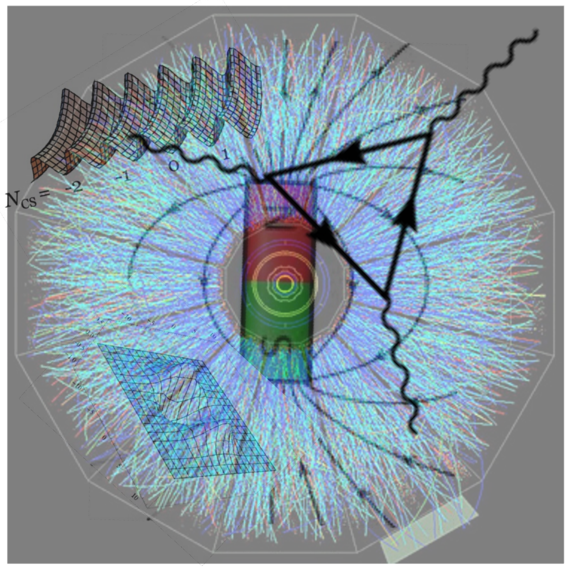
25TH INTERNATIONAL
SPIN PHYSICS
SYMPOSIUM

Sep. 25, 2023

The Most Spinning Baryonic Matter

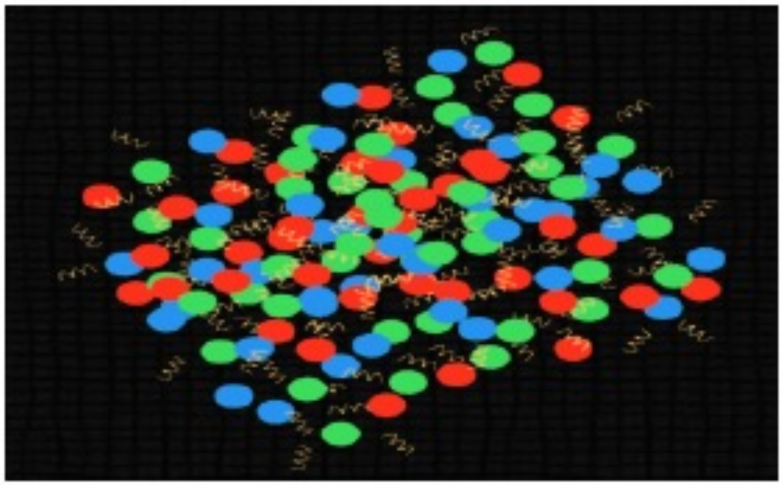


Jinfeng Liao

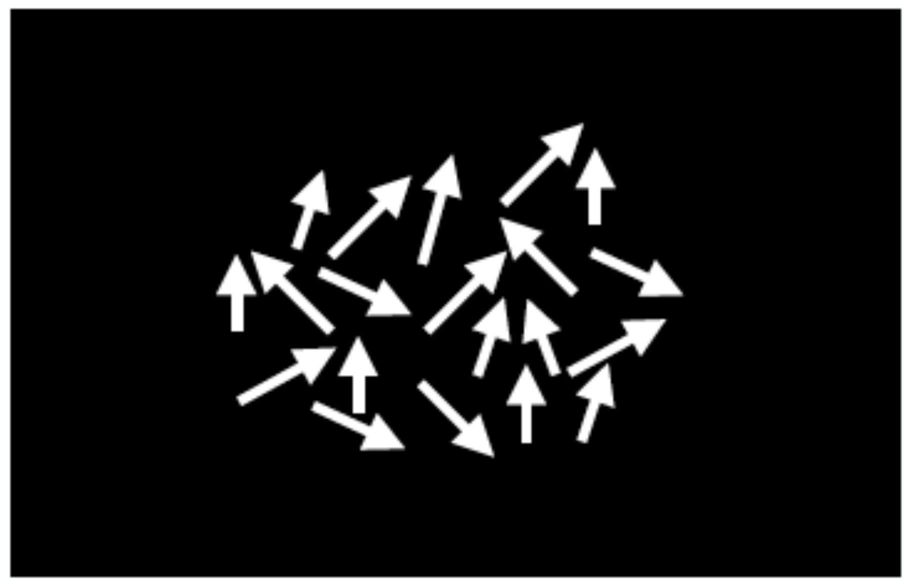
ndiana University, Physics Dept. & CEEM

A Quantum Fluid of Spin in HIC

A nearly perfect fluid (of energy-momentum)

