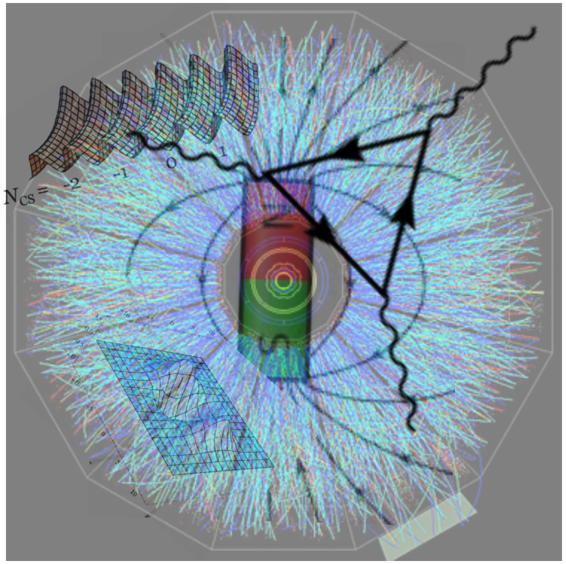
Status: CME Working Group



Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Outline

- *General developments in the field [very briefly]*
- *Experimental status & current challenge/ opportunity [new updates!]*
- *The BEST CME WG Efforts [major progress!]*
- *Outlook & Discussions*

Exciting physics of chirality, vorticity & magnetic field

Physics of Chirality, Vorticity and Magnetic Field

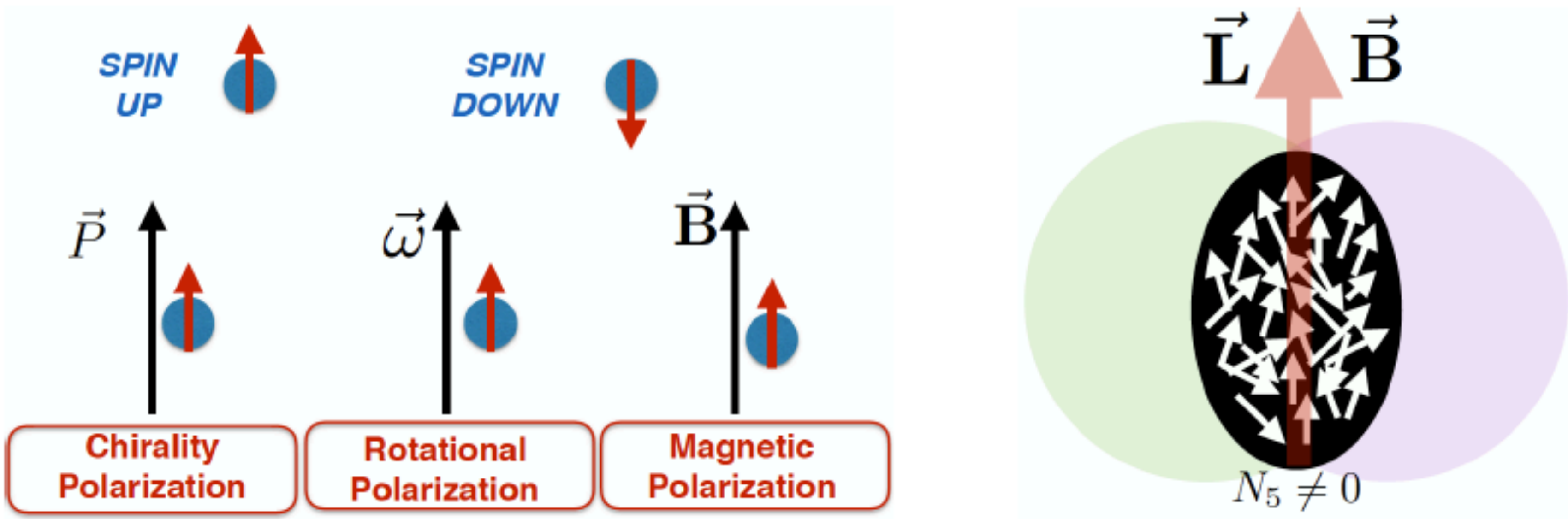


Fig. 1. (color online) Illustration of fermion spin polarization due to chirality, vorticity and magnetic field (left) and illustration of the fireball created in heavy ion collisions as a “spin fluid” under the presence of macroscopic chirality imbalance as well as extremely strong vorticity and magnetic field (right).

[QM19' "Chirality & Magnetic Field", arXiv:2004.00569]

arXiv:1906.00936

A Recent Review

Outline

Abstract

Keywords

1. Introduction

2. QCD and chiral symmetry

3. Phase diagram of QCD

4. Theory and phenomenology of th...

5. Theory and phenomenology of an...

6. The beam energy scan program a...

7. Discussions on BES-I results

8. Summary and outlook

ELSEVIER

Physics Reports

Volume 853, 13 April 2020, Pages 1-87

Mapping the phases of quantum chromodynamics with beam energy scan

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

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https://doi.org/10.1016/j.physrep.2020.01.005

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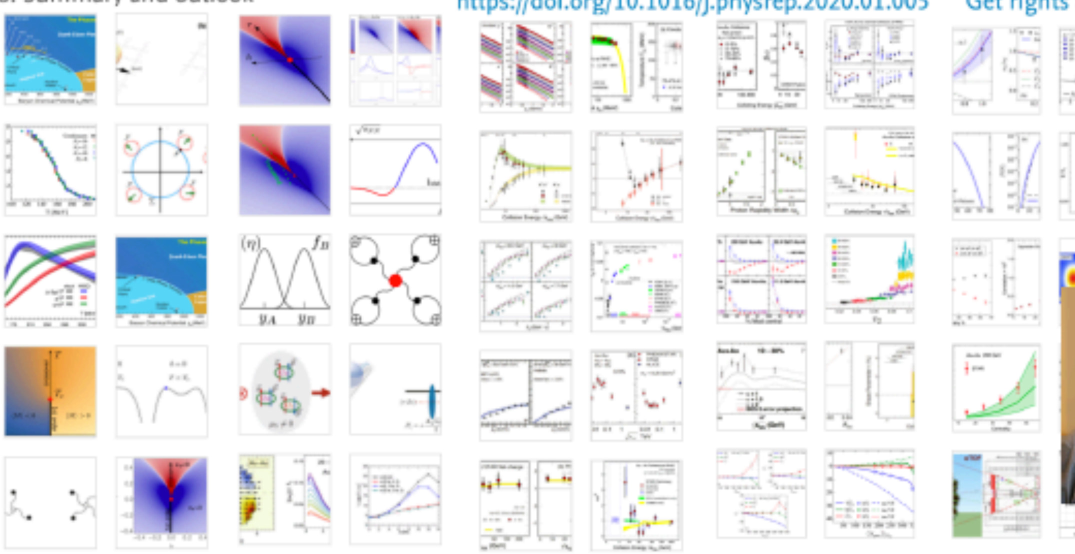
Part of special issue:

Mapping the phases of quantum chromodynamics with beam energy scan

Recommended articles



[slide from Nu Xu's talk at INT2020]

BEST: LBNL-UIC-IU

Many New Developments

- *Quantum (chiral / spin) transport theory (!!)*
- *Hydrodynamics with spin/chiral DOF (!)*
- *Polarization measurements at RHIC & LHC (!)*
- *Theoretical understanding of rotational polarization (!!)*
- *Hydro/transport modelings of polarization effects (!)*
- *Dynamical magnetic fields and related effects (!!)*
- *CME measurements: new observables (!)*
- *CME modeling: AVFD, B field, axial charge, backgrounds (!!)*
- *…*

Quark Matter 2019

Chirality 2020 (unfortunately delayed)

Ongoing INT Program (coming week!)

INT Program INT 20-1c

Online Program INT 20-1c

Criticality and Chirality:
Novel Phenomena in Heavy Ion Collisions

May 11 - 22, 2020

Week-2 “Chirality” Scientific Program

All time info in Pacific Standard Time (UTC -8), please convert accordingly. Zoom link will be available via announcement email, or by contacting liaoji[at]indiana.edu.

Monday, May 18, 2020

8:00 - 9:00	“Chirality: theoretical overview” Dmitri Kharzeev (Stony Brook / BNL)
9:10 - 10:10	“Chirality: experimental overview” Sergei Voloshin (Wayne State Univ)
10:20 - 11:00	Discussions
17:00 – 18:00	“Chiral transport and turbulence in supernovae” Naoki Yamamoto (Keio Univ)

https://sites.google.com/uw.edu/int/programs/current-program-schedule

5 days of exciting program, ~18 talks!

Magnetohydro / Chiral-hydro

P.~Glorioso and D.~T.~Son, ``Effective field theory of magnetohydrodynamics from generalized global symmetries,'' [arXiv:1811.04879 [hep-th]].

We can now write down the general MHD action at first derivative order, which is given by:

$$S_{(1)} = \int d^4x\sqrt{-g}\big(a_1\varepsilon^{ijk}m_i d_j v_k + a_2 T\varepsilon^{ijk}\partial_0 m_{ij}v_k + a_3\varepsilon^{ijk}d_i m_{jk}\big)\ , \tag{5.3}$$

BEST: U Chicago

S.~Shi, C.~Gale and S.~Jeon, ``From Chiral Kinetic Theory To Spin Hydrodynamics,'' [arXiv:2002.01911 [nucl-th]].

Spin-Hydro with Non-Equilibrium Correction:

$$J^\mu_\pm = n_\pm u^\mu + \nu^\mu_\pm \pm \hbar\Big(\frac{3J^\pm_{1,1}}{2T} - \frac{3\Pi}{2m^2}\Big)\omega^\mu \pm \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho\partial_\sigma\Big(\frac{G^{(1),\pm}_{4,1}}{D^\pm_{3,1}}\nu_{\pm,\lambda}\Big) \pm \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho\sigma_\sigma{}^\xi\Big(\frac{J^\pm_{2,2}}{2J^\pm_{4,2}}\pi_{\lambda\xi}\Big) \mp \frac{\hbar}{2}\omega_\lambda\Big(\frac{J^\pm_{2,2}}{2J^\pm_{4,2}}\pi^{\mu\lambda}\Big)$$

"normal" viscous hydro — CVE in eq.

$$\begin{aligned} T^{\mu\nu} =& \epsilon u^\mu u^\nu + (P_0+\Pi)(u^\mu u^\nu - g^{\mu\nu}) + \pi^{\mu\nu} + \hbar\frac{J^+_{2,1}-J^-_{2,1}}{2T}(u^\mu\omega^\nu + u^\nu\omega^\mu) + \hbar(I^+_{1,0}-I^-_{1,0})\omega^\mu u^\nu \\ &+ \hbar(u^\mu\Omega^\nu_+ + u^\nu\Omega^\mu_+) - \hbar(u^\mu\Omega^\nu_- + u^\nu\Omega^\mu_-) \\ &+ \frac{\hbar}{2}\Big(\frac{J^+_{3,2}}{2J^+_{4,2}} - \frac{J^-_{3,2}}{2J^-_{4,2}}\Big)\epsilon^{\mu\rho\sigma\lambda}u^\nu u_\rho(\partial_\sigma u^\xi)\pi_{\lambda\xi} + \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho\partial_\sigma\Big(\Big(\frac{J^+_{3,2}}{2J^+_{4,2}} - \frac{J^-_{3,2}}{2J^-_{4,2}}\Big)\pi^\nu_\lambda\Big) \\ &+ \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho(\partial_\sigma u^\nu)(K_+\nu_{+,\lambda} - K_-\nu_{-,\lambda}) + \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\nu}u_\rho(\partial_\sigma u^\lambda)(K_+\nu_{+,\lambda} - K_-\nu_{-,\lambda}) \\ &+ \hbar\omega^\mu(K_+\nu^\nu_+ - K_-\nu^\nu_-) + \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho u^\nu\partial_\sigma(\nu_{+,\lambda} - \nu_{-,\lambda}) + \frac{\hbar}{2}\epsilon^{\mu\rho\sigma\nu}u_\rho u^\lambda\partial_\sigma(\nu_{+,\lambda} - \nu_{-,\lambda}) \end{aligned}$$

$$K_\pm \equiv 1 + \frac{J^\pm_{3,1}J^\pm_{3,2} - J^\pm_{2,2}J^\pm_{4,1}}{D^\pm_{3,1}}$$

