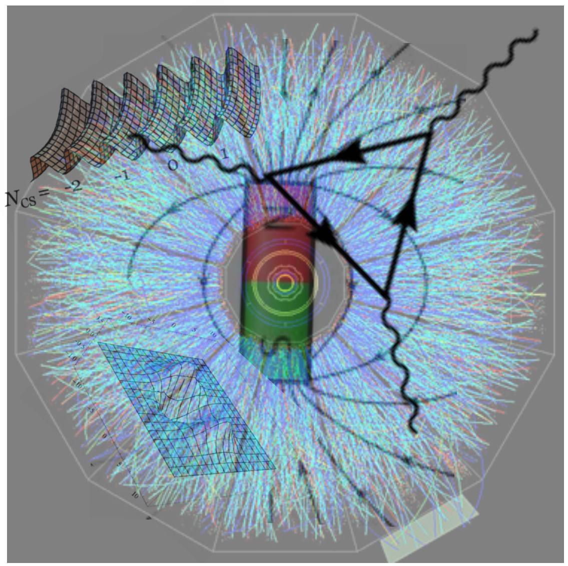
QCD Workshop @ Weihai

July 22, 2019

Quantifying CME in Heavy Ion Collisions



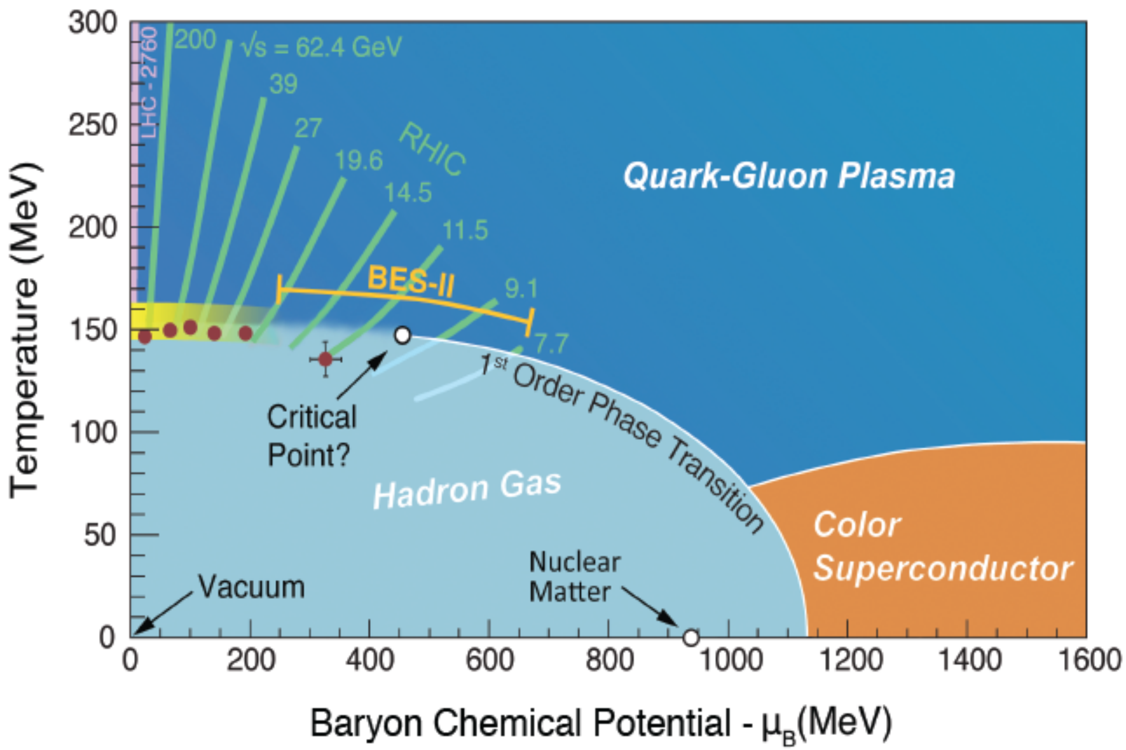
Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Beam Energy Scan: Mapping Out Phases of QCD



**** Establishing a chiral QGP at higher energy via anomalous chiral effects***
**** Searching for chiral critical point & 1st-order transition at lower energy***

NSFC Key Projects: Fudan, SDU, THU, USTC, CCNU,…

BEST COLLABORATION

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

A Recent Review: Collectivity, Criticality, Chirality

Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan

Adam Bzdak[a], ShinIchi Esumi[b], Volker Koch[c], Jinfeng Liao[d,e], Mikhail Stephanov[f], Nu Xu[c,e]

[a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Krakow, Poland
[b]Tomonaga Center for the History of the Universe, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[c]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[d]Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[e]Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China
[f]Physics Department, University of Illinois at Chicago, 845 W. Taylor St., Chicago IL 60607-7059, USA

Abstract

We review the present status of the search for a phase transition and critical point as well as anomalous transport phenomena in Quantum Chromodynamics (QCD), with an emphasis on the Beam Energy Scan program at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. We present the conceptual framework and discuss the observables deemed most sensitive to a phase transition, QCD critical point, and anomalous transport, focusing on fluctuation and correlation measurements. Selected experimental results for these observables together with those characterizing the global properties of the systems created in heavy ion collisions are presented. We then discuss what can be already learned from the currently available data about the QCD critical point and anomalous transport as well as what additional measurements and theoretical developments are needed in order to discover these phenomena.

Keywords: Heavy Ion Collision, Beam Energy Scan, QCD Phase Diagram, Critical Point, Chiral Magnetic Effect

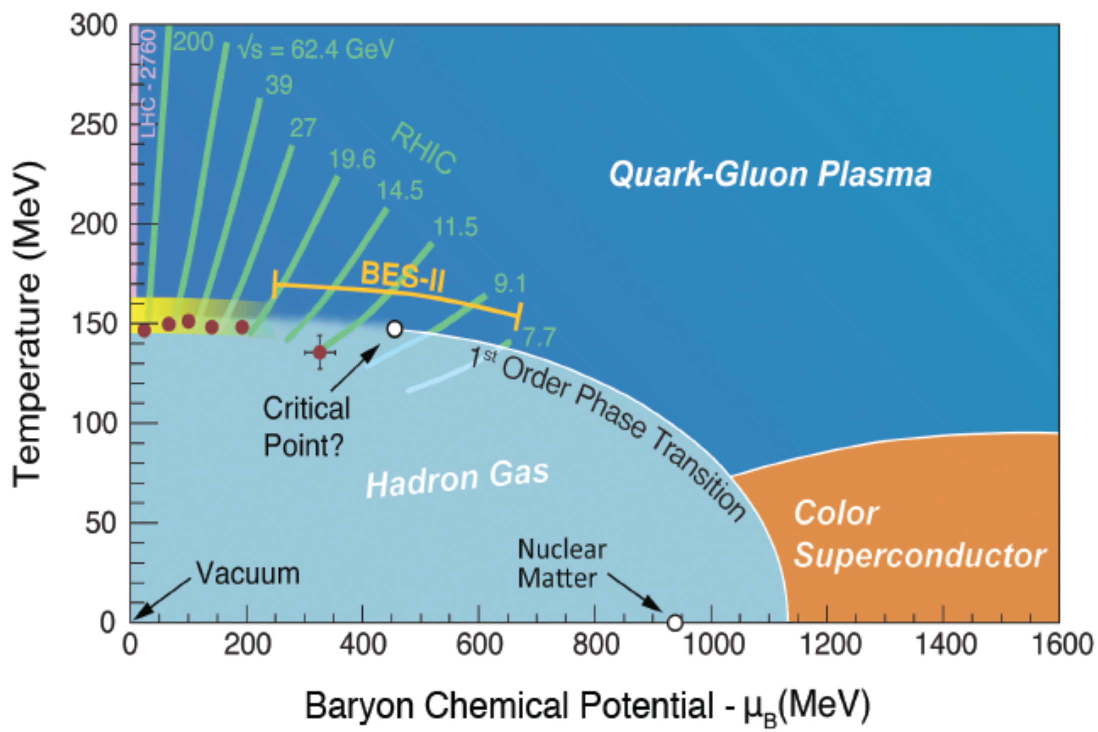
arXiv:1906.00936

INT Program 2020

Chirality and Criticality:
Novel Phenomena in Heavy Ion Collisions

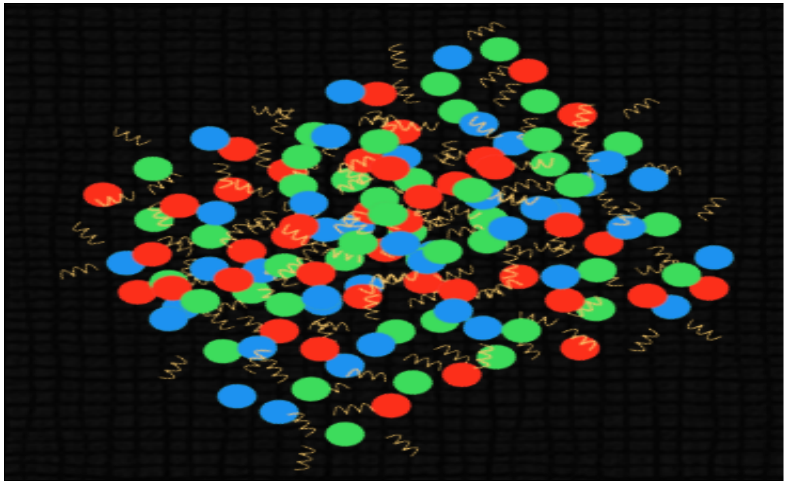
May 11 — June 5, 2020 (May18~22 workshop week)

Organizers: J. Liao, M. Stephanov, H.-U. Yee, Z. Xu

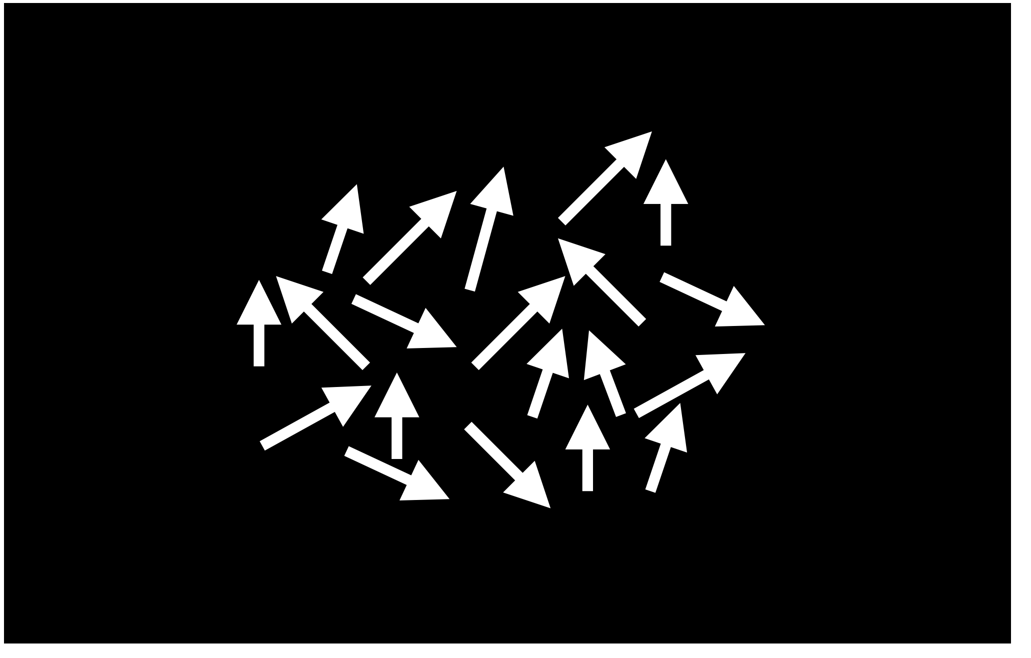


A New Paradigm: Quantum Fluid of Spin

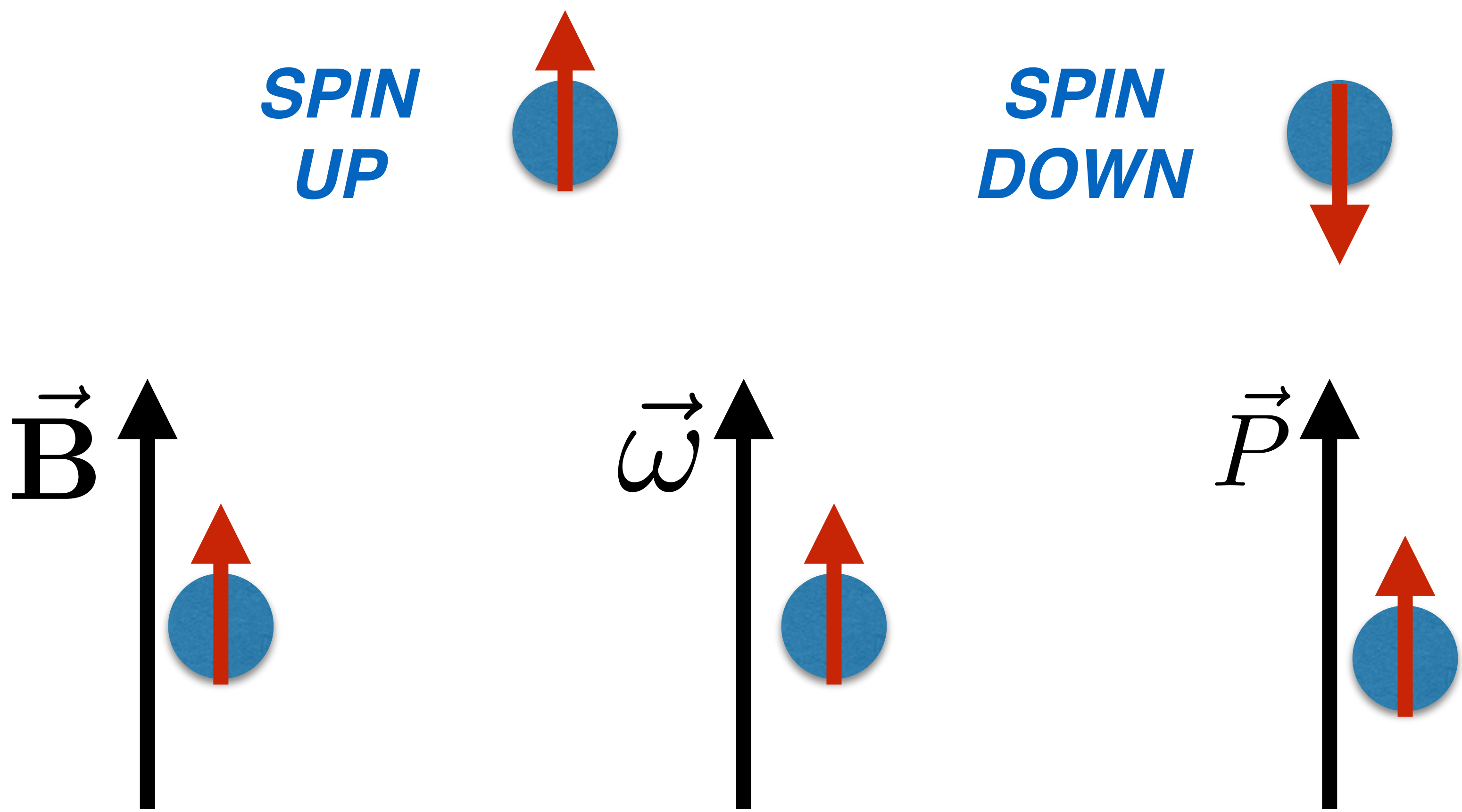
A nearly perfect fluid (of energy-momentum)



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



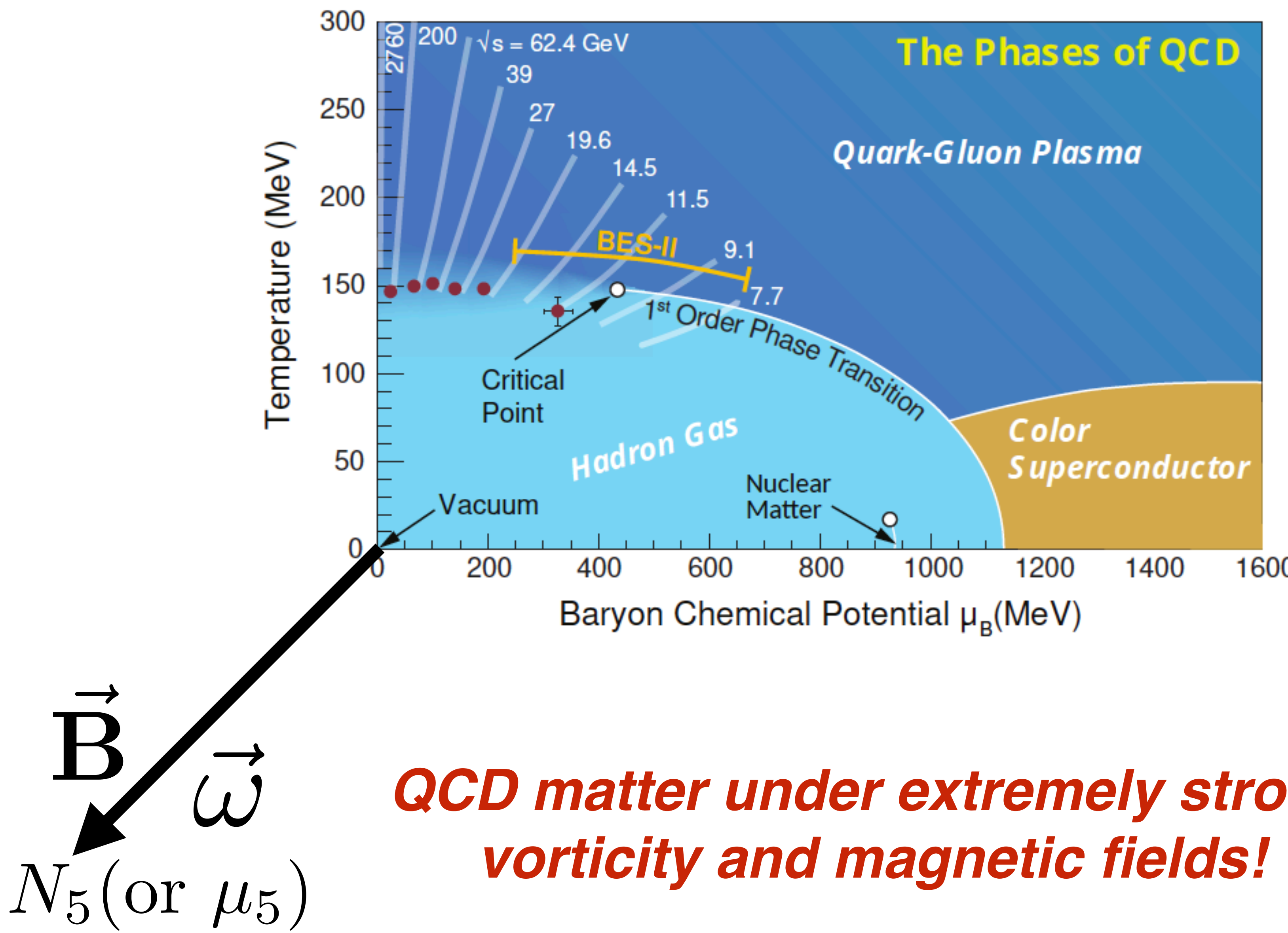
Spin: Chirality, Vorticity and Magnetic Field



Magnetic Polarization	Rotational Polarization	Chirality Polarization

Interesting interplay —> highly nontrivial phenomena!

QCD Matter under New Extreme Conditions



QCD matter under extremely strong vorticity and magnetic fields!

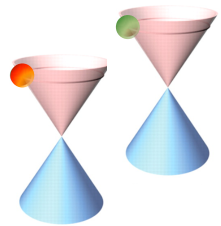
Chirality 2019 @ Tsinghua Beijing, Apr 2019

~100 people, 4.5 days

Chirality 2015,2016,2017 @ UCLA
Chirality 2018 @ Univ. Florence
Chirality 2019 @ Tsinghua Univ.

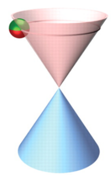
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

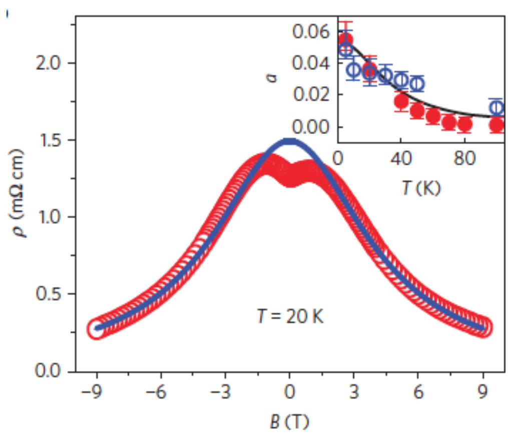


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2

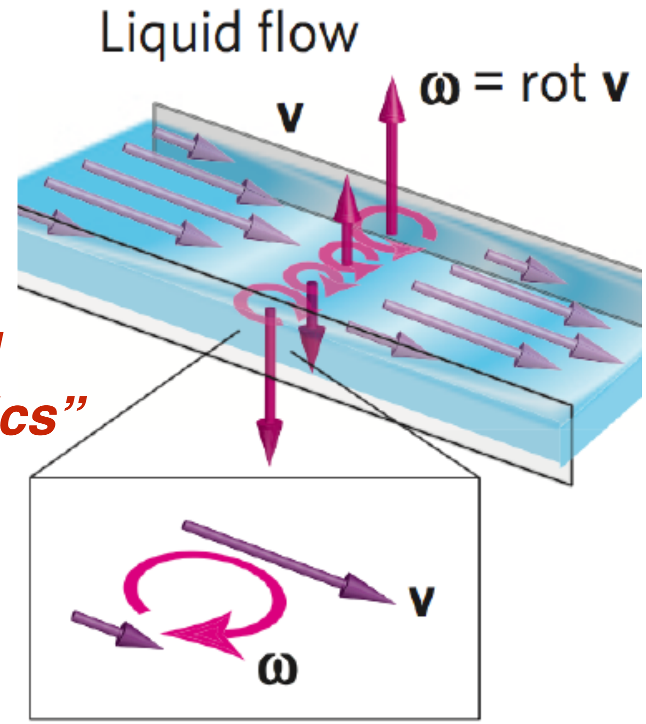


nature physics
LETTERS
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

Chiral magnetic effect in $ZrTe_5$

Qiang Li[1*], Dmitri E. Kharzeev[2,3*], Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1*]

"Spin hydrodynamic generation"
Takahashi, *et al*. Nat. Phys. (2016)



"Fluid Spintronics"

Condensed matter, cold atomic gases, neutron stars, cosmology, plasma physics, etc
[Chiral Matter workshops @ RIKEN, NTU]

Recent Reviews on Chirality Related Topic

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

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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[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*

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

Fukushima, arXiv:1812.08886, PPNP2019.