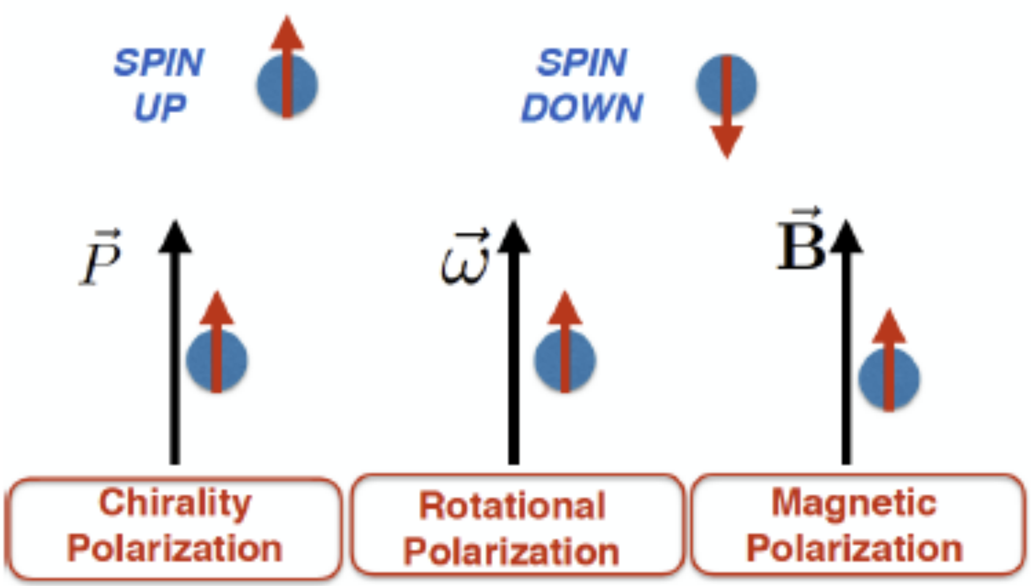


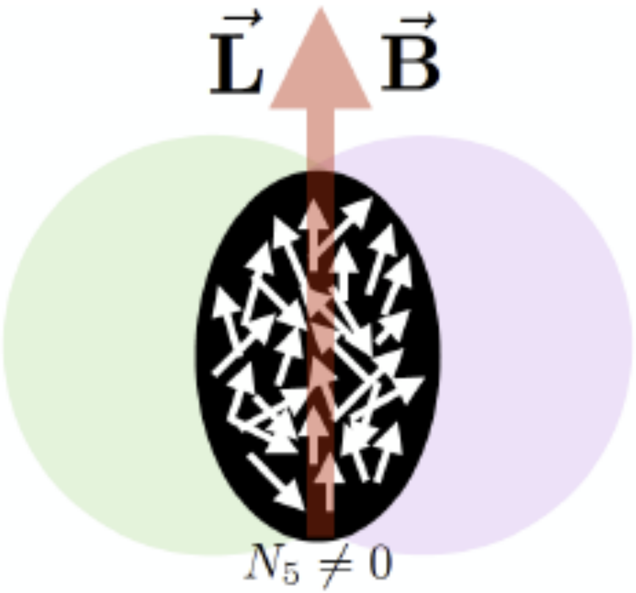
What happens to the spin DoF in the fluid???



Spin transport in a quantum fluid!

Spin @ Chirality, Vorticity and Magnetic Field

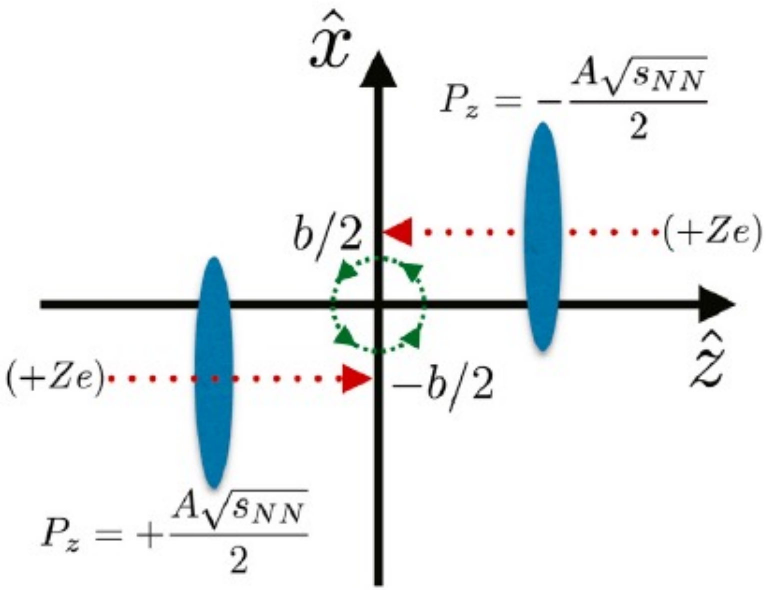




[arXiv:2004.00569]

The interplay of spin with chirality/vorticity/magnetic field
—> many novel phenomena across disciplines

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

Betz, Gyulassy, Torrieri ~ 2007: quantitative assessment of the effect

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

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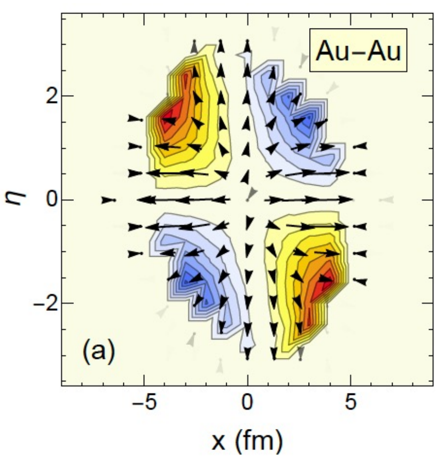
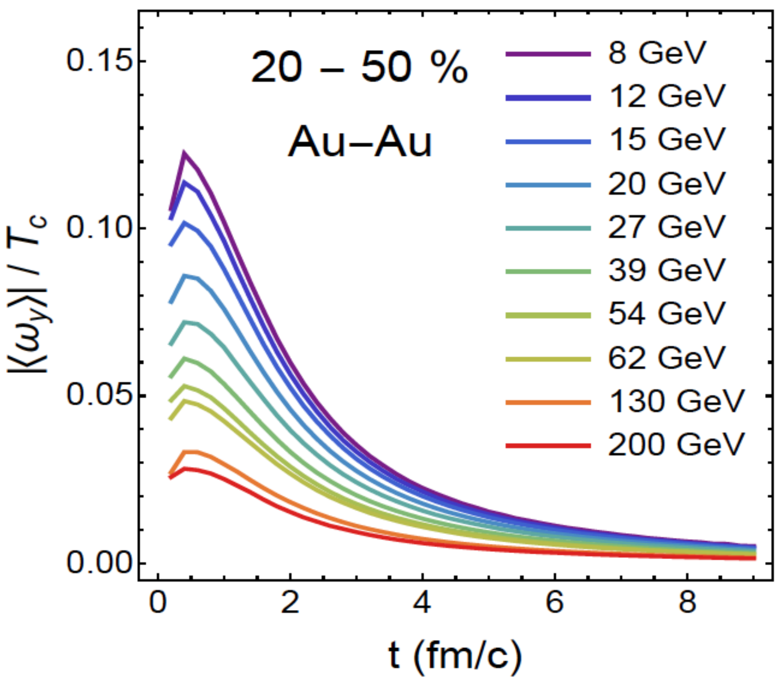
What fraction stays in fireball?
— up to ~20%, strongly depending on collision energy.

Is this portion conserved?
—YES!

How QGP accommodates this angular momentum?
— Fluid vorticity!

