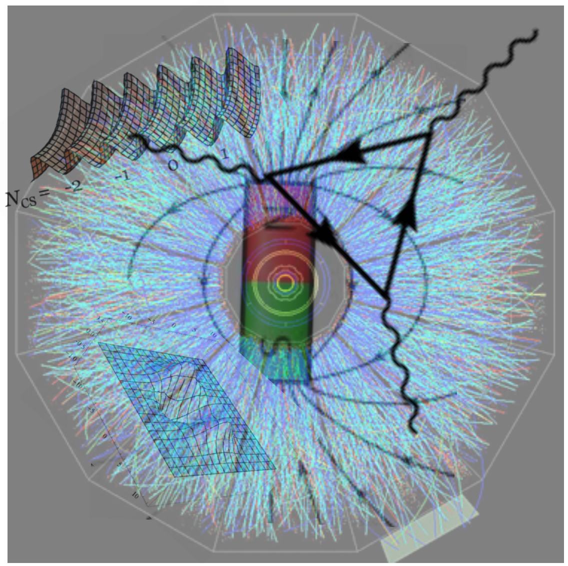
4th CBM-China @ Yichang *Apr. 12~14, 2019*

Vorticity and Magnetic Fields in Collisions at BES/FAIR/NICA Energies



Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Outline

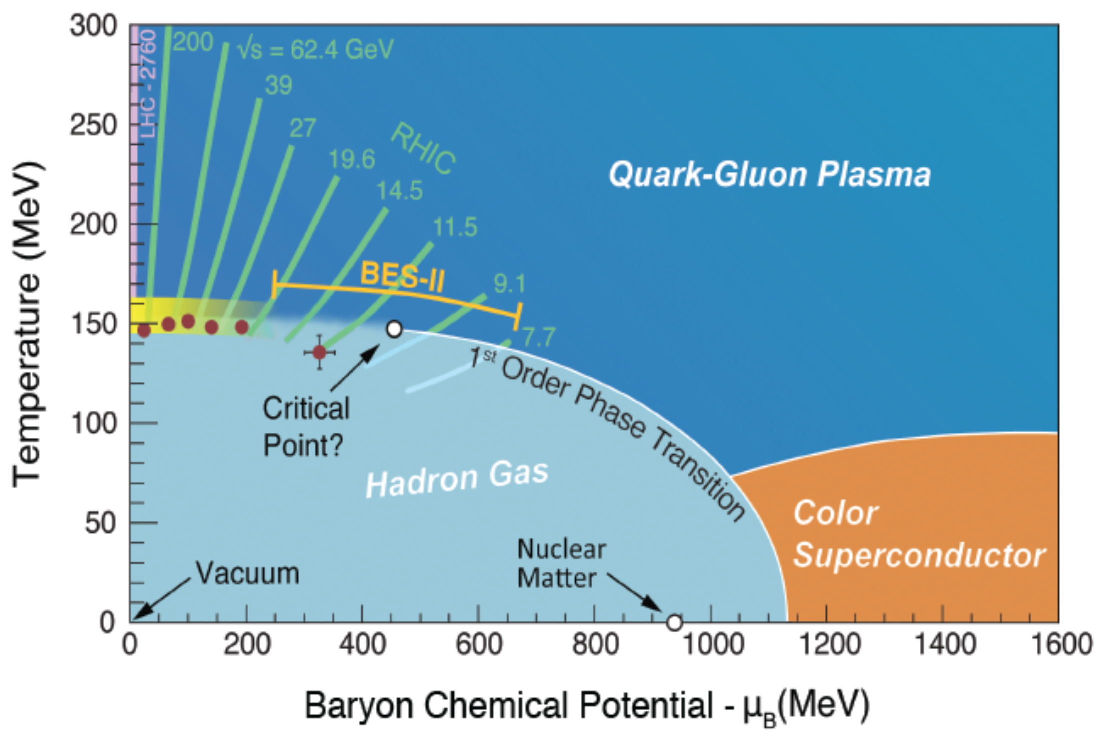
- *Brief Introduction*
- *Vorticity and Spin Polarization*
- *Magnetic Field at Low Collision Energy*
- *Discussions & Outlook*

INT Program 2020

Chirality and Criticality:
Novel Phenomena in Heavy Ion Collisions

May 11 — June 5, 2020

Organizers: J. Liao, M. Stephanov, H.-U. Yee, Z. Xu



An Upcoming Review

Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan

Adam Bzdak[a], ShinIchi Esumi[b], Volker Koch[c], Jinfeng Liao[d,f], Mikail Stephanov[e], Nu Xu[f,c]

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[d]Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[e]Physics Department, University of Illinois at Chicago, W. Taylor St., Chicago IL 60607-7059, USA
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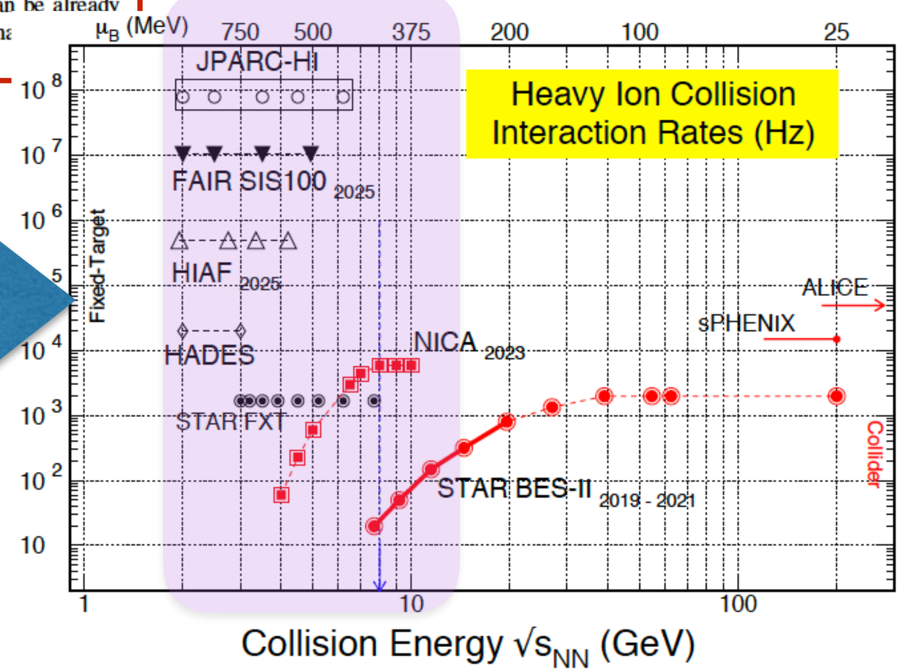
Abstract

We review the present status of the search for a QCD phase transition and critical point, as well as anomalous transport phenomena with an emphasis on the Beam Energy Scan program at the relativistic heavy ion collider at Brookhaven National Laboratory. We present the conceptual framework and discuss the observables deemed most sensitive to a phase transition, QCD critical point, and anomalous transport focusing on fluctuation and correlation measurements. The presently available experimental results for these observables together with those characterizing the global properties of the systems created in heavy ion collisions will be presented. We will then discuss what can be already learned from the presently available data about the QCD critical point and anomalous transport and wha[…] measurements and theoretical developments are needed in order to discover these phenomena.

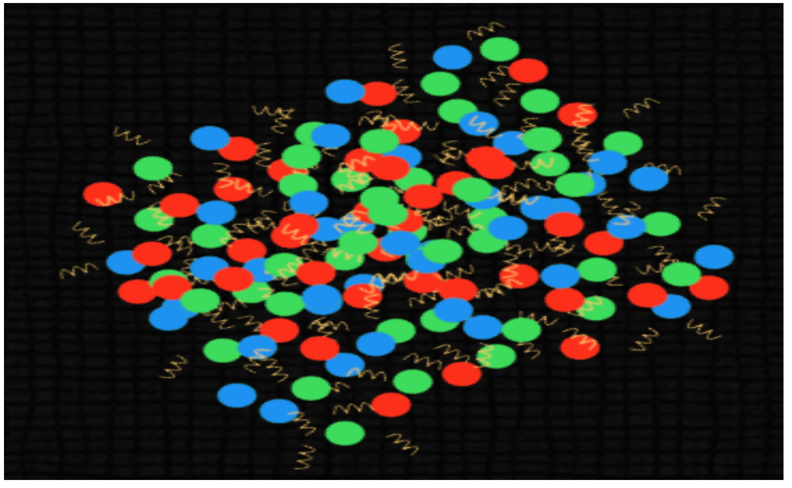


Future of nuclear collisions: high baryon density region!

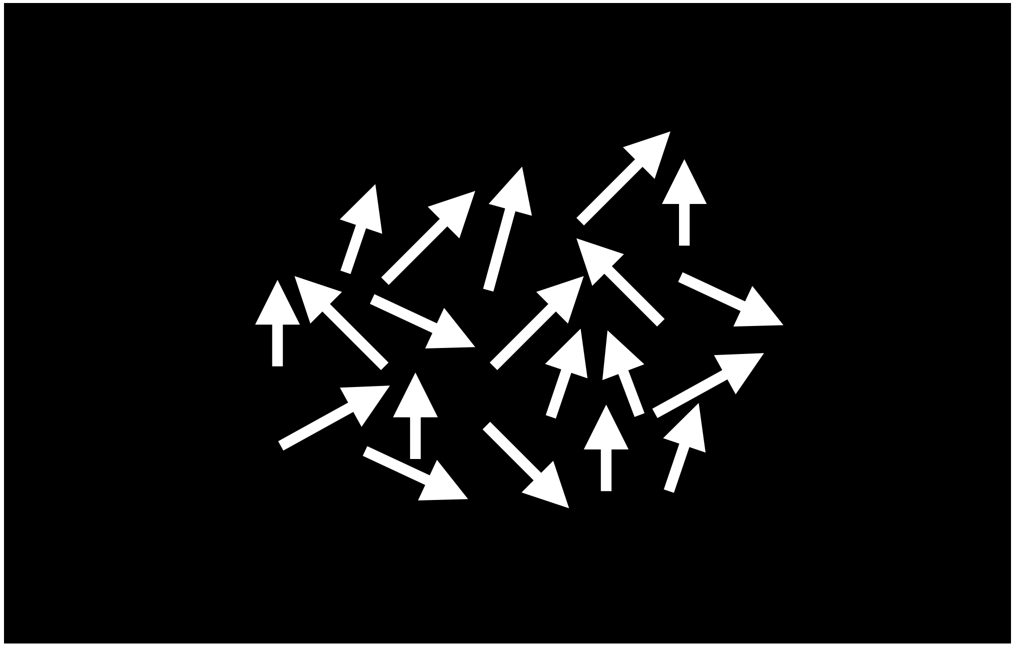
Introduction

A Fluid of Spin

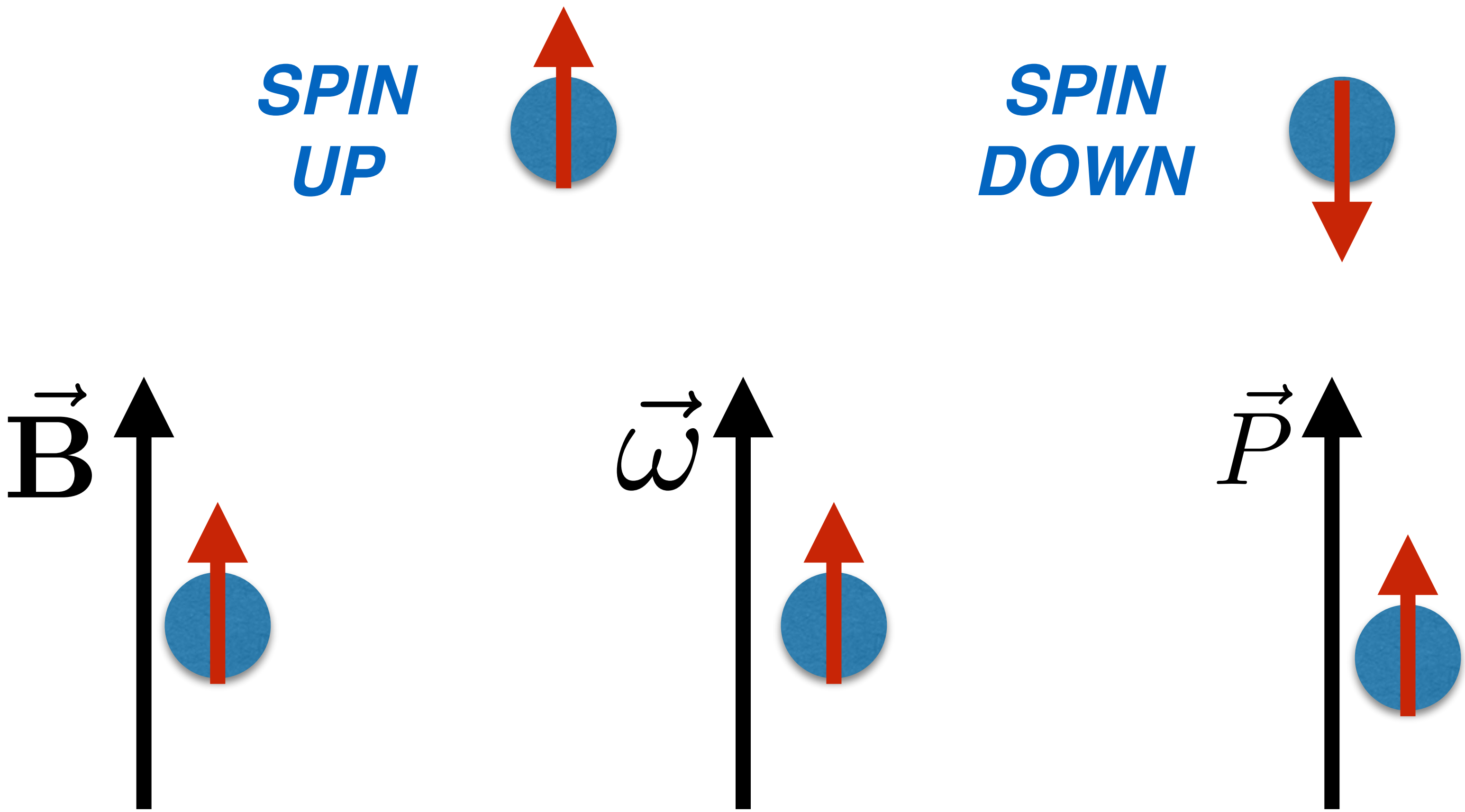
A nearly perfect fluid



What happens to the spin DoF in the fluid???



