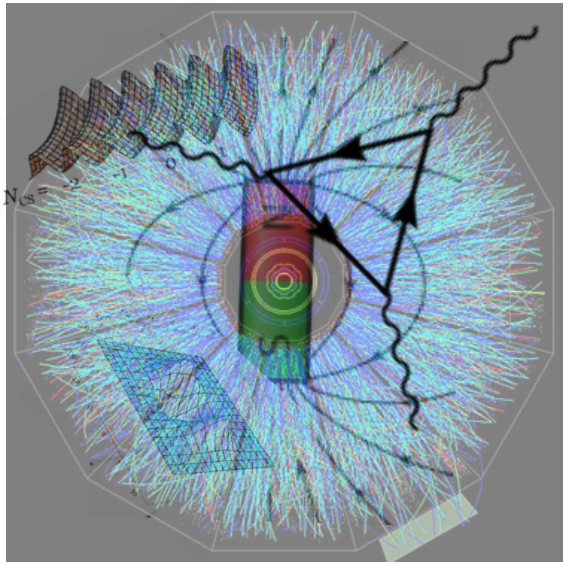
The Most Spinning Baryonic Matter



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

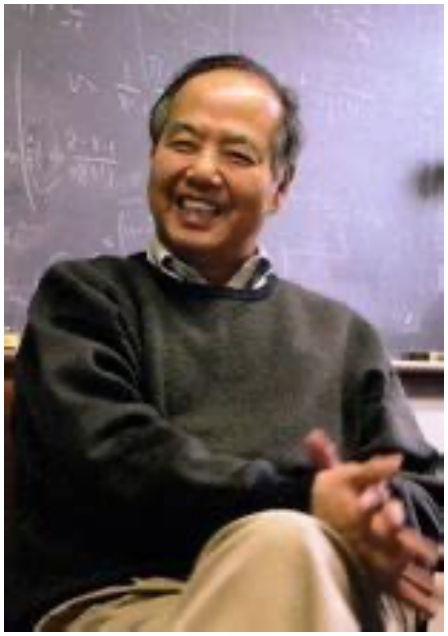
Some Personal Recollections

RBRC/CCAST SYMPOSIUM ON SPIN PHYSICS
LATTICE QCD AND RHIC PHYSICS

China Center of Advanced Science and Technology
(CCAST)
Beijing, China

April 7, 2003

I first "met" with Dima in Beijing 20 years ago…



Some Personal Recollections

The KLN "shockwave"

Manifestations of high density QCD in the first RHIC data #1

Dmitri Kharzeev (Brookhaven), Eugene Levin (Tel Aviv U.) (Aug, 2001)

Published in: *Phys.Lett.B* 523 (2001) 79-87 • e-Print: nucl-th/0108006 [nucl-th]

pdf DOI cite claim reference search 522 citations

Parton saturation and N(part) scaling of semihard processes in QCD #3

Dmitri Kharzeev (Brookhaven), Eugene Levin (Tel Aviv U. and DESY), Larry McLerran (Brookhaven) (Oct, 2002)

Color glass condensate at the LHC: Hadron multiplicities in pp, pA and AA collisions #4

61 (2003) 93-101 • e-Print: hep-ph/0210332 [hep-ph]

cite claim reference search 351 citations

Dmitri Kharzeev (Brookhaven), Eugene Levin (Brookhaven and Tel Aviv U.), Marzia Nardi (Brookhaven and Turin U.) (Aug, 2004)

Published in: *Nucl.Phys.A* 747 (2005) 609-629 • e-Print: hep-ph/0408050 [hep-ph]

pdf DOI cite claim reference search 313 citations

QCD saturation and deuteron nucleus collisions #5

Dmitri Kharzeev (Brookhaven), Eugene Levin (Tel Aviv U. and DESY), Marzia Nardi (Turin U. and INFN, Turin) (Dec, 2002)

Published in: *Nucl.Phys.A* 730 (2004) 448-459, *Nucl.Phys.A* 743 (2004) 329-331 (erratum) • e-Print: hep-ph/0212316 [hep-ph]

The Onset of classical QCD dynamics in relativistic heavy ion collisions #6

nce search 290 citations

Dmitri Kharzeev (Brookhaven), Eugene Levin (Tel Aviv U.), Marzia Nardi (Turin U. and INFN, Turin) (Nov, 2001)

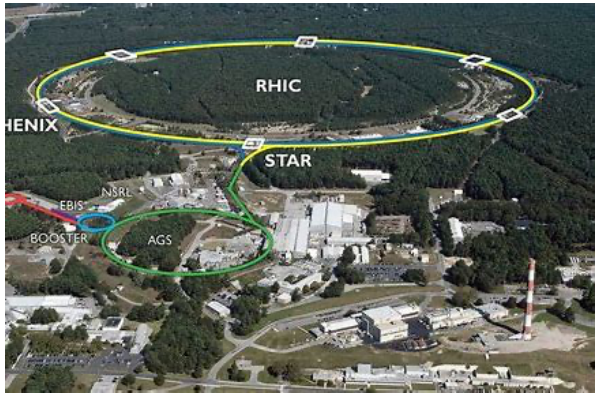
Published in: *Phys.Rev.C* 71 (2005) 054903 • e-Print: hep-ph/0111315 [hep-ph]

pdf DOI cite claim reference search 282 citations

Some Personal Recollections

Stony Brook

BNL



And there is the bulk viscosity …

Universal properties of bulk viscosity near the QCD phase transition #1

Frithjof Karsch (Brookhaven), Dmitri Kharzeev (Brookhaven), Kirill Tuchin (Iowa State U. and RIKEN BNL) (Nov, 2007)

Published in: *Phys.Lett.B* 663 (2008) 217-221 • e-Print: 0711.0914 [hep-ph]

pdf DOI cite claim reference search 370 citations

Bulk viscosity of QCD matter near the critical temperature #2

Dmitri Kharzeev (Brookhaven), Kirill Tuchin (Iowa State U. and RIKEN BNL) (May, 2007)

Published in: *JHEP* 09 (2008) 093 • e-Print: 0705.4280 [hep-ph]

pdf DOI cite claim reference search 260 citations

Some Personal Recollections

"The biggest news of QM2009" — — when I first learned the word "CME"

Possibility of spontaneous parity violation in hot QCD #7

Dmitri Kharzeev (RIKEN BNL), R.D. Pisarski (Brookhaven), Michel H.G. Tytgat (Brookhaven and Brussels U.) (Apr, 1998)

Published in: *Phys.Rev.Lett.* 81 (1998) 512-515 • e-Print: hep-ph/9804221 [hep-ph]

pdf DOI cite claim reference search 384 citations

Parity violation in hot QCD: Why it can happen, and how to look for it #1

Dmitri Kharzeev (Brookhaven) (Jun, 2004)

Published in: *Phys.Lett.B* 633 (2006) 260-264 • e-Print: hep-ph/0406125 [hep-ph]

The Effects of topological charge change in heavy ion collisions: 'Event by event P and CP violation' #2 reference search 580 citations

Dmitri E. Kharzeev (Brookhaven), Larry D. McLerran (Brookhaven and RIKEN BNL), Harmen J. Warringa (Brookhaven) (Nov, 2007)

Published in: *Nucl.Phys.A* 803 (2008) 227-253 • e-Print: 0711.0950 [hep-ph]

pdf DOI cite claim reference search 1,744 citations

The Chiral Magnetic Effect #1

Kenji Fukushima (Kyoto U., Yukawa Inst., Kyoto), Dmitri E. Kharzeev (Brookhaven), Harmen J. Warringa (Brookhaven) (Aug, 2008)

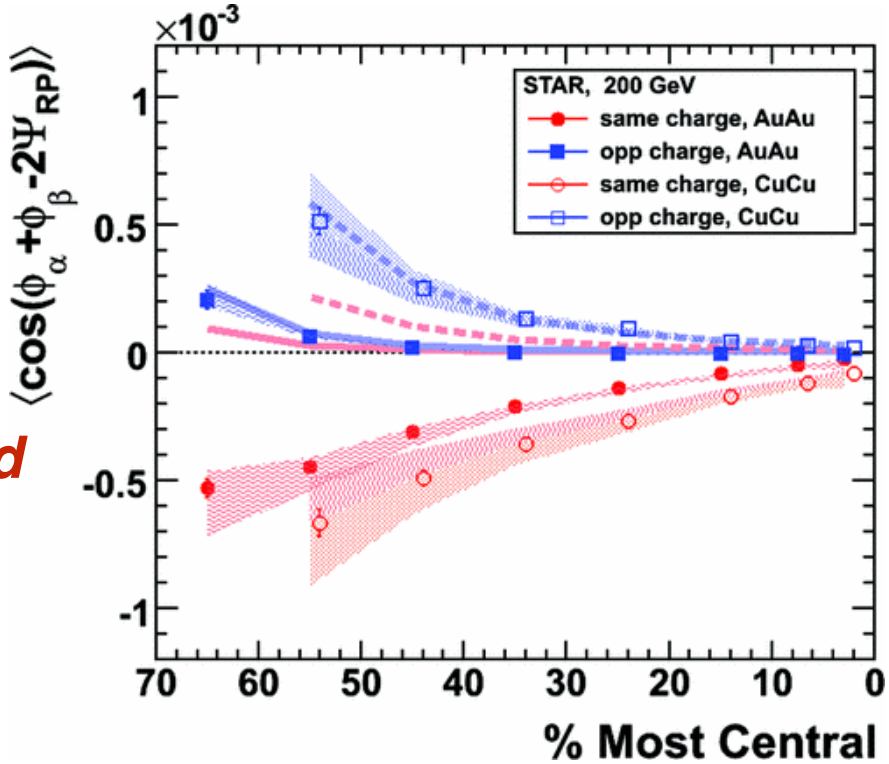
Published in: *Phys.Rev.D* 78 (2008) 074033 • e-Print: 0808.3382 [hep-ph]

pdf DOI cite claim reference search 1,823 citations

Some Personal Recollections

Several unexpected turns around late 2009 to mid 2010……

Background v.s. Signal



Despite all the intense debates, I was deeply convinced by the beauty and fundamental importance of Dima's CME idea

I became a BNL postdoc, only to find that Dima just "left" ……

Some Personal Recollections

A new way to manifest CME was proposed: Chiral Magnetic Wave

Chiral Magnetic Wave #1

Dmitri E. Kharzeev (SUNY, Stony Brook and Brookhaven), Ho-Ung Yee (SUNY, Stony Brook) (Dec, 2010)

