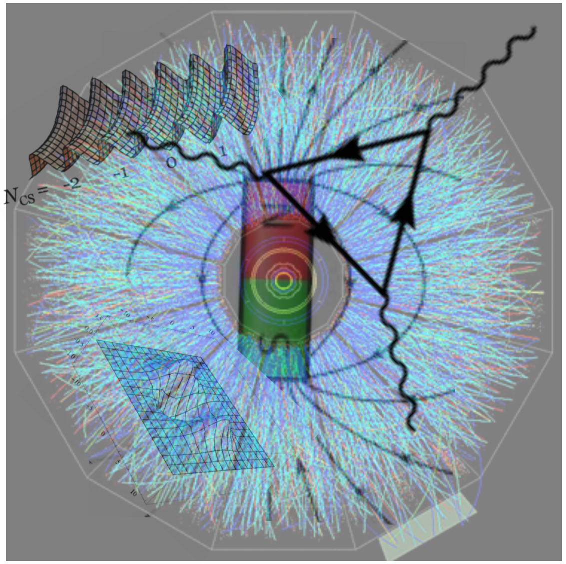
Workshop @ Guangzhou Nov. 11~13, 2018

Chiral Anomaly in Heavy Ion Collisions



Jinfeng Liao

INDIANA UNIVERSITY

Research Supported by U.S. NSF & DOE and by NSFC

BEST COLLABORATION

Chinese Physics C Vol. 42, No. 1 (2018) 011001

arXiv:1611.04586

Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics*

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Annals of Physics 394 (2018) 50–72

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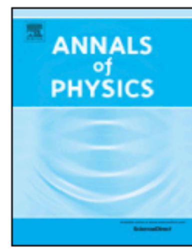

Check for updates

Anomalous chiral transport in heavy ion collisions from Anomalous-Viscous Fluid Dynamics

Shuzhe Shi[a,*], Yin Jiang[b,c], Elias Lilleskov[d,a], Jinfeng Liao[a,e,*]

arXiv:1711.02496

Shuzhe Shi (McGill; PhD @ IUB)

Yin Jiang (Beihang), Yi Yin (MIT), Elias Lilleskov (REU)

The EBE-AVFD "Warriors"

XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2018)

Chiral Magnetic Effect in Isobaric Collisions from Anomalous-Viscous Fluid Dynamics (AVFD)

Shuzhe Shi[a], Hui Zhang[b,a], Defu Hou[b], Jinfeng Liao*[a,b]

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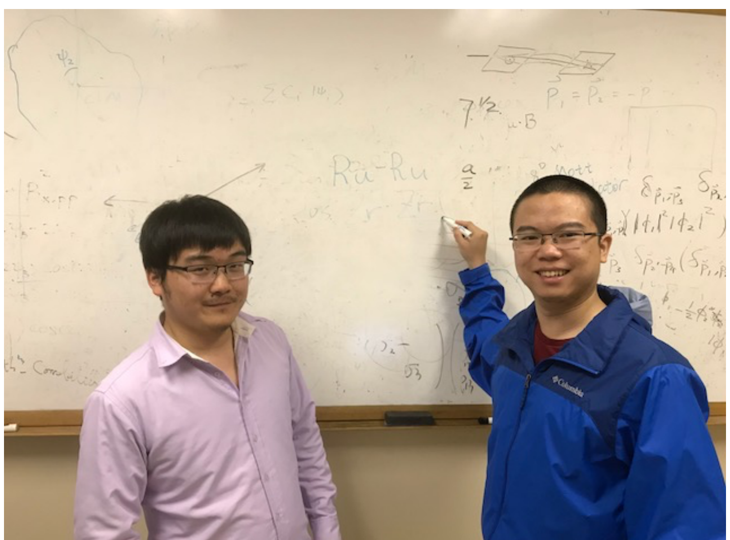
QM18 proceedings



Hui Zhang **Shuzhe Shi** **Defu Hou**

Exciting Progress: See Recent Reviews

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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

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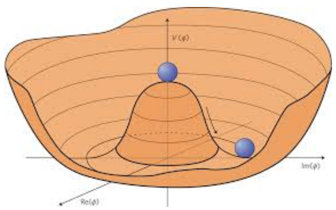
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

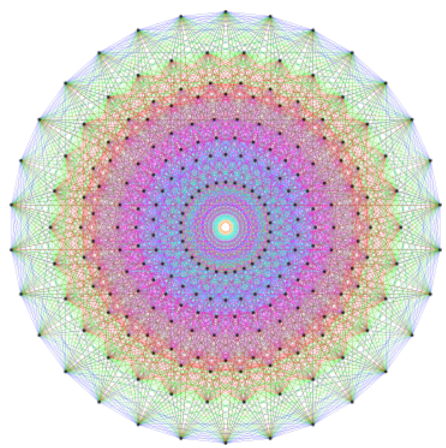
Chiral Symmetry & Chiral Anomaly

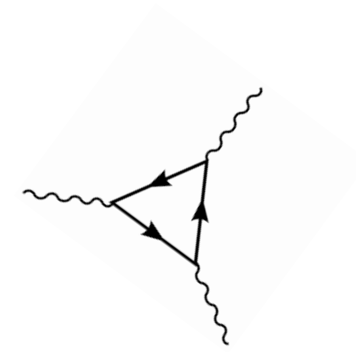
Symmetry

严格的
对称性



自发破缺的
对称性





经典对称性
的量子反常

明显破缺的
对称性

* *Spacetime symmetry*
* *Global symmetry: conserved quantum numbers*
* *Gauge symmetry:*
  *SU(3) strong force; SU(2)*U(1) electroweak force*

Chirality & Chiral Symmetry

If a Dirac fermion's mass is zero —> axial U(1) global phase symmetry!

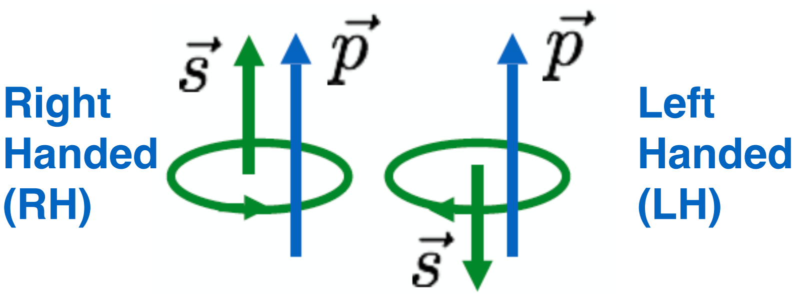
$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu \partial_\mu)\Psi$$

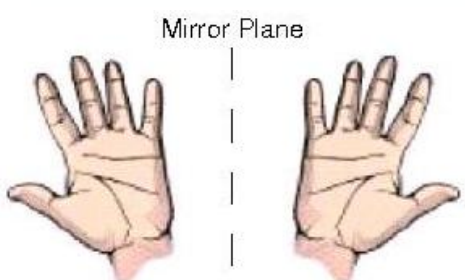
$$\Psi \rightarrow e^{i\alpha\gamma^5}\Psi \qquad \mathcal{L} \rightarrow \mathcal{L}$$

$$J_5^\mu = \bar{\Psi}\gamma^\mu\gamma^5\Psi \qquad \partial_\mu J_5^\mu = 0$$

Axial current **Classically conserved**

In this case, chirality becomes well defined.





$$\Psi_R = \frac{1+\gamma^5}{2}\Psi$$

$$\Psi_L = \frac{1-\gamma^5}{2}\Psi$$

$$\mathcal{L} \rightarrow \bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + \bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

Phase symmetries: independent U(1) for RH and LH sectors!

Chiral Symmetry: Explicit Breaking

If a nonzero Lagrangian mass term is added:
axial symmetry is explicitly broken.

$$m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right)$$

RH and LH get coupled together.
Axial current is no longer conserved:

$$\partial_\mu J_5^\mu = 2im\bar{\Psi}\gamma^5\Psi$$

The mass controls the degree of such breaking.

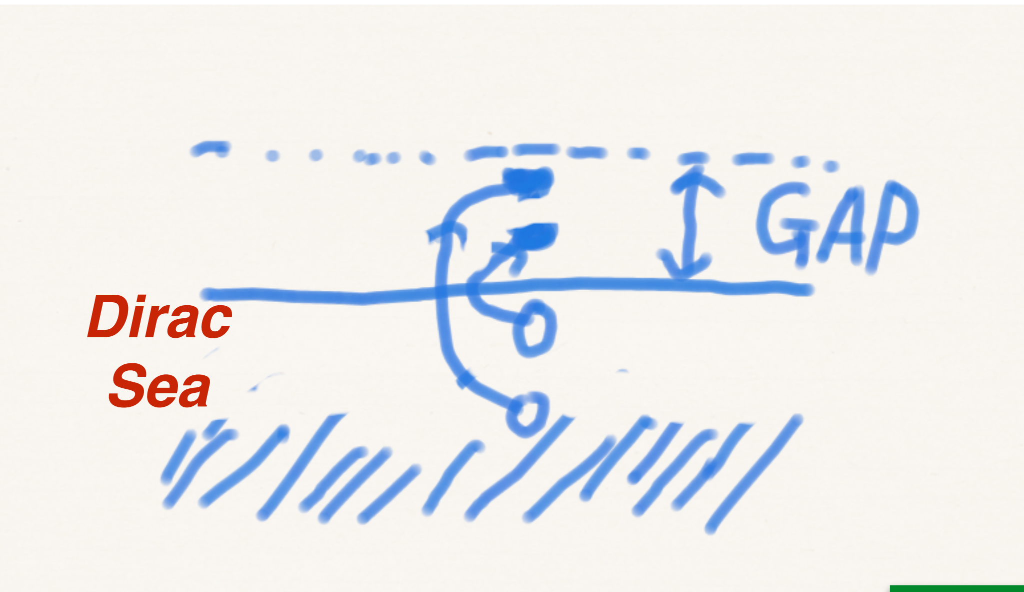
In QCD, for light flavors (u & d), Lagrangian mass is small:

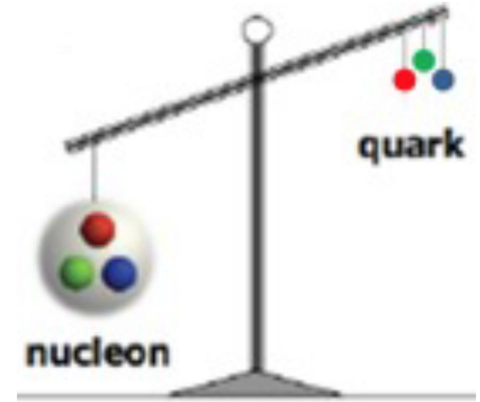
$$m_{u,d} \ll \Lambda_{QCD}$$

QCD has chiral symmetry (to very good approximation)!

Chiral Symmetry: Spontaneous Breaking

$m_\pi \approx 140 MeV$, $m_n \approx 940 MeV$



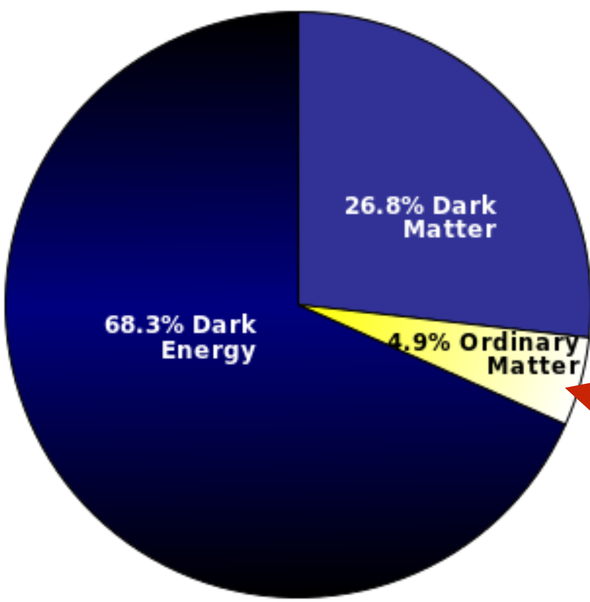


$$M = m - 2G \langle \bar{\psi}\psi \rangle$$

Constituent mass

Lagrangian (SM) mass

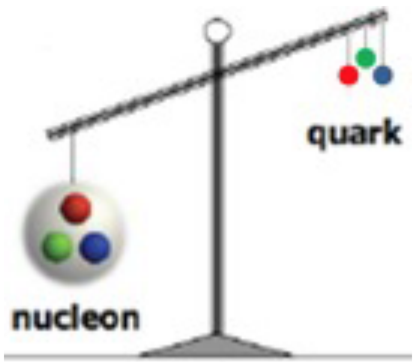
Vacuum condensate

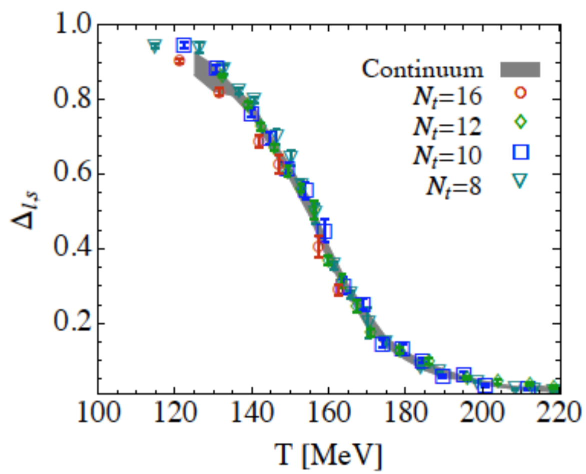


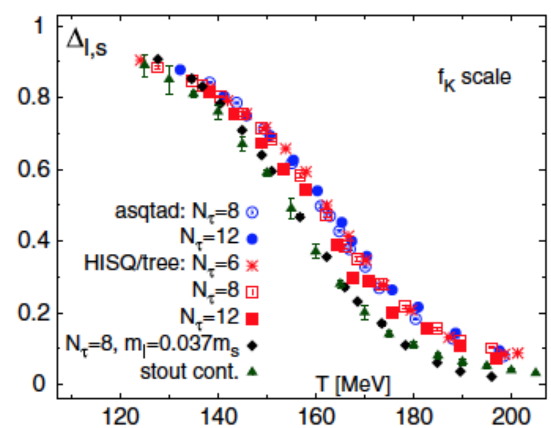
It accounts for 99% of the mass of our visible matter in universe.