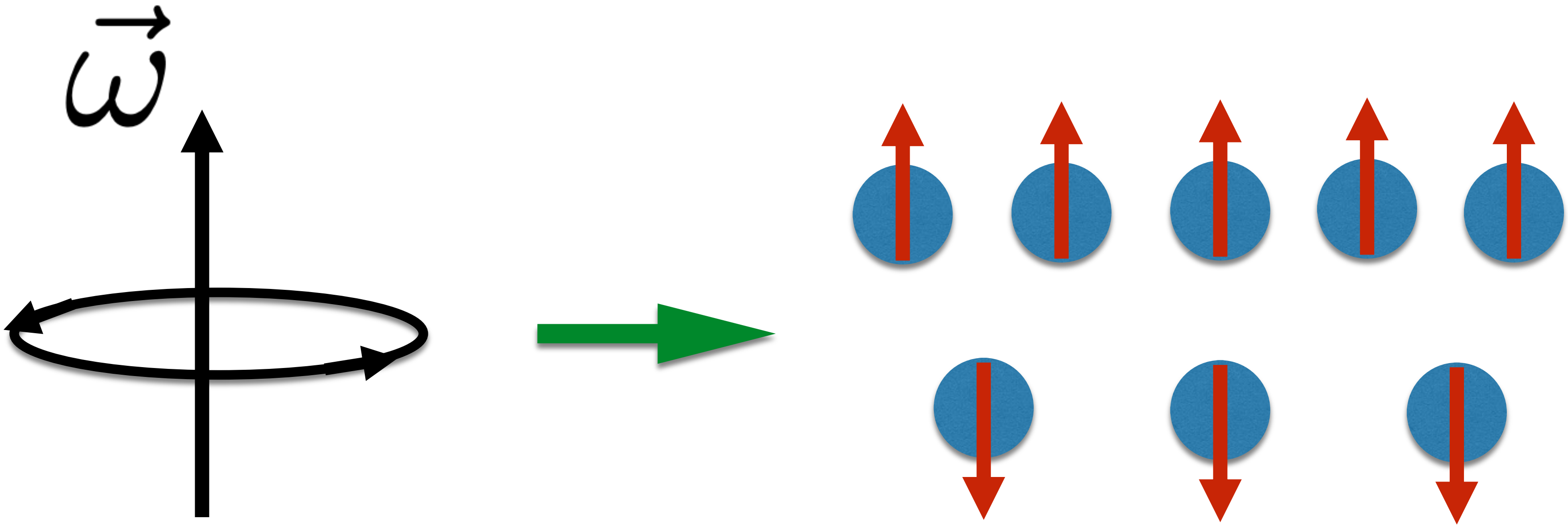




Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization

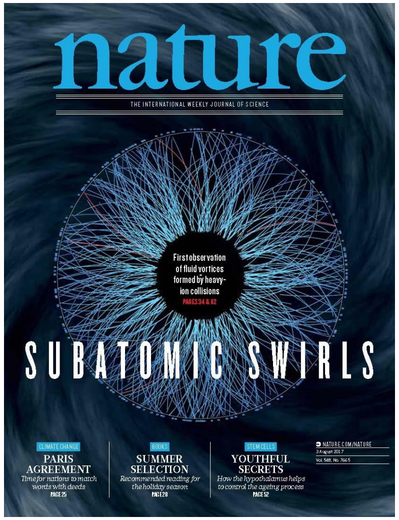


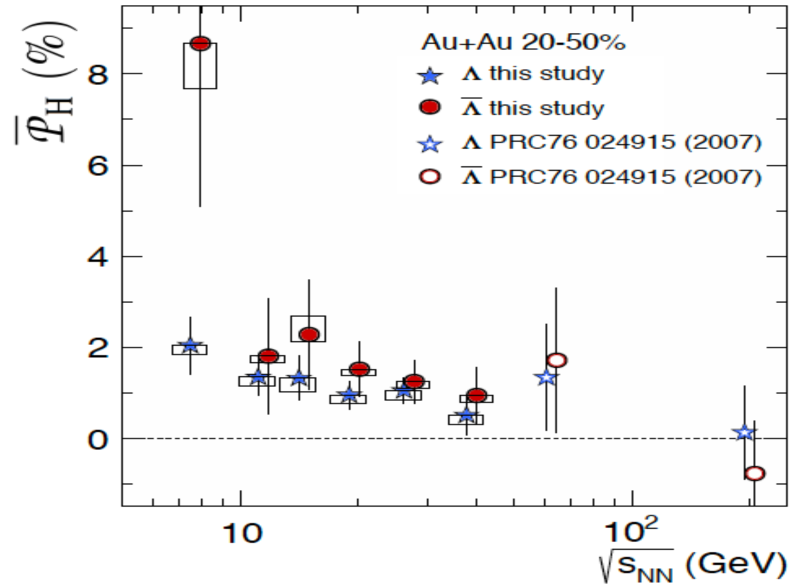
Macroscopic rotation; Global angular momentum

Microscopic spin alignment

"Fluid spintronics" in condensed matter systems

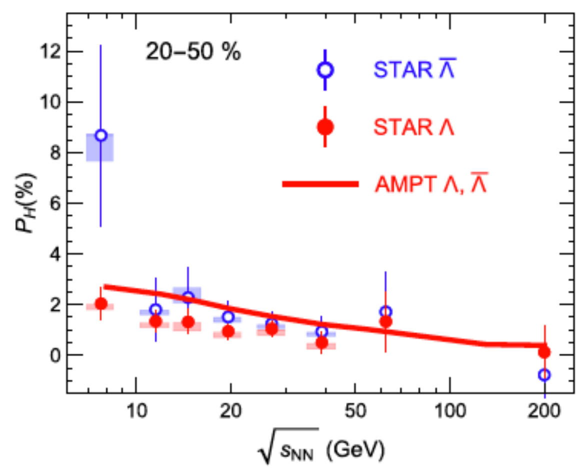
The Most Vortical Fluid





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

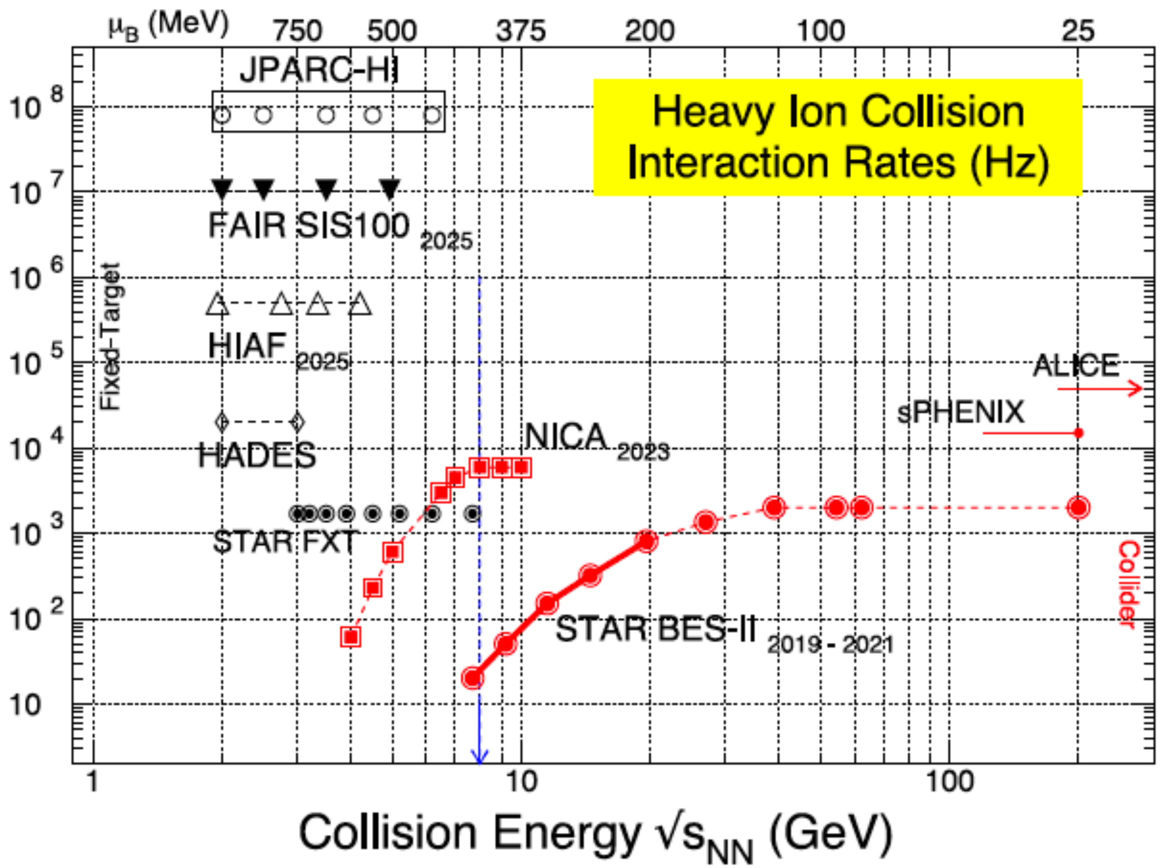
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$