Published in: *Phys.Rev.D* 83 (2011) 085007 • e-Print: 1012.6026 [hep-th]

pdf DOI cite claim reference search 331 citations

Chiral magnetic wave at finite baryon density and the electric quadrupole moment of quark-gluon plasma in heavy ion collisions #2

Yannis Burnier (SUNY, Stony Brook), Dmitri E. Kharzeev (SUNY, Stony Brook and Brookhaven), Jinfeng Liao (Brookhaven), Ho-Ung Yee (SUNY, Stony Brook) (Mar, 2011)

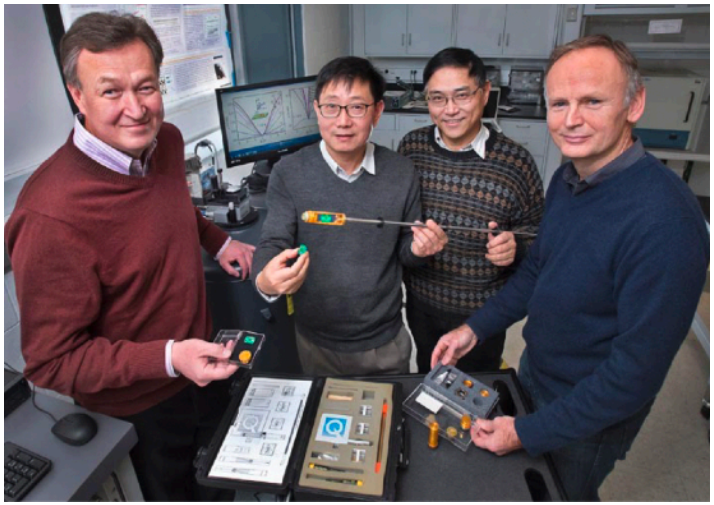
Published in: *Phys.Rev.Lett.* 107 (2011) 052303 • e-Print: 1103.1307 [hep-ph]

pdf DOI cite claim reference search 260 citations

Even though just for one year, learning from Dima as a postdoc was an incredible experience and had a huge impact on my subsequent career!

Some Personal Recollections

A new area of CME study in condensed matter!



Also a new period of CME in heavy ion collisions started:
— consensus to redefine the goal
— Chirality conference
— BEST Collaboration
— Isobar taskforce

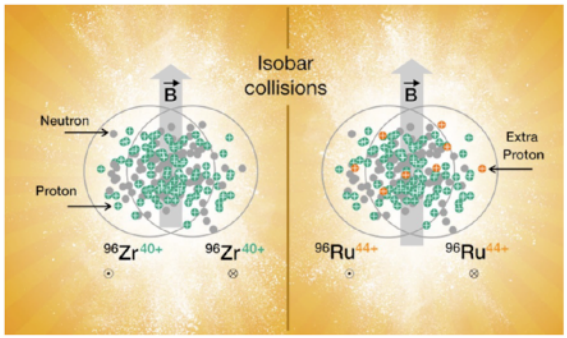
Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report #1

D.E. Kharzeev (Brookhaven and SUNY, Stony Brook and RIKEN BNL), J. Liao (Indiana U. and Indiana U., CEEM and RIKEN BNL), S.A. Voloshin (Wayne State U.), G. Wang (UCLA) (Nov 12, 2015)

Published in: *Prog.Part.Nucl.Phys.* 88 (2016) 1-28 • e-Print: 1511.04050 [hep-ph]

pdf DOI cite claim reference search 622 citations

Some Personal Recollections



nature reviews physics

Chiral magnetic effect reveals the topology of gauge fields in heavy-ion collisions

Dmitri E. Kharzeev & Jinfeng Liao

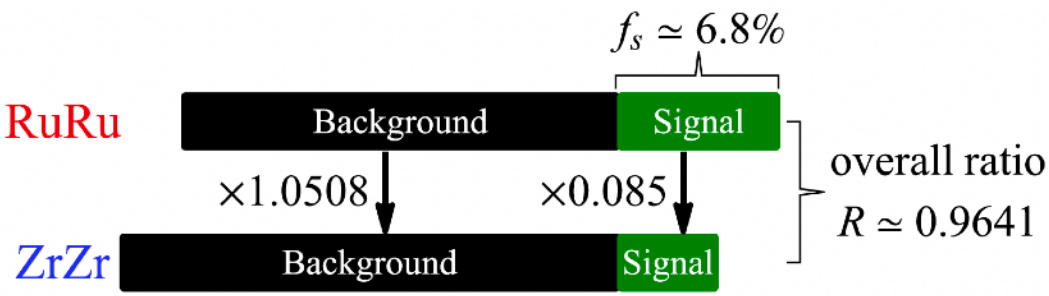
Nature Reviews Physics **3**, 55–63 (2021) | Cite this article

PHYSICAL REVIEW C **106**, L051903 (2022)

Letter

Implications of the isobar-run results for the chiral magnetic effect in heavy-ion collisions

Dmitri E. Kharzeev,[1,2,*] Jinfeng Liao,[3,†] and Shuzhe Shi[1,‡]



Shuzhe Shi

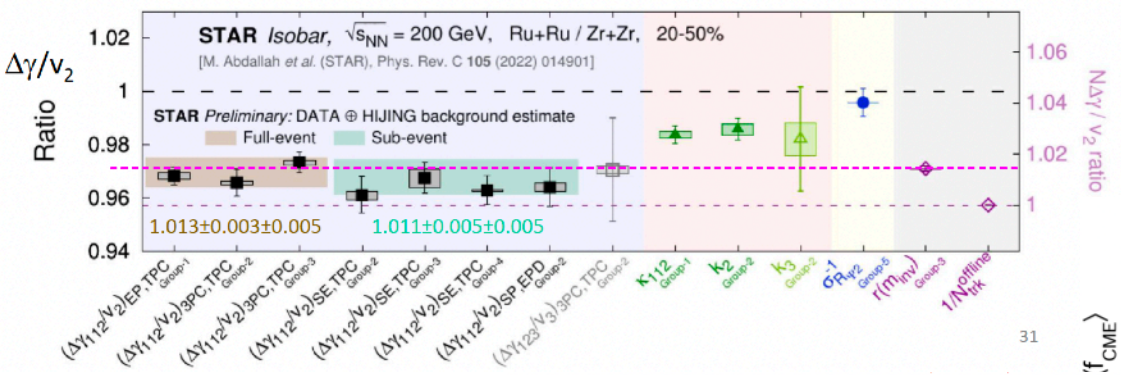
A delightful collaboration with new degree of "entanglement"

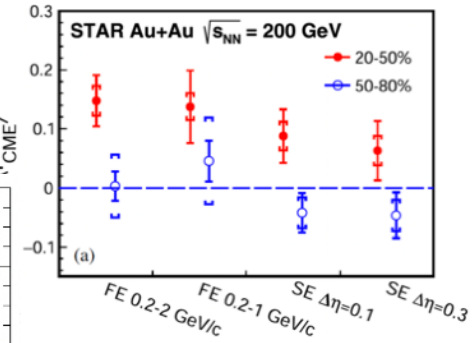
Some Personal Recollections

Current total uncertainty:
0.4%⊕0.3%⊕0.5% = 0.7%

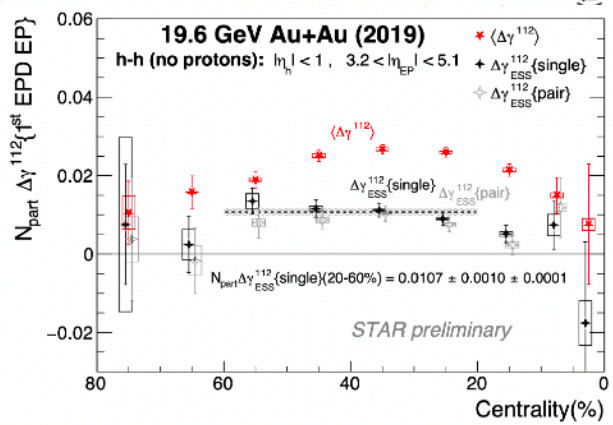
Assuming 15% B^2 diff:
δf_{CME} = 0.7%/15% = 5%

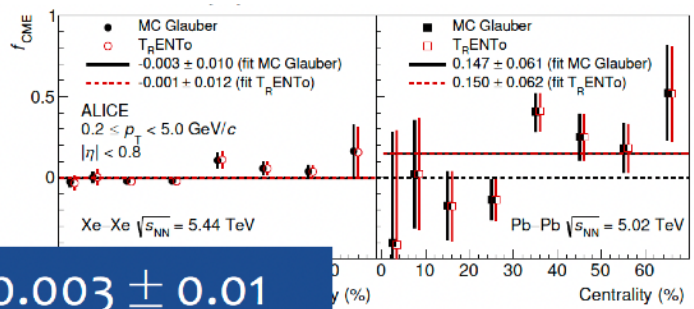
My conservative estimate:
f_{CME} < 10% at 98% CL



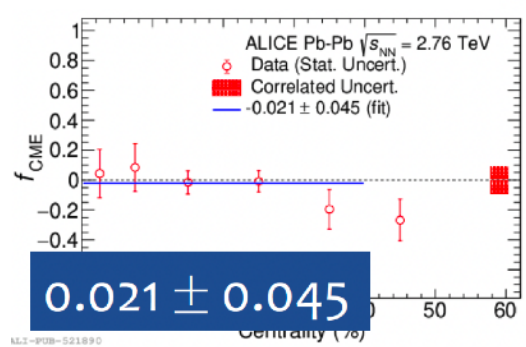


CME search is difficult, but we are not alone! Think about many other famous searches, e.g. for Higgs, gravitational wave, EDM, WIMP, 2-beta decay, …

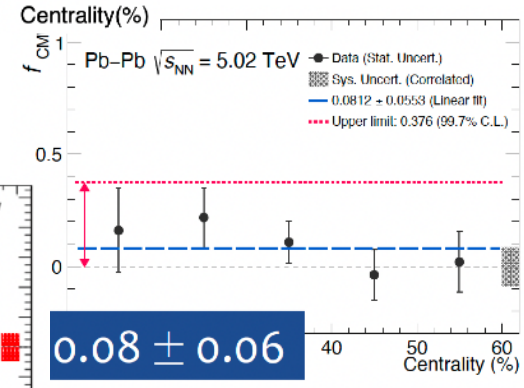




0.003 ± 0.01



0.021 ± 0.045



0.08 ± 0.06

Some Personal Recollections

So I ask myself: why mother Nature always kept us one step away from discovering CME in HIC so far?

