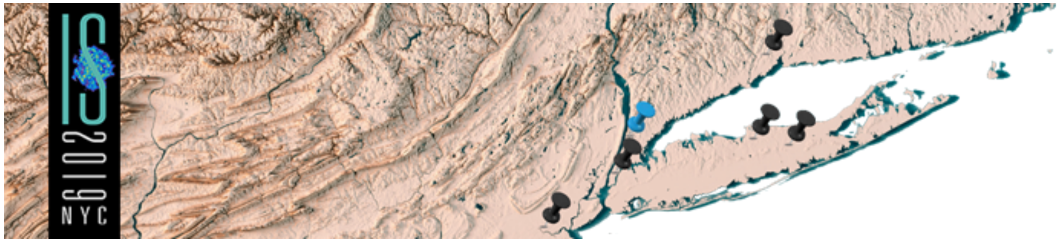
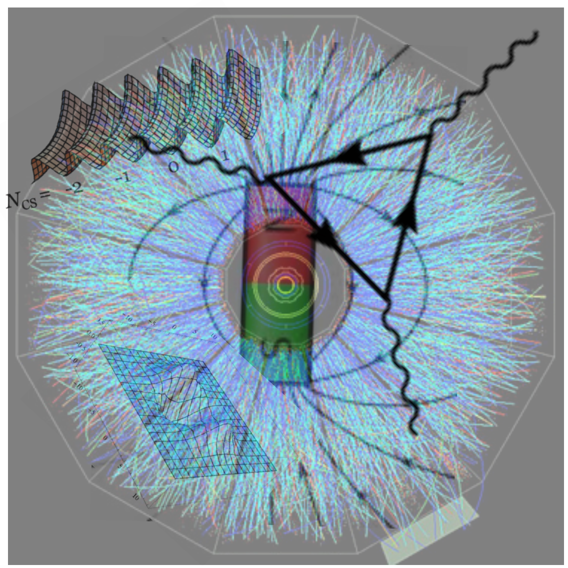


Jun. 24~28, 2019

Hunting for the Chiral Magnetic Effect



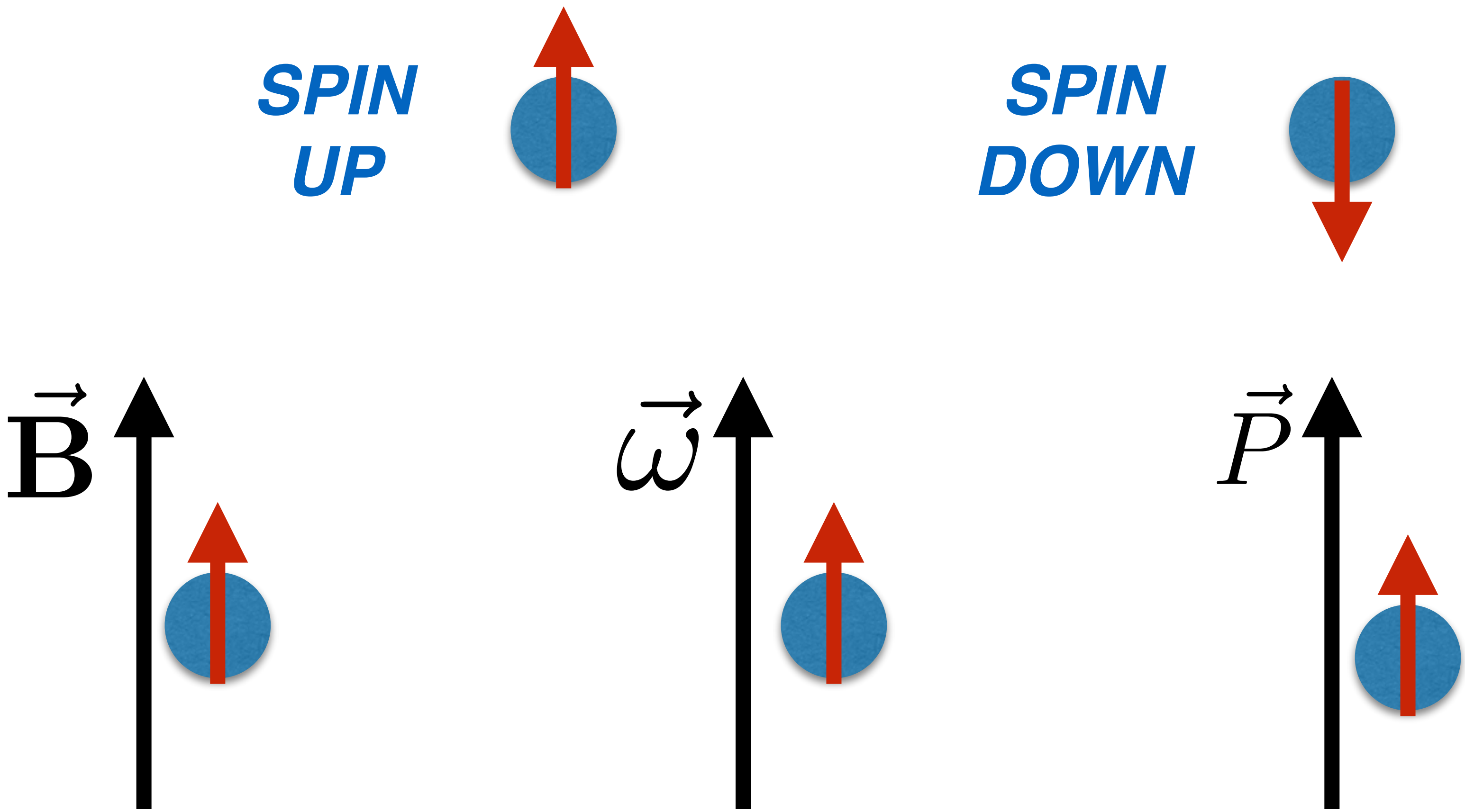
Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Spin: Chirality, Vorticity and Magnetic Field



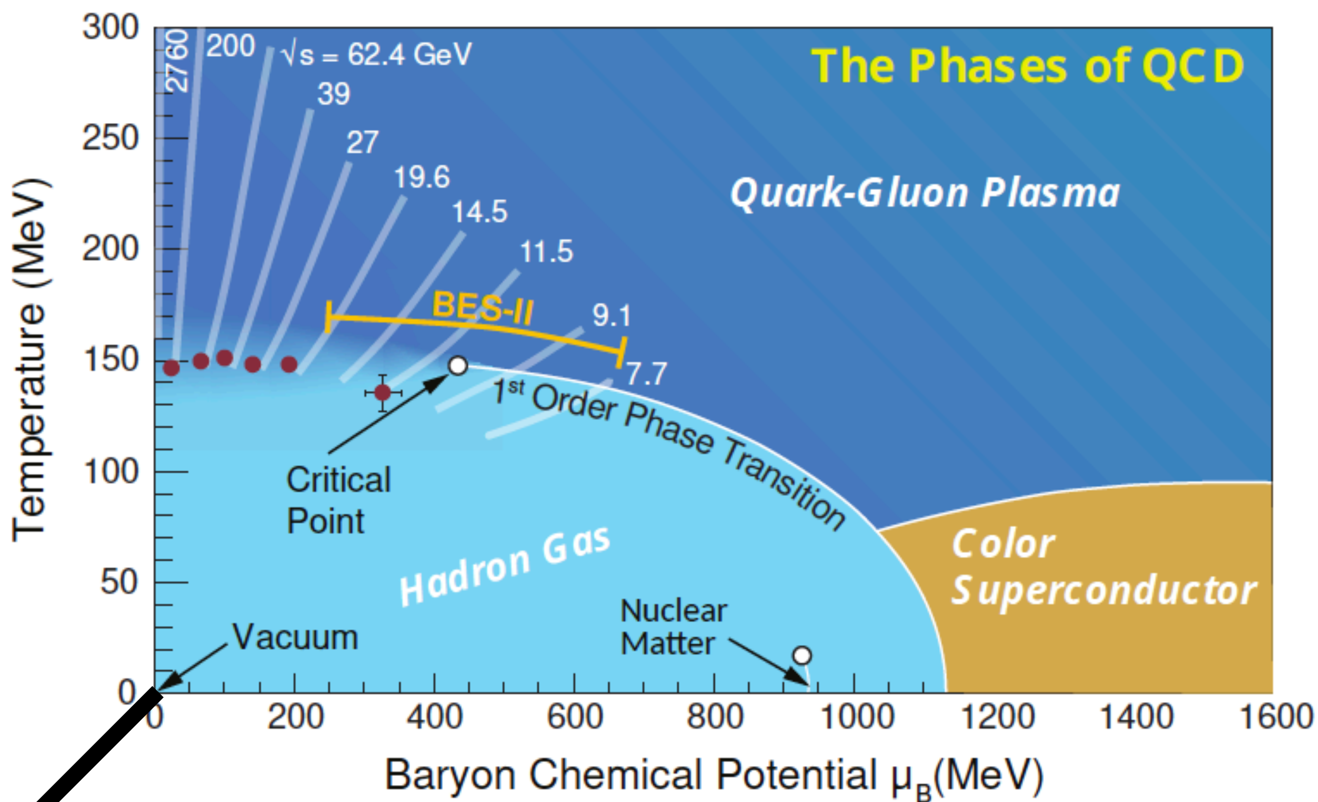
Magnetic Polarization

Rotational Polarization

Chirality Polarization

Interesting interplay —> highly nontrivial phenomena!

QCD Matter under New Extreme Conditions



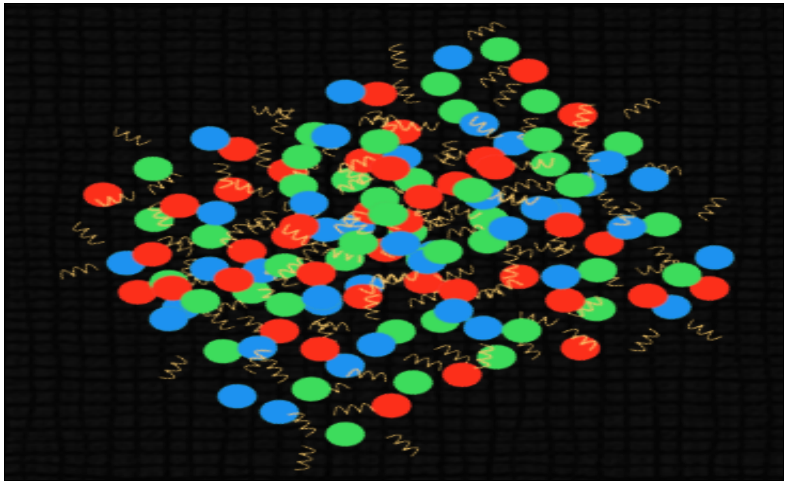
$\vec{\mathbf{B}}$ $\vec{\omega}$

$N_5(\text{or } \mu_5)$

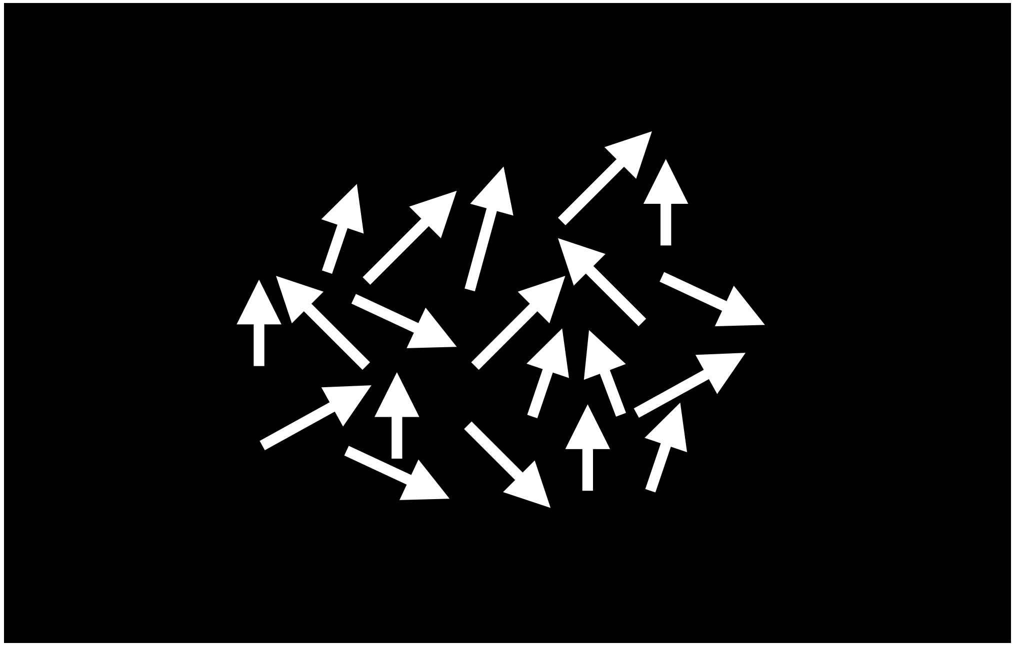
QCD matter under extremely strong vorticity and magnetic fields!

A Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)



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



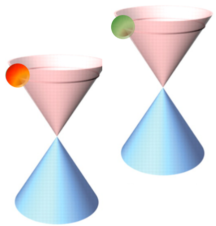
Chirality 2019 @ Tsinghua Beijing, Apr 2019

~100 people, 4.5 days

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

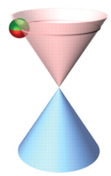
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

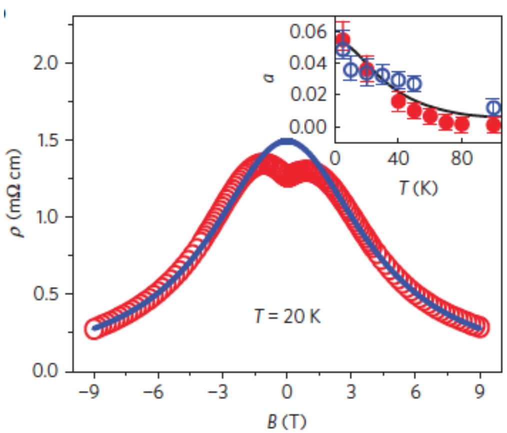


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



nature physics | LETTERS

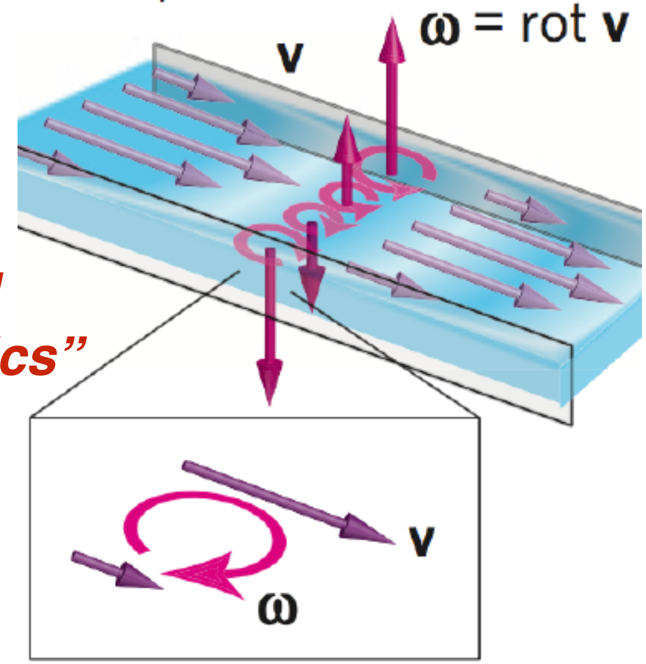
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

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)

Liquid flow



"Fluid Spintronics"

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

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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[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]].

Exciting Progress: See Recent Reviews

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.

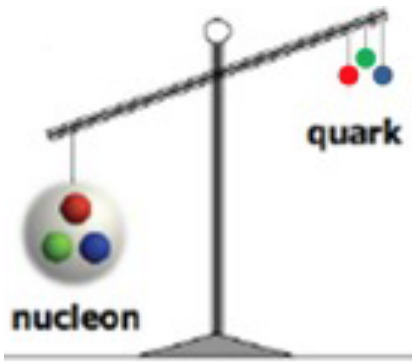
Keywords: Heavy Ion Collision, Beam Energy Scan, QCD Phase Diagram, Critical Point, Chiral Magnetic Effect

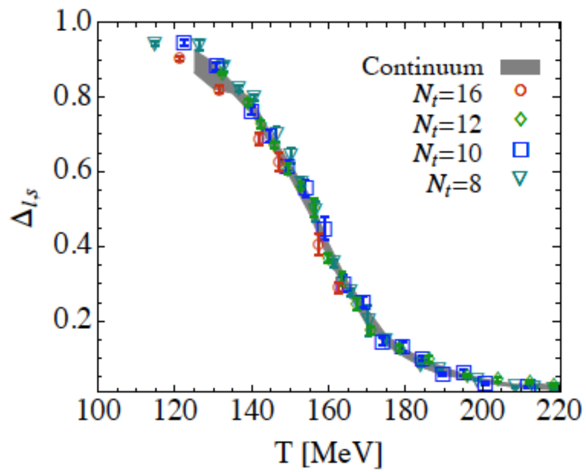
arXiv:1906.00936

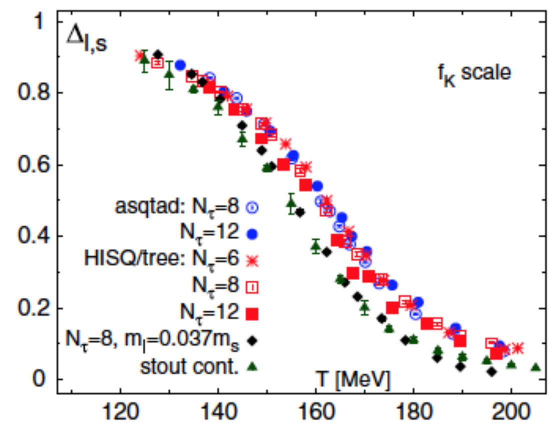
Chiral Magnetic Effect

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.