Many calculations based on hydro or transport models

Relativistic Nuclear Collisions @ O(1-10) GeV

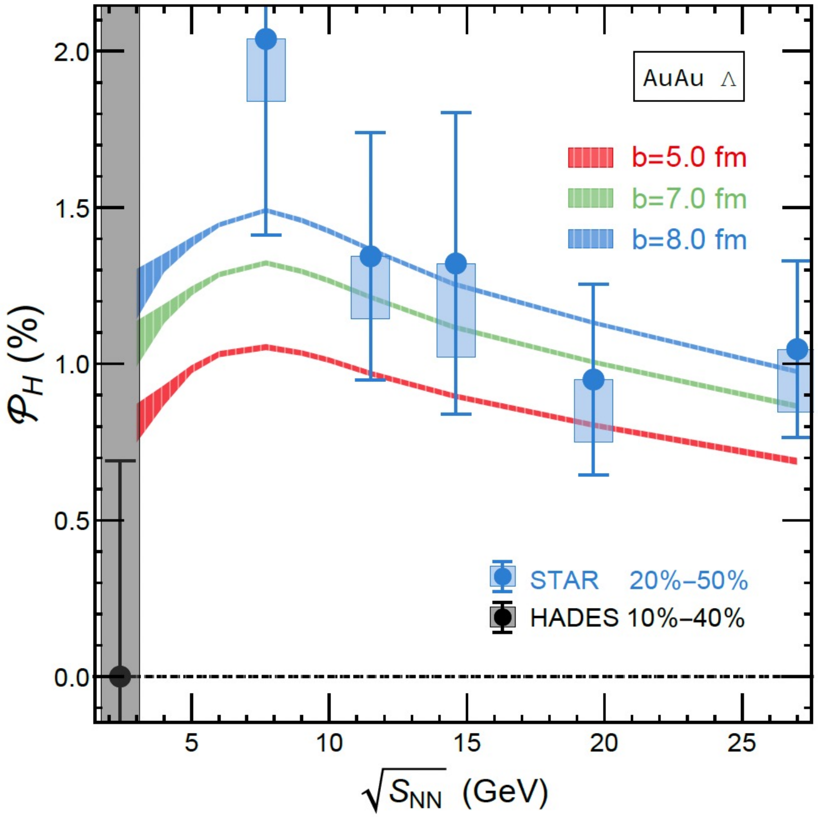
A number of current and planned experiments will explore the O(1) GeV regime of relativistic nuclear collisions



"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 ???



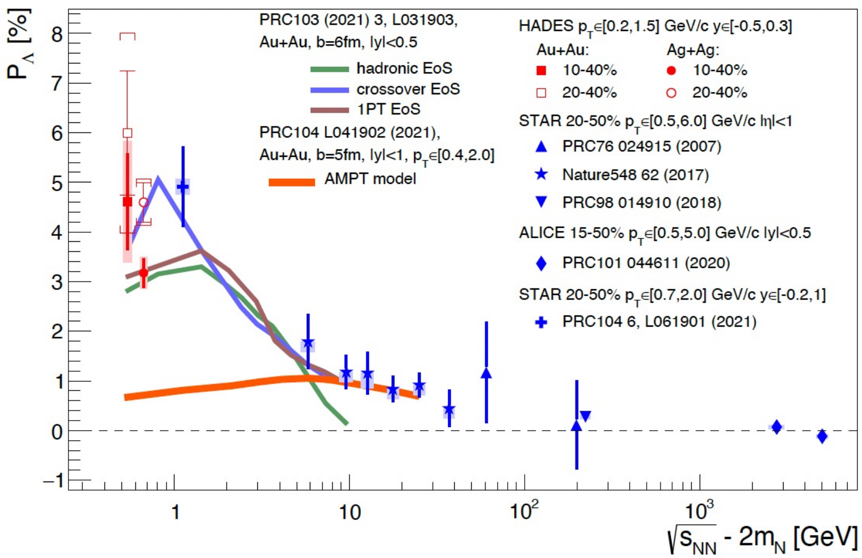
Yu Guo, et al, PRC2021 arXiv:2105.13481

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

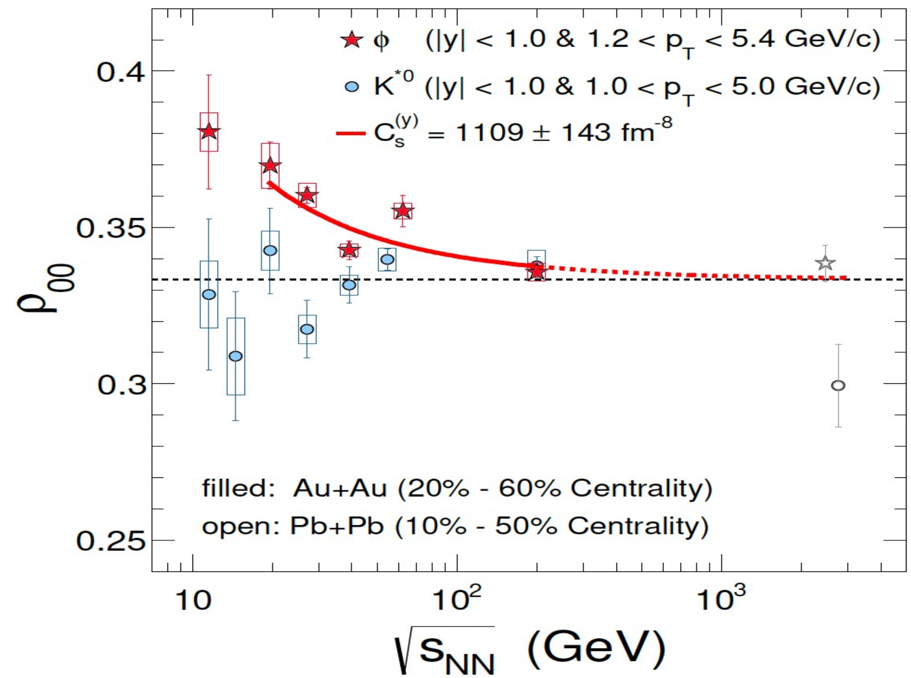
See also results for differential dependence and local polarization in the paper.