Crazy Ideas Radiating!

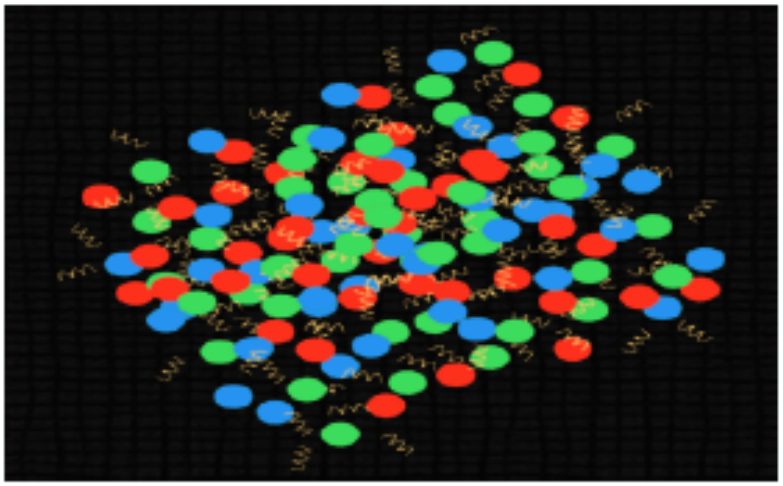
Perhaps she just wants to keep Dima busy ;-)

It would be a waste not to make full use of such a brilliant mind as Dima's for the good of science!

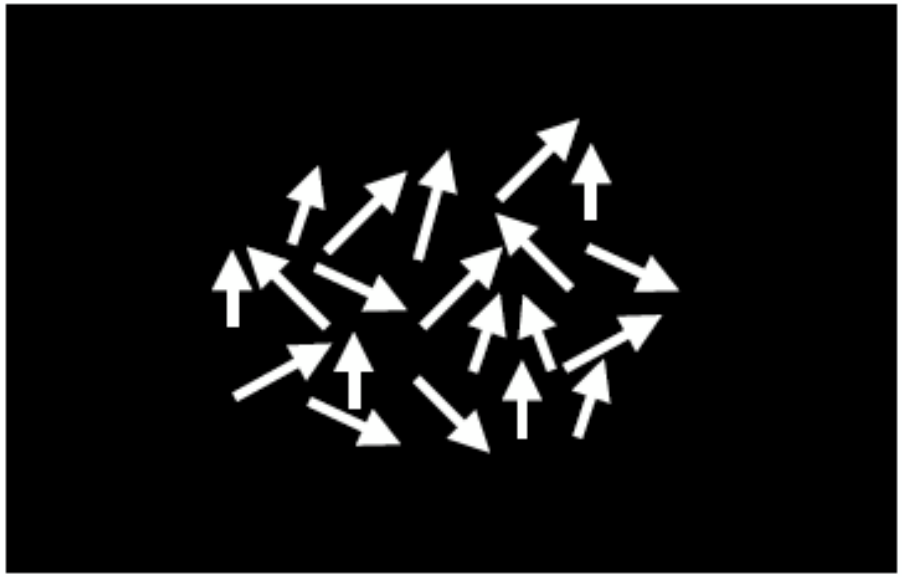
Dima, Happy Sixty !
Not yet time for rest: CME@2028? Chiral qubit@2033?
Happy innovating for the next sixty years!

A Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)

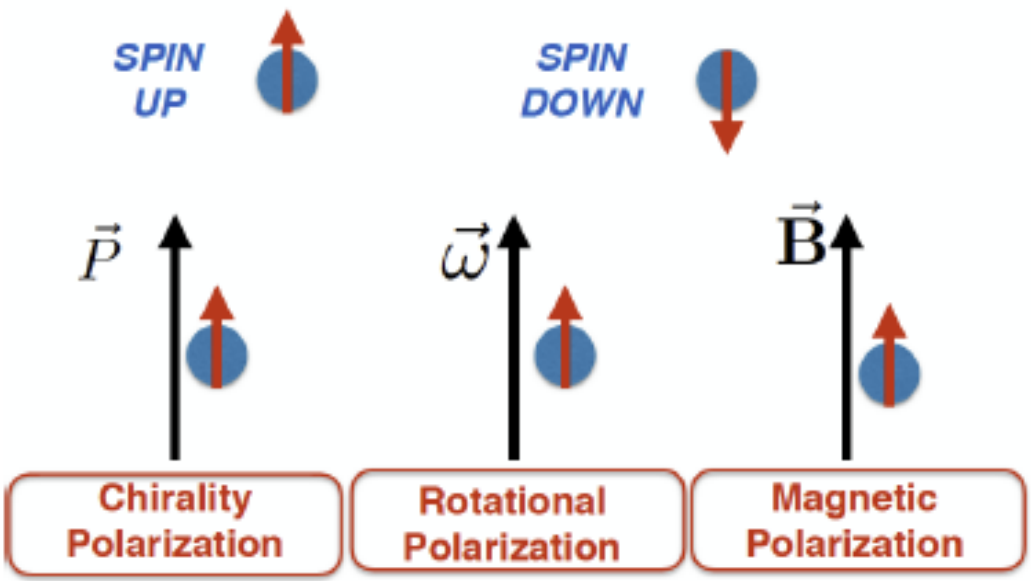


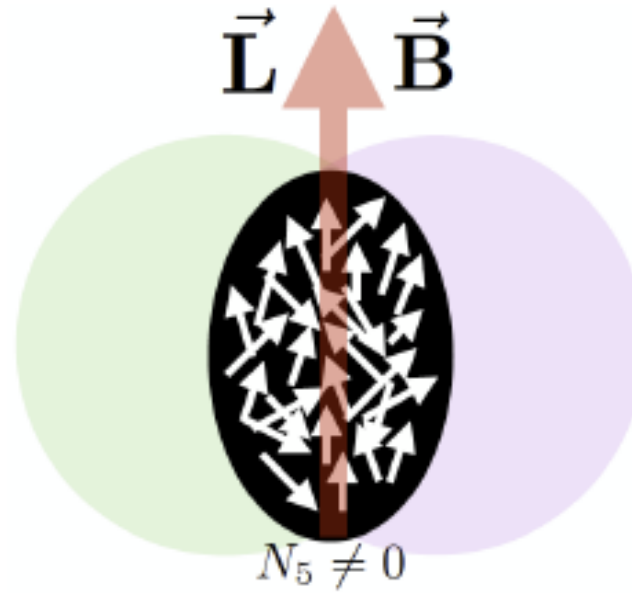
What happens to the spin DoF in the fluid???



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

Vorticity and Chiral Vortical Effect

Charge separation induced by P-odd bubbles in QCD matter #1

D. Kharzeev (Brookhaven), A. Zhitnitsky (British Columbia U.) (Jun, 2007)

Published in: *Nucl.Phys.A* 797 (2007) 67-79 • e-Print: 0706.1026 [hep-ph]

pdf DOI cite claim reference search 495 citations

Testing the chiral magnetic and chiral vortical effects in heavy ion collisions #2

Dmitri E. Kharzeev (SUNY, Stony Brook and Brookhaven), Dam T. Son (Washington U., Seattle) (Oct, 2010)

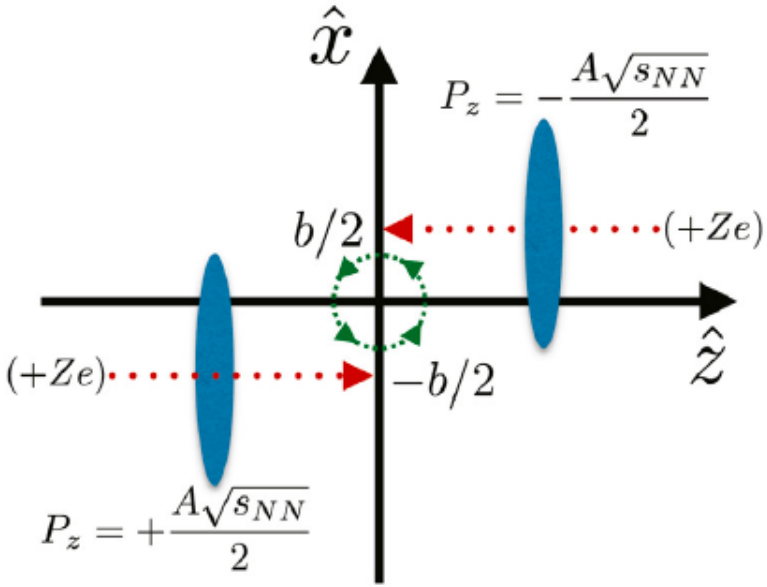
Published in: *Phys.Rev.Lett.* 106 (2011) 062301 • e-Print: 1010.0038 [hep-ph]

pdf DOI cite claim reference search 254 citations

$$\vec{\mathbf{J}}_Q^{2f} = \frac{N_c \mu_5}{2\pi^2}\left[\frac{5}{9}(e\vec{\mathbf{B}}) + \frac{2}{9}(\mu_B \vec{\boldsymbol{\omega}})\right], \qquad \vec{\mathbf{J}}_B^{2f} = \frac{N_c \mu_5}{2\pi^2}\left[\frac{1}{9}(e\vec{\mathbf{B}}) + \frac{4}{9}(\mu_B \vec{\boldsymbol{\omega}})\right]$$

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

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)

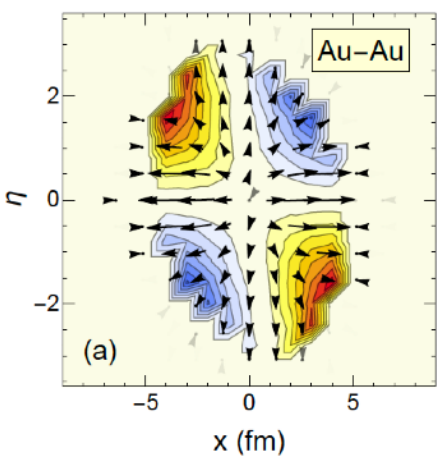
Rotating quark-gluon plasma in relativistic heavy-ion collisions