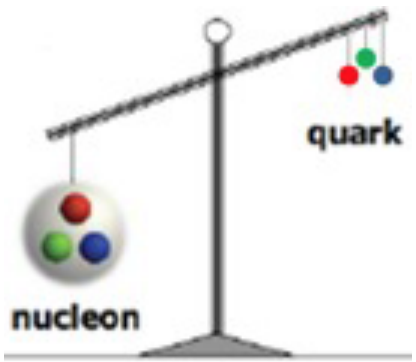
Zhao, Wang, arXiv:1906.11413, PPNP2019.

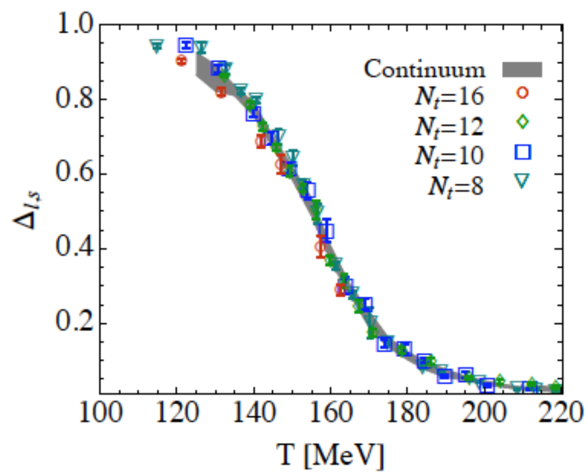
Hattori, Huang, Nucl. Sci. Tech., 28 (2017) no.2, 26.

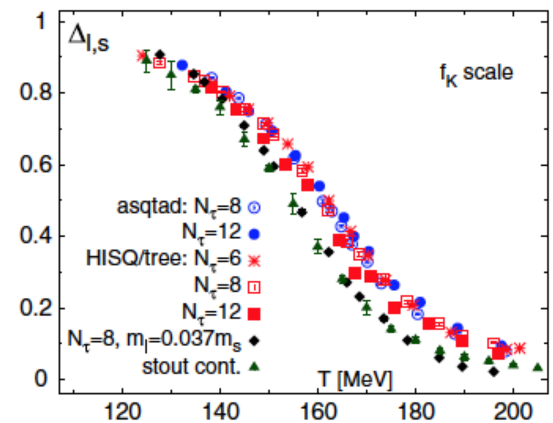
Chiral Magnetic Effect：
Many-Body Physics of Chirality, Anomaly, Topology

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?

Chiral Symmetry: Quantum Anomaly

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

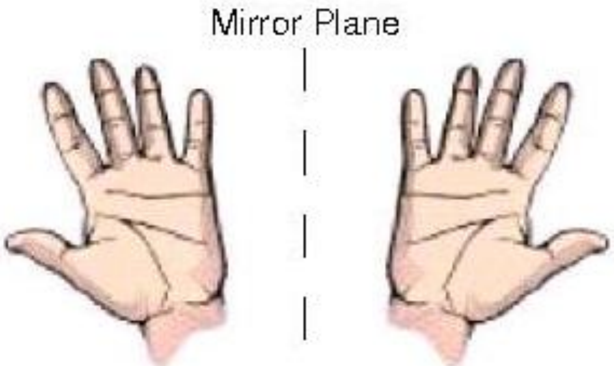
Classical symmetry:

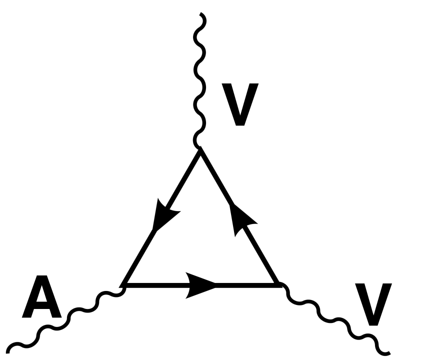
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

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





[e.g. pi0—> 2 gamma]

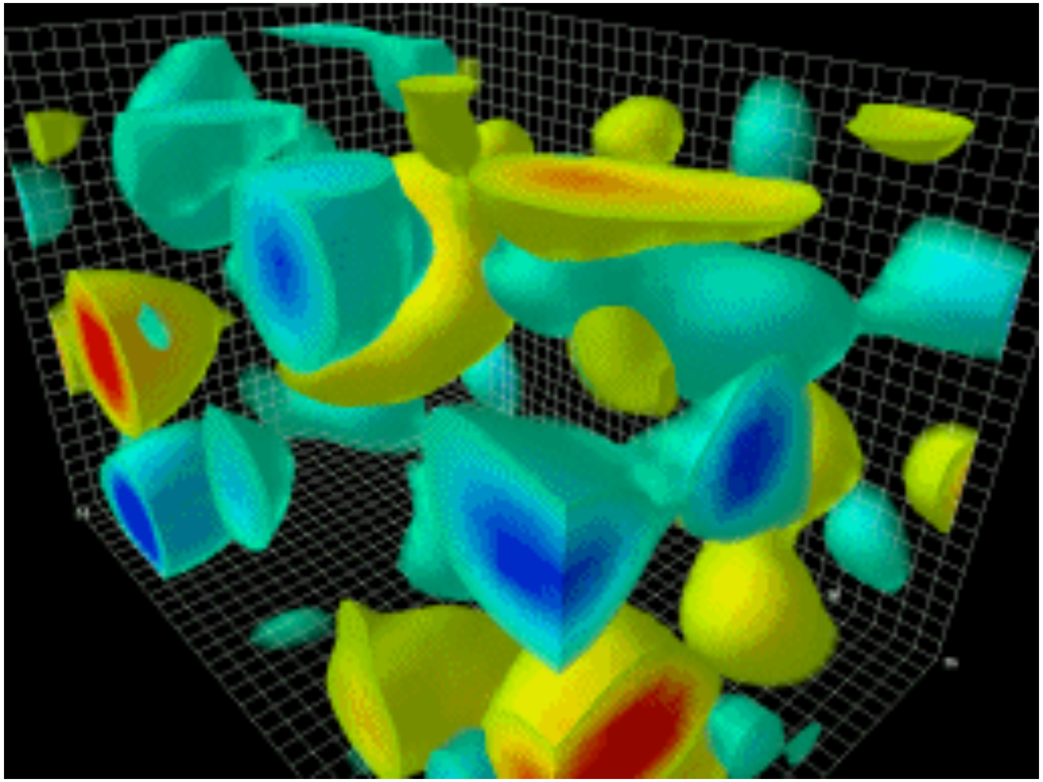
Broken at QM level:

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

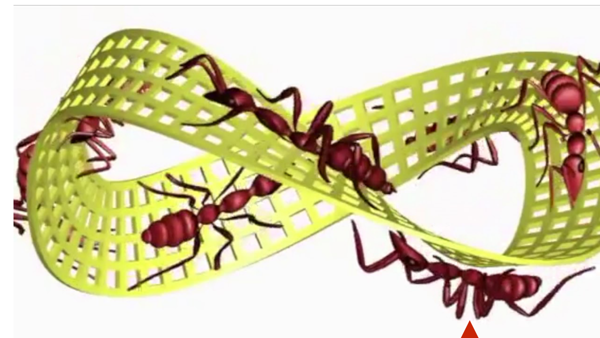
$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

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

From Gluon Topology to Quark Chirality



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



Quarks

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

QCD anomaly: gluon topology —> chirality imbalance

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

Net chirality <—> topo fluctuations & chiral restoration

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

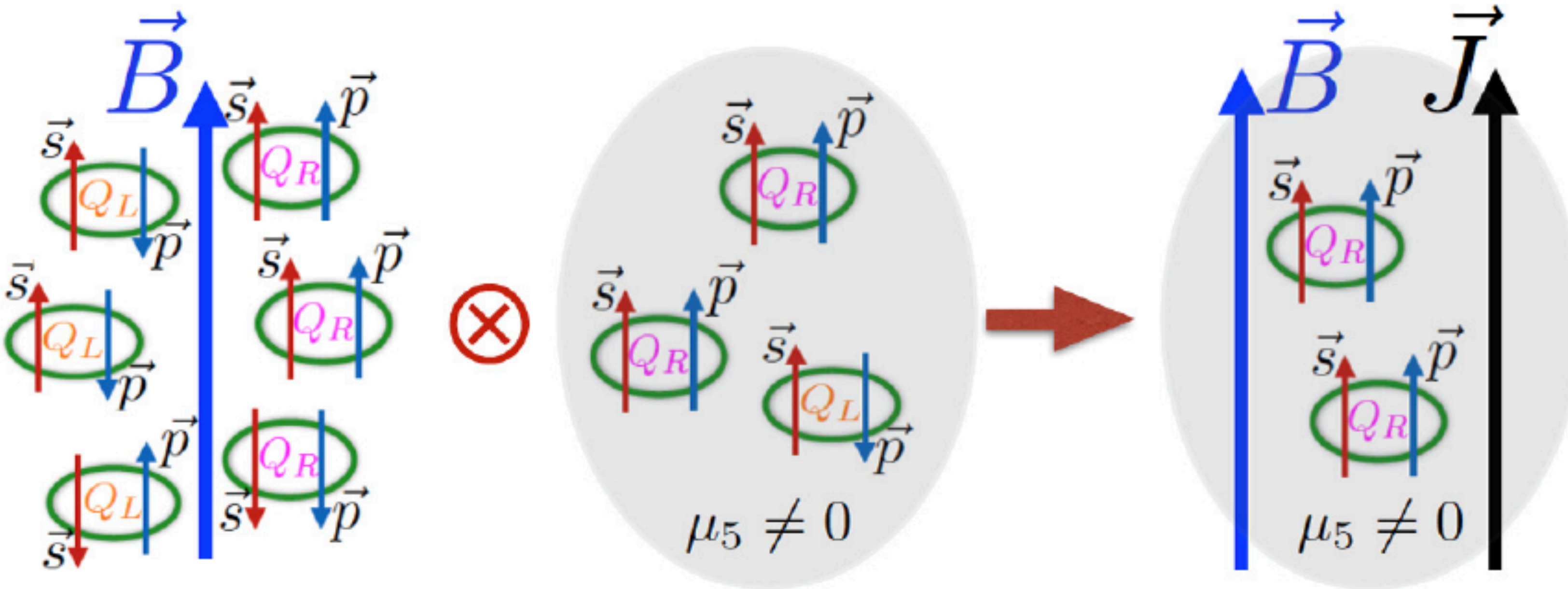
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current ← **Magnetic Field**

Q.M. Transport

[Kharzeev, Fukushima, Warringa, McLerran, ...]

Intuitive Picture of CME



Intuitive understanding of CME:

Magnetic polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

$\otimes$

Chiral imbalance —>
correlation between directions of
SPIN & MOMENTUM

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

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

Chiral Transport Theory

Usual (classical) transport equation:

$$\left\{\partial_t + \dot{\mathbf{x}}\cdot\vec{\nabla}_{\mathbf{x}} + \dot{\mathbf{p}}\cdot\vec{\nabla}_{\mathbf{p}}\right\} f^{(c)}(t,\mathbf{x},\mathbf{p}) = C[f^{(c)}] \ ,$$

$$\dot{\mathbf{x}} = \mathbf{v} = \vec{\nabla}_{\mathbf{p}} E_{\mathbf{p}} \ , \ \ \dot{\mathbf{p}} = q\,(\mathbf{E}+\mathbf{v}\times\mathbf{B}) \ .$$

Chiral transport equation:

$$\left\{\partial_t + \mathbf{G}_{\mathbf{x}}\cdot\nabla_{\mathbf{x}} + \mathbf{G}_{\mathbf{p}}\cdot\nabla_{\mathbf{p}}\right\} f^{(q)}(t,\mathbf{x},\mathbf{p}) = C[f^{(q)}] \ ,$$

$$\mathbf{G}_{\mathbf{x}} = \frac{1}{\sqrt{G}}\left[\widetilde{\mathbf{v}} + \hbar q(\widetilde{\mathbf{v}}\cdot\mathbf{b}_\chi)\mathbf{B} + \hbar q\widetilde{\mathbf{E}}\times\mathbf{b}_\chi\right] \ , \ \ \mathbf{G}_{\mathbf{p}} = \frac{q}{\sqrt{G}}\left[\widetilde{\mathbf{E}} + \widetilde{\mathbf{v}}\times\mathbf{B} + \hbar q(\widetilde{\mathbf{E}}\cdot\mathbf{B})\mathbf{b}_\chi\right]$$

[Son, Yamamoto; Stephanov, Yin; Chen, Wang, et al; Hidaka, Pu, Yang; Mueller, Venugopalan; Huang, Shi, Jiang, JL, Zhuang; …]

Fluid Dynamics That Knows Left & Right

Normal Hydrodynamics

$$\partial_\mu J^\mu = 0$$

$$J^\mu = n u^\mu + \nu^\mu$$

Viscous Current

$$\nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

Anomalous Hydrodynamics

$$\partial_\mu J^\mu = C_A E^\mu B_\mu$$

Anomaly

$$J^\nu = n u^\mu + \nu^\mu + \nu_a^\mu$$

Viscous Current *Anomalous Current*

$$\nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

$$\nu_a^\mu = \xi_B B^\mu$$

CME

$$+ \xi\, \omega^\mu$$

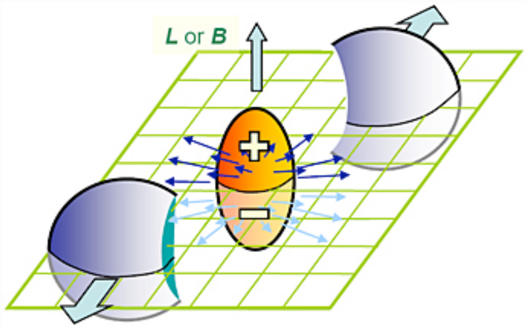
CVE

[Son, Surowka; Kharzeev, Yee; Hidaka, Yang; Shi, JL, et al; …]

A new type of hydrodynamics with macro. quantum effect!

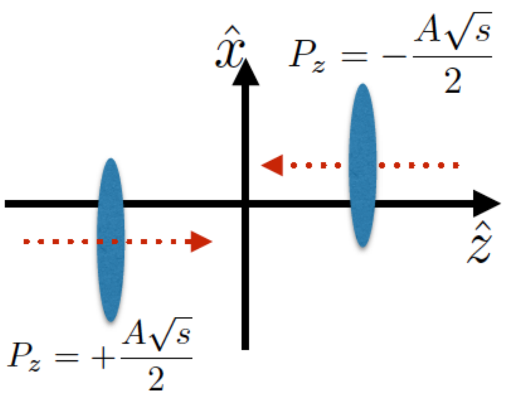
Extreme Vorticity and Magnetic Field

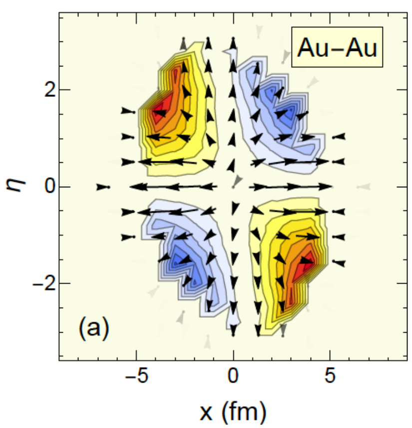
Rotating Quark-Gluon Plasma

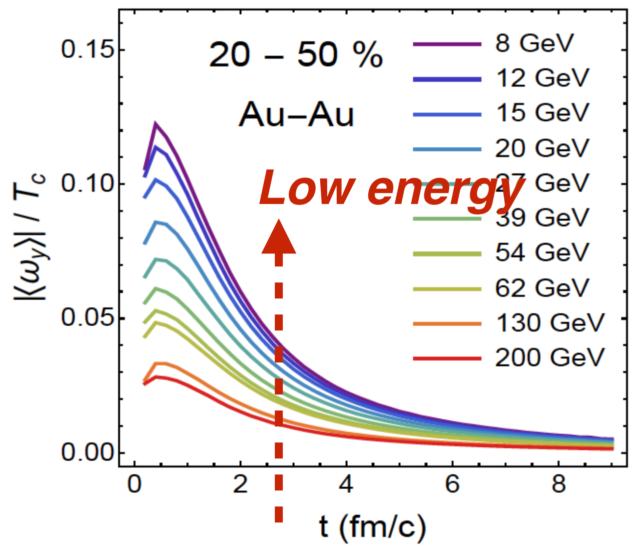


$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

Angular momentum —> nontrivial vorticity structure and spin polarization effect

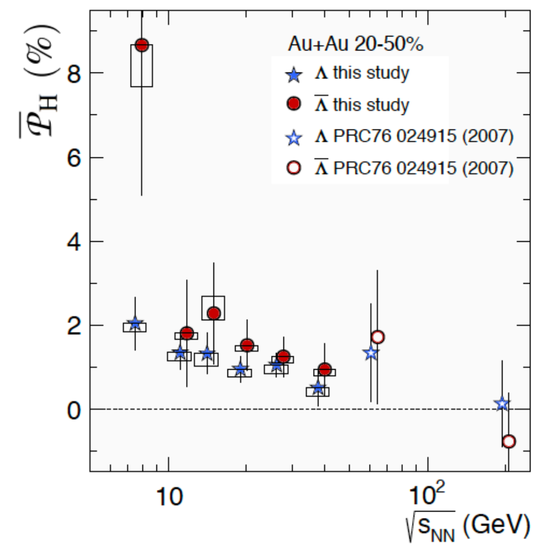






High energy

Jiang, Lin, JL, PRC2016

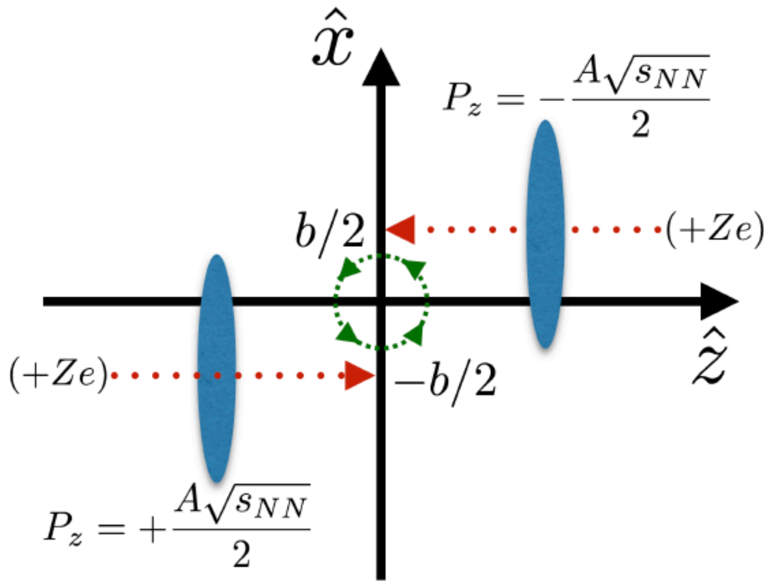


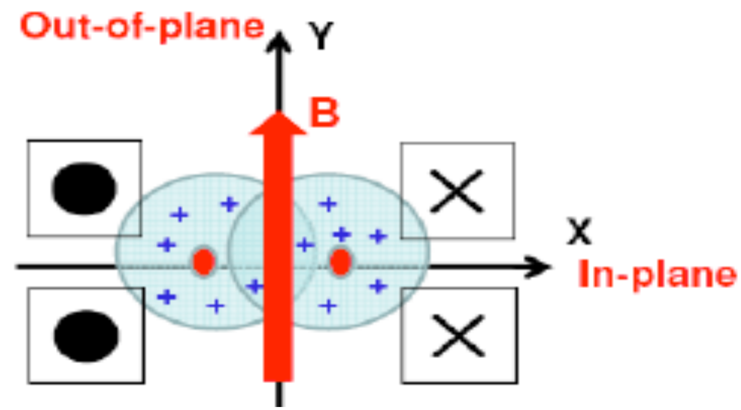
STAR, Nature 2017

[See talks yesterday]

Strong Electromagnetic Fields

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

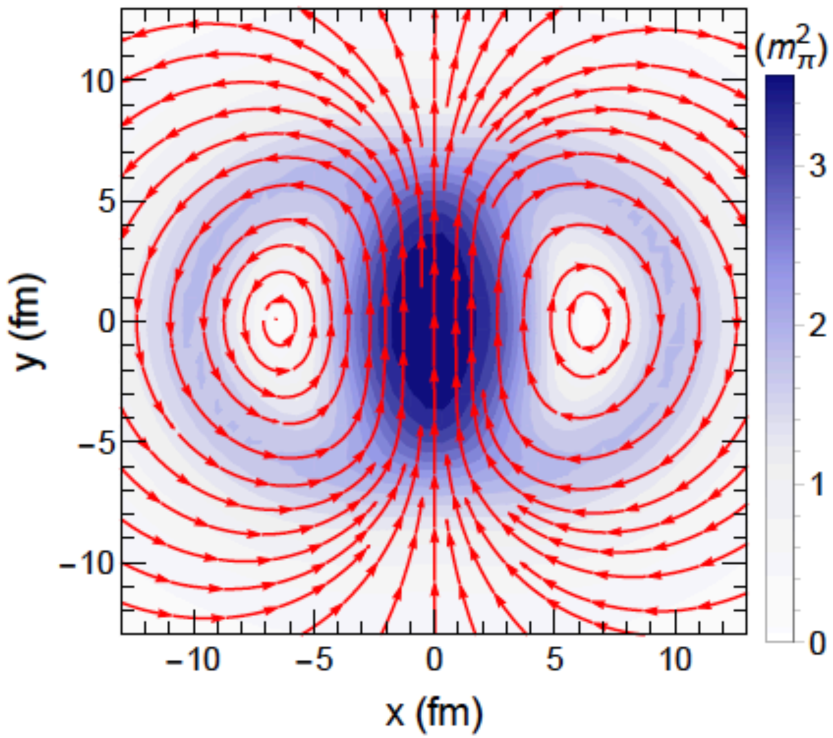




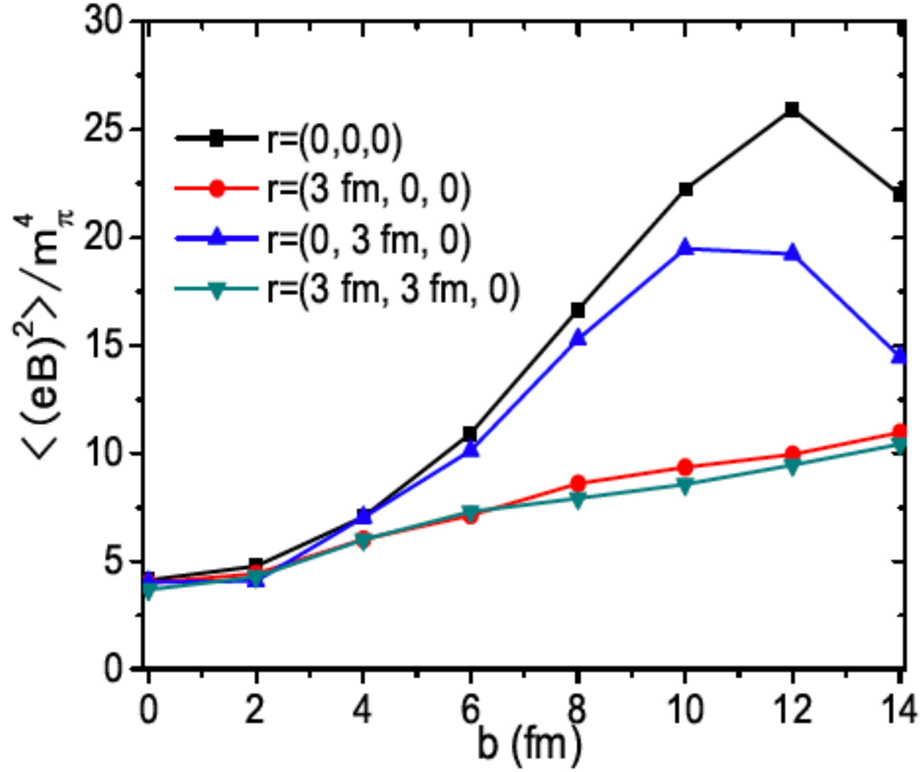
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

- 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!

