Relativistic Nuclear Collisions: Factory for Exotic Quantum Matter

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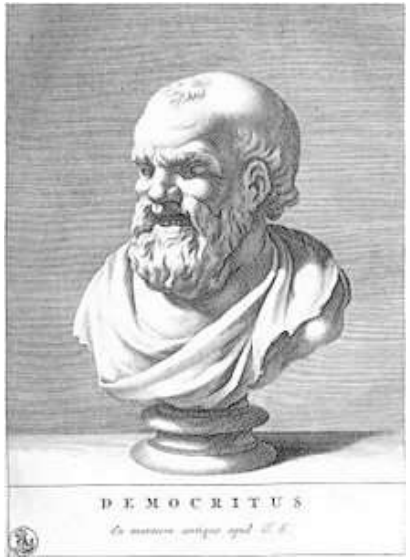
Research Supported by NSF & DOE

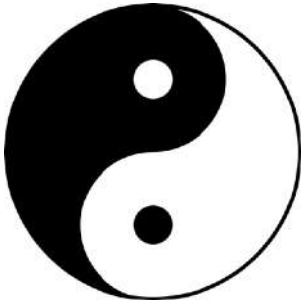
Structure of Matter: An Ancient Quest

Empedocles:
four elements ---
fire, air, water, earth



Democritus:
atomic hypothesis

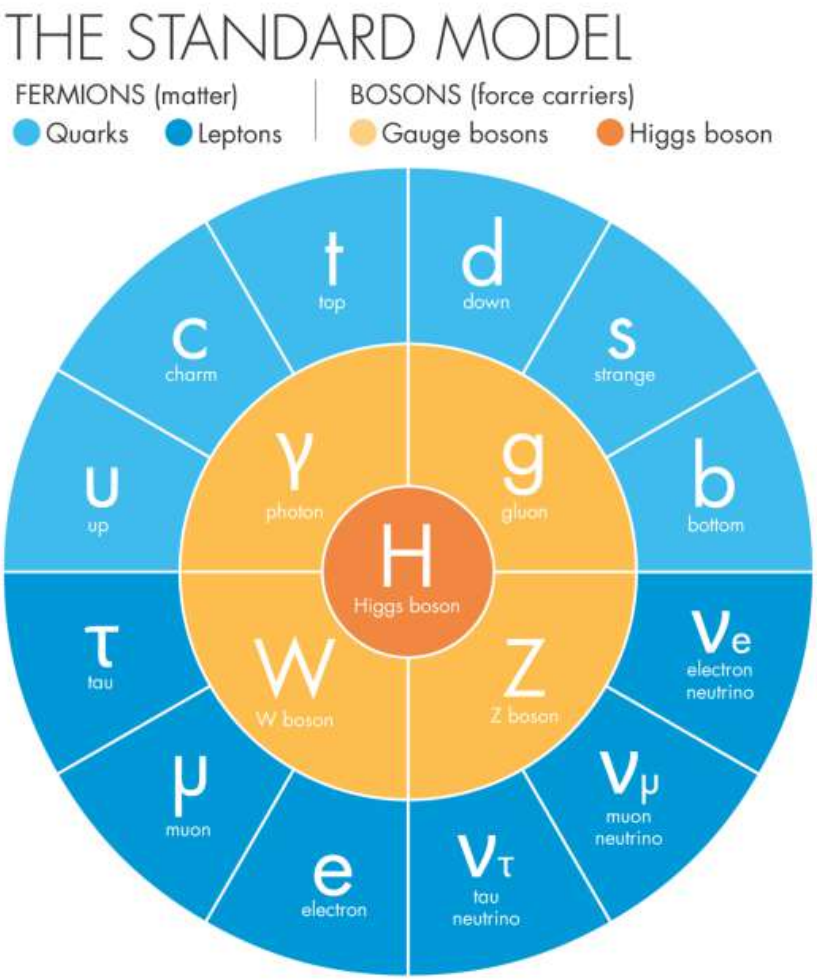
Laozi



道生一
一生二
二生三
三生万物

All matter is made from a set of fundamental entities

A Final Triumph after ~2000 Years



Nobel Prize 2013

What's next?

* ***Further "reductionism": even more fundamental structure***

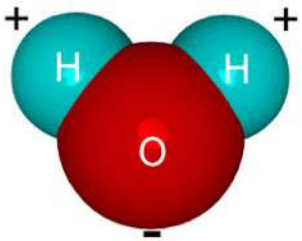
* ***"Integration" back: studying the emergent phenomena***

Nuclear Physics: Exploring the Heart of Matter

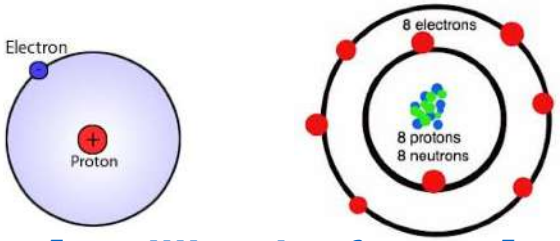
The physical world has a hierarchy of structures.

matter

molecule

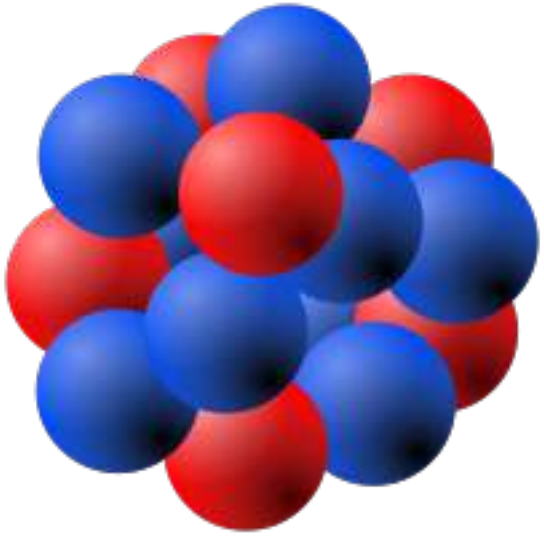


atoms



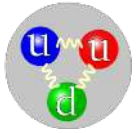
[a millionth of a mm]

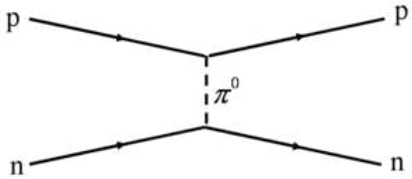
atomic nucleus



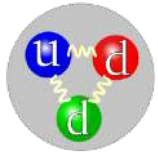
[a trillionth of a mm]

proton



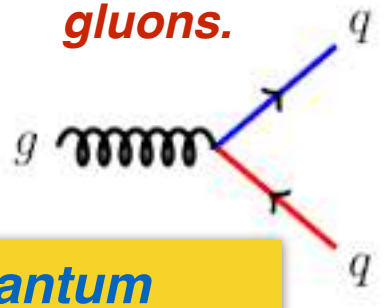


nuclear force



neutron

Most basic entities: quarks and gluons.



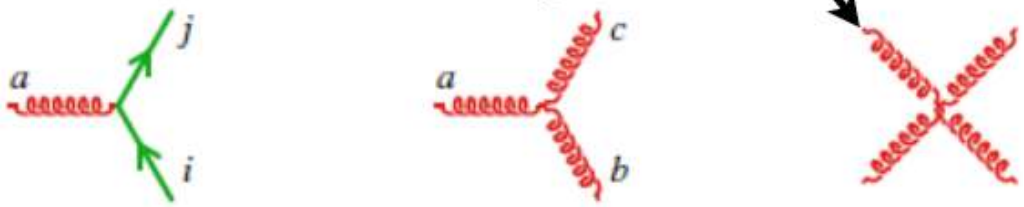
Quantum Chromodynamics (QCD)

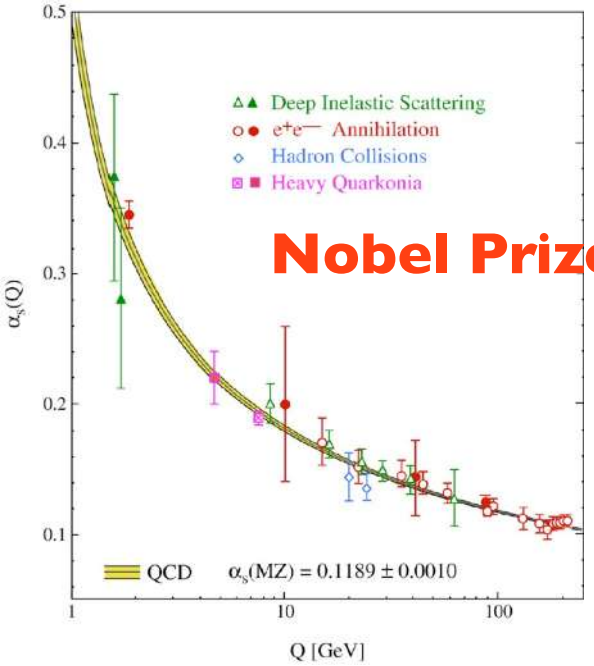
Quantum Chromodynamics (QCD)

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!

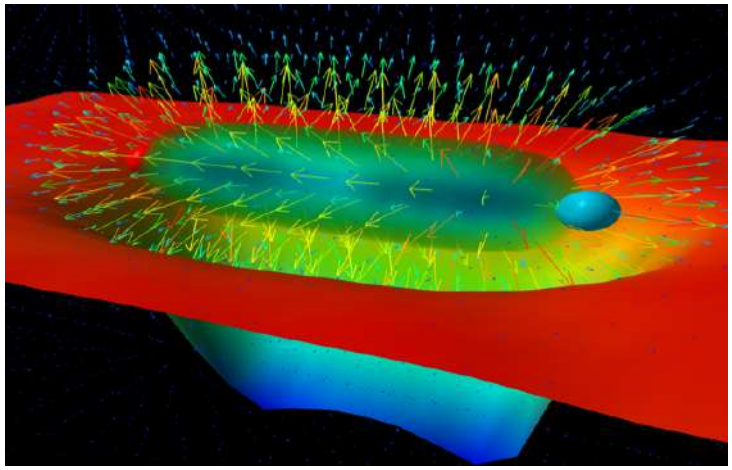
The QCD Vacuum: Confinement

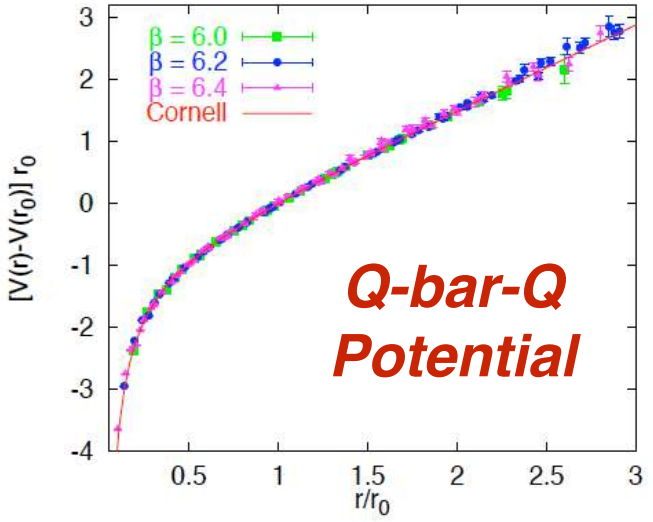
The missing particles: quarks & gluons (in the QCD lagrangian) are not seen in physically observed states.

Free Quark Searches

All searches since 1977 have had negative results.

from Particle Data Book

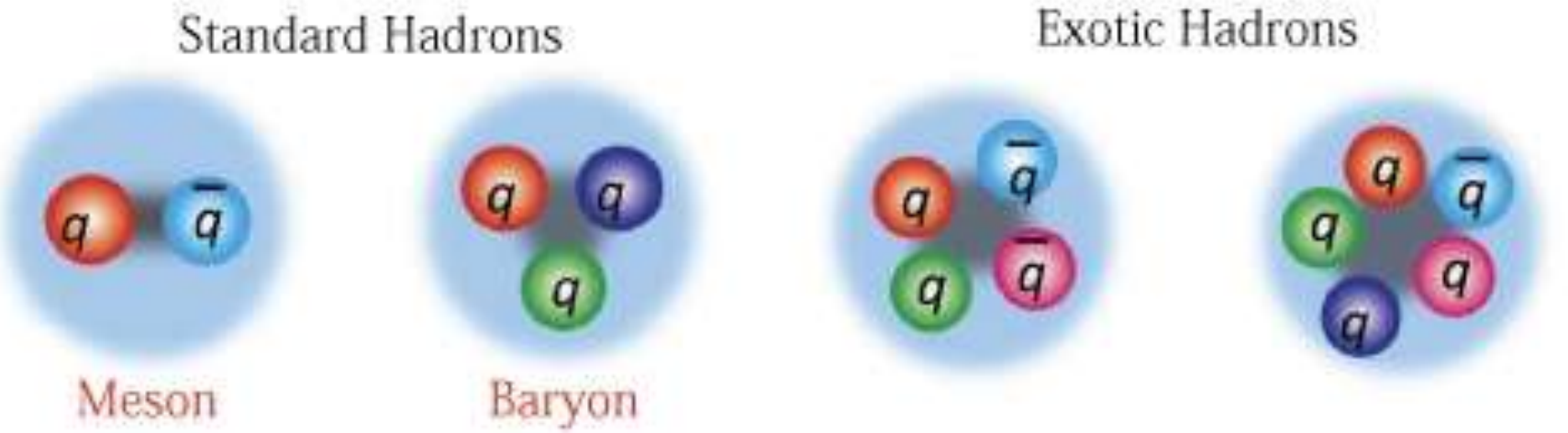




Q-bar-Q Potential

Non-perturbative QCD force holds the quarks together in hadrons.

The Quark Math/Mystery: Exotic Hadrons?!