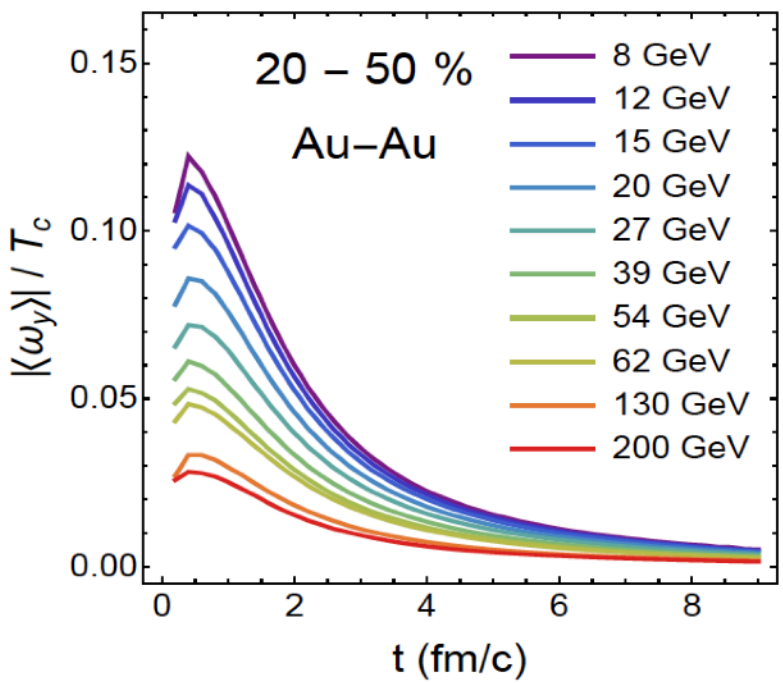
Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]
[1]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 North Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*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

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

Is this portion conserved? —YES!

How QGP accommodates this angular momentum? — Fluid vorticity!

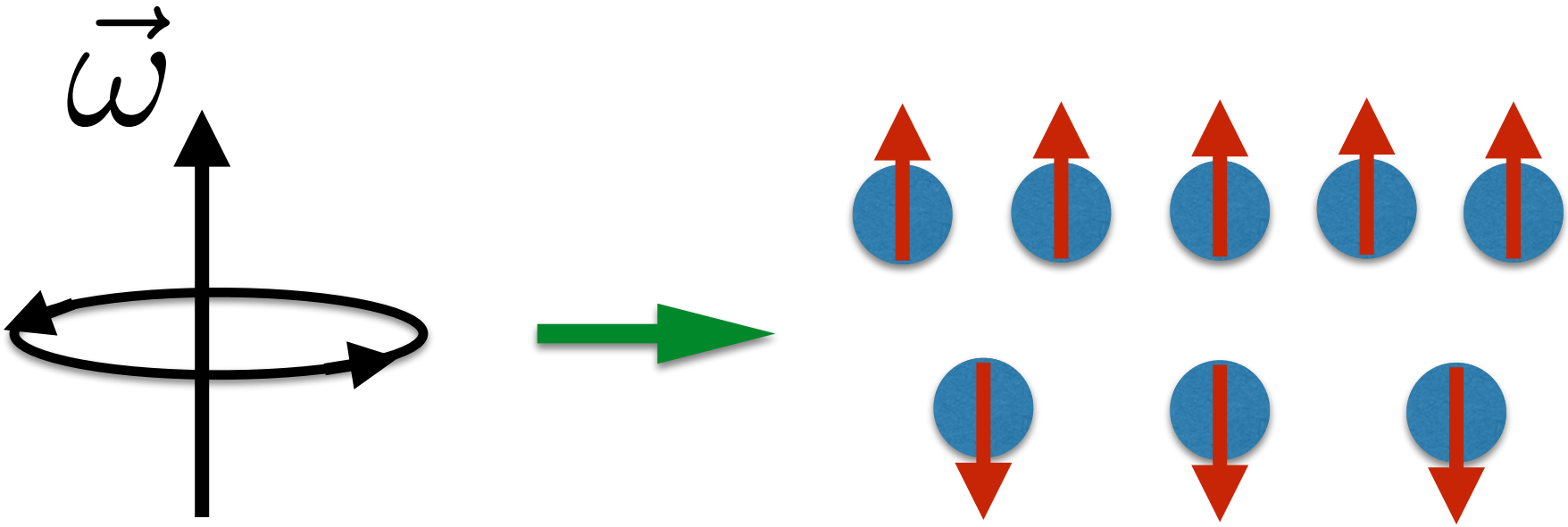




Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization

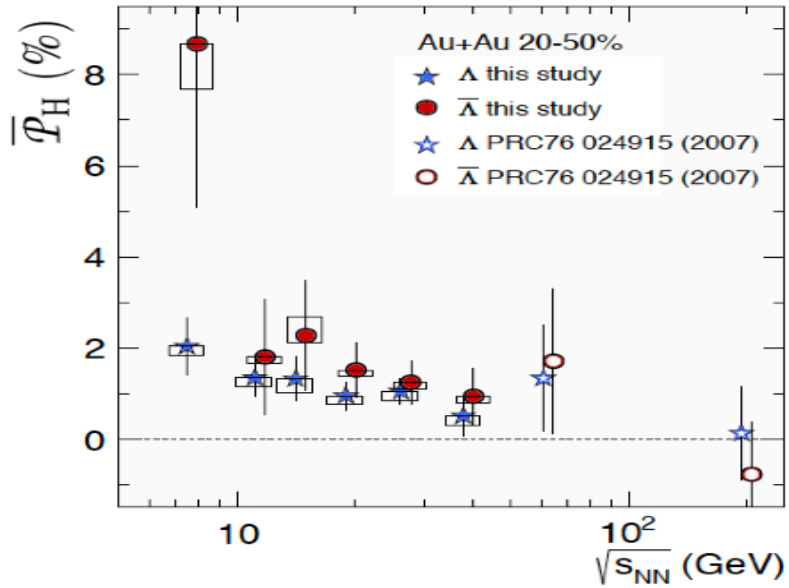


Macroscopic rotation; Global angular momentum

Microscopic spin alignment

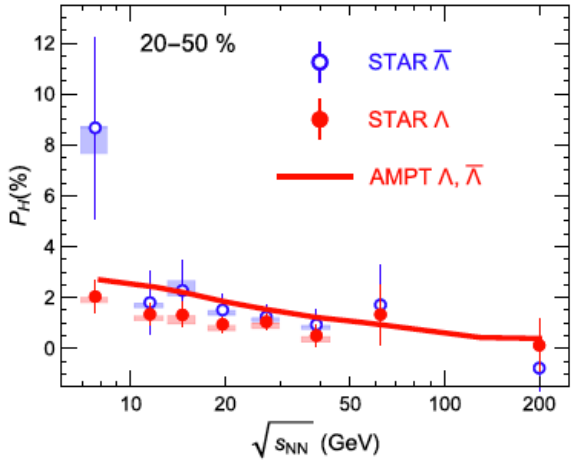
"Fluid spintronics" in condensed matter systems

The Most Vortical Fluid



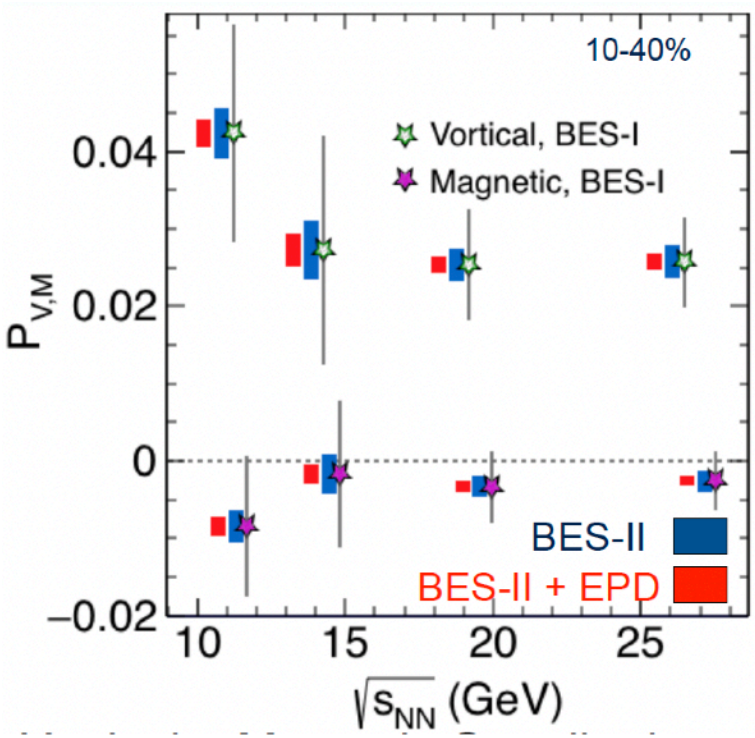
An exciting discovery from STAR Collaboration at RHIC: The most vortical fluid!

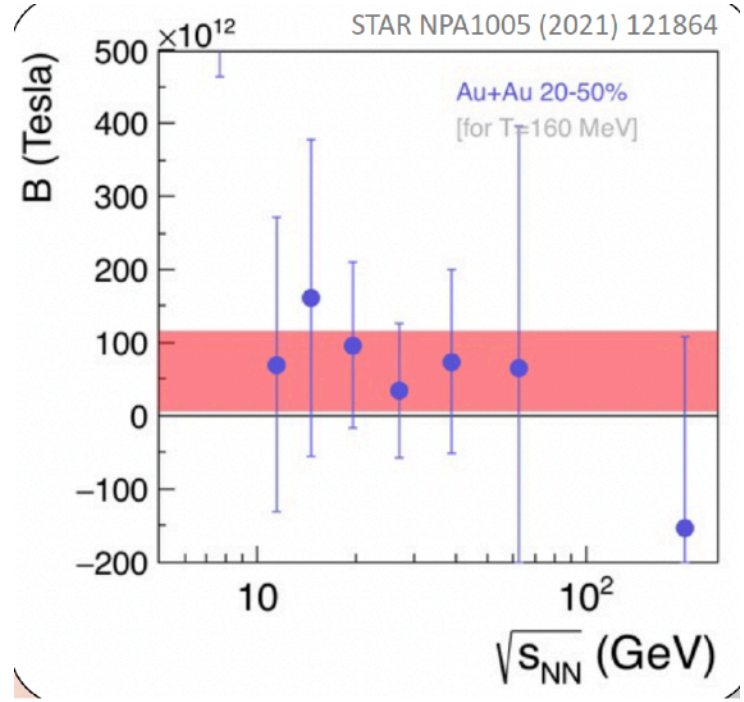
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$



Many calculations based on hydro or transport models

"Magnetic Polarization" at Low Energy?

