Local Λ polarization and local spin alignment

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The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

outline

- Global & local Λ polarization
  - From phenomenological aspect
  - A group of local polarization effects
  - Circular Λ polarization

- Local spin alignment of vector meson

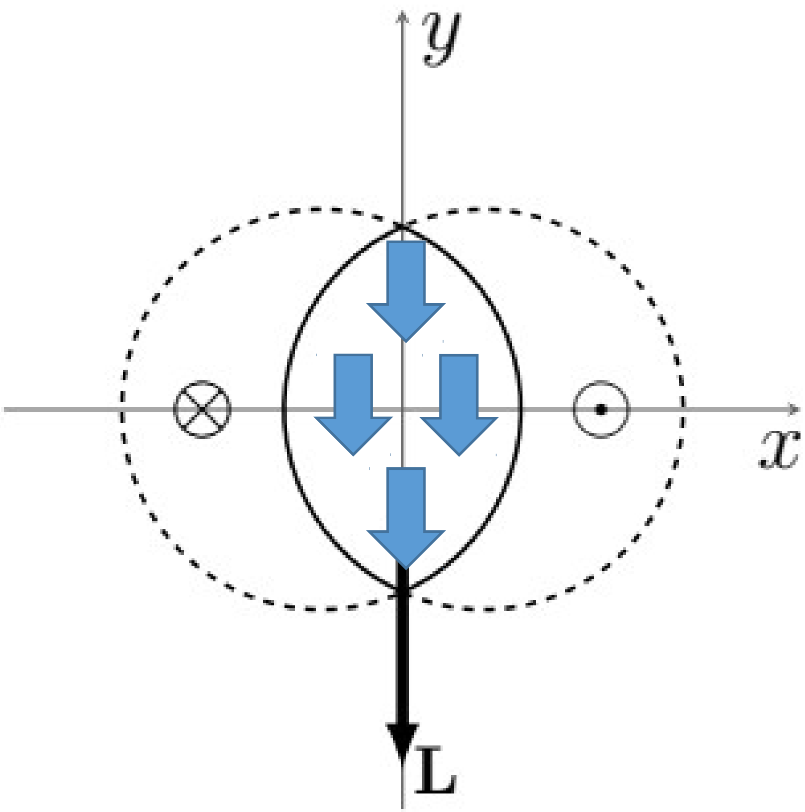
  [X.L. Xia, Hui Li, Xu-Guang Huang, in preparation]
  - Non-vanishing effect on global spin alignment.

Global polarization

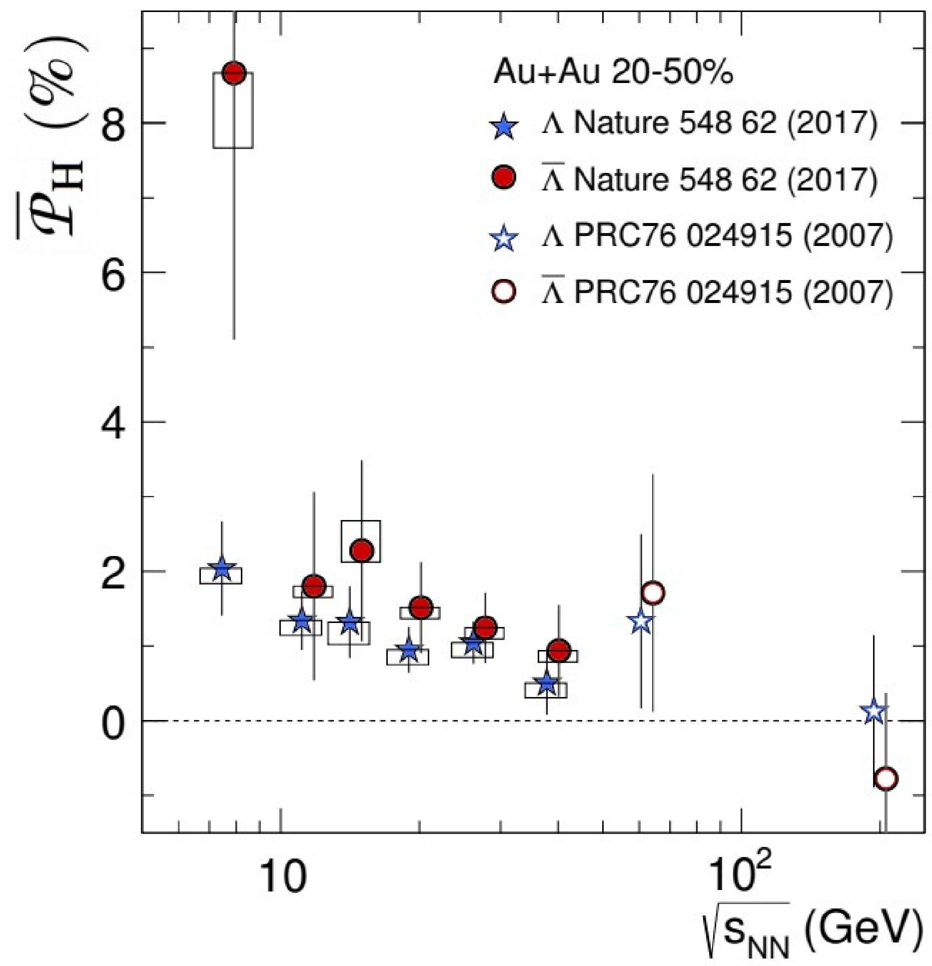
- Large angular momentum can transfer to the spin degrees of freedom.

  Liang, Wang, PRL (2005)

  Voloshin, nucl-th/0410089

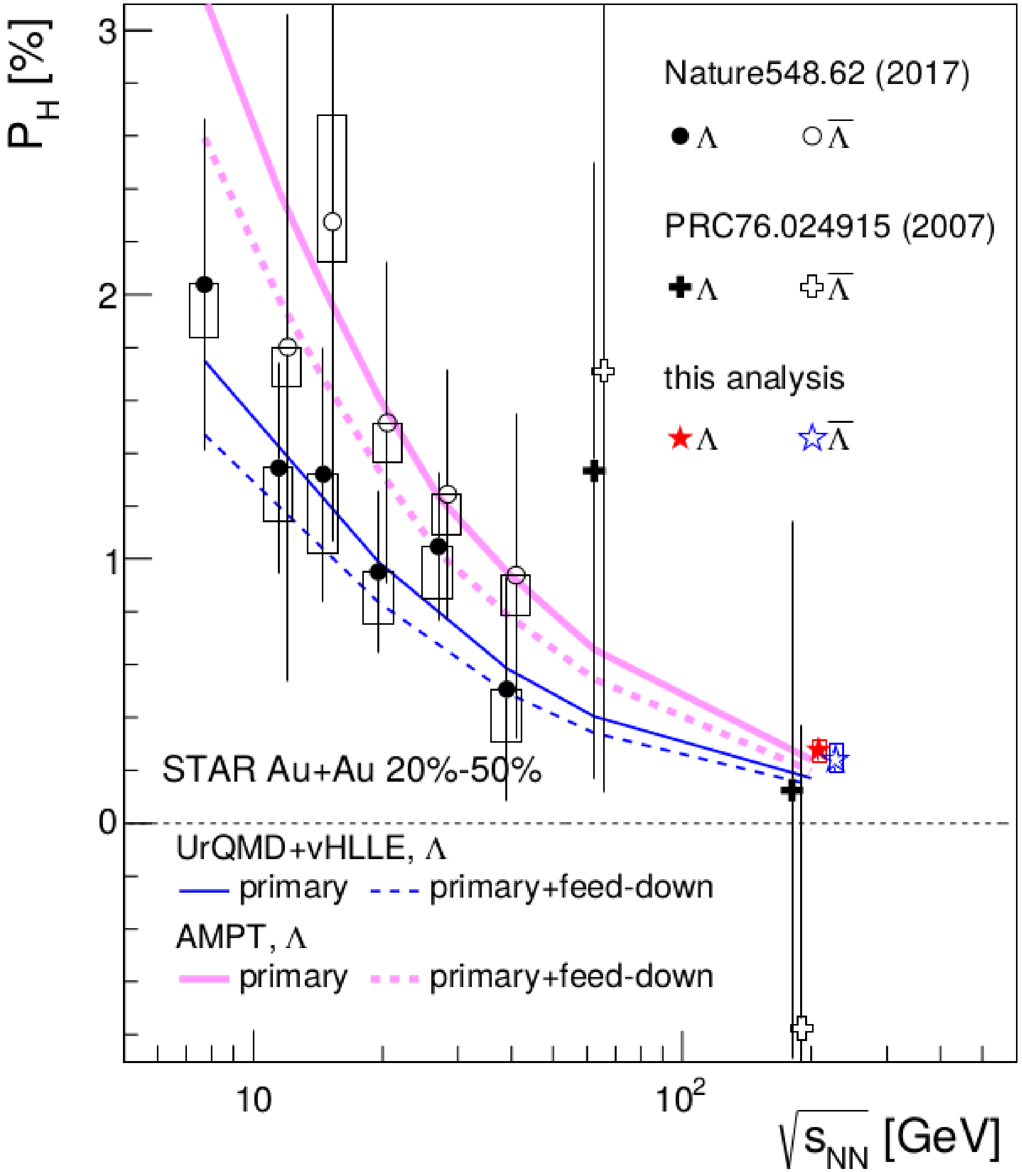


STAR Nature 548 62 (2017)



Beam energy dependence

STAR PRC 98, 014910 (2018)



Hydrodynamics:

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

- Karpenko-Becattini, EPJC (2017)
- Xie-Wang-Csernai, PRC (2017)

AMPT, map to fulid:

- Li-Pang-Wang-Xia, PRC (2017)
- Shi-Li-Liao, PLB (2019)
- Wei-Deng-Huang, PRC (2019)

CKT:

- Sun-Ko, PRC (2017)

Local Λ polarization

Like collective flow, polarization also has detailed structures.

