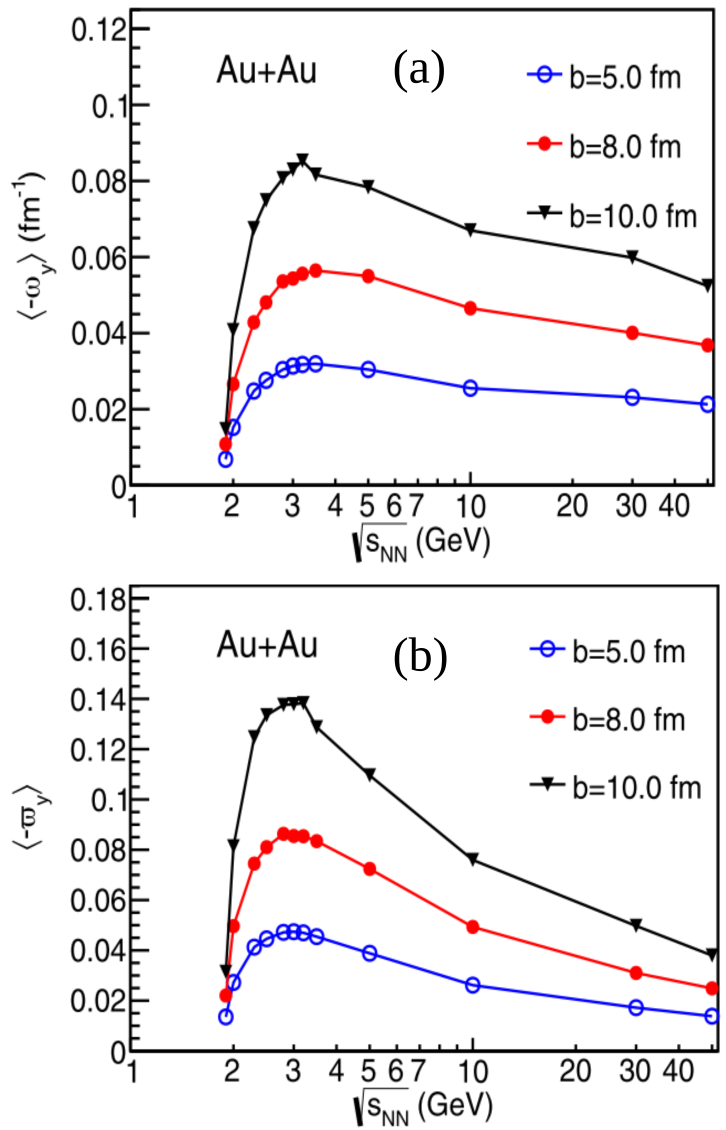


Fig. 7 The initial vorticities in **UrQMD**

[X. G. Deng et al. PRC 101, 064908 (2020)]