Manipulating the Spin



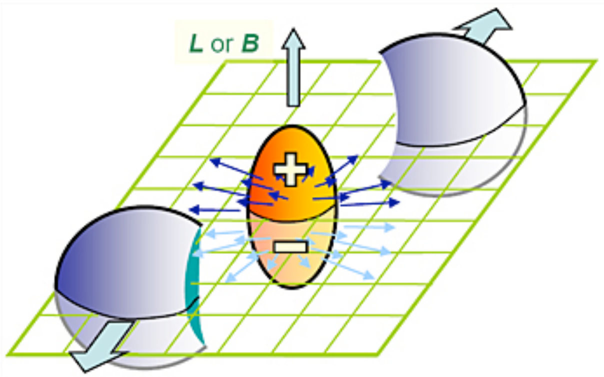
Magnetic Polarization

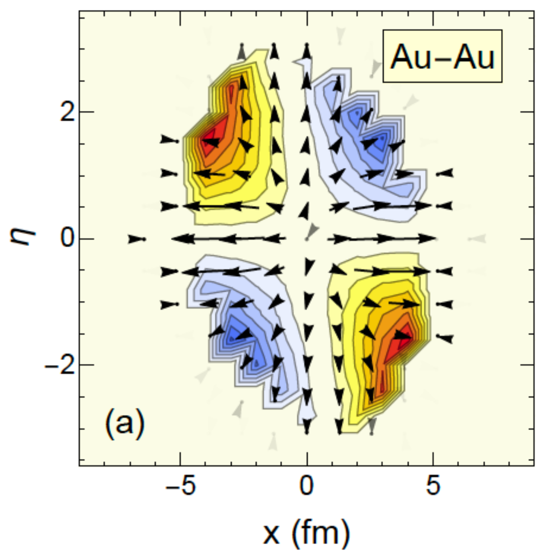
Rotational Polarization

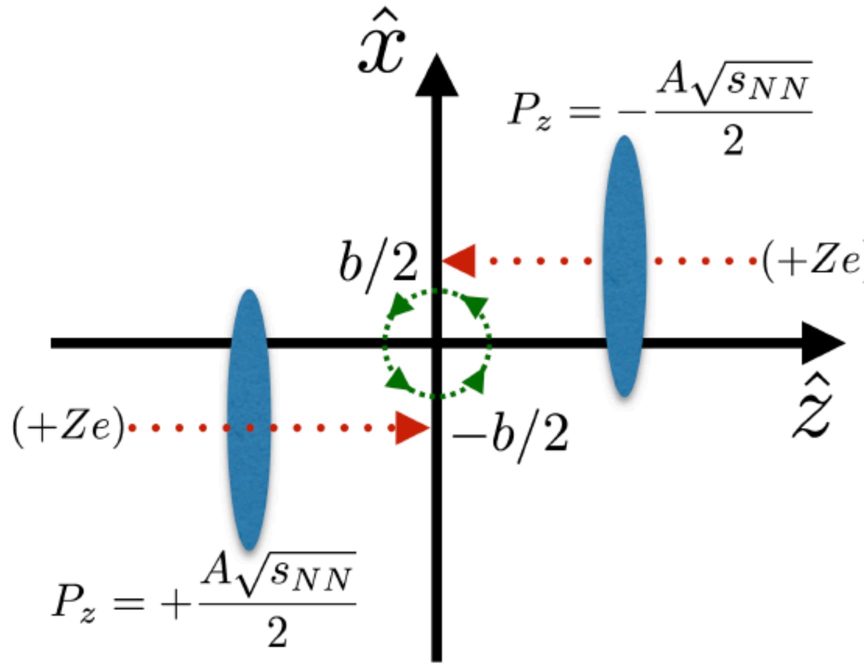
Chirality Polarization

Interesting interplay —> highly nontrivial phenomena!

Extreme Vorticity & EM Fields



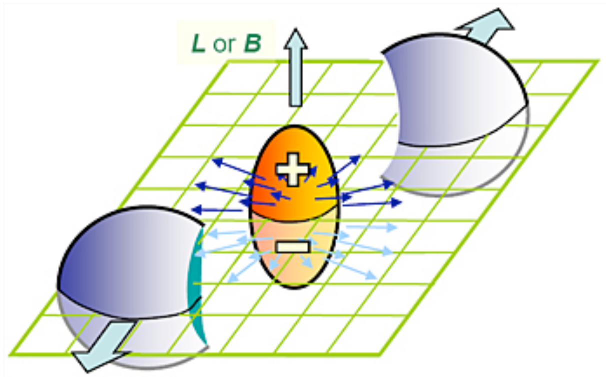


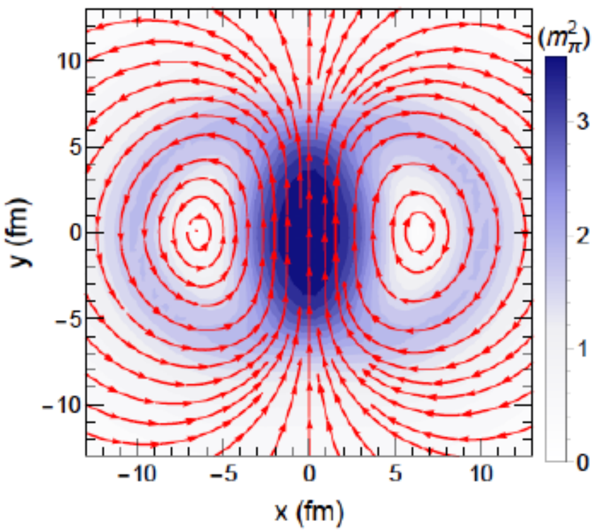


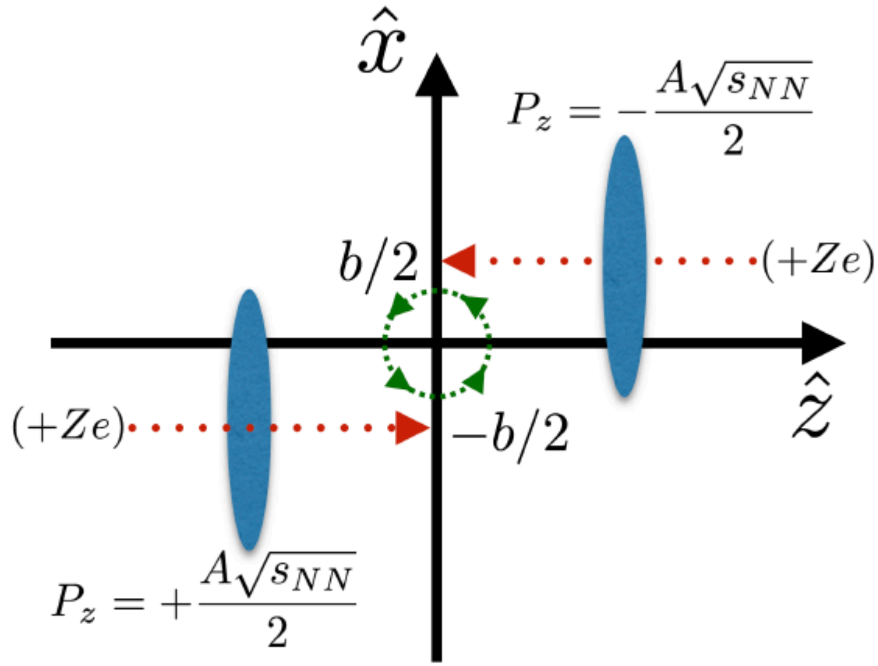
$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

Large angular momentum —> the most vortical fluid

Extreme Vorticity & EM Fields



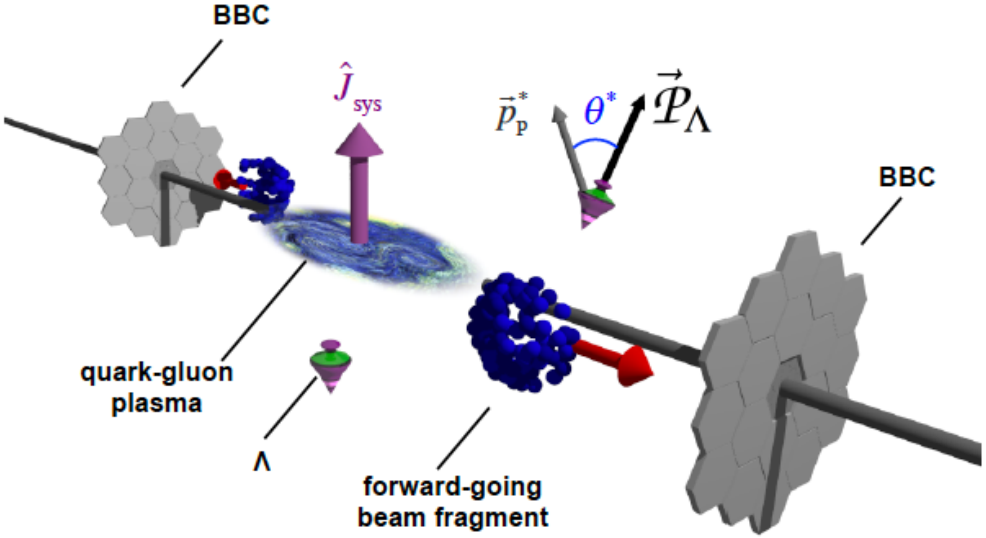


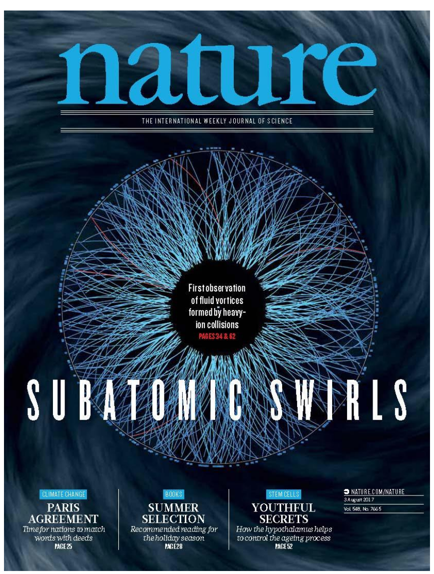


$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

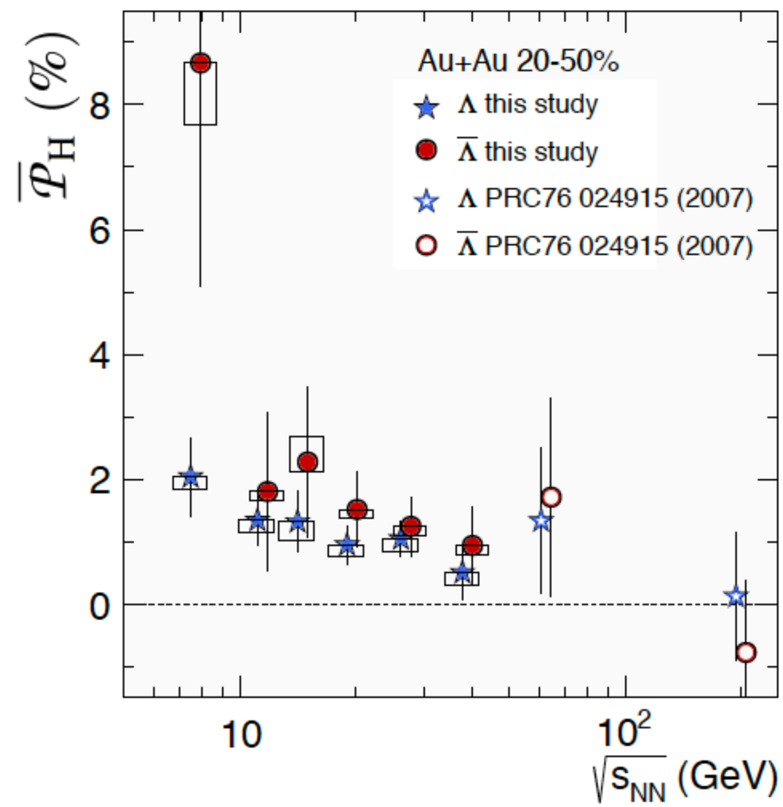
The angular momentum together with large (+Ze) nuclear charge —> the strongest magnetic field!

