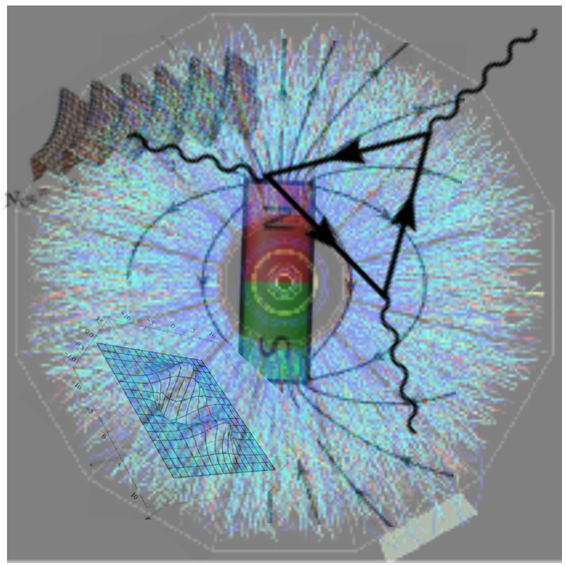
HUADA QCD School @ CCNU May.22~26 , 2017

Magnetic Field & Fluid Rotation in Heavy Ion Collisions



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Research Supported by NSF & DOE

BEST COLLABORATION

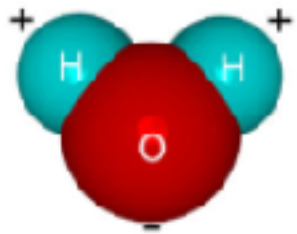
The Bigger Picture

Nuclear Matter: At the Heart of All Matter

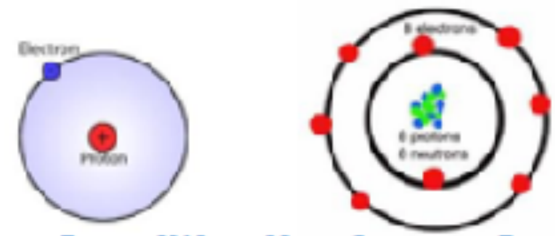
The physical world has a hierarchy of structures.

matter

molecule

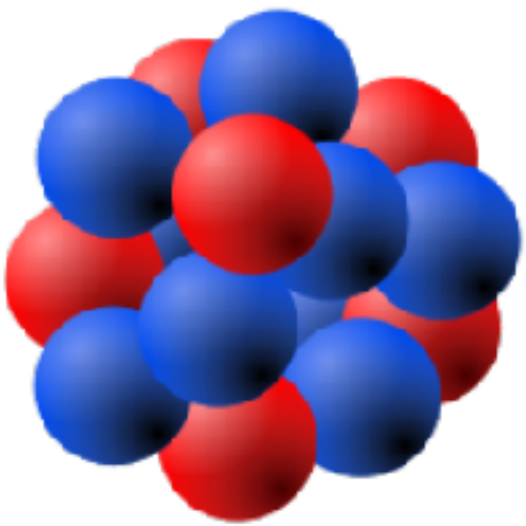


atoms



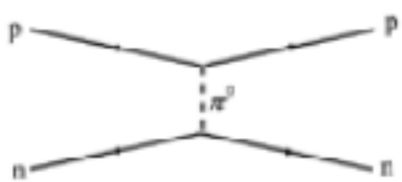
[a millionth of a mm]

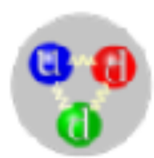
atomic nucleus



[a trillionth of a mm]

proton





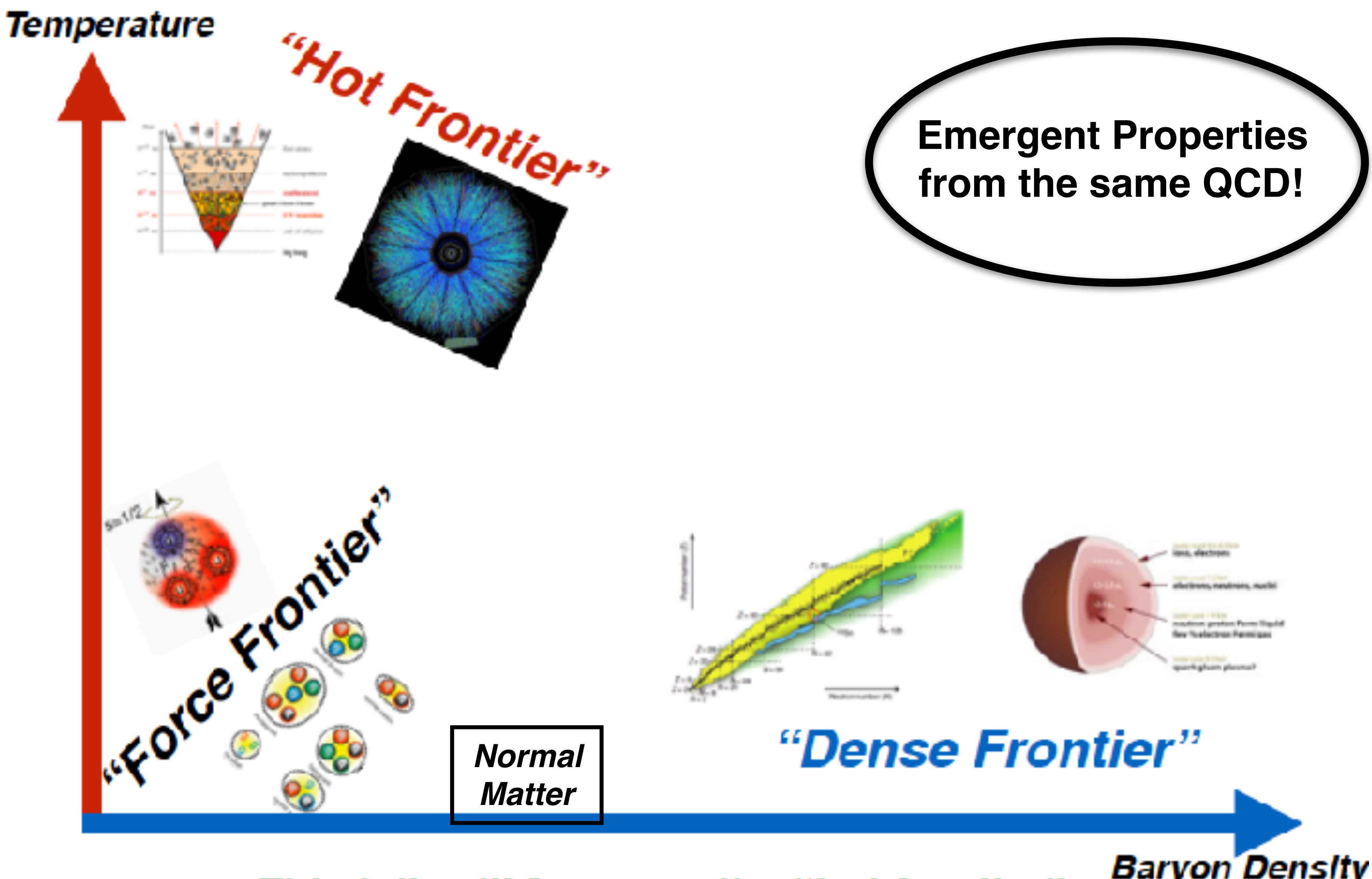
neutron

nuclear force

Most basic entities: quarks and gluons.

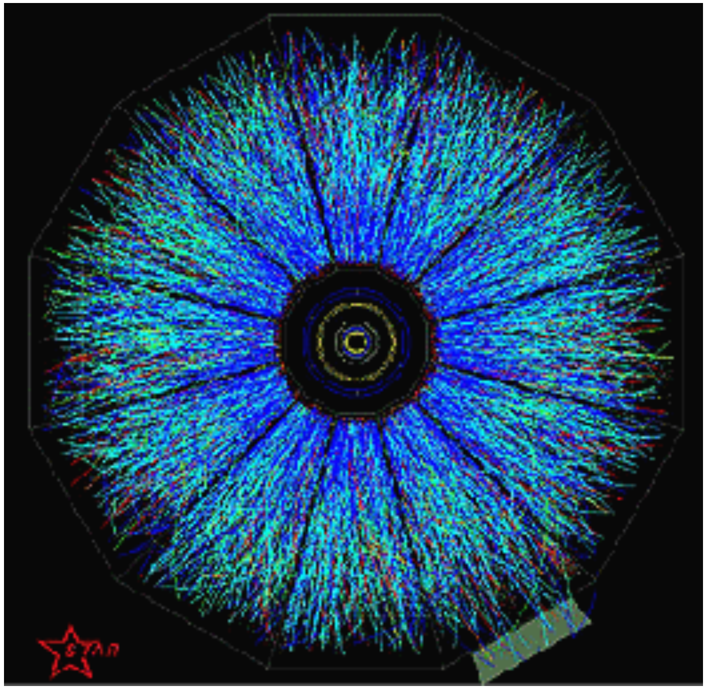
Quantum Chromodynamics (QCD)

A Map of Nuclear Matter



This talk will focus on the "hot frontier".