Chiral Symmetry Restoration

**** Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.***



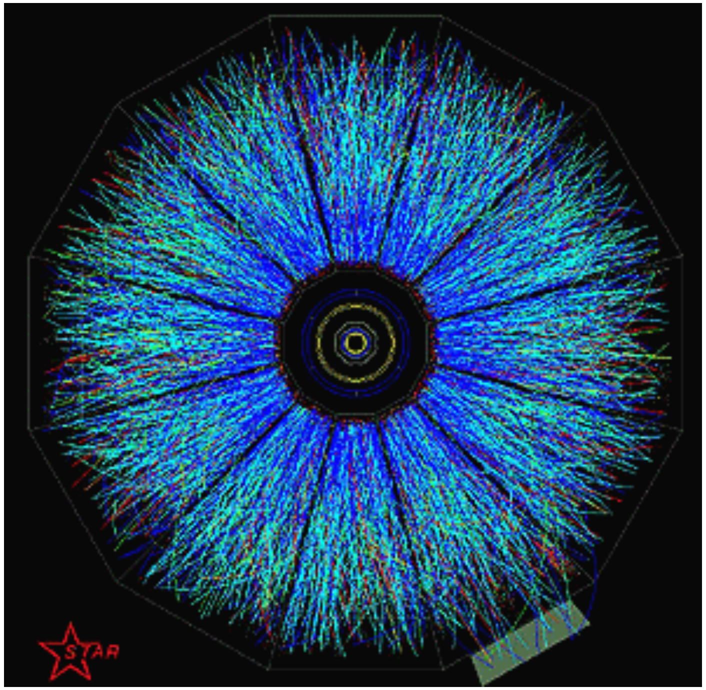


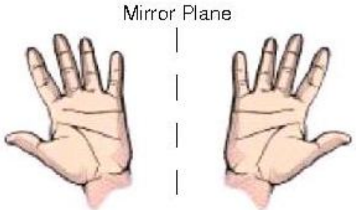


**** A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!***

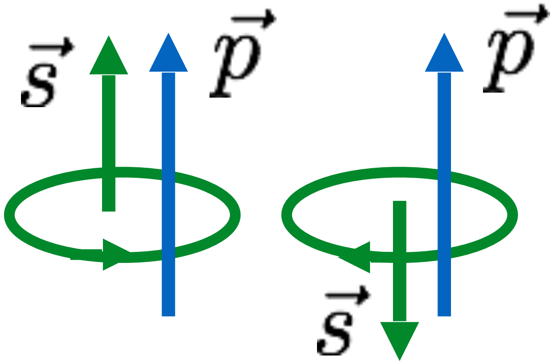
Could we see direct experimental evidence for that?

“Little Bang” in High Energy Nuclear Collision





CHIRAL FERMIONS



**** Quark-gluon plasma (QGP) is created in such collisions.***

**** It is PRIMORDIALLY HOT ~ trillion degrees ~ early universe.***

**** Is chiral symmetry restored?***

Chiral Symmetry: Quantum Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

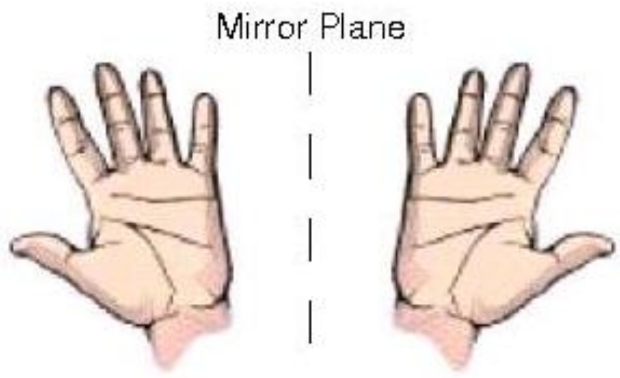
Classical symmetry:

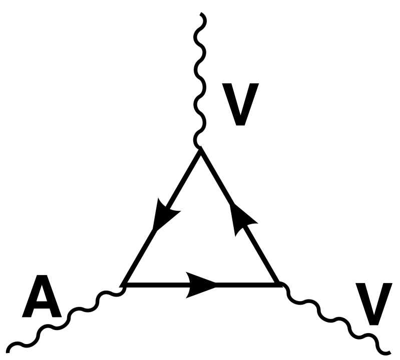
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

$$\mathcal{L} \to i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_\mu J_5^\mu = 0$$





[e.g. pi0—> 2 gamma]

Broken at QM level:

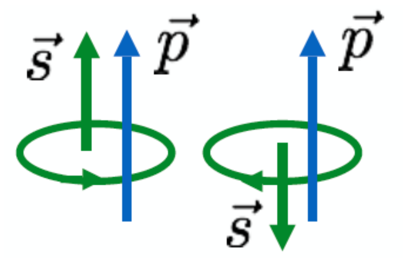
$$\partial_\mu J_5^\mu = C_A \vec{E}\cdot\vec{B}$$

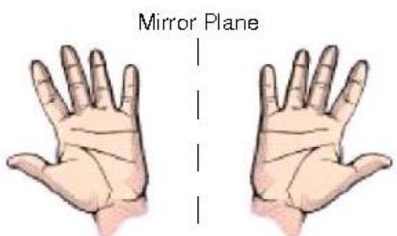
$$dQ_5/dt = \int_{\vec{x}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Recap: Chiral Symmetry in QCD

$$J_5^\mu = J_R^\mu - J_L^\mu$$





$$\partial_\mu J_5^\mu = 2iM\bar{\Psi}\gamma^5\Psi + C_A \vec{E}\cdot\vec{B}$$

Low T

Strong spon. breaking

Very small explicit breaking

High T

Quantum Anomaly

Look for pure quantum anomaly effect in hot QGP with chiral symmetry restoration!

Chiral Magnetic Effect (CME)

From Micro. Laws To Macro. Phenomena

Micro. Laws:

Symmetry;
Lagrangian;
Conservation laws;
……

Macro. Phenomena:

Thermodynamics;
Transport;
Fluid Dynamics;
……

Quantum Field Theory → *Weakly Interacting* → **Kinetic Theory** → *Strongly Interacting* → **Fluid Dynamics**

WHAT ABOU the "SEMI"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

The Chiral Magnetic Effect (CME)

Chirality & Anomaly & Topology

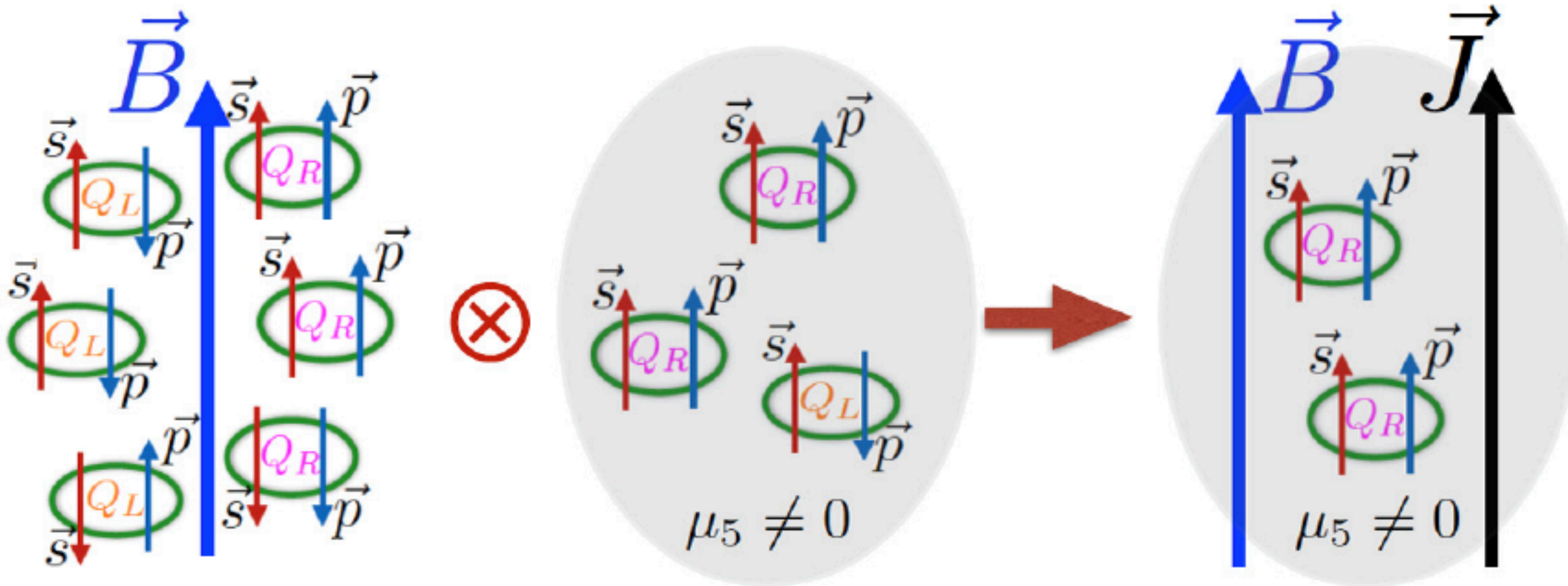
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current

Q.M. Transport

Magnetic Field

Intuitive Picture of CME



Intuitive understanding of CME:

Magnetic polarization —> correlation between micro. SPIN & EXTERNAL FORCE ⊗ **Chiral imbalance —> correlation between directions of SPIN & MOMENTUM**

Transport current along magnetic field

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

CME <=> Chiral Anomaly

Anomaly --> $\partial^\mu j^5_\mu = \frac{q^2}{2\pi^2} \boldsymbol{E}\cdot\boldsymbol{B}$ $\frac{dN_5}{dt d^3x} = \frac{q^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}$

Chirality --> $\int d^3x \boldsymbol{j}_{el}\cdot\boldsymbol{E} = \mu_5 \frac{dN_5}{dt} = \frac{q^2\mu_5}{2\pi^2}\int d^3x \mathbf{B}\cdot\boldsymbol{E}$

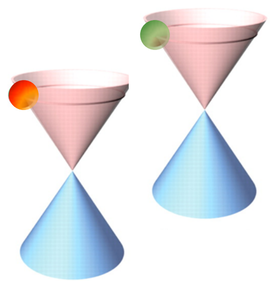
$\boldsymbol{E} \to 0$ $\boldsymbol{j}_{el} = (q^2\mu_5/2\pi^2)\boldsymbol{B}$

* This is a non-dissipative current!
* Indeed the chiral magnetic conductivity is P-odd but T-even!
(In contrast the Ohmic conductivity is T-odd and dissipative.)

Searching for CME in Laboratories

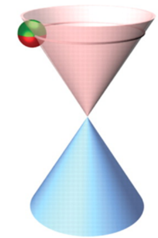
CME was observed via negative magnetoresistance in semimetals.

Weyl semimetal
(non-degenerated bands)



TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



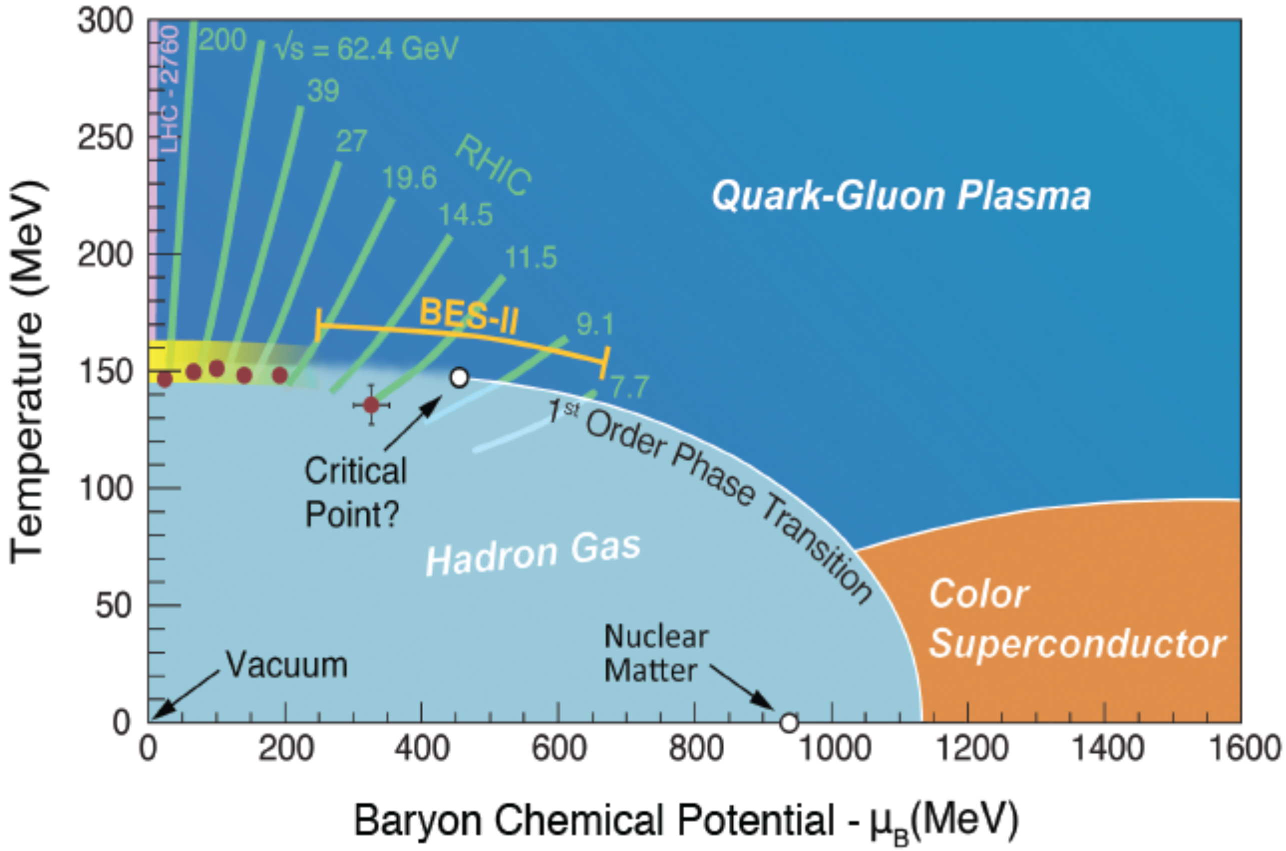
$ZrTe_5$
Na_3Bi,
Cd_3As_2

Observe CME for the subatomic chiral matter in heavy ion collisions?

