Λ polarization and spin correlations in a vortical fluid

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with
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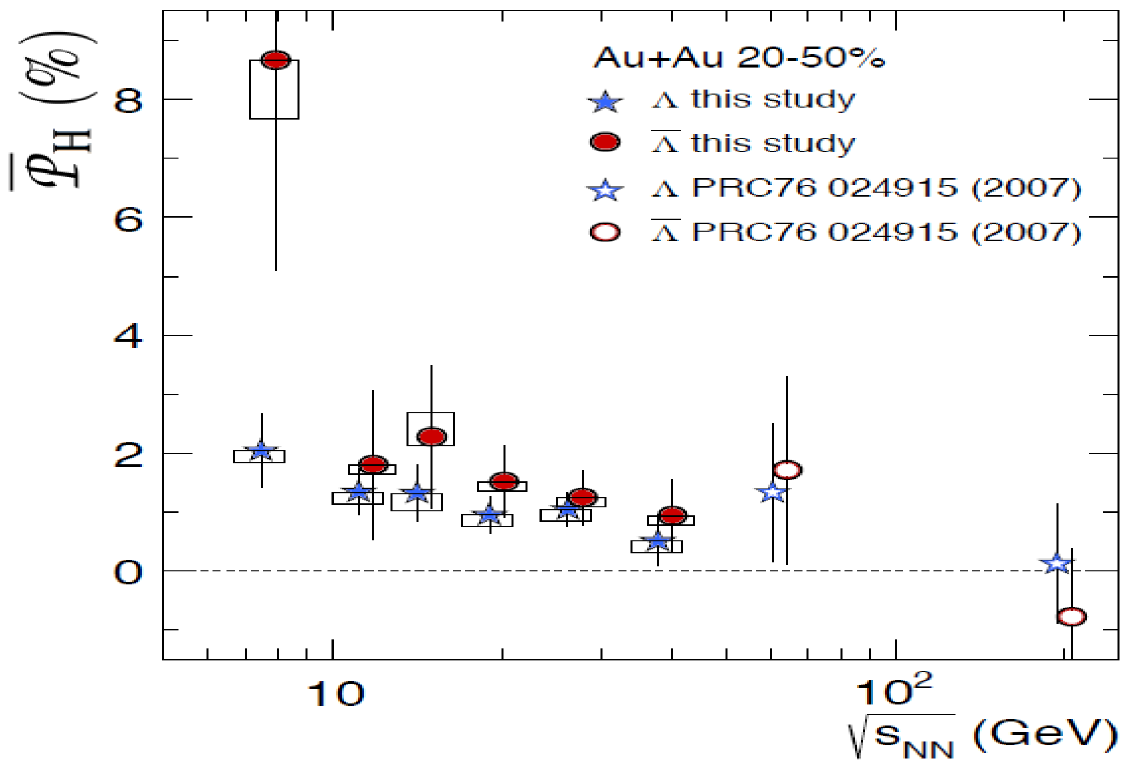
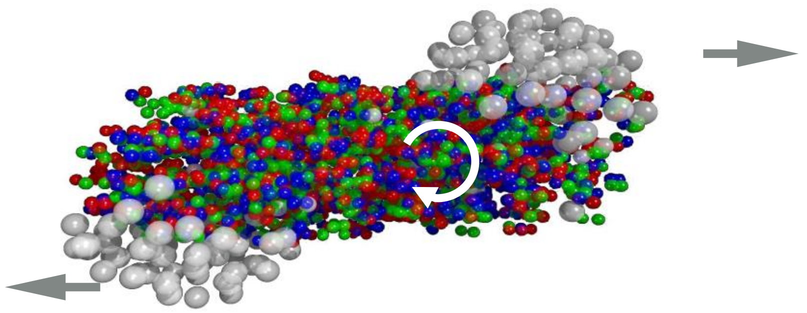
STAR collab., 1701.06657



