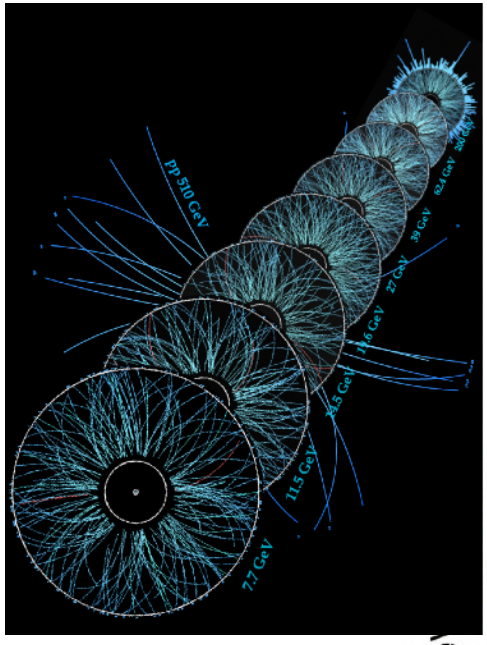
What Can We Learn from the Polarization Measurements at High Baryon Density?

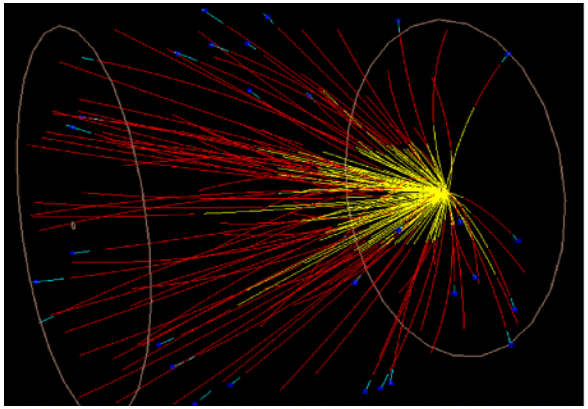
Jinfeng Liao

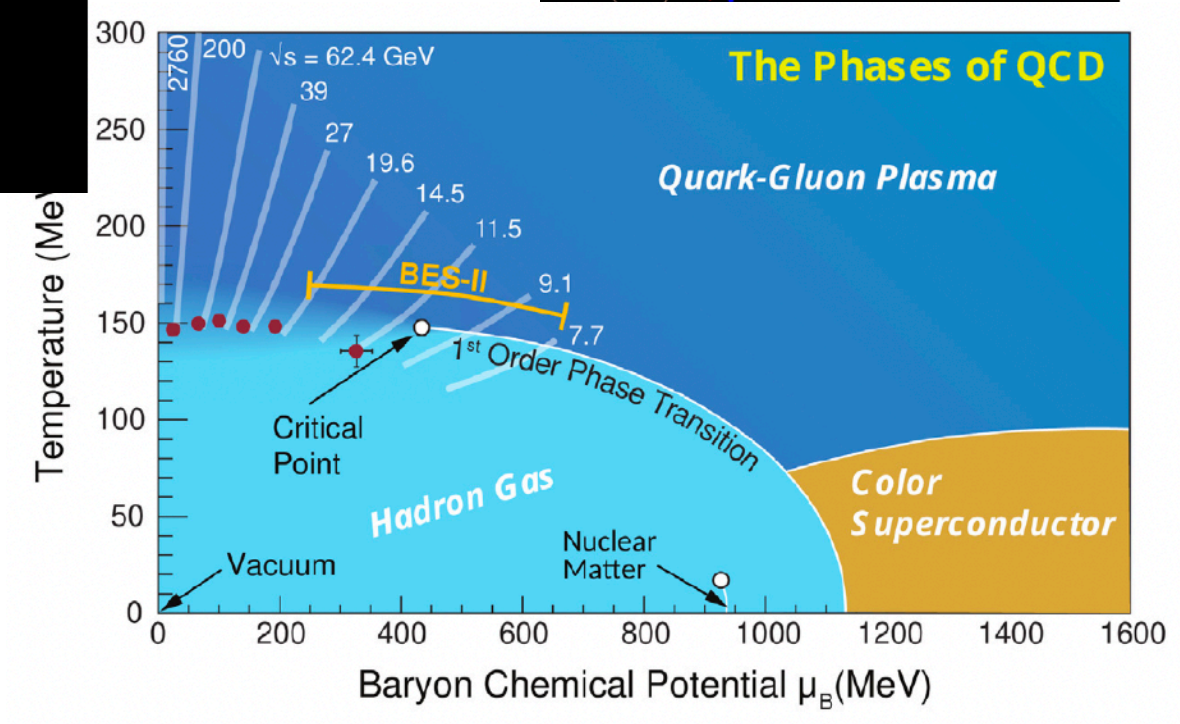
Indiana University, Physics Dept. & CEEM

Research Supported by NSF & DOE

Beam Energy Scan Program: Congratulations!





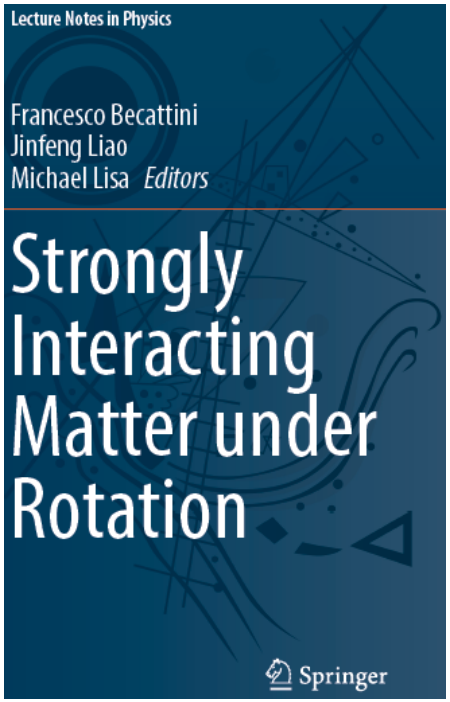


A wonderful BES "bonus" : hyperon spin polarization

Strongly Interacting Matter under Rotation

Opening doors for a whole new array of interesting studies:

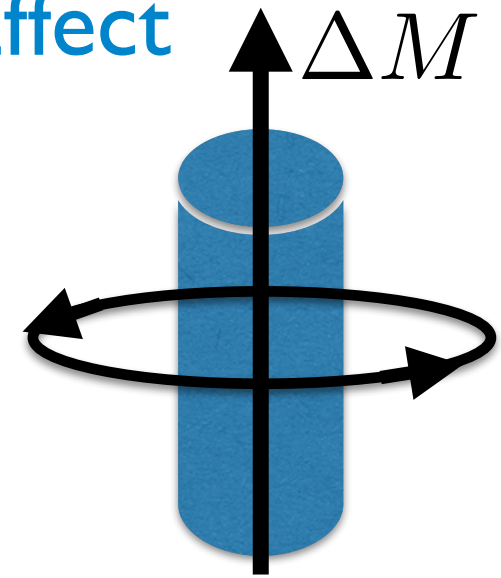
- ***Phase structure change? Equation of state change?***
- ***Global and local polarization? Vector mesons?***
- ***Spin transport theory? Spin hydrodynamics?***
- ***Novel transport processes?***
- ***……***



Many exciting new developments: see upcoming volume in Springer Lecture Notes in Physics!