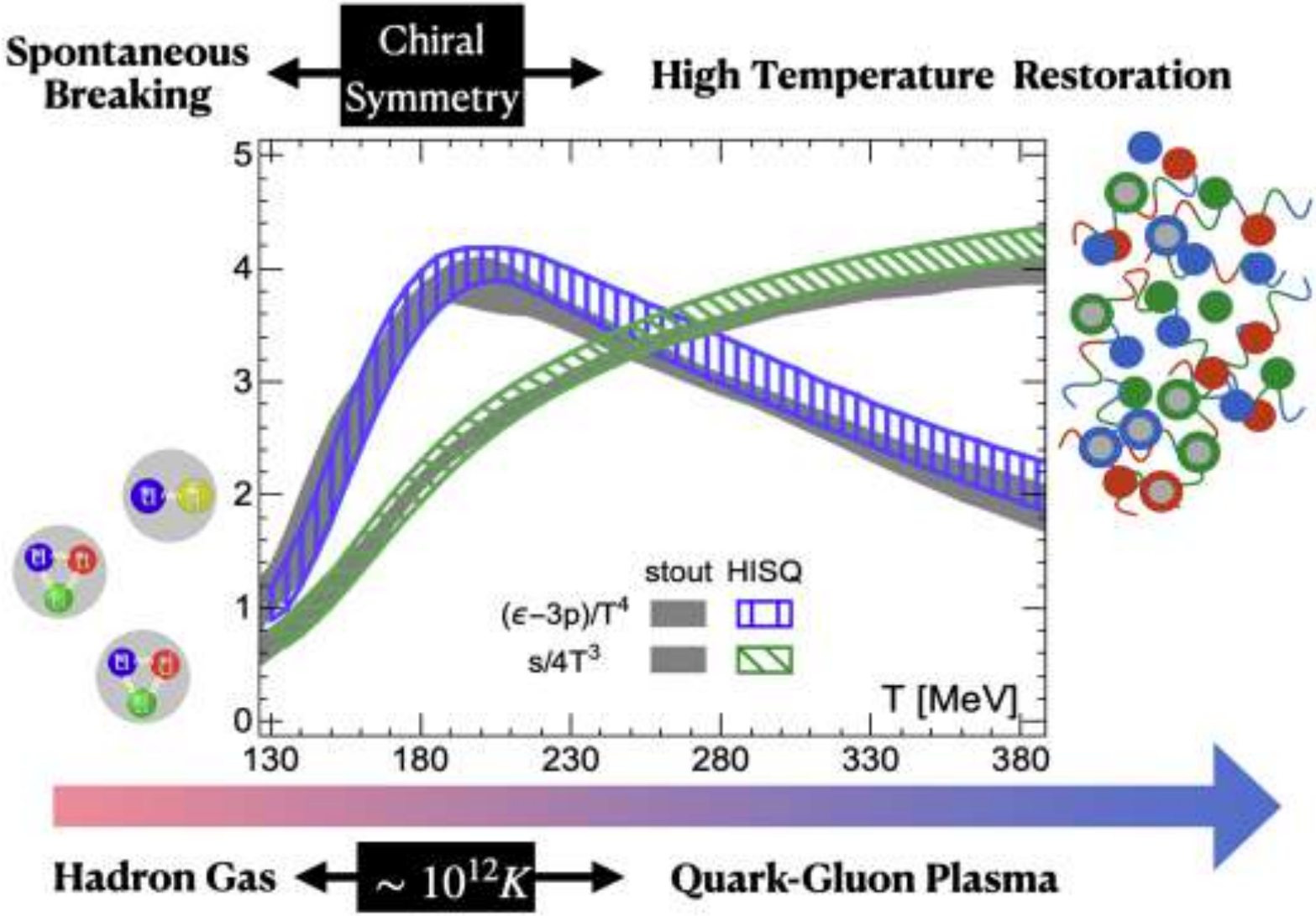


Understanding the "quark math" of hadrons:

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

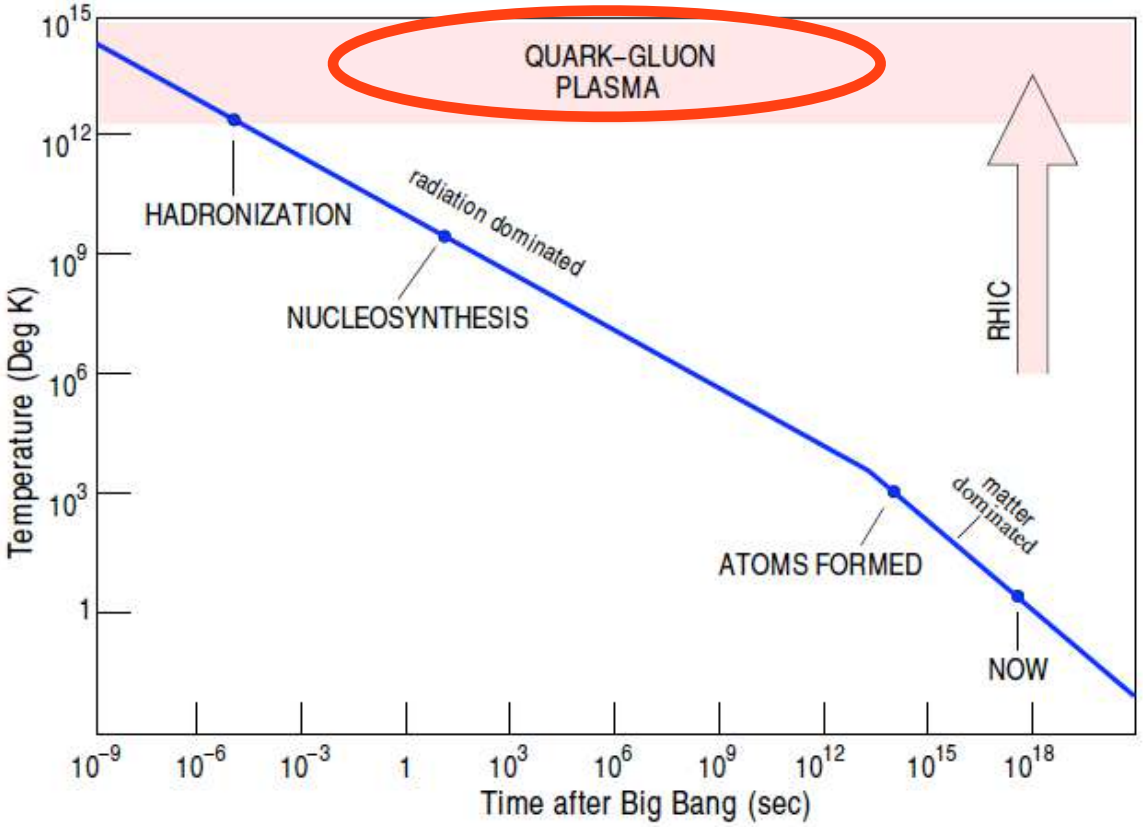
An exciting frontier of today's nuclear physics research

Cooking up a "Quark Soup"



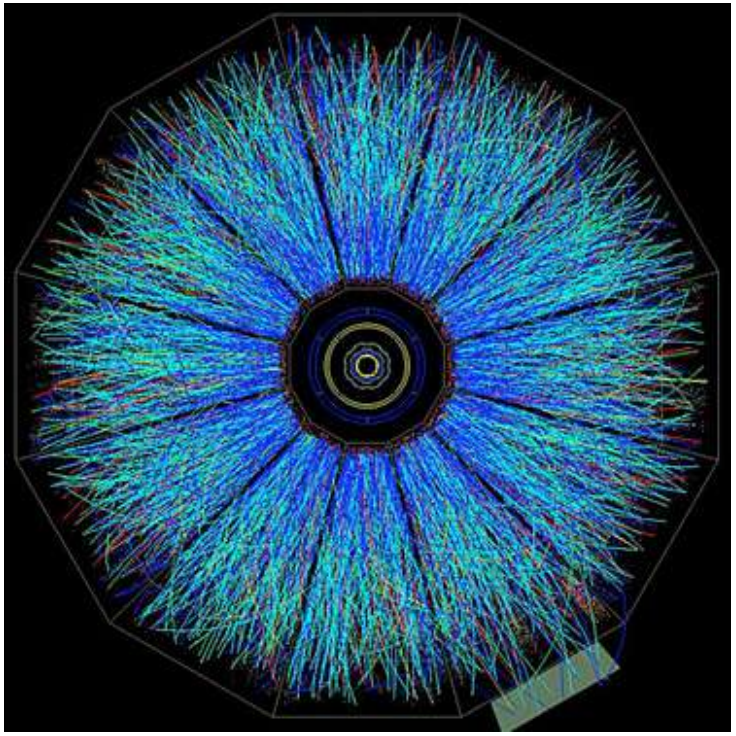
QGP: An Old Phase of Matter

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.



The quark-gluon plasm is an old phase of matter!

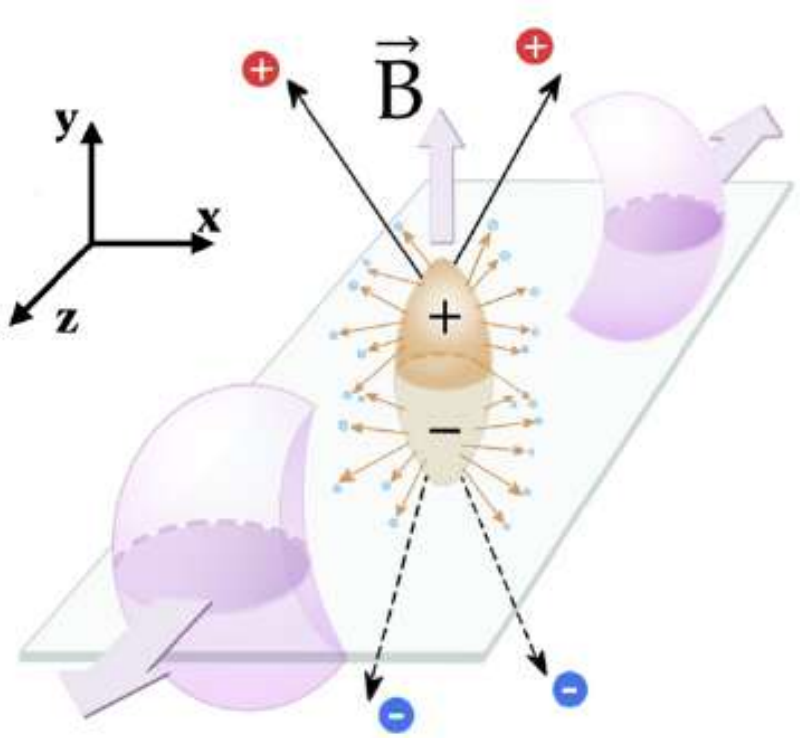
Little Bangs in Heavy Ion Collisions (HIC)



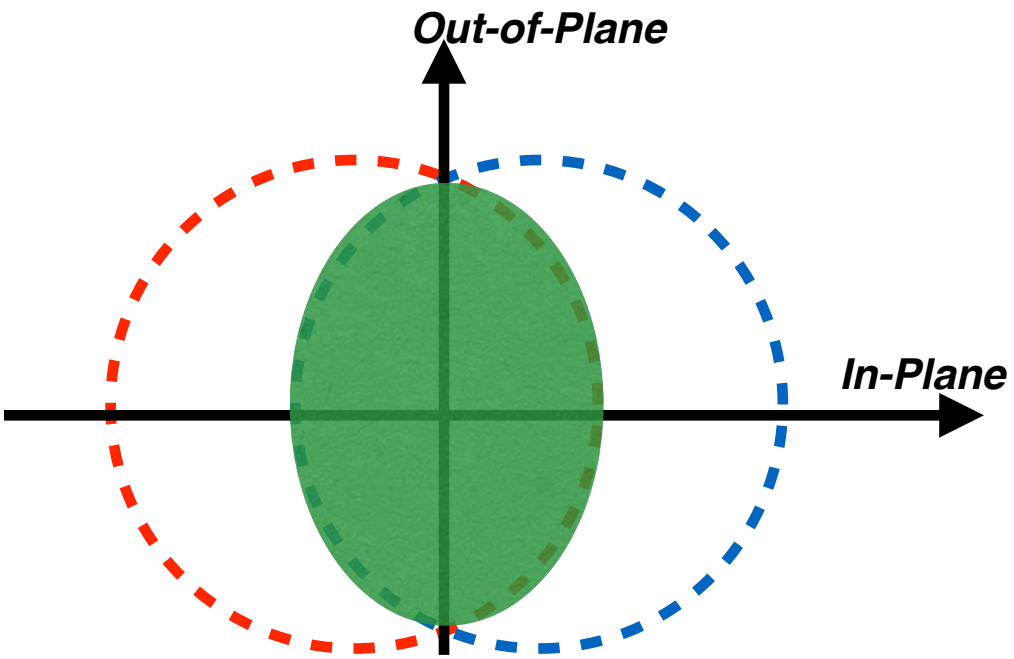
our most powerful heating machine ever

QGP: A New phase of matter

What Happens in a Heavy Ion Collision?



A typical (off-central) collision.

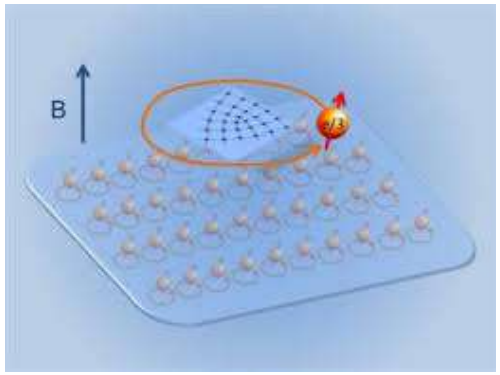


Quark-gluon plasma is created in such collisions!

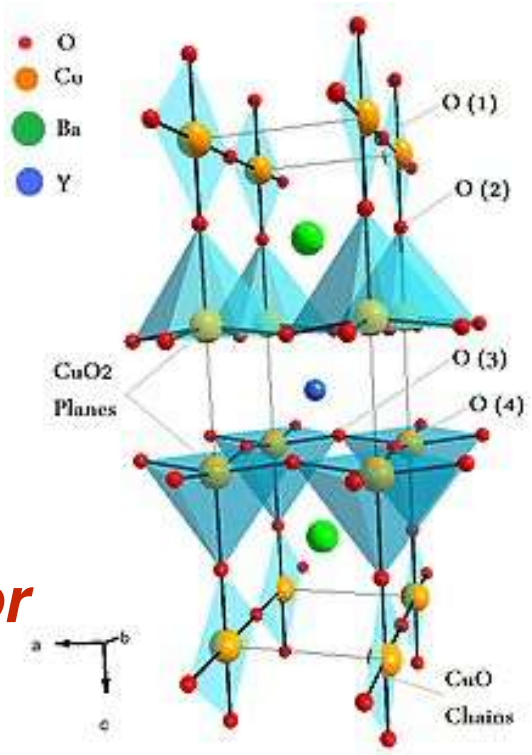
The hottest matter!
The most perfect fluid!