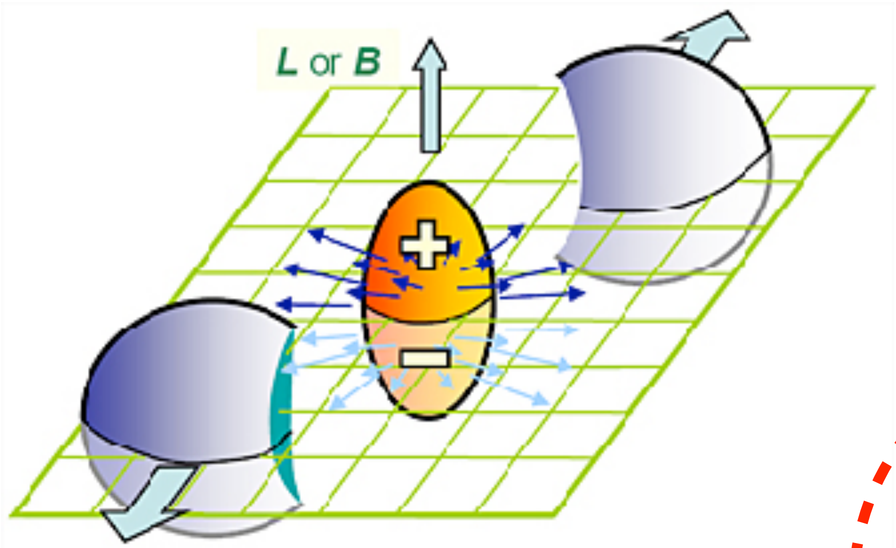
"Little Bang" in High Energy Nuclear Collision

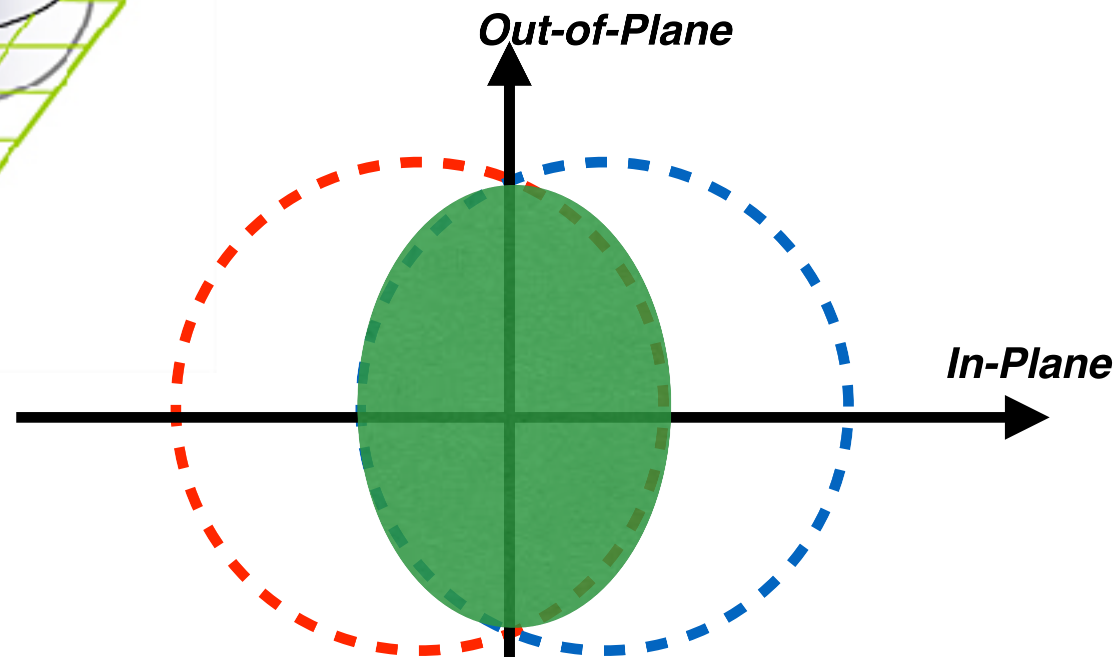


**** Quark-gluon plasma (QGP) is created in such collisions.***

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

New Phase & New Extreme Conditions

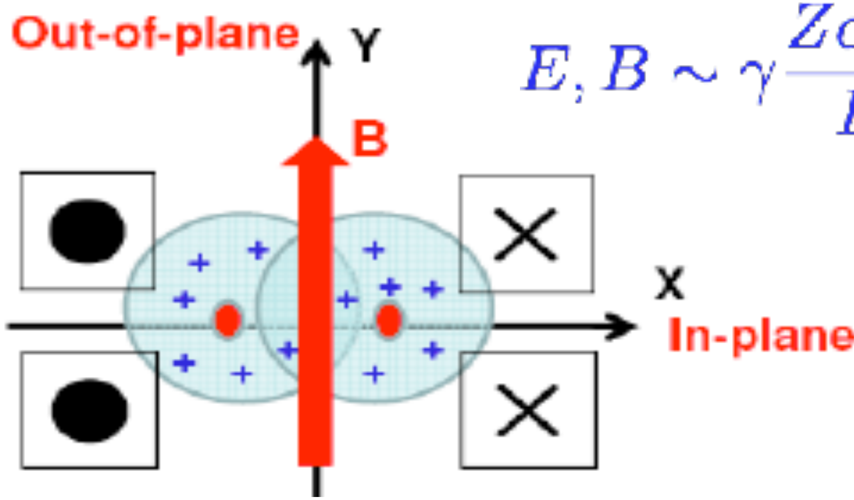




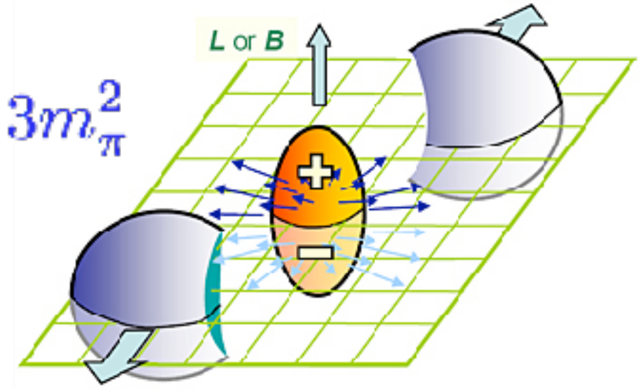
The quark-gluon plasma is a type of CHIRAL MATTER, with (approximately) chiral quarks.

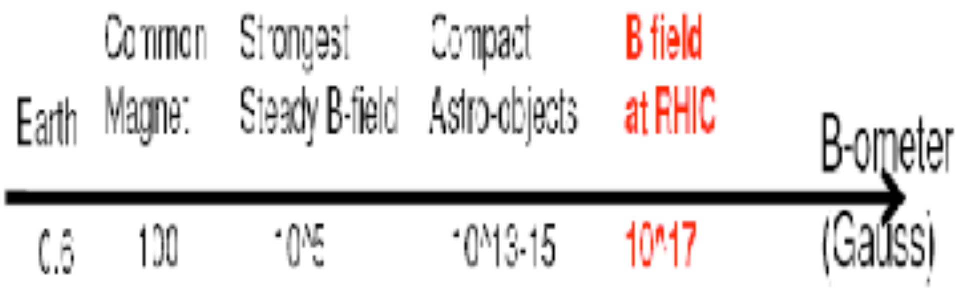
Heavy ion collision environment: extremely strong magnetic field and fluid rotation!

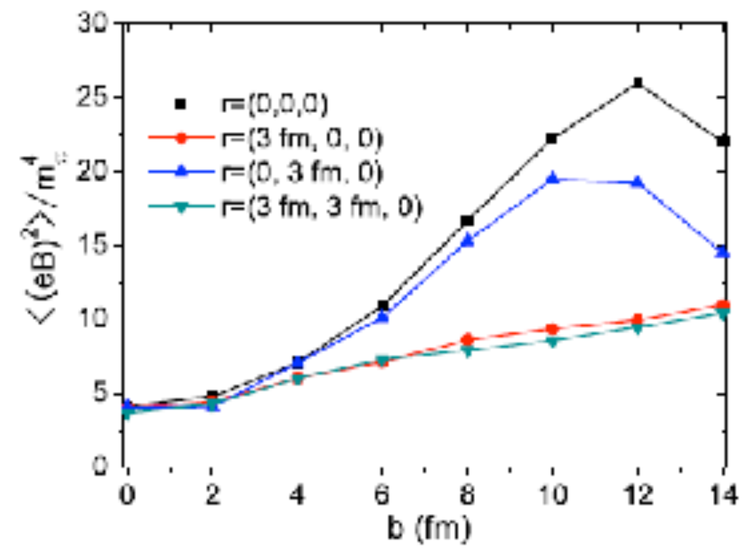
The Strongest EM Fields in Heavy Ion Collisions



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





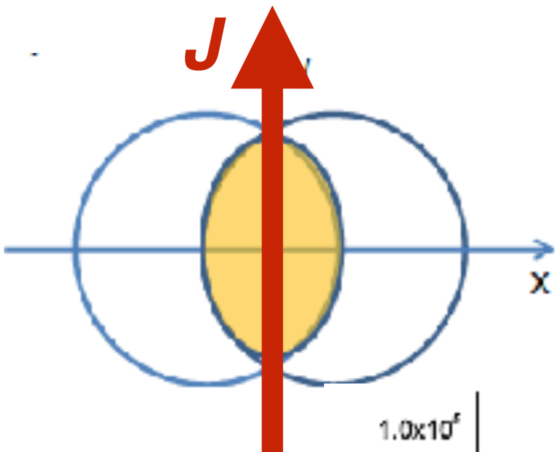


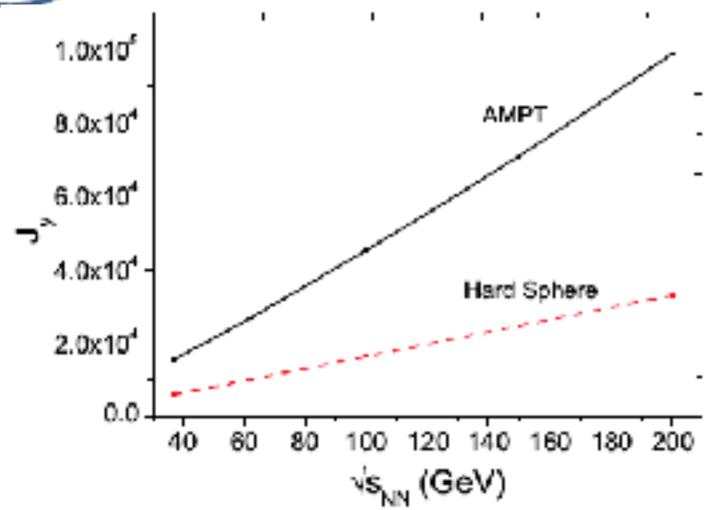
- **Strongest** B field (and strong E field as well) naturally arises!