BEST: McGill

Quantum Kinetic Theory

S.~Li and H.~U.~Yee,``Quantum Kinetic Theory of Spin Polarization of Massive Quarks in Perturbative QCD: Leading Log,'' Phys. Rev. D 100, no.5, 056022 (2019)

BEST: UIC

Density Matrix: $\hat{\rho}(\mathbf{p}) = \frac{1}{2} f(\mathbf{p}) + \mathbf{S}(\mathbf{p}) \cdot \overrightarrow{\sigma}$

$$\frac{\partial f(\mathbf{p},t)}{\partial t} = C_2(F)\frac{m_D^2 g^2 \log(1/g)}{(4\pi)}\sigma_f$$

$$\sigma_f = \nabla_{p^i}\Big(T(\frac{3}{4} - \frac{E_p^2}{4p^2} + \frac{\eta_p m^4}{4p^3 E_p})\nabla_{p^i} f(\mathbf{p}) + \mathbf{p}^i \frac{Tm^2}{4p^3 E_p}(\eta_p + \frac{3E_p}{p} - \frac{3\eta_p E_p^2}{p^2})\mathbf{p}\cdot\nabla_p f(\mathbf{p}) + \frac{\mathbf{p}^i}{2p^2}(E_p - \frac{\eta_p m^2}{p}) f(\mathbf{p})\Big)$$

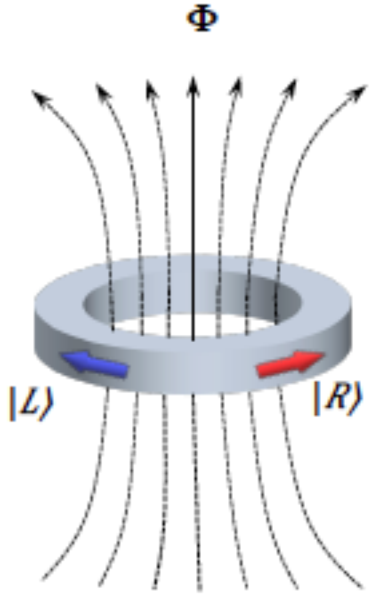
$$\frac{\partial \mathbf{S}(\mathbf{p},t)}{\partial t} = C_2(F)\frac{m_D^2 g^2 \log(1/g)}{(4\pi)}\frac{1}{2pE_p}\boldsymbol{\Gamma}_S$$

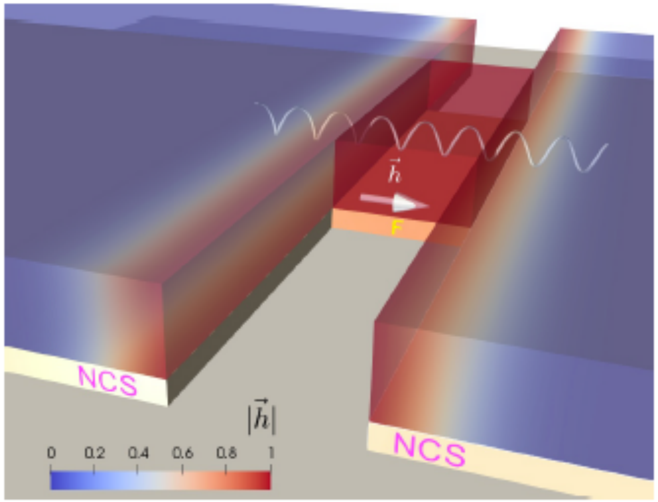
$$\boldsymbol{\Gamma}_S^i = (2p + \frac{TE_p}{p} - \frac{\eta m^2 T}{p^2})\mathbf{S}^i(p) + (pTE_p - \frac{m^2 TE_p}{2p} + \frac{\eta m^4 T}{2p^2})\nabla_p^2 \mathbf{S}^i(\mathbf{p}) + [\frac{\eta m^2 T}{2p^2}(1 - \frac{3E_p^2}{p^2}) + \frac{3m^2 TE_p}{2p^3}](\mathbf{p}\cdot\nabla_p)^2 \mathbf{S}^i(\mathbf{p}) + \frac{1}{p^2}[pE_p^2 - \frac{3m^2 TE_p}{2p} + \eta m^2(-E_p - \frac{T}{2} + \frac{3TE_p^2}{2p^2})](\mathbf{p}\cdot\nabla_p)\mathbf{S}^i(\mathbf{p})$$
$$+2T[\eta(\frac{1}{2} - \frac{E_p^2}{p^2} + \frac{mE_p}{2p^2} + \frac{E_p^3}{2p^2(E_p+m)}) + (\frac{E_p}{p} - \frac{m}{2p} - \frac{m^2}{2p(E_p+m)})]\mathbf{p}^i(\nabla_p\cdot\mathbf{S}(\mathbf{p})) - 2T[\eta(\frac{1}{2} - \frac{E_p^2}{p^2} + \frac{mE_p}{2p^2} + \frac{E_p^3}{2p^2(E_p+m)}) + (\frac{E_p}{p} - \frac{m}{2p} - \frac{m^2}{2p(E_p+m)})]\nabla_p^i(\mathbf{p}\cdot\mathbf{S}(\mathbf{p})) - \frac{T}{p^2}[\frac{E_p(E_p+2m)}{p(E_p+m)} + \frac{\eta m E_p}{E_p+m}(-\frac{3E_p}{p^2} + \frac{1}{E_p+m})]\mathbf{p}^i(\mathbf{p}\cdot\mathbf{S}(\mathbf{p}))$$

A.~Huang, S.~Shi, Y.~Jiang, J.~Liao and P.~Zhuang, ``Complete and Consistent Chiral Transport from Wigner Function Formalism,'' Phys. Rev. D 98, no.3, 036010 (2018)

BEST: IU

CME and Quantum Information





Chiral qubit based on CME

[Kharzeev, Li, arXiv:1903.07133]

Chiral magnetic Josephson junction

[M.~Chernodub, J.~Garaud and D.~Kharzeev, arXiv:1908.00392]

CME on quantum computer?!

