Vector meson spin alignment

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ECT* event: “Spin and Hydrodynamics in Relativistic Nuclear Collisions”

outline

- Quick review of global Λ polarization and global spin alignment of vector mesons

- Azimuthal angle dependence of Λ polarization, aka local Λ polarization

- Local spin alignment of vector mesons

  based on: XLX, Hui Li, Xu-Guang Huang, and Huan Zhong Huang, to appear on arXiv tomorrow (6^{th} Oct).

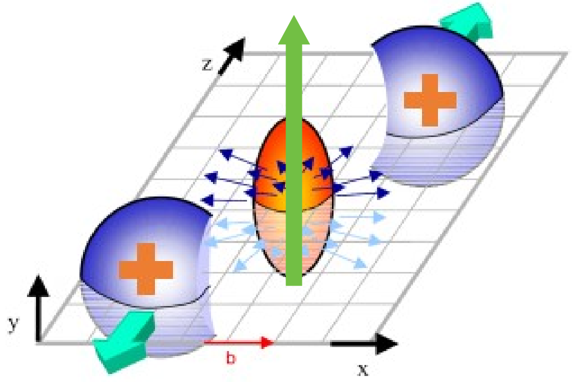
- Summary

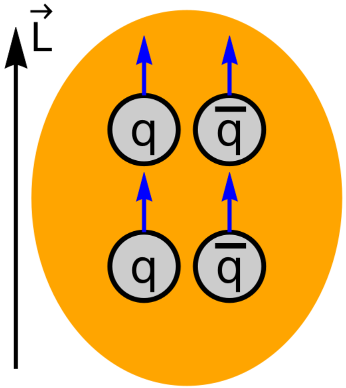
Spin polarization in a rotating system

- There is a huge orbital angular momentum (OAM) in non-central collisions.

- Due to spin-orbit coupling, such an OAM is partially transferred to spin polarization of particles in the system.

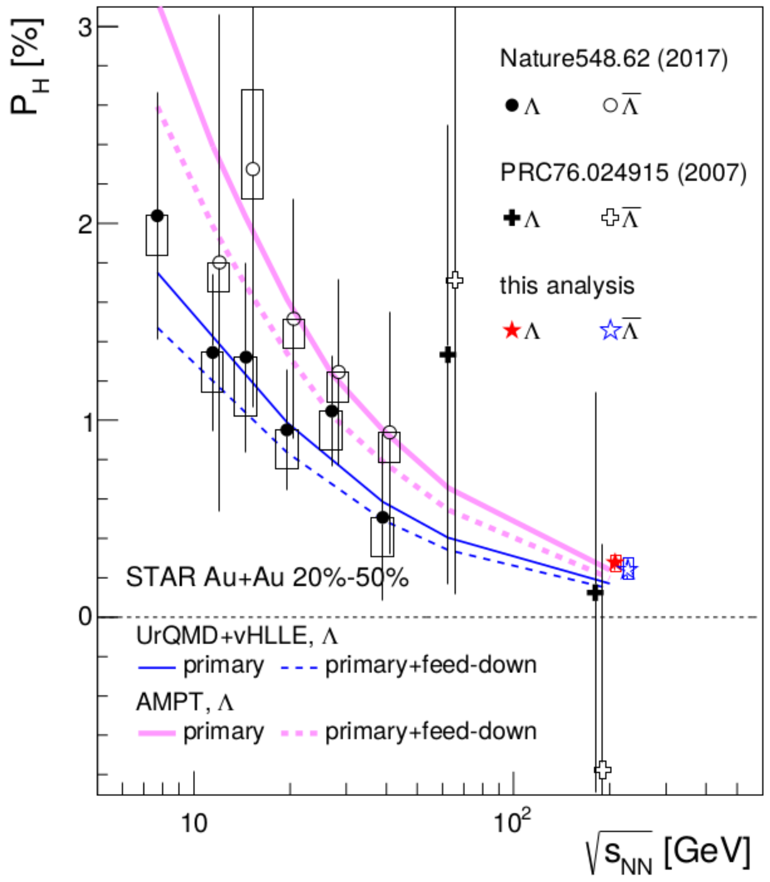
$$L \sim 10^5 - 10^7 \hbar$$

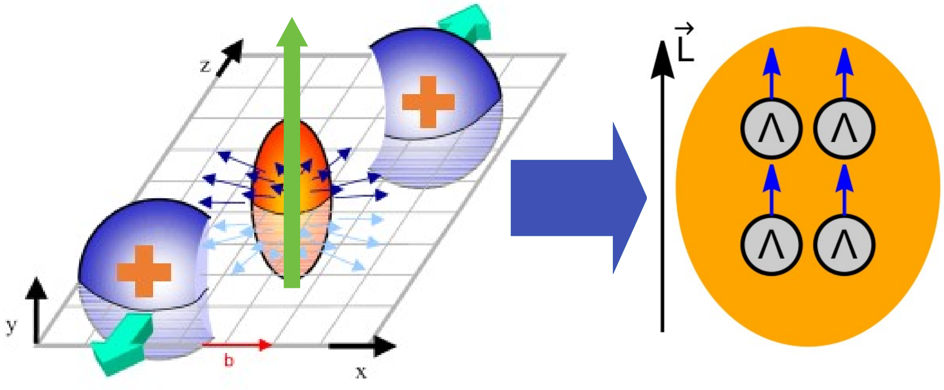




Global Λ polarization

STAR Nature 2017 & PRC 2018





Experiment data agrees with theoretical calculation:

- Hydrodynamics:

  Karpenko-Becattini, Xie-Wang-Csernai, Ivanov-Toneev-Soldatov
- Coarse grained transport models:

  Li-Pang-Wang-XLX, Shi-Li-Liao, Wei-Deng-Huang
- Chiral Kinetic Equation:

  Sun-Ko
- Other approaches, …

Global spin alignment of vector mesons

- Considering vector mesons which are produced by quark combination $q\bar{q} \to V$

Spin state of vector meson

$$\left\{ \begin{aligned} |11\rangle &= |\uparrow\uparrow\rangle \\ |10\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \\ |1\text{-}1\rangle &= |\downarrow\downarrow\rangle \end{aligned} \right\}$$

Spin-triplet state of quark and anti-quark

Global spin alignment of vector mesons

- Considering vector mesons which are produced by quark combination $q\bar{q} \to V$

Spin state of vector meson

$$|11\rangle = |\uparrow\uparrow\rangle$$
$$|10\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$
$$|1\text{-}1\rangle = |\downarrow\downarrow\rangle$$

Spin-triplet state of quark and anti-quark

- If quarks and anti-quarks are globally polarized, the vector meson will have different probabilities to occupy the three spin states.

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

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

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

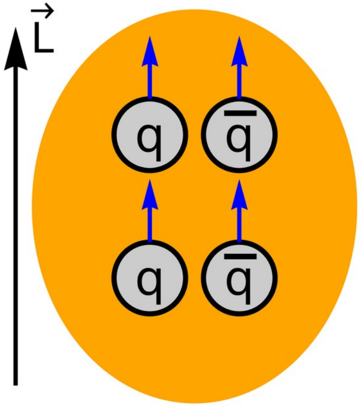
See:
Liang-Wang 2005.

- Among three diagonal elements of ρ^V, only ρ_{00} is measurable in experiments.

Global spin alignment of vector mesons

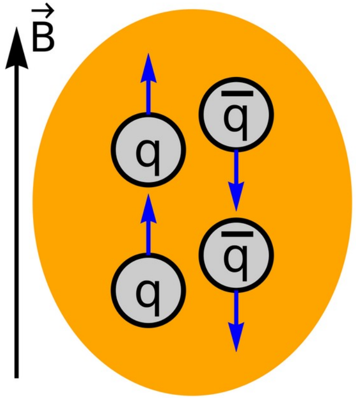
- Using the formula in the previous page, we can do some quick analysis:

Polarized along the same direction:
(induced by OAM or vorticity)



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

Polarized along opposite directions:
(caused by magnetic field, vector meson field or fragmentation)



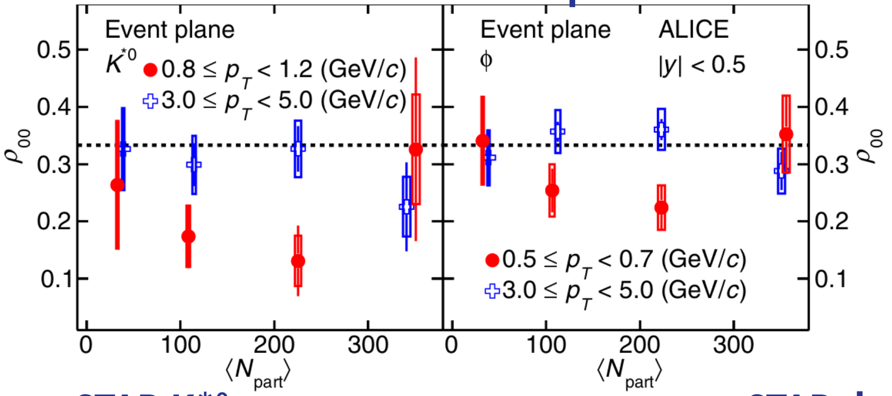
$$\rho_{00} = \frac{1 - P^q P^{\bar{q}}}{3 + P^q P^{\bar{q}}} > 1/3$$

See:
Liang-Wang 2005,
Yang etal 2018,
Sheng etal 2020.