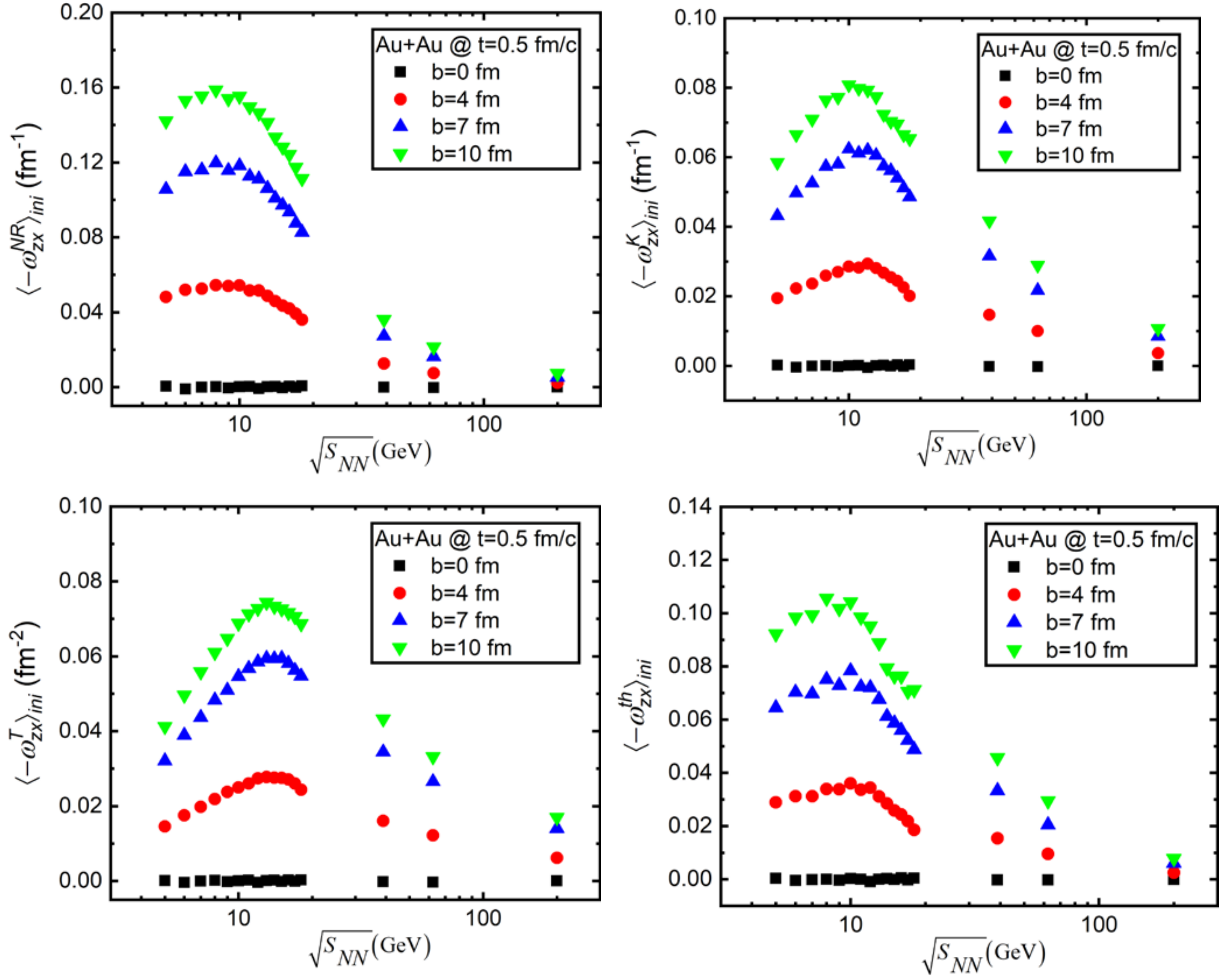
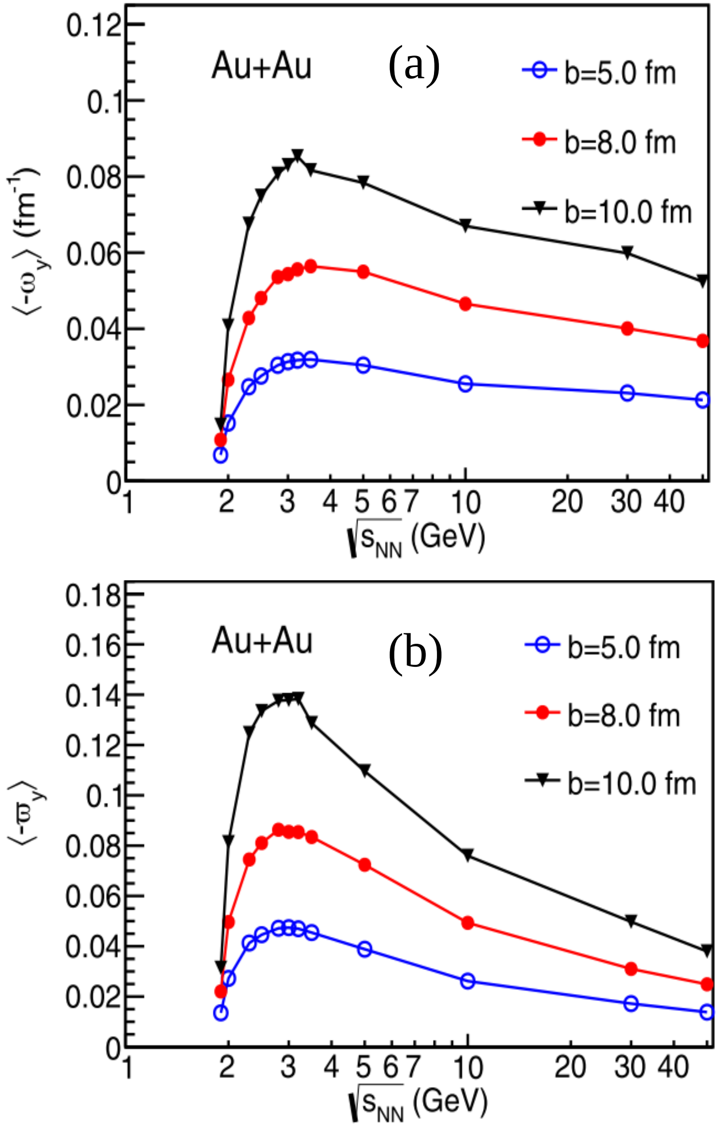