1) *(nearly) chiral quarks*
2) *chirality imbalance*
3) *strong magnetic field*

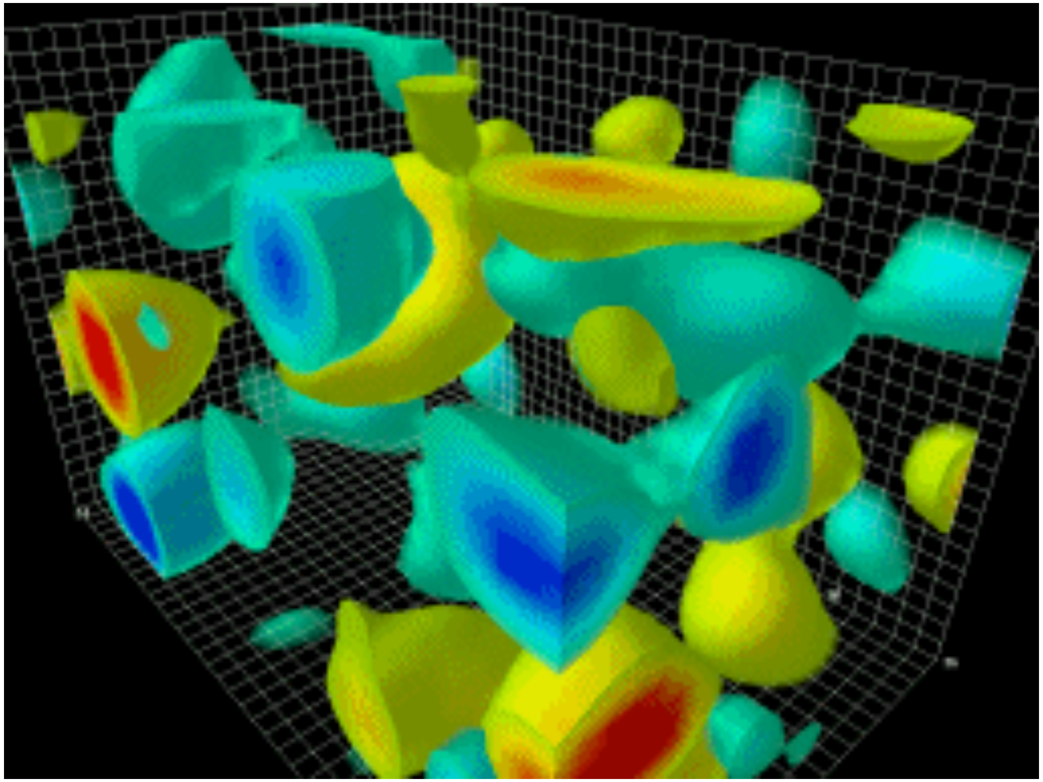
CME and Beam Energy Scan

Restoration of chiral symmetry only at high enough beam energy —> beam energy dependence is crucial!



**** We'd like to see a chiral QGP above certain threshold energy via CME***
**** We'd like to see its turning off at low enough energy***

From Gluon Topology to Quark Chirality



$$Q_w = \frac{1}{32\pi^2}\int d^4x\,(gG_a^{\mu\nu})\cdot(g\tilde{G}^a_{\mu\nu})$$

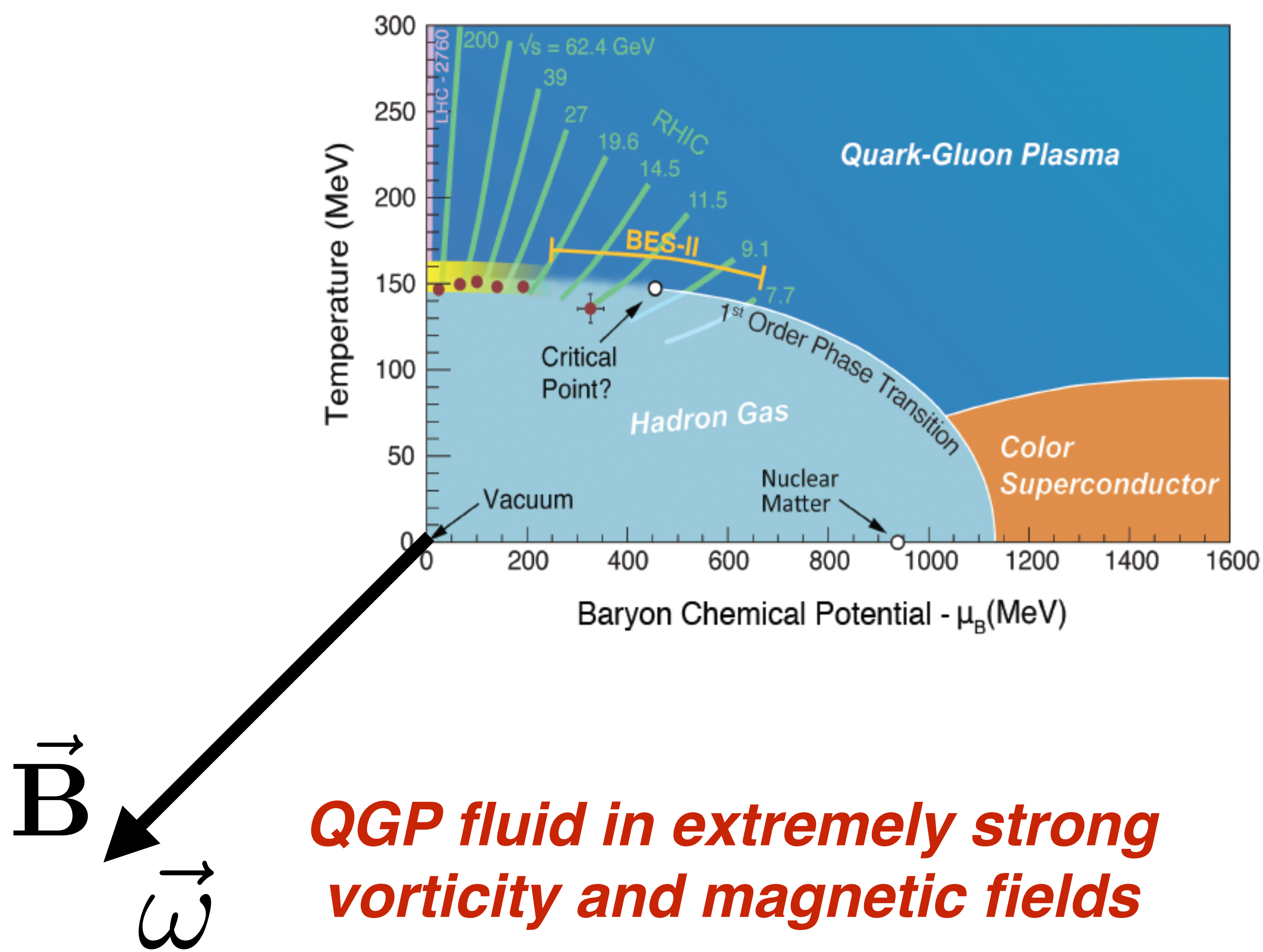
$$N_5(t\to+\infty) - N_5(t\to-\infty) = \frac{g^2}{16\pi^2}\int dt d^3\mathbf{r}\, G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

QCD anomaly: gluon topology —> chirality imbalance

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

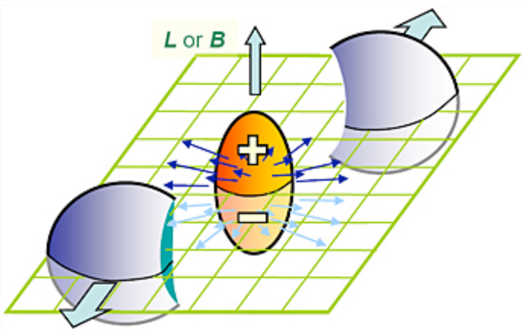
Rotation & Magnetic Fields in Heavy Ion Collisions

Fascinating New Frontiers

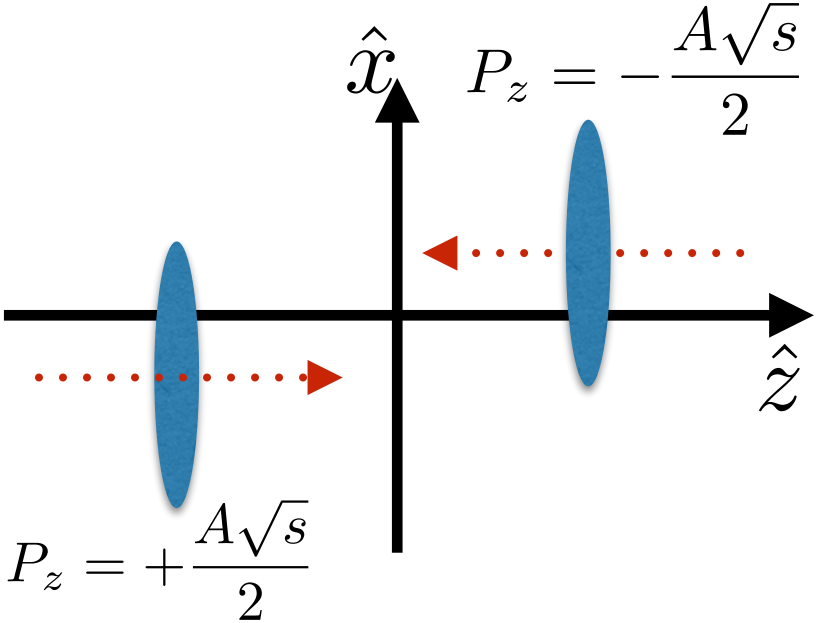


QGP fluid in extremely strong vorticity and magnetic fields

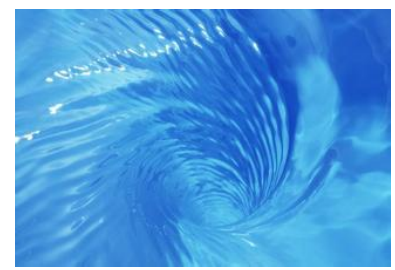
"Rotating" Quark-Gluon Plasma



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



QGP's way of accommodating this angular momentum: forming fluid vorticity!



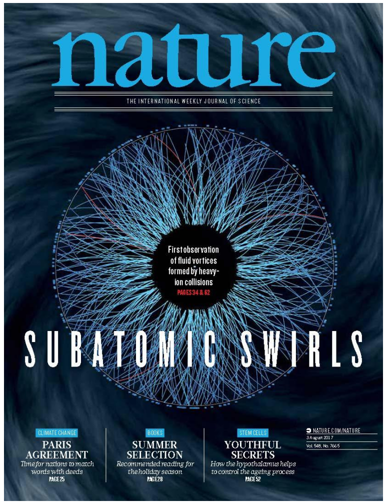
$$\vec{\omega} = \tfrac{1}{2}\nabla \times \vec{\mathbf{v}}$$

$$v \sim 0.1\,c \qquad \partial \sim \mathrm{fm}^{-1}$$

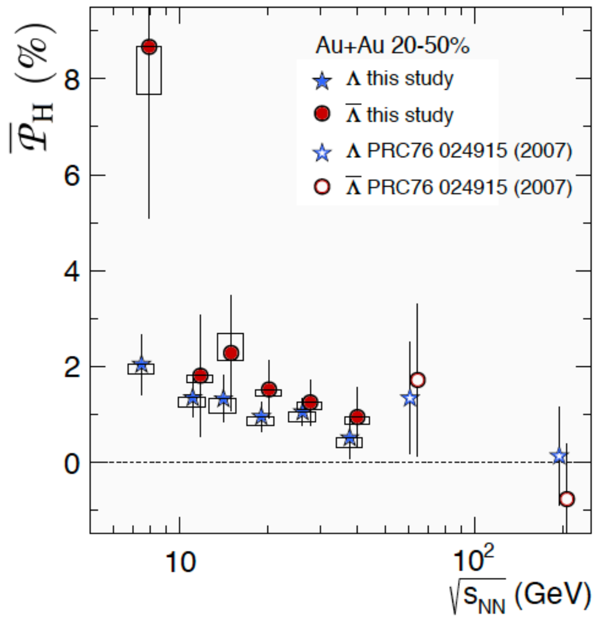
$$\rightarrow$$

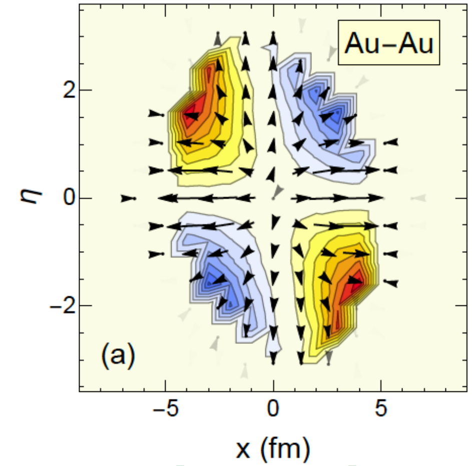
$$\omega \sim 10^{22}\,\mathrm{s}^{-1}$$

Global Polarization in the Most Vortical Fluid

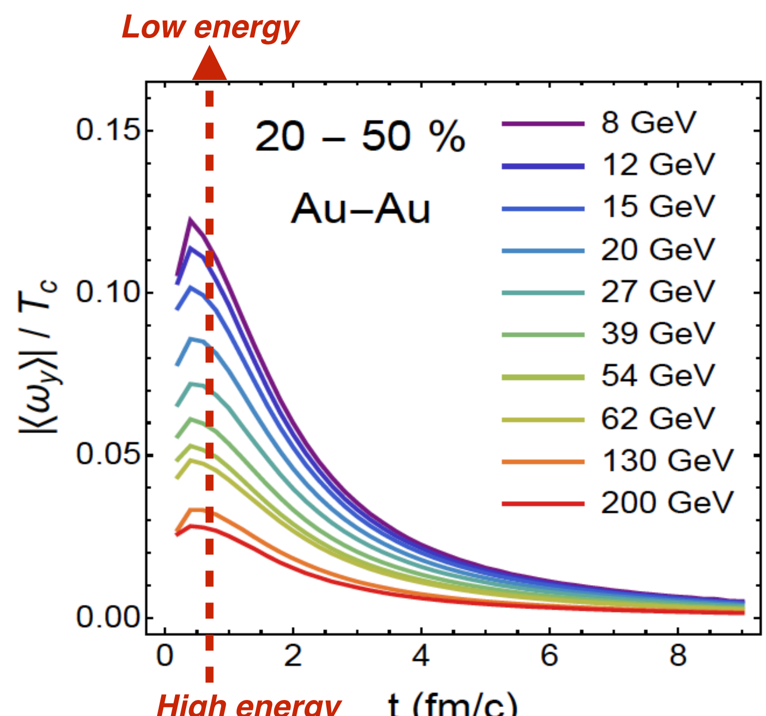


STAR Collaboration, Nature 2017





Jiang, Lin, JL, PRC2016

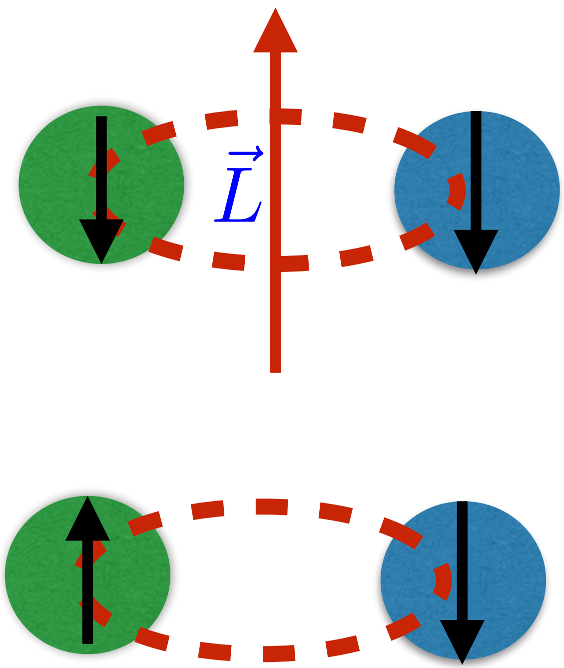


Rotational Suppression of Fermion Pairing

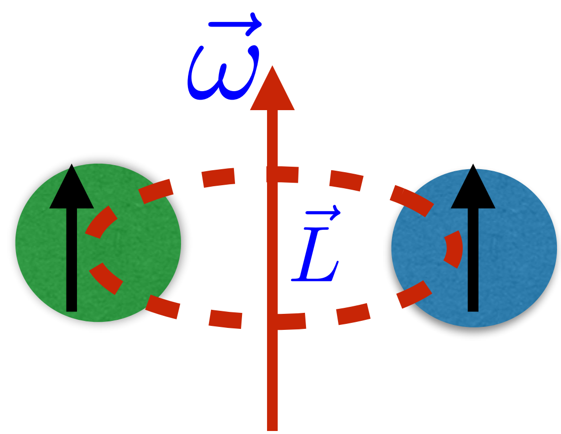
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