- In both cases, $\rho_{00} \neq 1/3$ is expected to signal nontrivial global polarization of quarks and anti-quarks.

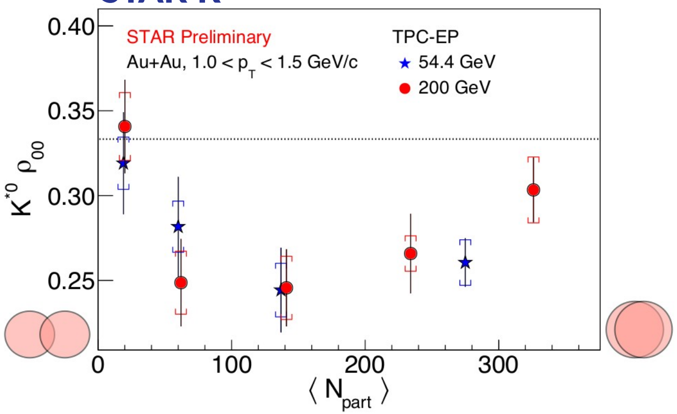
Experimental measurement of ρ_{00}

ALICE K^{*0} **ALICE ϕ**

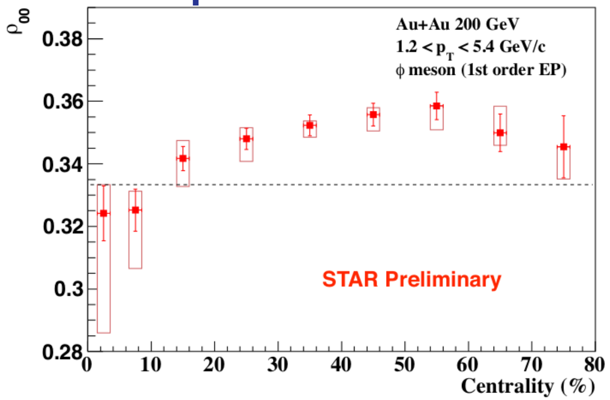


	K^{*0}	ϕ
ALICE	ρ_{00}<1/3	ρ_{00}<1/3
STAR	ρ_{00}<1/3	ρ_{00}<1/3 (central) ρ_{00}>1/3 (noncentral)

STAR K^{*0}



STAR ϕ



See:

ALICE 2020,

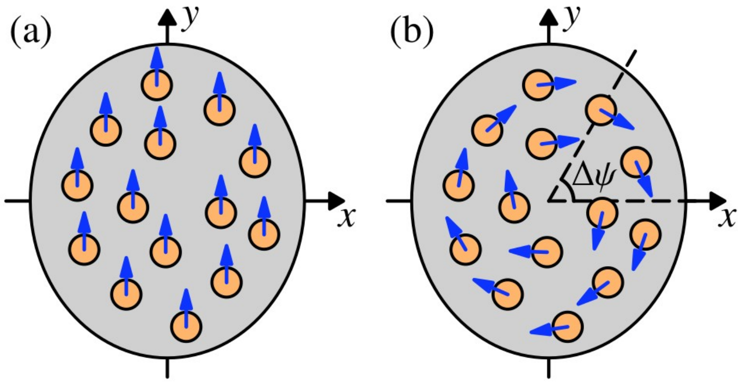
Talk by Zhou (STAR) at QM2018,

Talk by Singha (STAR) at QM2019.

- ρ_{00} for K^{*0} and ϕ deviates from 1/3 in a wide range of centrality.
- The unexpectedly large magnitude has not been understood.

Turn to local polarization

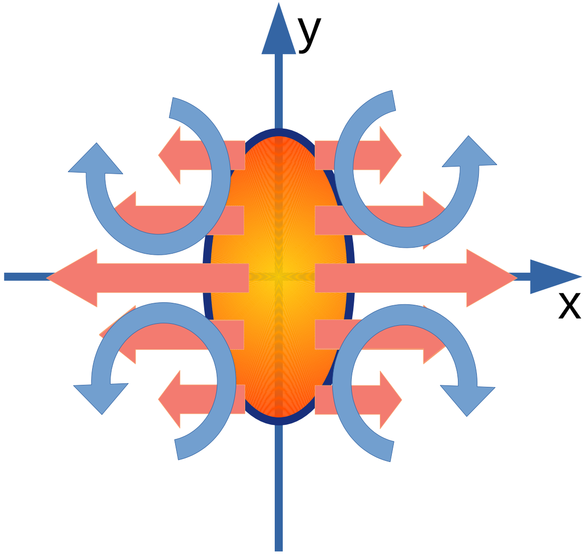
- In the analysis in previous pages, particles are assumed to be globally polarized along a specific direction, i.e. the OAM direction.



- However the global OAM is not the only source of vorticity and polarization.
- In fact, there is local vorticity, in which particles are locally polarized.

Longitudinal local polarization

- In noncentral collisions, the elliptic flow v_2 can produce a quadrupole pattern of the longitudinal vorticity on the transverse plane.
- Such a vorticity pattern leads to the longitudinal local polarization.



$$\omega_z \sim \partial_x v_y - \partial_y v_x \neq 0$$

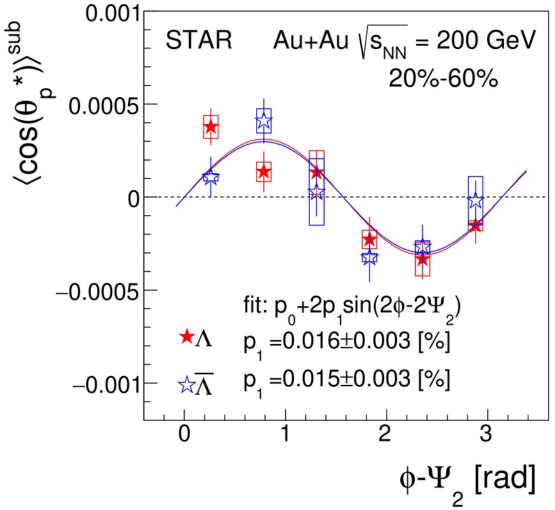
$$P_z(\Delta\psi) = F_{2z} \sin(2\Delta\psi) + F_{4z} \sin(2\Delta\psi) + \ldots$$

See:
Becattini-Karpenko 2018,
Voloshin 1710.08934

Longitudinal local polarization

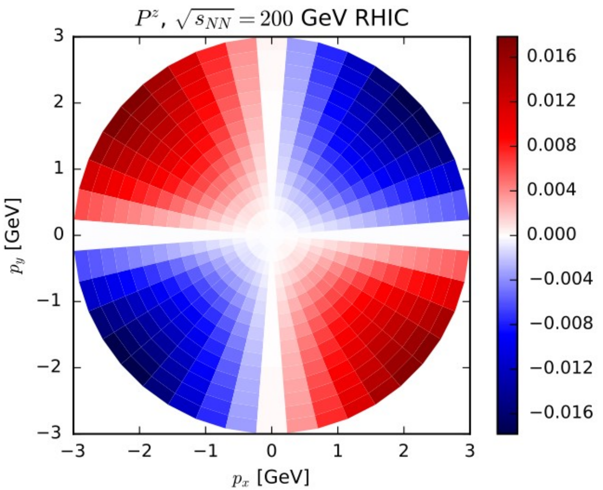
- There is a puzzle regarding the opposite sign in experiment data versus theoretical predictions.

STAR 2019



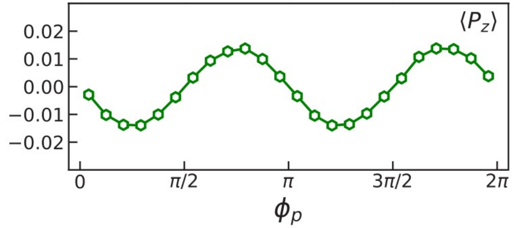
$F_z > 0$

Becattini-Karpenko 2018



$F_z < 0$

XLX-Li-Tang-Wang 2018

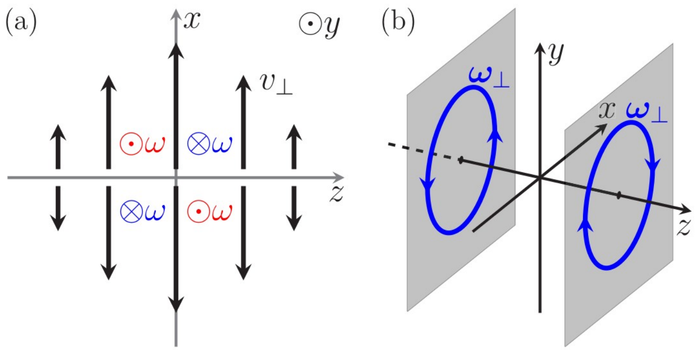


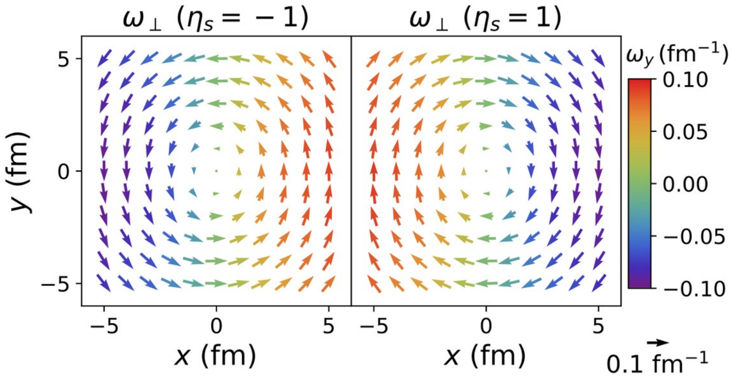
$$P_z(\Delta\psi) = F_z \sin(2\Delta\psi)$$

- The existence of the longitudinal local polarization has been evidenced.