Novel Phenomena: “Fluid Spintronics”



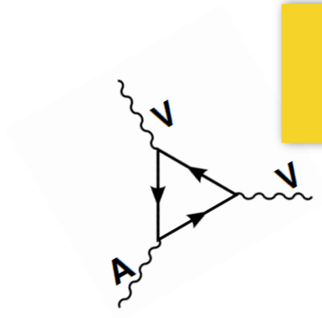


Rotation-induced Spin Polarization

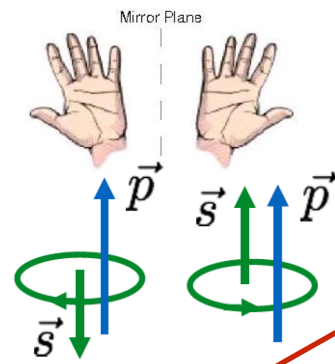


STAR Collaboration, Nature 2017

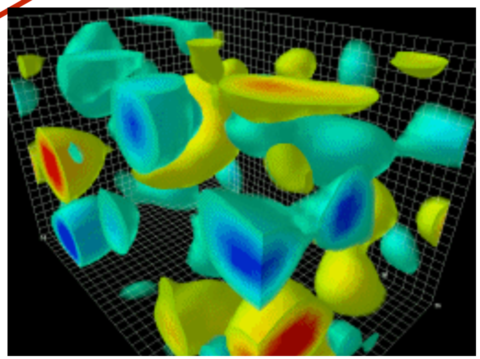
Chiral Magnetic Effect (CME)



Chirality & Anomaly



Chirality & Topology



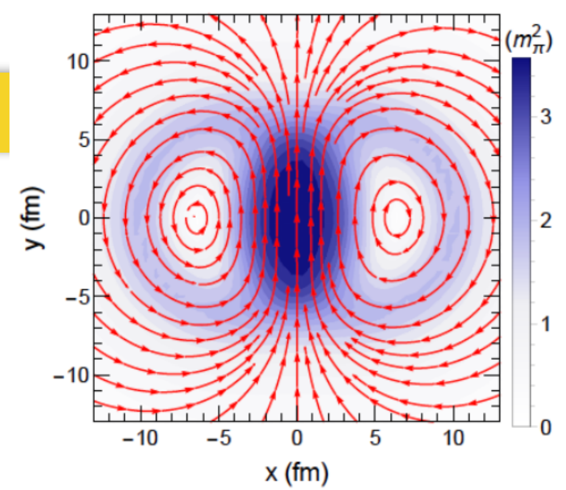
$$N_R - N_L = N_5 = 2Q_w$$

$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Anomalous Electric Current

Q.M. Transport

Magnetic Field

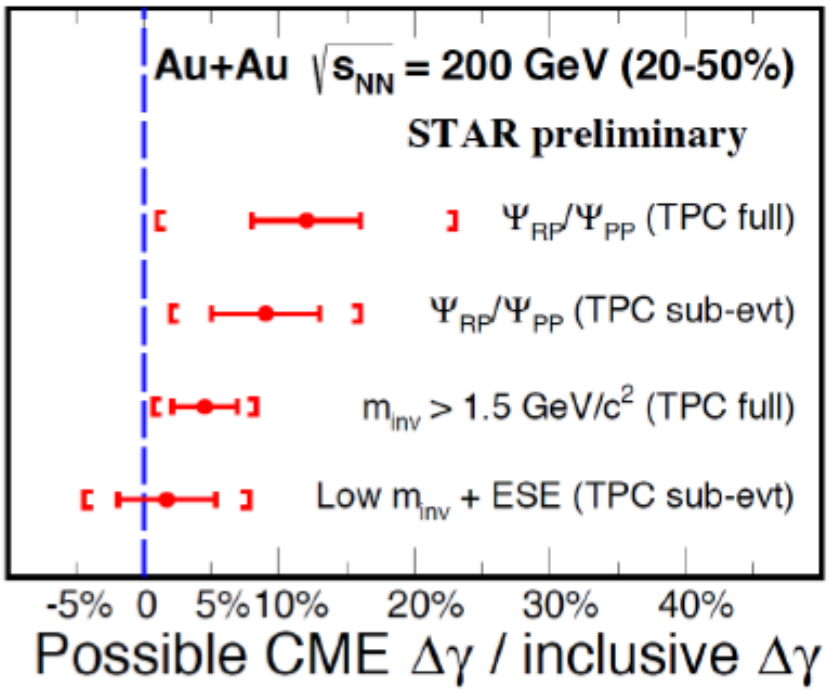


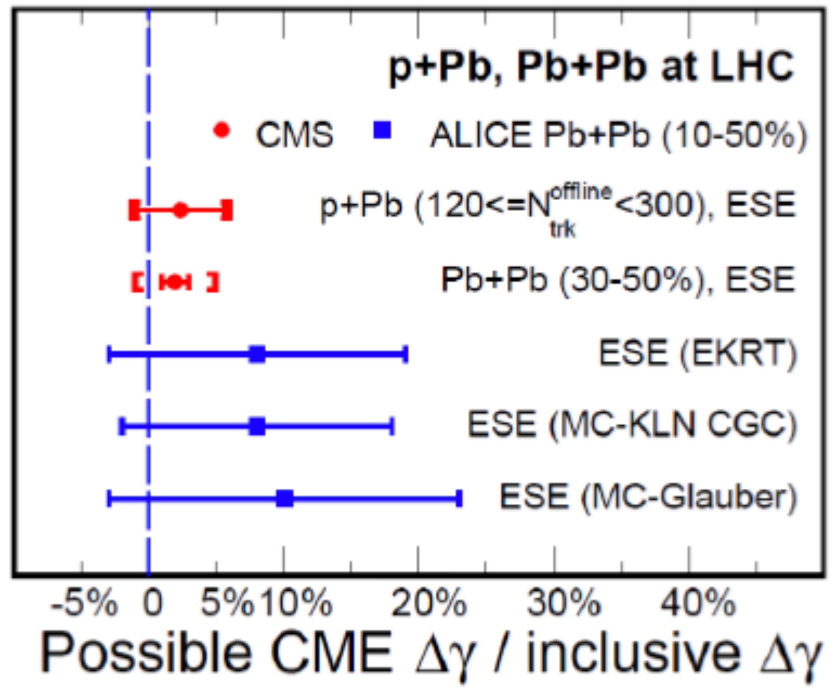
CME <—> macroscopic chiral anomaly

CME: a new type of (quantum) electricity

Exp. Search for CME

Most measurements based on:
gamma correlator + certain procedure to fight backgrounds

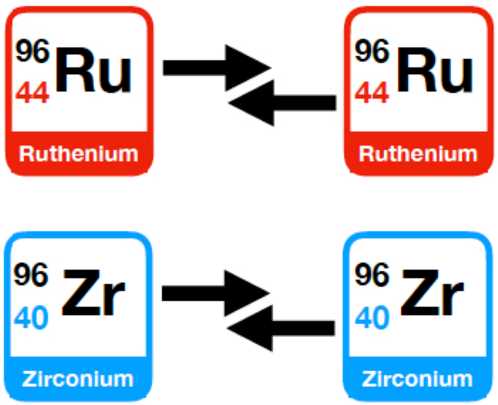




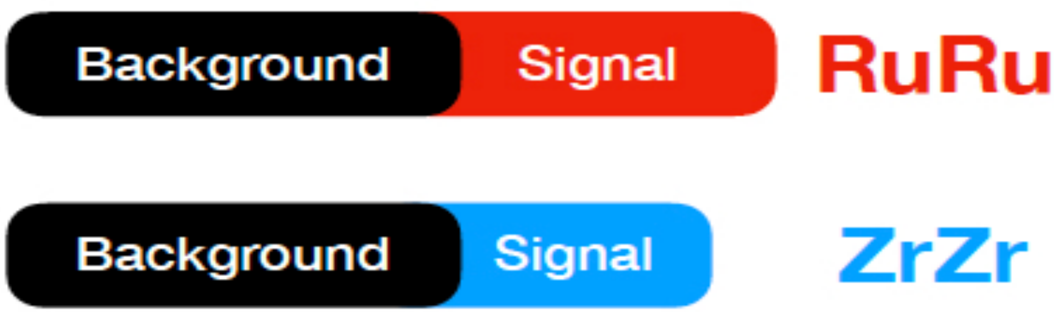
Slide from Fuqiang Wang @ Chirality 2019

Isobaric Collisions @ RHIC

New opportunity of potential discovery: Isobaric Collision @ RHIC

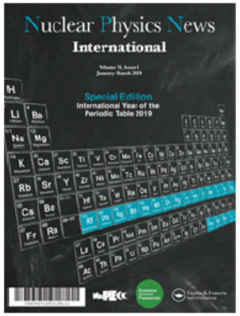


Charge Asymmetry Correlation Measurement



~2 billion data collected successfully in RHIC 2018 run; processing and analysis underway!

Real Near-Term Opportunity: Isobaric Collisions



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Nuclear Physics News

ISSN: 1061-9127 (Print) 1931-7336 (Online) Journal homepage: https://www.tandfonline.com/loi/gnpn20

feature article

Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

D. E. Kharzeev[1,2] and J. Liao[3]

versus the background level (horizontal axis). One expects that a 5 σ observation of the local parity violation will be possible if the background contributes less than two thirds of the measured correlation.

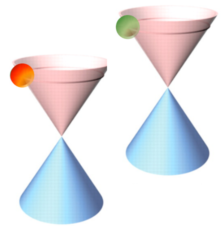
This decisive experiment for the search of CME had just begun in the spring 2018 RHIC run. If a conclusive observation of CME is achieved, it would amount to the experimental discovery of the restoration of chiral symmetry in hot QCD matter and to the first direct experimental observation of the topological fluctuations in QCD. We will be holding our breath awaiting the outcome of this ground-breaking experiment.

D. E. Kharzeev

J. Liao

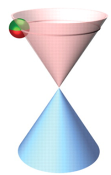
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

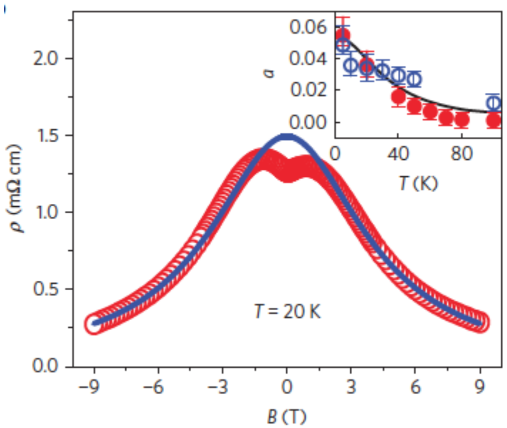


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



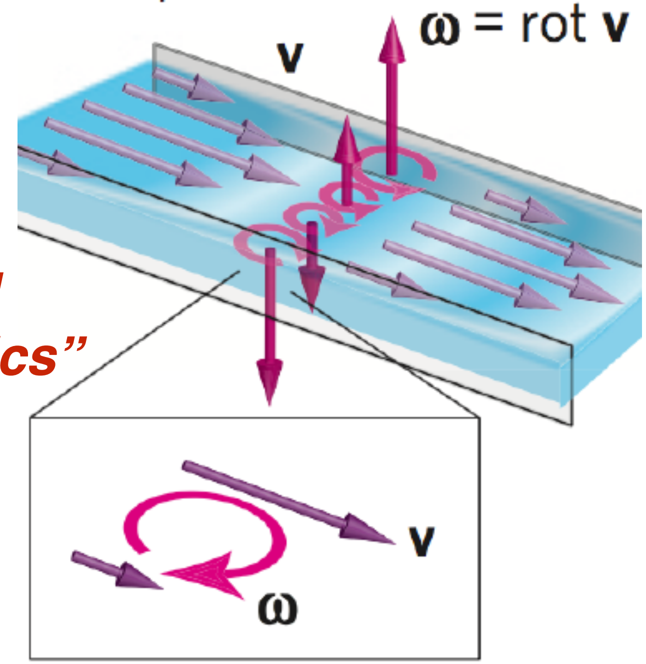
nature physics
LETTERS
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

Chiral magnetic effect in $ZrTe_5$

Qiang Li[1]*, Dmitri E. Kharzeev[2,3]*, Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1]*

"Spin hydrodynamic generation"
Takahashi, *et al*. Nat. Phys. (2016)

Liquid flow



"Fluid Spintronics"

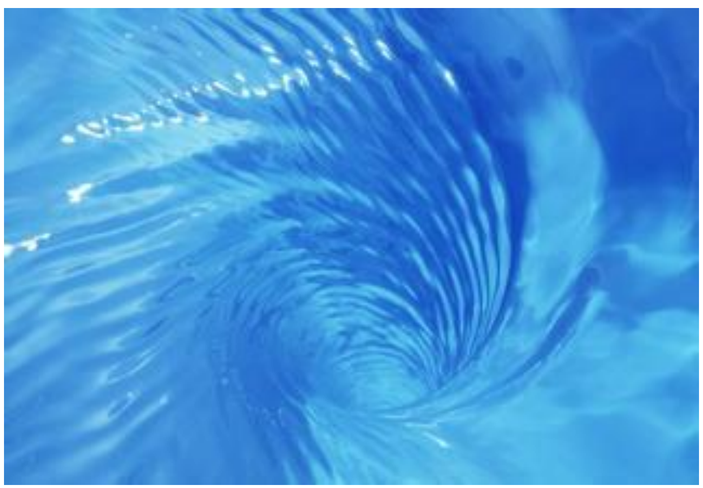
Condensed matter, cold atomic gases, neutron stars, cosmology, plasma physics, etc

