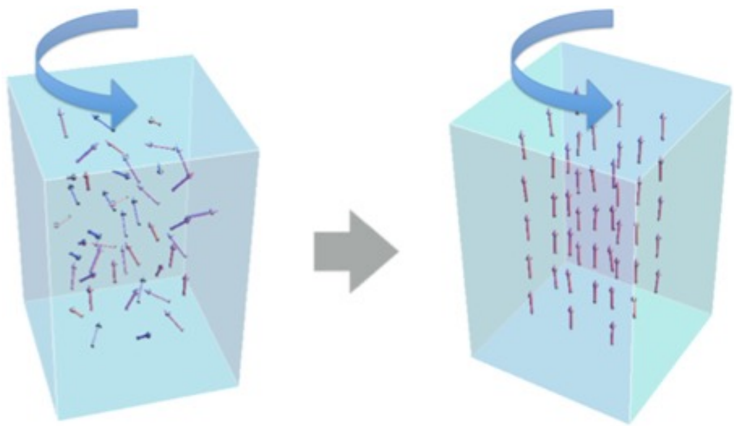
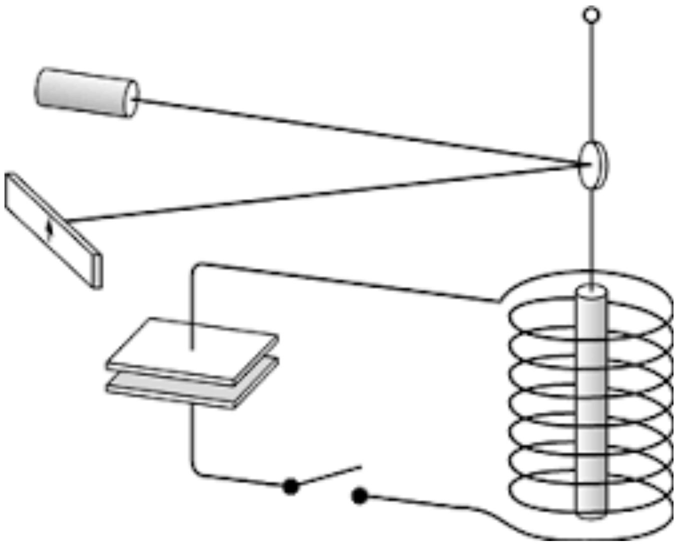
Measurements of Global Spin Alignment in Heavy-ion Collisions

Aihong Tang
Chirality Workshop, UCLA Dec. 2022

Barnett Effect and Einstein-de Haas Effect





Rotation ➔ Polarization

Polarization ➔ Rotation

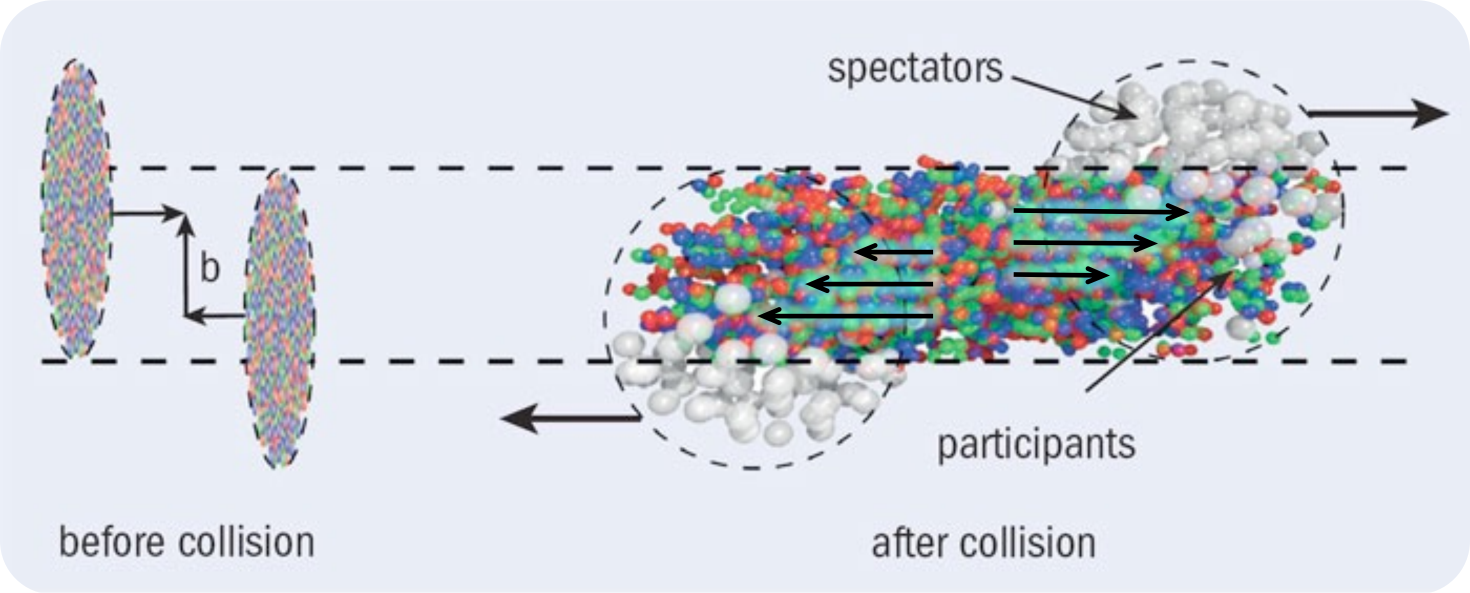
•Spontaneous magnetization
•Polarizaton (spin-orbital coupling)

•Magnetic field causes polarization of electrons
• $\Delta L_{mechanical} = - \Delta L_{electron}$

Barnett, Phys. Rev. 6 (4) 239, (1915)
Barnett, Rev. Mod. Phys. 7, 129 (1935)

Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

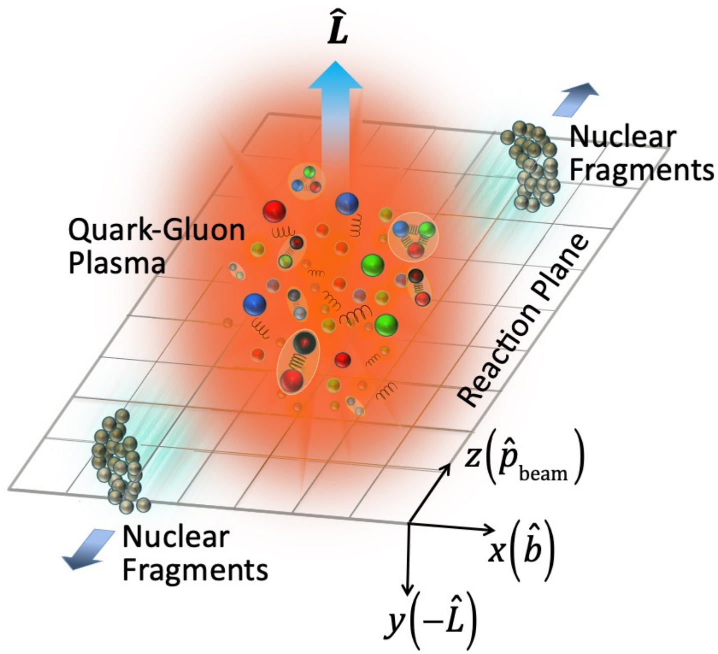
Relativistic Heavy-Ion Collisions

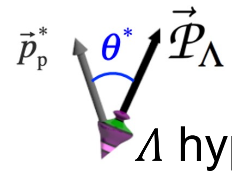


In non-central collisions, large orbital angular momentum L (~$10^3\hbar$ at RHIC energies) is deposited in the interaction region.

Viscosity dissipates the vorticity to QGP fluid at a larger scale.

Hyperon Global Polarization





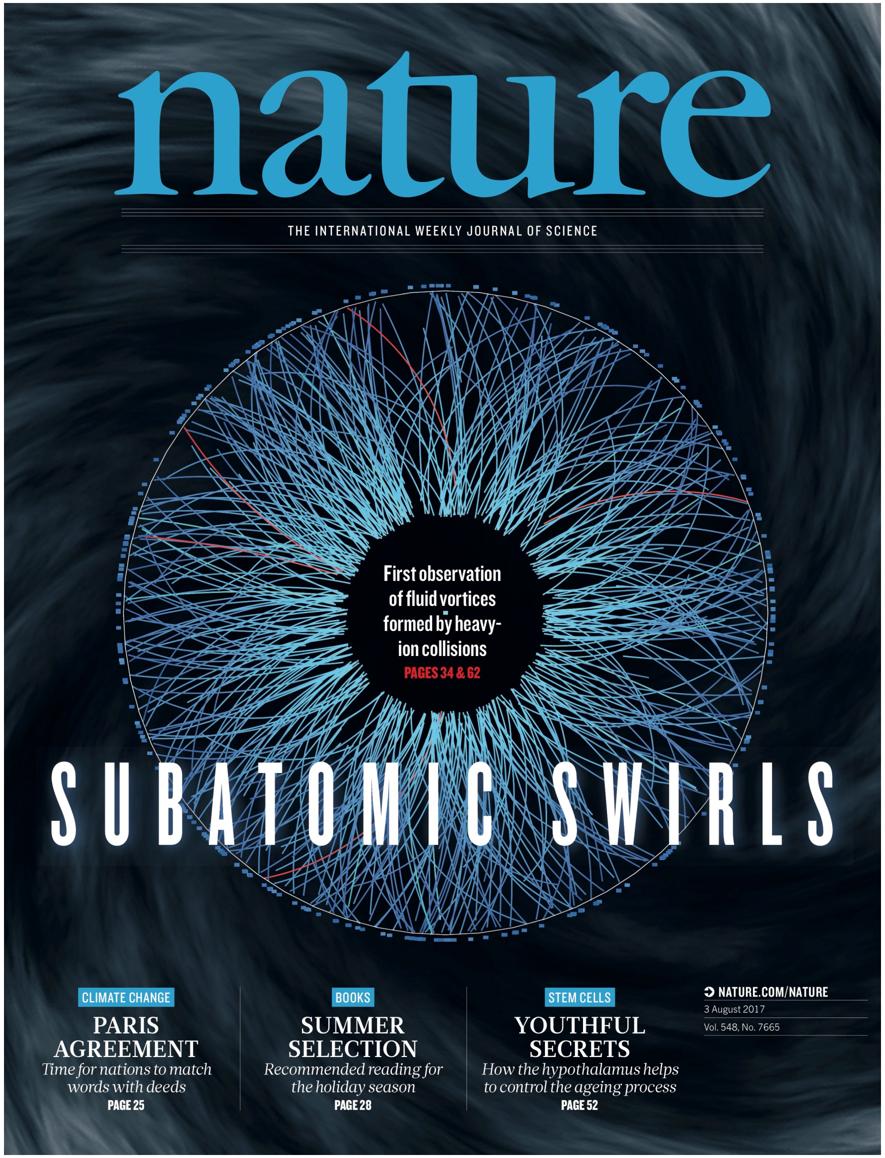
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H \left|\vec{P}_H\right| \cos\theta^*\right)$$

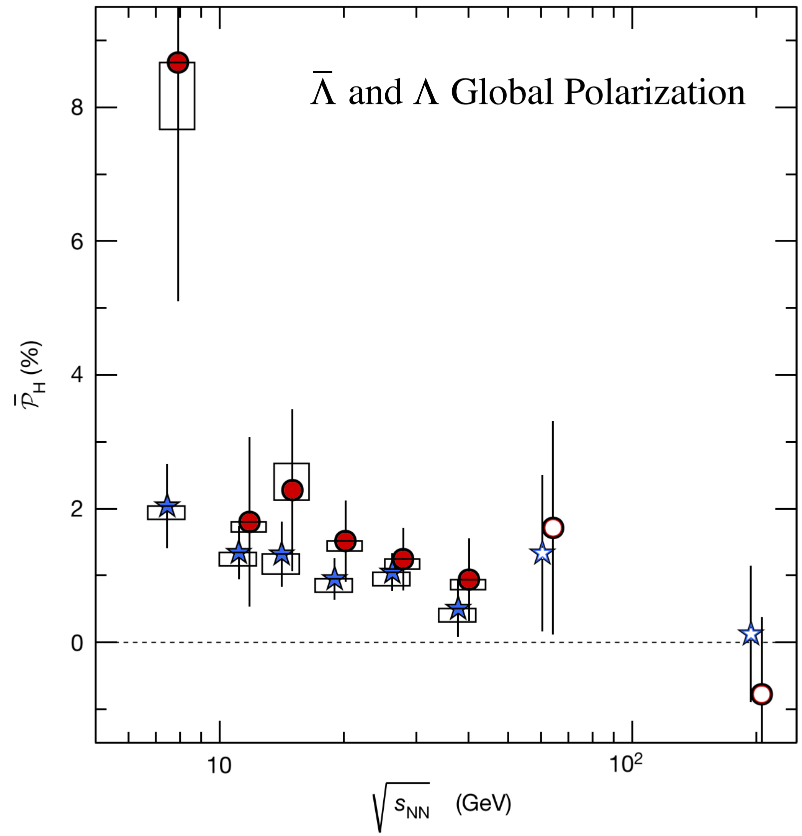
$\Lambda \rightarrow p + \pi^-$

Λ hyperons are "self-analyzing". The proton tends to be emitted along the spin direction of the parent Λ.