[arXiv:2102.00933; 2010.08937; 2009.04803; 2101.04963; 2004.04050; 2011.09974; 1908.10244; 2007.04029; 2001.00359; 2108.00586; …]

A Long Story: Barnett Effect



SEPTEMBER 24, 1909] SCIENCE 413

Lehrbuch der Kristalloptik, by E. B. Wilson; "Notes"; "New Publications."

SPECIAL ARTICLES

ON MAGNETIZATION BY ANGULAR ACCELERATION

Some time ago, while thinking about the origin of the earth's magnetism, it occurred to me that any magnetic substance must, according to current theory, become magnetized by receiving an angular velocity.

Thus consider a cylinder of iron or other substance constituted of atomic or molecular

fectly definite and unquestionable, but exceedingly difficult to account for, viz., a magnetization along the rod in a definite direction independent of the direction of rotation and of the direction of the original residual magnetism of the rod. It was not due to the jarring of the cylinder as it was rotated in the earth's field, nor to a possible minute change in the direction of its axis produced by the pull of the motor. In magnitude this effect was several times as great as the other, which became manifest only at the higher of the two speeds used.

Second Series. *October, 1915* *Vol. VI., No. 4*

Rotating solid sample —> magnetization

$$\Delta J \Rightarrow \Delta M$$

THE

PHYSICAL REVIEW.

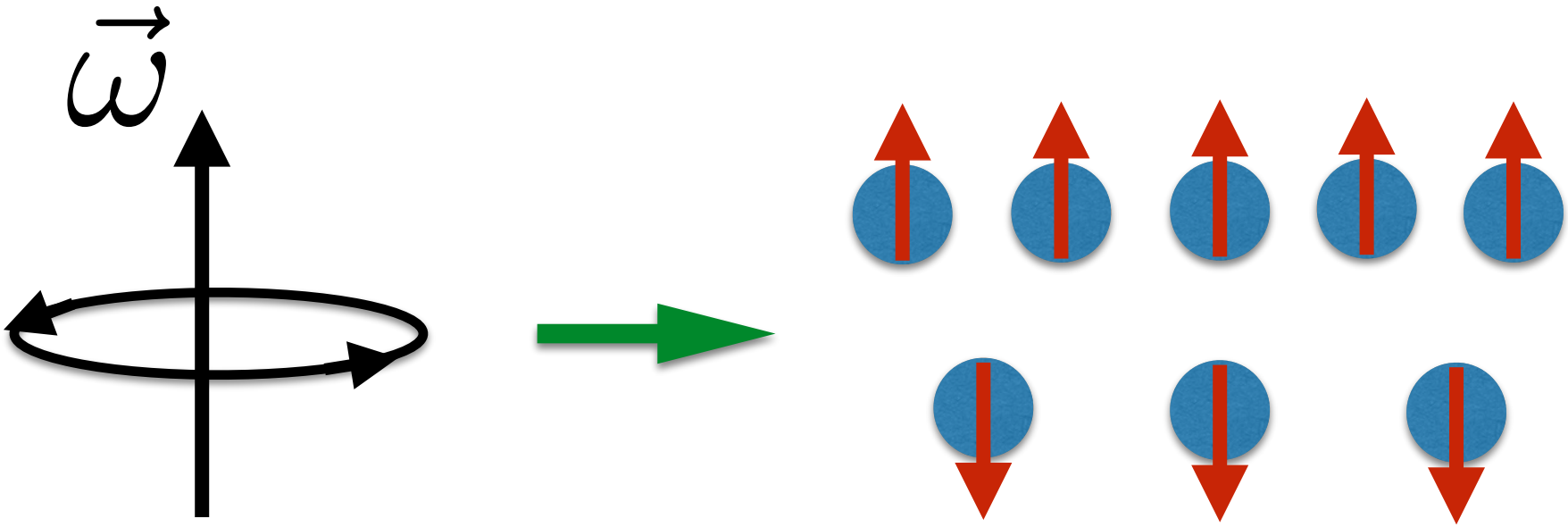
MAGNETIZATION BY ROTATION.[1]

BY S. J. BARNETT.

§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.

In Short: Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization



Macroscopic rotation; Global angular momentum

Microscopic spin alignment

It however is tricky to be directly observed for a flowing fluid.

Rotational Polarization in Condensed Matter

Spin hydrodynamic generation

R. Takahashi, M. Matsuo, M. Ono, K. Harii, H. Chudo, S. Okayasu, J. Ieda, S. Takahashi, S. Maekawa & E. Saitoh

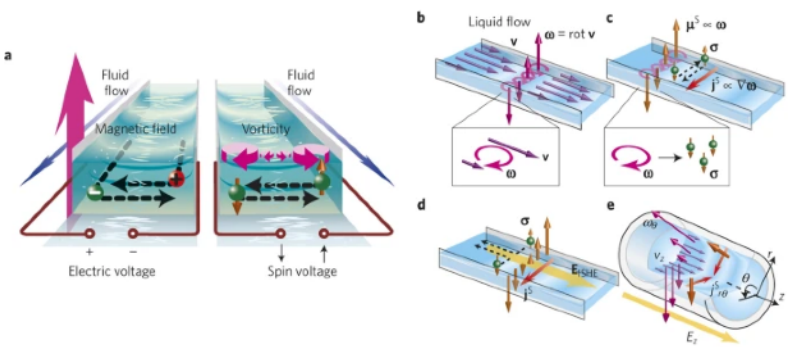
Nature Physics **12**, 52–56(2016) | Cite this article

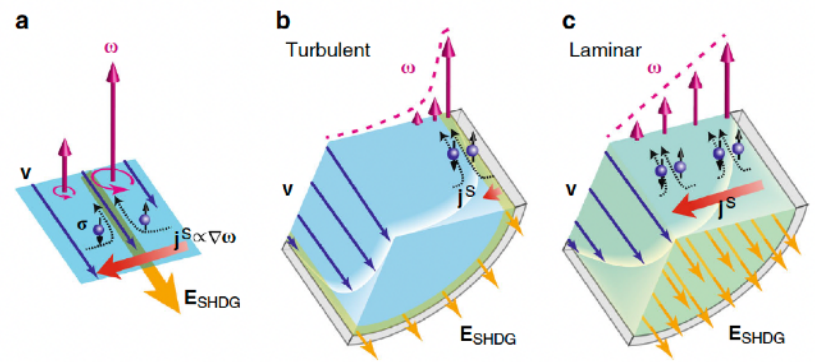
Viscous fluid flow —> vorticity —> spin polarization

