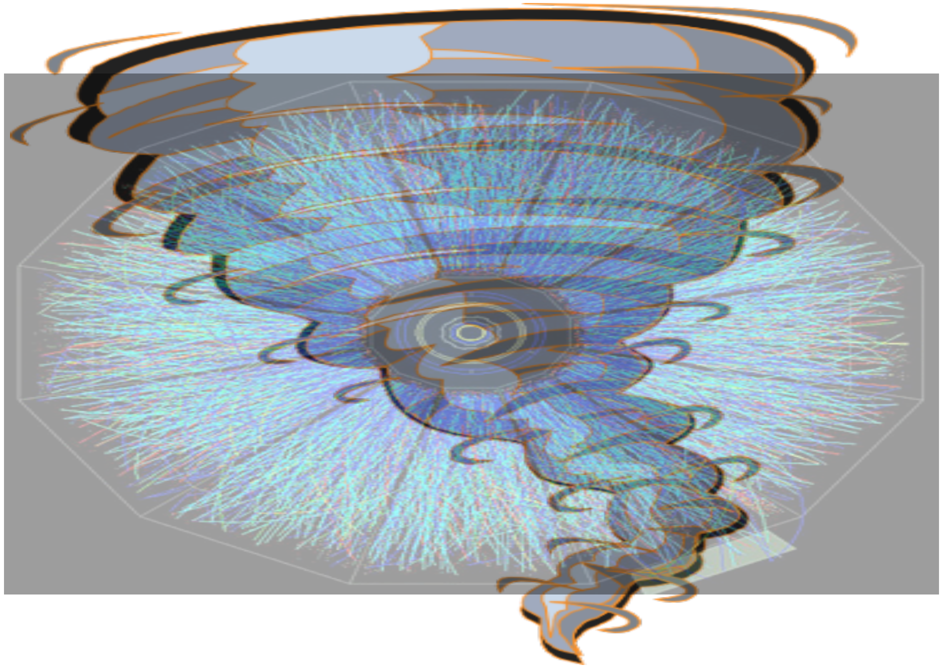
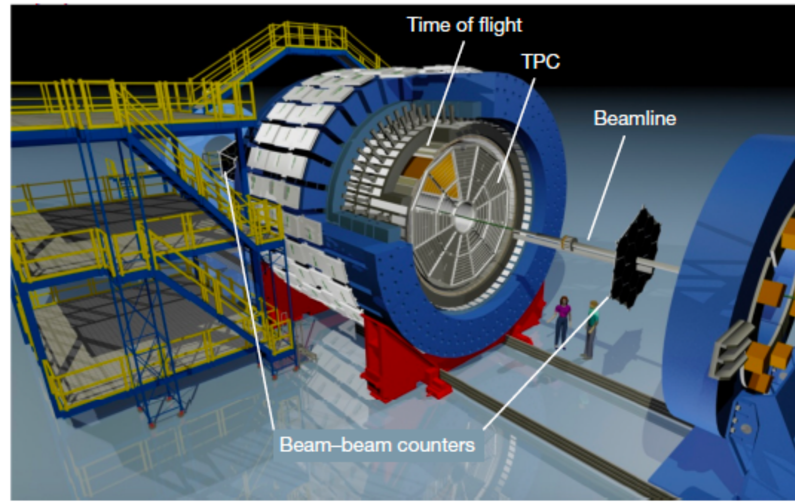
Strongly Interacting Matter Under Rotation



Jinfeng Liao 廖劲峰

Subatomic Swirls



An exciting discovery from STAR Collaboration at RHIC: The most vortical fluid!

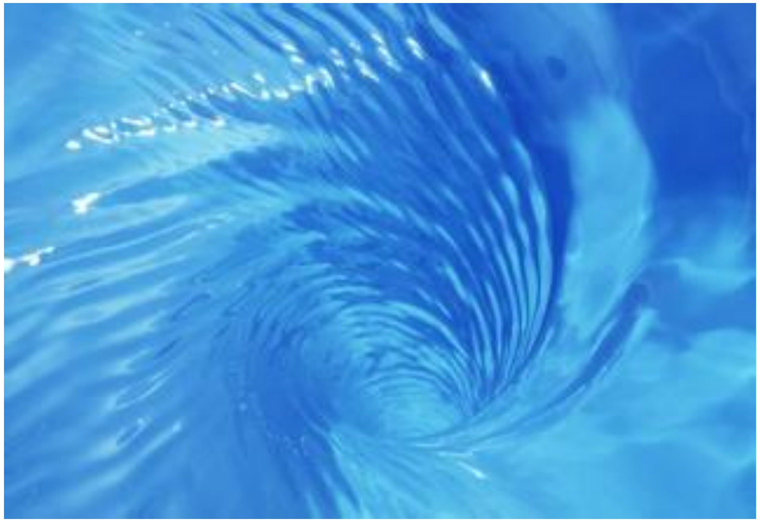
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

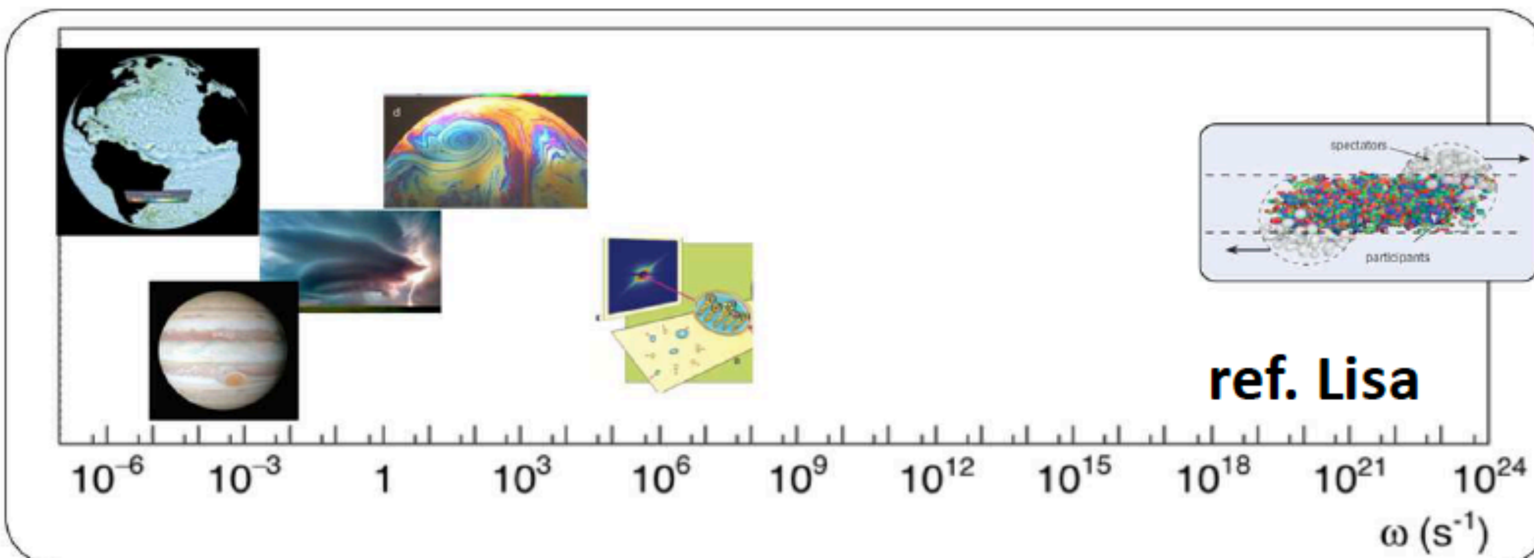
Quantifying Fluid Rotation



$\vec{\mathbf{v}}$

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

UR $\Omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$



Analogy Between Rotation & B Field

EM vector field $\vec{A}$

Magnetic field $\vec{B} = \vec{\nabla} \times \vec{A}$

Lorentz force

$$\vec{F}_{Lorentz} = e\,\vec{v} \times \vec{B}$$

$\vec{V}$ Fluid velocity field

$\vec{\omega} = \vec{\nabla} \times \vec{V}$ Fluid vorticity

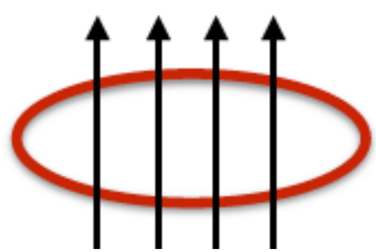
Coriolis force

$$\vec{F}_{cor} = 2m\,\vec{v} \times \vec{\omega}$$

Magnetic Polarization

Charged particle's spin —> magnetic moment —> align with B field

$\vec{\omega}$ or $\vec{B}$



Rotational Polarization

Global rotation —> "equal-partition" for angular momentum —> individual spin & orbital angular momentum align with rotation

Description of Slowly Rotating Fermion System

Dirac Lagrangian in rotating frame:

$$g_{\mu\nu} = \begin{pmatrix} 1-\vec{v}^2 & -v_1 & -v_2 & -v_3 \\ -v_1 & -1 & 0 & 0 \\ -v_2 & 0 & -1 & 0 \\ -v_3 & 0 & 0 & -1 \end{pmatrix}$$

$$\vec{v} = \vec{\omega} \times \vec{x}.$$

$$\bar{\gamma}^\mu = e_a{}^\mu \gamma^a$$

$$\Gamma_\mu = \frac{1}{4} \times \frac{1}{2}[\gamma^a, \gamma^b]\Gamma_{ab\mu}$$

$$\mathcal{L} = \bar{\psi}\left[i\bar{\gamma}^\mu(\partial_\mu + \Gamma_\mu) - m\right]\psi$$

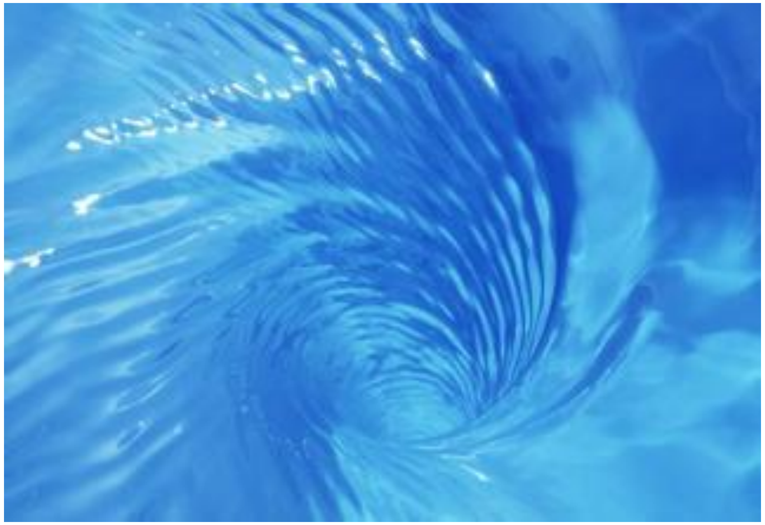
Under slow rotation:

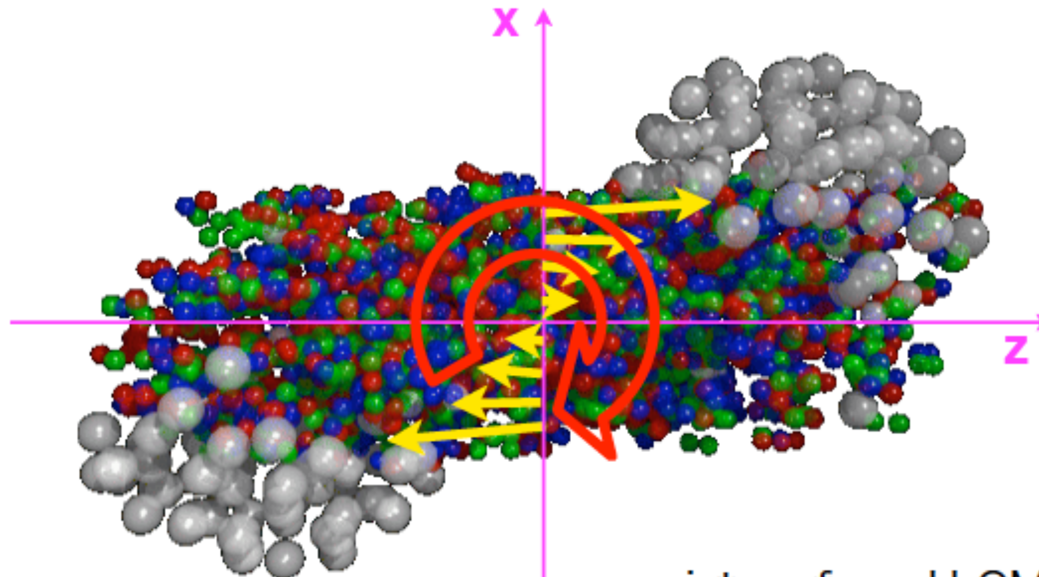
$$\mathcal{L} = \psi^\dagger\left[i\partial_0 + i\gamma^0\vec{\gamma}\cdot\vec{\partial} + (\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times4}\right]\psi$$

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

Rotational polarization effect!