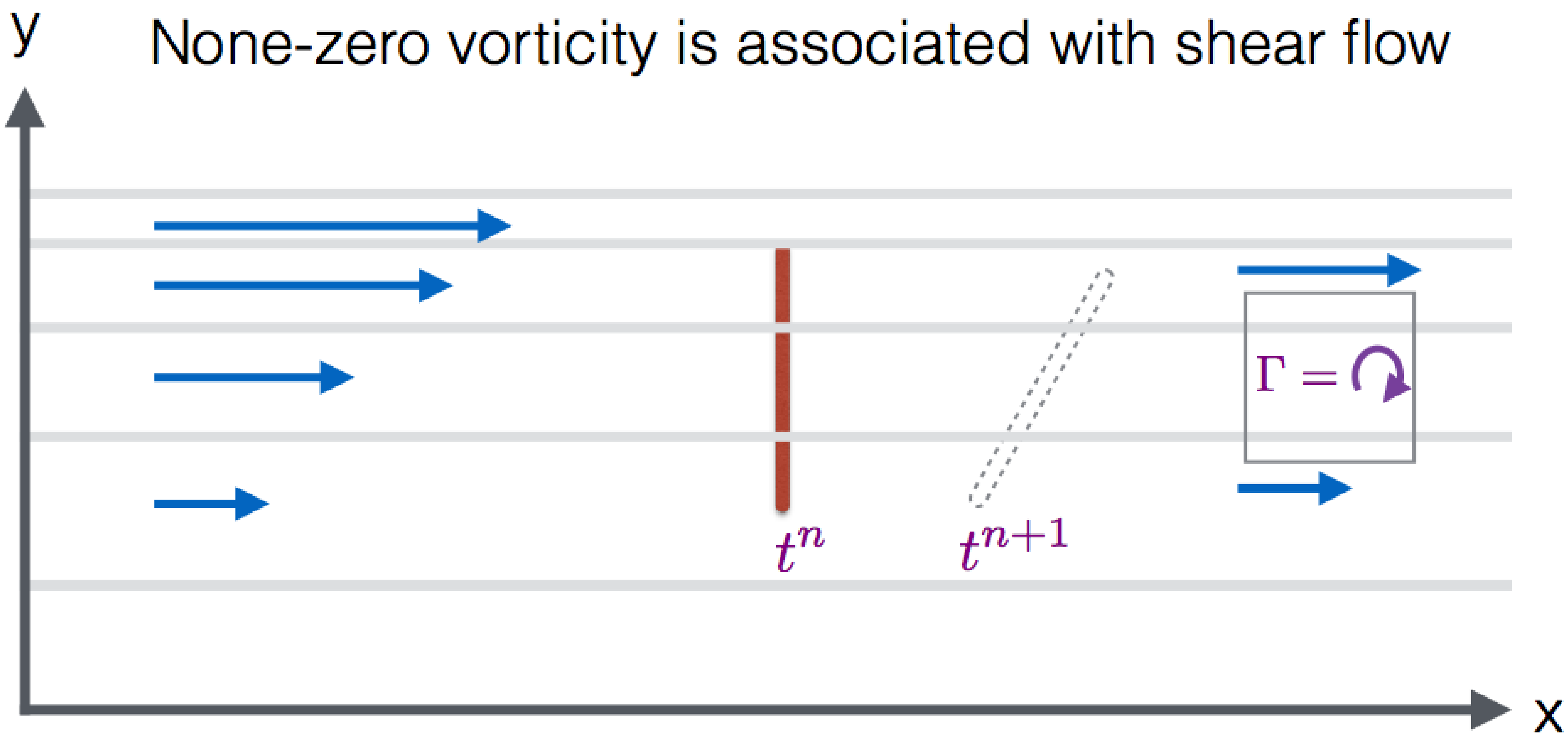


$\Lambda(uds) \to \pi^- + p$

- self analyzing
- weak decay

- Low energy > high energy
  - Bjorken scaling at high energy
  - Thermal vorticity
- $\bar{\Lambda} > \Lambda > 0$
  - Pauli-blocking
  - Spin-Magnetic coupling

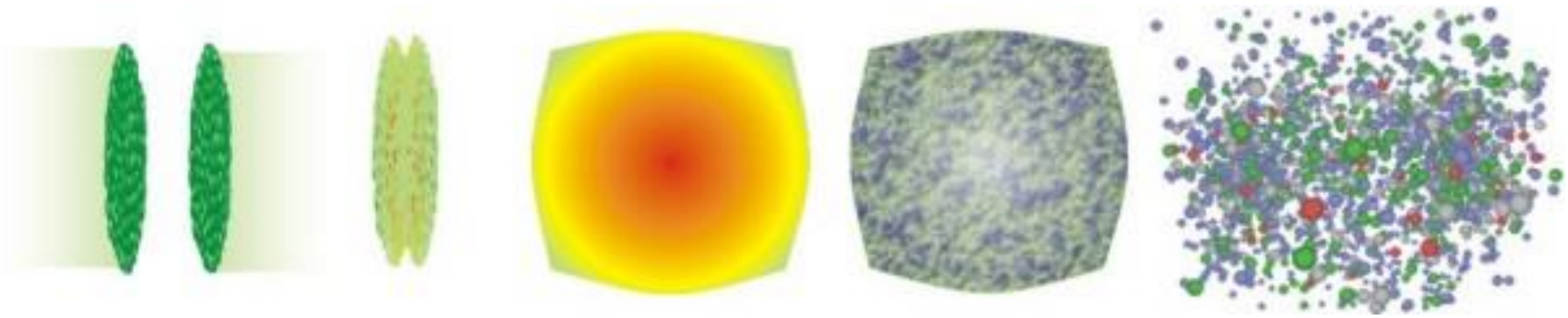
Z. T. Liang, X. N. Wang, PRL. 94, 102301(2005)， F. Becattini, F. Piccinini, Ann. Phys. 323, 2452 (2008); F. Becattini, F. Piccinini, J. Rizzo, PRC 77, 024906 (2008)



vorticity: $$\omega_z = \partial_x v_y - \partial_y v_x$$

circulation: $$\Gamma = \oint \vec{v} \cdot d\vec{r} = \iint \nabla \times \vec{v} \cdot d\vec{A} = \iint \vec{\omega} \cdot d\vec{A}$$

Fig from Steffen A. Bass



$$\nabla_\mu T^{\mu\nu} = 0 \tag{1}$$

$$\Delta^{\mu\nu\alpha\beta} u^\lambda \nabla_\lambda \pi_{\alpha\beta} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\rm NS}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\nabla_\lambda u^\lambda \tag{2}$$

where

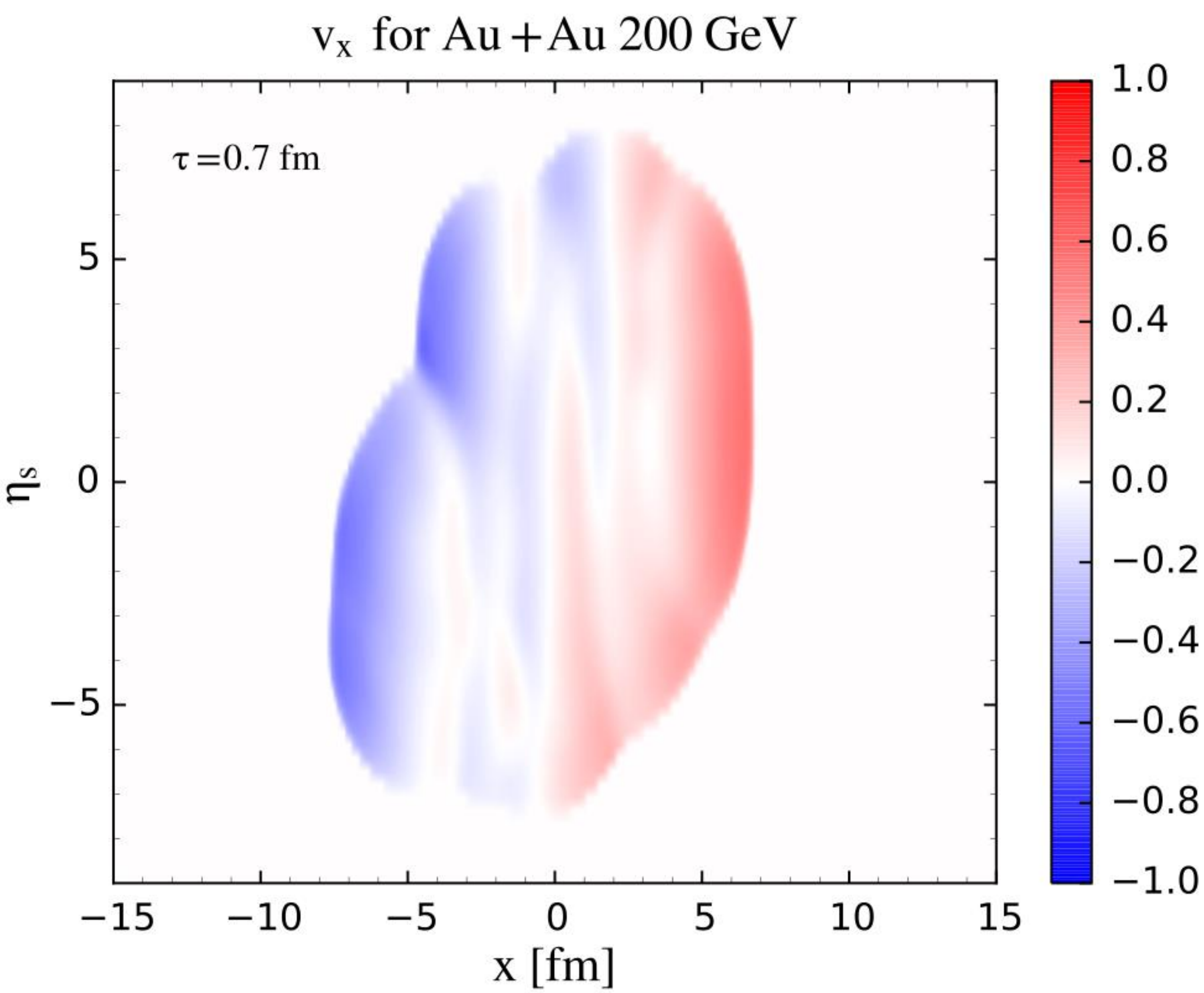
$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu} \tag{3}$$