Giant spin hydrodynamic generation in laminar flow

R. Takahashi, H. Chudo, M. Matsuo, K. Harii, Y. Ohnuma, S. Maekawa & E. Saitoh

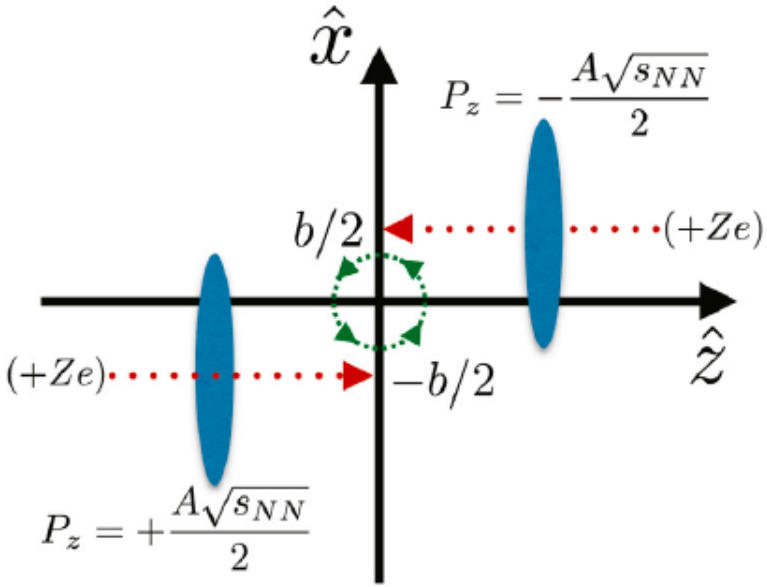
Nature Communications **11**, Article number: 3009 (2020) | Cite this article





"Fluid Spintronics":
Based on spin-fluid-vorticity coupling

Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions at high energy

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

Liang & Wang ~ 2005:
orbital L —> spin polarization via partonic collision processes

Becattini, et al ~ 2008, 2013: A fluid dynamical scenario

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}\, p_\sigma \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\varpi_{\nu\rho} n_F(1-n_F)}{\int_\Sigma \mathrm{d}\Sigma \cdot p n_F}$$

$$\varpi_{\mu\nu} = \frac{1}{2}\left[\partial_\nu\left(\frac{1}{T}u_\mu\right) - \partial_\mu\left(\frac{1}{T}u_\nu\right)\right]$$

"Rotating" Quark-Gluon Plasma

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

PHYSICAL REVIEW C **94**, 044910 (2016)

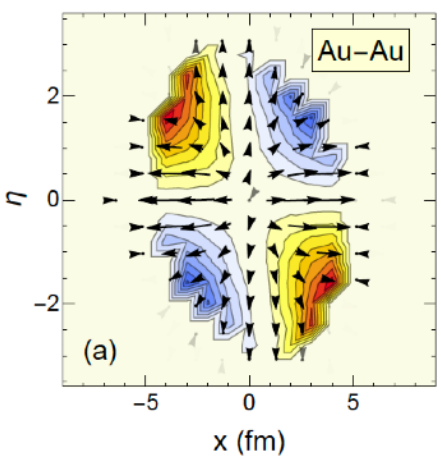
Rotating quark-gluon plasma in relativistic heavy-ion collisions

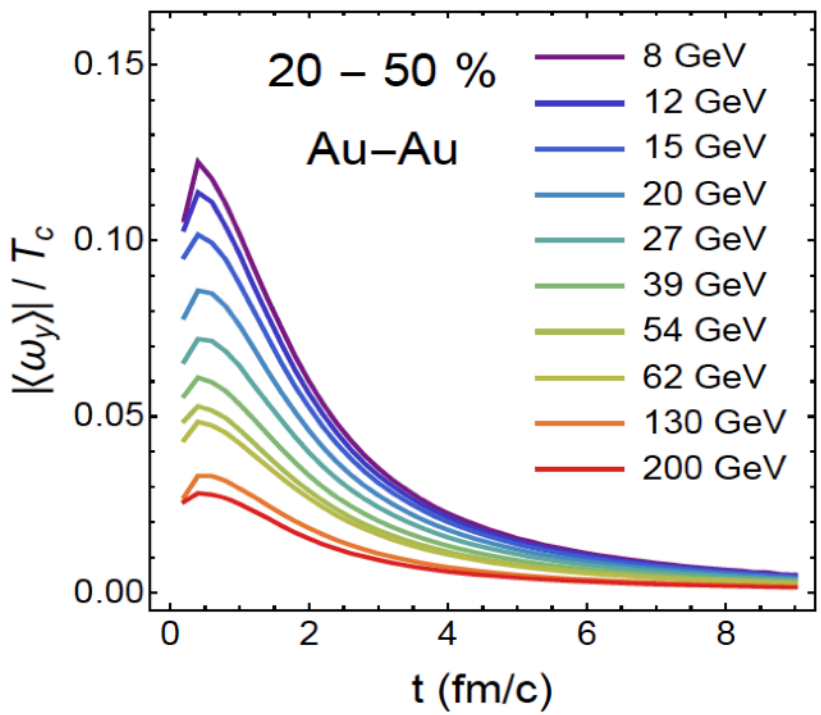
Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]
[1]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 North Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*
[3]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

What fraction stays in QGP? — up to ~20%, depending on collision energy.

Is this portion conserved? —YES!

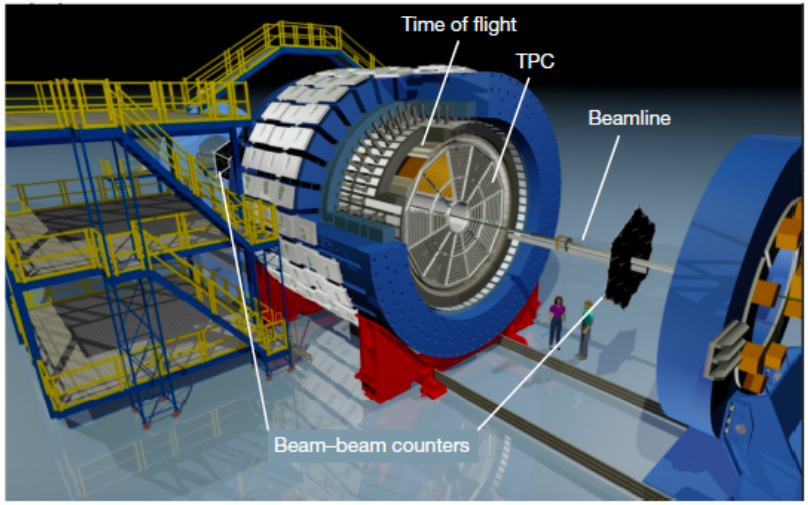
How QGP accommodates this angular momentum? — Fluid vorticity!





Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

The Most Vortical Fluid



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

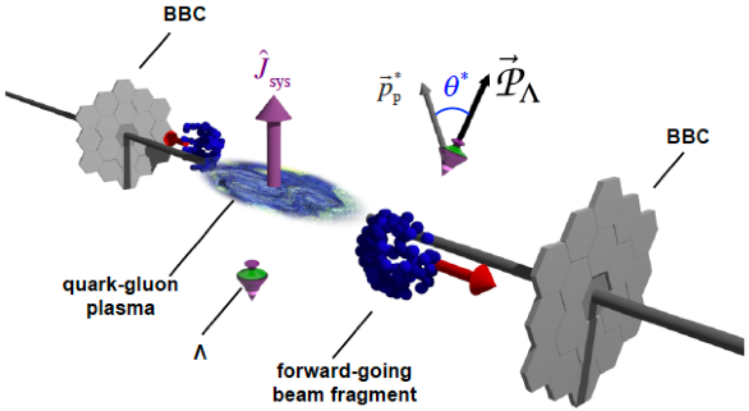
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

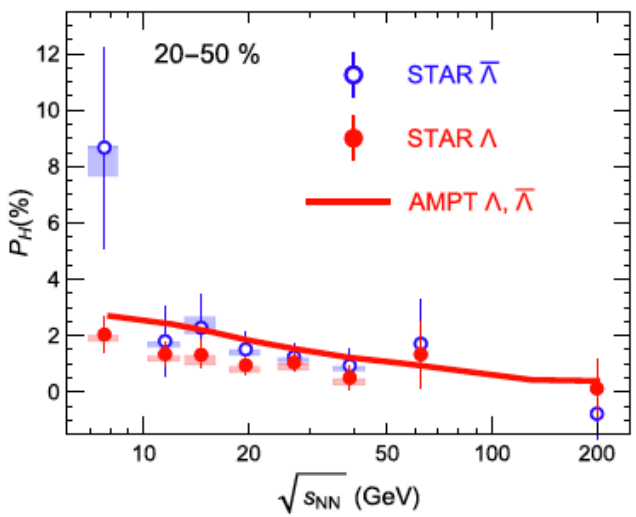
Spin Polarization in the Subatomic Swirls

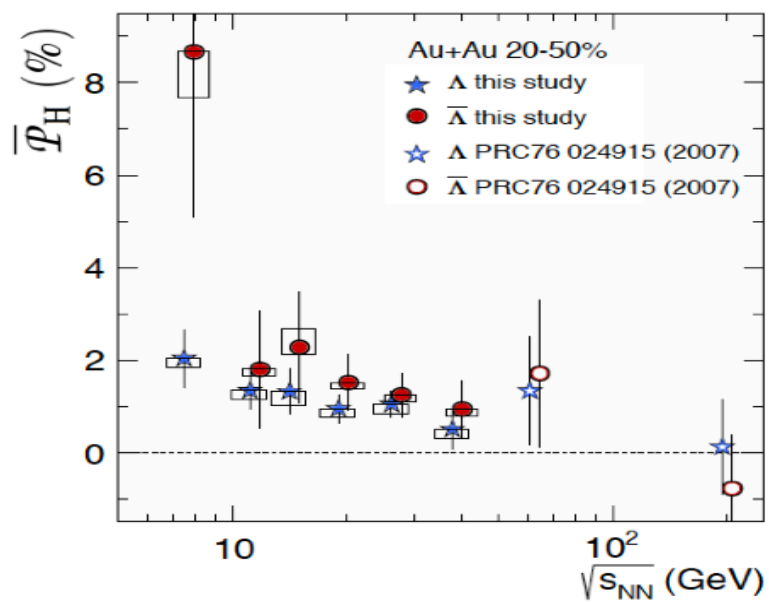


STAR Collaboration, Nature 2017

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

The most vortical fluid!



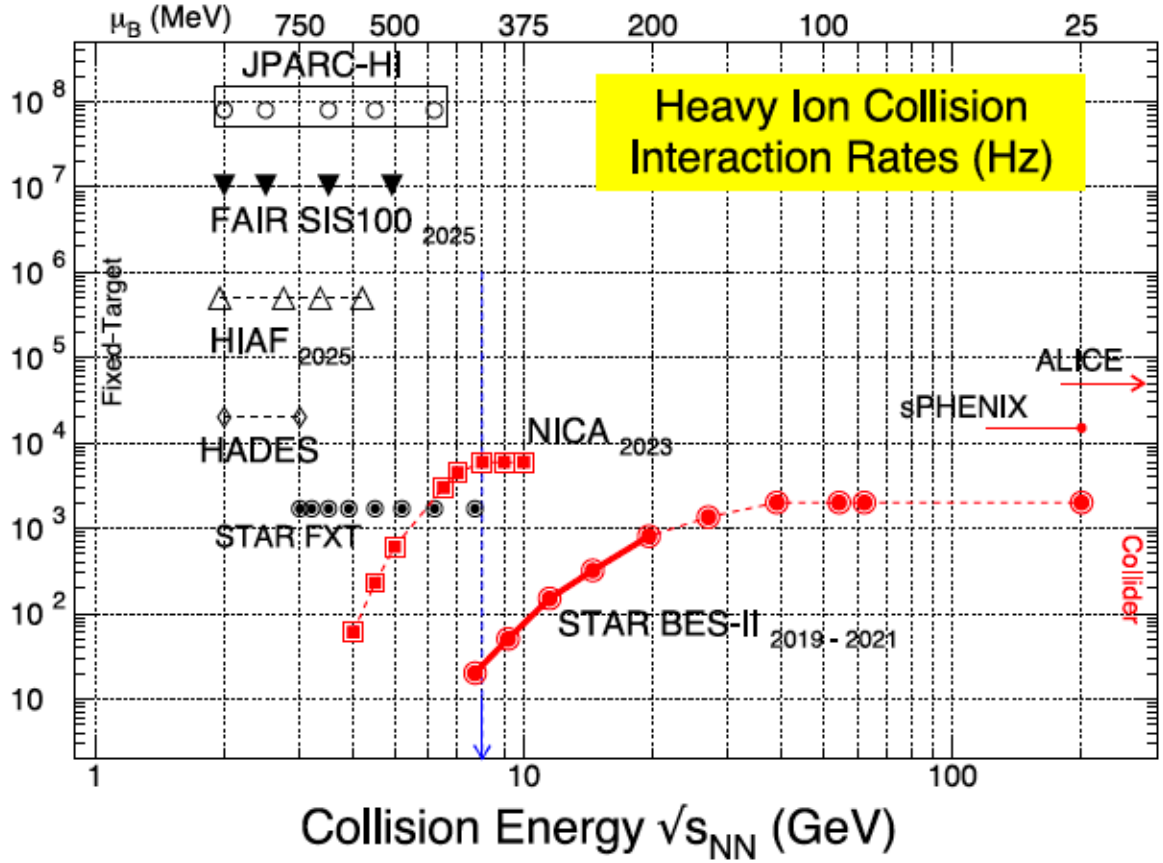


Many calculations based on hydro or transport models

Next Question: Trend toward sub-10 GeV ???