Effects from Rotational Polarization





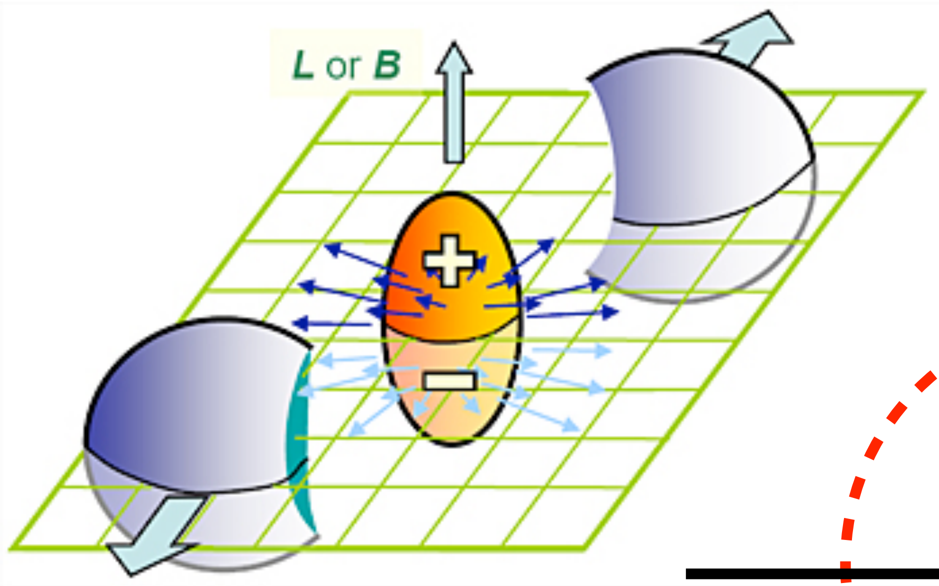
picture from UrQMD

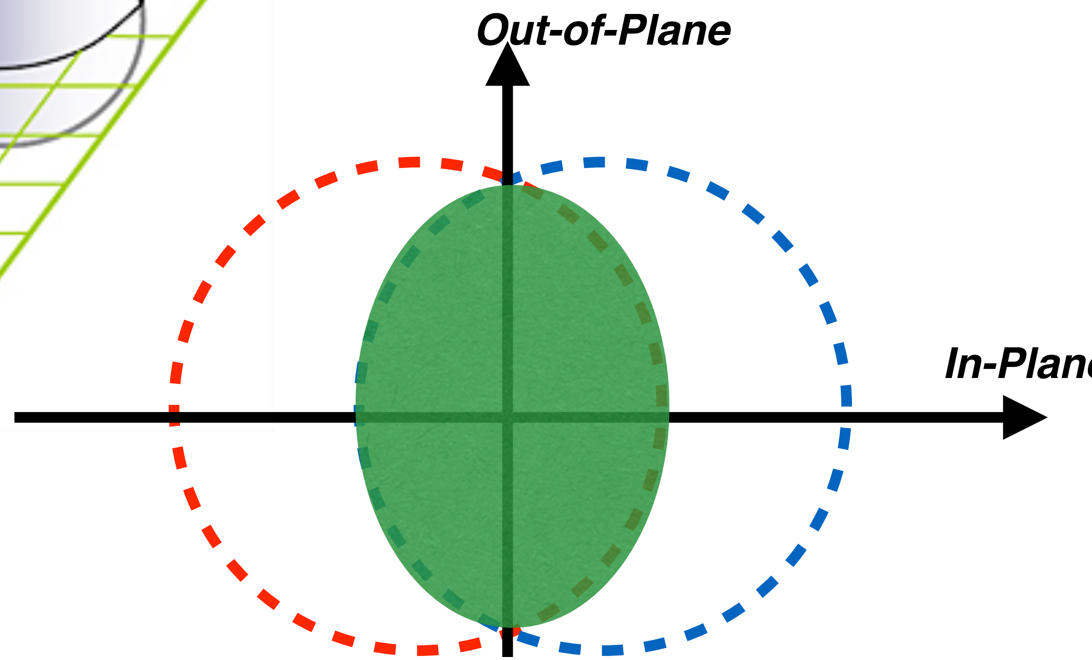
* Is there strong rotational motion (vortical structures) in heavy ion collisions? YES!

* Possible physical effects due to rotational polarization? YES!

Vorticity & Polarization

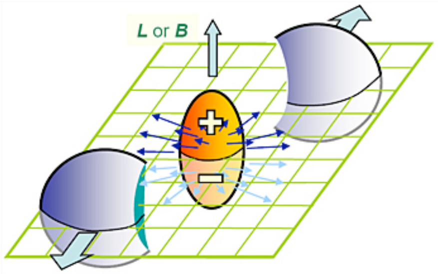
The Setup of Heavy Ion Collision



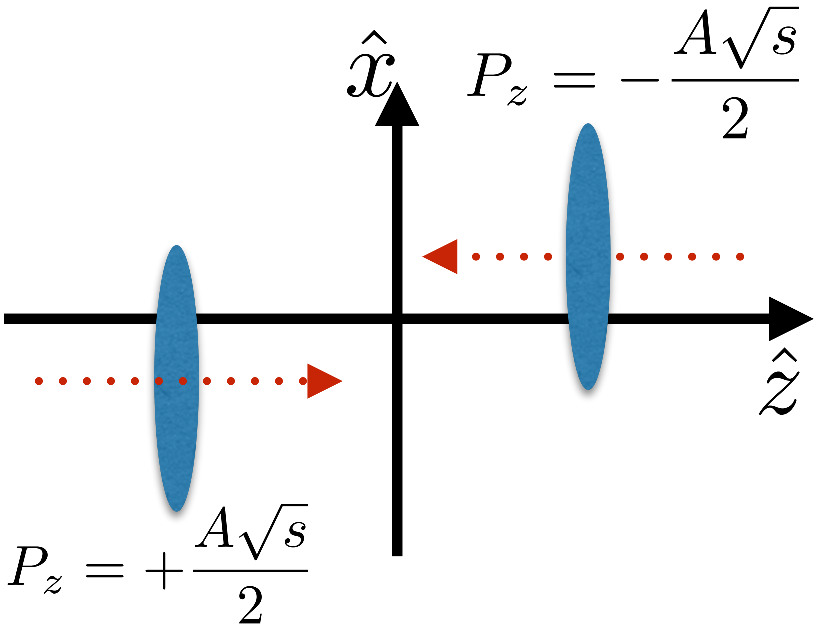


A typical off-central collision.

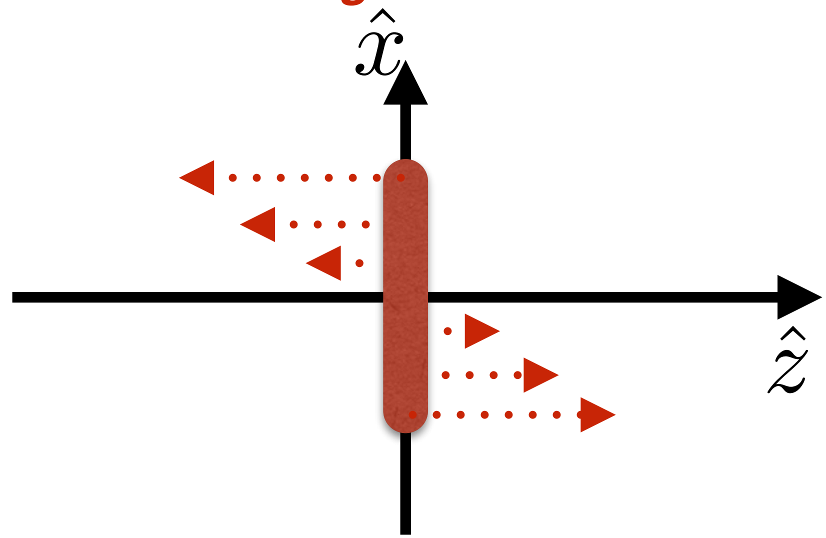
Rotating Quark-Gluon Plasma



$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$



QGP's way of accommodating this angular momentum

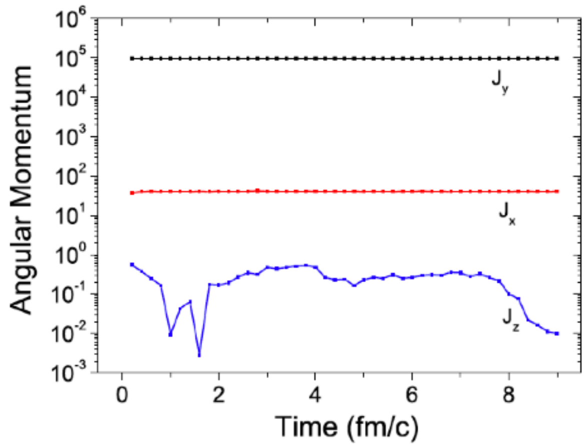


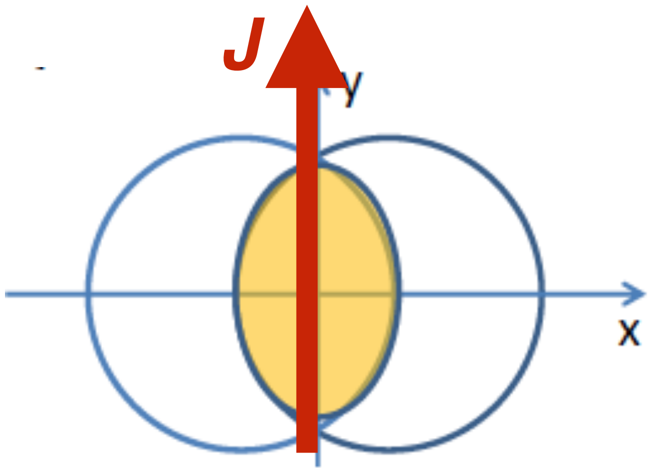
Issues:

**** Spectators taking away lots of L ?!***

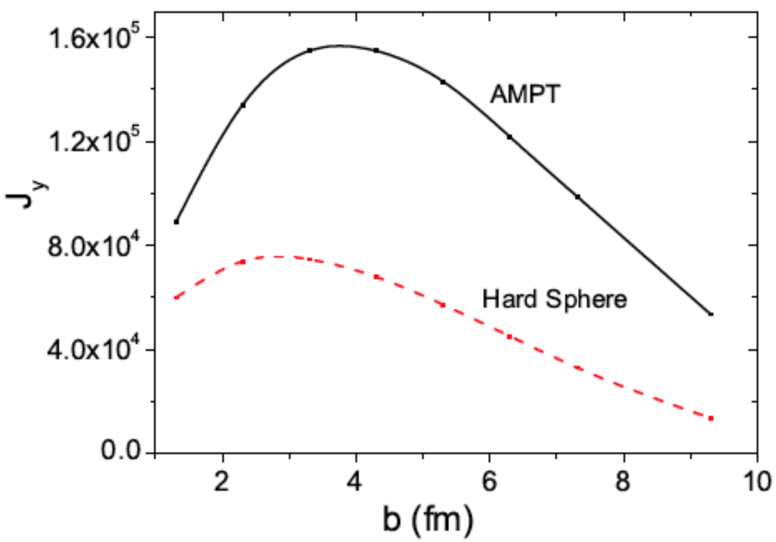
**** Is the L residing in fireball conserved in time?***

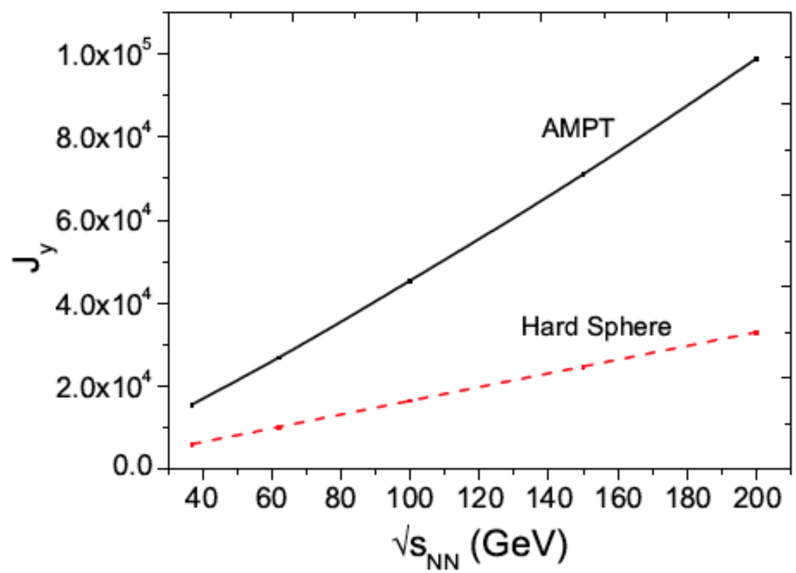
Rotating Quark-Gluon Plasma





Angular momentum is conserved in time.