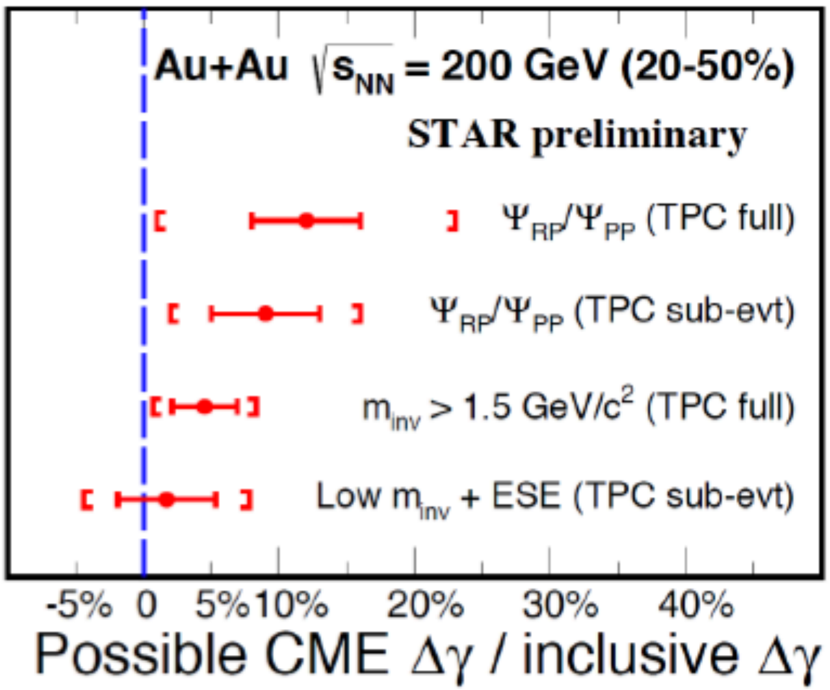
[Kharzeev and Kikuchi, ``Real-time chiral dynamics from a digital quantum simulation,''[arXiv:2001.00698 [hep-ph]].]

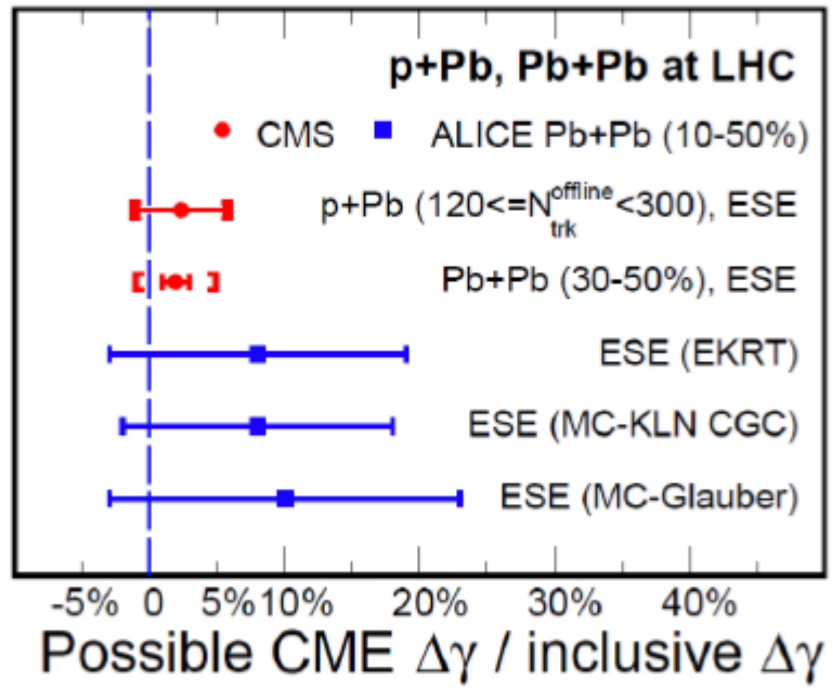
BEST: SBU / BNL

CME: Exp. Status, Challenge & Opportunity

Exp. Search for CME (early 2019)

Most measurements based on:
gamma correlator + certain procedure to fight backgrounds

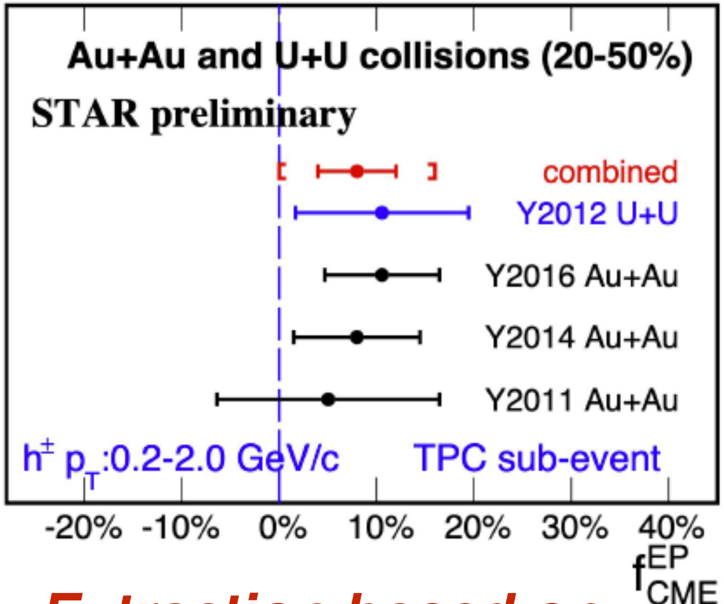




Talks @ Chirality 2019 by:
H. Huang, F. Wang, R. Lacey, A. Tang, G. Wang, J. Zhao, Q. Shou

Key challenge: weak signal versus strong backgrounds.
Many new measurements at RHIC and LHC to help address this.