Transverse local vorticity

- In both central and noncentral collisions, the gradient of the radial flow along the z axis can generate transverse vorticity loops at finite rapidity.





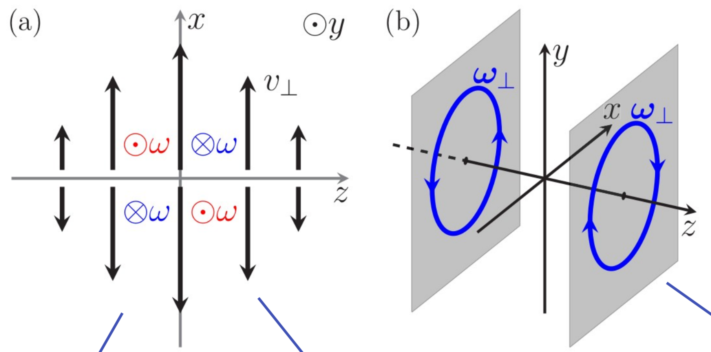
$$\omega_\perp = (\omega_x, \omega_y) \sim \partial_z v_\perp \mathbf{e}_\phi$$

$$\mathbf{e}_\phi = (-\sin(\Delta\psi), \cos(\Delta\psi))$$

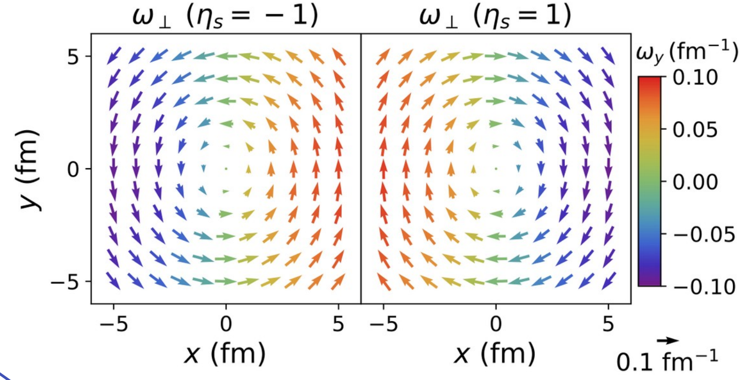
See:
XLX-Li-Tang-Wang 2018,
Wei-Deng-Huang 2019,
Jiang etal 2016,
Baznat etal 2016,
Teryaev-Usubov 2015,
and others.

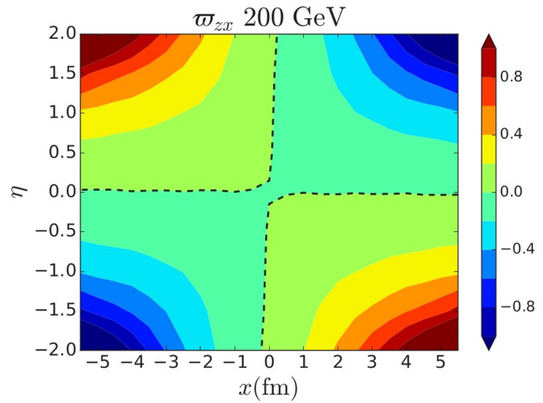
Transverse local vorticity

- The transverse local vorticity pattern has been observed in various model calculations, for example:

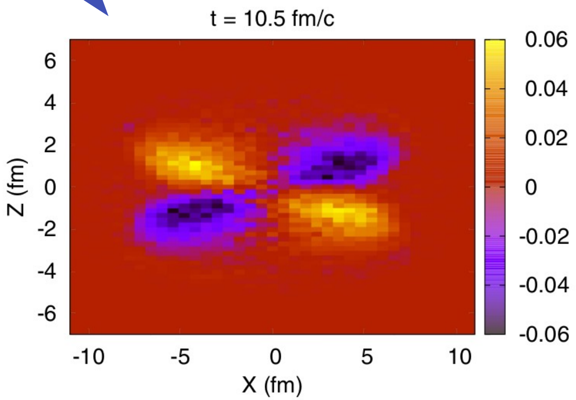


XLX-Li-Tang-Wang 2018

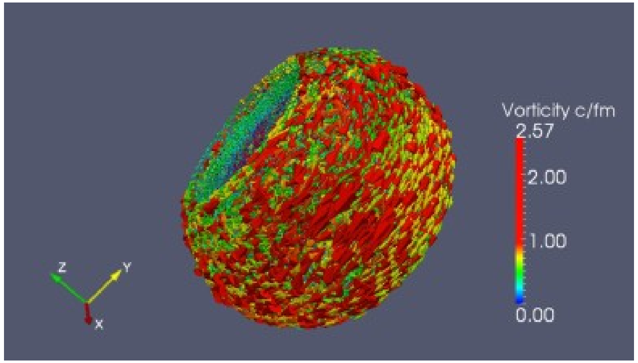




Li-Pang-Wang-XLX 2017

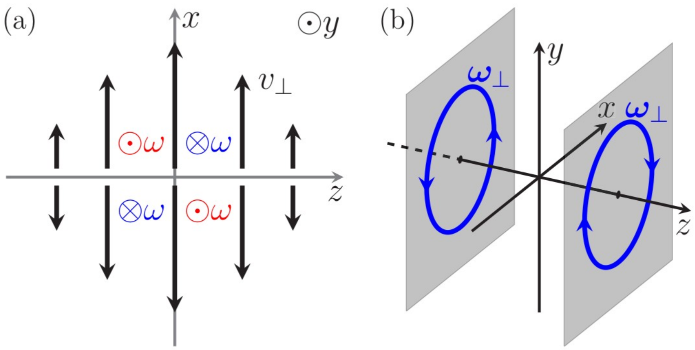


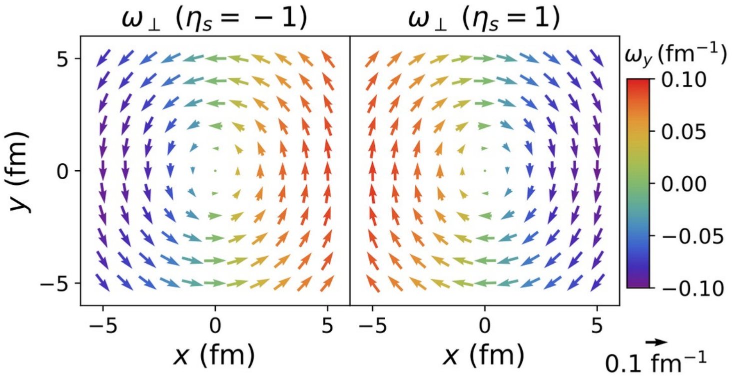
Teryaev-Usubov 2015



Baznat etal 2016

Transverse local polarization





- Such a vorticity pattern leads to the transverse local polarization.

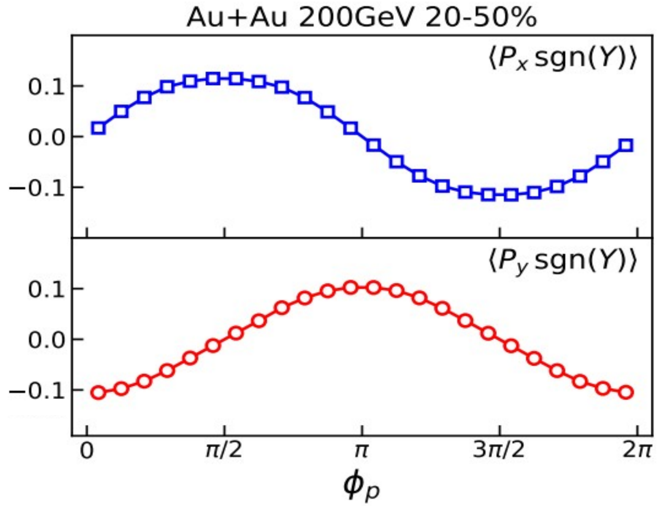
$$\omega_\perp = (\omega_x, \omega_y) \sim \partial_z v_\perp \mathbf{e}_\phi$$

$$P_x(\Delta\psi) = \quad F_x \sin(\Delta\psi)$$

$$P_y(\Delta\psi) = -F_y \cos(\Delta\psi)$$

See:
XLX-Li-Tang-Wang 2018,
Wei-Deng-Huang 2019.