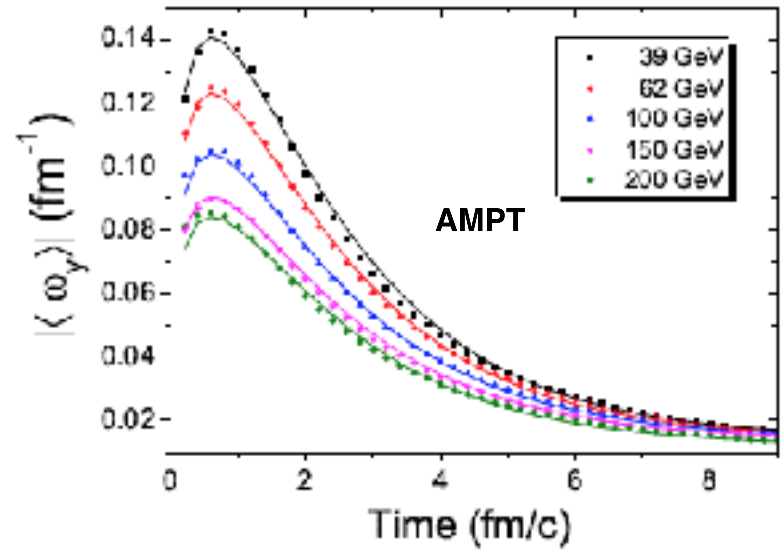
[Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; Tuchin; ...]

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

The Most Vortical Fluid in Heavy Ion Collisions







Yin Jiang, Zi-Wei Lin, JL, arXiv:1602.06580[hep-ph]

The fluid created in heavy ion collisions carries extremely large angular momentum and local vorticity.

Properties of Matter under New Conditions

Very strong magnetic field —> Magnetic Polarization!

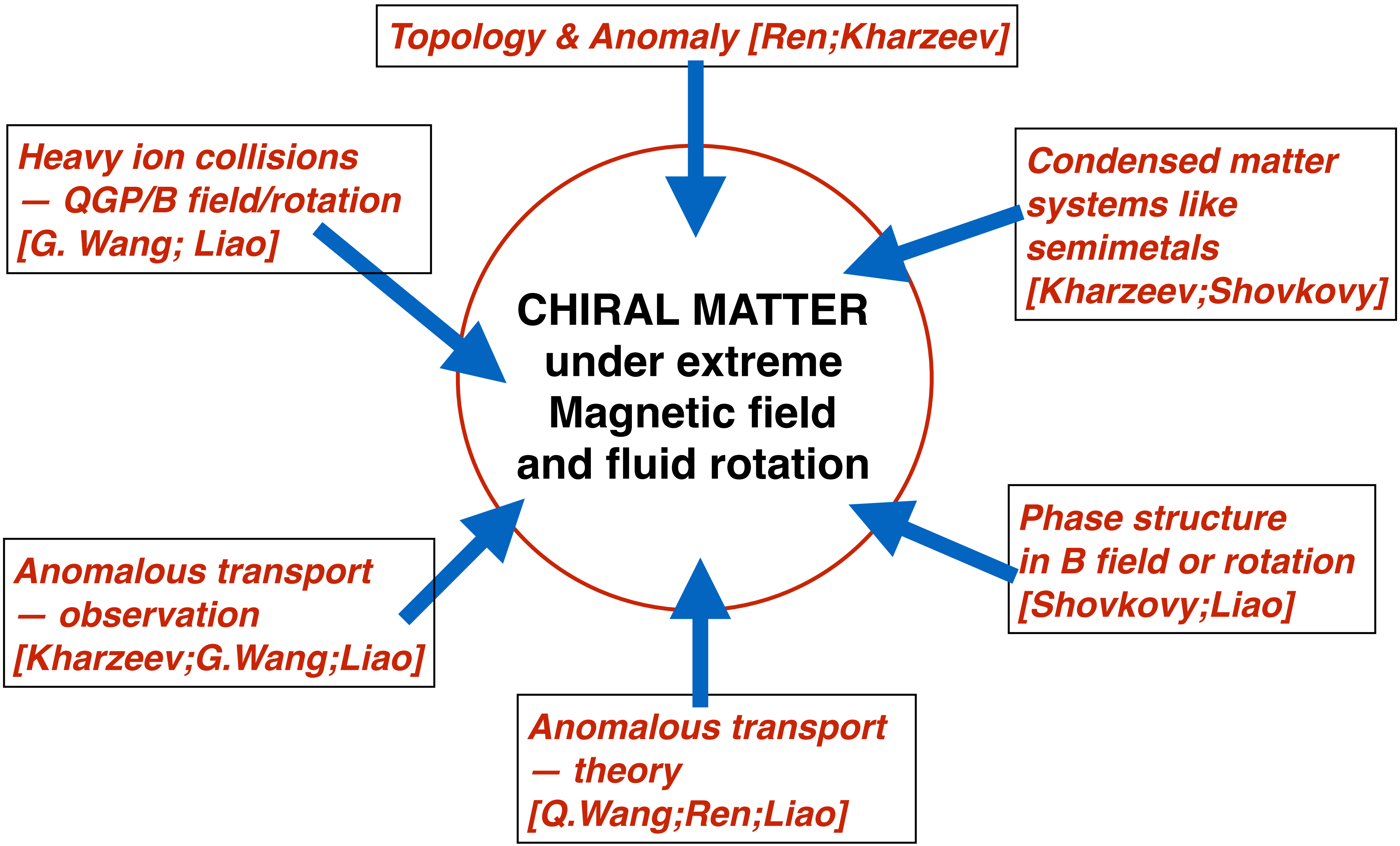
Very strong global rotation —> Rotational Polarization!

Nontrivial interplay between external conditions & internal degrees of freedom (spin/momentum/angular momentum)

Thermodynamic properties of matter:
- ***Equation of State***
- ***Phase Structure***
- ***Macroscopic Polarization***
- ***……***

Transport properties of matter:
- ***Transport coefficients***
- ***Anomalous transport effects***
- ***……***

An Overall Look at the Present Summer School



Quantifying External Conditions in H.I.C.

In the first three lectures,

I will give you

a hands-on tutorial

on how to compute

such new external conditions as

magnetic field and fluid rotation

in heavy ion collisions.

Computing Magnetic Fields in Heavy Ion Collisions

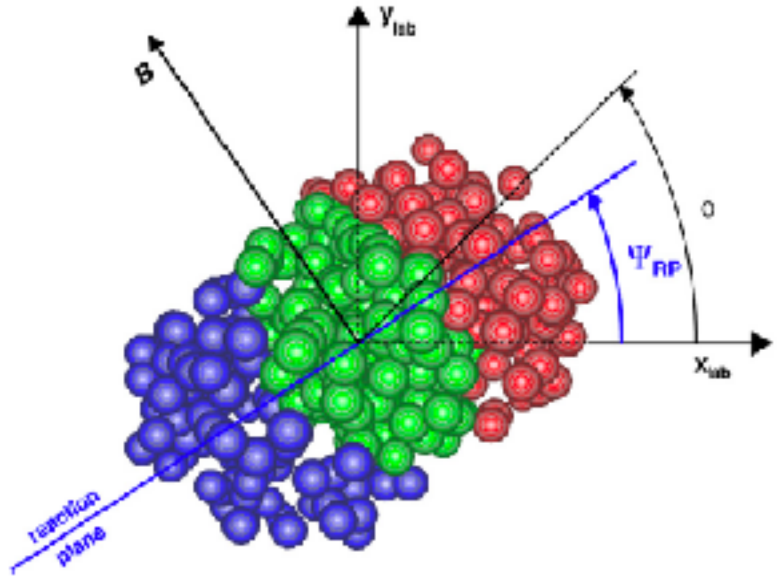
A (very incomplete!) list of recent references on computation of magnetic fields

* Deng, Huang, arXiv:1201.5108 ; * Bzak, Skokov, arXiv:1111.1949
* Blocynski, Huang, Zhang, Liao, 1209.6594
* McLerran, Skokov, arXiv:1305.0774; * Tuichin, arXiv:1305.5806
* Li, Sheng, Q. Wang, 1602.02223
* Inghirami, Zanna, Beraudo, Moghaddam, Becattinni, Bleicher, arXiv:1609.03042
* ……

Magnetic Field in Heavy Ion Collisions

Blackboard

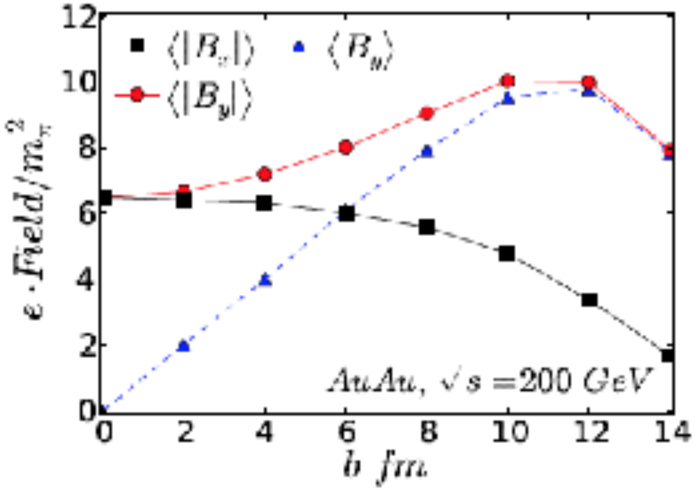
More Realistic Computations

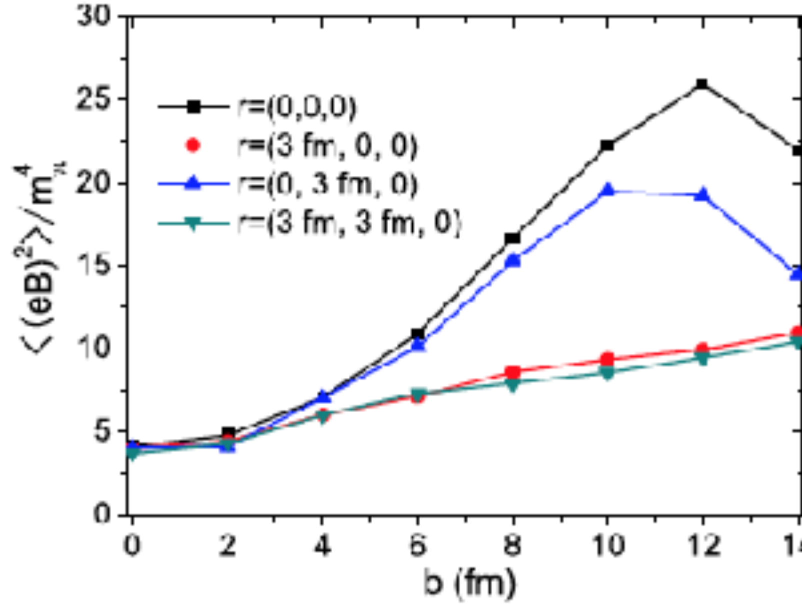


- *Glauber model (with discrete nucleons)*
- *Event-by-event with Monte-Carlo*
- *Finite size of proton*
- *Azimuthal angule fluctuations*
- *Time evolution further in medium??????*