Relativistic Nuclear Collisions @ O(1-10) GeV

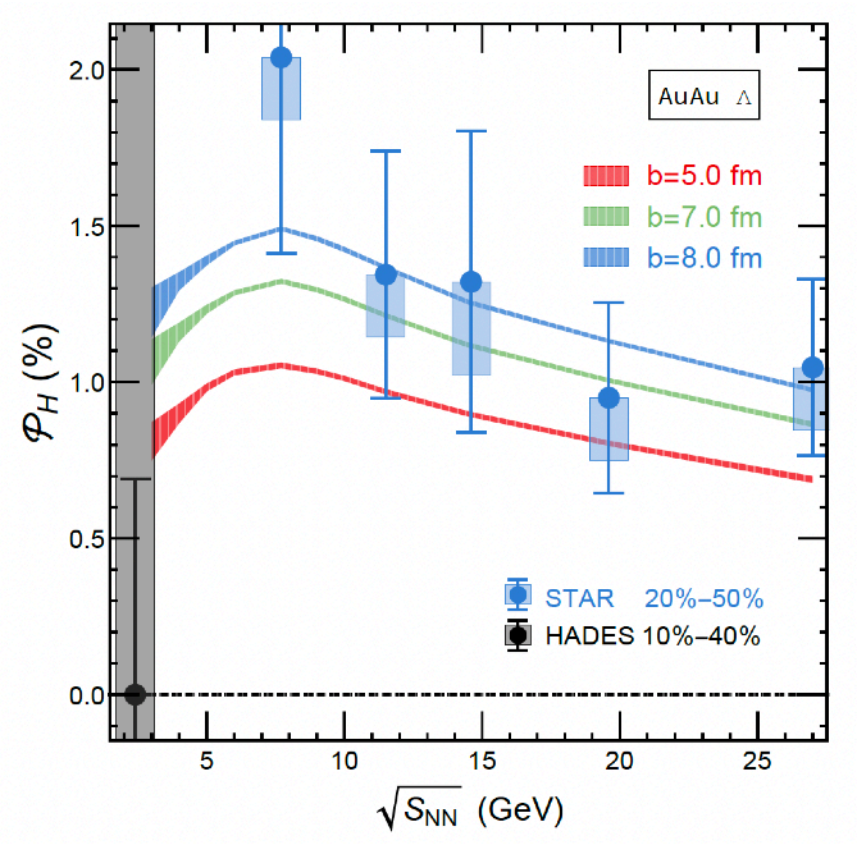
A number of current and planned experiments will explore the O(1) GeV regime of relativistic nuclear collisions



"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87. [arXiv:1906.00936]

Trend of Global Polarization toward O(1) GeV

The Question: Trend for global hyperon polarization @ O(1~10) GeV ???



Yu Guo, et al, arXiv:2105.13481

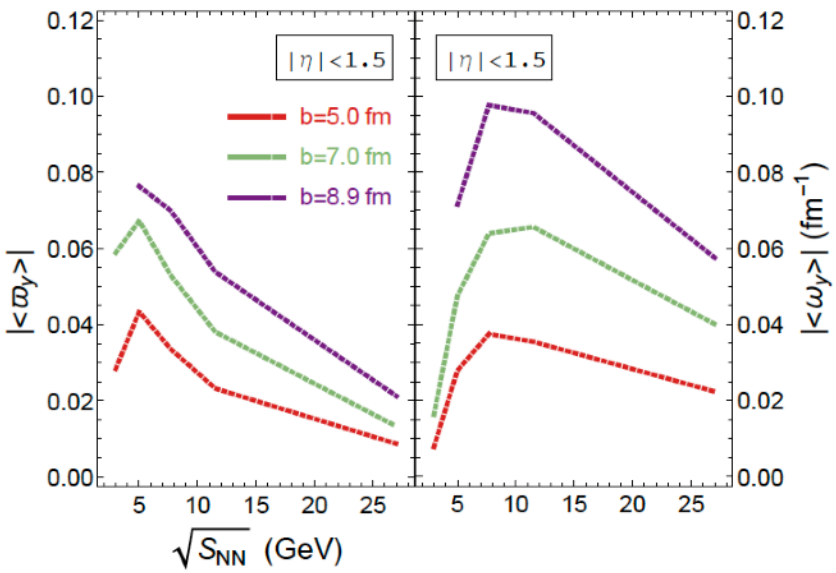
AMPT calculations predict non-monotonic behavior in the dependence of global polarization on beam energy —> maximum around 7.7 GeV

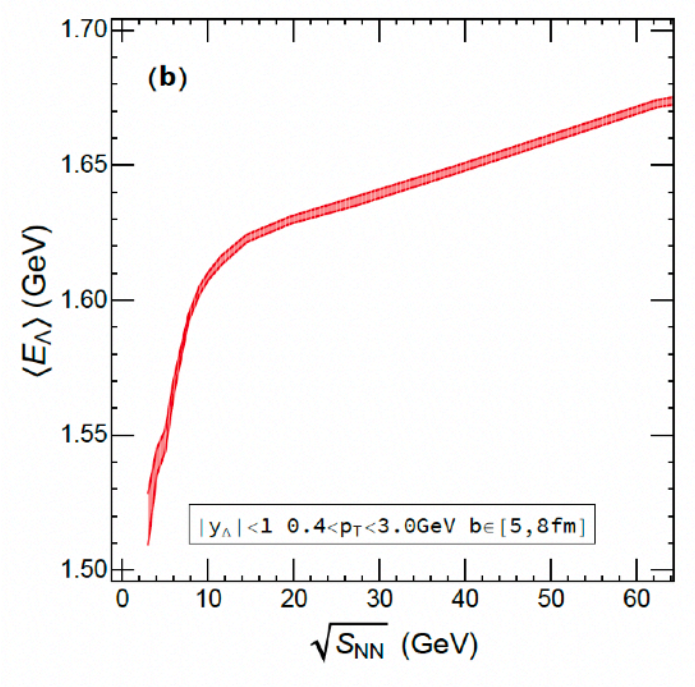
See also results for differential dependence and local polarization in the paper.

Understanding the Trend

"Thermal model" formula for spin d.o.f.

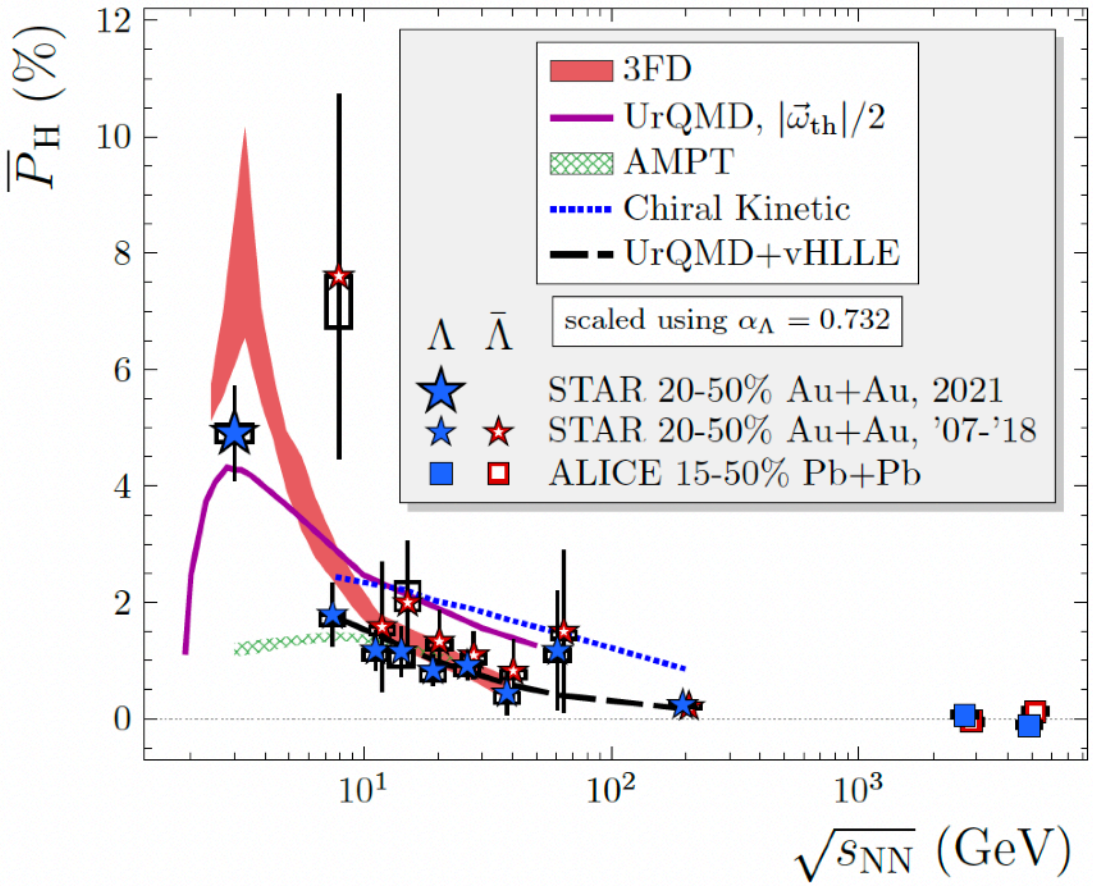
$$S^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}\, p_{\sigma}\, \frac{\int_{\Sigma} \mathrm{d}\Sigma \cdot p\varpi_{\nu\rho} n_F (1-n_F)}{\int_{\Sigma} \mathrm{d}\Sigma \cdot p n_F} \qquad \varpi_{\mu\nu} = \frac{1}{2}\left[\partial_{\nu}\left(\frac{1}{T}u_{\mu}\right) - \partial_{\mu}\left(\frac{1}{T}u_{\nu}\right)\right]$$