[Many interesting B-field induced effects: di-electron; polarization splitting; quarkonium v2; D meson v1; …]

Strong Electromagnetic Fields

Physics Letters B 718 (2013) 1529–1535

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

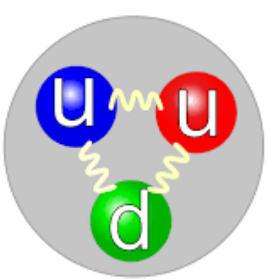
Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

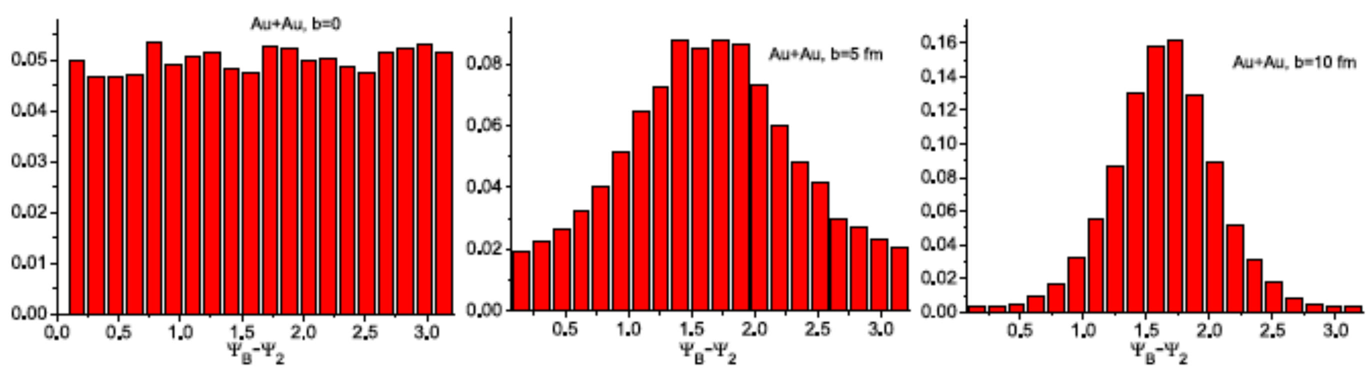
John Bloczynski [a], Xu-Guang Huang [a,*], Xilin Zhang [a], Jinfeng Liao [a,b]

[a] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
[b] *RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA*

Huang, Liao, et al PLB2012

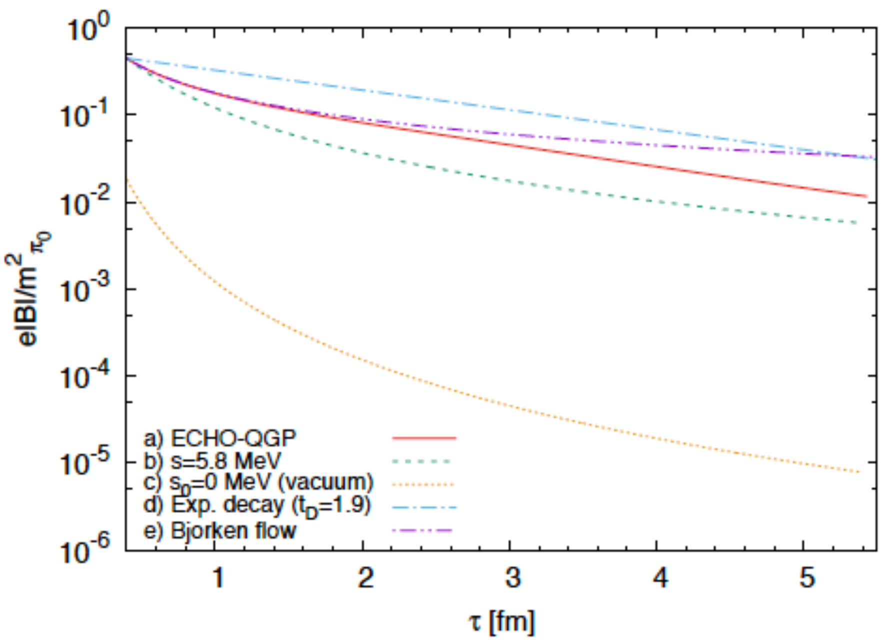
Two very important points in this paper:
**** azimuthal correlation/de-correlation between B fiend and geometry***
**** finite size of proton must be taken into account***

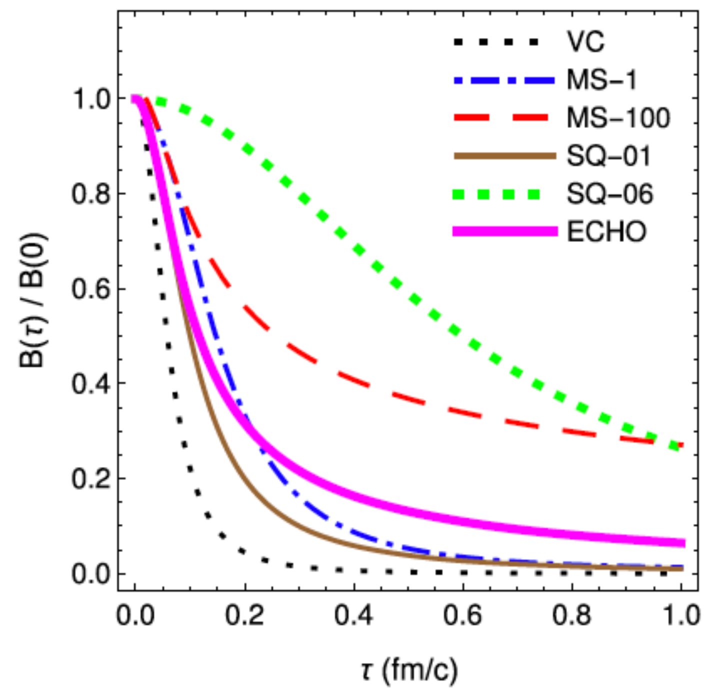




Dynamical Magnetic Fields

Magnetic field may last much longer than vacuum field due to plasma medium feedback effect.





**** Ideal RMHD simulations (ECHO-QGP) [Inghirami, et al, 1609.03042]***

See also works by:

Deng, Huang; Q. Wang, et al; Tuichin; Skokov, McLerran; …

Toward Synergy of B and Rotation

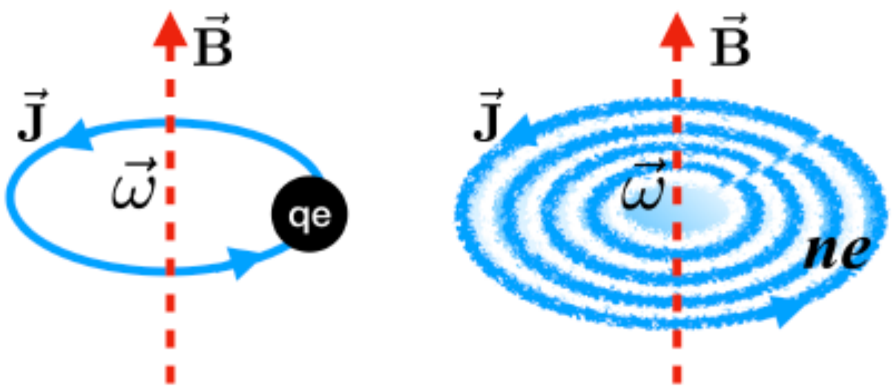
A possible new mechanism: charged fluid + rotation —> magnetic field

Simple example: single charged particle that is swirling

$$B_0 = B_z(\rho = 0) = \frac{I}{2R_0} = \frac{(qe)\ \omega_0}{4\pi R_0}$$

A more relevant example: Charged fluid vortex

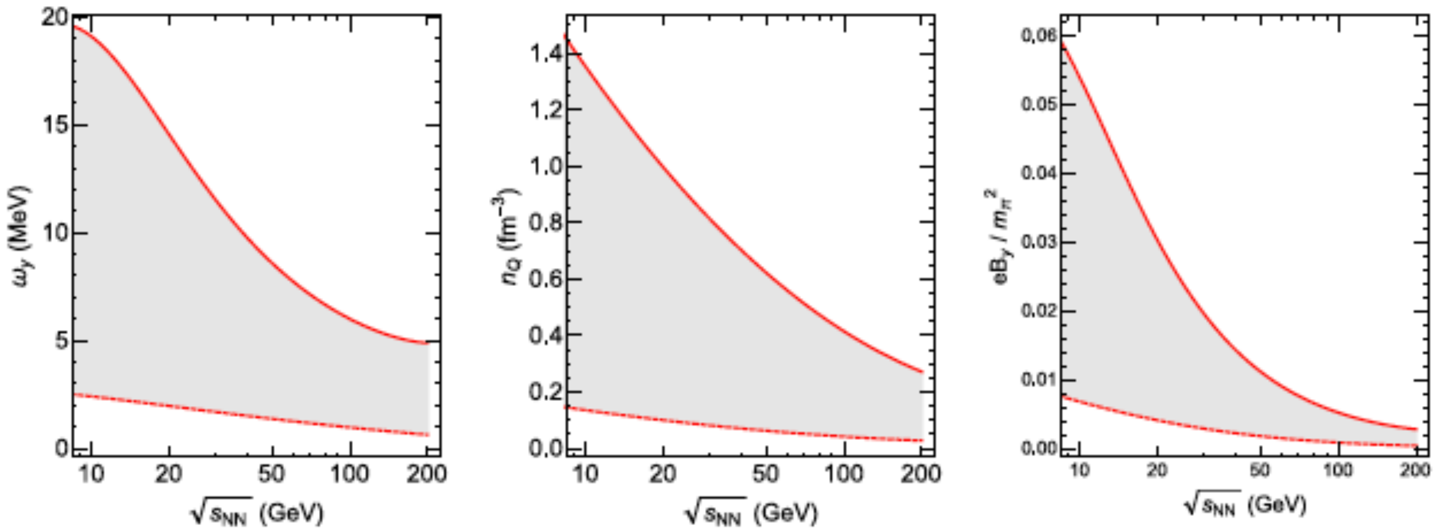
$$\begin{aligned} ne\omega^\mu &= \epsilon^{\mu\nu\rho\sigma} u_\nu \omega_{\rho\sigma} \\ &= 2\epsilon^{\mu\nu\rho\sigma} u_\nu \partial_\rho \partial^\lambda F_{\lambda\sigma} \\ &= \epsilon^{\mu\nu\rho\sigma} u_\nu \Box F_{\rho\sigma}. \end{aligned}$$



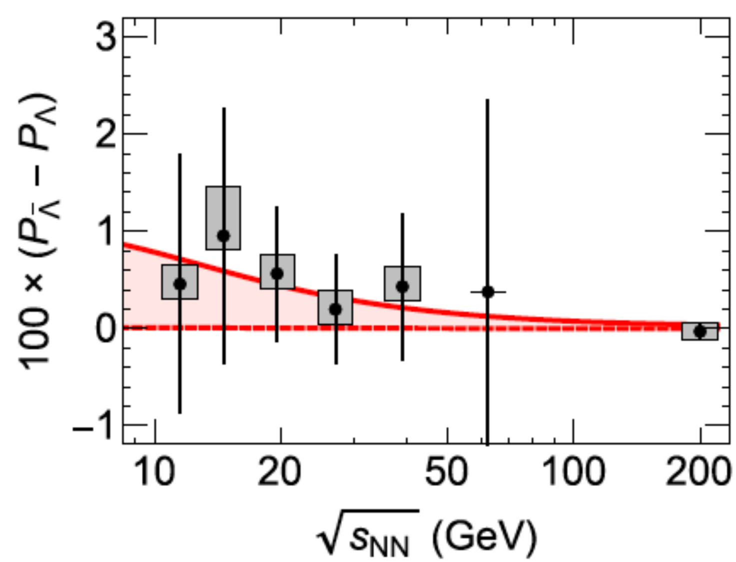
$$e\bar{\mathbf{B}} = \frac{e^2}{4\pi} nA\bar{\omega}$$

[X. Guo, JL, E. Wang: arXiv:1904.04704]

New Mechanism for Long-Lived B Field



$$e\bar{\mathbf{B}} = \frac{e^2}{4\pi} nA\bar{\omega}$$

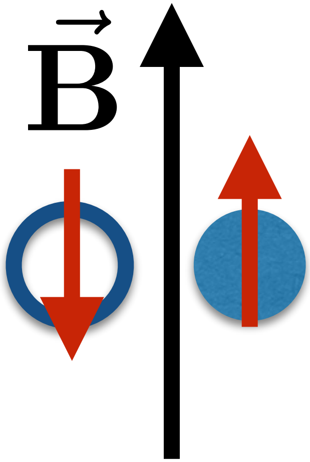


Important at low beam energy!

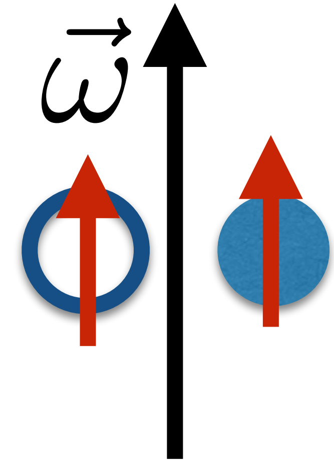
Maybe induce considerable polarization splitting!

[X. Guo, JL, E. Wang: arXiv:1904.04704]

Magnetic Filed Induced Polarization



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



For Lambda:

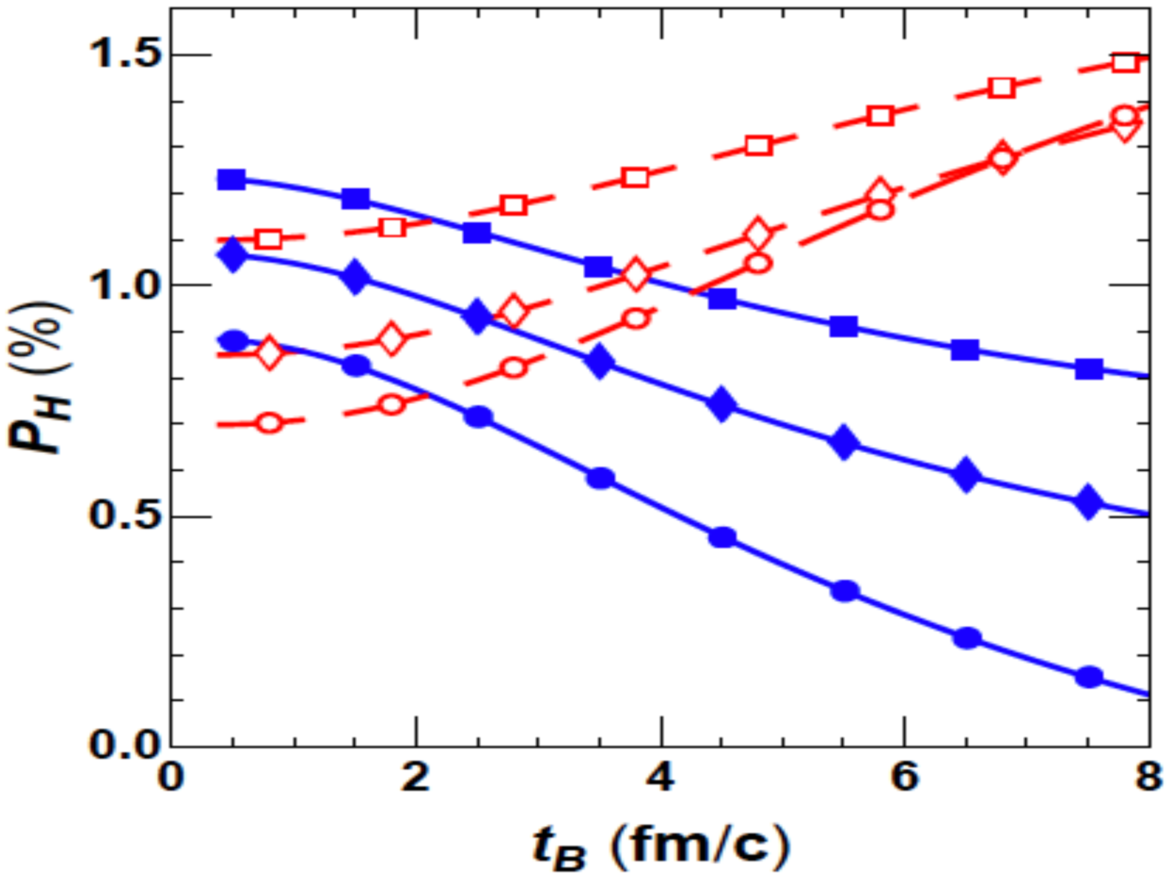
$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} - 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

For anti-Lambda:

$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} + 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

Magnetic Filed Induced Polarization



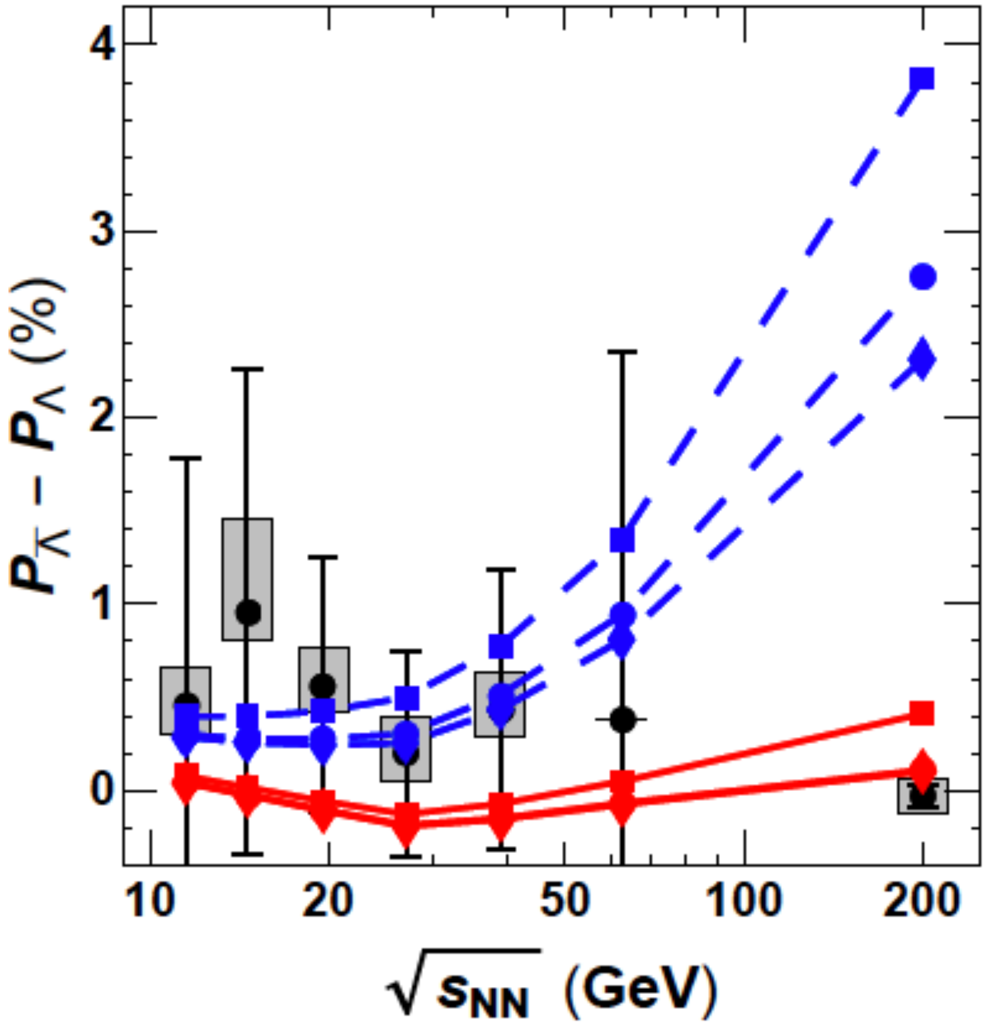
Type-1: , $F_B(t_B, t) \equiv \frac{1}{1+(t-t_0)^2/t_B^2}$ (see e.g. [63, 64]);

Type-2: $F_B(t_B, t) \equiv \frac{1}{\left[1+(t-t_0)^2/t_B^2\right]^{3/2}}$ (see e.g. [48]);

Type-3: $F_B(t_B, t) \equiv e^{-|t-t_0|/t_B}$ (see e.g. [43]).