Up to now, following terms have been studied (for Au+Au and Pb+Pb):

$$\begin{aligned} P_x &= f_{1x}\sin(\phi), \\ P_y &= f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi), \\ P_z &= f_z\sin(2\phi), \end{aligned}$$

Harmonic expansion

- $f_0,\ f_{1x},\ f_{1y},\ f_2,\ f_z$ are functions of p_{T} and η.
- ϕ is azimuthal angle w.r.t. EP/RP.
- f_{1x} and f_{1y} are rapidity-odd;
  $f_0,\ f_2,\ f_z$ are rapidity-even (see next slides)

Reference:

Becattini-Karpenko, PRL (2018), Voloshin, SQM2017 proceeding
Xia-Li-Tang-Wang, PRC (2018), Wei-Deng-Huang, PRC (2019)
talks by T. Niida and Y.-L. Xie, this workshop

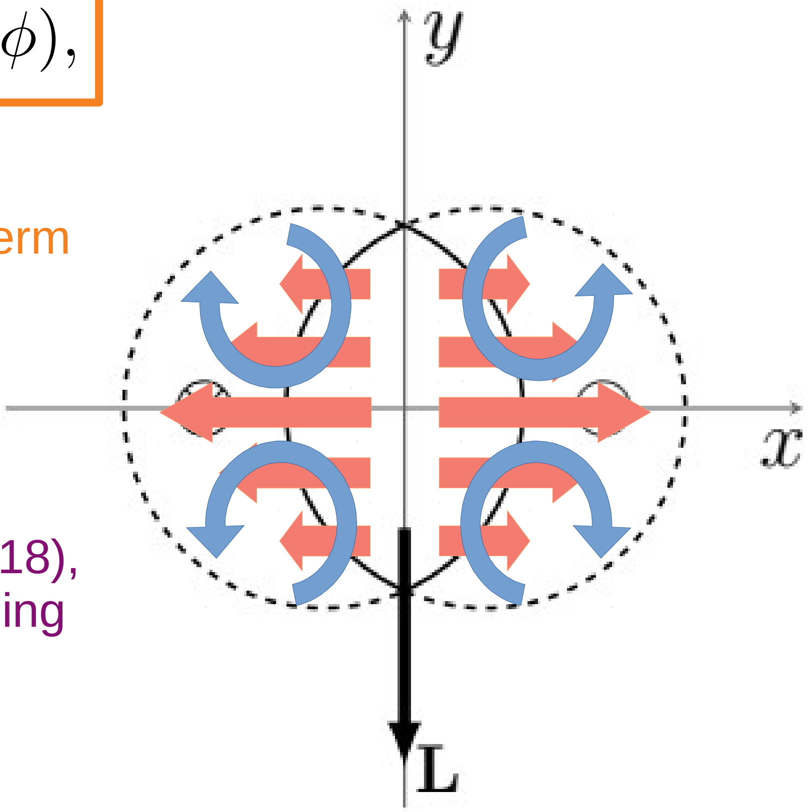
Local Λ polarization

$$P_x = f_{1x}\sin(\phi),$$
$$P_y = f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi),$$
$$P_z = f_z\sin(2\phi),$$

the leading term

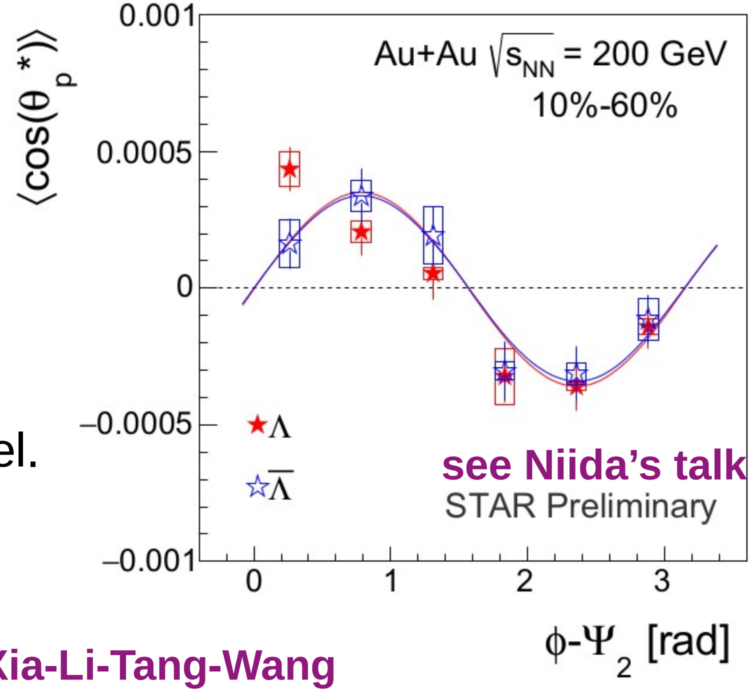
$$P_z = \sum_n f_n \sin(2n\phi)$$

Becattini-Karpenko, PRL (2018),
Voloshin, SQM2017 proceeding



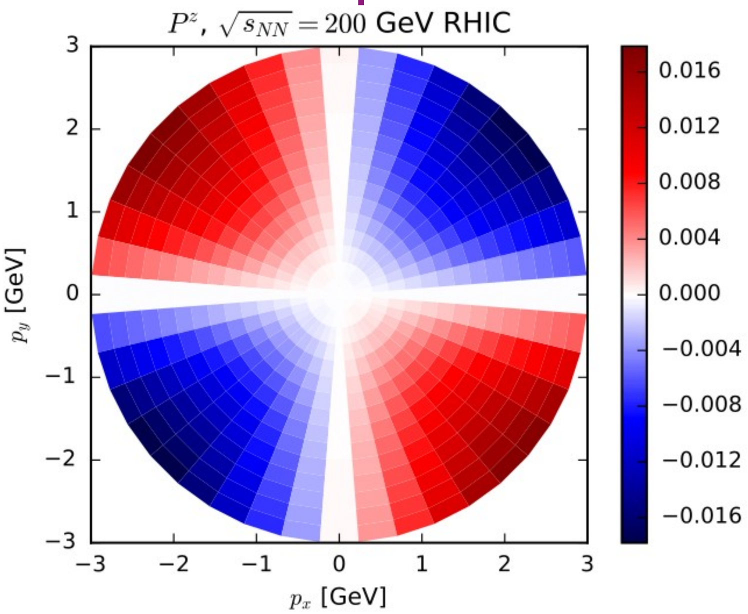
Local Λ polarization

$$P_x = f_{1x}\sin(\phi),$$
$$P_y = f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi),$$
$$P_z = f_z\sin(2\phi),$$

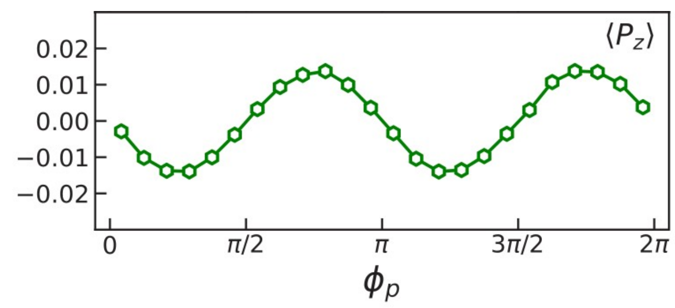


- Opposite trend to hydrodynamic and AMPT model.
- B-W model can fit data. See Niida's Talk.