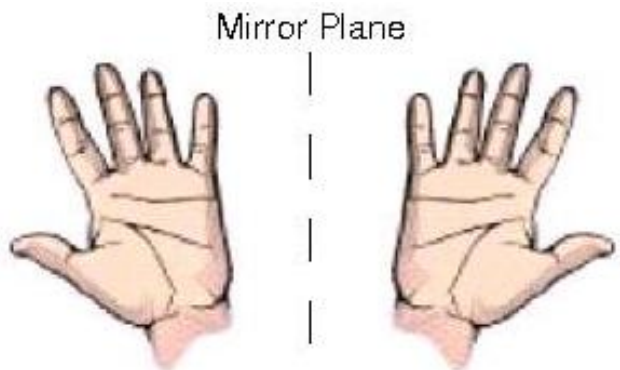
Classical symmetry:

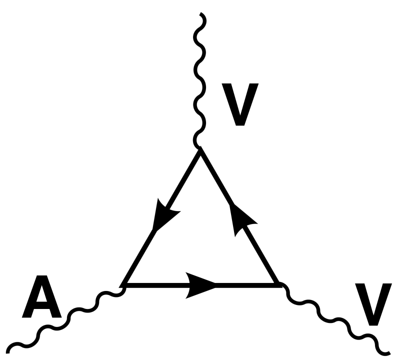
$$\mathcal{L} = i\bar{\Psi}\gamma^{\mu}\partial_{\mu}\Psi$$

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

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

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





[e.g. pi0—> 2 gamma]

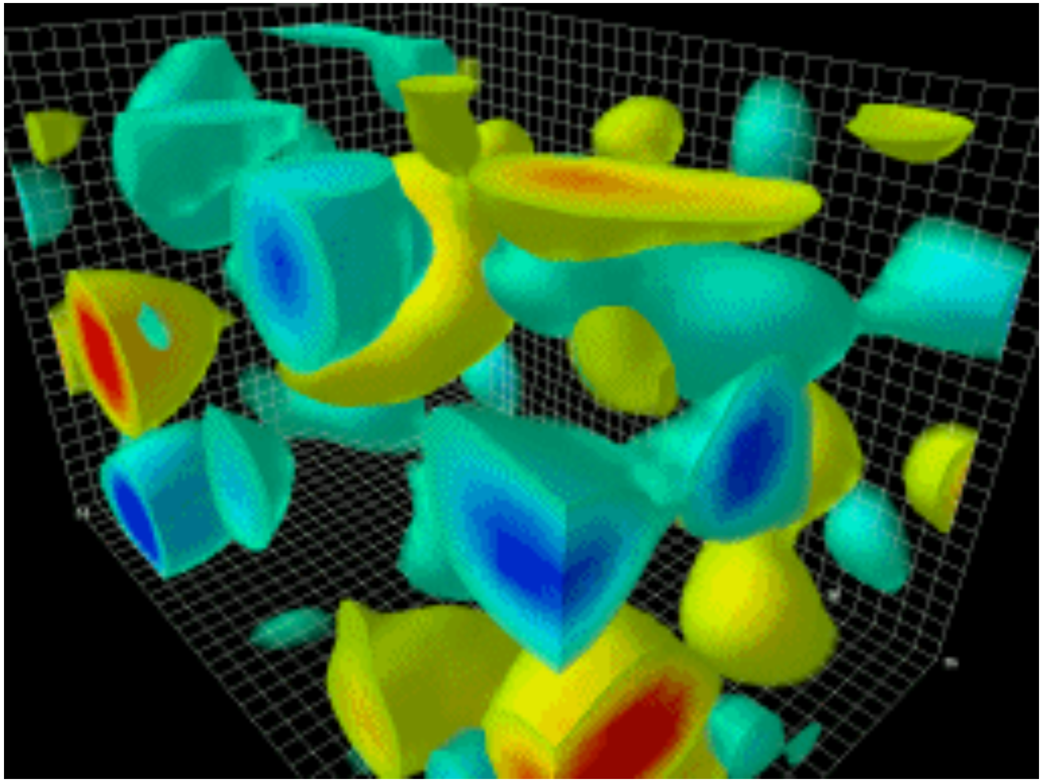
Broken at QM level:

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

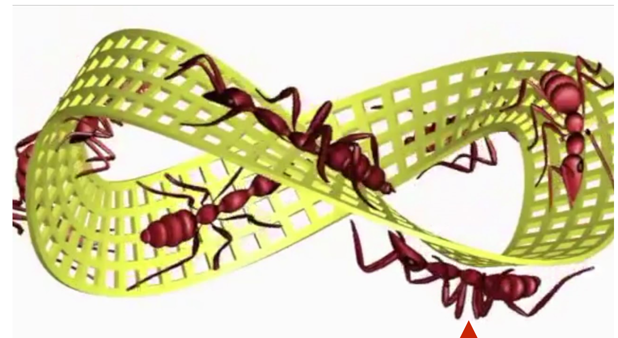
$$dQ_5/dt = \int_{\vec{x}} C_A\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

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

From Gluon Topology to Quark Chirality



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



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

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

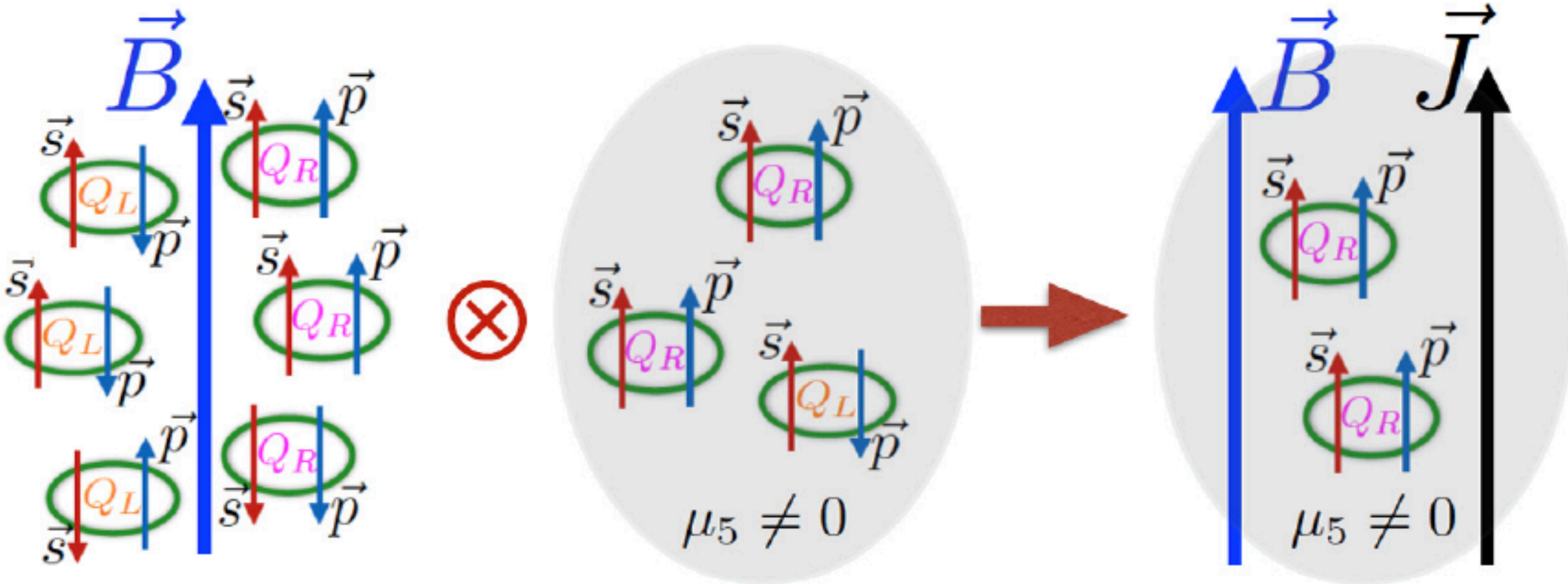
Electric Current

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

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

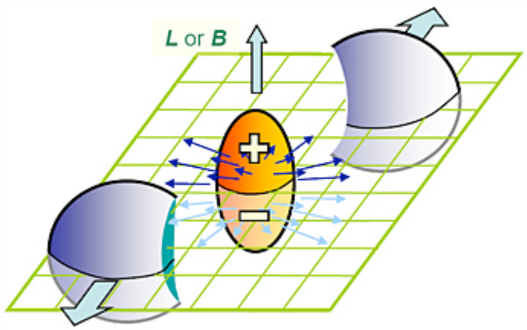
CVE

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

A new type of hydrodynamics with macro. quantum effect!

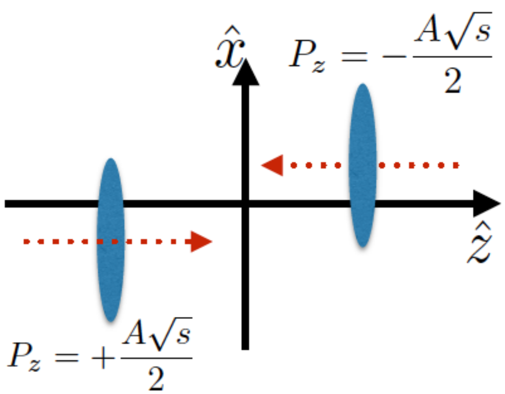
Search for CME at RHIC & LHC

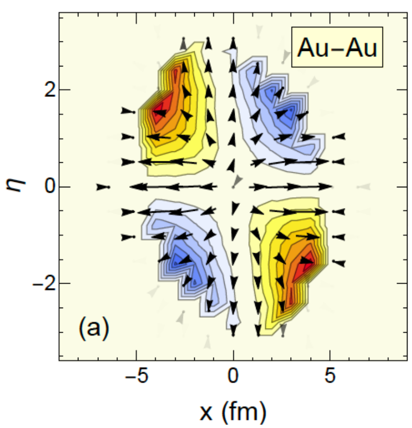
Rotating Quark-Gluon Plasma

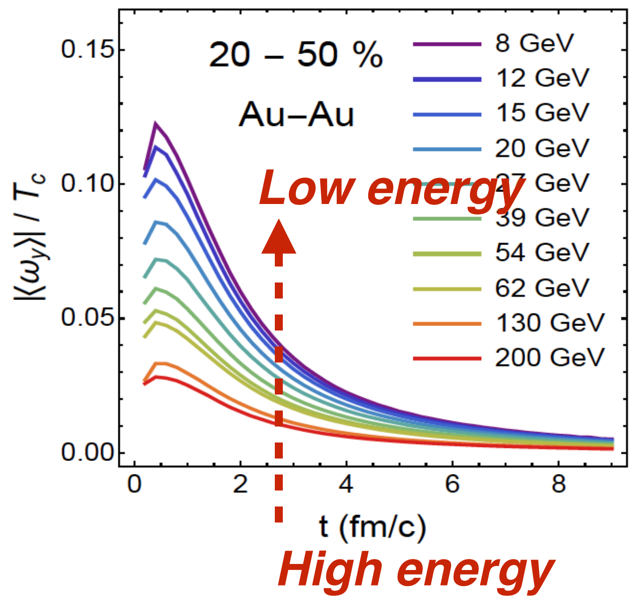


$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

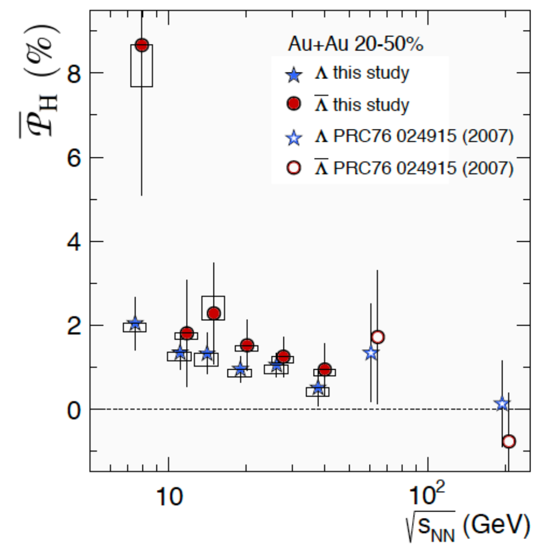
Angular momentum —> nontrivial vorticity structure and spin polarization effect







Jiang, Lin, JL, PRC2016

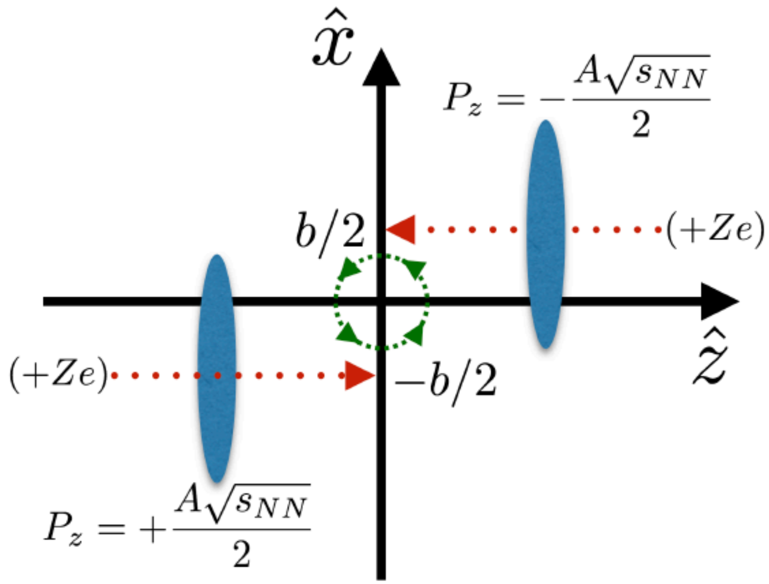


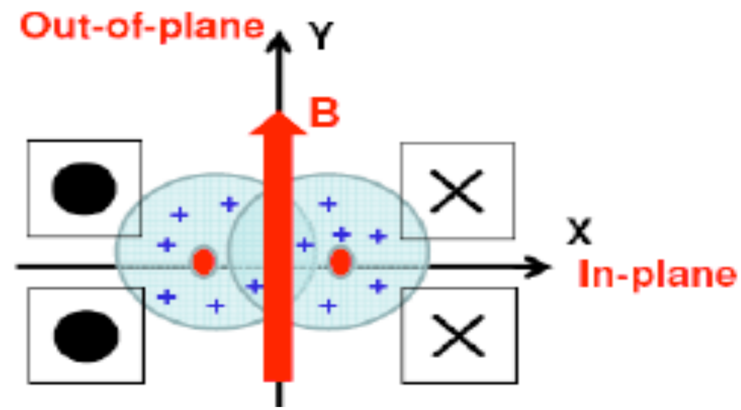
STAR, Nature 2017

[Talk by Ryblewski]

Strong Electromagnetic Fields

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

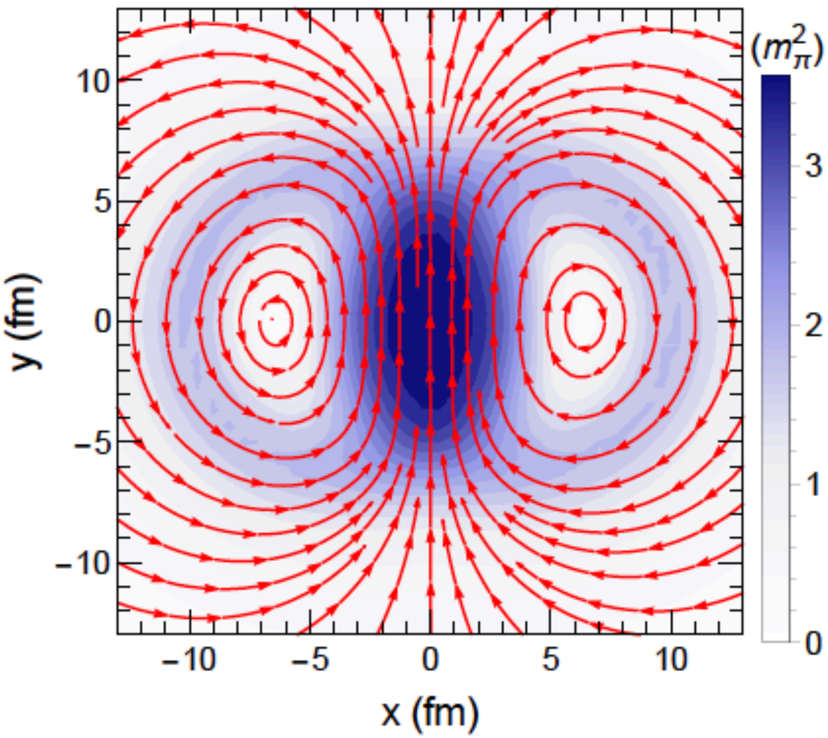




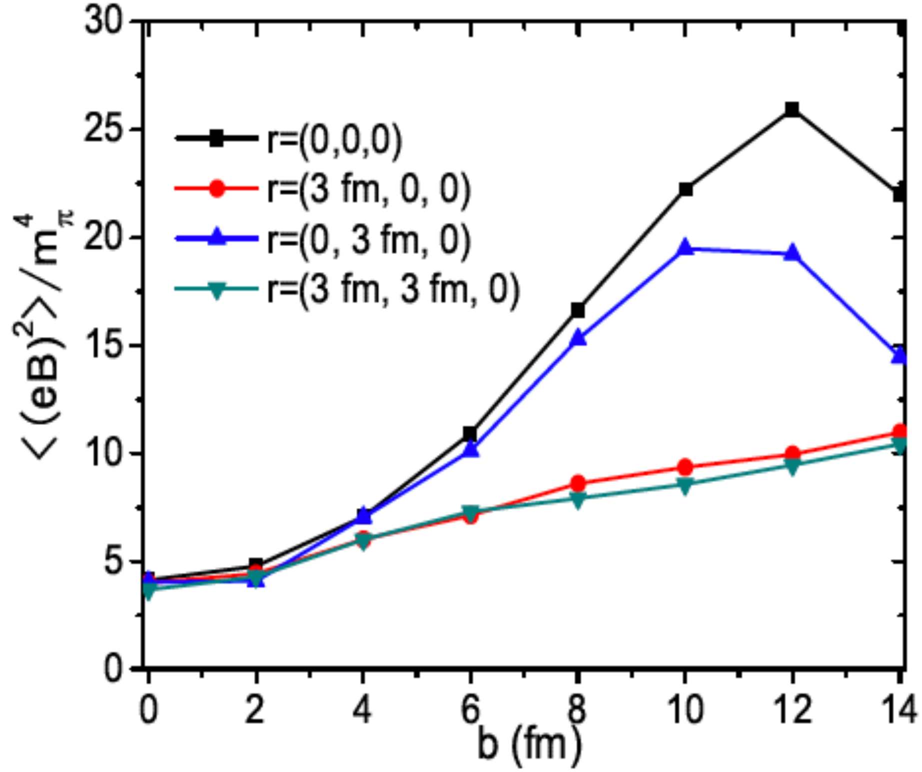
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

- 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



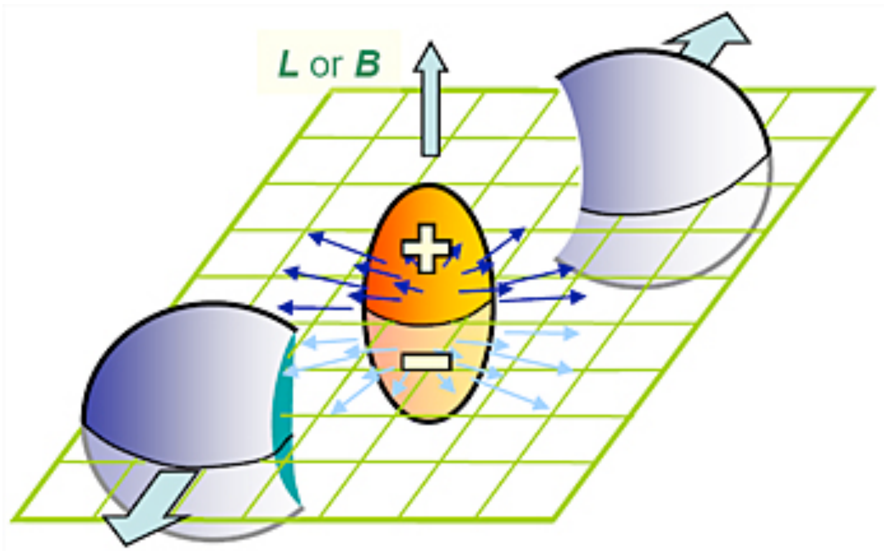
Huang, Liao, et al PLB2012



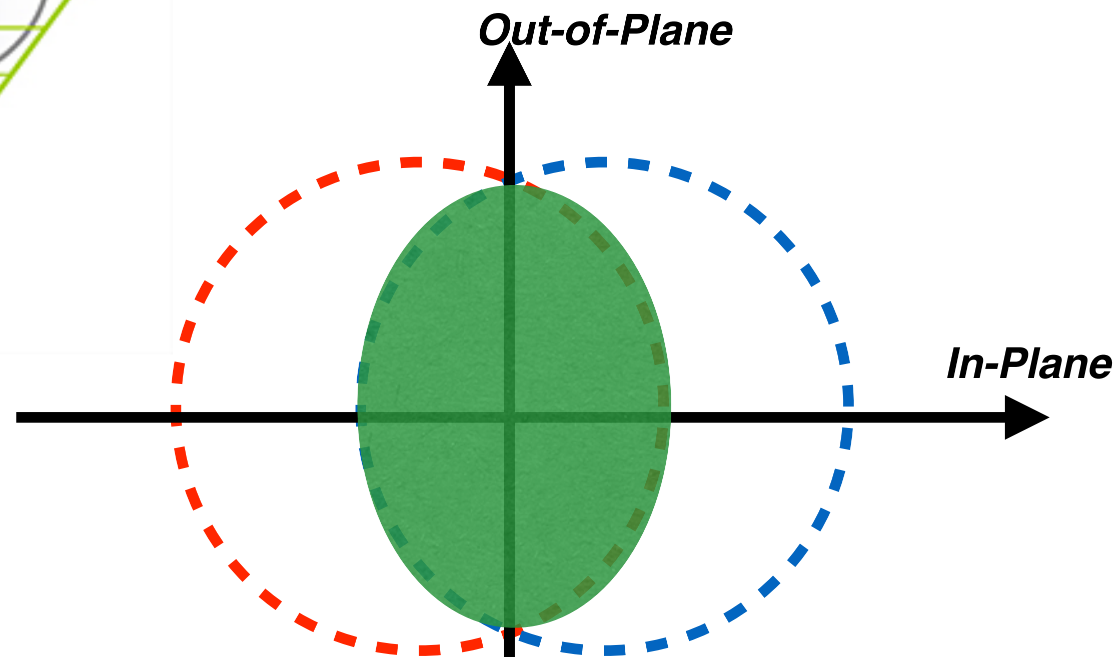
Quantitative simulations confirm the existence of such extreme fields!