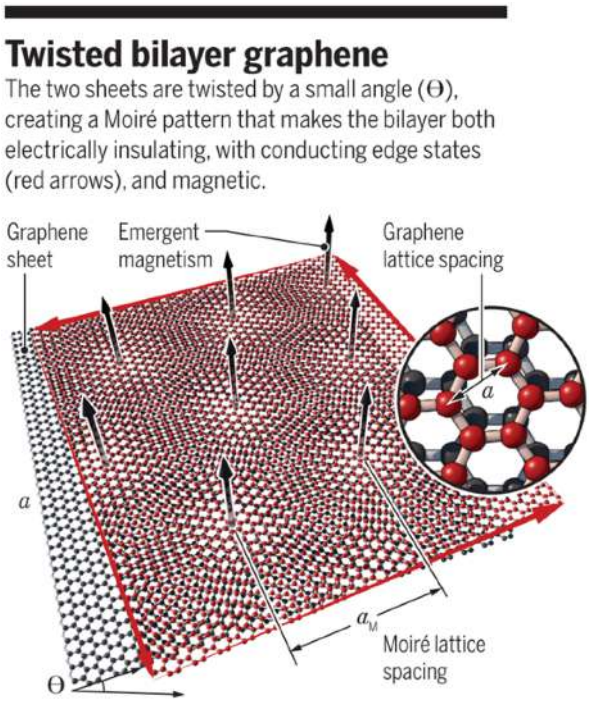
What's Next? Wisdom from CMP

Quantum hall effect



High-Tc superconductor

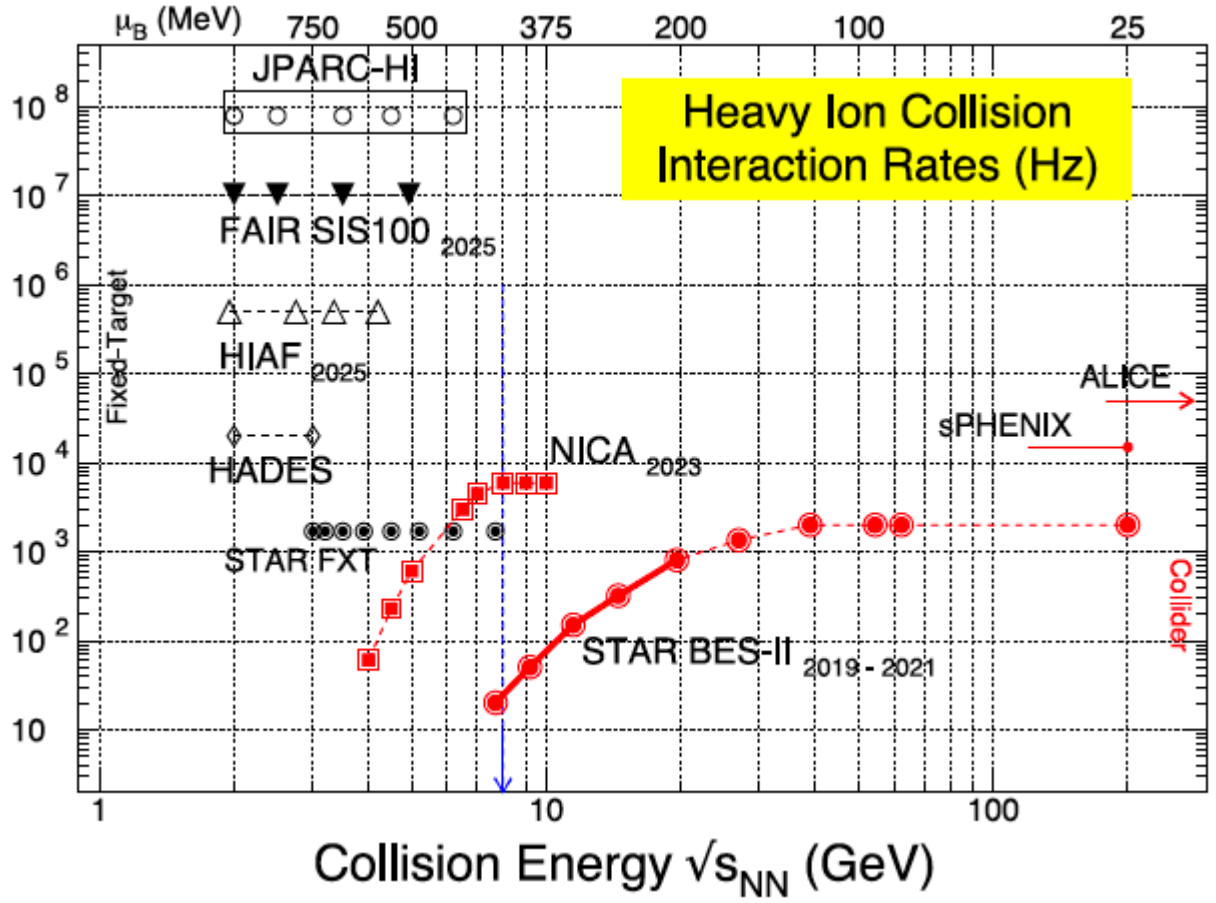




"Magic angle"

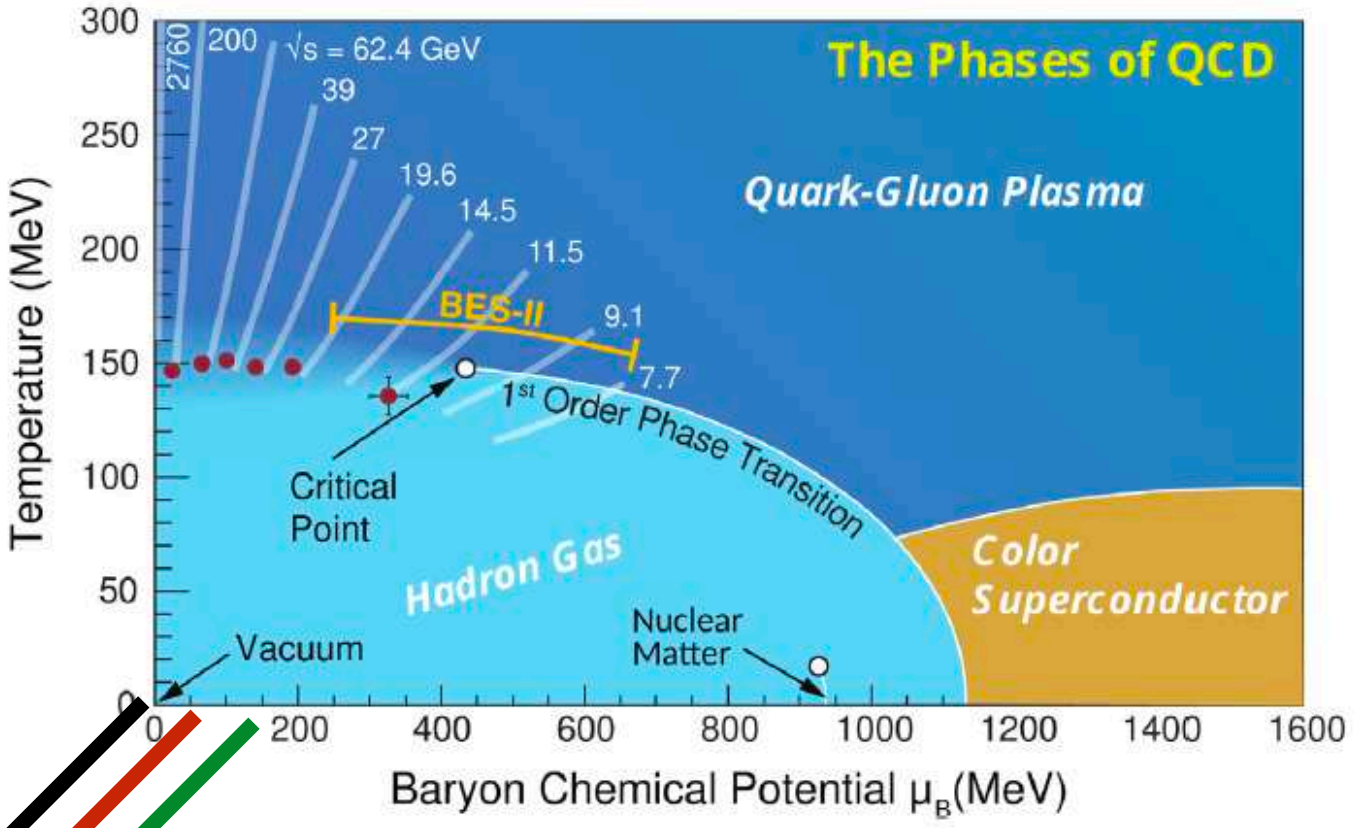
Collisions Across Wide Beam Energy Span

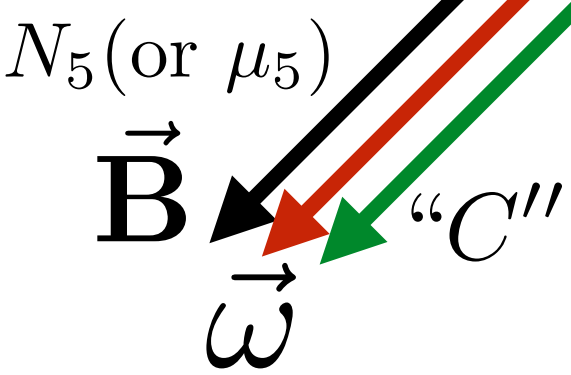
Relativistic nuclear collisions have been and will continue to be done from O(1) GeV to O(1000) GeV beam energy!



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

Factory for Exotic Quantum Matter

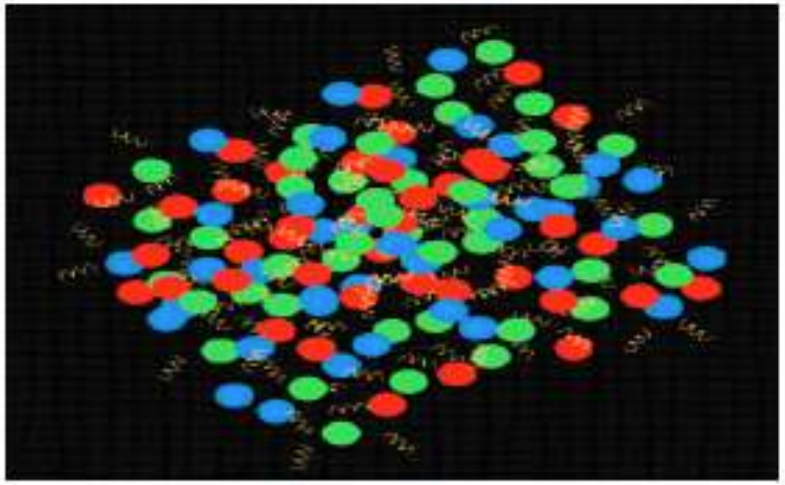




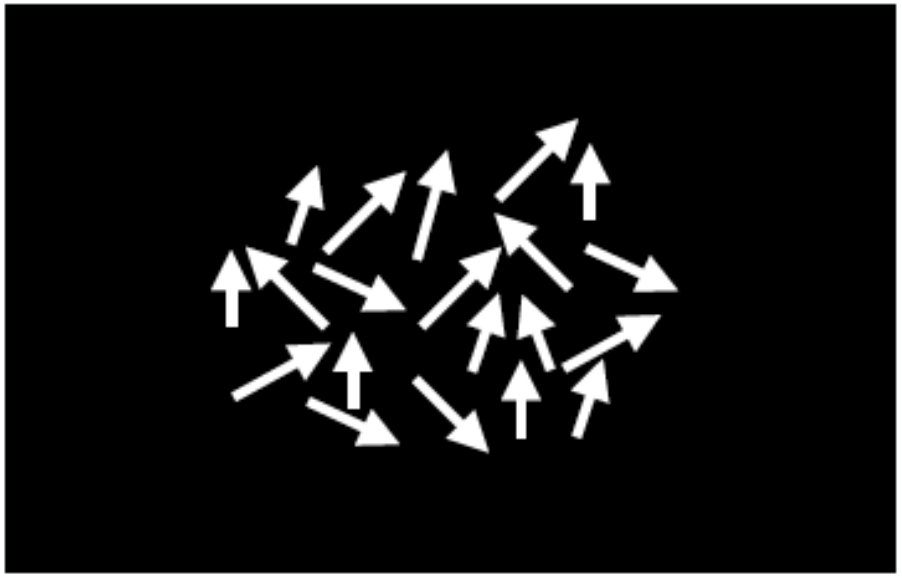
Opening novel dimensions of the "nuclear matter universe"!

A New Paradigm: A Quantum Spin Fluid?!

A nearly perfect fluid (of energy-momentum)

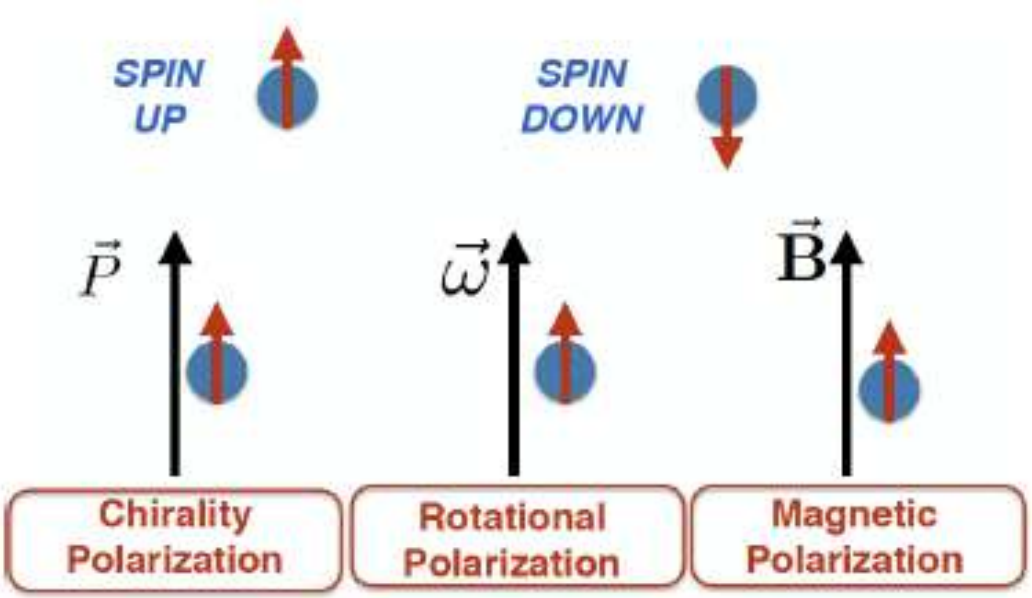


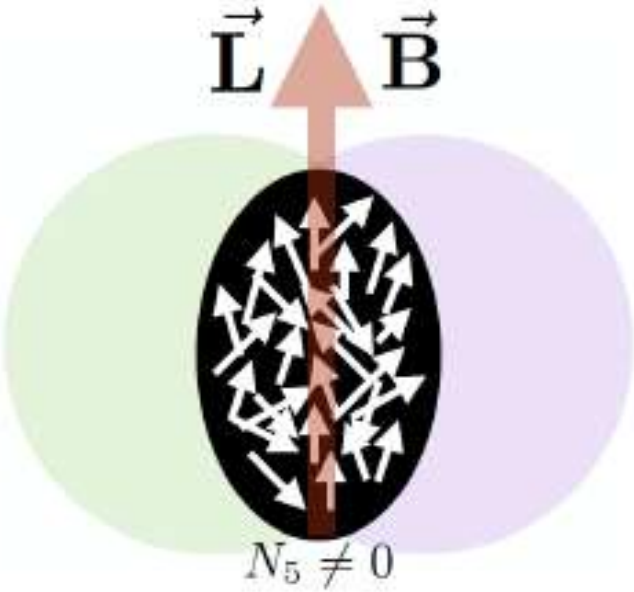
What happens to the spin DoF in the fluid???