Becattini-Karpenko

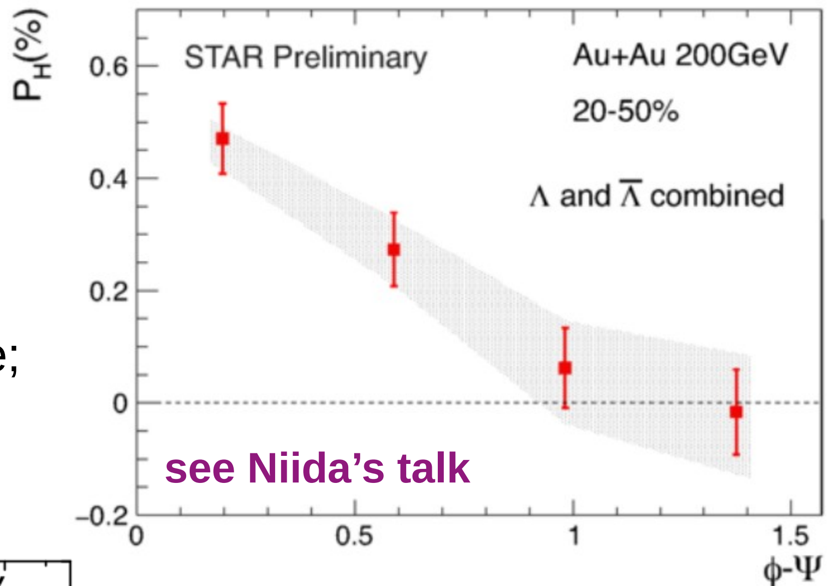


Xia-Li-Tang-Wang



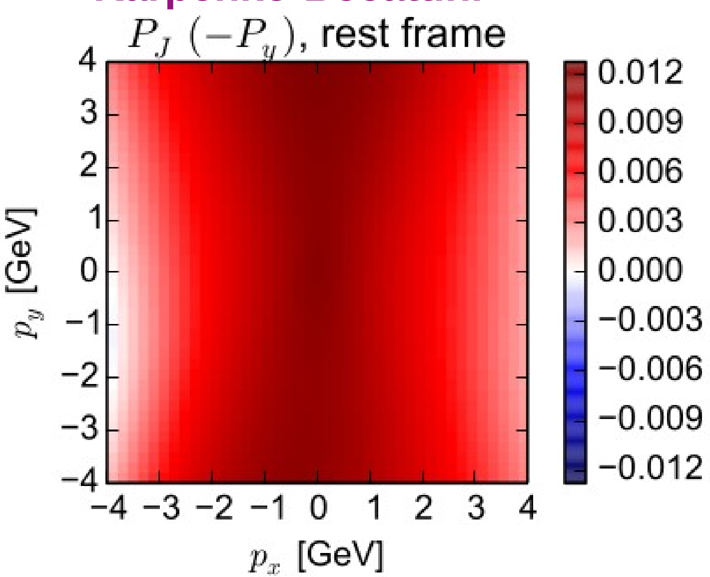
Local Λ polarization

$$P_x = f_{1x}\sin(\phi),$$
$$P_y = f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi),$$
$$P_z = f_z\sin(2\phi),$$

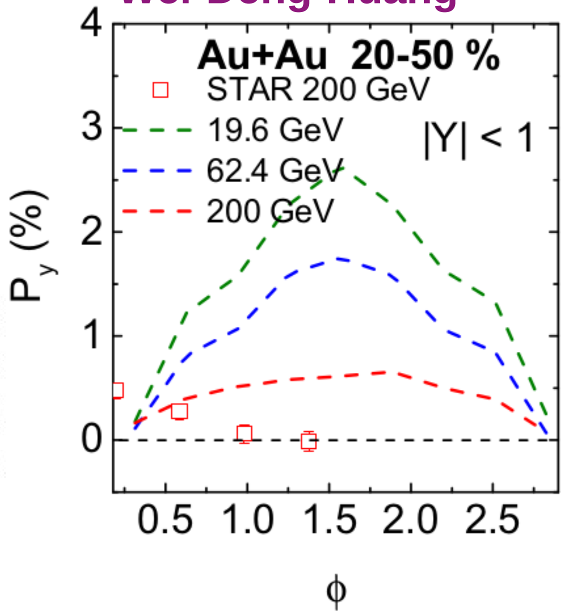


- Experiment: larger polarization in reaction plane;
- Current models: the opposite.

Karpenko-Becattini



Wei-Deng-Huang



circular vorticity

$$P_x = \quad f_{1x}\sin(\phi),$$
$$P_y = f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi),$$
$$P_z = \quad f_z\sin(2\phi),$$

$$\boldsymbol{\omega}_\perp = \frac{1}{2}\partial_z v_\perp(r,z)\mathbf{e}_\phi,$$

f_{1x} and f_{1y} are rapidity-odd

f_0, f_2, f_z are rapidity-even

Xia, Li, Tang, Wang, PRC (2018)

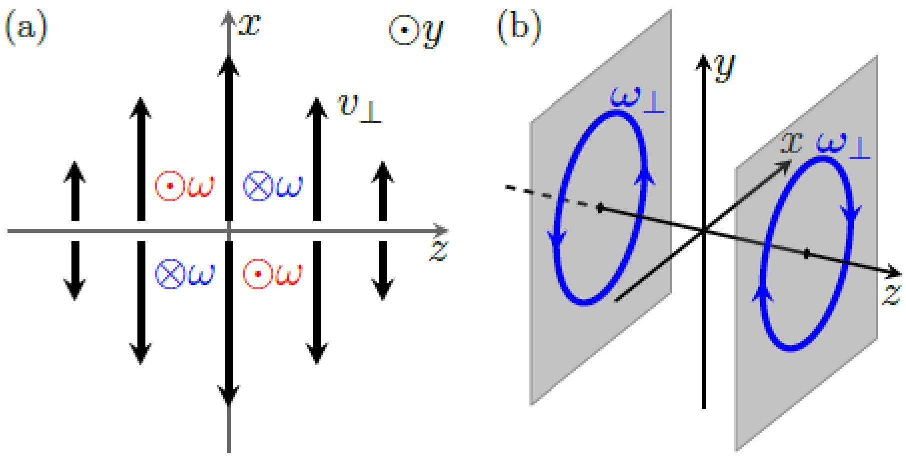


FIG. 2. Left: Schematic illustration of the quadrupole pattern of ω_y generated from $\partial_z v_\perp$ in the reaction plane, where the vorticity is along the $-y$ direction ($\otimes$) in the $xz > 0$ quadrants and the y direction ($\odot$) in the $xz < 0$ quadrants. Right: A three dimensional view of the circular structure of the transverse vorticity $\omega_\perp = (\omega_x, \omega_y)$.

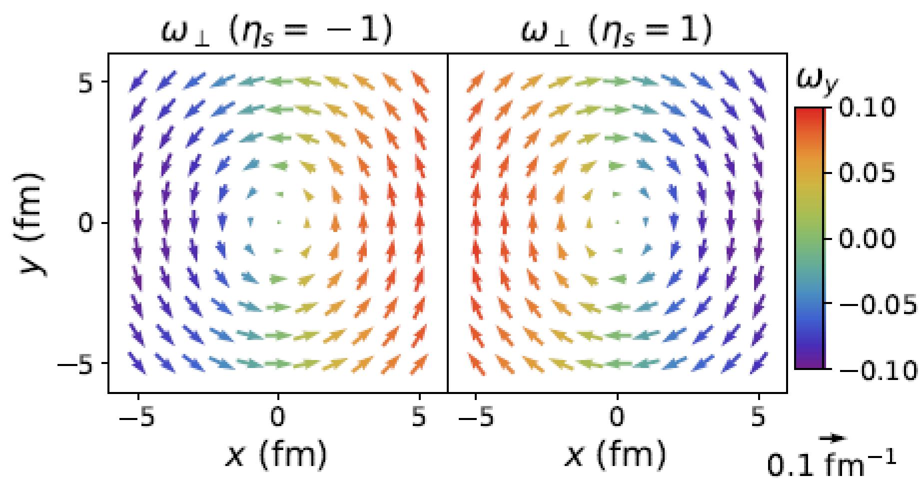
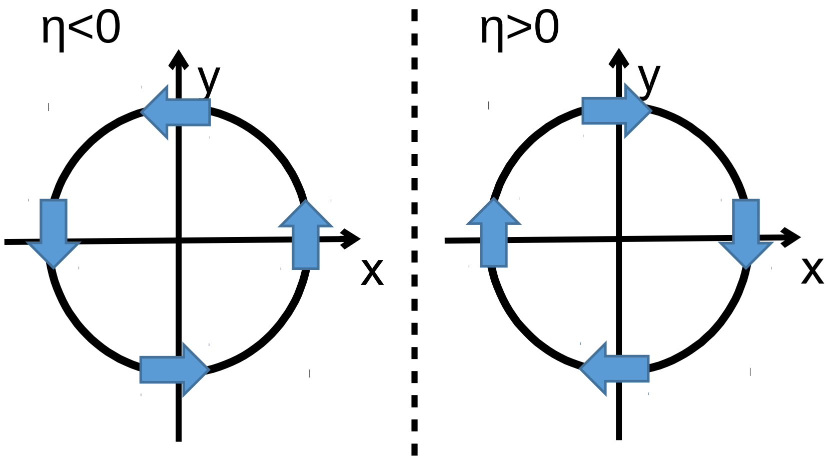
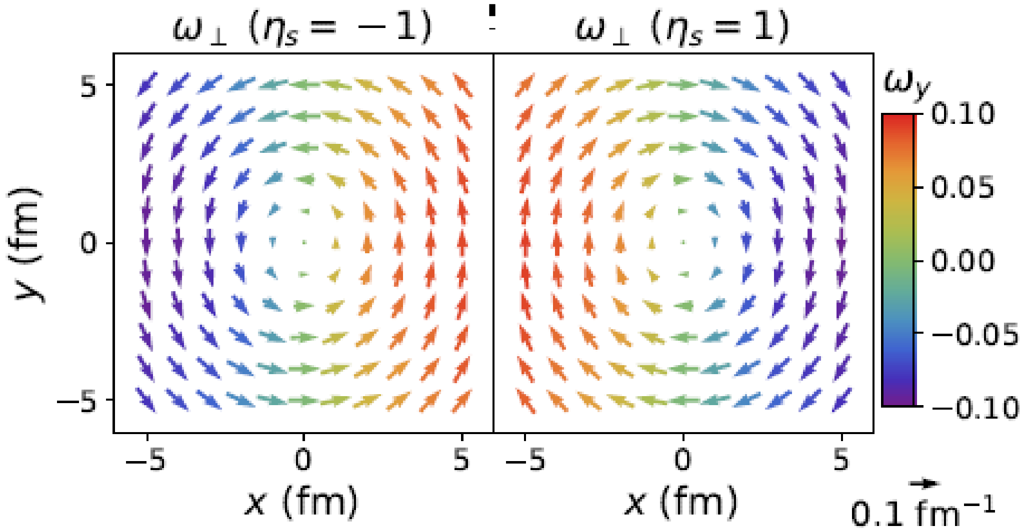


