Hyperon Global Polarization in Nucleus-Nucleus Collisions at sub-10-GeV Beam Energy

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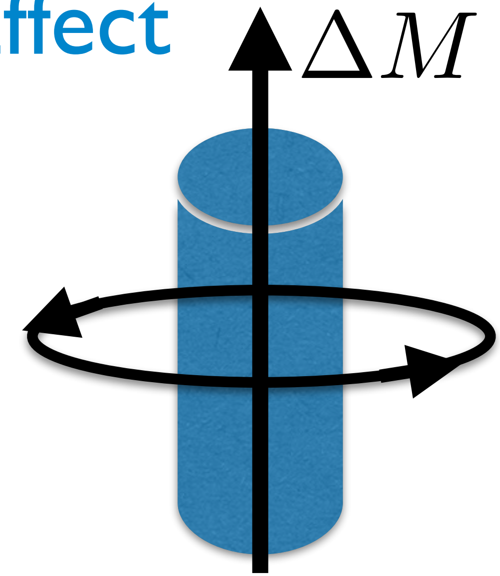
Research Supported by NSF & DOE

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.

Rotating solid sample
—> magnetization

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

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

THE

PHYSICAL REVIEW.

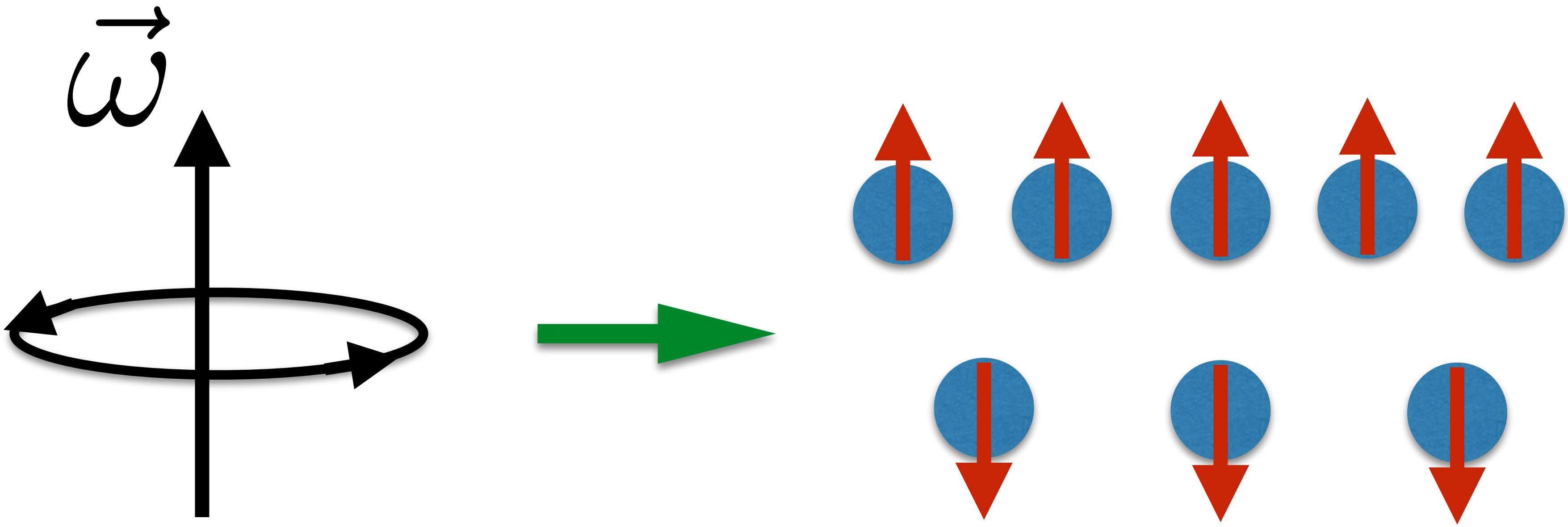
MAGNETIZATION BY ROTATION.[1]