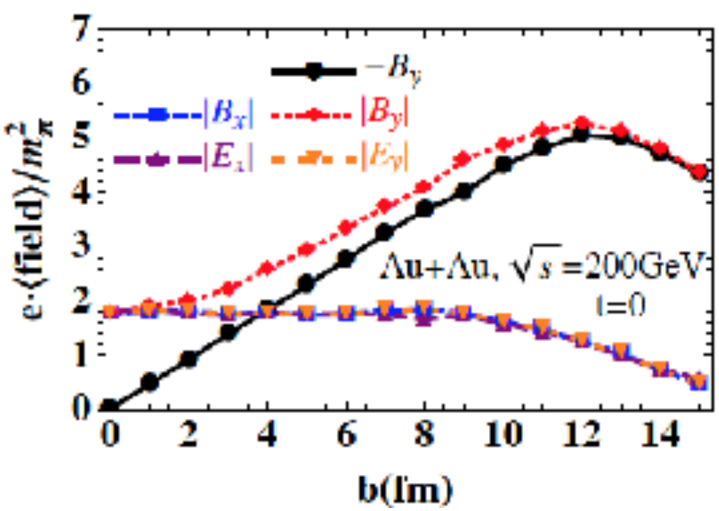
Event-By-Event Magnetic Fields

Bzdak & Skokov, arXiv:1111.1949

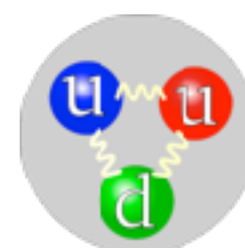




PLB 718 (2013) 1529 [arXiv:1209.6594]

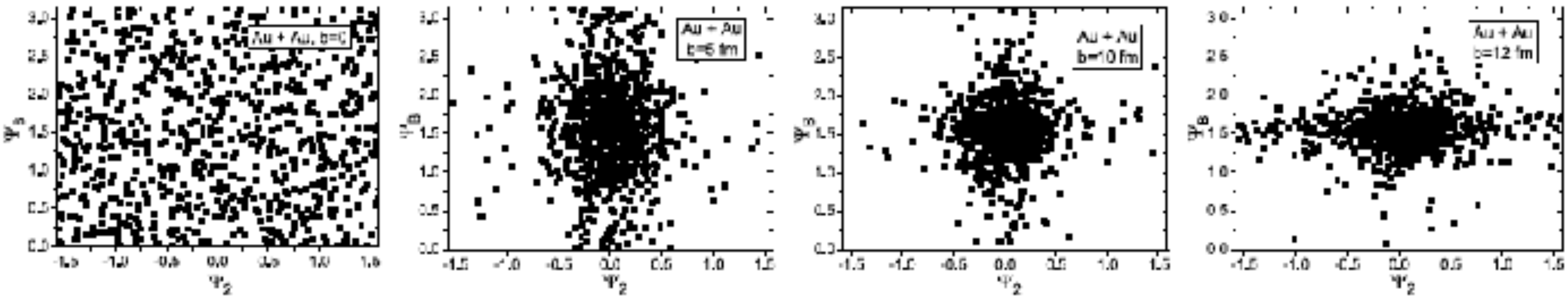


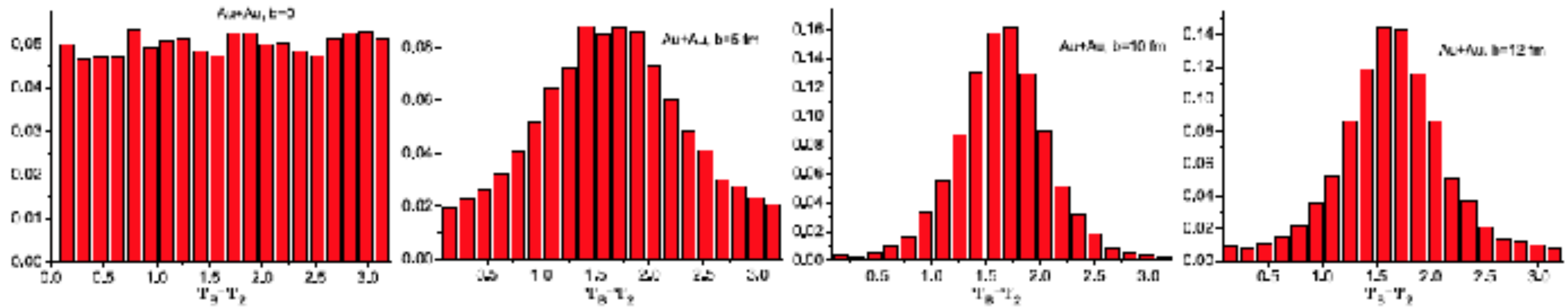
Deng & Huang, arXiv:1201.5108

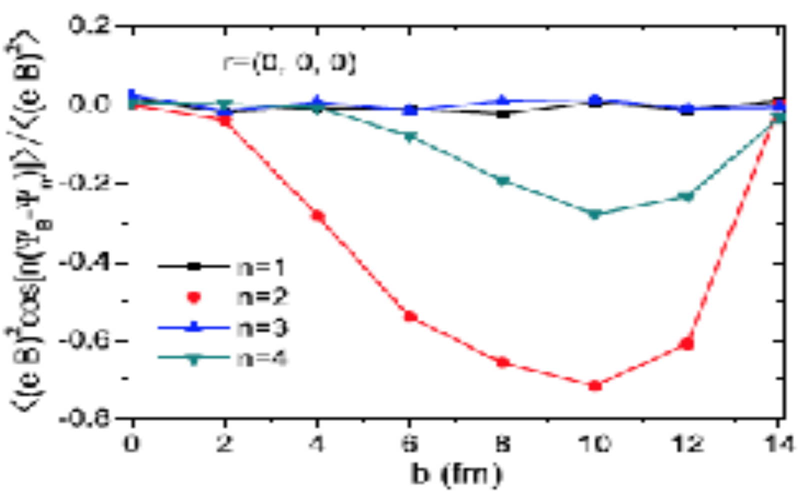


Proton is a finite size object!

Event-By-Event Magnetic Fields





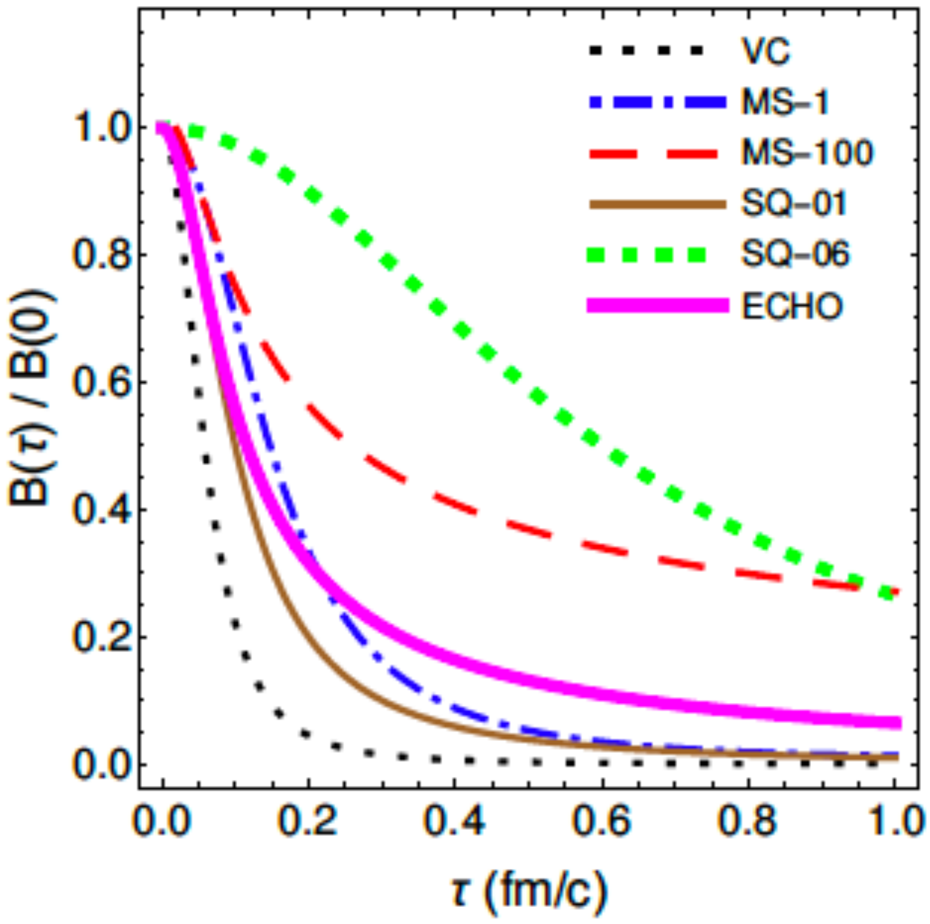


Measurable effects (CME, CMW, photon v2,…) are controlled by:

$$\langle (e\mathbf{B})^2 \cos(2\bar{\Psi}_\mathbf{B}) \rangle$$

PLB 718 (2013) 1529 [arXiv:1209.6594]

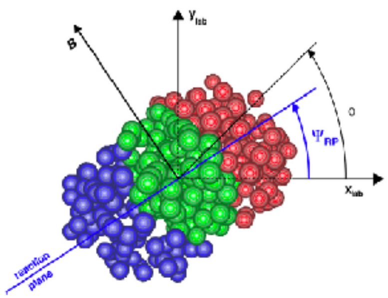
Time Evolution of Magnetic Field



The single biggest uncertainty in current understanding of magnetic fields in heavy ion collisions!