FIG. 3. The distribution of the transverse vorticity $\omega_\perp = (\omega_x, \omega_y)$ in the transverse plane at longitudinal positions $\eta_s = -1$ (left) and $\eta_s = 1$ (right) at time $t = 5$ fm/c in 20-30% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The color represents the value of the component ω_y.

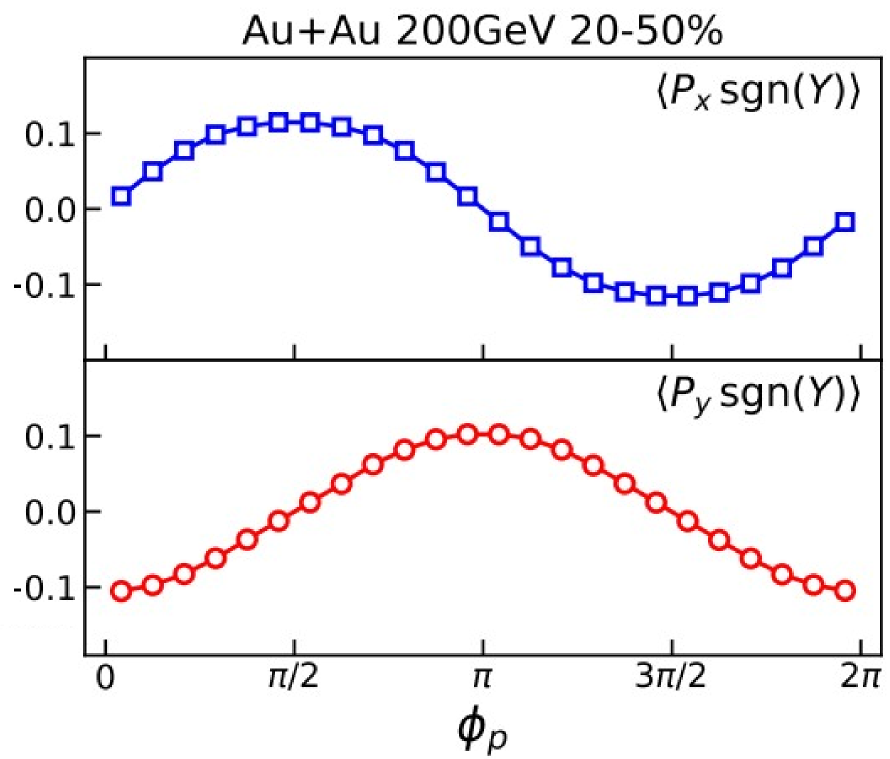
circular Λ polarization



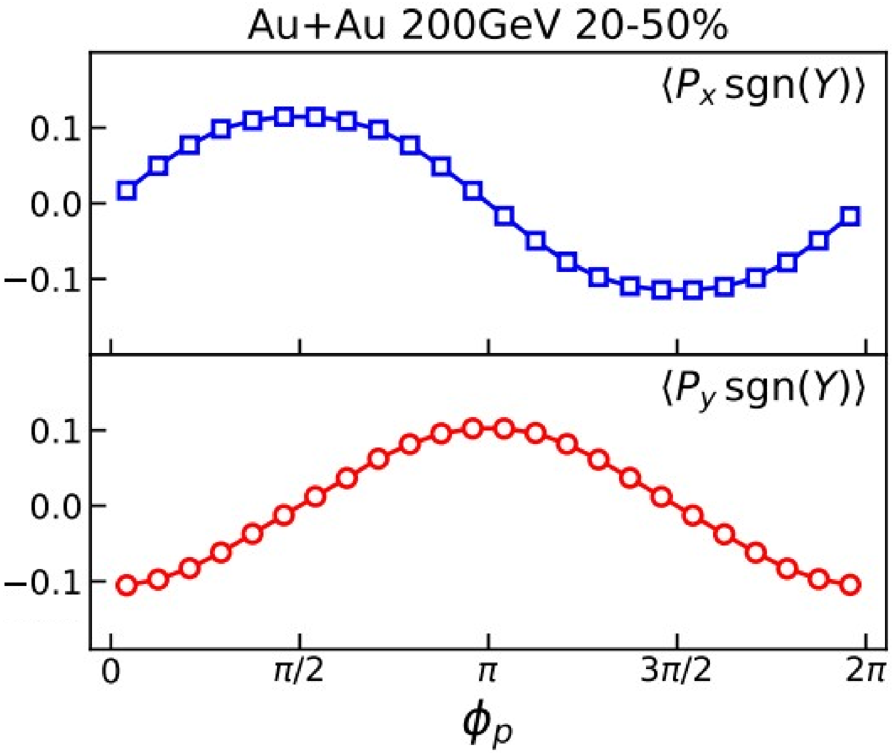


To measure this effect,
divides Λs into azimuthal angle bins,
measure P(ϕ) at η>0 and η<0 separately.

Xia, Li, Tang, Wang, PRC (2018)

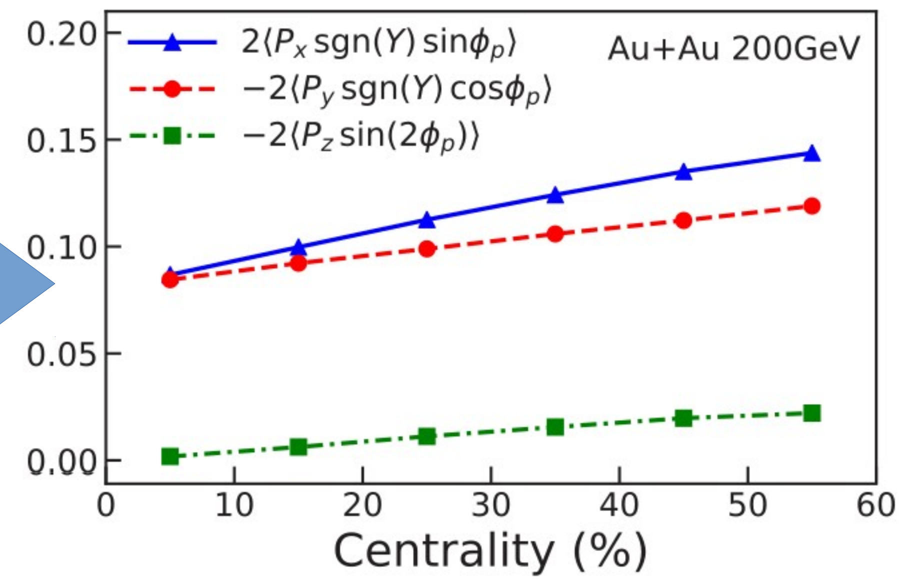


circular Λ polarization



magnitude

Xia, Li, Tang, Wang, PRC (2018)



$$
\begin{aligned}
P_x &= \quad f_{1x}\sin(\phi), \\
P_y &= f_0 - f_{1y}\cos(\phi) + f_2\cos(2\phi), \\
P_z &= \quad f_z \sin(2\phi),
\end{aligned}
$$