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

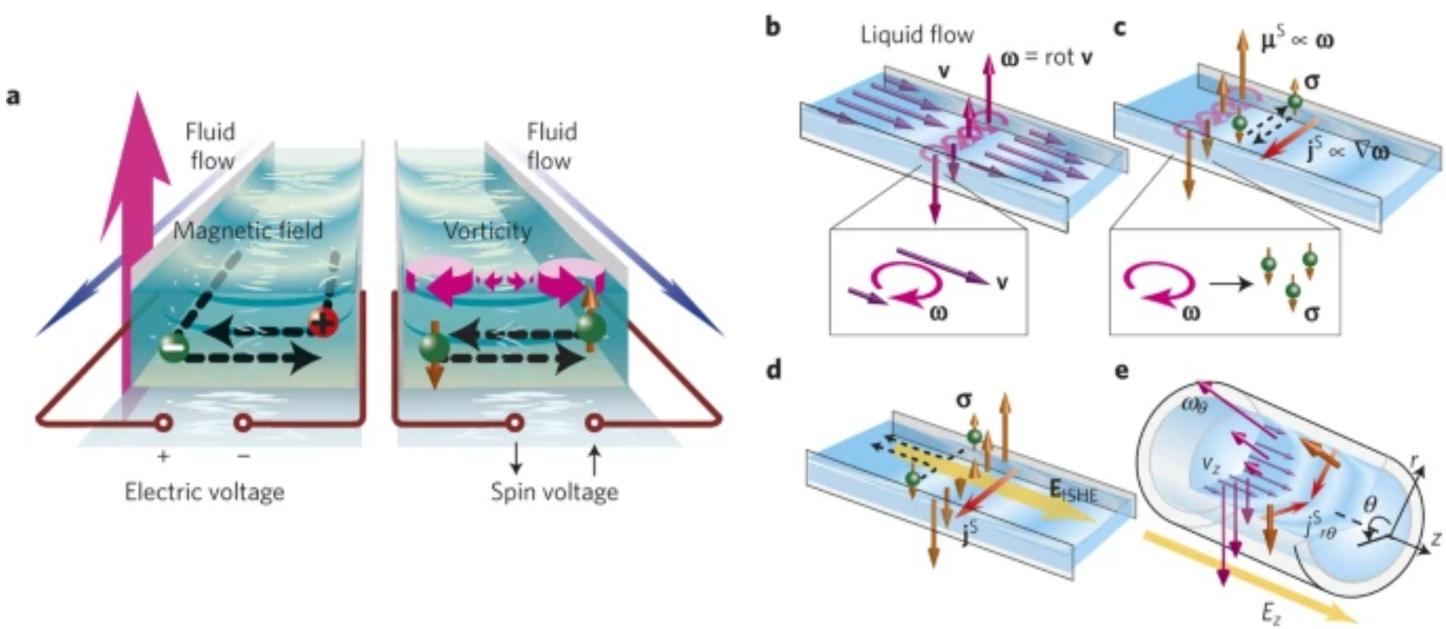
Spin hydrodynamic generation

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

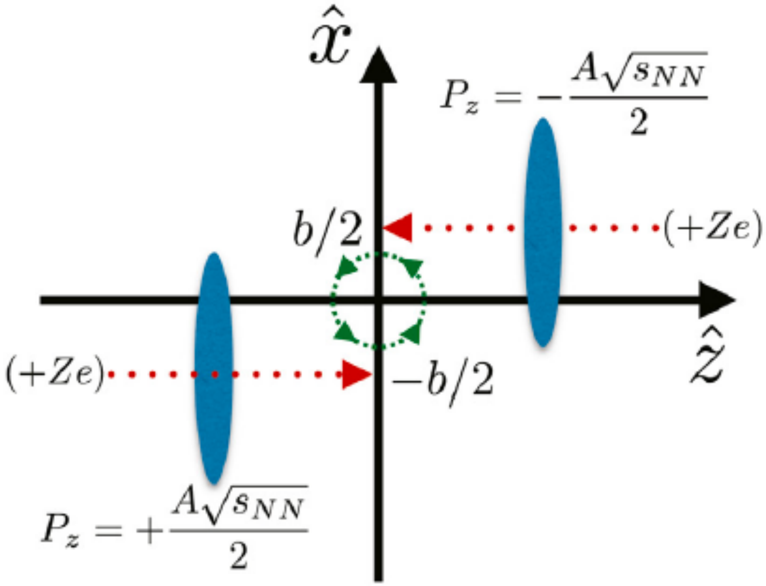
Nature Physics **12**, 52–56(2016) | Cite this article

Viscous fluid flow —> vorticity —> spin polarization

"Fluid Spintronics"



Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions

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

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

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

$$S^\mu = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\nu\varpi_{\rho\sigma} \qquad \varpi_{\mu\nu} = \frac{1}{2}\left[\partial_\nu\left(\frac{1}{T}u_\mu\right) - \partial_\mu\left(\frac{1}{T}u_\nu\right)\right]$$

"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*

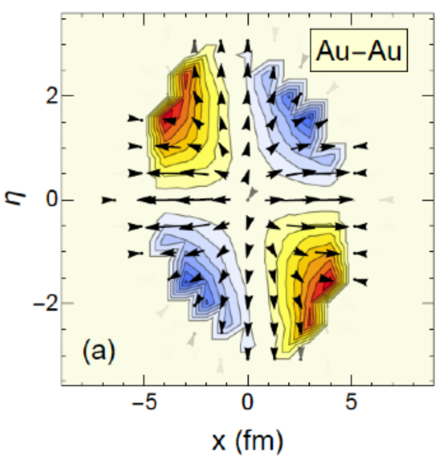
[2] *Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

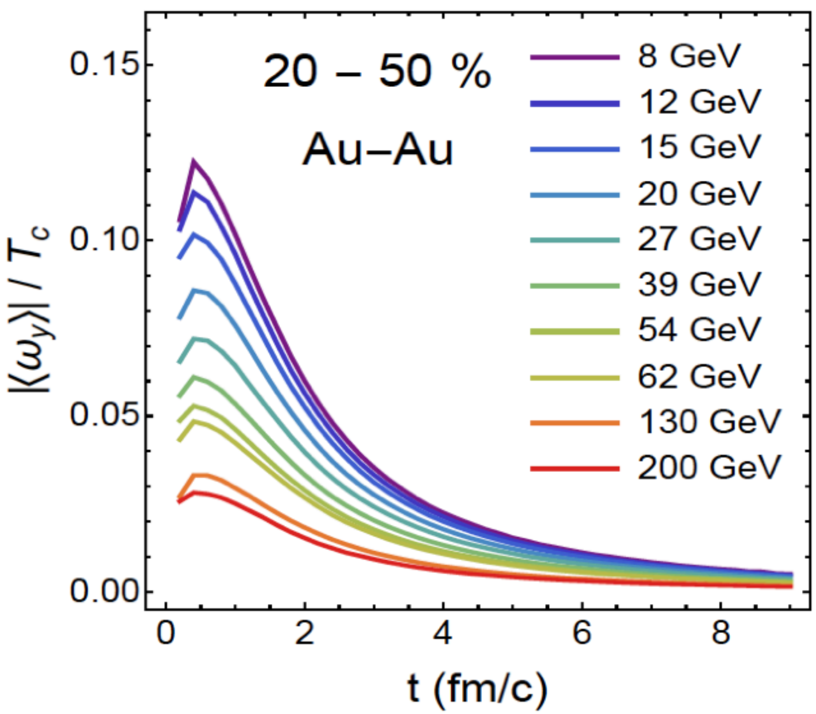
[3] *RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

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

Is this portion conserved? —YES!