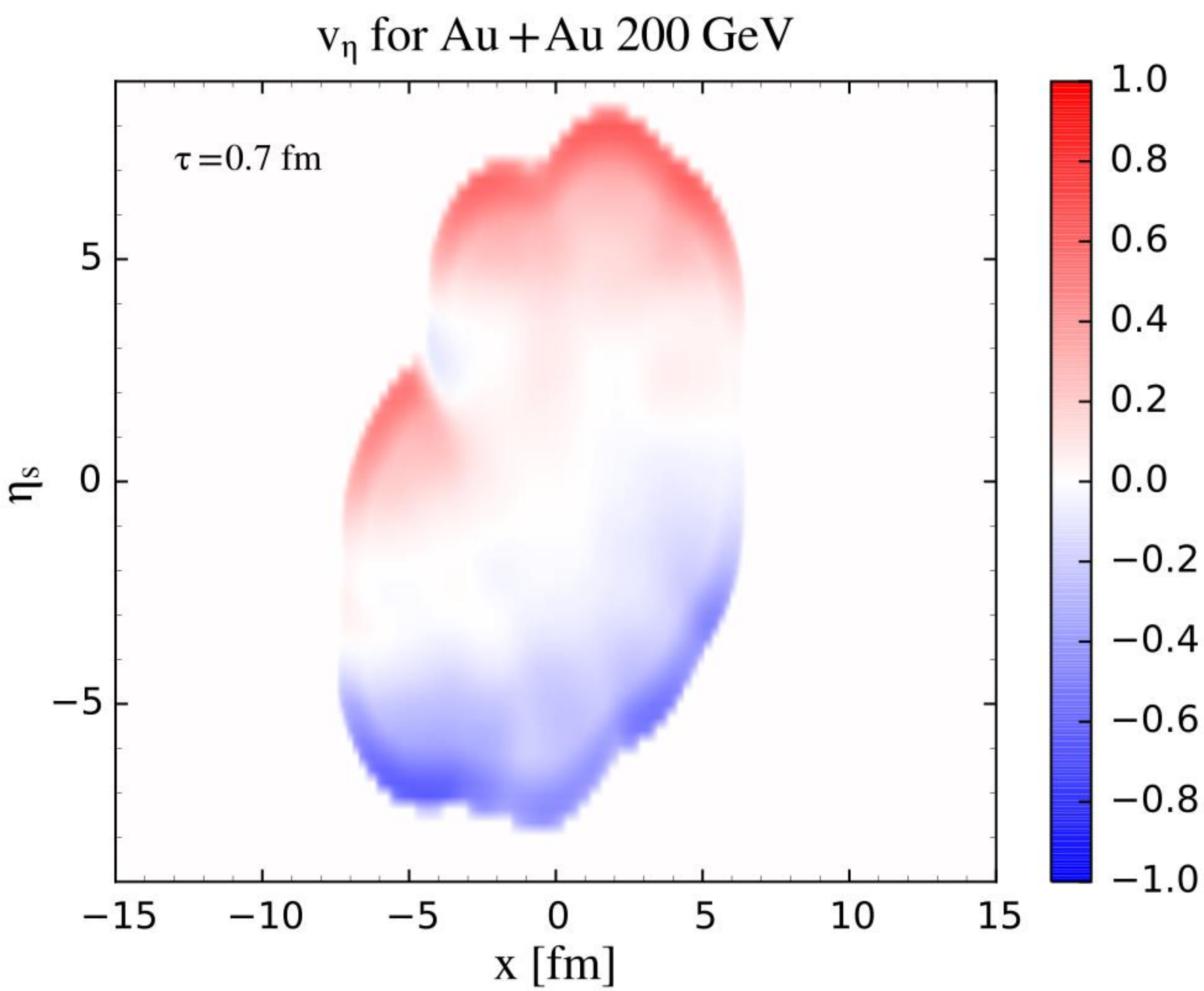
$$\Delta^{\mu\nu\alpha\beta} = \frac{1}{2}(\Delta^{\mu\alpha}\Delta^{\nu\beta} + \Delta^{\nu\alpha}\Delta^{\mu\beta}) - \frac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta} \tag{4}$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu, \;\; g^{\mu\nu} = diag(1, -1, -1, -\tau^{-2}) \tag{5}$$