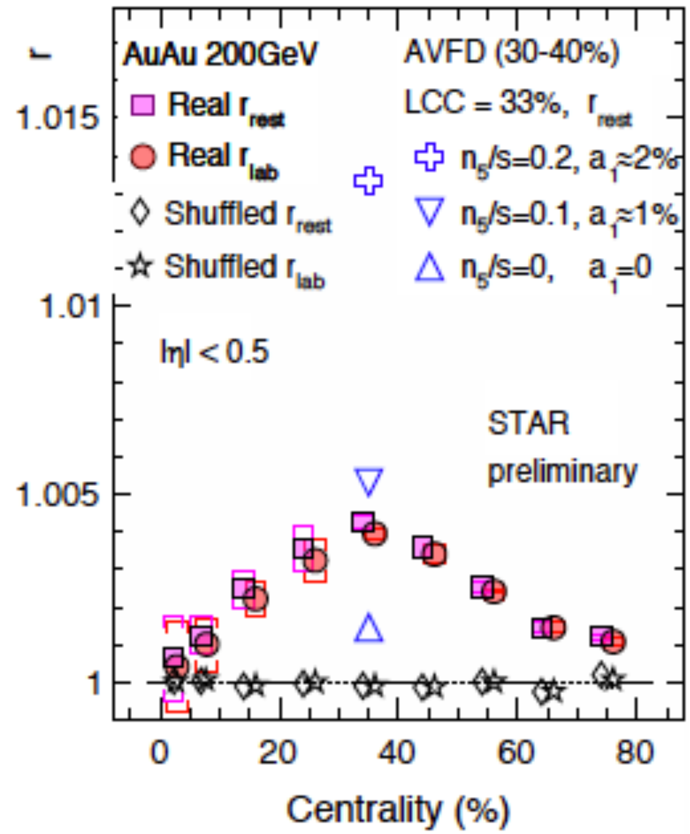
Chiral Magnetic Effect: Exp. Status



Extraction based on different angle correlation between B and EP / RP

the combined result is (8±4±8)%

[R-correlator results support nonzero signal by R. Lacey et al (shown at QM2018)]



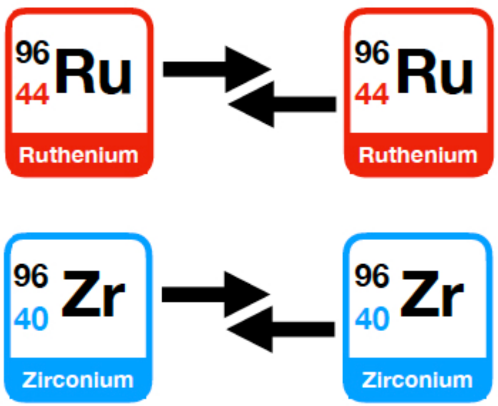
Charged balance function: supportive for nonzero signal!

Talks by M. Lisa; Z. Xu; J. Zhao; Y. Lin @QM19

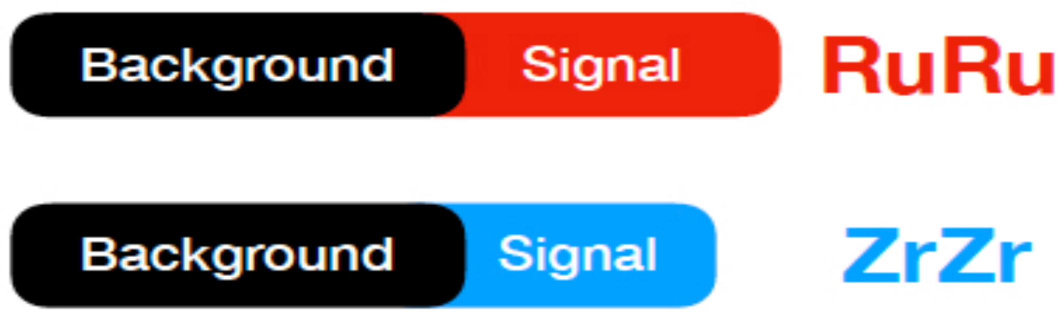
Challenge: observable sensitivity! ***[Next week INT program!]***

New Opportunity: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC



Charge Asymmetry Correlation Measurement



Data taking; blinding; quality assurance; analysis code freezing; actual analysis; unblinding; …

In a few months (by August??): keep fingers crossed…

The experimental status cries for a detailed dynamical modeling

* *that makes quantitative predictions for CME signal;*
* *that provides realistic characterization of backgrounds.*

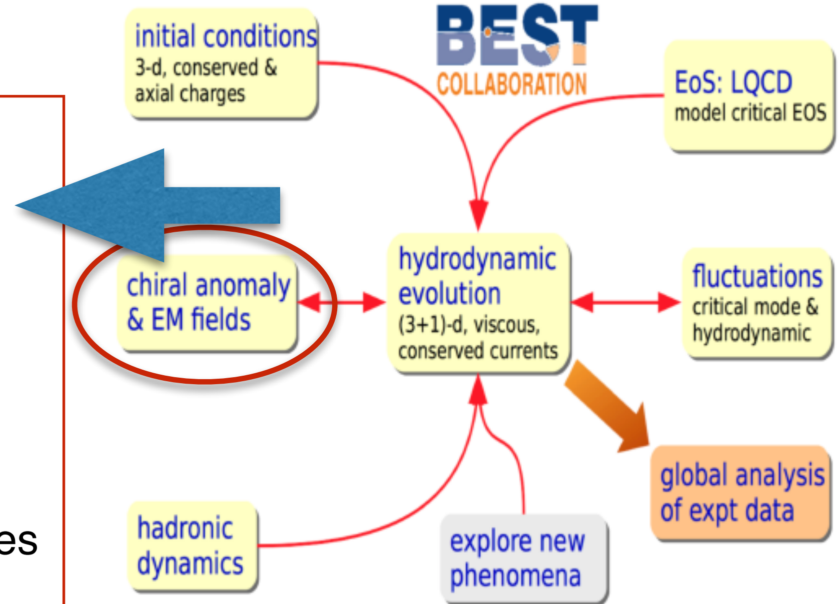
BEST CME WG Efforts

Task: to build such a comprehensive theoretical framework and meet the experimental needs for CME discovery.