Model calculation using AMPT:



Local polarization

- Up to the leading harmonics in Fourier series, the polarization vector can be written as

$$
\begin{aligned}
P_x(\Delta\psi) &= \phantom{P_{\rm global}} F_x \sin(\Delta\psi) \\
P_y(\Delta\psi) &= P_{\rm global} - F_y \cos(\Delta\psi) \\
P_z(\Delta\psi) &= \phantom{P_{\rm global}} F_z \sin(2\Delta\psi)
\end{aligned}
$$

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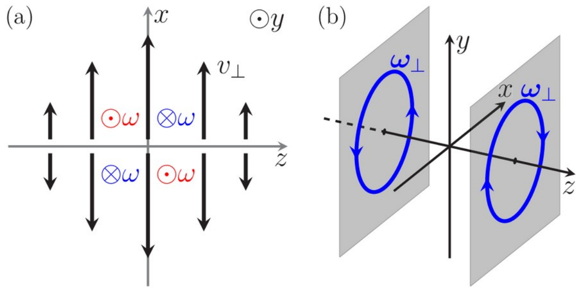
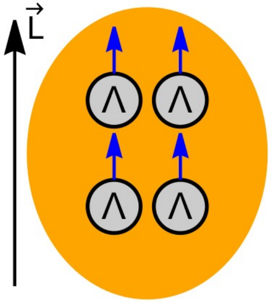
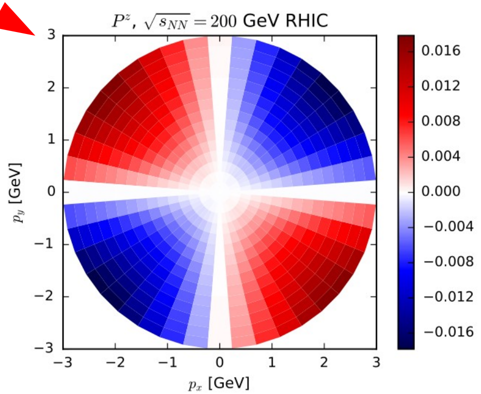






- Note: the above equation mainly includes the contribution of vorticity.
- There are other sources of polarization, such as magnetic field.

Local polarization

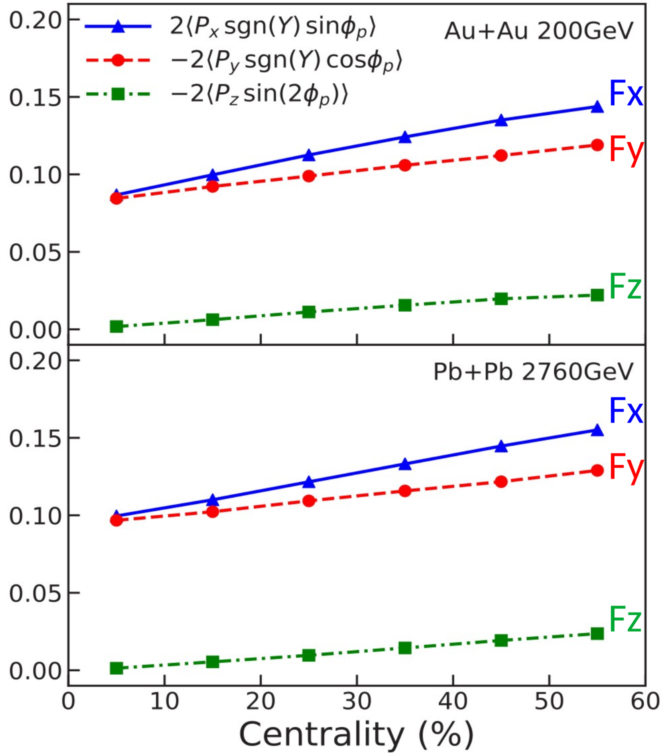
- Up to the leading harmonics in Fourier series, the polarization vector can be written as

$$
\begin{aligned}
P_x(\Delta\psi) &= \qquad\quad F_x \sin(\Delta\psi) \\
P_y(\Delta\psi) &= P_{\text{global}} - F_y \cos(\Delta\psi) \\
P_z(\Delta\psi) &= \qquad\quad F_z \sin(2\Delta\psi)
\end{aligned}
$$

According to model calculation using AMPT:

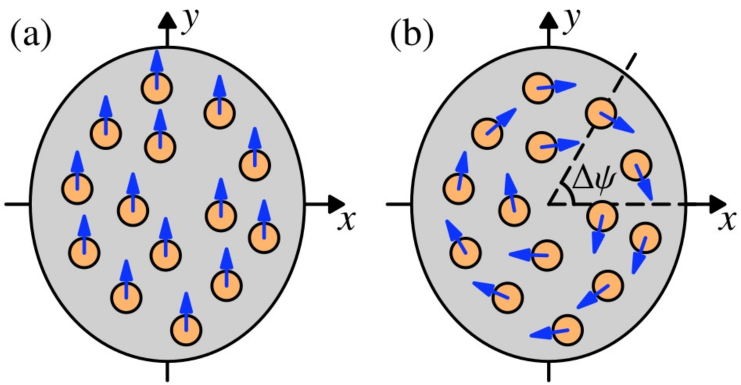
- In central collisions, $P_{\text{global}} = F_z = 0$, and $F_x = F_y$.
- In noncentral collisions, $P_{\text{global}}, F_z \neq 0$, and $F_x \neq F_y$.
- $F_{x,y} > P_{\text{global}}, F_z$ and $|F_x - F_y|$.

XLX-Li-Tang-Wang 2018



Local spin alignment

- We have known that particles are locally polarized in QGP.
- The local polarization is the consequence of the bulk geometry of the QGP fireball, and thus can survive after averaging over many events.

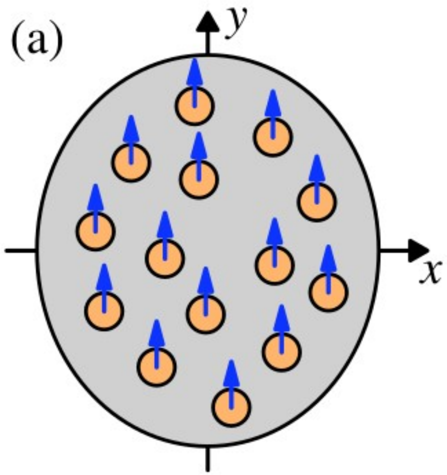


- Then a question arises:

  What is the effect of the local polarization on spin alignment?

Recall the global spin alignment

- Quarks and anti-quarks are assumed to be polarized along the OAM direction (the y axis).



$$\mathbf{P}^{q,\bar{q}} = (0, P_y^{q,\bar{q}}, 0)$$

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

$$\rho^V = \frac{U\rho^q \otimes \rho^{\bar{q}} U^\dagger}{\mathrm{tr}(U\rho^q \otimes \rho^{\bar{q}} U^\dagger)} \qquad U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

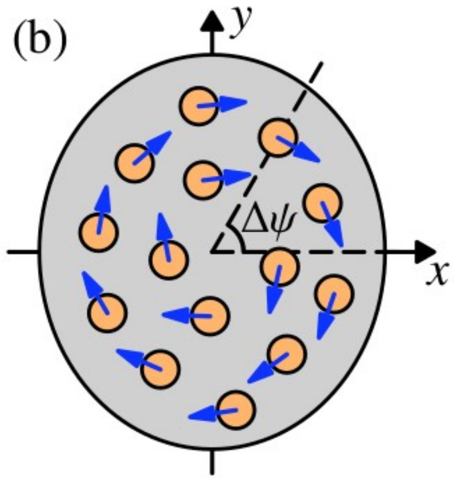
$$\rho^V = \begin{pmatrix} \frac{(1+P_y^q)(1+P_y^{\bar{q}})}{3+P_y^q P_y^{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P_y^q P_y^{\bar{q}}}{3+P_y^q P_y^{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P_y^q)(1-P_y^{\bar{q}})}{3+P_y^q P_y^{\bar{q}}} \end{pmatrix}$$

See:
Liang-Wang 2005.

- In the case of global polarization, the spin density matrix is a diagonal matrix.

Spin density matrix of vector mesons

- In the local spin alignment, quarks and anti-quarks can be polarized along arbitrary directions.



$$\mathbf{P}^{q,\bar{q}} = (P_x^{q,\bar{q}}, P_y^{q,\bar{q}}, P_z^{q,\bar{q}})$$

$$\rho^{q,\bar{q}} = \frac{1}{2}\begin{pmatrix} 1 + P_y^{q,\bar{q}} & P_z^{q,\bar{q}} - iP_x^{q,\bar{q}} \\ P_z^{q,\bar{q}} + iP_x^{q,\bar{q}} & 1 - P_y^{q,\bar{q}} \end{pmatrix}$$

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$$\rho_{11} = \frac{(1 + P_y^q)(1 + P_y^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$\rho_{-1-1} = \frac{(1 - P_y^q)(1 - P_y^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$\rho_{10} = \rho_{01}^* = \frac{(1 + P_y^q)(P_z^{\bar{q}} - iP_x^{\bar{q}}) + (P_z^q - iP_x^q)(1 + P_y^{\bar{q}})}{\sqrt{2}(3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}})}$$

$$\rho_{0-1} = \rho_{-10}^* = \frac{(1 - P_y^q)(P_z^{\bar{q}} - iP_x^{\bar{q}}) + (P_z^q - iP_x^q)(1 - P_y^{\bar{q}})}{\sqrt{2}(3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}})}$$

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Spin density matrix of vector mesons