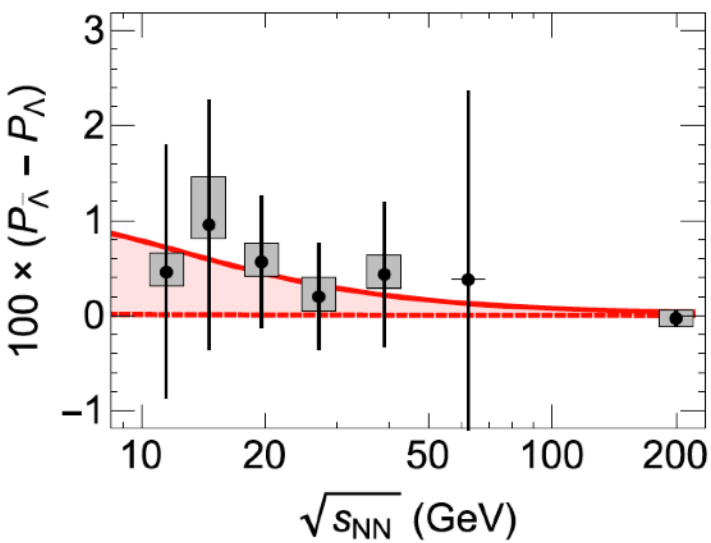


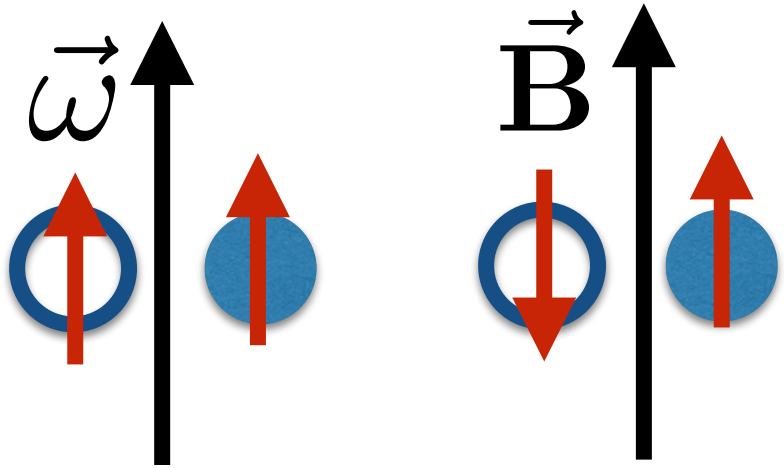


Access to possible dynamical in-medium B-field and magnetic polarization phenomenon

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;

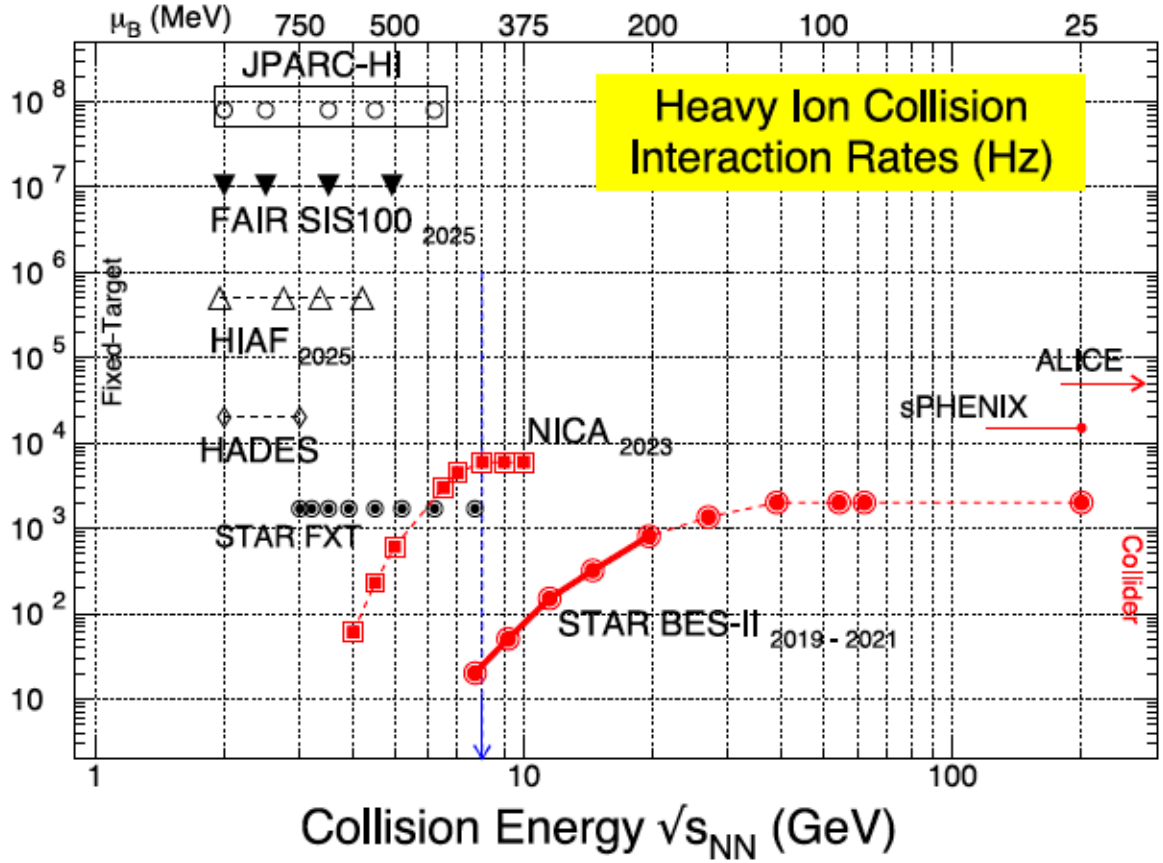
[Guo, Shi, Feng, JL, arXiv:1905.12613, PLB2019; Mueller, Schaefer, 1806.10907]

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

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

Relativistic Nuclear Collisions @ O(1-10) GeV

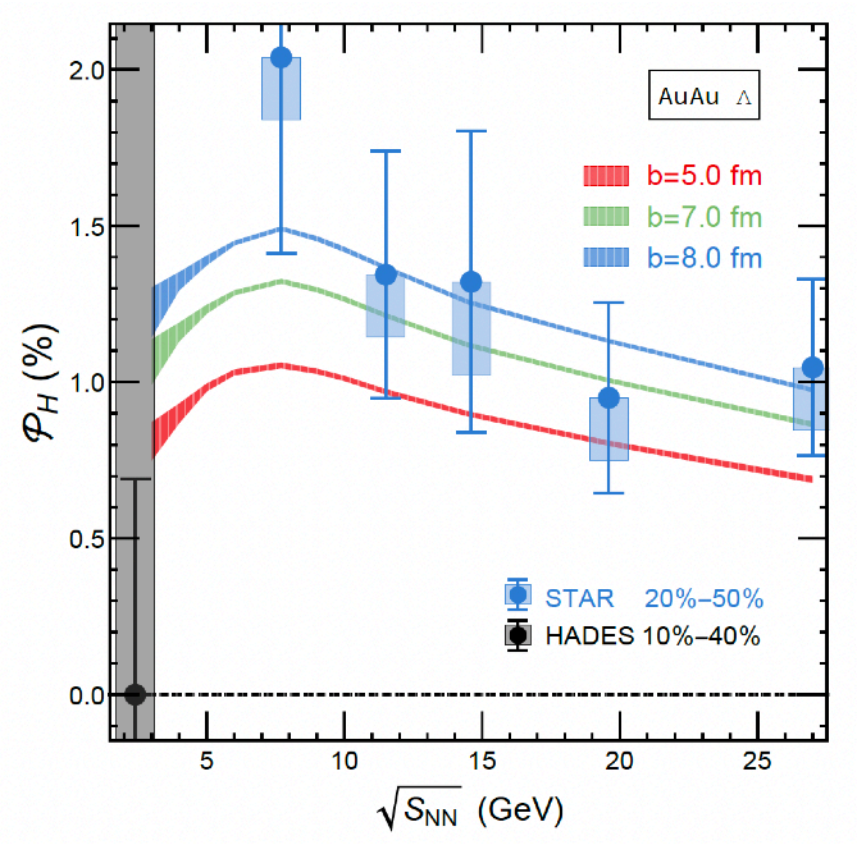
A number of current and planned experiments will explore the O(1) GeV regime of relativistic nuclear collisions



"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

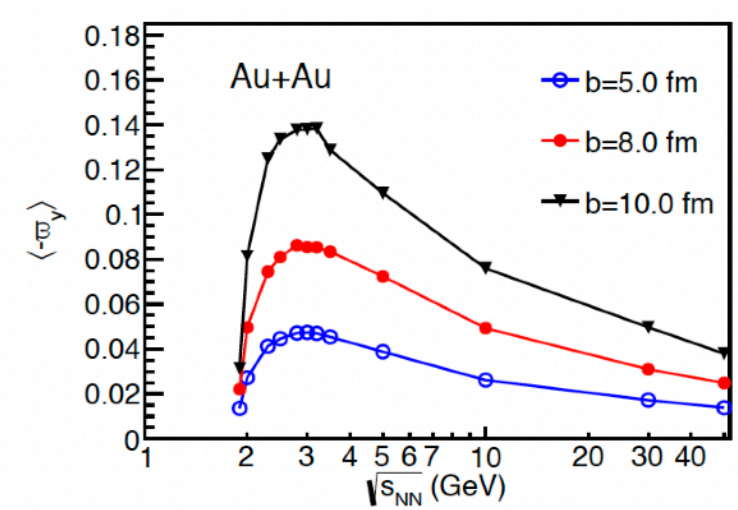
AMPT calculations predict non-monotonic behavior in the dependence of global polarization on beam energy —> maximum around 7.7 GeV