Highly Polarized Fluid at Low Beam Energy

HADES, arXiv: 2207.05160



STAR, Nature 2023,
arXiv: 2204.02302



Surprisingly large signal
even very close to threshold?!

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

How the fireball gets its angular momentum?

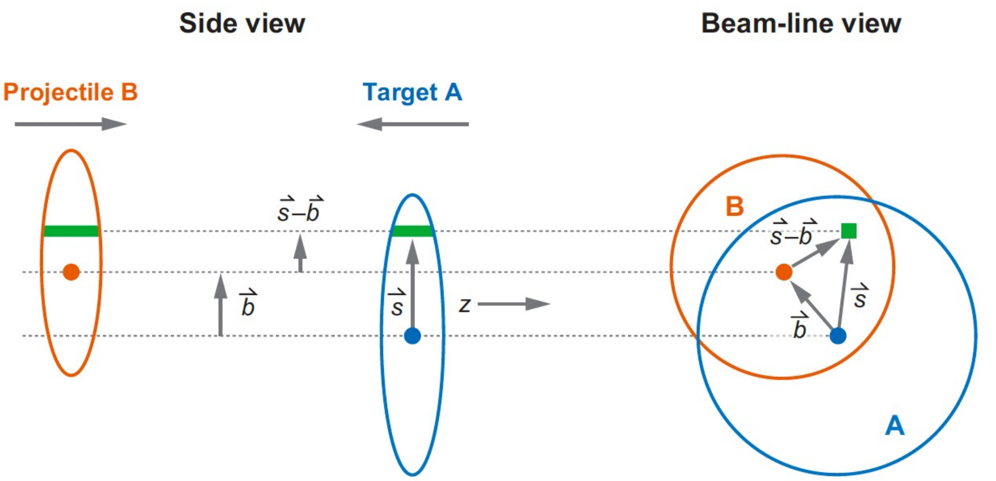
Nuclear Stopping & Angular Momentum

Total angular momentum monotonically increases with beam energy

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

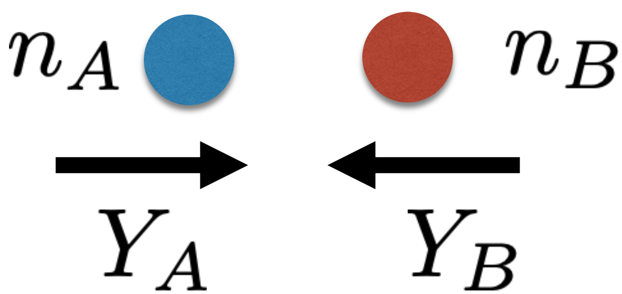
But what is relevant to measurements is the amount of angular momentum being stopped in mid rapidity.

This is quantitatively related to the baryon stoping and can be calibrated with baryon number measurements.

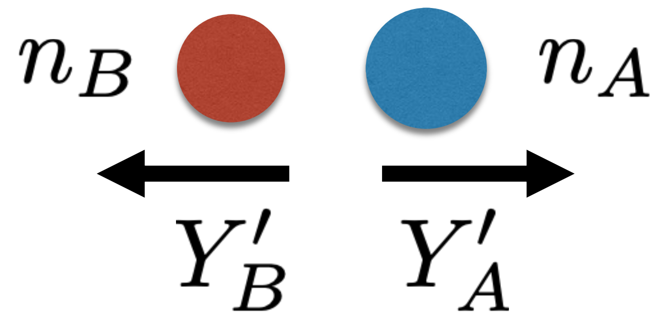


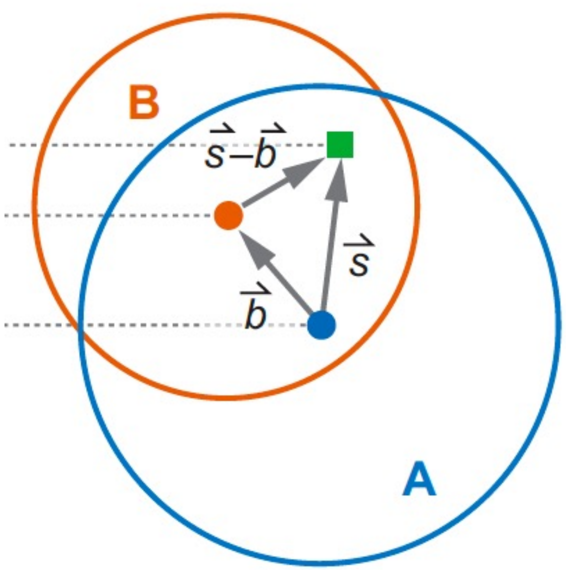
Nuclear Stopping & Angular Momentum

The key is to understand the rapidity loss in the initial collision.



$$e = \frac{Y'_B - Y'_A}{Y_B - Y_A}$$





Various spots on the overlapping zone —> A "spread-out" (i.e. distribution) along rapidity