Fig. 24 Results from **PACIAE**

Results: initial vorticity



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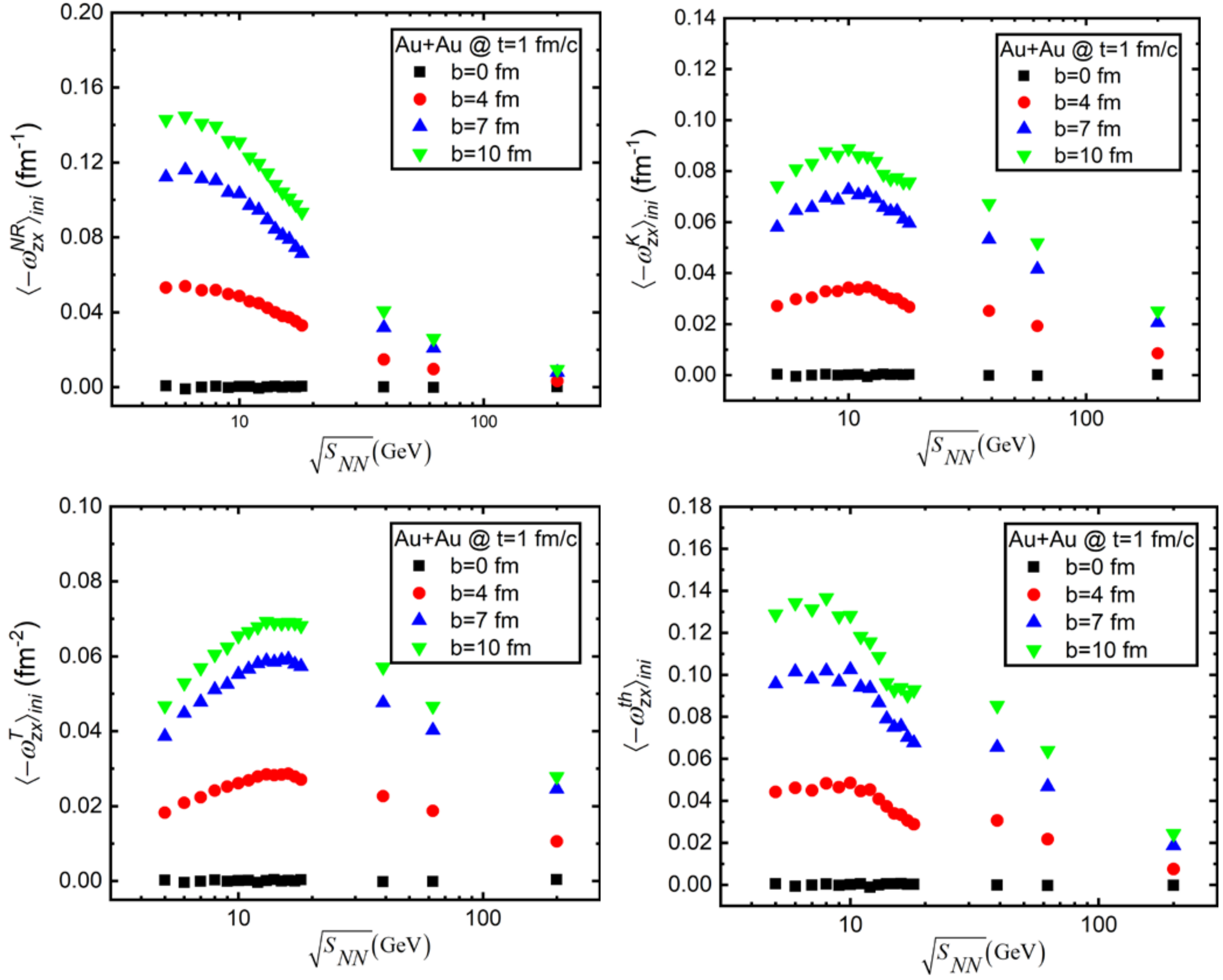


Fig. 25 Results from **PACIAE**

Results: initial vorticity of Hadronic Matter

UrQMD: hadron transport model,
hadron only (Mean-Field, resonances…) ,
without parton