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

Magnetic Filed Induced Polarization



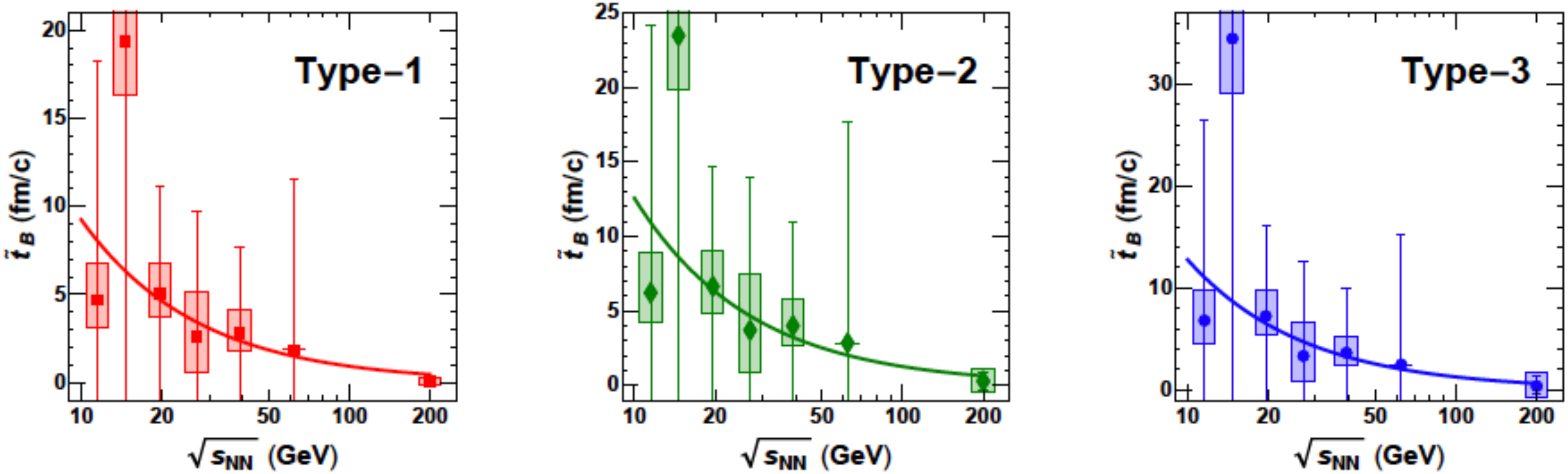
t_B: 4 fm/c

t_B: 1 fm/c

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

Magnetic Filed Induced Polarization

We extract optimal t_B at each beam energy according to observed polarization splitting.



$$t_B \simeq \frac{115\mathrm{GeV}\cdot\mathrm{fm/c}}{\sqrt{s_{NN}}}$$

Much longer than vacuum field:

$$t_{vac} \simeq \frac{26\mathrm{GeV}\cdot\mathrm{fm/c}}{\sqrt{s_{NN}}}$$

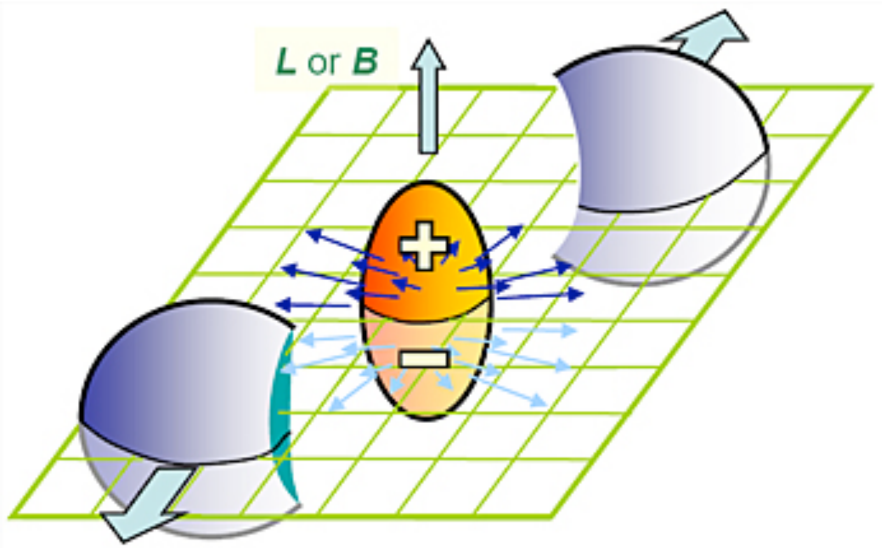
Indicating significant in-medium magnetic fields due to medium effect!

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

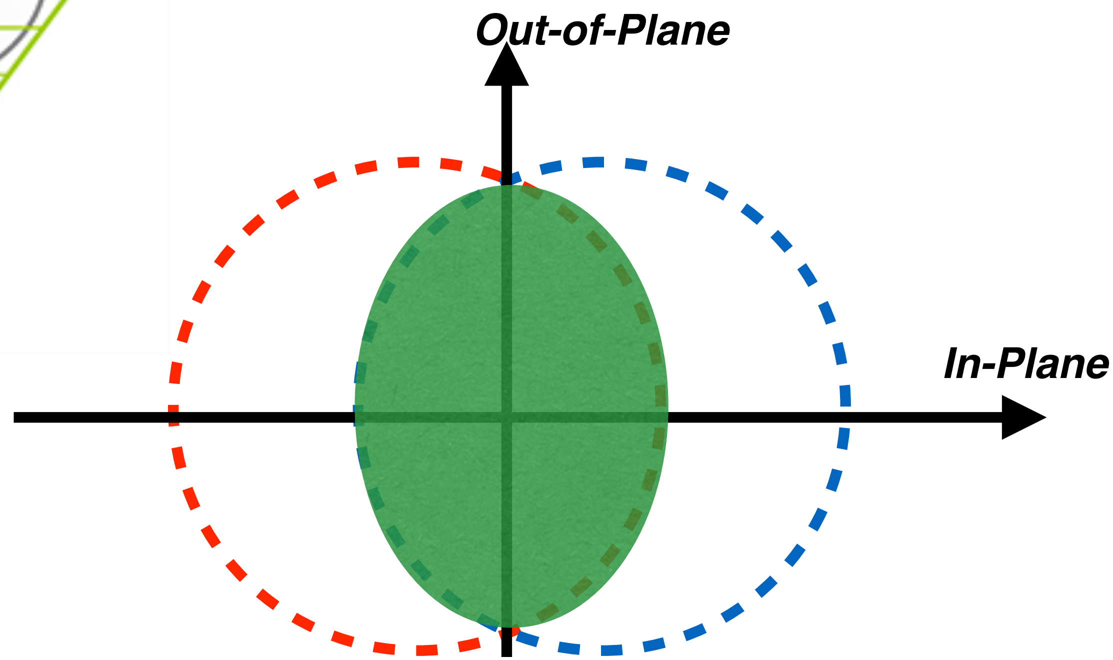
Search for CME at RHIC & LHC

[See Fuqiang's talk]

Search for CME in Heavy Ion Collisions



The quark-gluon plasma is a subatomic CHIRAL MATTER.

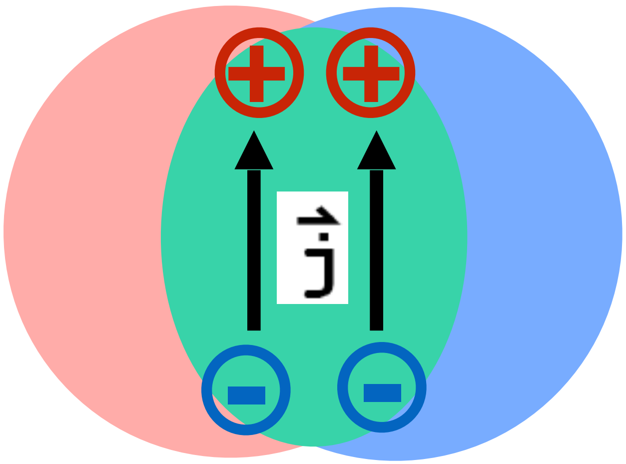


Can we observe CME in heavy ion collisions??

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

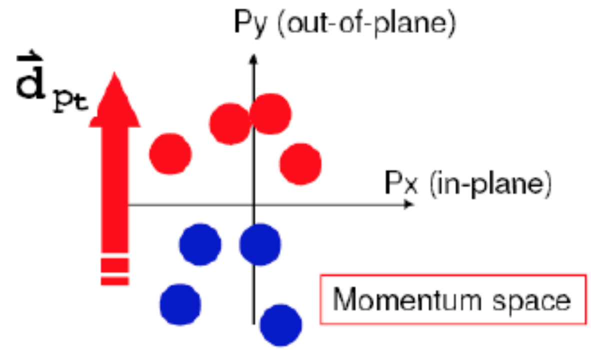
1) *(nearly) chiral quarks*
2) *chirality imbalance*
3) *strong magnetic field*

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***

Fighting with Backgrounds

A two-component decomposition model:

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

$\delta = F + H$

F: Bulk Background

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

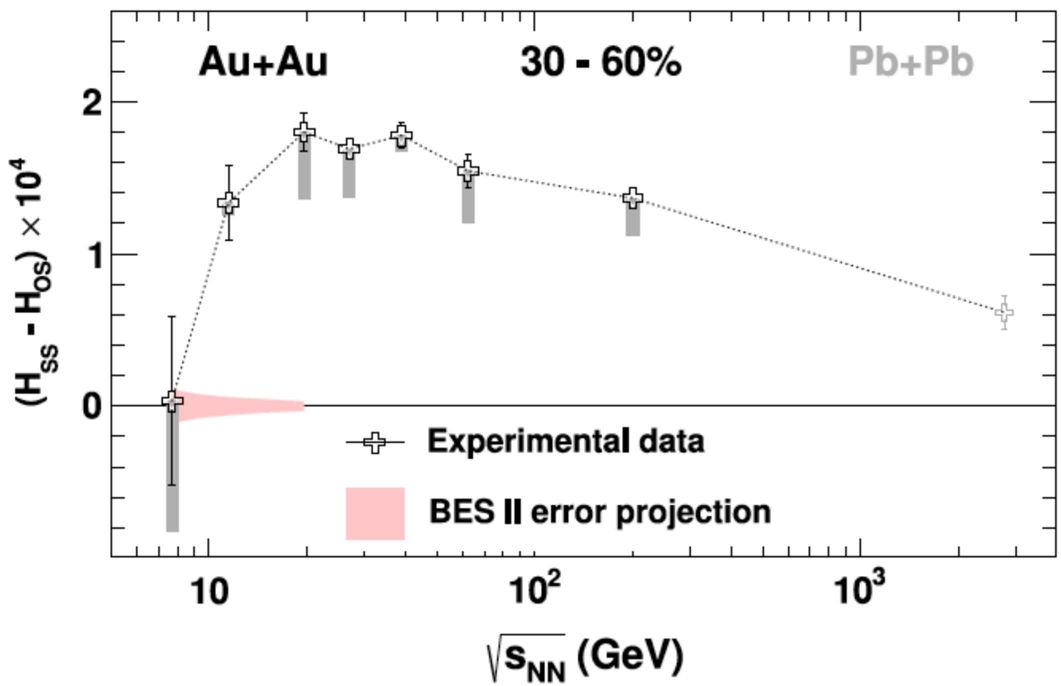
Bzdak, Koch, JL, 2012

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

Many interesting proposals of new observables!

Vary v2 for fixed B:
AuAu v.s. UU;
Varying event-shape;
2-component subtraction.

Vary B for fixed v2:
Isobaric collisions with
RuRu v.s. ZrZr

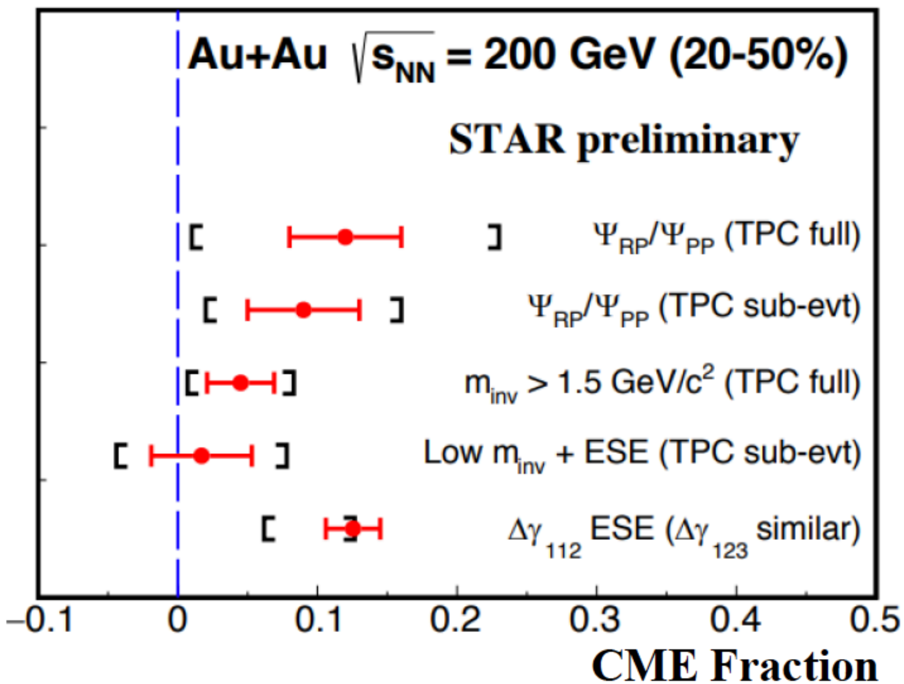


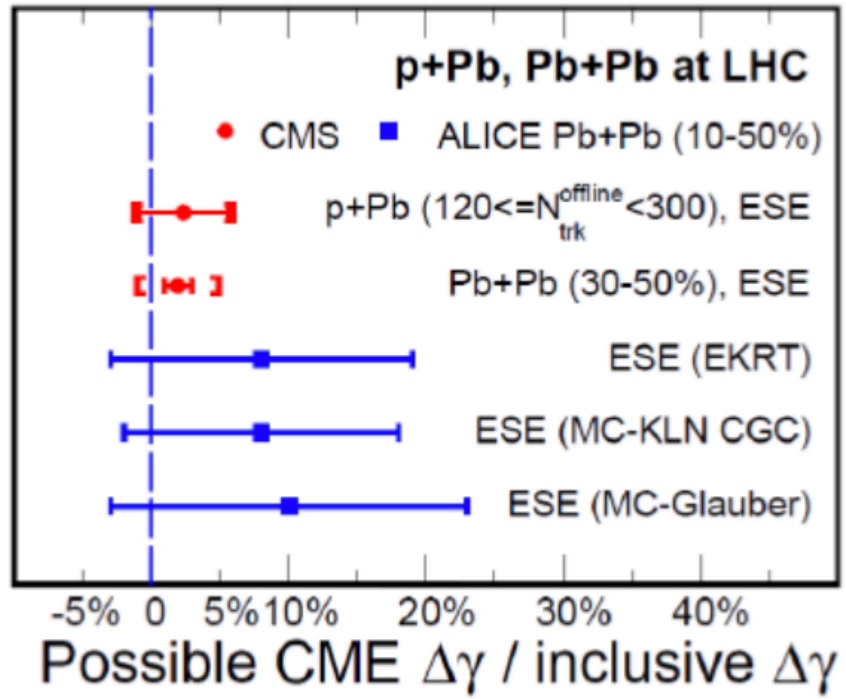
STAR PRL2014

Current Experimental Status for CME

Key challenge: weak signal versus strong backgrounds.

Many new measurements at RHIC and LHC:
gamma correlator + certain procedure to constrain backgrounds





Lacey, Magdy, et al: R-correlator consistent with a1~1% at RHIC

Current data provide encouraging hints, esp. @ RHIC energy!

Need quantitative modeling of signal+bkg to help exp search!

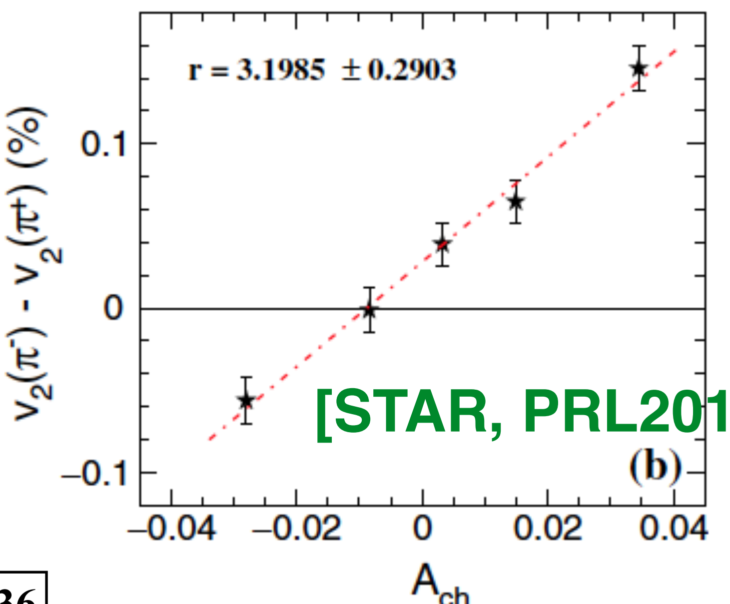
Chiral Magnetic Wave

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

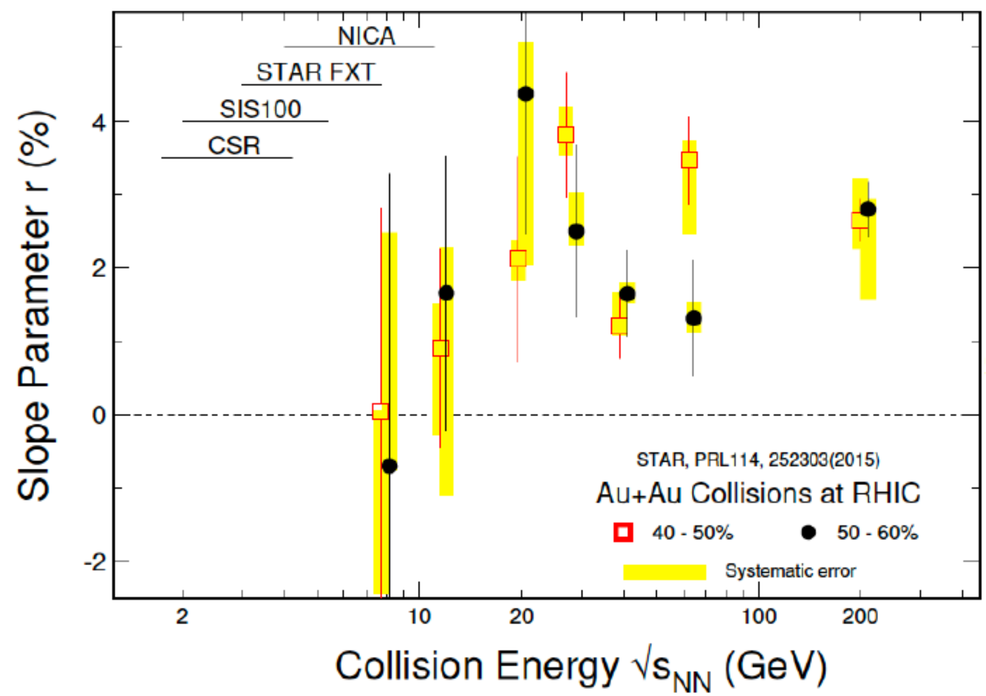
[Burnier, Kharzeev, JL, Yee, PRL2011; & arXiv: 1208.2537]

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

charge quadrupole due to CMW transport



[STAR, PRL2015]



A consistent trend as CME: Turning-off at low energy

Quantitative Modeling of CME

Integrate CME into Bulk Evolution

*** Approach based on fluid dynamics (AVFD)**

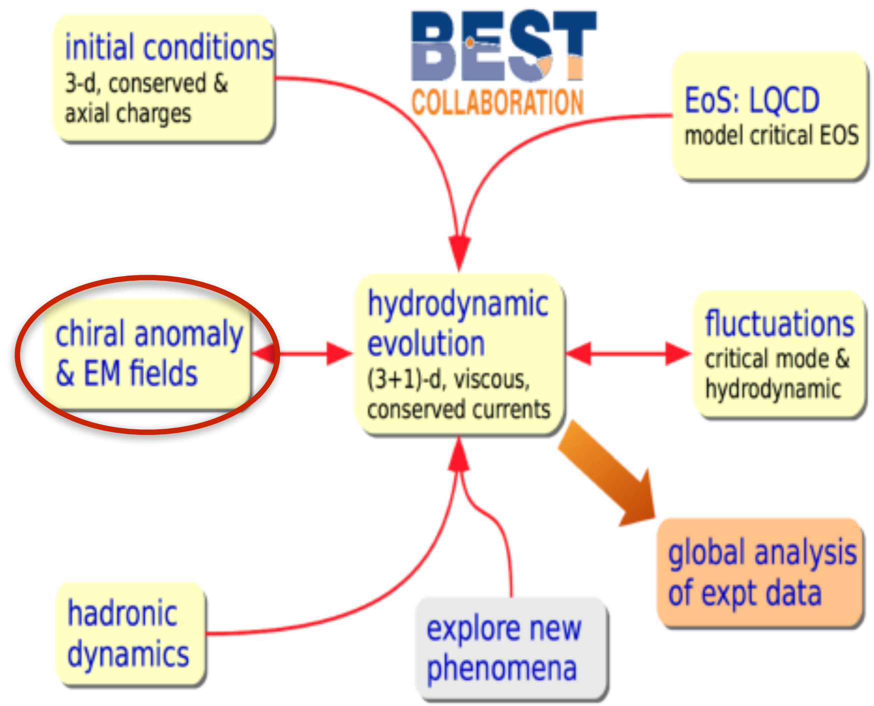
— our focus in this talk

*** Approach based on transport models.**

— AMPT based (Guoliang Ma, Yugang Ma, and collaborators)

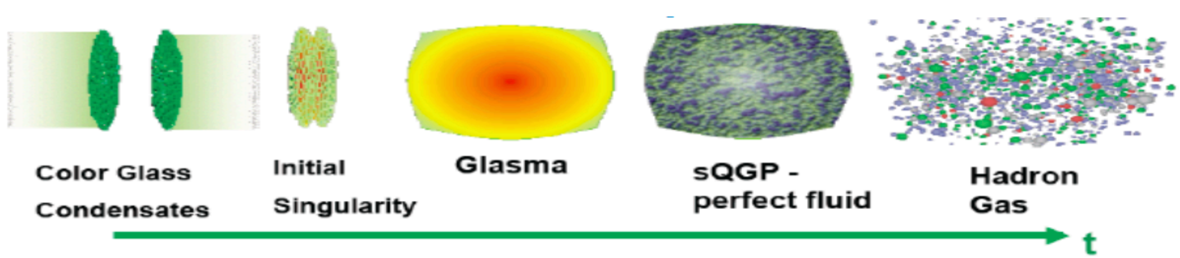
— Chiral kinetic transport based (Che-ming Ko and collaborators)

Beam Energy Scan Theory (BEST) Collaboration

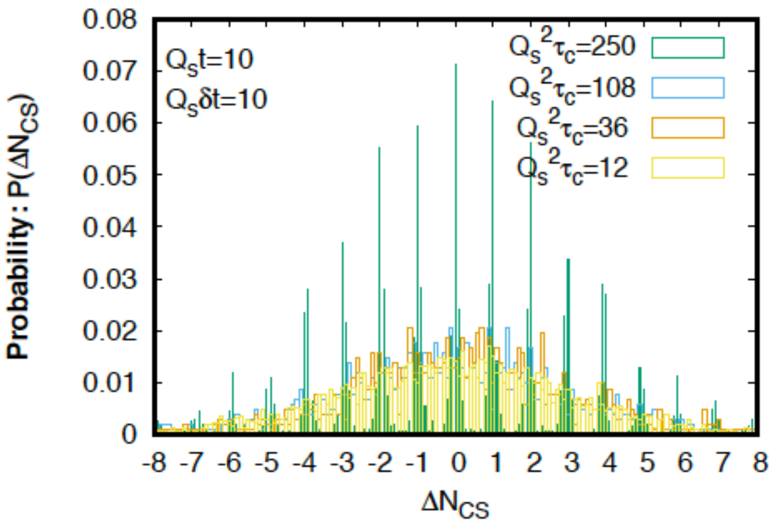


CME Working Group

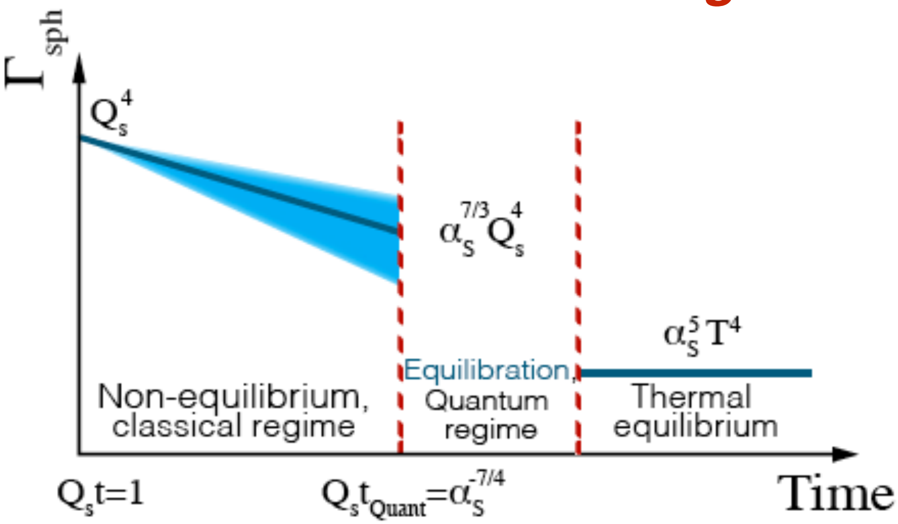
- ***Initial conditions***
- ***Dynamical magnetic fields***
- ***Non-equilibrium anomalous transport coefficient***
- ***Fluid dynamics framework with anomalous current***
- ***Quantification of both signal and backgrounds***