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

Search for CME in Heavy Ion Collisions



The quark-gluon plasma is a subatomic CHIRAL MATTER.

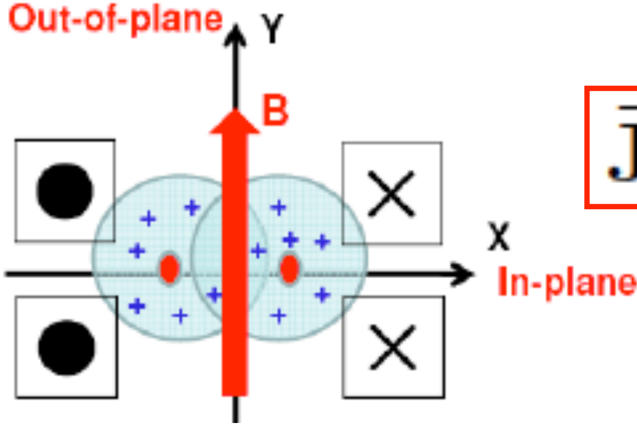


Can we observe CME in heavy ion collisions??

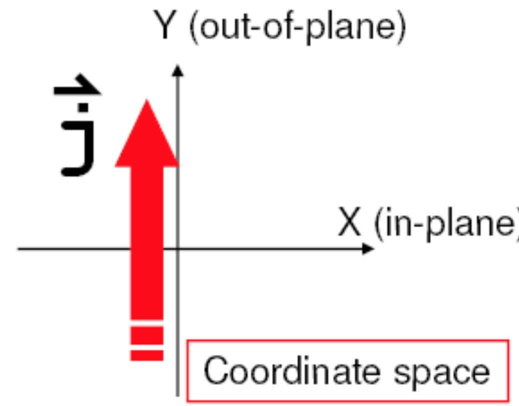
$$\boxed{\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}}$$

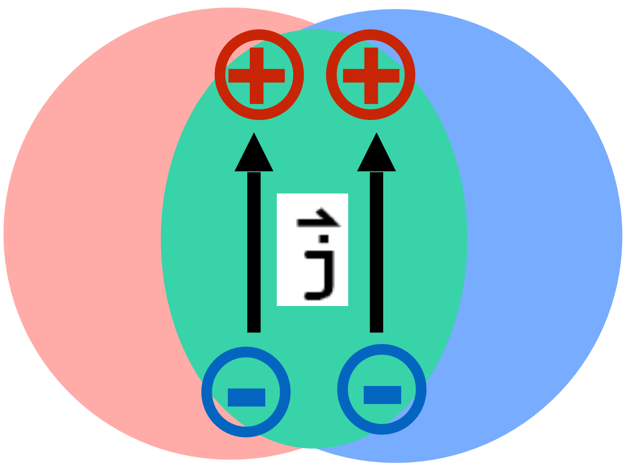
1) *(nearly) chiral quarks*
2) *chirality imbalance*
3) *strong magnetic field*

From CME Current to Charge Separation

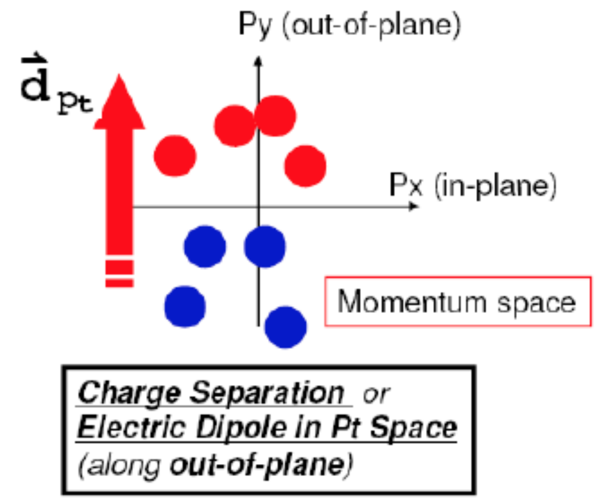


$$\boxed{\vec{J} = \sigma_5 \mu_5 \vec{B}}$$





strong radial blast:
position —> momentum



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

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

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

Experimental Observable

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

charge separation $\Rightarrow$ charge dept. two-particle correlation

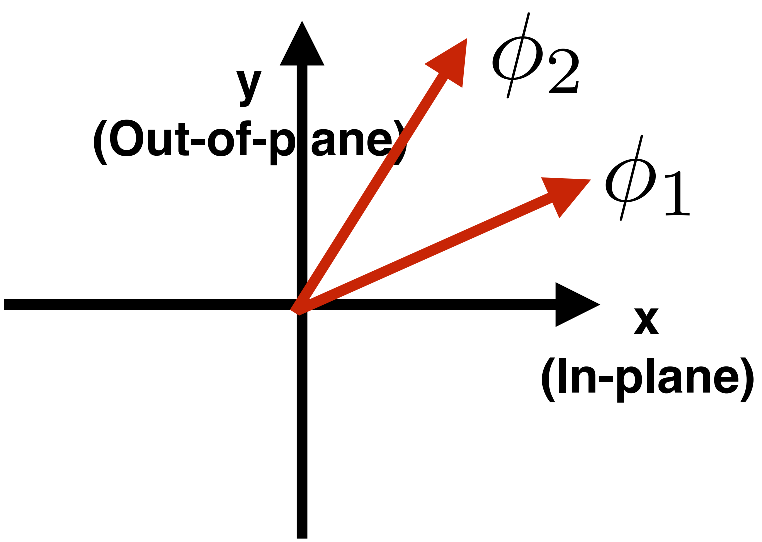
Voloshin, 2004

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

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

These correlations are sensitive to CME contributions, however they are also sensitive to many non-CME backgrounds!

[F. Wang; S. Pratt; Bzdak, Koch, JL; ……]



CME & Backgrounds

CME expectation:

$$\gamma_{SS} < 0 \,, \delta_{SS} > 0$$

$$\gamma_{OS} > 0 \,, \delta_{OS} < 0$$

Transverse Momentum Conservation (TMC)

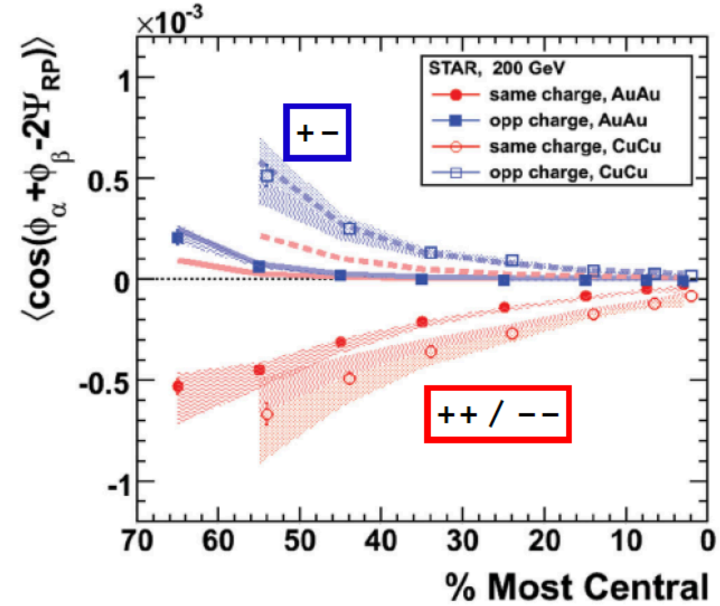
$$\gamma < 0 \,, \delta < 0$$

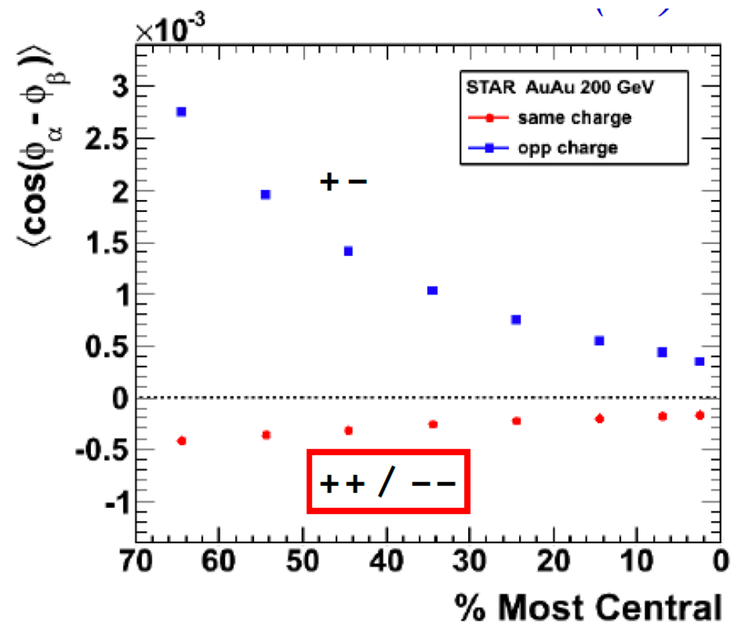
Local Charge Conservation (LCC)

$$\gamma_{OS} > 0 \,, \delta_{OS} > 0$$

Resonance decay: similar to LCC

Background contribution to gamma is due to nonzero v2!!





Fighting with Backgrounds

A two-component decomposition model:

$$\gamma = \kappa\, v_2\, F - H \qquad\qquad F\text{: Bulk Background}$$

$$\delta = F + H \qquad\qquad H\text{: Possible Pure CME Signal} = (a_{1,CME})^2$$

Bzdak, Koch, JL, 2012

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

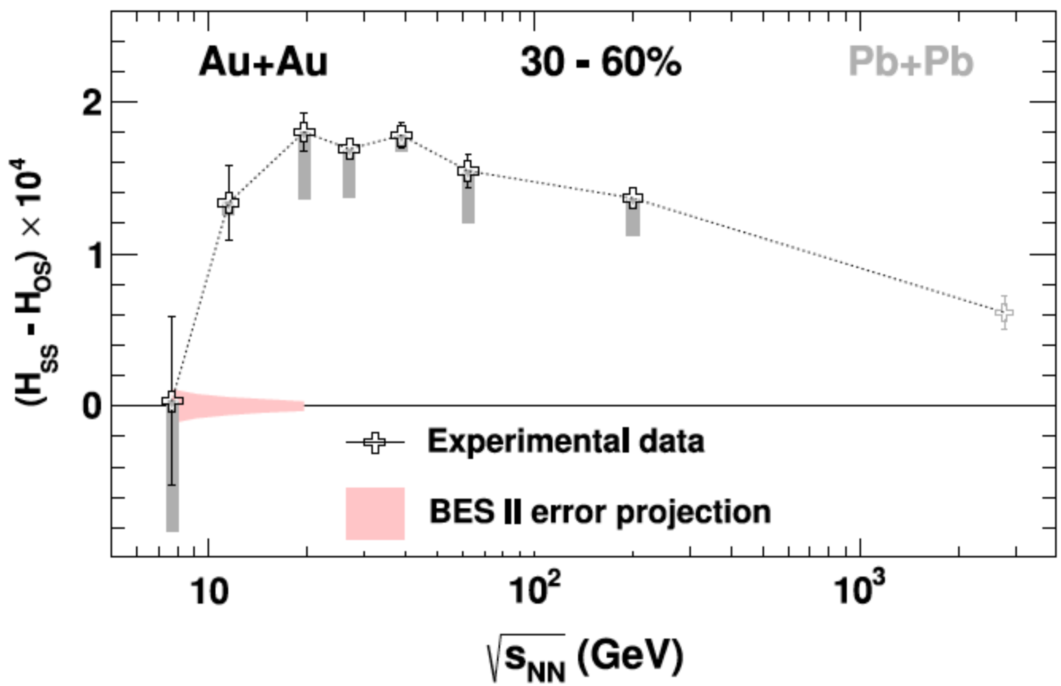
Many interesting proposals of new observables!

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

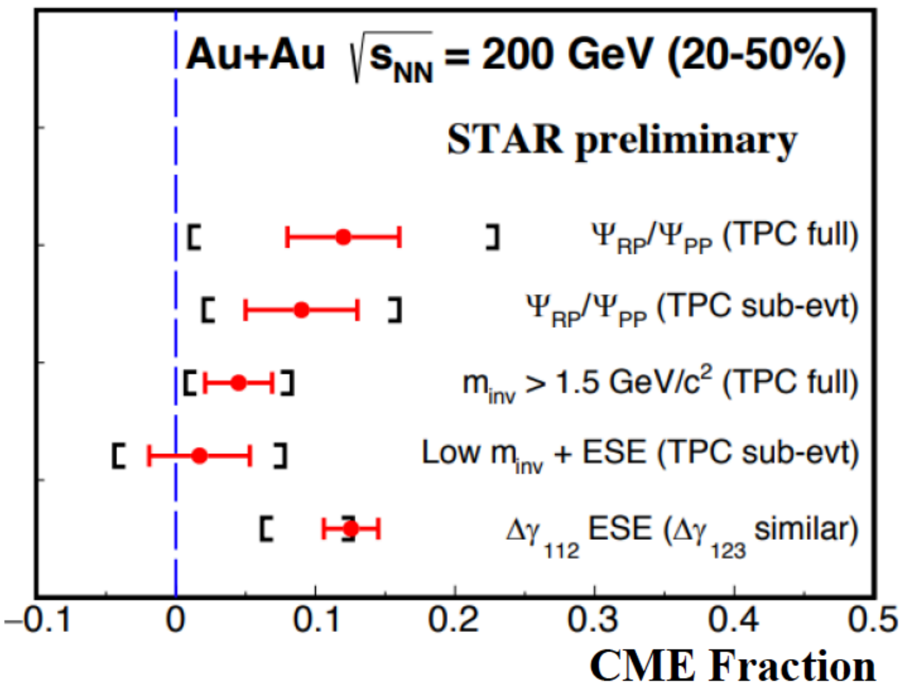


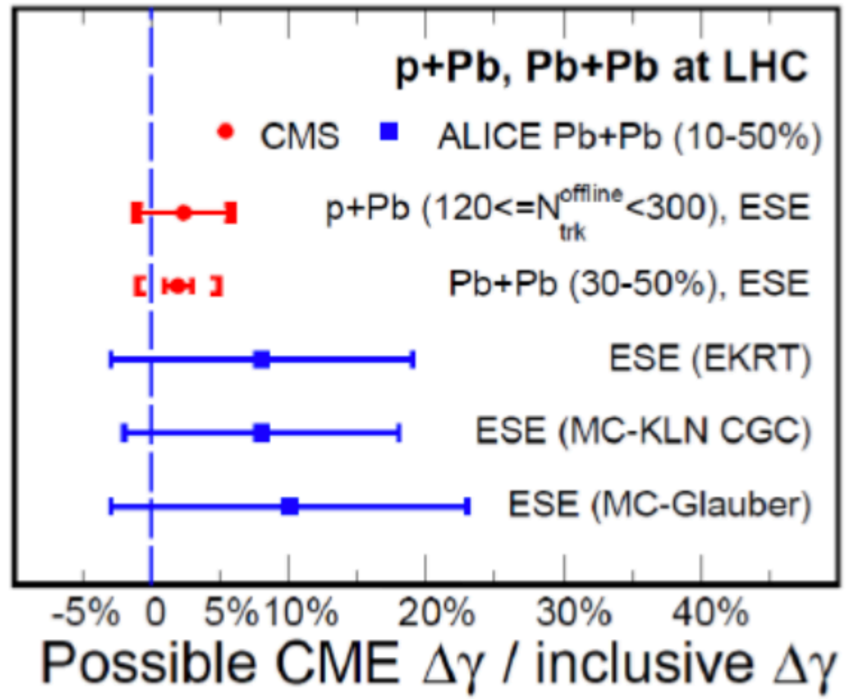
STAR PRL2014

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!

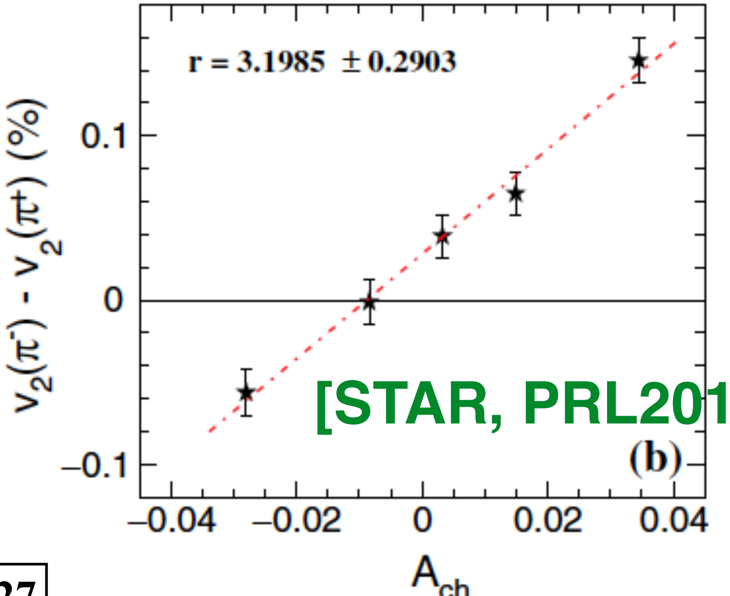
Chiral Magnetic Wave

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

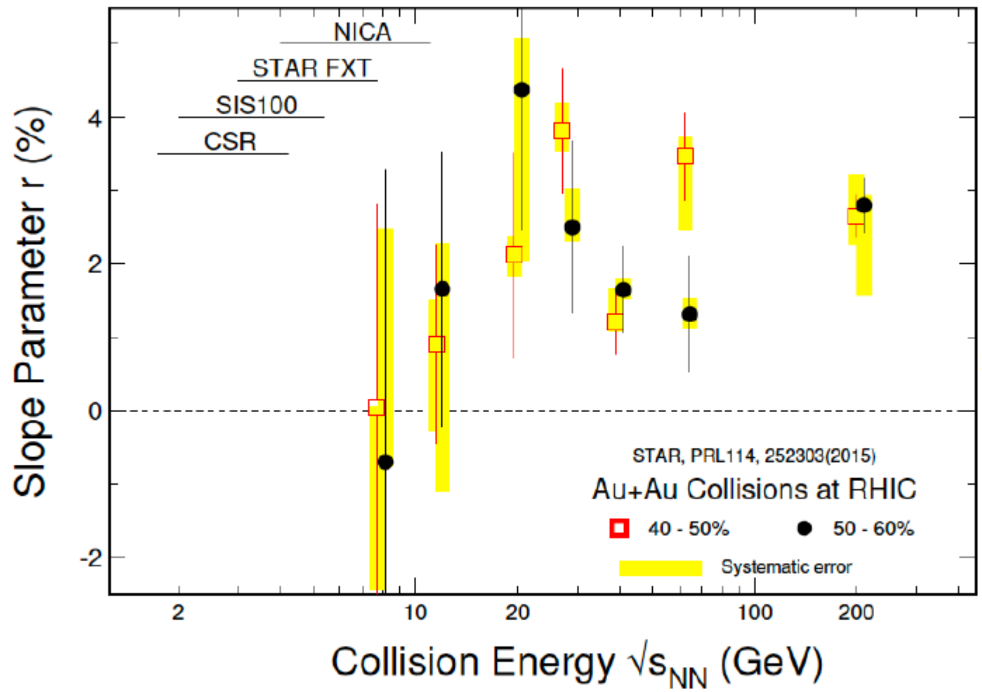
[Burnier, Kharzeev, JL, Yee, PRL2011; & arXiv: 1208.2537]