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$$\rho_{11} = \frac{(1+P_y^q)(1+P_y^{\bar{q}})}{3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}}}$$

$$\rho_{00} = \frac{1-P_y^qP_y^{\bar{q}}+P_x^qP_x^{\bar{q}}+P_z^qP_z^{\bar{q}}}{3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}}}$$

$$\rho_{-1-1} = \frac{(1-P_y^q)(1-P_y^{\bar{q}})}{3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}}}$$

$$\rho_{10} = \rho_{01}^* = \frac{(1+P_y^q)(P_z^{\bar{q}}-iP_x^{\bar{q}})+(P_z^q-iP_x^q)(1+P_y^{\bar{q}})}{\sqrt{2}(3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}})}$$

$$\rho_{0-1} = \rho_{-10}^* = \frac{(1-P_y^q)(P_z^{\bar{q}}-iP_x^{\bar{q}})+(P_z^q-iP_x^q)(1-P_y^{\bar{q}})}{\sqrt{2}(3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}})}$$

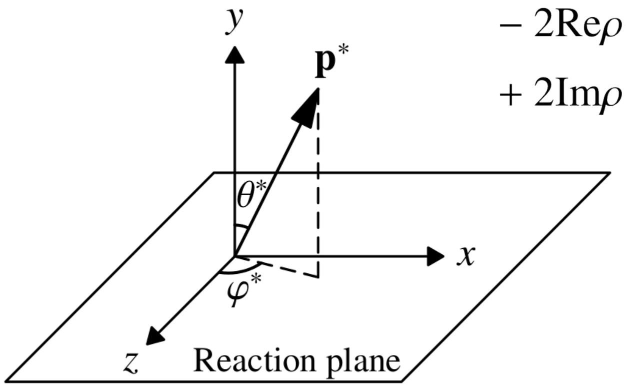
$$\rho_{1-1} = \rho_{-11}^* = \frac{(P_z^q-iP_x^q)(P_z^{\bar{q}}-iP_x^{\bar{q}})}{3+\mathbf{P}^q\cdot\mathbf{P}^{\bar{q}}}$$

- ρ_{00} not only receives contribution from P_y, but also from P_x and P_z.
- In the presence of P_x and P_z, the off-diagonal elements of ρ^V are nonzero.
- The contribution of P_x and P_z is **not** included in the previous studies on spin alignment.

How to measure spin of vector mesons

- In experiments, spin information of vector mesons (ϕ and K^{*0}) is extracted from angular distribution of decay products in their strong decays $\phi \to KK$ and $K^{*0} \to K\pi$:

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



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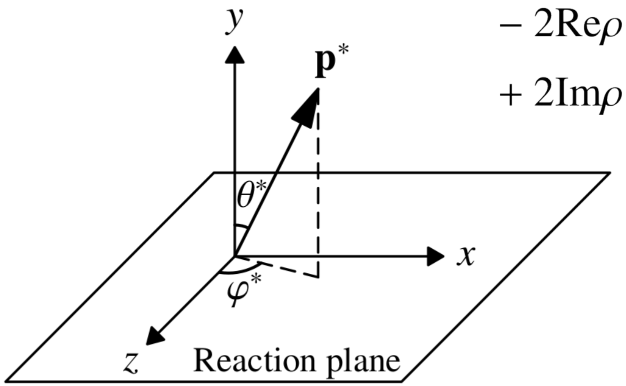


Measurable elements:

$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar q} + P_x^q P_x^{\bar q} + P_z^q P_z^{\bar q}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

$$-\sqrt{2}(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1}) = -\frac{2(P_y^q P_z^{\bar q} + P_z^q P_y^{\bar q})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

$$\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1}) = -\frac{2(P_x^q P_y^{\bar q} + P_y^q P_x^{\bar q})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

$$-2\mathrm{Re}\rho_{1-1} = -\frac{2(P_z^q P_z^{\bar q} - P_x^q P_x^{\bar q})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

$$2\mathrm{Im}\rho_{1-1} = -\frac{2(P_x^q P_z^{\bar q} + P_z^q P_x^{\bar q})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

Polarization vector is not measurable:

$$\mathbf{P}^V = \frac{2(\mathbf{P}^q + \mathbf{P}^{\bar q})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar q}}$$

Spin configuration of quarks and anti-quarks

- In noncentral collisions, the polarization of quarks and anti-quarks is

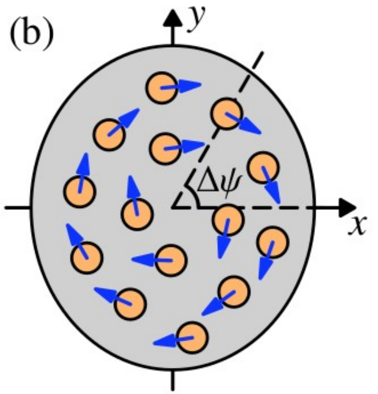
$$P_x^{q,\bar{q}}(\Delta\psi) = F_x \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = P_{\text{global}} - F_y \cos(\Delta\psi)$$

$$P_z^{q,\bar{q}}(\Delta\psi) = F_z \sin(2\Delta\psi)$$

In above equtions, F_x and F_y may dominate over P_{global} and F_z.

- In the most central collisions, rotational symmetry around z axis leads to



$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi) \qquad F_\perp \equiv F_x = F_y$$

$$P_z^{q,\bar{q}}(\Delta\psi) = 0 \qquad P_{\text{global}} = F_z = 0$$

- What will happen to the spin alignment in the presence of the above polarization pattern?

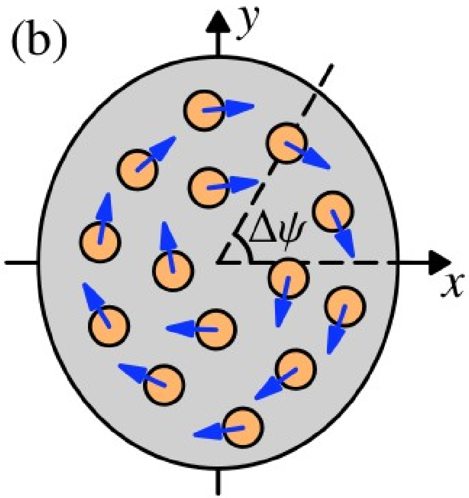
ρ_{00} vs azimuthal angle

$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$



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

ρ_{00} vs azimuthal angle

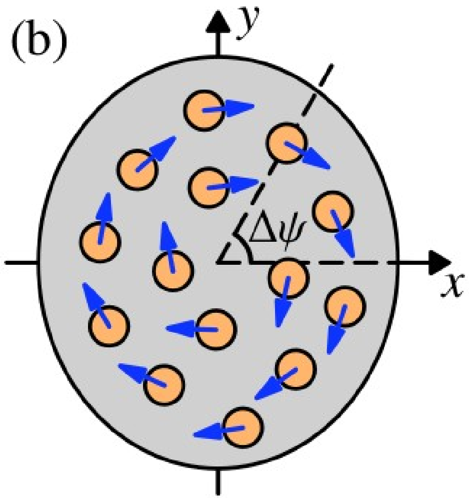
$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

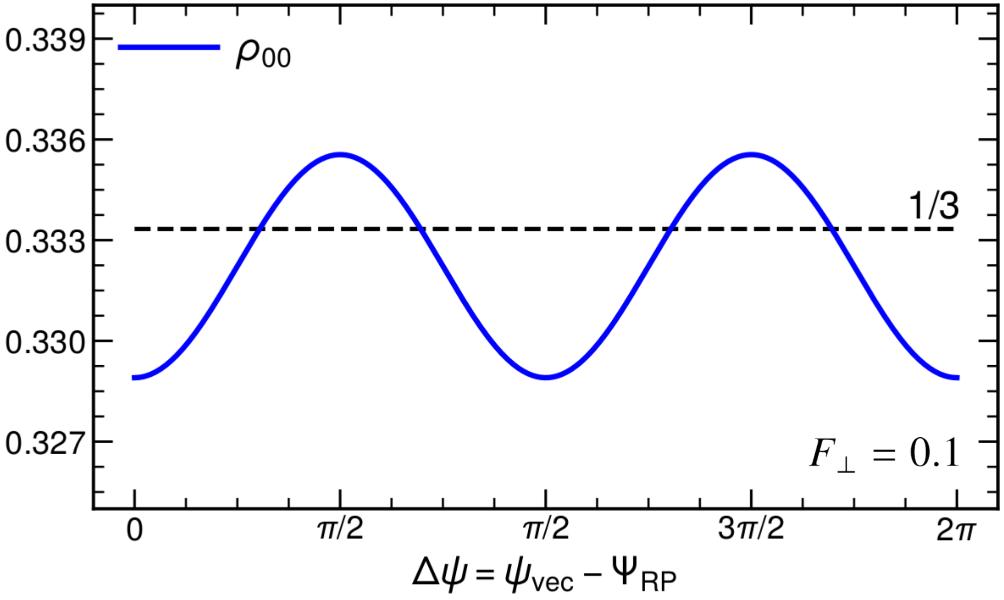
$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$