AMPT (version string-melting) :
parton & hadron mixed phase, without gluon

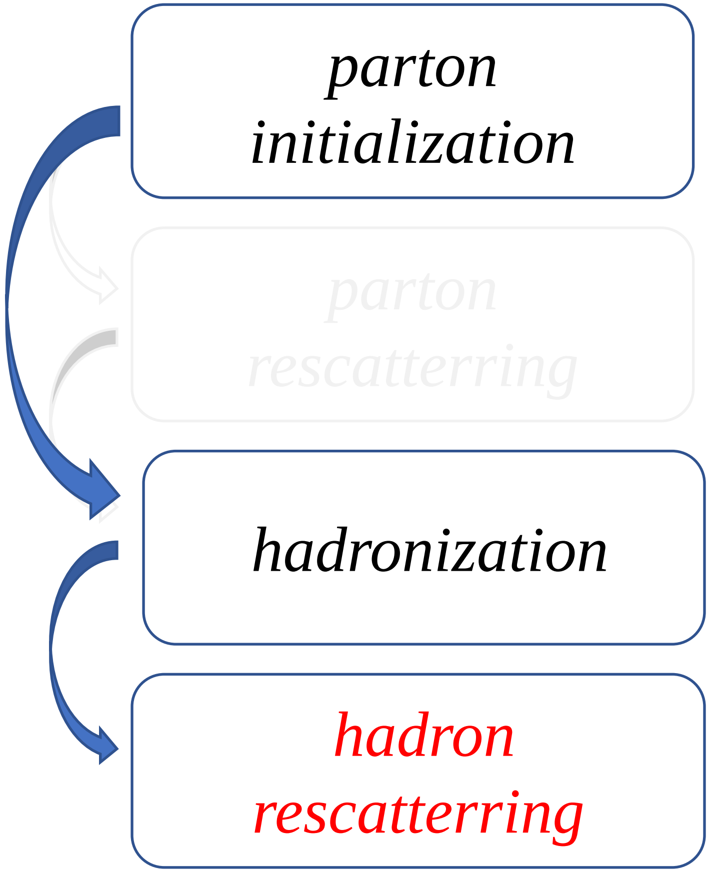
PACIAE: with quark & gluon, but instant freeze-out

↓

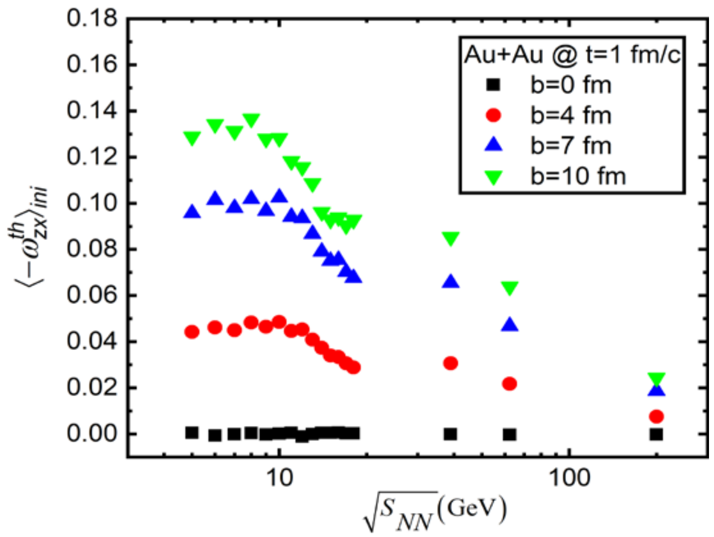
close the partonic evolution stage at low energies

↓

Pure Hadronic Matter



Results: initial vorticity of Hadronic Matter



Thermal vorticity of partons in **PACIAE**

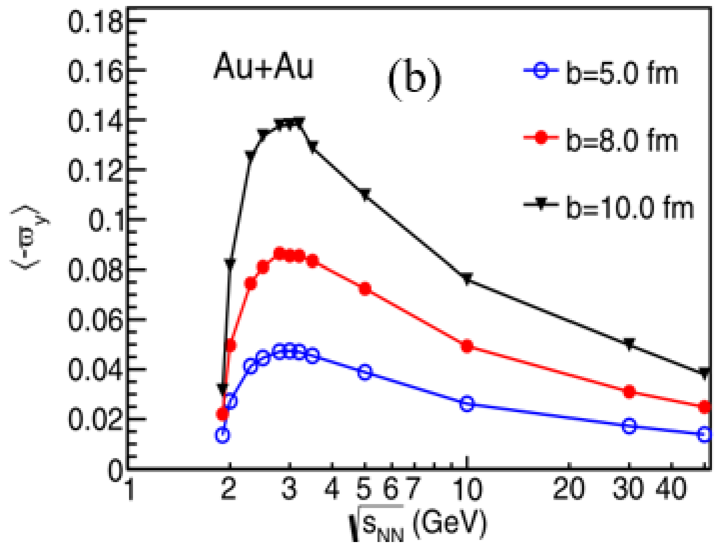


Fig. 7 The initial vorticities in **UrQMD**

[X. G. Deng et al. PRC 101, 064908 (2020)]