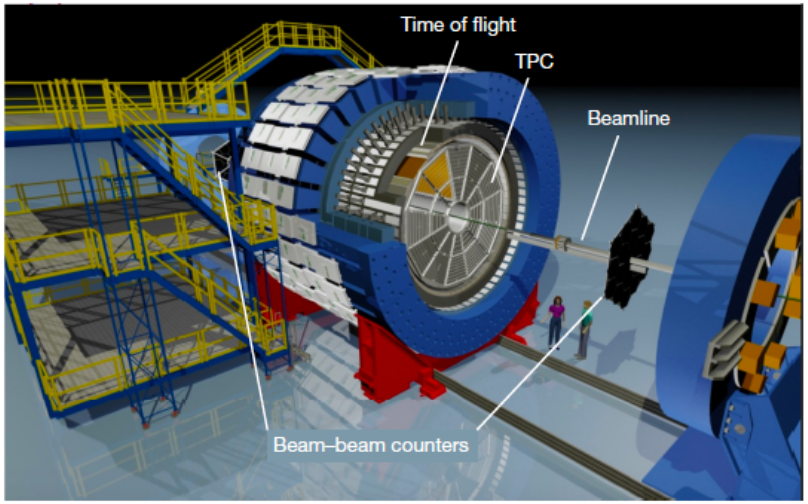
How QGP accommodates this angular momentum? — Fluid vorticity!





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

The Most Vortical Fluid



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

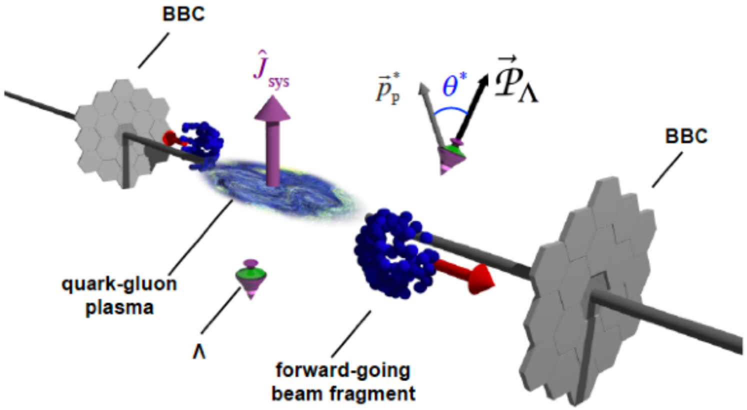
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

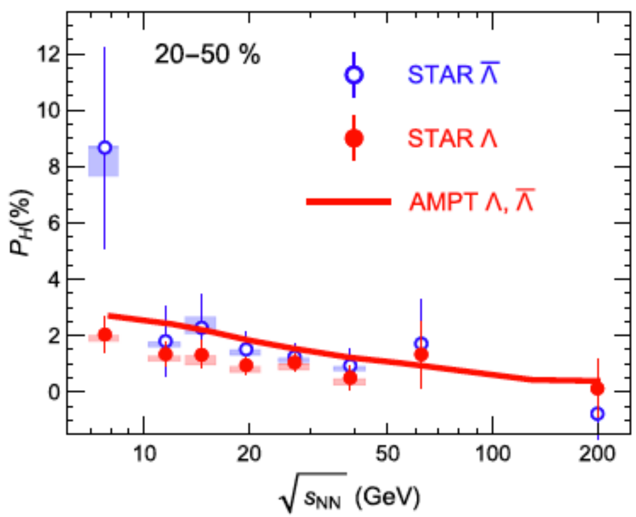
Spin Polarization in the Subatomic Swirls

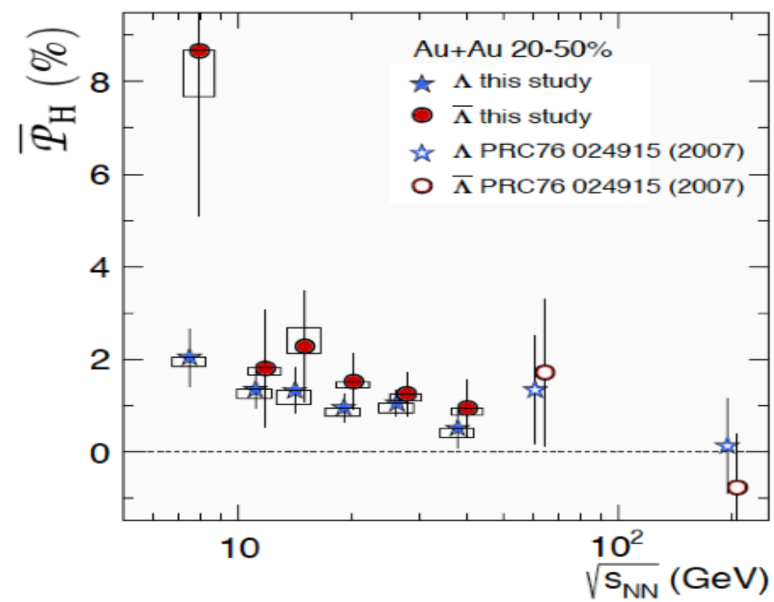


STAR Collaboration, Nature 2017

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

The most vortical fluid!