Polarization of the Λ hyperon (P_Λ) is carried solely by the strange quark s.

Spin Polarization in Heavy-ion Collisions

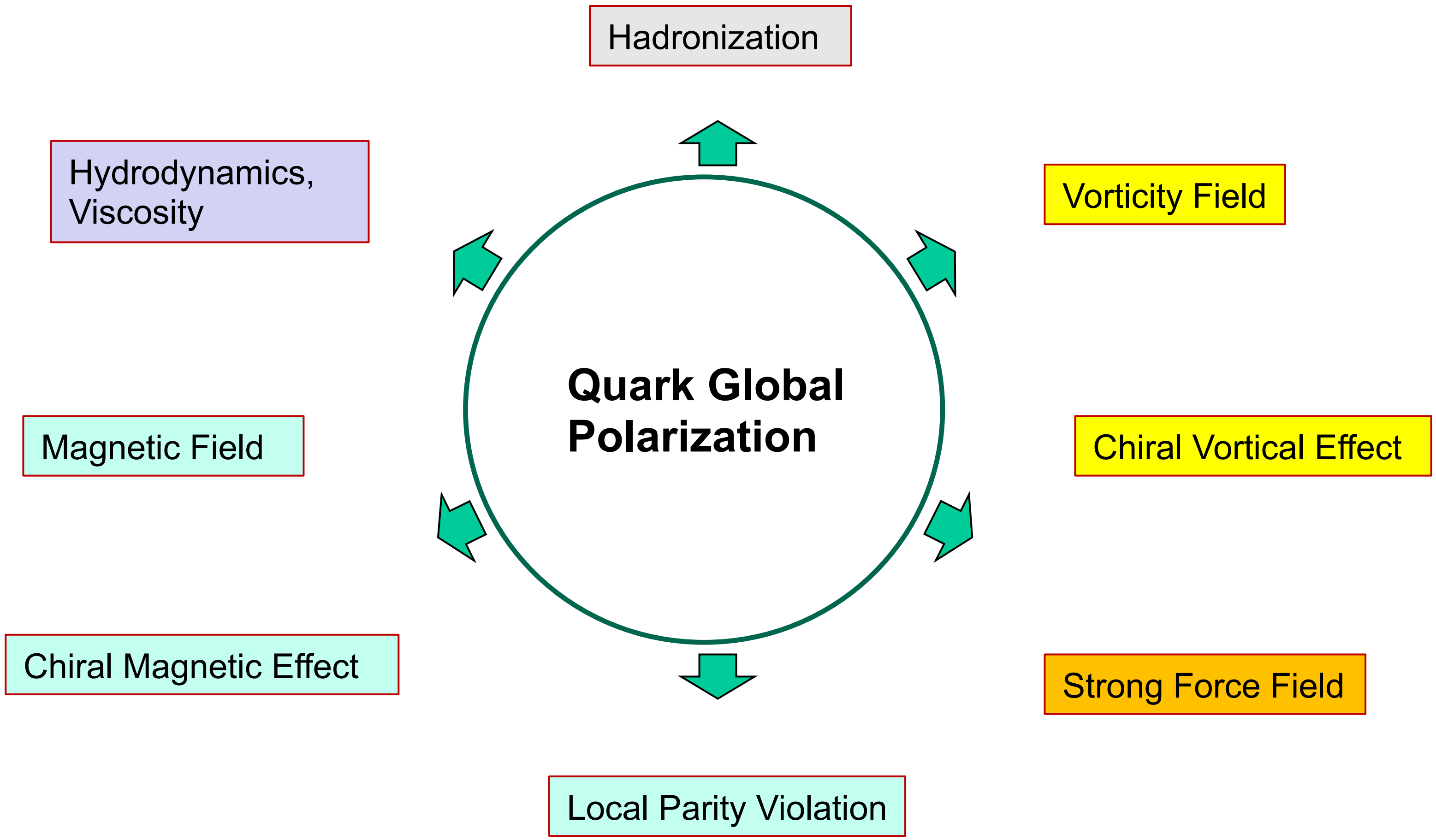




STAR Collaboration, NATURE 548 62 (2017)

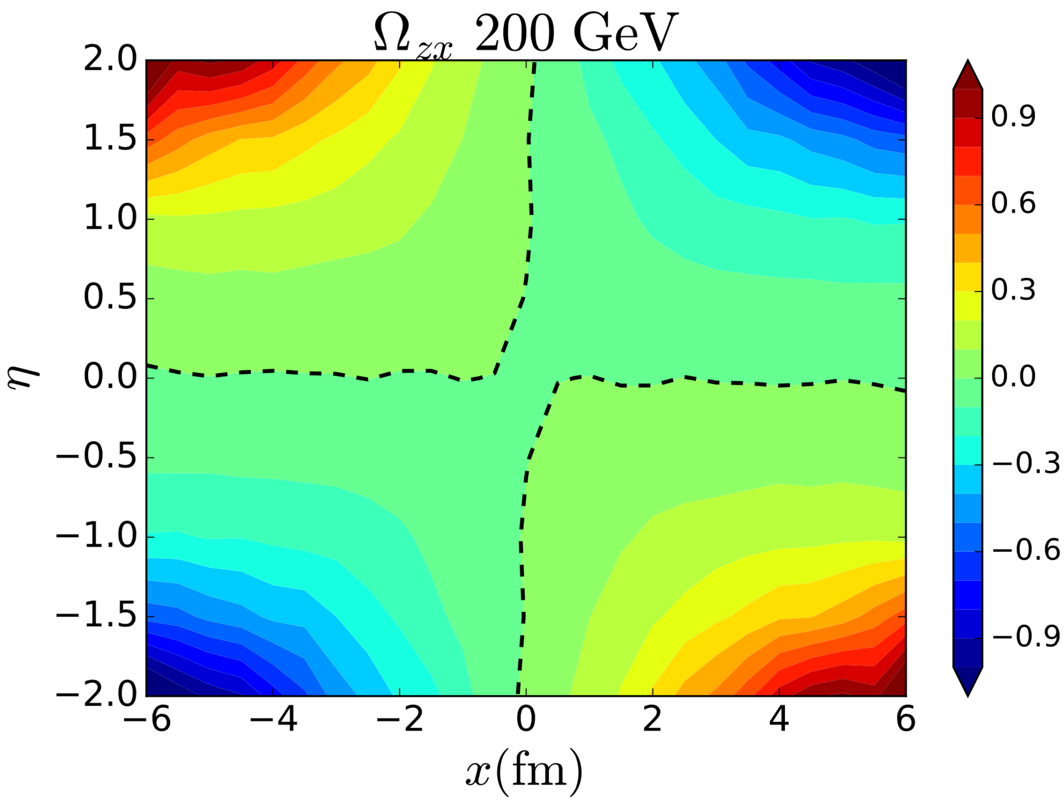
Fluid produced at RHIC:
the least viscous and the most vortical !

Interconnections



Insight to rich physics !

Vorticity Field



Odd function of x and η.

Λ polarization cancel each other when taking average.

Cancellation is severe at high energy for which the vorticity is more close to perfect odd function.

No cancellation for global spin alignment.

Y. Jiang, Z. W. Lin and J. Liao, Phys. Rev. C 94, no. 4, 044910 (2016)
F. Becattini et al., Eur. Phys. J. C 75, no. 9, 406 (2015)
O. Teryaev and R. Usubov, Phys. Rev. C 92, no. 1, (2015)
H. Li, L. G. Pang, Q. Wang and X. L. Xia, PRC 96, 054908 (2017)
B Fu, et al. PRL 127 14 142301 (2021)
F. Becattini et al., PRL 127 27 272302 (2021)
...

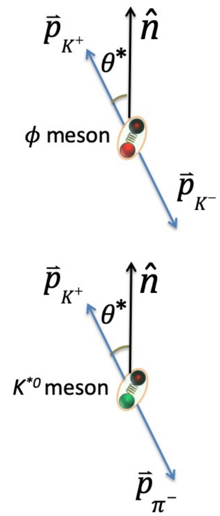
Vector Meson Global Spin Alignment

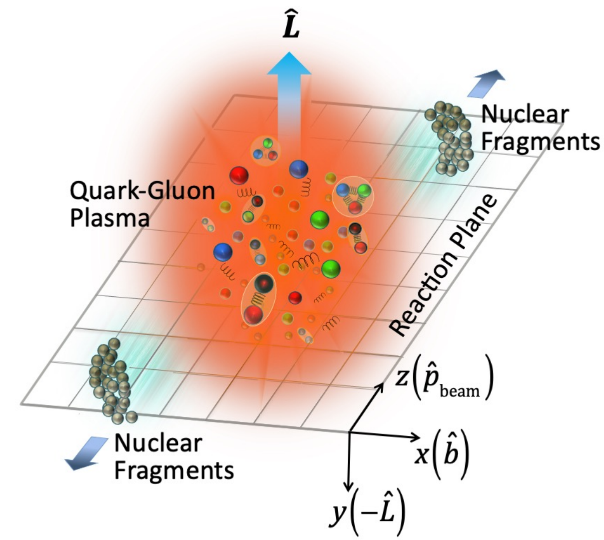
The spin state of a vector meson can be described by a 3x3 spin density matrix.

The diagonal element ρ_{00} corresponds to the probability of finding a vector meson in spin state 0 out of 3 possible spin states of -1, 0 and 1.

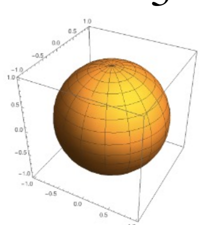
A deviation of ρ_{00} from 1/3 would indicate a non-zero spin alignment.

