Novel Dimensions for Exploring QCD Matter in Heavy Ion Collisions

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INDIANA UNIVERSITY

NSF

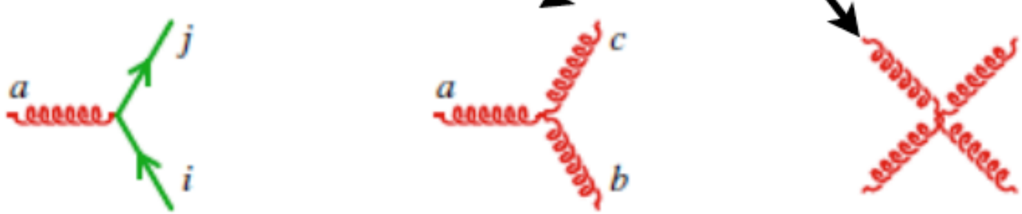
BEST COLLABORATION

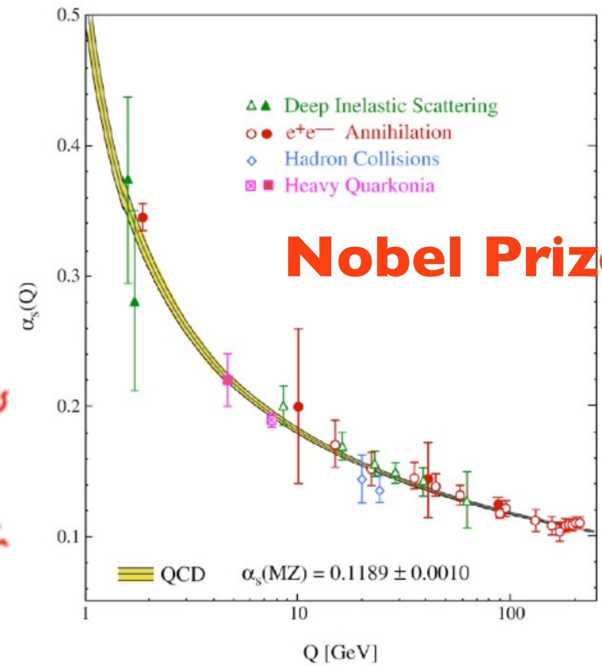
Quantum Chromodynamics (QCD)

The fundamental theory of strong nuclear force:
QCD, a non-Abelian gauge theory of quarks and gluons

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - M - g A\!\!\!/_a G^a)\psi - \frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$





Nobel Prize 2004

Asymptotic Freedom: coupling becomes large
at low energy or long distance scale.

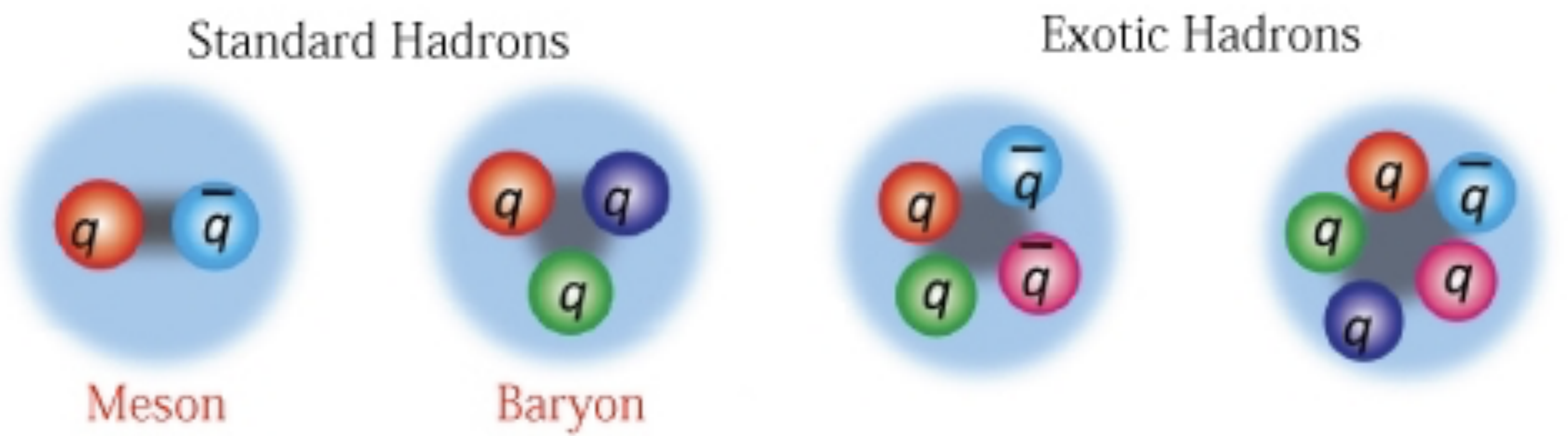
$$\Lambda_{QCD} \sim 200\text{MeV} \qquad R \sim 1\,\text{fm}$$

where "quark math" becomes very hard!

The Quark Math/Mystery: Exotic Hadrons?!

Confinement: non-perturbative force binds quarks in hadrons.

What are possible? Why some are possible and some not?

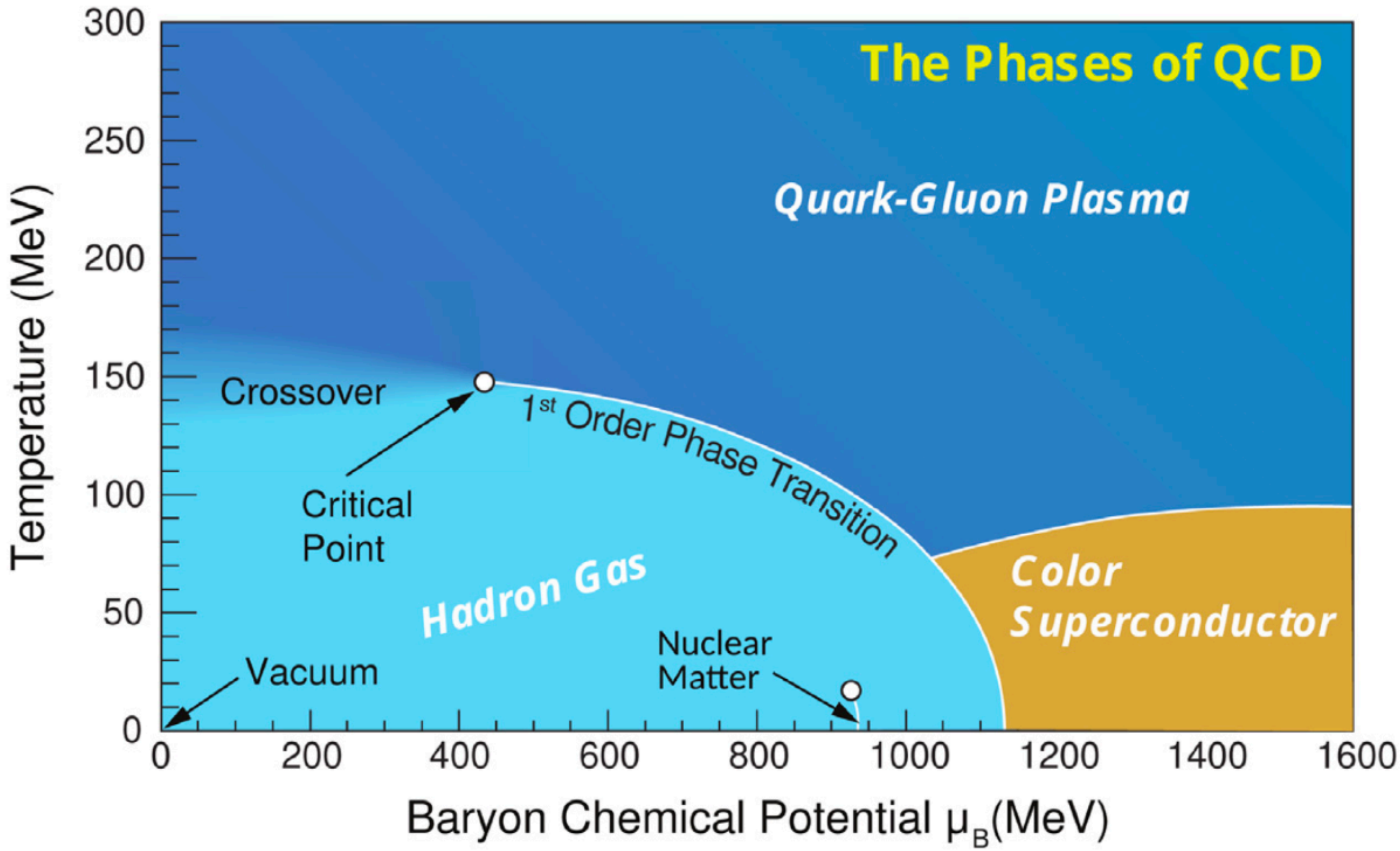


Understanding the "quark math" of hadrons:

Unravel the mysteries of nonperturbative QCD force between quarks/antiquarks;

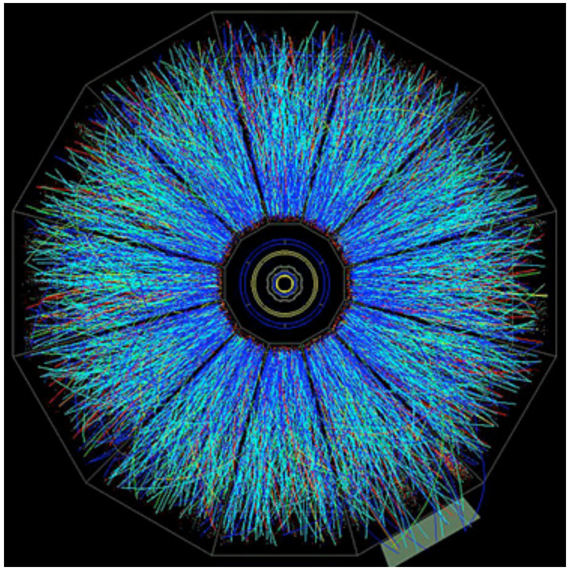
An exciting frontier of today's nuclear physics research

Cooking up a "Quark-Gluon Soup"



Tuning external controls like temperature and density to explore QCD matter under extreme conditions

Little Bangs in Heavy Ion Collisions (HIC)



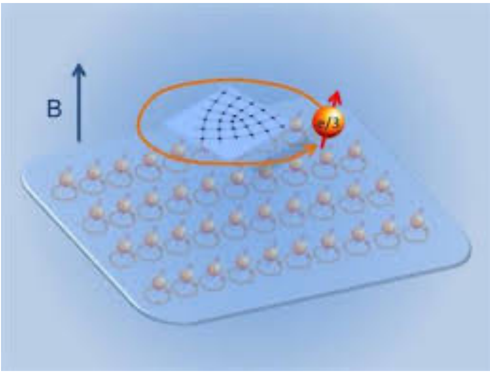
our most powerful heating machines ever

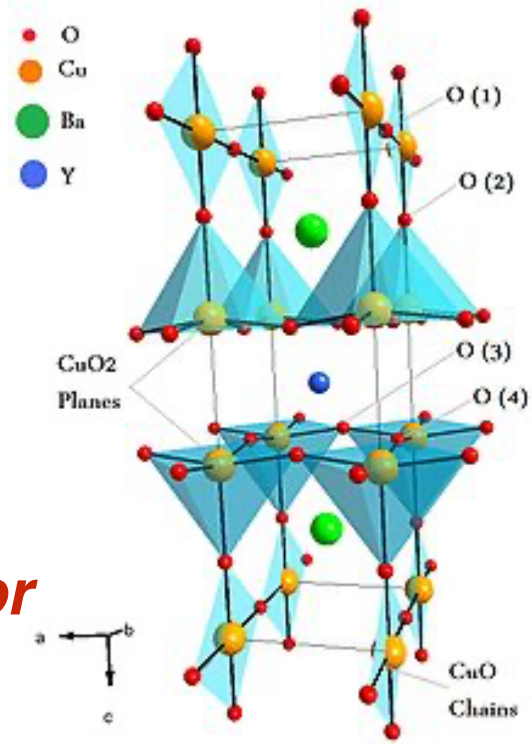
Quark-gluon plasma is created in high energy collisions!

The hottest matter!
The most perfect fluid!

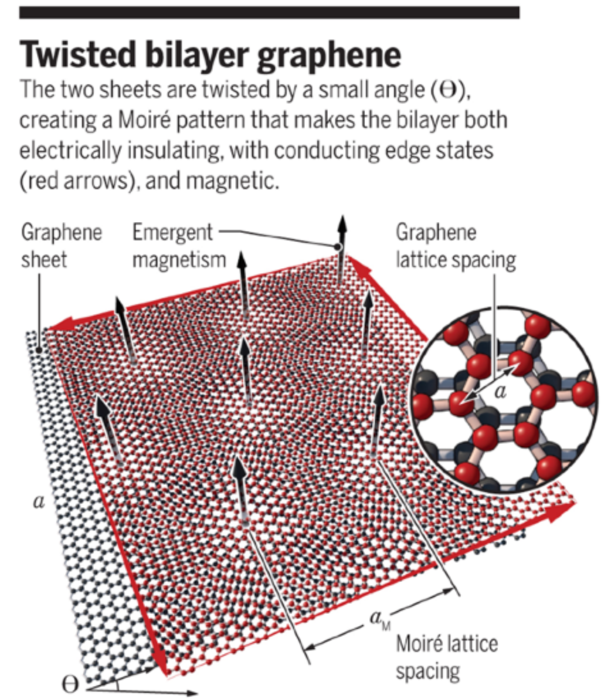
What's Next? Dialing All Knobs You've Got!