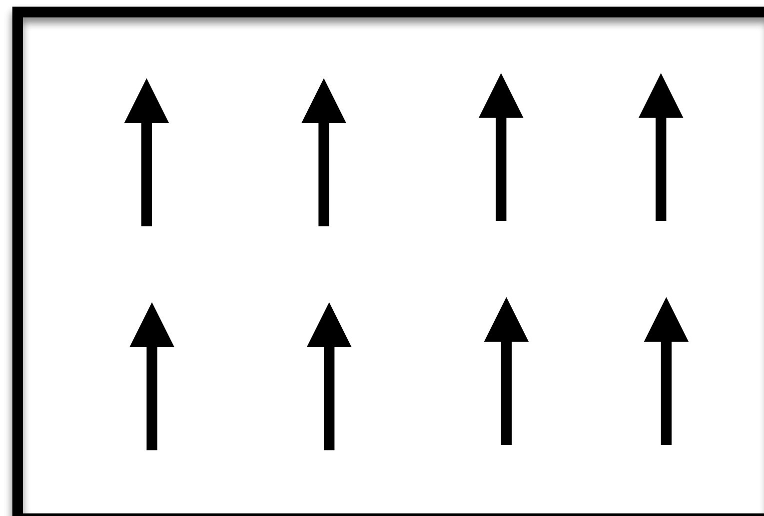
Vorticity & Spin Polarization

Fluid with Angular Momentum

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

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





Fluid vorticity

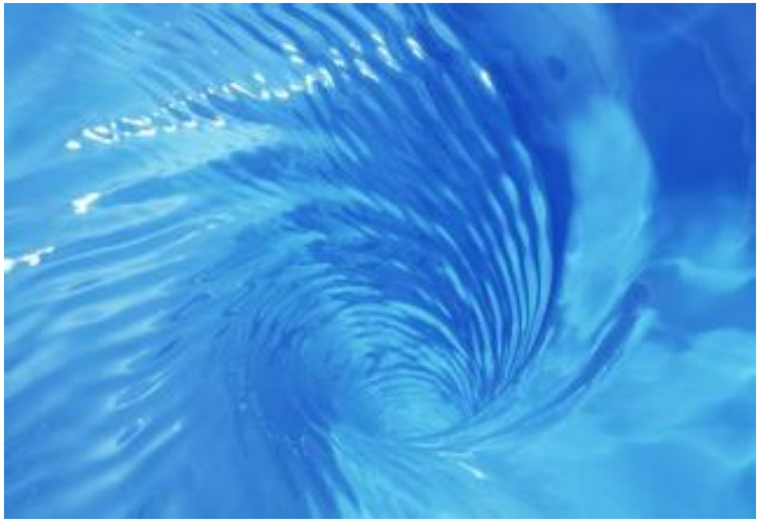
???

Individual spin

Macroscopic

Microscopic

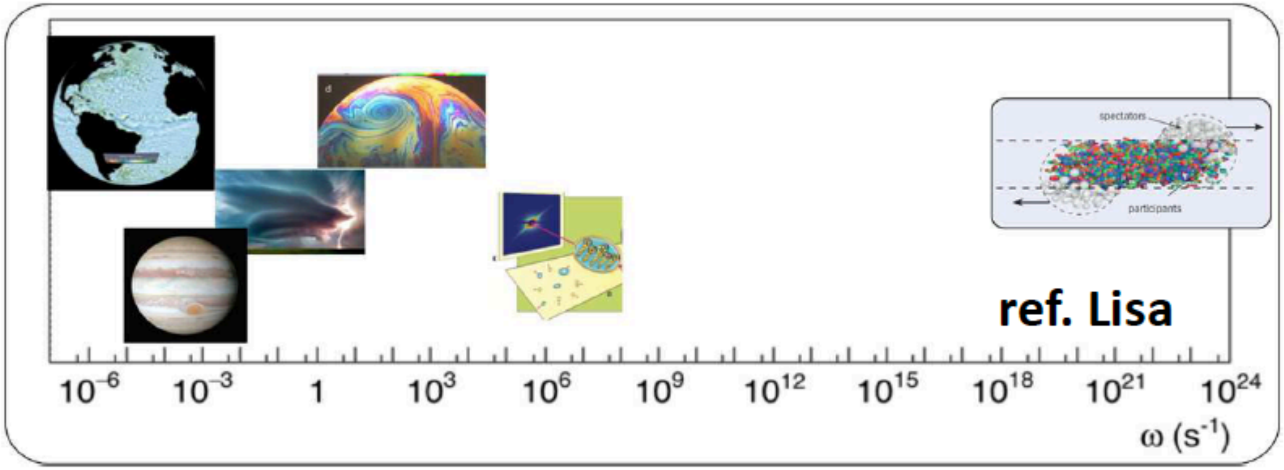
Quantifying Fluid Rotation



$$\vec{\mathbf{v}}$$

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

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



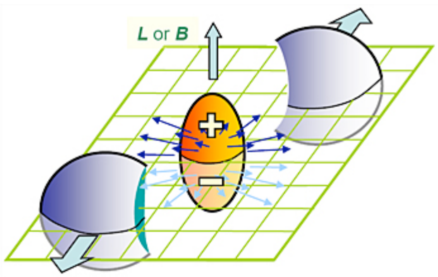
Heavy ion collisions:

$v \sim 0.1\,c$

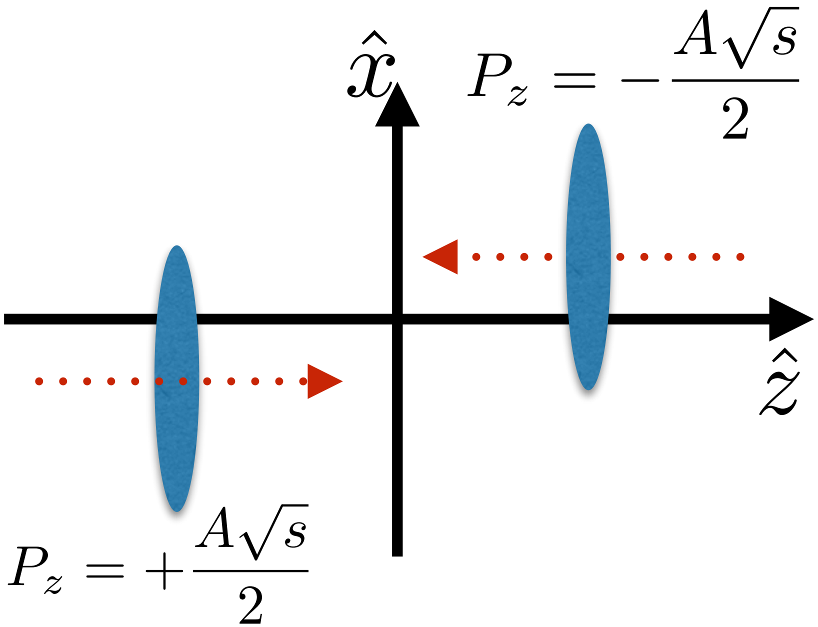
$\partial \sim \mathrm{fm}^{-1}$

$\omega \sim 10^{22}\,\mathrm{s}^{-1}$

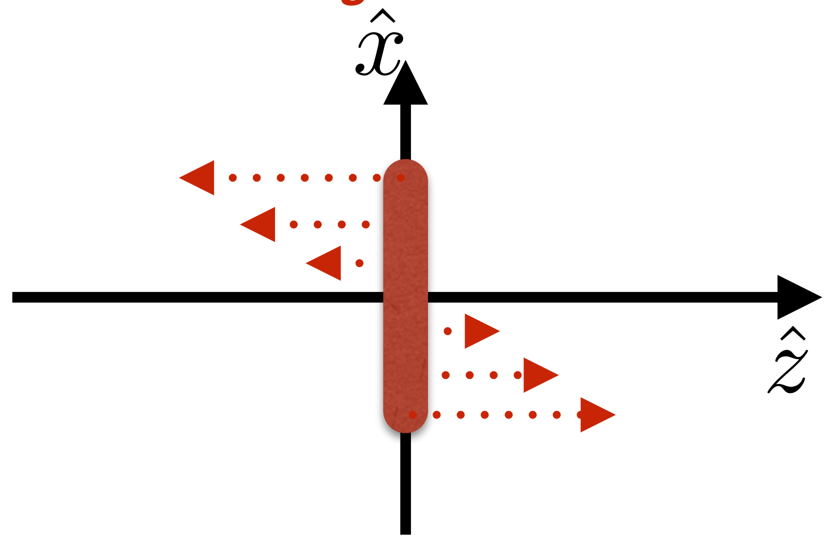
Rotating Quark-Gluon Plasma (1/3)



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

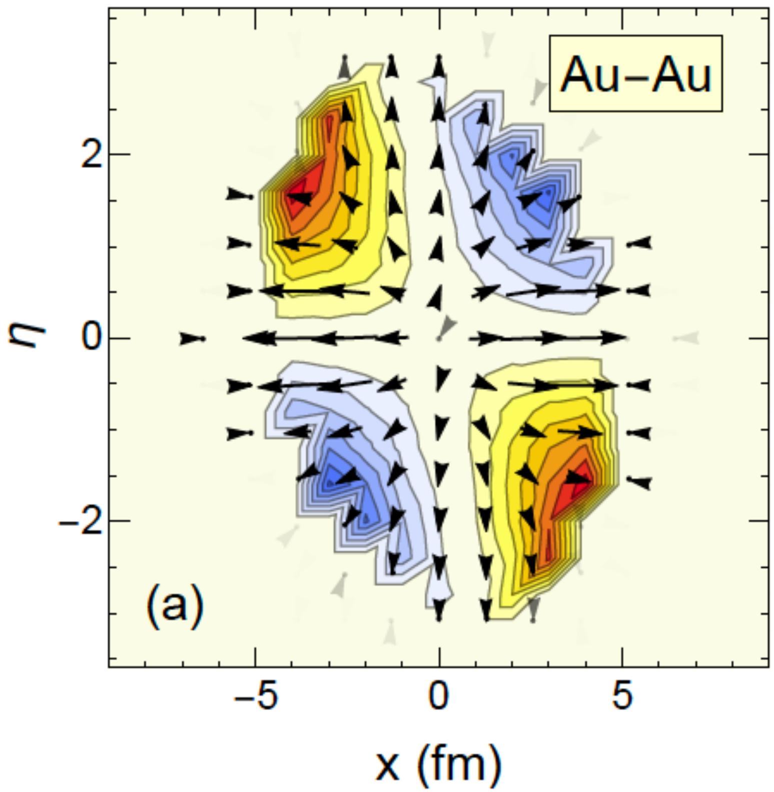


QGP's way of accommodating this angular momentum



Issue: Spectators taking away lots of L ?!
(will come back to this point later)

Rotating Quark-Gluon Plasma (2/3)



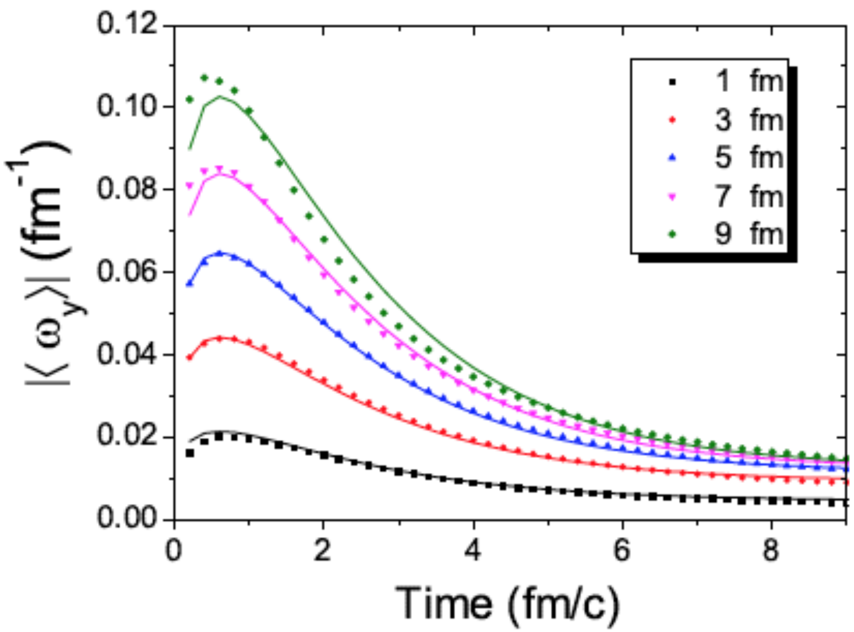
$$\vec{v}(\rho,\phi,\eta) = \hat{e}_\rho v_0(\rho,\eta)[1 + 2c_2(\rho,\eta)\cos 2\phi]$$