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





ρ_{00} vs azimuthal angle

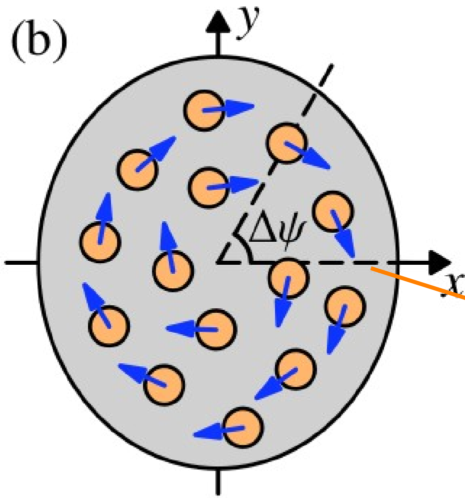
$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

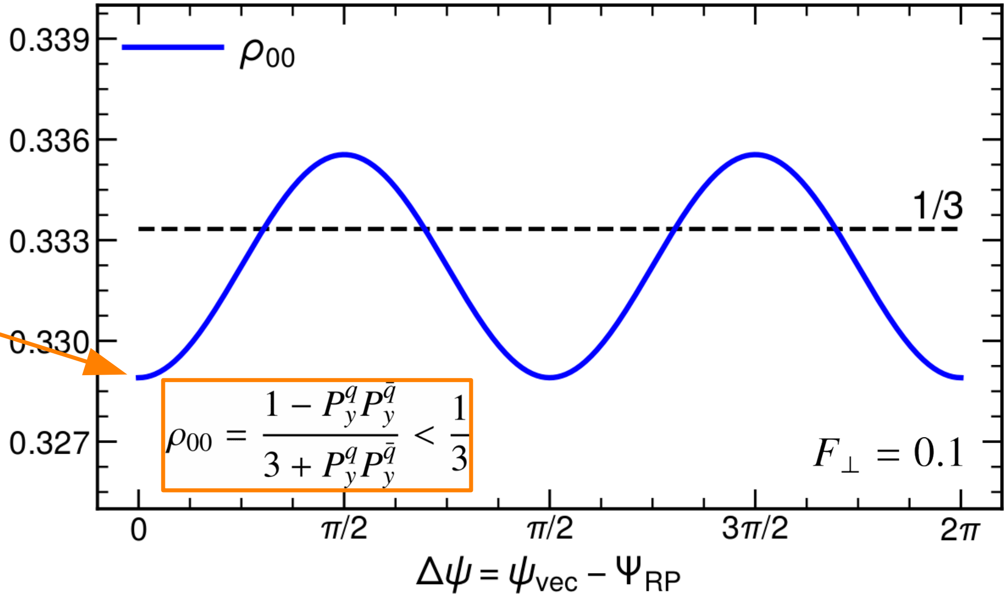
$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$

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





ρ_{00} vs azimuthal angle

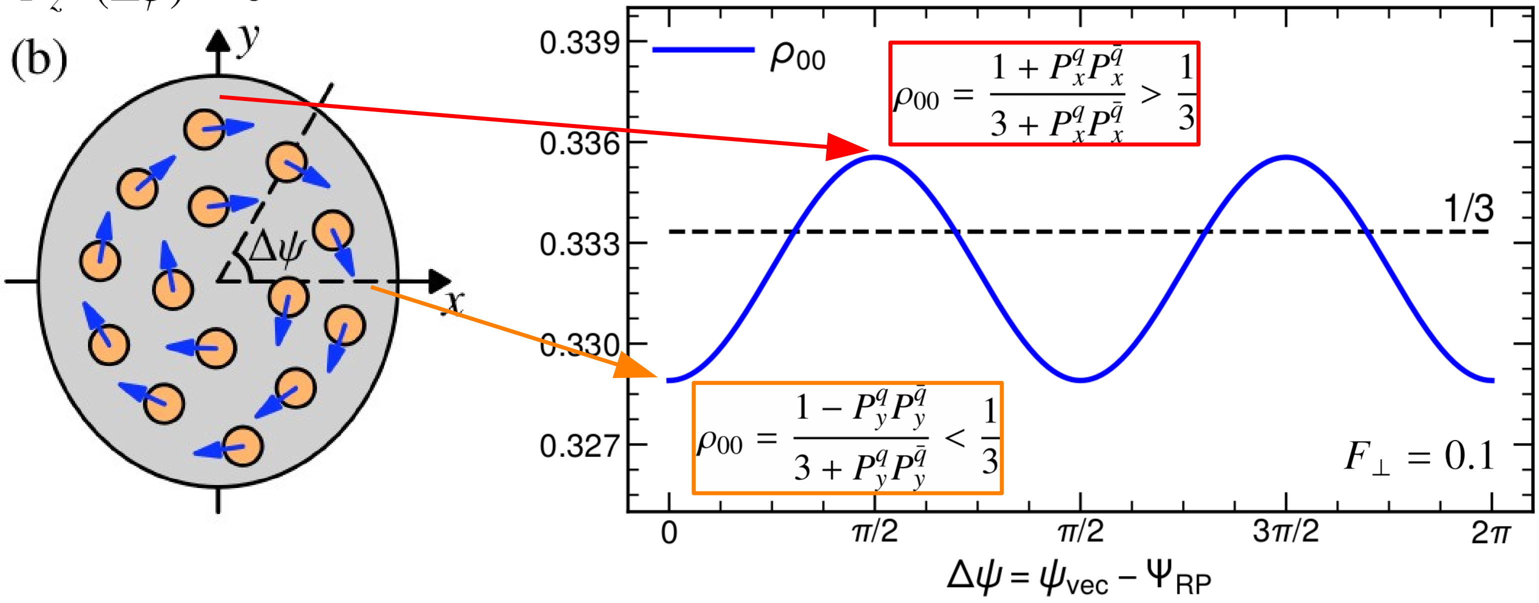
$$\rho_{00} = \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$

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

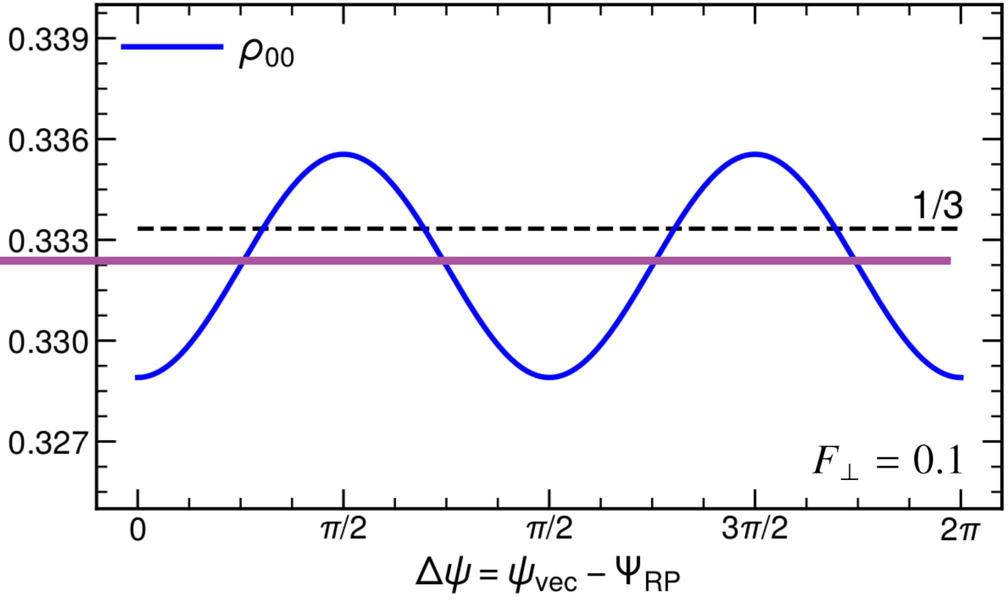


Average ρ_{00}

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

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

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



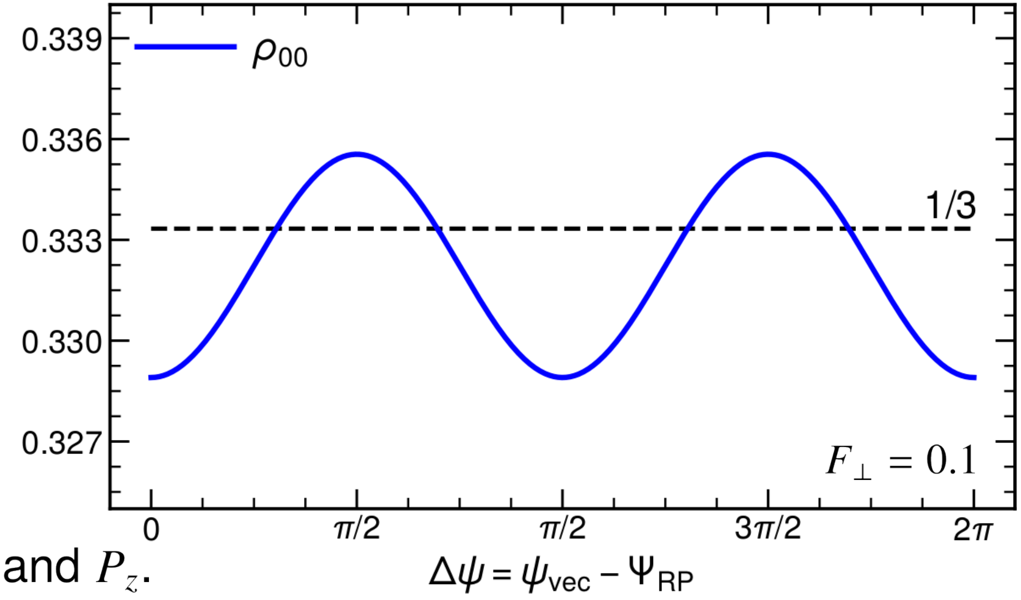
- $\langle \rho_{00} \rangle$ is smaller than 1/3, though the average polarization of quarks and anti-quarks is zero, i.e., $\langle \mathbf{P}^{q,\bar{q}} \rangle = 0$.