Axial Charge Initial Conditions



Important information at the initial stages



In the glasma framework:

**** Computed topological Chern-Simons number evolution***

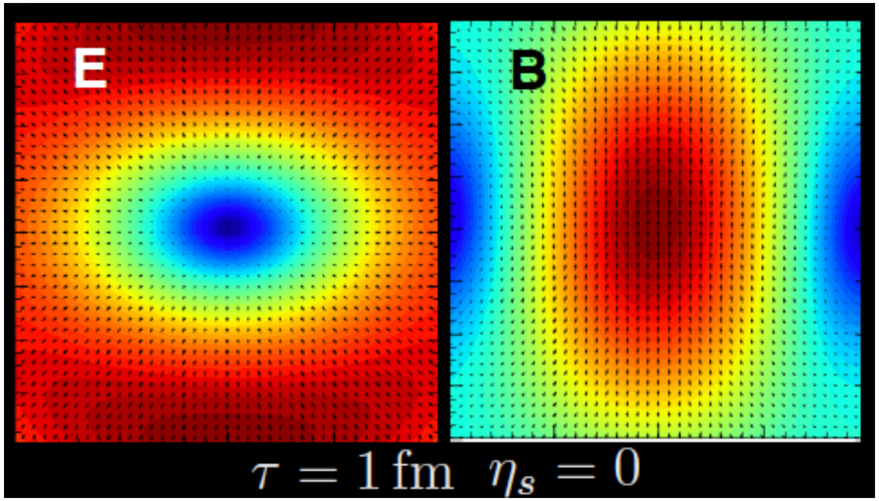
**** Extracted significant non-equilibrium sphaleron rate***

**** Anomalous transport during the pre-thermal stage***

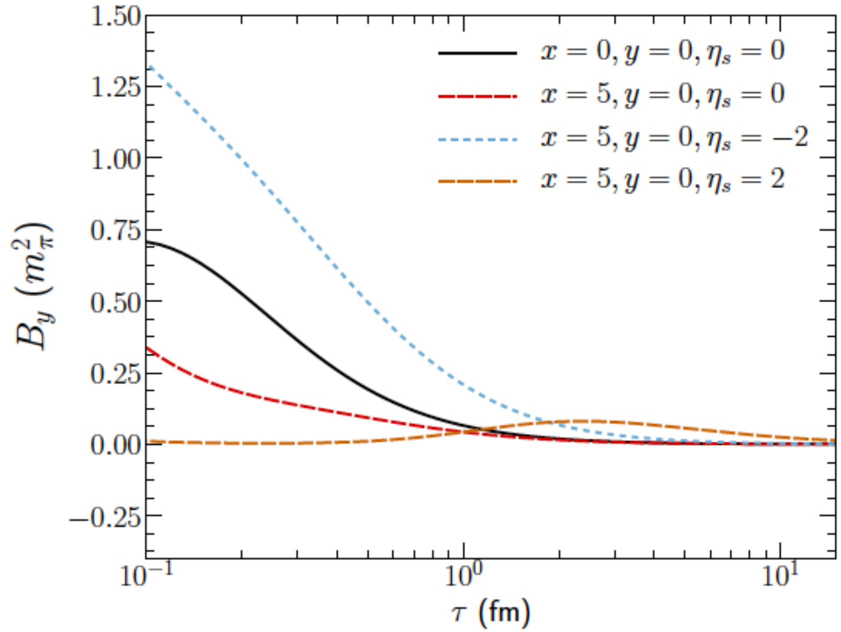
[Mace, Schtliting, Venugopalan, PRD2016; Mace, Muller, Schtliting, Sharma,PRD2017]

Will be integrated into the initial condition for further modeling of CME during hydro stage

Dynamical Magnetic Fields



Important information at the initial stages



A significant step forward toward full magneto-hydrodynamics (MHD)

Code package available:

https://bitbucket.org/bestcollaboration/heavy-ion-em-fields

[Gursoy, Kharzeev, Rajagopal,Shen, et al, PRC2018]

A viable and practical way to integrate dynamical B field!

Attempting Anomalous Hydro

Physics Letters B 756 (2016) 42–46

Contents lists available at ScienceDirect

Physics Letters B

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PHYSICS LETTERS B

Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

CrossMark

Yi Yin[a,*], Jinfeng Liao[b,c]

[a] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[b] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[c] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA

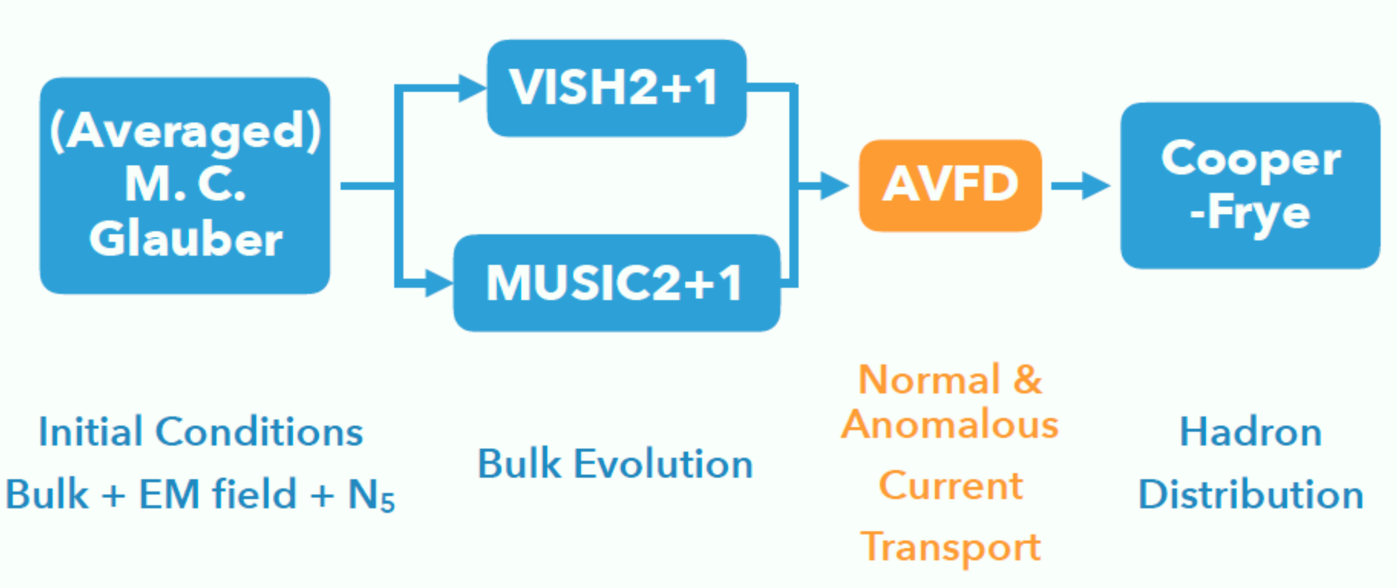
A good first try: albeit assuming ideal hydro charge transport.

To be consistent and realistic: need viscous + anomalous

[Yin, Liao, PLB2016]

AVFD Framework

Establishment of Anomalous-Viscous Fluid Dynamics (AVFD):
Hydrodynamical realization of CME in HIC.
[newest developments: EBE-AVFD; AVFD+axial dynamics; AVFD+LCC]



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

[S. Shi, JL, et al: arXiv:1611.04586; arXiv:1711.02496]

AVFD Framework

Note: bulk properties fully data-validated

[arXiv:1611.04586; arXiv:1711.02496]

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

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

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

CME

Viscous Effect

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

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

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

arXiv:1611.04586

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

Yin Jiang(姜寅)[1] Shuzhe Shi(施舒哲)[2] Yi Yin(尹伊)[3] Jinfeng Liao(廖劲峰)[2,4;1)]

[1] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[2] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[3] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
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Annals of Physics 394 (2018) 50–72

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ANNALS of PHYSICS

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

Check for updates

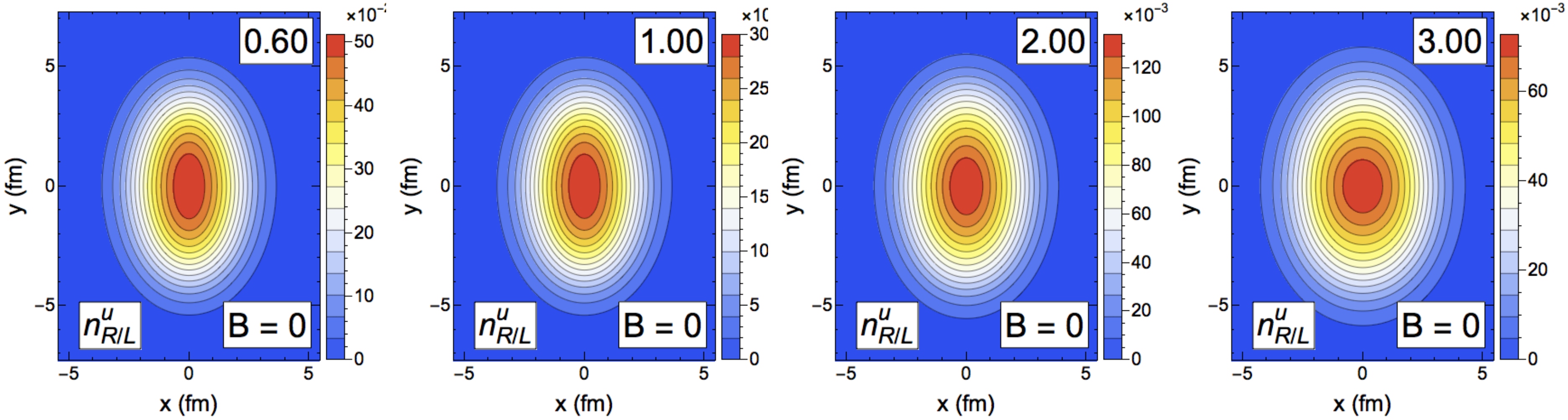
Shuzhe Shi [a,*], Yin Jiang [b,c], Elias Lilleskov [d,a], Jinfeng Liao [a,e,*]

arXiv:1711.02496

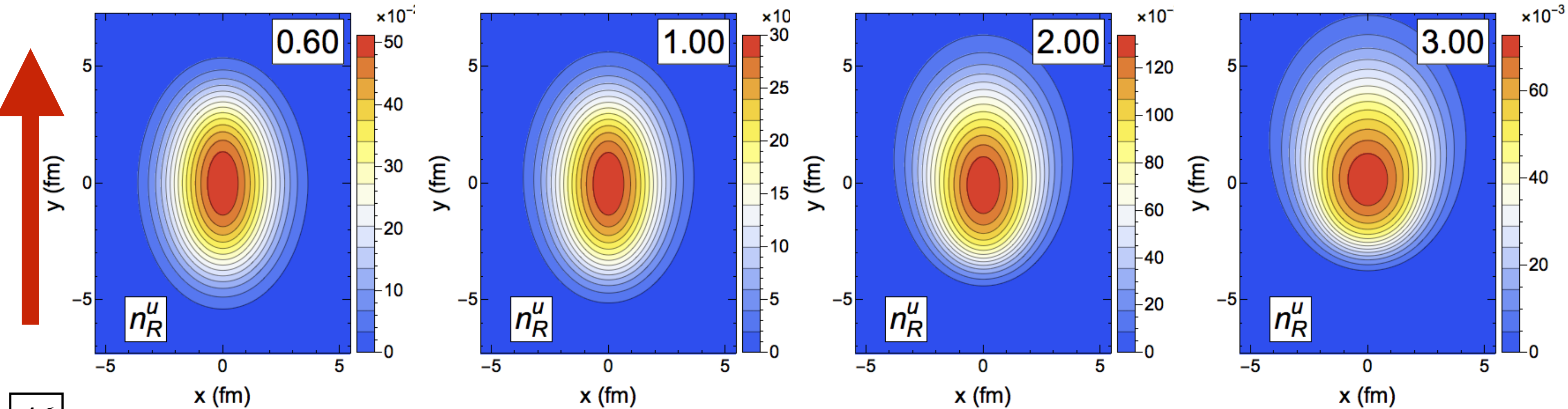
Shuzhe Shi
(McGill; PhD @ IUB)

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

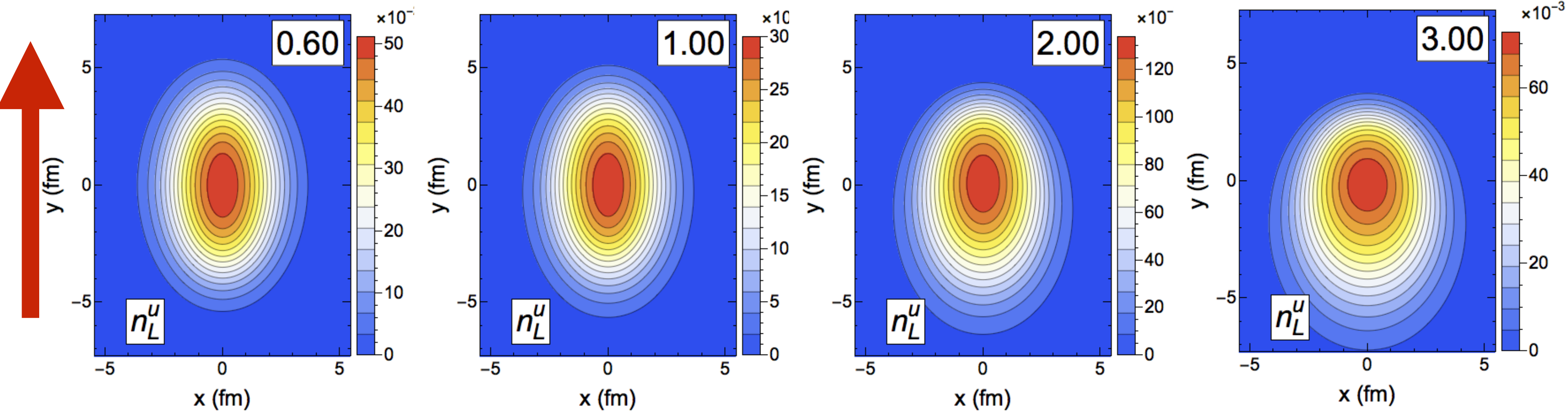
Demonstrating the AVFD



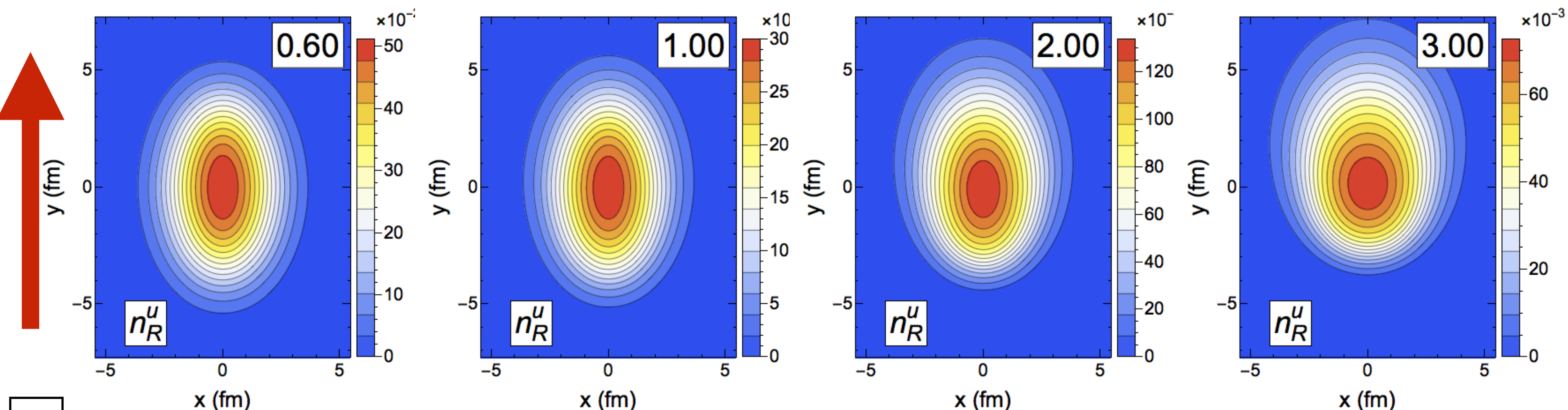
Upper: NO magnetic field
Lower: with B field (along y+ direction)



