Spin polarization of hyperons and vector mesons in HIC

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HENPIC online seminar

outline

- Angular momentum and vorticity
- Global spin polarization
- Local spin polarization
- Vector meson spin alignment
- Summary

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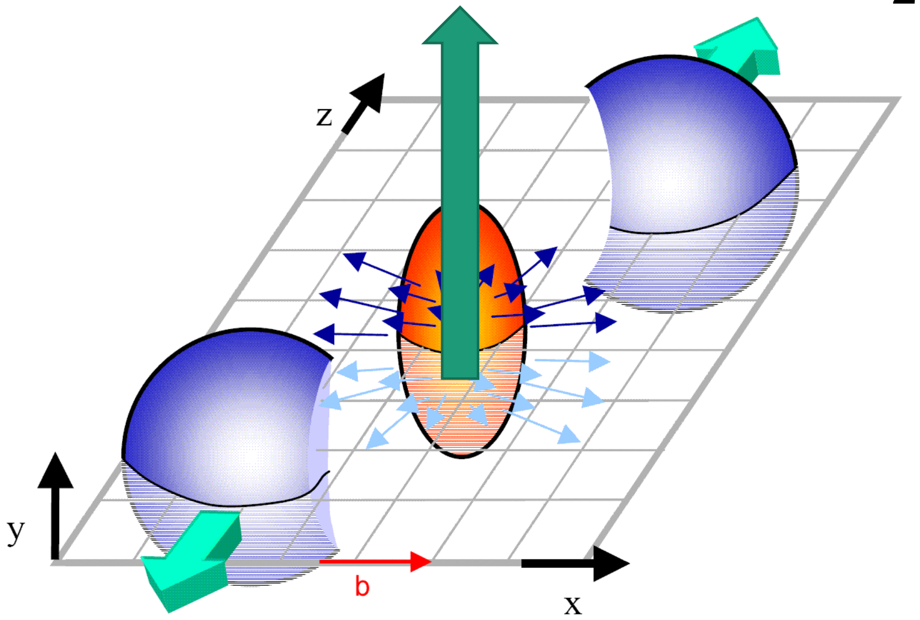
Global angular momentum and vorticity

$$L = |\vec{b} \times \vec{p}| \simeq bA\frac{\sqrt{s_{\mathrm{NN}}}}{2}$$



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

Global angular momentum

Global angular momentum and vorticity

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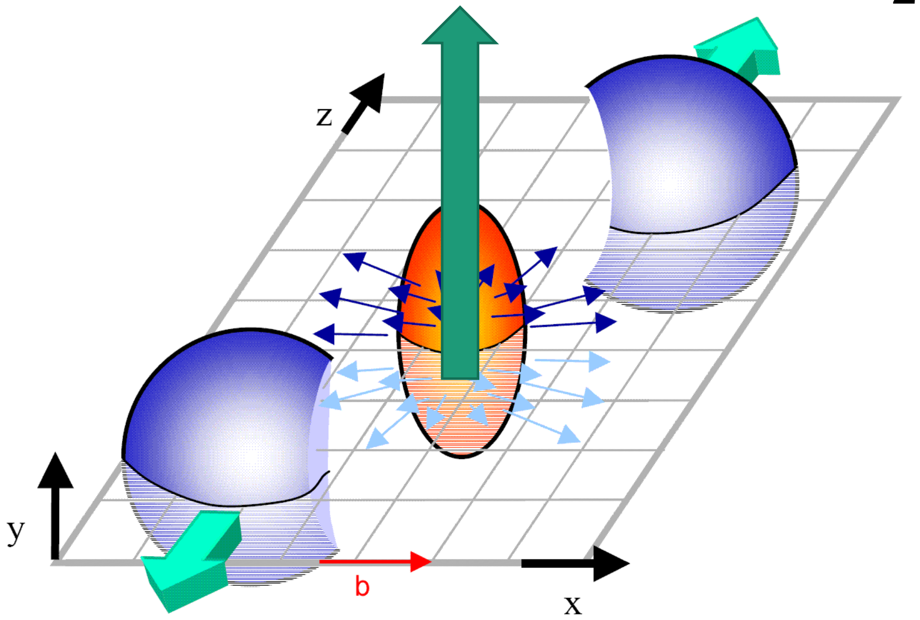

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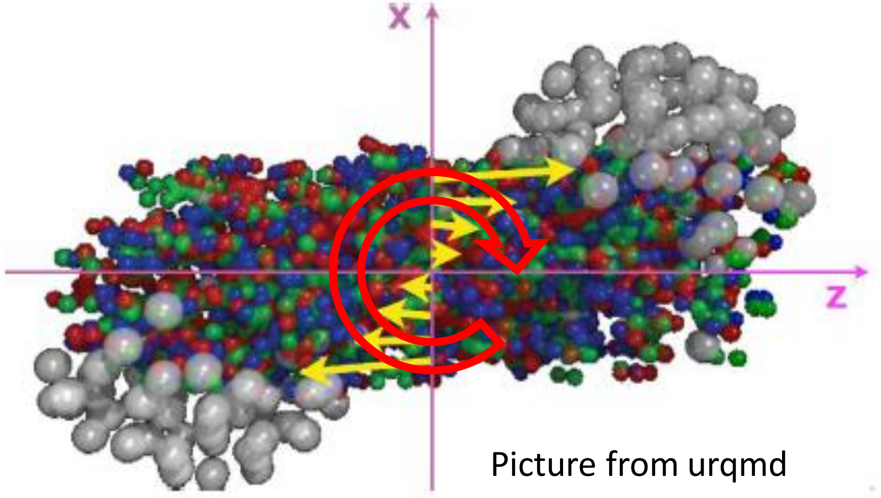
Global angular momentum



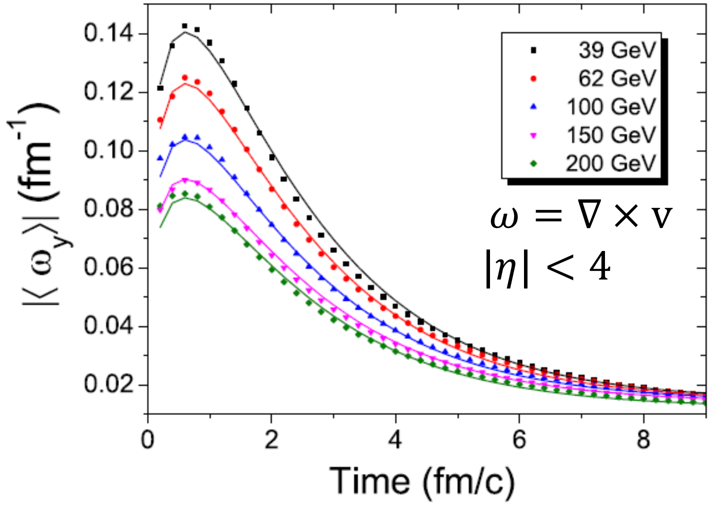
Picture from urqmd

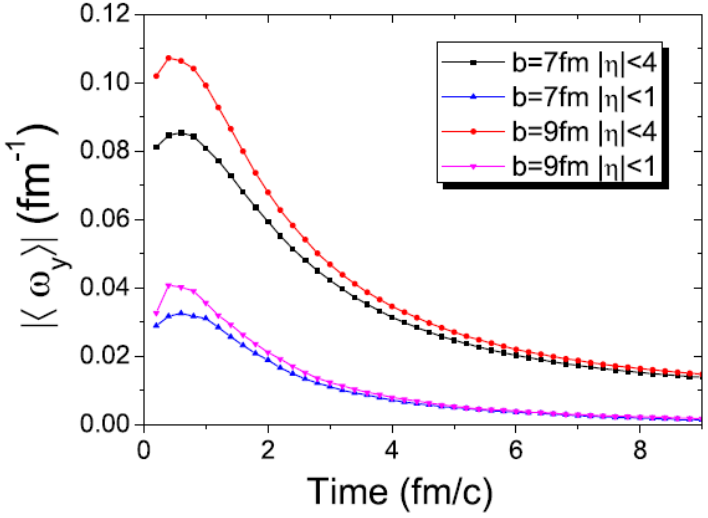
$$\omega = \frac{1}{2}\nabla \times \mathrm{v}$$

Vorticity

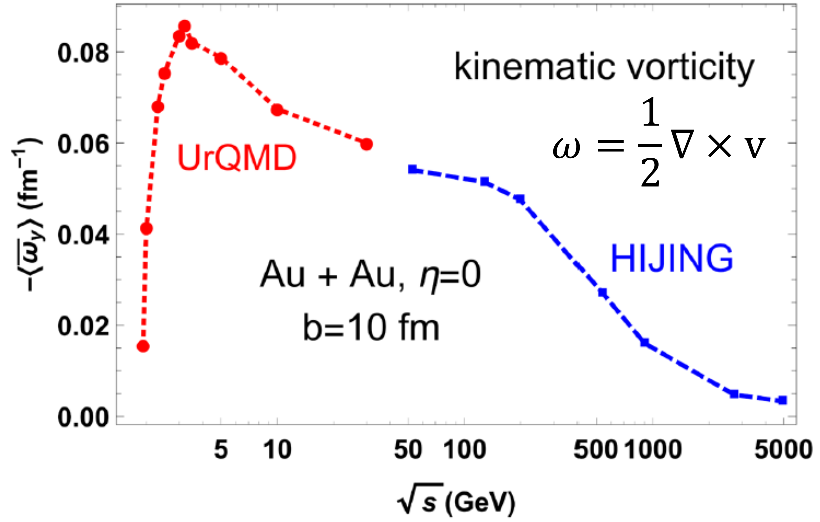
Vorticity by global angular momentum

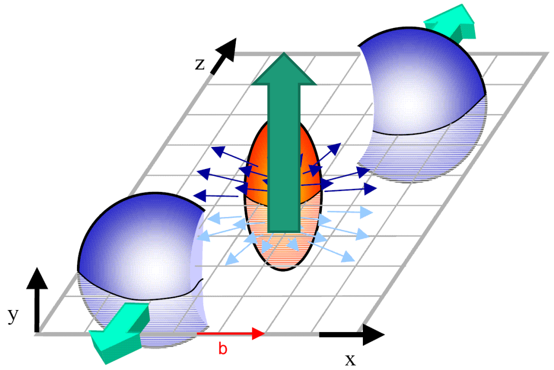
AMPT, Jiang-Lin-Liao 2016





HIJING, Deng-Huang 2016
UrQMD, Deng-Guang-Ma-Zhang 2020

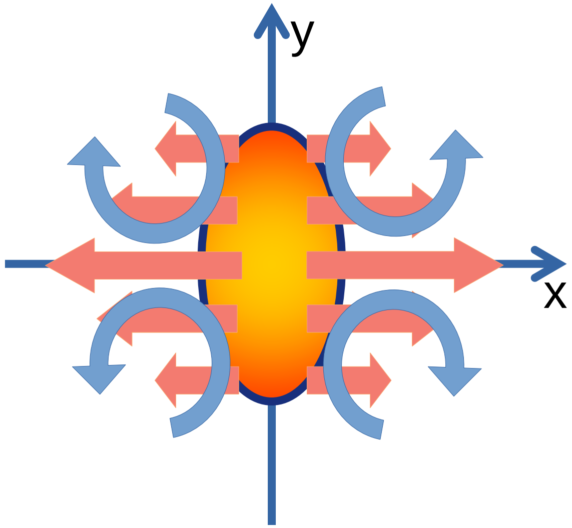




- Highest known vorticity: $\omega \sim 0.1\ \mathrm{fm} \sim 10^{22}\ \mathrm{s}^{-1}$.
- ω decreases with the increase of $\sqrt{s_{\mathrm{NN}}}$ at mid-rapidity @ RHIC & LHC energies.
- ω increases with the increase of rapidity.