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \right]$$

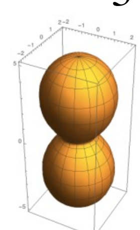




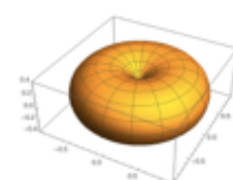
$\rho_{00} = \frac{1}{3}$



$\rho_{00} > \frac{1}{3}$



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



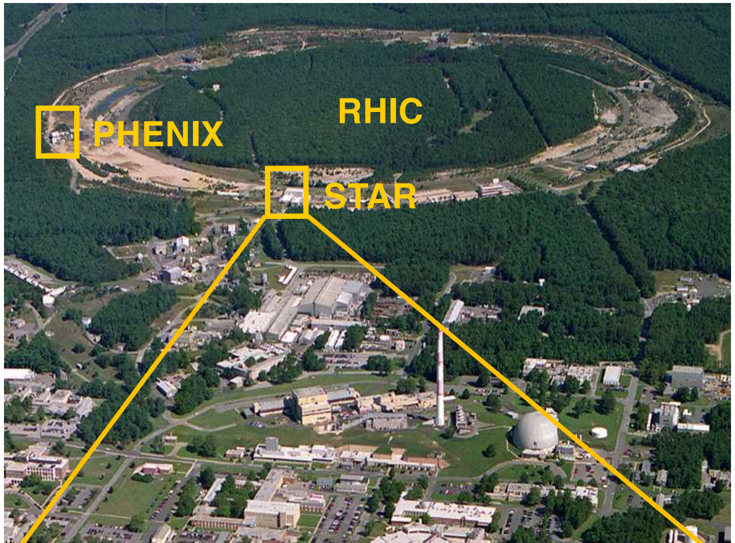
Why Vector Meson Global Spin Alignment ?

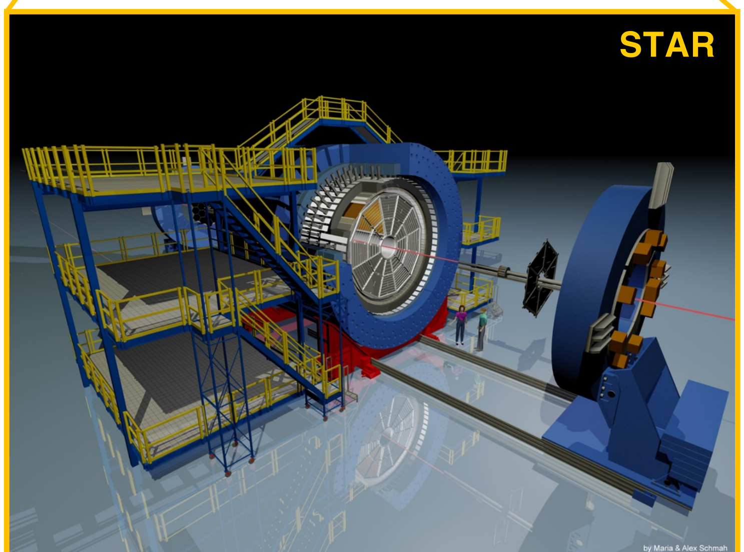
• No local cancelation when integrating over phase space as opposed to spin-1/2 particles.

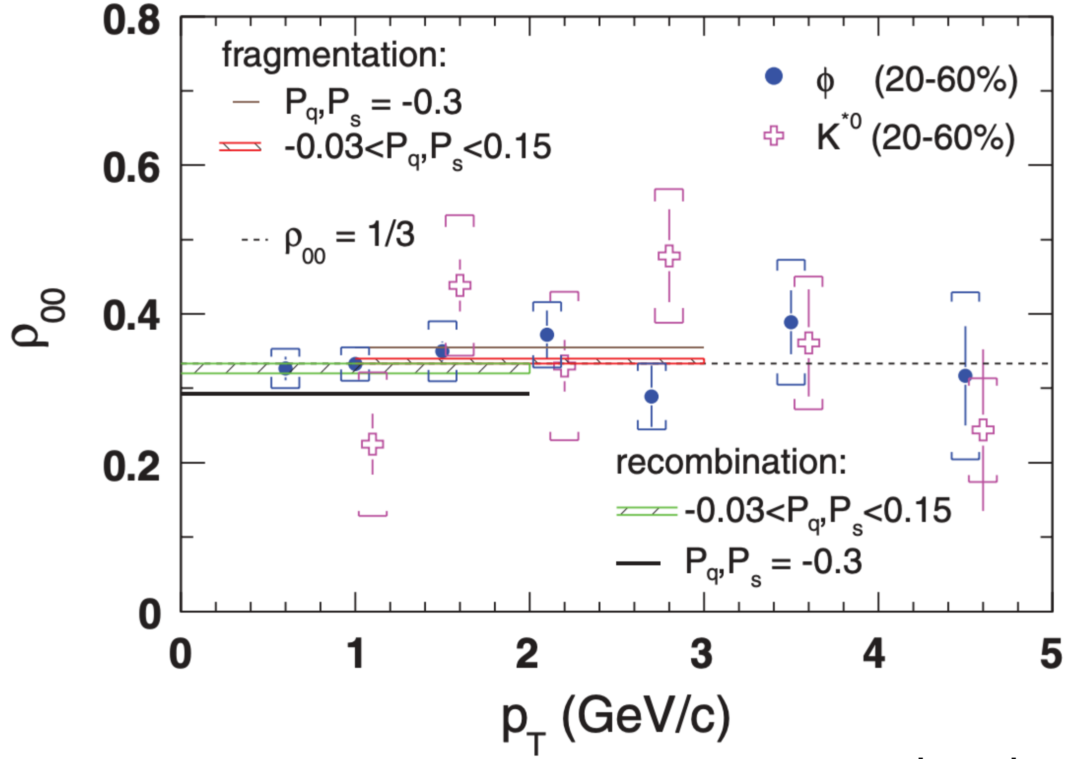
• Access to spin-orbital force $\mathbf{S} \cdot (\mathbf{E}_{\phi} \times \mathbf{P})$, a term which is canceled in Λ polarization.

• Some mesons, like ϕ, are expected to originate predominantly from primordial production ➔ less decay contributions if compared to hyperons, more sensitive to early dynamics.

Global Spin Alignment : Early Efforts at RHIC







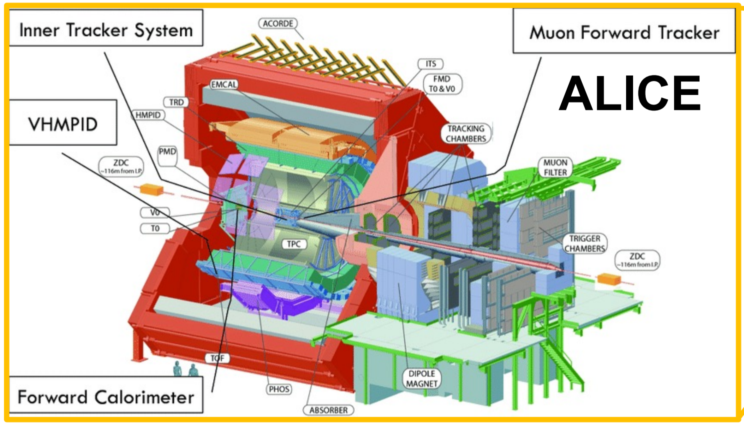
$\phi \rightarrow k^+ + k^-$

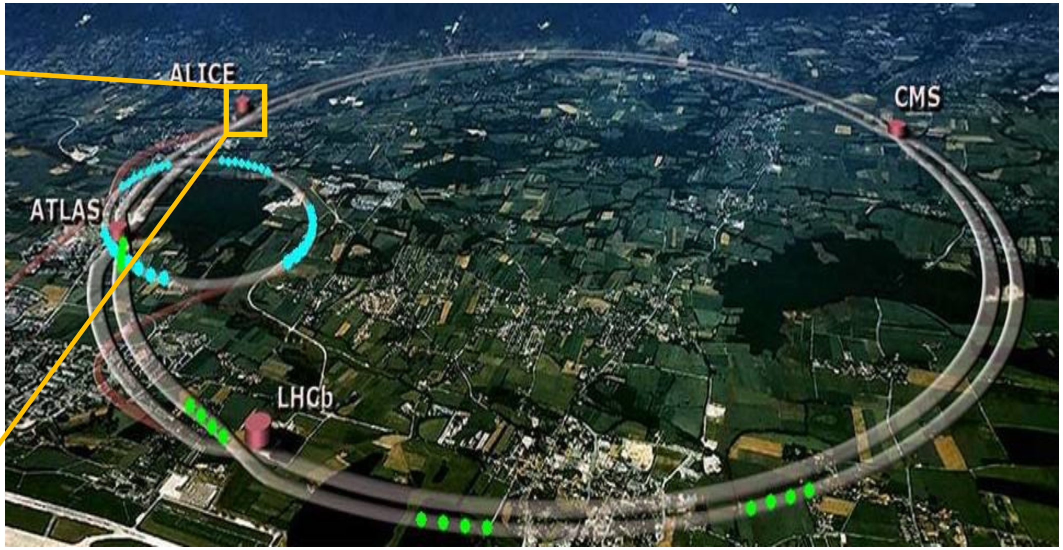
$k^{*0} \rightarrow k^+ + \pi^-$

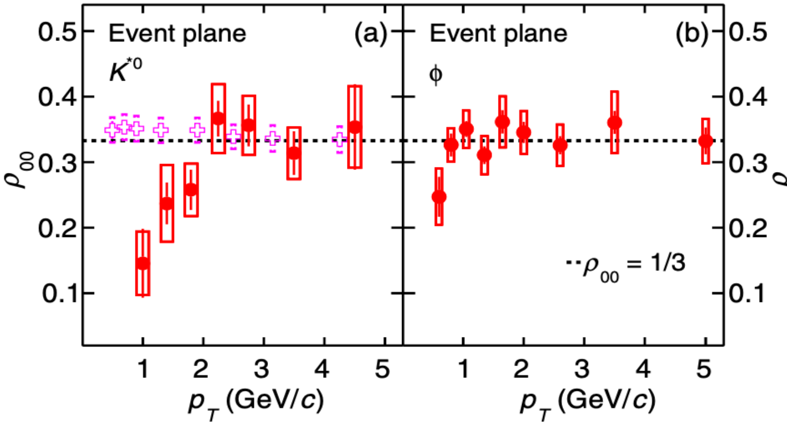
STAR Collaboration, PRC 77 061902 (R) (2008)

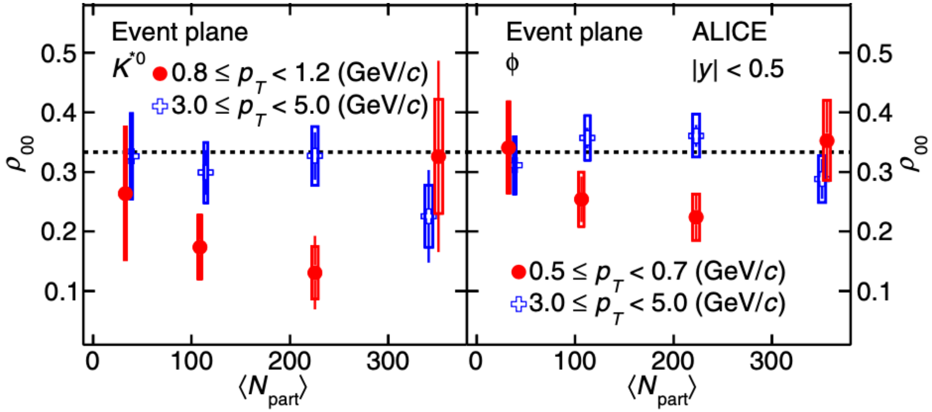
No significant results reported, due to limited statistics.