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

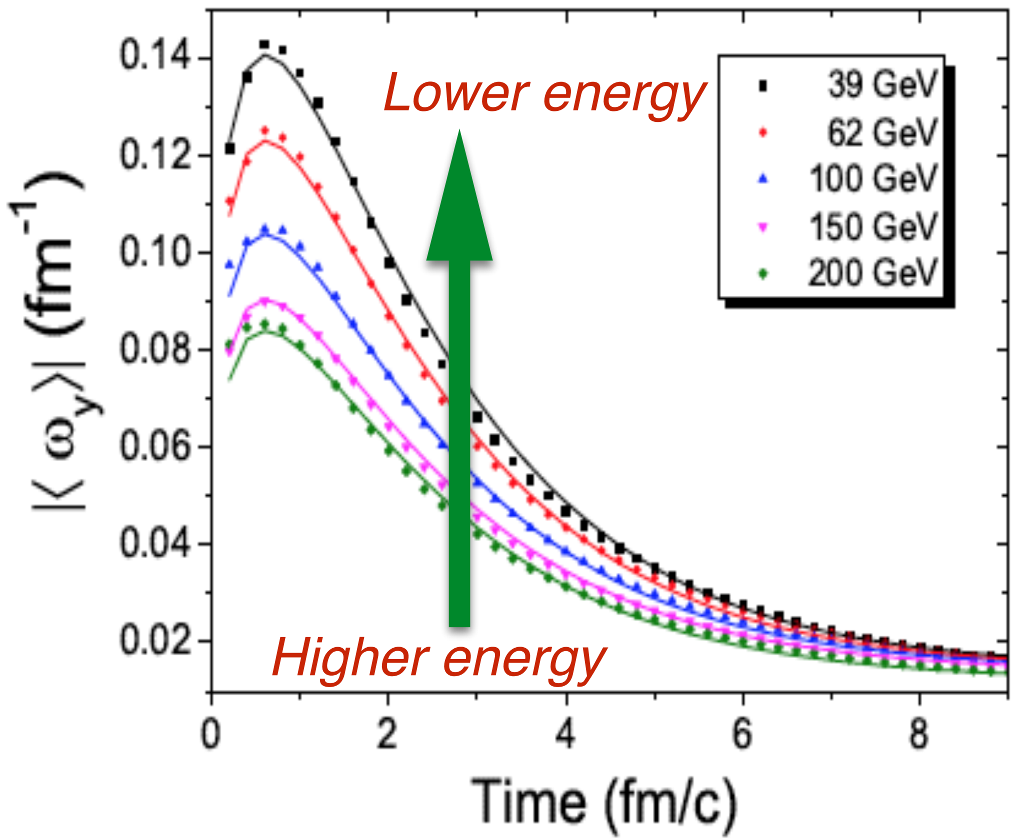
The local vorticity pattern is strongly influenced by the bulk flow.
The averaged vorticity reflects the global orbital angular momentum.

Yin Jiang, Zi-Wei Lin, JL, PRC2016

Rotating Quark-Gluon Plasma (3/3)



Centrality trend



Beam Energy Dependence Nontrivial !!

Yin Jiang, Zi-Wei Lin, JL, PRC2016

Rotational Polarization (1/3)

Dirac Lagrangian in rotating frame:

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

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

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

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

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

Under slow rotation:

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

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

Rotational polarization effect!

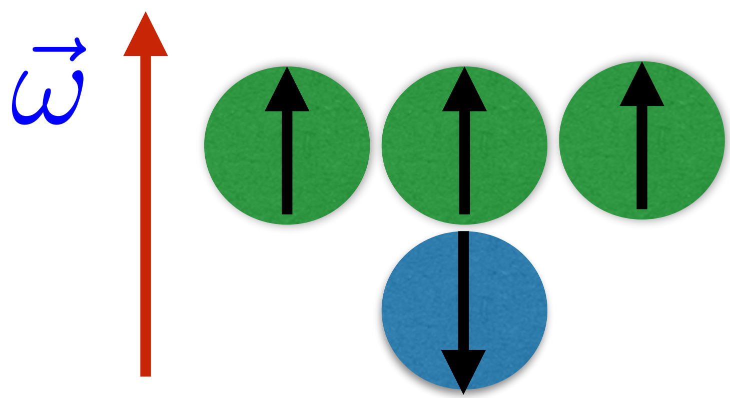
Rotational Polarization (2/3)

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

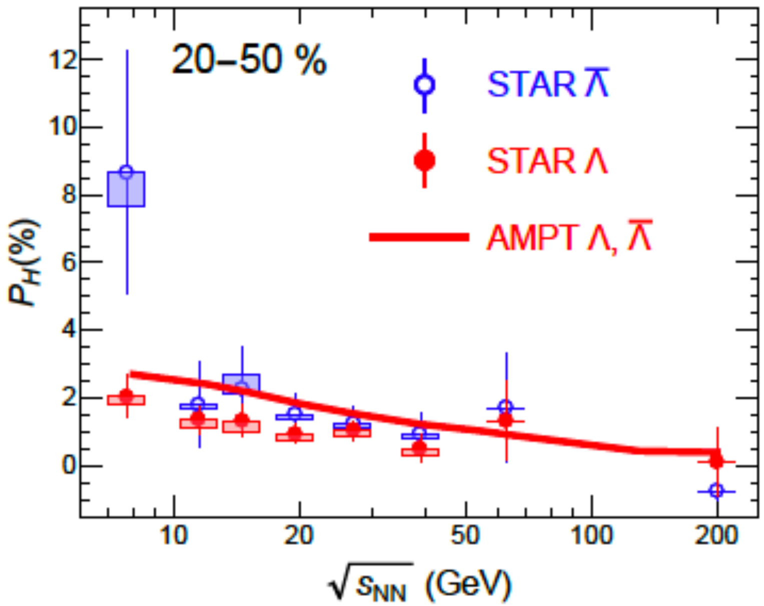
Rotational polarization effect!

For thermally produced particles: "equal-partition" of angular momentum

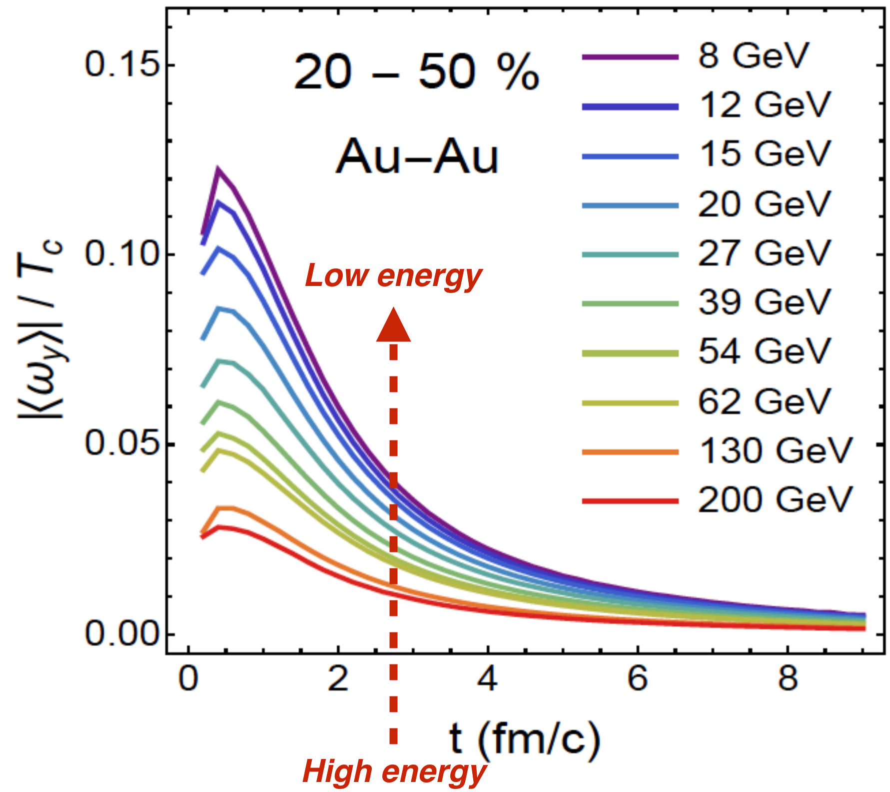
$$dN \propto e^{\frac{\vec{\omega}\cdot\vec{J}}{T}}$$



Rotational Polarization (3/3)



Jiang, Lin, JL, PRC2016;
Shi, Li, JL, PLB2019



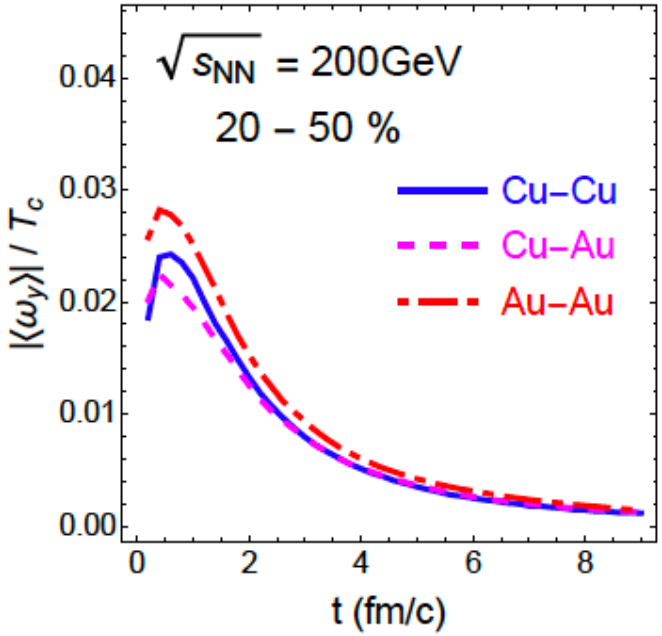
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$

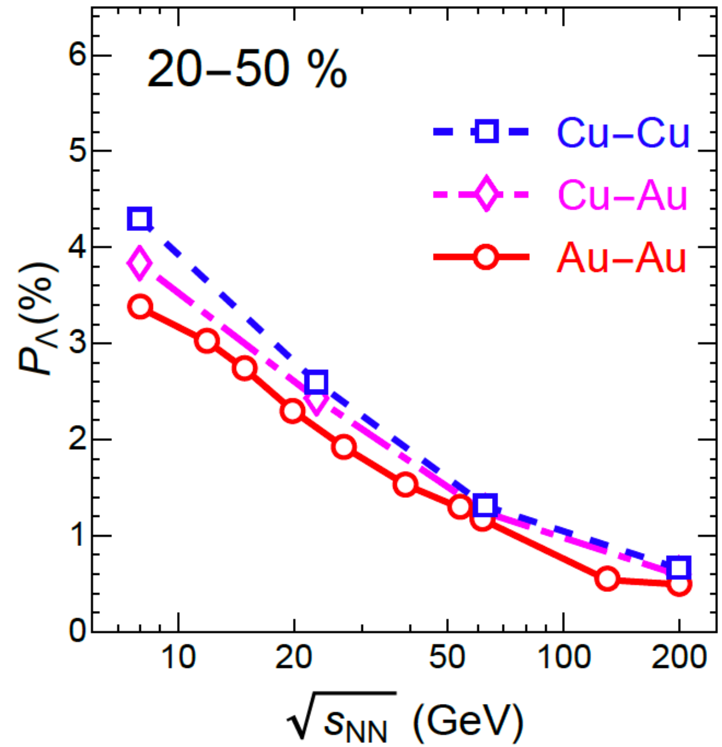
The most vortical fluid!

*** Important at low collision energy!!**
*** Puzzle: why difference in hyperons and anti-hyperons??**

Predictions for Smaller Systems

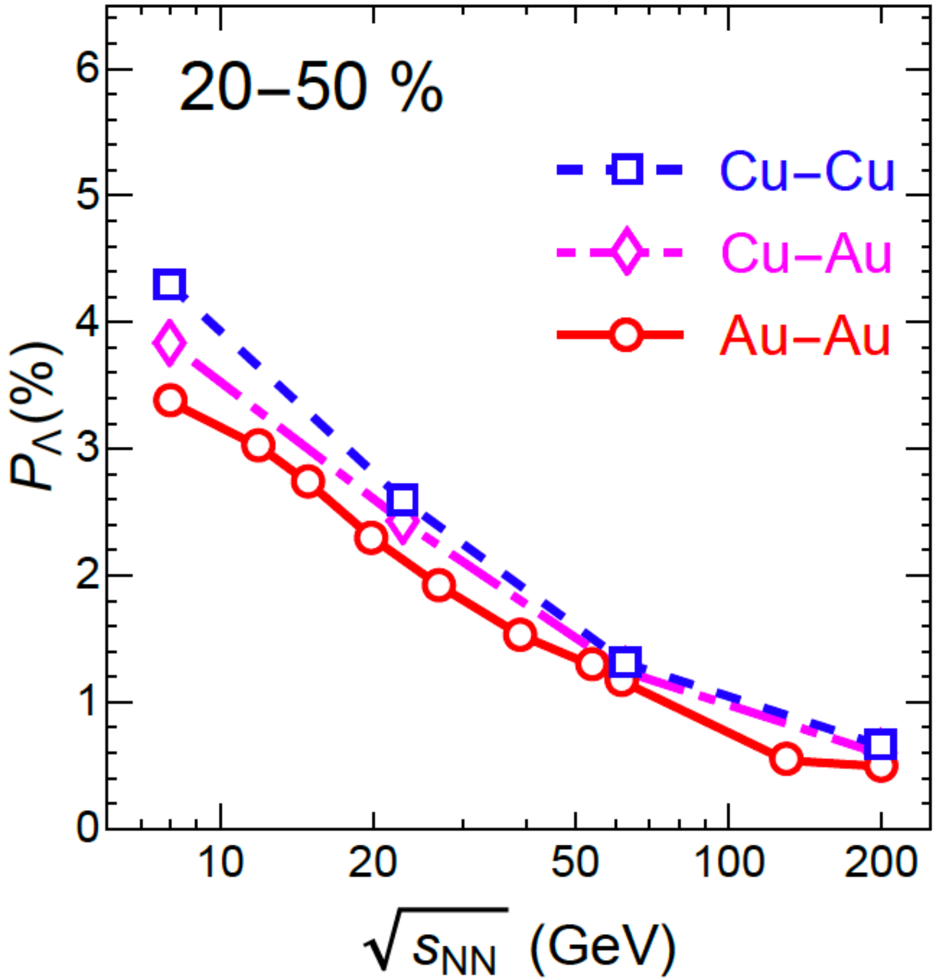
Polarization effect in CuCu and CuAU collisions should be sizable!