Quantum hall effect





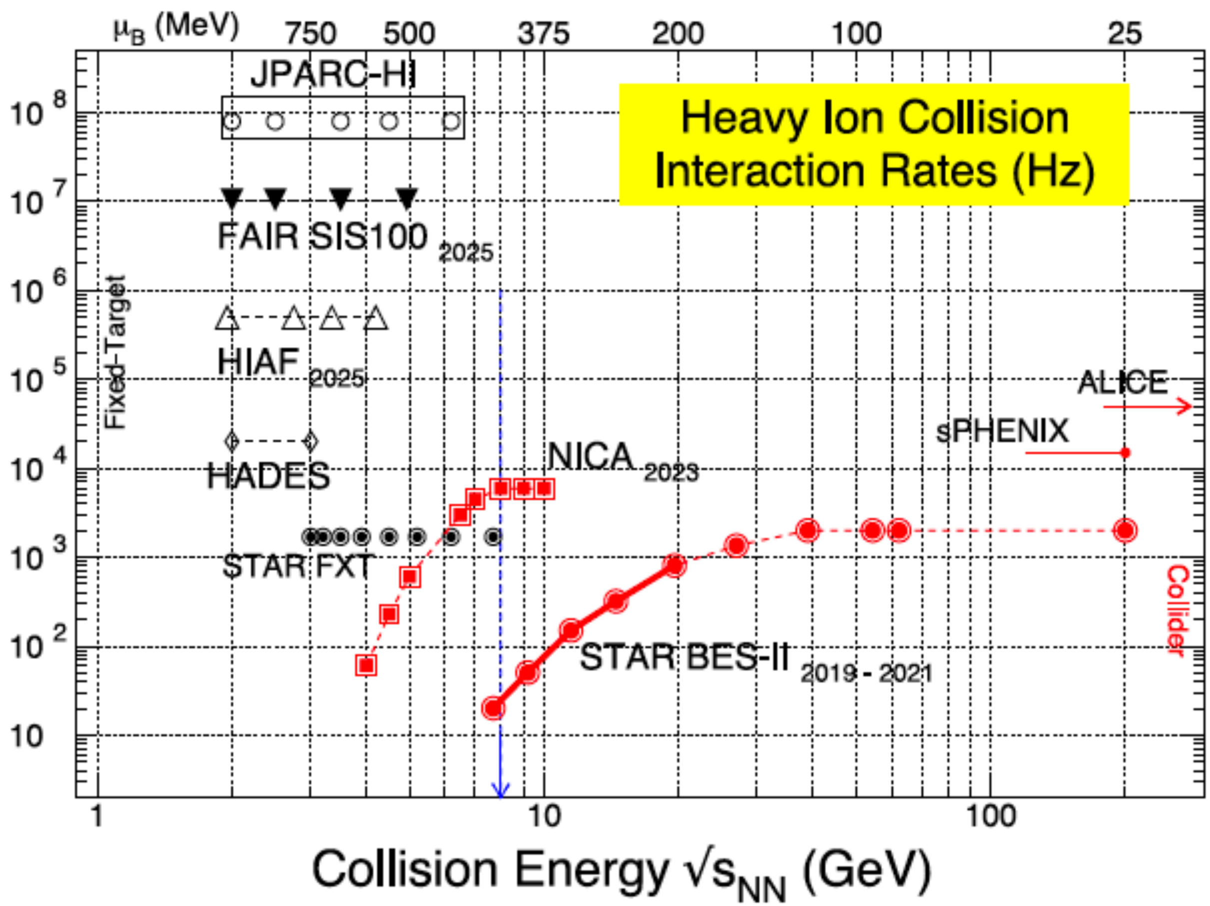
High-Tc superconductor



"Magic angle"

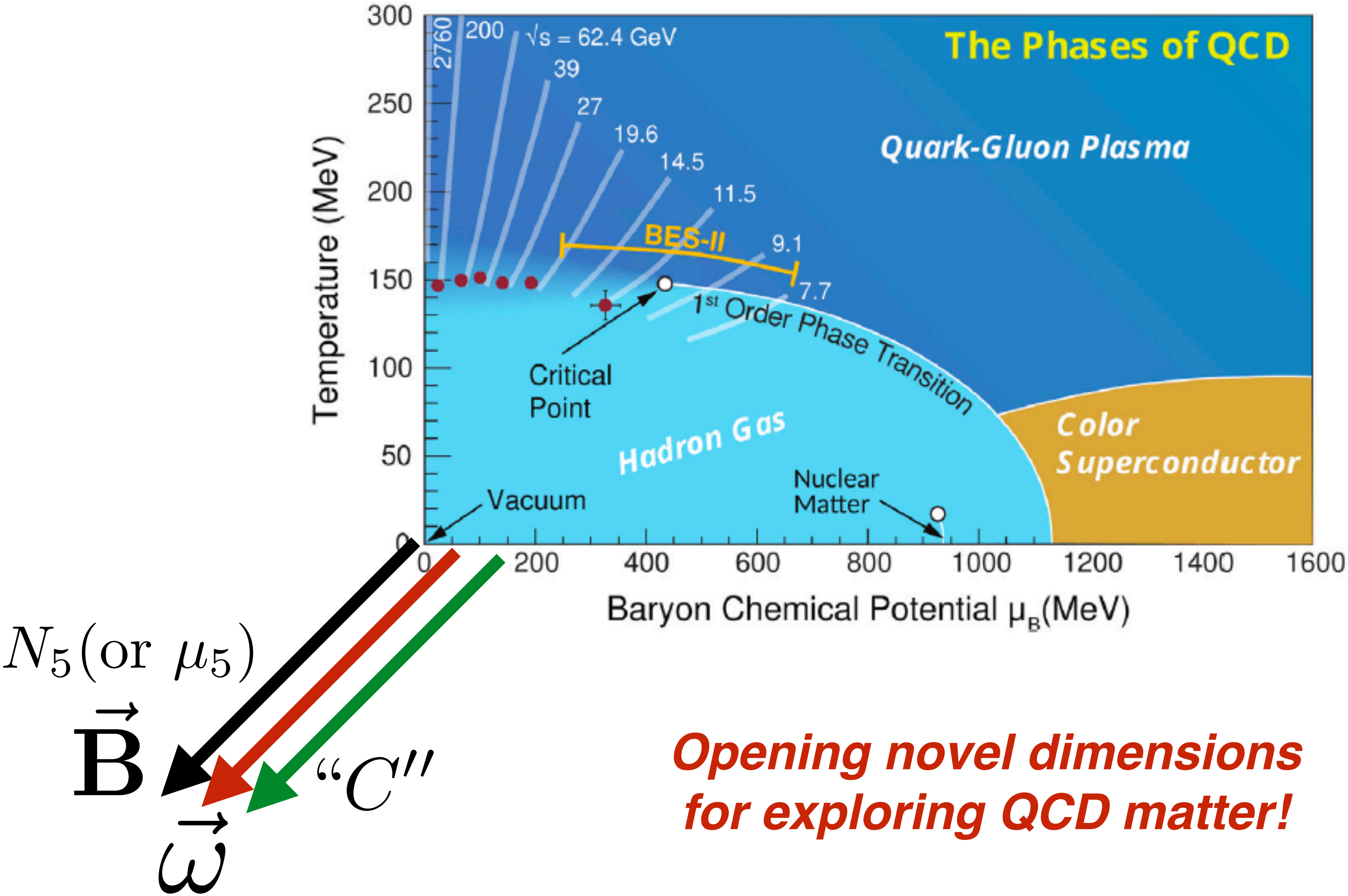
Collisions Across Wide Beam Energy Range

Relativistic nuclear collisions have been and will continue to be done from O(1) GeV to O(1000) GeV beam energy!



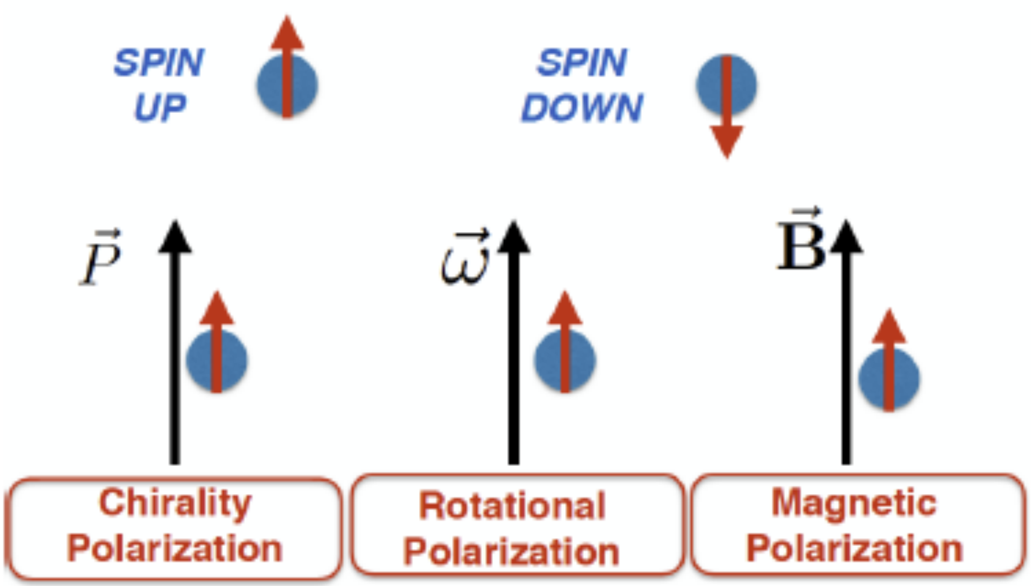
"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87.

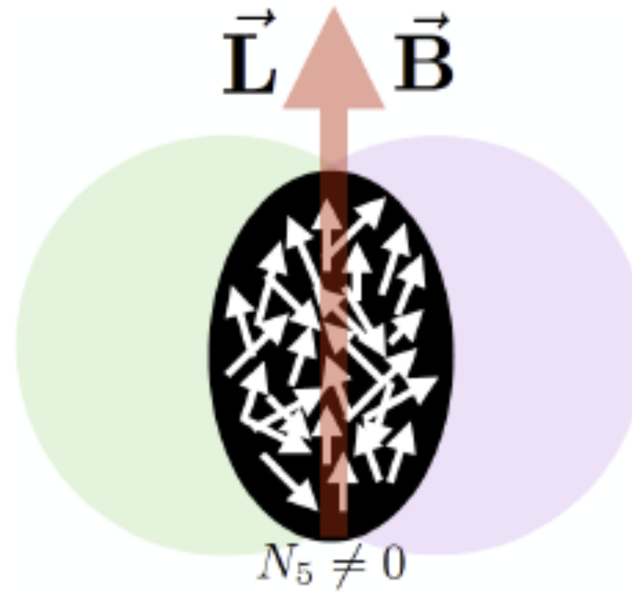
Novel Dimensions Enabled by BES



Opening novel dimensions for exploring QCD matter!

Spin @ Chirality, Vorticity and Magnetic Field



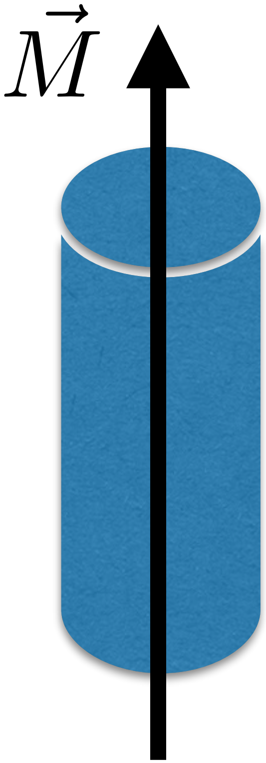


[arXiv:2004.00569]

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

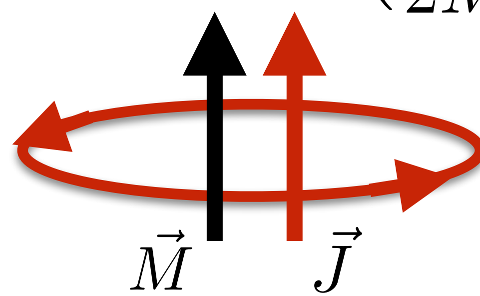
Einstein-de Hass Effect

Richardson,~1908; Einstein-de Hass,~1915:
Change of a free body's magnetic momentum —>
Mechanical rotation of the sample



Orbital contribution:

$$\Delta M = \left(\frac{q}{2M}\right)\Delta J$$

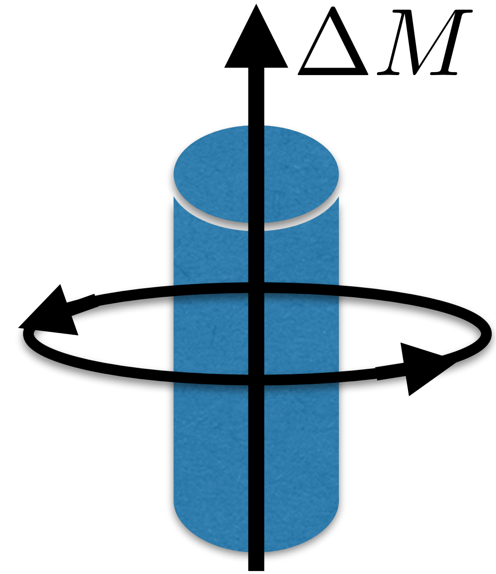


Spin contribution:

$$\Delta M = \left(\frac{2 \times q}{2M}\right)\Delta J$$

Barnett (OSU), ~1915:
1st correct measurement, supporting the g~2,
Indicating dominant spin contributions in magnetization.

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.

The opposite should also happen:

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

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

THE

PHYSICAL REVIEW.

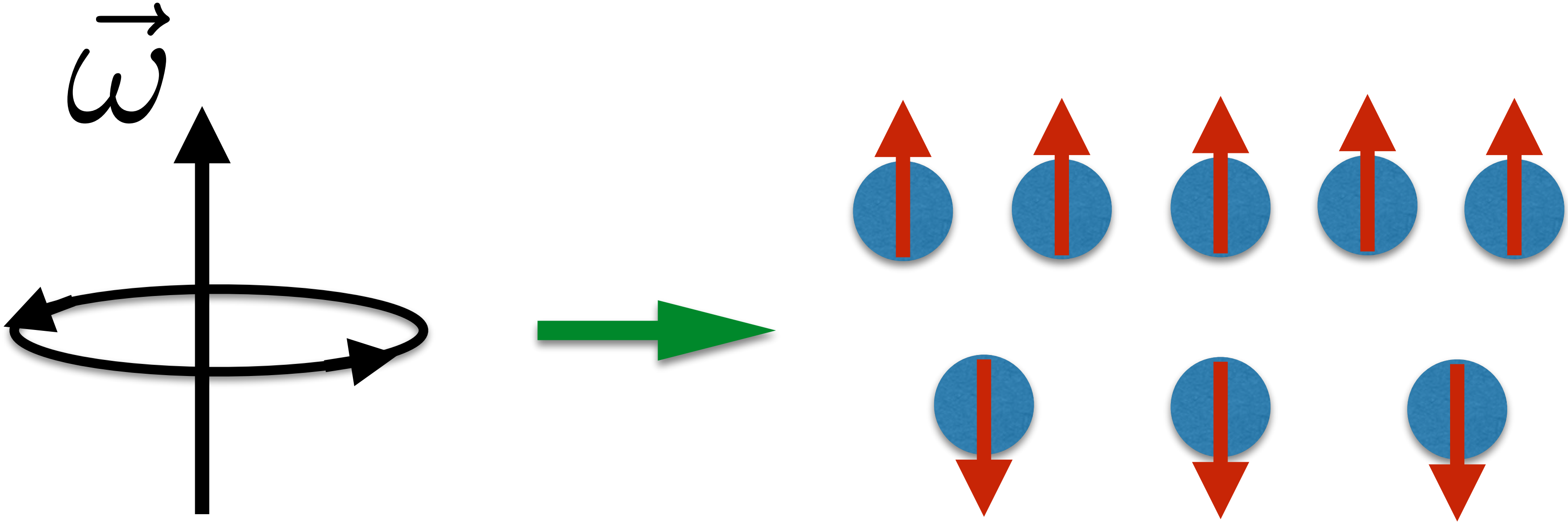
MAGNETIZATION BY ROTATION.[1]

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.

Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization



Macroscopic rotation; Global angular momentum

Microscopic spin alignment

It however is a lot tricker to be directly observed for a liquid/fluid.