Global Spin Alignment : ALICE Results





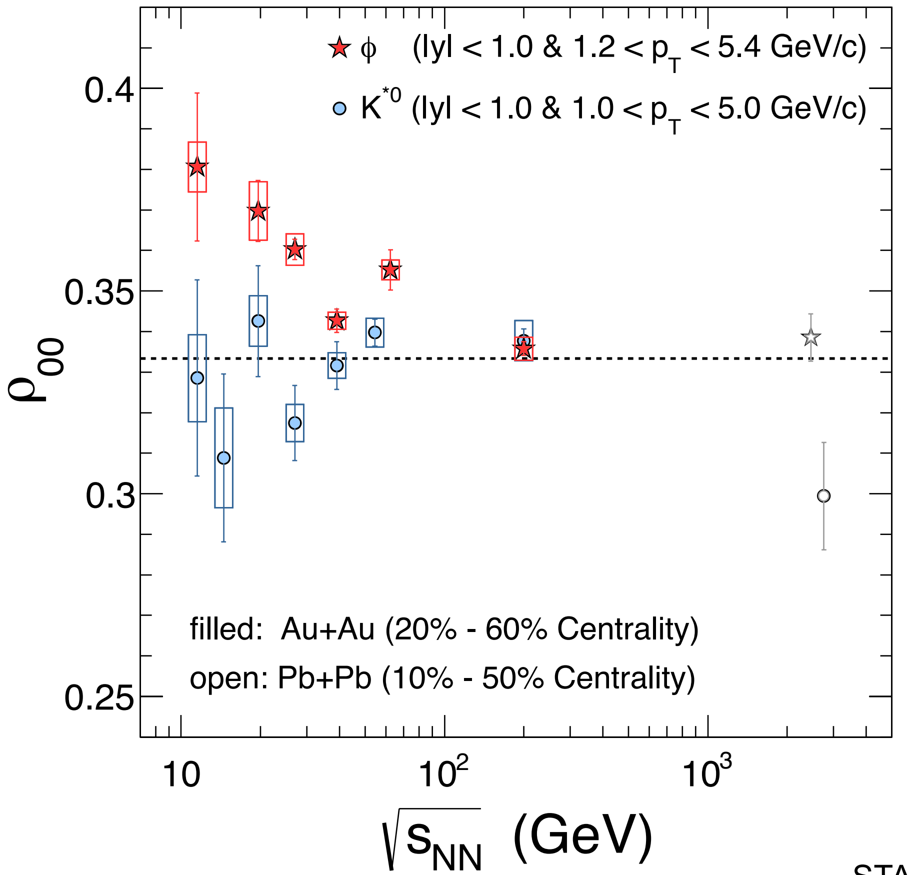




ALICE Collaboration, PRL 125 012301 (2020)

Evidence of Spin-Orbital Angular Momentum interaction.

Global Spin Alignment : STAR Results



STAR, arXiv : 2204.02302
Nature in production

ϕ possesses surprisingly large global spin alignment while K* possesses little.

Can We Explain the Large ρ_{00} of ϕ-meson ?

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
c_L: Local spin alignments[4]	< 1/3
c_A: Turbulent color field[5]	< 1/3
c_ϕ: Vector meson strong force field[6]	> 1/3 (Can accommodate large positive signal)

$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\varepsilon + C_E + C_F + C_L + C_A + C_\phi$$

[1]. Liang et., al., Phys. Lett. B 629, (2005);
Yang et., al., Phys. Rev. C 97, 034917 (2018);
Xia et., al., Phys. Lett. B 817, 136325 (2021);
Beccattini et., al., Phys. Rev. C 88, 034905 (2013)
[2]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Yang et., al., Phys. Rev. C 97, 034917 (2018)
[3]. Liang et., al., Phys. Lett. B 629, (2005)
[4]. Xia et., al., Phys. Lett. B 817, 136325 (2021);
Gao, Phys. Rev. D 104, 076016 (2021)
[5]. Muller et., al., Phys. Rev. D 105, L011901 (2022)
[6]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Phys. Rev. D 102, 056013 (2020);
arXiv:2205.15689 (2022); arXiv:2206.05868 (2022)

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$$C_\Lambda \equiv -\frac{4}{9}\left\langle P_{\Lambda}^{y} P_{\bar{\Lambda}}^{y} \right\rangle$$

$$C_\Lambda = -\frac{1}{9}\left\langle \omega_y^2 \right\rangle + \frac{Q_s^2}{9 m_s^2 T_{eff}^2}\left\langle B_y^2 \right\rangle$$

Constrained by P_Λ , ~ 10^{-5}

[1]. Liang et., al., Phys. Lett. B 629, (2005);
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C_ε : Electric component of vorticity tensor

10^{-4} as calculated by (3+1) D viscous Hydrodynamic model

[1]. Liang et., al., Phys. Lett. B 629, (2005);
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C_E : Electric field

10^{-5} with peak value from PHSD model

[2]. Sheng et., al., Phys. Rev. D 101, 096005 (2020); Yang et., al., Phys. Rev. C 97, 034917 (2018)

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$$\boldsymbol{\rho}_{00}(\boldsymbol{\phi}) = \frac{1}{3} + C_{\boldsymbol{\Lambda}} + C_{\boldsymbol{\varepsilon}} + C_E + C_F + C_L + C_A + C_{\boldsymbol{\phi}}$$

$$\boldsymbol{\rho}_{00}^{frag} = \frac{1+\beta P_q^2}{3-\beta P_q^2}, \quad P_{\bar{q}}^{frag} = -\beta P_q, \quad \beta \approx 0.5$$

C_F : Fragmentation contributes ~ 10^{-5}

[3]. Liang et., al., Phys. Lett. B 629, (2005)

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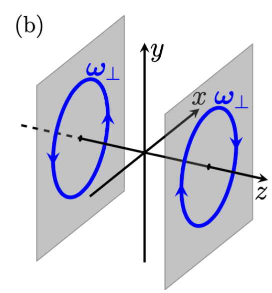
$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\varepsilon + C_E + C_F + C_L + C_A + C_\phi$$

C_T : Local spin alignments

Helicity polarization $-\frac{1}{9}\langle P_{\bar{q}}^h P_q^h \rangle$

Circular polarization $-\frac{1}{9} F_\perp^2$



Both < 1/3

[4]. Xia et., al., Phys. Lett. B 817, 136325 (2021); Gao, Phys. Rev. D 104, 076016 (2021)

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$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\varepsilon + C_E + C_F + C_L + C_A + C_\phi$$

C_A : Fluctuating axial charge current

$$\rho_{00}(K^{*0}) < \rho_{00}(\phi) < 1/3$$

[5]. Muller et., al., Phys. Rev. D 105, L011901 (2022)

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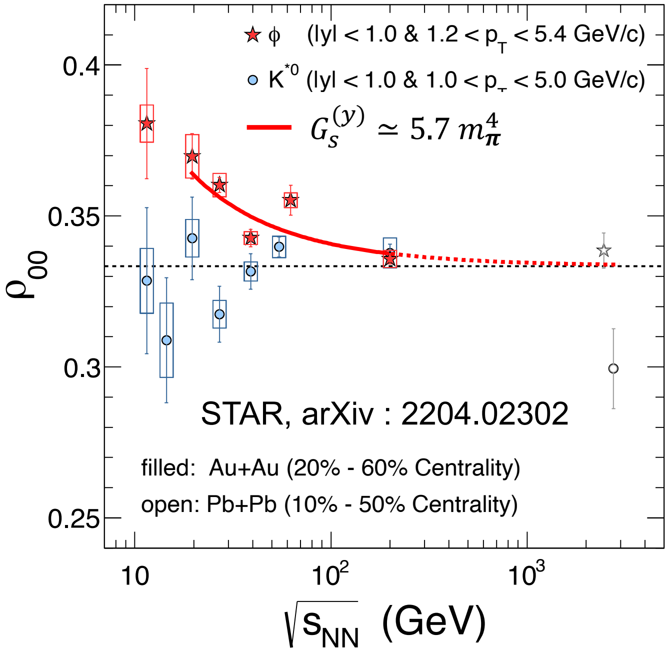


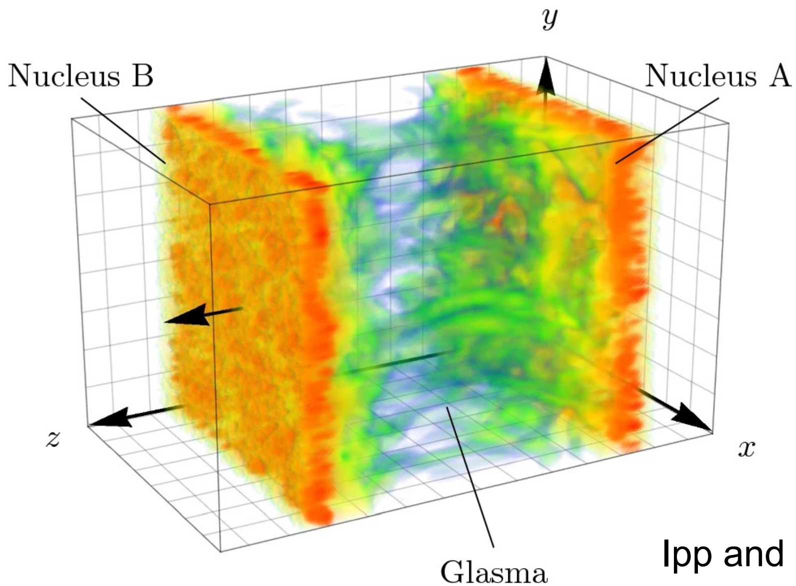
$$C_\phi = \frac{G_s^{(y)}}{27 m_s^2 T_{eff}^2}, \quad G_s^{(y)} = g_\phi^2 \left[3\langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

Model with vector meson strong force field can accommodate the large signal.

[6]. Sheng et., al., Phys. Rev. D 101, 096005 (2020); Phys. Rev. D 102, 056013 (2020); arXiv:2205.15689 (2022); arXiv:2206.05868 (2022)

HIC : A Highly Volatile Environment

Gribov, Levin, Ryskin, 1981
McLerran, Venugopalan
hep-ph/9309289



Ipp and Muller. EPA 56 243 (2020)

Fluctuation of quark and gluon fields ⇒ local net-quark current.

ϕ-meson Vector Field

Like electric charges in motion can generate an EM field, s and $\bar{s}$ quarks in motion can generate an effective ϕ-meson field.

The ϕ-meson field can polarize s and $\bar{s}$ quarks with a large magnitude due to strong interaction, in analogy to how EM field polarize (anti)quarks.

$$P^{y}_{s/\bar{s}}(\mathrm{t}, \mathbf{x}, \mathbf{P}_{s/\bar{s}}) = \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}} \cdot (\varepsilon \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{vorticity}$$

$$\pm \frac{Q_s}{2m_s T} B_y \pm \frac{Q_s}{2m_s^2 T}\hat{\mathbf{y}} \cdot (\boldsymbol{E} \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{EM field}$$

$$\pm \frac{g_\phi}{2m_s T} B_{\phi,y} \pm \frac{g_\phi}{2m_s^2 T}\hat{\mathbf{y}} \cdot (\boldsymbol{E}_\phi \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{strong force field}$$

Quark version of the spin-orbit force. Not accessible via P_Λ.

"magnetic" components

"electric" components

The strong force field is a mechanism that may lead to global spin alignment.