Shuzhe Shi, Kangle Li, JL, PLB2019.

Prediction for Polarization in CuCu and AuAu



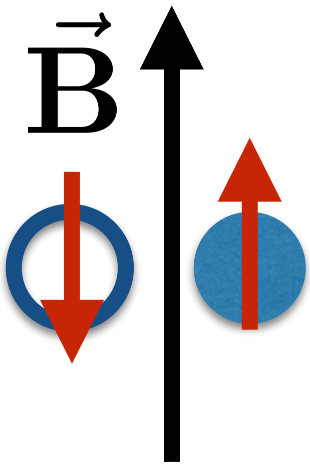
Our surprising finding of the signal hierarchy: CuCu > CuAu > AuAu !

WHY SO?

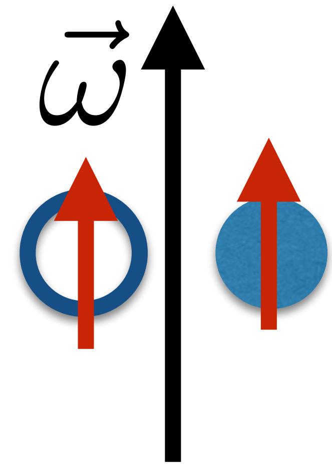
Shuzhe Shi, Kangle Li, JL, arXiv:1712.00878.

Magnetic Field at Low Collision Energy

Magnetic Filed Induced Polarization



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



For Lambda:

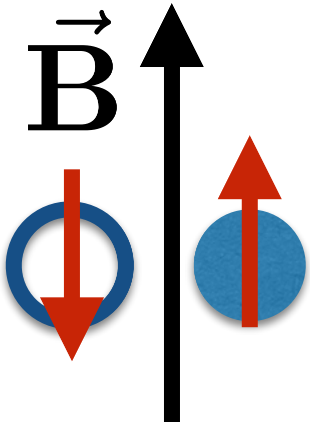
$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} - 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

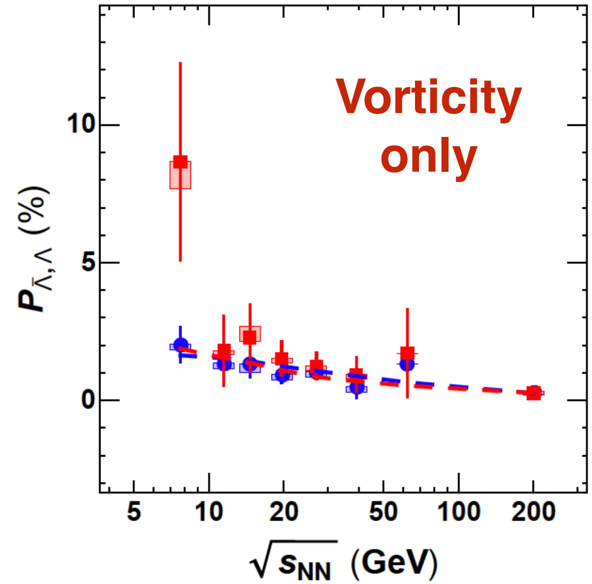
For anti-Lambda:

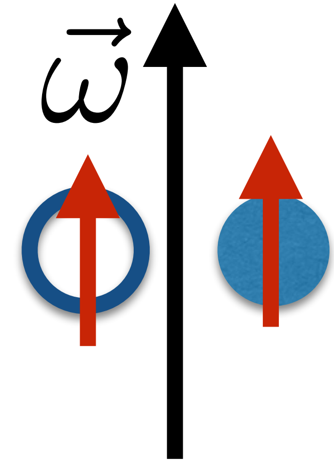
$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} + 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

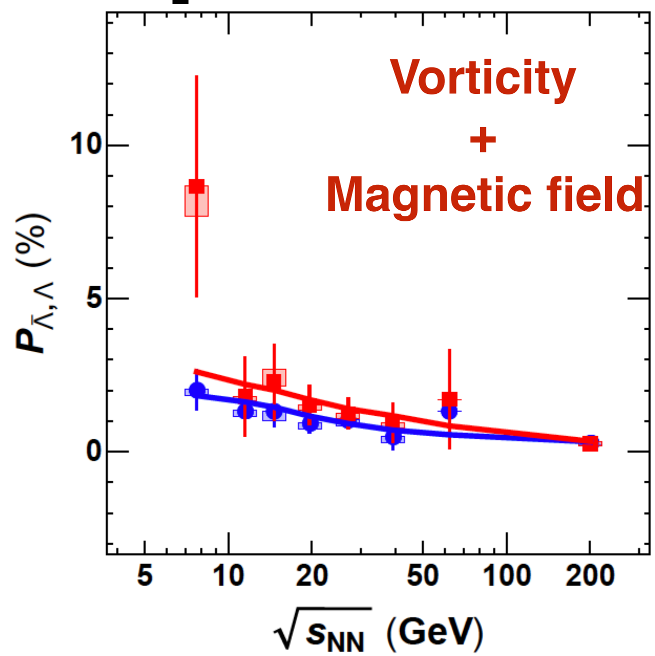
[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, in preparation.]

Magnetic Filed Induced Polarization







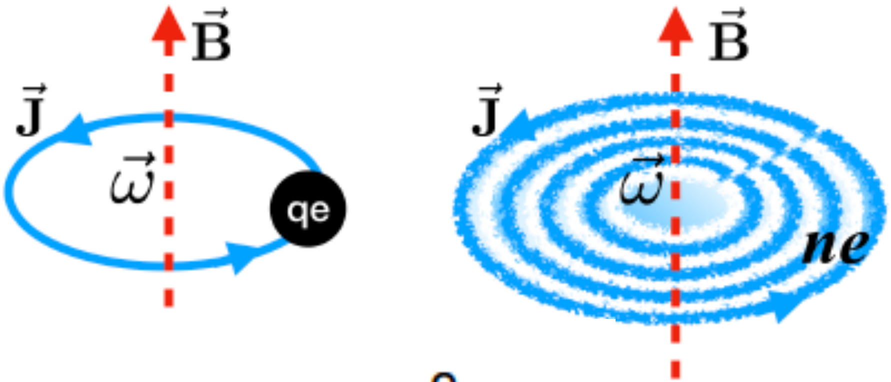


For this to work:
Requires long-lived late time magnetic field.

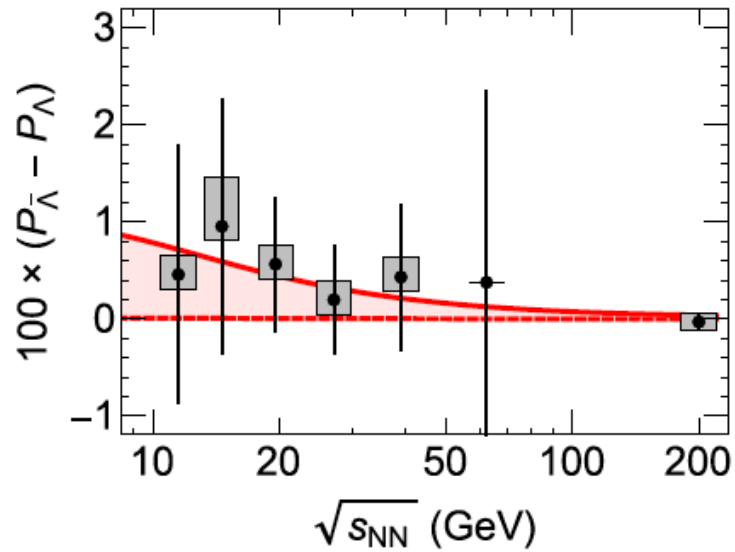
Where does that come from??

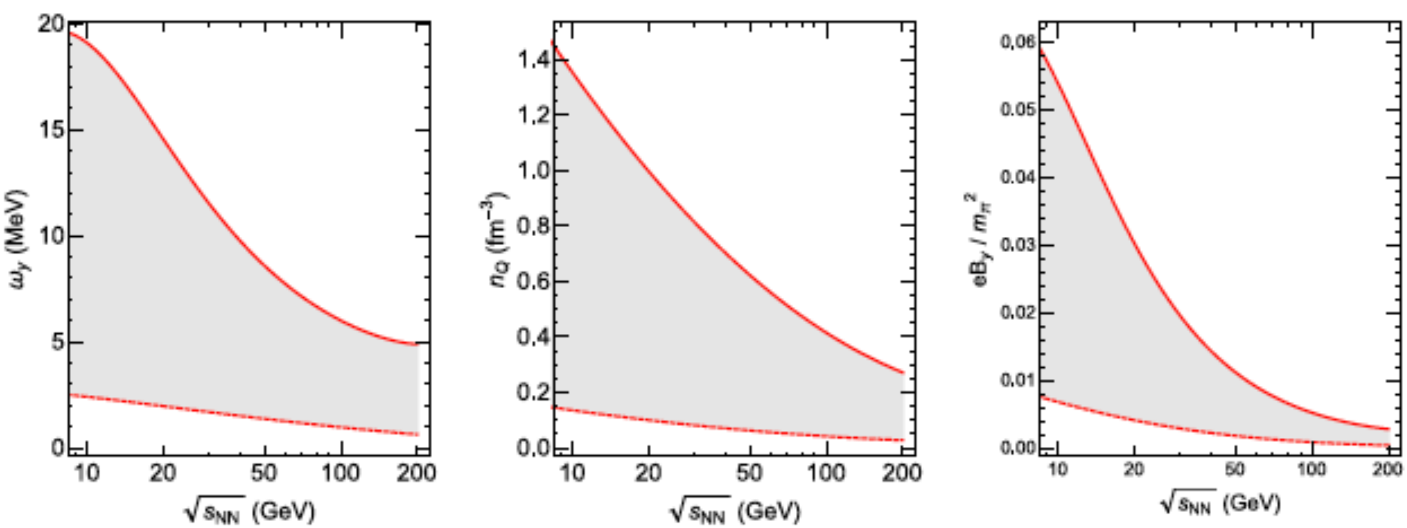
[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, in preparation.]

Connecting Magnetic Field and Fluid Rotation



$$e\bar{\mathbf{B}} = \frac{e^2}{4\pi} n A \bar{\omega}$$



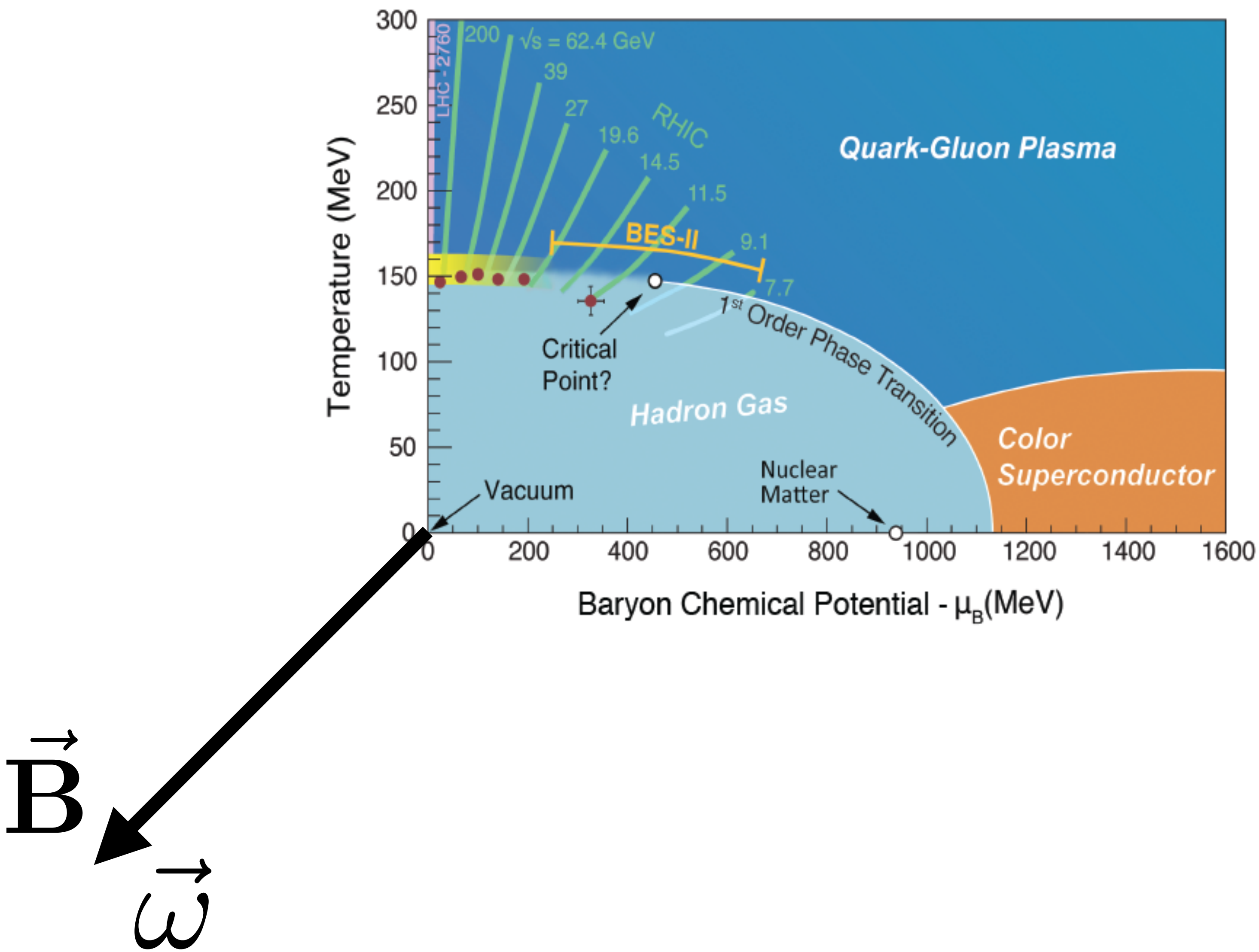


Important at low beam energy!