Need probes to play with spin!

Spin @ Chirality, Vorticity and Magnetic Field





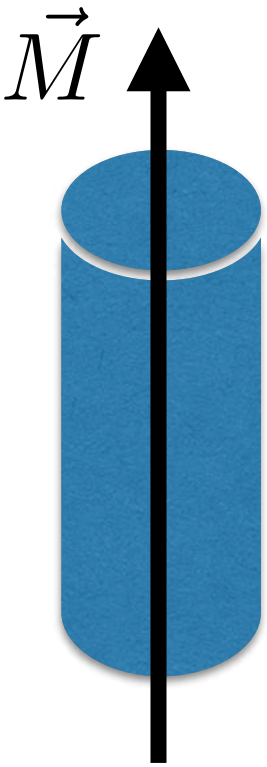
[arXiv:2004.00569]

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

[Further source: Miransky & Shovkovy, Phys.Rept. 576 (2015) 1-209 · e-Print: 1503.00732 [hep-ph]]

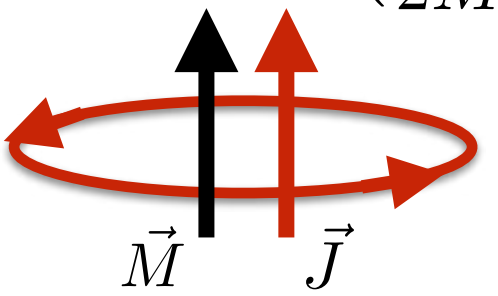
Einstein-de Hass Effect

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



Orbital contribution:

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

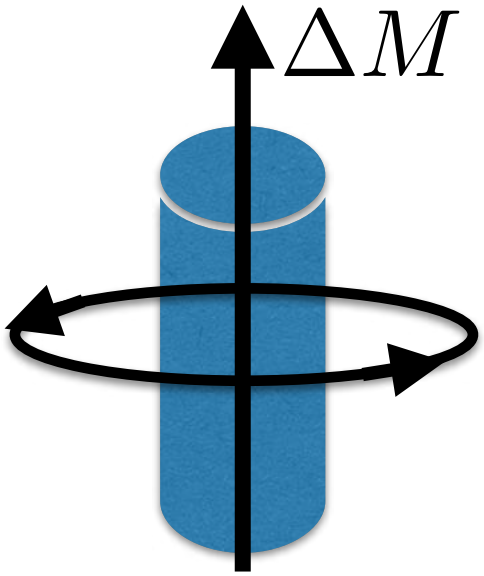


Spin contribution:

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

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.

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

The opposite should also happen:

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

THE

PHYSICAL REVIEW.

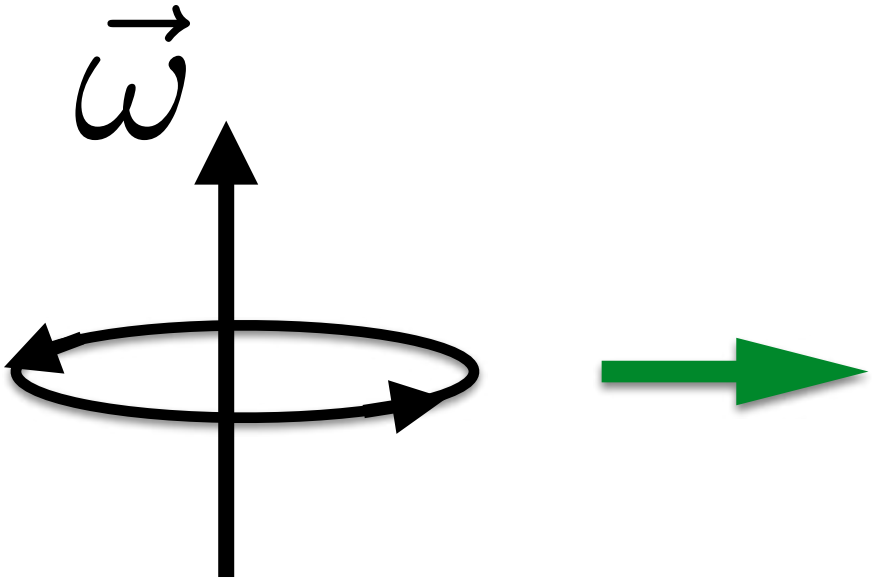
MAGNETIZATION BY ROTATION.[1]

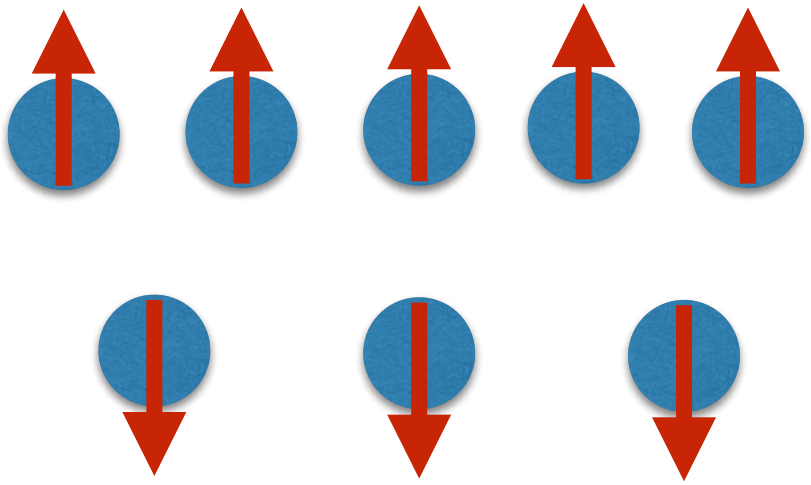
BY S. J. BARNETT.

§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.

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 see for a liquid/fluid.

Rotational Polarization in Condensed Matter

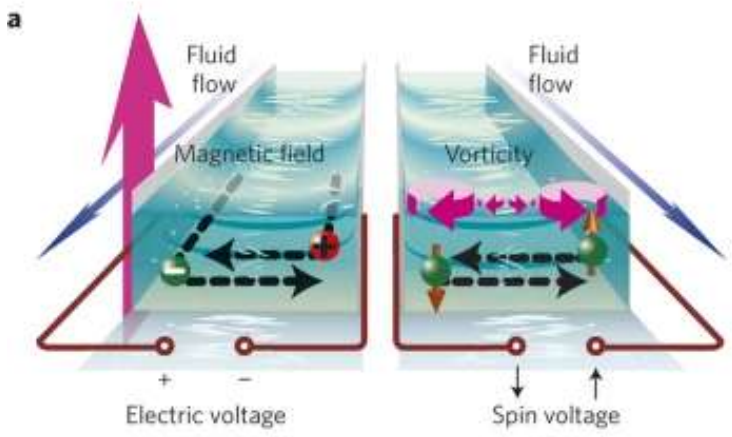
Spin hydrodynamic generation

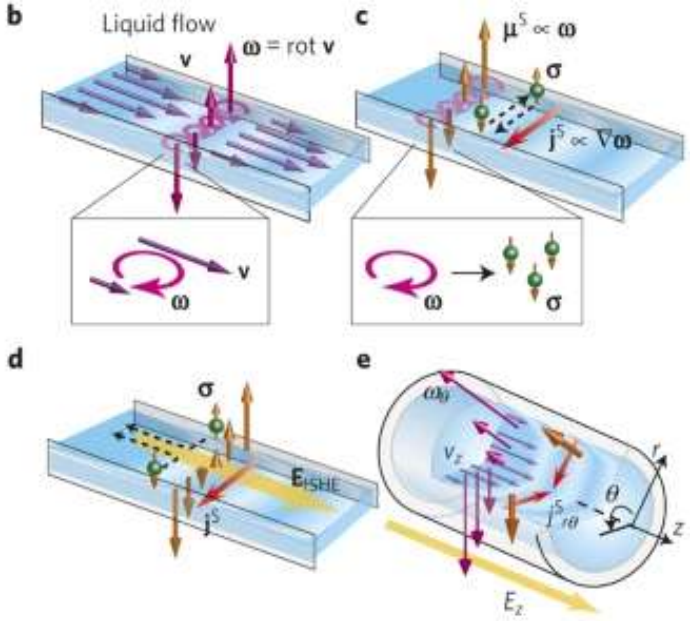
R. Takahashi ✉, M. Matsuo, M. Ono, K. Harii, H. Chudo, S. Okayasu, J. Ieda, S. Takahashi, S. Maekawa & E. Saitoh ✉

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

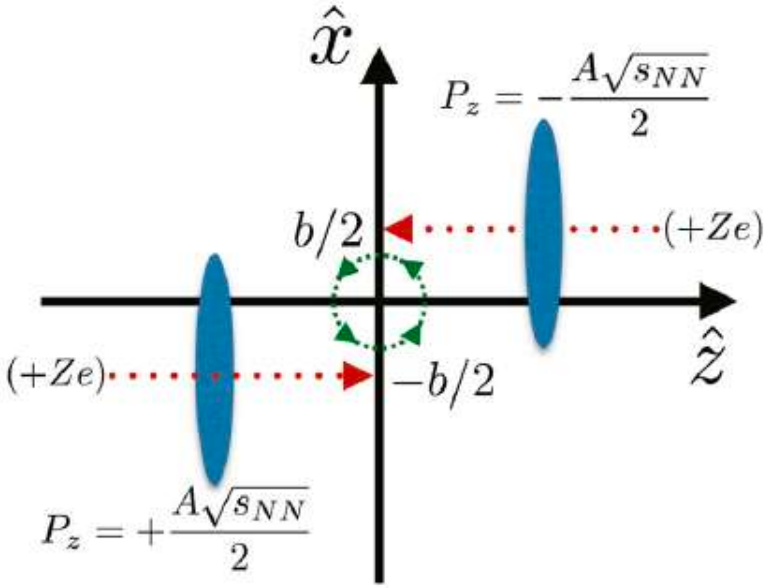
Viscous fluid flow
—> vorticity —>
spin polarization

"Fluid Spintronics"





Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions

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

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

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

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

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

"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*

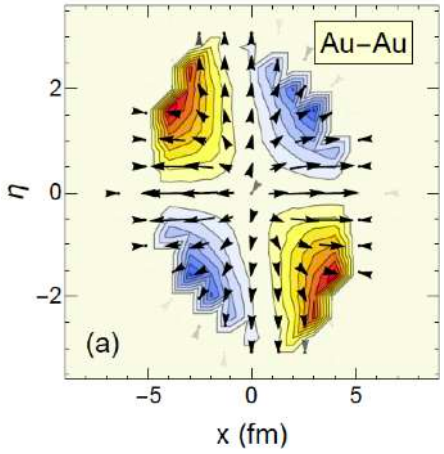
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

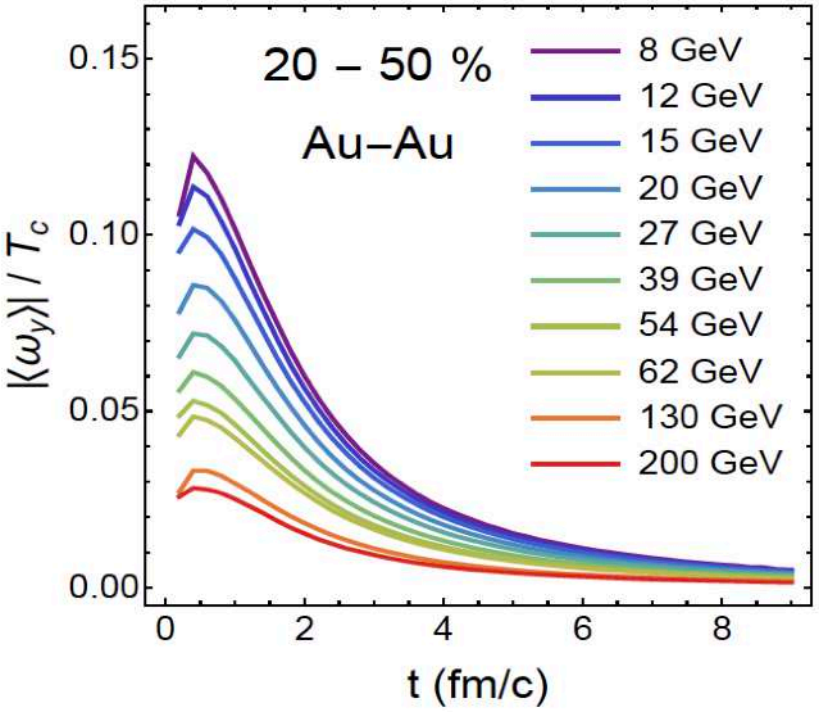
[3]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

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

Is this portion conserved? —YES!

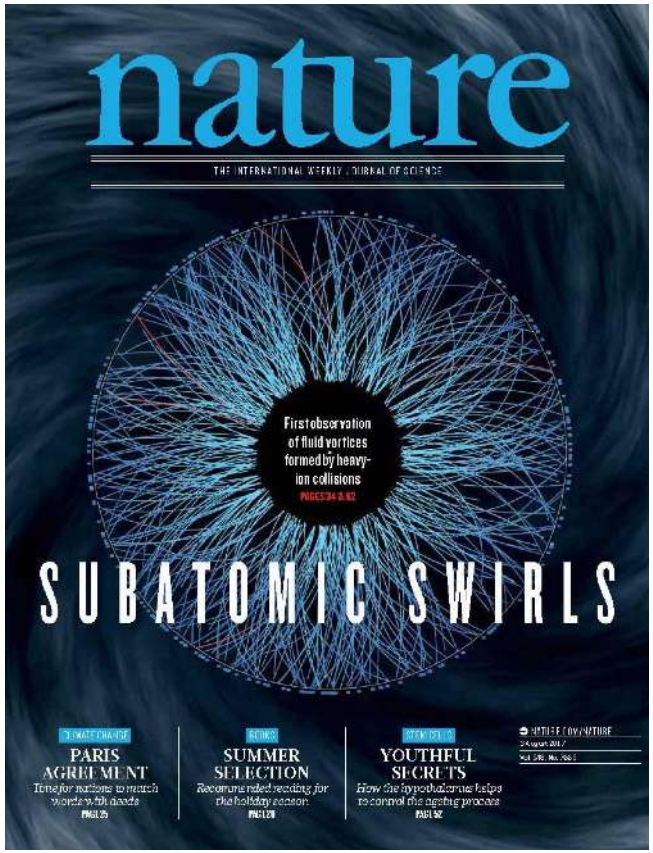
How QGP accommodates this angular momentum? — Fluid vorticity!