Vorticity by fireball expansion

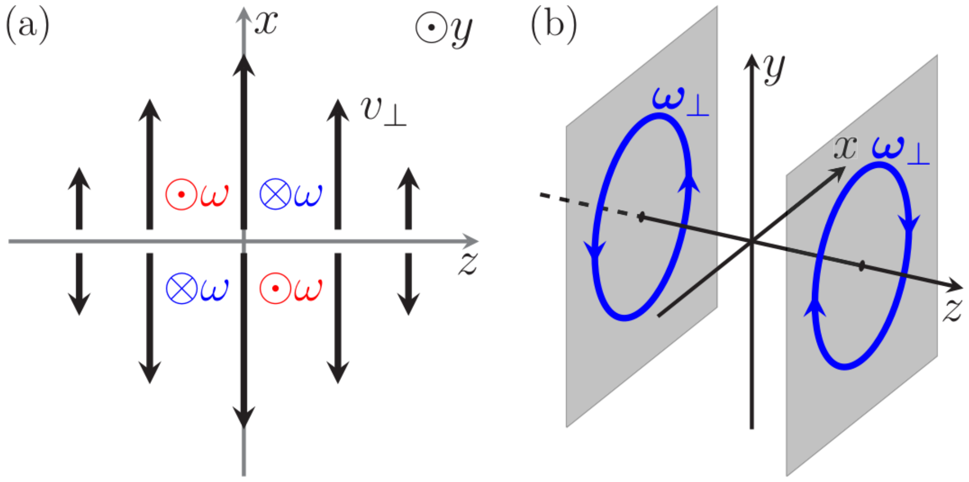
Becattini-Karpenko; Voloshin 2018



$$\omega_z \sim \partial_x v_y - \partial_y v_x$$

Longitudinal local vorticity
(in non-central collisions)

XLX-Li-Tang-Wang 2018



$$\omega_\perp \sim \partial_z v_r$$

Transverse local vorticity
(in central & non-central collisions)

- **Local** vorticity does not contribute to the **global** angular momentum.
- It leads to the local spin polarization.

- Angular momentum and vorticity
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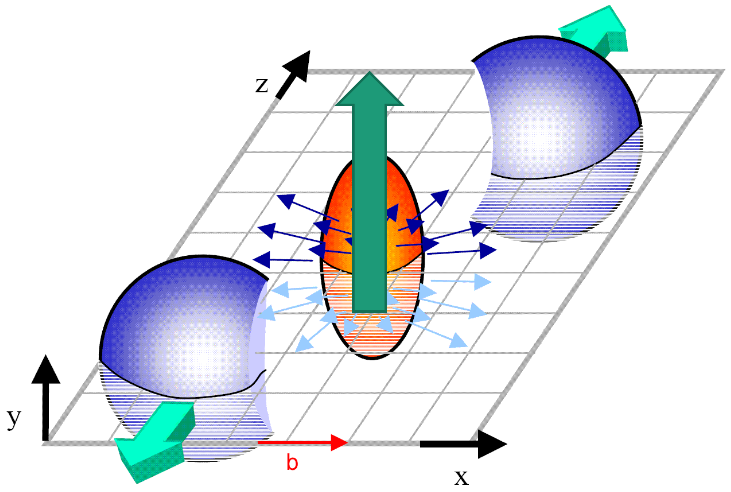
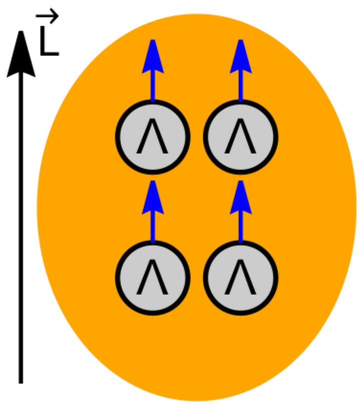
Global spin polarization

- Early idea (based on particle scattering): (Liang-Wang 2005; Voloshin 2004)

$$\frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\sigma_\uparrow + d\sigma_\downarrow} \propto \vec{n} \cdot (\vec{x}_T \times \vec{p}) \quad \Rightarrow \quad P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$





Global spin polarization

- Statistical mechanics (assuming thermal equilibrium):

$$\rho \propto e^{-(H_0 - \boldsymbol{\omega}\cdot\mathbf{J})/T} \quad \Rightarrow \quad \mathbf{P} \approx \frac{\boldsymbol{\omega}}{2T}$$

- Relativistic: (Becattini etal 2013; Fang etal 2016; Liu etal 2020)

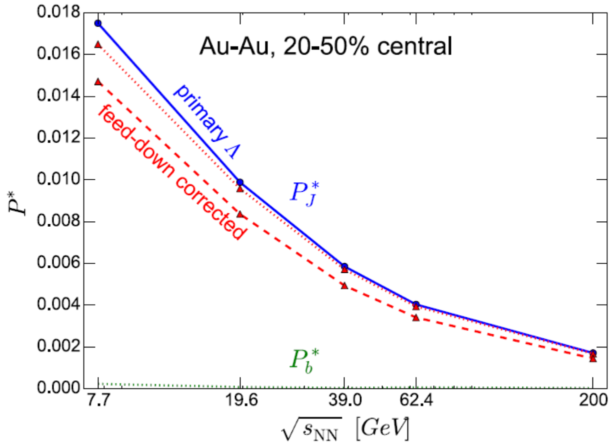
$$S^\mu \approx -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\nu \varpi_{\rho\sigma}$$

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

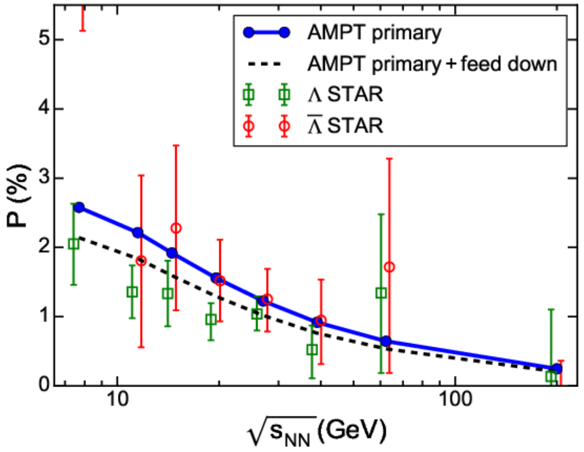
- Other approaches: chiral kinetic theory (Sun-Ko 2017), axial vortical effect (Baznat etal 2018; Ivanov 2020), particle scattering (Zhang-Fang-Wang-Wang 2018)