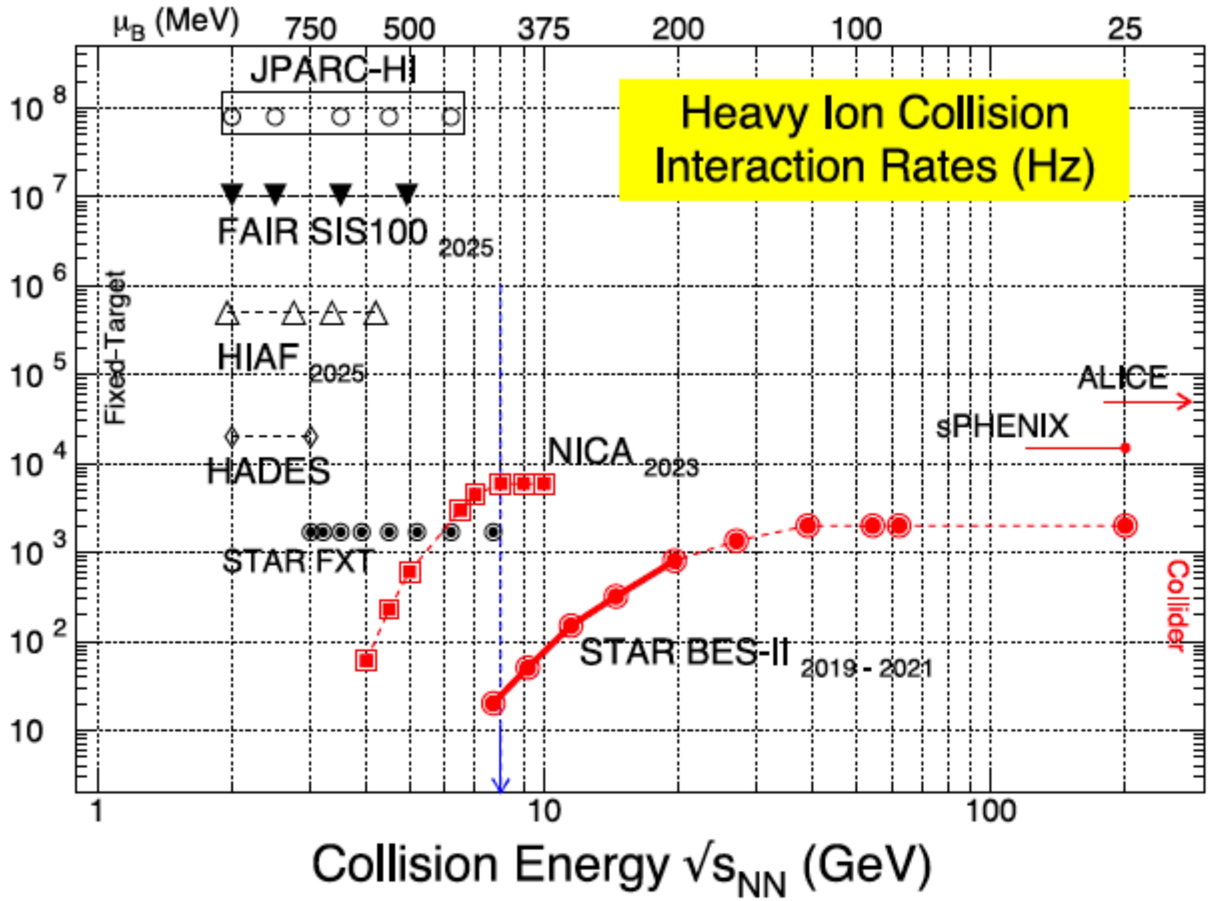


Many calculations based on hydro or transport models

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

Relativistic Nuclear Collisions @ O(1-10) GeV

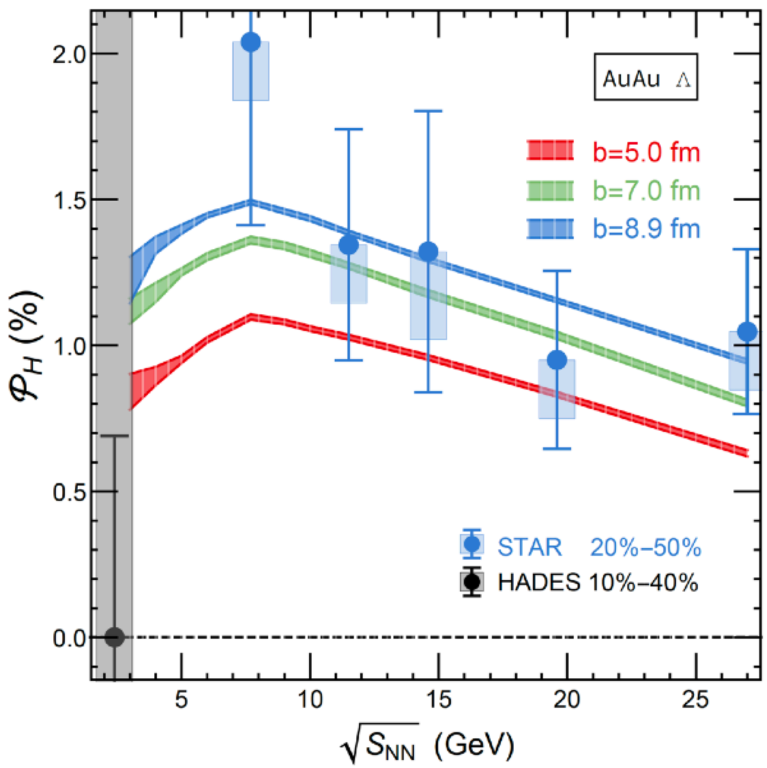
A number of current and planned experiments will explore the O(1) GeV regime of relativistic nuclear collisions

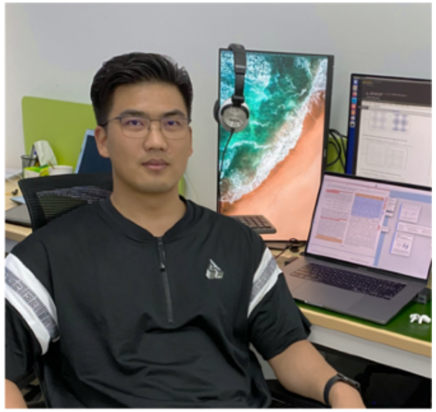


"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87.