Rotational Polarization in Condensed Matter

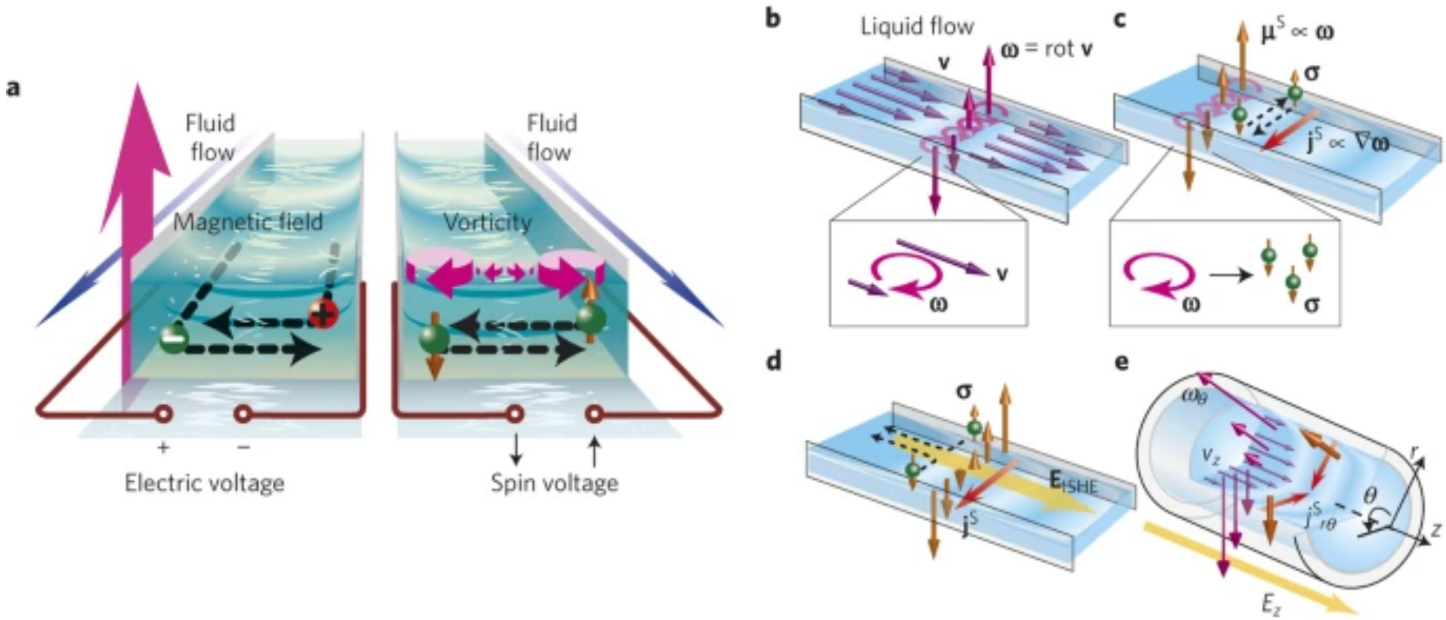
Spin hydrodynamic generation

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

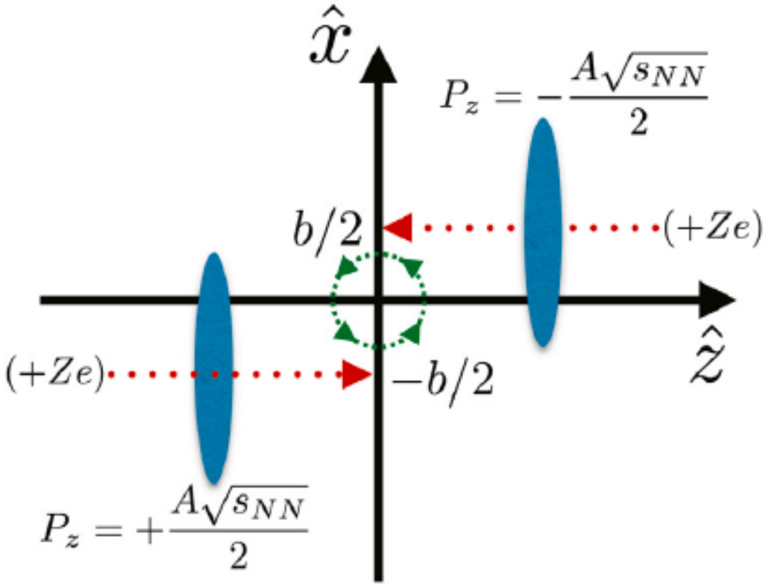
Nature Physics **12**, 52–56(2016) | Cite this article

Viscous fluid flow —> vorticity —> spin polarization

"Fluid Spintronics"



Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions

$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim 5}\hbar$$

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*

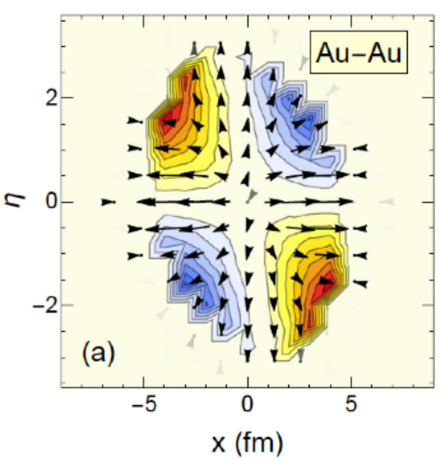
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

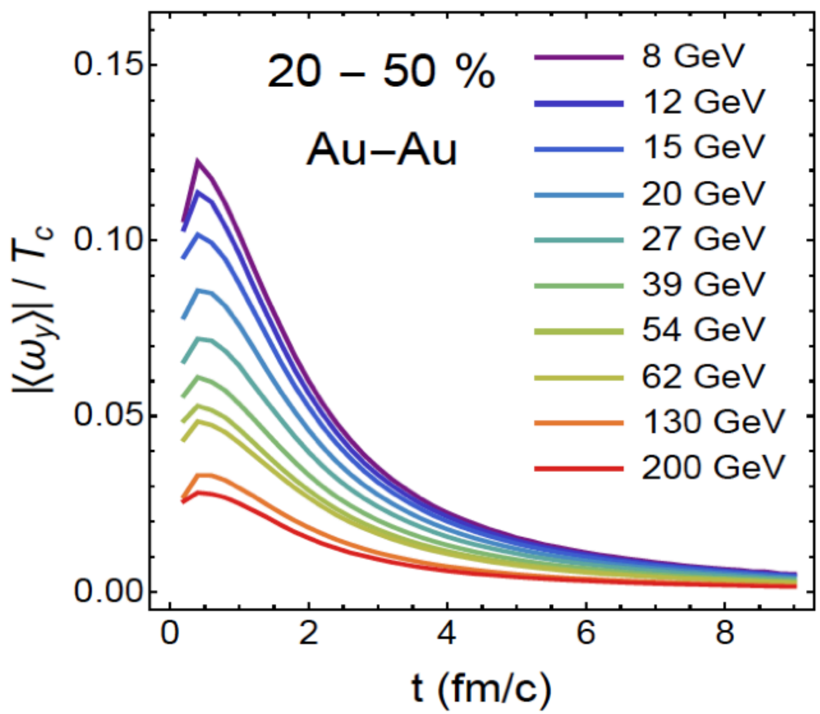
[3]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

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

Is this portion conserved? —YES!

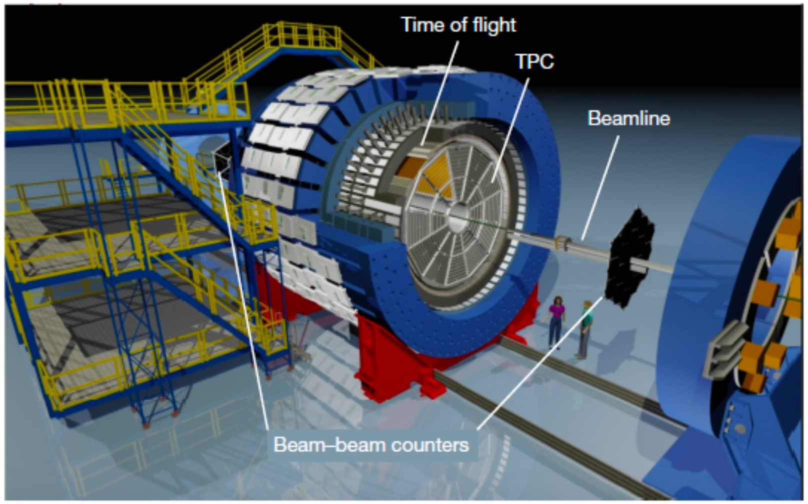
How QGP accommodates this angular momentum? — Fluid vorticity!





O(1~10) GeV is the region to look at!!

The Most Vortical Fluid



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

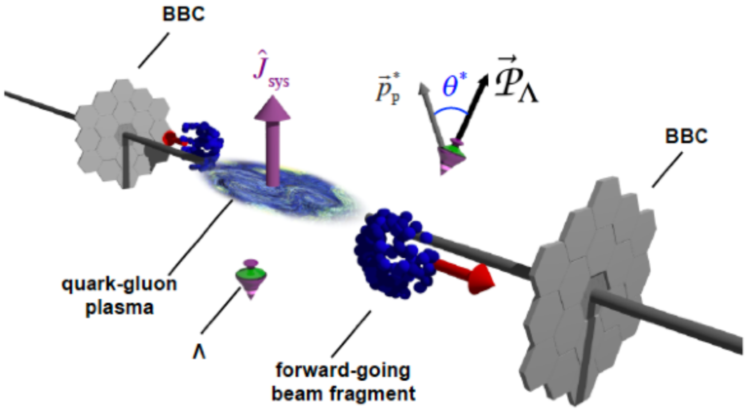
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

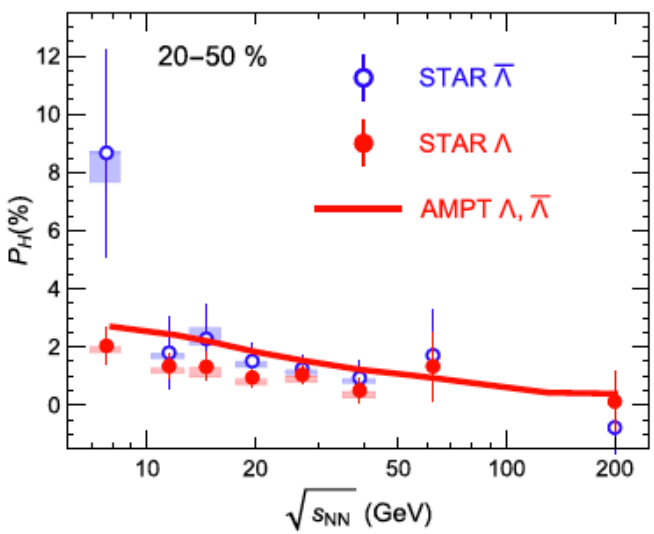
Spin Polarization in the Subatomic Swirls

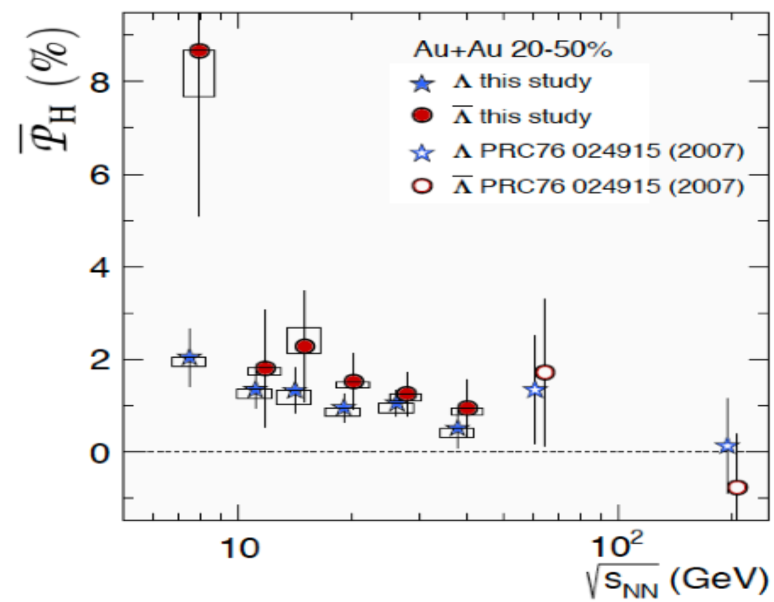


STAR Collaboration, Nature 2017

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

The most vortical fluid!

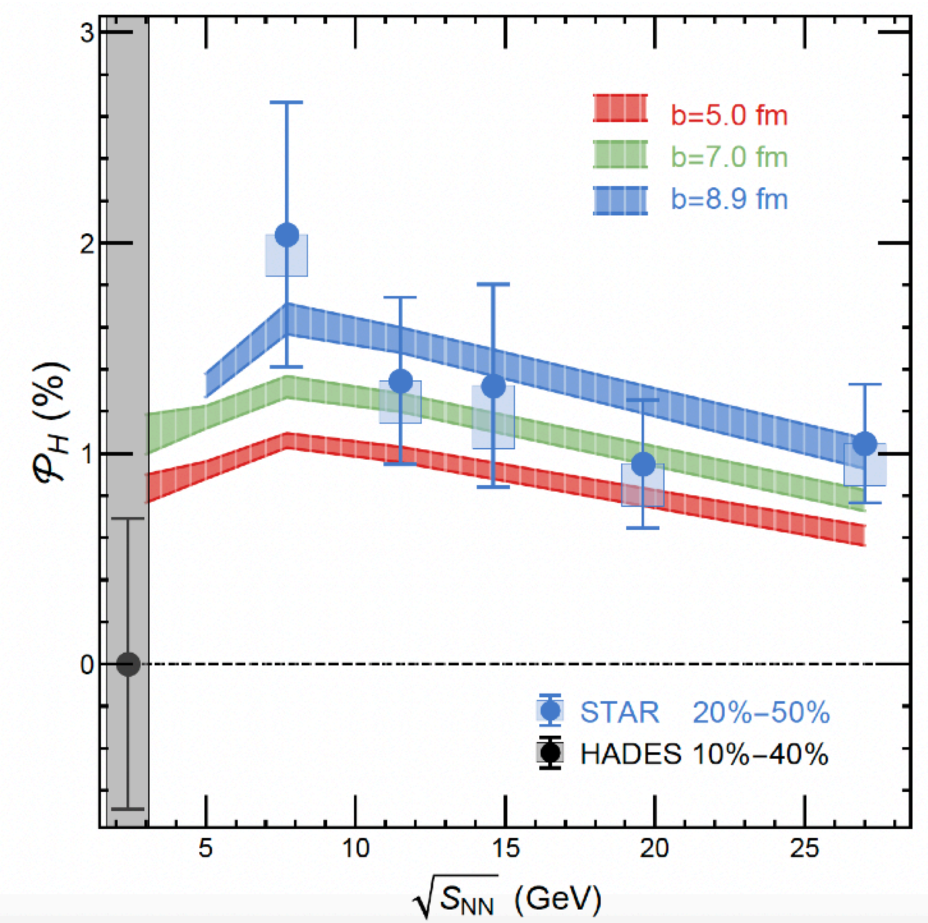




Next Question: Trend toward sub-10 GeV ???