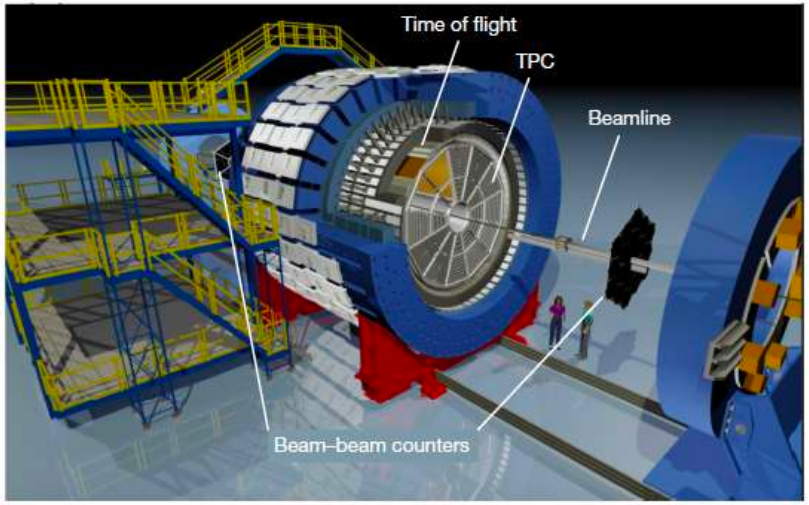




O(1~10) GeV is the region to look at!!

The Most Vortical Fluid





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

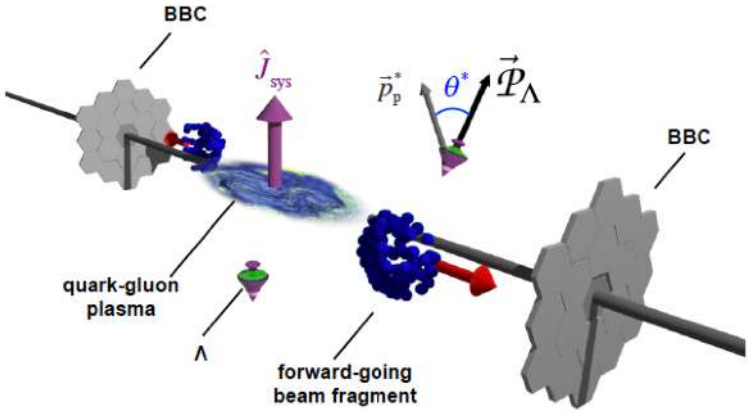
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

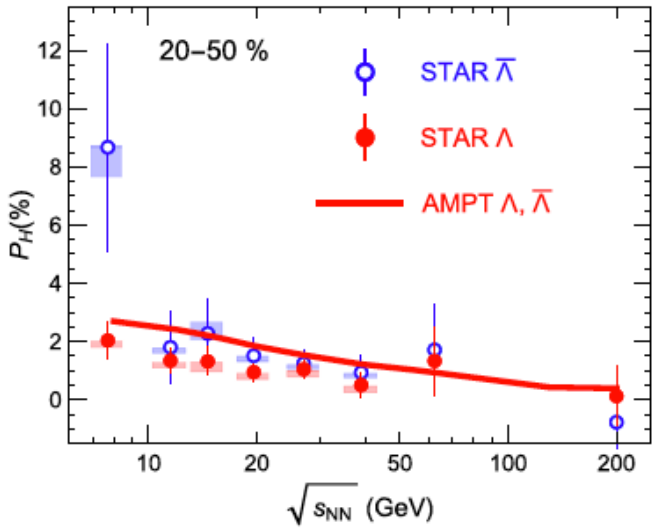
Spin Polarization in the Subatomic Swirls



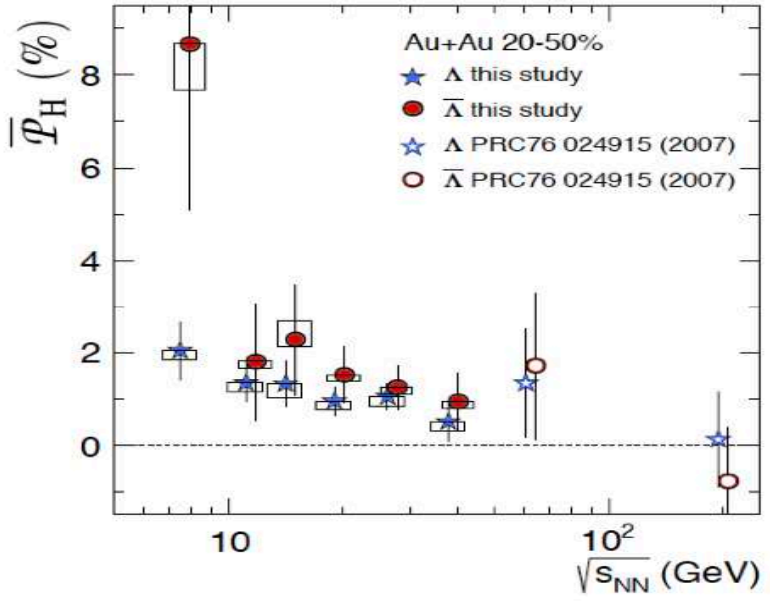
STAR Collaboration, Nature 2017

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

The most vortical fluid!



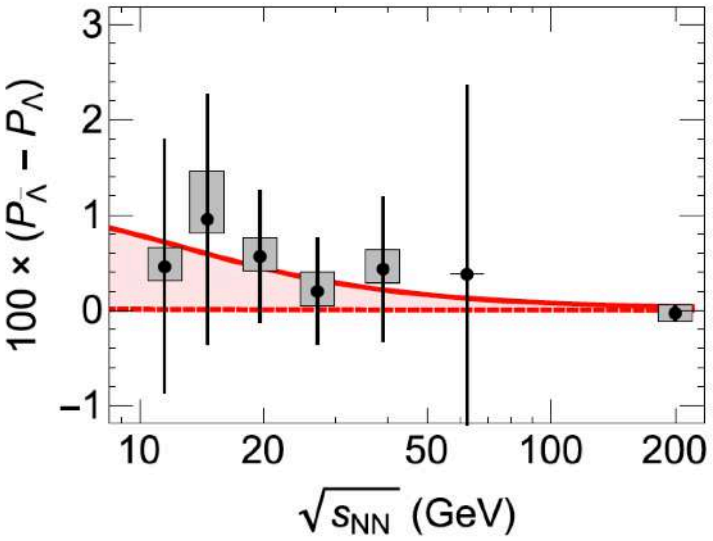
Shi, Li, JL, PLB2018

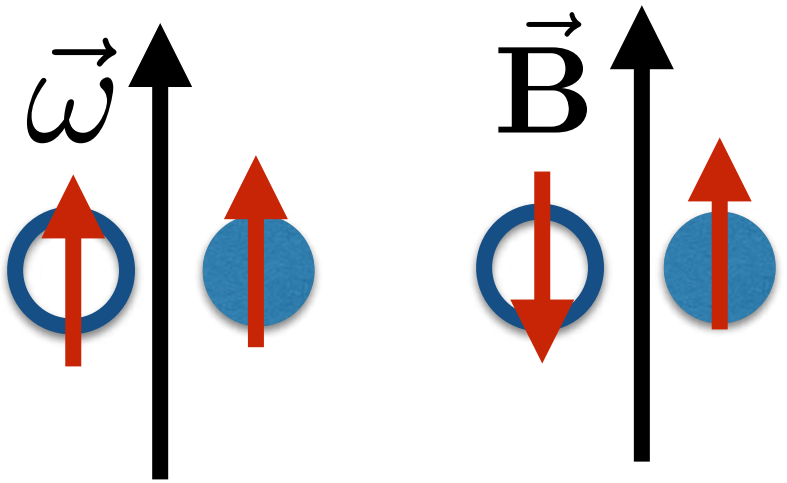


[Trend at O(1)GeV?!
Yu Guo, Hui Zhang, et al: to appear soon.]

A Subatomic Version of Barnett Effect

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





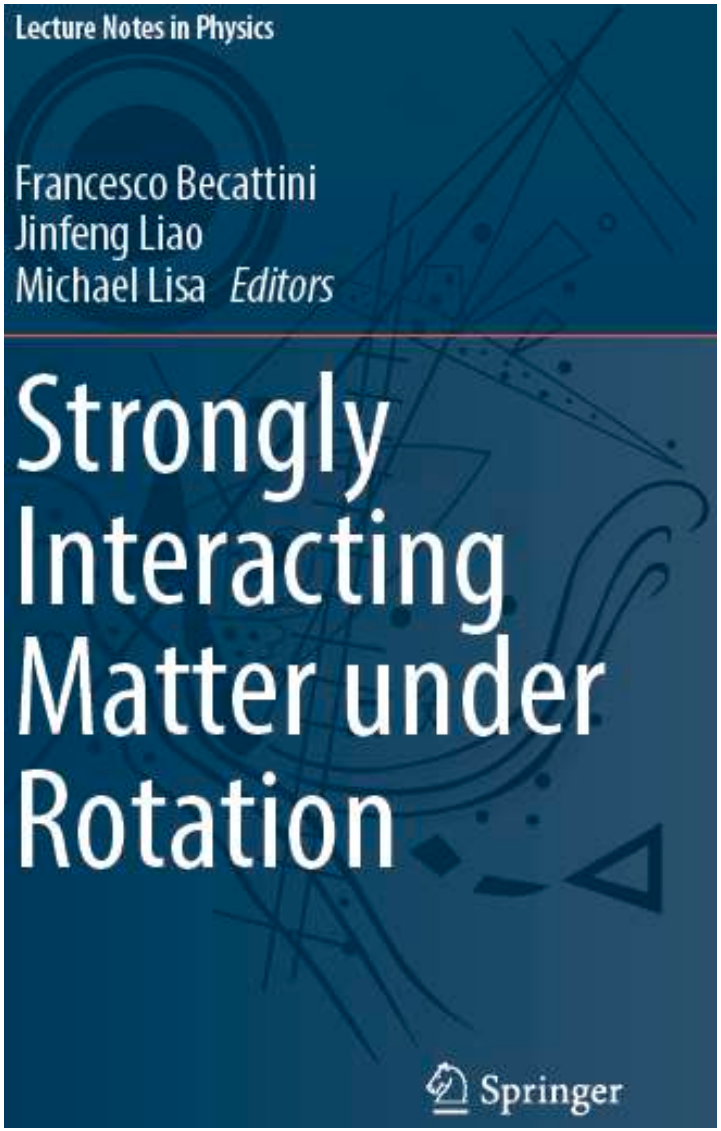
$$\tilde{S}^{\mu} = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\nu} \left[\varpi_{\rho\sigma} \mp 2(eF_{\rho\sigma})\mu_{\Lambda}/T_f\right]$$

Late-time magnetic field could explain the difference;

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

[Guo, Shi, Feng, JL, PLB2019; Guo, JL, Wang, Scientific Reports 2020]

Further Sources on Rotation



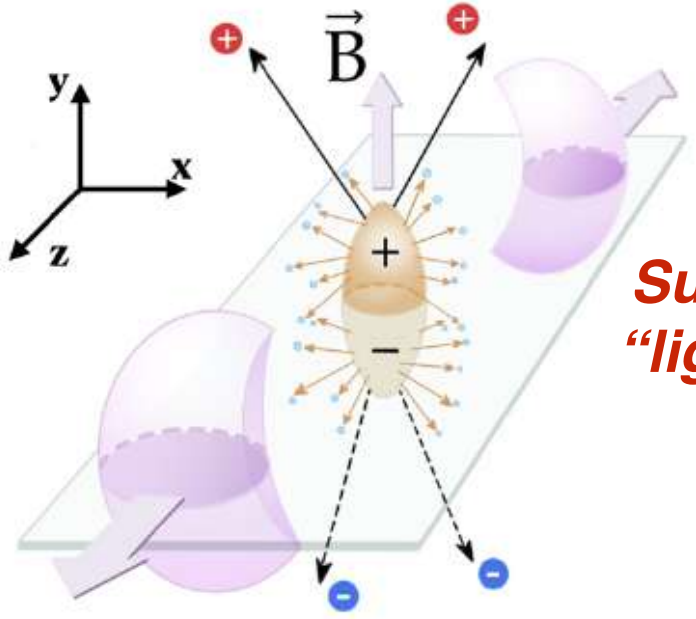
Many exciting new developments: see upcoming LNP volume!

Strongly Interacting Matter Under Rotation: An Introduction

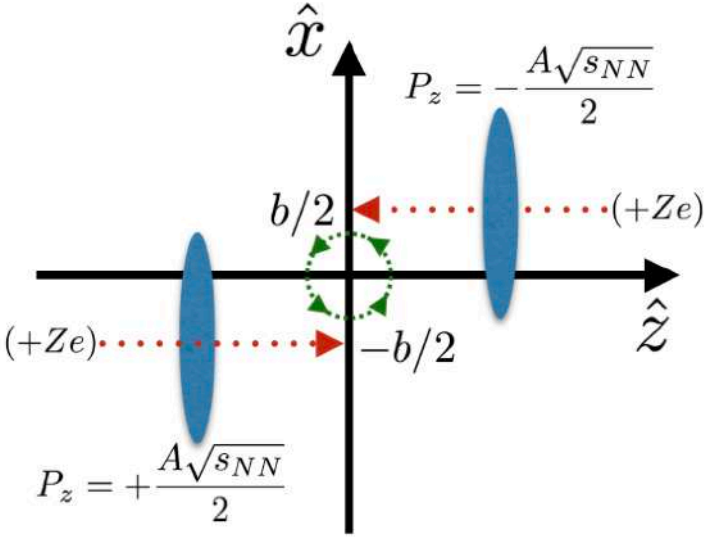
Francesco Becattini, Jinfeng Liao, and Michael Lisa

[arXiv:2102.00933]

The Most Magnetized Fluid



Subatomic "lightning"!