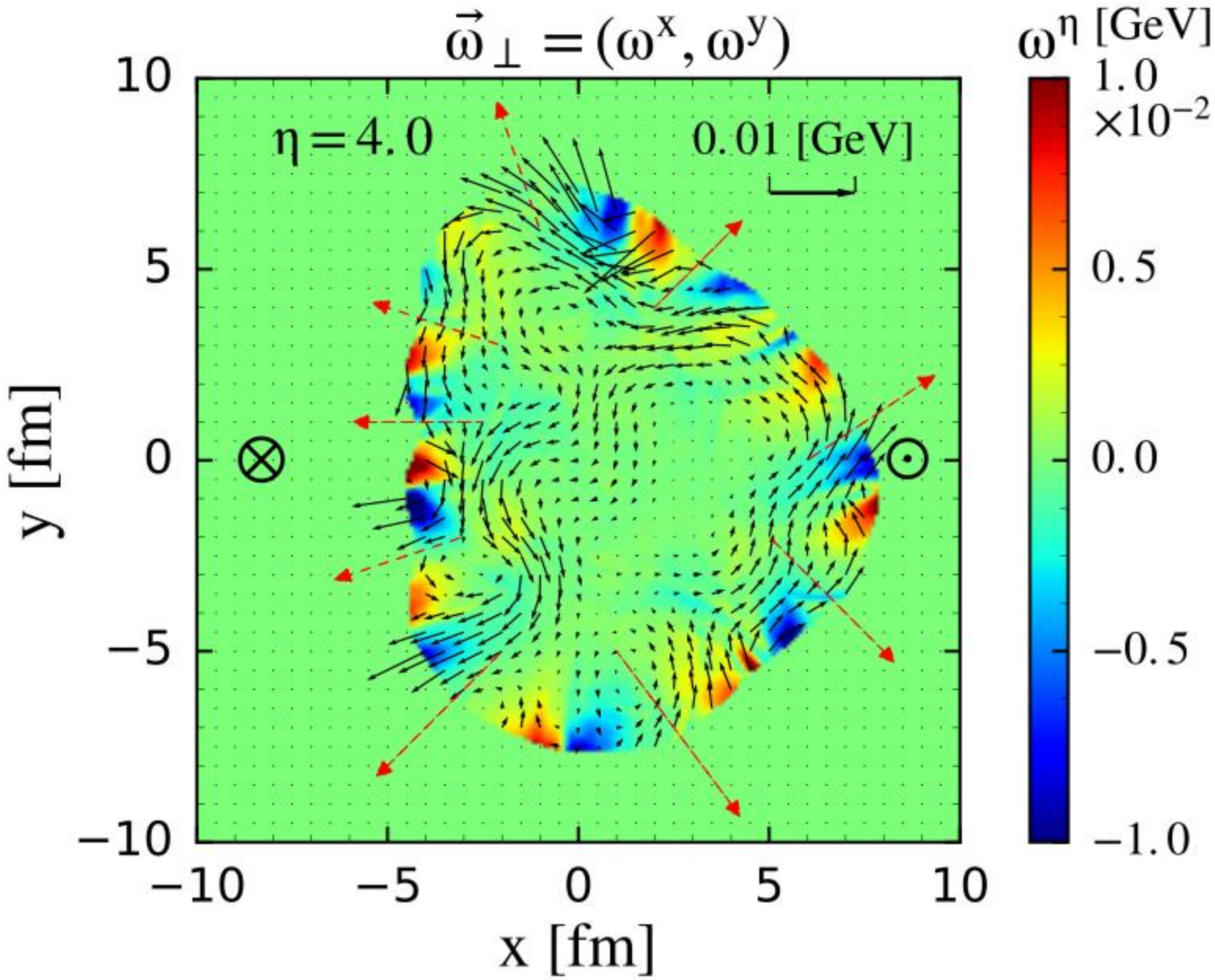
ε and P are the energy density and pressure, u^μ is the fluid velocity vector. ∇_μ is the covariant derivative.

- Constraints: $P = P(\varepsilon)$, $u_\mu u^\mu = 1$, $u_\mu \pi^{\mu\nu} = 0$, $\pi^\mu_\mu = 0$.



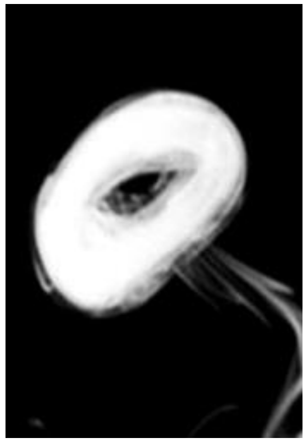


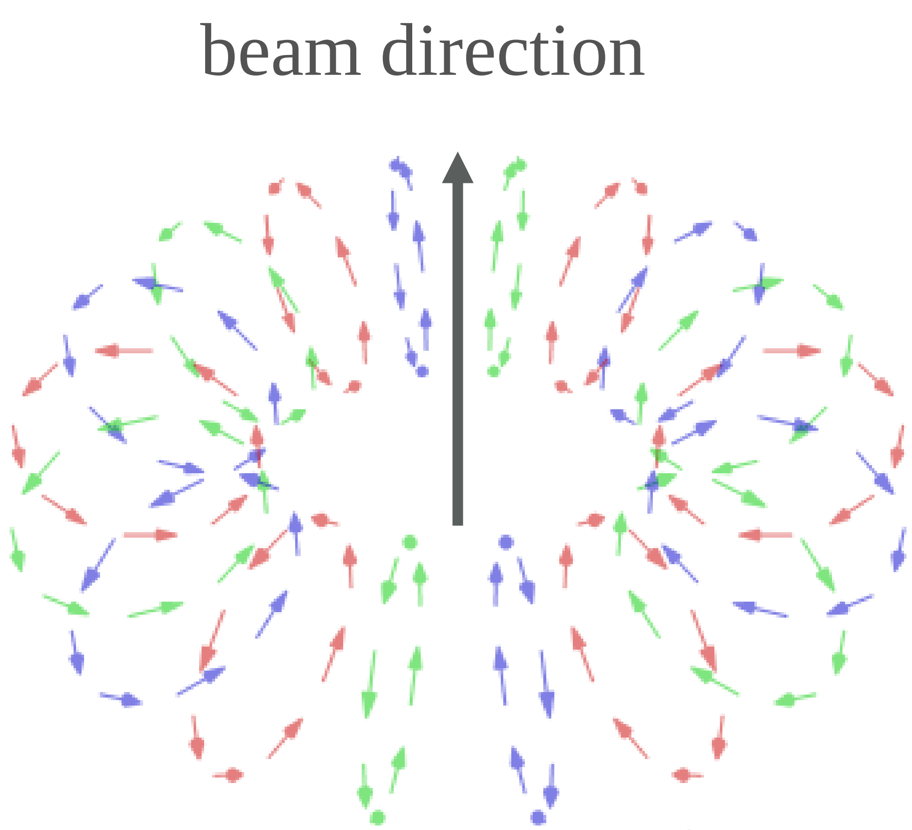
- AMPT initial condition + hydrodynamics
- Start with: $v_x = v_y = v_\eta = 0$ at $\tau = 0.4$fm



L.G.Pang, H.Petersen, Q.Wang & XNW
PRL 117, 192301 (2016)

- Vortex pair in 2D
- Vortex ring in 3D = Toroidal (smoke ring) vortical fluid





by Lucas V. Barbosa
from WiKi Pedia

- Vortex ring appears in the longitudinal direction
- Ridge-like vortex pairs in the transverse plane.