Locating THE Most Vortical Fluid !

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





Yu Guo, et al: to appear soon.

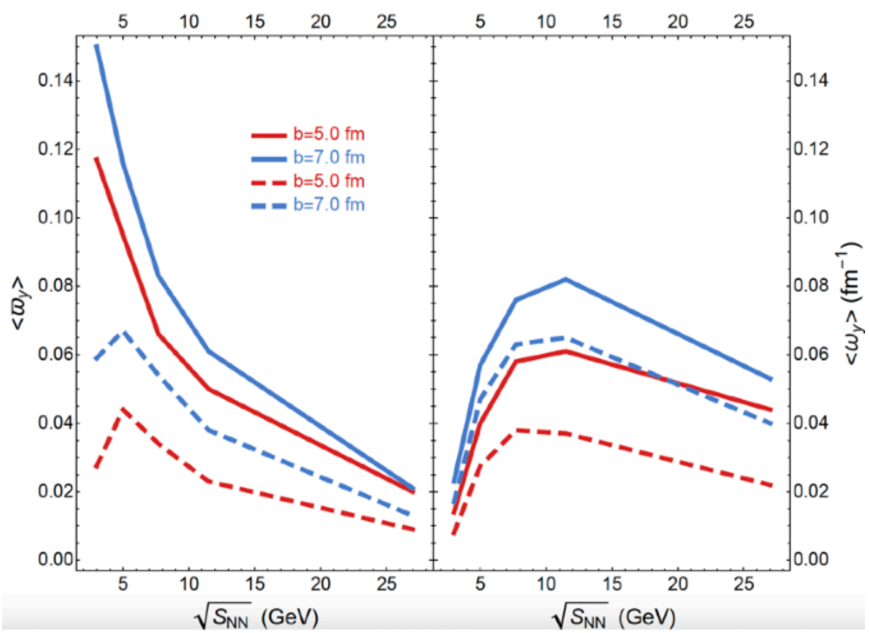
Calculations predict non-monotonic behavior in the dependence of global polarization on beam energy —> maximum around 7.7 GeV !

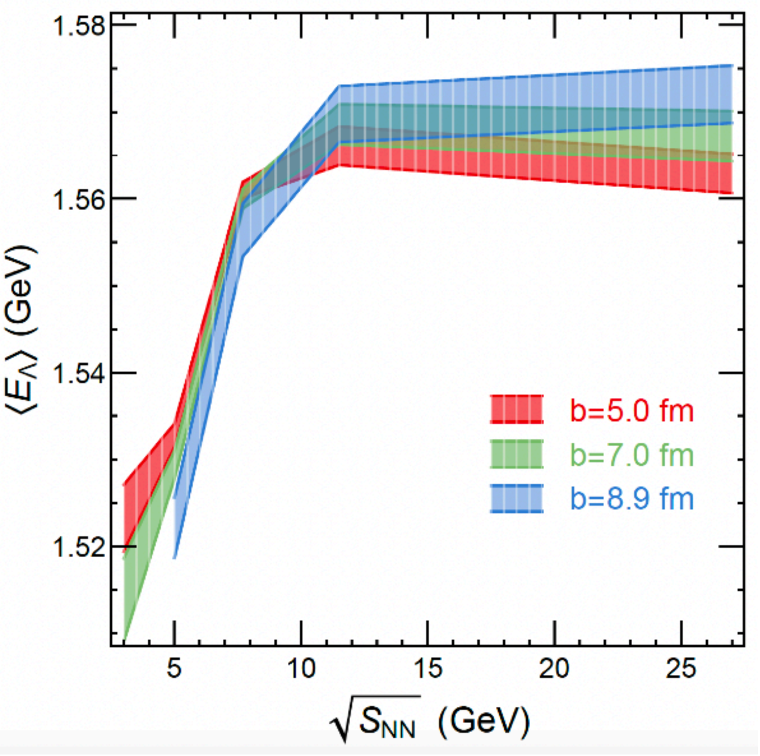
Why the Decrease toward O(1) GeV?

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

Strong decrease toward O(1) GeV region in both vorticity and produced hyperon energy

Yu Guo, et al: to appear soon.