The decrease of polarization toward O(1) GeV region is due to the decrease in both vorticity and the produced hyperon energy.

STAR Results



STAR, arXiv:2108.00044

See also Helen's talk on Monday

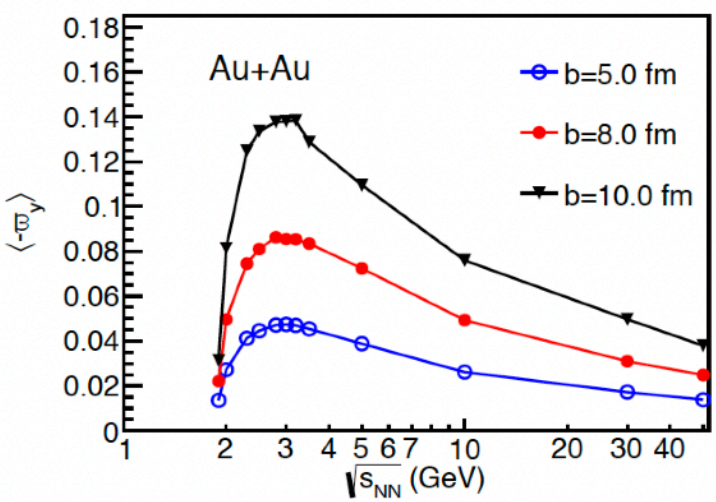
Somewhat surprisingly large signal at 3GeV …

$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

Digesting the STAR Results

URQMD

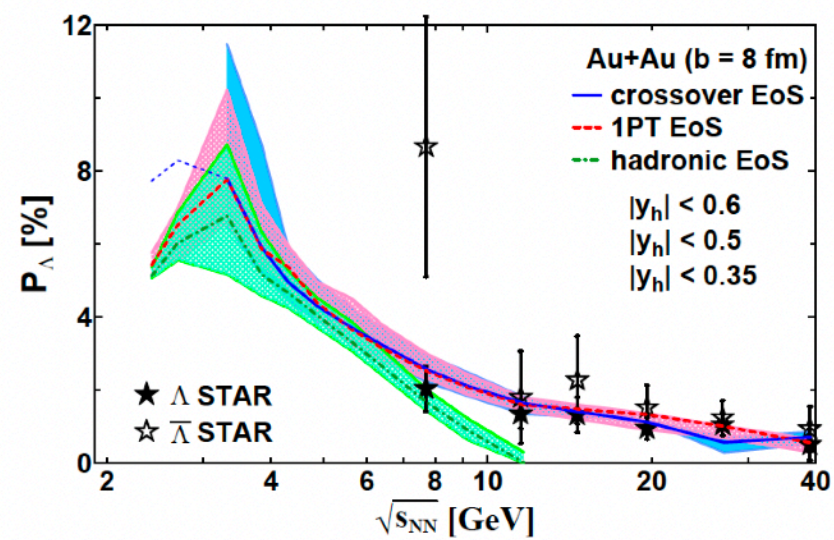
Deng, Huang, Ma, Zhang, arXiv:2001.01371



— only computed the vorticity
— URQMD & AMPT results for vorticity are CONSISTENT.

3FD

Ivanov, arXiv:2012.07597



— Many model details could be quite different
— No details of vorticity, freeze out, hyperon production
— Likely having more spectator-participant interactions
— Shall one worry about too much angular momentum?

Digesting the STAR Results

What can go "wrong" in calculating the hyperon global polarization?

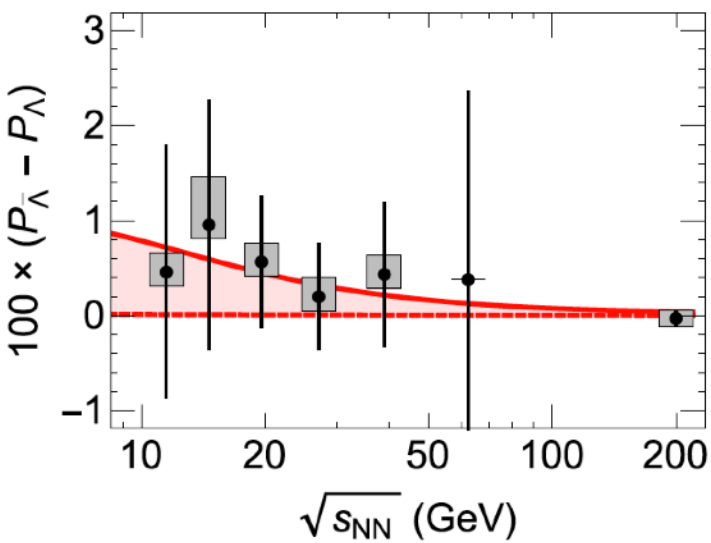
$$S^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\sigma} \frac{\int_{\Sigma} \mathrm{d}\Sigma \cdot p \varpi_{\nu\rho} n_F (1 - n_F)}{\int_{\Sigma} \mathrm{d}\Sigma \cdot p n_F}$$

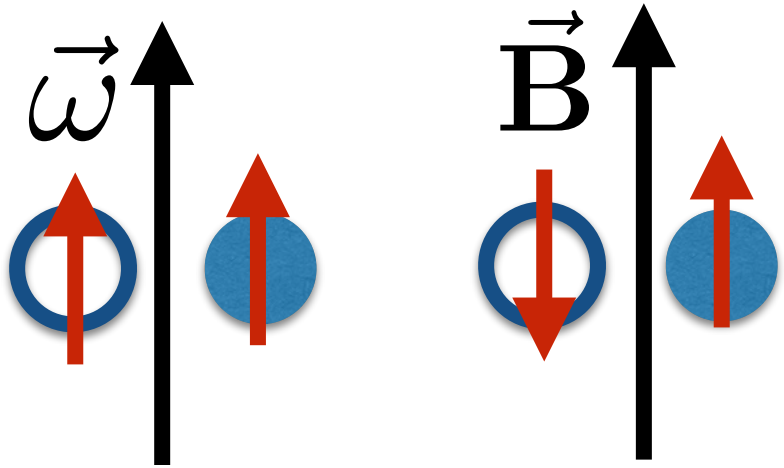
- ***complete fail of fluid-vorticity-polarization scenario***
- ***substantial out-of-equilibrium correction***
- ***inaccurate bulk fluid property (e.g. thermal vorticity)***
- ***particle production mechanism (e.g. hadronic versus partonic)***

The low AMPT signal could indicate:
A shift of dominance in hyperon production from partonic coalescence to direct hadronic reaction.