Many theoretical calculations

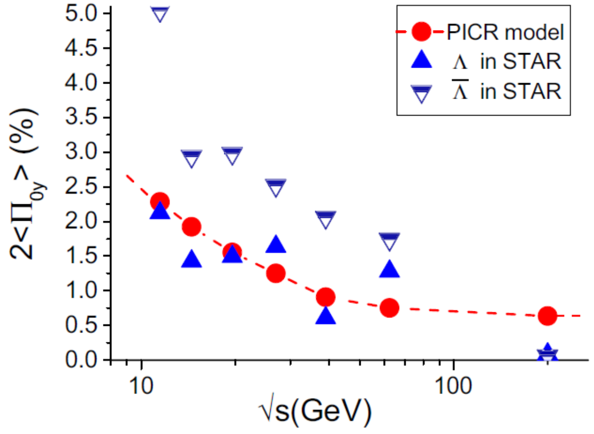
UrQMD+hydro, Karpenko-Becattini 2017



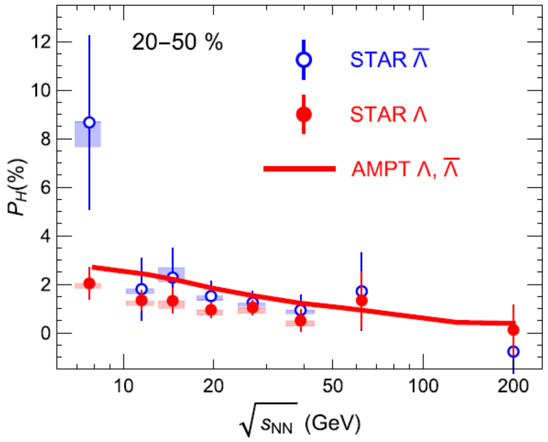
AMPT, Li-Pang-Wang-XLX 2017



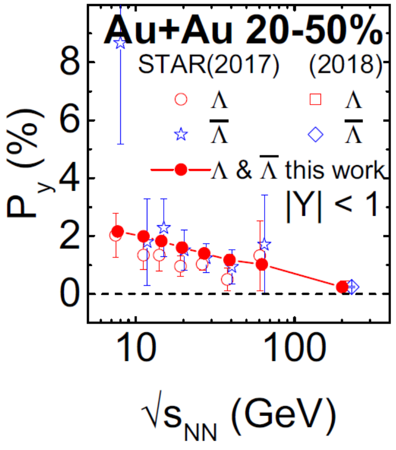
PICR, Xie-Wang-Csernai 2017



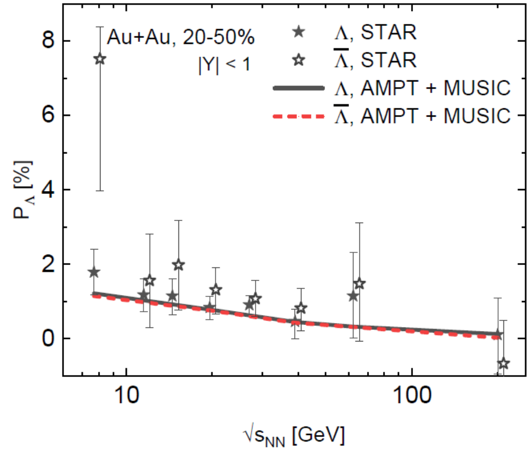
AMPT, Shi-Li-Liao 2019



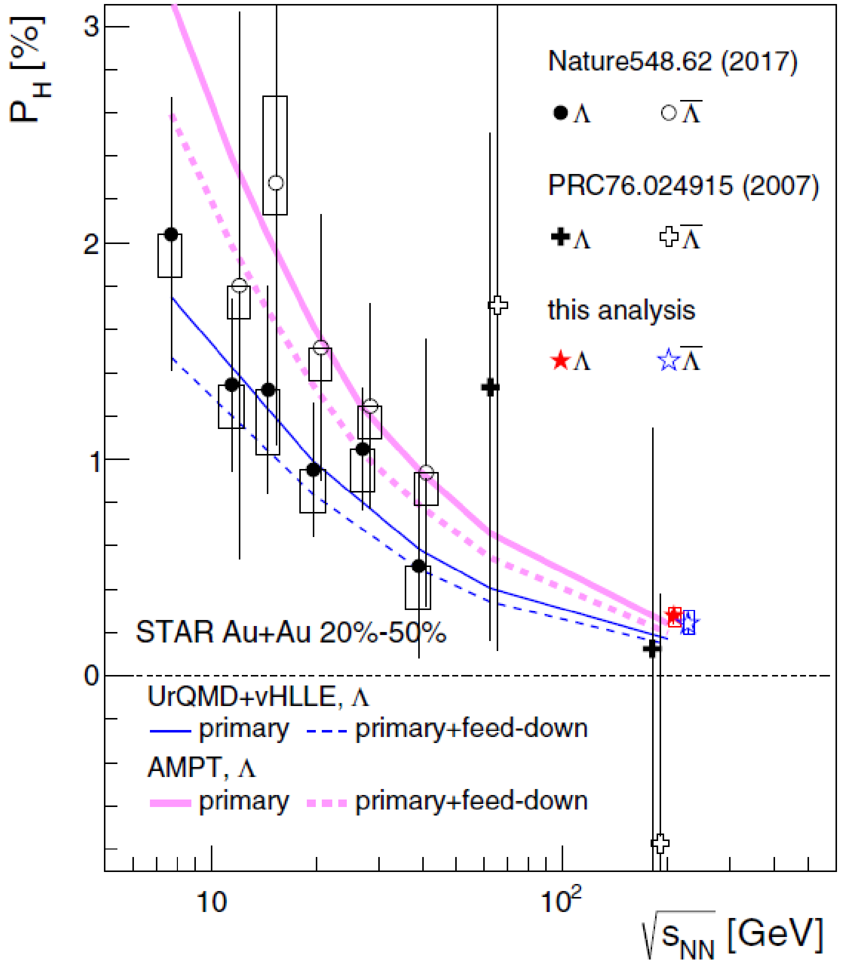
AMPT, Wei-Deng-Huang 2019



AMPT+hydro, Fu-Xu-Huang-Song 2020



Global Λ polarization

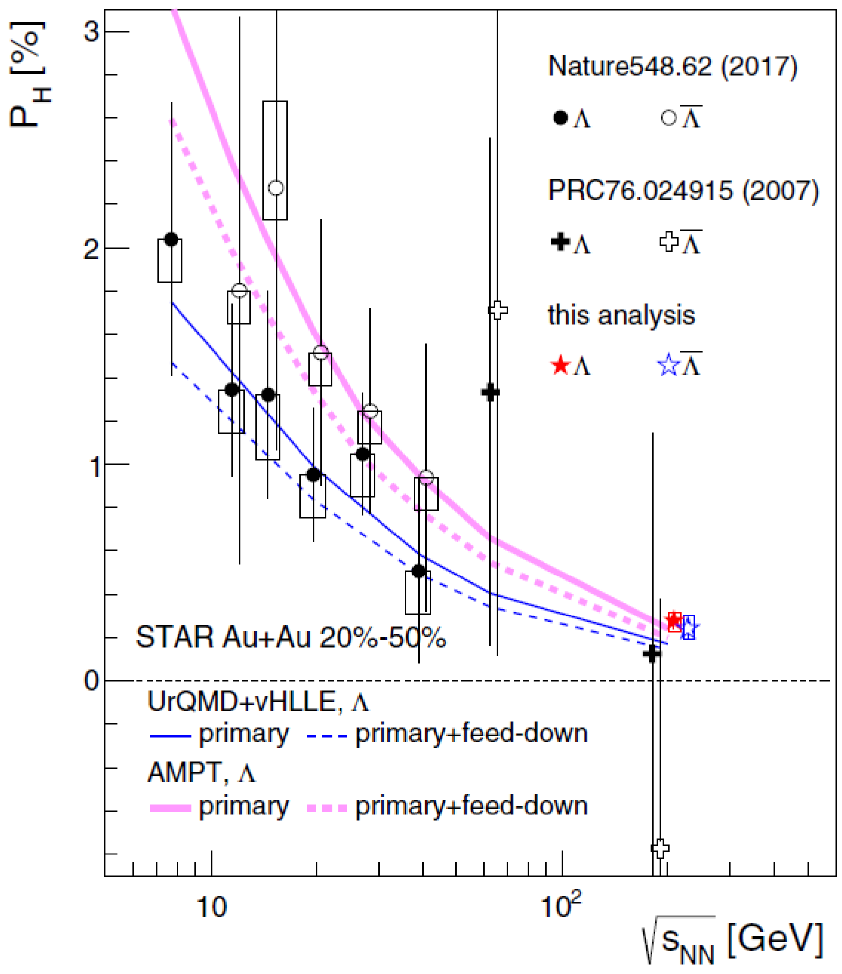


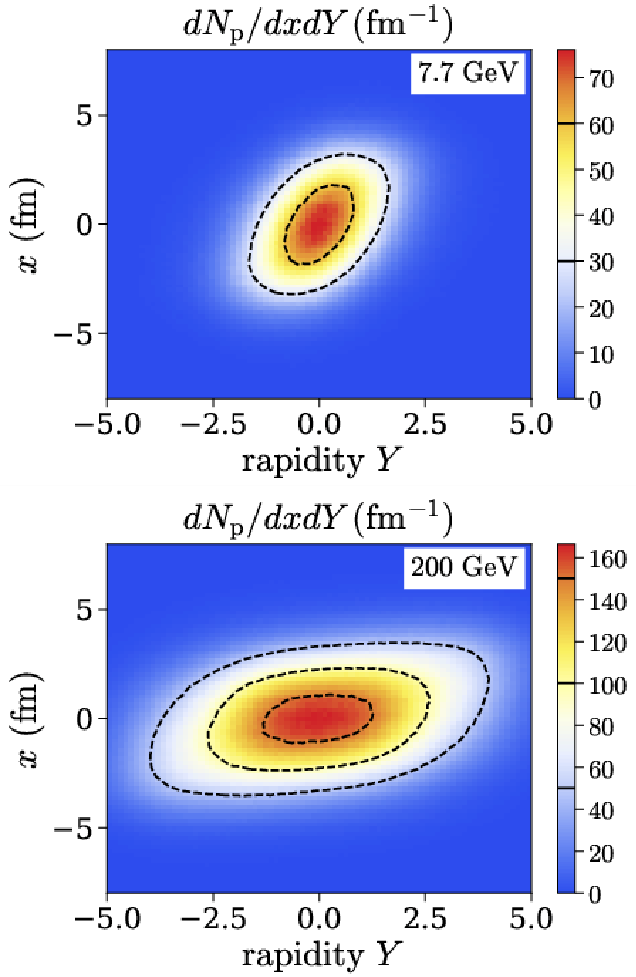
- Experiment = Theory.

- The most vorticial fluid: $\omega \sim 10^{22}\ \mathrm{s}^{-1}$.

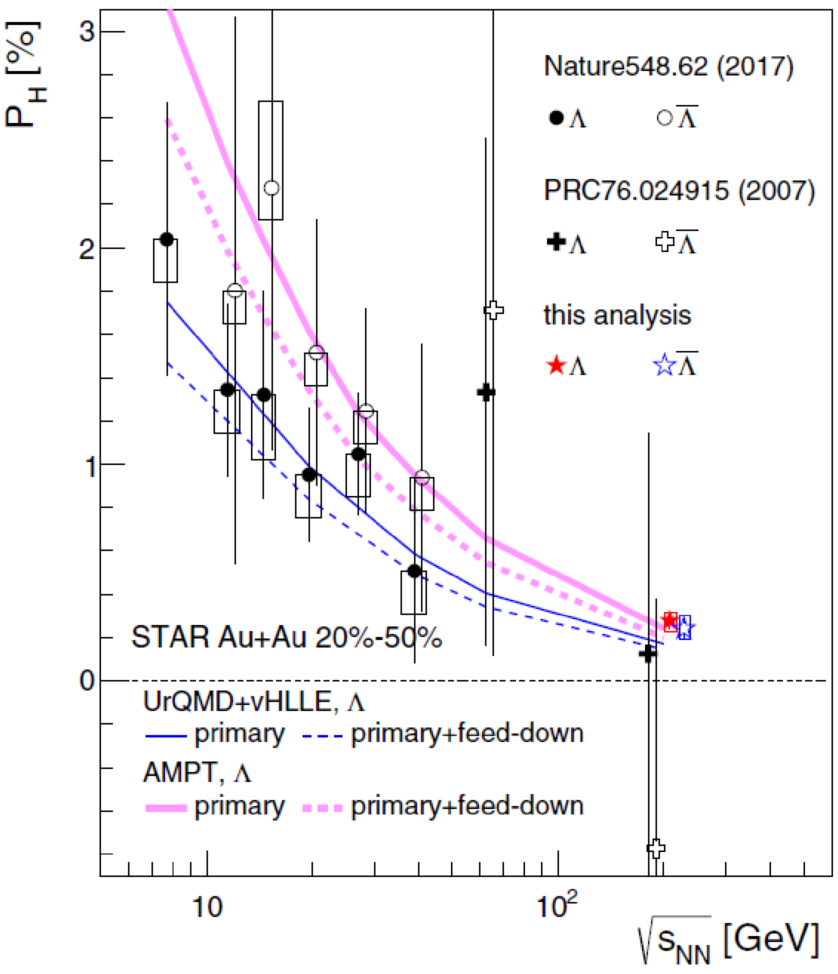
- P_Λ decreases with the increase of $\sqrt{s_{\mathrm{NN}}}$.
  → The Bjorken boost invariance is less broken at higher energy.