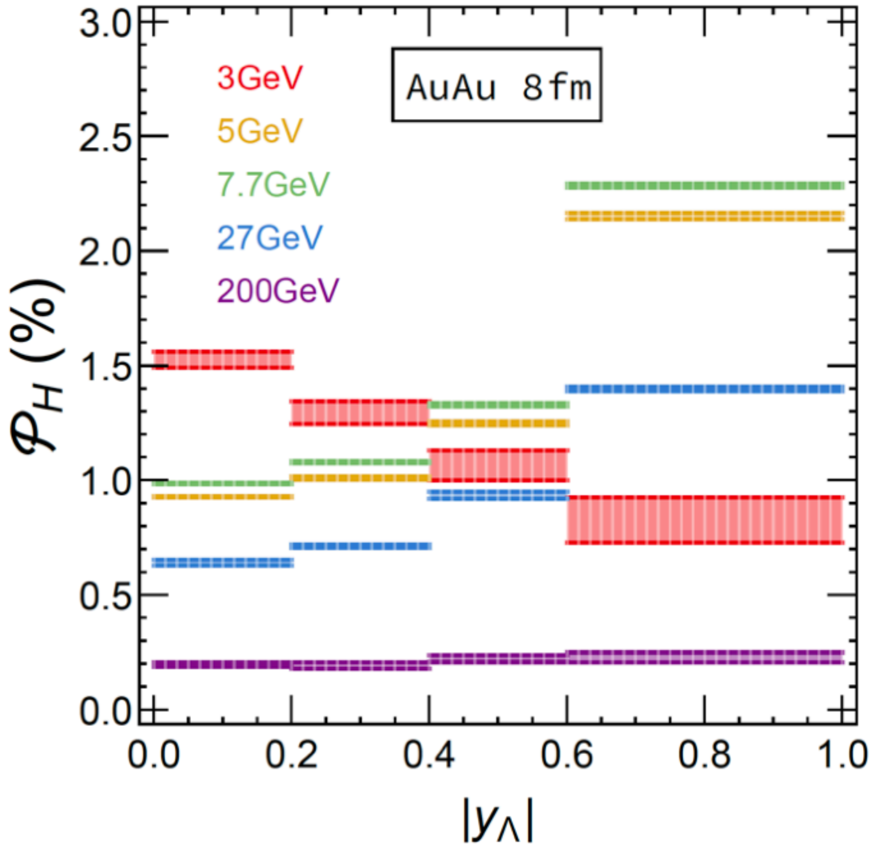




[For vorticity, see also URQMD results in: Deng, Huang, Ma, Zhang, arXiv:2001.01371]

Differential Behavior of Global Polarization

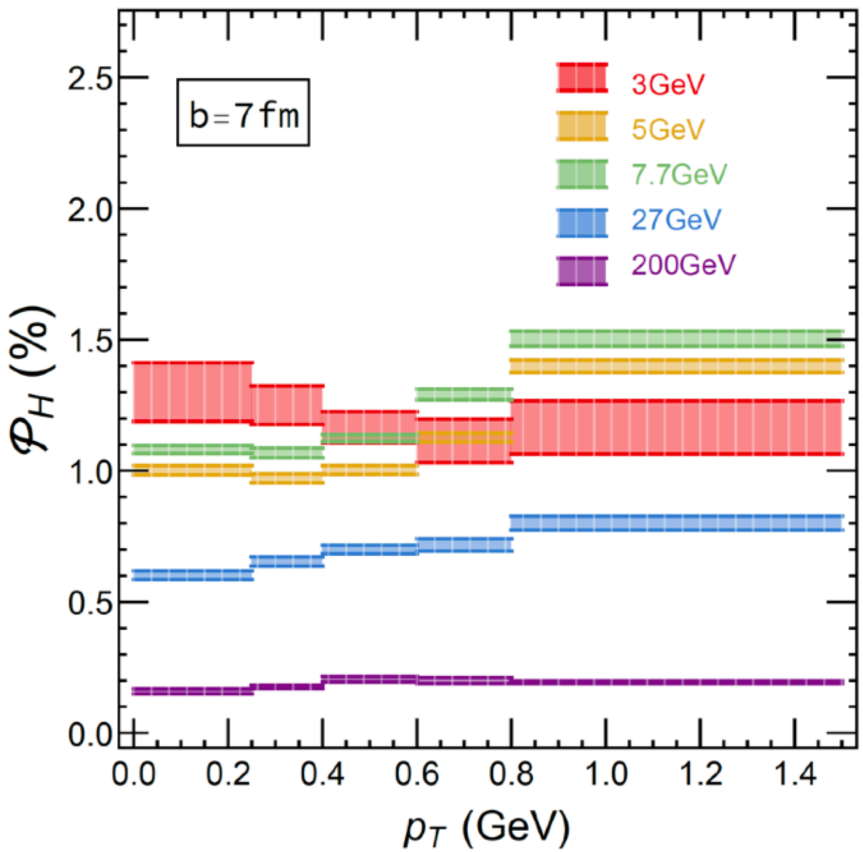
Yu Guo, et al: to appear soon.



Interesting change of pattern @ 3 GeV

Differential Behavior of Global Polarization

Yu Guo, et al: to appear soon.