We consider scalar pairing state, with J=0.

$$\vec{S} = \vec{s}_1 + \vec{s}_2 \qquad \vec{J} = \vec{L} + \vec{S}$$

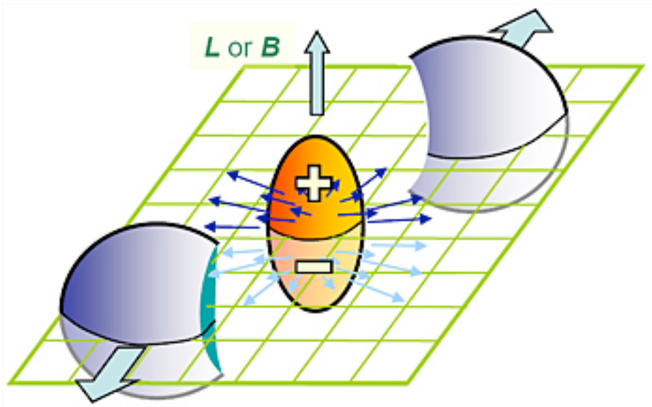


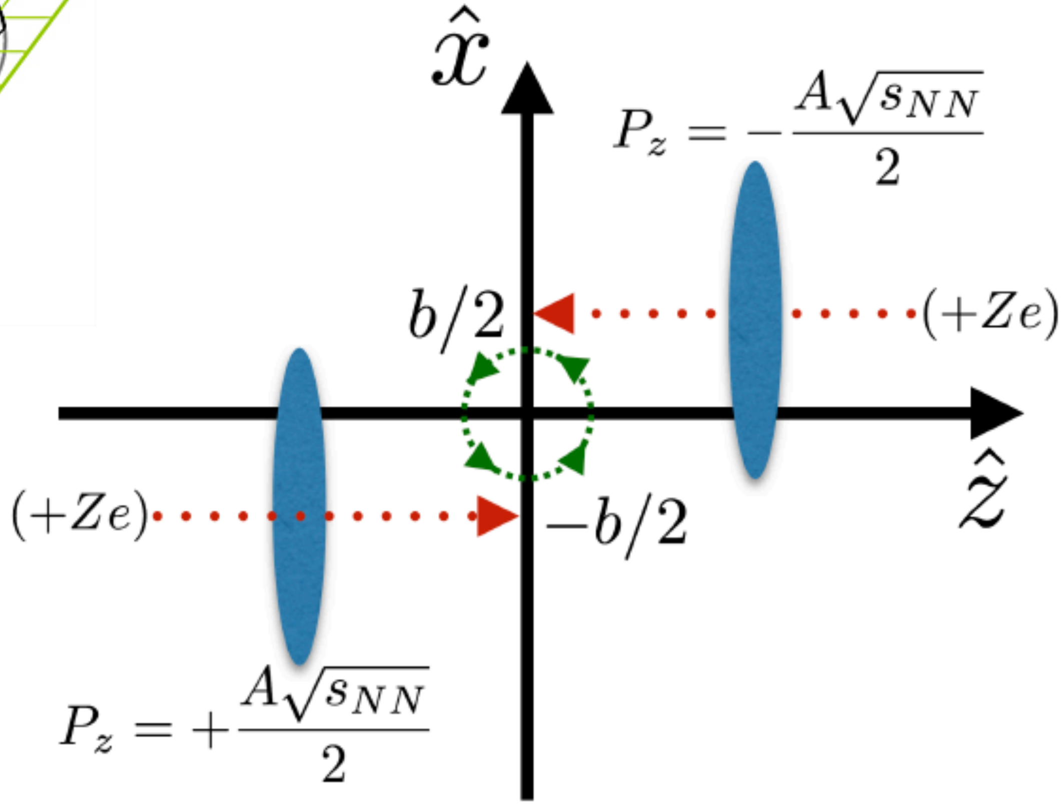
Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing.



[Yin Jiang, JL, PRL2016]

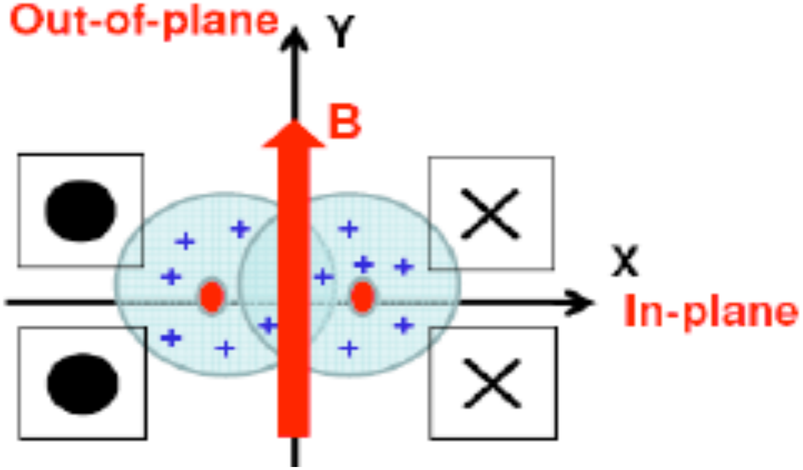
Strong Electromagnetic Fields



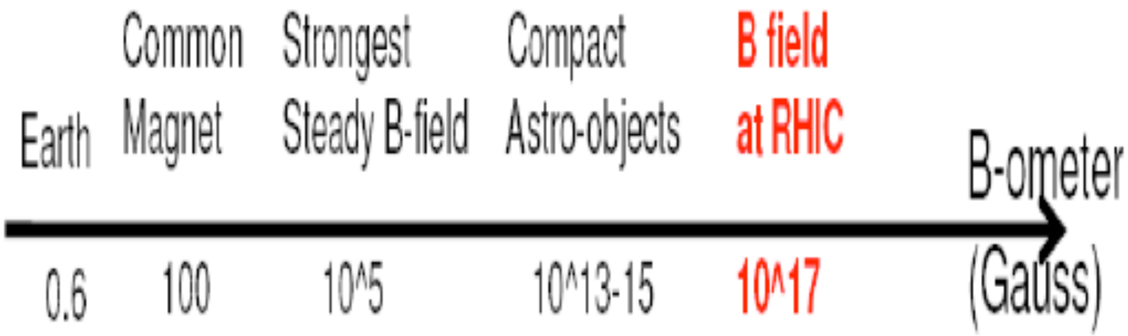


Large angular momentum together with large (+Ze) nuclear charge —> strong magnetic field!

Strong Electromagnetic Fields



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



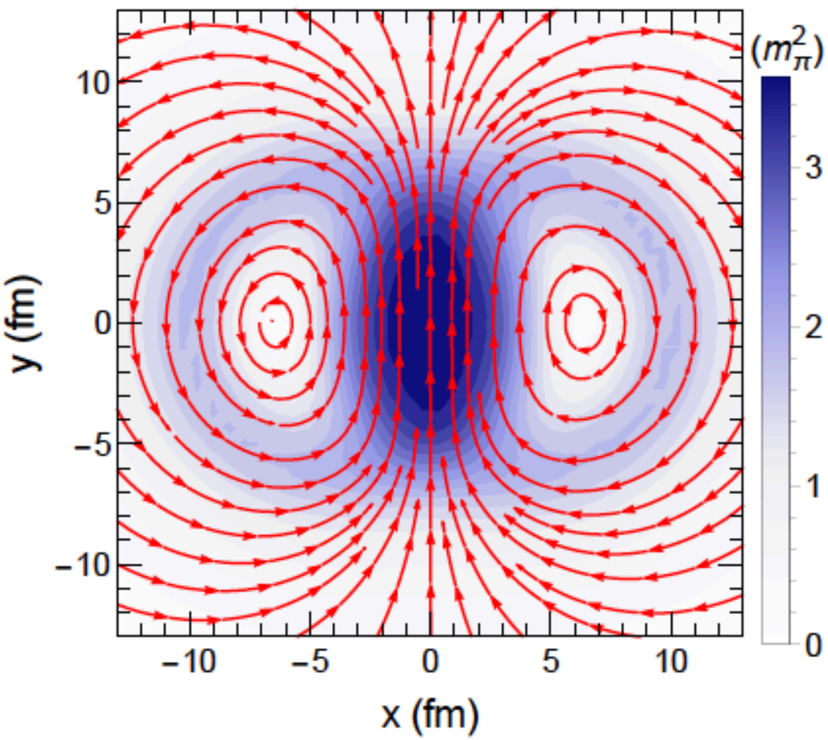
- Strongest B field (and strong E field as well) naturally arises!

[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Skokov-McLerran;Tuchin; ...]

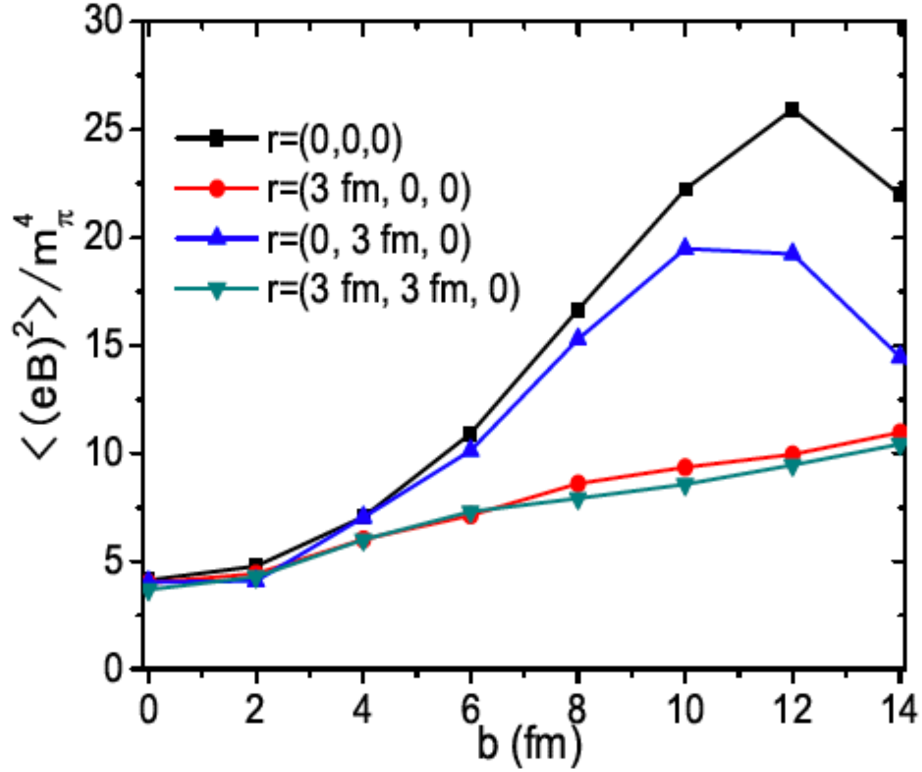
- "Out-of-plane" orientation (approximately)

[Bloczynski-Huang-Zhang-Liao]

Strong Electromagnetic Fields



Huang, Liao, et al PLB2012

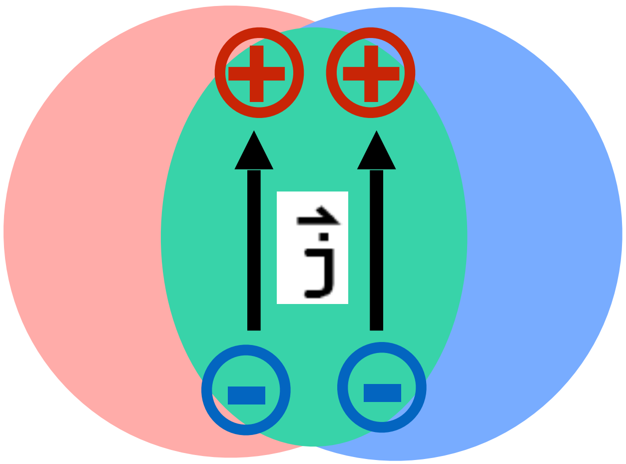


Quantitative simulations confirm the existence of such extreme fields!