A Subatomic Version of Barnett Effect

A possible solution to a puzzle in STAR data at low energy: polarization difference between particle/anti-particle





$$\tilde{S}^{\mu} = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\nu}\left[\varpi_{\rho\sigma} \mp 2(eF_{\rho\sigma})\mu_{\Lambda}/T_f\right]$$

Late-time magnetic field could explain the polarization difference;

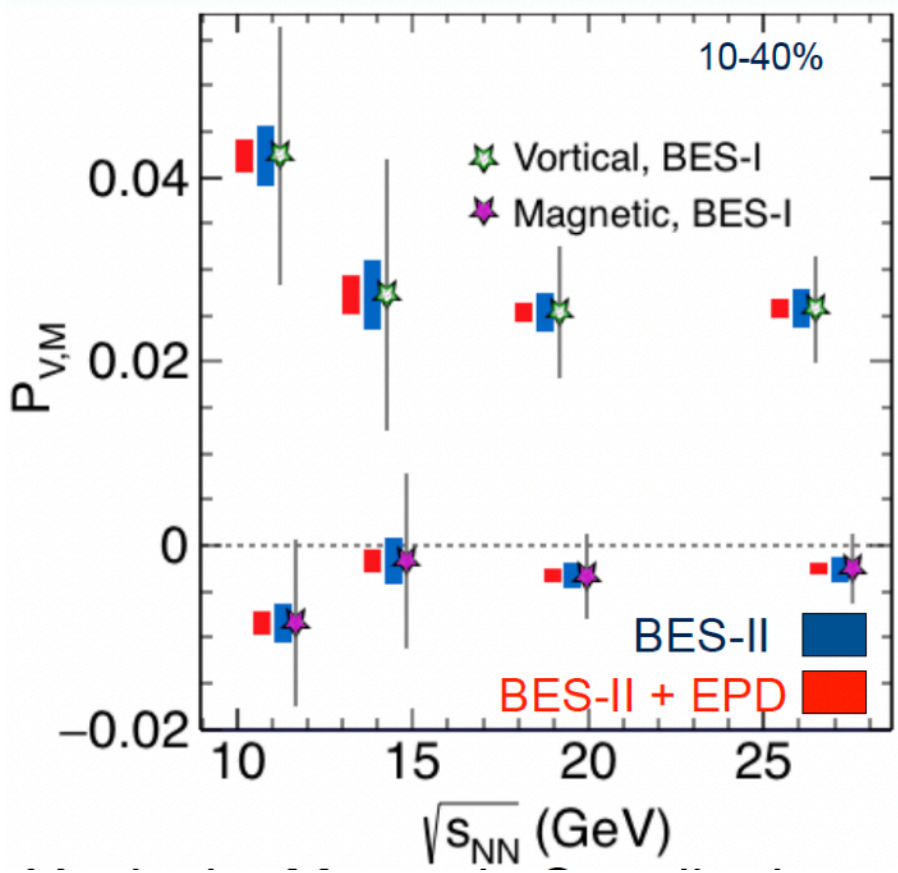
[Guo, Shi, Feng, JL, arXiv:1905.12613, PLB2019; Mueller, Schaefer, 1806.10907]

Charged rotating fluid contributes to late-time B field via Barnett-like mechanism.

[Guo, JL, Wang, arXiv:1904.04704, Scientific Reports 2020]

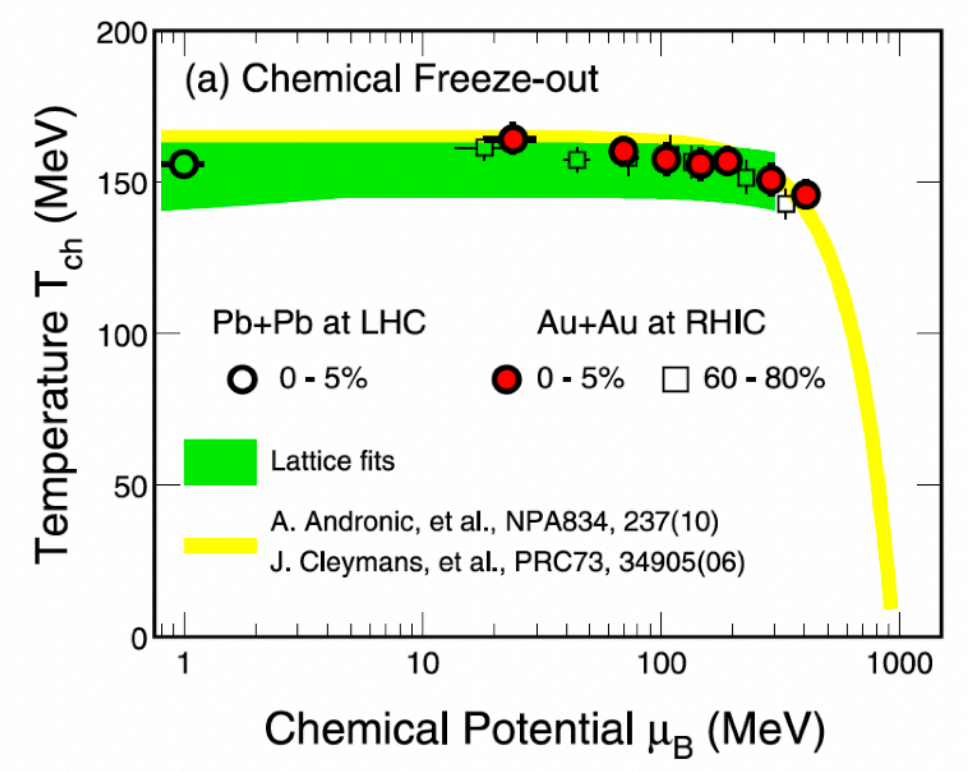
Accessing Magnetic Field at Low Energy

See Helen's talk on Monday



This may not just be about access to initial B-field, but more about access to dynamical in-medium B-field!