Small v.s. Large and Low v.s. High Energy

Why we do NOT expect CME in pA collisions?

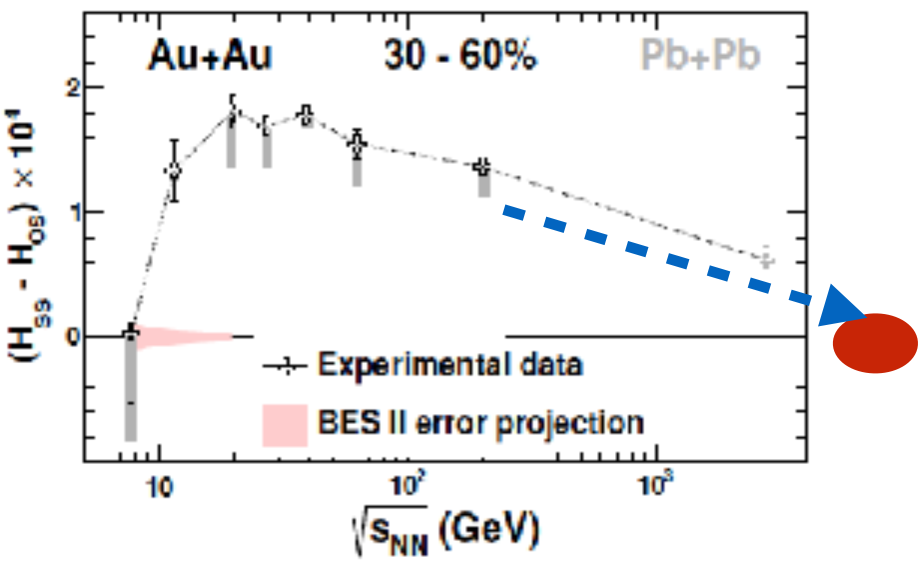


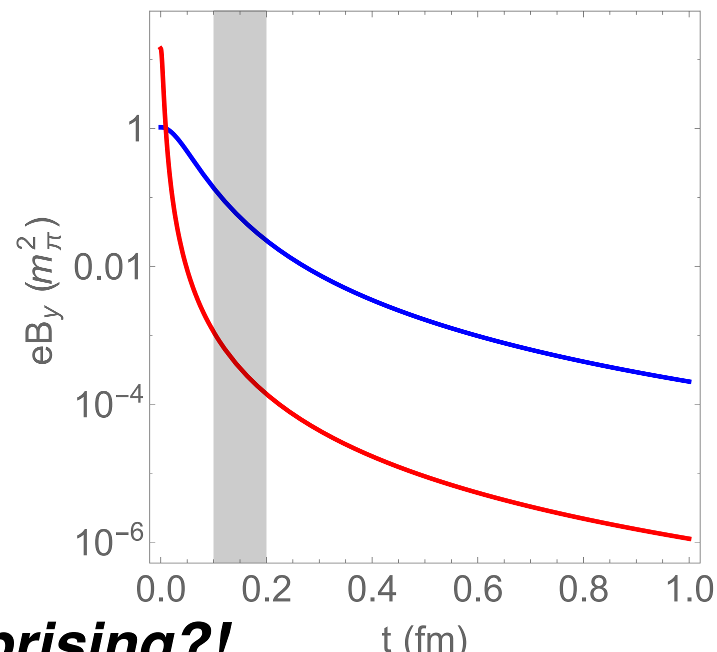
Angle de-correlation between B and event plane!!

$$\cos[2(\Psi_B - \Psi_2)]$$

CMS reported nice measurements at 5TeV.

Why CME may be expected to disappear at 5TeV?





Perhaps not surprising?!

Computing Fluid Rotation in Heavy Ion Collisions

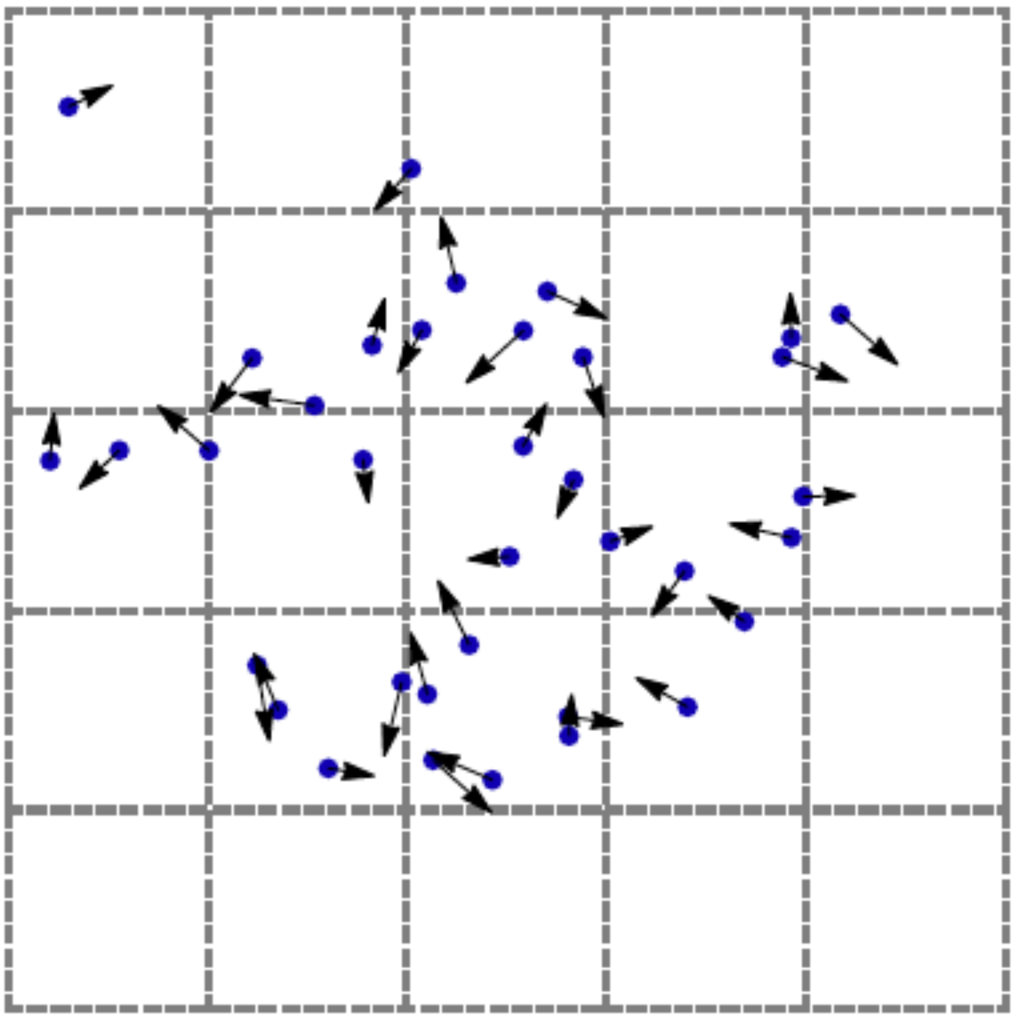
A (very incomplete!) list of recent references on computation of fluid rotation

*** Jiang, Lin, JL, arXiv:1602.06580**
*** Deng, Huang, arXiv:1603.06117**
*** Pang, Petersen, Q. Wang, X.-N. Wang, arXiv:1605.04024**
*** Becattinni, et al, arXiv:1501.04468**
*** Csernai, Magas, arXiv:1302.5310**
*** ……**

Fluid Rotation in Heavy Ion Collisions

Blackboard

Fluid Rotation in Heavy Ion Collisions



$$\vec{J} = \int d^3r \vec{r} \times \vec{p}(\vec{r}).$$

$$\vec{v}(\vec{r}) = \vec{p}(\vec{r})/\epsilon(\vec{r})$$

$$\vec{\omega} = \nabla \times \vec{v}$$

Simulations with AMPT model
[Jiang,Lin,Liao, PRC2016]