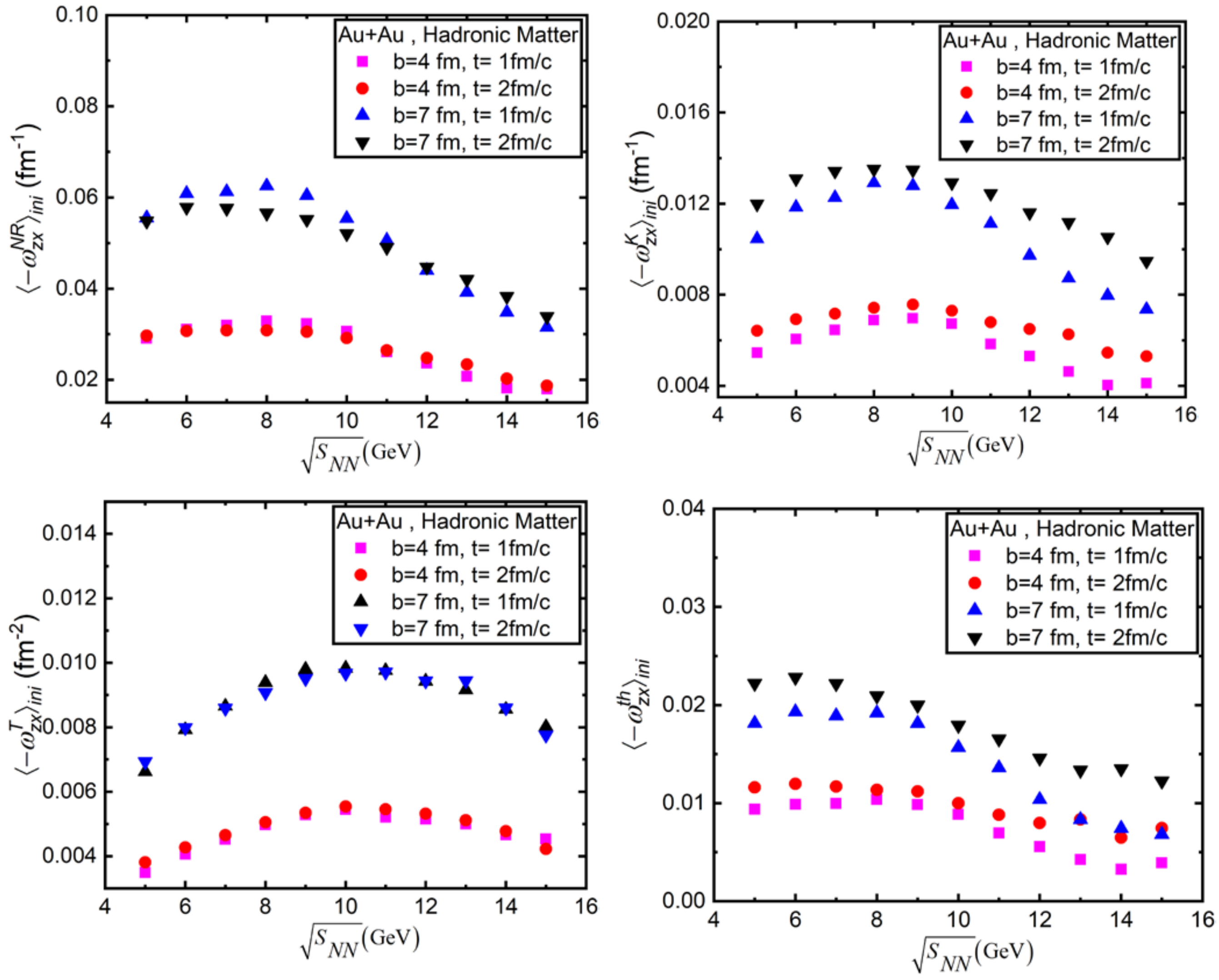


Fig. 26 Results from **PACIAE**

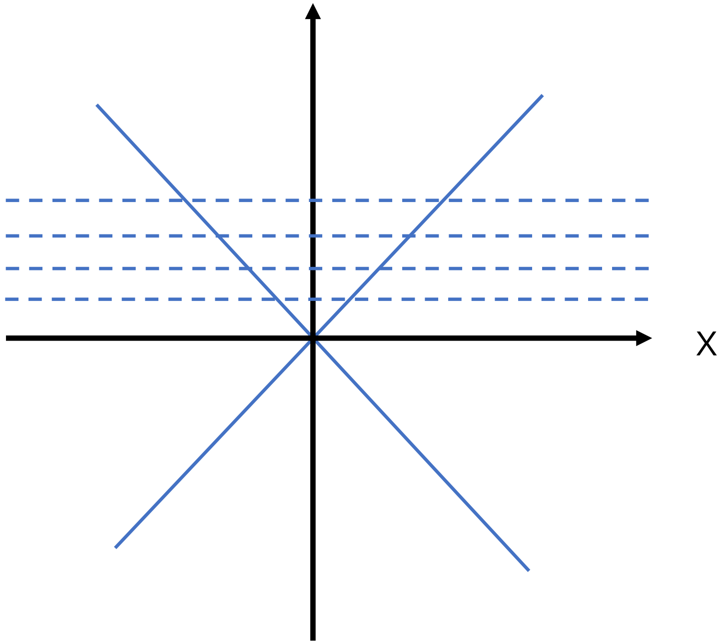
Summary

- We gave a systematic study of four types of vorticities in PACIAE.
- The non-monotonic dependence of the initial vorticities on the collision energies was reconfirmed. ~ 10-15 GeV