[STAR measurements of di-electron — direct hint?! PRL2018]

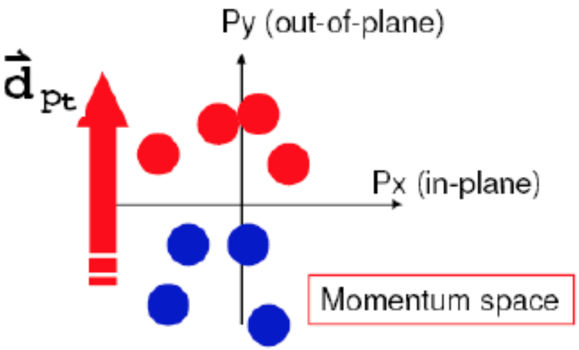
CME Signal in Heavy Ion Collisions

From CME Current to Charge Separation



$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$

strong radial blast:
position —> momentum



Charge Separation *or*
Electric Dipole in Pt Space
*(along **out-of-plane**)*

[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

$$\frac{dN_{\pm}}{d\phi} \propto ... + a_{\pm} \sin(\phi - \Psi_{RP})$$

$$< a_{\pm} >\sim \pm < \mu_5 > B$$

Very difficult measurement:
* * Zero average, only nonzero variance;*
* * Correlation measurement with significant backgrounds;*
* * Signal likely very small*

Experimental Observable

charge separation ⇒ charge dept. two-particle correlation

Voloshin, 2004

$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

$$\gamma = \kappa v_2 F - H$$

$$\delta = F + H$$

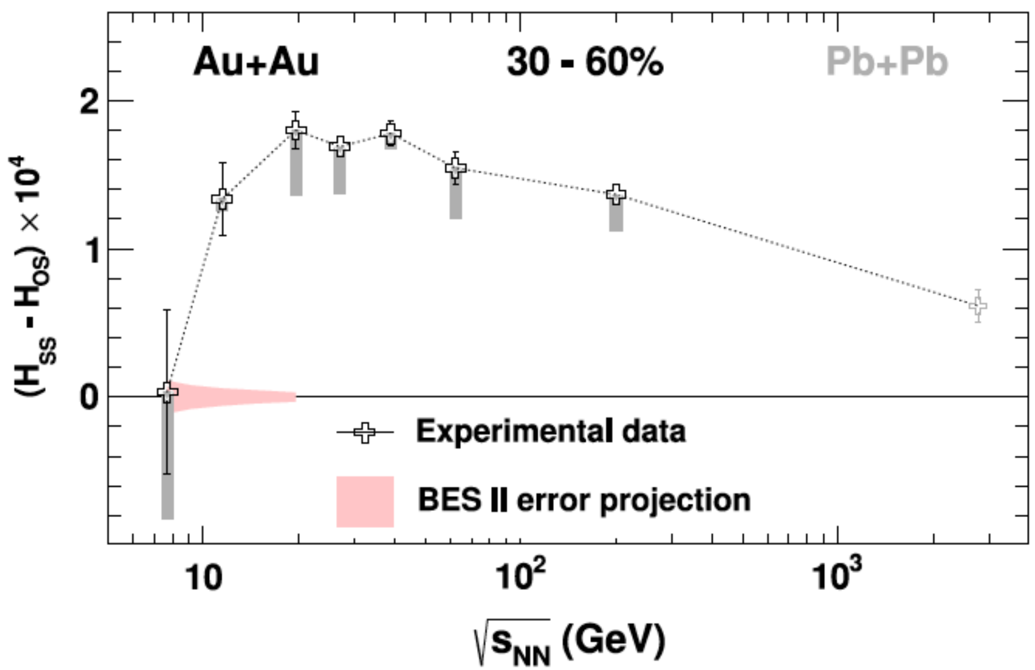
F: Bulk Background

H: Possible Pure CME Signal = $(a_{1,CME})^2$

Bzdak, Koch, JL, 2012

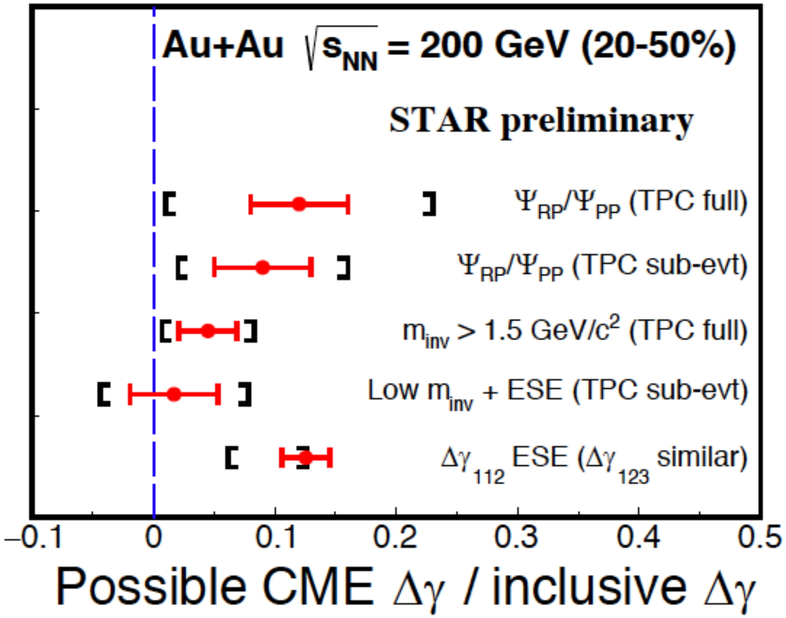
$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

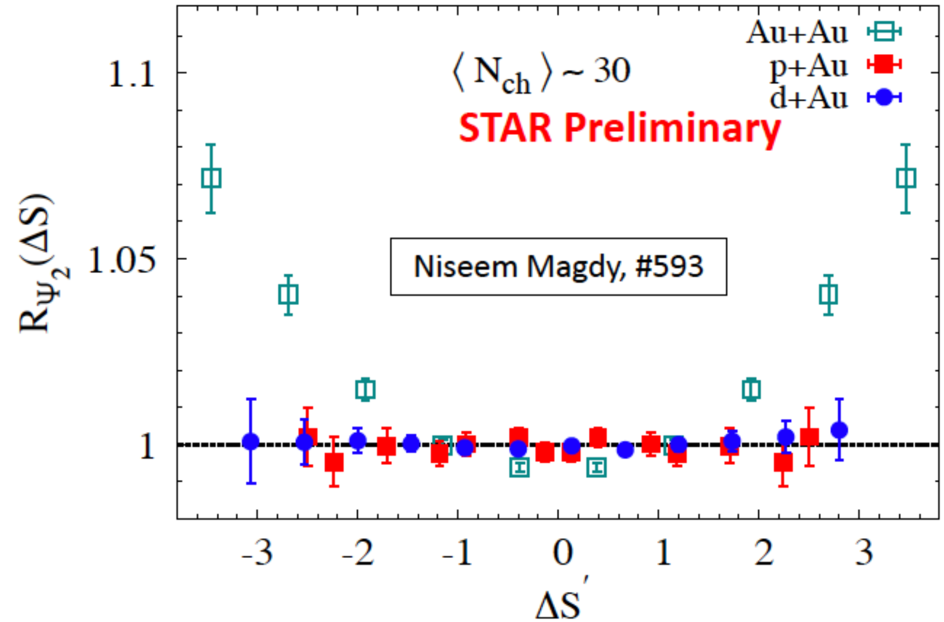
Many interesting proposals of new observables!



STAR PRL2014

Recent Exp. Search Status





[From Z. Ye, STAR Summary Talk @ QM2018]

STAR @ RHIC 200GeV: " naive" statistical interpretation: (8.5 +/- 1.2) %

ALICE @ LHC 2.76TeV: signal level possibly about 8~10% (upper limit ~30%)

CMS @ LHC 5.02TeV: signal level no more than 7%

The trend with beam energy seems in line with expectation!

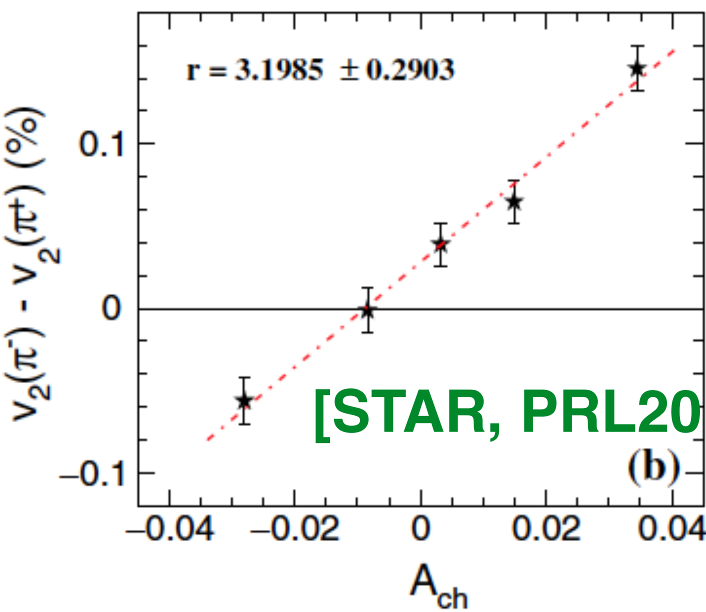
Chiral Magnetic Wave

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

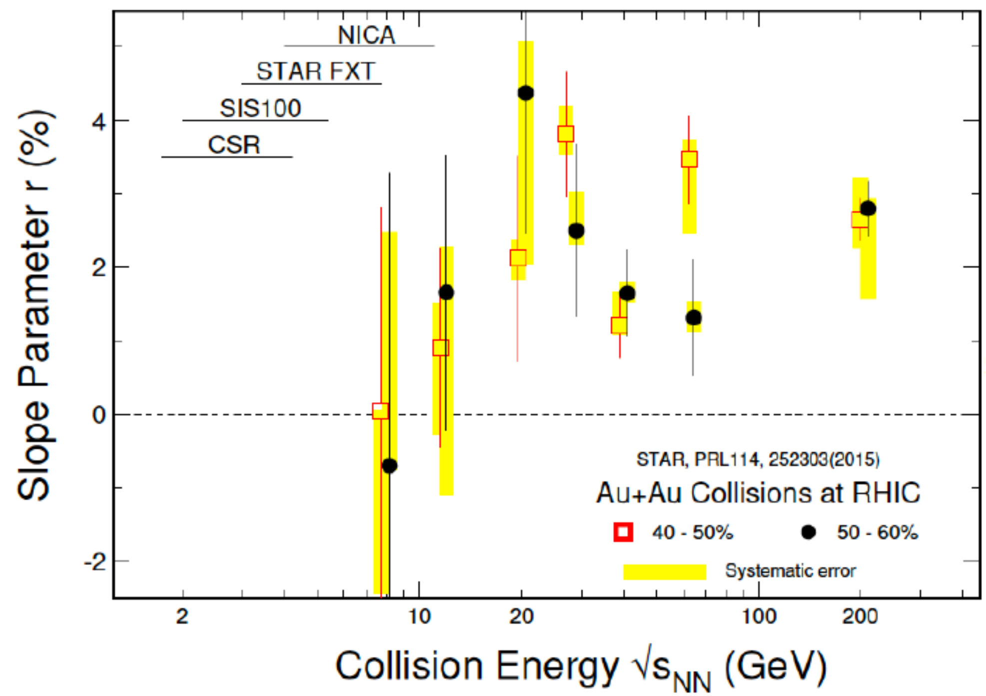
[Burnier, Kharzeev, JL, Yee, PRL2011; & arXiv: 1208.2537]

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

charge quadrupole due to CMW transport



[STAR, PRL2015]



Fluid Dynamics with Chiral Anomaly

[Not discussed here: calculations based on transport framework, e.g. works by X. Huang, G. Ma, Y. Ma, J. Xu, C.M. Ko, ……]

Fluid Dynamics That Knows Left & Right

conservation law: $\partial_\mu J^\mu = 0 \longrightarrow \partial_\mu J^\mu = C E^\mu B_\mu$

constituent relation: $J^\mu = n u^\mu + \nu^\mu$

$\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu$$

[Son, Surowka, 2009;…]

CVE CME

Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

Fluid Dynamics That "Knows" Left & Right

17～18世纪：Newton，Euler，…

19世纪：Navier，Stokes，…

20世纪上半叶：Landau，Eckart，…

20世纪下半叶：Israel，Stewart，…

21世纪初：Son，Surowka，…

非相对论理想流体

非相对论粘滞流体

相对论性粘滞流体（一阶）

相对论性粘滞流体（二阶自洽）【重离子碰撞的发展是极重要推动因素】

反常流体力学（一阶）【含反常输运】

微观对称性与守恒律 → 宏观流体力学

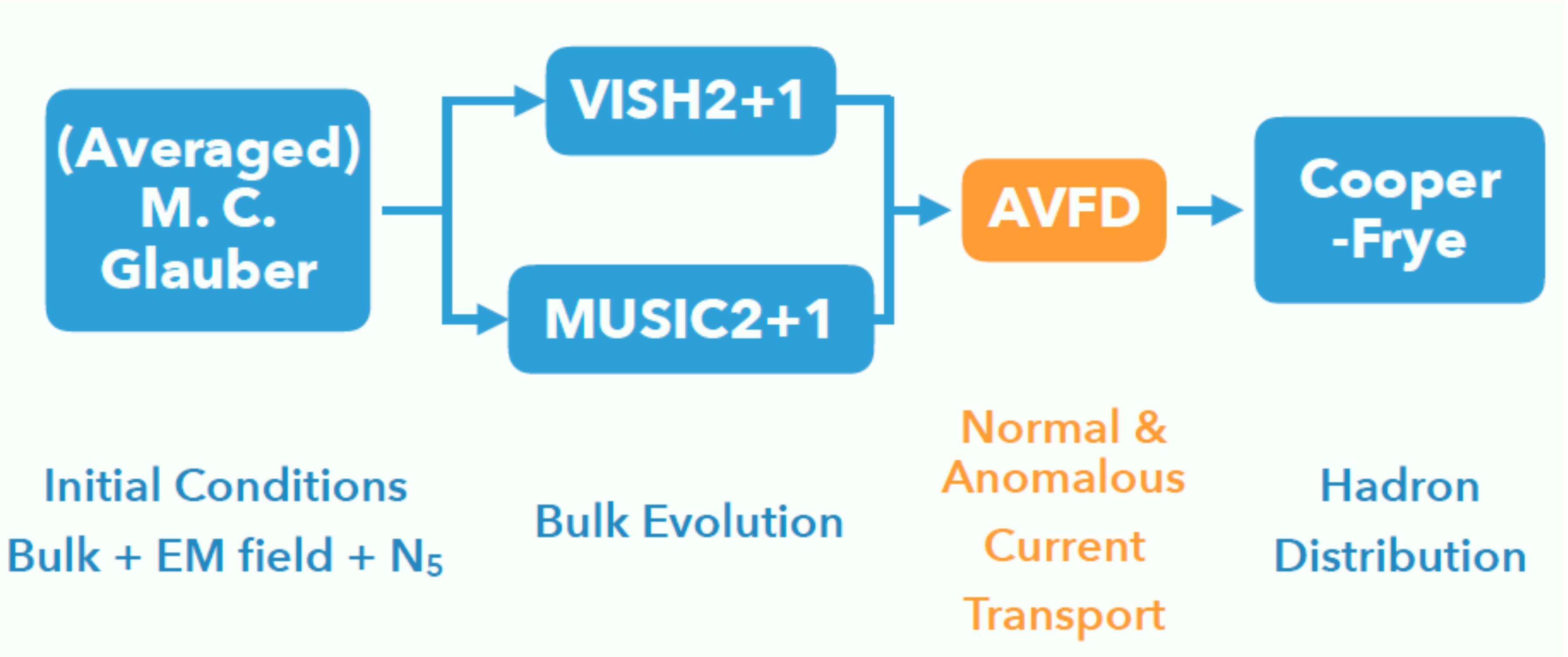
微观对称的量子反常 → 宏观反常流体力学

It would be remarkable to actually "see" this new hydrodynamics at work in real world materials!