Predictions for Global Polarization at O(1) GeV

An Interesting Question:
Trend from O(10) toward O(1) GeV ???



Yu Guo, et al:
to appear soon.

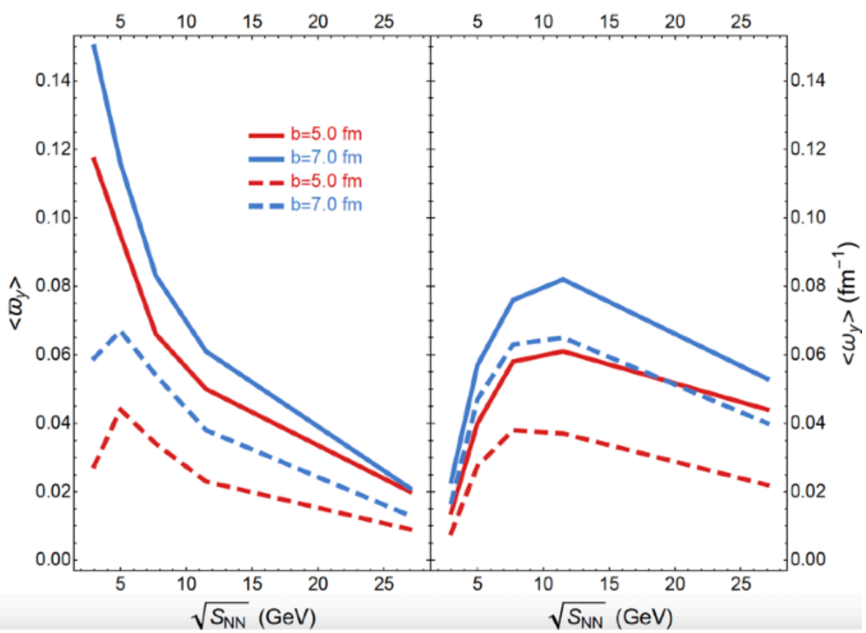
Calculations predict non-monotonic behavior in global polarization, with possible maximum in 5~10 GeV. More findings in forthcoming paper.

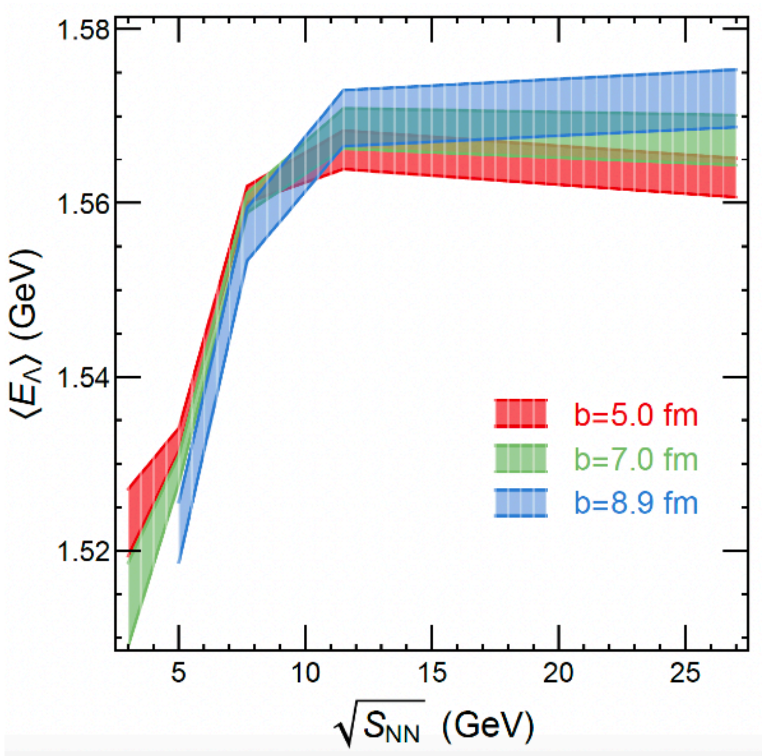
Why the Decrease toward O(1) GeV?

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

Due to strong decrease toward O(1) GeV region in both vorticity and produced hyperon energy

Yu Guo, et al: to appear soon.



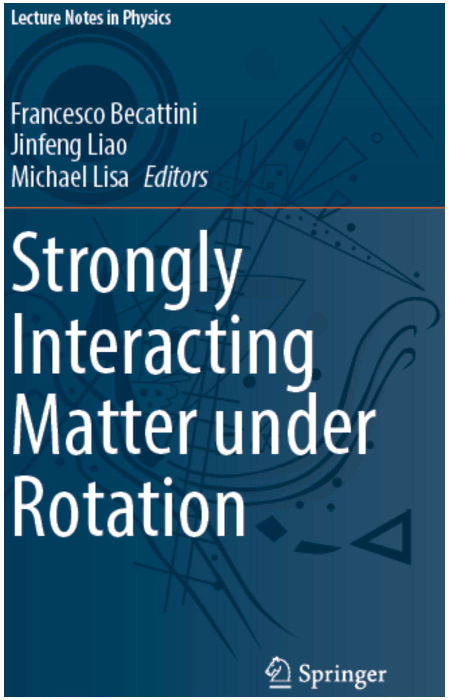


[For vorticity, see also URQMD results in: Deng, Huang, Ma, Zhang, arXiv:2001.01371]

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?***
- ***……***

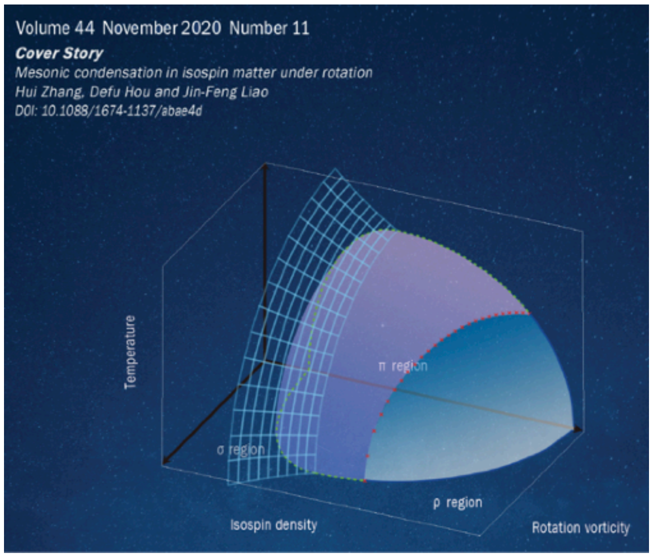


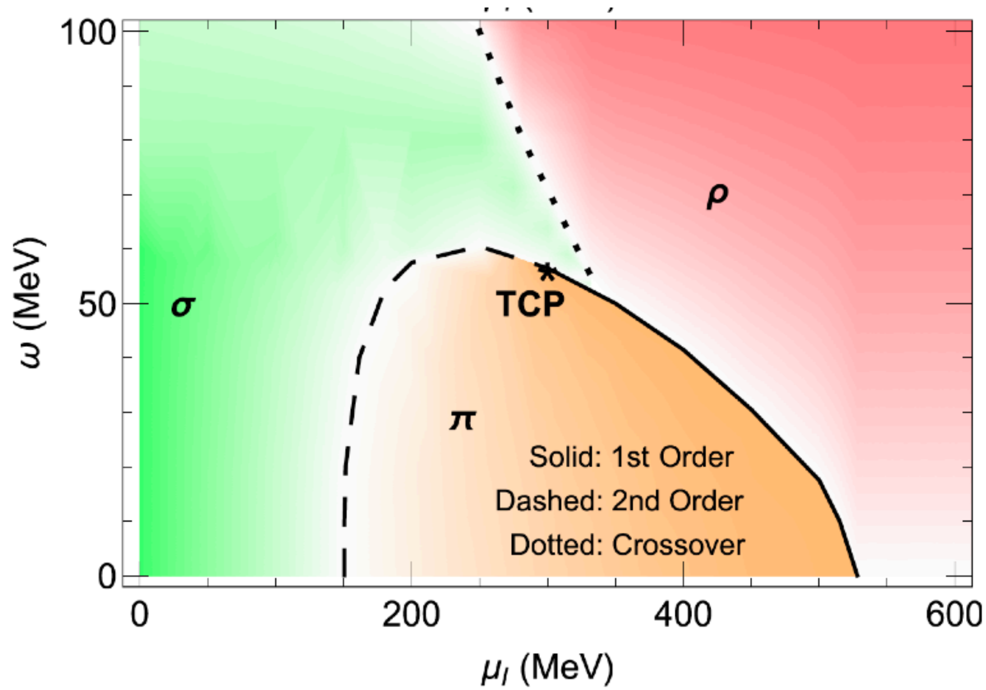
Many exciting new developments: see upcoming volume in Springer Lecture Notes in Physics!

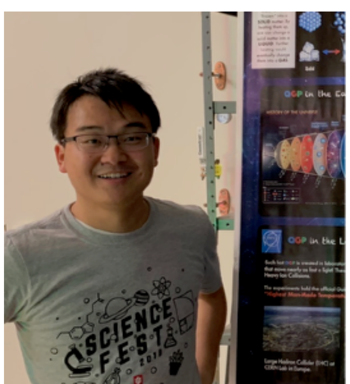
[arXiv:2102.00933; 2010.08937; 2009.04803; 2101.04963; 2004.04050; 2011.09974; 1908.10244; 2007.04029; 2001.00359; …]

Isospin Matter under Rotation

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





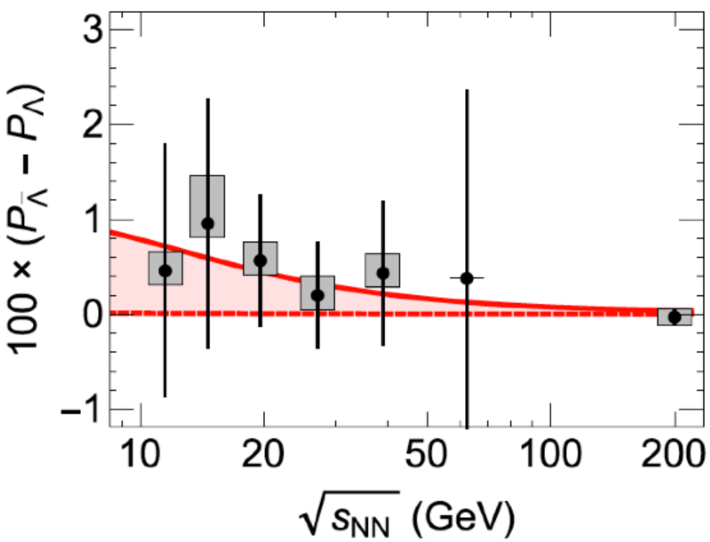


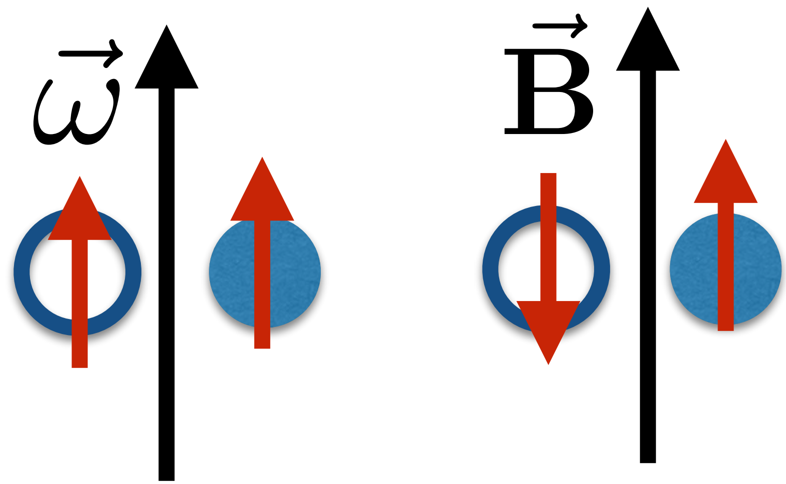
Rich phase structures found;
Could be relevant to low energy HIC
or neutron star matter

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

A Subatomic Version of Barnett Effect

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





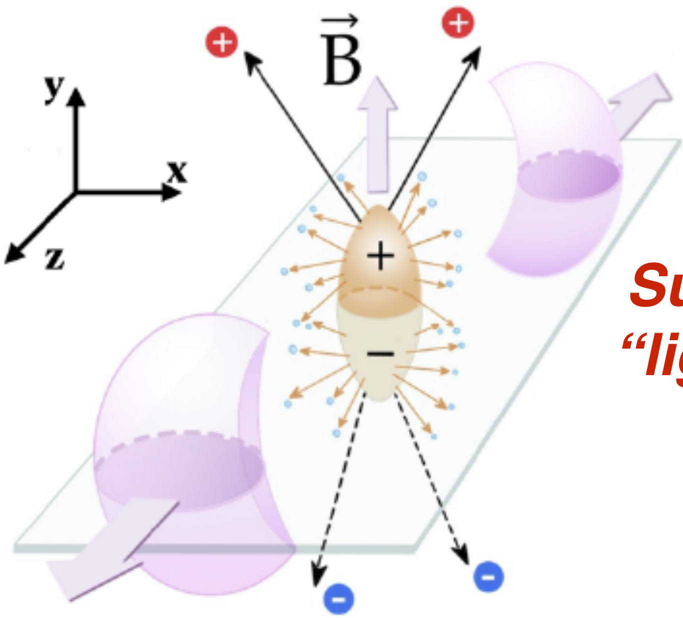
$$\tilde{S}^{\mu} = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\nu}\left[\varpi_{\rho\sigma} \mp 2(eF_{\rho\sigma})\mu_{\Lambda}/T_f\right]$$

Late-time magnetic field could explain the difference;

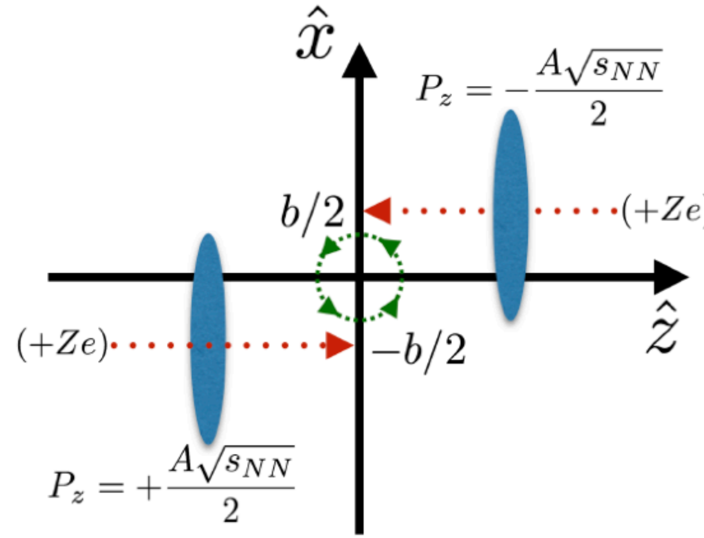
Charged fluid may enhance B field lifetime via Barnett-like mechanism.