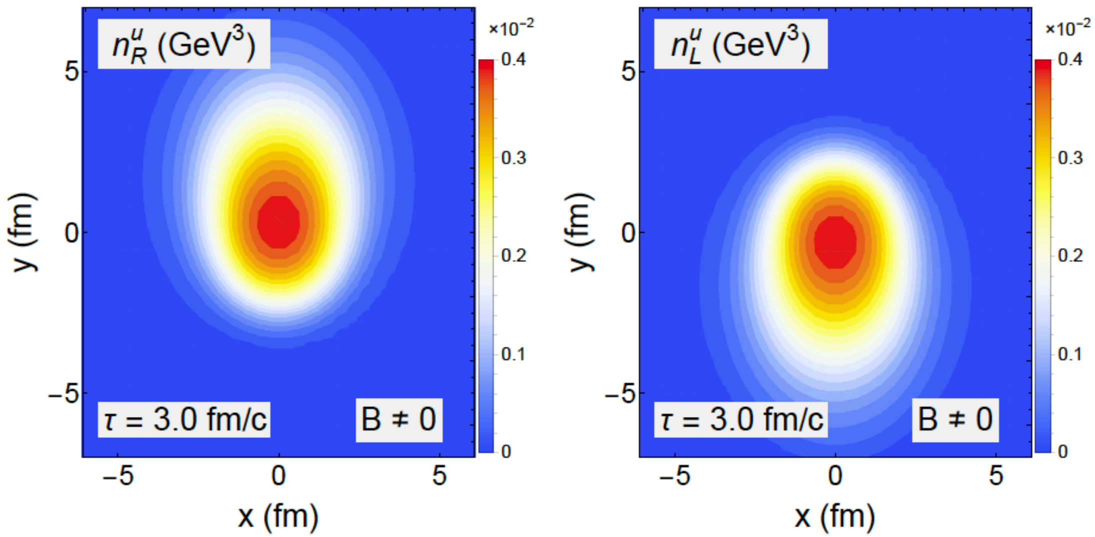
Demonstrating the AVFD



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

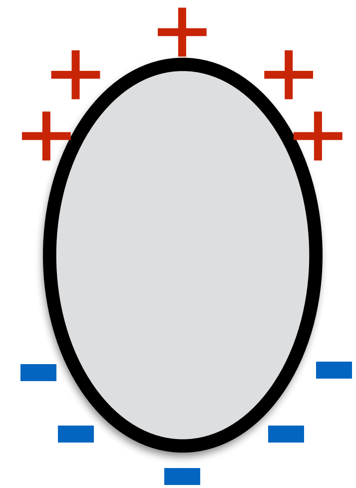


The Charge Separation from AVFD



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

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

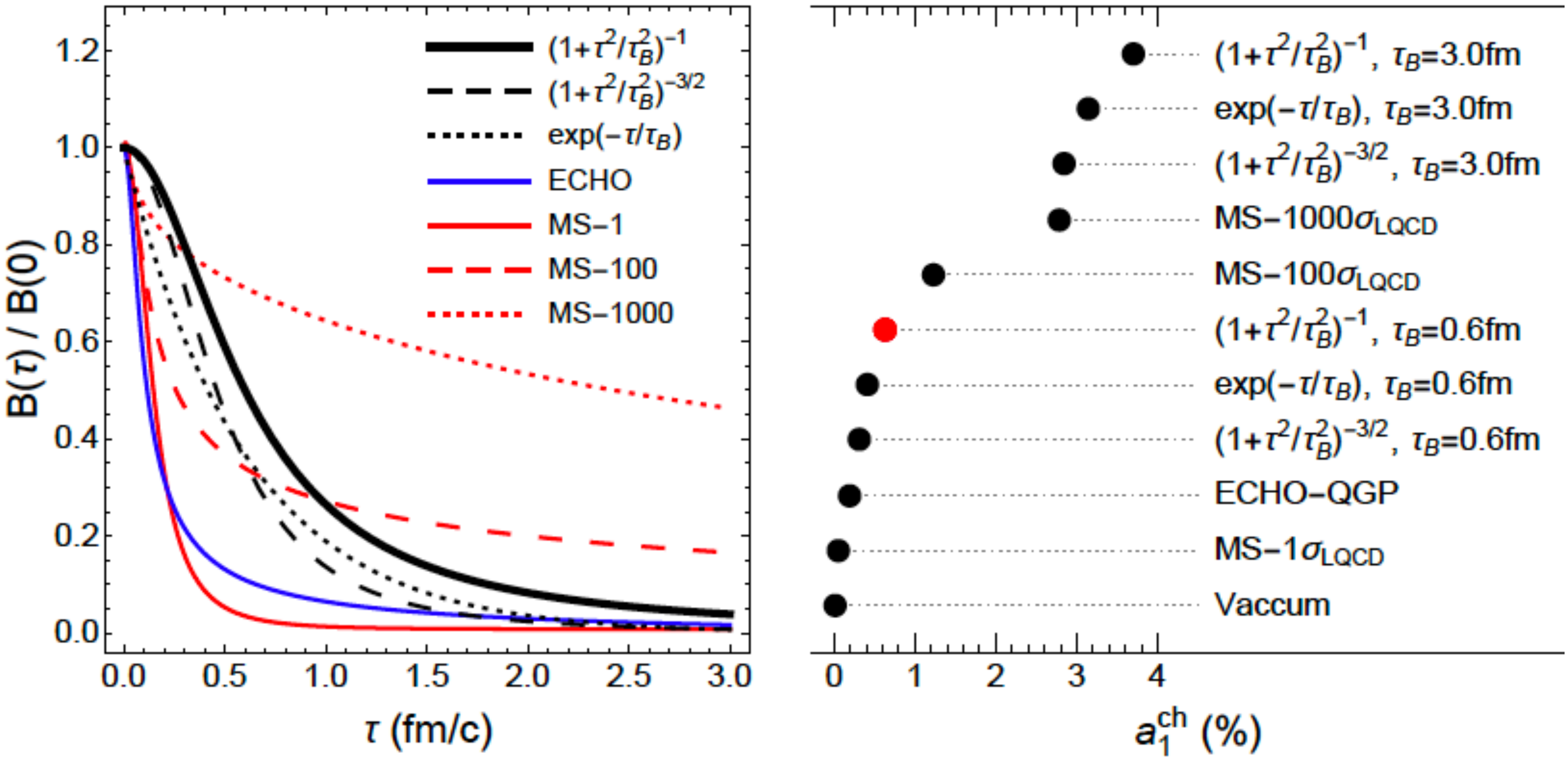


B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

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

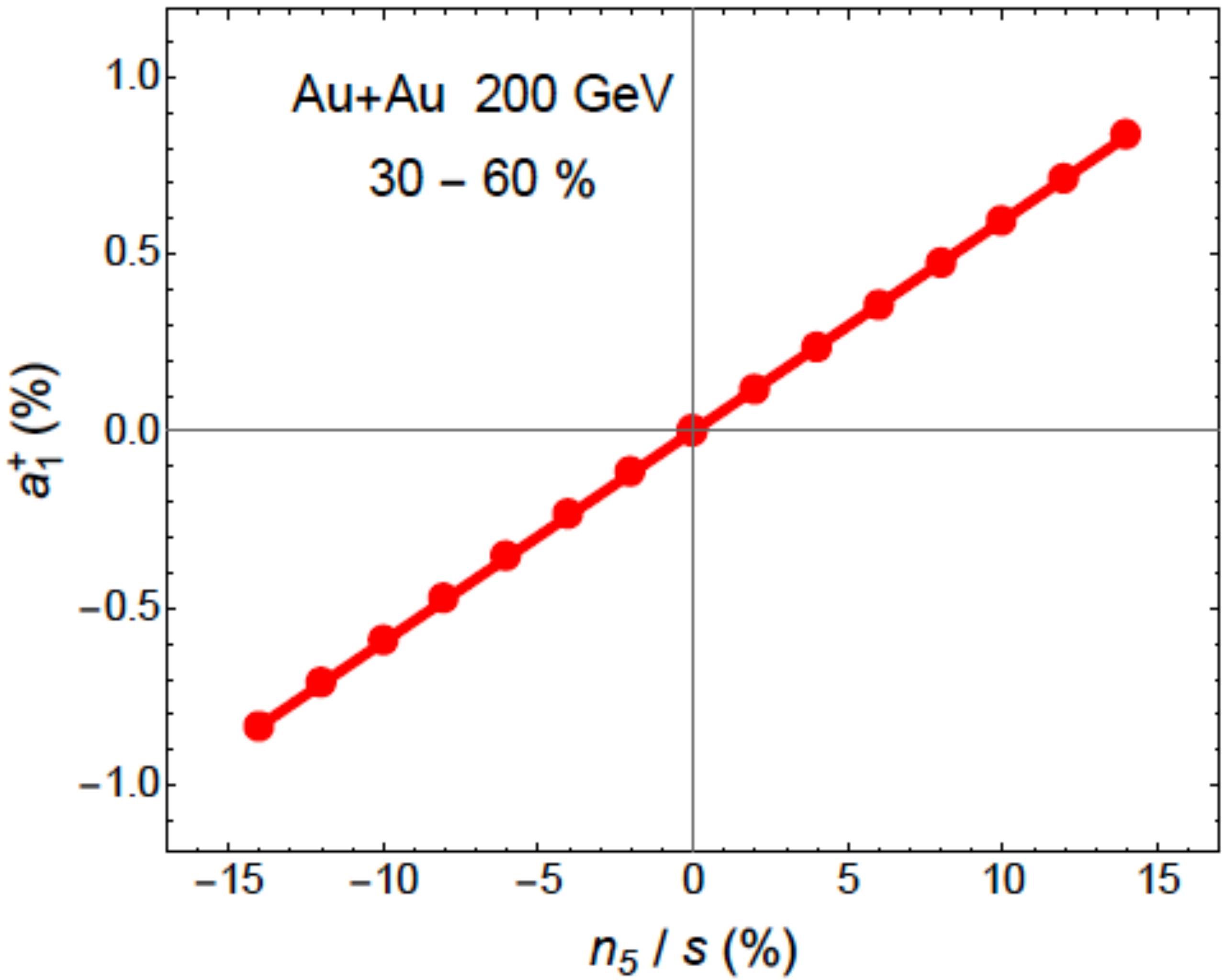
$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

The Influence of the Magnetic Field



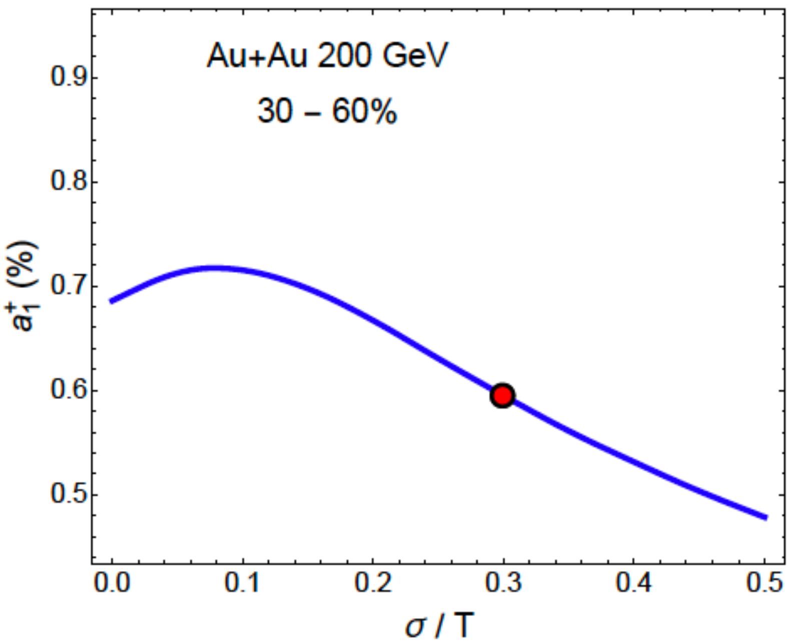
Strong influence by B field evolution;
Significant theoretical uncertainty!

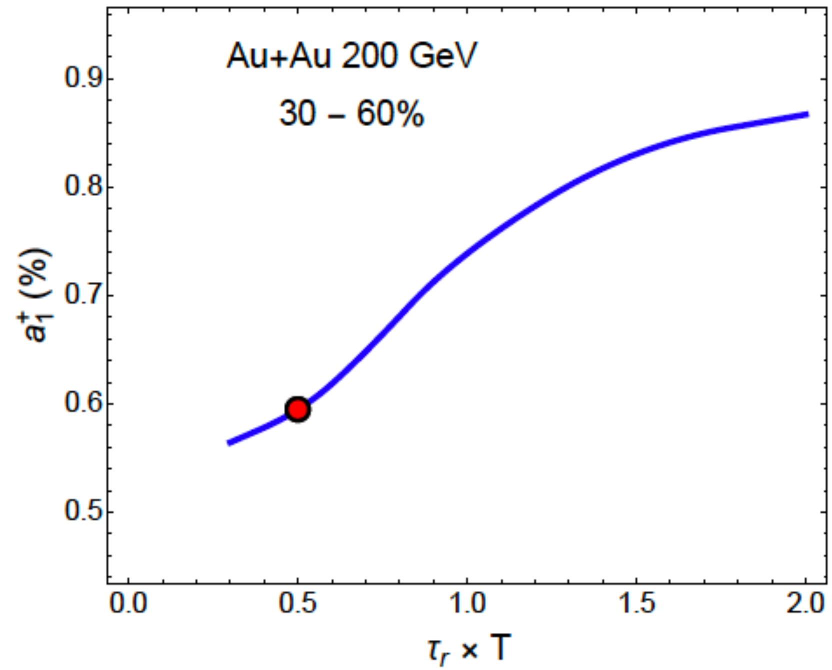
The Axial Charge Initial Condition



Very sensitive to initial axial charge; Significant theoretical uncertainty!

The Influence of the Viscous Transport



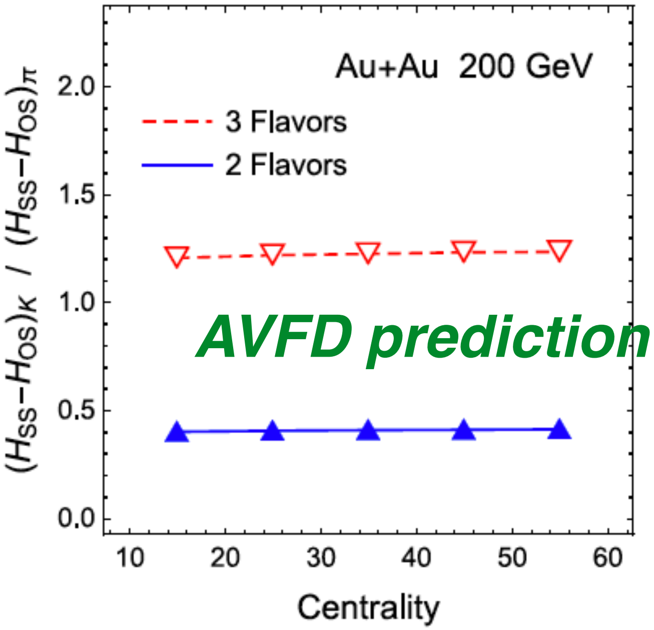


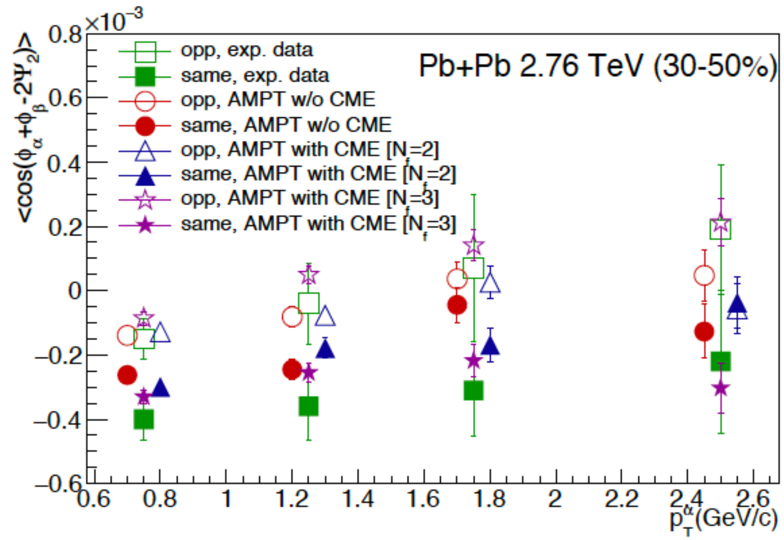
$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}\left(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu}\right)$$

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

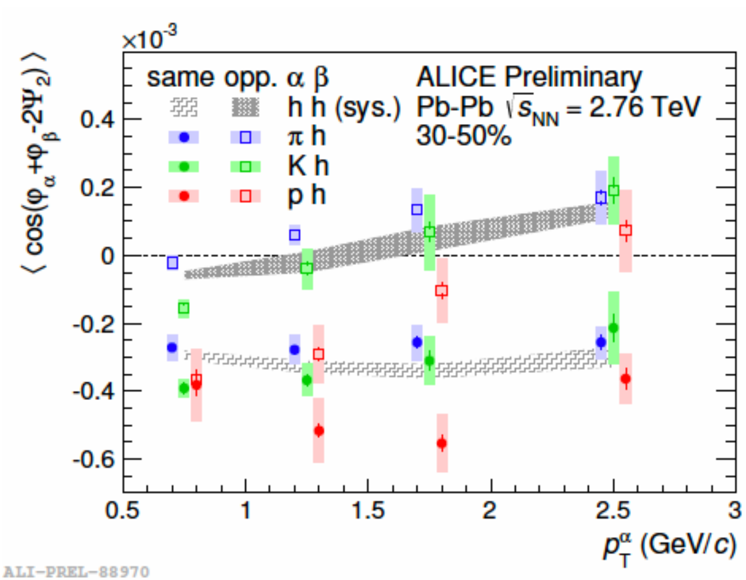
First calibration for the influence of the viscous transport on charge separation signal!

Flavor Dependence





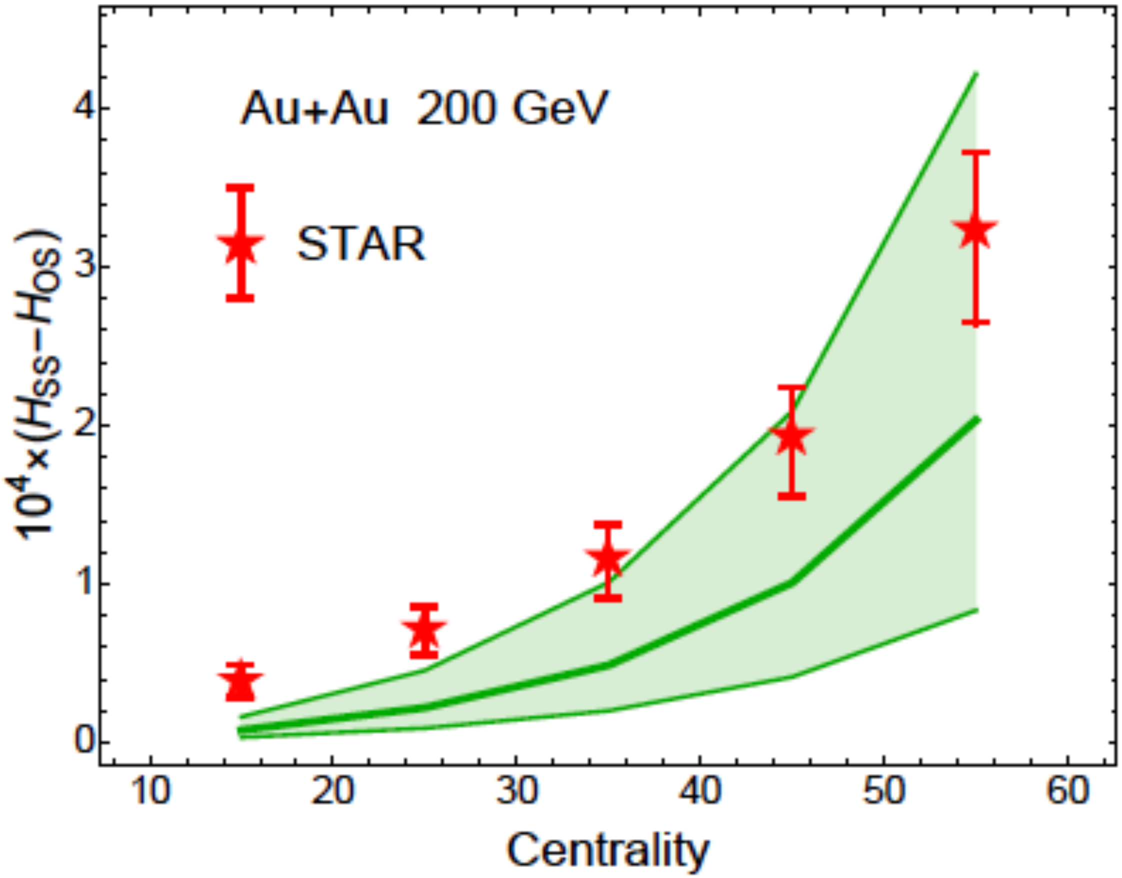
Huang, Ma, Ma, PRC2018



ALICE 2.76TeV

Kaons are sensitive to anomalous transport of s-quarks.

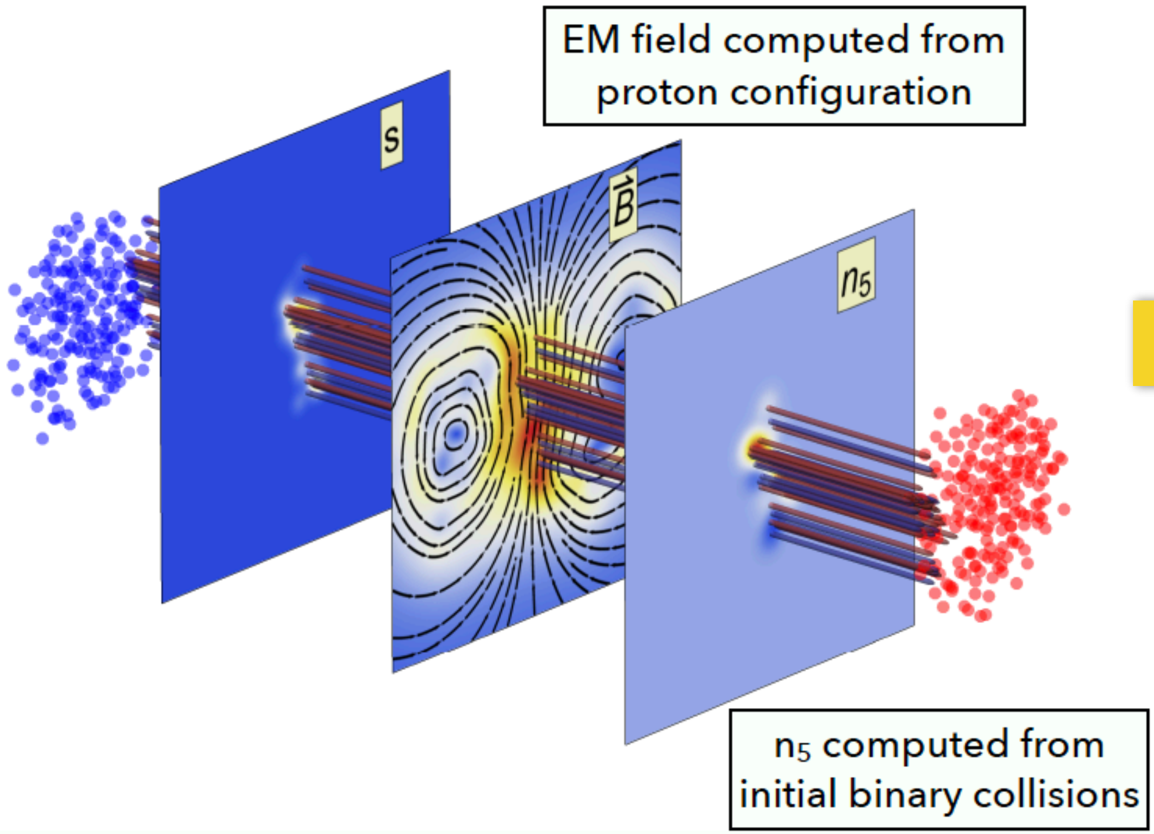
AVFD for AuAu Collisions



CME is quantitatively viable for describing relevant experimental observable.

***[A lot of detailed results in:
Shi, Yin, JL, …, arXiv:1611.04586; arXiv:1711.02496]***

Event-By-Event AVFD



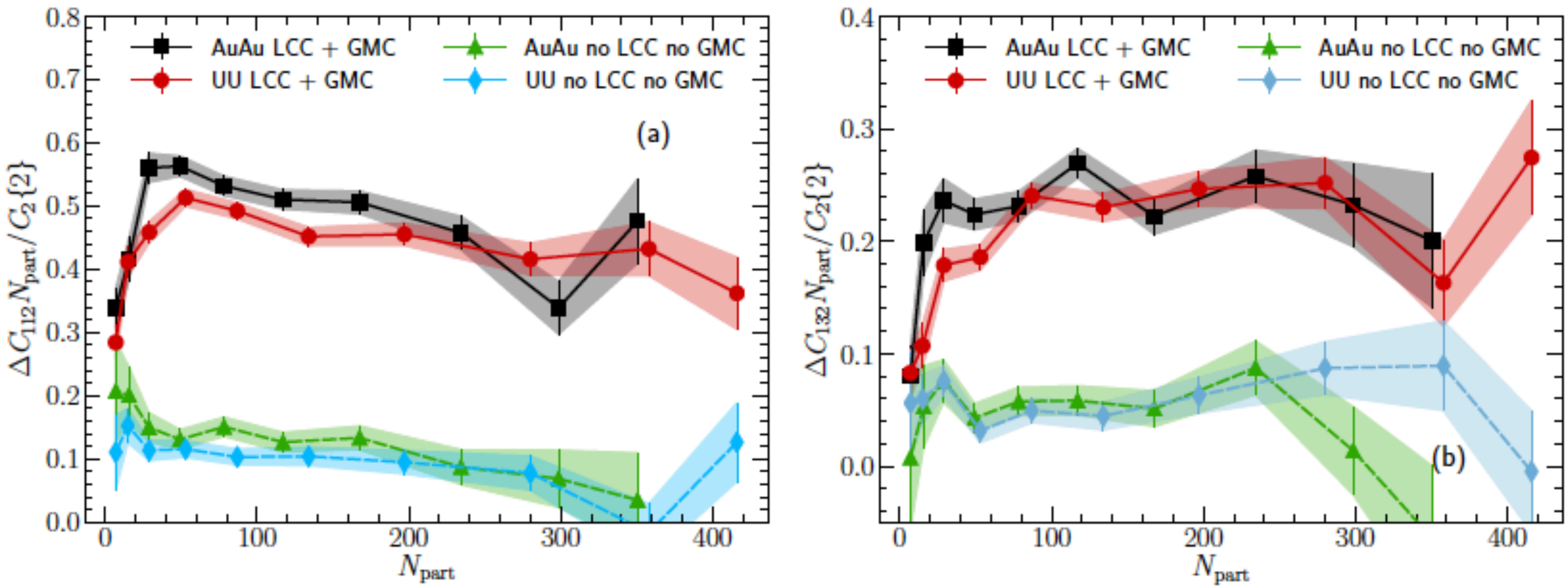
Include EBE fluctuations:

- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade
  (~ half of all bkg.)

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

Shuzhe Shi, Hui Zhang, Defu Hou, JL, to appear soon; QM2018 proceedings.