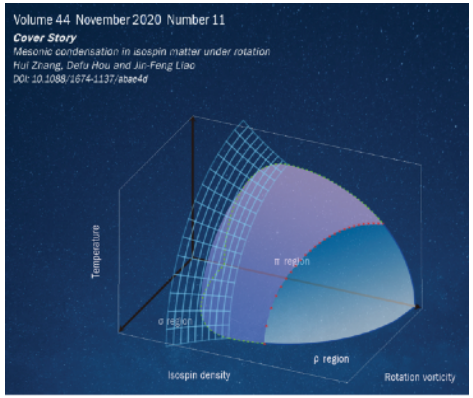
The Low Energy Region

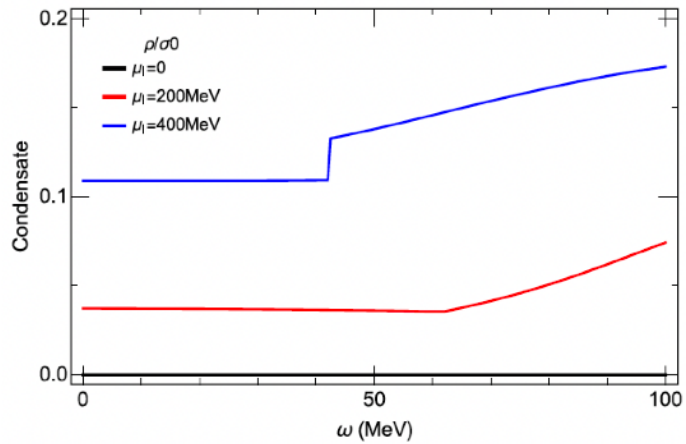


High baryon density
High vorticity field
High isospin density

Isospin Matter under Rotation

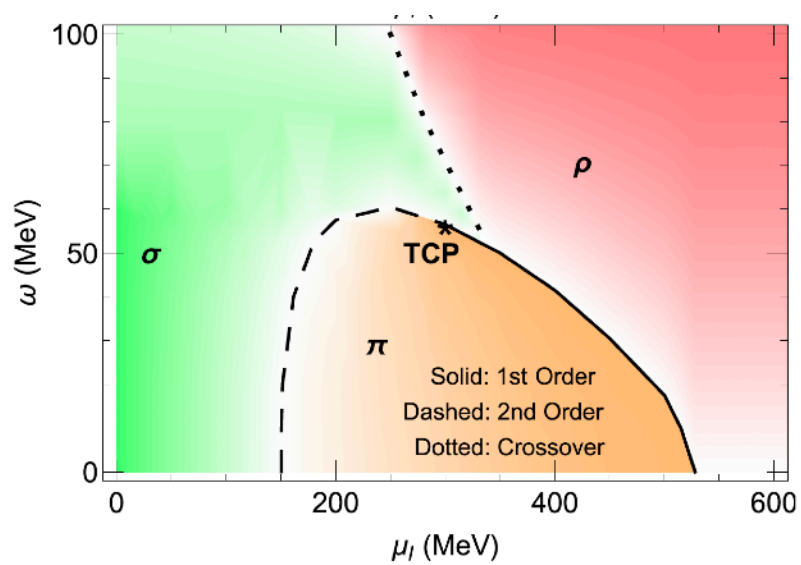
Vacuum: sigma condensate;
Static isospin matter: pion superfluidity;
Isospin matter under rotation: emergence of rho condensate!
This effect is more significant at high baryon density.





[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Rich phase structures;
Relevant to low energy HIC or neutron star matter;
Look for properties that would be sensitive to rho!

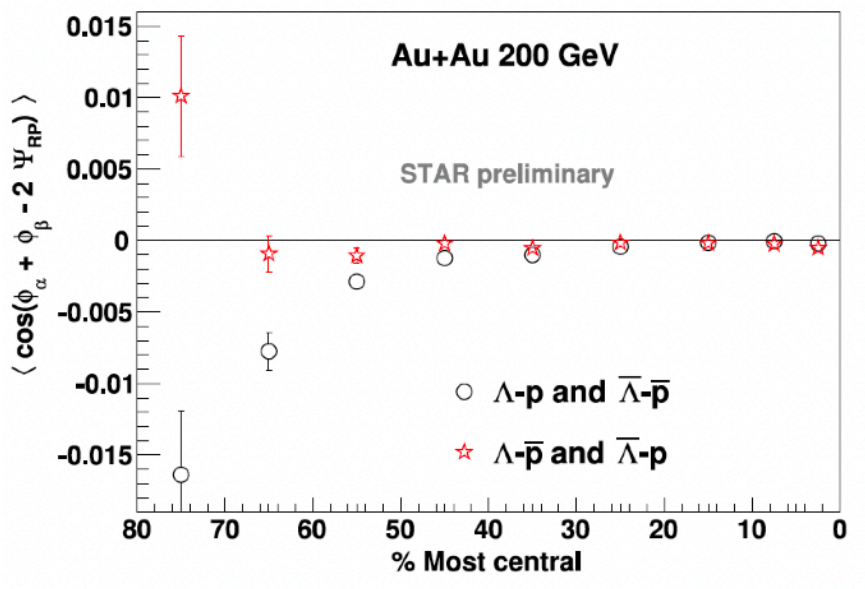


Chiral Vortical Effect

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

$$\vec{\mathbf{J}}_B^{3f} = \frac{N_c \mu_5}{2\pi^2}\left[0 \times (e\vec{\mathbf{B}}) + \frac{2}{3}(\mu_B \vec{\boldsymbol{\omega}})\right]$$

See more discussions in arXiv: 1511.04050

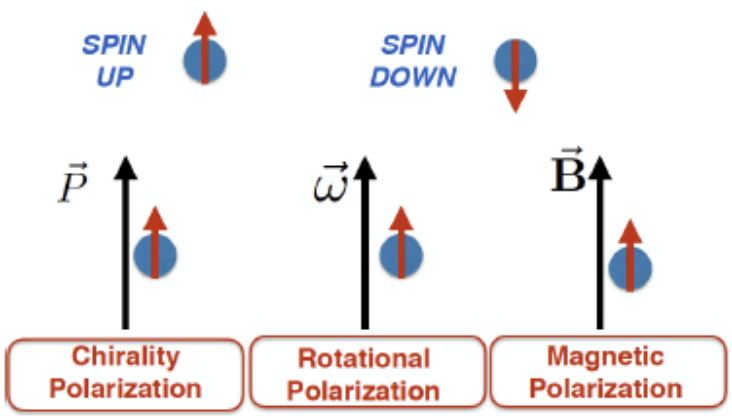
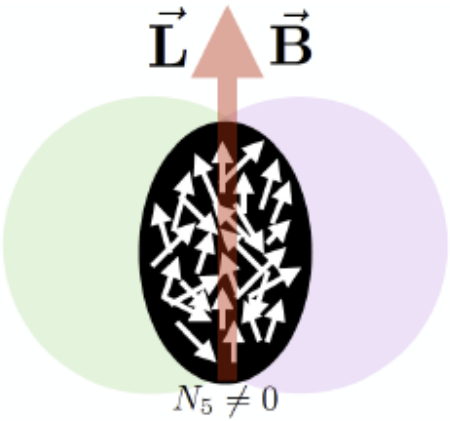


— It would be nice to have more CVE-related measurements, especially at low energy.
— One does not necessarily need both baryons and anti-baryons.
— One could simply look for an up-down asymmetry of all baryons along global angular momentum direction.

Summary

What Can We Learn from the Polarization Measurements at High Baryon Density?

- ***Angular momentum seems VERY efficiently turning into bulk fluid vorticity and spin polarization of produced particles.***

What Can We Do Next at High Baryon Density?

- ***New d.o.f.: a spin fluid with high angular momentum***
- ***Mapping the angular momentum transport***
- ***Spin phenomena such as polarization and chiral effect***
- ***Possible imprints on phase structures***