[Guo, Shi, Feng, JL, arXiv:1905.12613, PLB2019]
[Guo, JL, Wang, arXiv:1904.04704, Scientific Reports 2020]

The Most Magnetized Fluid



Subatomic "lightning"!

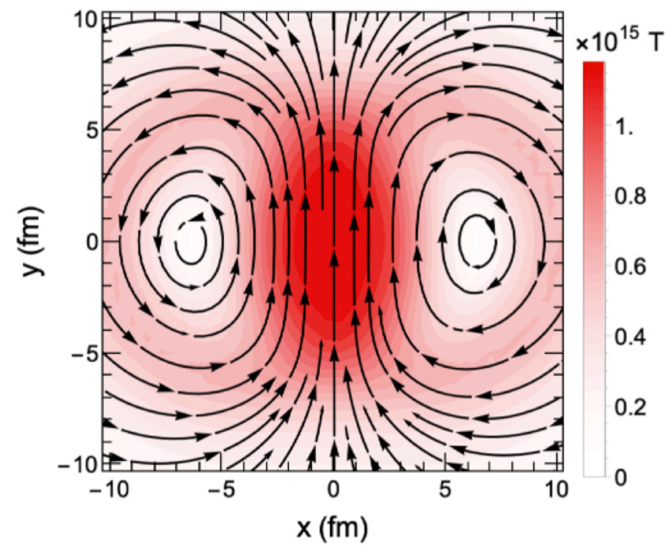


The strongest B field ~ 10^15 Tesla

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

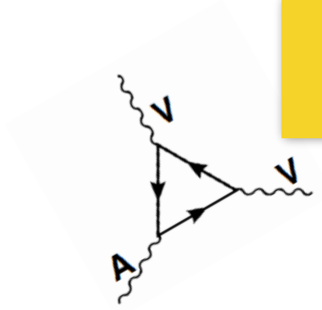
However, short-lived

$$\tilde{t}_B = \frac{A}{\sqrt{s_{NN}}} \quad \text{with} \quad A = 115 \pm 16 \ \text{GeV} \cdot \text{fm/c}$$

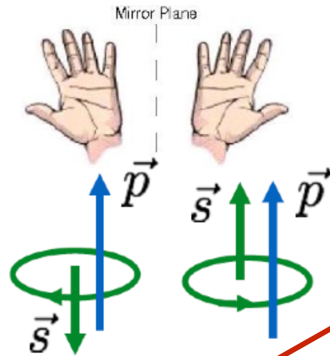


Optimal range for B-effects O(~100) GeV

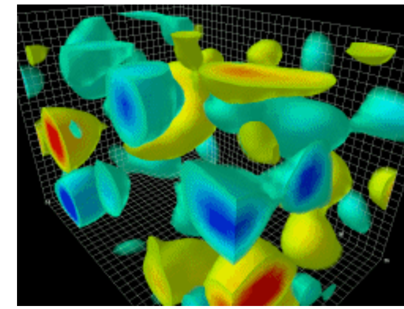
Chiral Magnetic Effect (CME)



Chirality & Anomaly



Chirality & Topology



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

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

Anomalous Electric Current

Magnetic Field

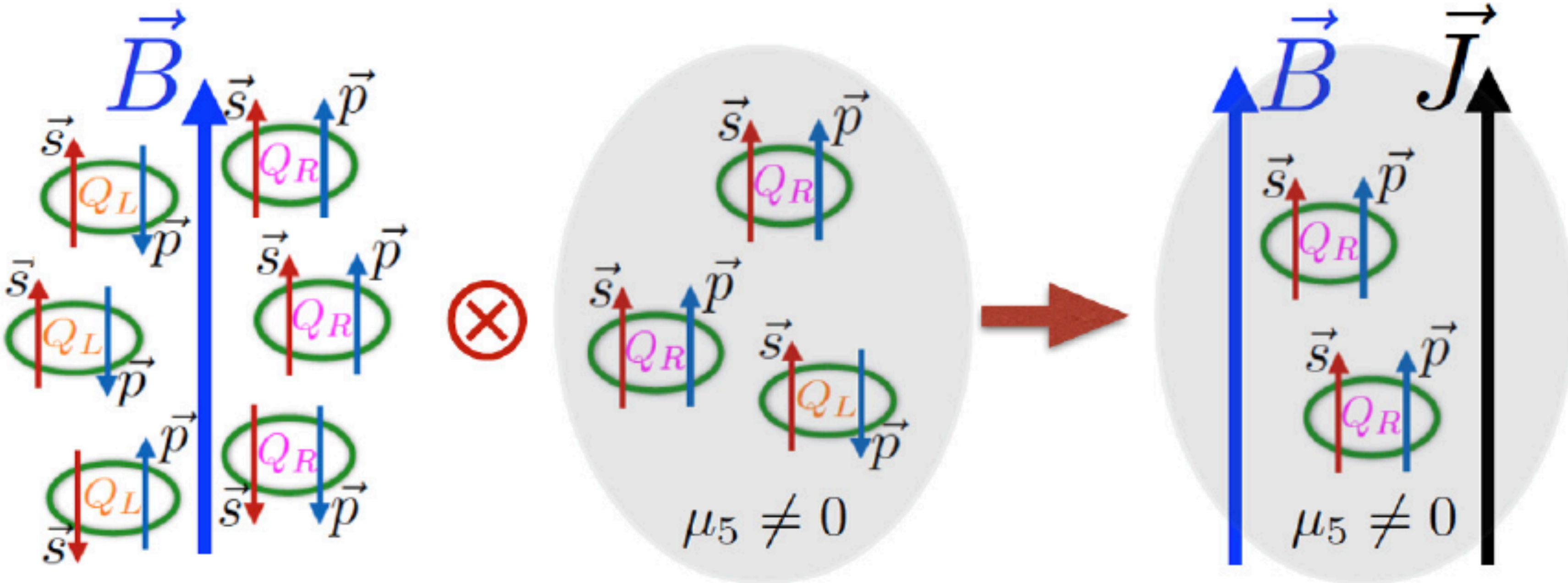
Q.M. Transport

CME <—> macroscopic chiral anomaly

CME: a new quantum, non-dissipative electricity

CME: strong interdisciplinary interests

CME: Interplay of B- and Chirality- Polarizations



Intuitive understanding of CME:

Magnetic Polarization —> **correlation between micro. SPIN & EXTERNAL FORCE**

$\otimes$

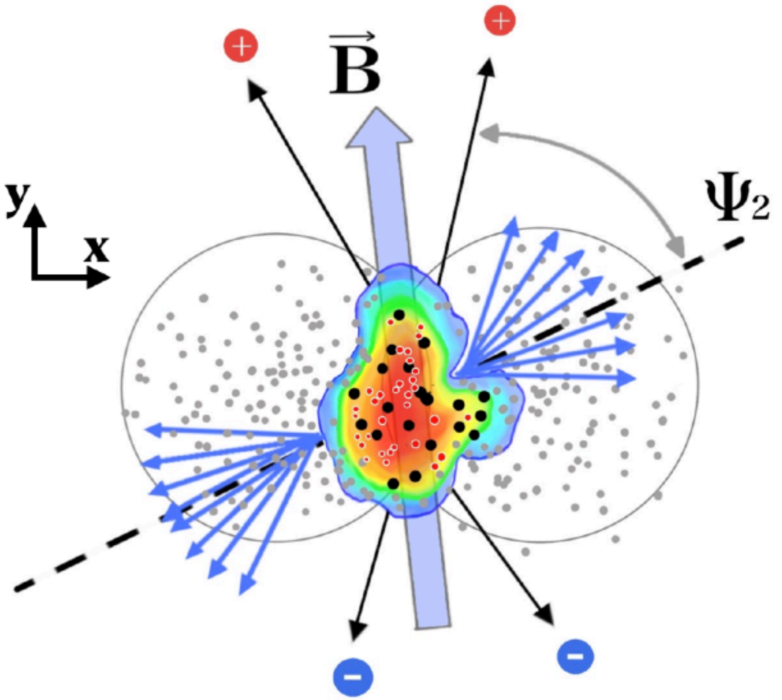
Chirality Polarization —> **correlation between directions of SPIN & MOMENTUM**

→ ***Transport current along magnetic field***

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

Looking for CME Signals in Nuclear Collisions

CME transport induces a charge dipole distribution along magnetic field direction in the QGP fluid.



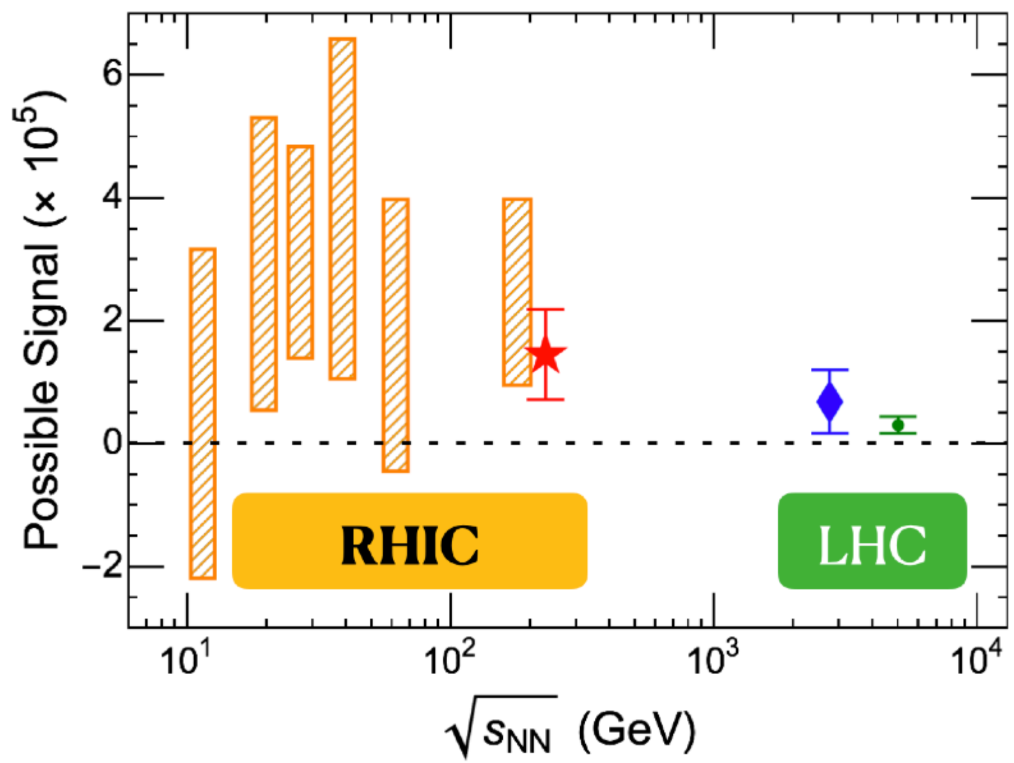
Gamma-correlator;
Gamma + v2 subtraction;
Gamma + event shape;
Gamma RP versus EP;
Gamma + invariant mass;
Signed balance function;
R-correlator

A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

Have We Seen the CME?

- *First measurement ~ 2009 by STAR;*
- *Efforts in past decades by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, PbPb*

It proves to be a very difficult search: Very small signal contaminated by very strong background correlations!



Experimental data: very positive hints, yet inconclusive.

Optimal range: O(~100) GeV

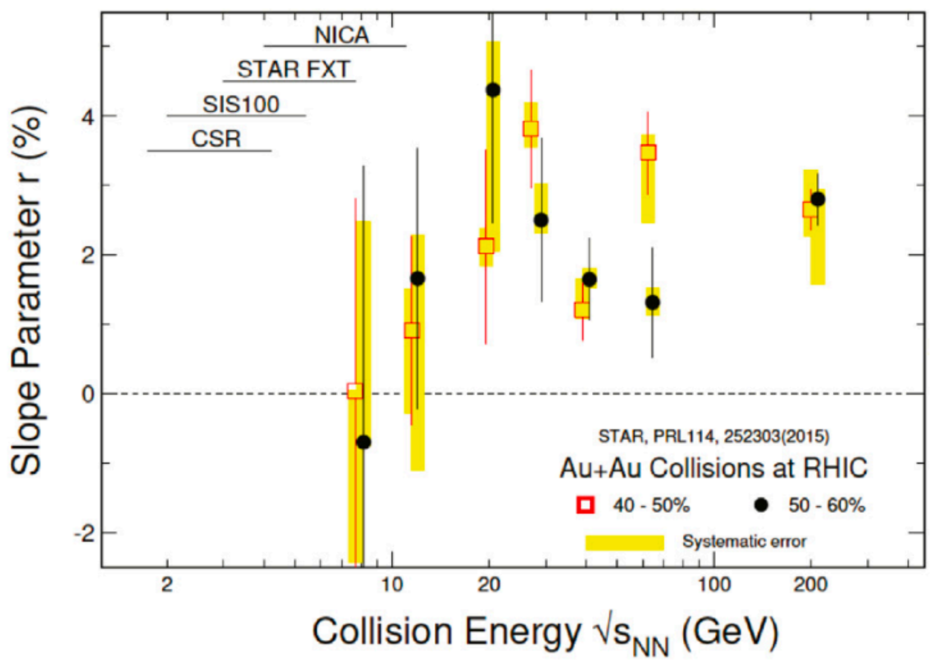
A related search: chiral magnetic wave (CMW)

Chiral Magnetic Wave

A related search: chiral magnetic wave (CMW)

CMW —> charge quadrupole of QGP —> elliptic flow splitting

[Burnier, Kharzeev, JL, Yee, PRL2011; and arXiv: 1208.2537]



$$v_2^- - v_2^+ = r_e A$$

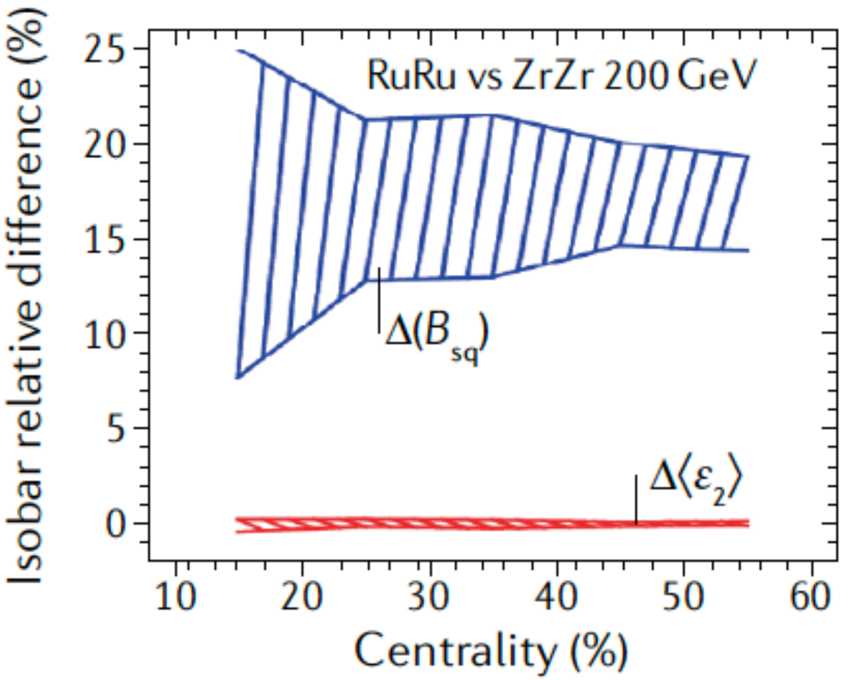
Experimental data: very positive hints, yet inconclusive.