- The initial vorticities of pure Hadronic Matter (Hadron Gas) at 5-15 GeV were studied.

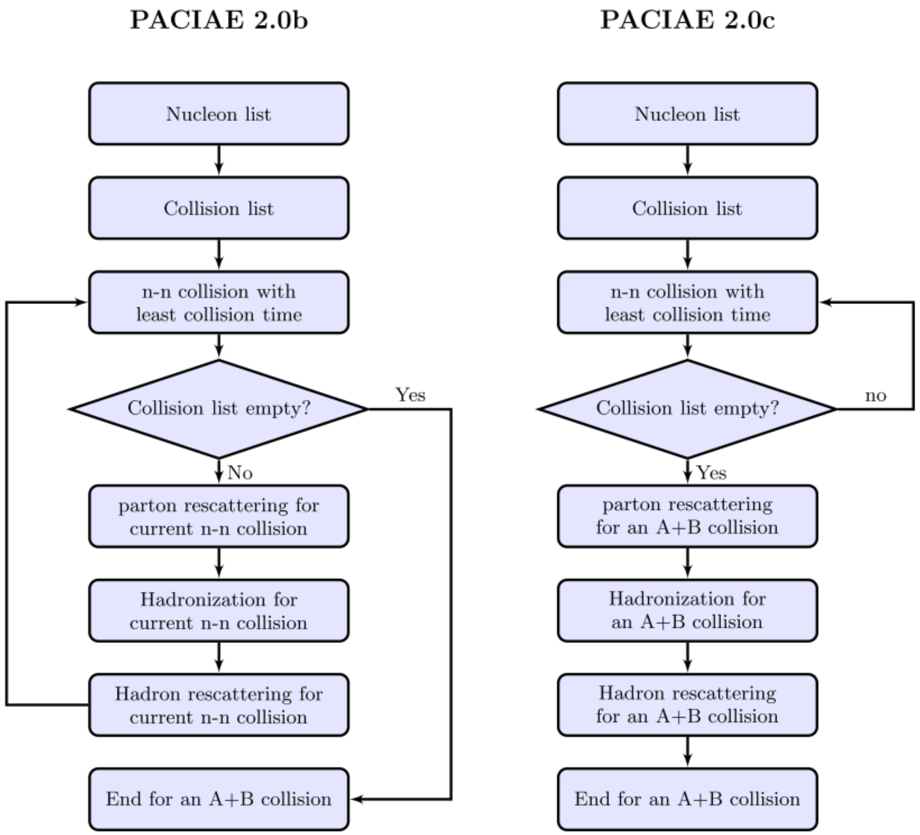
Thanks !

Thank Prof. Larissa and Evgeny for their hospitality during my visit in Norway.
Thank Prof. Yilong for helpful discussion.