- Polarization at freezeout hypersurface

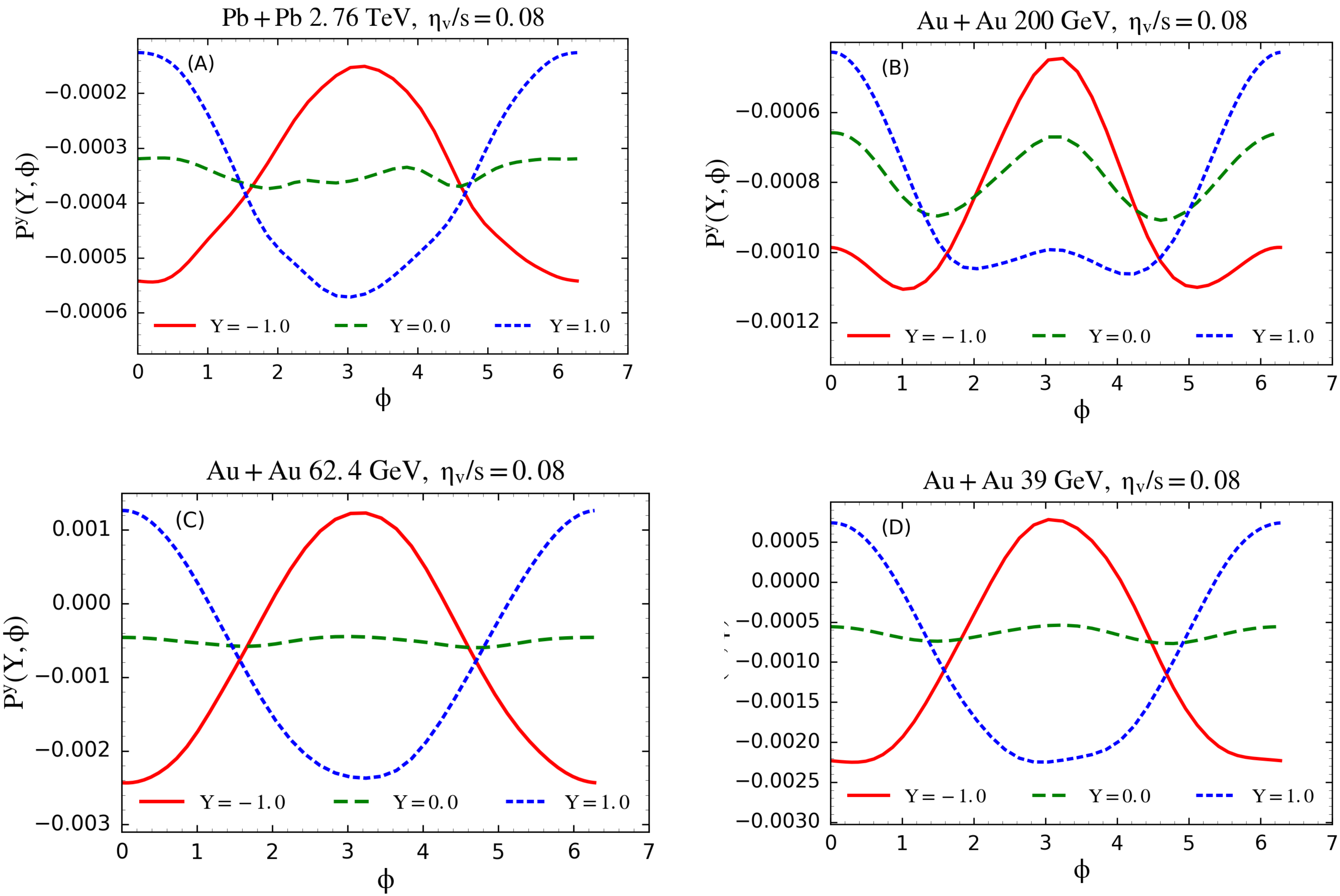
$$P^{\mu} \equiv \frac{d\Pi^{\mu}(p)/d^3p}{dN/d^3p} = \frac{\hbar}{4m}\frac{\int d\Sigma_{\alpha}p^{\alpha}\tilde{\Omega}^{\mu\nu}p_{\nu}n_f(1-n_f)}{\int d\Sigma_{\alpha}p^{\alpha}n_f}$$

where $\tilde{\Omega}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\partial_{\rho}(u_{\sigma}/T)$ is the thermal vorticity

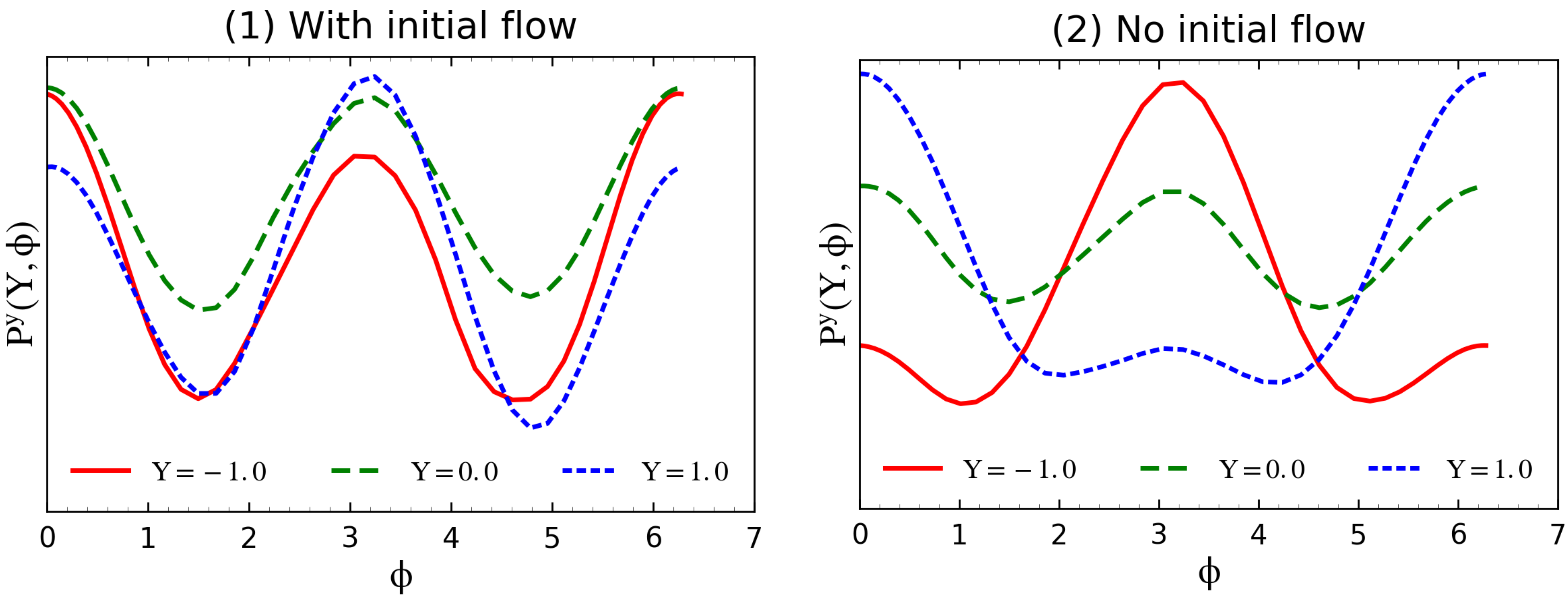
- Spatial distribution of local vorticity is correlated to momentum distribution (pt, rapidity and azimuthal angle) of baryon spin density by strong collective flow.