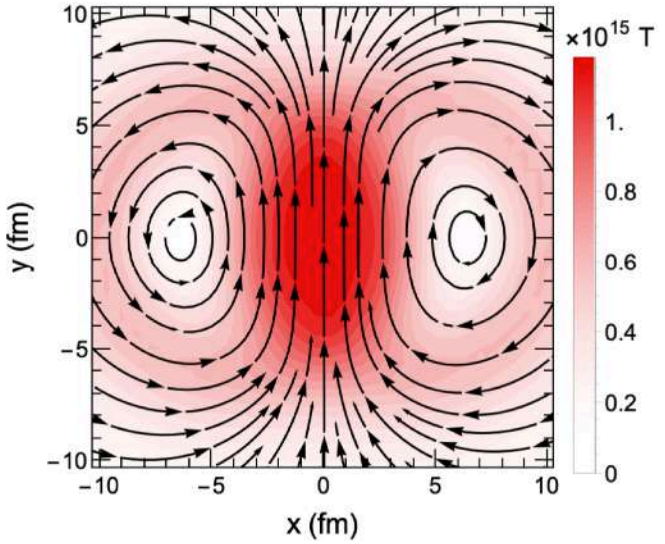


The strongest B field ~ 10^15 Tesla

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

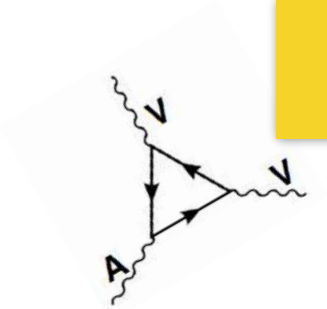
However, short-lived

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

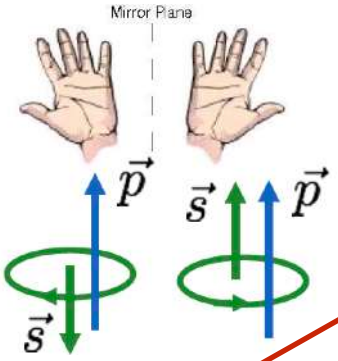


Optimal range for B-effects O(~100) GeV

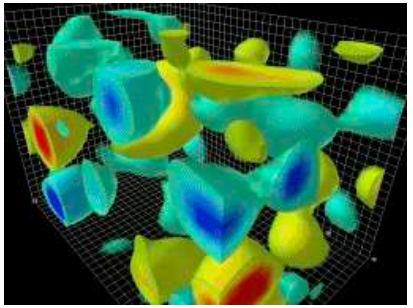
Chiral Magnetic Effect (CME)



Chirality & Anomaly

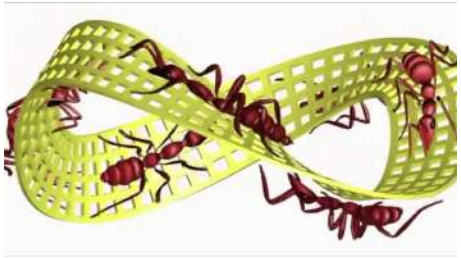


Chirality & Topology



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

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



Anomalous Electric Current

Q.M. Transport

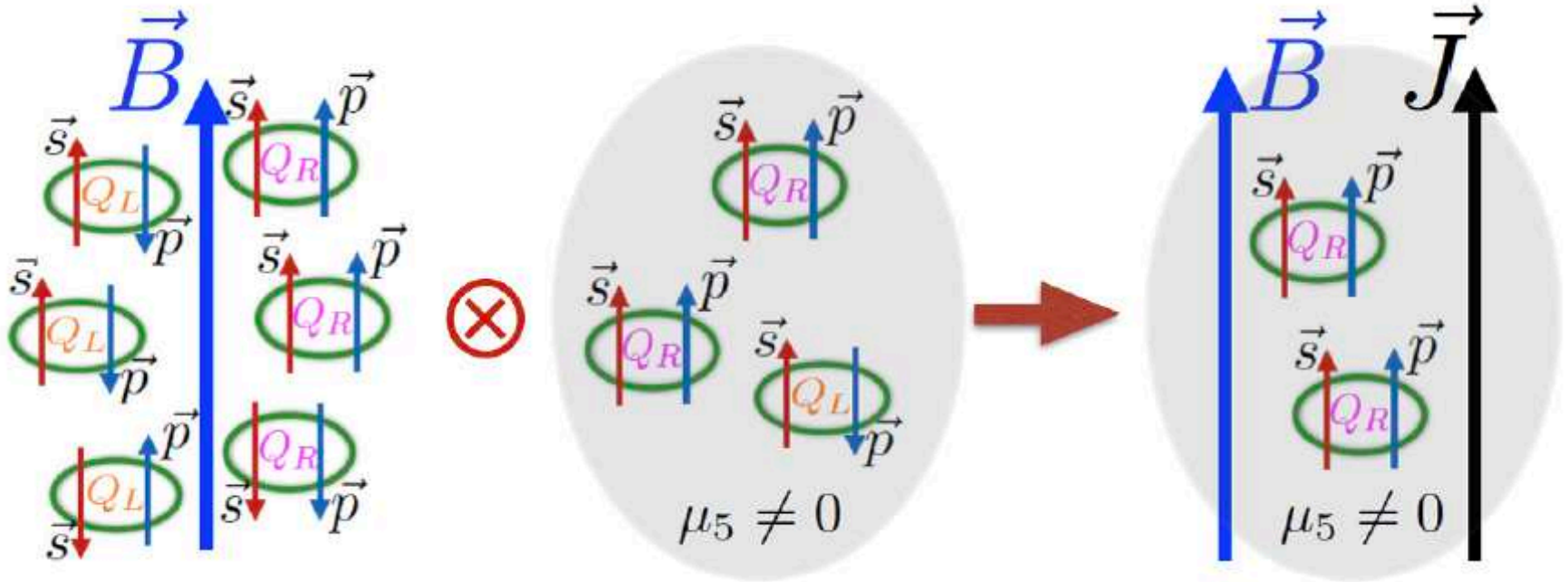
Magnetic Field

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**

⊗

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

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

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

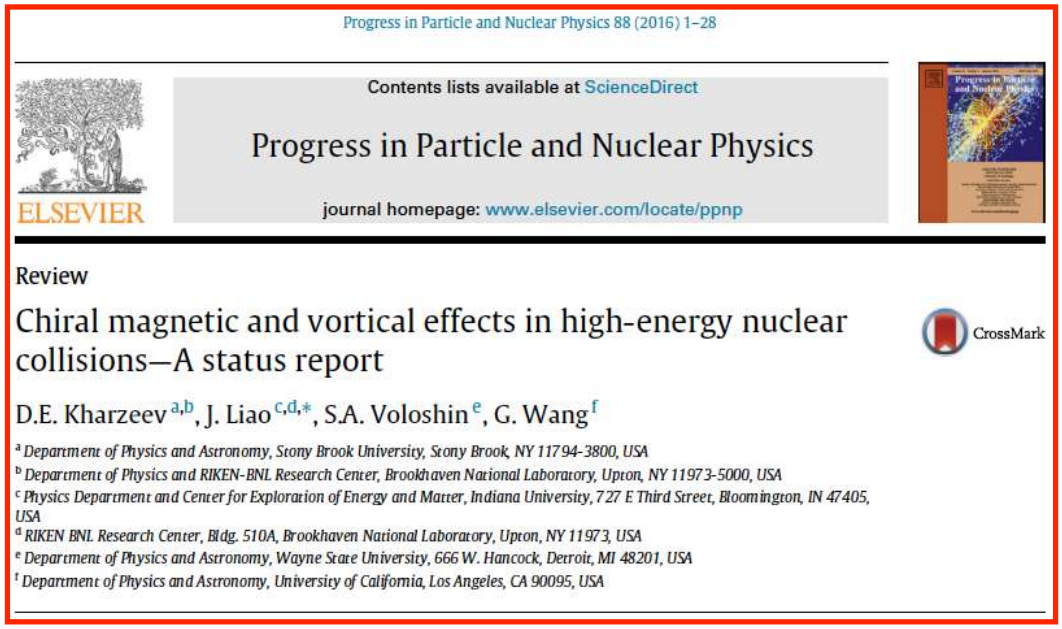
Further Sources on CME

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

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

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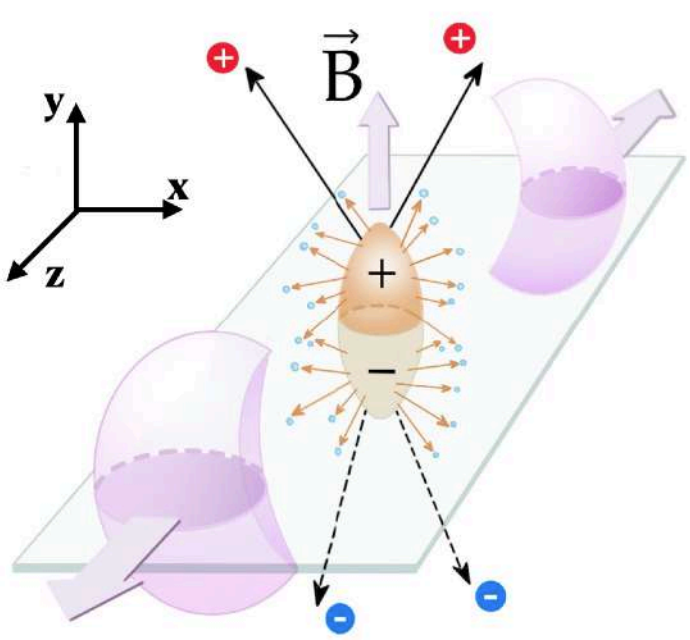
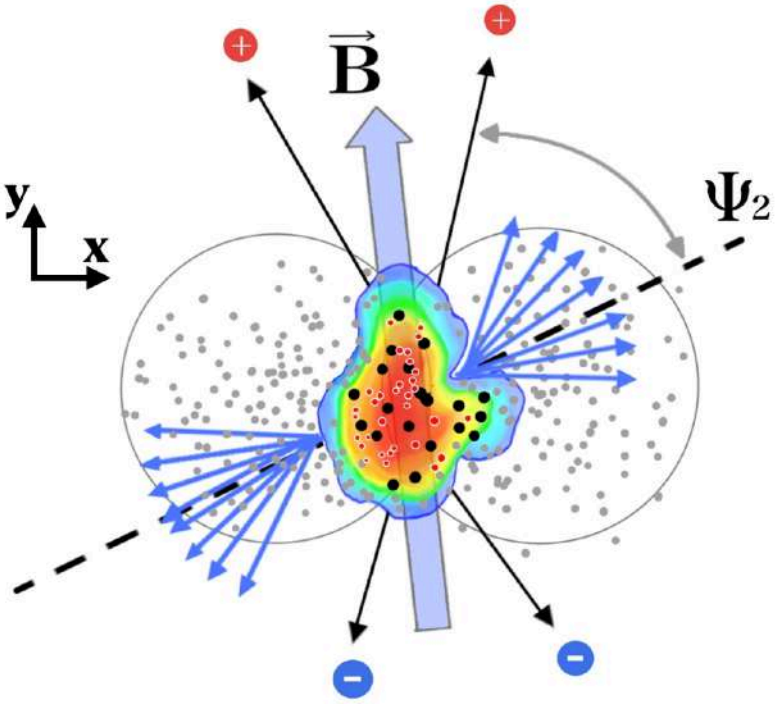
[b] Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[c] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 727 E Third Street, Bloomington, IN 47405, USA
[d] RIKEN BNL Research Center, Bldg. 510A, Brookhaven 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

Looking for CME Signals in Nuclear Collisions

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



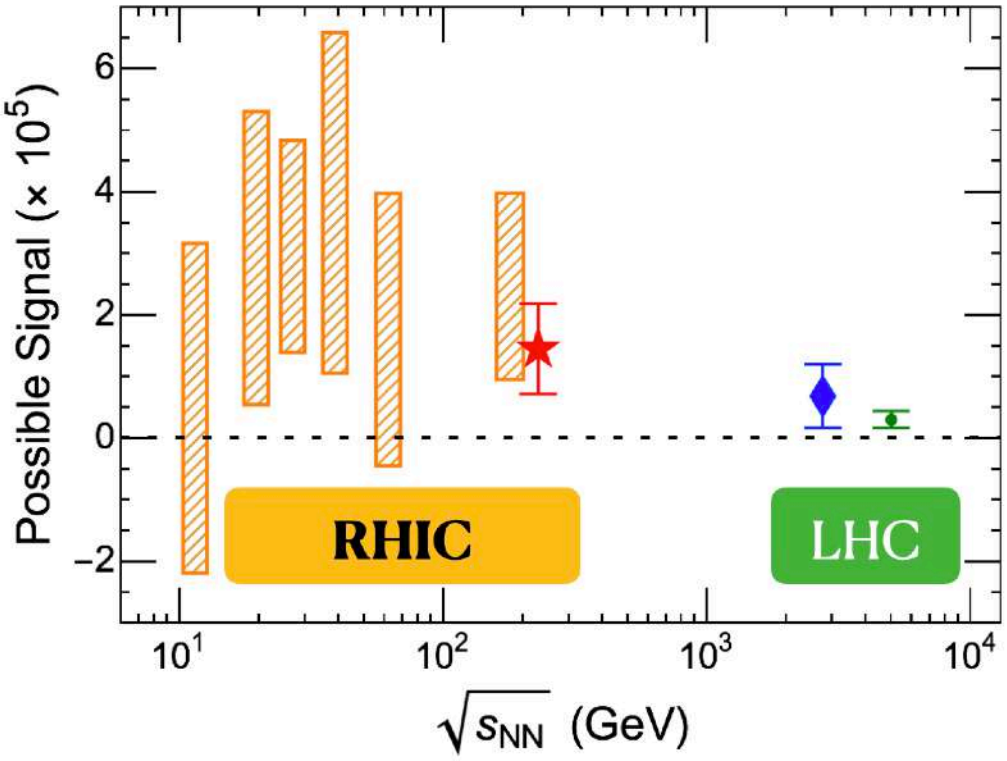


A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

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!