Implementing Local Charge Conservation (LCC)



To quantify background correlations in state-of-art hydro framework

[Schenke, Shen, Tribedy, 2019]

New development of particlization: the best way to quantify LCC

[Koch, Oliinychenko, 2019]

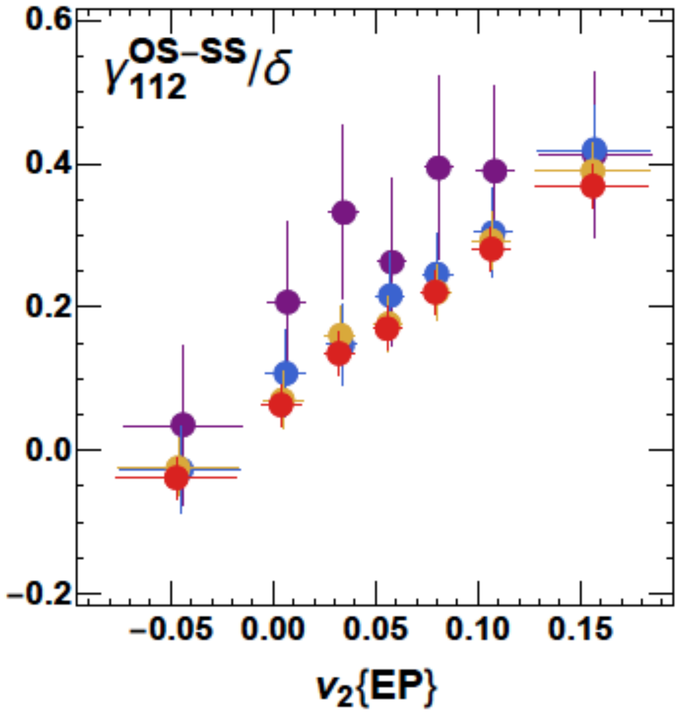
EBE-AVFD+LCC: Event Shape Engineering

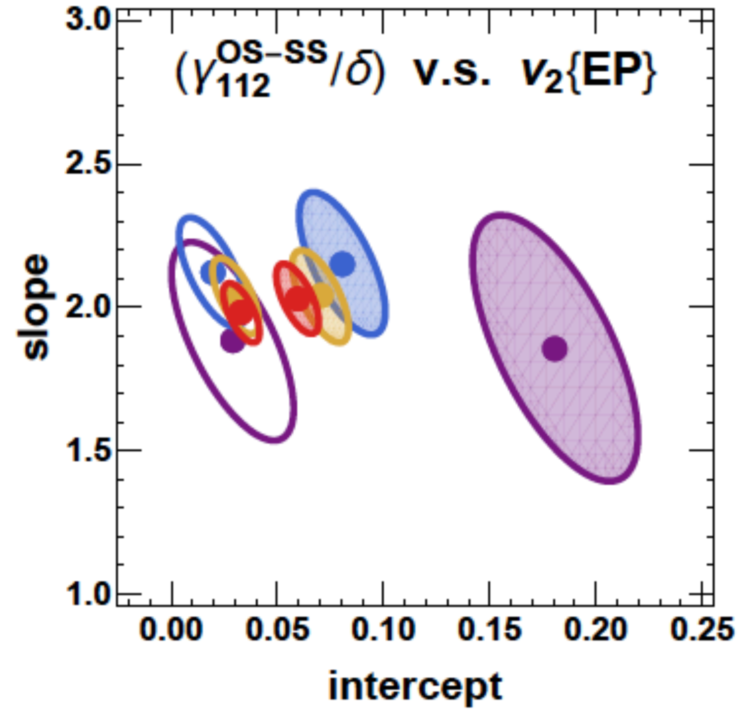
$\gamma = \kappa\, v_2\, F - H$

$\delta = F + H$

filled: w/ CME
open: w/o CME

P_{LCC} = 0.00, 0.33, 0.67, 1.00

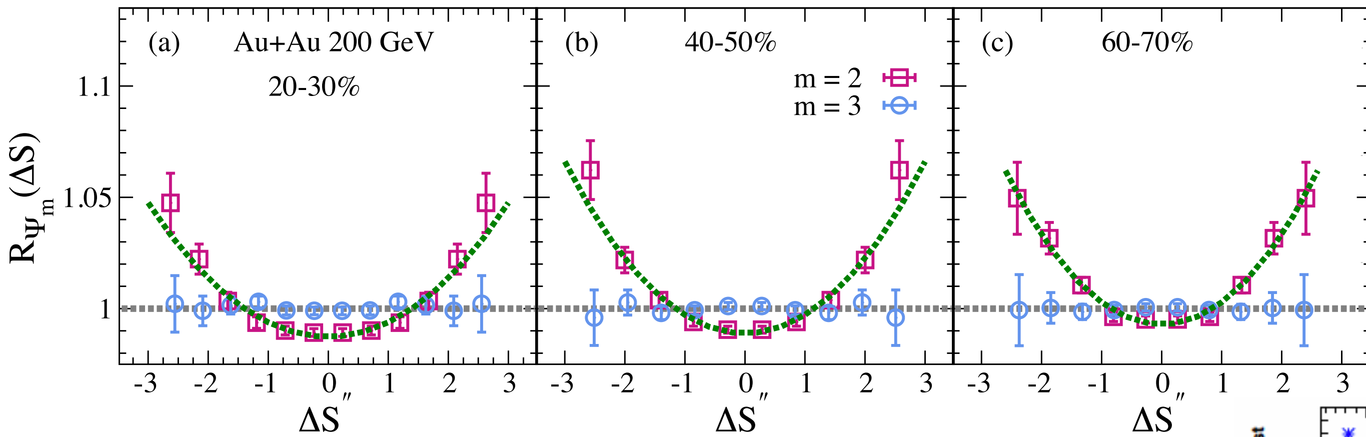




First time: full characterization of signal + known major backgrounds

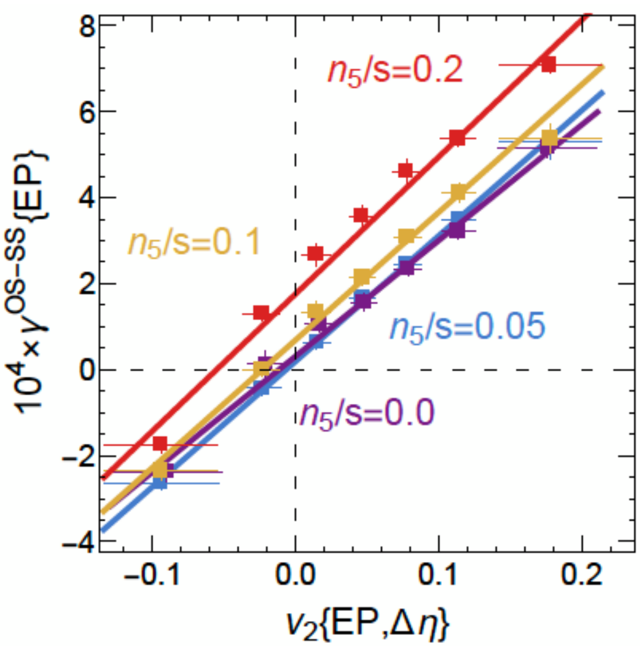
[Shi, JL, et al, in prepration.]

EBE-AVFD for Testing Observables

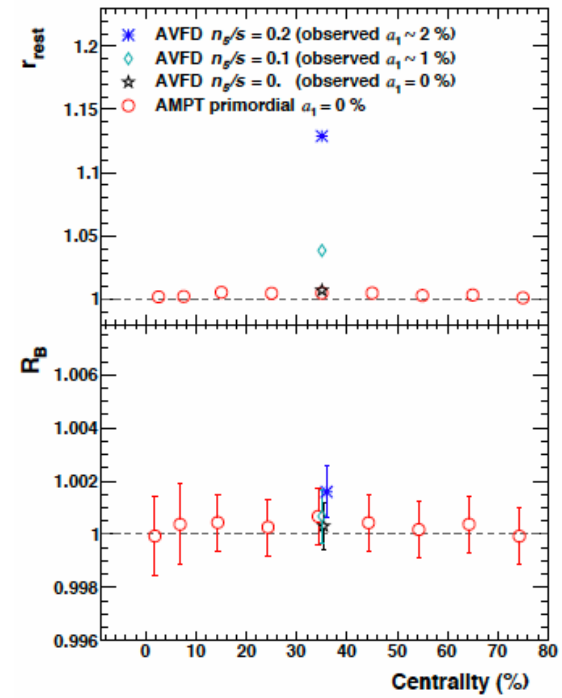


Lacey, Nagdy, et al

Tang



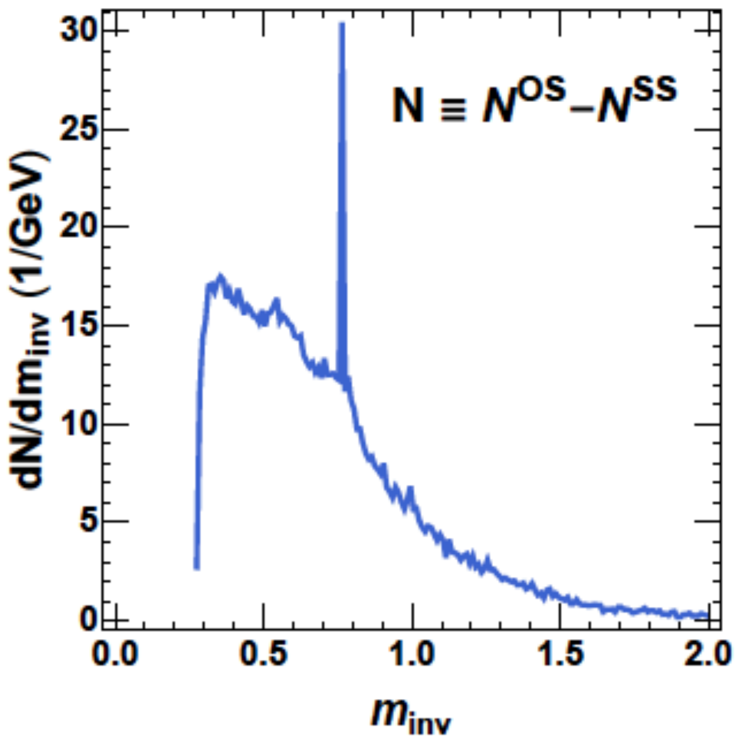
ESE

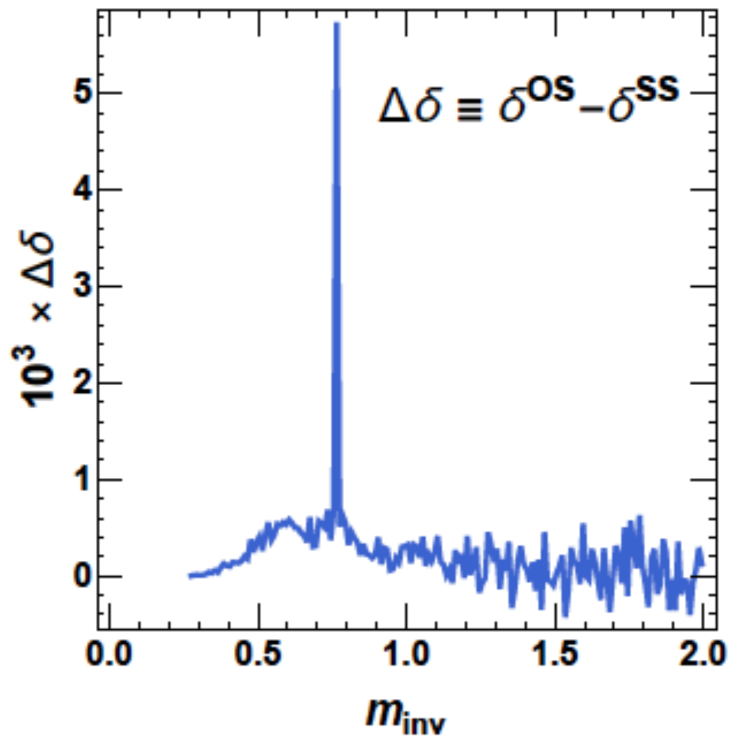


Now a key tool for understanding different observables' responses and sensitivity to signal and backgrounds

EBE-AVFD for Testing Observables

Invariant mass methods

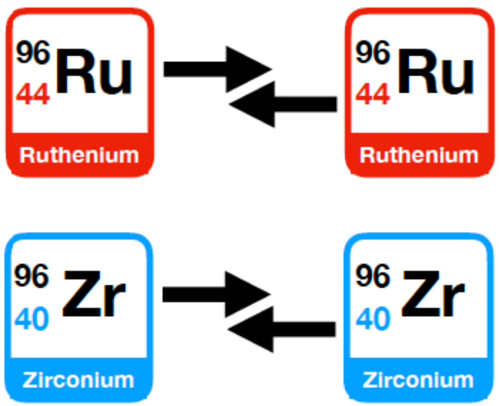




Isobaric Collision

A Decisive Experiment: Isobaric Collisions

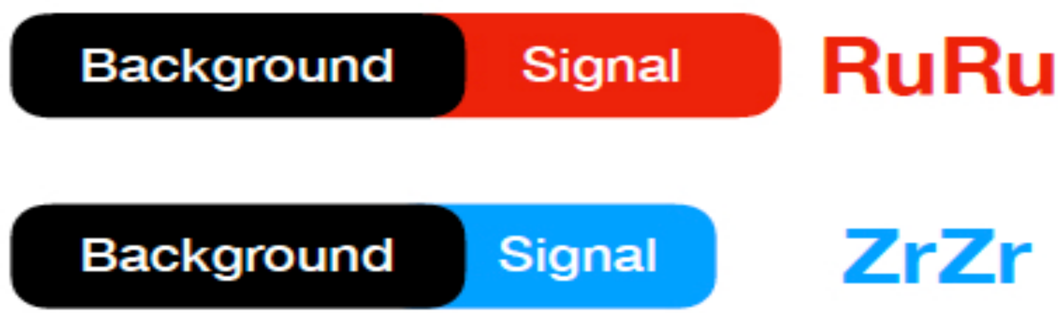
New opportunity of potential discovery: Isobaric Collision @ RHIC



[Koch, et al, arXiv: 1608.00982]

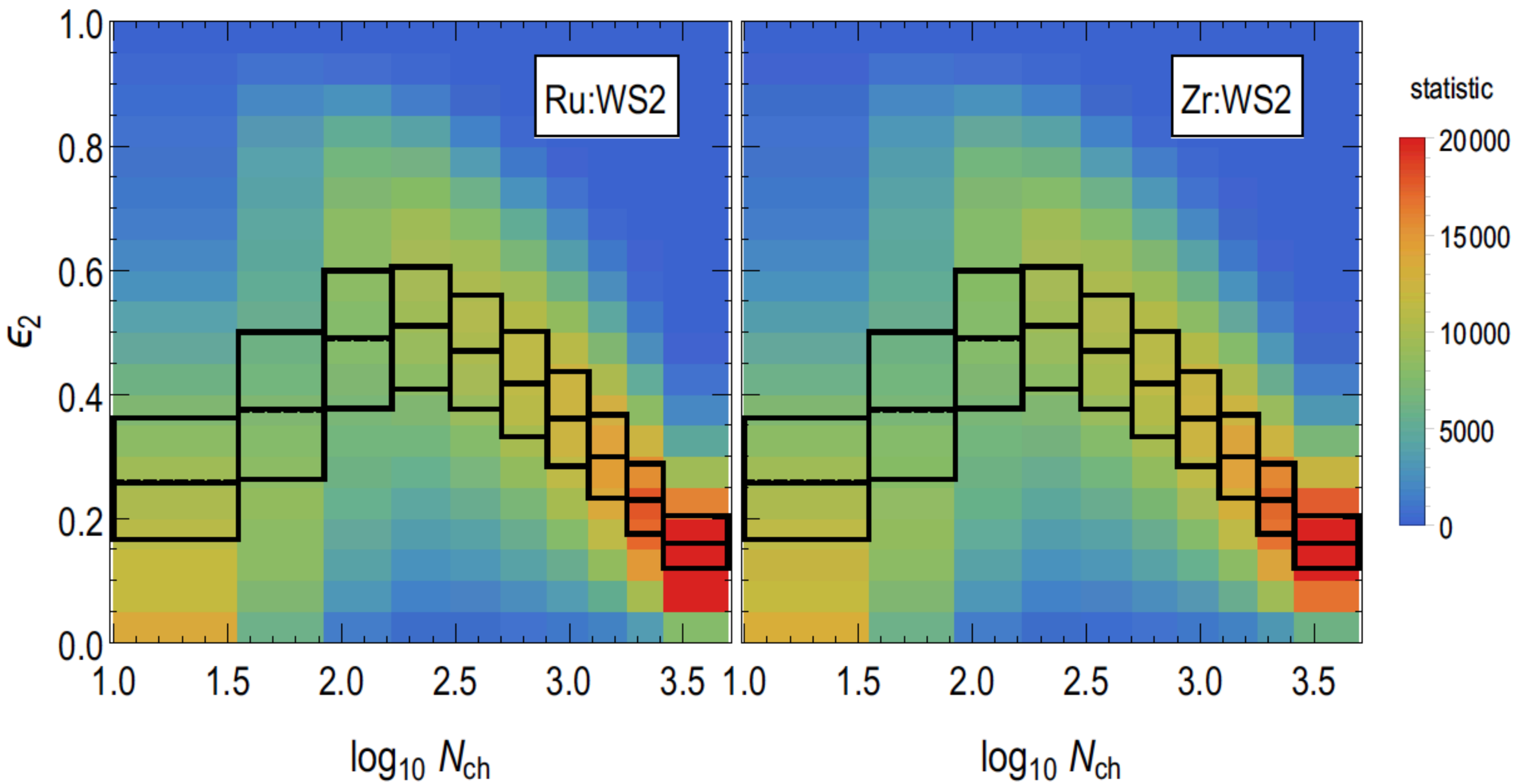
Key idea: contrasting two systems with identical bulk, varied magnetic fields.

Charge Asymmetry Correlation Measurement



~2 billion data collected successfully in RHIC 2018 run; processing and analysis underway!

Isobars: How to Choose Identical Systems?

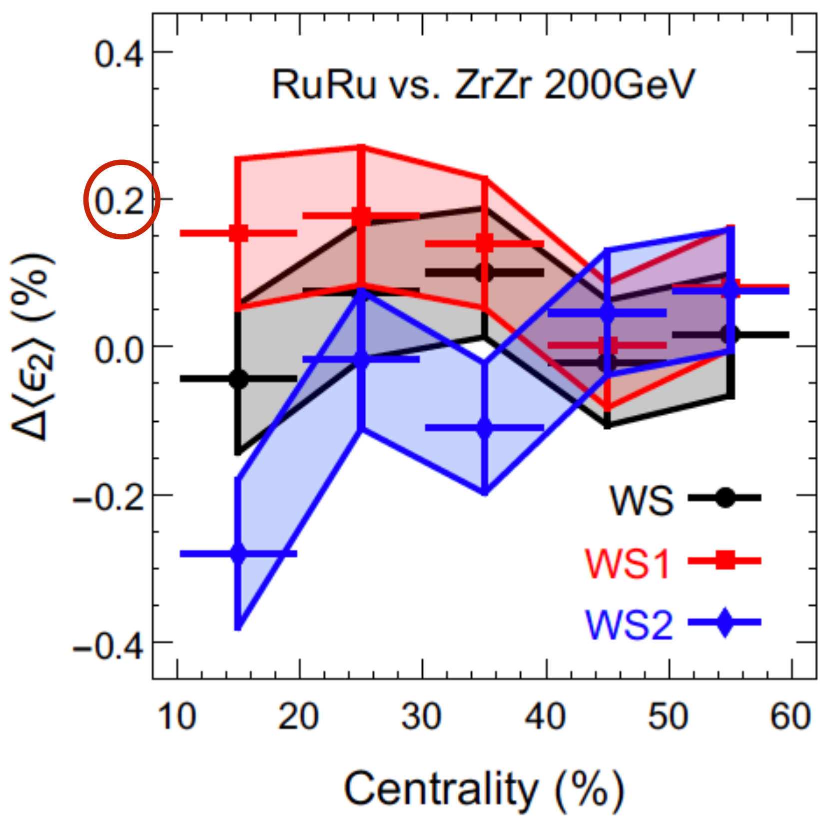


Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

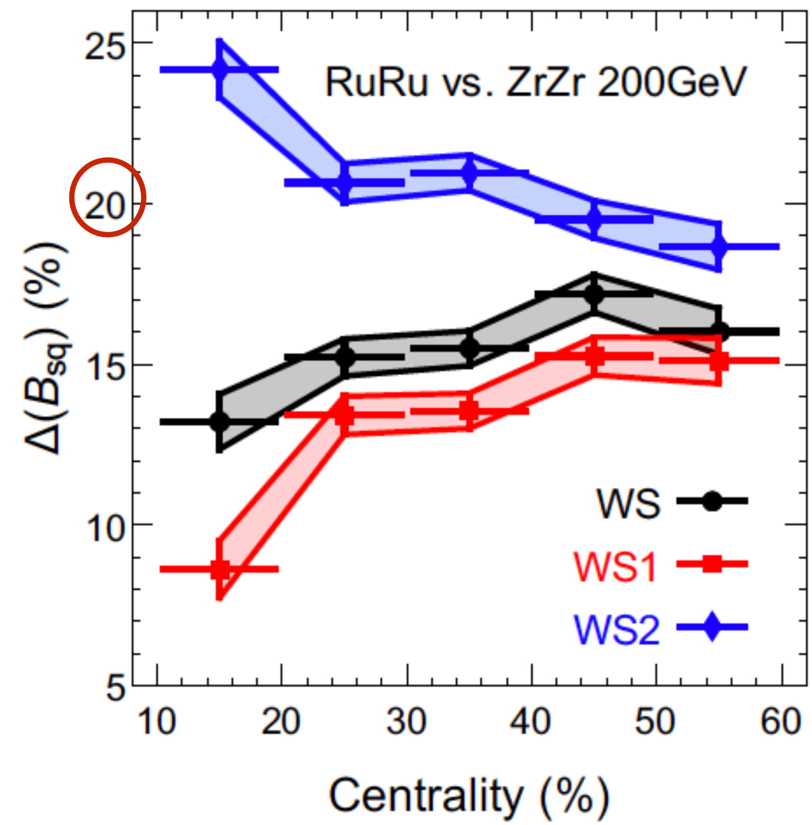
[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

Isobars: How to Choose Identical Systems?

Eccentricity is guaranteed the same!

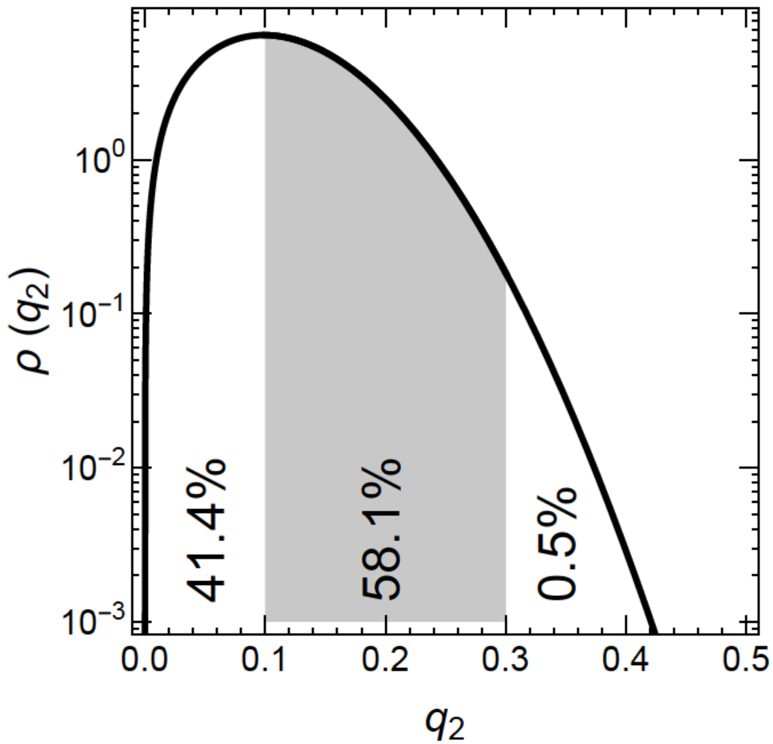


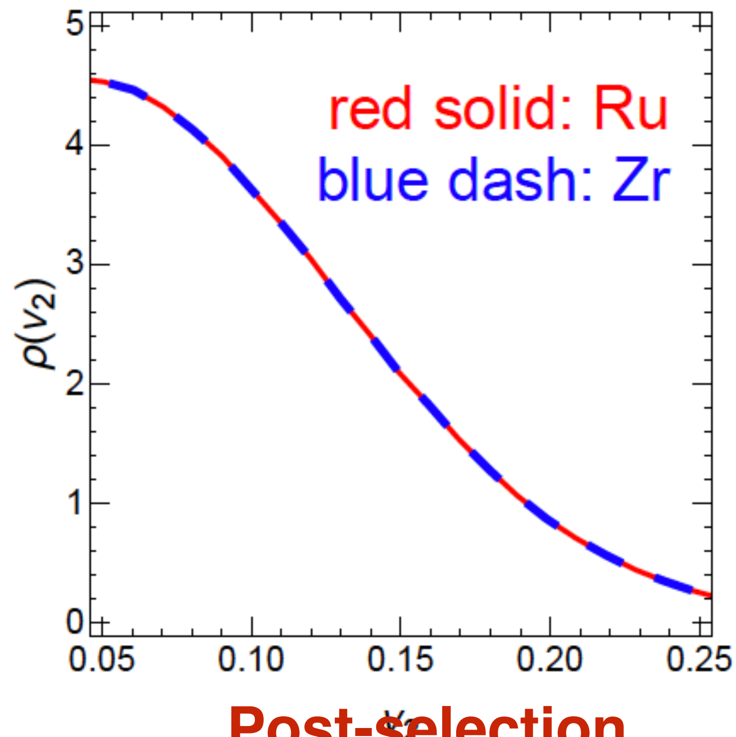
B field differs by 12~20% !