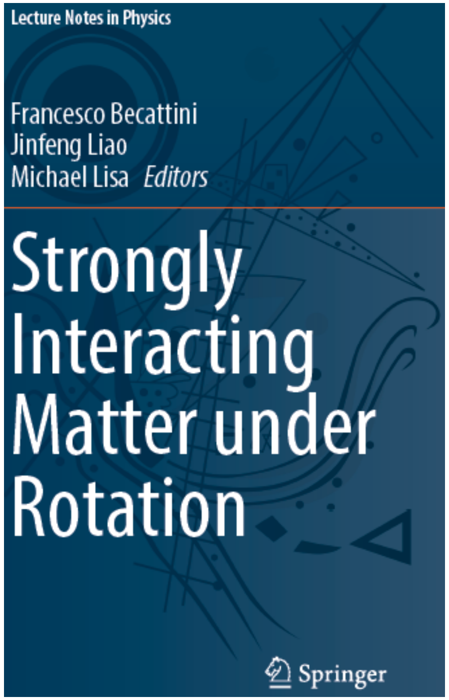


Interesting change of pattern @ 3 GeV

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?***
- ***……***

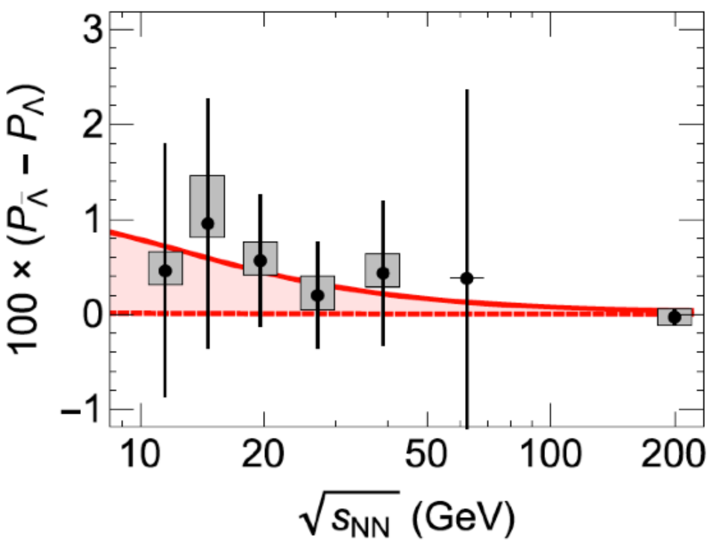


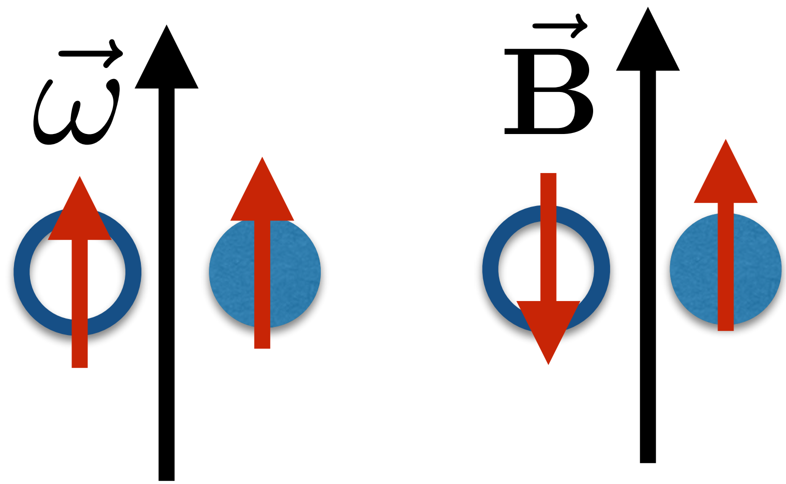
Many exciting new developments: see upcoming volume in Springer Lecture Notes in Physics!

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

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;

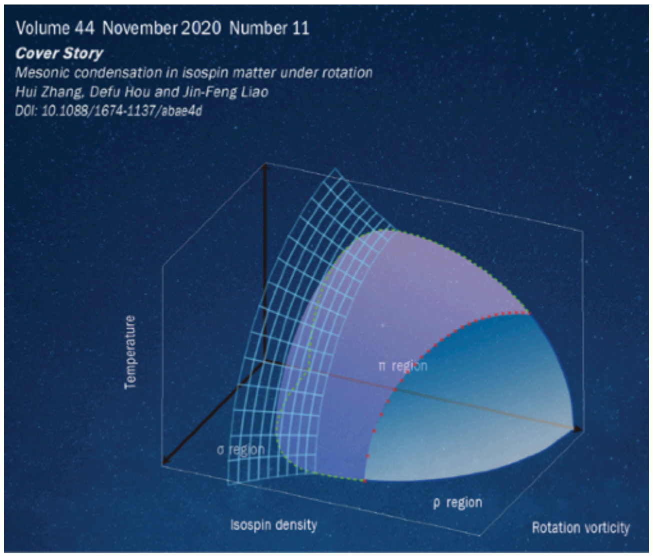
[Guo, Shi, Feng, JL, arXiv:1905.12613, PLB2019]

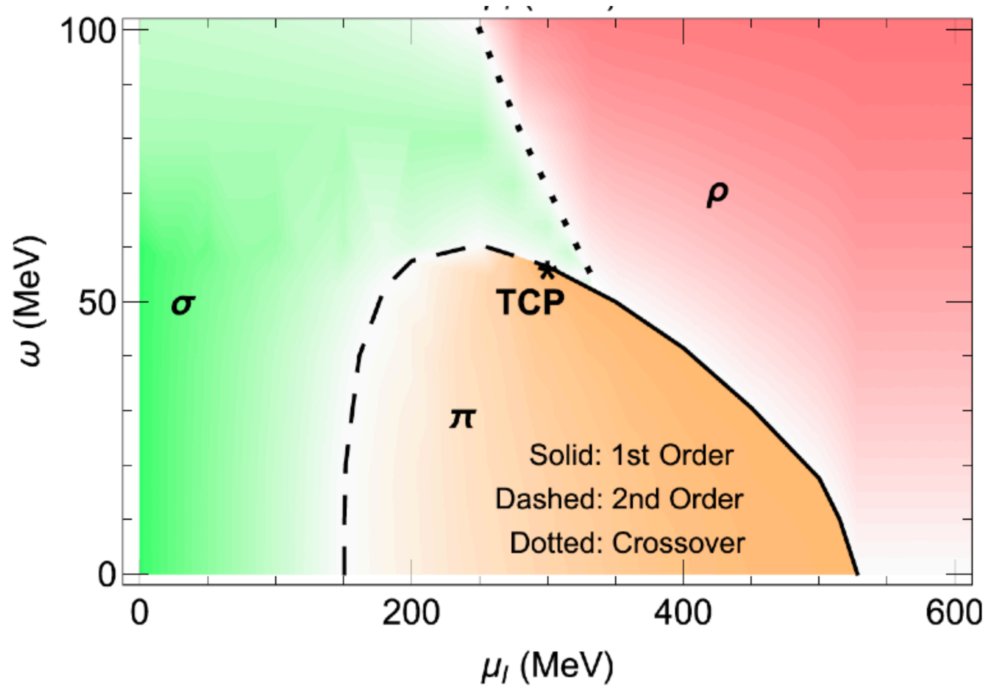
Charged rotating fluid contributes to late-time B field via Barnett-like mechanism.