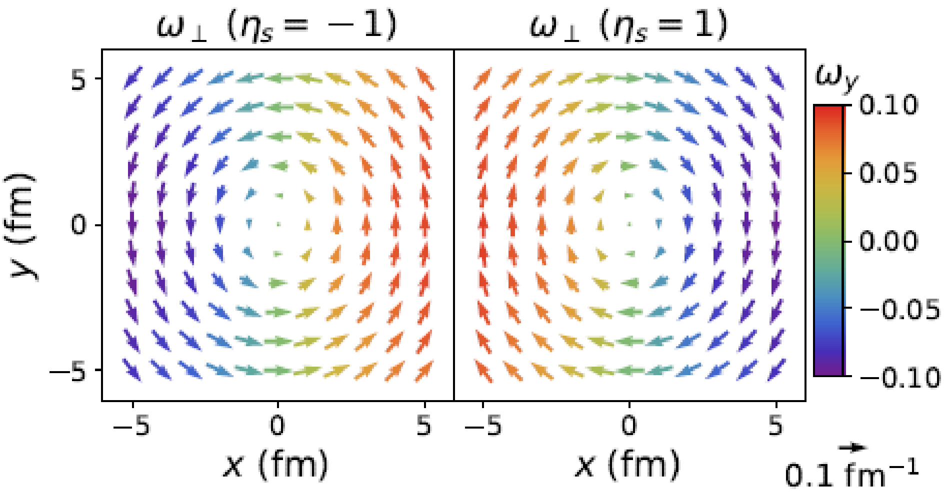
$f_{1x} > f_{1y}$ in non-central collisions based on AMPT calculation.

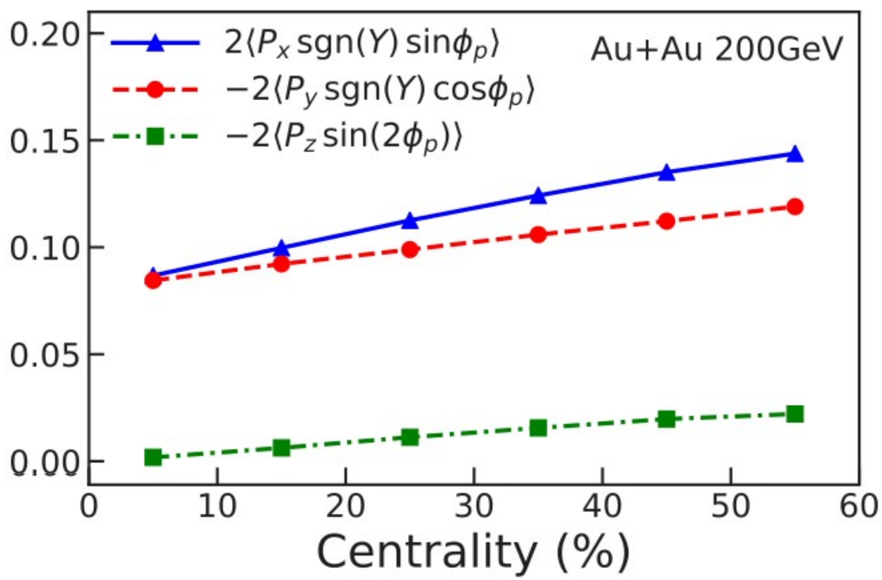
Need be tested in experiment.

Pz from circular vorticity

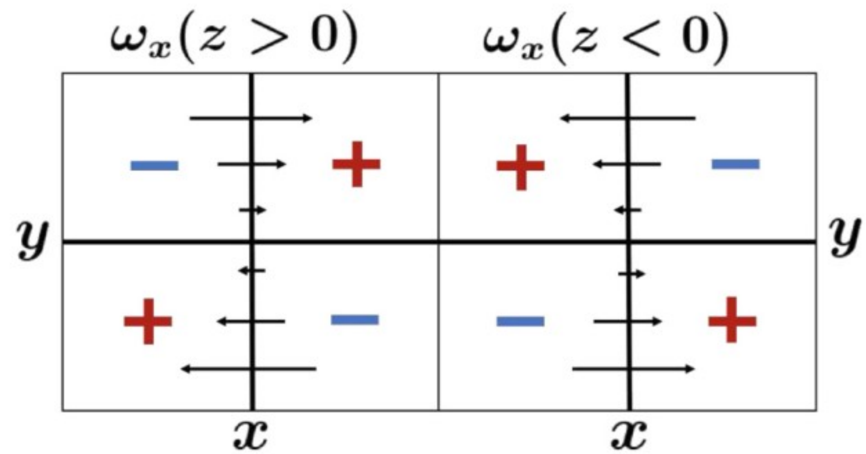
See Ko's talk

Xia, Li, Tang, Wang, PRC (2018)





Sun, Ko, PRC (2019)

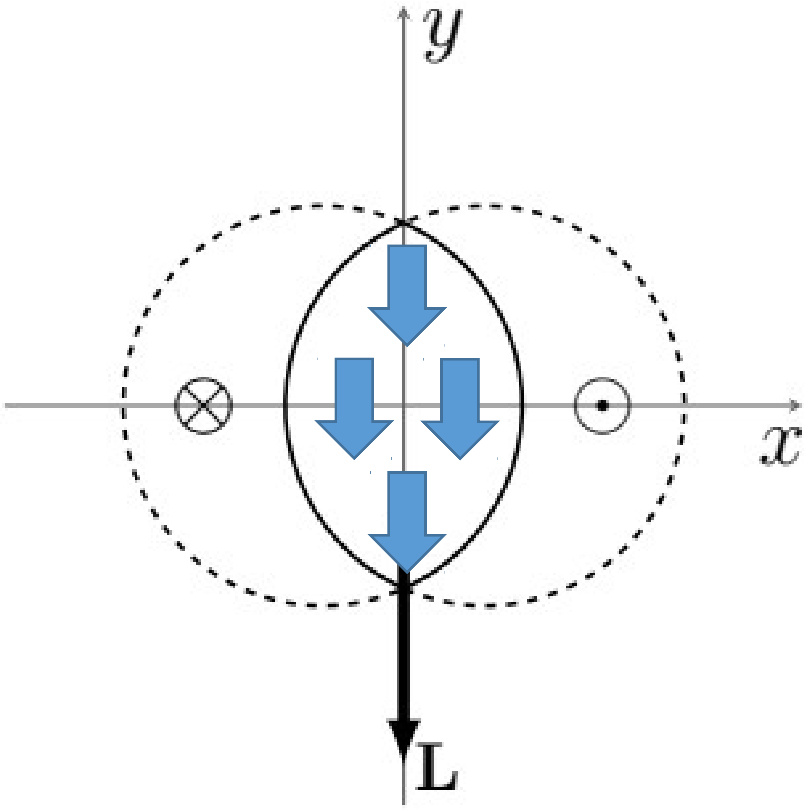


- Circular vorticity => axial charge redistribution.
- Axial charge with rapidity => quadrupole of Pz.
- Condition: ω_x > ω_y >> ω_z.

Evidence for circular vorticity?

Need test by measuring circular polarization directly.