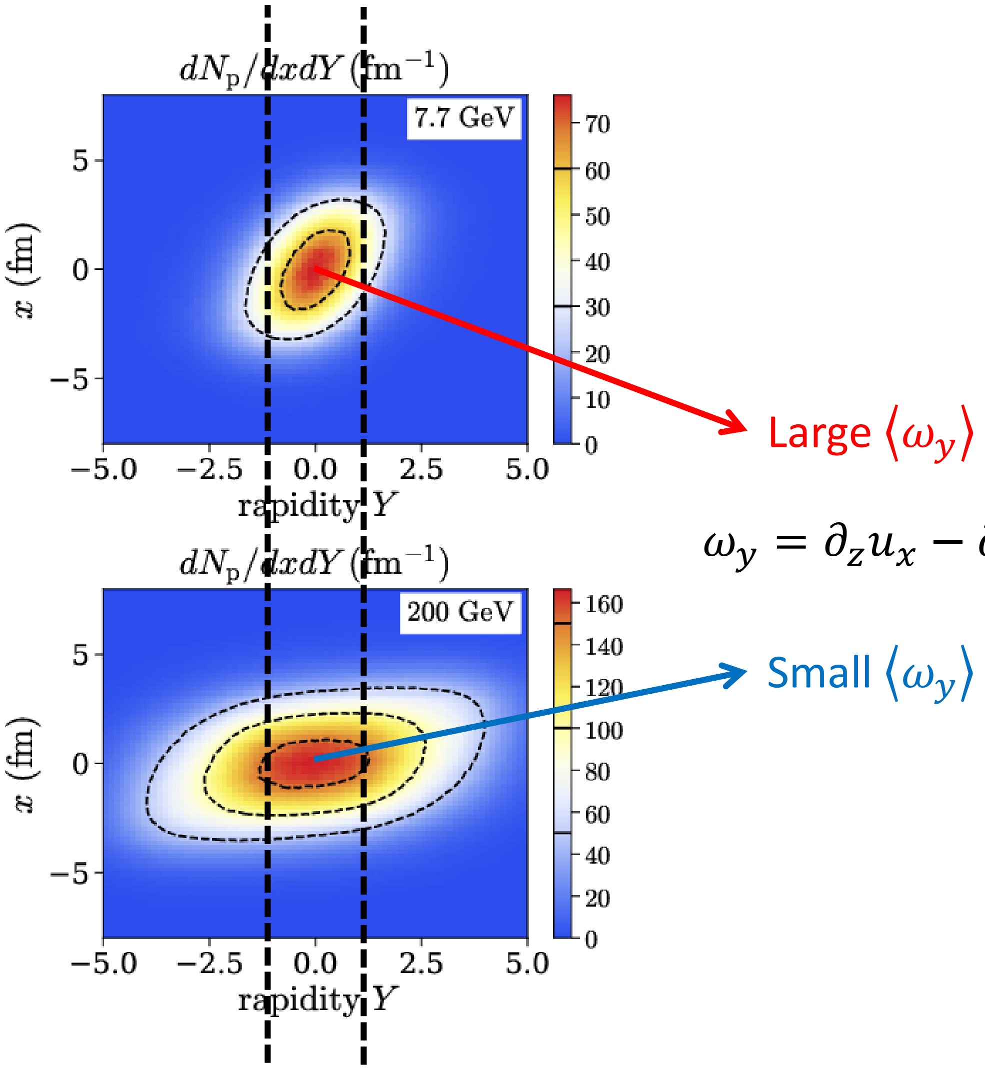
Global Λ polarization





Global Λ polarization

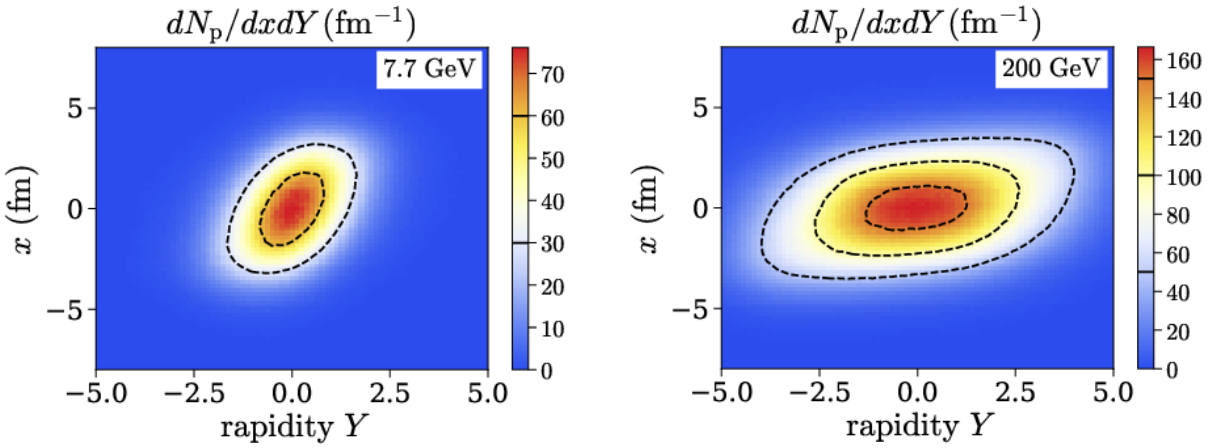




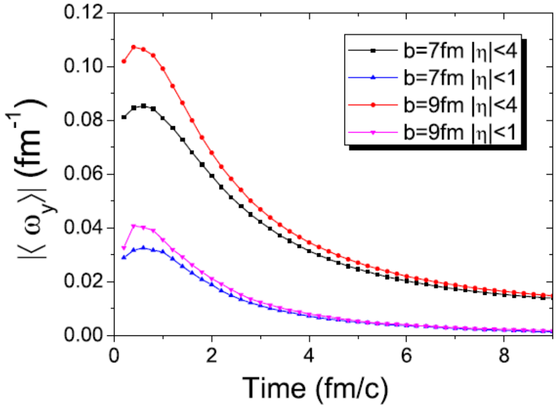
$$\omega_y = \partial_z u_x - \partial_x u_z$$

Rapidity dependence

- At larger rapidity: more *tilted* source → higher vorticity.

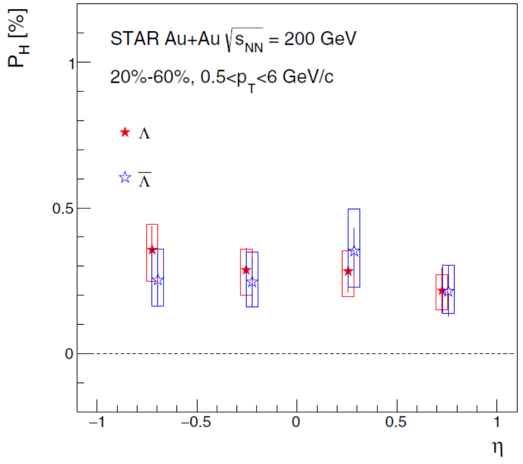


AMPT, Jiang-Lin-Liao 2016

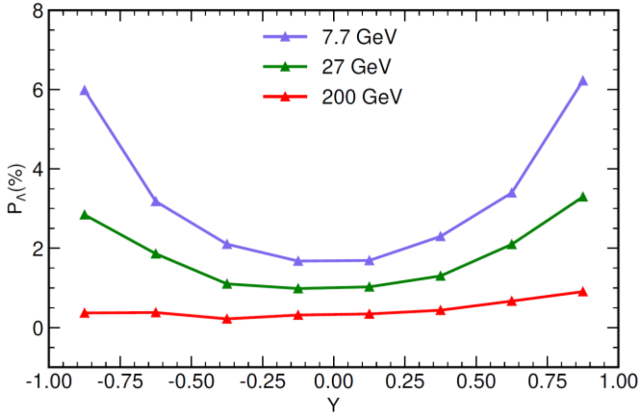


- Rapidity dependence of the global polarization:

STAR, 2018



AMPT, Li-XLX-Huang-Huang, in preparation



- Angular momentum and vorticity
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- <u>Local spin polarization</u>
- Vector meson spin alignment
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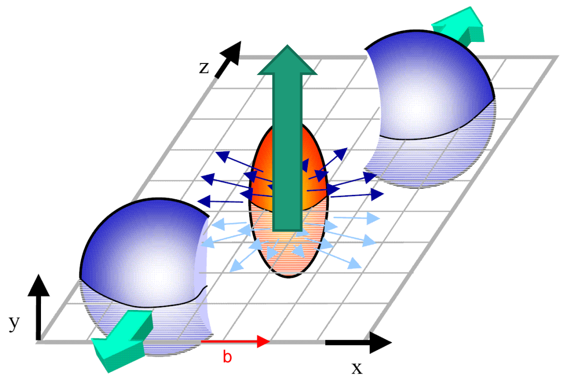
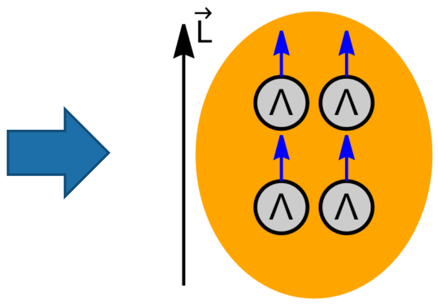
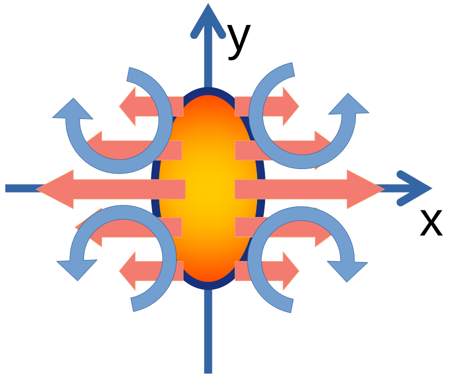
Motivation

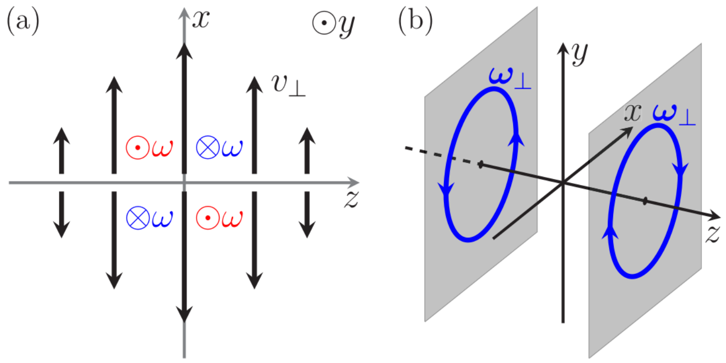
- Global spin polarization measures the average vorticity.





- Rich pattern of local vorticity:

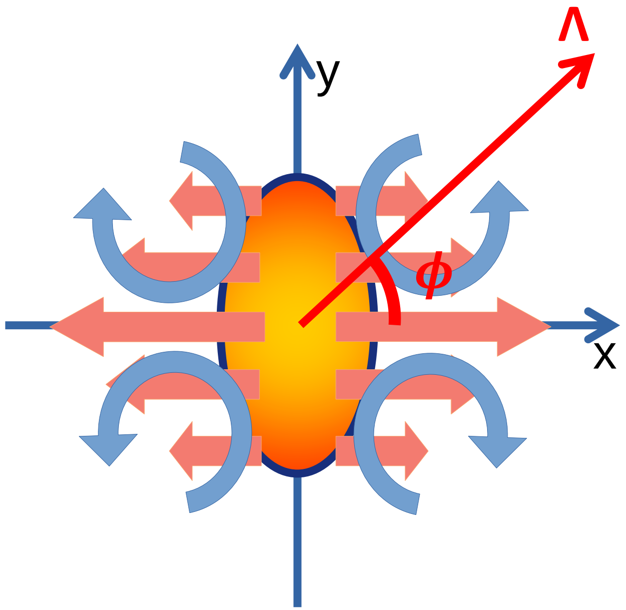




$\omega_z \sim \partial_x\, v_y - \partial_y\, v_x$

$\omega_\perp \sim \partial_z\, v_r$

Local Λ polarization Pz

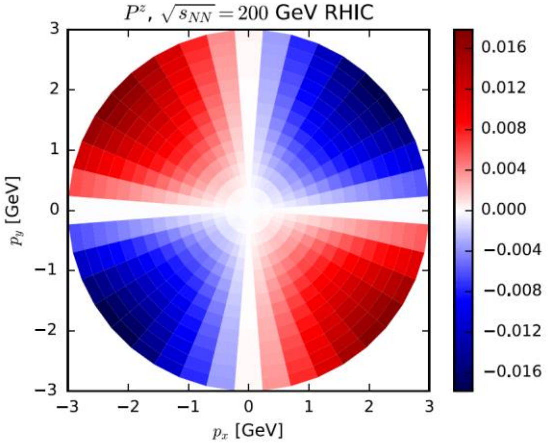


$\omega_z \sim \partial_x\, v_y - \partial_y\, v_x$

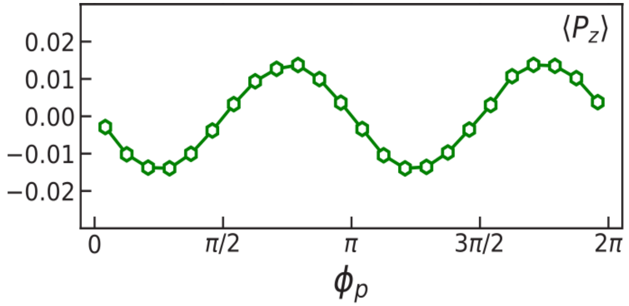
Longitudinal local vorticity
(in non-central collisions)