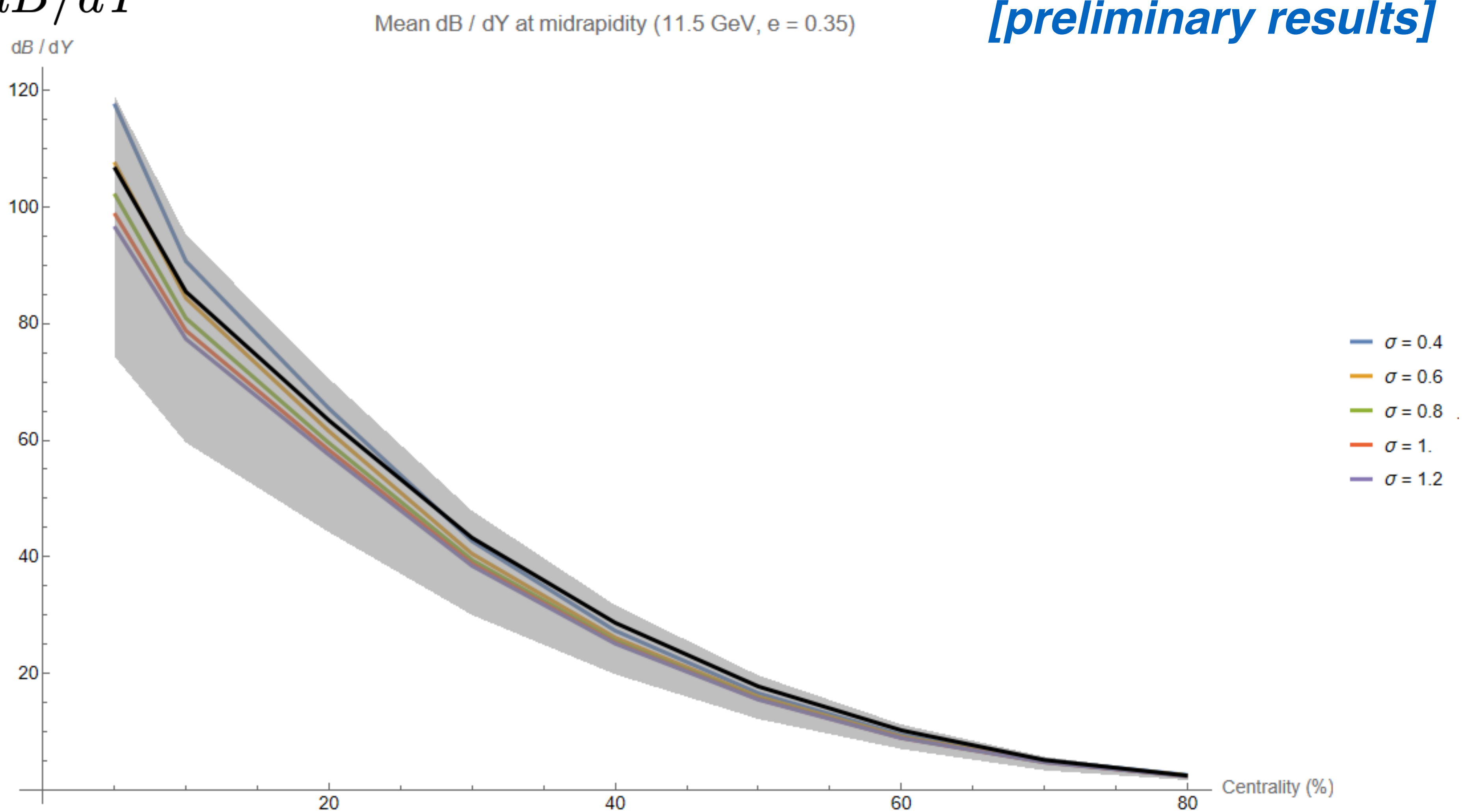
Fluctuations at each spot —> Additional "spread-out" along rapidity

Both net baryon and angular momentum come from this "spread-out"

Initial Rapidity Distribution

dB/dY

[preliminary results]