Anomalous Viscous Fluid Dynamics (AVFD)

AVFD:
Anomalous-Viscous Fluid Dynamics

The AVFD Framework



We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

arXiv:1611.04586 ***arXiv:1711.02496***

The AVFD Framework

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

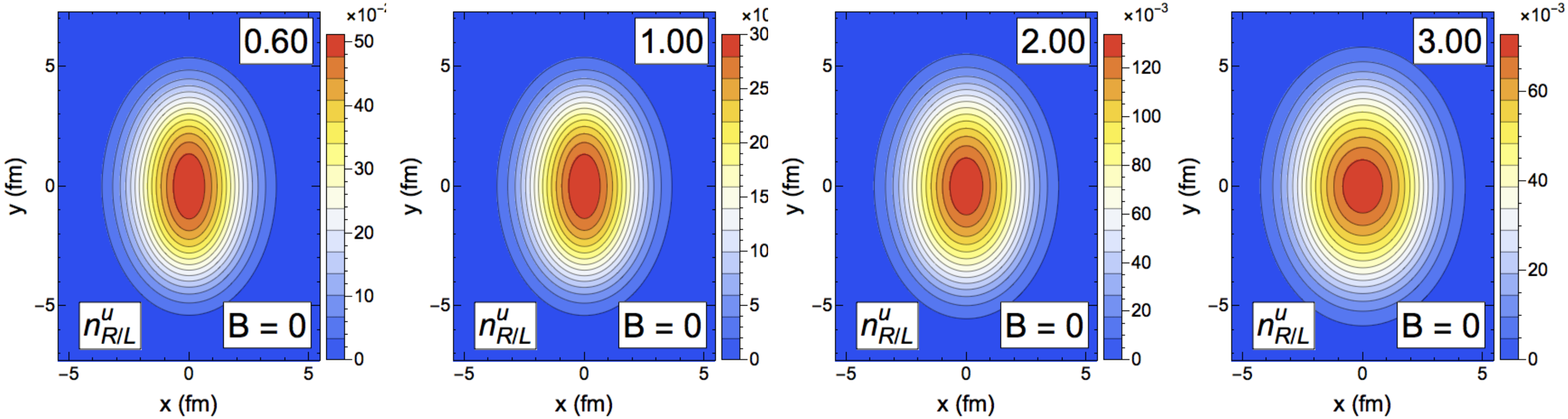
$$\Delta^\mu{}_\nu \, d\, \nu_{R,L}^\nu = - \frac{1}{\tau_{rlx}} (\nu_{R,L}^\mu - \nu_{NS}^\mu)$$

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

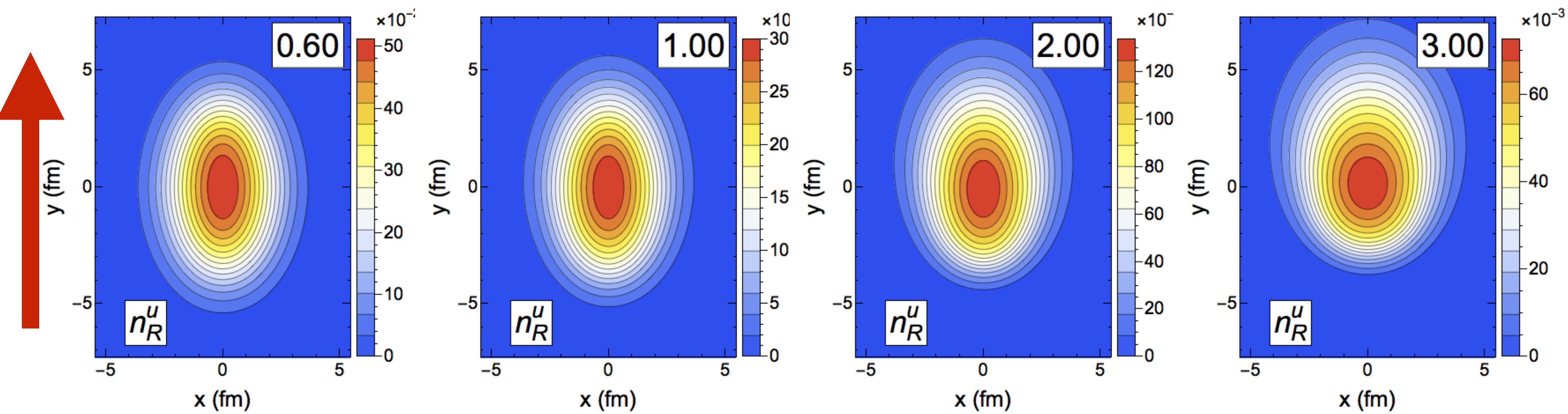
on top of VISH2+1D –– OSU Group

[We now also have MUSIC-AVFD!]

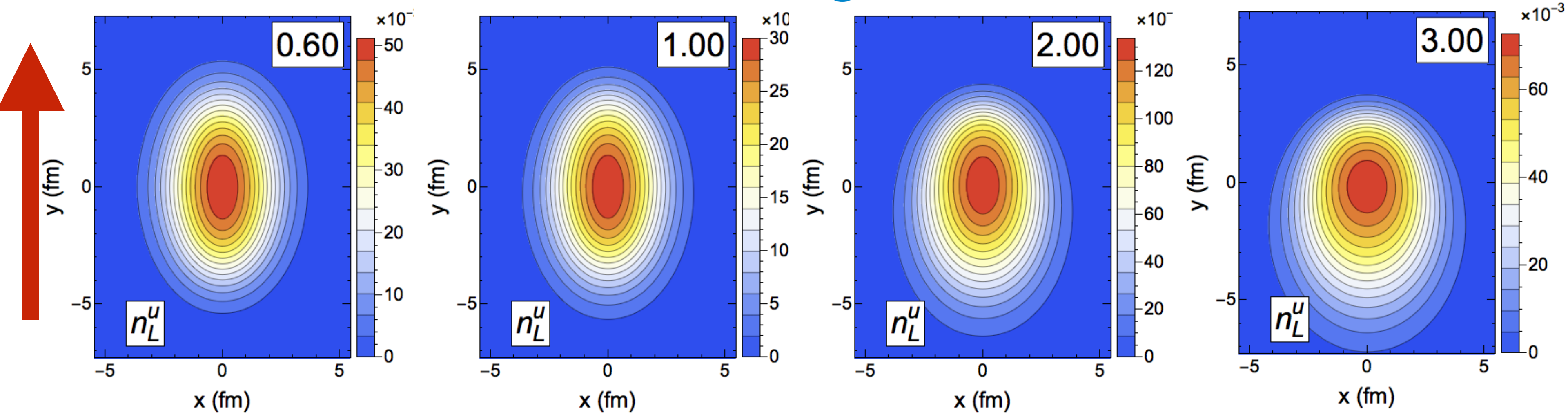
Demonstrating the AVFD



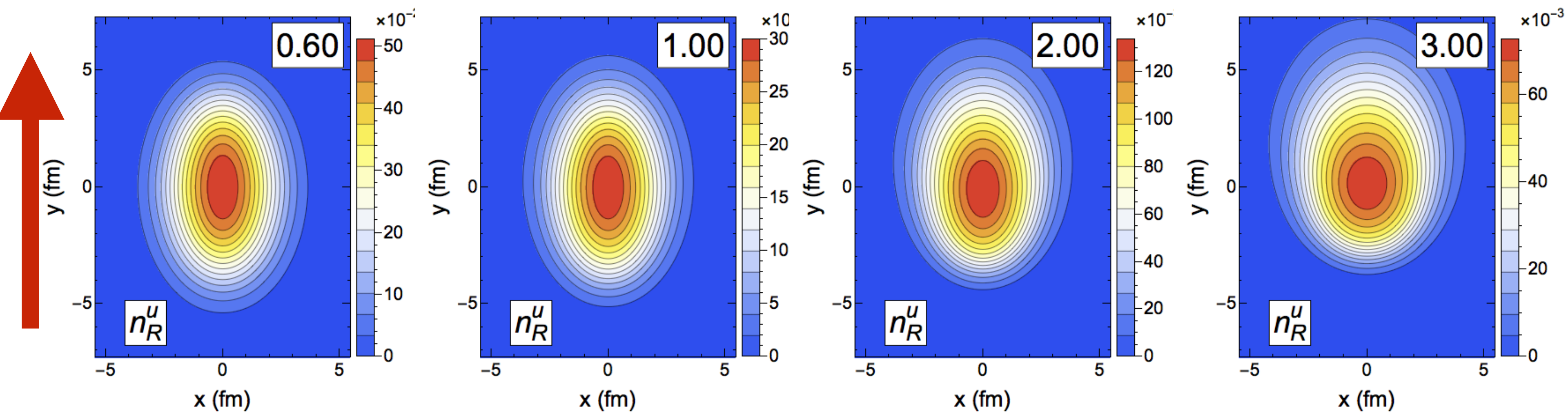
Upper: NO magnetic field
Lower: with B field (along y+ direction)



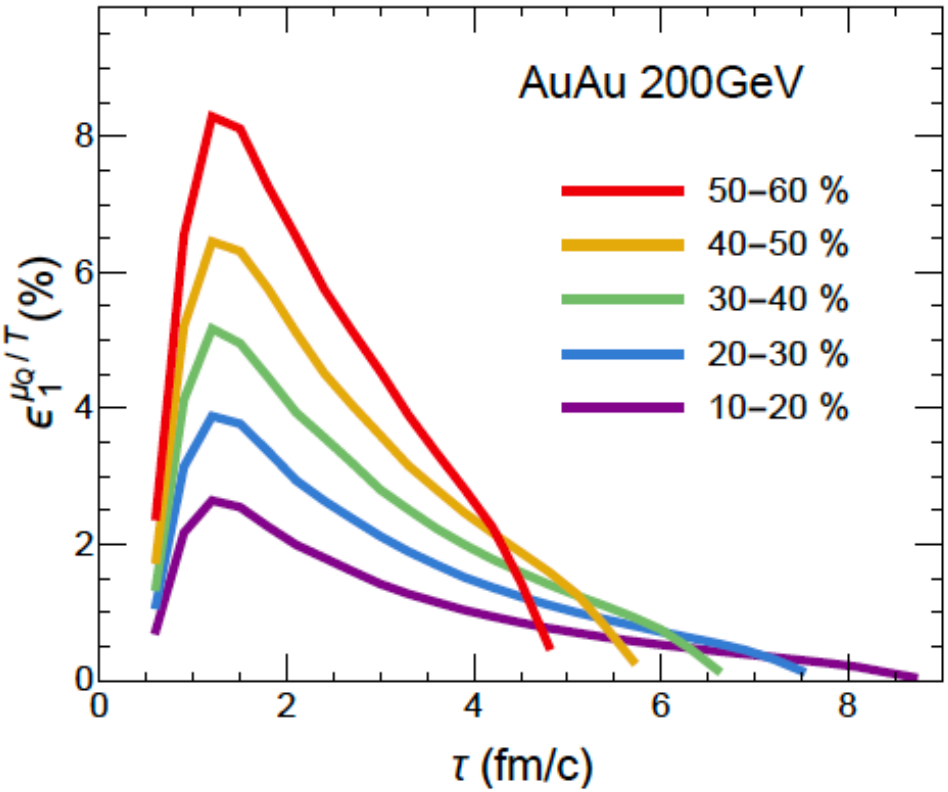
Demonstrating the AVFD



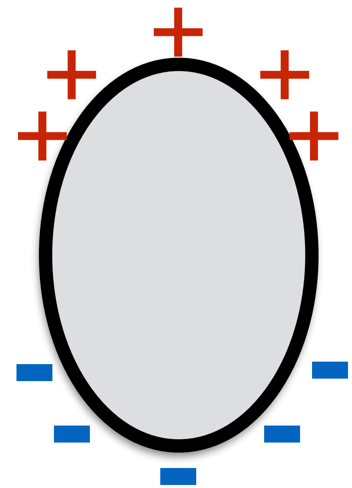
Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)



The Charge Separation from AVFD



$$E\frac{dN}{d^3p}(x^\mu, p^\mu) = \frac{g}{(2\pi)^3}\int_{\Sigma_{\rm fo}} p^\mu d^3\sigma_\mu f(x,p)$$

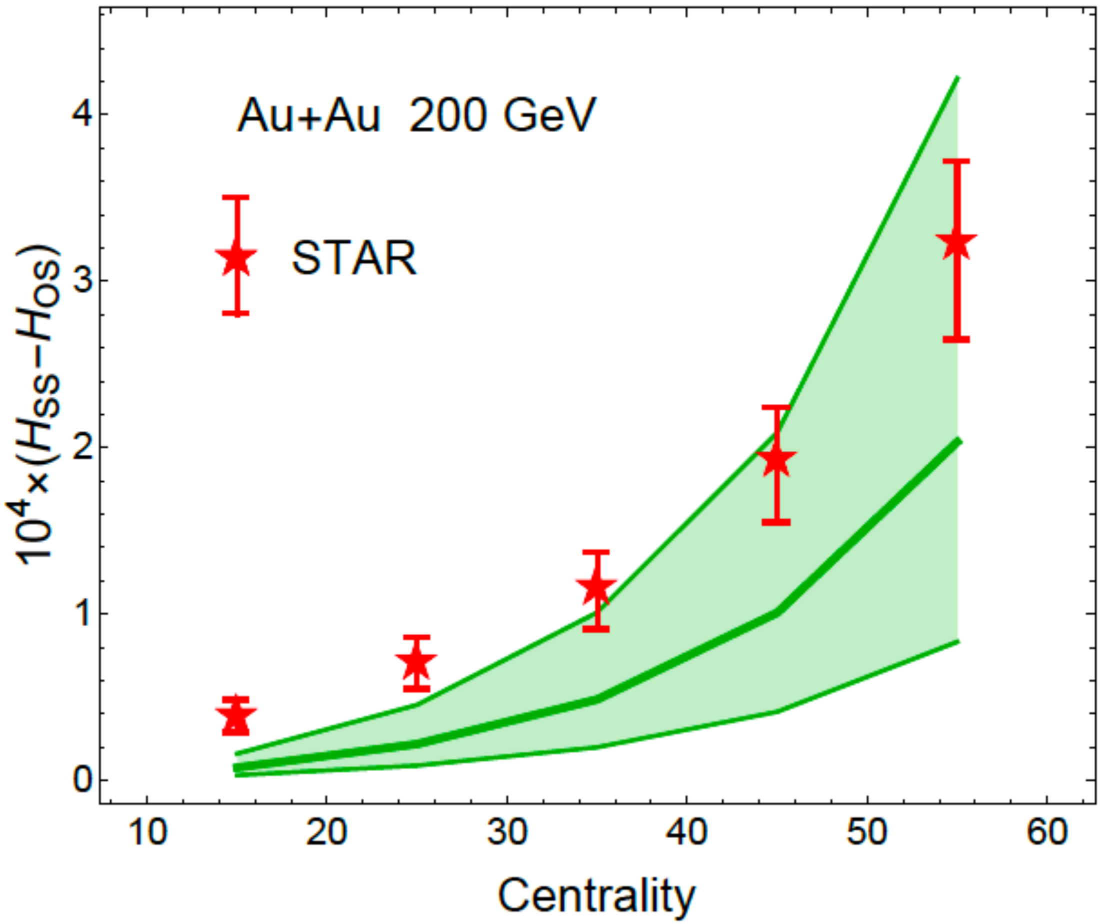


B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

$dN_\pm/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$

$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

AVFD Predictions v.s Experimental Data



$$B(\tau) = \frac{B_0}{1 + (\tau/\tau_B)^2}$$

$$\tau_B = 0.6\mathrm{fm/c}$$

$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4 \, (\pi \rho_{tube}^2 \tau_0) \sqrt{N_{coll.}}}{16\pi^2 \, A_{overlap}}$$

Good agreement !