Theoretical predictions:

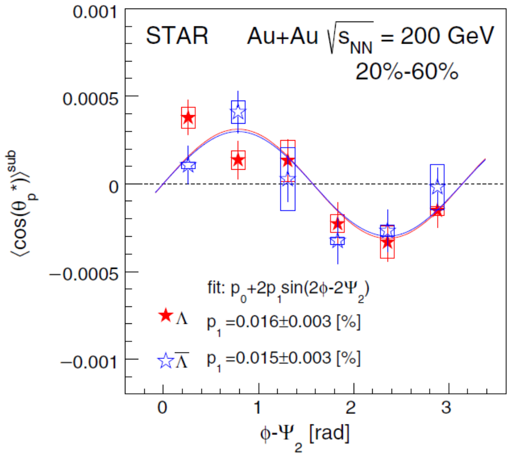
Becattini-Karpenko 2018



XLX-Li-Tang-Wang 2018



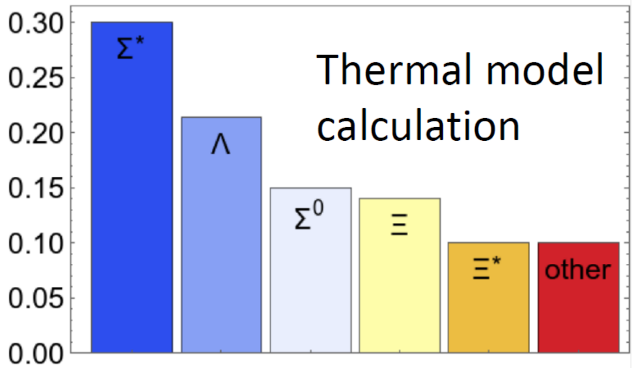
Experiment:

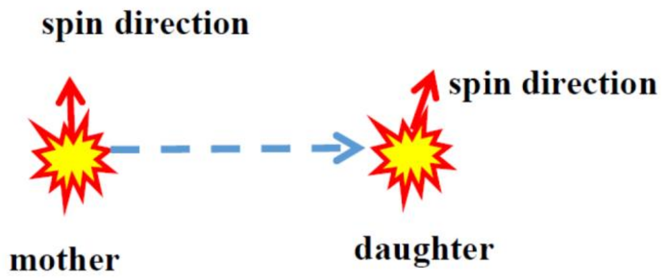


- $P_z = F_2 \cos(2\phi)$
- Puzzle: opposite sign between experiment and theory.

Feed-down contribution

- About 80% of final Λ's are from decays of higher lying particles.





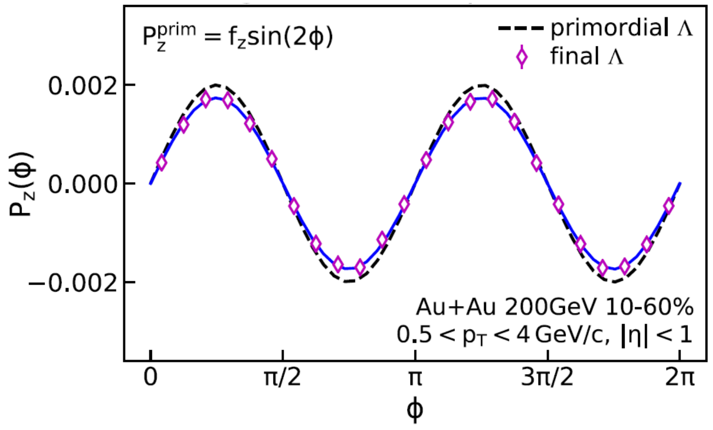
- Spin transfer in decay: (XLX-Li-Huang-Huang 2019; Becattini-Cao-Speranza 2019)

	spin and parity	$(1/N)dN/d\Omega^*$	$\mathbf{P}_D$	$\langle \mathbf{P}_D \rangle / \mathbf{P}_P$
strong decay	$1/2^+ \to 1/2^+0^-$	$1/(4\pi)$	$2(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\hat{\mathbf{p}}^* - \mathbf{P}_P$	-1/3
strong decay	$1/2^- \to 1/2^+0^-$	$1/(4\pi)$	$\mathbf{P}_P$	1
strong decay	$3/2^+ \to 1/2^+0^-$	$3\left[1-2\Delta/3-(1-2\Delta)\cos^2\theta^*\right]/(8\pi)$	Too long to be shown; see ref.	1
strong decay	$3/2^- \to 1/2^+0^-$	$3\left[1-2\Delta/3-(1-2\Delta)\cos^2\theta^*\right]/(8\pi)$		-3/5
weak decay	$1/2 \to 1/2\ 0$	$(1+\alpha P_P \cos\theta^*)/(4\pi)$		$(2\gamma+1)/3$
EM decay	$1/2^+ \to 1/2^+1^-$	$1/(4\pi)$	$-(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\hat{\mathbf{p}}^*$	-1/3

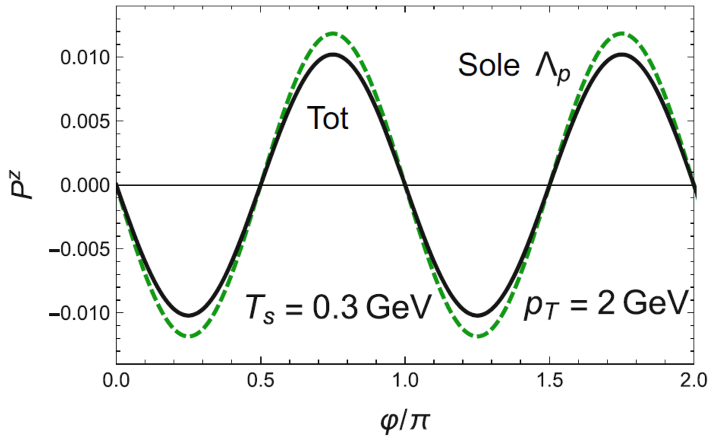
Feed-down contribution

- Feed-down effects reduce 10% primordial Λ polarization. Do not solve the puzzle.

(XLX-Li-Huang-Huang 2019)

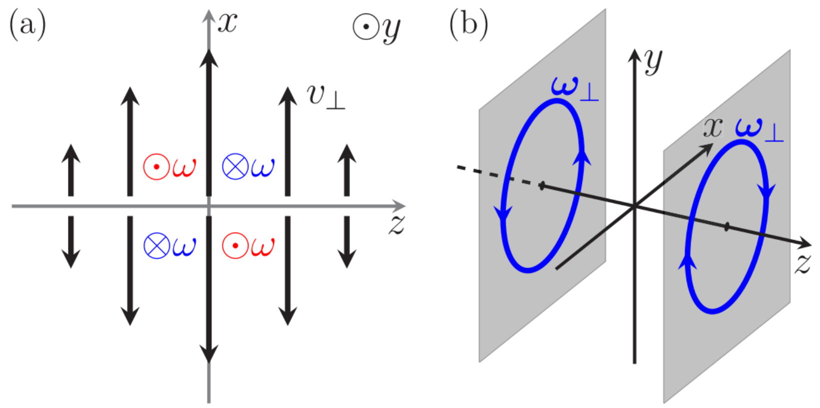


(Becattini-Cao-Speranza 2019)



- Other efforts to resolve the puzzle:
  - spin hydrodynamics (Florkowski etal 2018; Hattori etal 2019; …)
  - spin kinetic theory (Gao-Liang 2019; Weickgenannt etal 2019; Hattori etal 2019; Wang etal 2019; Liu etal 2020; …)
  - chiral vortical effect (Liu-Sun-Ko 2019)
  - other spin chemical potential (Florkowski etal 2019; Wu etal 2019)
  - …
- The puzzle is still unsolved.

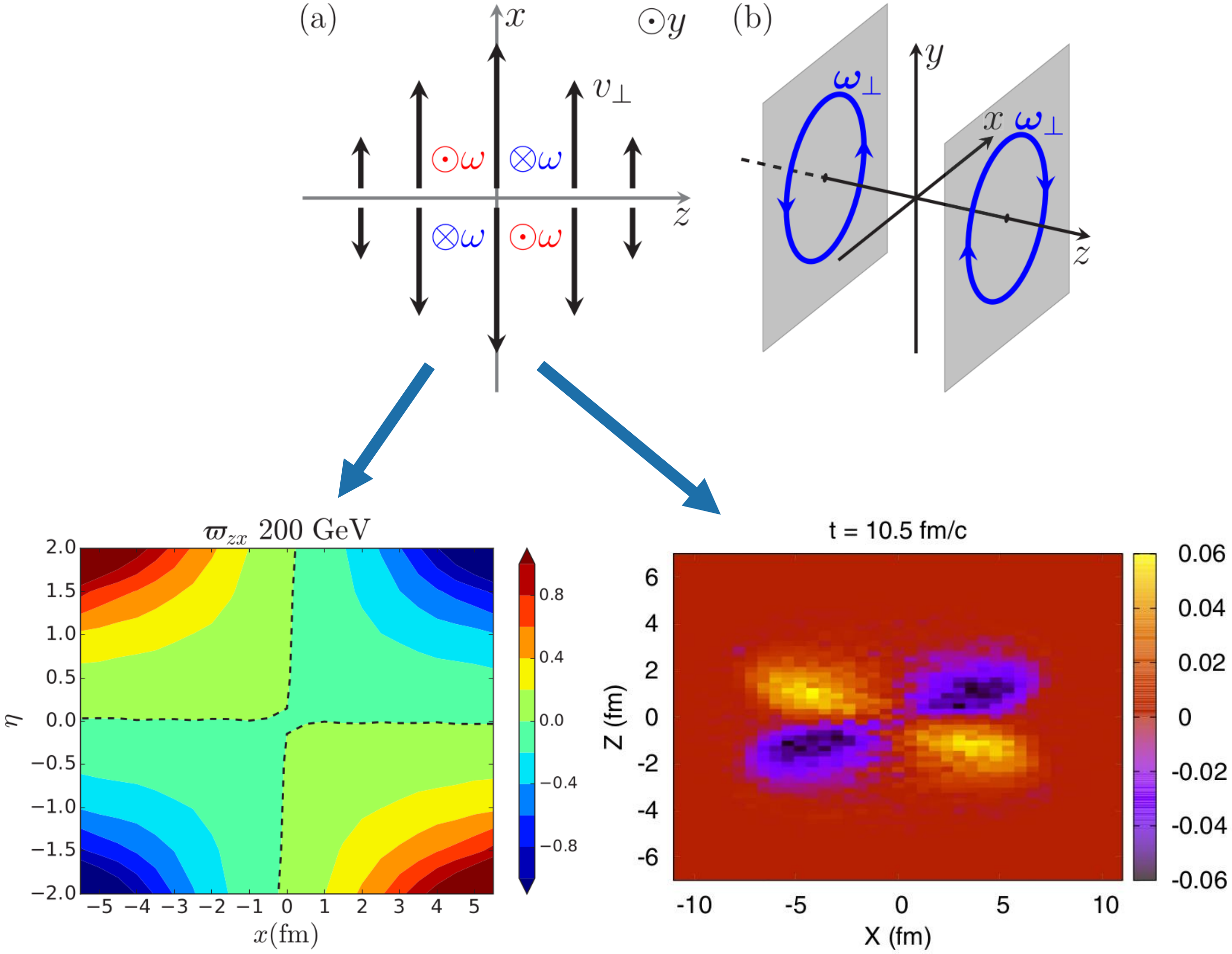
Transverse local vorticity



$\omega_{\perp} \sim \partial_z \, v_r$

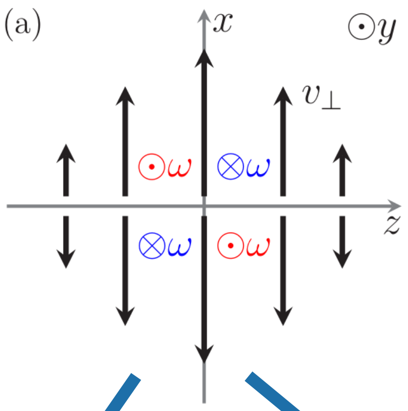
Transverse local vorticity
(in central & non-central collisions)