Global spin alignment



$$\rho_{\text{vec}} = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

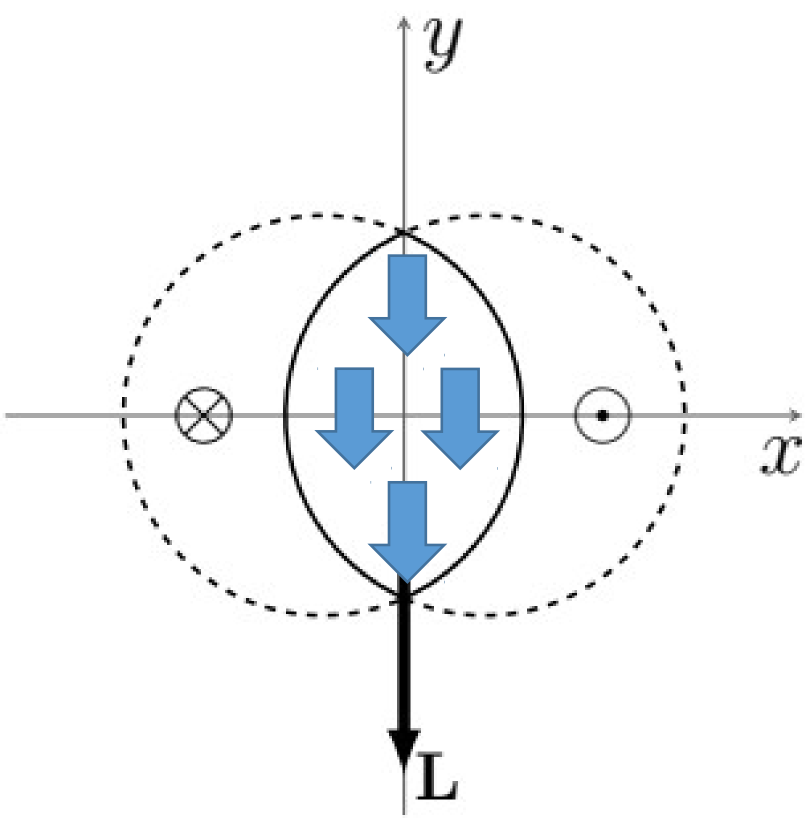
$q\bar{q} \to \text{V}:$

Liang-Wang, PLB (2005)

$$\rho_q \otimes \rho_{\bar{q}} \Rightarrow \rho_{00} = \frac{1 - P_y^2}{3 + P_y^2}$$

$$\rho_{00} < 1/3$$

Spin alignment



- **Spin alignment is measured by angular distribution of decay daughter**

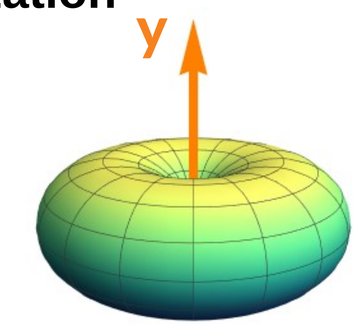
$$\phi \to \mathrm{K}^+ + \mathrm{K}^-$$

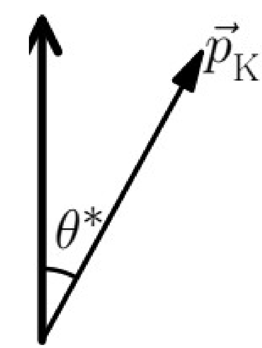
$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

see Singh's talk

$$\rho_{00} < 1/3:$$

- **More distribution perpendicular to polarization**





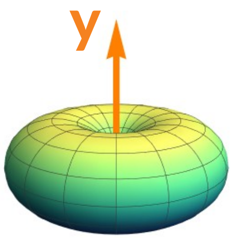
✖ $P_y = \rho_{11} - \rho_{-1-1}$

☺ $\rho_{00} = 1 - (\rho_{11} + \rho_{-1-1})$

Local spin alignment

- Global spin alignment

the 'doughnut' distribution is along y-axis.



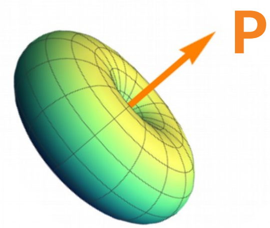
$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

Liang-Wang, PLB (2005)

$$\rho_{00} = \frac{1-P_y^2}{3+P_y^2}$$

- Local spin alignment

the 'doughnut' distribution orientates to local polarization vector.



$$\begin{aligned}\frac{dN}{d\Omega^*} = \frac{3}{8\pi}\Big[& (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \\ & - \sqrt{2}\,(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\varphi^* \\ & + \sqrt{2}\,(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\varphi^* \\ & - 2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\varphi^*) \\ & + 2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\varphi^*)\Big].\end{aligned}$$

$$\rho_{00} = \frac{1-P_y^2+P_x^2+P_z^2}{3+P^2}$$

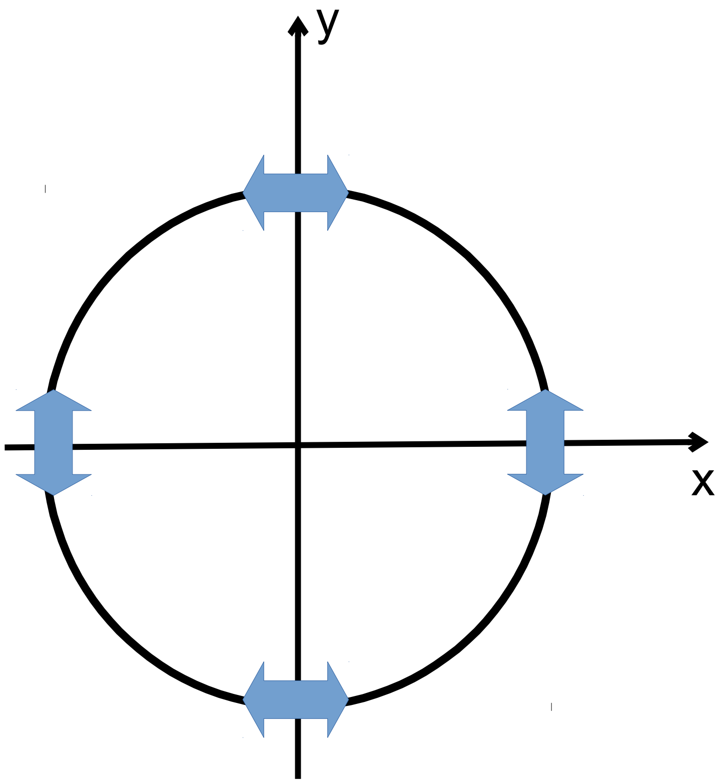
Xia-Li-Huang in preparation

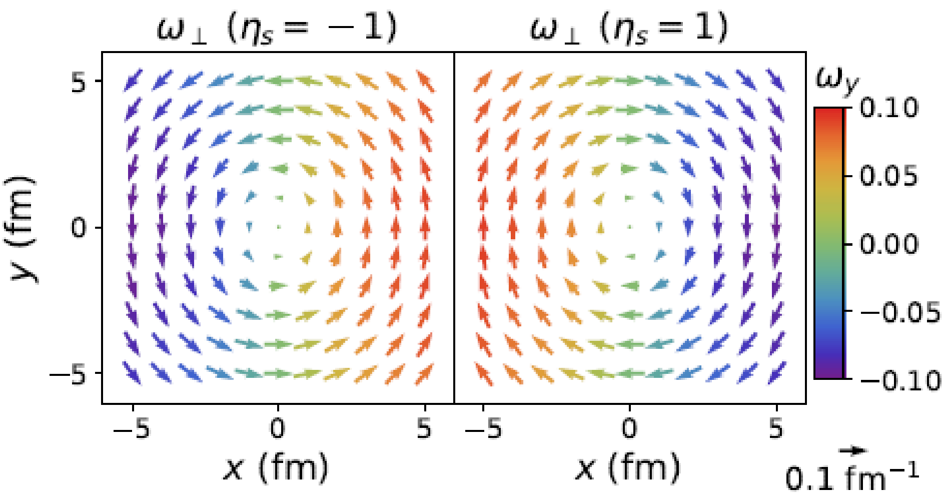
θ^*: angle between daughter and y-axis.

φ^*: angle of daughter in z-x plane.

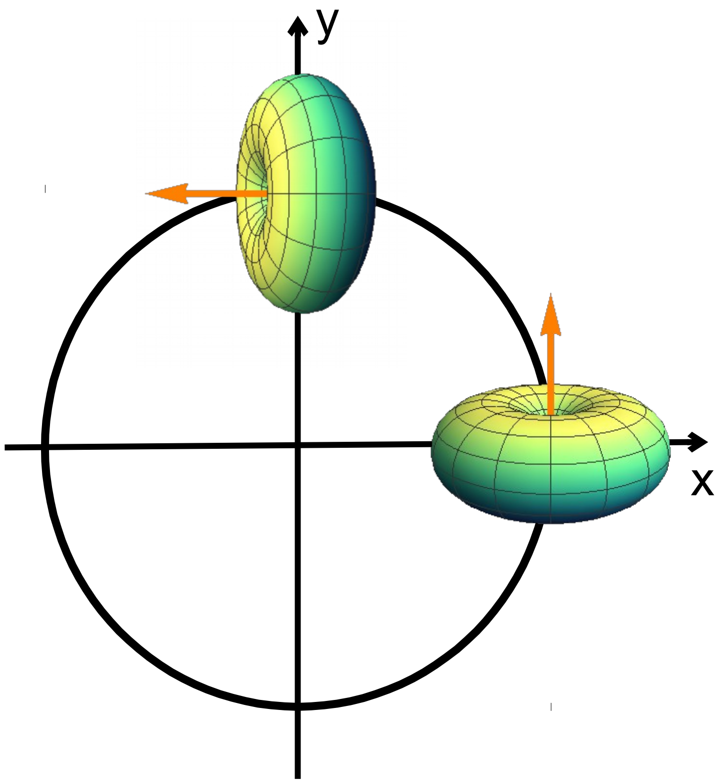
Local spin alignment

Circular polarization in most-central collisions:





Local spin alignment



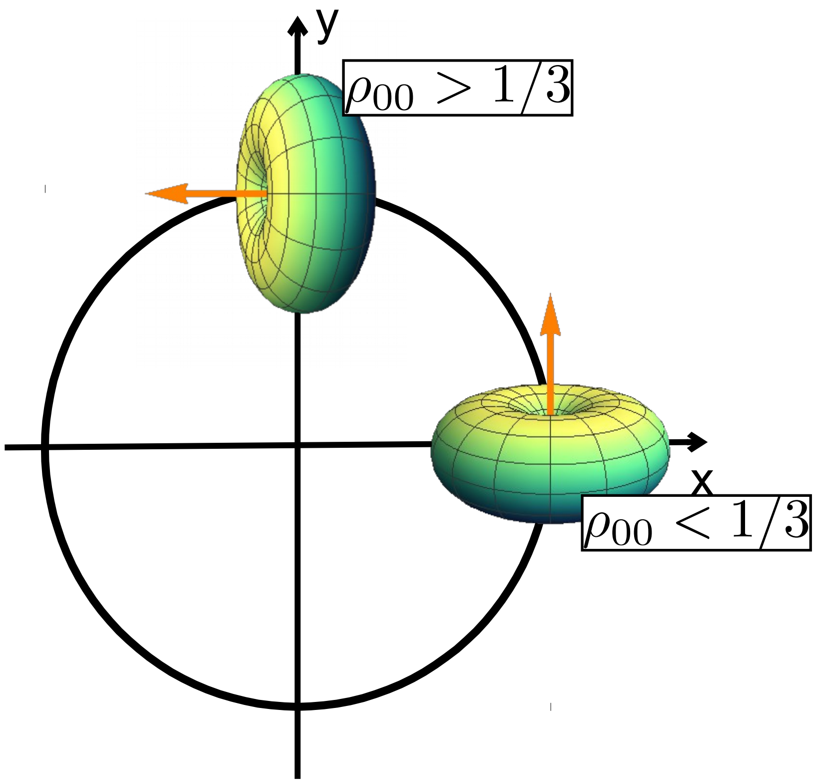
$$\frac{dN}{d\Omega^*} = \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* - \sqrt{2}\,(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\varphi^* + \sqrt{2}\,(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\varphi^* - 2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\varphi^*) + 2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\varphi^*)\Big].$$

θ^*: angle between daughter and y-axis.
φ^*: angle of daughter in z-x plane.

Elements of spin density matrix are functions of position on vorticity loop.

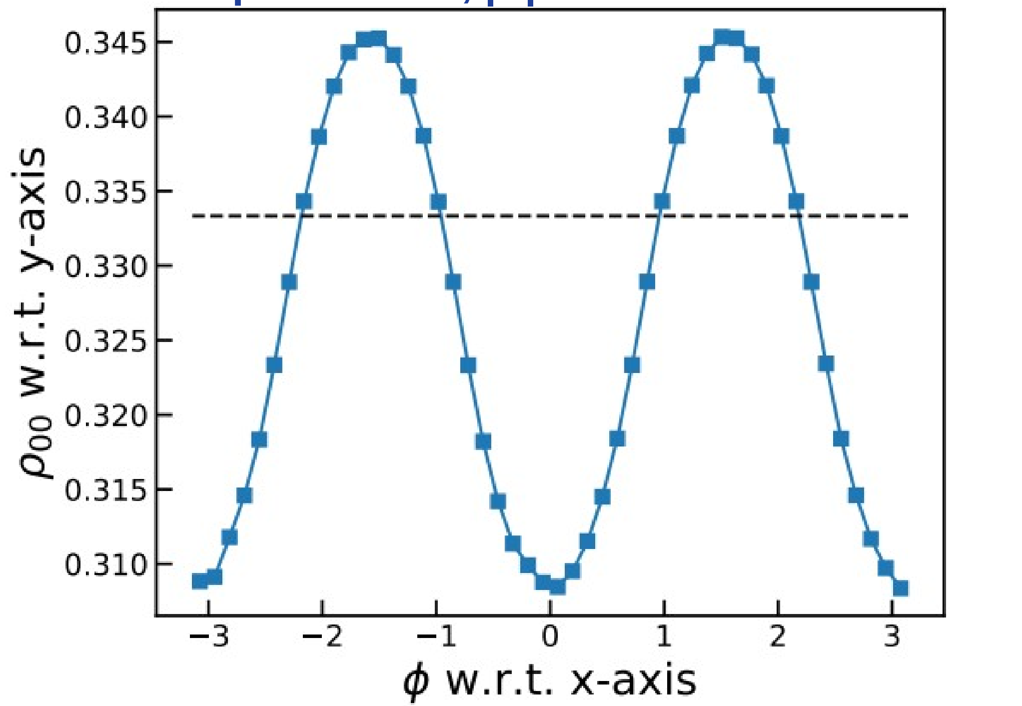
Local spin alignment

$$\frac{dN}{d\Omega^*} = \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$
$$-\sqrt{2}\,(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\varphi^*$$
$$+\sqrt{2}\,(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\varphi^*$$
$$-2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\varphi^*)$$
$$+2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\varphi^*)\Big].$$



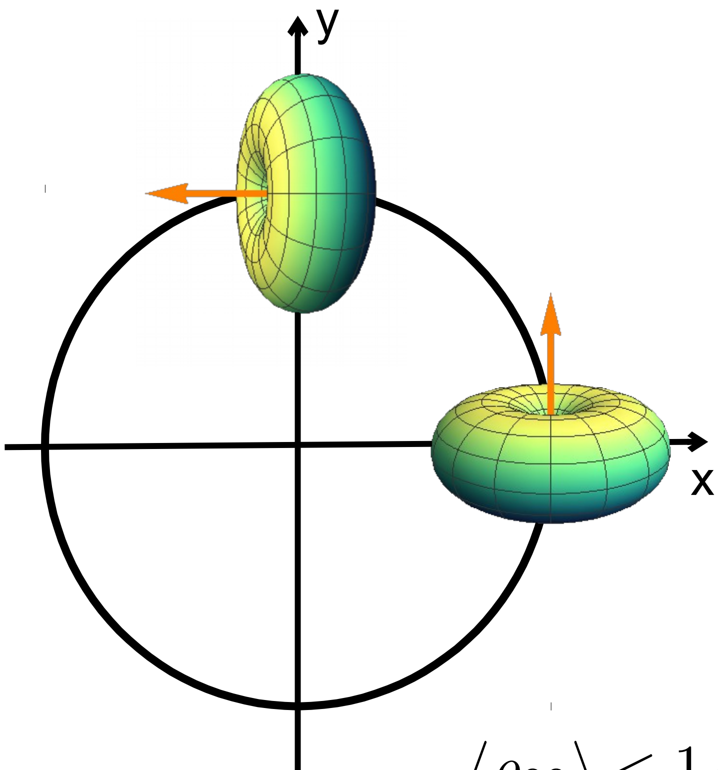
Au+Au 200 GeV, b=0 fm
1.2<pT<5.4 GeV, |Y|<1

Xia, Li, Huang
in preparation



Local spin alignment

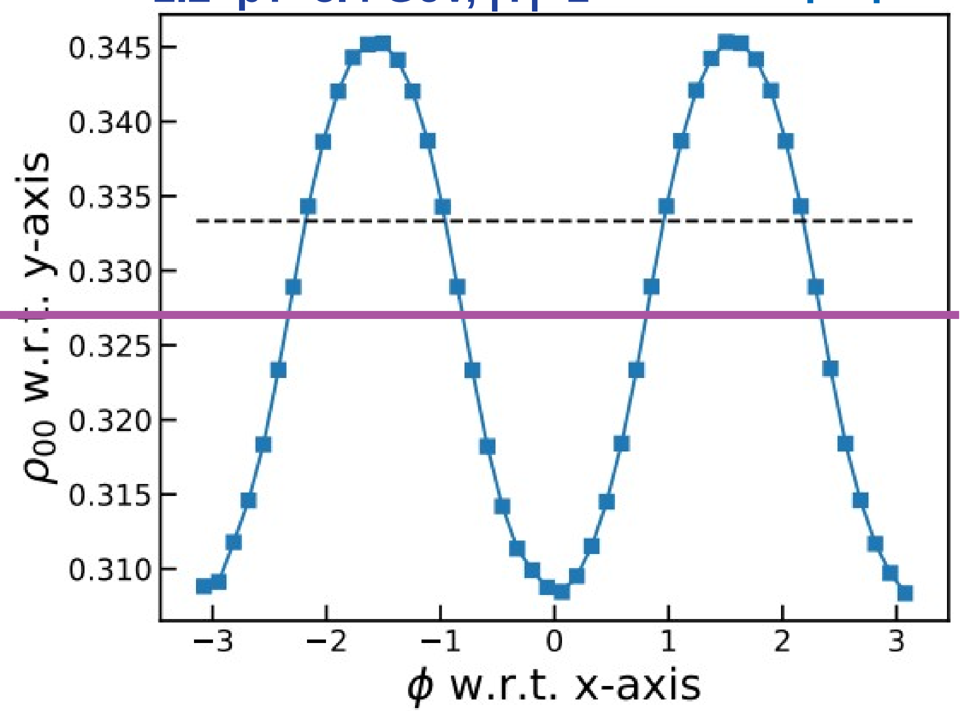
$$\frac{dN}{d\Omega^*} = \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* - \sqrt{2}\,(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\varphi^* + \sqrt{2}\,(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\varphi^* - 2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\varphi^*) + 2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\varphi^*)\Big].$$