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

Analyzing Actual EBE-AVFD Events for Isobars





Millions of EBE-AVFD events: Subject to joint-cut

Post-selection double-check: Identical v2 !

$$64 < N_{ch,\,|y|<1} < 96$$

$$0.1 < q_2 < 0.3$$

Guaranteed to have two identical sample of isobar events for contrast!

AVFD Predictions for Isobars

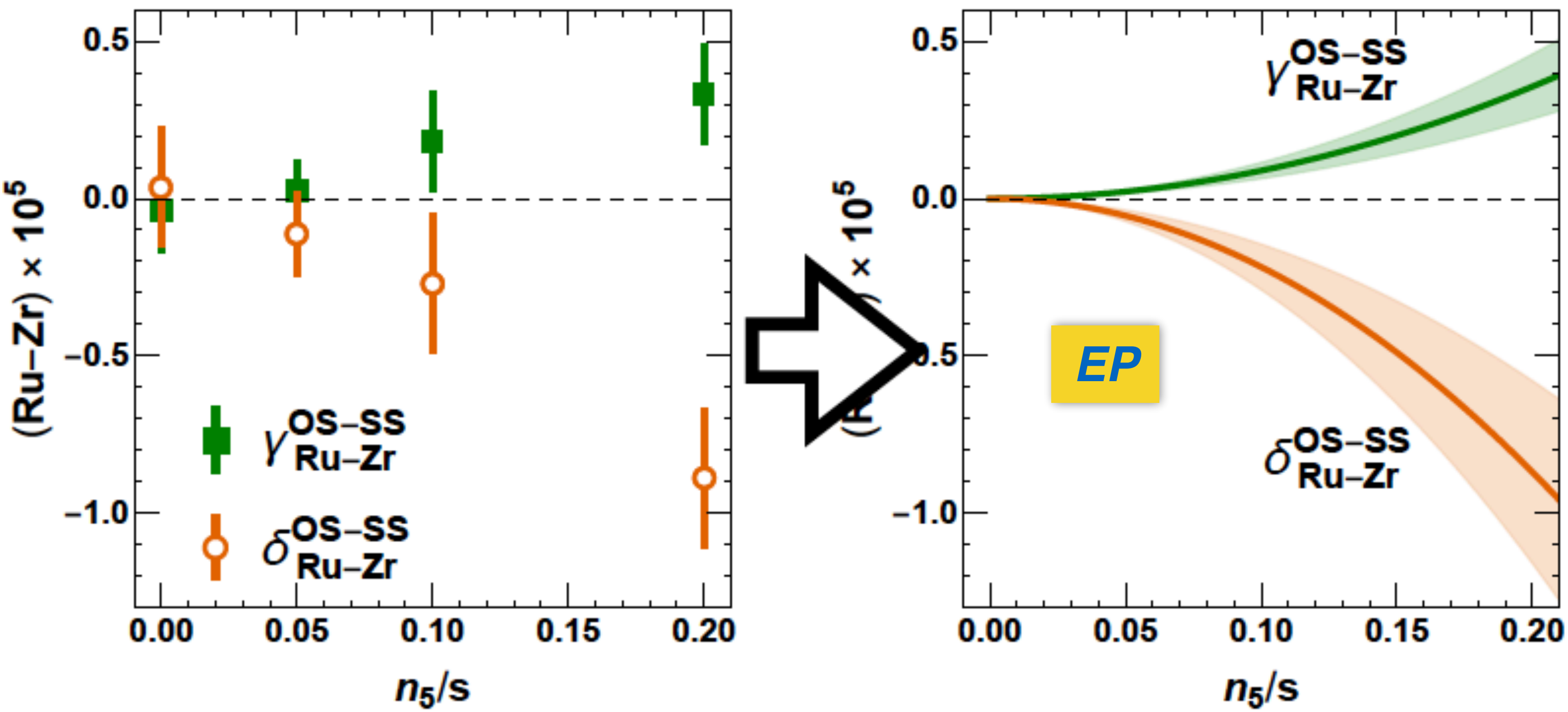
$-1 < \eta < 1$

$64 < N_{ch} < 96$

$0.05 < v_2^{ref} < 0.25$

Statistics: 10^7 events in AVFD simulation

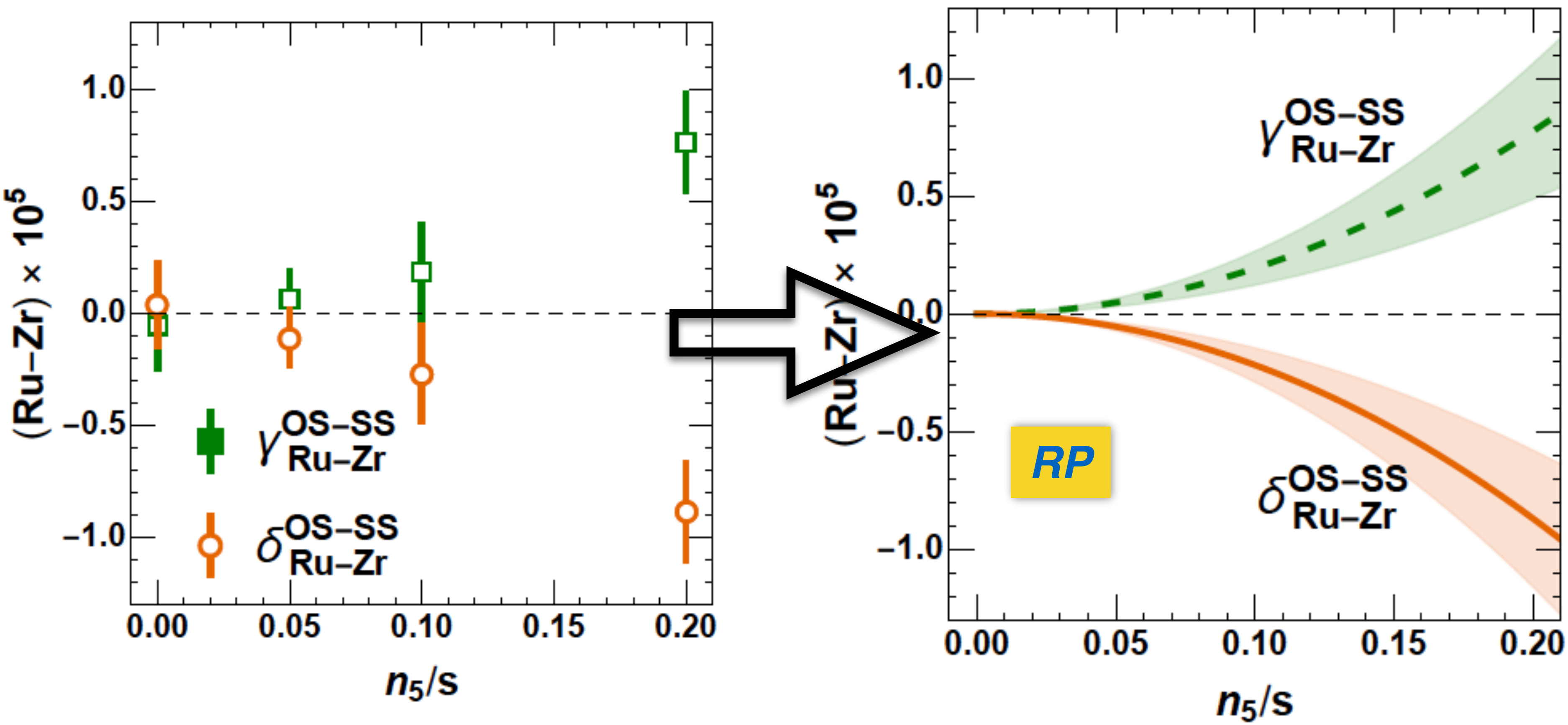
~ 3×10^8 events in experiment



Look for absolute difference between isobars (after joint-cut)!
Look for consistency between delta- and gamma-correlators!

[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

AVFD Predictions for Isobars



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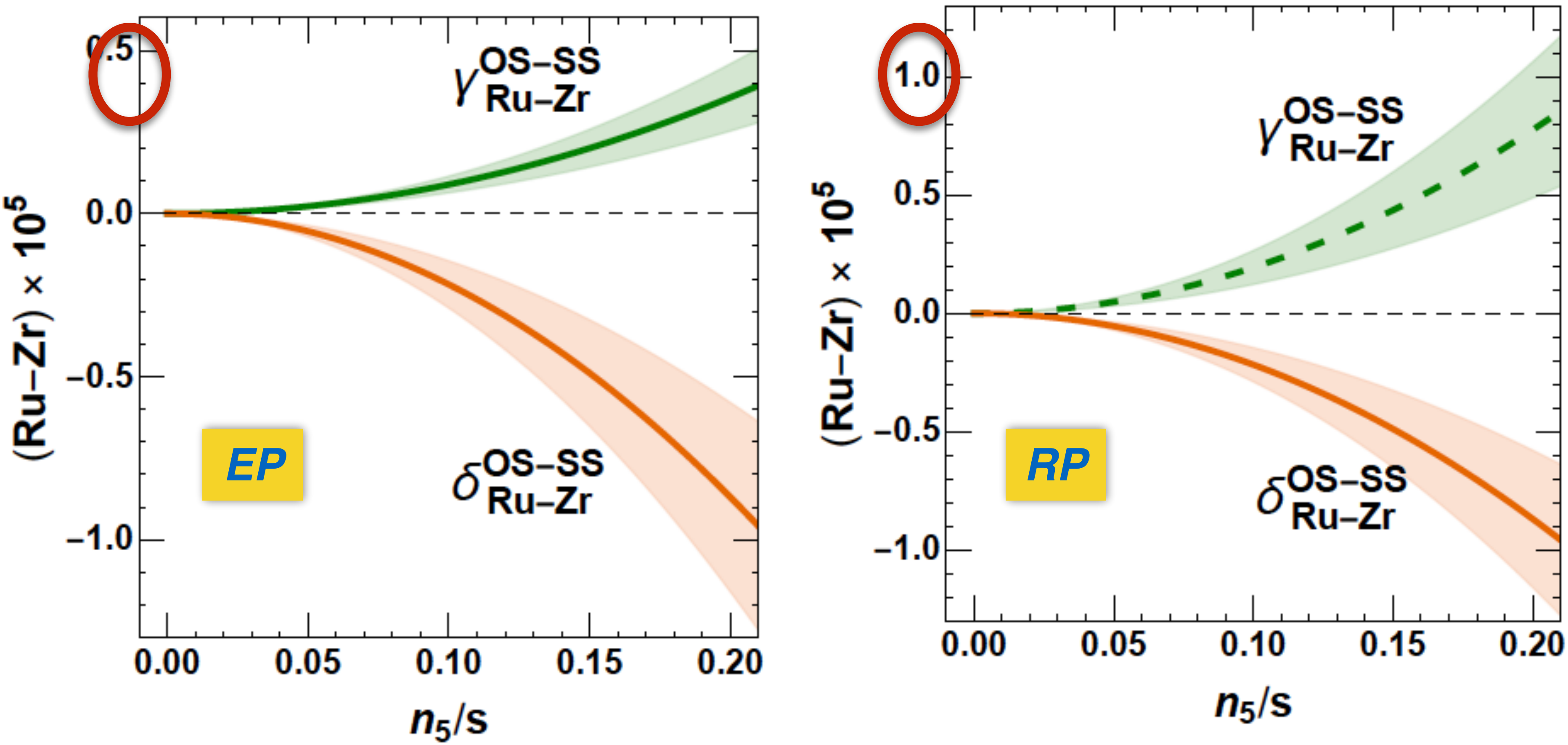
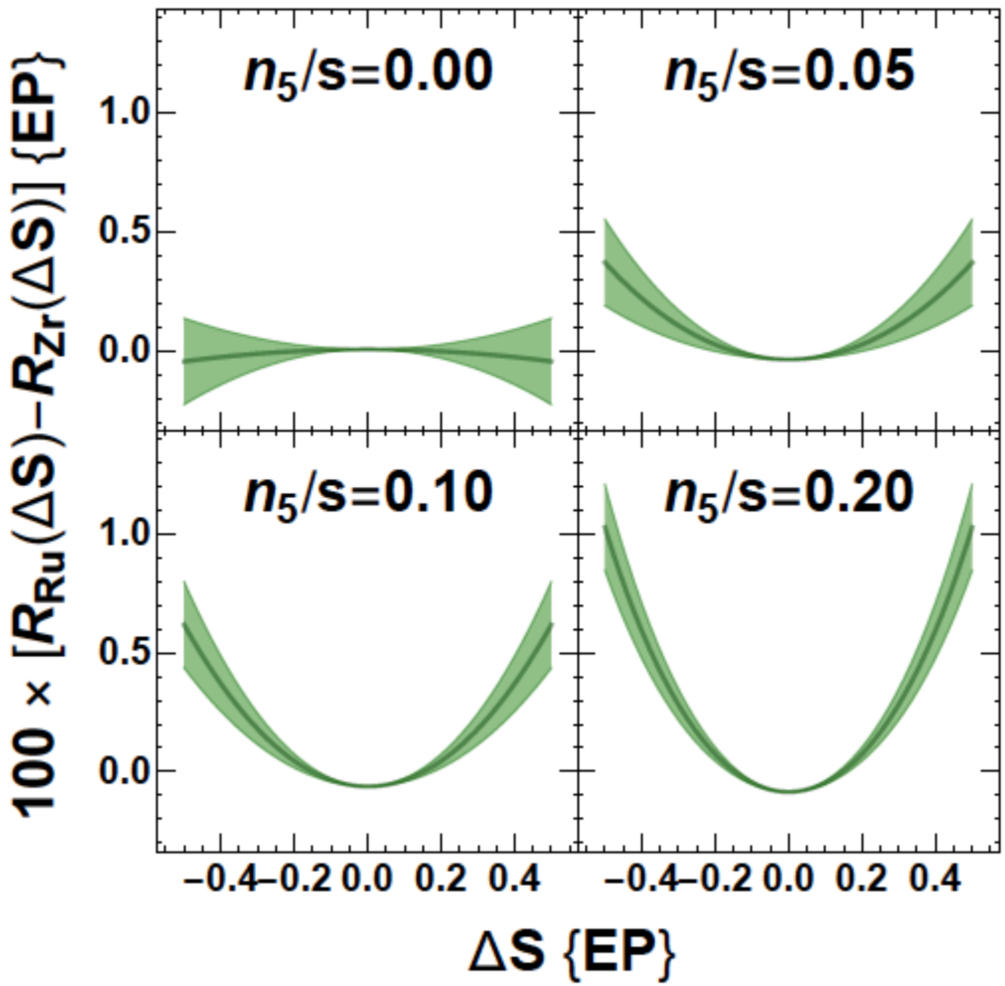


Look for absolute difference between isobars (after joint-cut)!

Look for contrast between EP / RP!

[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

AVFD Predictions for Isobars



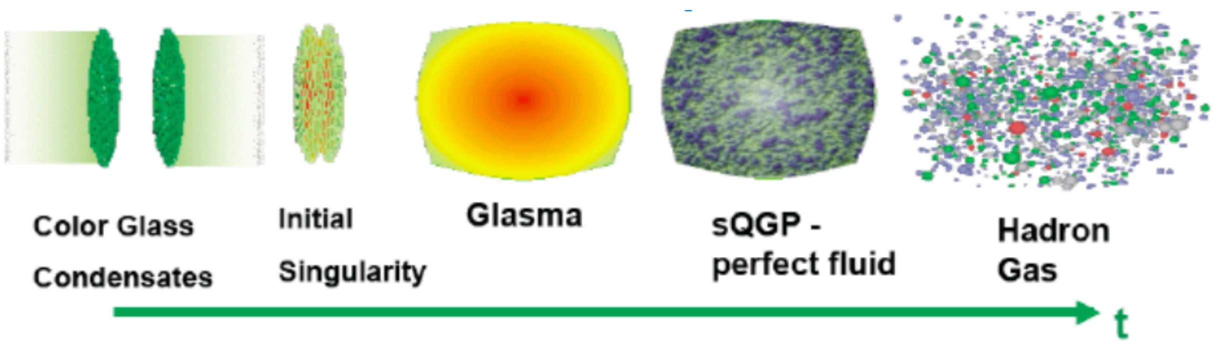
Look for absolute difference between isobars (after joint-cut)!
Look for R-correlator shape!

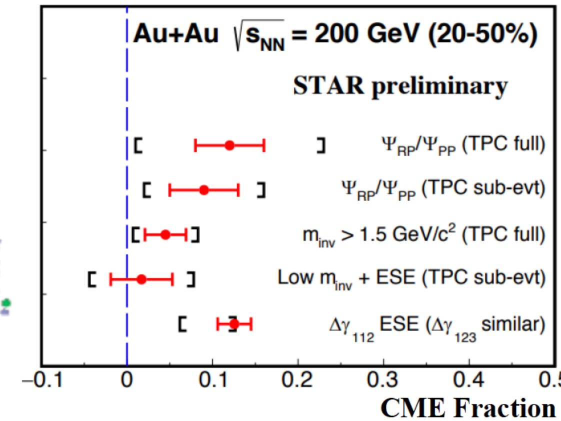
[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

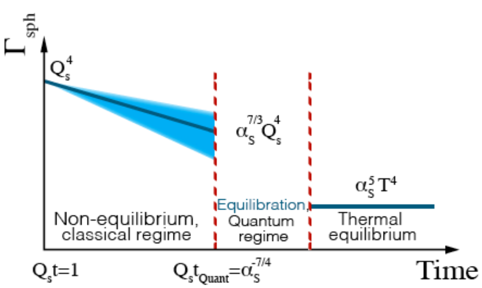
Summary & Outlook

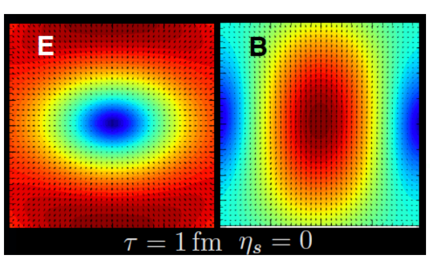
Summary: Toward Synergy of Key Ingredients

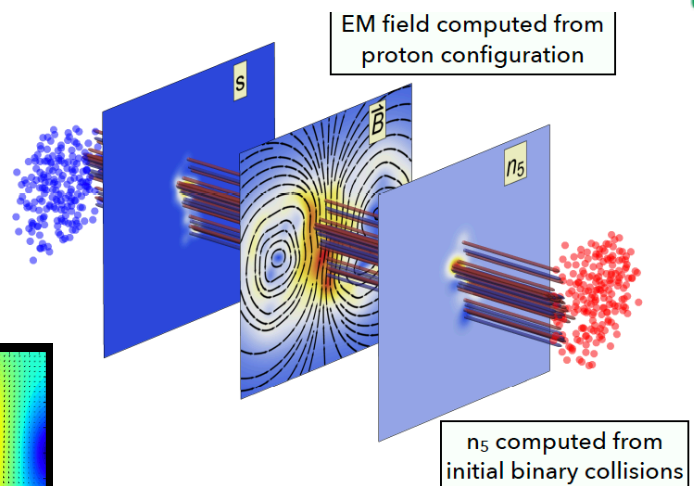
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

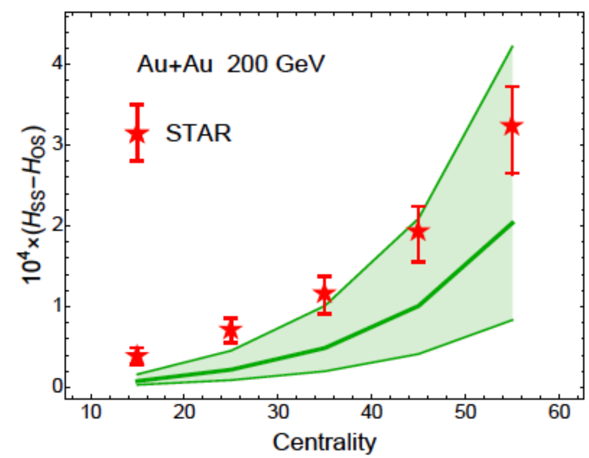












An exciting time: things are converging!

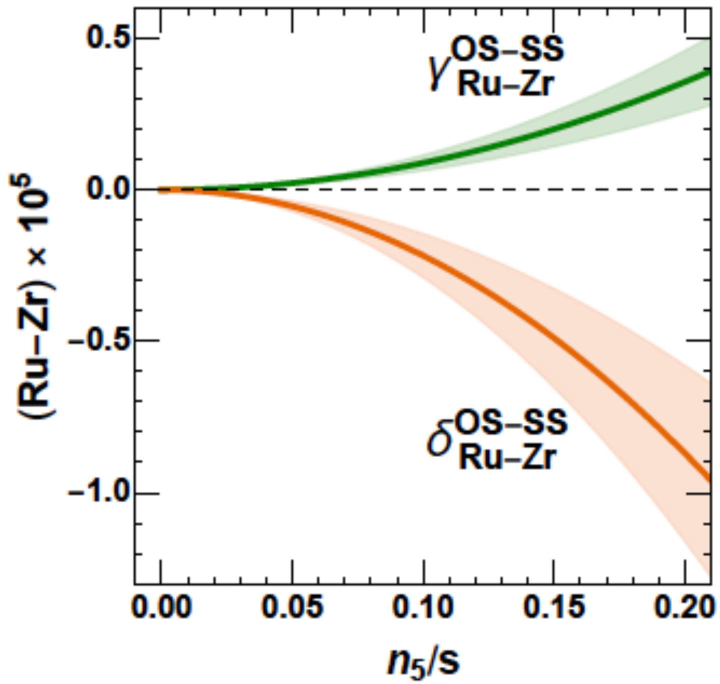
Outlook: Isobaric Collisions

Charge Asymmetry Correlation Measurement

Background	Signal	RuRu
Background	Signal	ZrZr

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

- ***Many observables: consistency?***
- ***Very important: understanding observables & their relations!!***
- ***Use sophisticated modeling tools (signal+bkg.) to help***



Exciting time(~2020): Stay tuned!