F. Becattini, et al., Ann. Phys. 338, 32 (2013)
RH. Fang, LG. Pang, Q.Wang & XN.Wang, PRC 94,192301(2016)

Local polarization distributions, 20-30%



- Local polarization along y direction is
  - Larger for lower beam energies
  - Larger for larger rapidities than mid-rapidity
  - Azimuthal angle distributions are anti-symmetric for forward and backward rapidity
  - For mid-rapidity, $P^y(Y, \phi) \approx P^y(Y, \phi + \pi)$
  - Shifted by global orbital angular momentum



- $|P^y(Y,\phi) - P^y(Y,\phi+\pi)|$ is much smaller when there is initial fluid velocity
- The effect of asymmetric energy density distribution along x is suppressed by initial flow.

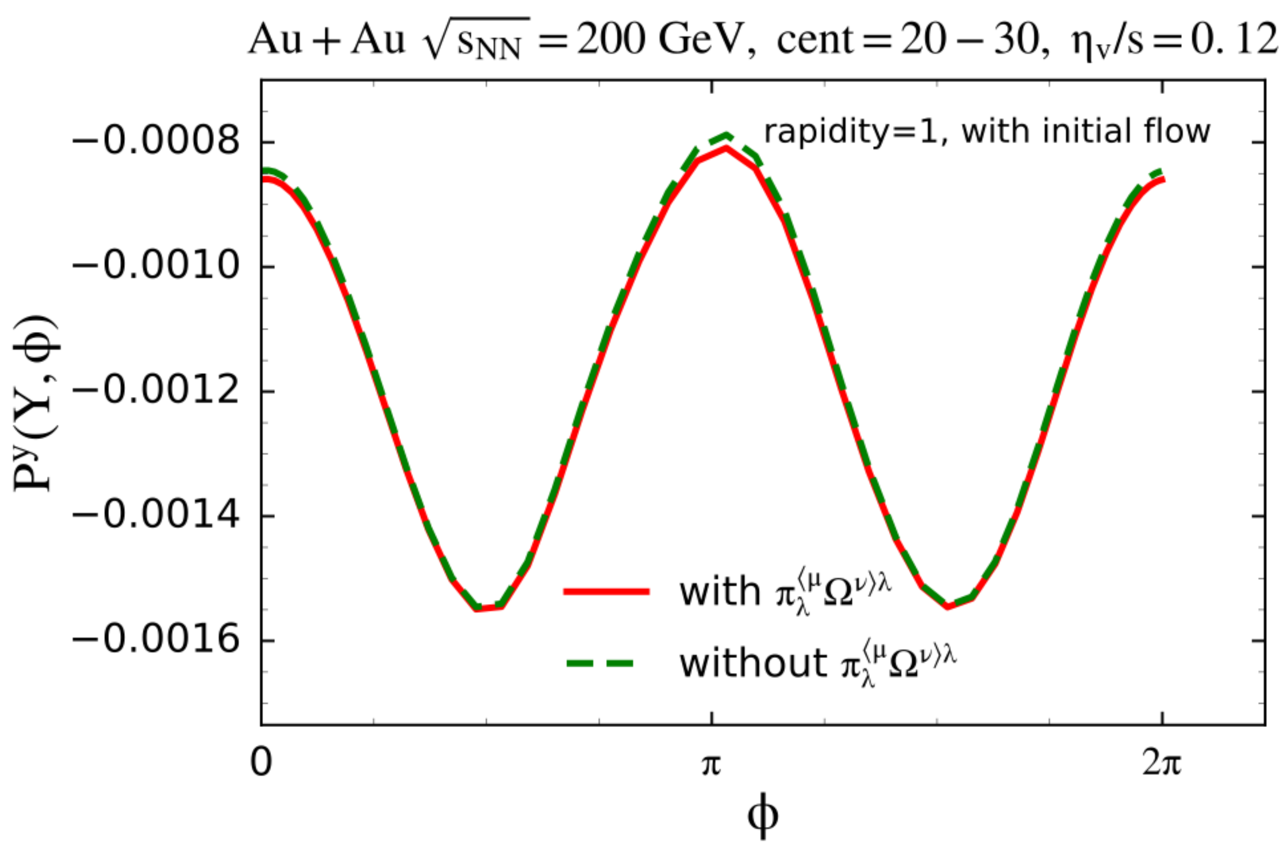
$$\Delta^{\mu\nu\alpha\beta}u^\lambda\nabla_\lambda\pi_{\alpha\beta} = -\frac{\pi^{\mu\nu}-\eta_v\sigma^{\mu\nu}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\nabla_\lambda u^\lambda + 2\pi_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} - \frac{\lambda_3}{\tau_\pi}\omega_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda}$$