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

Other Calculations

URQMD

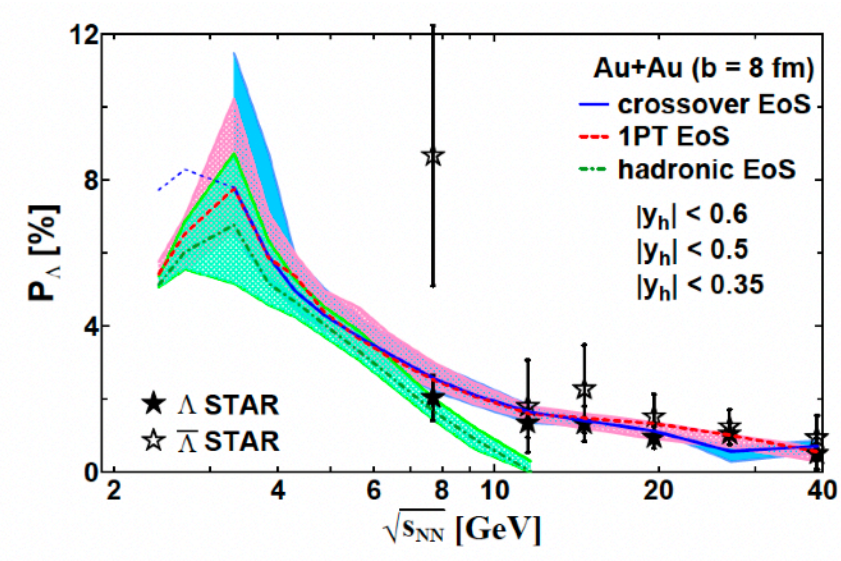
Deng, Huang, Ma, Zhang, arXiv:2001.01371



— URQMD & AMPT results for vorticity are consistent

3FD

Ivanov, arXiv:2012.07597

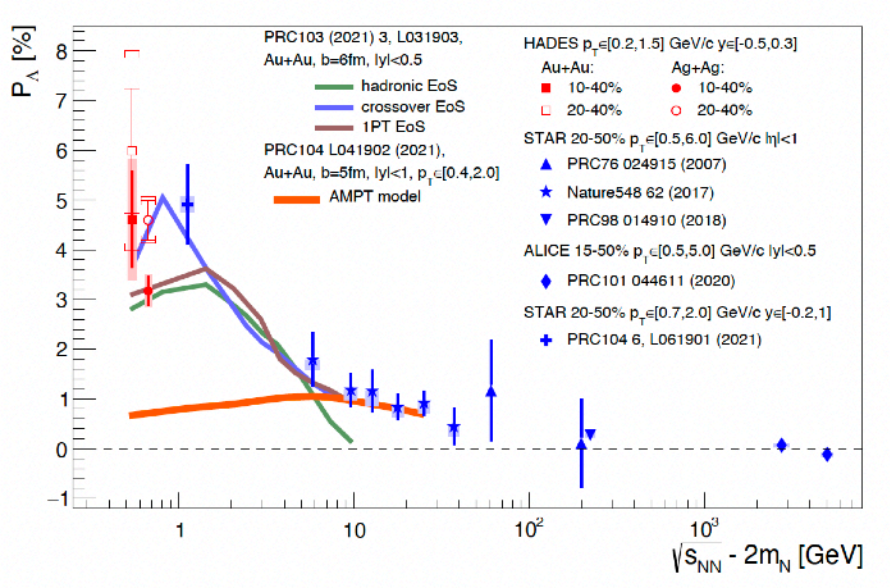


— Many model details could be quite different and need to be understood

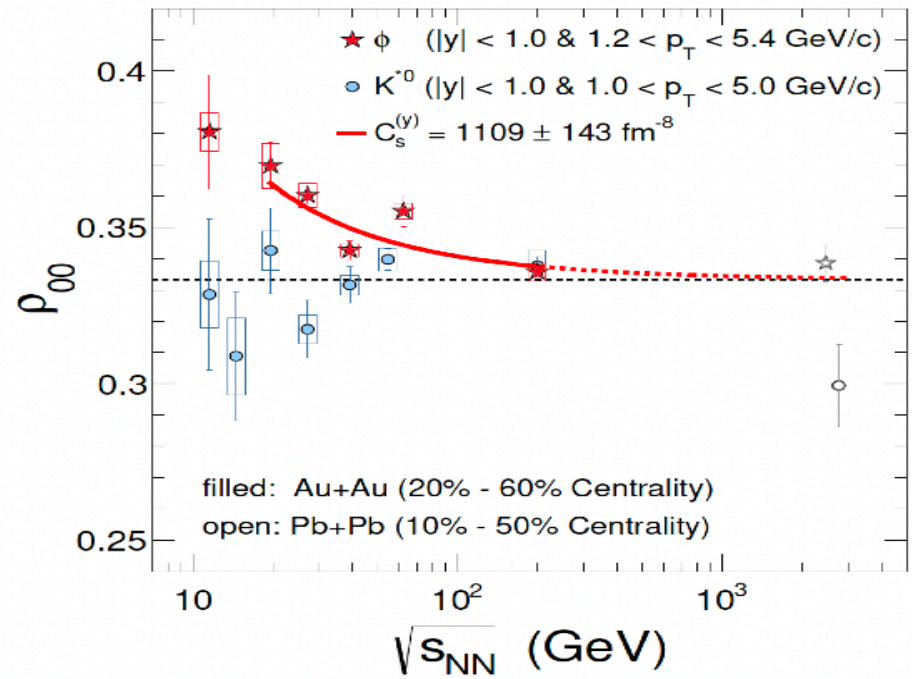
— Likely having more spectator-participant interactions and angular momentum transport

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?!

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

How the fireball gets its angular momentum?

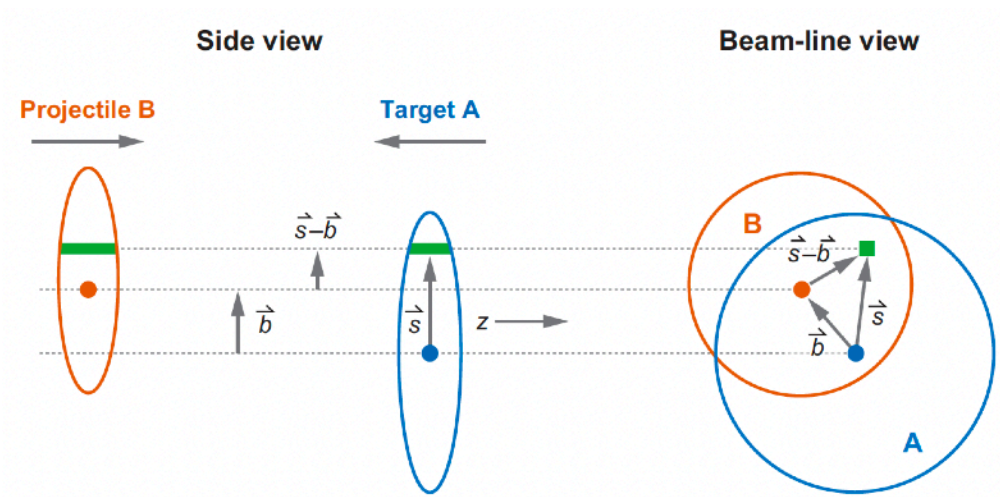
Nuclear Stopping & Angular Momentum

Total angular momentum monotonically increases with beam energy

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

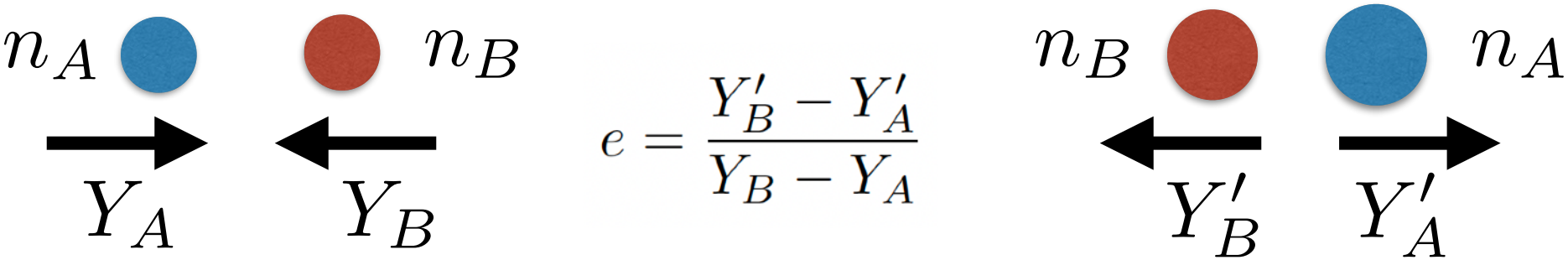
But what is relevant to measurements is the amount of angular momentum being stopped in mid rapidity.