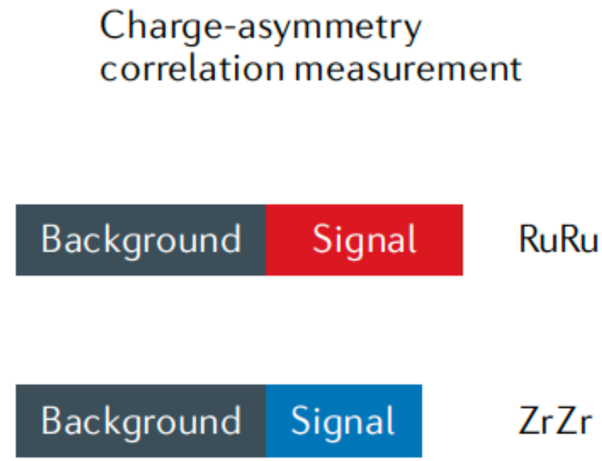
Optimal range: O(~100) GeV

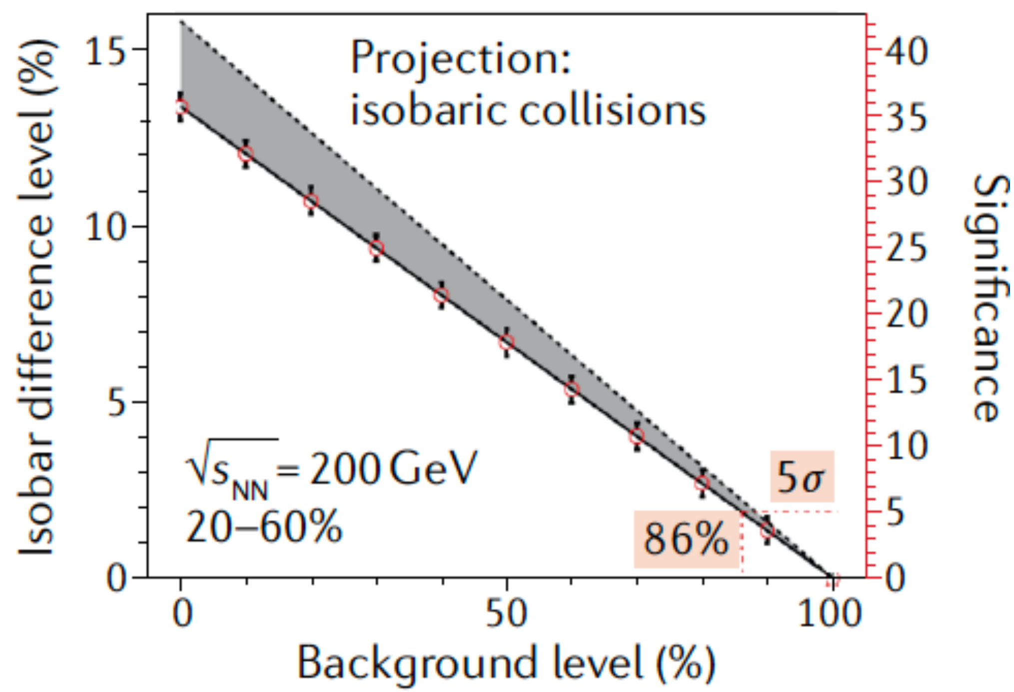
From:Phys. Rep. 853(2020)1-87.

A Decisive Experiment: Isobar Collision

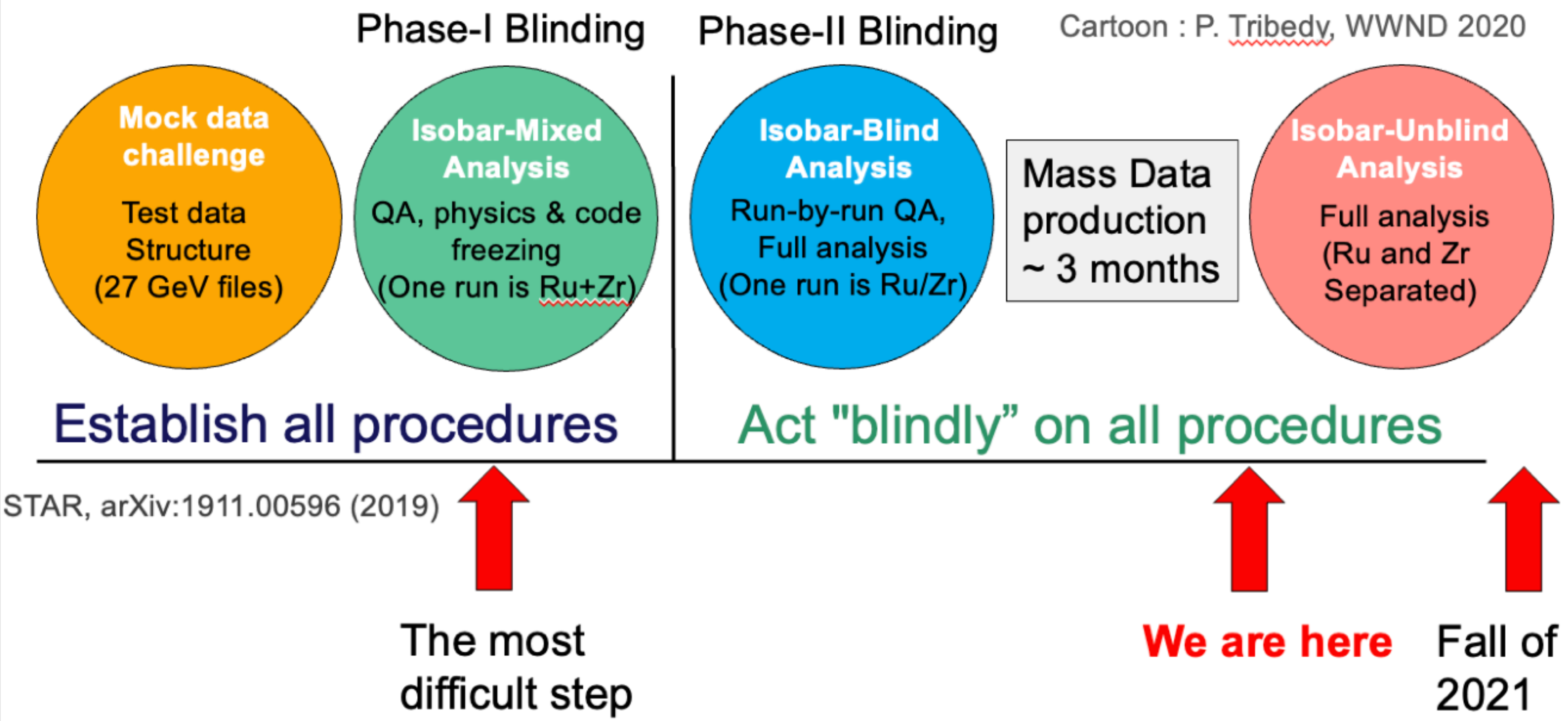
Exciting opportunity of discovery: 3 billion events collected for each system; results in ~ months!!!







Status of Isobar Analysis



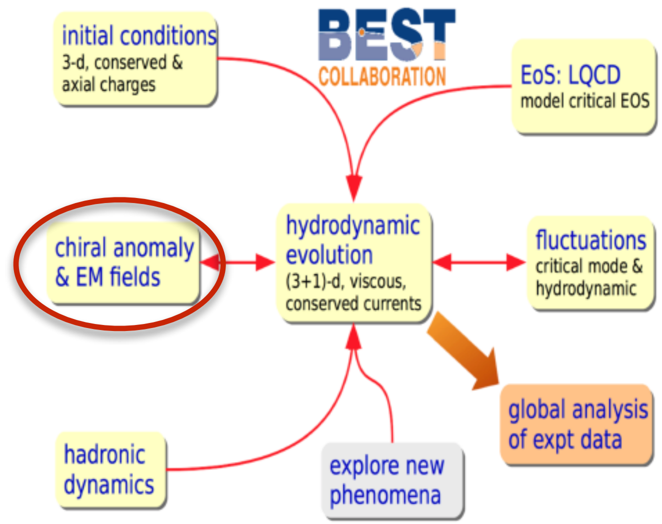
Tang for STAR, PAC Mtg, Sept. 2020.

- Program Advisory Committee Recommendation:
  - The PAC strongly recommends that any STAR publication regarding CME observables should contain the result after unblinding and without any additional corrections applied after unblinding that are deemed necessary by STAR. If such additional corrections are needed, then a paper containing both the unblinded and post-unblinded results should be published for reference in papers reporting the isobar data.

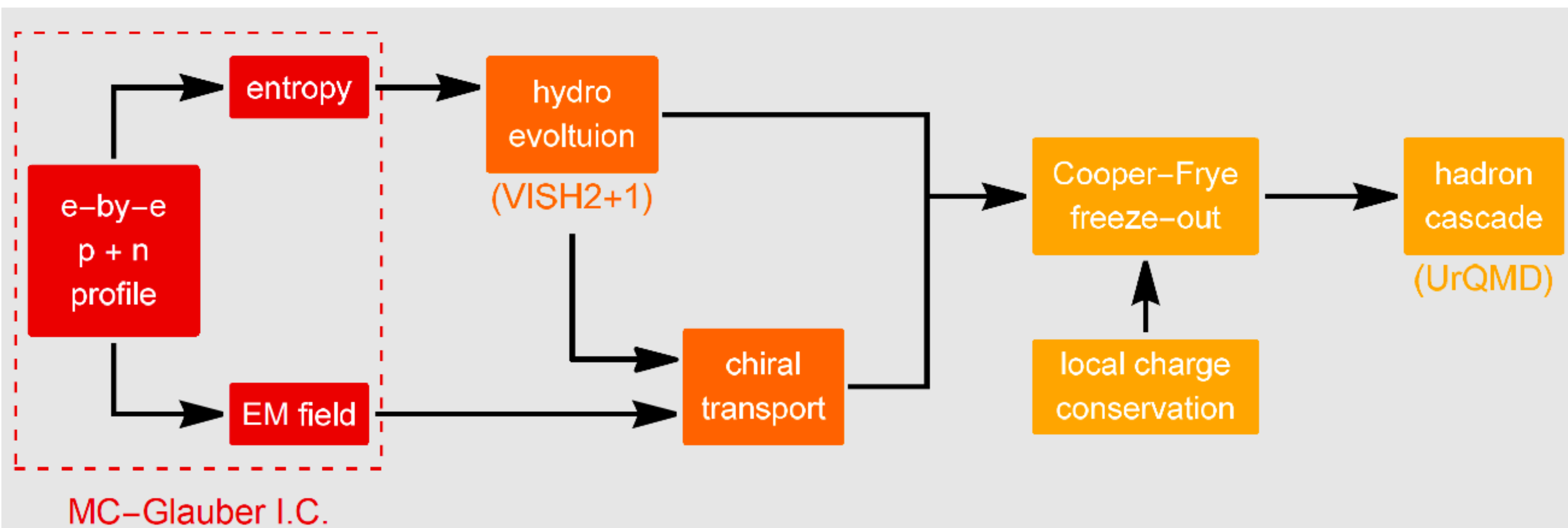
From: Aihong Tang

CME Working Group @ BEST Collaboration

Theoretical tool for quantitative predictions of CME and related backgrounds is crucial!



EBE-AVFD:
event-by-event anomalous-viscous fluid dynamics



[Shuzhe Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

EBE-AVFD

Anomalous-Viscous Fluid Dynamics

$$D_\mu J_R^\mu = +\frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = -\frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2}\mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2}\mu_L B^\mu$$

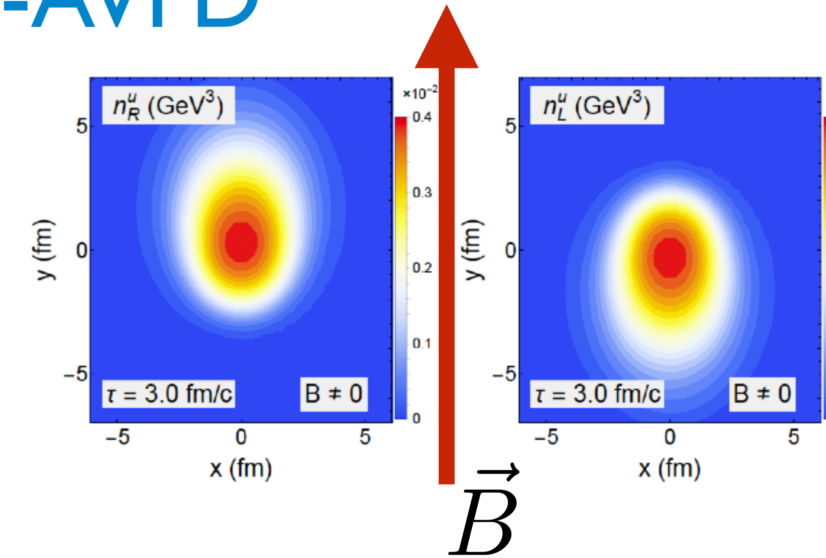
CME

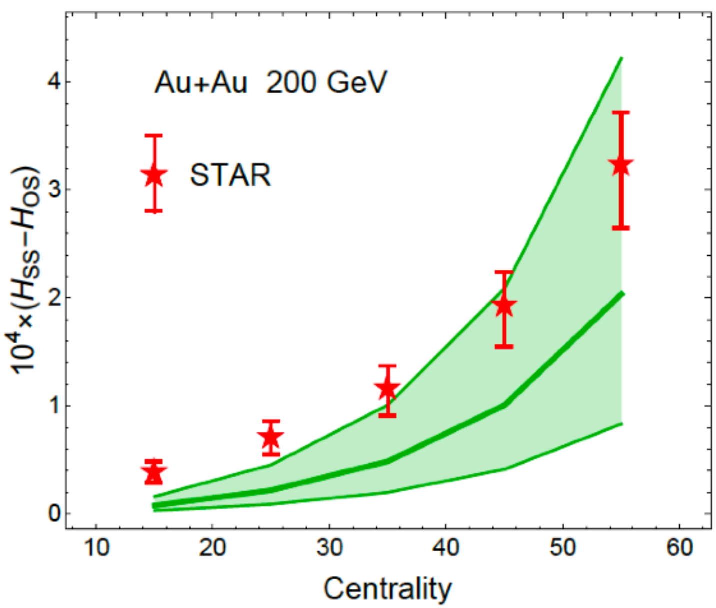
Viscous Effect

$$\Delta^\mu{}_\nu d\, \nu_{R,L}^\nu = -\frac{1}{\tau_{rlx}}(\nu_{R,L}^\mu - \nu_{NS}^\mu)$$