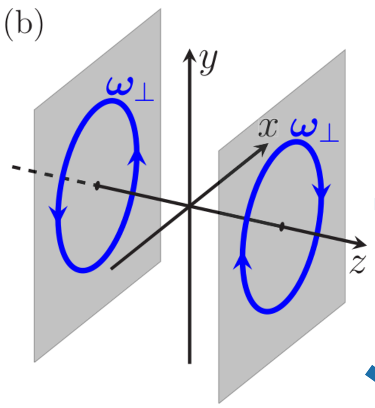
Transverse local vorticity



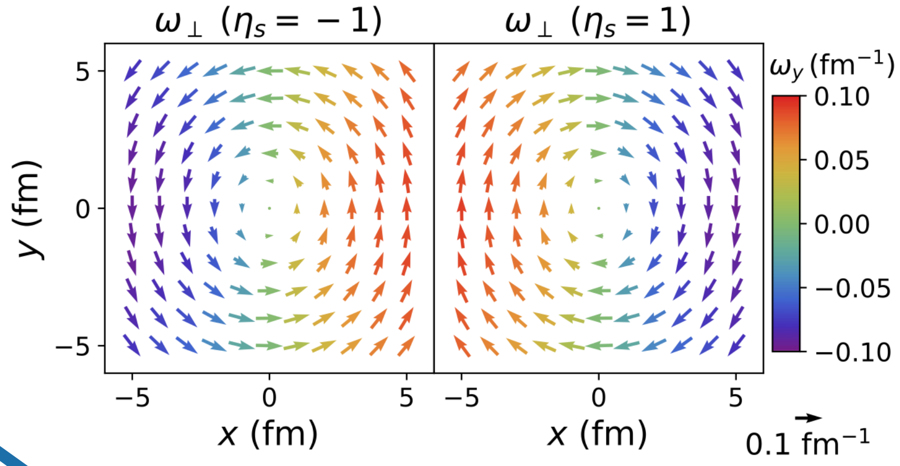
AMPT, Li-Pang-Wang-XLX 2017 HSD, Teryaev-Usubov 2015

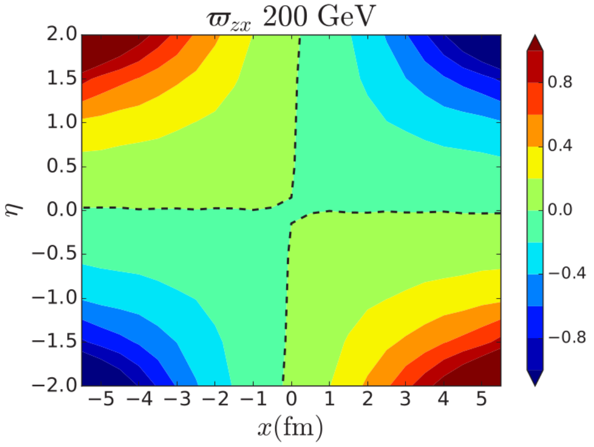
Transverse local vorticity



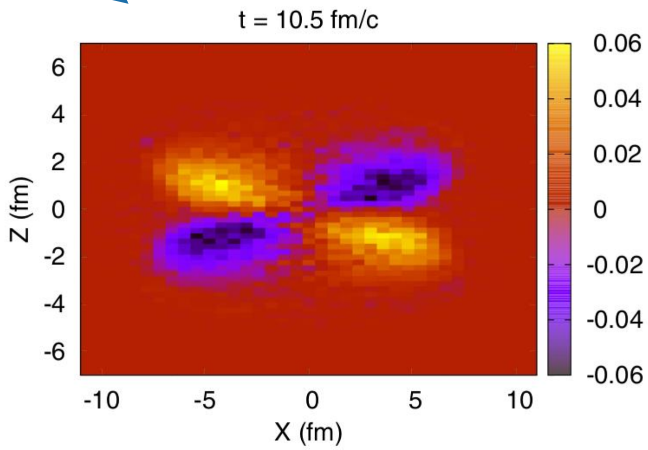


AMPT, XLX-Li-Tang-Wang 2018

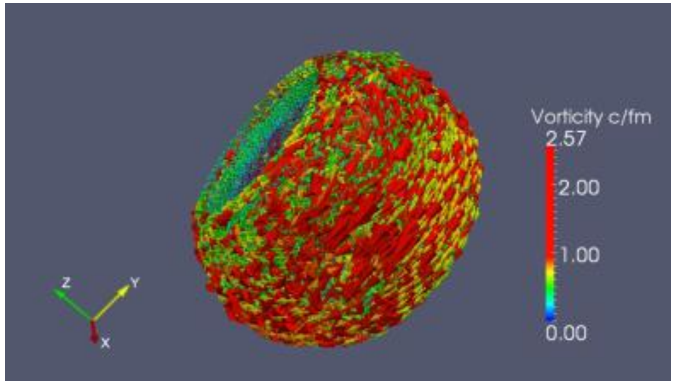




AMPT, Li-Pang-Wang-XLX 2017

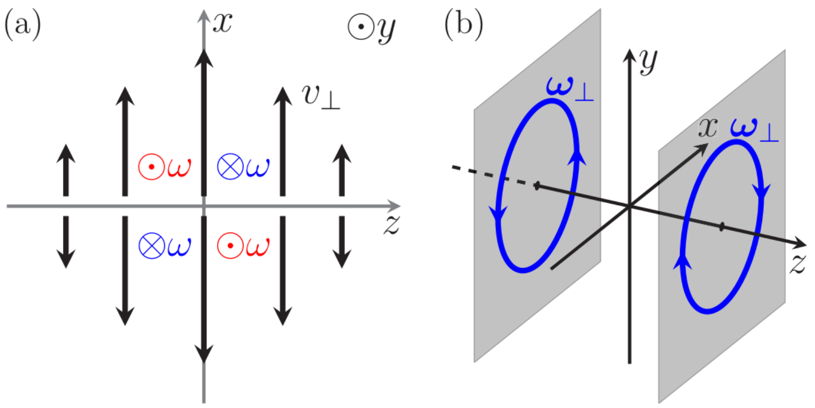


HSD, Teryaev-Usubov 2015

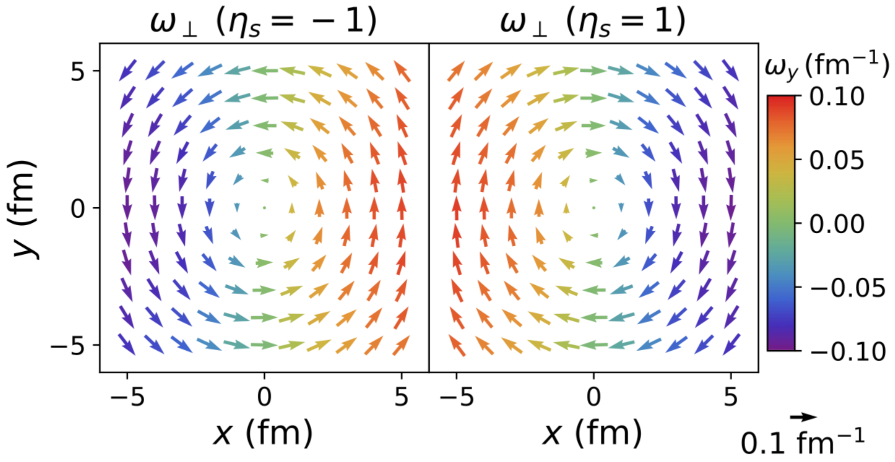


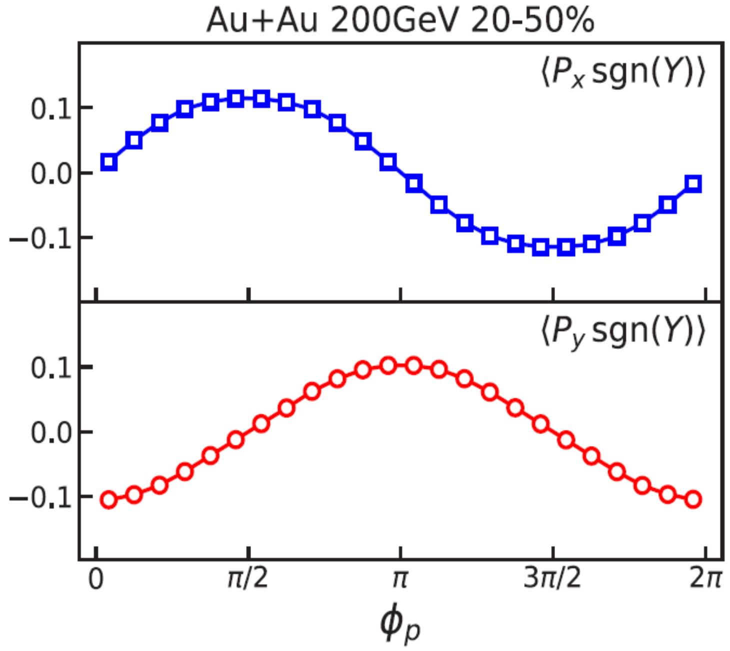
QGSM, Baznat etal 2016

Transverse local vorticity & polarization



AMPT, XLX-Li-Tang-Wang 2018





- Clockwise ($\eta_s > 0$); anti-clockwise ($\eta_s < 0$).
- Does not contribute to the global polarization.

$$P_x = F_\perp \sin\phi$$
$$P_y = -F_\perp \cos\phi$$

- The magnitude (∼0.1) is much larger than the global polarization (∼0.01).