Backup



Time slice division



Topological structure of PACIAE version b and c

Backup: extracting temperature in PACIAE b

- multiplicity weighted p_t distribution fitting

$$P(p_t)_{\text{sys}} = \frac{1}{p_t}\frac{dN}{dp_t}$$

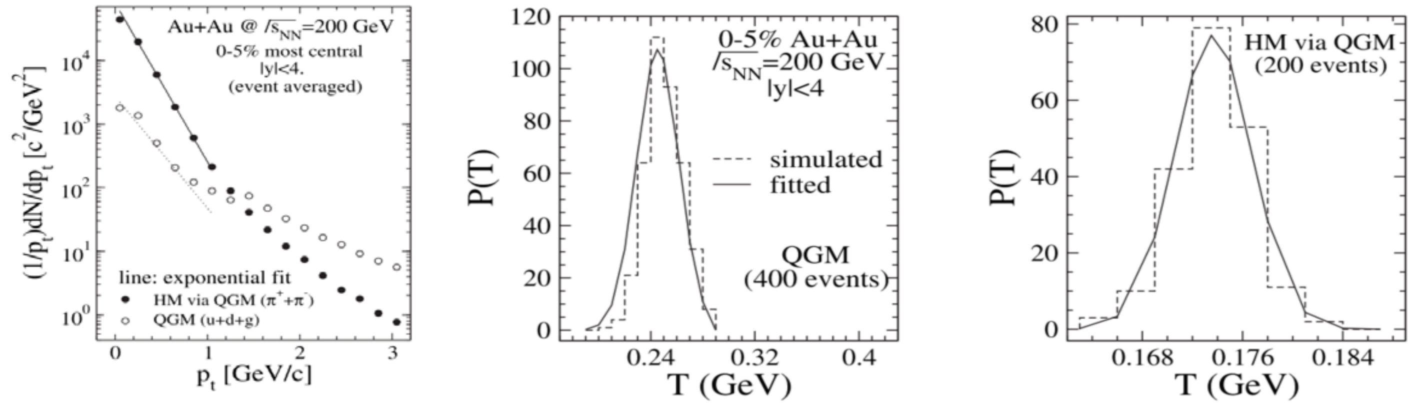
fitting

$$P_T(p_t)_{\text{sys}} = Aexp[-\frac{p_t}{T}]$$

A : normalization factor
p_t : transverse momentum of particles
T : average temperature of the system

$$P(p_t)_{\text{HM}} = \frac{M_{\pi^+}}{M_{\pi^+}+M_{\pi^-}}P(p_t)_{\pi^+} + \frac{M_{\pi^-}}{M_{\pi^+}+M_{\pi^-}}P(p_t)_{\pi^-}$$

$$P(p_t)_{\text{QGM}} = \frac{M_u}{M_u+M_d+M_g}P(p_t)_u + \frac{M_d}{M_u+M_d+M_g}P(p_t)_d + \frac{M_g}{M_u+M_d+M_g}P(p_t)_g$$



p_t temperature fitting and distribution
(Sa, Li et al. 2007)

Backup: extracting temperature in PACIAE b

$$\frac{1}{p_t}\frac{dN}{dp_t} \rightarrow Aexp[-\frac{p_t}{T}]$$

A : normalization factor

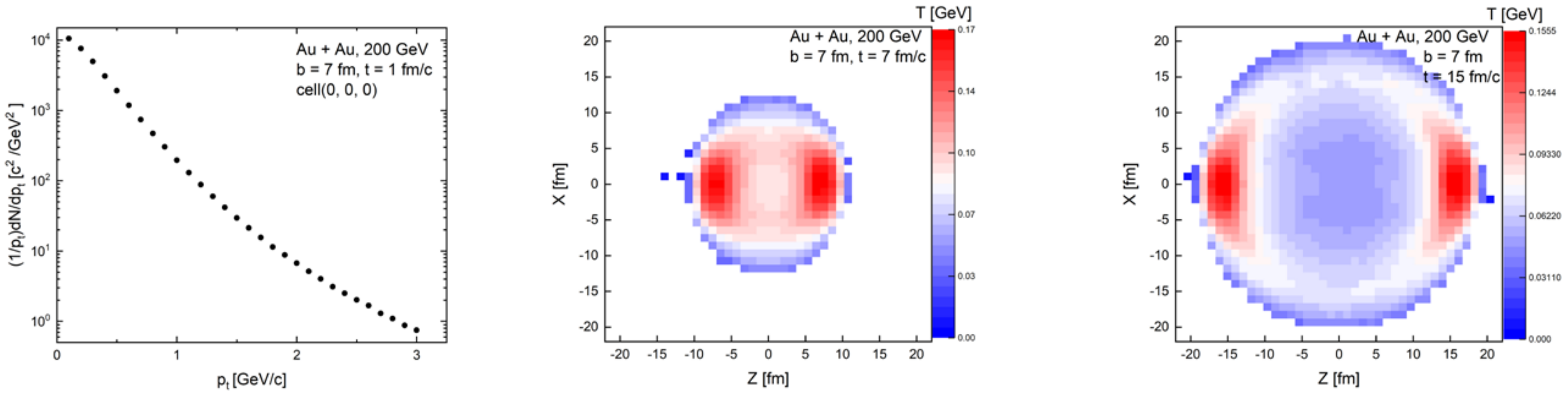
$$P(p_t)_{sys} = \frac{M_q}{M_{tot}}P(p_t)_q + \frac{M_q}{M_{tot}}P(p_t)_g + \frac{M_q}{M_{tot}}P(p_t)_H$$

$M_{tot} = Mq + Mg + MH$ quark + gluon + hadron

In single cell,

$$Ti = \frac{-p_t}{ln\left(\left(\frac{1}{p_t}\frac{dN}{dp_t}\right)_i / A\right)}$$