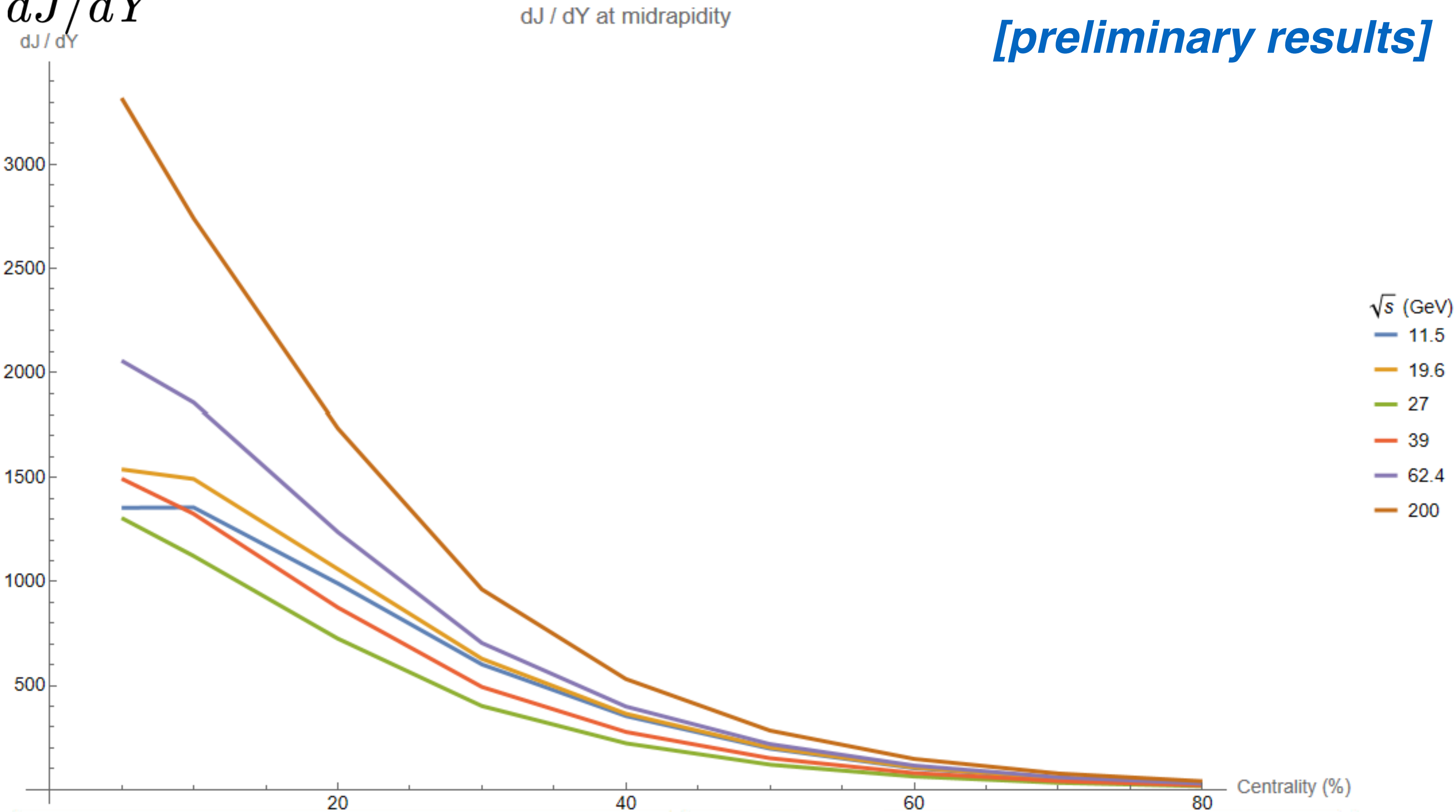


One could use measured net baryons to constrain stopping parameters

Initial Rapidity Distribution

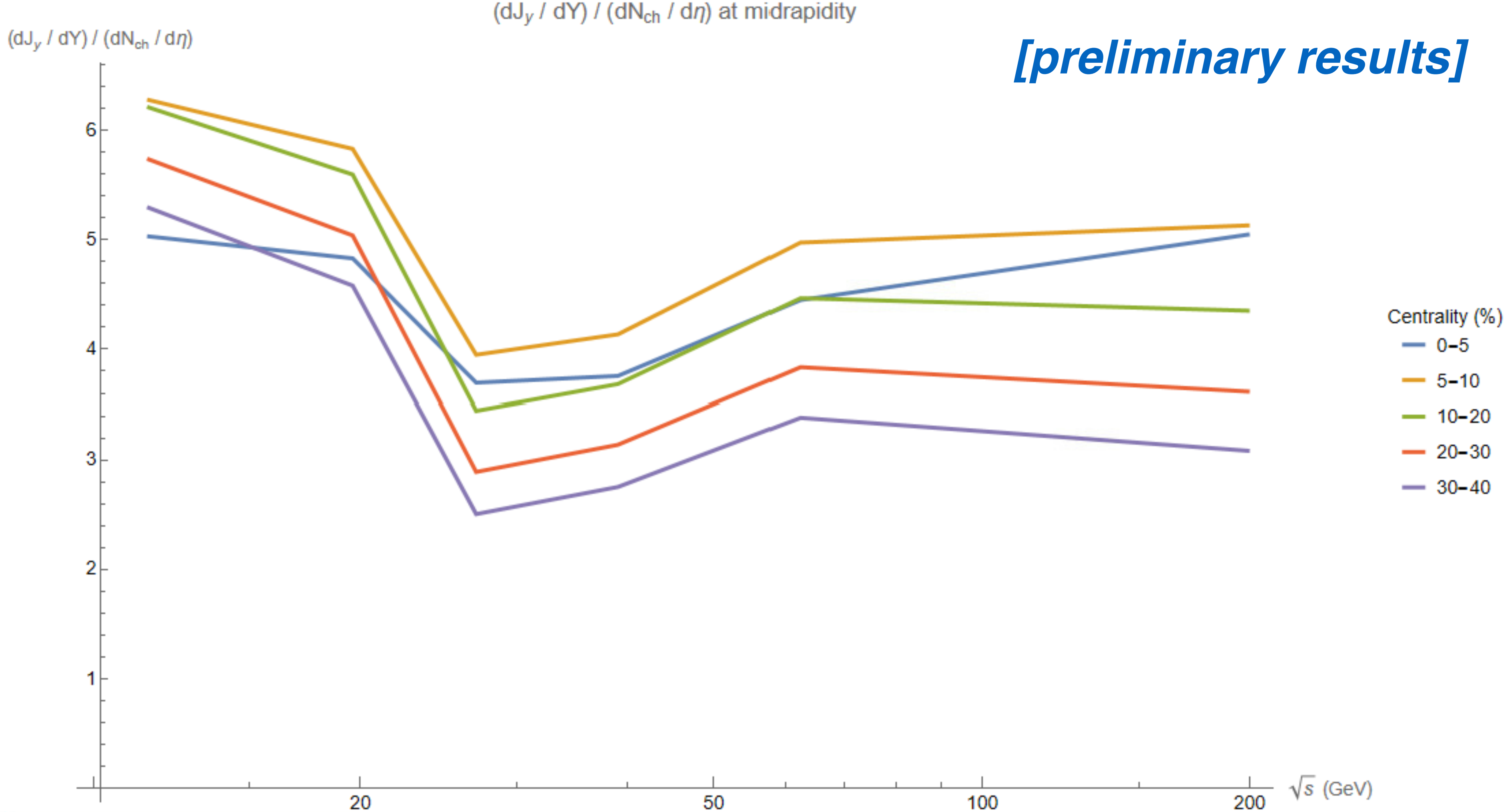
dJ/dY

[preliminary results]



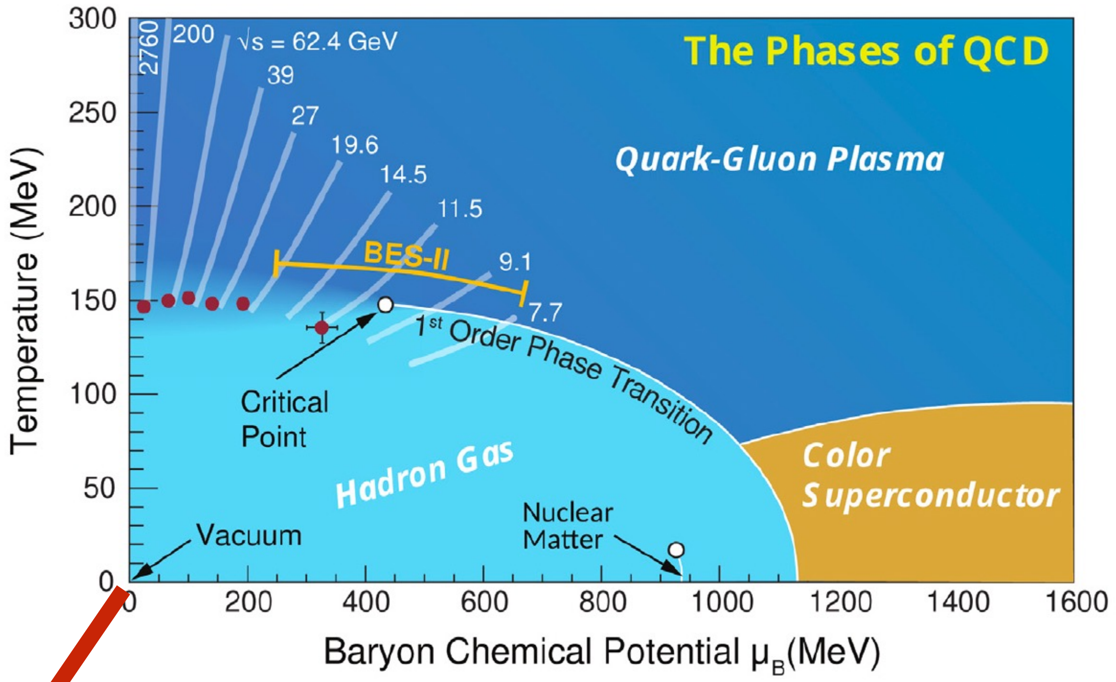
Then compute the stopped angular momentum at mid rapidity

Mid Rapidity Angular Momentum Per Nch



Somewhat surprising: very mild dependence on collision energy!
Why different from spin polarization? Orbital motion of fluid?