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

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)*

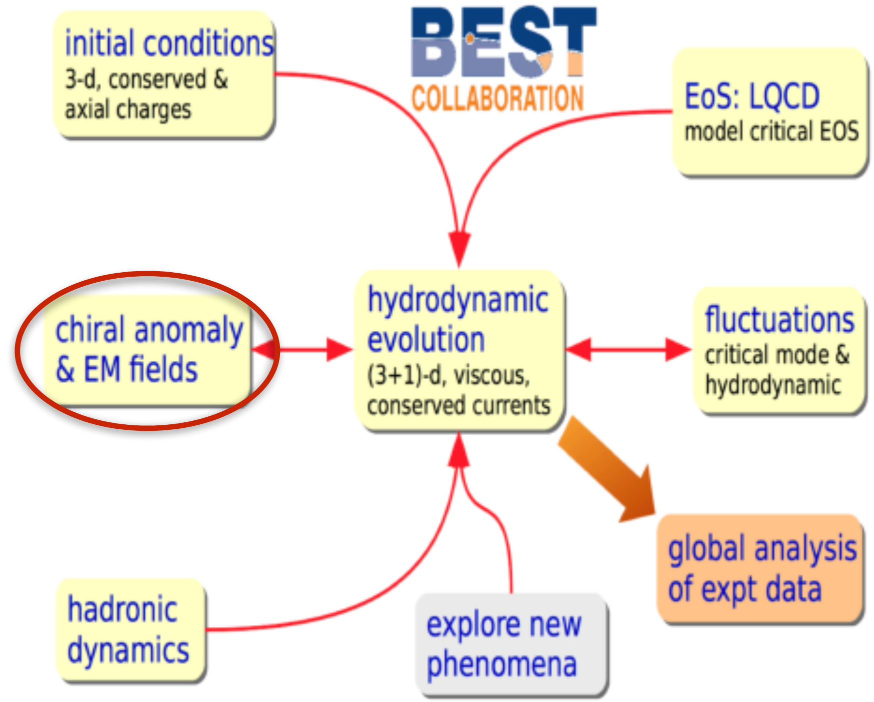
— our focus here

** Approach based on transport models.*

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

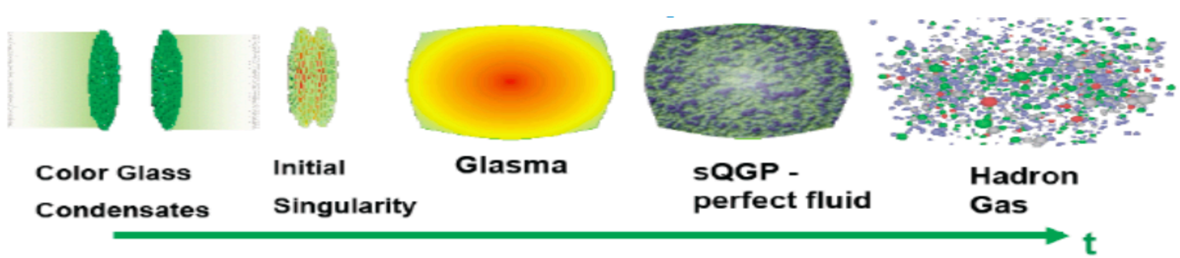
— Chiral kinetic transport based (Che-ming Ko and collaborators)

Beam Energy Scan Theory (BEST) Collaboration

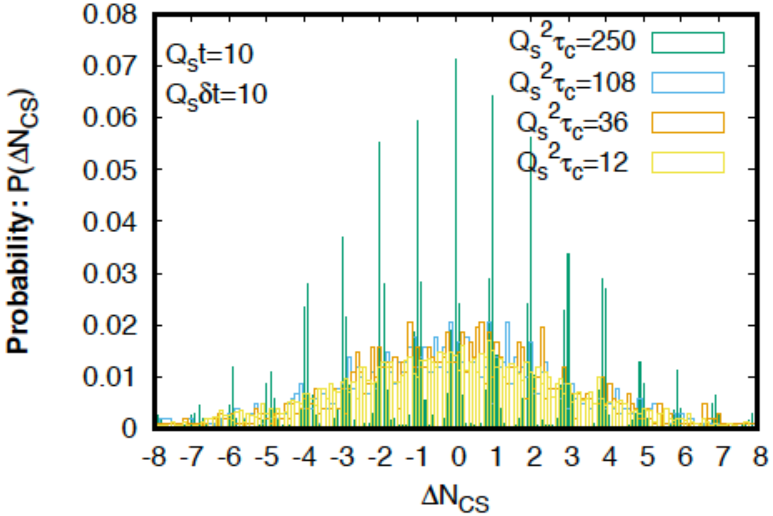


CME Working Group

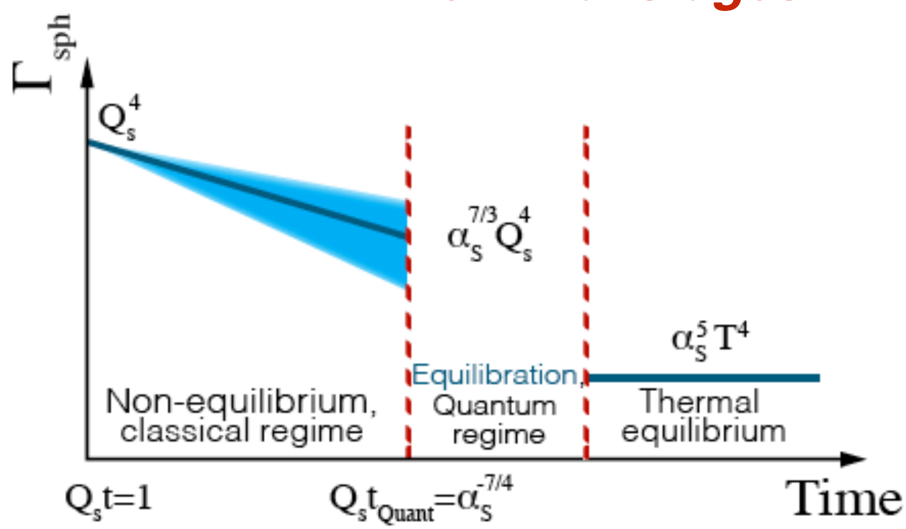
- ***Initial conditions***
- ***Dynamical magnetic fields***
- ***Non-equilibrium anomalous transport coefficient***
- ***Fluid dynamics framework with anomalous current***
- ***Quantification of both signal and backgrounds***



Axial Charge Initial Conditions



Important information at the initial stages



In the glasma framework:

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

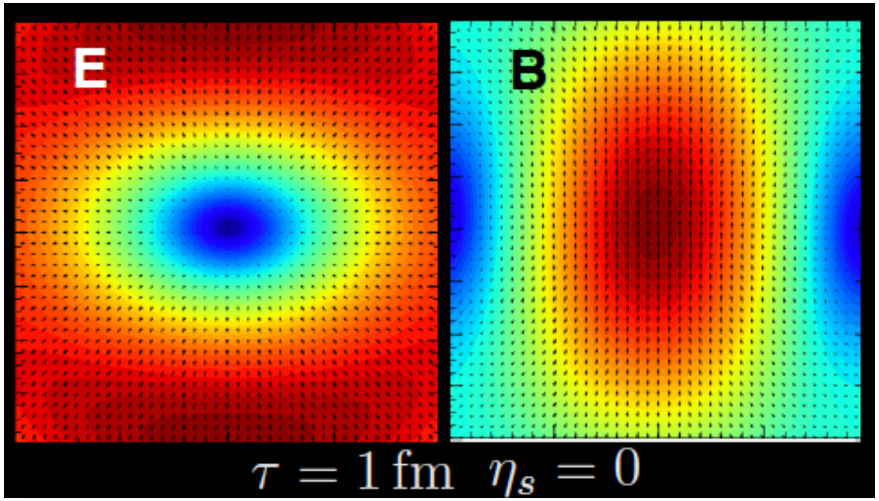
**** Extracted significant non-equilibrium sphaleron rate***

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

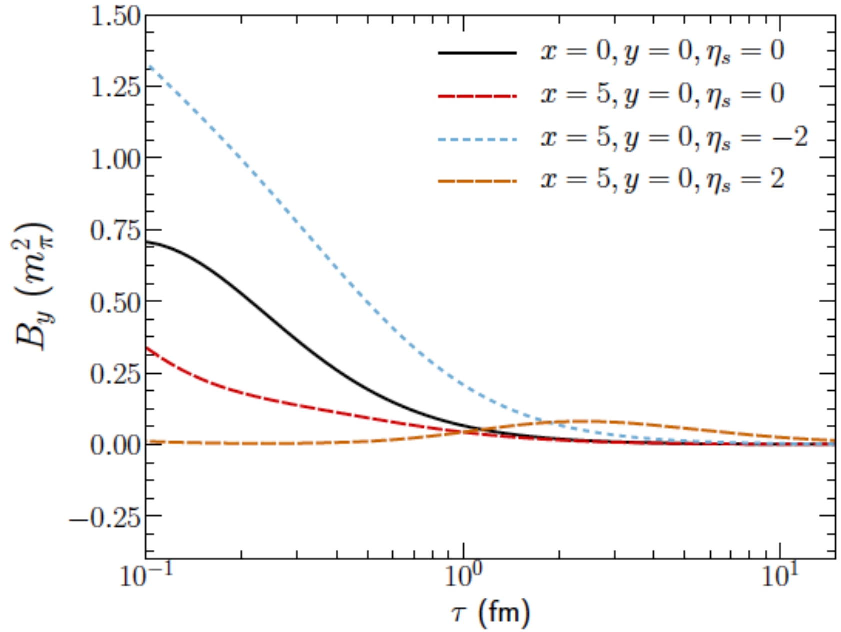
[Mace, Schtliting, Venugopalan, PRD2016; Mace, Muller, Schtliting, Sharma,PRD2017]

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:

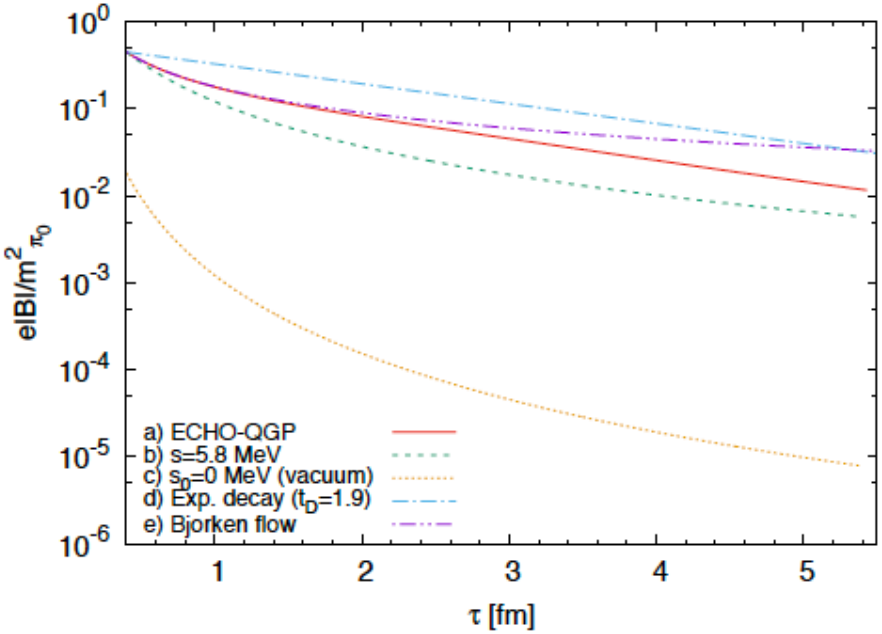
https://bitbucket.org/bestcollaboration/heavy-ion-em-fields

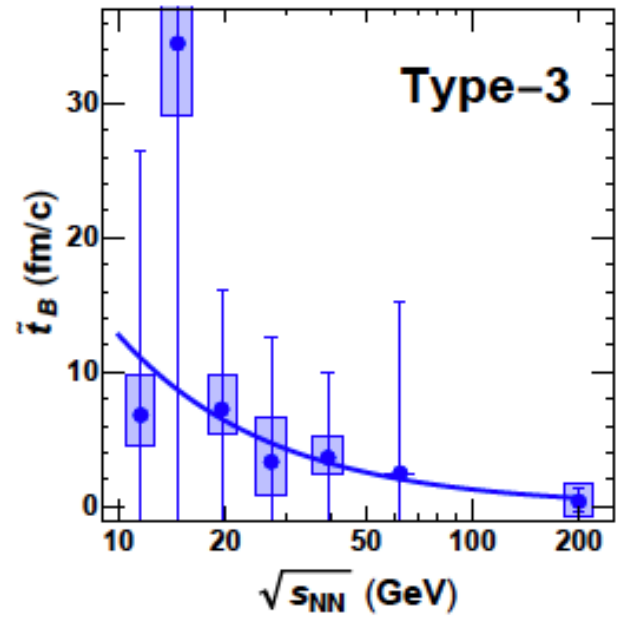
[Gursoy, Kharzeev, Rajagopal,Shen, et al, PRC2018]

A viable and practical way to integrate dynamical B field!

Dynamical Magnetic Fields

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



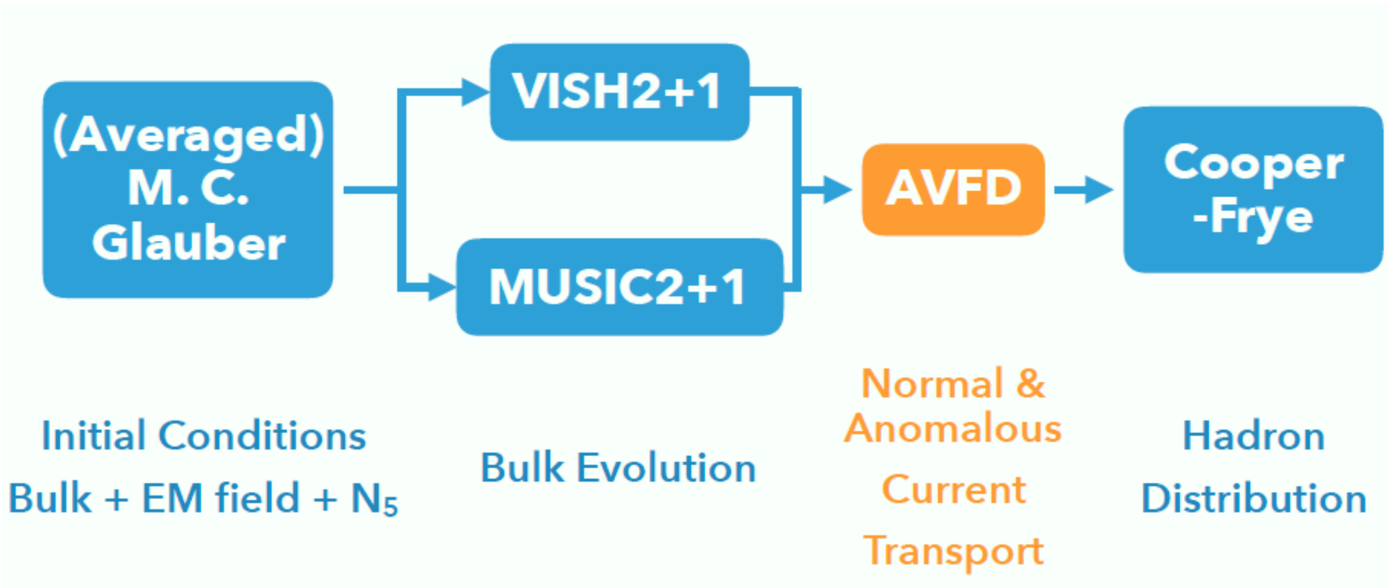


**** Phenomenological constraint from hyperon-anti-hyperon polarization [Schafer-Muller, 1806.10907; Guo-Liao-Wang, 1904.04704; Guo-Shi-Feng-Liao, 1905.12613]***

It seems plausible for t_B ~ 0.5 fm/c at 200GeV.

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]

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

CME

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

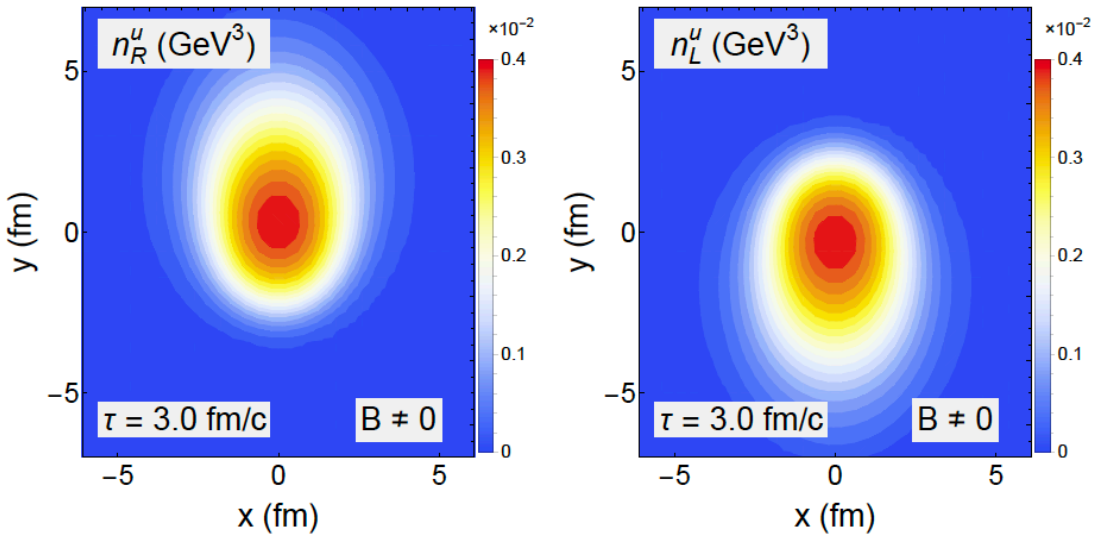
$$J_L{}^\mu = n_L\, u^\mu + \nu_L{}^\mu - \frac{N_c q}{4\pi^2}\, \mu_L\, B^\mu$$

Viscous Effect

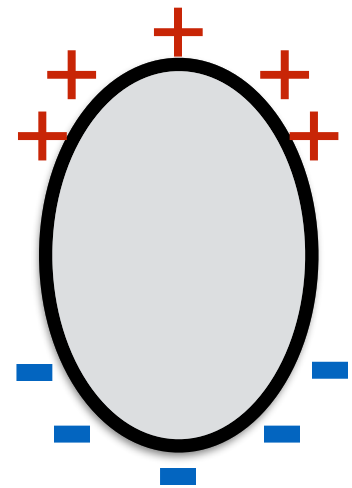
$$\Delta^\mu{}_\nu\, d\, \nu_{R,L}{}^\nu = -\frac{1}{\tau_{rlx}}(\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