[X. Guo, et al, arXiv:1904.04704]

Discussions & Outlook

QCD Phase Structures under Extreme Fields

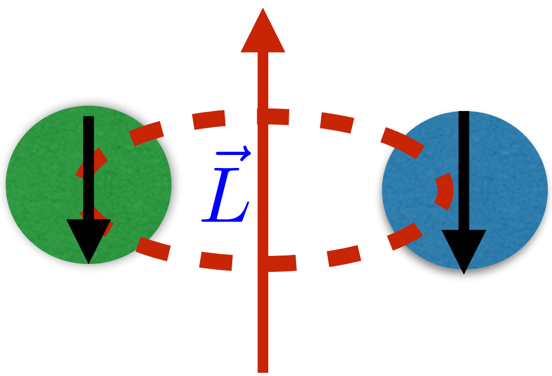


Rotational Suppression of Scalar Pairing

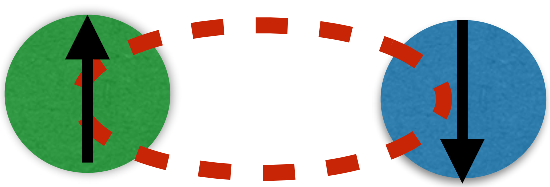
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, ...

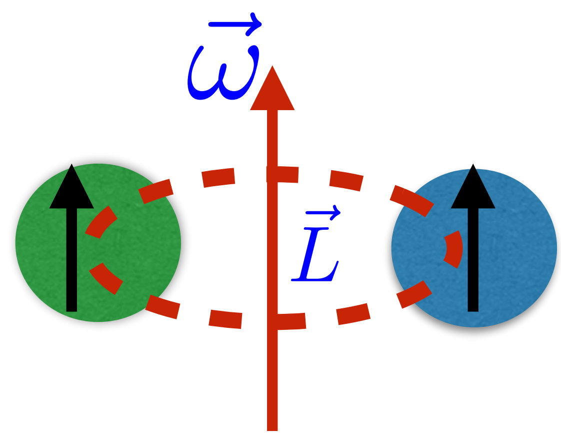
We consider scalar pairing state, with J=0.

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



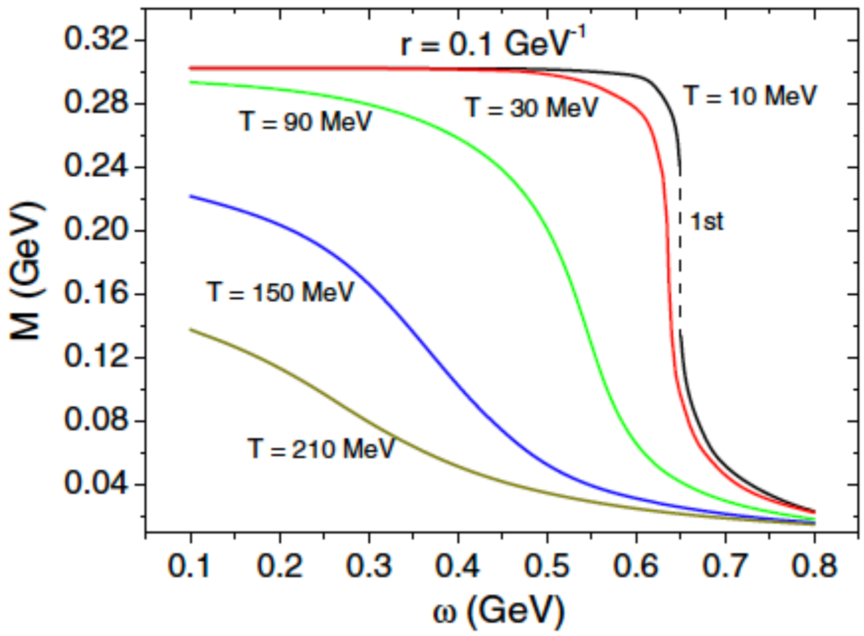
Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing.

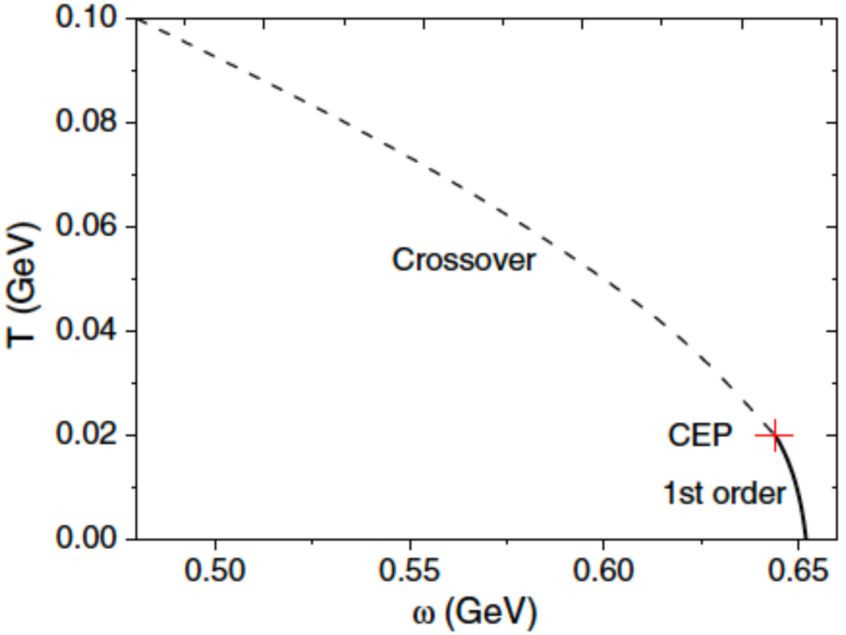




[Yin Jiang, JL, PRL2016]

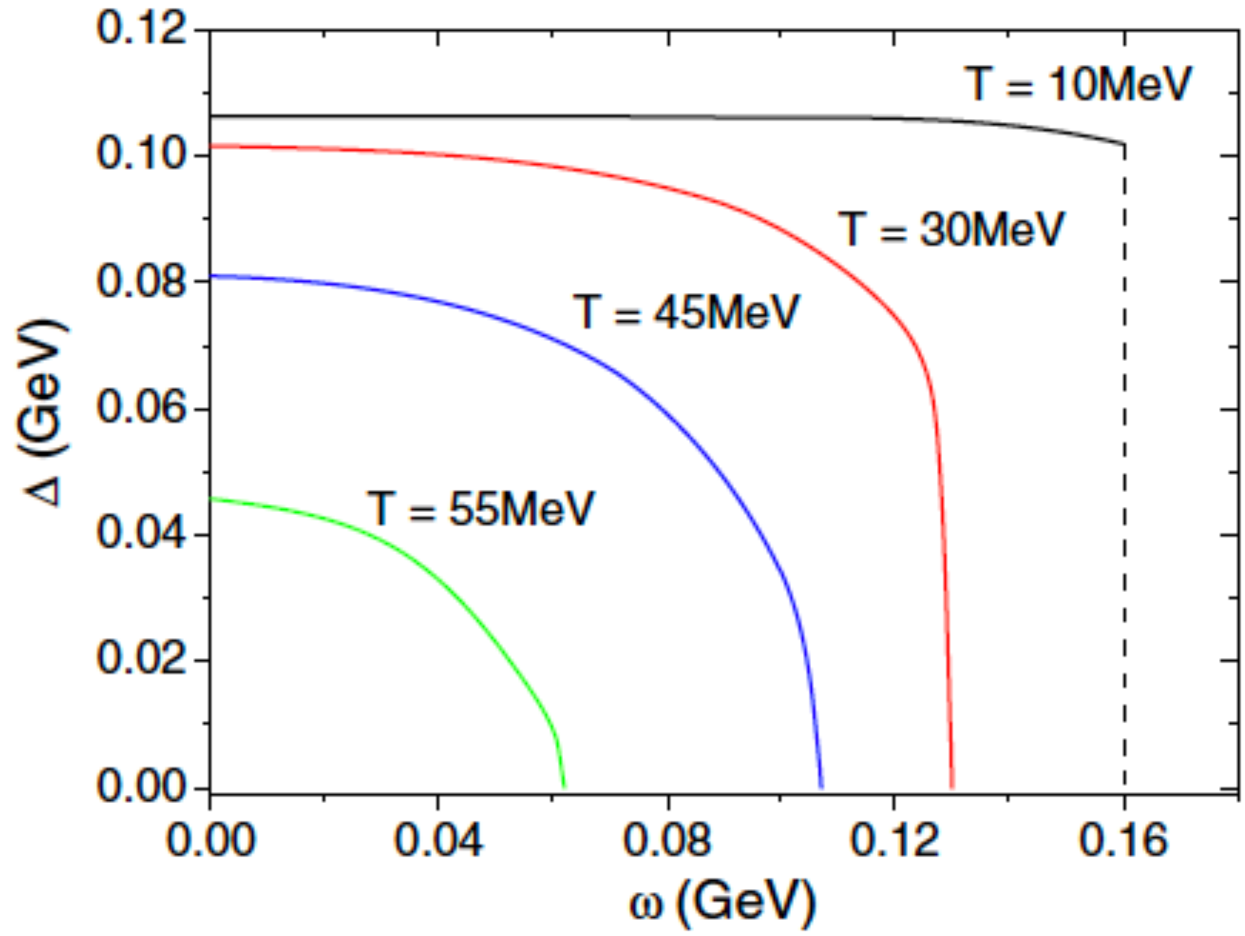
Chiral Phase Transition





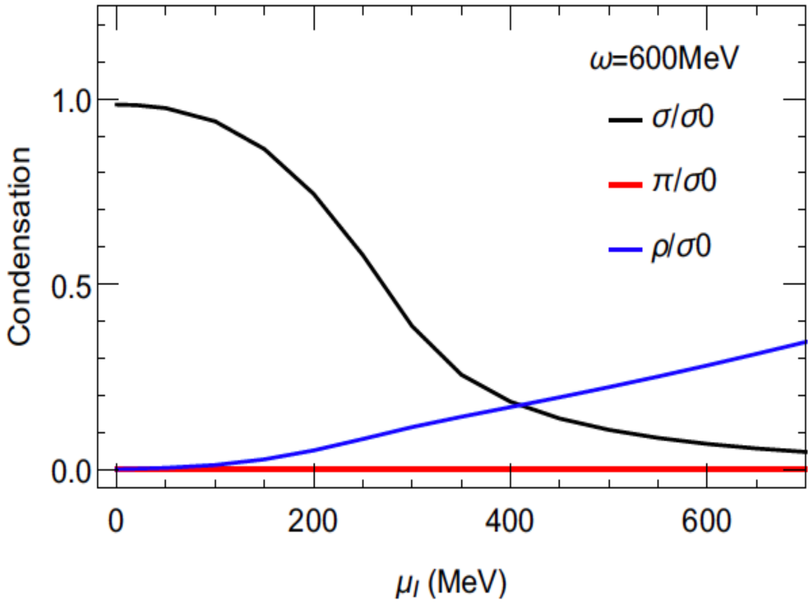
Maybe in low energy collisions:
In-medium mass correction due to rotation??