Angular Momentum Carried by Fireball

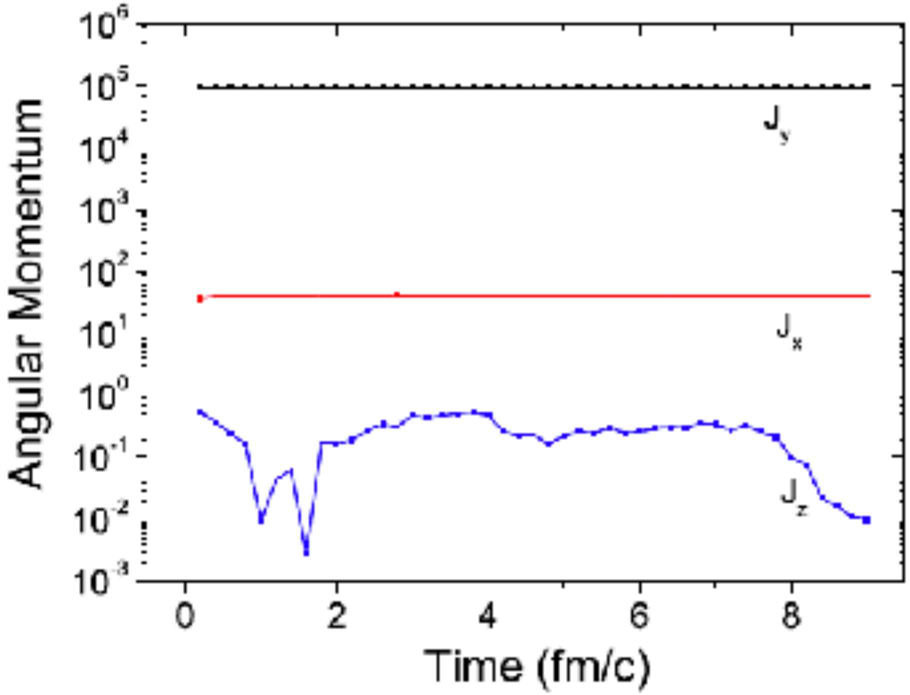
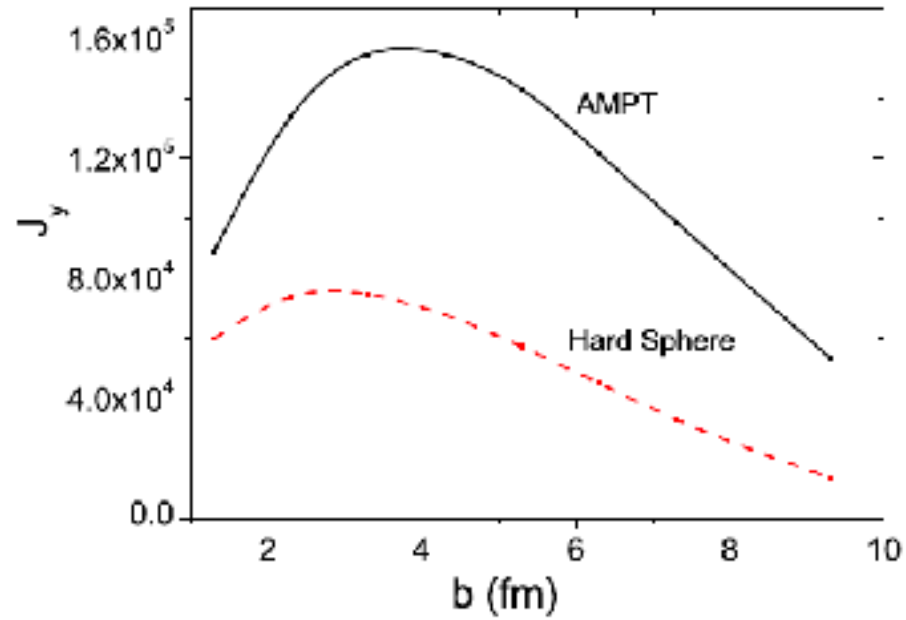
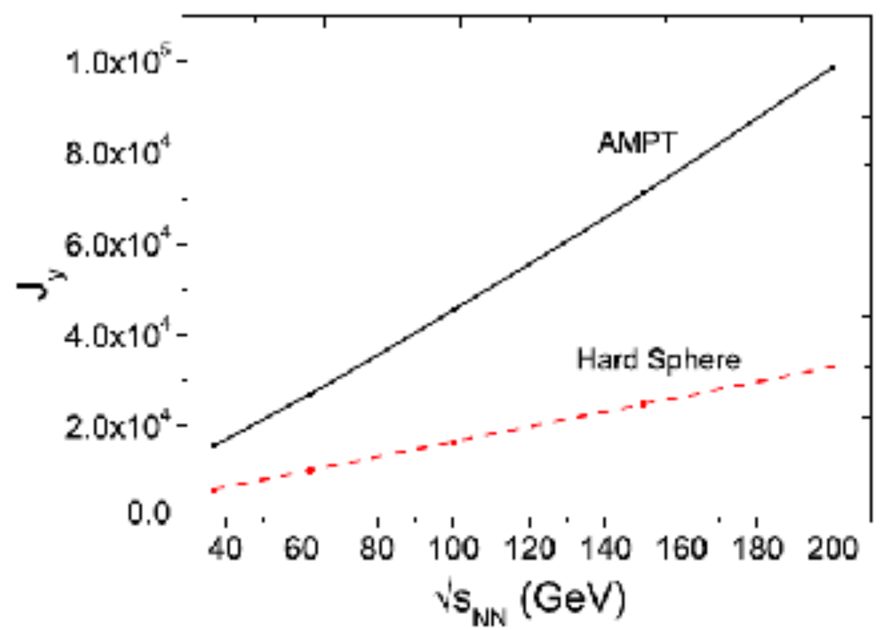


FIG. 2. Angular momentum from the AMPT model at $b = 7$ fm and $\sqrt{s_{NN}} = 200$ GeV.

Simulations with AMPT model [Jiang,Lin,Liao, PRC2016]





Fluid Rotation in Heavy Ion Collisions

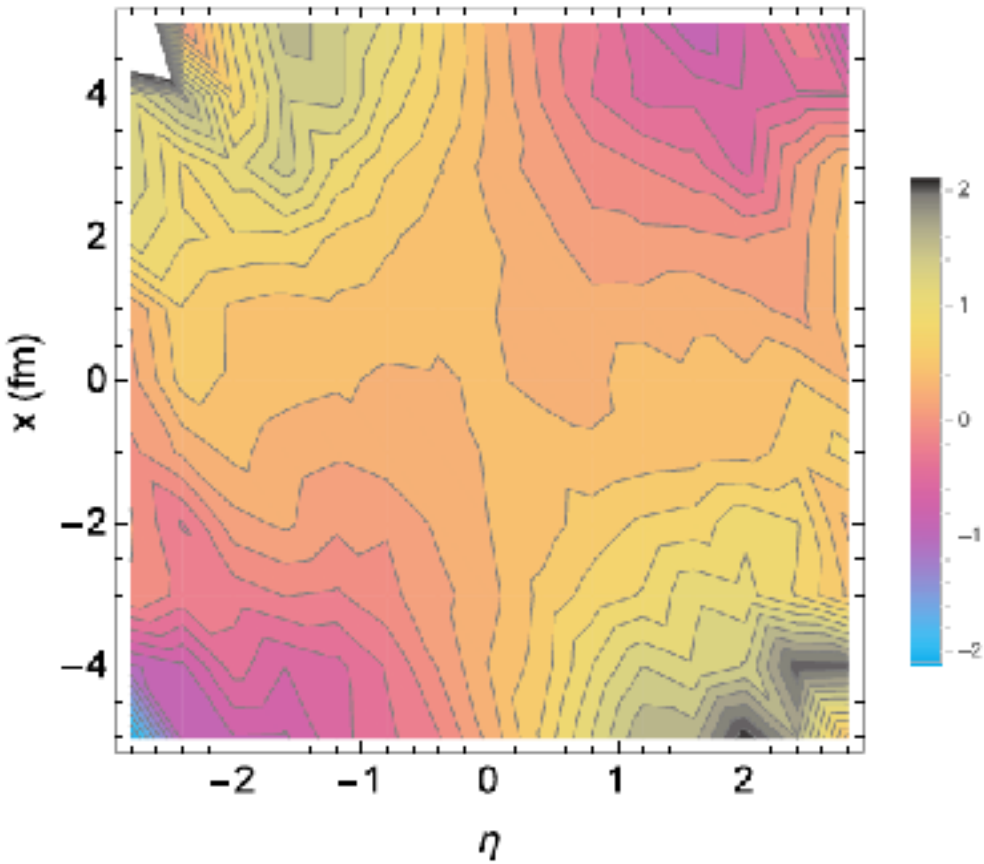


FIG. 5. ω_y (in the unit of fm^{-1}) profile at $y = 0$ and $t = 1$ fm/c, with $b = 7$ fm and $\sqrt{s_{NN}} = 200$ GeV.

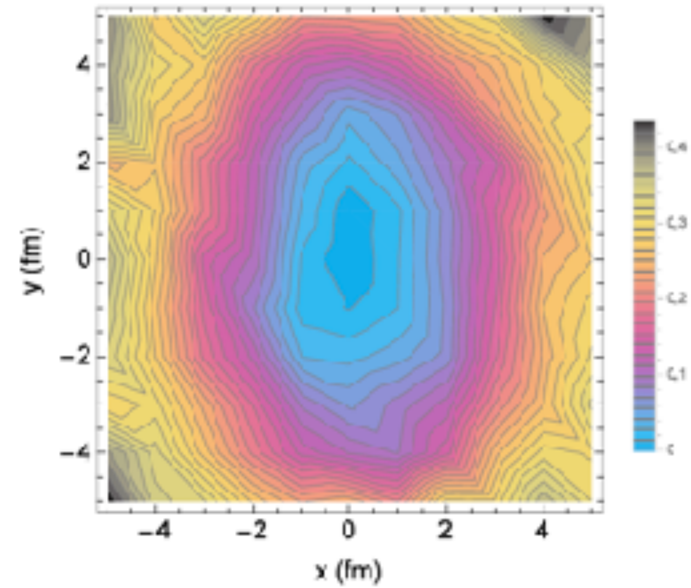


FIG. 10. Radial velocity profile at $\eta = 1$ and $t = 1$ fm/c, with $b = 7$ fm and $\sqrt{s_{NN}} = 200$ GeV.

$$\vec{v}(\rho,\phi,\eta) = \hat{e}_\rho v_0(\rho,\eta)[1 + 2c_2(\rho,\eta)\cos 2\phi],$$

$$\begin{aligned}\omega_y &= \frac{\partial v_\rho}{\partial z}\cos\phi \\ &= \frac{2}{t}(ch\eta)^2\,\partial_\eta(v_0 + 2v_0c_2\cos 2\phi)\cos\phi \\ &= \frac{2}{t}(ch\eta)^2\left(\frac{x}{\rho}\right)\partial_\eta\left[v_0 + 2v_0c_2\left(2\frac{x^2}{\rho^2} - 1\right)\right].\end{aligned}$$