Summary

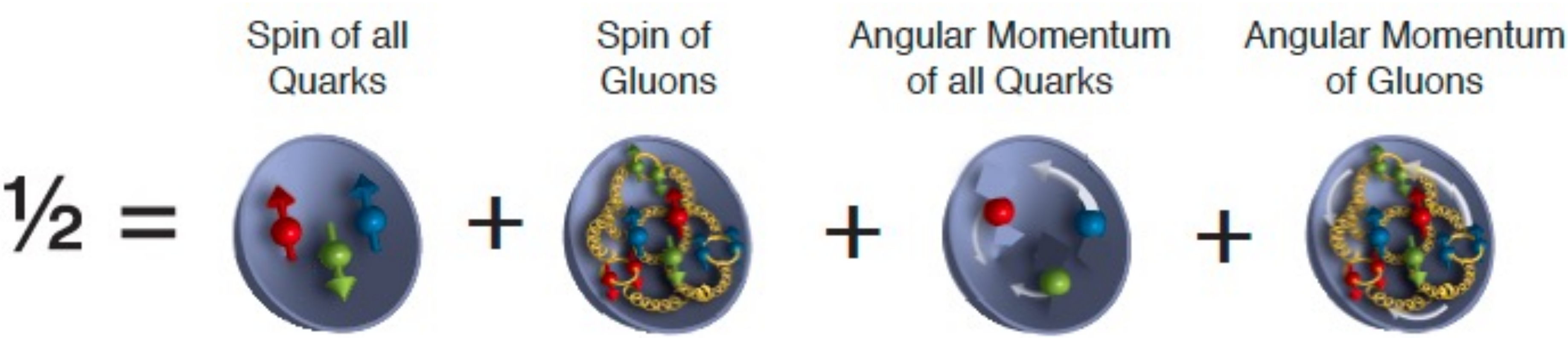


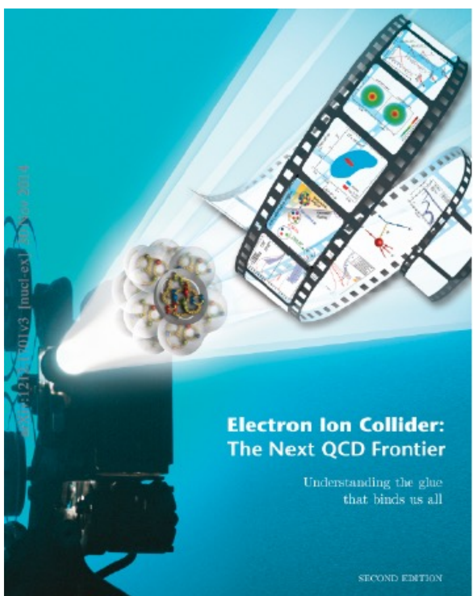
$\vec{J}$

Exciting new regime of studying the most spinning baryonic matter!

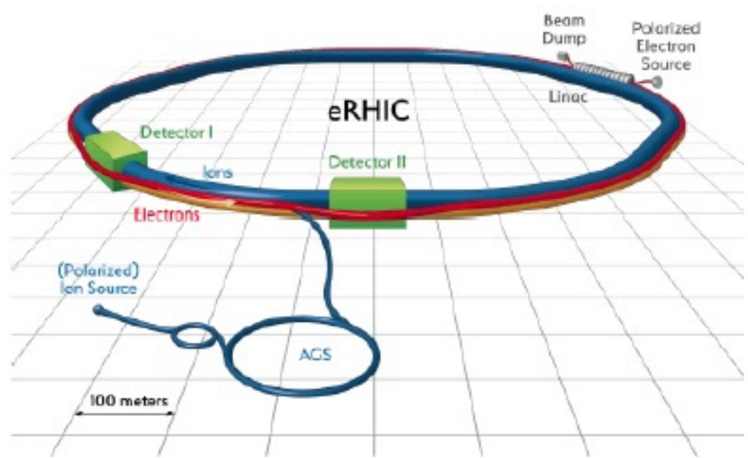
QCD with Angular Momentum: Proton Spin

Putting quarks/gluons back together into a proton is a lot harder then one would naively expect…



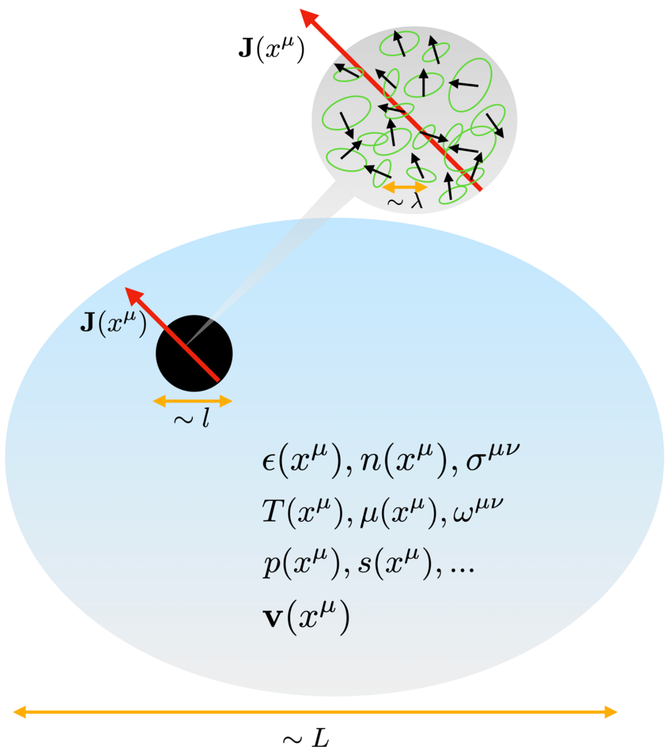


arXiv:1212.1701



Electron Ion Collider (EIC) Running ~2030

QCD with Angular Momentum: Fluid Matter



"Spin physics" of a fluid cell

$$\partial_\mu J^{\mu\alpha\beta} = 0,$$

$$J^{\mu\alpha\beta} = \left(x^\alpha T^{\mu\beta} - x^\beta T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta} .$$

Many interesting questions:

— decomposition of spin/orbital

— gradients and viscous terms

— phenomenological modeling

— EOS and phase structures

— ……

[She, Huang, You, JL, Science Bulletin 67(2022)2265-2268 (arXiv:2105.04060)]