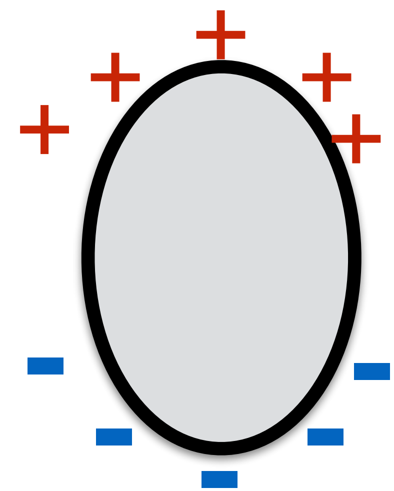
$$\nu_{NS}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

on top of VISH2+1D –– OSU Group





Chirality imbalance
–>
R/L asymmetry
–>
charge asymmetry



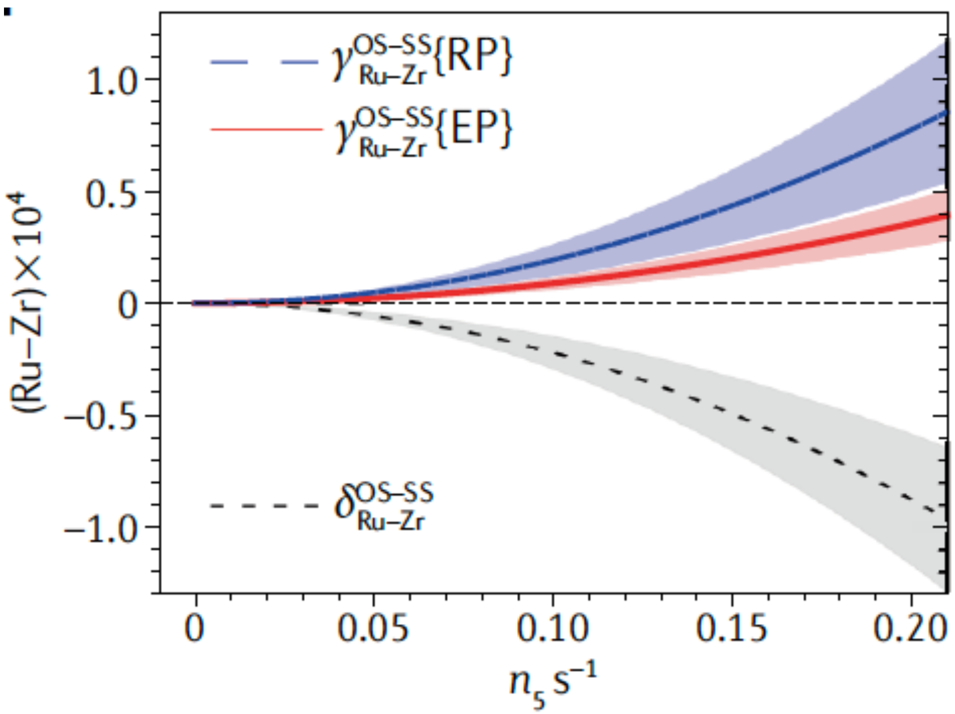
[Shi, JL, …, arXiv:1611.04586; 1711.02496; 1910.14010]

Predictions for Isobars

PHYSICAL REVIEW LETTERS **125,** 242301 (2020)

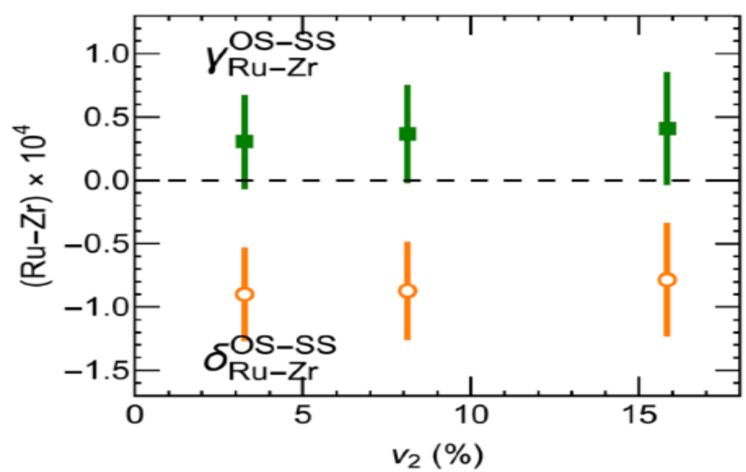
Signatures of Chiral Magnetic Effect in the Collisions of Isobars

Shuzhe Shi,[1] Hui Zhang,[2,3,4] Defu Hou,[2,*] and Jinfeng Liao[5,†]



$$\zeta^{RP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{RP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{RP}} \simeq -(0.90 \pm 0.45)$$

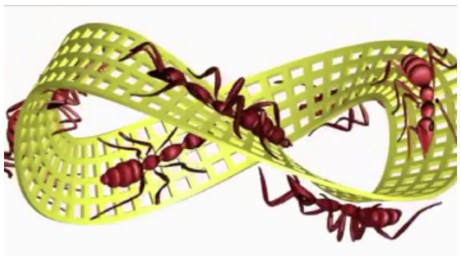
$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$



Stay tuned!

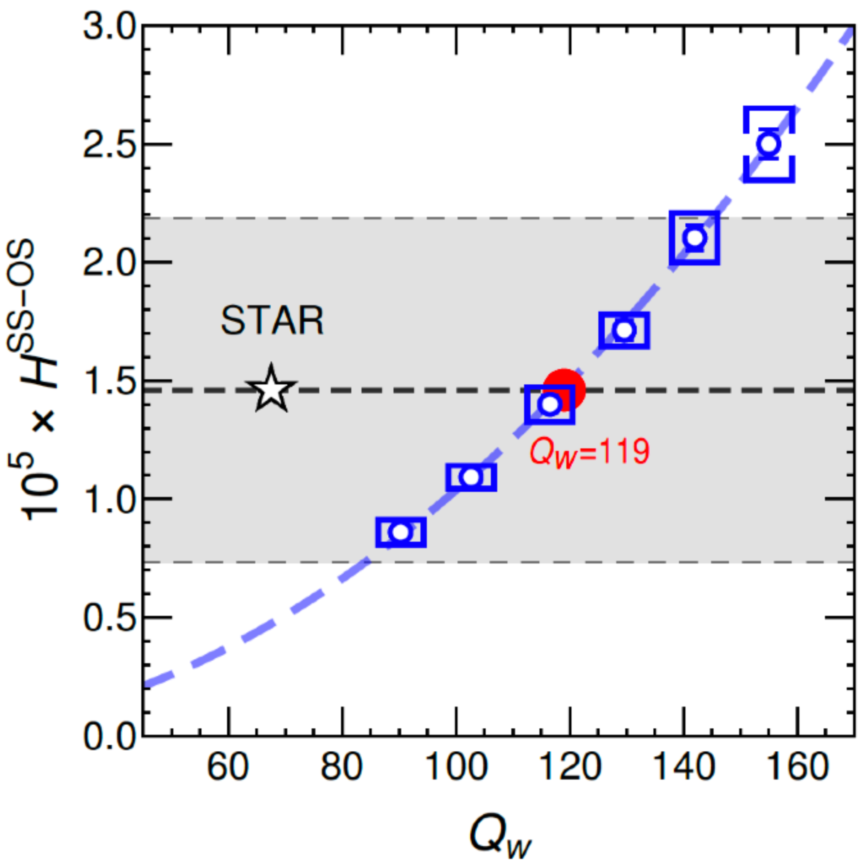
Counting Topological Twists of Gluon Fields

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



Gluon topology Qw
<—> Chirality imbalance
<—> CME signal

Need: AVFD +
stochastic dynamics
of axial charge



Anping Huang, et al,
to appear soon.

Further Sources on CME

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

Dmitri E. Kharzeev and Jinfeng Liao

Nature Reviews Physics 3, 55-63 (2021) [arXiv:2102.06623]

Prog. Part. Nucl. Phys. 88(2016)1-28 [arXiv: 1511.04050]

Progress in Particle and Nuclear Physics 88 (2016) 1–28

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journal homepage: www.elsevier.com/locate/ppnp

Review

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

CrossMark

D.E. Kharzeev [a,b], J. Liao [c,d,*], S.A. Voloshin [e], G. Wang [f]

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[b] Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[c] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 727 E Third Street, Bloomington, IN 47405, USA
[d] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48201, USA
[f] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

Further Sources on CME

Li, Wang, arXiv:2002.10397, Ann. Rev. Nucl. Part. Sci. 2020

Fukushima, arXiv:1812.08886, PPNP2019.

Zhao, Wang, arXiv:1906.11413, PPNP2019.

Wang, Zhao, Nucl. Sci. Tech., 29 (2018) no.12, 179.

Hattori, Huang, Nucl. Sci. Tech., 28 (2017) no.2, 26.

Liu, Huang, Nucl. Sci. Tech., 31 (2020) no.6, 56.

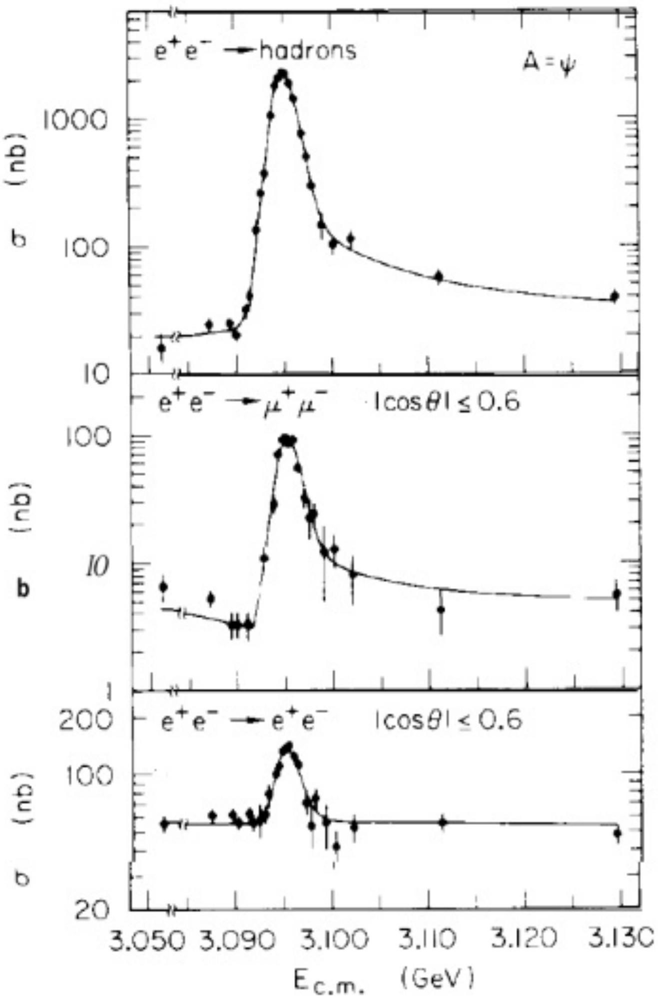
Miransky & Shovkovy, Phys. Rept. 576(2015)1.

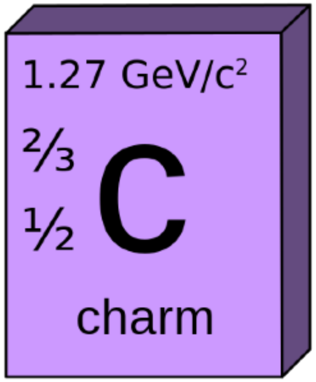
Kharzeev, Ann. Rev. Nucl. Part. Sci. 65(2015)193.

Liao, Pramana 84(2015)5.

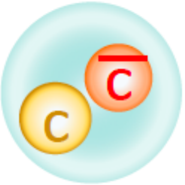
Coming Back to A Few Quarks

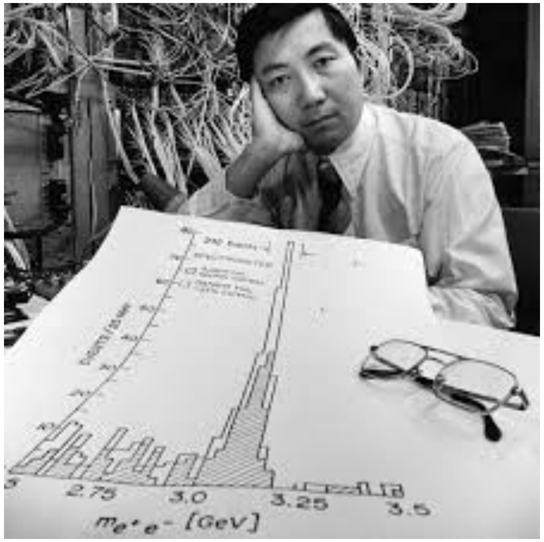
Let us focus on the so-called charm quark sector





Charmonium



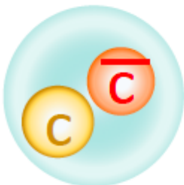


J/Psi discovery: Nov revolution (1974)

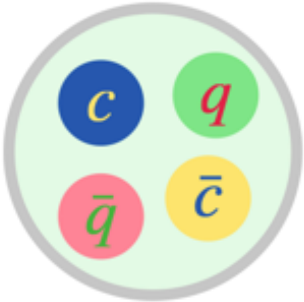
Heavy Exotica

The c-c-bar system offers unique opportunities for exotic hadrons!

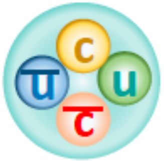
Charmonium



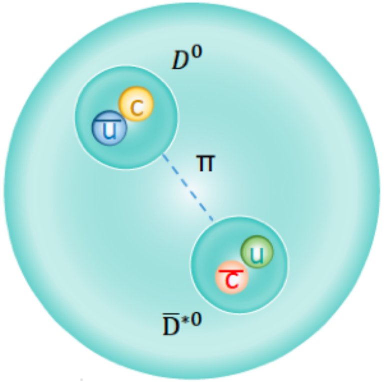
c-cbar-q-q-bar?!



While theoretical speculations were made early on, the exotics started to be found only in the new century (2003).



X(3872): a compact tetra-quark? Or a loose hadronic molecule?



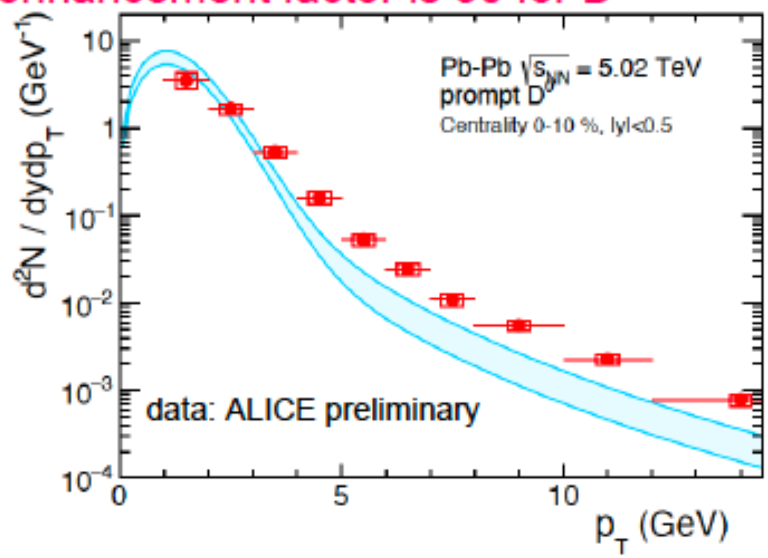
We are still far from completely understanding the secrets of QCD forces.