ϕ-meson Vector Field

PHYSICAL REVIEW C **99**, 021901(R) (2019)

Rapid Communications

Λ and $\bar{\Lambda}$ spin interaction with meson fields generated by the baryon current in high energy nuclear collisions

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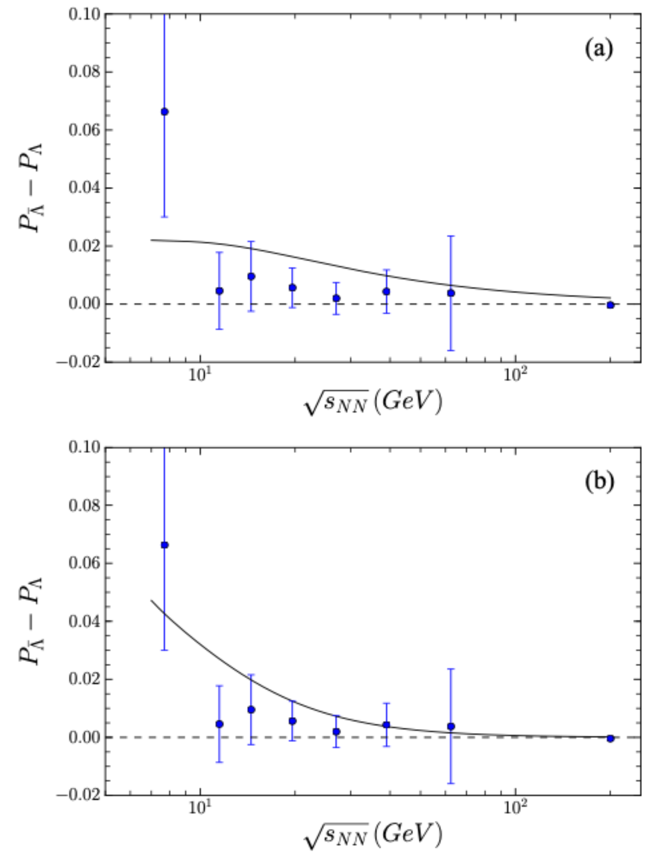
[1]*Institute of Physics and Technology, University of Bergen, Allegaten 55, 5007 Bergen, Norway*

[2]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

(Received 1 August 2018; revised manuscript received 12 December 2018; published 19 February 2019)

We propose a dynamical mechanism which provides an interaction between the spins of hyperons and antihyperons and the vorticity of the baryon current in noncentral high energy nuclear collisions. The interaction is mediated by massive vector and scalar bosons, which is well known to describe the nuclear spin-orbit force. It follows from the Foldy-Wouthuysen transformation and leads to a strong-interaction Zeeman effect. The interaction may explain the difference in polarizations of Λ and $\bar{\Lambda}$ hyperons as measured by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider. The signs and magnitudes of the meson-baryon couplings are closely connected to the binding energies of hypernuclei and to the abundance of hyperons in neutron stars.

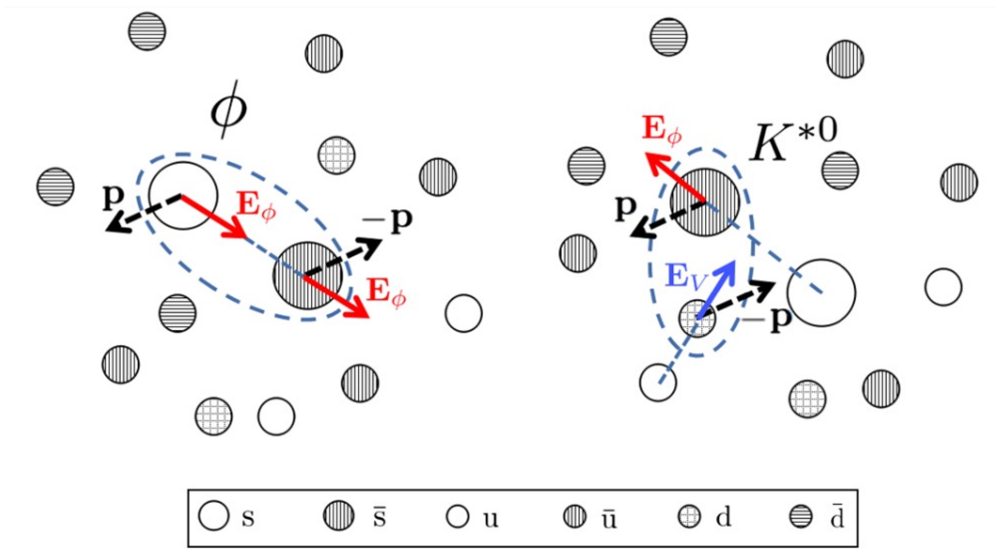


Similar idea to explain $P_{\Lambda} - P_{\overline{\Lambda}}$

What About K*0 meson ?

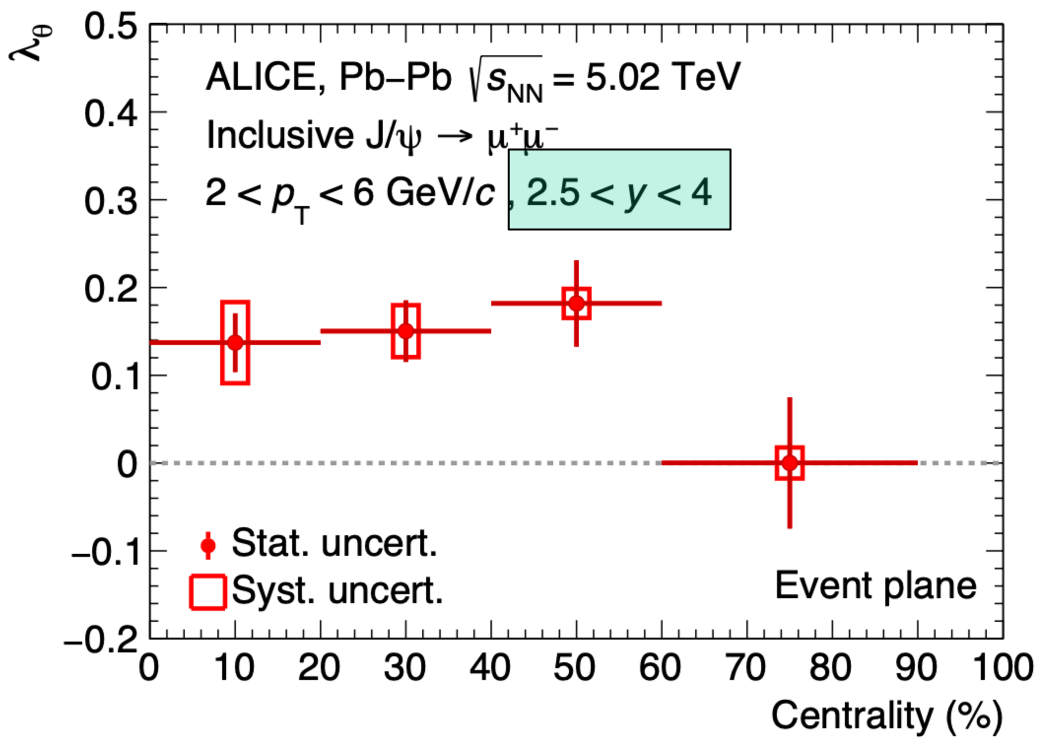
Particle Species	Quark content	Mass (GeV/c²)	Spin	Lifetime (fm/c)
ϕ	$s\bar{s}$	1.092	1	45
K*0	$d\bar{s}$	0.896	1	4

Sheng et., al., Phys. Rev. D 102, 056013 (2020)



Little field correlation for K^{*0}, causing $\langle P_{\bar{q}} P_q \rangle$ to diminish.

J/ψ $(c\bar{c})$



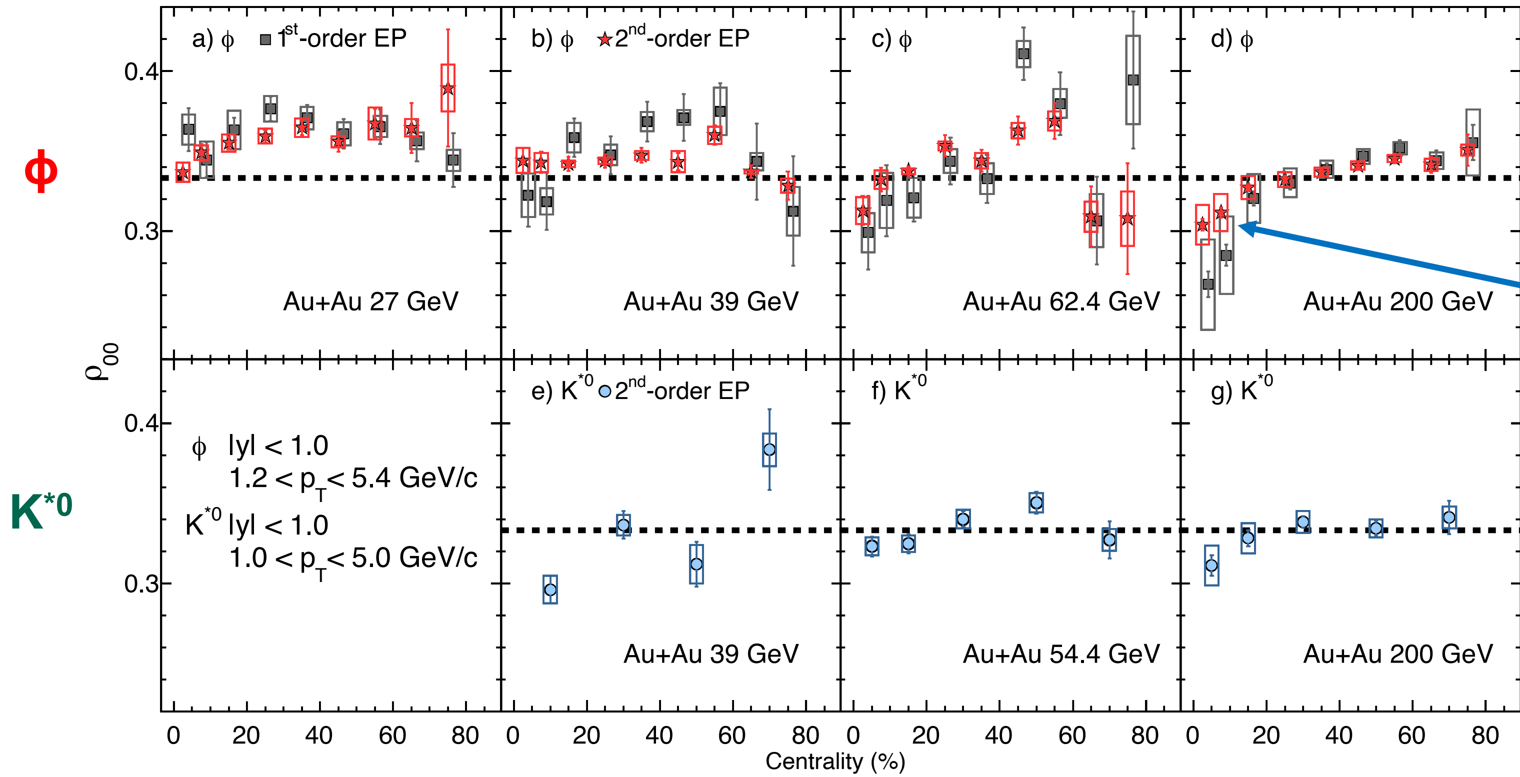
ALICE, arXiv : 2204.10171

$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$$

$\lambda_\theta > 0 \Leftrightarrow \rho_{00}$ < 1/3

Does J/ψ $(c\bar{c})$ result corroborates the idea of correlated strong force for $(q\bar{q})$ configuration ? Needs measurement at midrapidity.