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Vector meson spin alignment

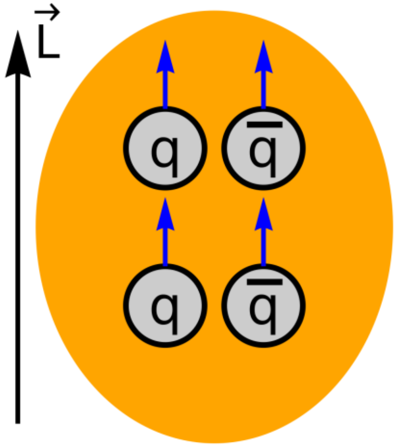
- Consider quark recombination: $q + \bar{q} \to V$.
- If q and $\bar{q}$ are polarized, V has different probabilities to occupy three spin states:

$$|11\rangle = |\uparrow\uparrow\rangle$$

$$|10\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1\text{-}1\rangle = |\downarrow\downarrow\rangle$$

- For global polarization:



$$\rho^{q,\bar{q}} = \frac{1}{2}\begin{pmatrix} 1 + P^{q,\bar{q}} & 0 \\ 0 & 1 - P^{q,\bar{q}} \end{pmatrix}$$

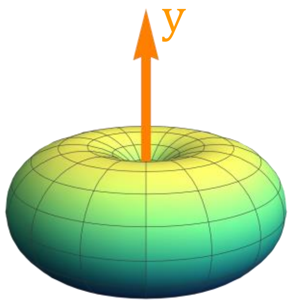
$$\rho^{V} = \begin{pmatrix} \frac{(1+P^q)(1+P^{\bar{q}})}{3+P^q P^{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P^q P^{\bar{q}}}{3+P^q P^{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P^q)(1-P^{\bar{q}})}{3+P^q P^{\bar{q}}} \end{pmatrix}$$

(Liang-Wang 2005)

Vector meson spin alignment

$$\rho^V = \begin{pmatrix} \frac{(1+P^q)(1+P^{\bar{q}})}{3+P^qP^{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P^qP^{\bar{q}}}{3+P^qP^{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P^q)(1-P^{\bar{q}})}{3+P^qP^{\bar{q}}} \end{pmatrix}$$

- Among $(\rho_{11}, \rho_{00}, \rho_{-1-1})$,
  - only ρ_{00} is measurable.
  - $(\rho_{11} - \rho_{-1-1}) = P_y$ is not measurable.
    (The decay distribution does not change by replacing $y \to -y$)
- E.g., $\phi \to KK$:

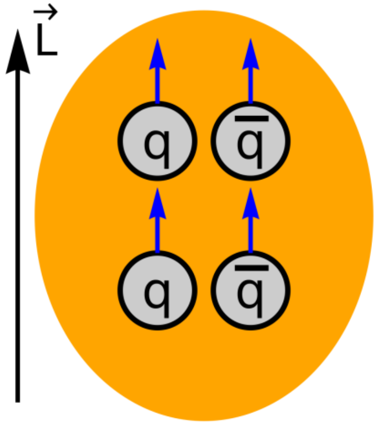


$\rho_{00} < 1/3$

$\rho_{00} > 1/3$

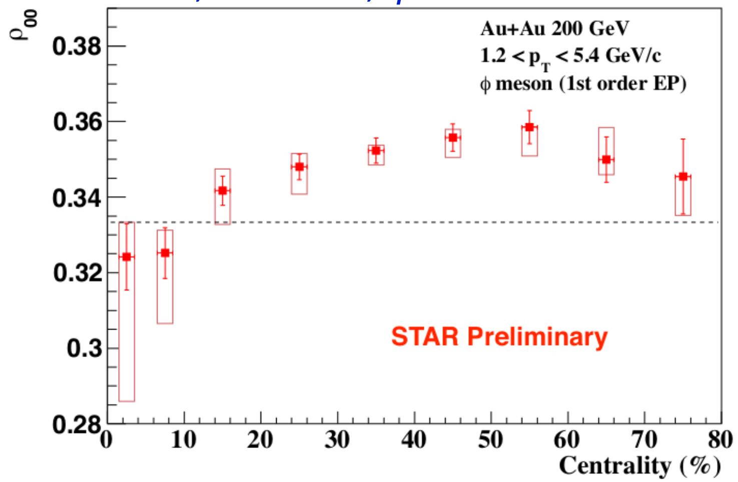
Vector meson spin alignment

global polarization

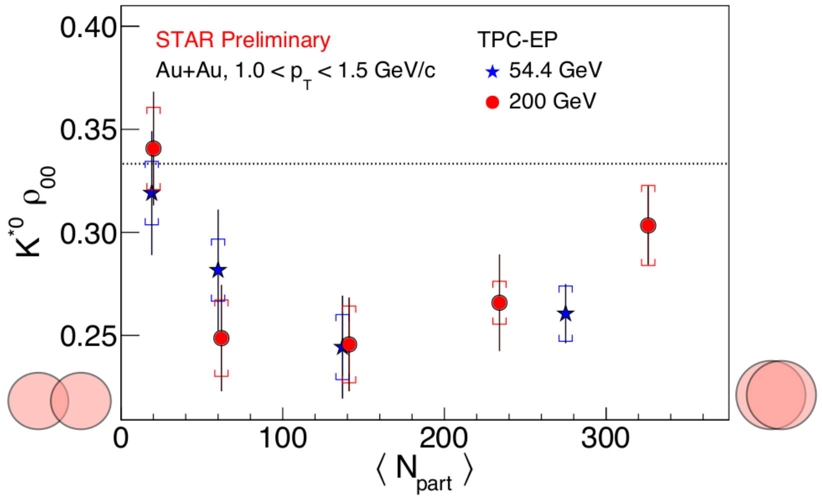


$$\rho_{00} = \frac{1 - P^q P^{\bar{q}}}{3 + P^q P^{\bar{q}}} < 1/3$$

STAR, QM2018, ϕ meson



STAR, QM2019, K^{*0}



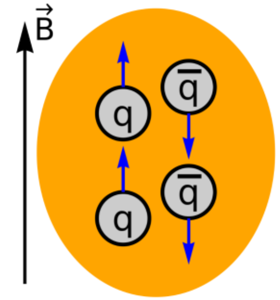
Puzzle 1:

$\rho_{00} > 1/3$ in non-central collisions.

Magnetic field?

Meson mean field?

(Sheng-Oliva-Wang 2020)



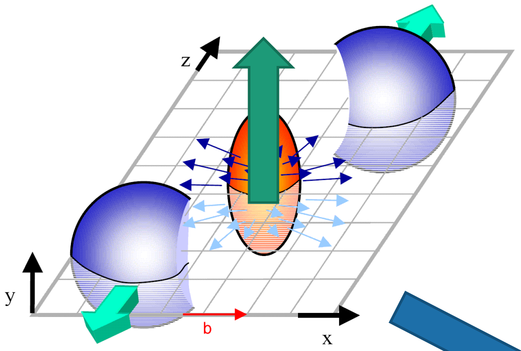
Puzzle 2:

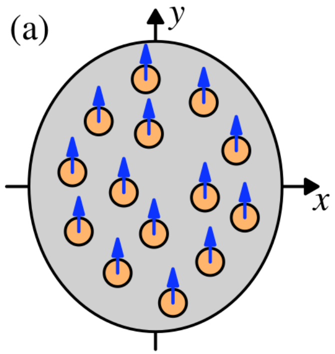
$\rho_{00} < 1/3$ in central collisions.

Local spin alignment?

(XLX-Li-Huang-Huang 2020)

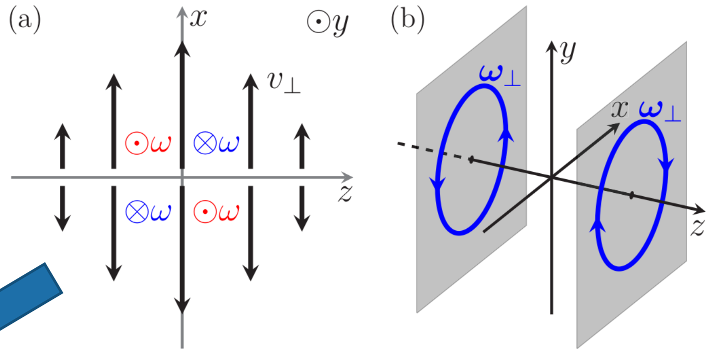
Global vs Local spin alignment

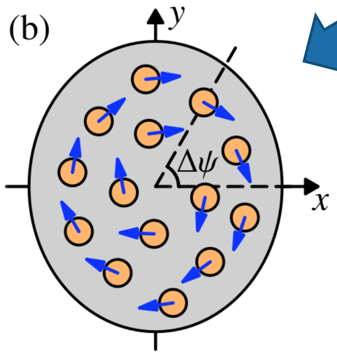




Global polarization

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





$(\eta_s > 0)$

Local polarization

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

(XLX-Li-Huang-Huang 2020)

- Such local polarization exists in central collisions.

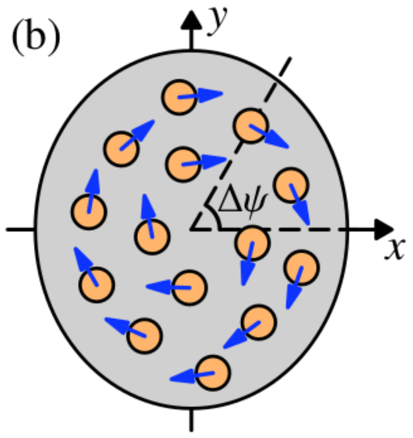
Local spin alignment

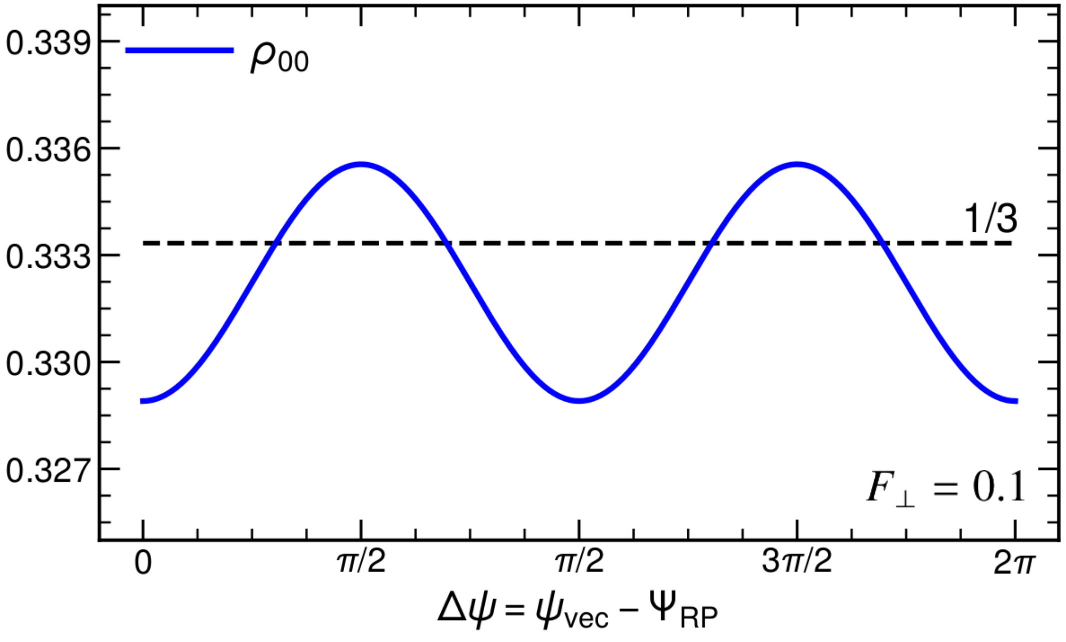
- In central collisions:

$$P_x = F_\perp \sin(\Delta\psi)$$
$$P_y = -F_\perp \cos(\Delta\psi)$$
$$P_z = 0$$

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

$$\rho_{00}(\Delta\psi) = \frac{1 - F_\perp^2 \cos(2\Delta\psi)}{3 + F_\perp^2} \approx \frac{1}{3} - \frac{F_\perp^2}{9} - \frac{F_\perp^2}{3}\cos(2\Delta\psi)$$





(XLX-Li-Huang-Huang 2020)