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

The Charge Separation from AVFD



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



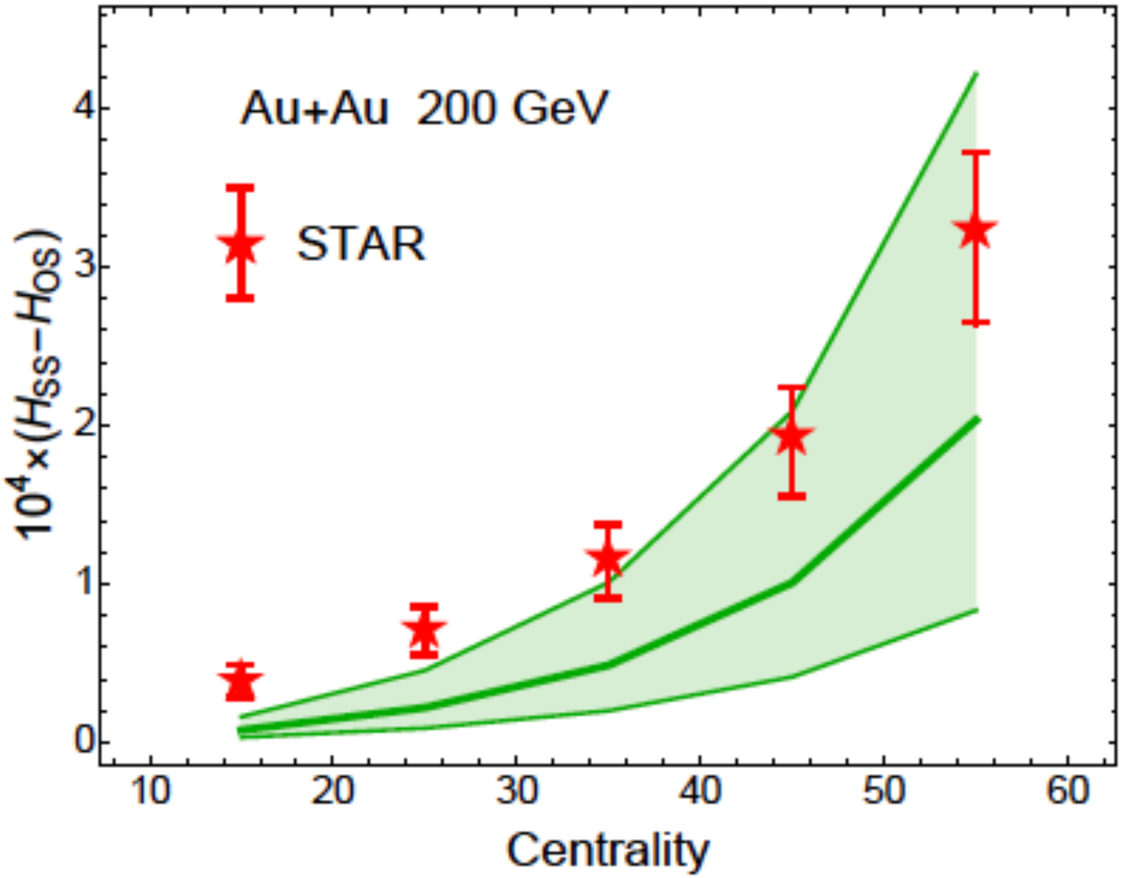
Chirality imbalance —> R/L asymmetry —> charge asymmetry

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

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

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

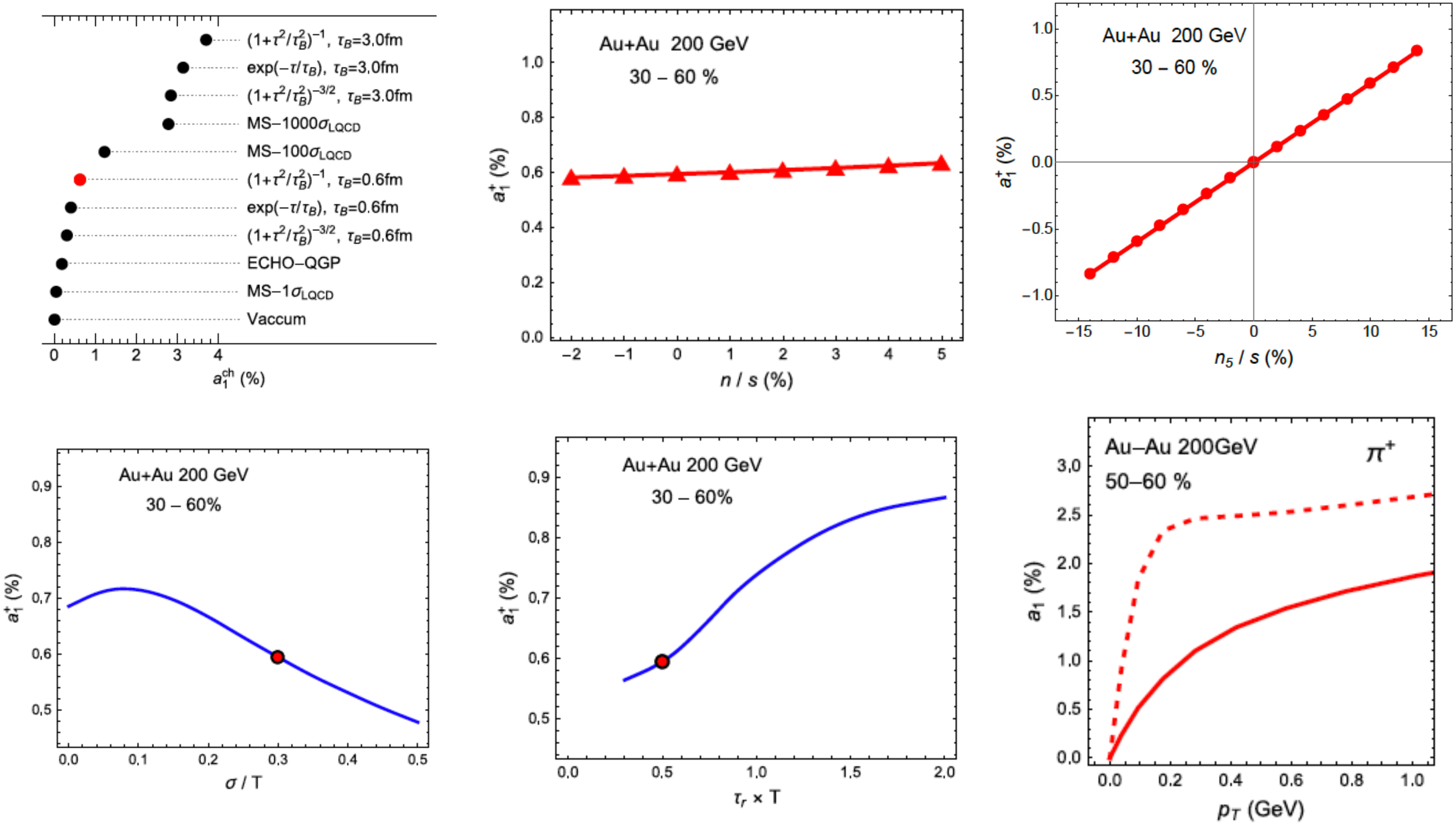
AVFD for AuAu Collisions



CME is quantitatively viable for describing relevant experimental observable.

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

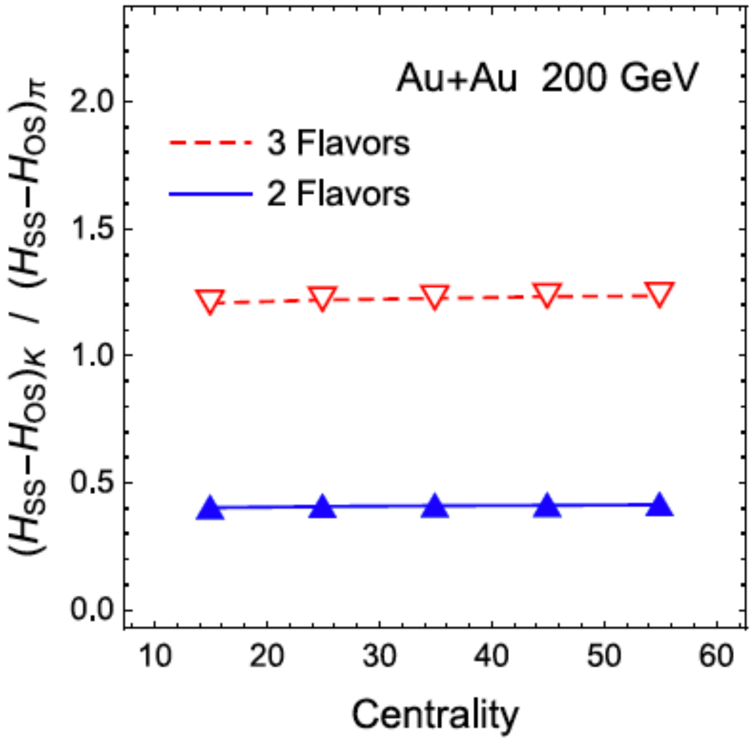
AVFD for AuAu Collisions



AVFD provides the tool to quantify various features of CME signals.

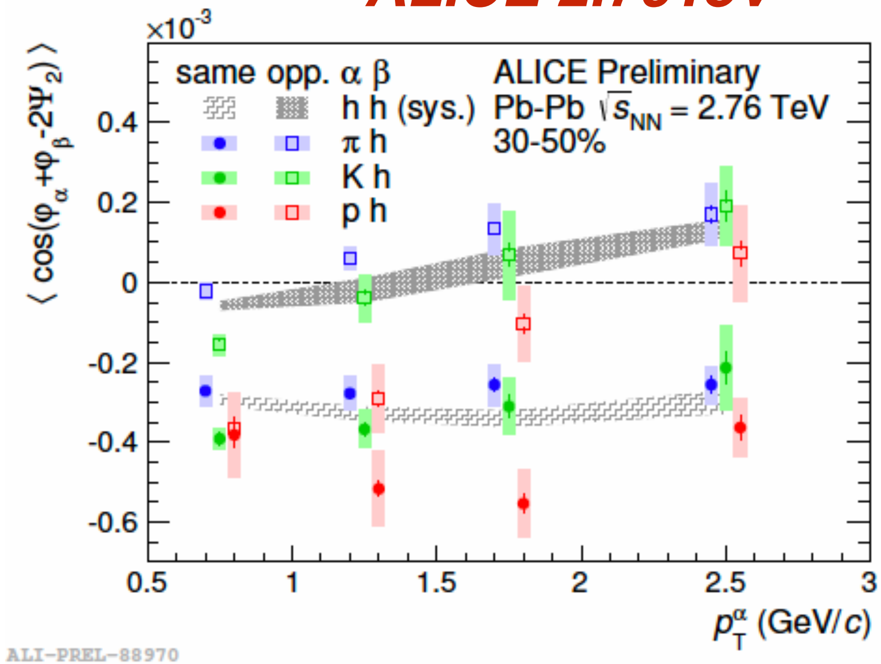
[A lot of detailed results in:
Shi, Yin, JL, …, arXiv:1611.04586; arXiv:1711.02496]

One Example: Flavor Dependence



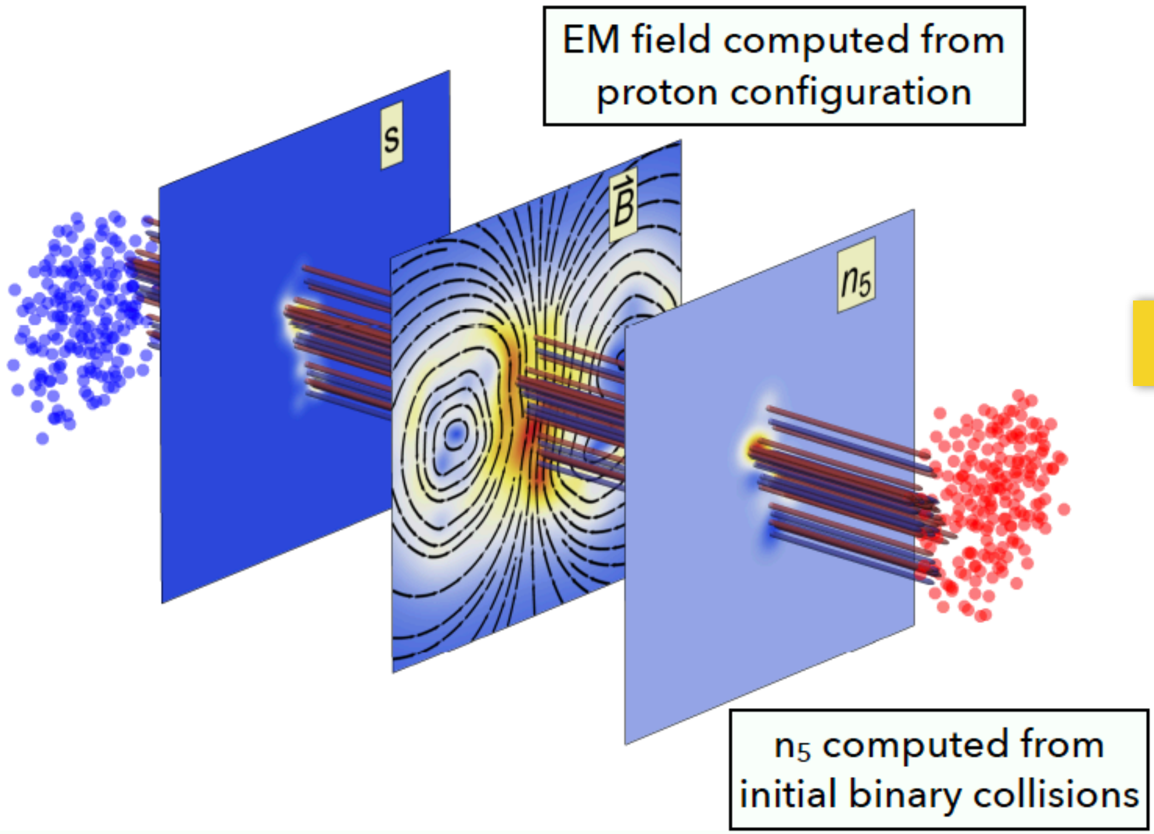
AVFD prediction (2017)

ALICE 2.76TeV



Kaons are sensitive to anomalous transport of s-quarks.
Theory analysis (S. Lin, D. Hou, …): u,d ~ s

Event-By-Event AVFD

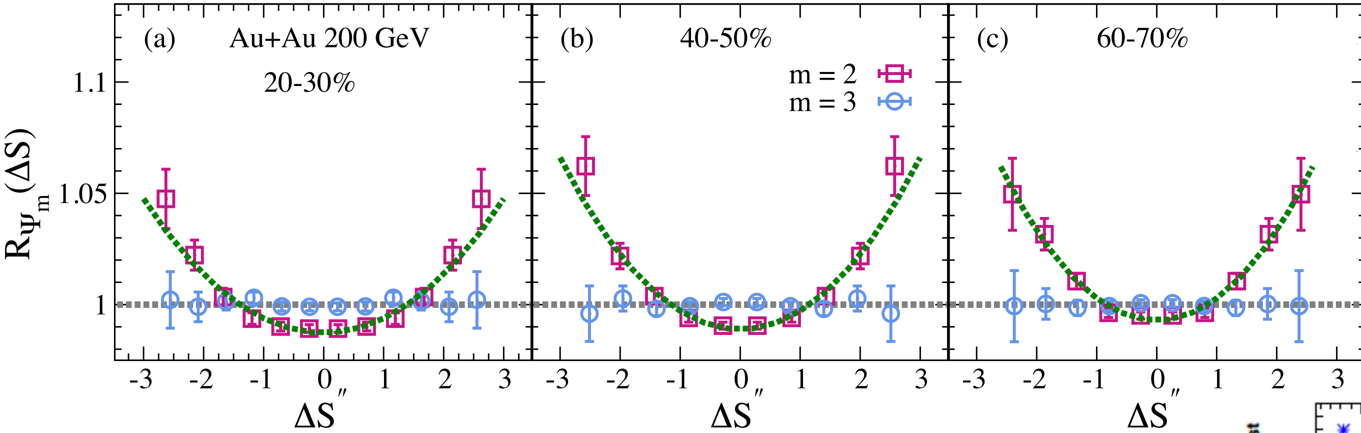


Include EBE fluctuations:

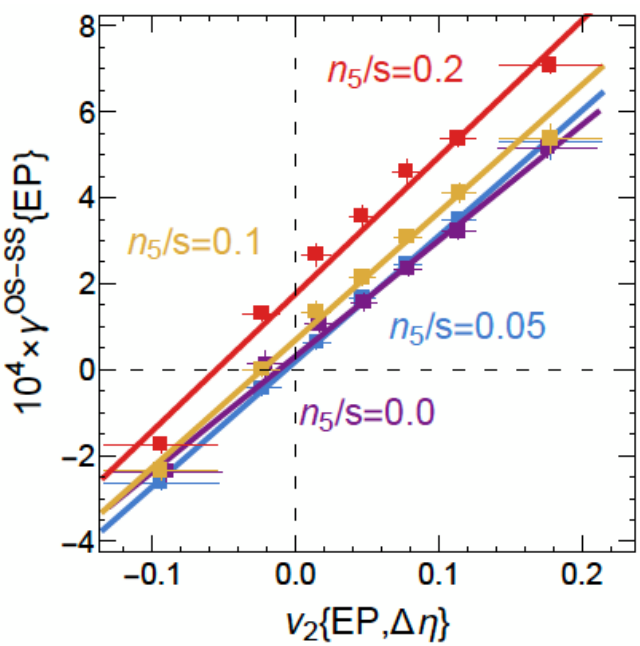
- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade *(~ half of all bkg.)*

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

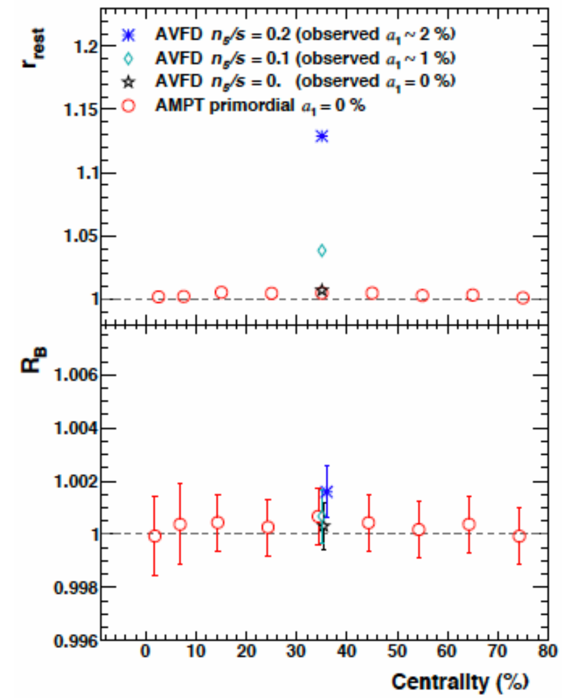
EBE-AVFD for Testing Observables



Lacey, Nagdy, et al

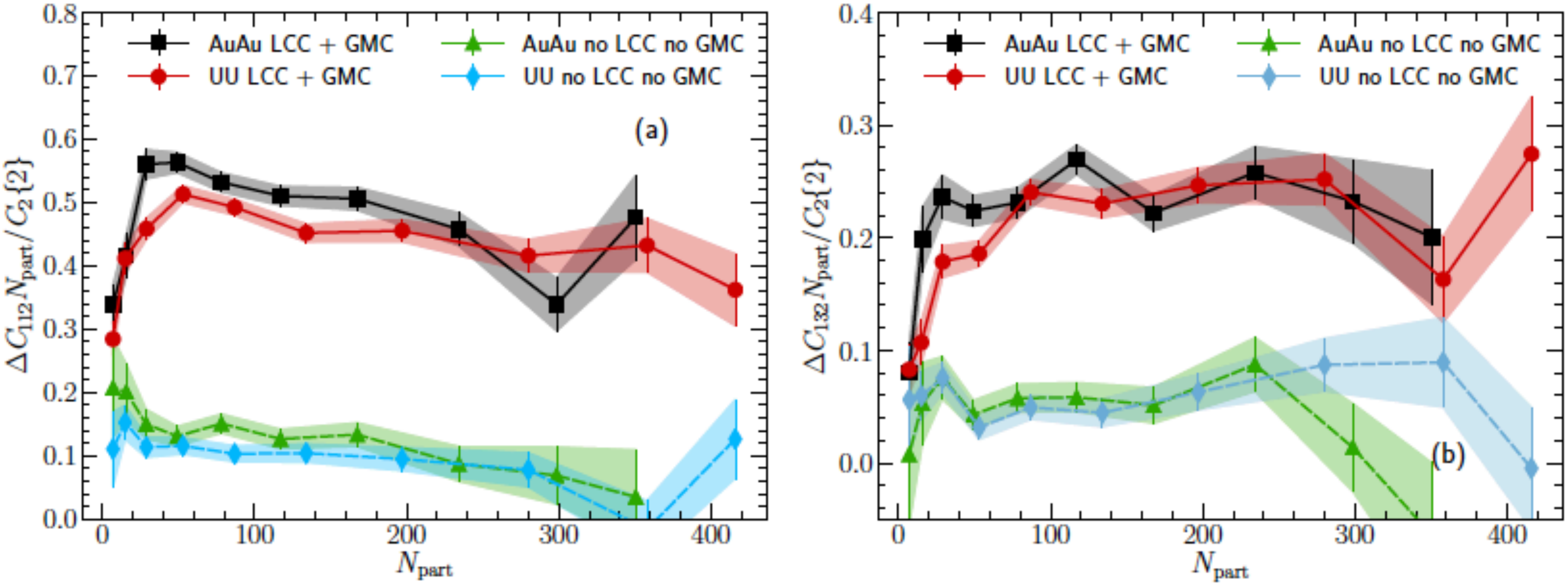


Tang



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

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]