Simulations with AMPT model [Jiang,Lin,Liao, PRC2016]

Fluid Rotation in Heavy Ion Collisions

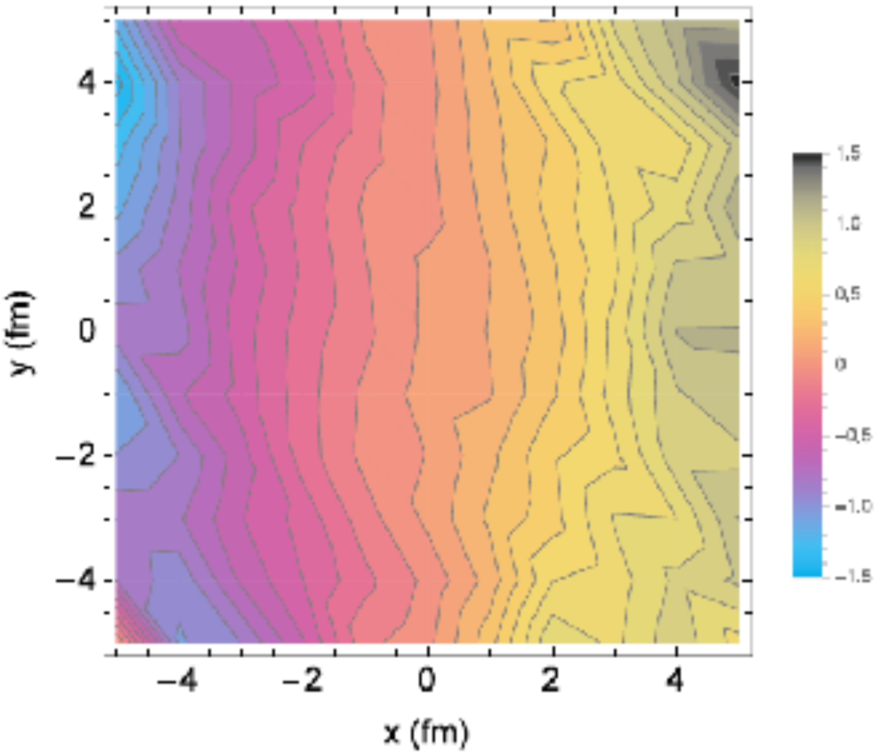


FIG. 7. ω_y profile at $\eta = -1$ and $t = 1$ fm/c, with $b = 7$ fm and $\sqrt{s_{NN}} = 200$ GeV.

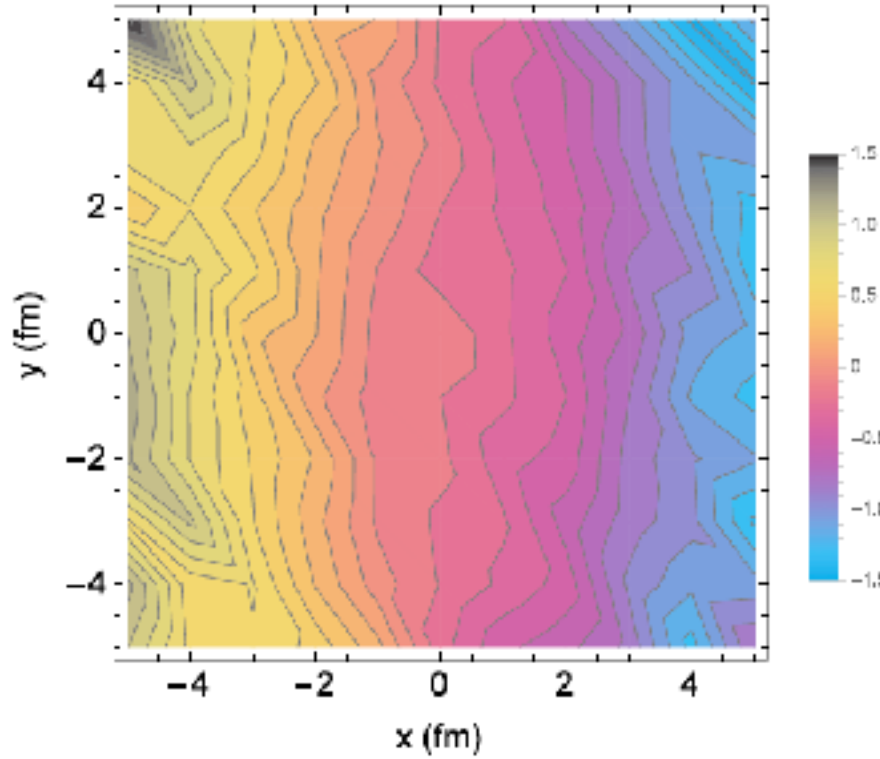
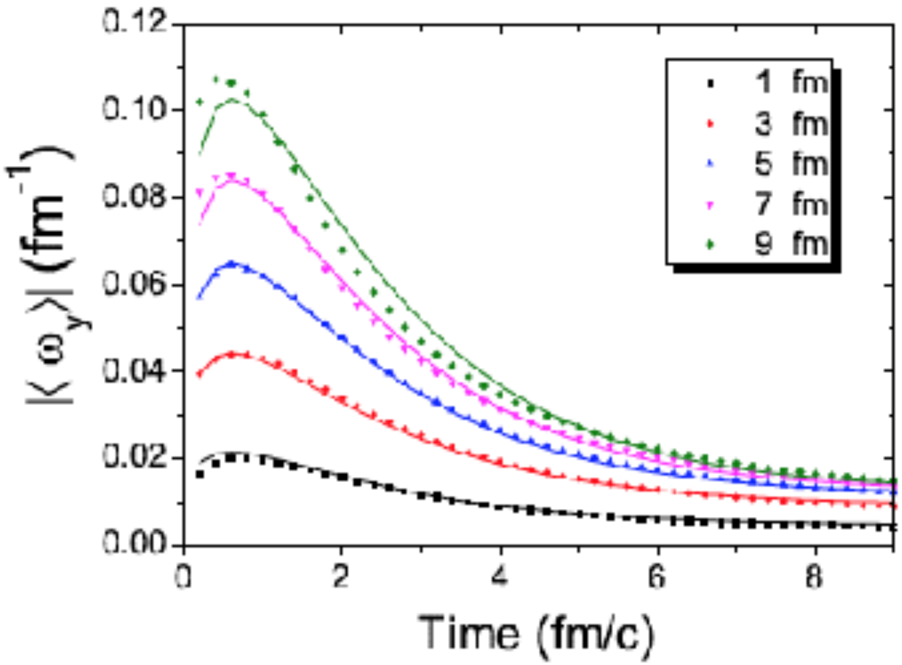
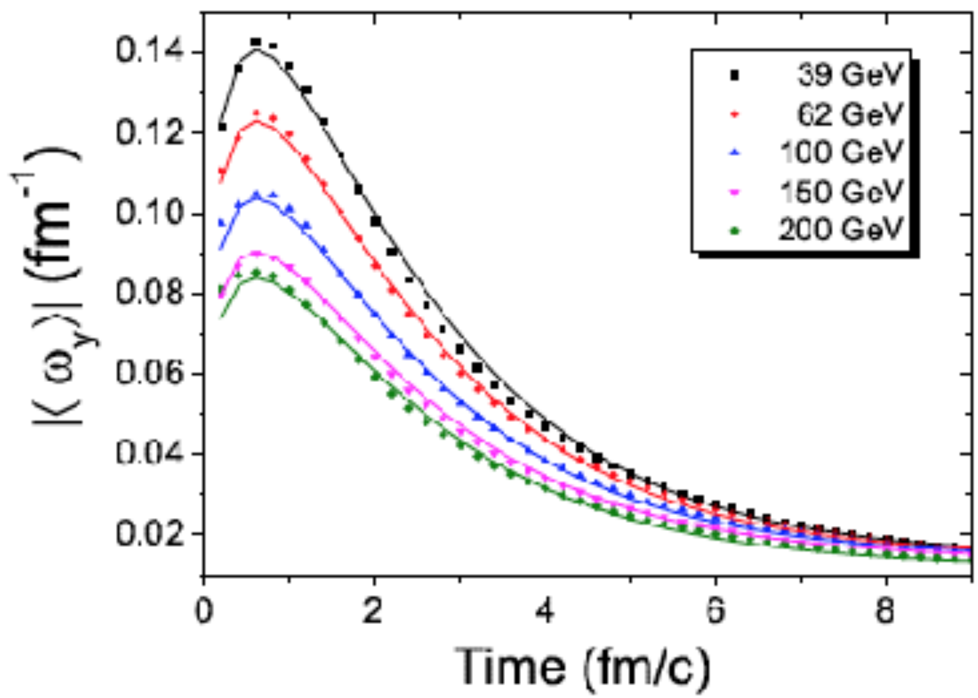


FIG. 6. ω_y profile at $\eta = 1$ and $t = 1$ fm/c, with $b = 7$ fm and $\sqrt{s_{NN}} = 200$ GeV.