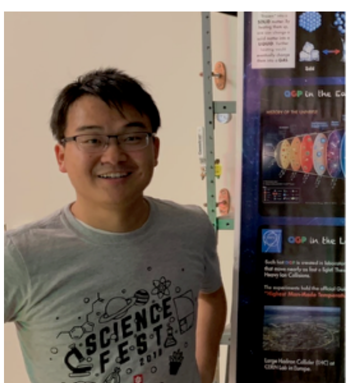
[Guo, JL, Wang, arXiv:1904.04704, Scientific Reports 2020]

Isospin Matter under Rotation

Vacuum: sigma condensate;
Static isospin matter: pion superfluidity;
Isospin matter under rotation: emergence of rho condensate!



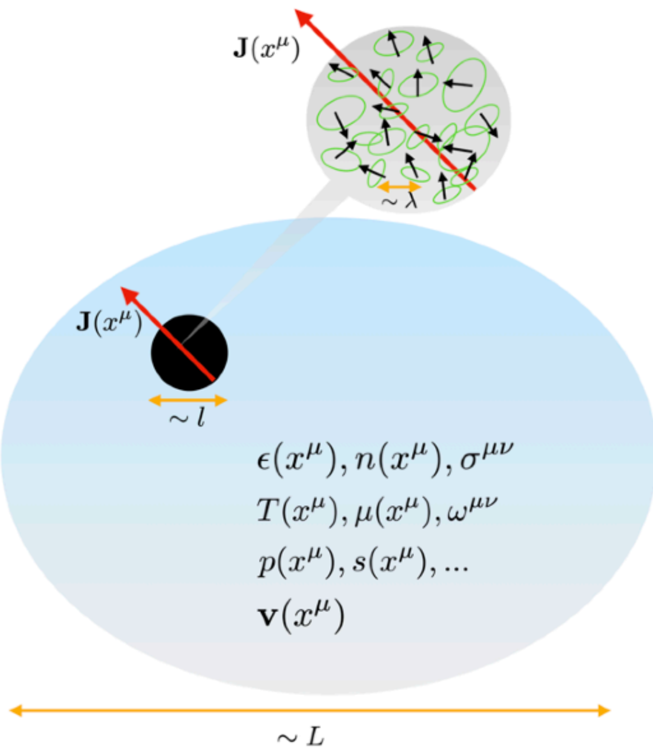




Rich phase structures found;
Could be relevant to low energy HIC
or neutron star matter;
Look for properties sensitive to rho!

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

Viscous Hydro with Angular Momentum



$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + \widetilde{\Sigma}^{\mu\alpha\beta}$$

$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + 2u^{[\alpha}\Delta^{\mu\beta]}\Phi + 2u^{[\alpha}\tau_{(s)}^{\mu\beta]} + 2u^{[\alpha}\tau_{(a)}^{\mu\beta]} + \Theta^{\mu\alpha\beta}.$$

$$\Phi = -\chi_1 u^\alpha \nabla^\beta \left(\frac{\omega_{\alpha\beta}}{T}\right), \quad (25)$$

$$\tau_{(s)}^{\mu\beta} = -\chi_2 u^\alpha \left[\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} + \Delta^{\mu\rho}\Delta^{\beta\gamma}\right) - \frac{2}{3}\Delta^{\mu\beta}g^{\rho\gamma}\right] \nabla_\gamma \left(\frac{\omega_{\alpha\rho}}{T}\right) \quad (26)$$

$$\tau_{(a)}^{\mu\beta} = -\chi_3 u^\alpha \left(\Delta^{\beta\rho}\Delta^{\mu\gamma} - \Delta^{\mu\rho}\Delta^{\beta\gamma}\right) \nabla_\gamma \left(\frac{\omega_{\alpha\rho}}{T}\right), \quad (27)$$

$$\Theta^{\mu\alpha\beta} = -\chi_4 \left(u^\beta u^\rho \Delta^{\alpha\delta} - u^\alpha u^\rho \Delta^{\beta\delta}\right) \Delta^{\mu\gamma}\nabla_\gamma \left(\frac{\omega_{\delta\rho}}{T}\right) + \chi_5 \Delta^{\alpha\delta}\Delta^{\beta\rho}\Delta^{\mu\gamma}\nabla_\gamma \left(\frac{\omega_{\delta\rho}}{T}\right). \quad (28)$$

The 2nd law of thermodynamics helps fix the hydrodynamic terms for viscous transport of angular momentum at first order of gradient expansion.

Duan She, et al, arXiv:2105.04060

Summary

– *An interesting new regime for hyperon global polarization:*

O(10) —> O(1) GeV collisions with strong exp activities

– *Calculations predict non-monotonic behavior in this regime:*

Most vortical fluid around 7.7 GeV;

Differential pattern change around 3 GeV

Yu Guo, et al: to appear soon.

– *An interesting regime for exploring magnetic polarization*

– *An interesting regime for isospin matter under rotation*

– *Many theoretical questions to be fully explored!*