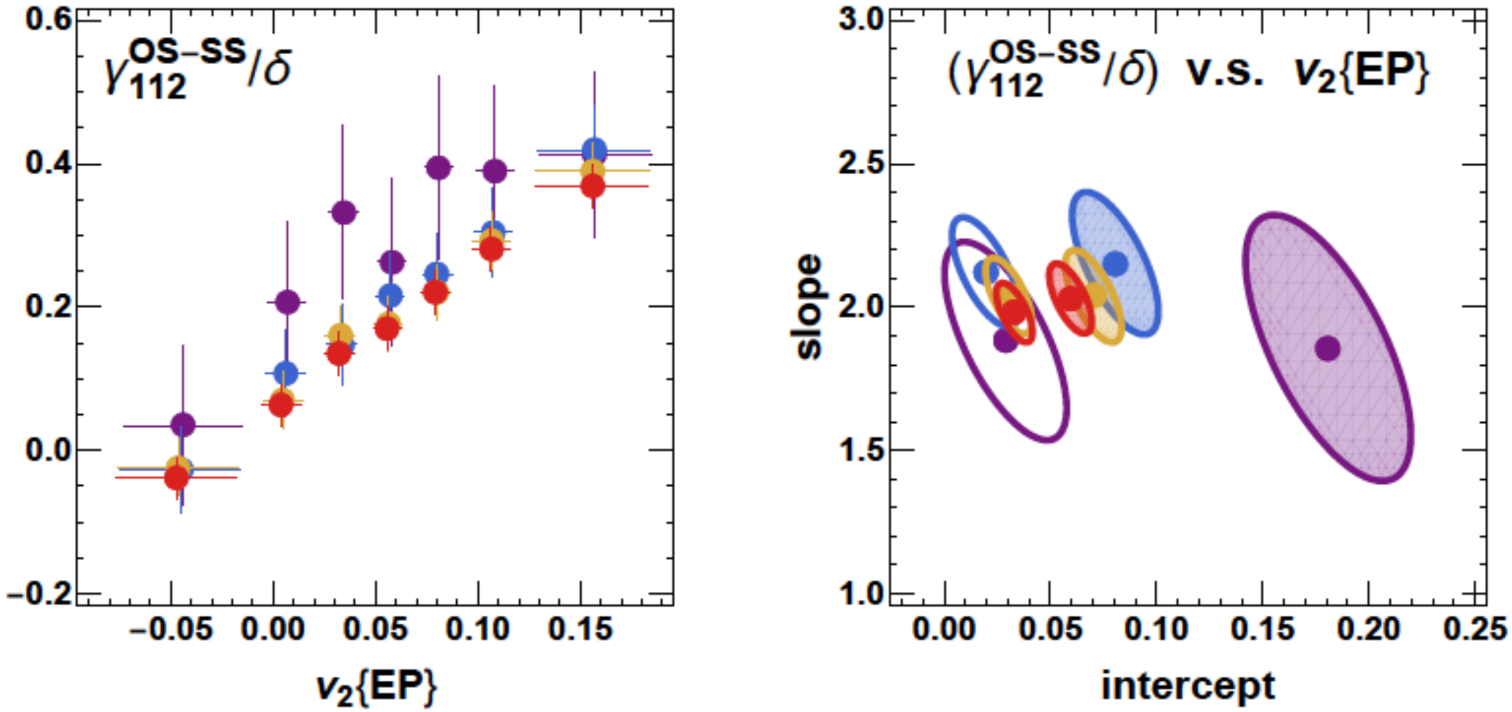
EBE-AVFD+LCC: Event Shape Engineering

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

$\delta = F + H$

filled: w/ CME
open: w/o CME

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



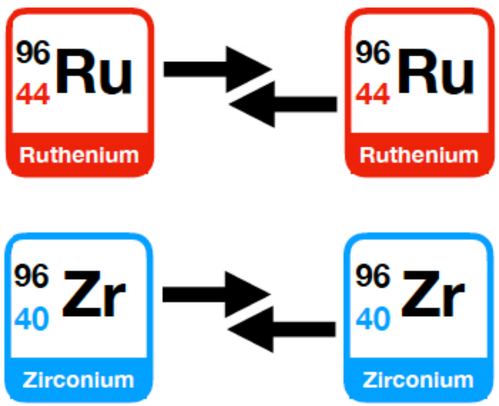
First time: full characterization of signal + known major backgrounds

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

Isobaric Collision

A Decisive Experiment: Isobaric Collisions

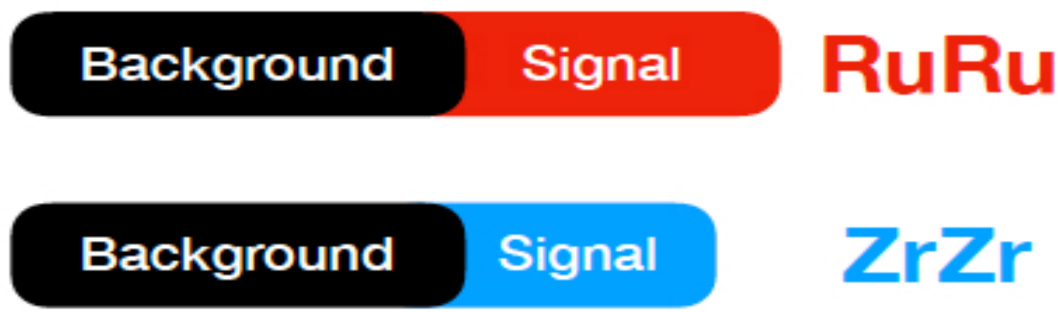
New opportunity of potential discovery: Isobaric Collision @ RHIC



[Koch, et al, arXiv: 1608.00982]

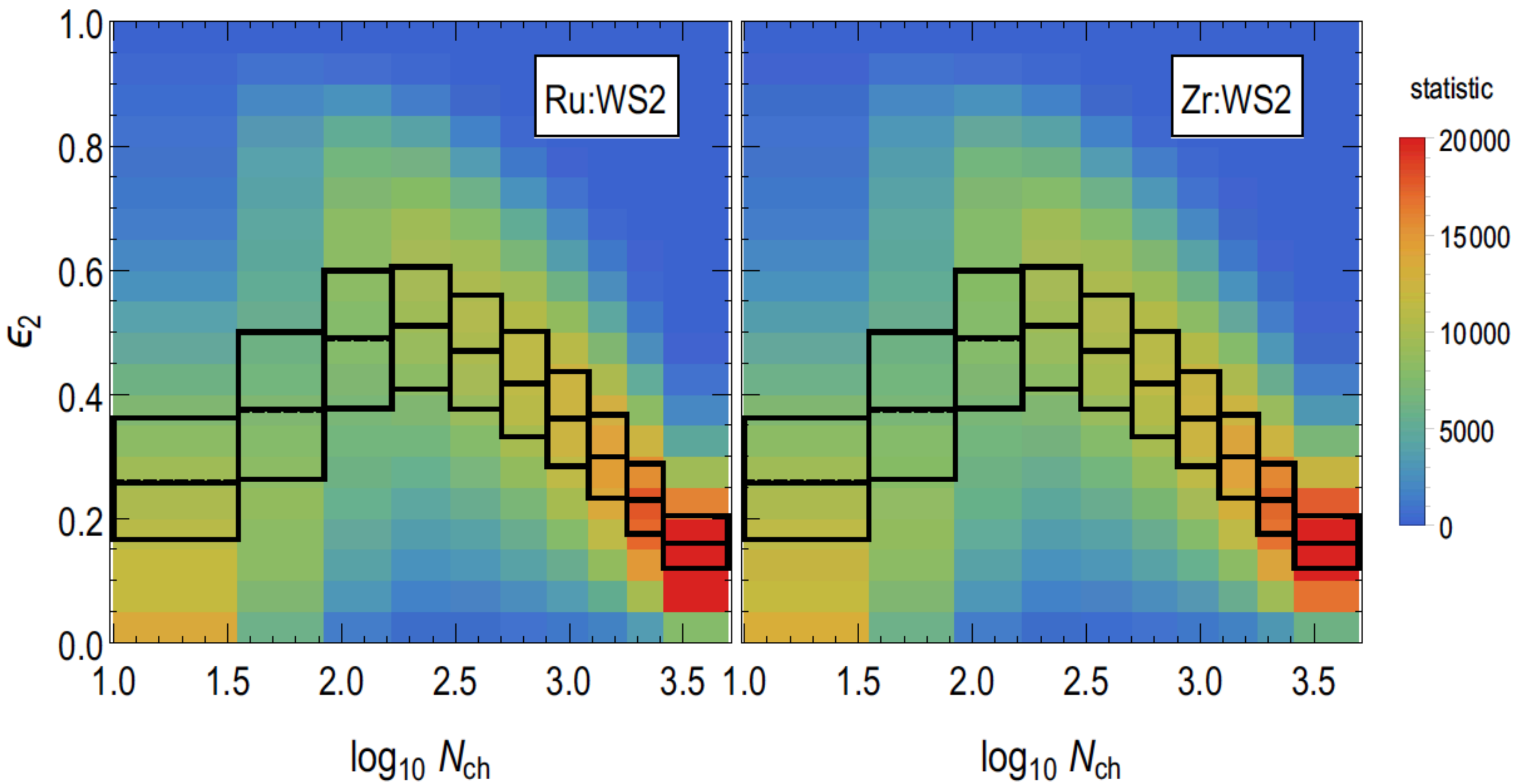
Charge Asymmetry Correlation Measurement

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



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

Isobars: How to Choose Identical Systems?

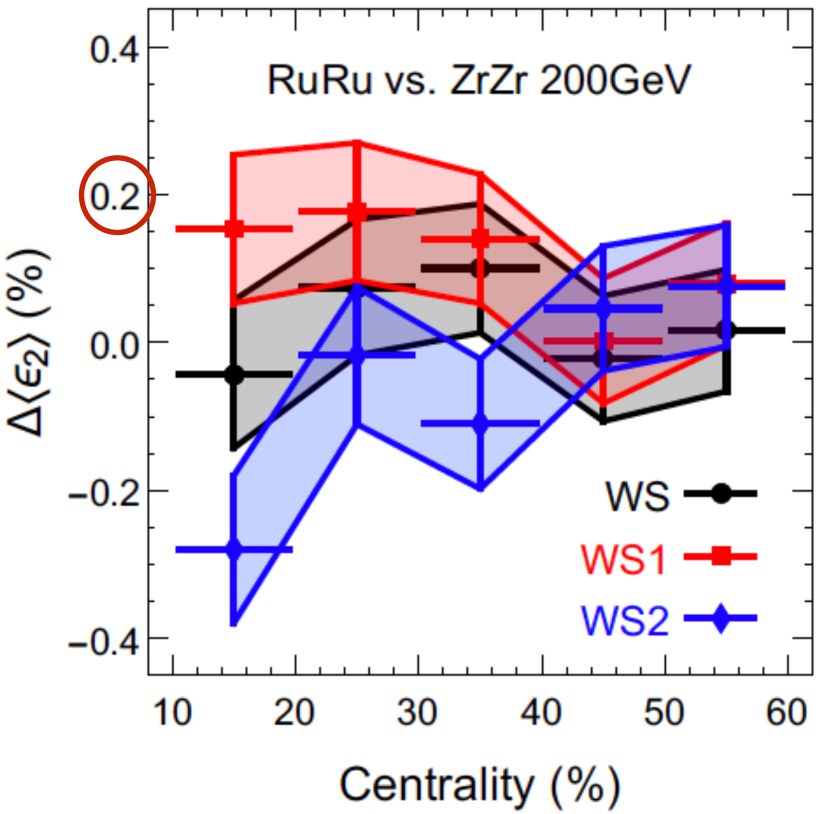


Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

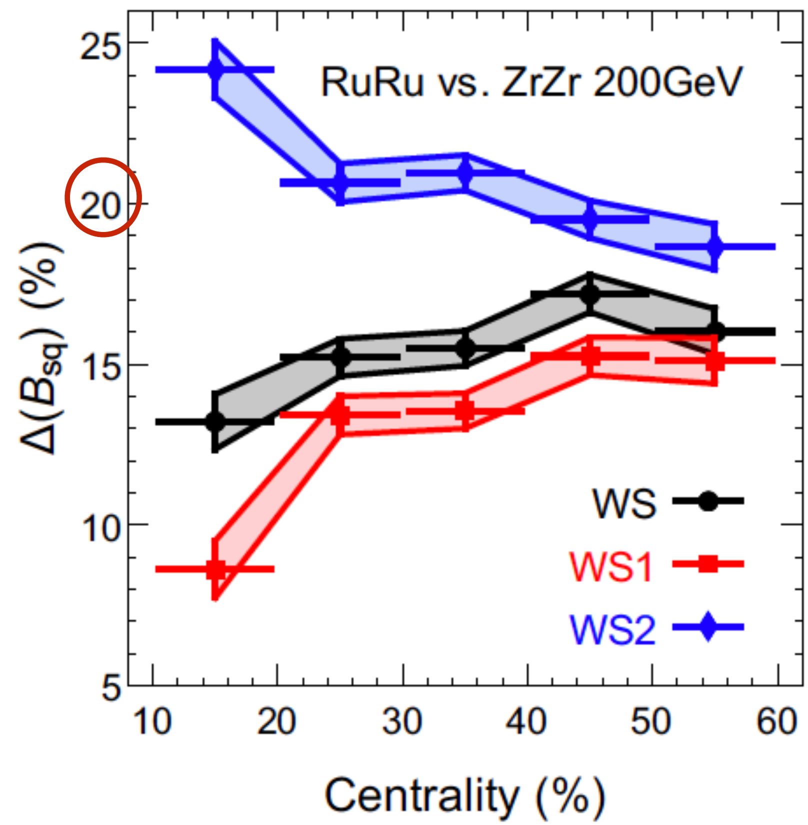
[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

Isobars: How to Choose Identical Systems?

Eccentricity is guaranteed the same!

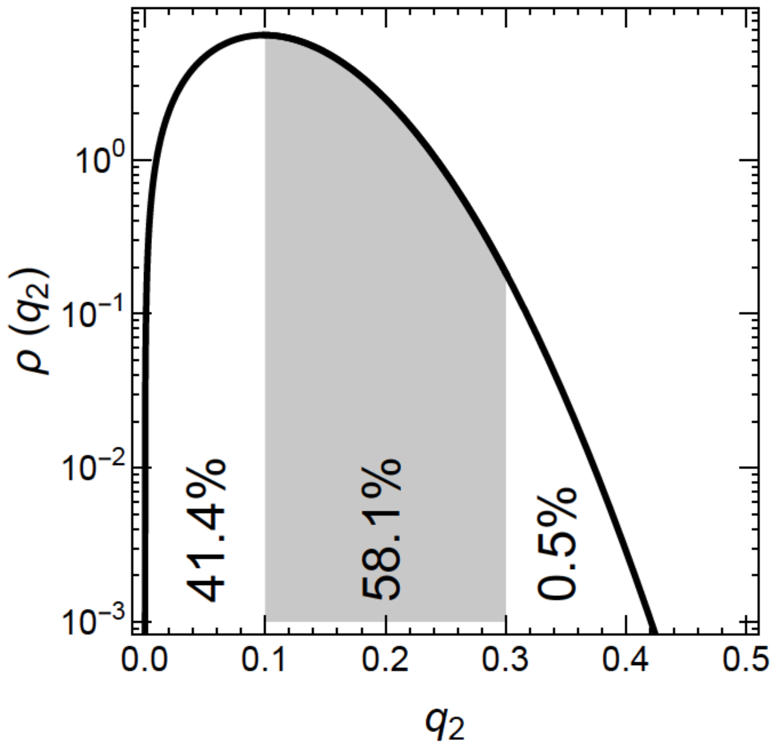


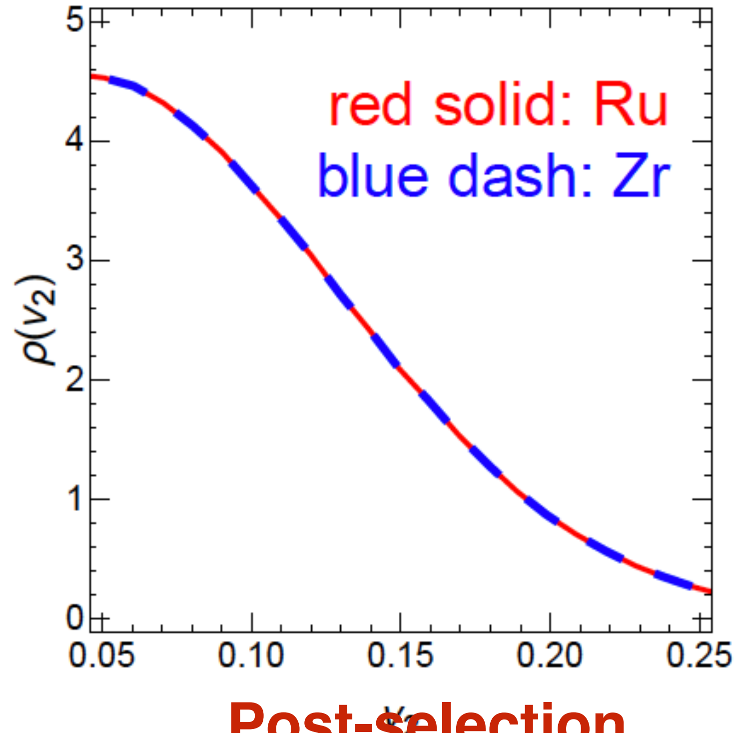
B field differs by 12~20% !



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

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

$$0.1 < q_2 < 0.3$$

Post-selection double-check: Identical v2 !