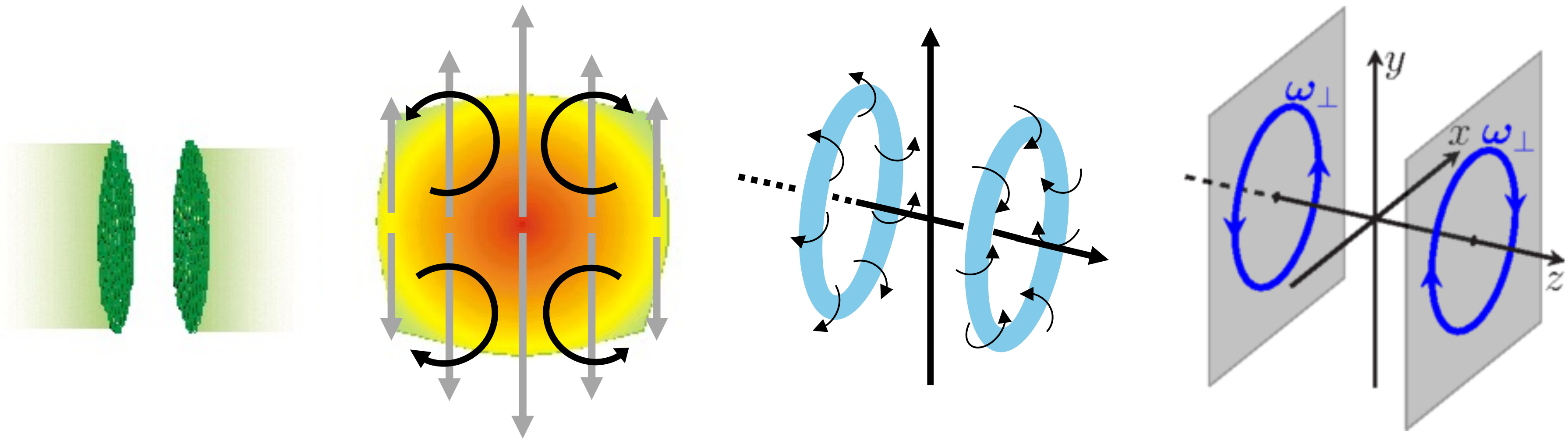
Differential ρ_{00} of ϕ and K^{*0}



Could be due to local spin alignments.

STAR, arXiv : 2204.02302

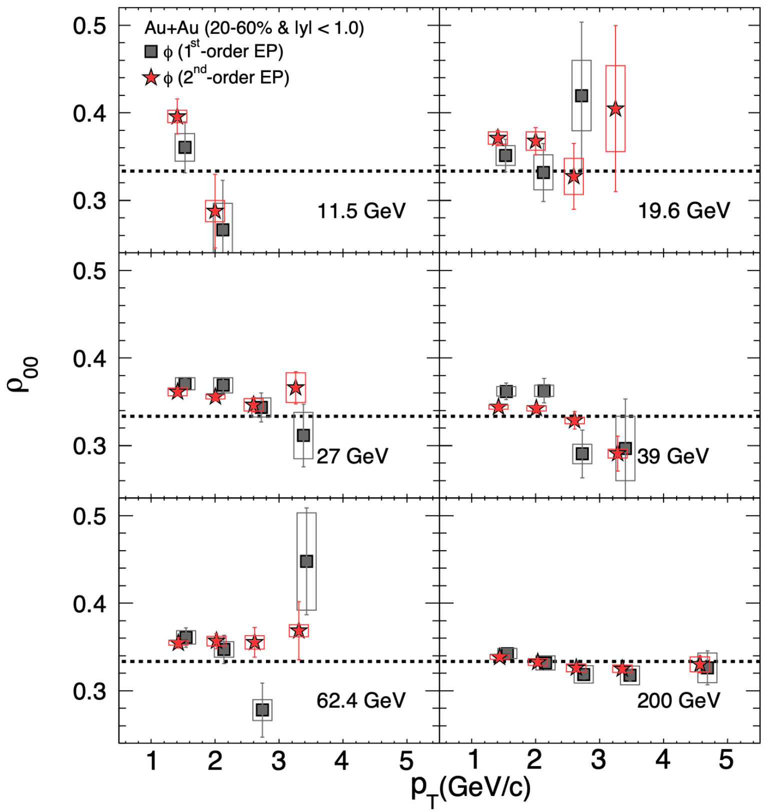
Circular Polarization

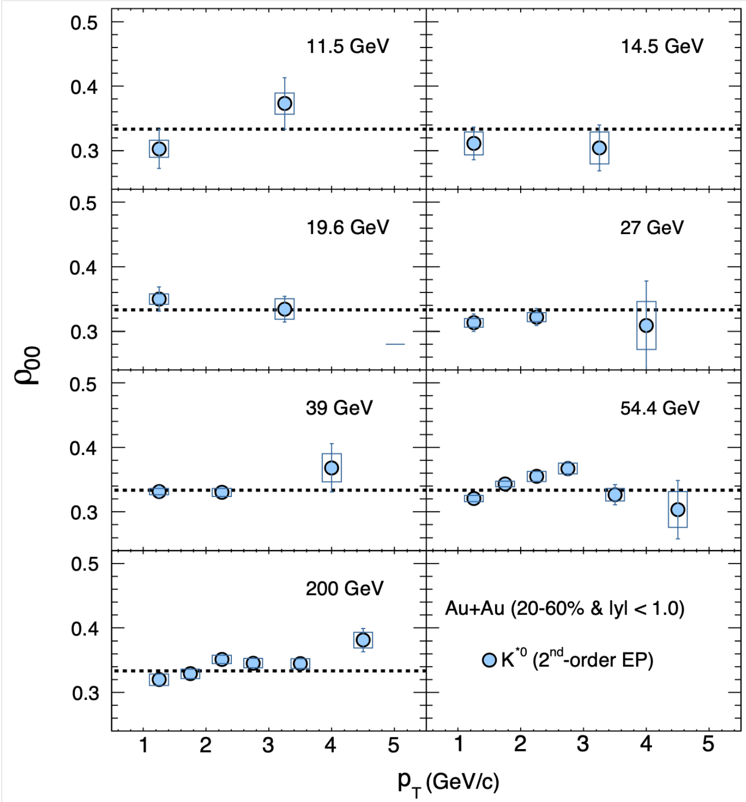


circular polarization $-\frac{1}{9}F_\perp^2$

[4]. Xia et., al., Phys. Lett. B 817, 136325 (2021);

Differential ρ_{00} of ϕ and K^{*0}

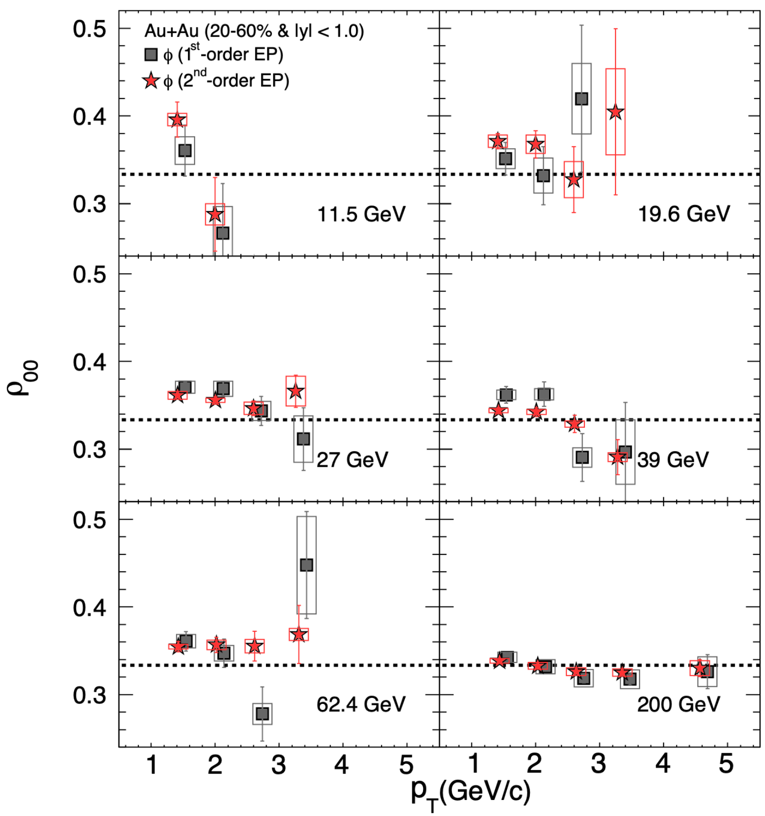




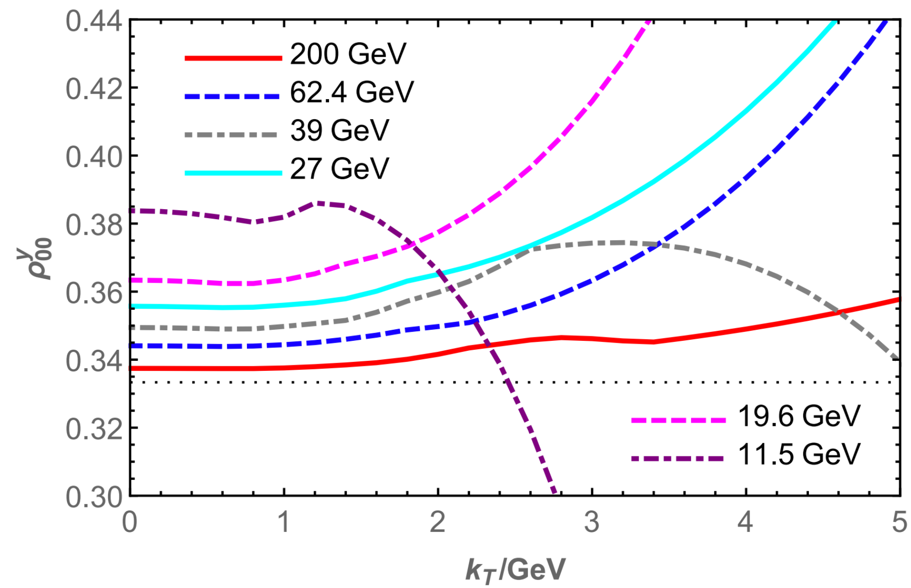
STAR, arXiv : 2204.02302

Rich features of p_T dependence

Differential ρ_{00} of ϕ and K^{*0}



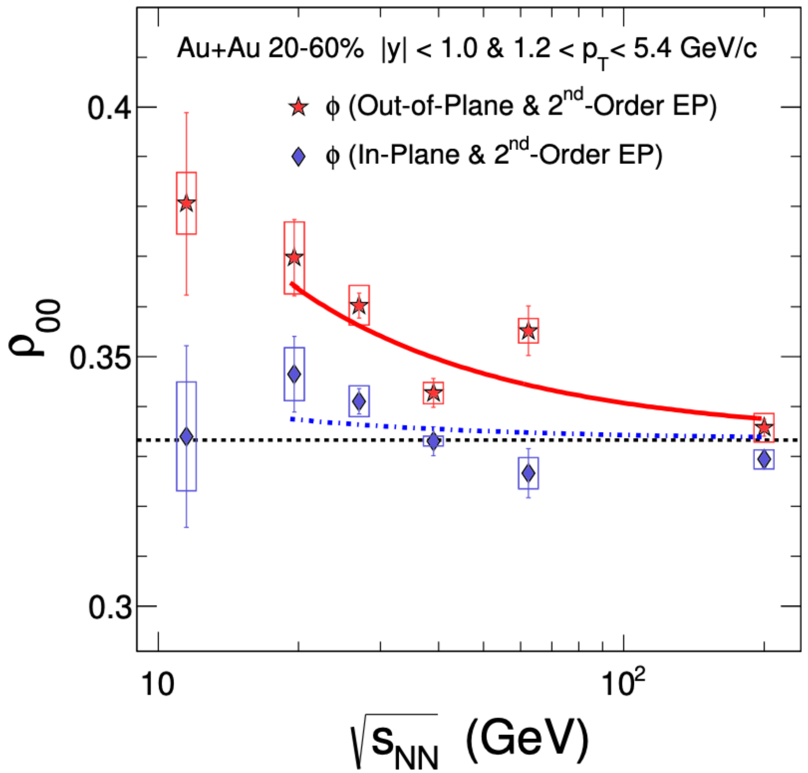
STAR, arXiv : 2204.02302

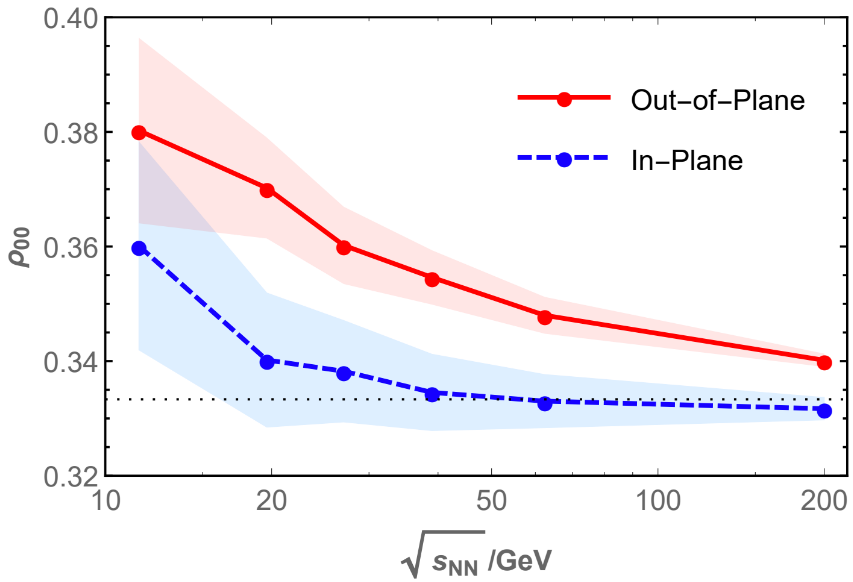


Sheng et., al., arXiv:2205.15689 (2022);