Color Superconducting Pairing



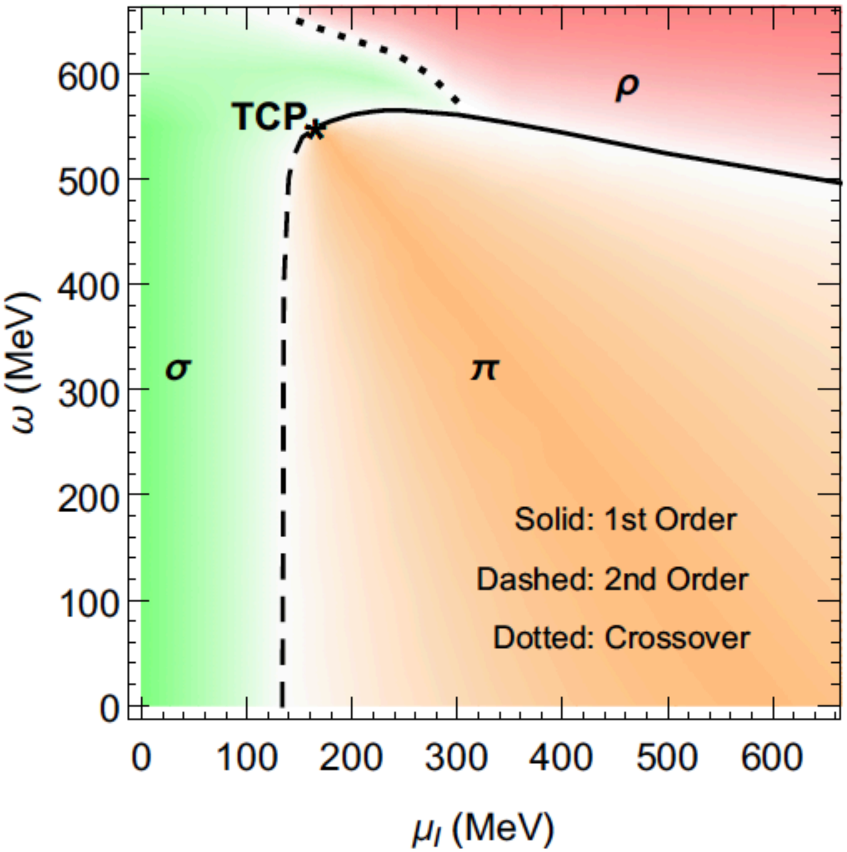
Maybe also for nucleon-pairing?!

Isospin Matter



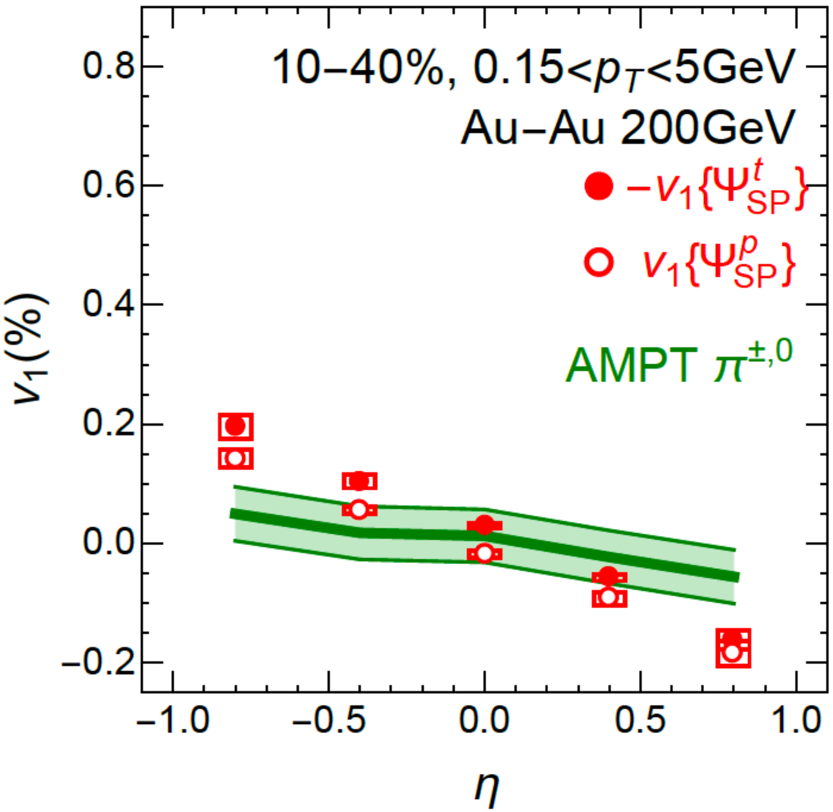
Spin-1 Rho condensation is favored by rotation!

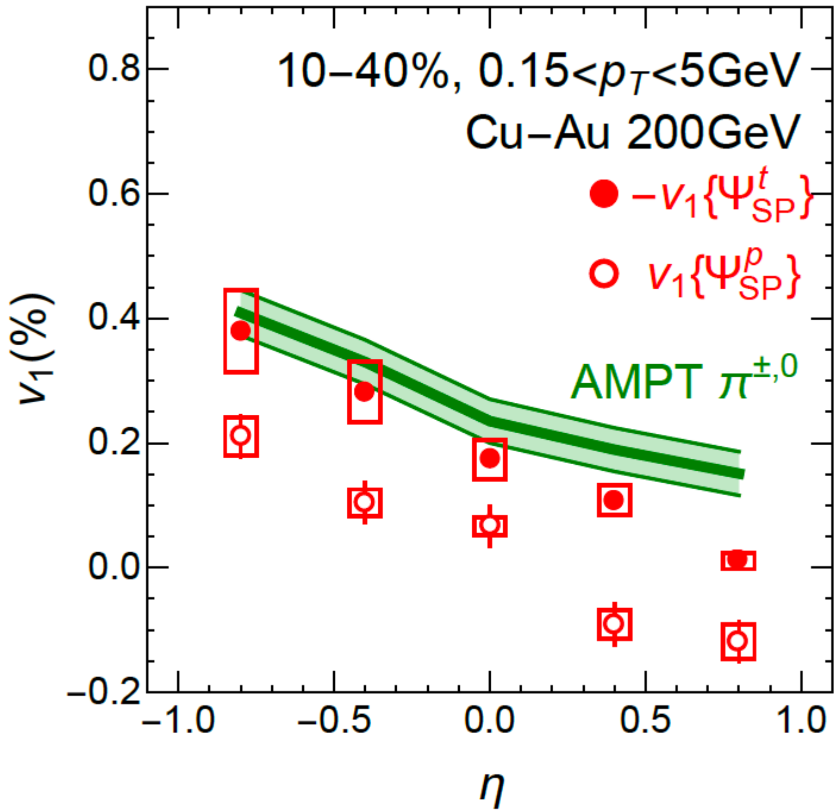
[Hui Zhang, Defu Hou, JL, arXiv: 1812.11787.]



Large isospin density in low energy collision: Possible effect from rotation?

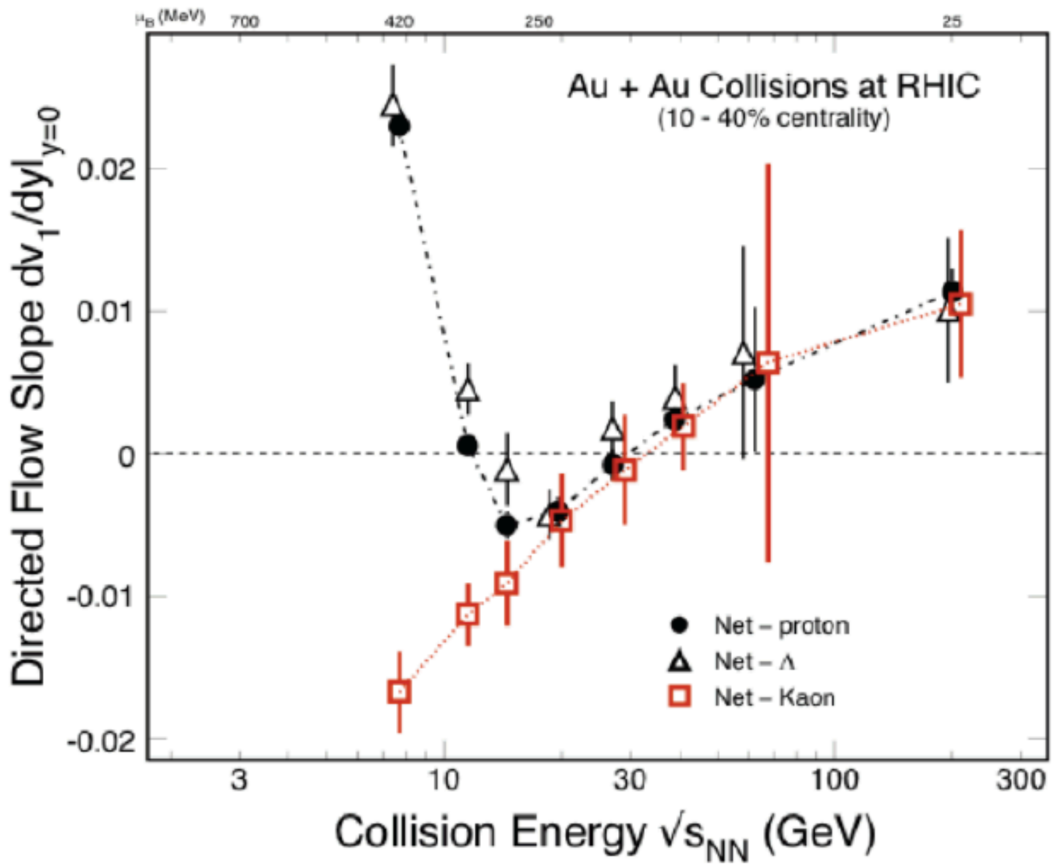
Directed Flow





It is important to understand directed flow and vorticity simultaneously.

Directed Flow



Possible nontrivial implications for vorticity/rotation at very low beam energy??

Forward/backward vorticity & polarization?!

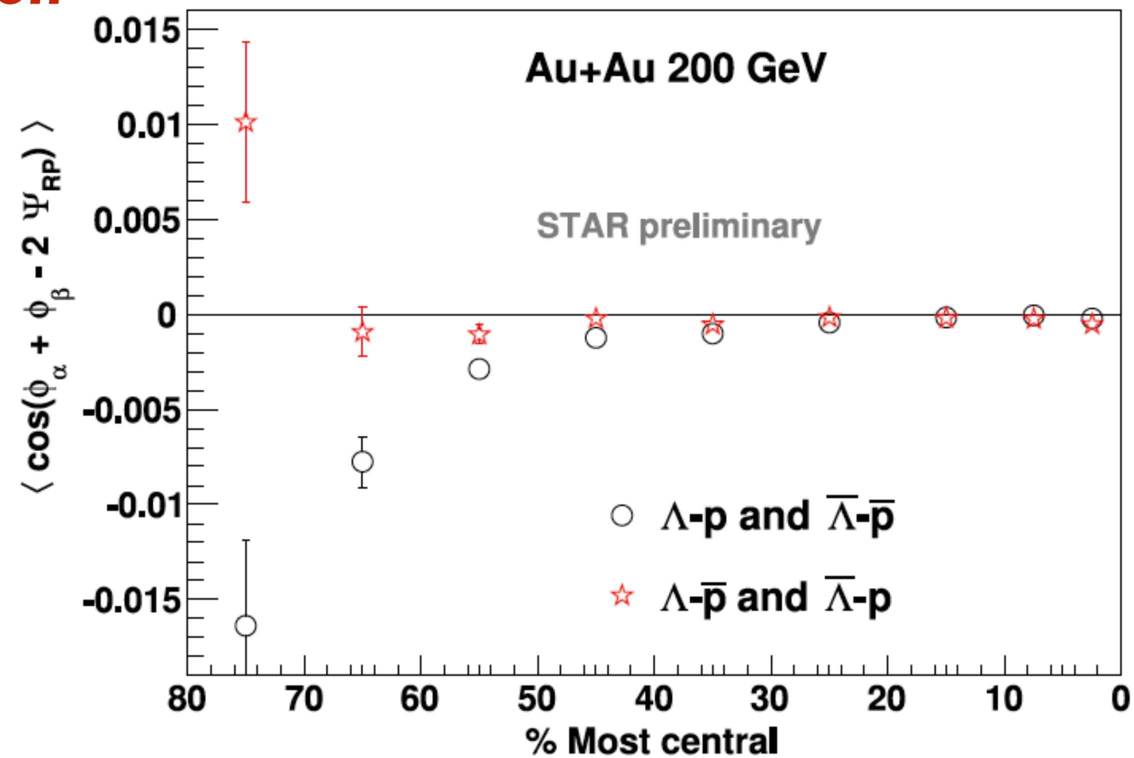
Potential Signal of Chiral Vortical Effect (CVE)

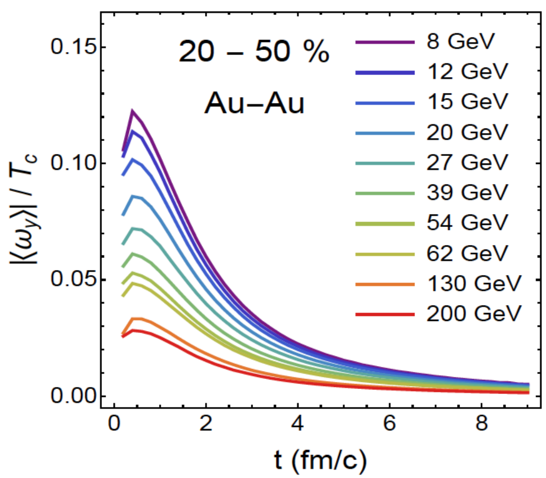
CVE —> Baryon separation across reaction plane.

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

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

QM2014





Vortical effects at low energy ?!

Outlook

Nuclear matter under extreme fields (magnetic field and fluid rotation): Possibility of a very interesting and novel physics topical line at FAIR/NICA?!

- ***Vorticity structure and directed flow***
- ***Magnetic field from rotation***
- ***Vorticity-induced transport effects***
- ***Mass shift / phase line shift due to extreme fields***
- ***Isospin matter***
- ***Hadronic level effects***