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

AVFD Predictions for Isobars

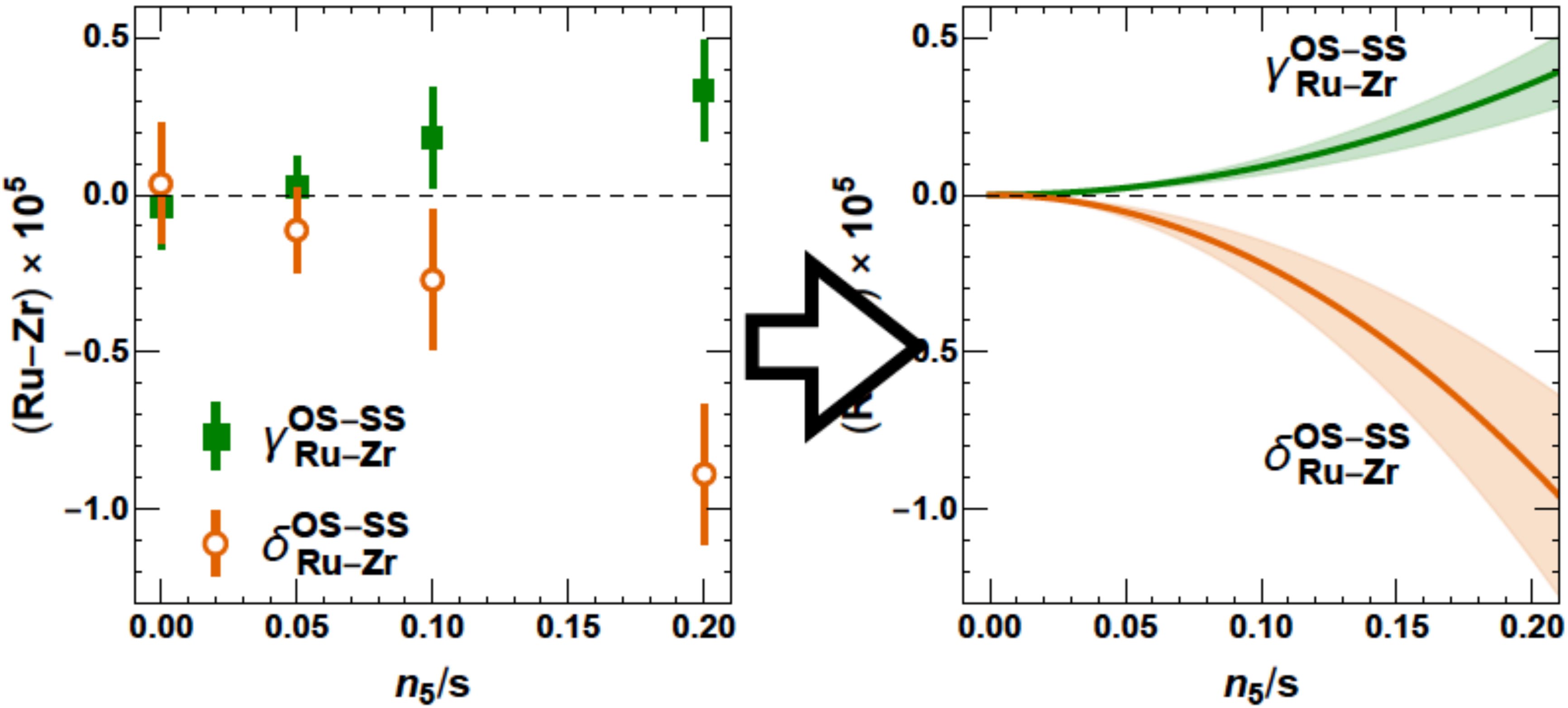
-1 < η < 1

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)!

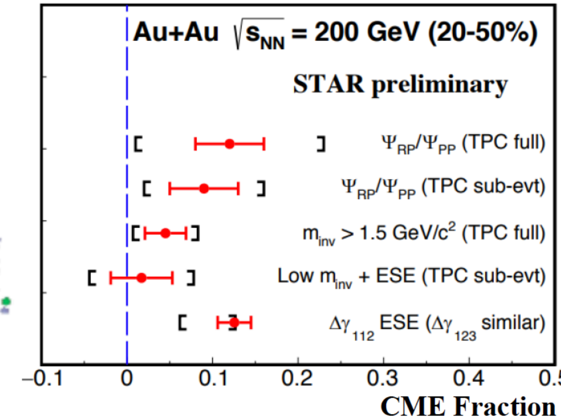
Look for consistency between delta- and gamma-correlators!

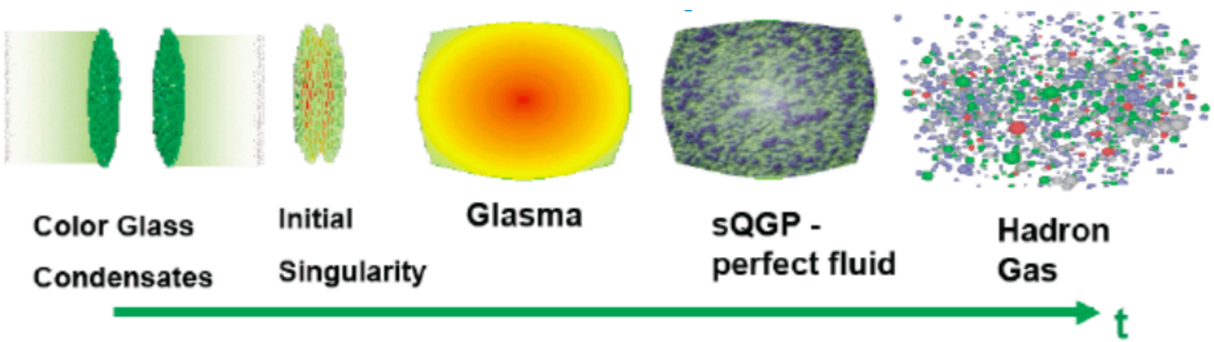
[Shi, Zhang, Hou, JL, arXiv:1807.05604; paper in preparation]

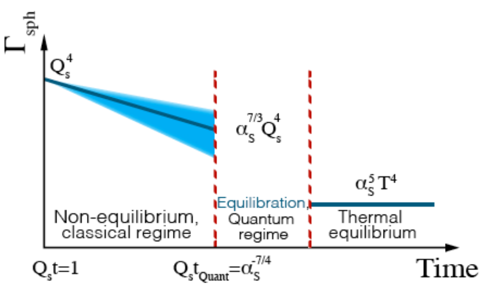
Summary & Outlook

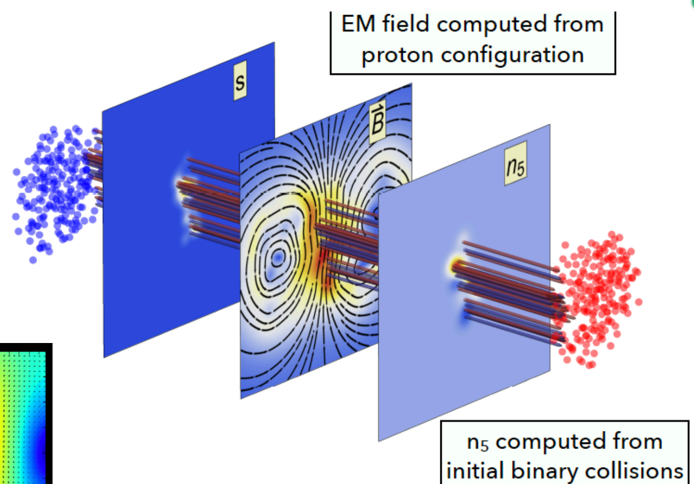
Summary: Toward Synergy of Key Ingredients

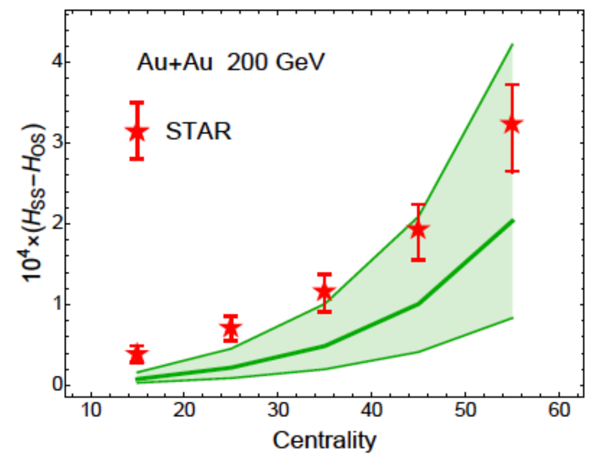
$$\boxed{\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}}$$

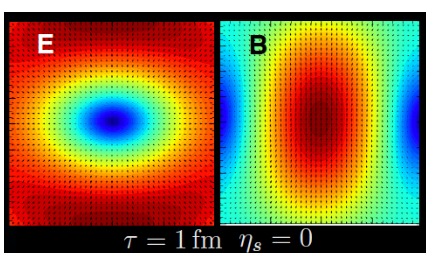












An exciting time: things are converging!

Outlook: Isobaric Collisions

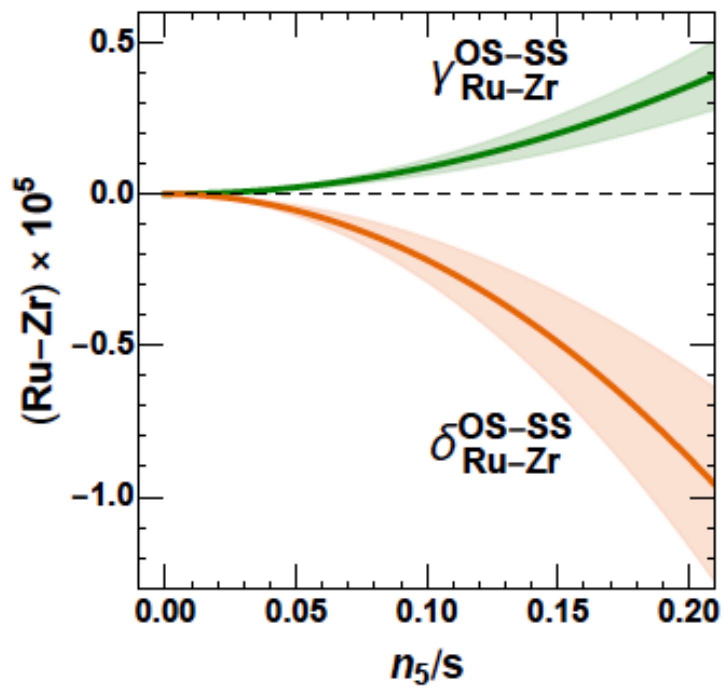
Charge Asymmetry Correlation Measurement

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

Background | Signal **RuRu**

Background | Signal **ZrZr**

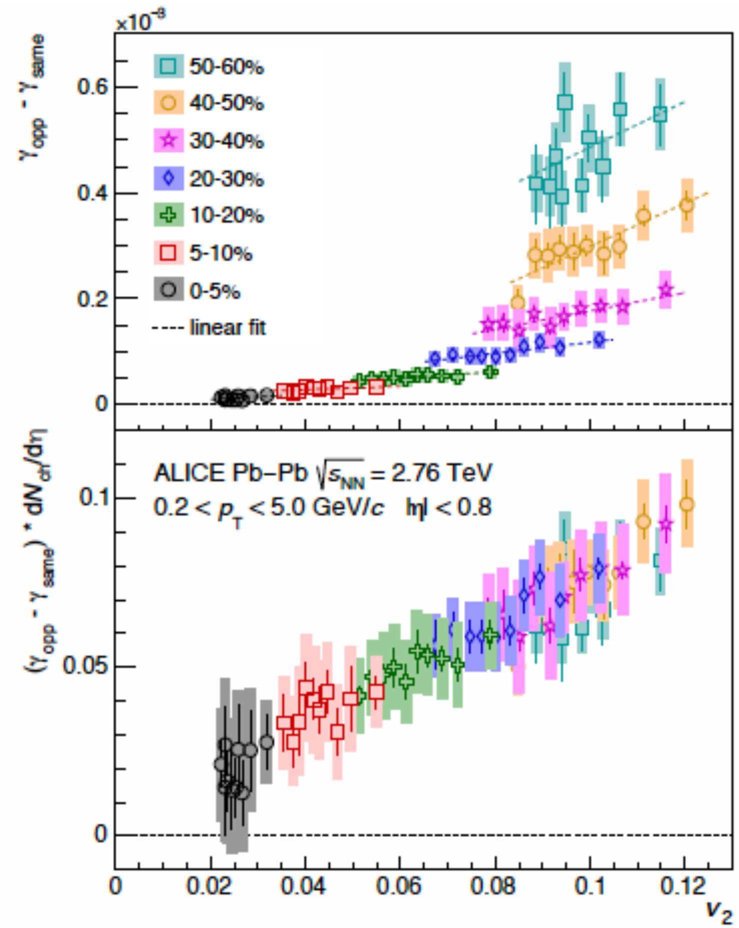
- ***Many observables: consistency?***
- ***Very important: understanding observables & their relations!!***
- ***Use sophisticated modeling tools (signal+bkg.) to help***



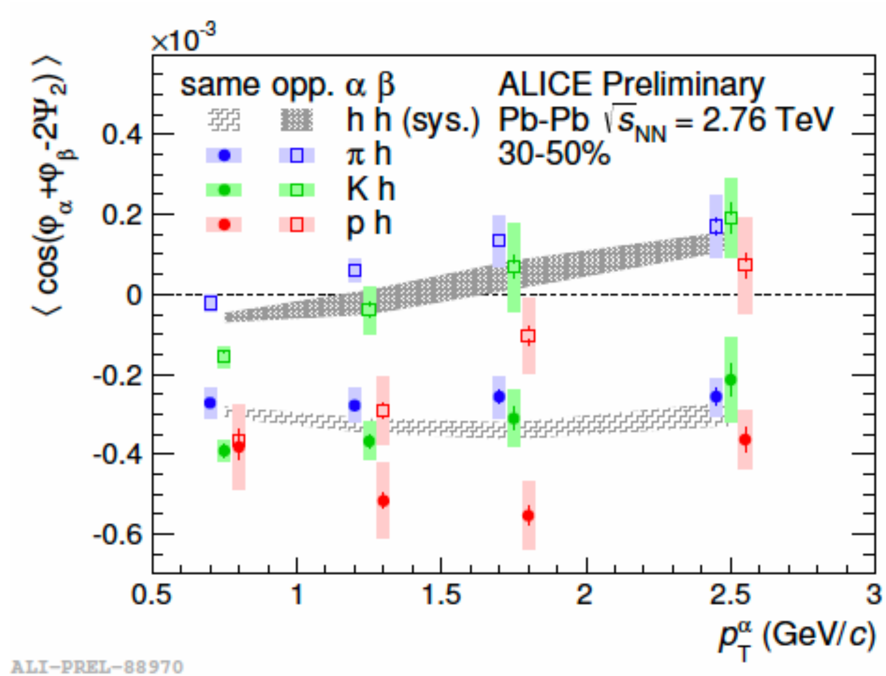
Exciting time(~2020): Stay tuned!

Backup Slides

Exp. Search for CME

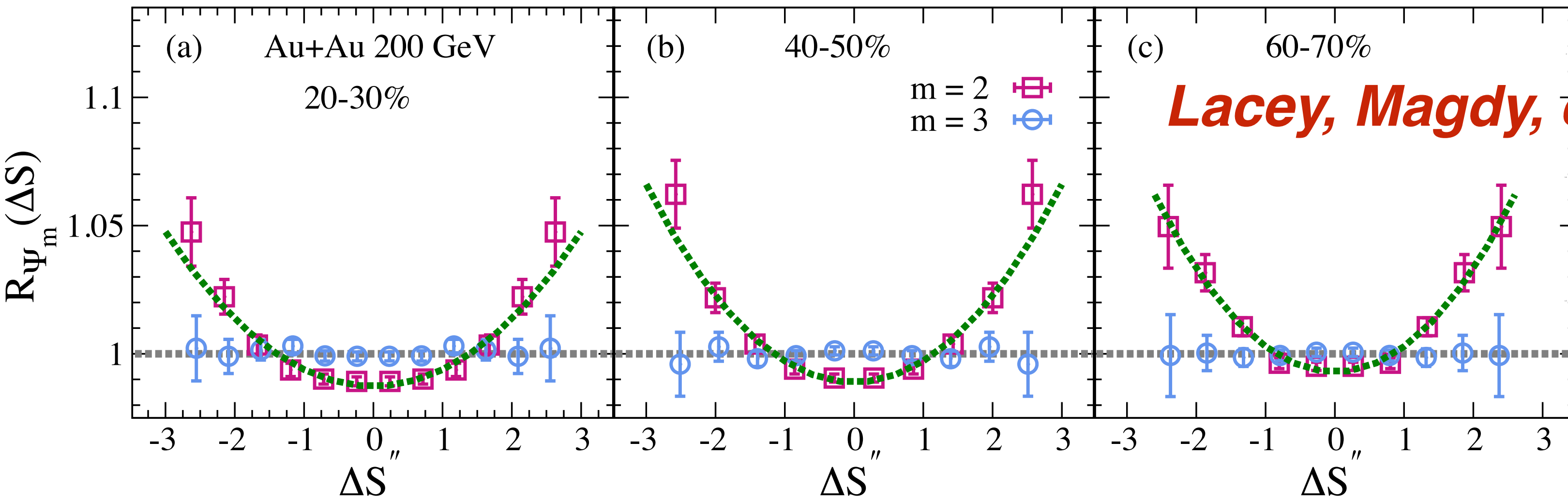


Flavor dependence is very interesting!



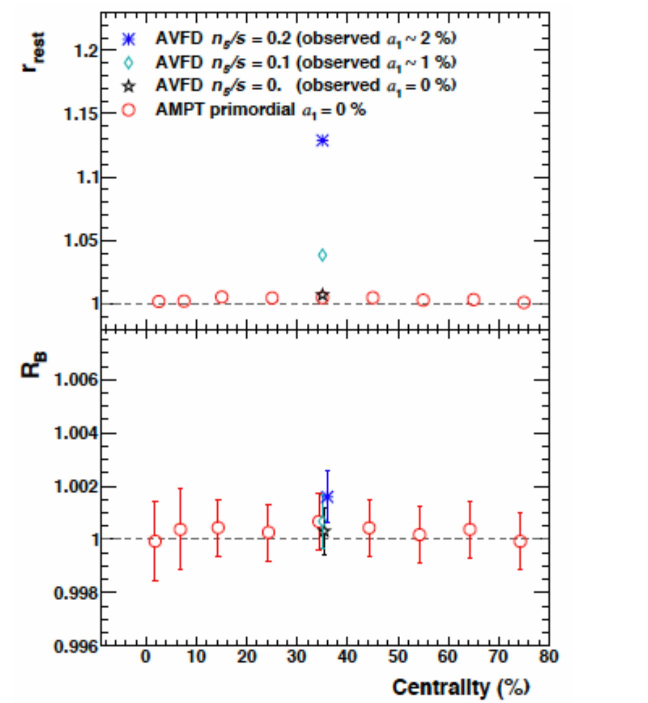
Talks by: H. Huang, F. Wang, R. Lacey, A. Tang, G. Wang, J. Zhao, Q. Shou

Exp. Search for CME



Lacey, Magdy, et al

New observables



A. Tang

CME <=> Chiral Anomaly

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

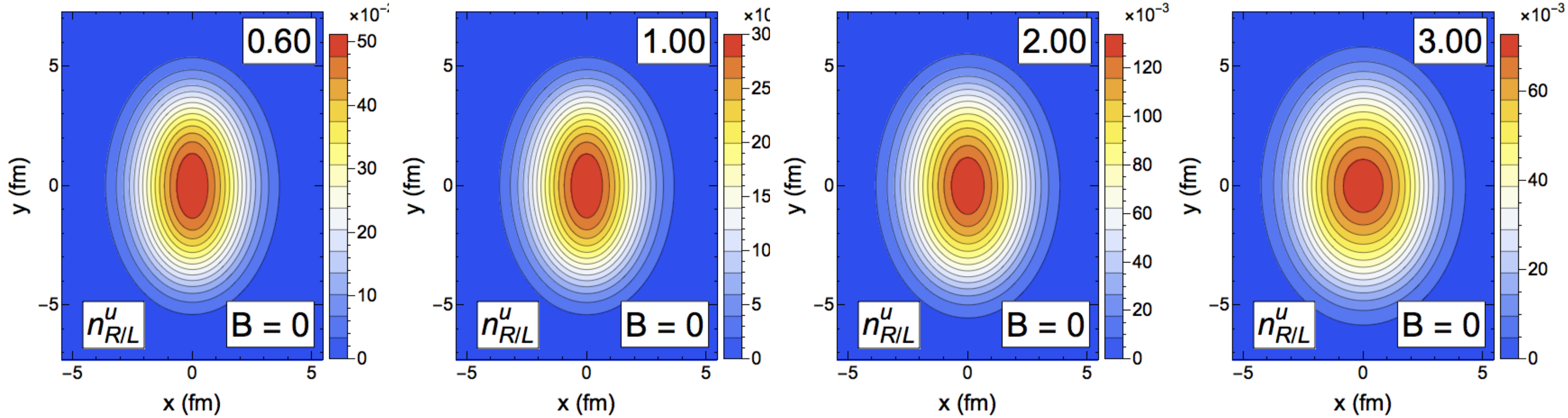
Chirality -->
$$\int d^3x \boldsymbol{j}_{el}\cdot\boldsymbol{E} = \mu_5 \frac{dN_5}{dt} = \frac{q^2\mu_5}{2\pi^2}\int d^3x \mathrm{B}\cdot\boldsymbol{E}$$

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

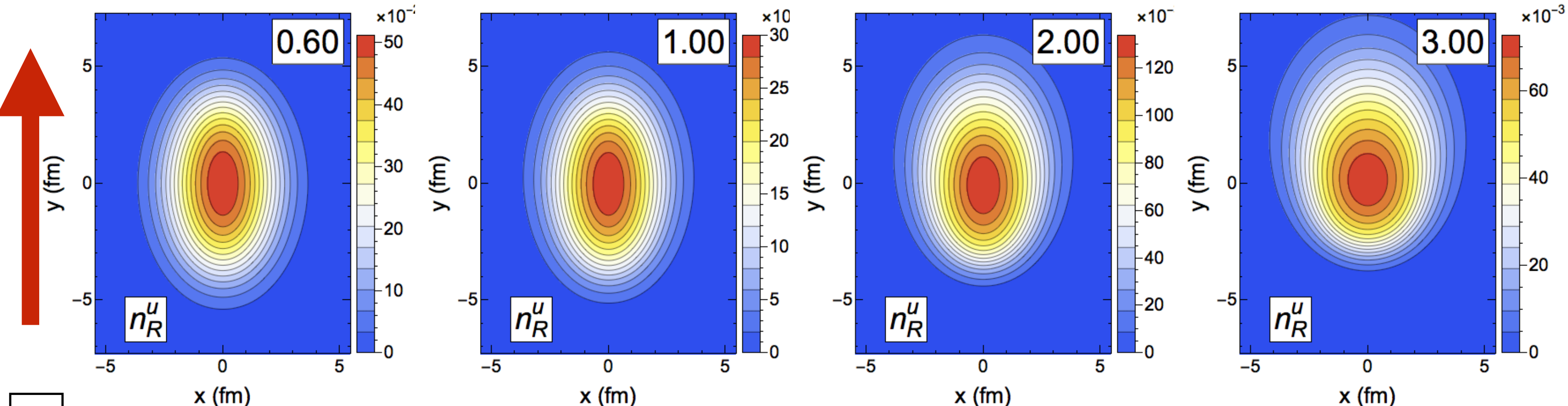
* This is a non-dissipative current!
* Indeed the chiral magnetic conductivity is P-odd but T-even!
(In contrast the Ohmic conductivity is T-odd and dissipative.)