— We are almost there!!

CME Working Group Goals

– Model the fluctuating initial conditions for the baryon-asymmetry and for axial charges.
– Develop magneto-hydrodynamic code and incorporate anomalous hydrodynamic terms. Use this code to quantitatively study the signals as well as backgrounds for CME and CMW for top RHIC
– Determine the pertinent anomalous transport coefficients in higher orders from chiral kinetic the-ory and other frameworks and estimate their realistic values to be used in modeling.
– Quantitatively characterize the experimental signals of CME and other anomalous chiral trans-port effects in heavy ion collisions, thus providing the means for directly accessing the gluon topological fluctuations in QCD.
– Systematically determine the evolution of CME signals with collision energy in the RHIC beam energy scan region, thus providing unique evidence for the boundary between phases of bro-ken/restored chiral symmetry in QCD.



CME Working Group Goals

– ***Initial conditions***

– ***Dynamical magnetic fields***

– ***Non-equilibrium anomalous transport coefficient***

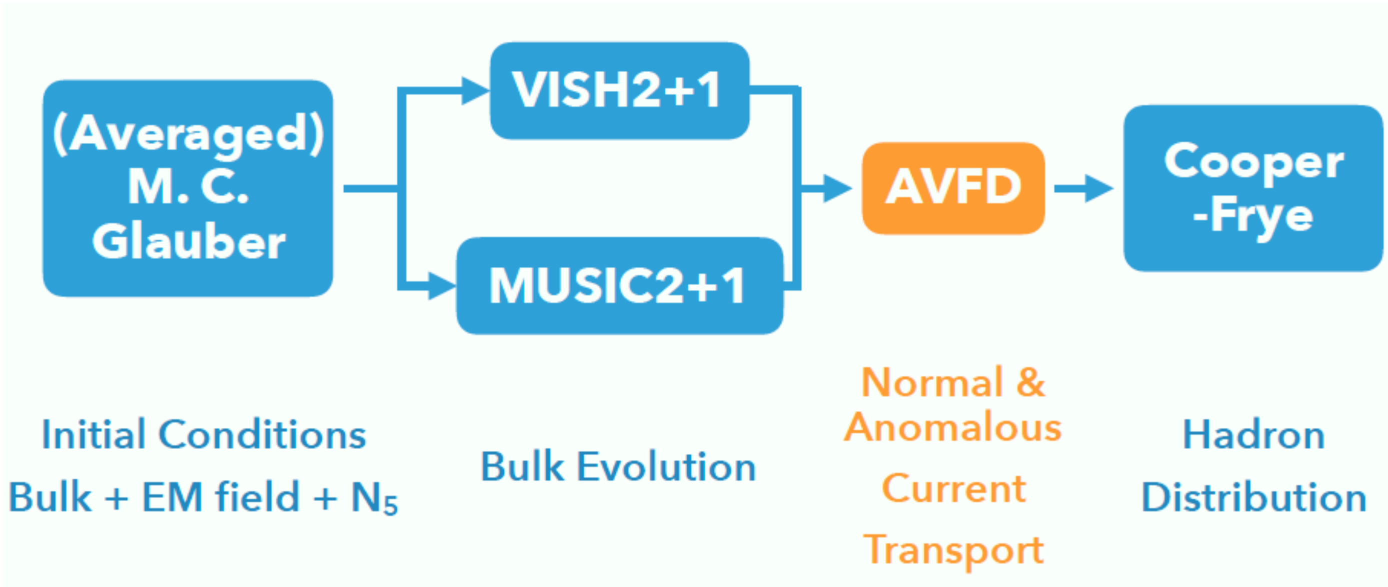
– ***Fluid dynamics framework with anomalous current***

– ***Quantification of both signal and backgrounds***

Strategic new focus:
The opportunity of potential discovery in isobaric collisions!

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!

[Shi, Yin, JL, …, : CPC2018, Annals of Physics 2018; arXiv:1910.14010]

Talk by: Shuzhe Shi ***BEST: IU & McGill***

AVFD Framework

BEST: IU & McGill

Anomalous-Viscous Fluid Dynamics Packages 04

1st generation: [1611.04586 & 1711.02496]

Smooth IC + Hydro + Cooper-Frye Dist. + Res. Decay

(Glauber) (VISH) (iS) (iS)

2nd generation: [1910.14010]

EbE IC + Hydro + grand-canonical sampler + Had. Cascade

(superMC) (VISH) (iSS w/ PLCC) (UrQMD)

3rd generation:

EbE IC + Hydro + micro-canonical sampler + Had. Cascade

(AVFD-MC) (MUSIC) (Oliinychenko-Koch) (smash)

Consistency is checked across generations.

[From talk by Shuzhe Shi]

EBE-AVFD-LCC

— EBE-AVFD-LCC is the 2nd generation for quantitative study of CME signal and backgrounds together.

— LCC implementation based on Schenke, Shen, Tribedy, PRC2019

— It has now been widely used for studying observables.

— A package has been shared for STAR and now widely used for understanding features of observables.