Magnitude and energy dependence, ✔
Tension at intermediate/large p_T 🤔

Differential ρ_{00} of ϕ and K^{*0}



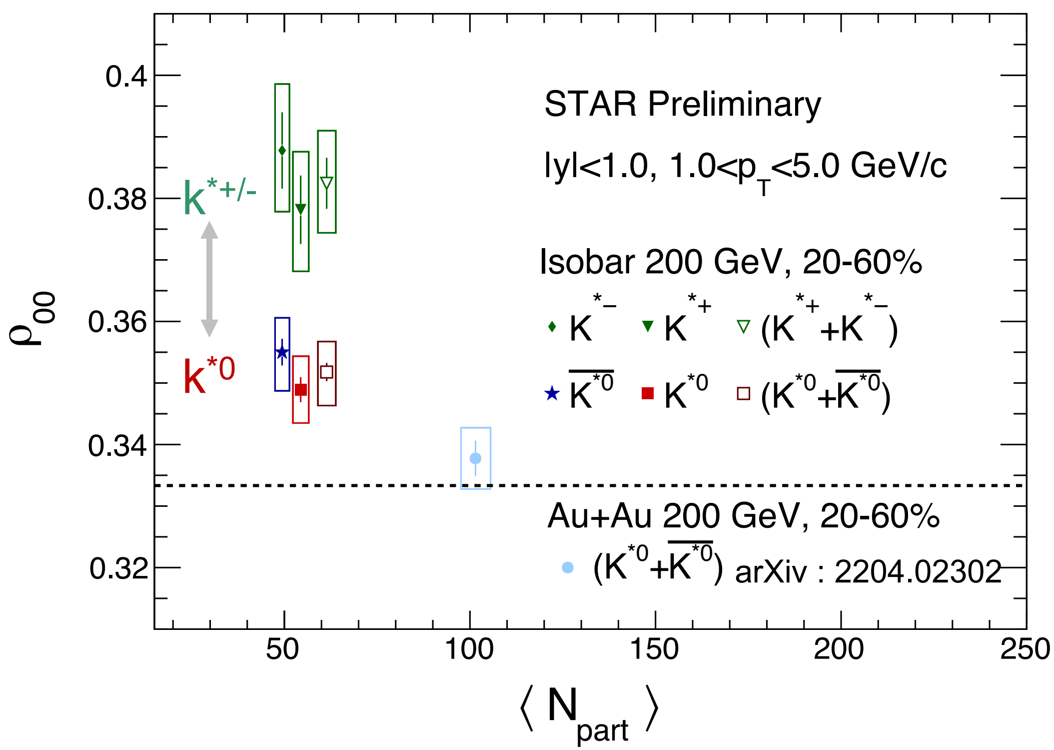


STAR, arXiv : 2204.02302

Sheng et., al., arXiv:2205.15689 (2022);

Difference in ρ_{00} between in-plane and out-of-plane can be described reasonably well by model invoking strong force field.

K^* ρ_{00} from Ru+Ru and Zr+Zr collisions



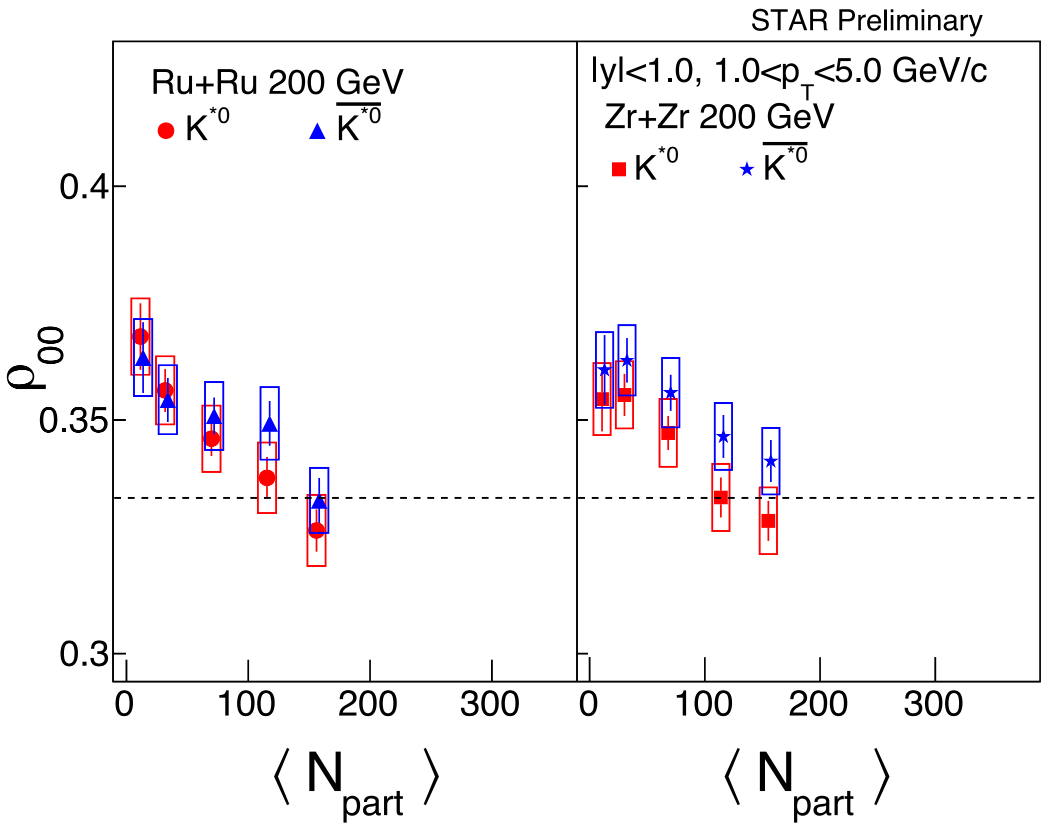
$k^{*+} \rightarrow k_s^0 + \pi^+$

$\quad \hookrightarrow \pi^+ + \pi^-$

S. Singha for STAR, QM2022

$\rho_{00}(K^{*+/-}) > \rho_{00}(K^{*0})$. More inputs from theory are needed to interpret the result.

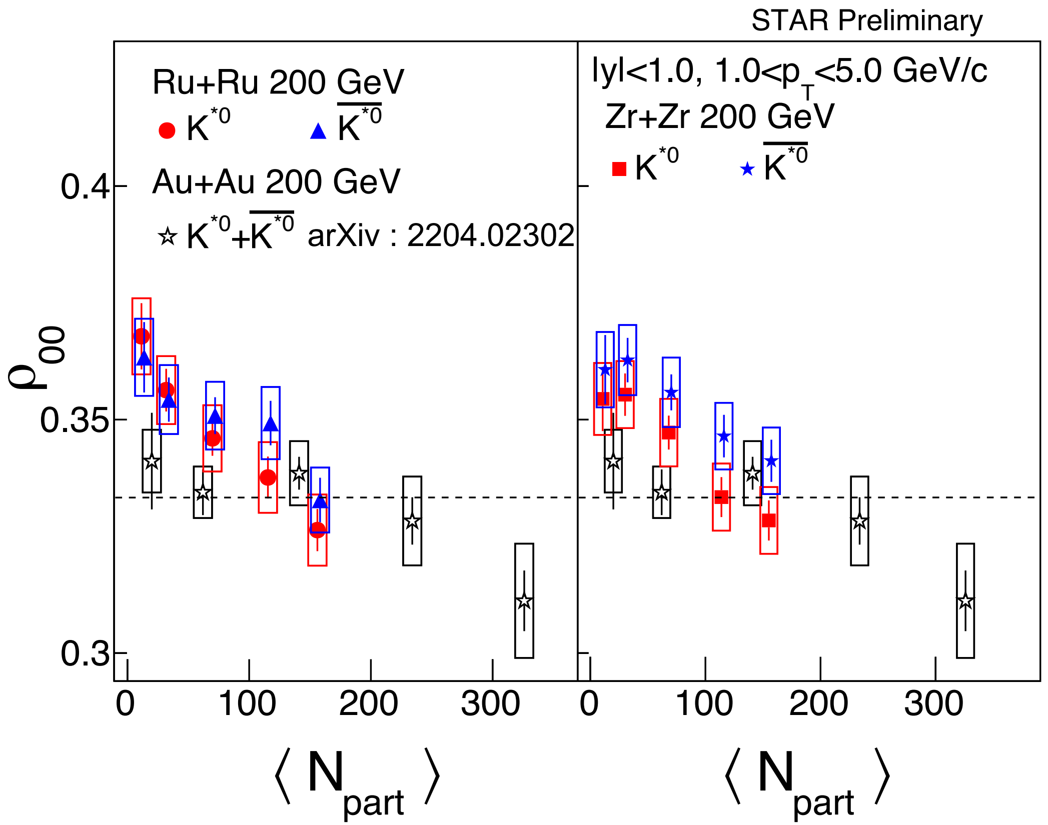
K* ρ_{00} from Ru+Ru and Zr+Zr collisions



S. Singha for STAR, QM2022

$\rho_{00}(K^{*0}) \sim \rho_{00}(\overline{K^{*0}})$.

K* ρ_{00} from Ru+Ru and Zr+Zr collisions



S. Singha for STAR, QM2022

$\rho_{00}(K^{*0}) \sim \rho_{00}(\overline{K^{*0}})$.
ρ_{00} Au+Au < ρ_{00} Ru+Ru ~ ρ_{00} Zr+Zr

Summary and Outlook

- A surprisingly large global spin alignment for ϕ-meson is observed. It cannot be explained by conventional mechanisms. However, it can be accommodated by a model with strong force field.
- The explanation is subject to debate and further verification is needed. The model has yet to confront rich, differential measurements from RHIC and LHC.

It is desirable to expand the study to other vector mesons [J/ψ, $\Upsilon(1s)$, D-mesons, B-mesons. etc.].

10x more statistics is expected during 2023 & 2025 at STAR, good news for statistics hungry analyses.

We wish for more theoretical development to advance our understandings.