$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

Average ρ_{00}

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

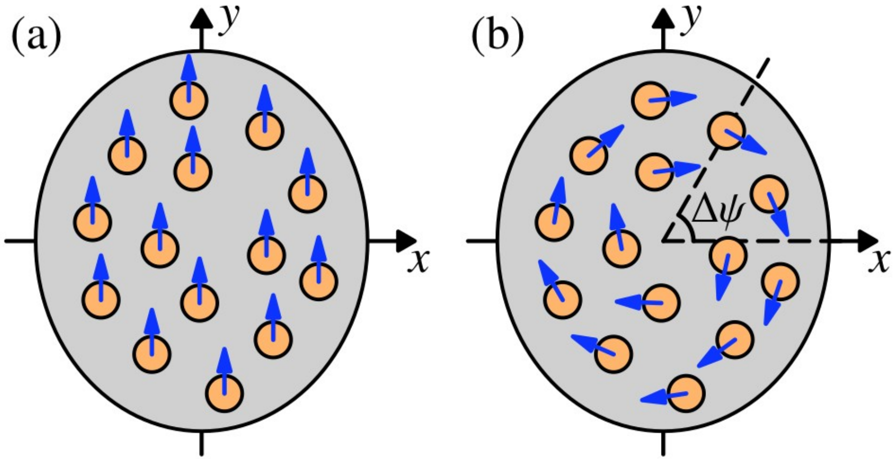


- P_y contributes more to ρ_{00} than P_x and P_z.

$$\boxed{\begin{aligned}\rho_{00} &= \frac{1 - P_y^q P_y^{\bar{q}} + P_x^q P_x^{\bar{q}} + P_z^q P_z^{\bar{q}}}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}} \\ &\approx \frac{1}{3} - \frac{4}{9} P_y^q P_y^{\bar{q}} + \frac{2}{9} P_x^q P_x^{\bar{q}} + \frac{2}{9} P_z^q P_z^{\bar{q}}\end{aligned}}$$

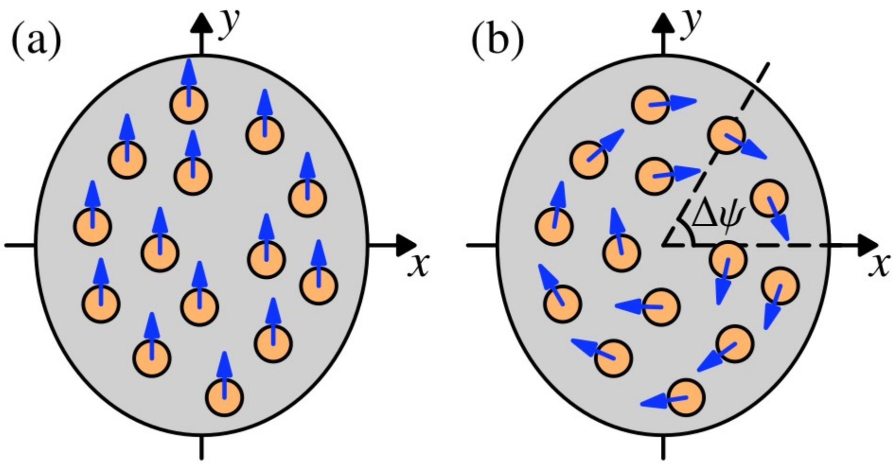
$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$
$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

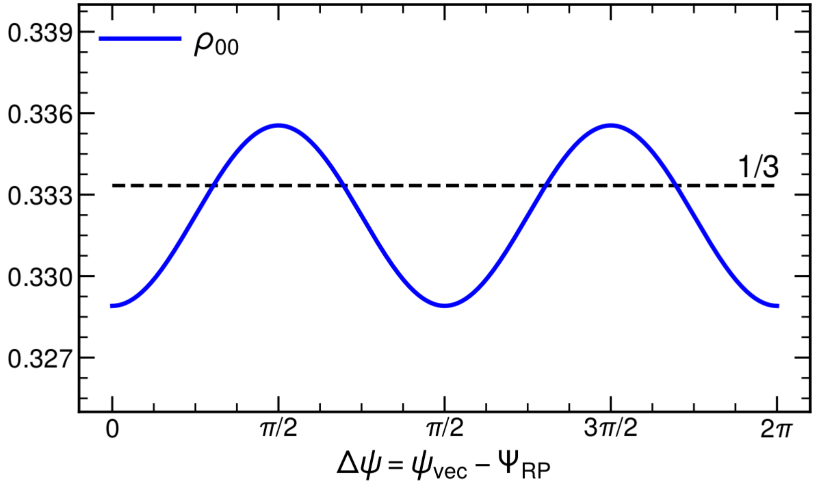
Global vs Local spin alignments



- Both global and local spin alignments can cause $\langle\rho_{00}\rangle \neq 1/3$.
- Which scenario is dominant in heavy-ion collisions?
- How to separate the contribution of two scenarios?

Global vs Local spin alignments (1)





Although $\langle \rho_{00} \rangle \neq 1/3$ in both cases, the $\Delta\psi$ dependence of ρ_{00} is different:

- In the global spin alignment, ρ_{00} is almost invariant vs $\Delta\psi$.
- In the local spin alignment, ρ_{00} oscillates in $\Delta\psi$.

Global vs Local spin alignments (2)

- In the global spin alignment, the off-diagonal elements are zero.
- In the local spin alignment, the off-diagonal elements are nonzero:

$$-\sqrt{2}(\mathrm{Re}\rho_{10} - \mathrm{Re}\rho_{0-1}) = -\frac{2(P_y^q P_z^{\bar{q}} + P_z^q P_y^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1}) = -\frac{2(P_x^q P_y^{\bar{q}} + P_y^q P_x^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$-2\mathrm{Re}\rho_{1-1} = -\frac{2(P_z^q P_z^{\bar{q}} - P_x^q P_x^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$2\mathrm{Im}\rho_{1-1} = -\frac{2(P_x^q P_z^{\bar{q}} + P_z^q P_x^{\bar{q}})}{3 + \mathbf{P}^q \cdot \mathbf{P}^{\bar{q}}}$$

$$\Rightarrow$$

$$\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1}) = \frac{2F_\perp^2}{3 + F_\perp^2}\sin(2\Delta\psi)$$