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

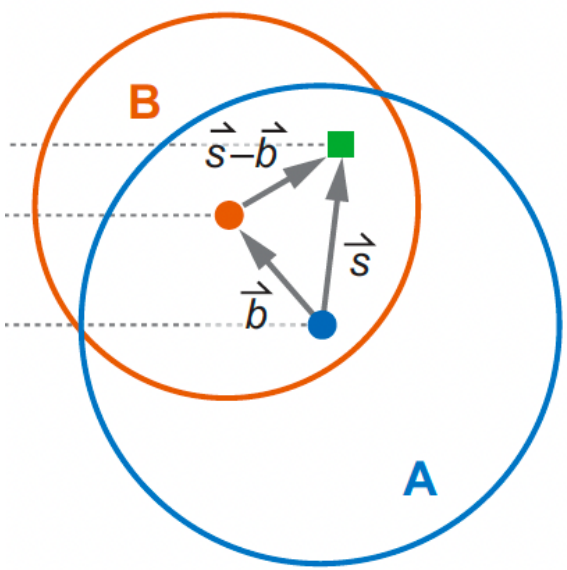


Nuclear Stopping & Angular Momentum

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



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



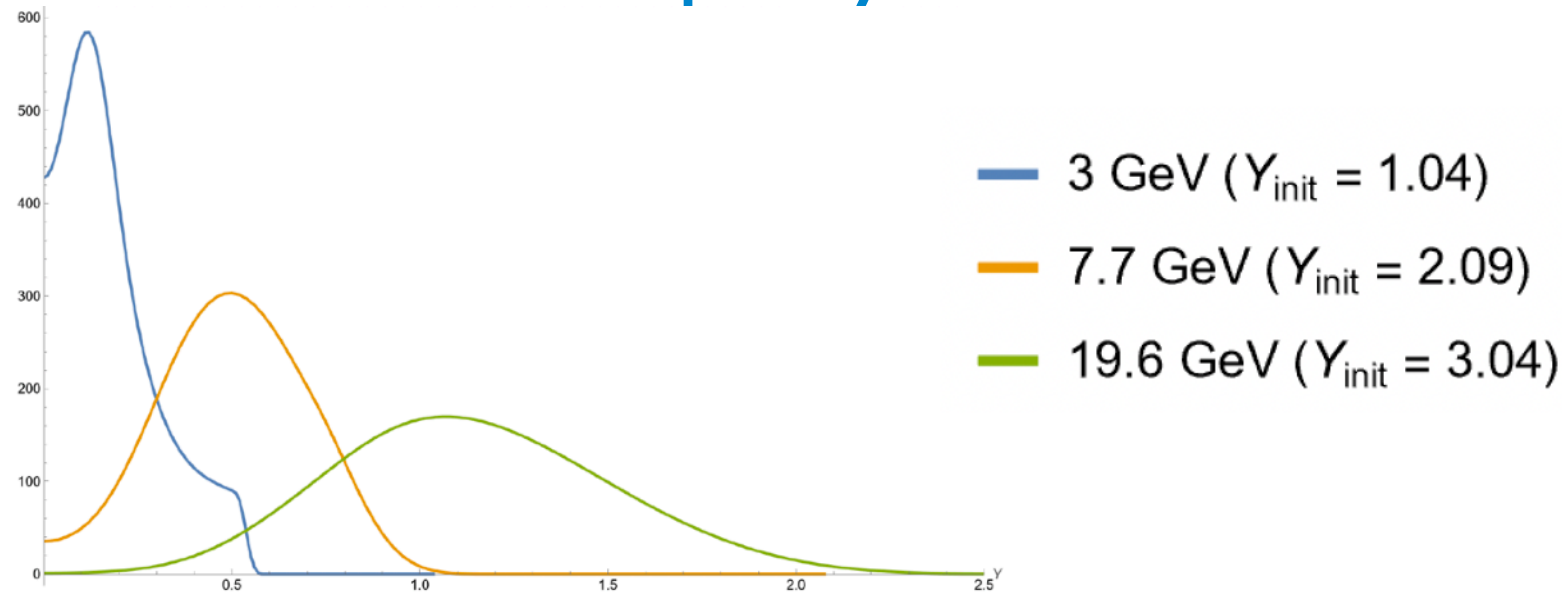
Various spots on the overlapping zone —> A "spread-out" (i.e. distribution) along rapidity

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

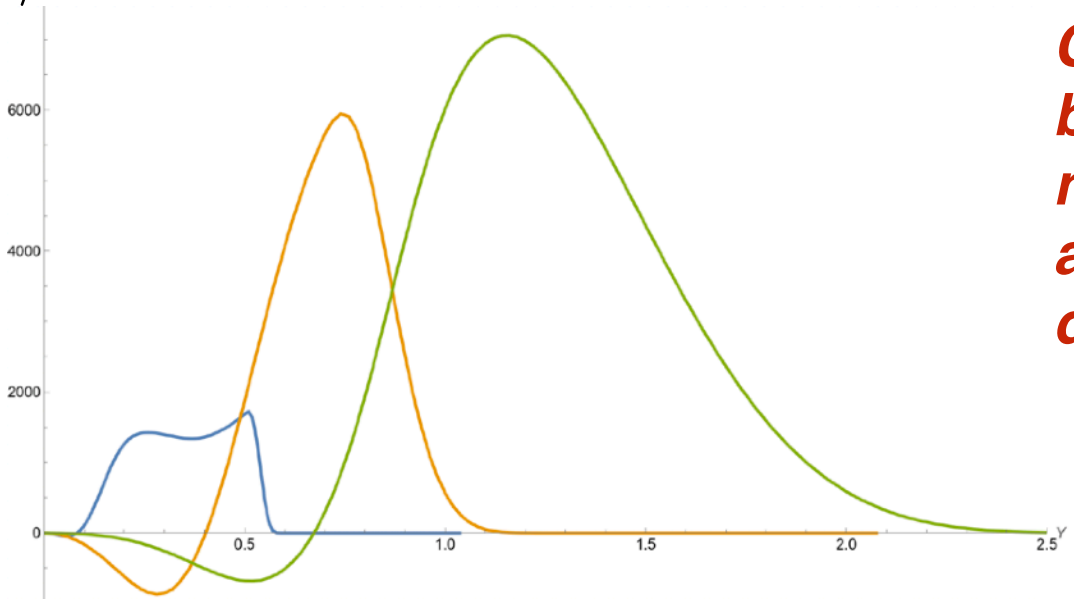
Both net baryon and angular momentum come from this "spread-out"

Initial Rapidity Distribution

dB/dY

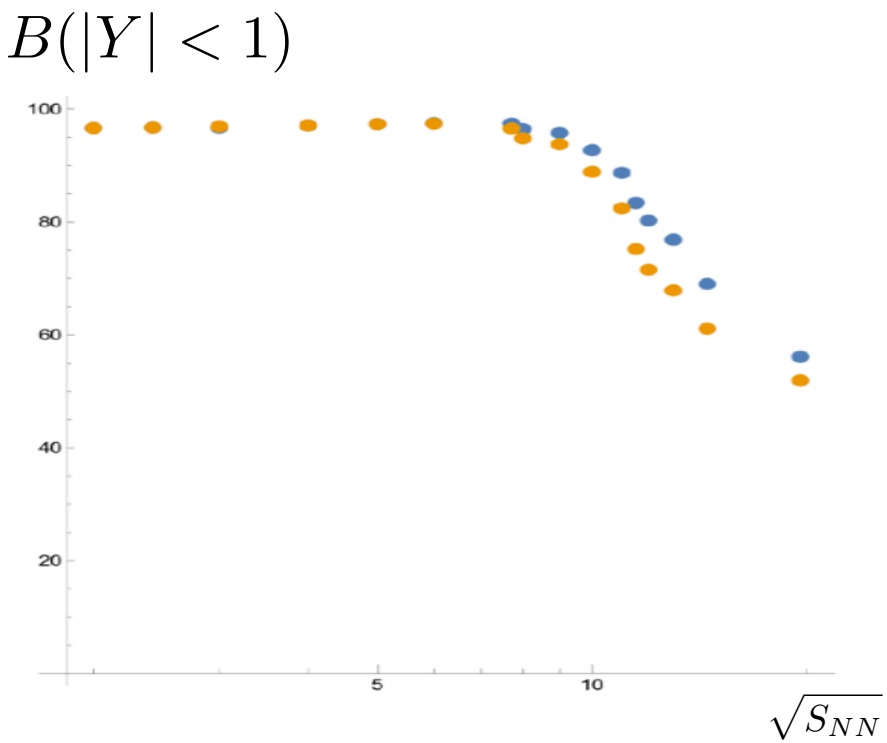


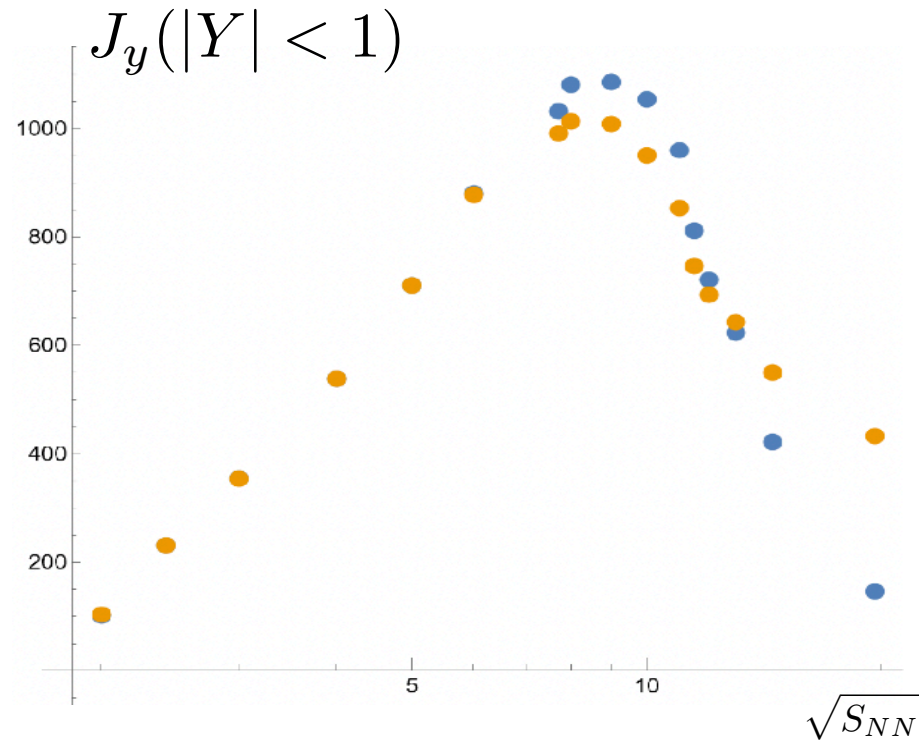
dJ/dY

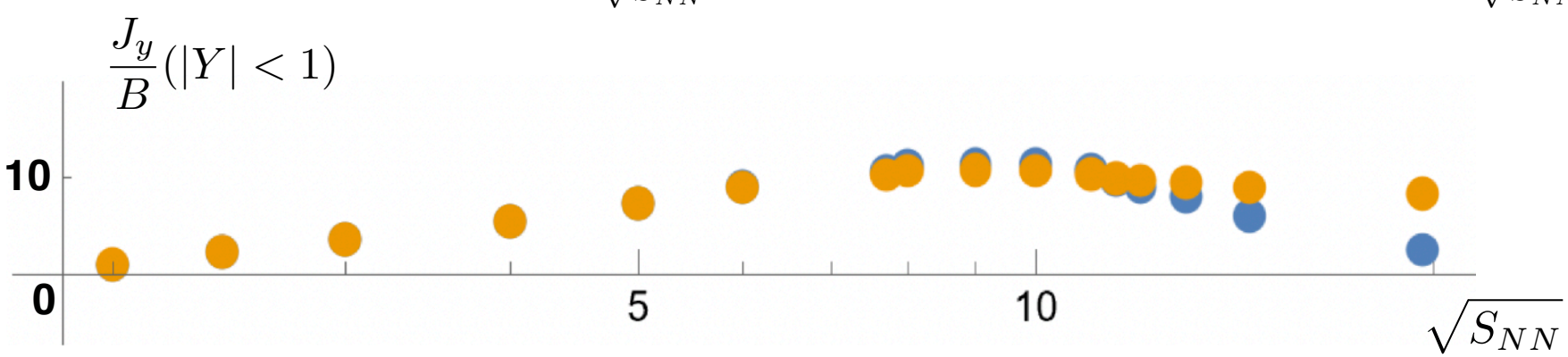


Clear correlation between net baryons and angular momentum distributions.