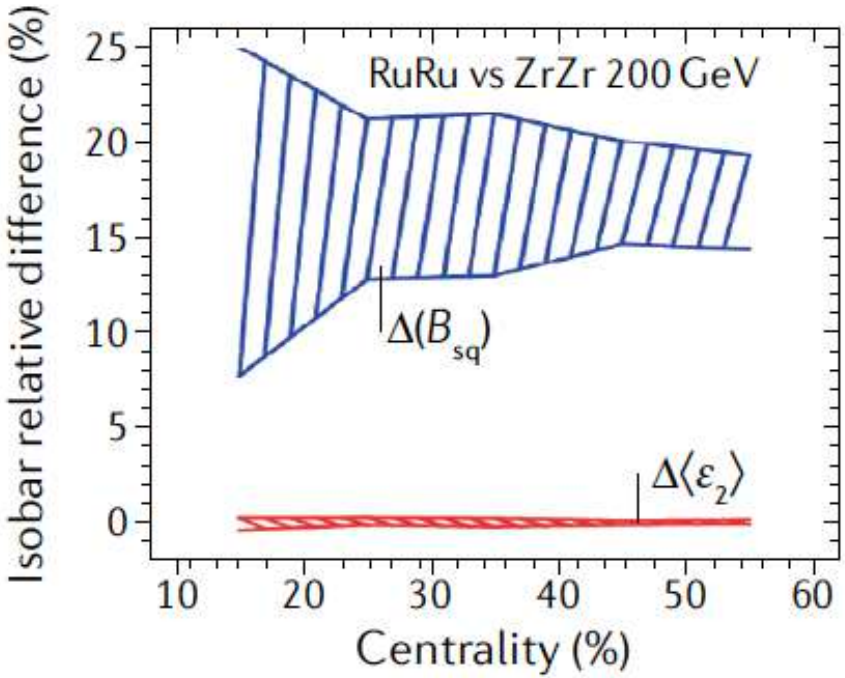
Experimental data are encouraging, but inconclusive.

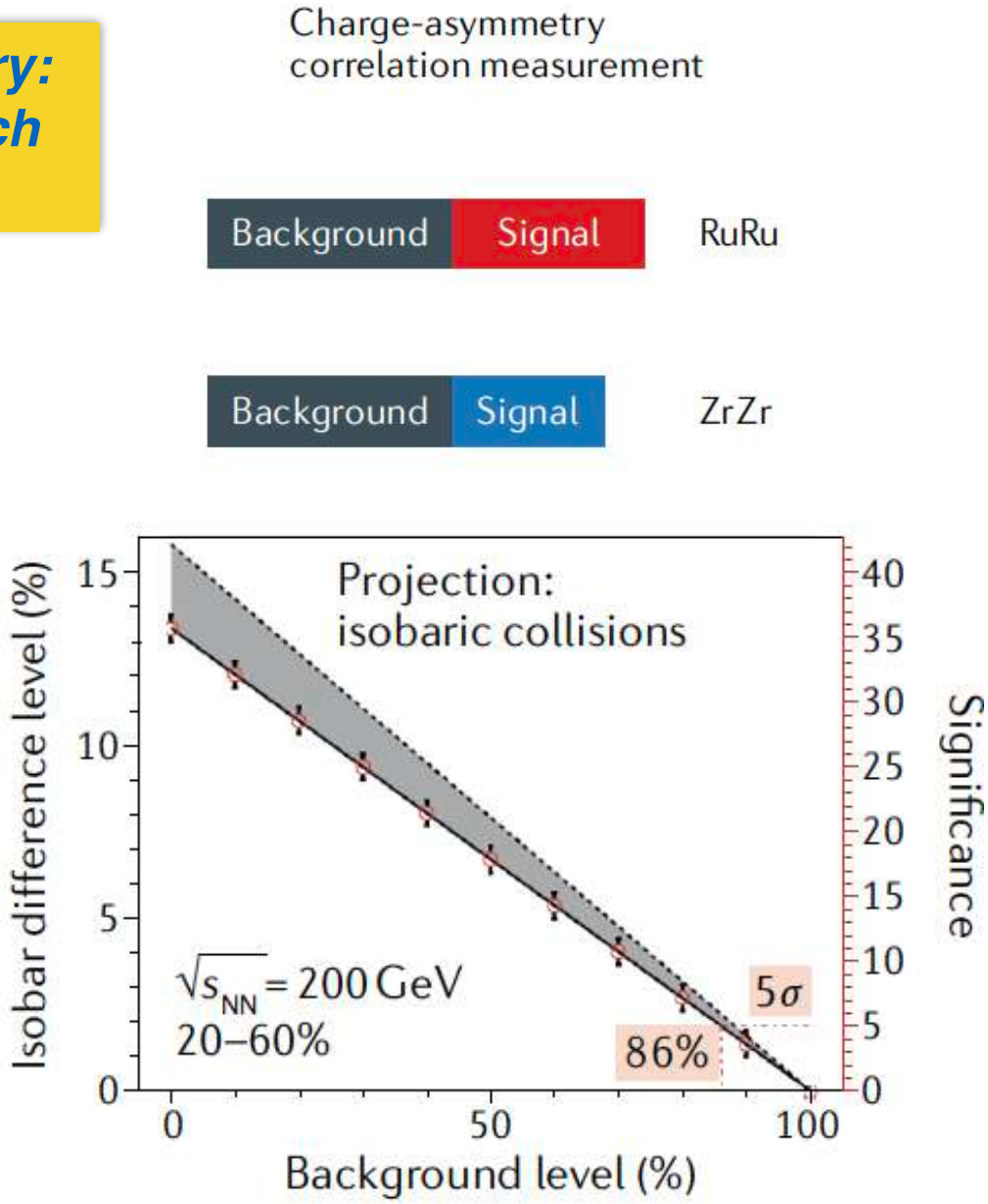
Optimal range: O(~100) GeV

A related search: chiral magnetic wave (CMW)

Isobar Collision Experiment

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





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

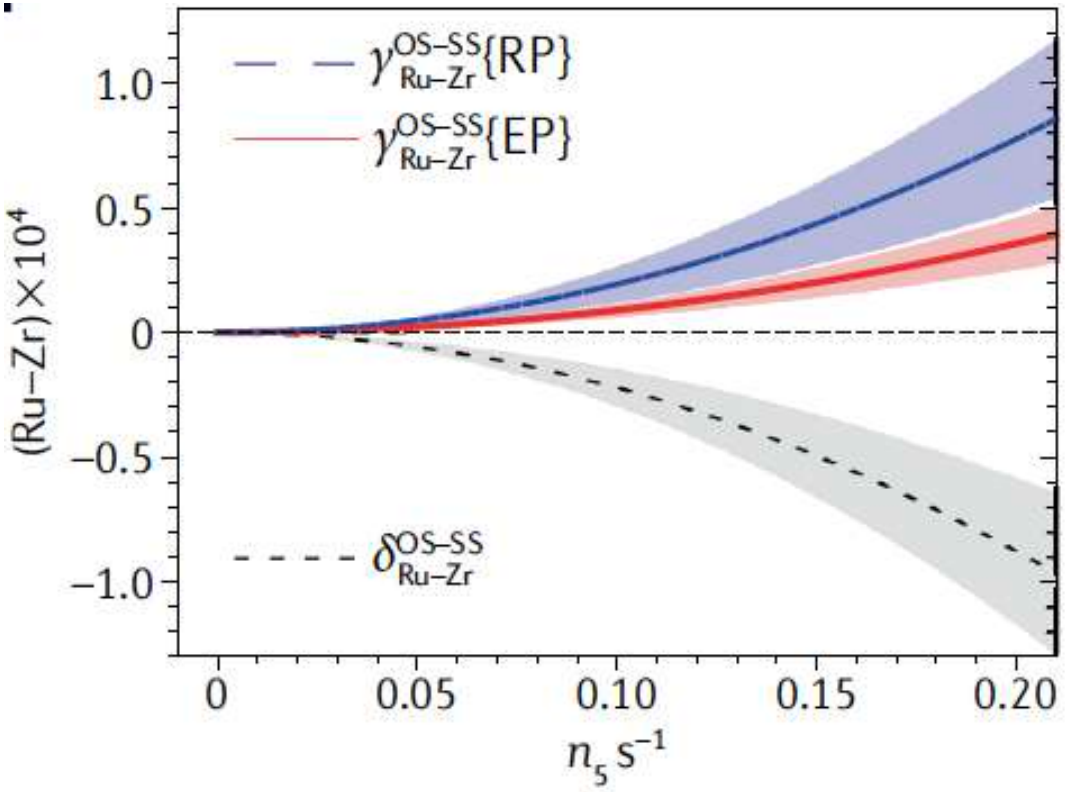
Theoretical Predictions from EBE-AVFD

Theoretical tool for quantitative predictions of CME and related backgrounds is crucial: EBE-AVFD (BEST Collaboration effort)

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,†]



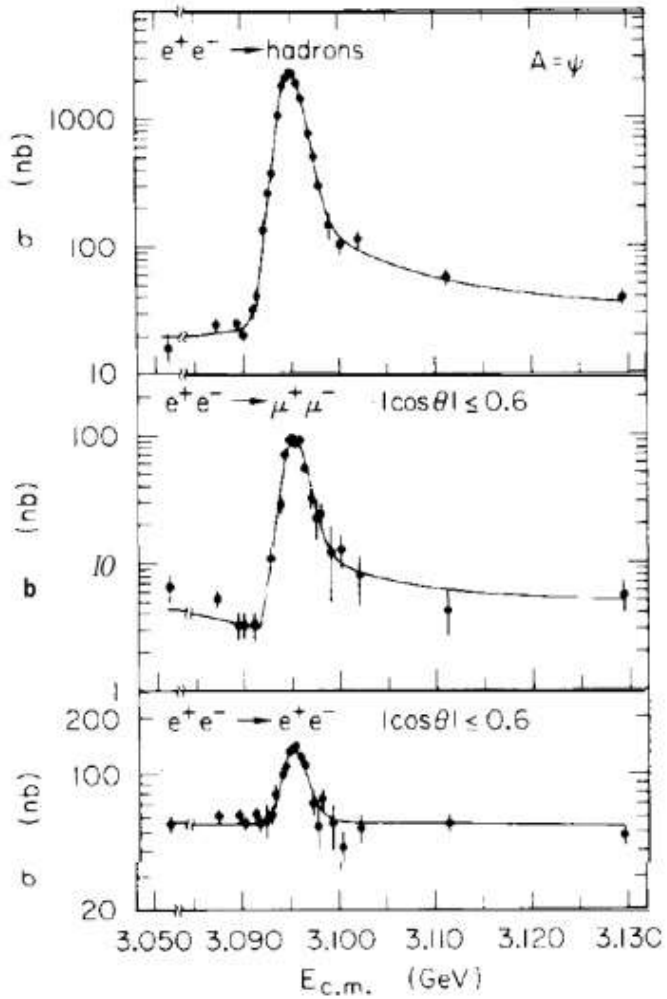
$$\zeta^{RP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{RP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{RP}} \simeq -(0.90 \pm 0.45)$$

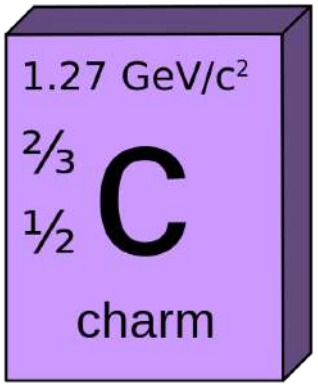
$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$

Stay tuned!

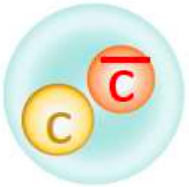
Coming Back to A Few Quarks

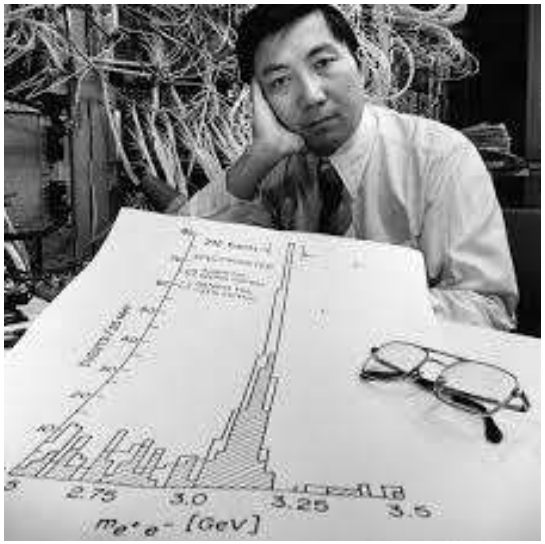
Let us focus on the so-called charm quark sector





Charmonium



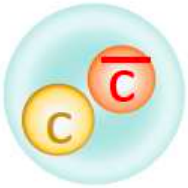


J/Psi discovery: Nov revolution (1974)

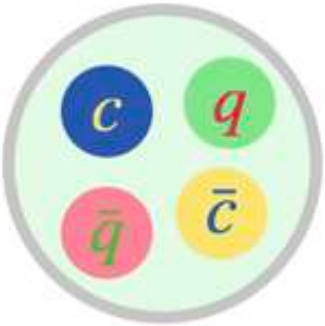
Heavy Exotics

The c-c-bar system offers unique opportunities for exotics!

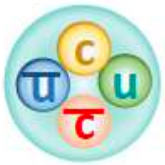
Charmonium



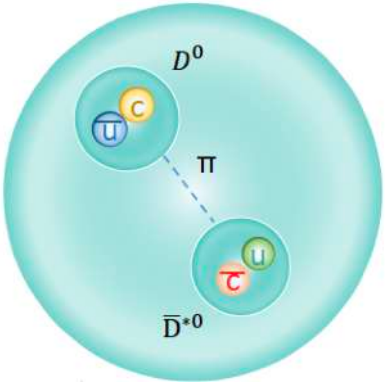
c-cbar-q-q-bar?!



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?