where

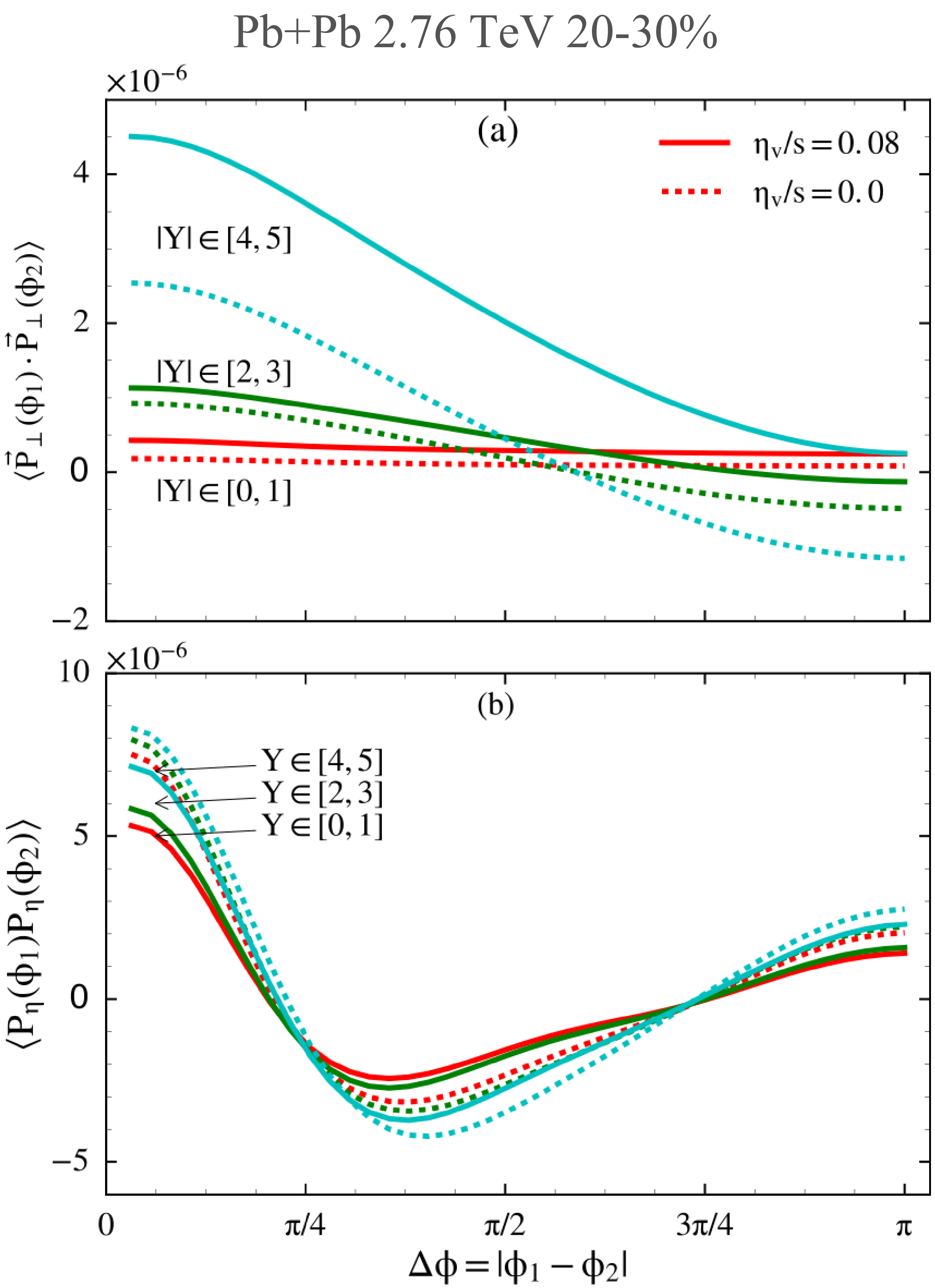
$$\omega^{\mu\nu} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(\nabla_\alpha u_\beta - \nabla_\beta u_\alpha)$$

$$A^{\langle\mu\nu\rangle} \equiv \Delta^{\mu\nu\alpha\beta}A_{\alpha\beta}$$

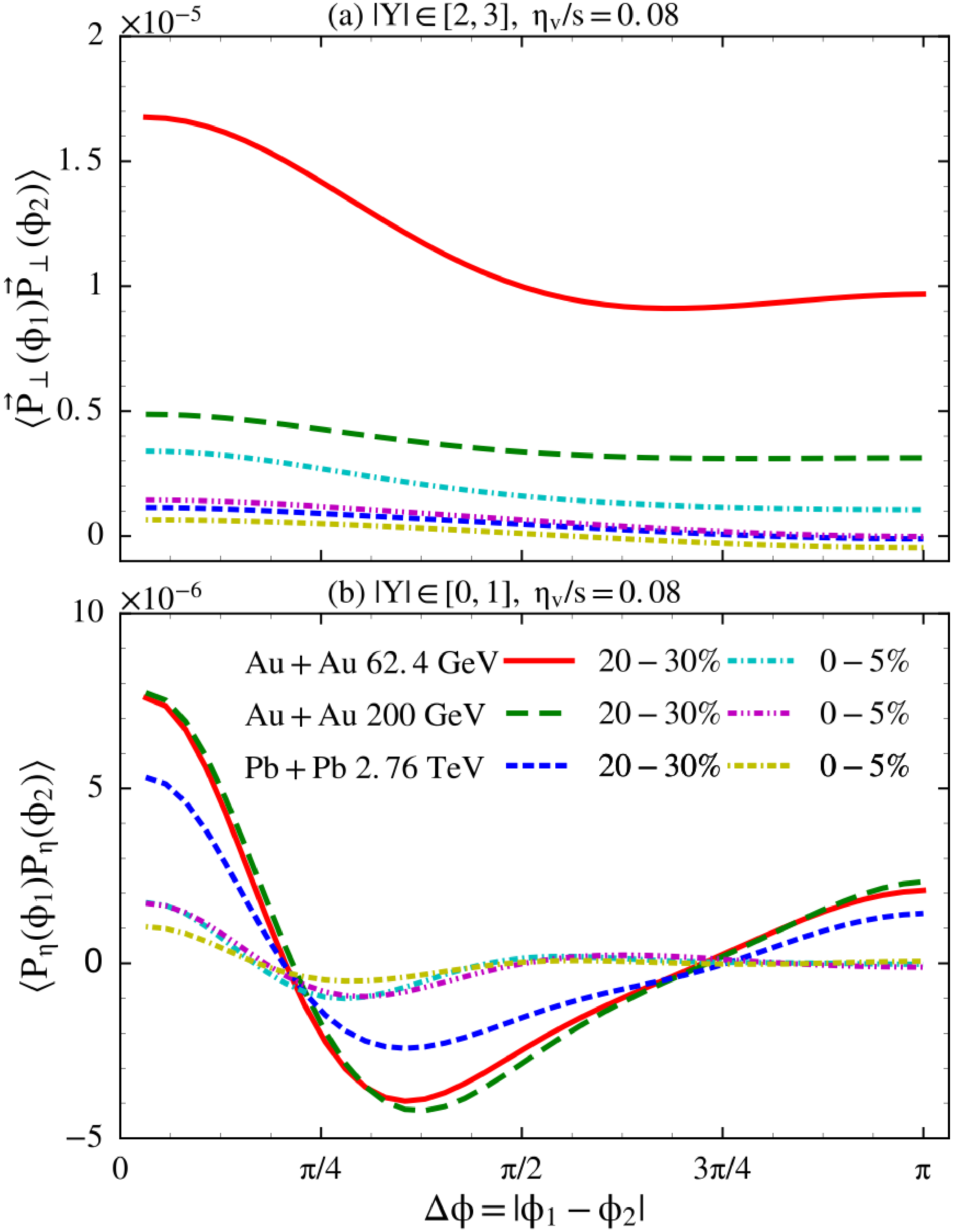
small effect



- Unknown λ_3
- For $\lambda_3 = 1$
  - Code is unstable with fluctuating initial conditions



- (a) $\cos(\Delta\phi)$ azimuthal distribution due to local polarization (vortex ring).
- Shear viscosity increases global polarization
- (b) The dependence of longitudinal spin correlation on rapidity is weak



- (a) Polarization are stronger at lower beam energies and peripheral collisions.
- (b) The longitudinal spin correlation is coupled to the transverse collision geometry
- The beam energy dependence for longitudinal spin is weak.