Mid Rapidity Baryon and Angular Momentum

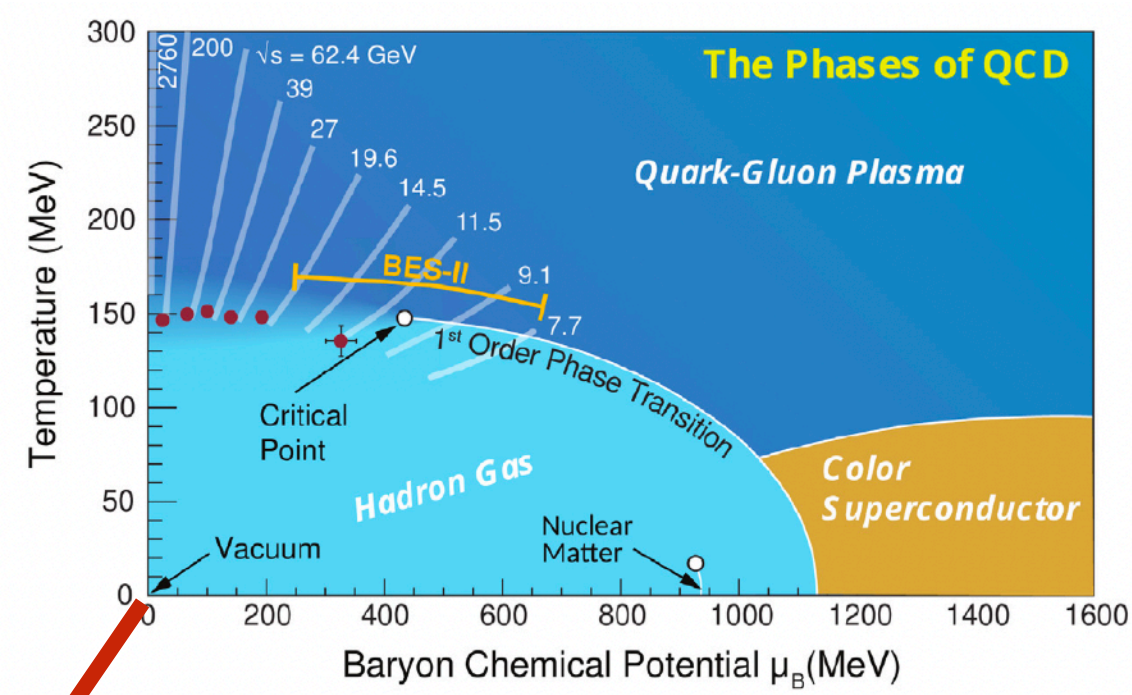






a measure of spinning baryonic matter

Summary



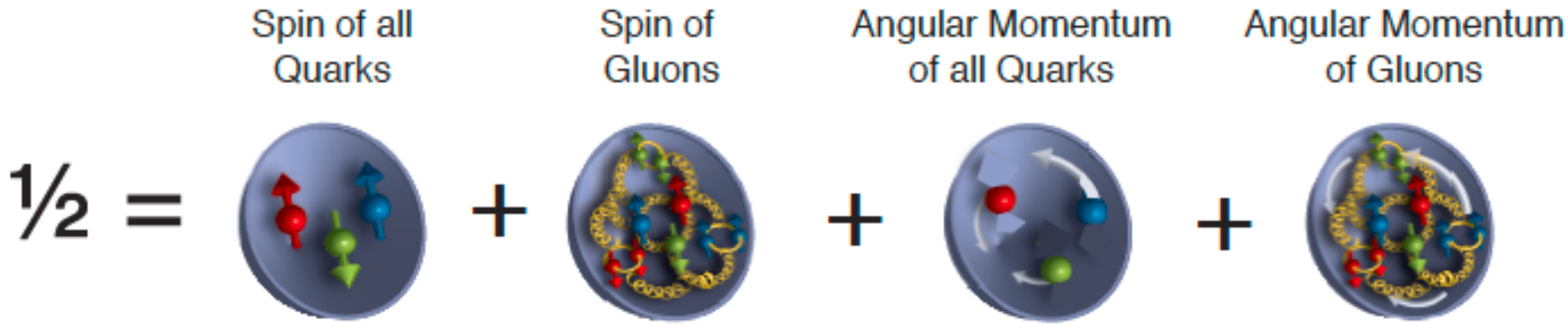
$\vec{J}$

Exciting new regime of studying the most spinning baryonic matter!

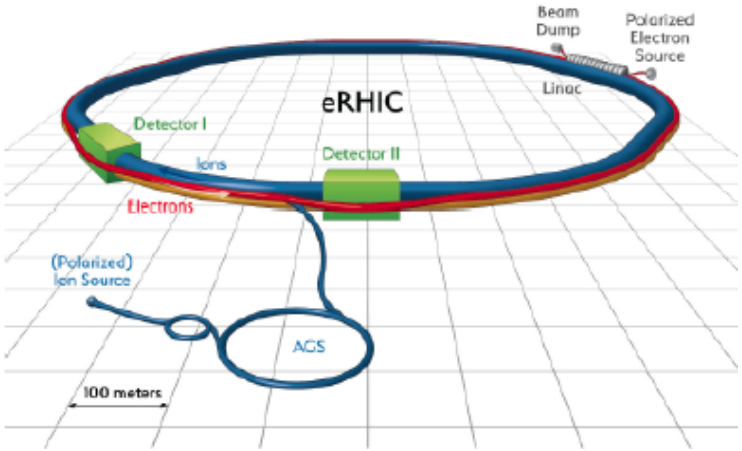
$$\frac{J}{B} \sim \hat{O}(10)$$

QCD with Angular Momentum: Proton Spin

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

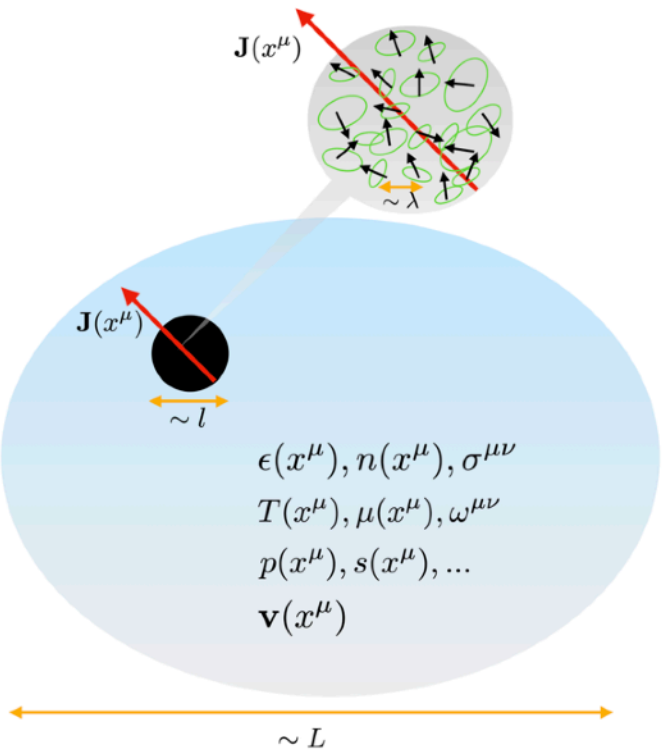


arXiv:1212.1701



Electron Ion Collider (EIC)
Running ~2030

QCD with Angular Momentum: Fluid Matter



"Spin physics" of a fluid cell

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

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

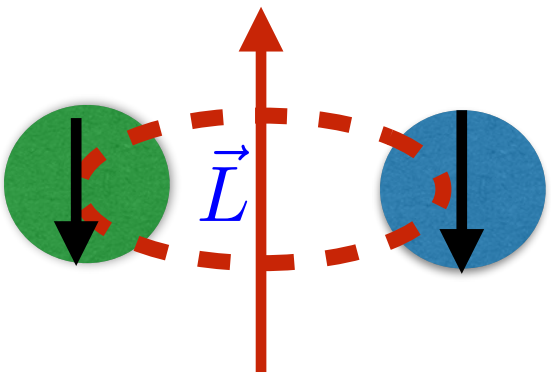
Many interesting questions:
— decomposition of spin/orbital
— gradients and viscous terms
— phenomenological modeling
— .....

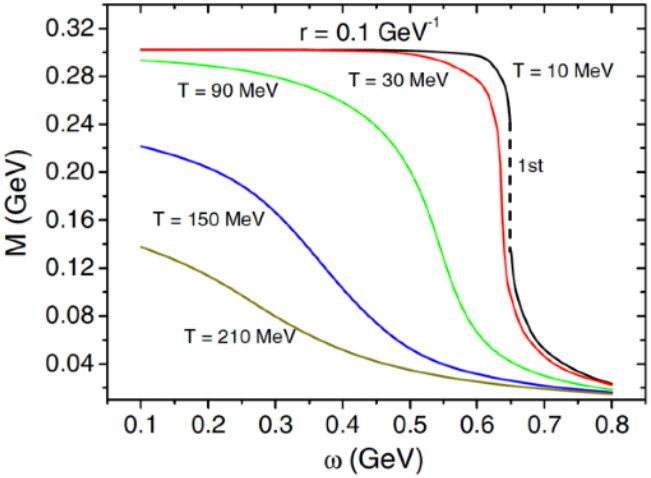
[She, Huang, You, JL, Science Bulletin 67(2022)2265-2268 (arXiv:2105.04060)]

Phase Structures under Rotation

Can phase structures be influenced by the spin dof? Yes!

Especially: pairing phenomenon in fermion systems.
Many examples: chiral condensate,
diquark color superconductivity, mesonic superfluidity, …





— ***Rotational suppression of scalar pairing (chiral condensate; color superconductivity)***

— ***Rotational enhancement of rho condensation at high isospin***

[Yin Jiang, JL, PRL117 (2016) 19, 192302]
[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]