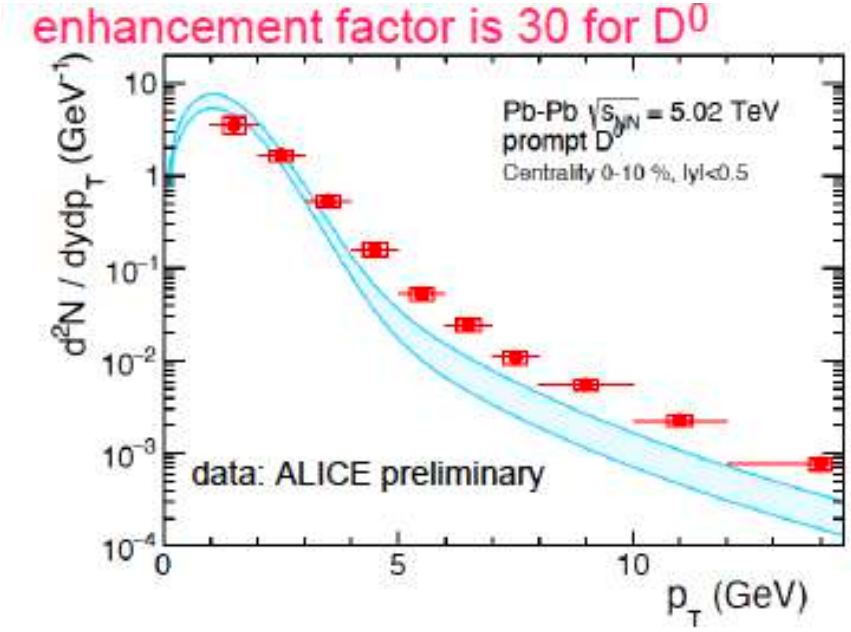


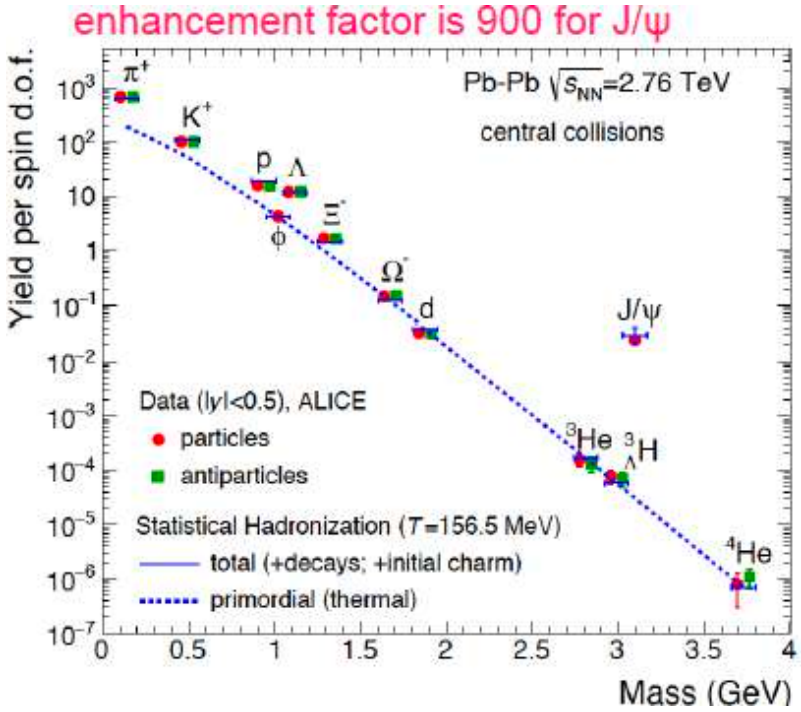
We are still far from completely understanding the secrets of QCD forces.

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

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

Plots from Peter Braun-Munzinger





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!!!

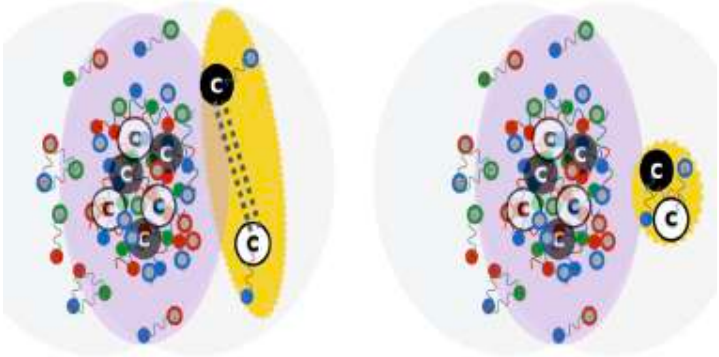
[First set of X-measurements from CMS and LHCb ~2019]

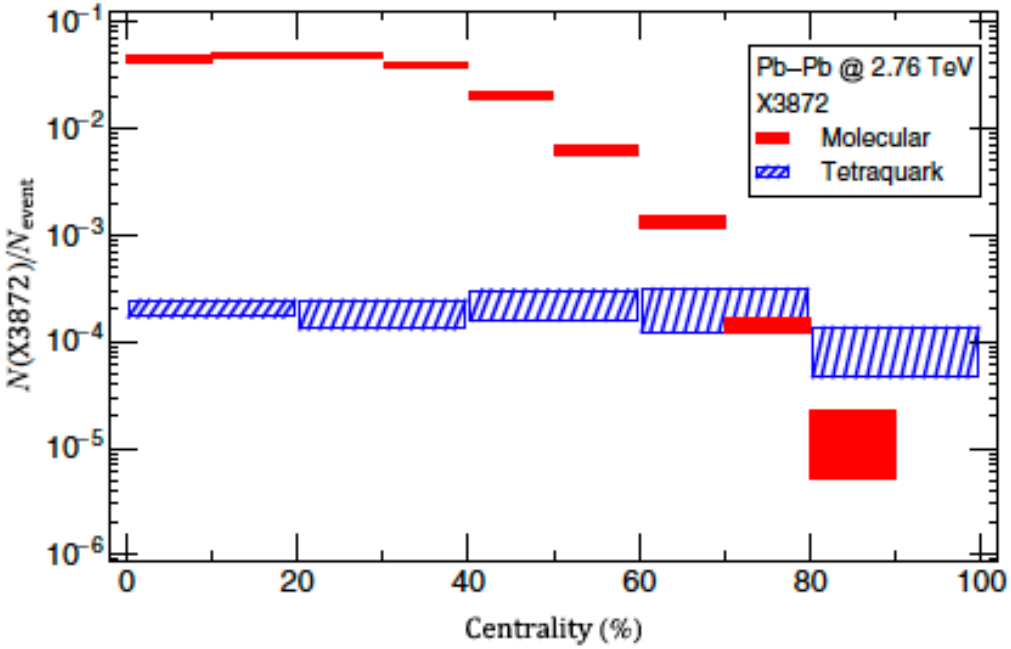
Nailing Down X(3872) Structure

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

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

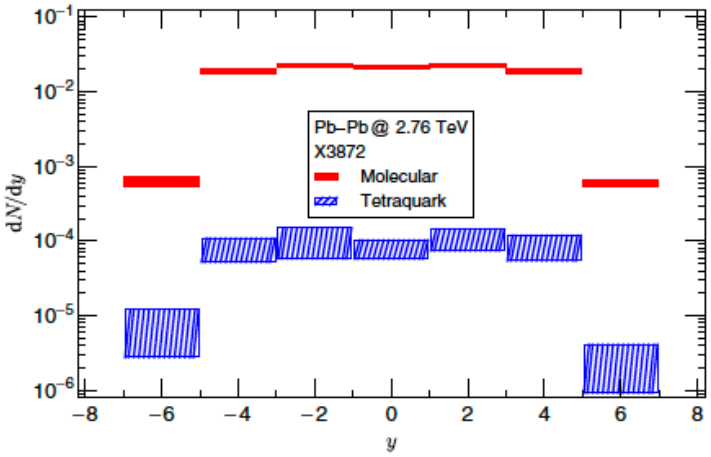
Hui Zhang,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] Qian Wang,[1,2,4,§] and Hongxi Xing[1,2,‖]

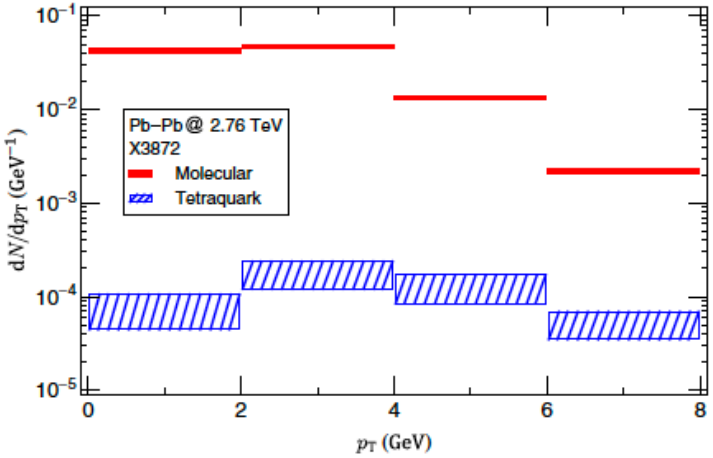


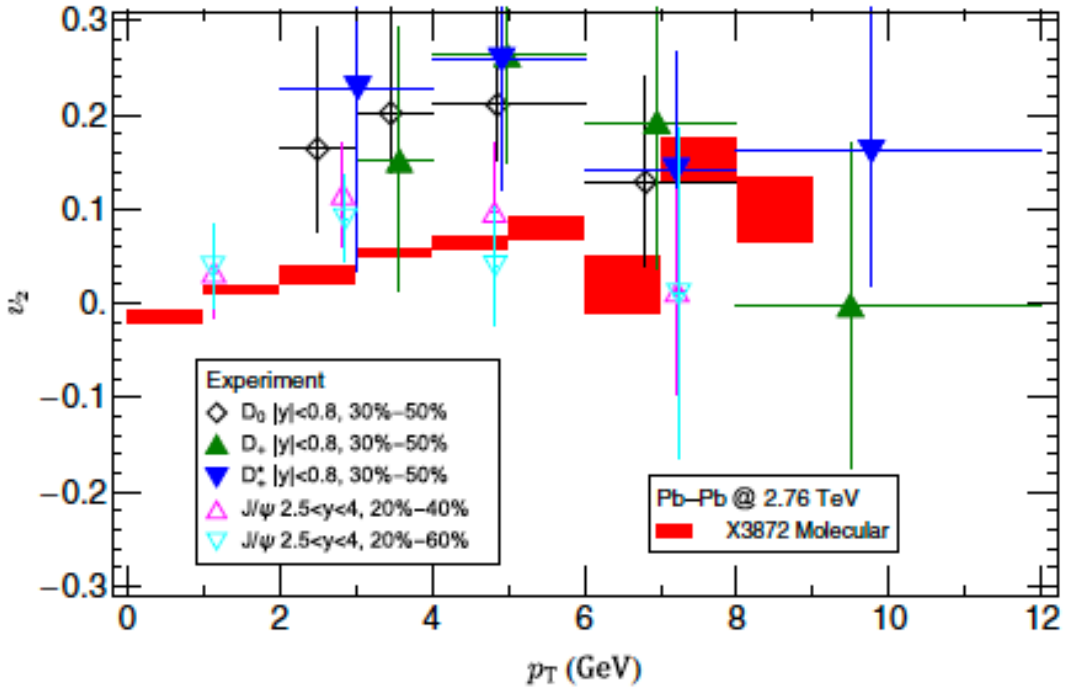


Hadron molecule v.s. tetraquark: Two orders of magnitude difference in the yield; Drastically different centrality dependence.

Nailing Down X(3872) Structure

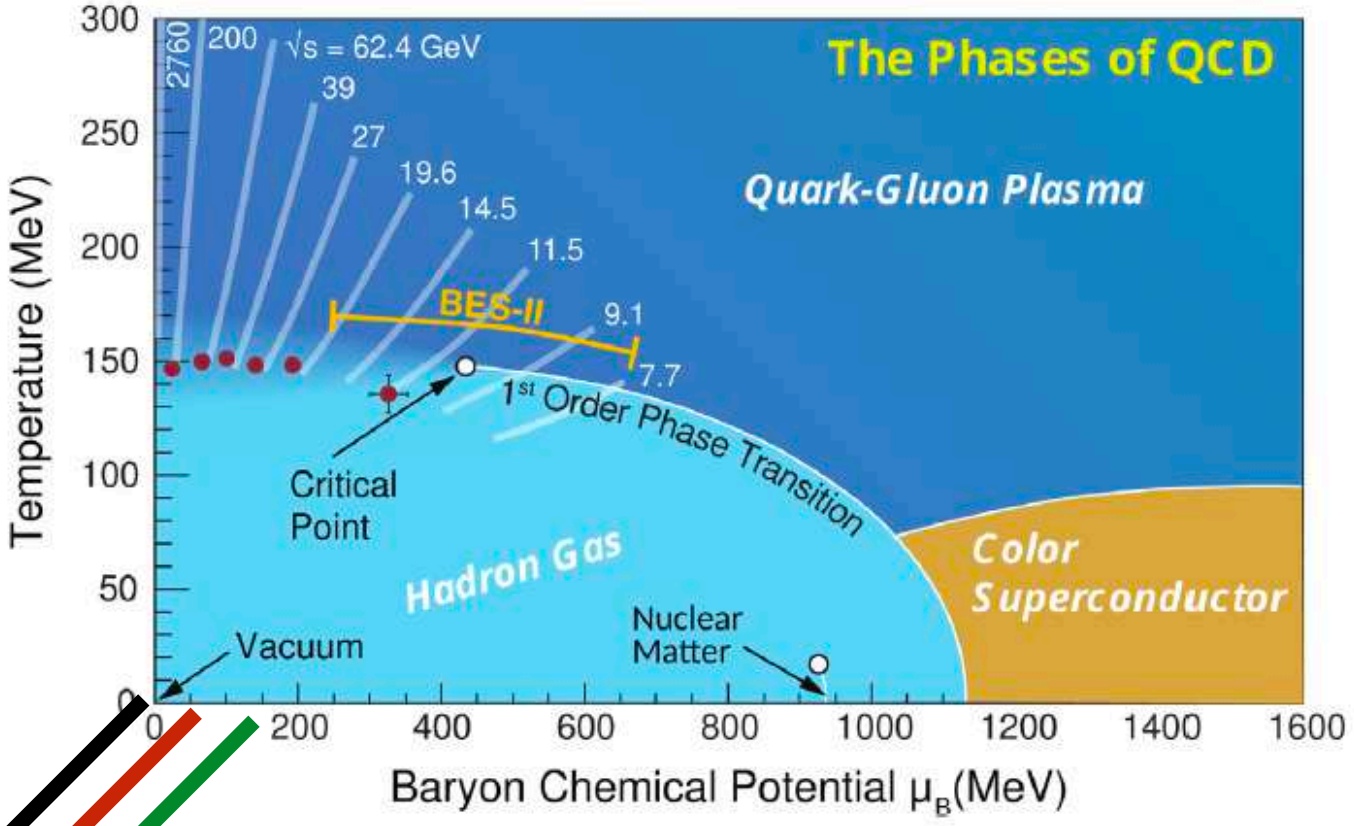


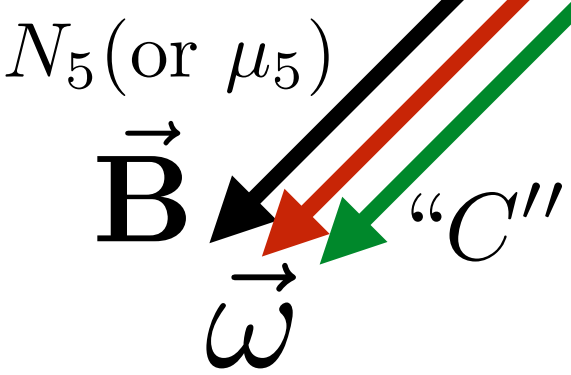




"It is tempting to envision an exciting time of vibrant and coherent theory and experiment efforts for exploring heavy ion collisions as a massive production factory of exotic hadrons to its fullest extent."

Summary: Factory for Exotic Quantum Matter





Nuclear collisions from O(1) to O(1000) GeV:

Opening novel dimensions of the "nuclear matter universe"!