Backup Slides

Energy splitting ($\mathcal{O}(\partial^0)$) also induces spin alignment

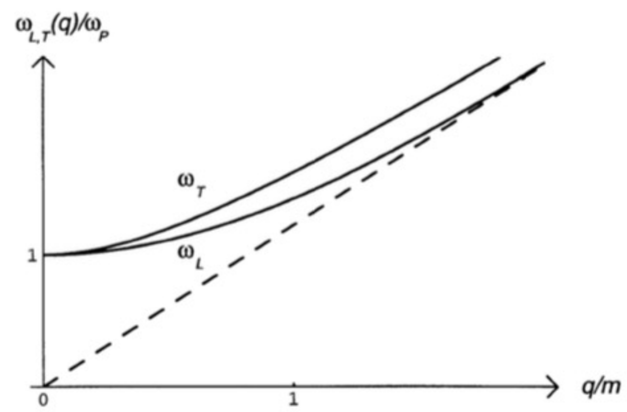
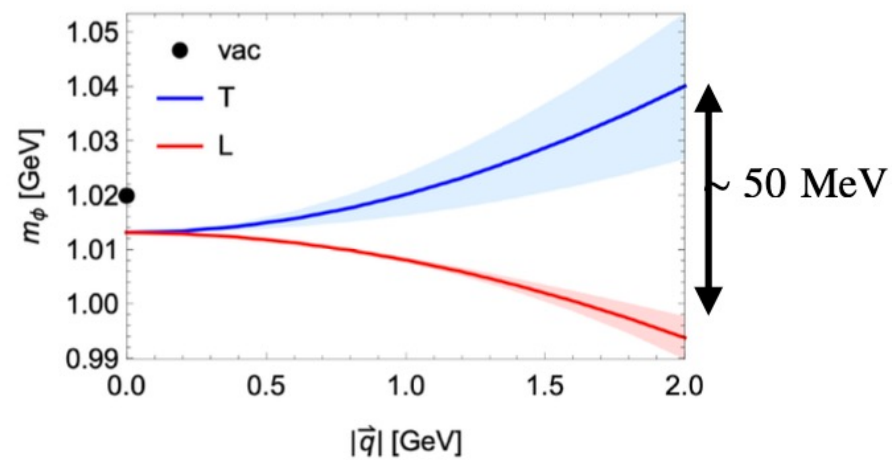


Fig. 6.2 Dispersion laws for transverse and longitudinal photons.

Bellac's textbook



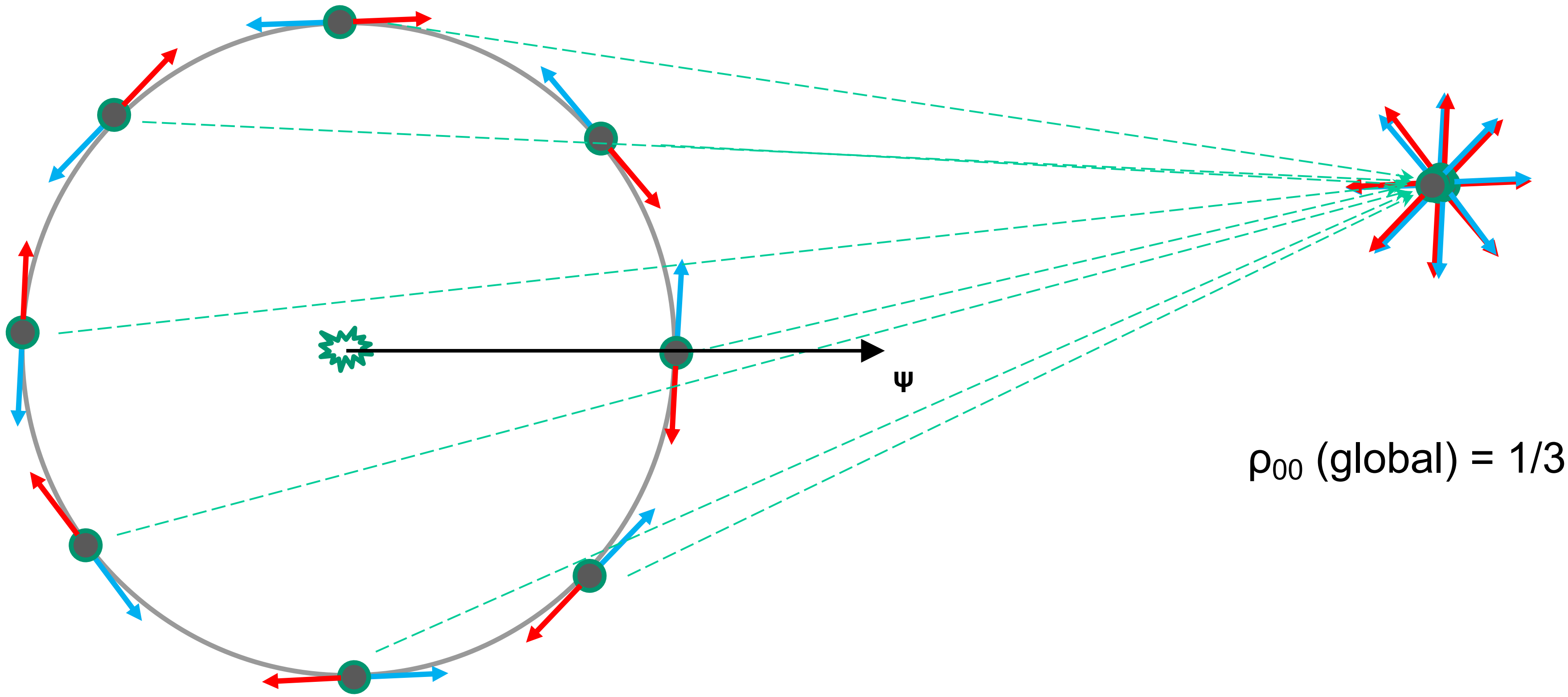
ϕ dispersion at normal nuclear density n_0 from sum rule analysis, Kim-Gubler, PLB 20'.

- Splitting of E_T, E_L induces spin alignment. (benchmark for ρ_{00} in-medium is NOT 1/3)

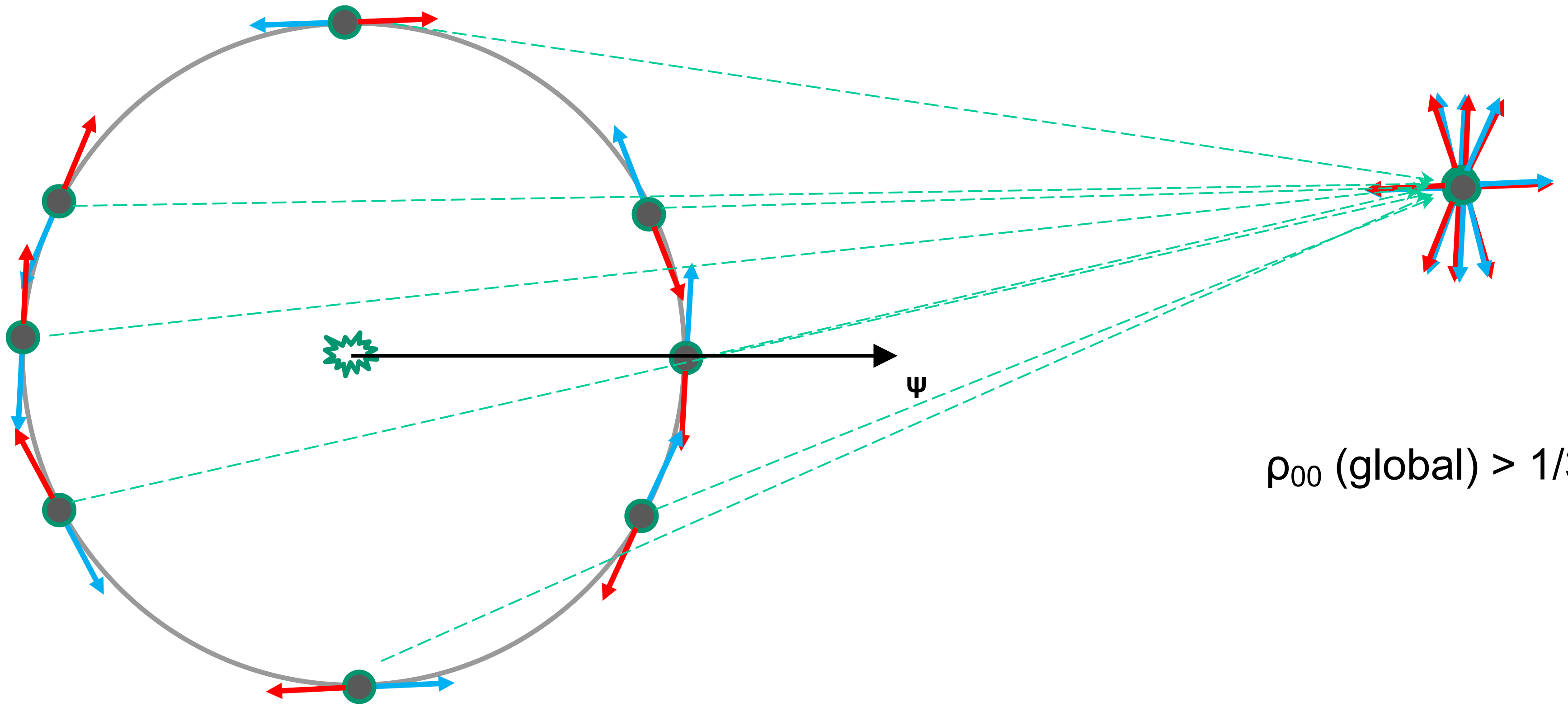
$$\delta\rho_{00}^{(0)}(\hat{n}) \approx \int_{x,p} \frac{E_L(p) - E_T(p)}{9T} \left[(\hat{n} \cdot \vec{v})^2 - \frac{1}{3} \right]$$

Spin alignment serve as a new probe to in-medium properties.

Yi Yin, Reimei workshop 2022



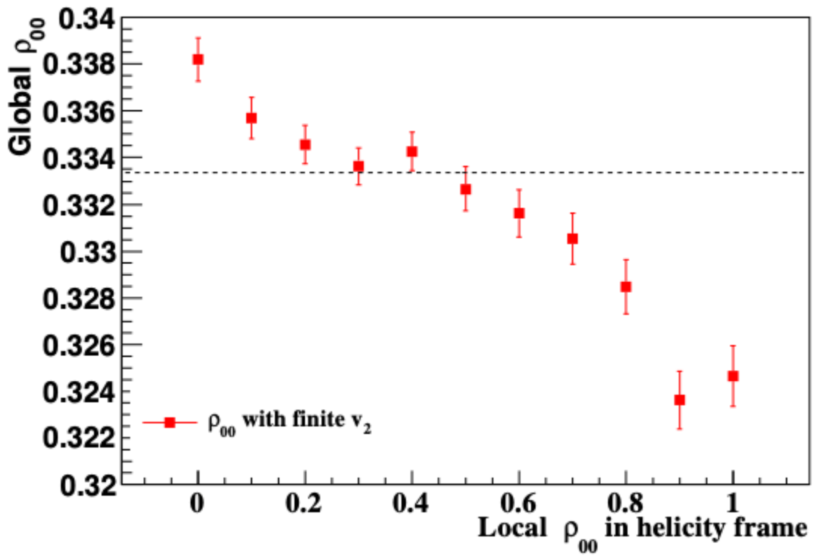
ρ_{00} (Helix) < 1/3 and v_2=0



ρ_{00} (global) > 1/3

ρ_{00} (Helix) < 1/3 and v_2>0

Backup Slides



A STAR collaboration effort that spanned over ~6 years, led by :

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Xu Sun (UIC),
Aihong Tang (BNL)
Chensheng Zhou (FDU)

Subhash Singha

Xu Sun

Chensheng Zhou

Thanks ！