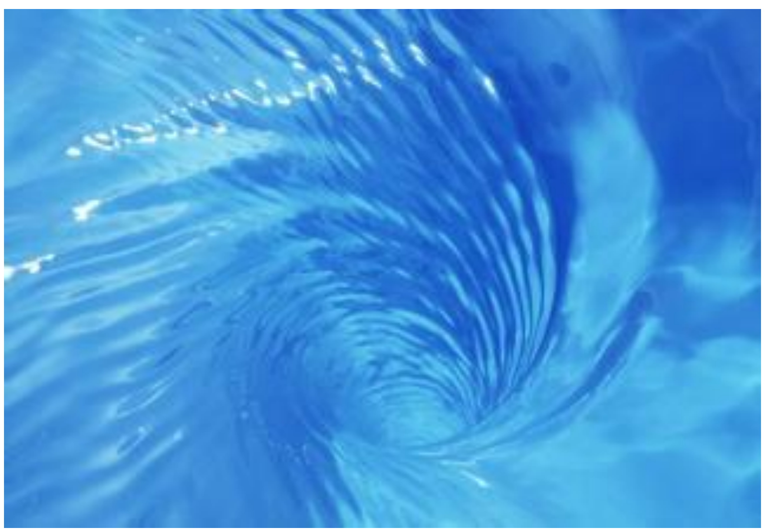
Yin Jiang, Zi-Wei Lin, JL, arXiv:1602.06580[hep-ph][PRC2016]

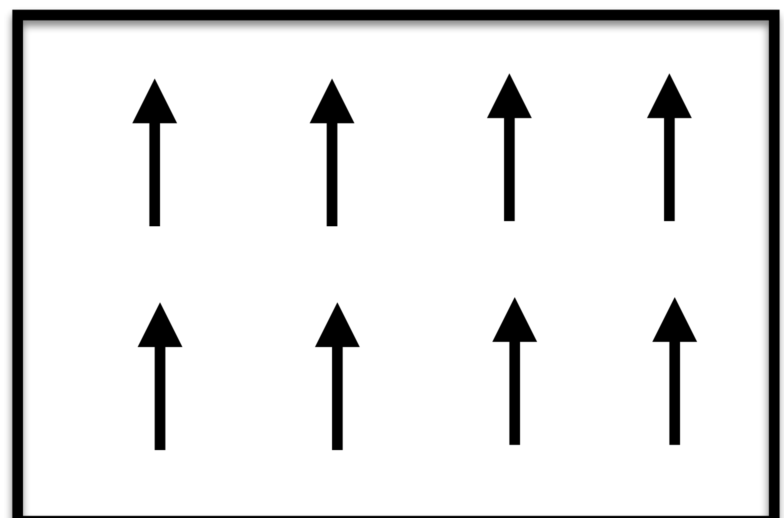
Rotating Quark-Gluon Plasma

How does this many-body system cope with a sizable angular momentum?

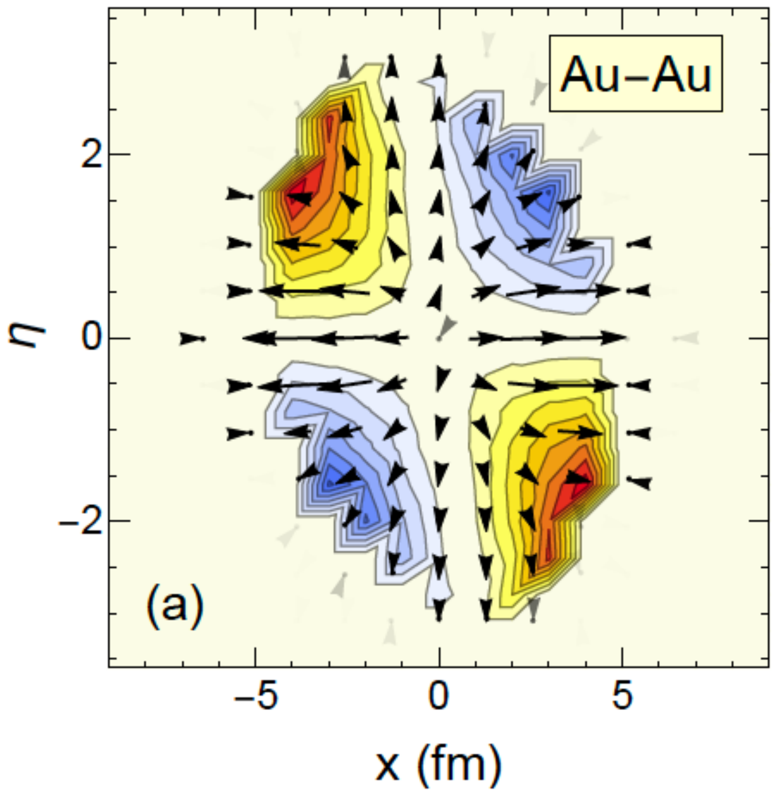
Orbital motion (vorticity);
Spin alignment (polarization).

Both must occur, à la "equal-partition"





Rotating Quark-Gluon Plasma



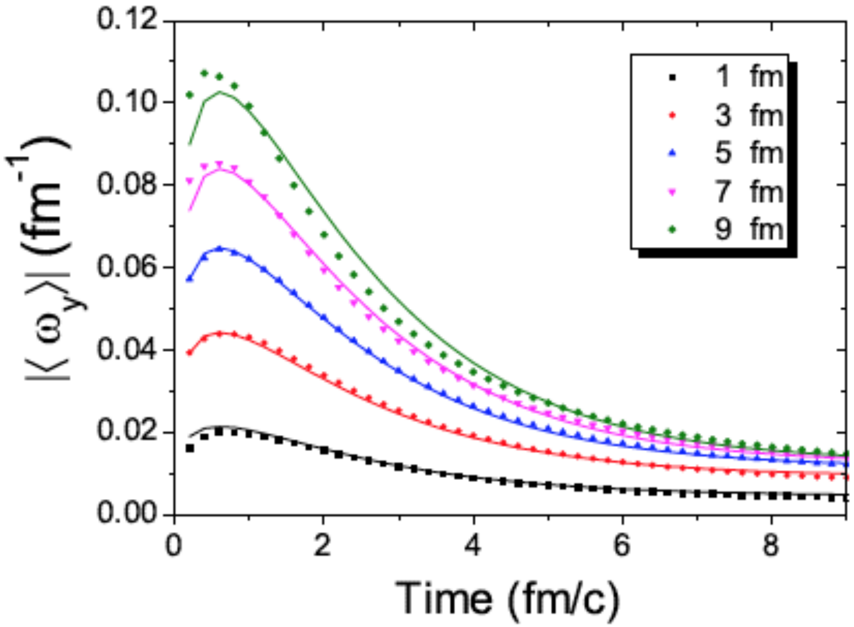
$$\vec{v}(\rho,\phi,\eta) = \hat{e}_\rho v_0(\rho,\eta)[1 + 2c_2(\rho,\eta)\cos 2\phi]$$

$$\begin{aligned}\omega_y &= \frac{\partial v_\rho}{\partial z}\cos\phi \\ &= \frac{2}{t}(ch\eta)^2\ \partial_\eta(v_0 + 2v_0c_2\cos 2\phi)\cos\phi \\ &= \frac{2}{t}(ch\eta)^2\left(\frac{x}{\rho}\right)\partial_\eta\left[v_0 + 2v_0c_2\left(2\frac{x^2}{\rho^2} - 1\right)\right]\end{aligned}$$

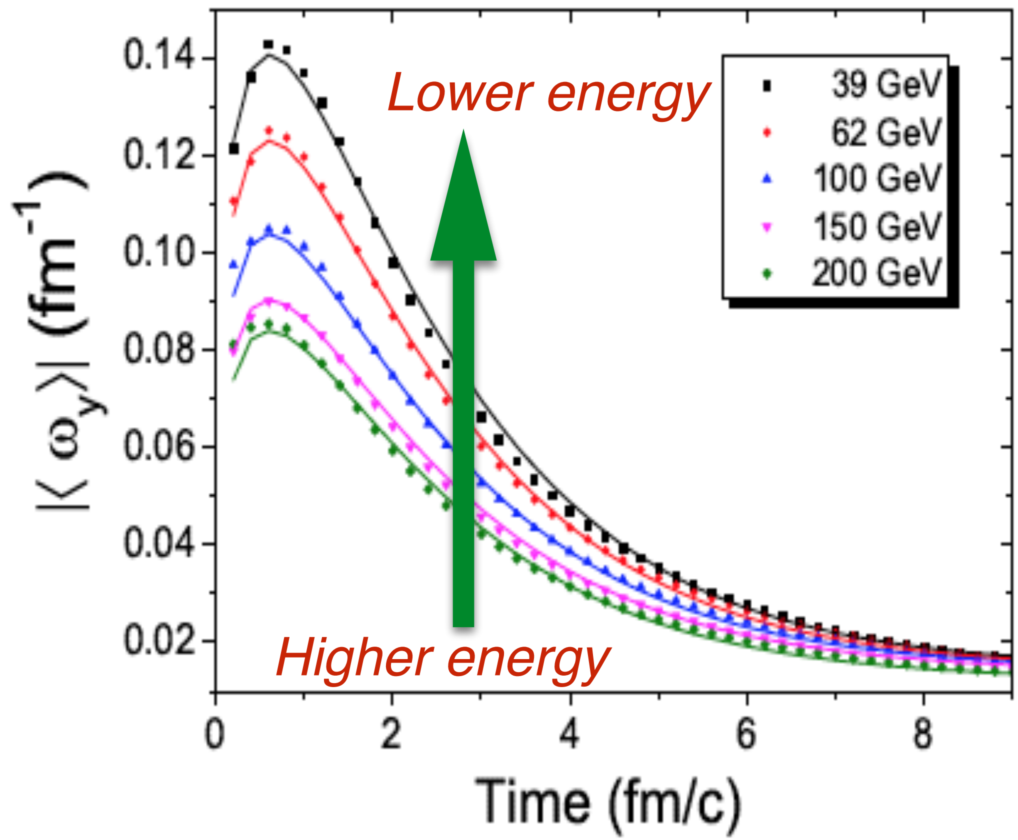
The local vorticity pattern is strongly influenced by the bulk flow.
The averaged vorticity reflects the global orbital angular momentum.

Yin Jiang, Zi-Wei Lin, JL, PRC2016

Rotating Quark-Gluon Plasma



Centrality trend



Beam Energy Dependence

Yin Jiang, Zi-Wei Lin, JL, PRC2016

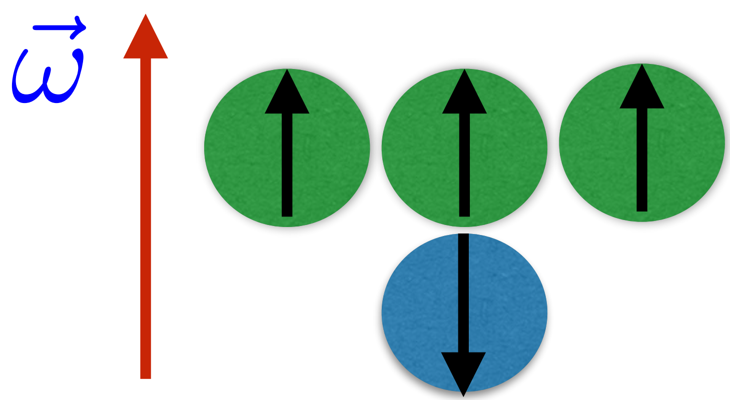
Rotational Polarization

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

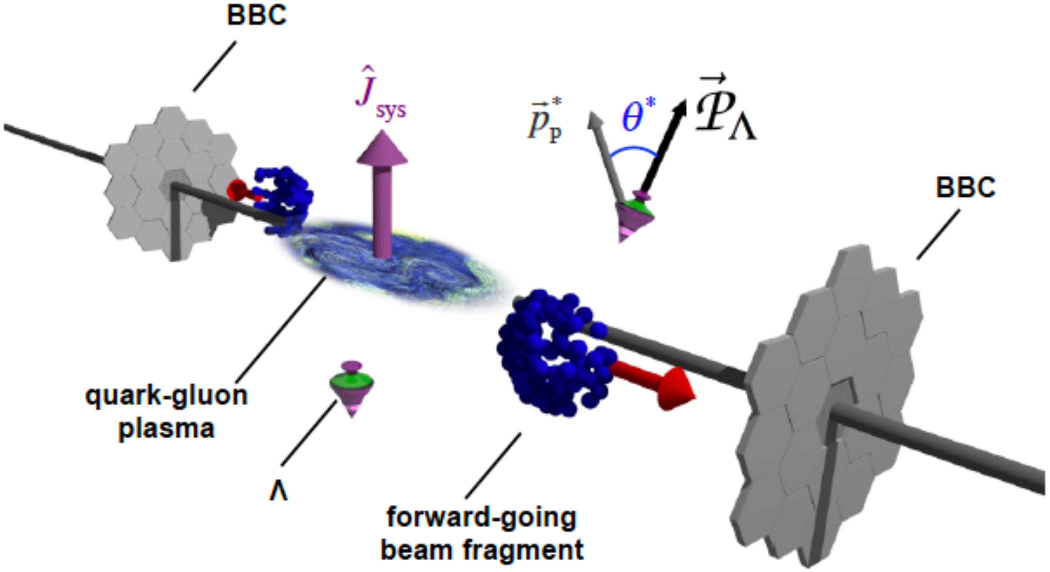
Rotational polarization effect!