Can we help resolving the quark math from relativistic nuclear collisions?

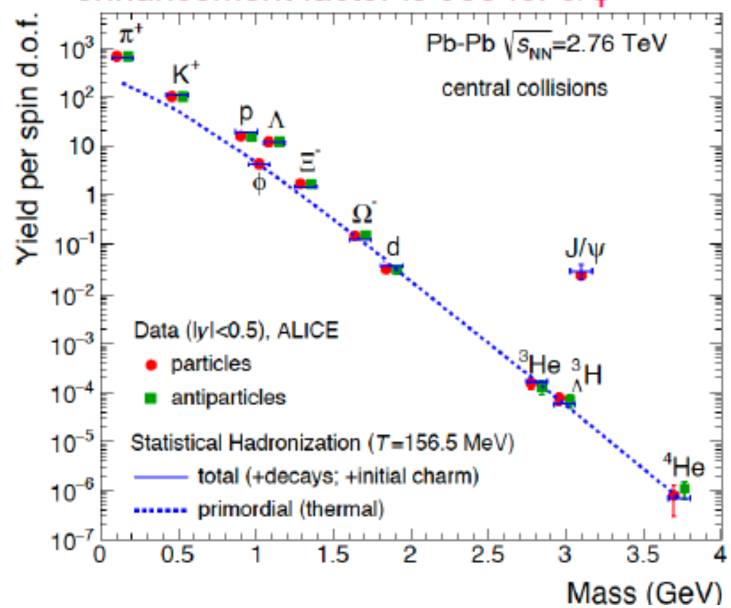
A "High-C" QGP at O(~1000) GeV

Plots from Peter Braun-Munzinger

enhancement factor is 30 for D^0



enhancement factor is 900 for J/ψ



My key message here:
The QGP produced @ LHC O(~1000) GeV collisions,
is a "heavy-doping" QGP, with a "large" number of charms
—> a high-"C" QGP
—> ideal for producing heavy exotics!!!

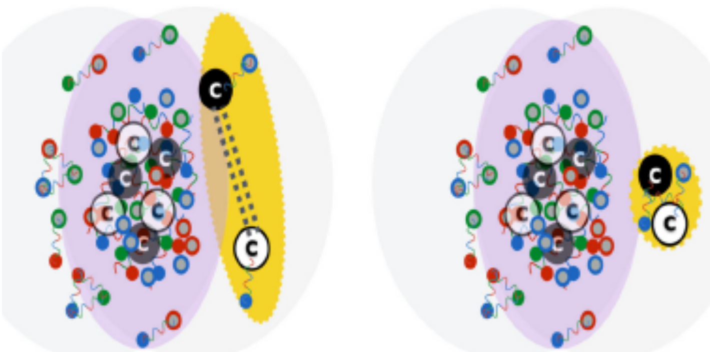
[First set of X-measurements from CMS and LHCb ~2019]

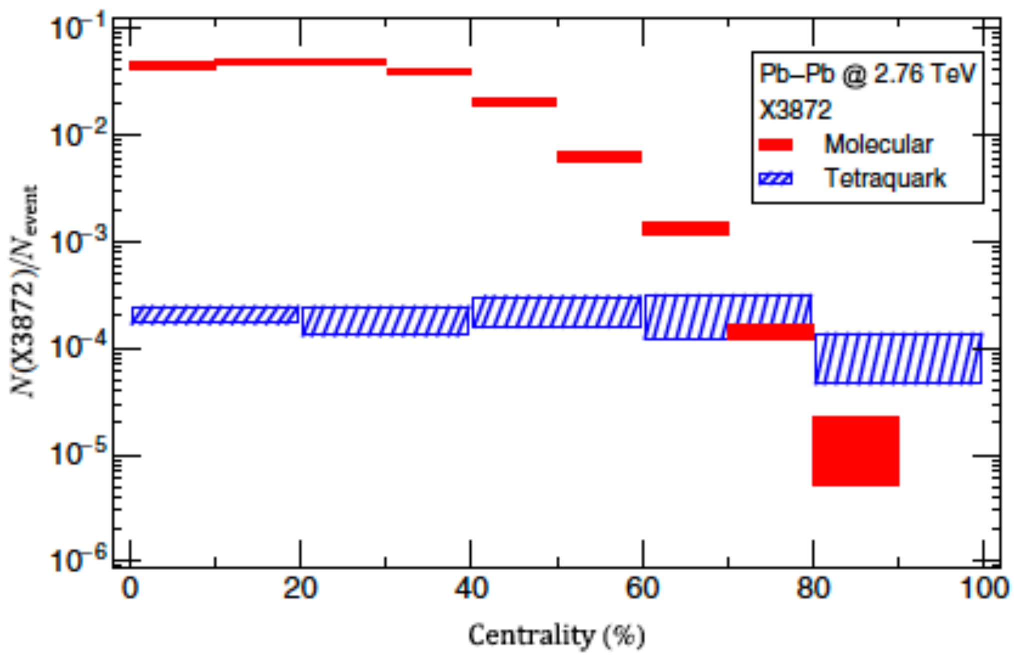
Nailing Down X(3872) Structure

PHYSICAL REVIEW LETTERS **126,** 012301 (2021)

Deciphering the Nature of X(3872) in Heavy Ion Collisions

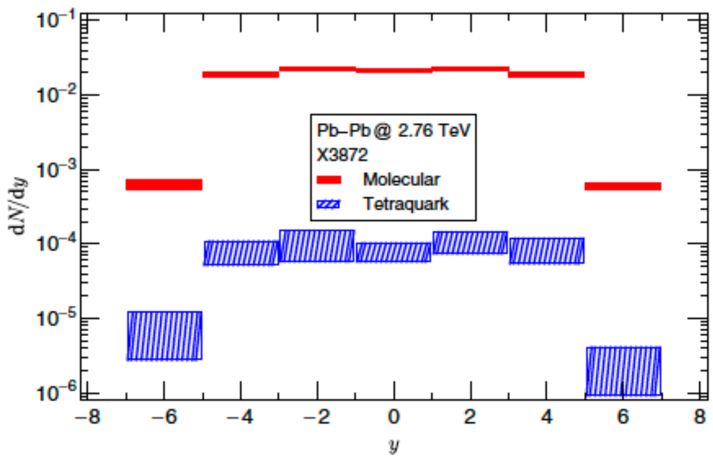
Hui Zhang,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] Qian Wang,[1,2,4,§] and Hongxi Xing[1,2,‖]

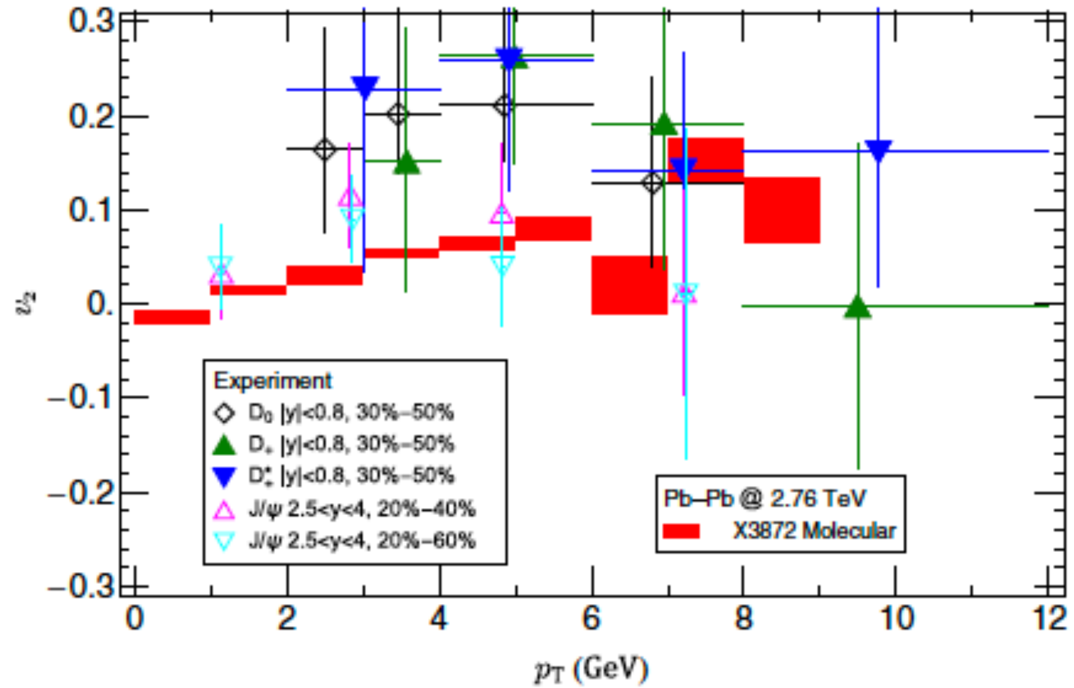


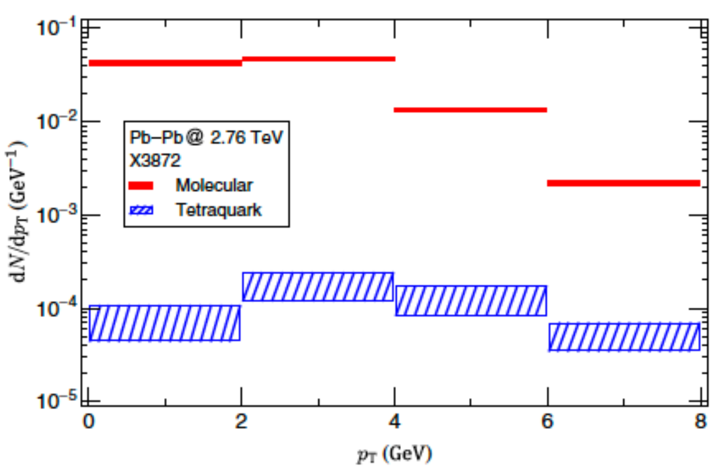


Hadron molecule v.s. tetraquark: Two orders of magnitude difference in the yield; Drastically different centrality dependence.

Nailing Down X(3872) Structure



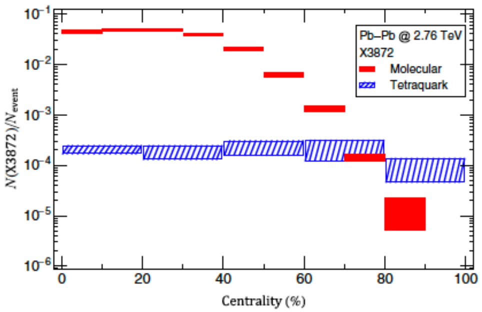


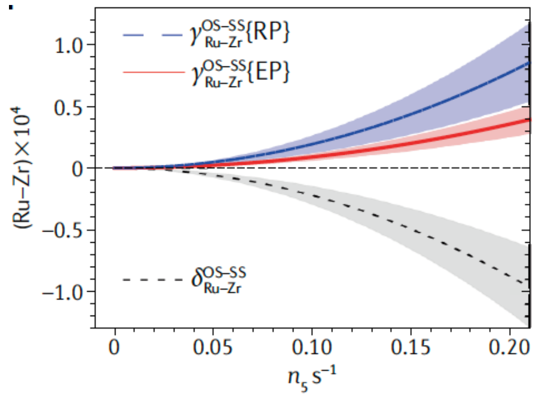


"It is tempting to envision an exciting time of vibrant and coherent theory and experiment efforts for exploring heavy ion collisions as a massive production factory of exotic hadrons to its fullest extent."

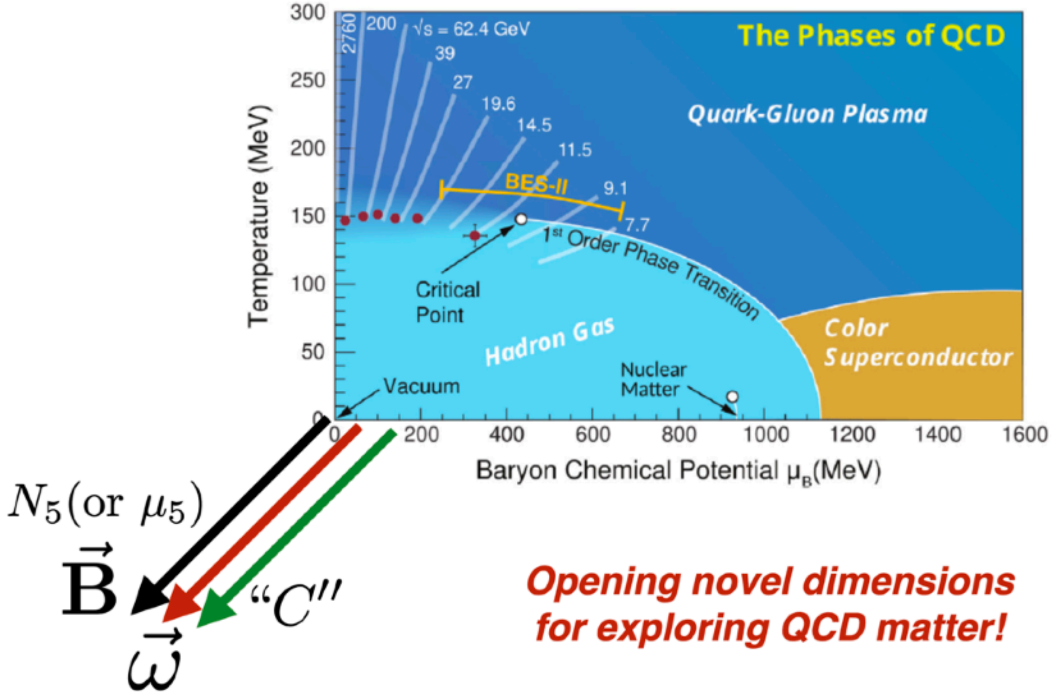
Summary

O(~1000)GeV: Charm exotica

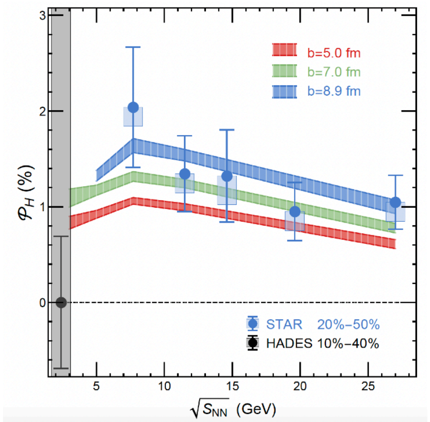




O(~100)GeV: Chiral Magnetic Effect



Opening novel dimensions for exploring QCD matter!



O(1~10)GeV: vorticity & polarization