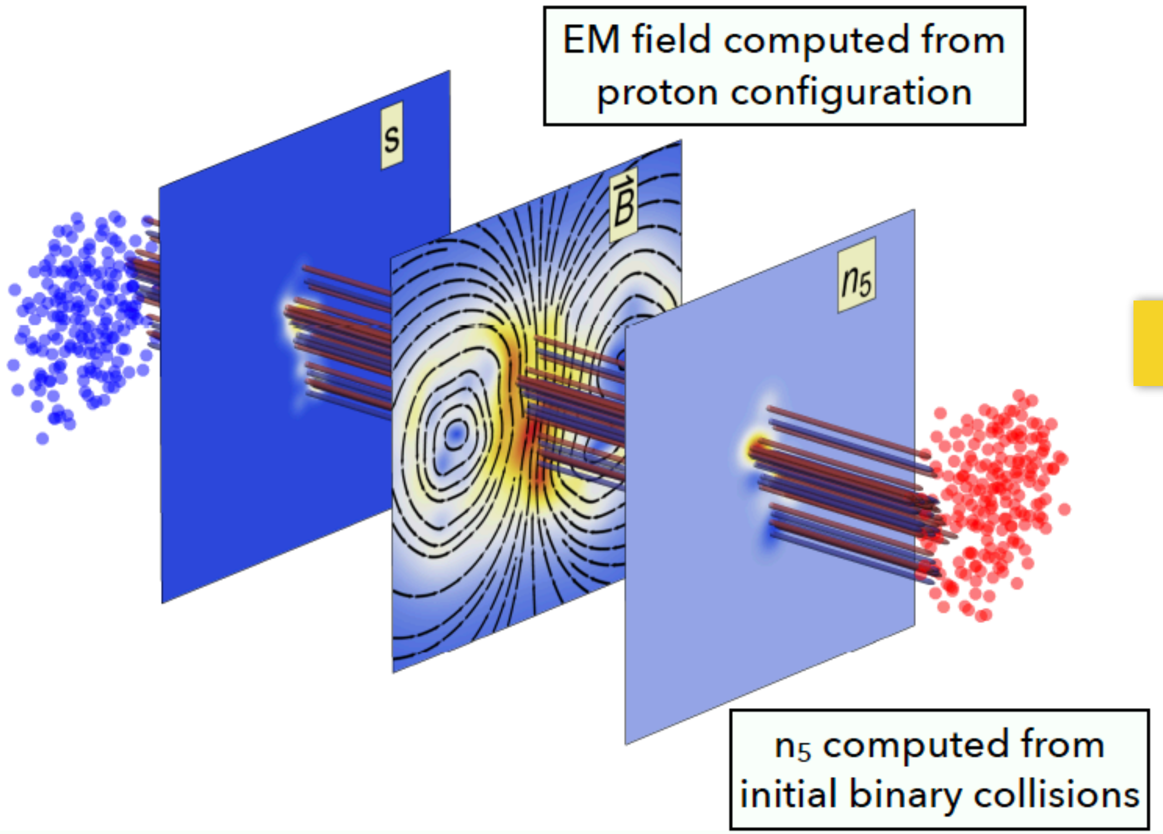
centrality bin	10-20%	20-30%	30-40%	40-50%	50-60%
$eB_0(m_\pi^2)$	2.34	3.10	3.62	4.01	4.19
n_5/s	0.065	0.078	0.095	0.119	0.155

Table 1. Centrality dependence of magnetic field peak strength and the initial chirality imbalance. The n_5/s shown here is obtained with a saturation scale $Q_s^2 = 1.25\mathrm{GeV}^2$.

EBE-AVFD Predictions for CME in Isobaric Collisions (Newest results!)

Shi, Zhang, Hou, JL, in final preparation, to appear soon;
Shi, Zhang, Hou, JL, contribution in QM18 proceedings.

Event-By-Event AVFD

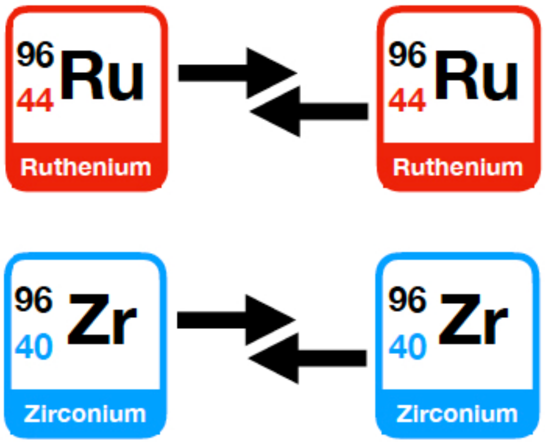


Include EBE fluctuations:

- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade

Important for better understanding:
**** Interplay between signal and BKG;***
**** Experimental analysis methods***

Using Isobaric Collisions for CME Search

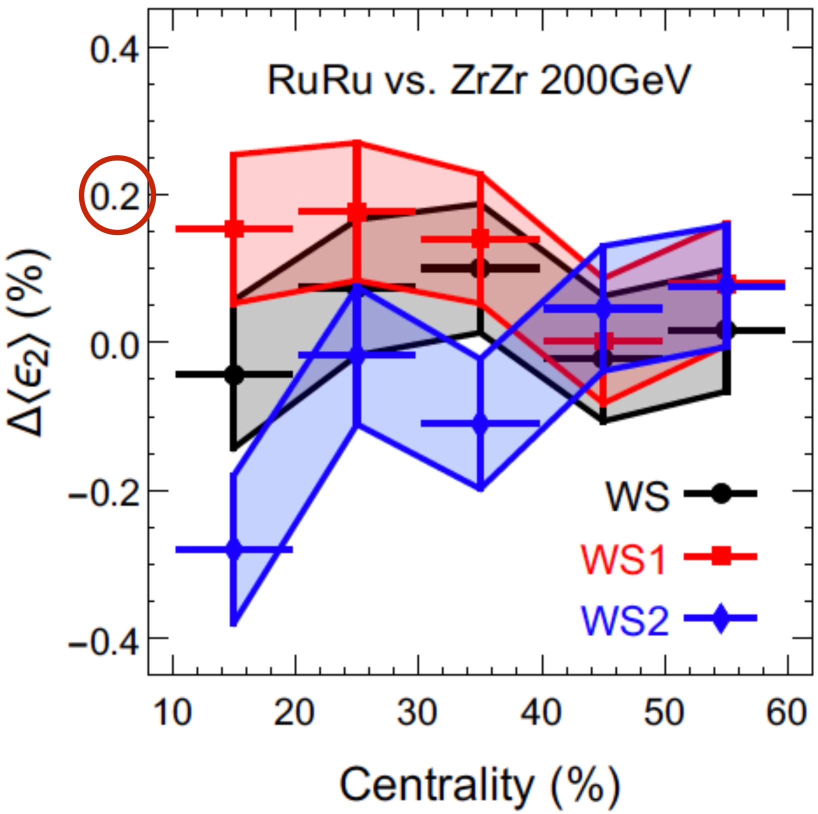


Key idea: contrasting two systems with identical bulk, varied magnetic fields.

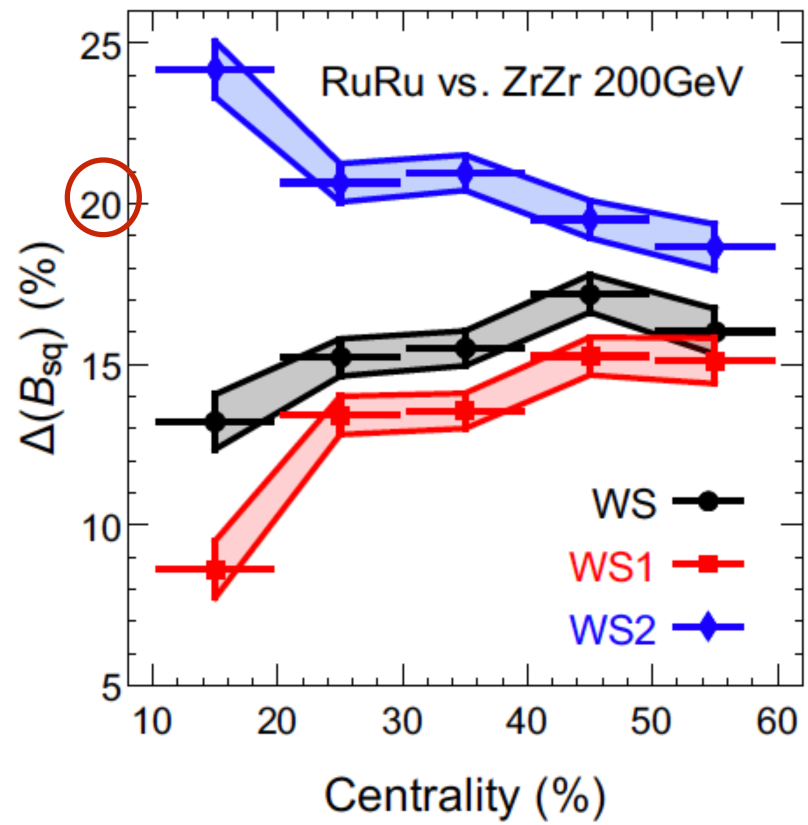
Charge Asymmetry Correlation Measurement

How to Choose Identical Systems?

Eccentricity is guaranteed the same!

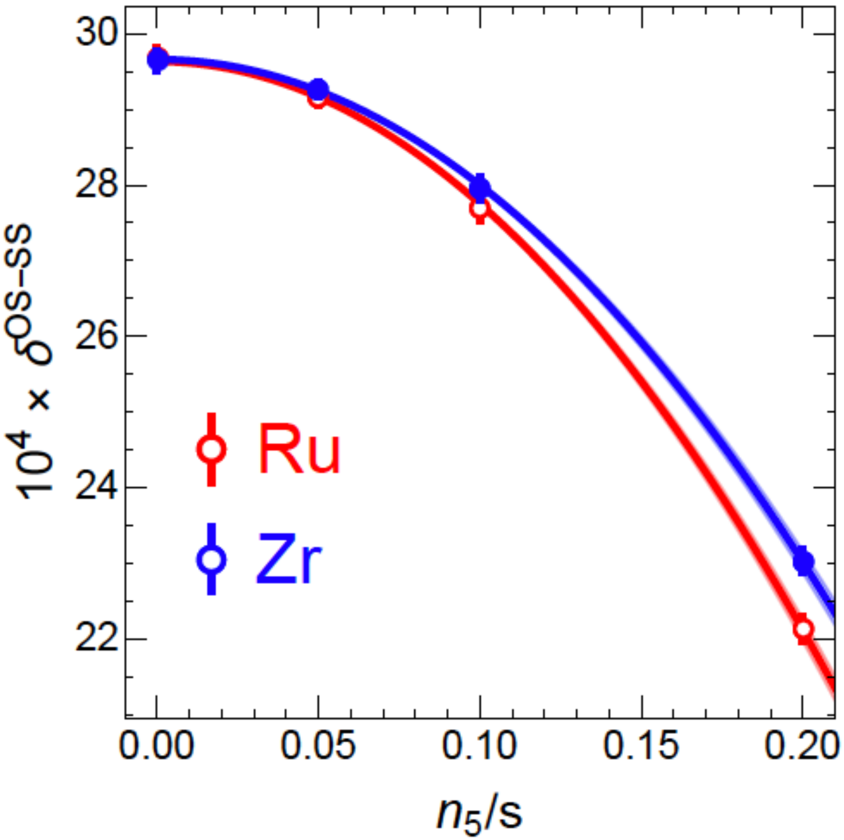


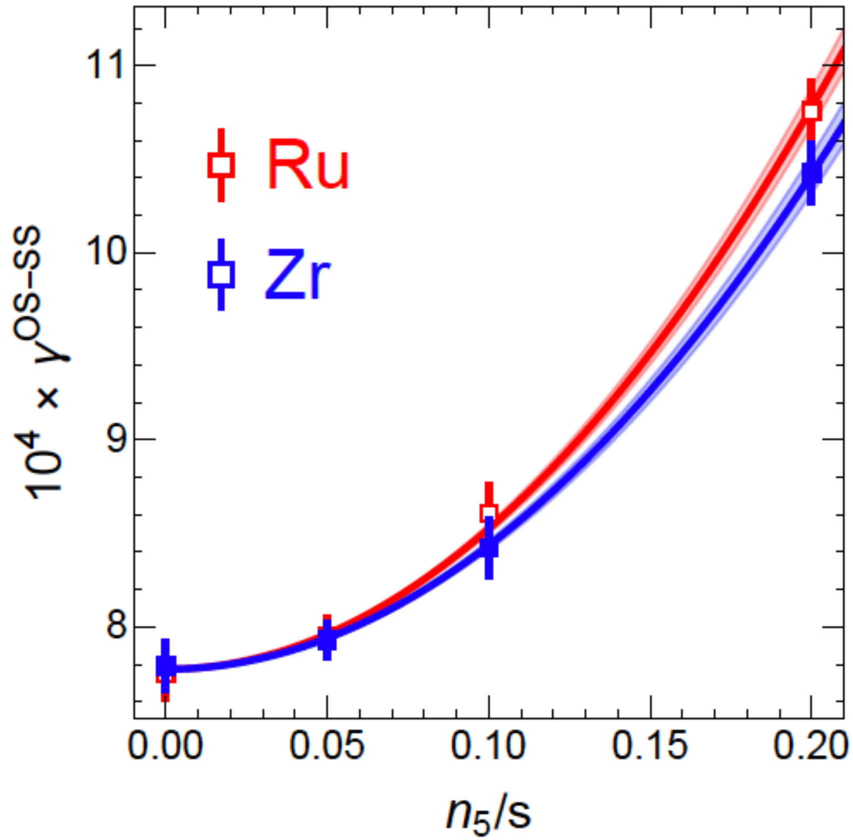
B field differs by 12~20% !



Joint multiplicity-geometry cut:
Vanishing difference in bulk properties,
Sizable difference in magnetic fields!!!