Local spin alignment

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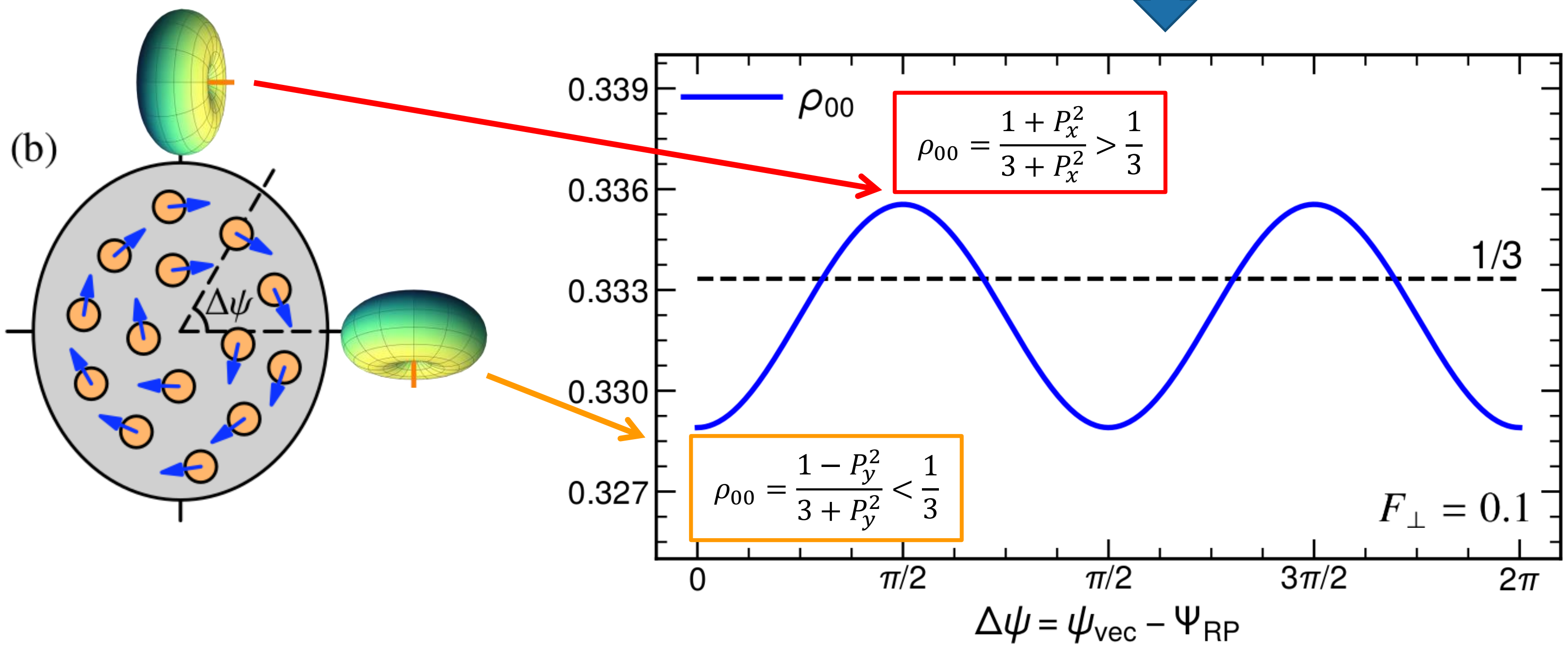

(XLX-Li-Huang-Huang 2020)

Local spin alignment

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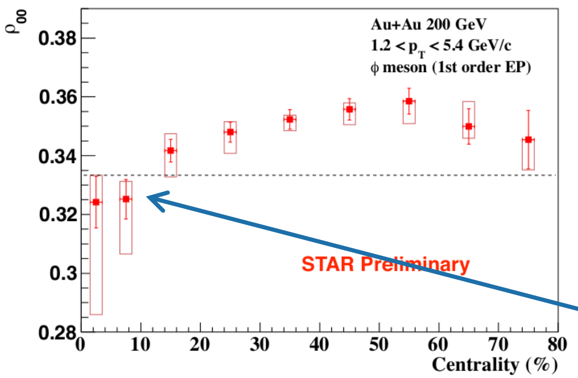
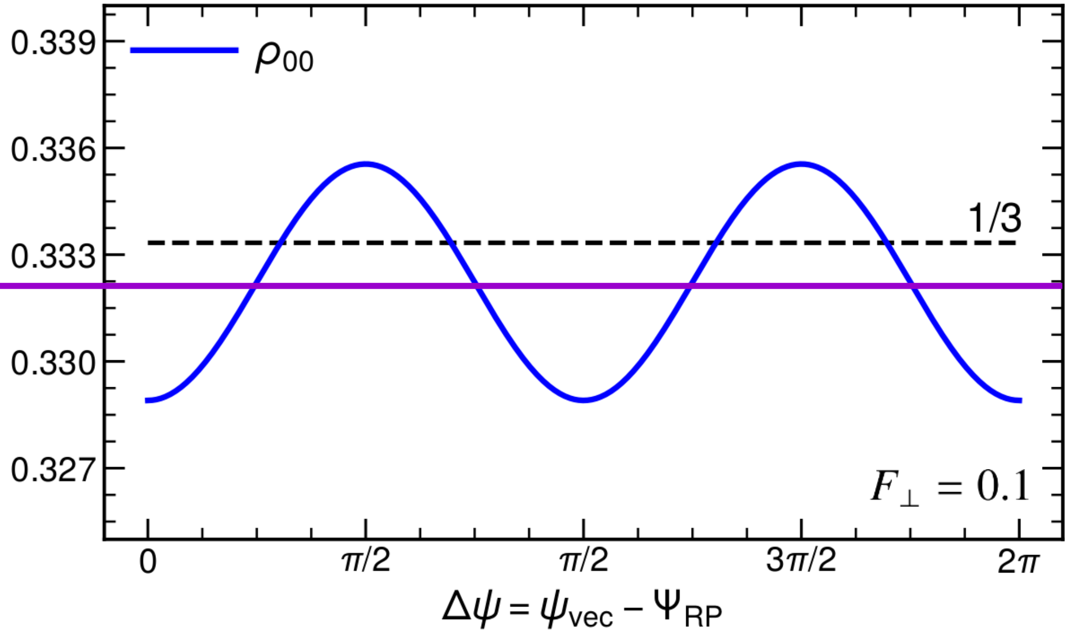


$$\langle\rho_{00}\rangle \approx \frac{1}{3} - \frac{F_\perp^2}{9}$$



(XLX-Li-Huang-Huang 2020)

- The average polarization is zero;
- But average ρ_{00} is smaller than 1/3.

- Need to check the $\Delta\psi$-modulation in experiment.

Summary

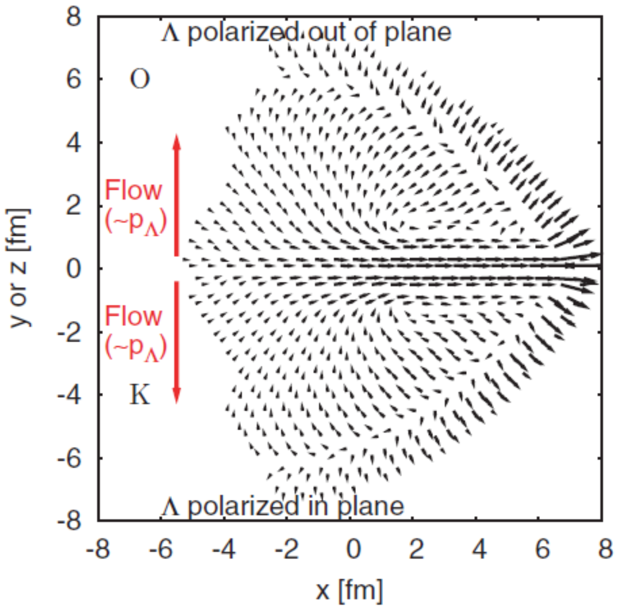
- Strong global angular momentum and vorticity are produced in heavy-ion collisions. Spin polarization can be used to probe such rotational motion.
- There are multiple sources for spin polarization:
  - **Global polarization** is caused by the global angular momentum. It is well understood through thermal vorticity. It is interesting to further study the rapidity dependence.
  - **Local polarization** can be induced by the local vorticity pattern arising from fireball's expansion. The "sign problem " is still a puzzle.
- The local spin alignment could explain the smaller-than-1/3 ρ_{00} in central collisions.

Thank you

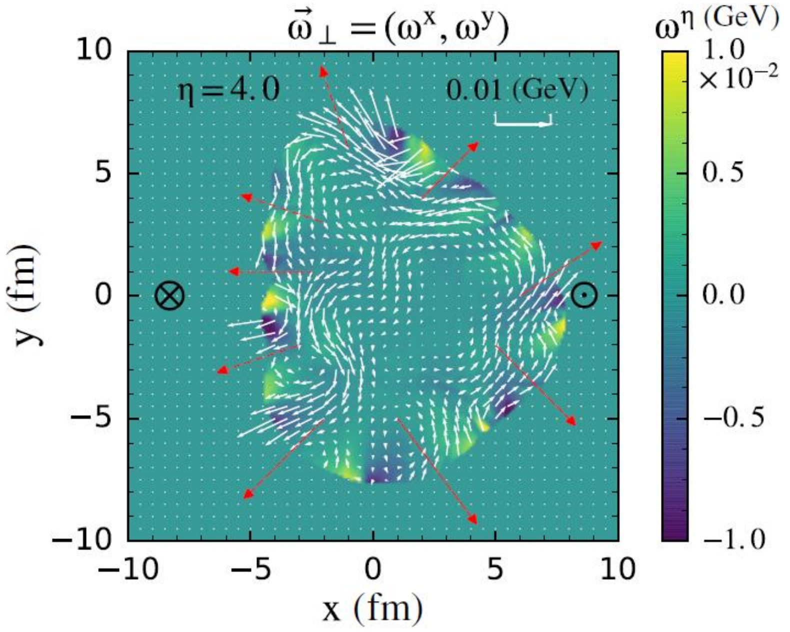
Back Up

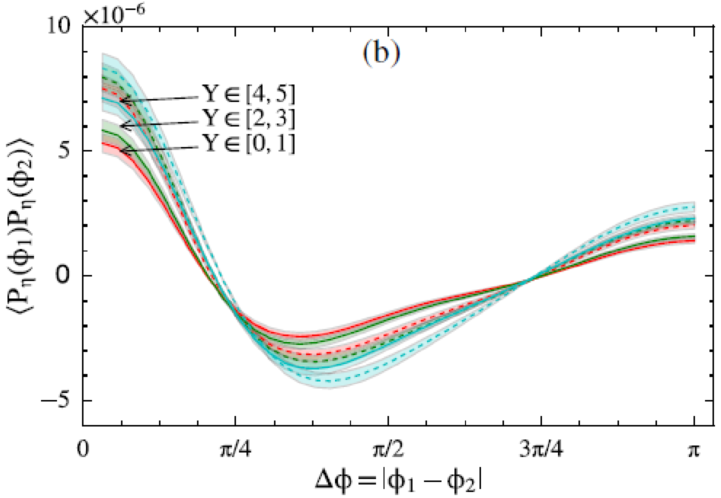
Vorticity by jet & fluctuations

Betz-Gyulassy-Torrieri 2007



Pang-Petersen-Wang-Wang 2016





- Vorticity pair around a fast-moving jet-like fluctuation.
- It leads to the spin-spin correlation of a near-side Λ pair.