CME (0->weak->strong)

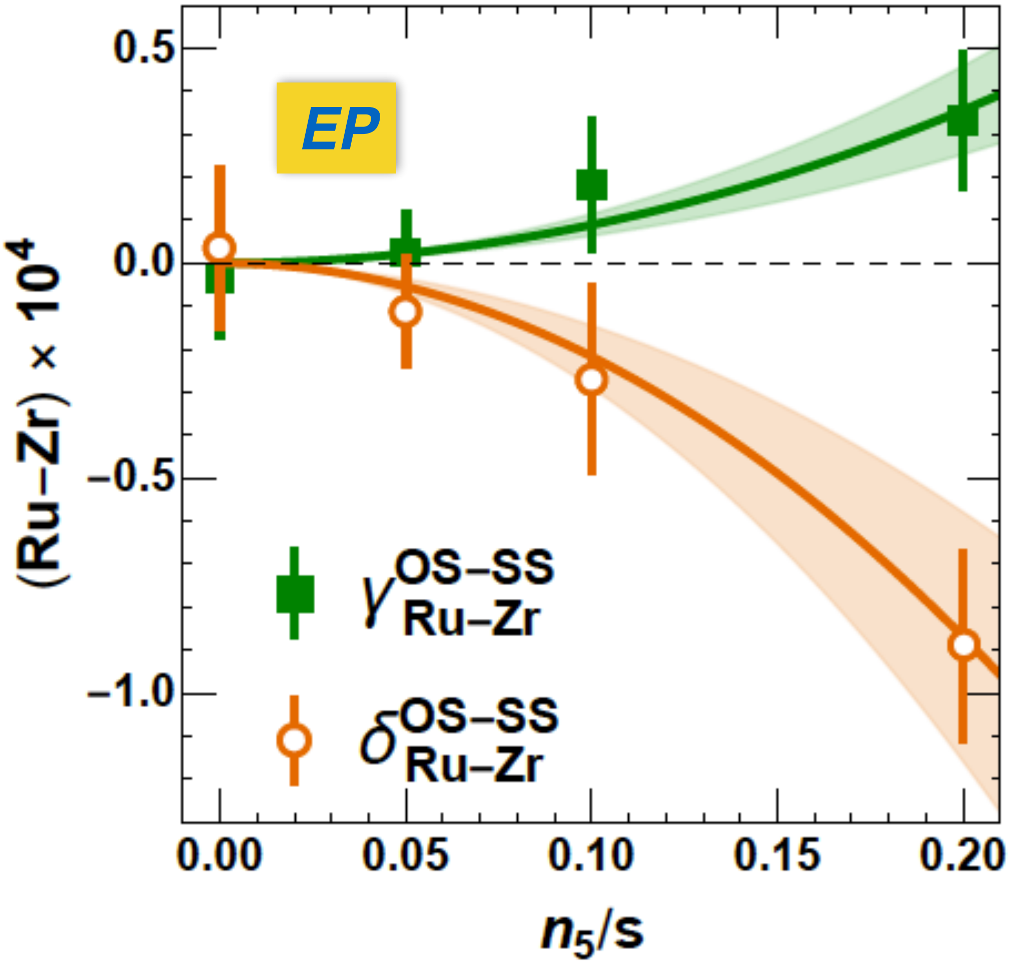
LCC (0->weak->strong)

Hadron cascade (on/off)

— Calibration with AuAu data: LCC ~ hadron cascades

AVFD Predictions for Isobars

[Shi, Zhang, Hou, JL, arXiv:1910.14010]



<<— theoretical uncertainty —>>

$$\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP} \simeq (0.89 \pm 0.51) \times 10^{-3} \times \left(\frac{n_5}{s}\right)^2$$

$$\delta^{OS-SS}_{Ru-Zr}\Big|_{EP} \simeq -(2.17 \pm 0.72) \times 10^{-3} \times \left(\frac{n_5}{s}\right)^2$$

Use gamma and delta together to remove uncertainty! [unique feature of pure signal!]

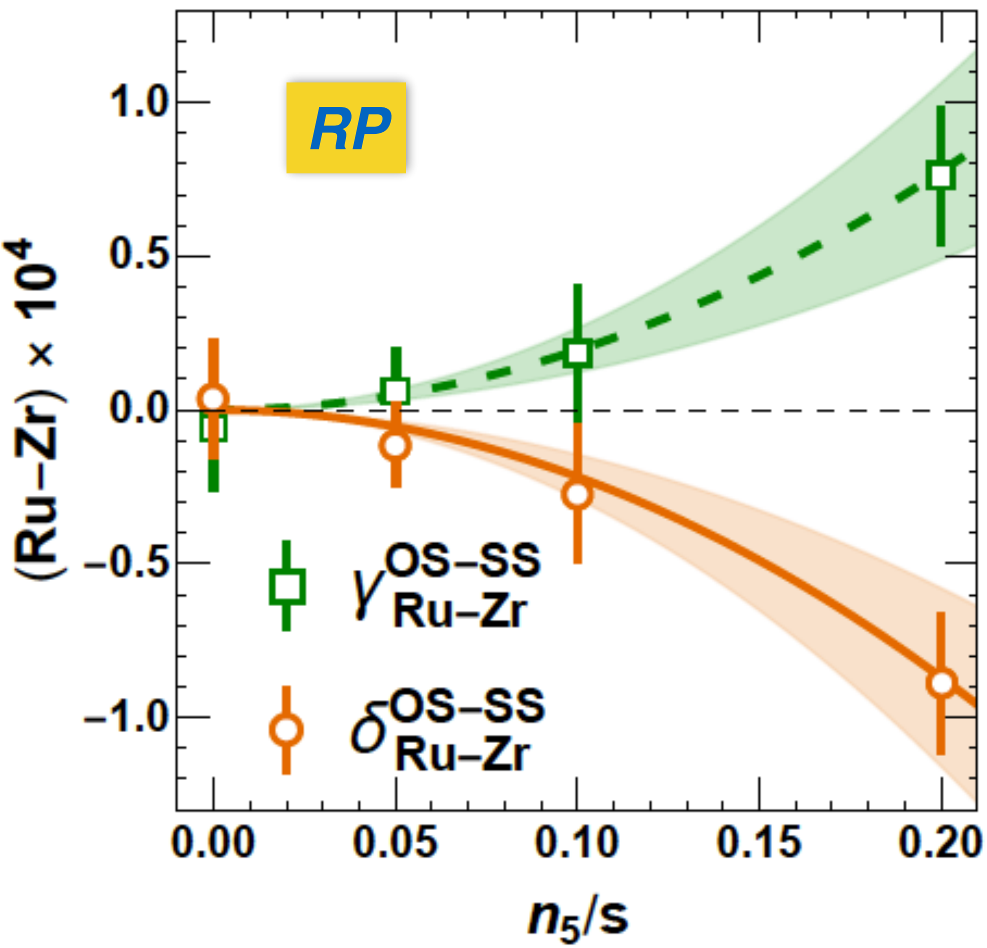
$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$