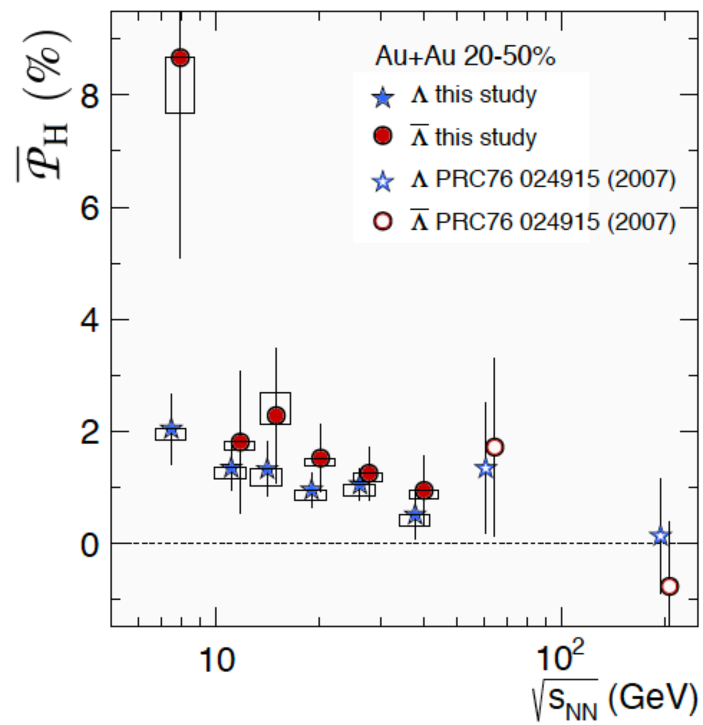
For thermally produced particles:

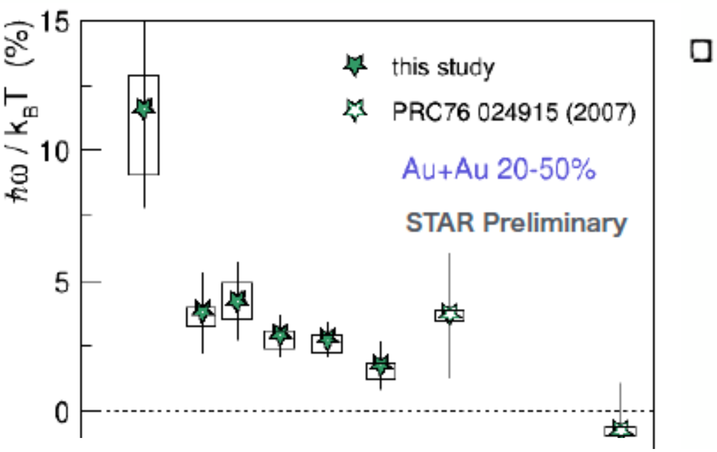
$$dN \propto e^{-\frac{\vec{\omega}\cdot\vec{J}}{T}}$$



Rotational Polarization Observed!







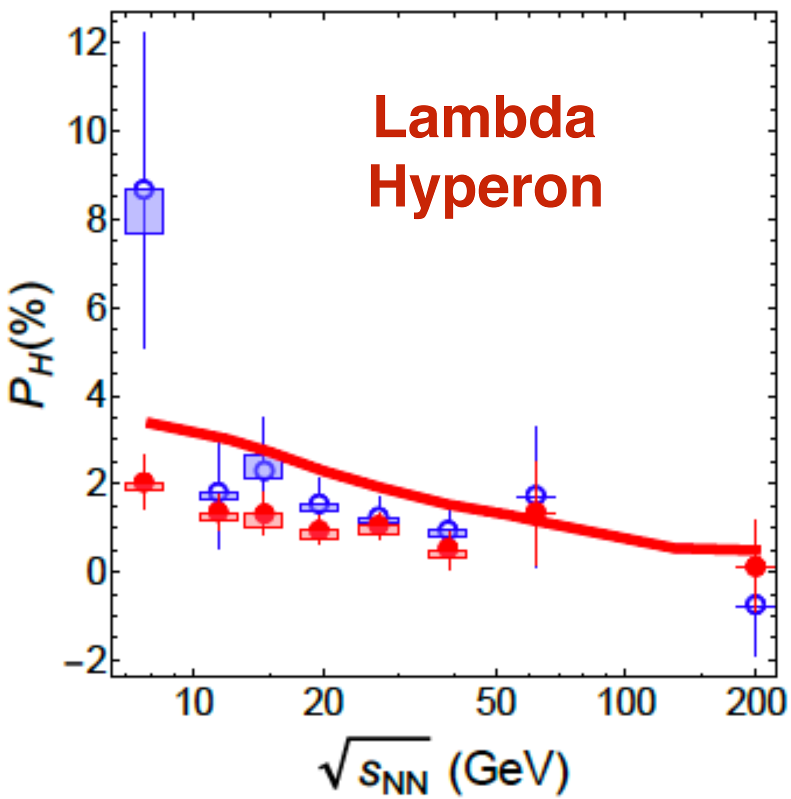
$$\omega \approx k_B T(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'})/\hbar$$

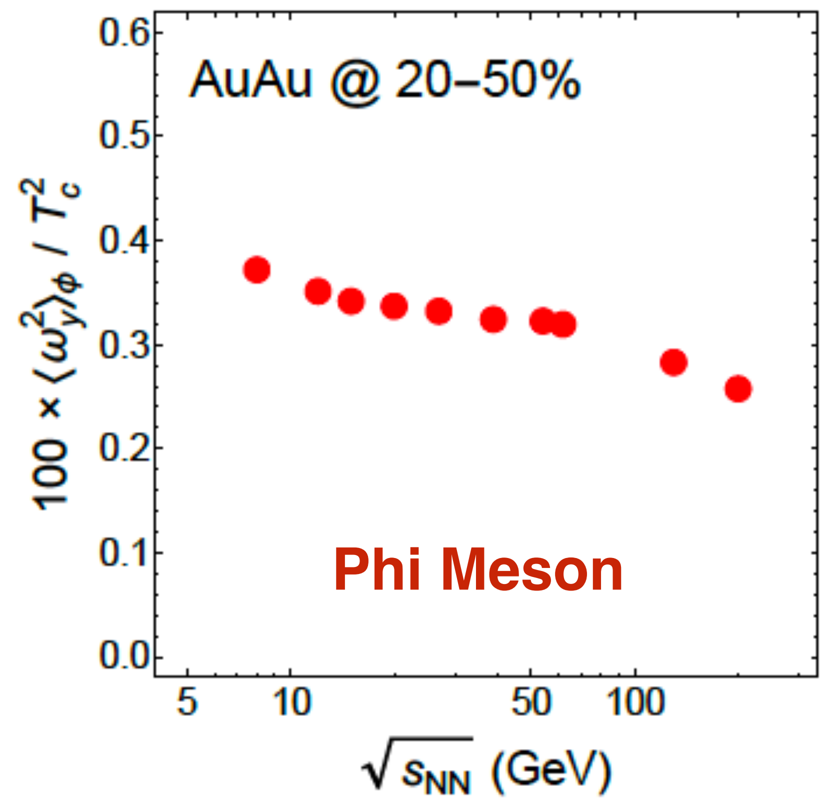
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$

The most vortical fluid!

STAR Collaboration, Nature 2017

Estimating Polarization Effect



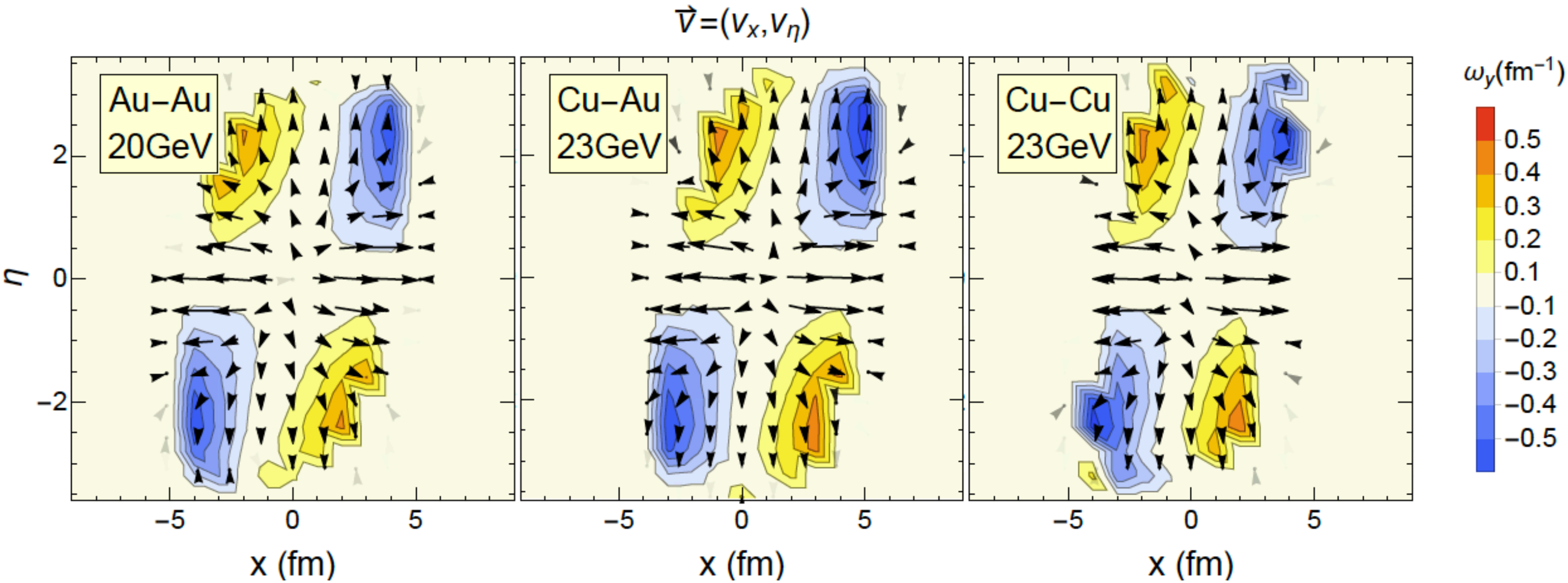


$$\rho_{00}^{\text{thermal}} = \frac{f_{BE}(E)}{f_{BE}(E+\omega_y) + f_{BE}(E) + f_{BE}(E-\omega_y)} \approx \frac{1}{3} - \frac{1}{9}\frac{\omega_y^2}{T_{fo}^2}$$

Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

Different Colliding Systems

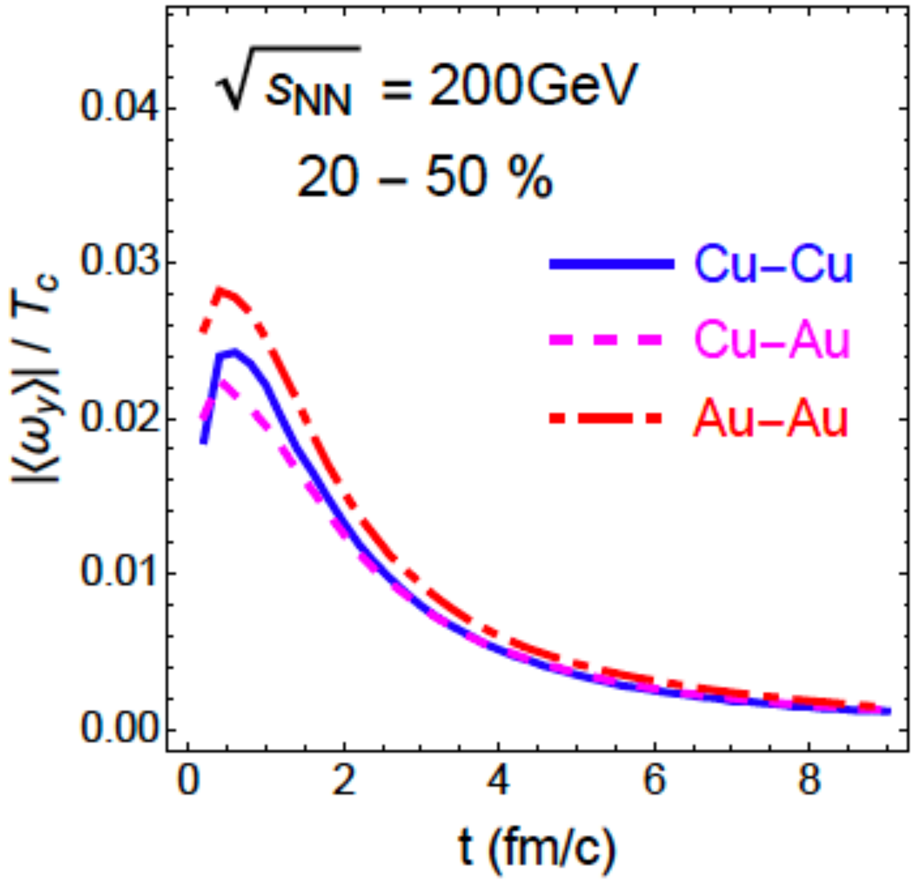
Using different colliding systems for independent check!



Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

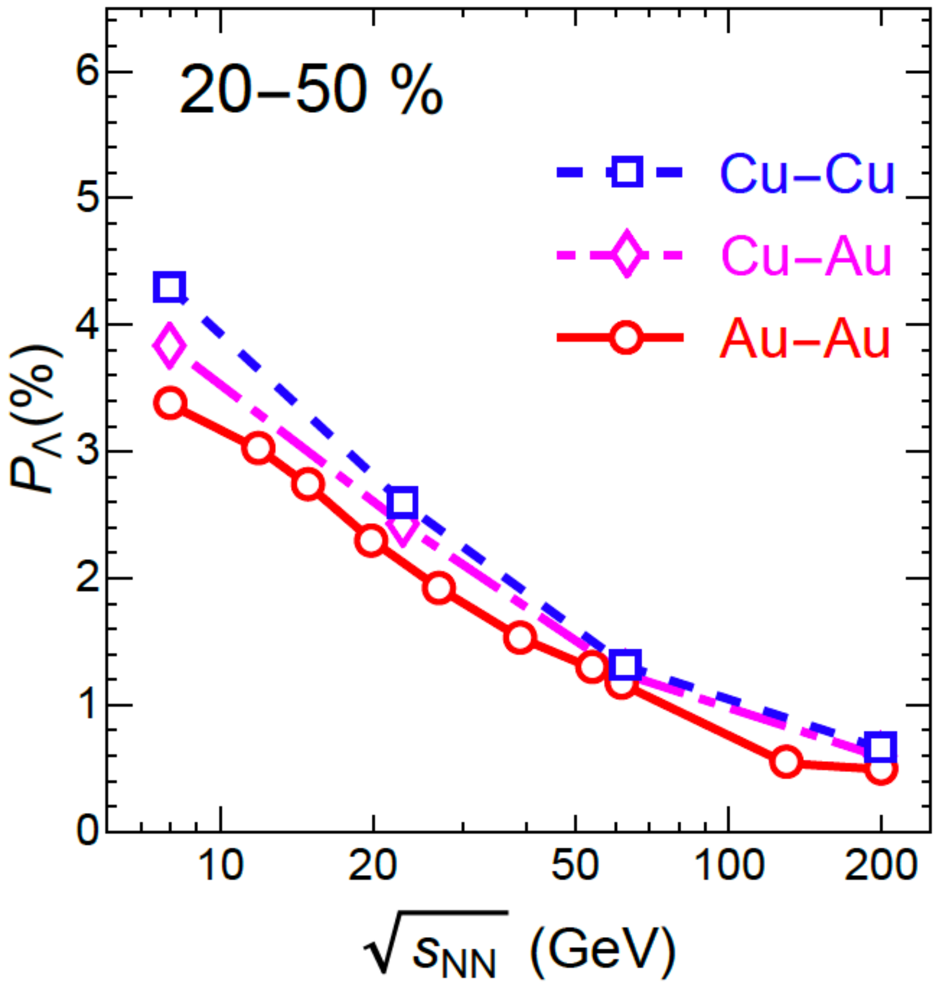
Interesting System Size Dependence

The polarization effect in CuCu collisions should be sizable!



Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

Prediction for Polarization in CuCu and AuAu

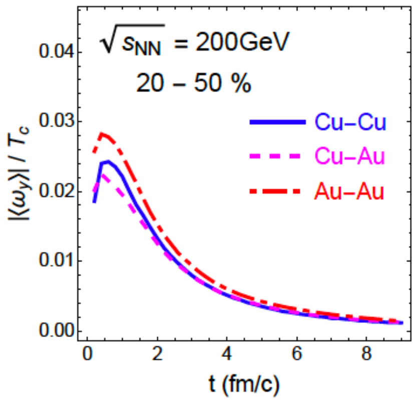


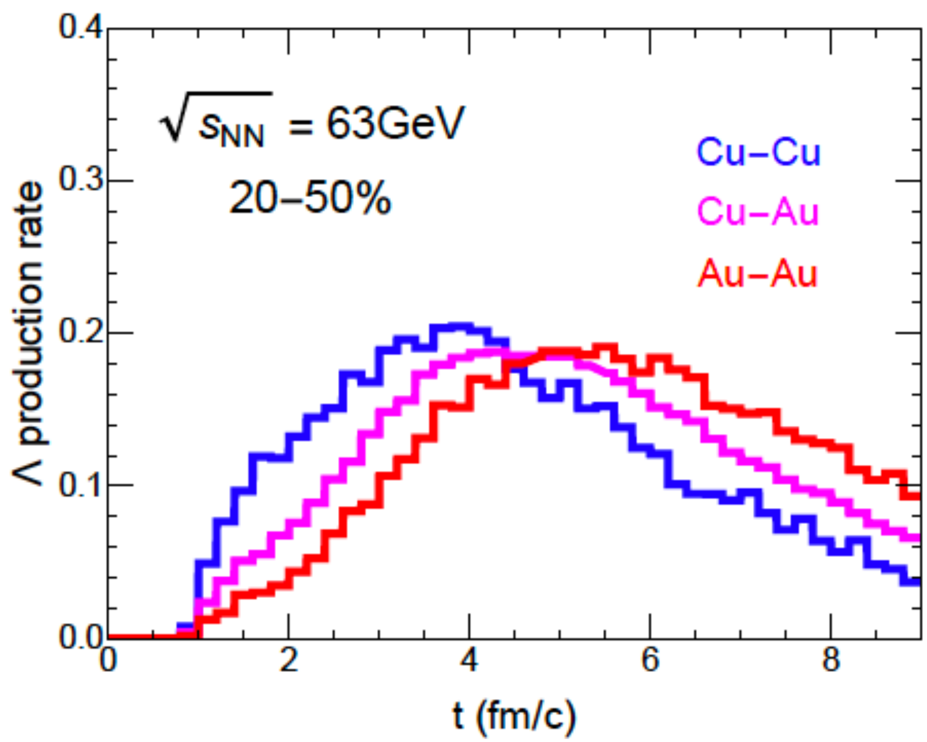
Our surprising finding of the signal hierarchy: CuCu > CuAu > AuAu !

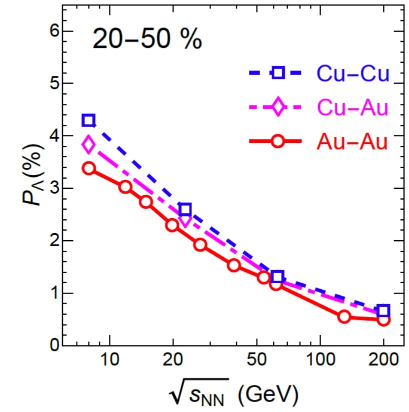
WHY SO?

Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

Prediction for Polarization in CuCu and AuAu



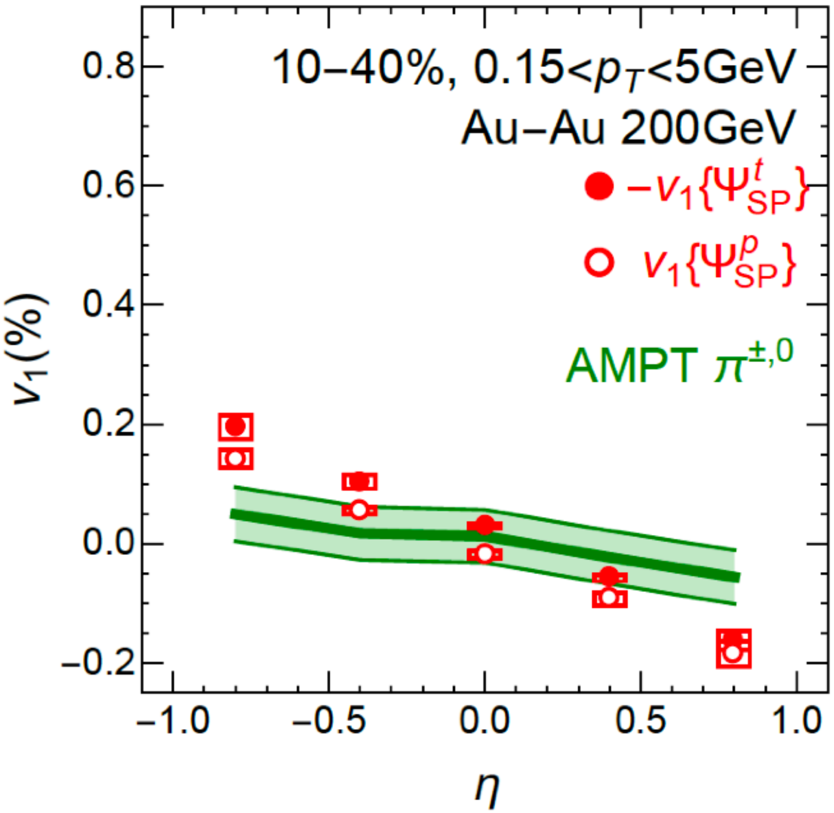


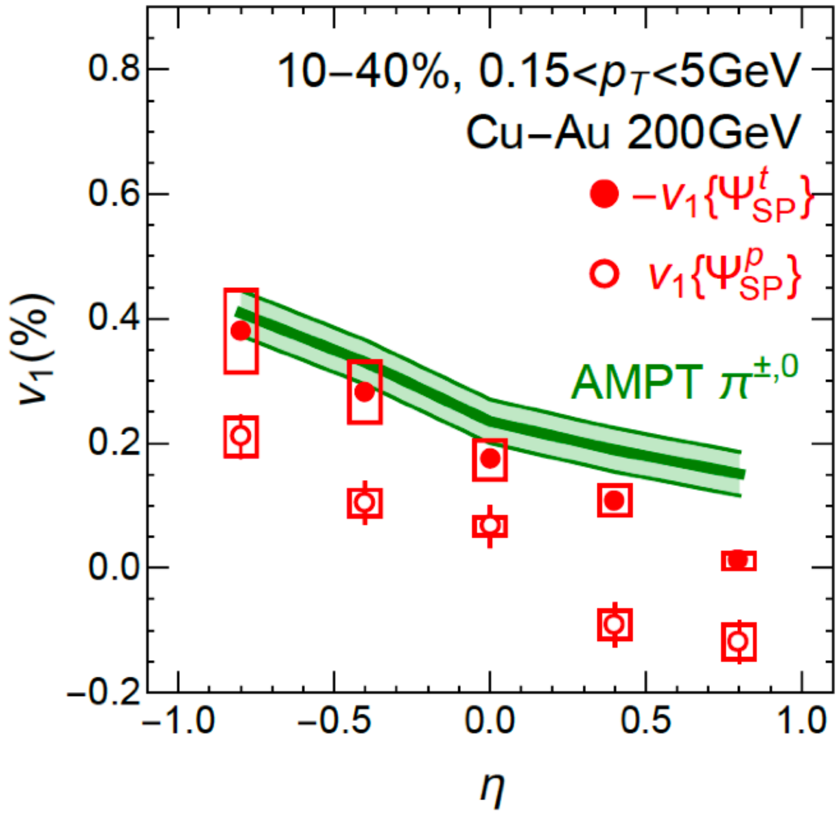


The hierarchy is due to an interesting interplay between vorticity time evolution and hyperon production timing!

Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

Directed Flow

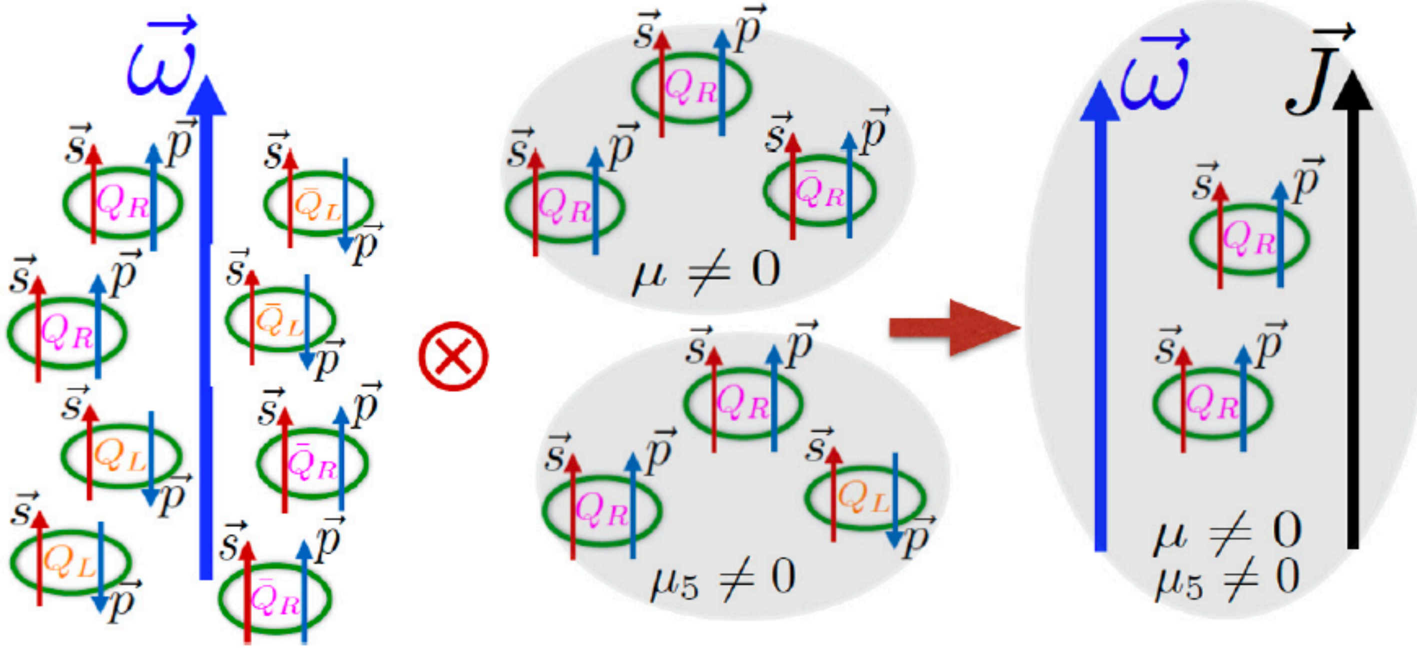




It is important to understand directed flow and vorticity simultaneously.

Anomalous Transport Under Rotation

Intuitive Picture of CVE



Intuitive understanding of CVE:

rotational polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

$\otimes$

Chiral imbalance —>
correlation between directions of
SPIN & MOMENTUM

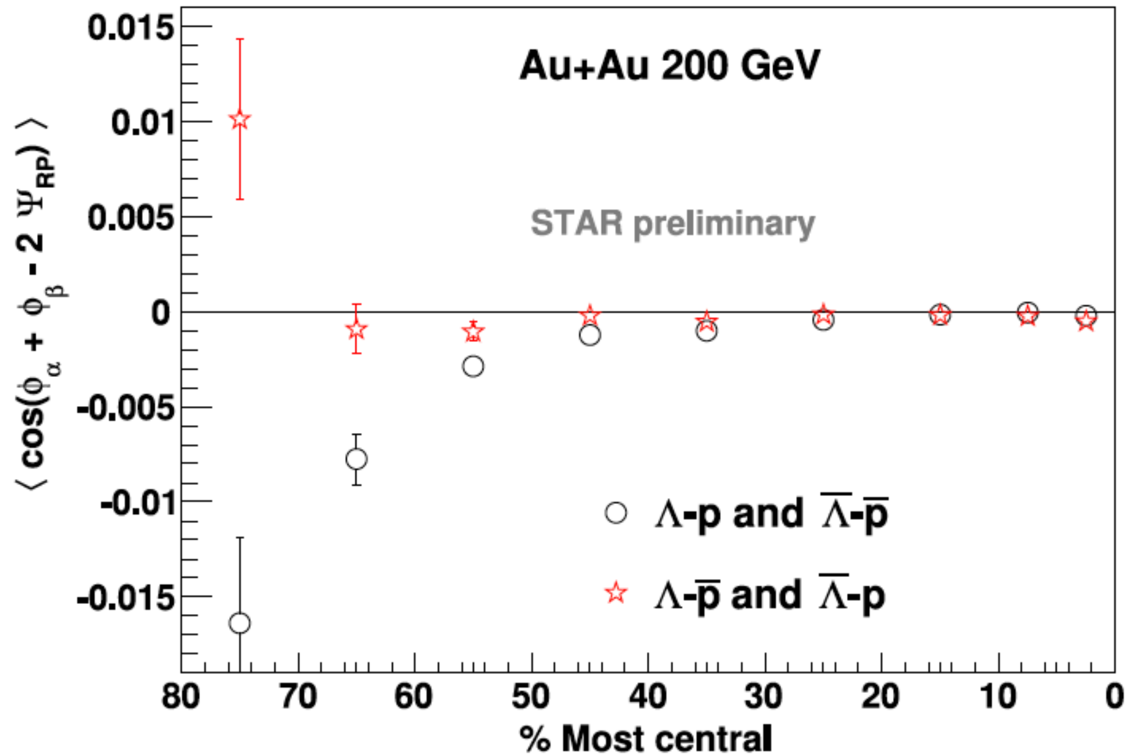
→ ***Current along fluid rotation axis!***

$$J_V = \frac{1}{\pi^2}\mu\mu_5\omega$$

Potential Signal of CVE

$$\vec{\mathbf{J}}_Q^{2f} = \frac{N_c \mu_5}{2\pi^2}\left[\frac{5}{9}(e\vec{\mathbf{B}}) + \frac{2}{9}(\mu_B \vec{\omega})\right]$$

$$\vec{\mathbf{J}}_B^{2f} = \frac{N_c \mu_5}{2\pi^2}\left[\frac{1}{9}(e\vec{\mathbf{B}}) + \frac{4}{9}(\mu_B \vec{\omega})\right]$$

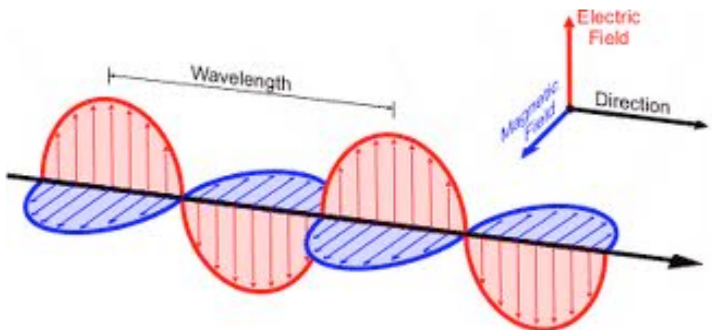


CVE —> Baryon separation across reaction plane.

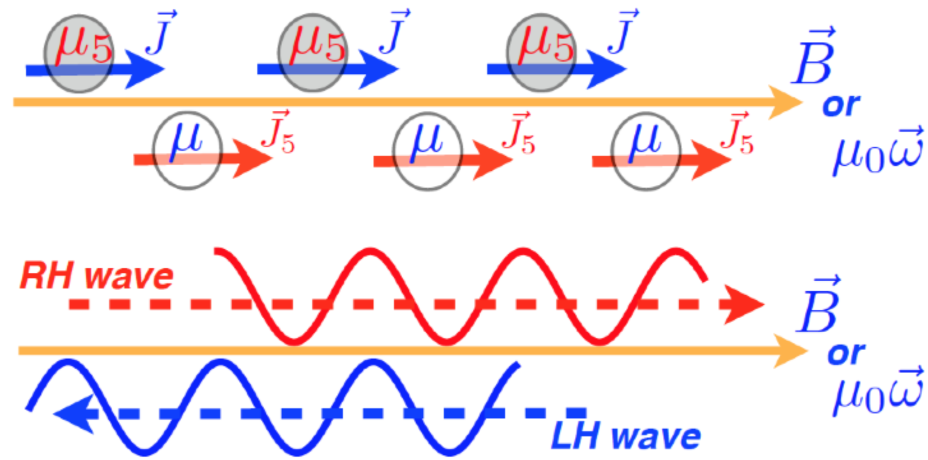
The lower beam energy collisions: better for CVE search!

Chiral Vortical Wave

Wave: propagating "oscillations" of two coupled quantities
e.g. sound wave (pressure & density); EM wave (E & B fields)



EM wave



Chiral Density Wave

Chiral Magnetic Wave

$$\left(\partial_0 \pm \frac{(Qe)}{(4\pi^2)\chi}\vec{\mathbf{B}}\cdot\nabla\right)\delta J^0_{R/L} = 0$$

[Kharzeev, Yee, PRD2010;
Burnier, Kharzeev, JL, Yee, PRL2011]

Chiral Vortical Wave

$$\left(\partial_0 \pm \frac{\mu_0}{(2\pi^2)\chi_{\mu_0}}\vec{\omega}\cdot\nabla\right)\delta J^0_{R/L} = 0$$

[Jiang, Huang, JL, arXiv:
1504.03201, PRD2015]

Exciting Progress: See Recent Reviews

Progress in Particle and Nuclear Physics 88 (2016) 1–28

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journal homepage: www.elsevier.com/locate/ppnp

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Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

CrossMark

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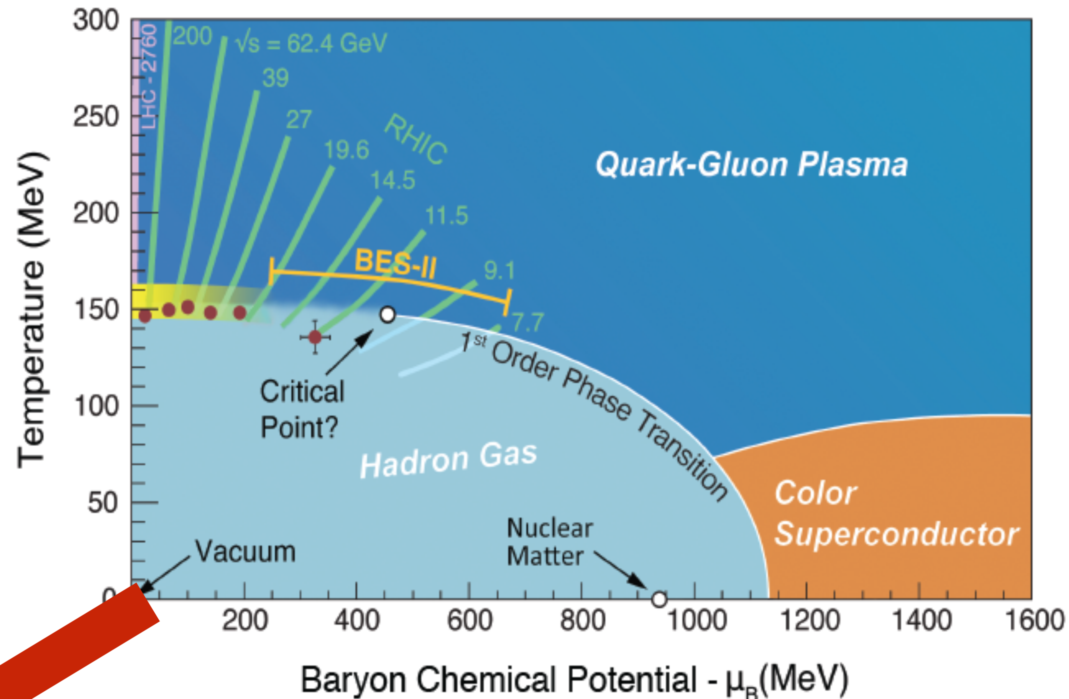
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

Phase Structure Under Rotation

New Dimensions of the Phase Diagram



Putting the strongly interaction matter under strong magnetic field or fluid rotation!