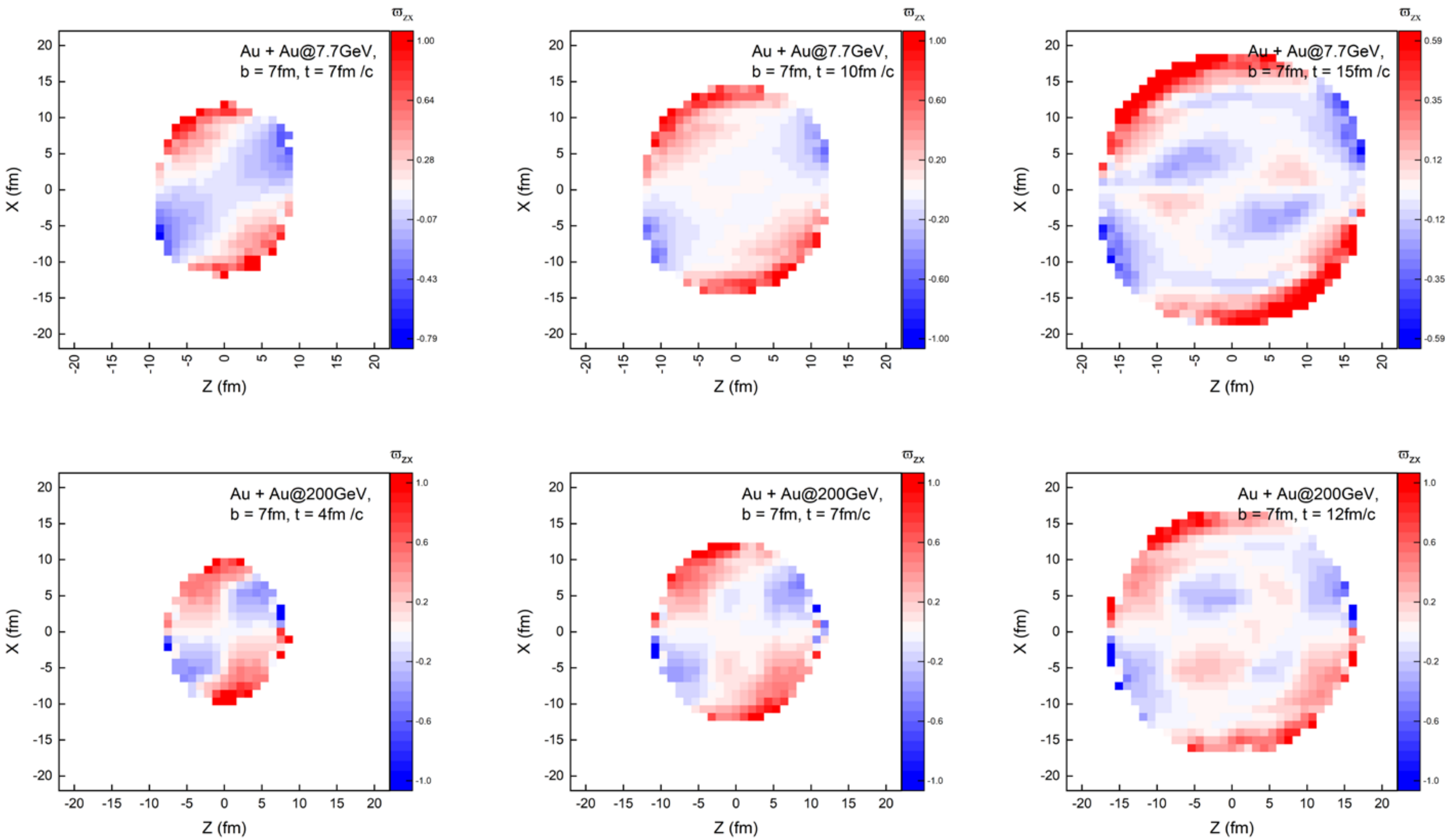
$$T_{cell} = \sum_i^N \frac{T_i}{N}$$



p_t spectrum in cell (0,0,0) , temperature distribution on the reaction plane at diffirent time

i, N: the selected distribution point of p_t

Backup: vorticity in PACIAE b



$$\boldsymbol{\varpi}_T = (\varpi_{0x}, \varpi_{0y}, \varpi_{0z}) = \frac{1}{2}\left[\nabla\left(\frac{\gamma}{T}\right) + \partial_t\left(\frac{\gamma \mathbf{v}}{T}\right)\right]$$

$$\boldsymbol{\varpi}_S = (\varpi_{yz}, \varpi_{zx}, \varpi_{xy}) = \frac{1}{2}\nabla \times \left(\frac{\gamma \mathbf{v}}{T}\right).$$