CME is macroscopic chiral anomaly — a remarkable phenomenon!

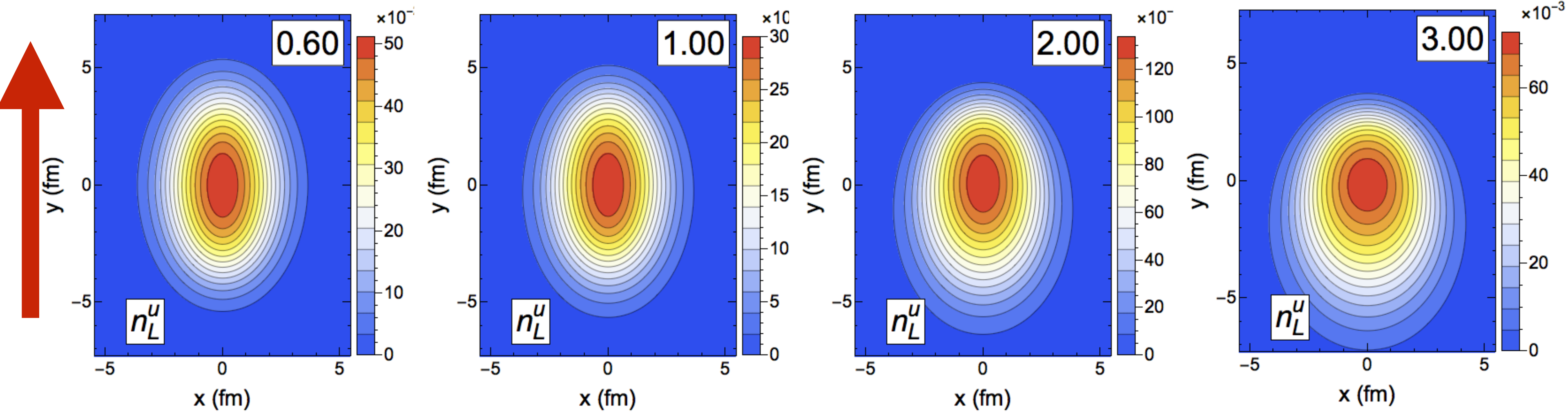
Demonstrating the AVFD



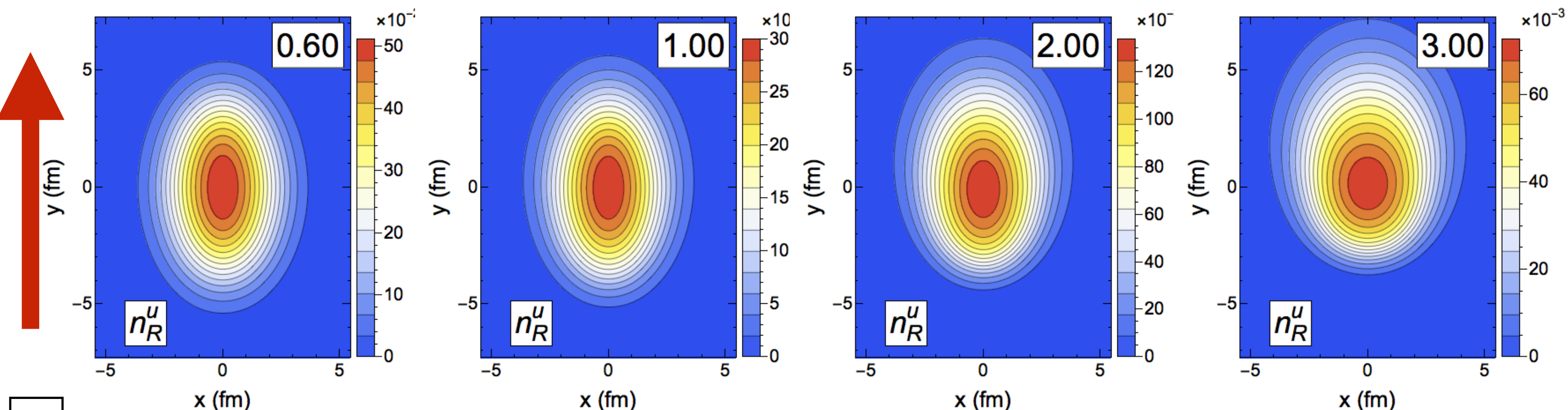
Upper: NO magnetic field
Lower: with B field (along y+ direction)



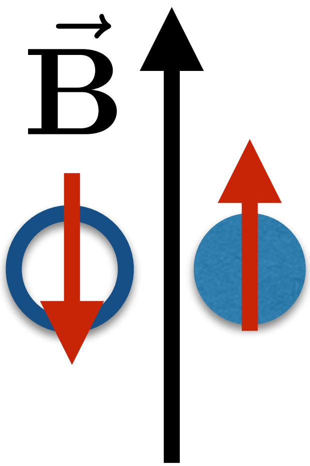
Demonstrating the AVFD

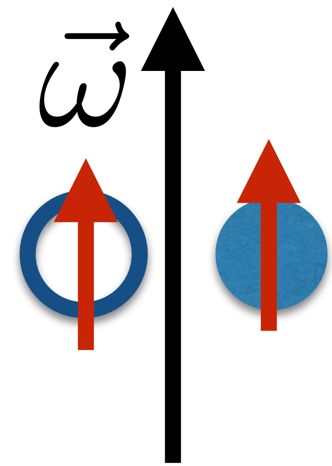


Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)



Magnetic Filed Induced Polarization





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

For Lambda:

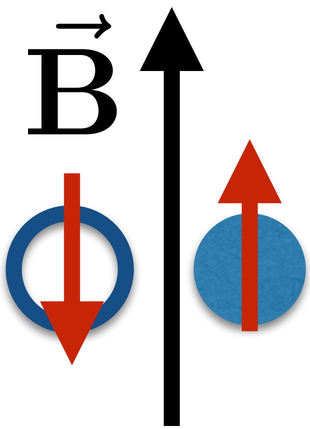
$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} - 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

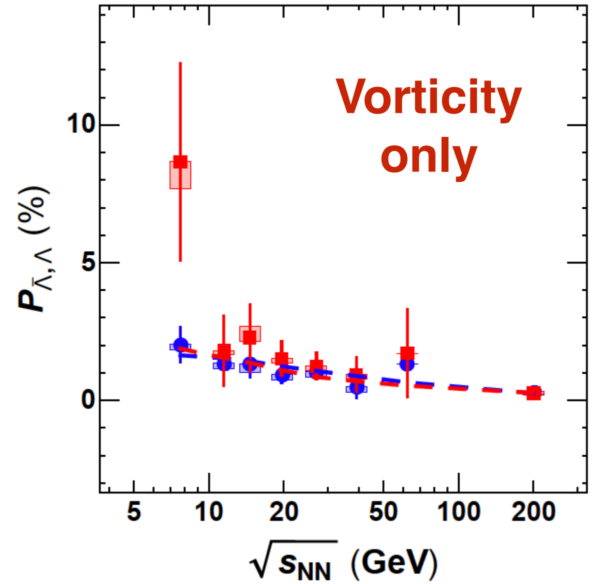
For anti-Lambda:

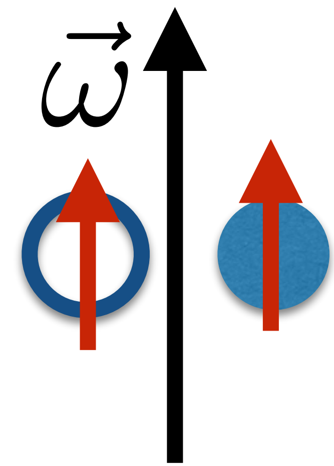
$$\varpi_{\rho\sigma} \to \left[\varpi_{\rho\sigma} + 2\left(\frac{0.61}{2M_p}\right)\frac{eF_{\rho\sigma}}{T}\right]$$

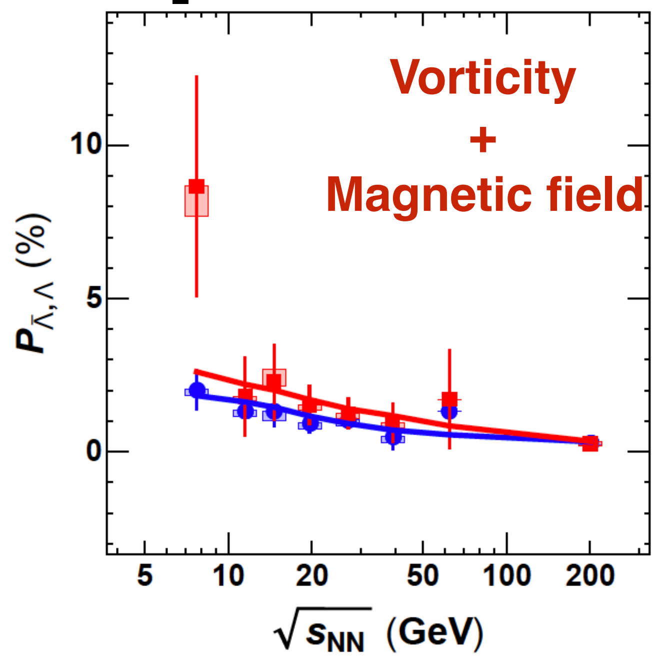
[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

Magnetic Filed Induced Polarization







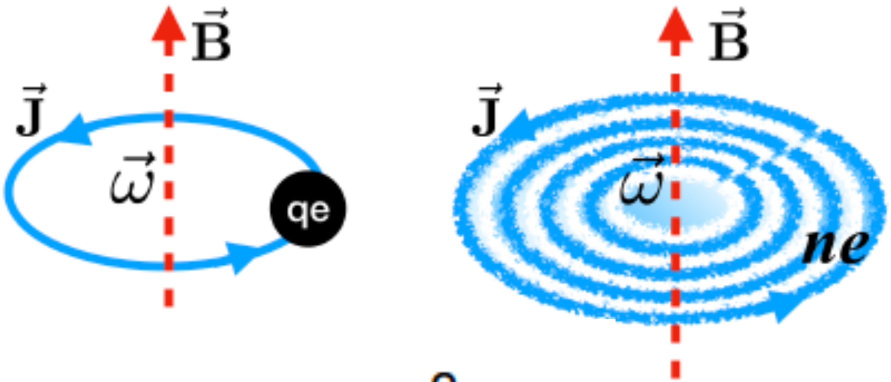


For this to work:
Requires long-lived late time magnetic field.

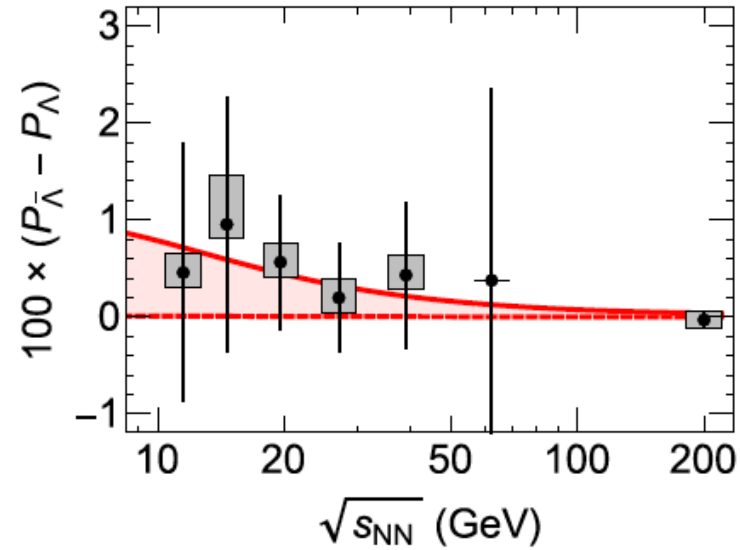
Where does that come from??

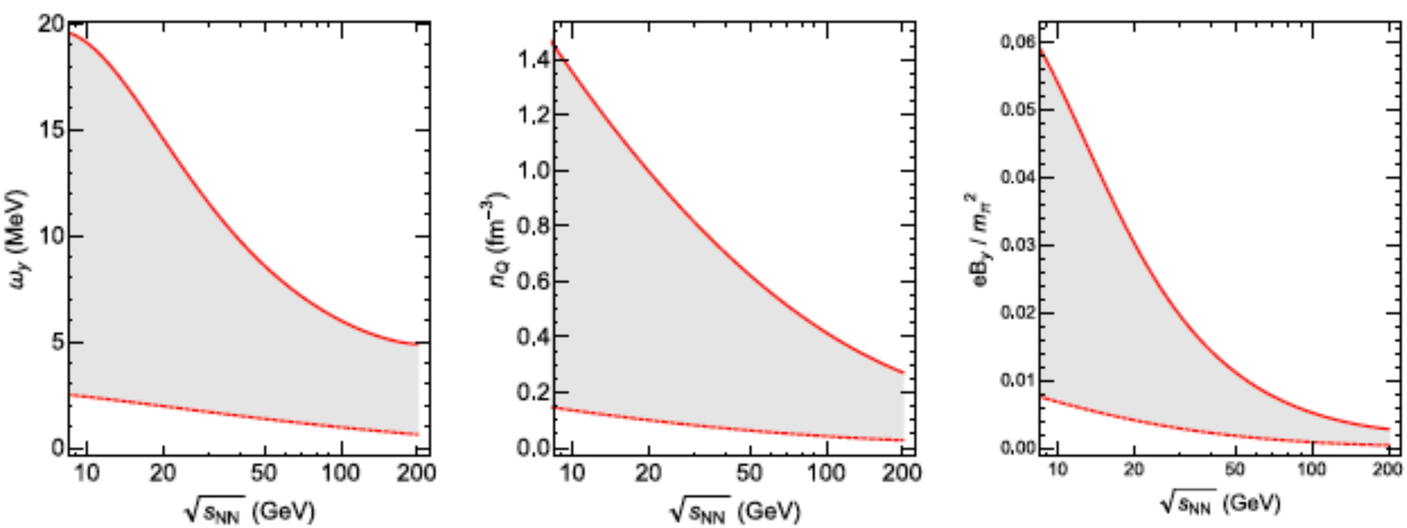
[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]

Connecting Magnetic Field and Fluid Rotation



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





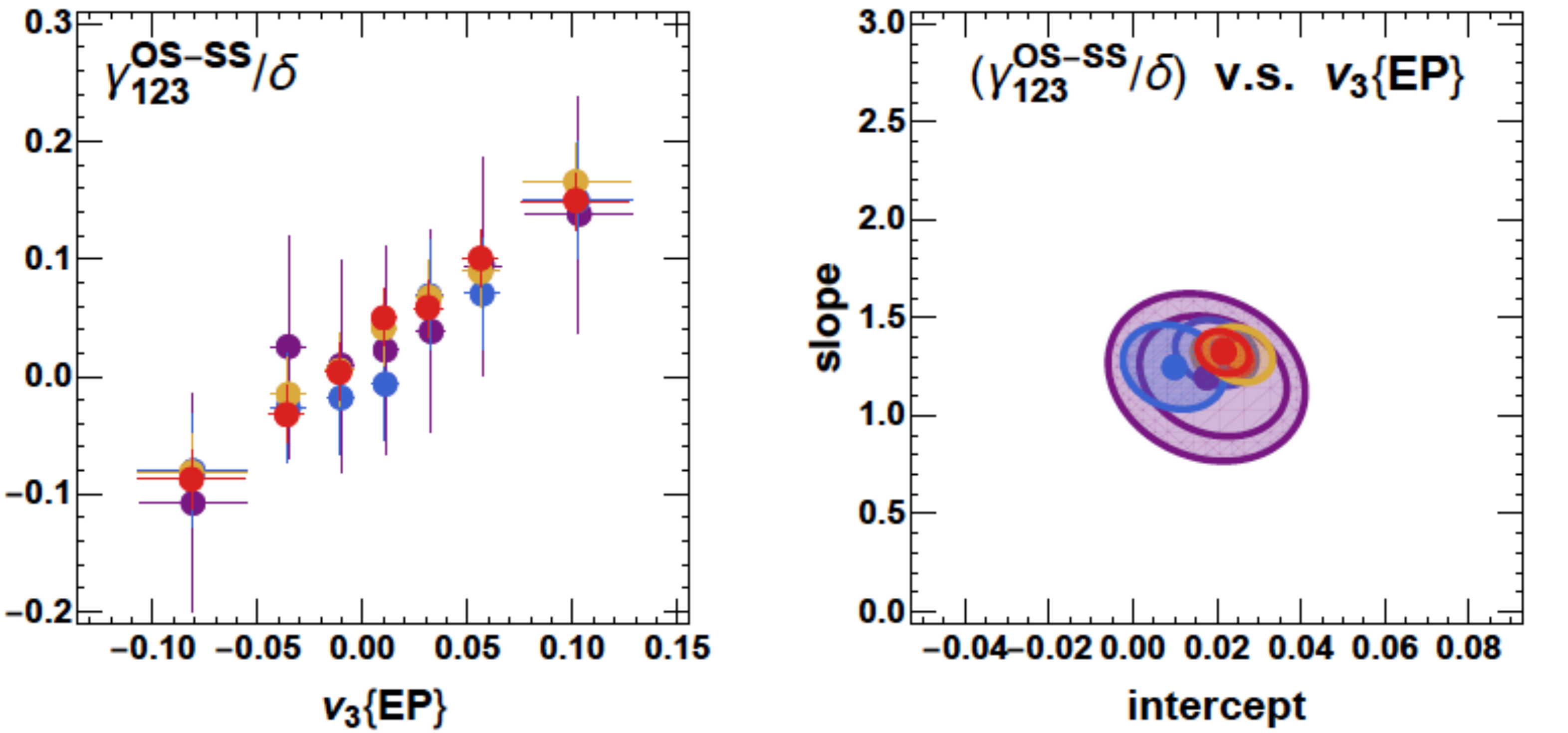
Important at low beam energy!

[X. Guo, et al, arXiv:1904.04704]

EBE-AVFD+LCC: Event Shape Engineering

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.]