Simulations with AMPT model
[Jiang,Lin,Liao, PRC2016]

Quantifying Rotation of QGP





Convenient parameterization:

$$\langle\omega_y\rangle(t, b, \sqrt{s_{NN}}) \;=\; A(b, \sqrt{s_{NN}}) + B(b, \sqrt{s_{NN}})\,(0.58t)^{0.35}\; e^{-0.58t}$$

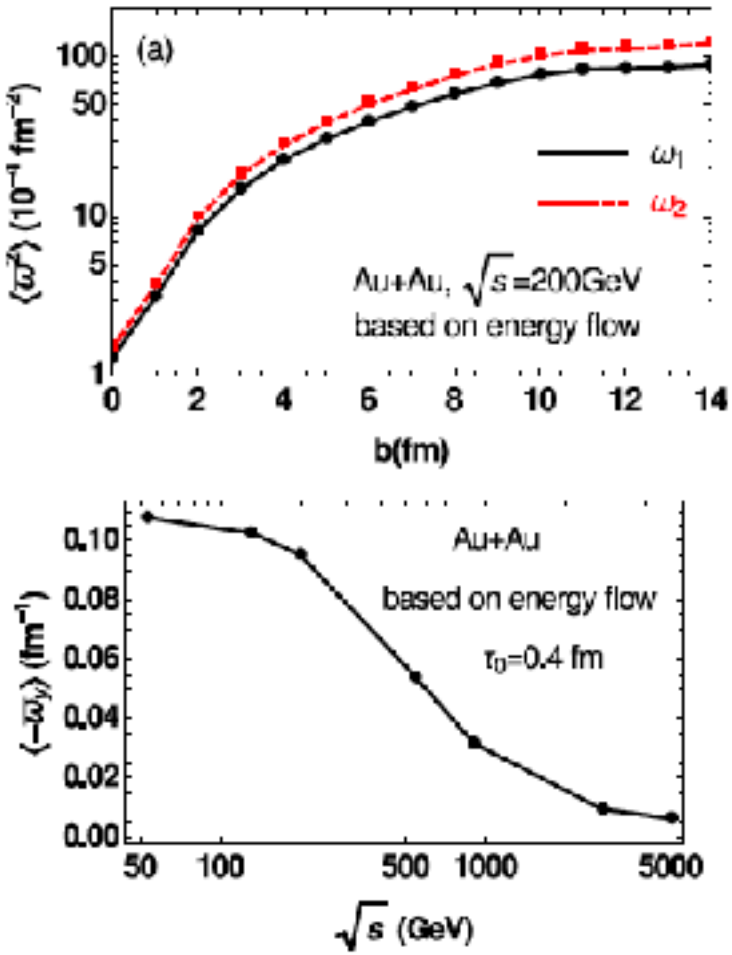
$$A \quad \left[e^{-0.016\, b\, \sqrt{s_{NN}}} + 1\right] \times \tanh(0.28\, b) \times [0.001775 \tanh(3 - 0.015\sqrt{s_{NN}}) + 0.0128]$$

$$B \;=\; \left[e^{-0.016\, b\, \sqrt{s_{NN}}} + 1\right] \times [0.02388\, b + 0.01203] \times [1.751 - \tanh(0.01\sqrt{s_{NN}})] \;.$$

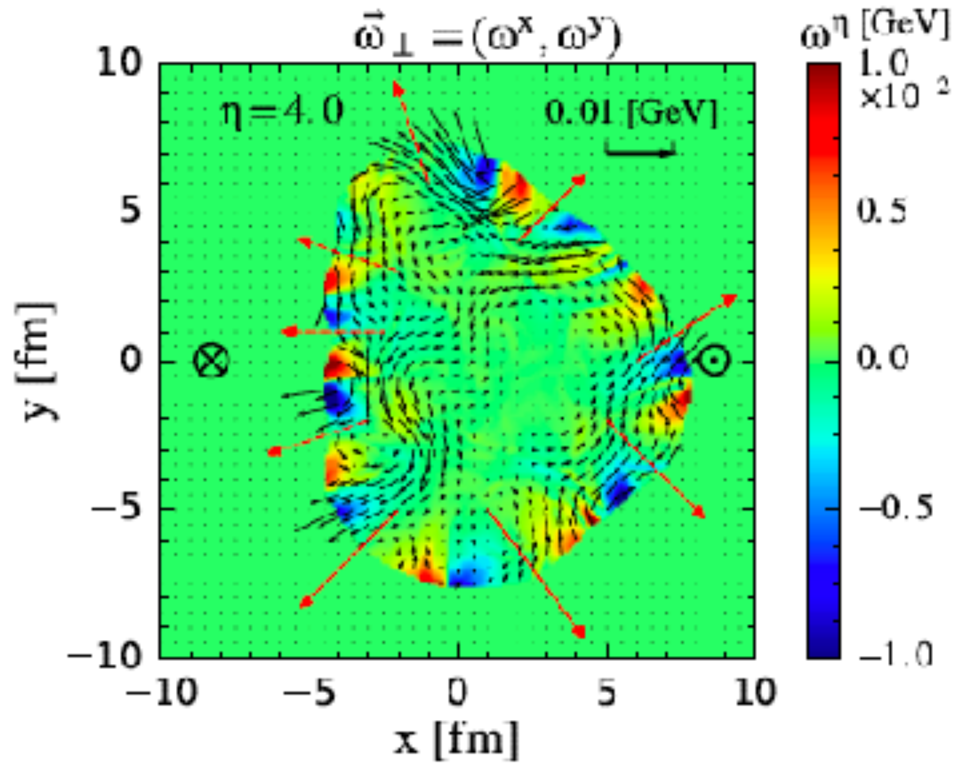
Yin Jiang, Zi-Wei Lin, JL, arXiv:1602.06580[hep-ph]

Quantifying Rotation of QGP

From HIJING



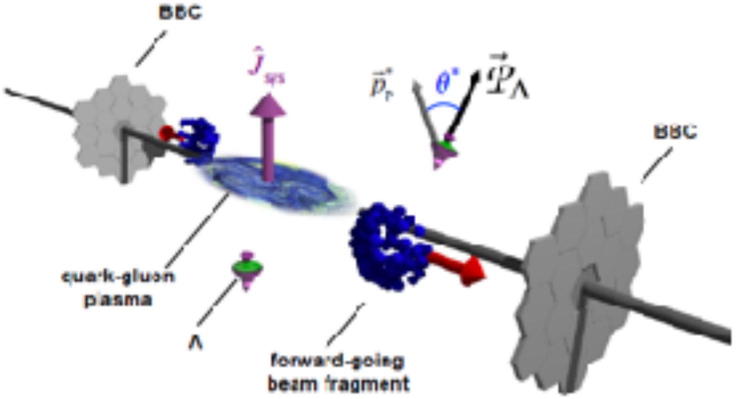
From 3D hydro

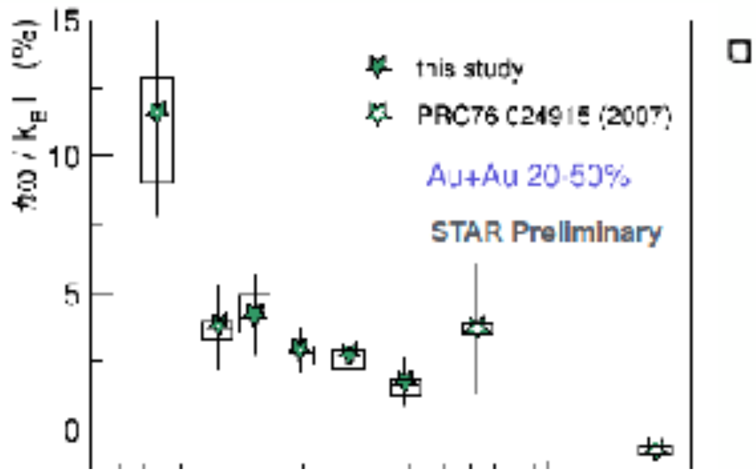


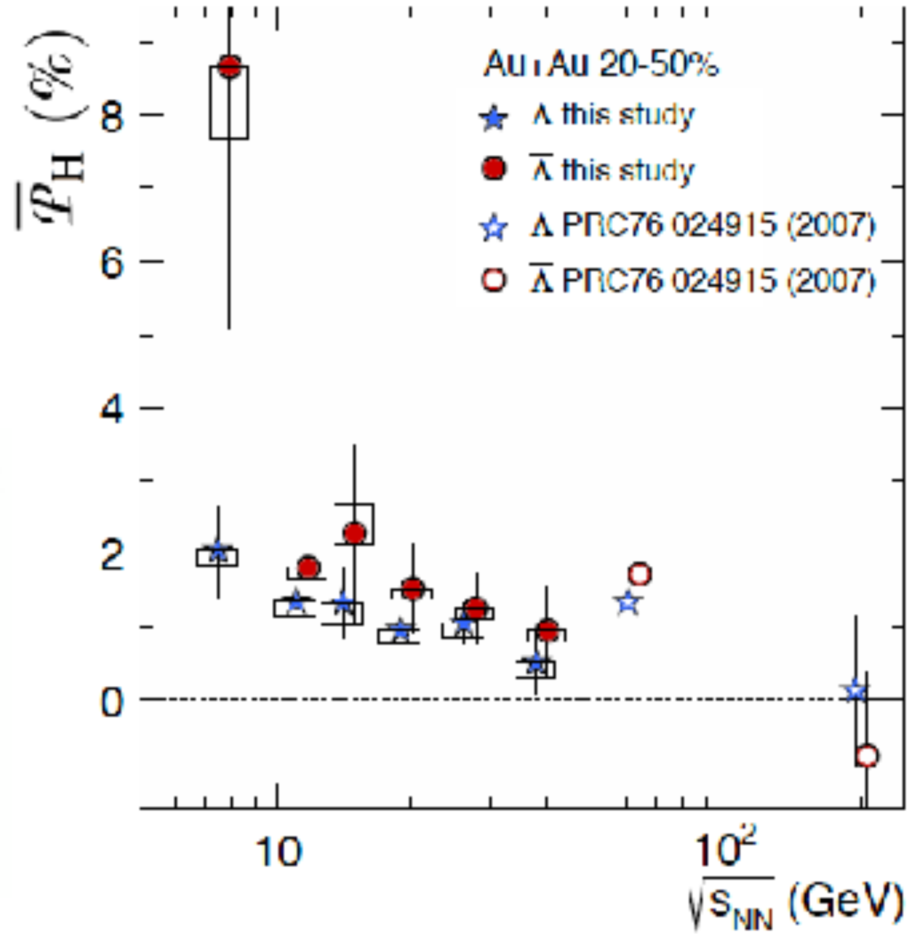
Deng, Huang,
arXiv:1603.06117

Pang, Petersen, Wang, Wang
arXiv:1605.04024

The Most Vortical Fluid







STAR Collaboration, arXiv:1701.06657

Some Concluding Remarks

Q & A