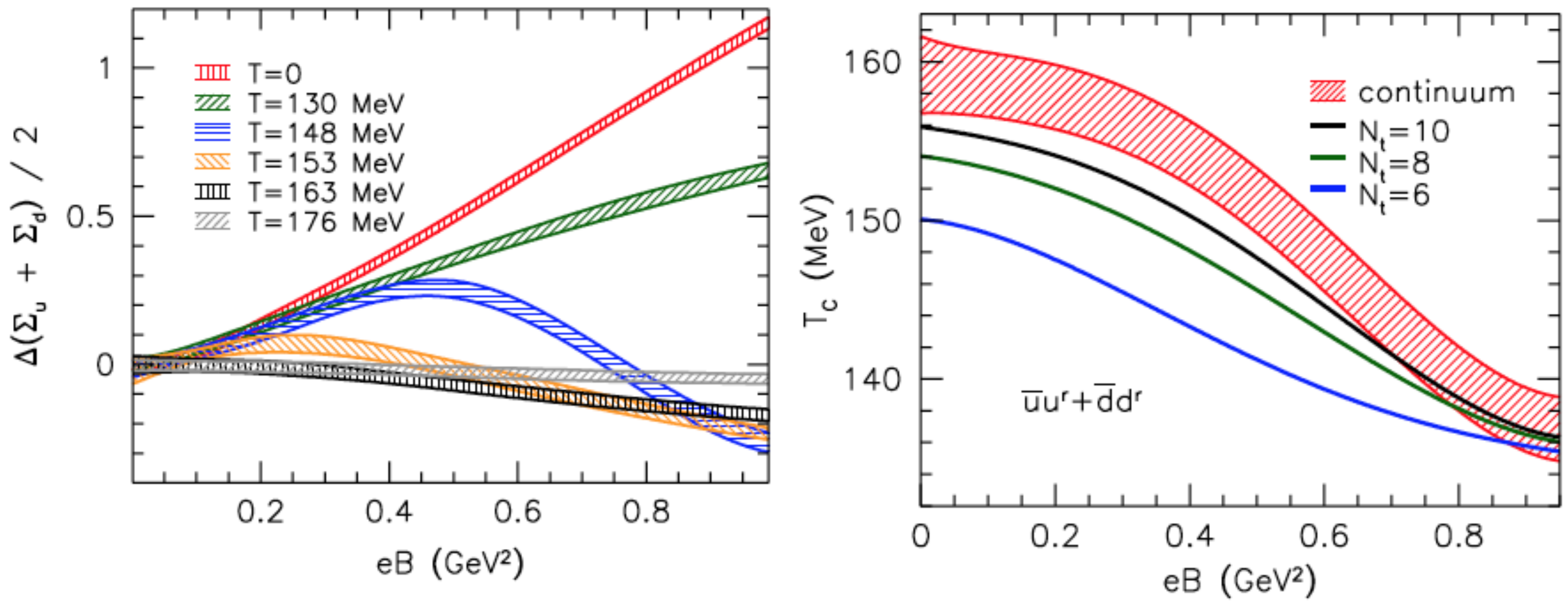
$\vec{\mathrm{B}}$

$\vec{\omega}$

Opening up new dimensions: Toward Hyper-Phase-Diagram!

Influence of Rotation on Phase Structure?

We know that magnetic fields can change the thermodynamic properties and phase structure of QCD matter.



[Lattice results by Bali, et al]

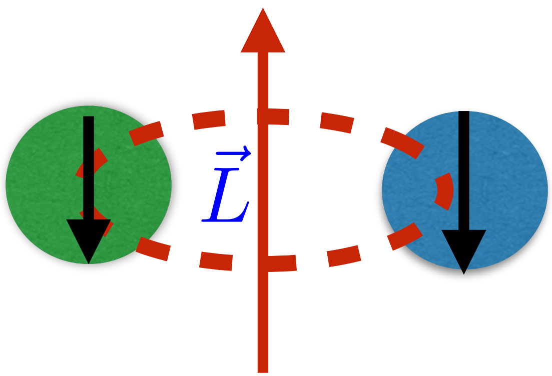
And we know the similarity between B field and rotation.
It is thus tempting to ask:
influence of rotation on phase structure?
[BTW: it could be studied on lattice,
c.f. Yamamoto & Hirono, 2013]

Rotational Suppression of Scalar Pairing

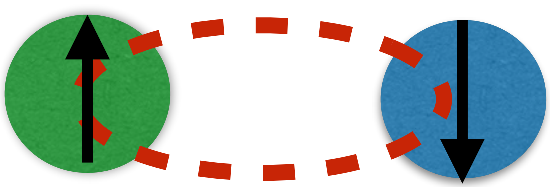
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

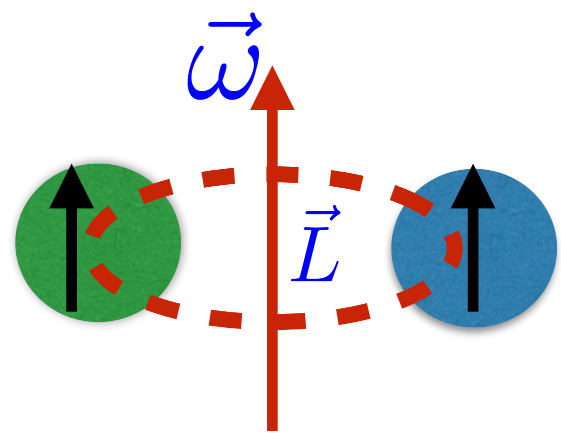
We consider scalar pairing state, with J=0.

$$\vec{S} = \vec{s}_1 + \vec{s}_2 \qquad \vec{J} = \vec{L} + \vec{S}$$



Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing.

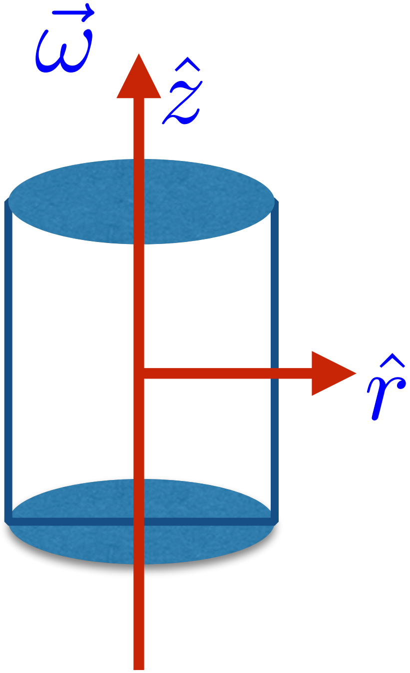




[Yin Jiang, JL, PRL2016;
See also: Chen, Fukushima, Huang, Mameda, arXiv:1512.08974]

Description of Slowly Rotating Fermion System

Eigenstates of free Hamiltonian: $\hat{H}, \hat{p}_z, \hat{\vec{p}}_t^2, \hat{J}_z, \hat{h}_t \equiv \gamma^5\gamma^3\vec{p}_t\cdot\vec{S}$



$$u_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}}e^{ik_z z}e^{in\theta}\begin{pmatrix} J_n(k_t r) \\ s\,e^{i\theta}J_{n+1}(k_t r) \\ \frac{k_z - is\,k_t}{E_k+m}J_n(k_t r) \\ \frac{-s\,k_z+ik_t}{E_k+m}e^{i\theta}J_{n+1}(k_t r)\end{pmatrix}$$

$$v_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}}e^{-ik_z z}e^{in\theta}\begin{pmatrix} \frac{k_z - is\,k_t}{E_k+m}J_n(k_t r) \\ \frac{s\,k_z-ik_t}{E_k+m}e^{i\theta}J_{n+1}(k_t r) \\ J_n(k_t r) \\ -s\,e^{i\theta}J_{n+1}(k_t r)\end{pmatrix}$$

Interaction: NJL type 4-fermion

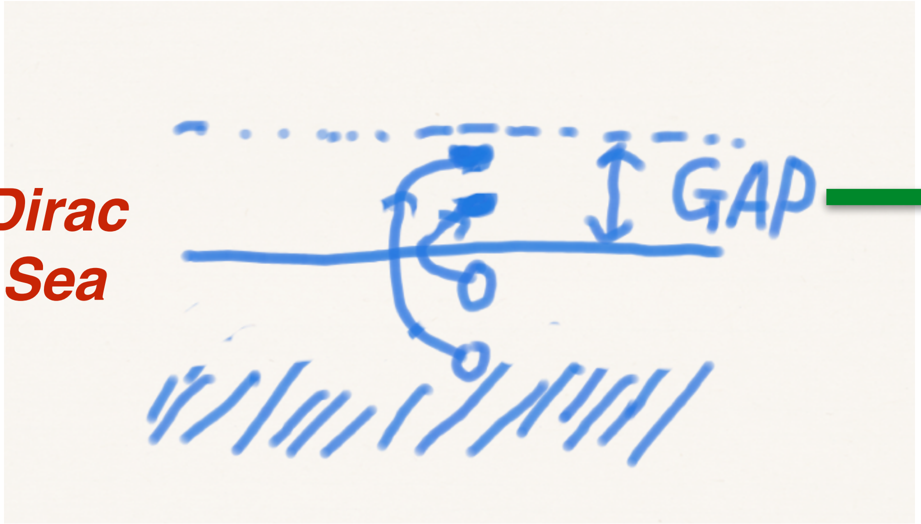
$$\mathcal{L}_{I_{eff}} = G(\bar{\psi}\psi)^2 + G_d(i\psi^T C\gamma^5\psi)(i\psi^\dagger C\gamma^5\psi^*)$$

widely used for studying fermion pairings

[Yin Jiang, JL, PRL2016.]

The Chiral Condensate: Q-bar-Q Pairing

Dirac Sea



Constituent mass — **Lagrangian (SM) mass**

$$M = m - 2G \langle \bar{\psi}\psi \rangle$$

Pairing states: L=1, S=1, and J=0

$$\Omega = \int d^3\vec{r} \Big\{ \frac{(M-m)^2}{4G} - \frac{1}{4\pi^2} \sum_n \int dk_t^2 \int dk_z \times \left[J_n(k_t r)^2 + J_n(k_t r)^2 \right] \times T \Big[\ln\left(1 + e^{(\epsilon_n - \mu)/T}\right) + \ln\left(1 + e^{-(\epsilon_n - \mu)/T}\right) + \ln\left(1 + e^{(\epsilon_n + \mu)/T}\right) + \ln\left(1 + e^{-(\epsilon_n + \mu)/T}\right) \Big] \Big\}$$

$$\epsilon_n = \sqrt{k_z^2 + k_t^2 + M^2} - (n + \tfrac{1}{2})\omega$$

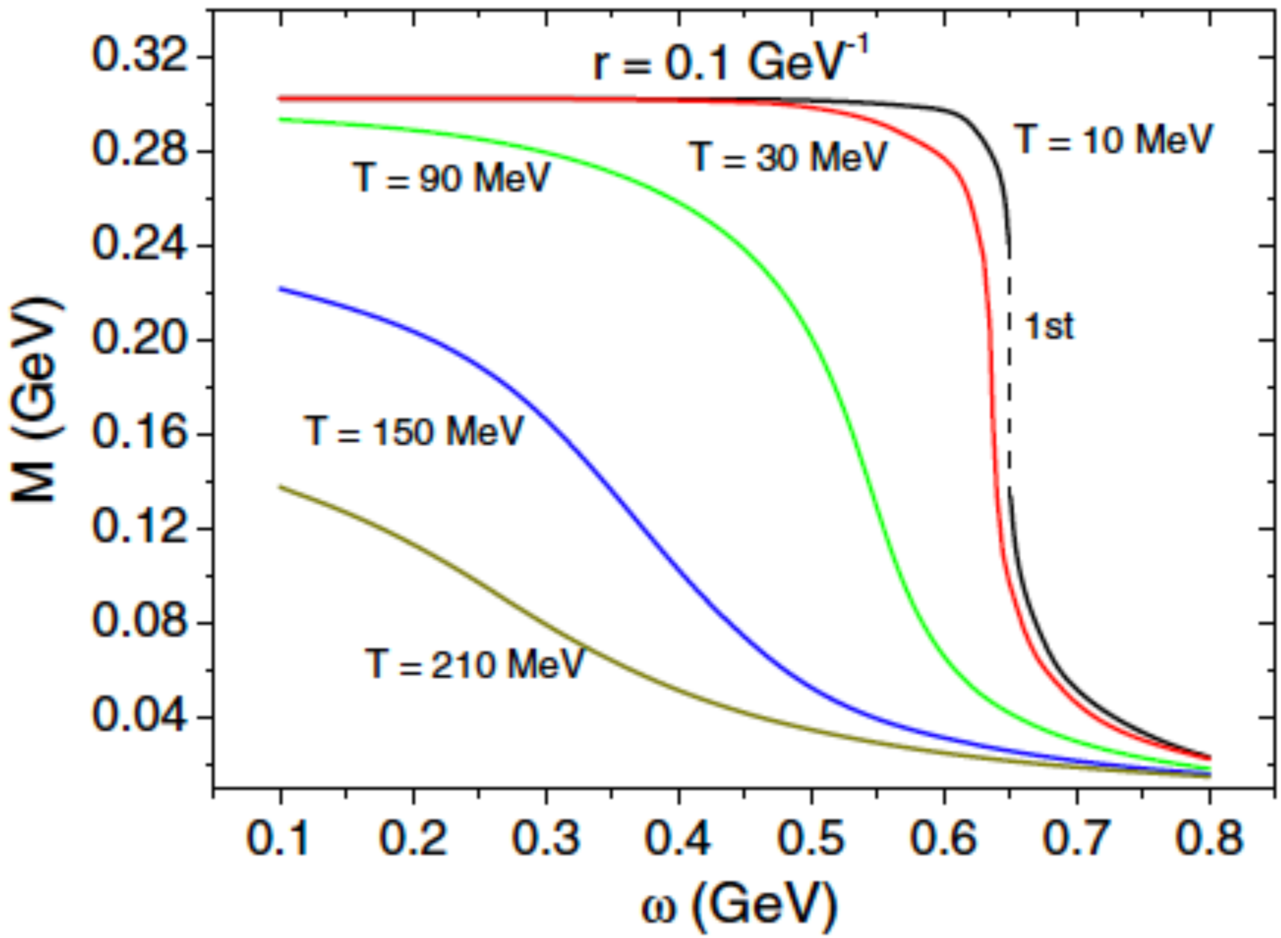
Gap equation:

$$\frac{\delta \Omega}{\delta M(r)} = 0$$

$$\frac{\delta^2 \Omega}{\delta M(r)^2} > 0$$

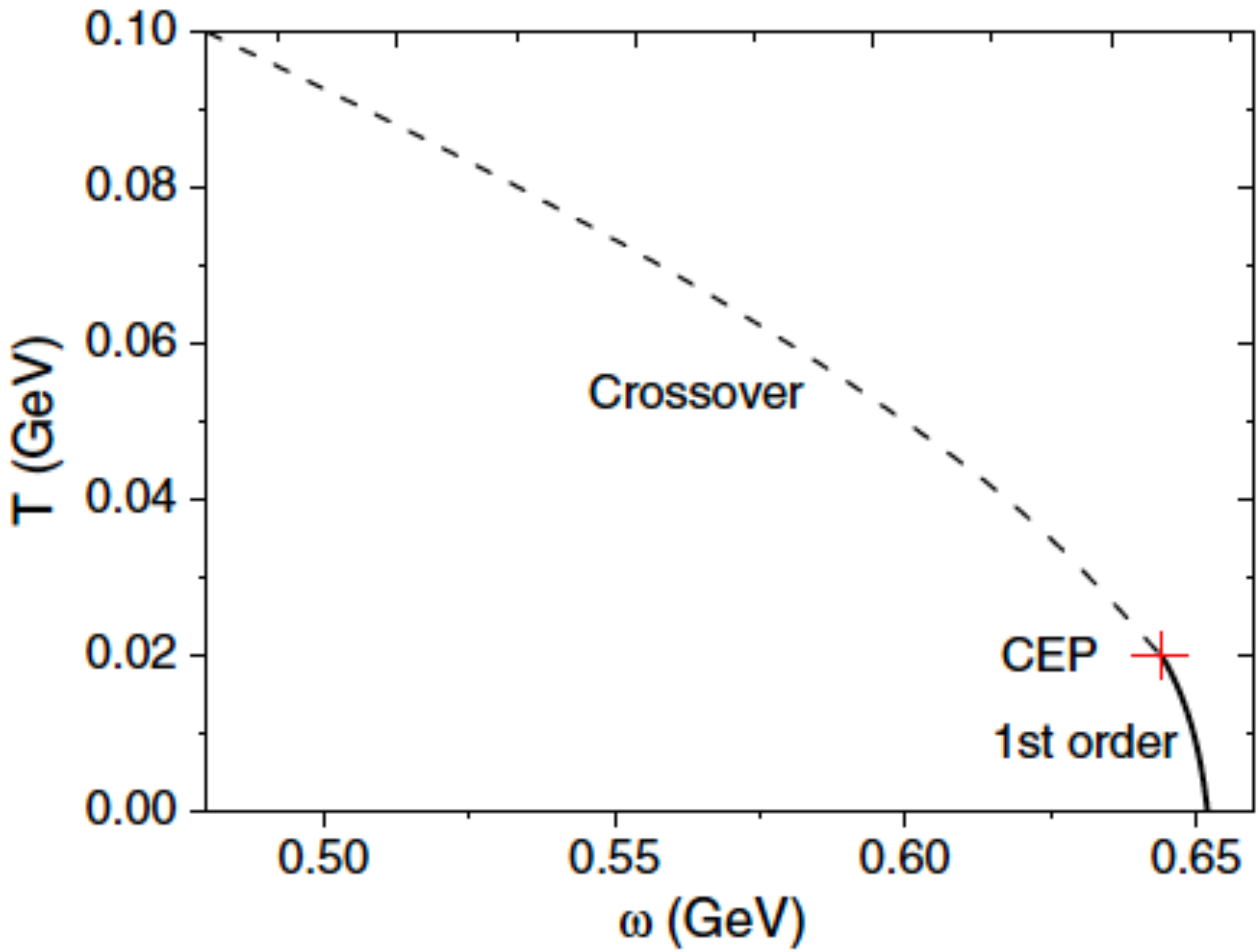
[Yin Jiang, JL, PRL2016.]

Rotational Suppression of Scalar Pairing



[Yin Jiang, JL, PRL2016.]

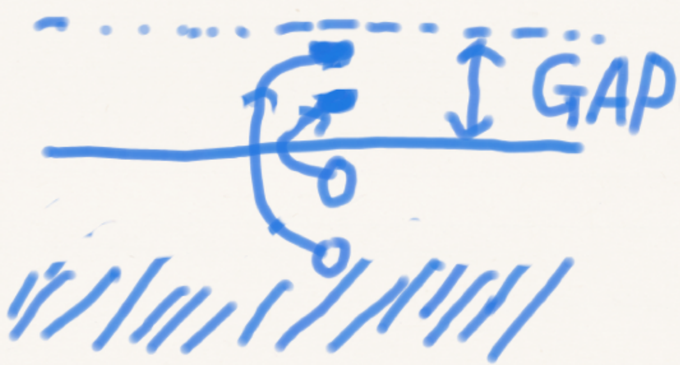
A Possible New Critical Point



[Yin Jiang, JL, PRL2016.]

The Diquark Condensate: Q-Q Pairing

Fermi Sea



Color superconductivity:

$$\Delta = -2G_d \langle i\psi^T C \gamma^5 \psi \rangle$$

Pairing states:
L=0, S=0, and J=0

$$\epsilon_n^{\Delta\pm} = [(\sqrt{k_z^2 + k_t^2 + m^2} \pm \mu)^2 + \Delta^2]^{\frac{1}{2}} - (n + \tfrac{1}{2})\omega$$

$$\begin{aligned}\Omega \;=\; & \int d^3\vec{r} \Big\{ \frac{\Delta^2}{4G_d} - \frac{1}{4\pi^2} \sum_n \int dk_t^2 \int dk_z \\ & \times \quad [J_n(k_t r)^2 + J_n(k_t r)^2] \\ & \times T \Big[\ln\left(1 + e^{\epsilon_n^{\Delta+}/T}\right) + \ln\left(1 + e^{-\epsilon_n^{\Delta+}/T}\right) \\ & + \ln\left(1 + e^{\epsilon_n^{\Delta-}/T}\right) + \ln\left(1 + e^{-\epsilon_n^{\Delta-}/T}\right) \Big] \Big\}\end{aligned}$$

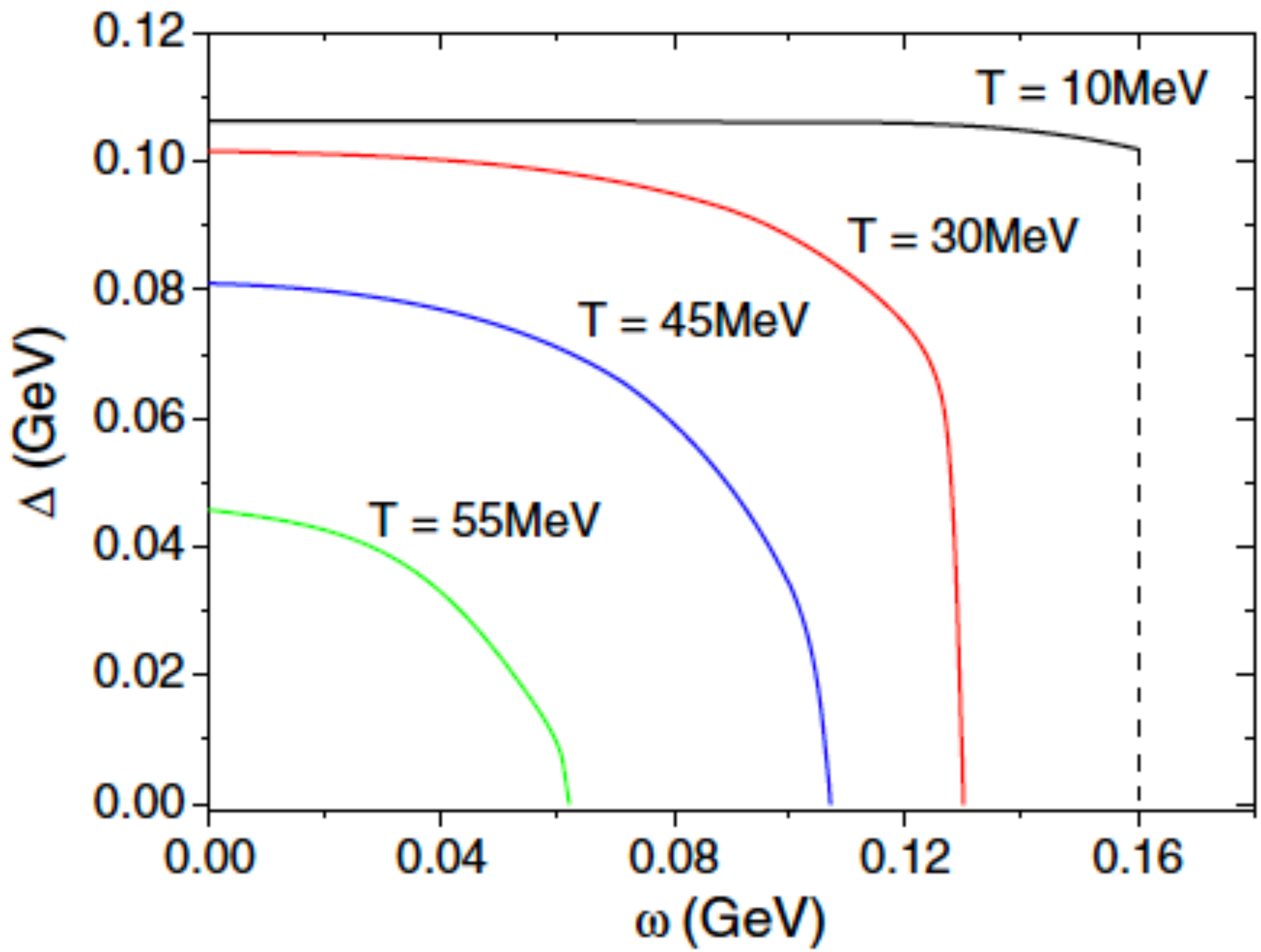
Gap equation:

$$\frac{\delta\Omega}{\delta\Delta(r)} = 0$$

$$\frac{\delta^2\Omega}{\delta\Delta(r)^2} > 0$$

[Yin Jiang, JL, to appear.]

Rotational Suppression of Scalar Pairing



[Yin Jiang, JL, PRL2016.]

Summary & Outlook

Summary & Outlook

Properties of strongly interacting matter under rotation are interesting.

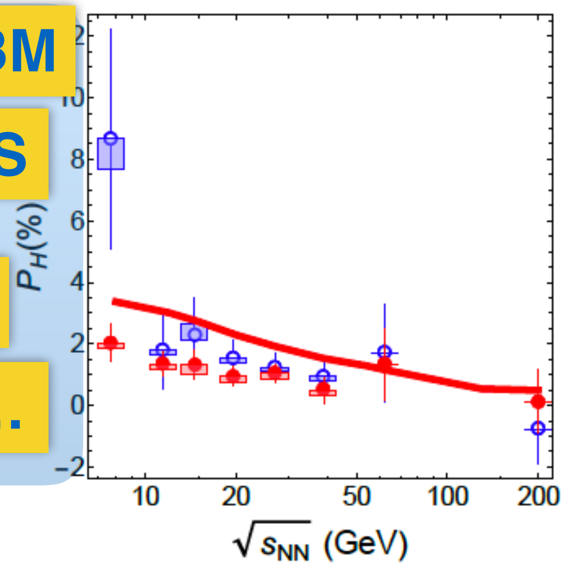
Rotation leads to rotational polarization: particle polarization; chiral vortical effects; change of phase structures; …

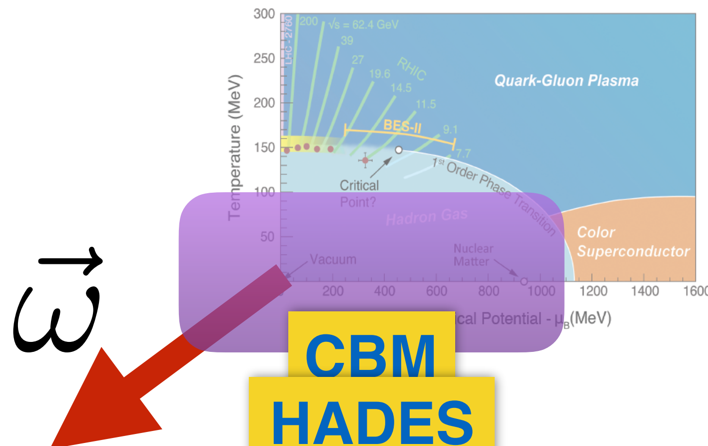
CBM

HADES

CEE

……





CBM

HADES

CEE

……

Exploring rotating QCD matter at low beam energy heavy ion collisions!