$$-2\mathrm{Re}\rho_{1-1} = \frac{2F_\perp^2}{3 + F_\perp^2}\sin^2(\Delta\psi)$$

$$P_x^{q,\bar{q}}(\Delta\psi) = F_\perp \sin(\Delta\psi)$$

$$P_y^{q,\bar{q}}(\Delta\psi) = -F_\perp \cos(\Delta\psi)$$

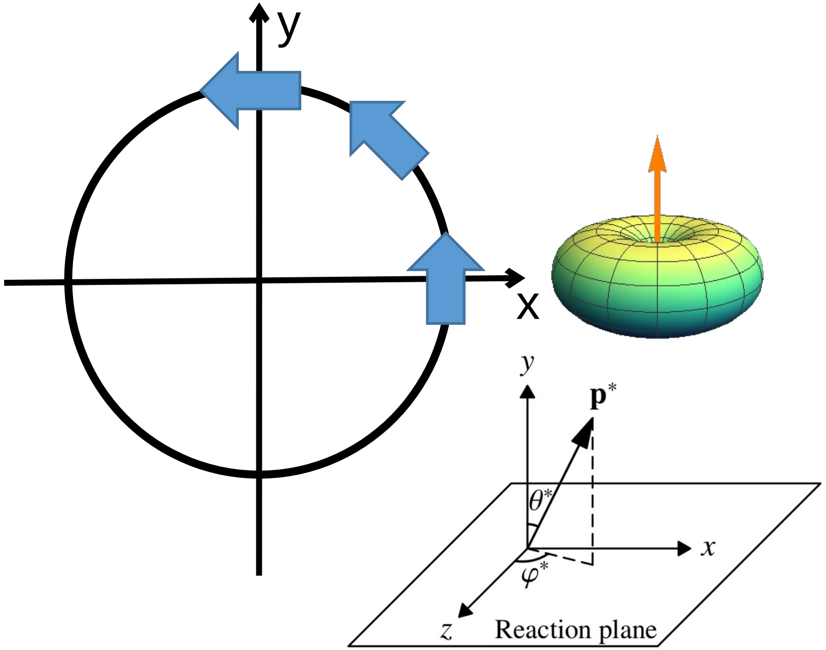
$$P_z^{q,\bar{q}}(\Delta\psi) = 0$$

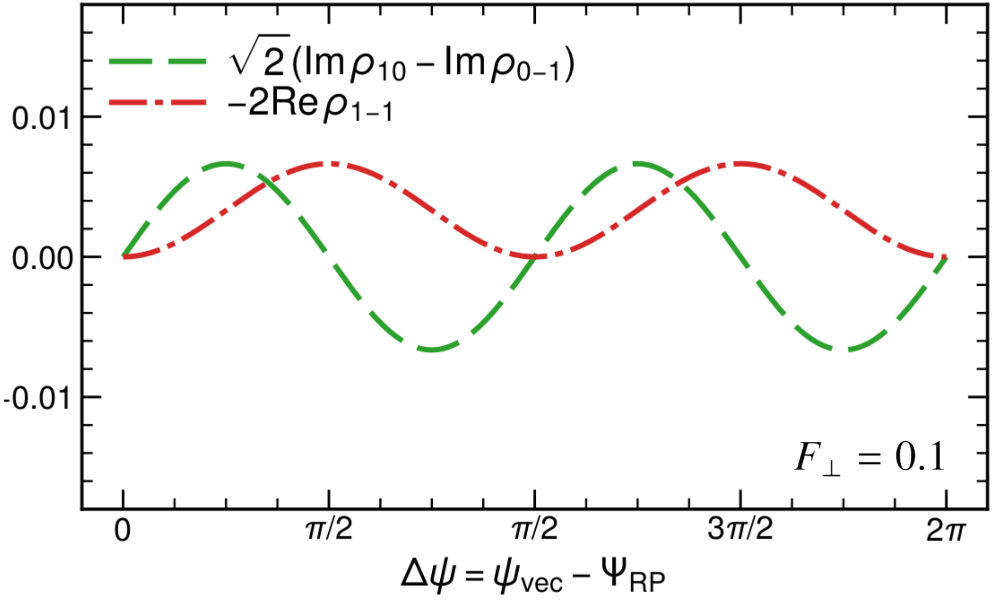
Global vs Local spin alignments (2)

- Nonzero off-diagonal elements indicate the angular distribution of the vector-meson decay has a non-trivial shape in φ^*.

$$\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1}) = \frac{2F_\perp^2}{3+F_\perp^2}\sin(2\Delta\psi)$$

$$-2\mathrm{Re}\rho_{1-1} = \frac{2F_\perp^2}{3+F_\perp^2}\sin^2(\Delta\psi)$$



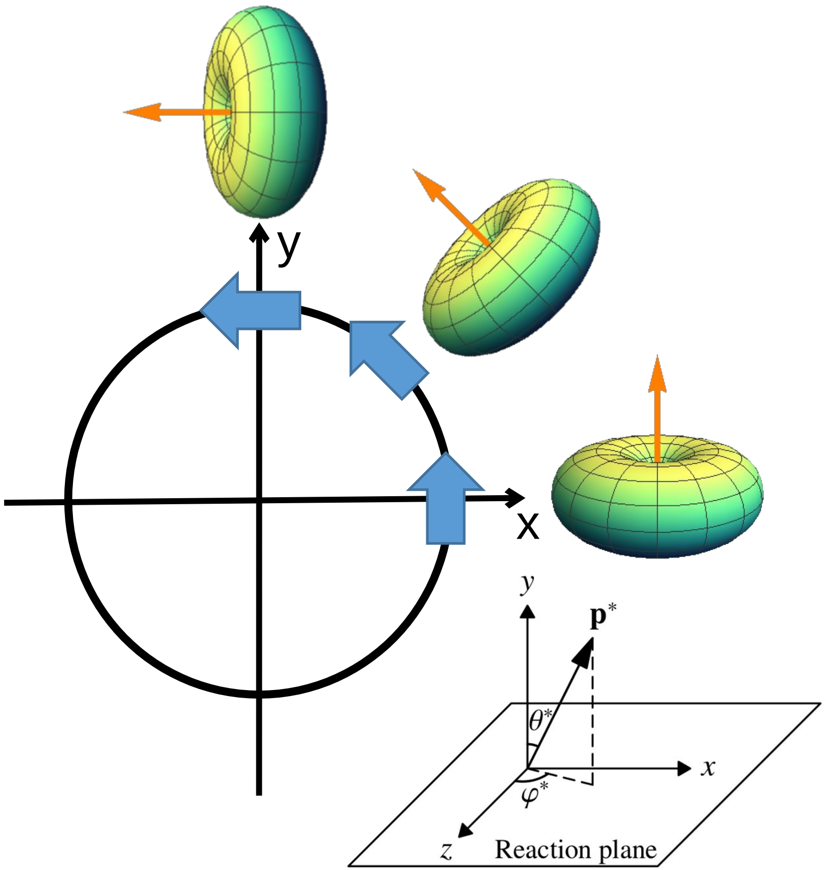


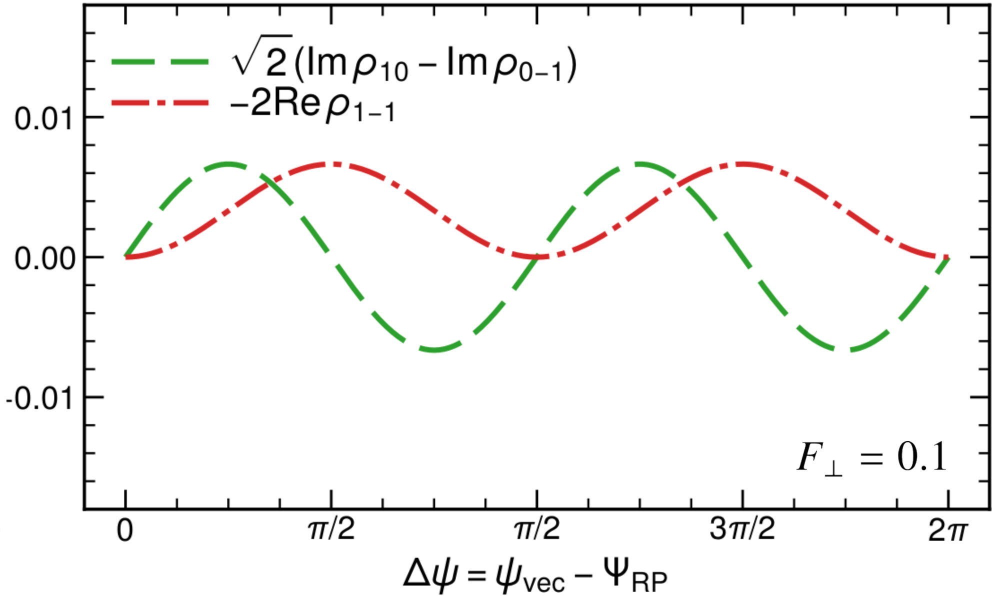
Global vs Local spin alignments (2)

- Nonzero off-diagonal elements indicate the angular distribution of the vector-meson decay has a non-trivial shape in φ^*.

$$\sqrt{2}(\mathrm{Im}\rho_{10} - \mathrm{Im}\rho_{0-1}) = \frac{2F_\perp^2}{3 + F_\perp^2}\sin(2\Delta\psi)$$

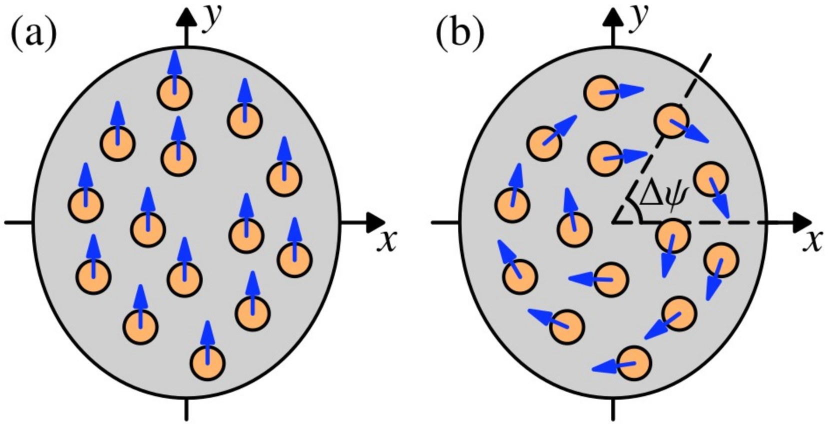
$$-2\mathrm{Re}\rho_{1-1} = \frac{2F_\perp^2}{3 + F_\perp^2}\sin^2(\Delta\psi)$$





Global vs Local spin alignments (3)

- In experiments, the value of $\langle \rho_{00} \rangle$ is determined from the distribution of θ^*.
- One can define θ^* with respect to different event planes, and study how $\langle \rho_{00} \rangle$ will change.



- The local spin alignment is insensitive to rotation of the event plane around z axis.
- In the global spin alignment, $\langle \rho_{00} \rangle - 1/3$ will flip its sign, if the event plane is rotated form x-z plane to y-z plane.

Summary

- We studied the spin alignment of vector mesons arising from locally polarized quarks and anti-quarks (local spin alignment).
- Besides P_y, ρ_{00} also receives contribution from P_x and P_z. Such contribution is not included in the previous studies on spin alignment.
- $\langle\rho_{00}\rangle \neq 1/3$ does not signal the global polarization along the OAM, but may also originate from local spin polarization induced by local vorticity.
- We propose the measurements of $\Delta\psi$-dependence of ρ_{00}, the off-diagonal elements in ρ^V, and $\langle\rho_{00}\rangle \neq 1/3$ w.r.t. different event plane.
- Such measurements can be used to separate the local spin alignment from the global one, and help us to better understand the local vorticity structure and spin polarization phenomena in heavy-ion collisisons.

Thank you!