- Velocity: average all particles in cells over 10^6 events

$$\mathbf{v}(x, y, \eta) = \frac{\sum_i \sum_j \mathbf{p}_{ij}}{\sum_i \sum_j E_{ij}}$$

- Vorticity: computed from velocity by finite differential method (FDM)
  - Non-relativistic vorticity:

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

  - Relativistic vorticity:

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

Spin (pseudo)vector in covariant form

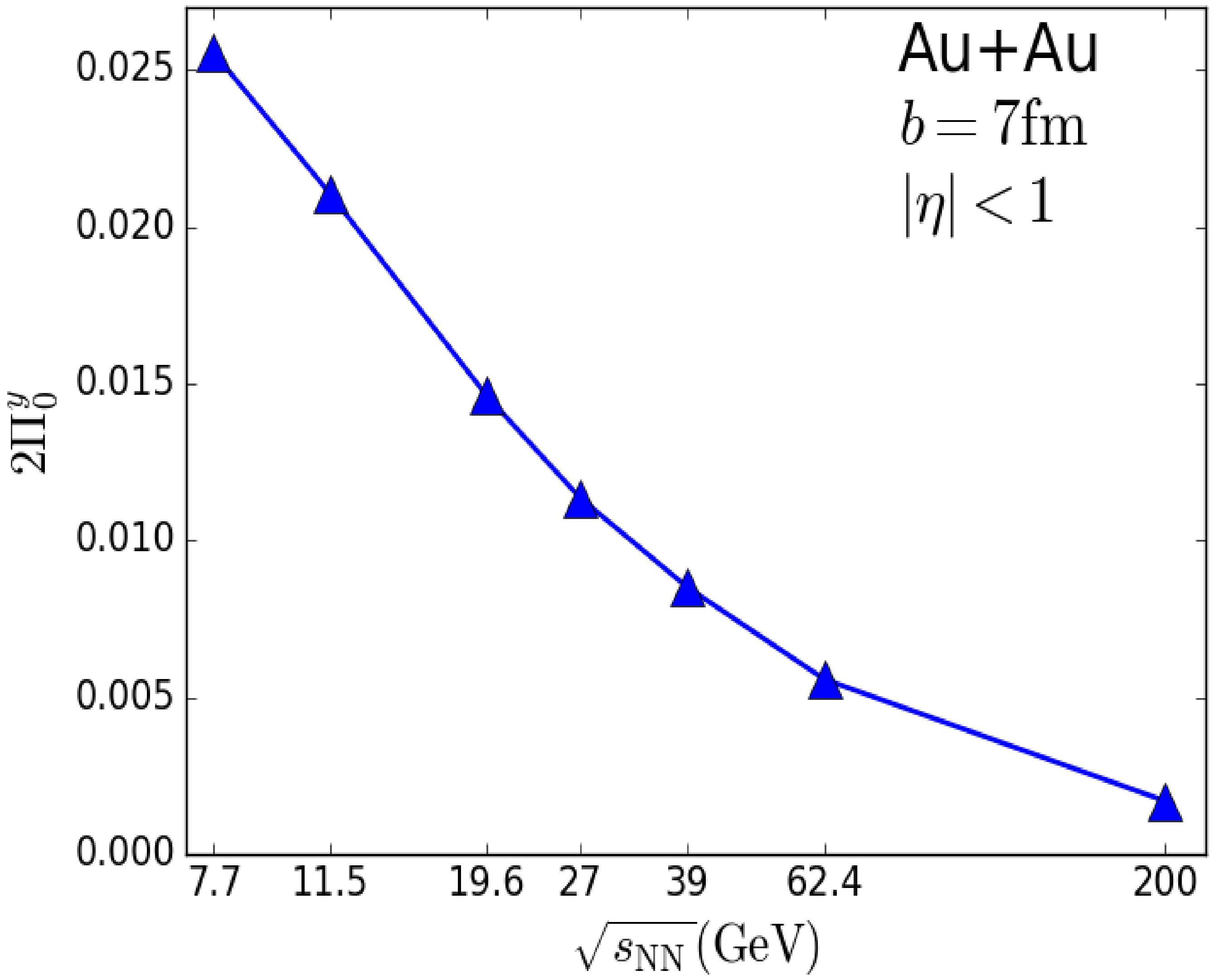
$$S^\mu(x,p) = -\frac{1}{8mT}\epsilon^{\mu\nu\rho\sigma}p_\nu\tilde{\omega}_{\rho\sigma},$$
$$\tilde{\omega}_{\mu\nu} = \frac{1}{2}\left(\partial_\nu u_\mu - \partial_\mu u_\nu\right).$$

In Lab frame (Λ has momentum)

$$\mathbf{S}_0(x,p) = \mathbf{S} - \frac{\mathbf{p}\cdot\mathbf{S}}{\epsilon\,(m+\epsilon)}\mathbf{p}.$$

Mean polarization

$$\mathbf{\Pi}_0 = \langle \mathbf{S}_0 \rangle$$



Hui Li, Xia, LGP, Wang, work in progress

- Global polarization
  - Signal is strong at beam energy scan region
  - Possible to estimate the magnitude of magnetic field
  - Small at top RHIC and LHC energy
- Spin correlation
  - Transverse spin distribution/correlation is sensitive to initial fluid velocity.
  - Longitudinal spin correlation survives at LHC energy and mid-rapidity (unique opportunity—strong signal with high statistics)

Outlook

- Ingredients for quantitative studies
  - Net baryon density in initial condition, equation of states and transport coefficients
  - Spin-magnetic coupling, relativistic magneto-hydrodynamics
  - Initial fluid velocity