$\langle\rho_{00}\rangle < 1/3$

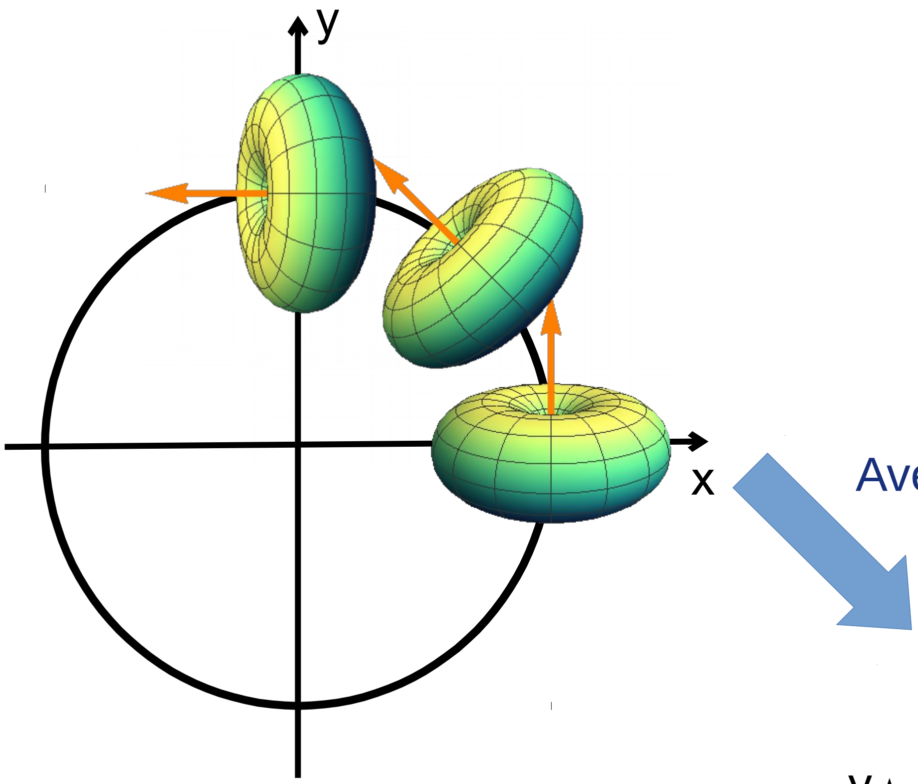
Au+Au 200 GeV, b=0 fm
1.2<pT<5.4 GeV, |Y|<1

Xia, Li, Huang in preparation

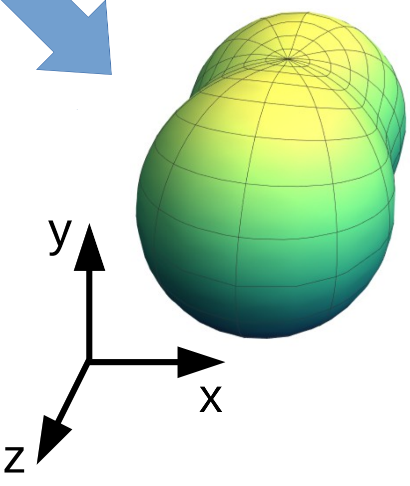


Local spin alignment

$$\frac{dN}{d\Omega^*} = \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$
$$-\sqrt{2}\,(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1})\sin(2\theta^*)\cos\varphi^*$$
$$+\sqrt{2}\,(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1})\sin(2\theta^*)\sin\varphi^*$$
$$-2\mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos(2\varphi^*)$$
$$+2\mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin(2\varphi^*)\Big].$$



Average over all ‘doughnuts’

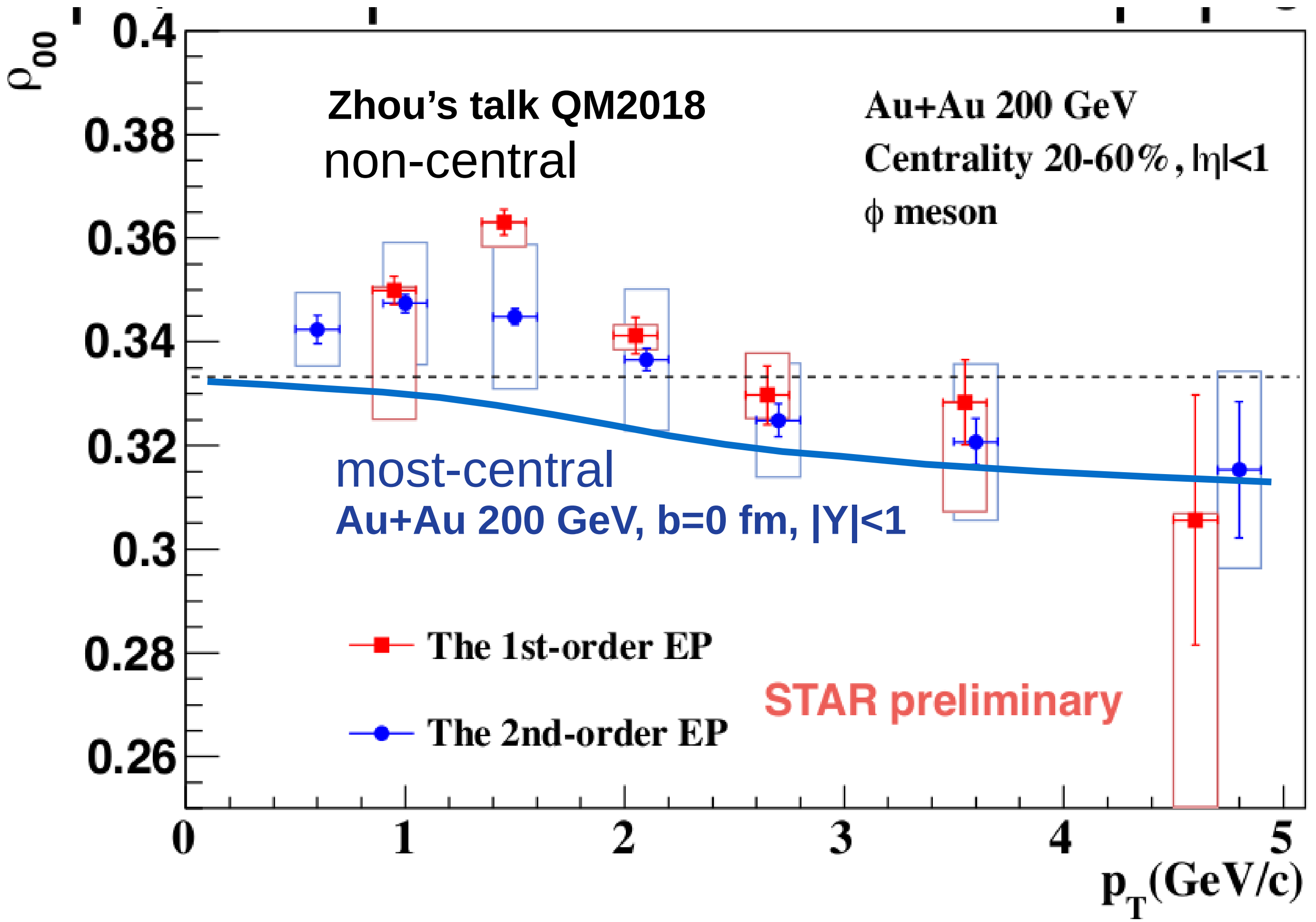


Equal in x and y axes,
More distribution in z axis.

$$\langle\rho_{00}\rangle < 1/3$$

pT dependence

- Local spin alignment provides a new baseline for global spin alignment and additional effects in non-central case.



summary

- Polarization can be from different sources.
- Three local polarization effects are discussed.

  Two of them are unsolved puzzles.
- Circular polarization needs measurement in experiment.
- When circular polarization is applied to local spin alignment, it provides a new baseline below 1/3.

Thank you!