Correlation Observables of Isobars from AVFD



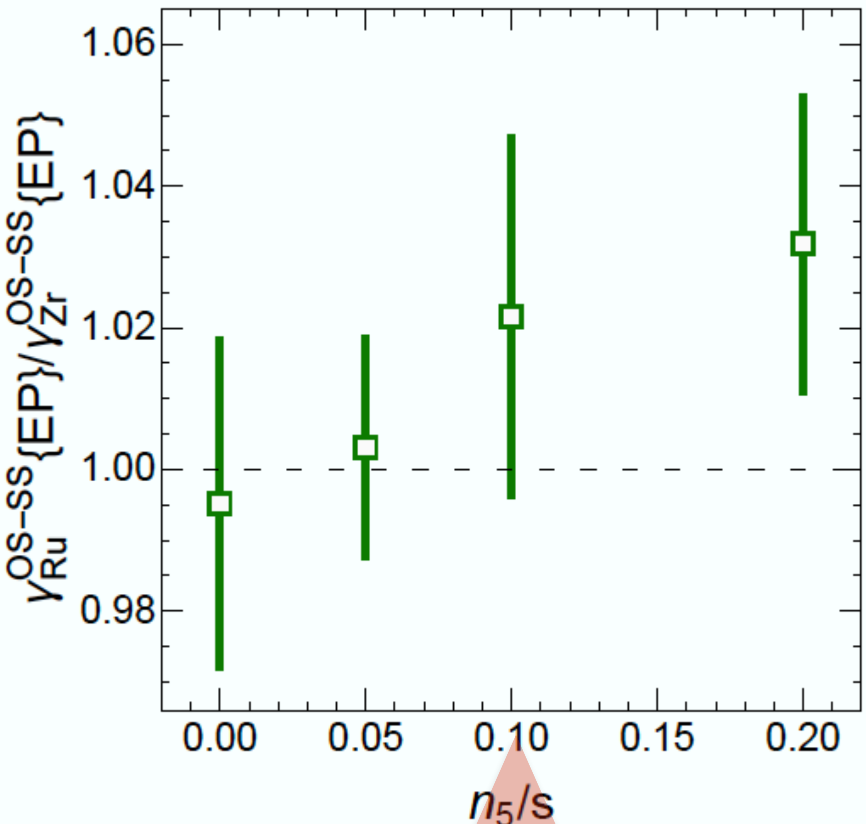


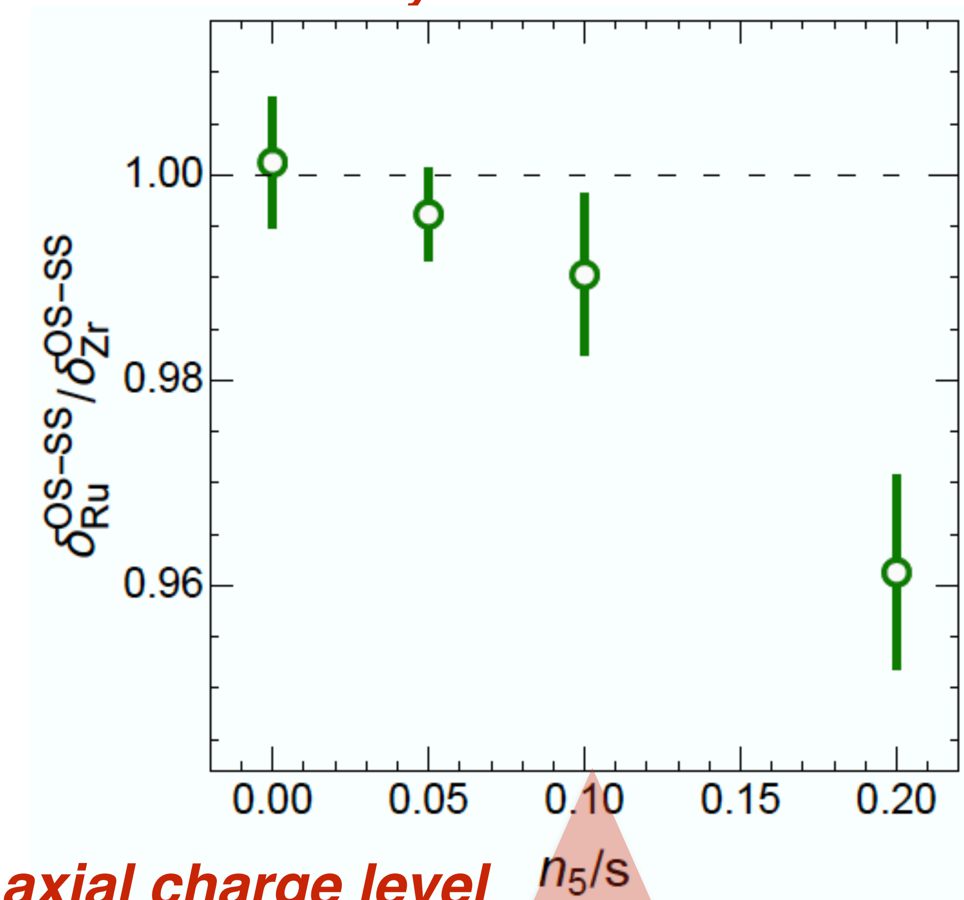
Difference in correlations is very sensitive to CME contribution!

Both gamma and delta are important to look at!

Correlation Observables of Isobars from AVFD

Exp. statistics are expected to shrink error bar by a factor of ~10

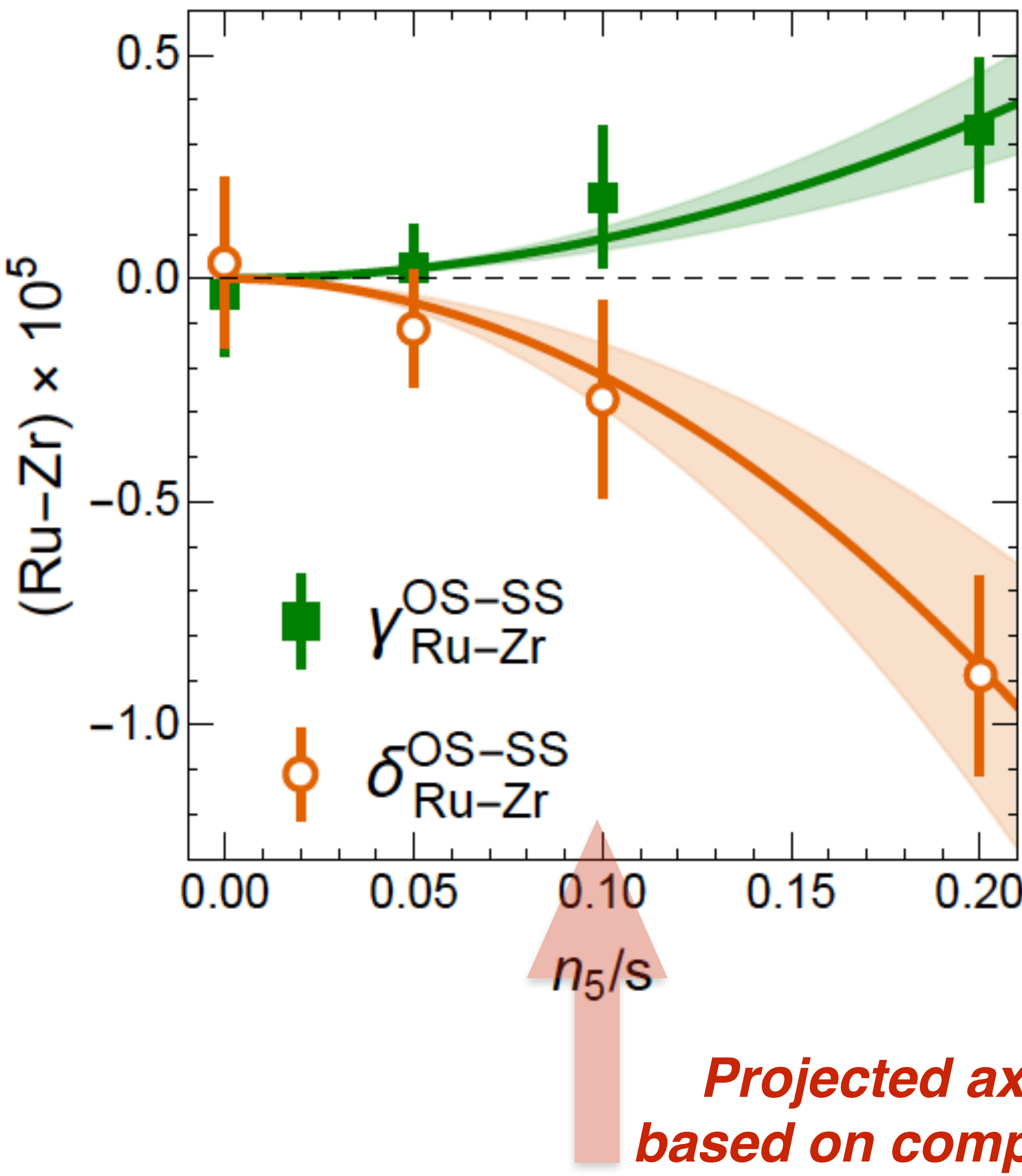




Projected axial charge level based on comparison AuAu data

Both gamma and delta are important to look at!

Absolute Difference between Isobars from AVFD



Exp. statistics are expected to shrink error bar by a factor of ~10

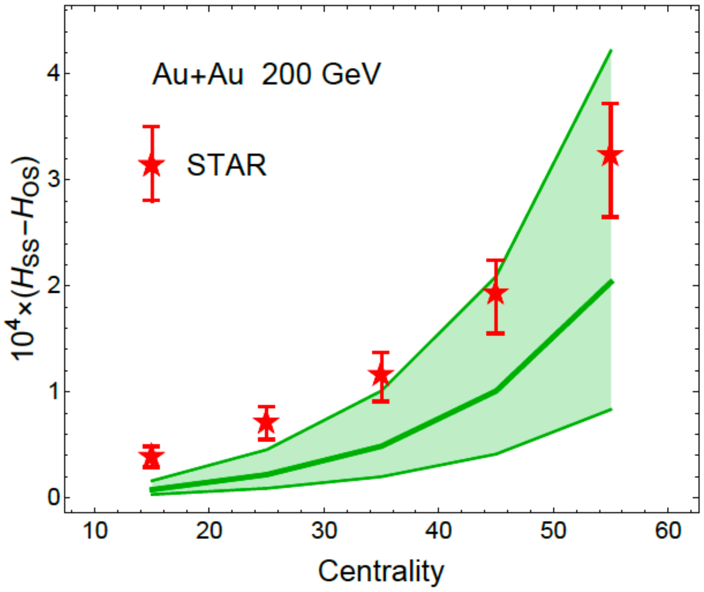
The absolute difference between isobars, after identical multiplicity + elliptic flow cuts: very sensitive and clean probe of CME signal !

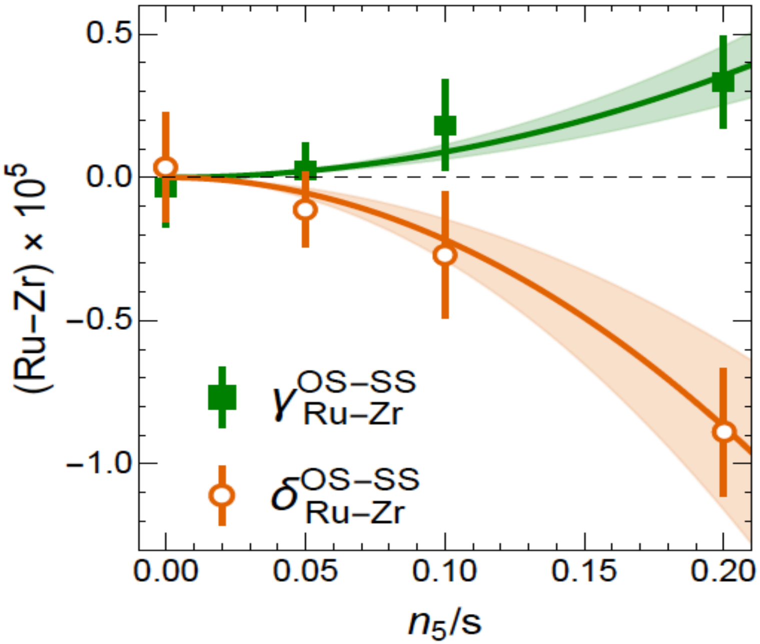
Projected axial charge level based on comparison AuAu data

Summary & Outlook

Summary

AVFD:
A versatile tool for an era of quantitative study of CME signals in heavy ion collisions !



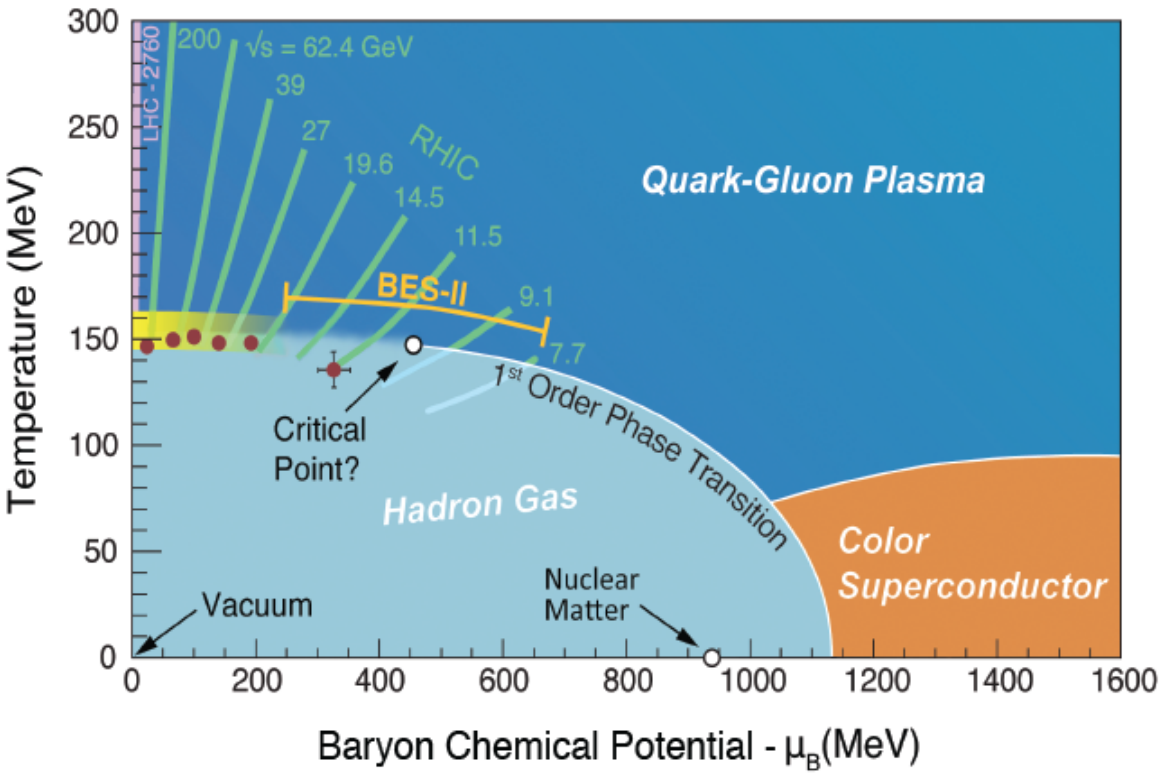


EBE-AVFD for the Isobars:

1) Event selection for truly identical bulk!
2) Both gamma & delta needed!
2) Absolute difference in correlations sensitive to CME!

Mapping Out the Phases of QCD Matter

**** Establishing a chiral QGP at higher energy via anomalous chiral effects***
**** IF hints of CME at 200GeV —> Isobar exp. at BES energies is crucial!***



BEST COLLABORATION

Stay tuned for exciting news in the near future!

Beam Energy Scan Theory (BEST) Collaboration:
BNL, IU, LBNL, McGill U, Michigan State U, MIT, NCSU, OSU, Stony Brook U, U Chicago, U Conn, U Huston, UIC