This ratio is independent of initial axial charge! [unique feature of pure signal!]

$$\langle \cos(2\Psi_B - 2\Psi_{EP}) \rangle \simeq -0.46$$

AVFD Predictions for Isobars

[Shi, Zhang, Hou, JL, arXiv:1910.14010]



<<— theoretical uncertainty —>>

$$\gamma^{OS-SS}_{Ru-Zr}\Big|_{RP} \simeq (1.94 \pm 0.72) \times 10^{-3} \times \left(\frac{n_5}{s}\right)^2$$

$$\delta^{OS-SS}_{Ru-Zr}\Big|_{RP} \simeq -(2.17 \pm 0.72) \times 10^{-3} \times \left(\frac{n_5}{s}\right)^2$$

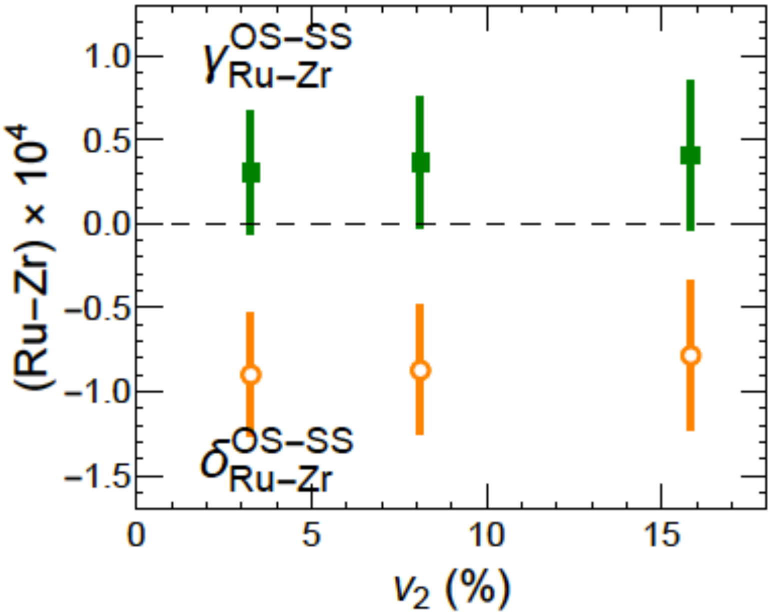
Use gamma and delta together to remove uncertainty! [unique feature of pure signal!]

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

This ratio is independent of initial axial charge! [unique feature of pure signal!]

$$\langle \cos(2\Psi_B - 2\Psi_{RP}) \rangle \simeq -0.95$$

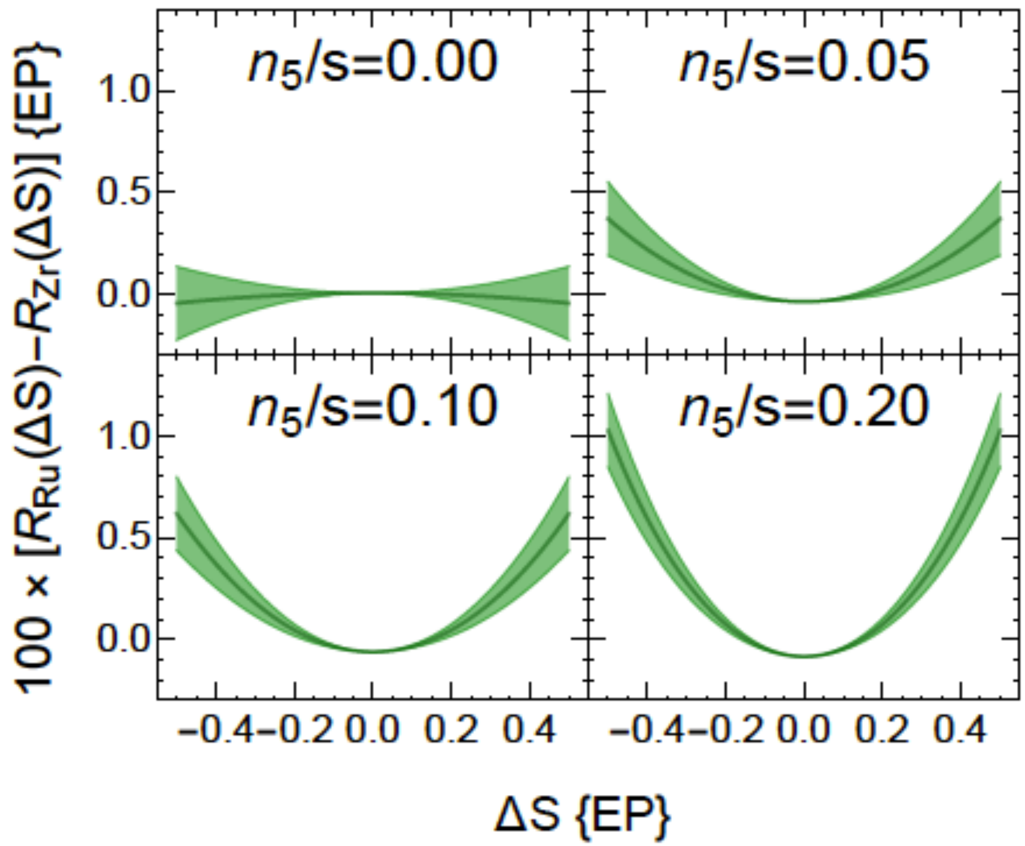
AVFD Predictions for Isobars



[Shi, Zhang, Hou, JL, arXiv:1910.14010]

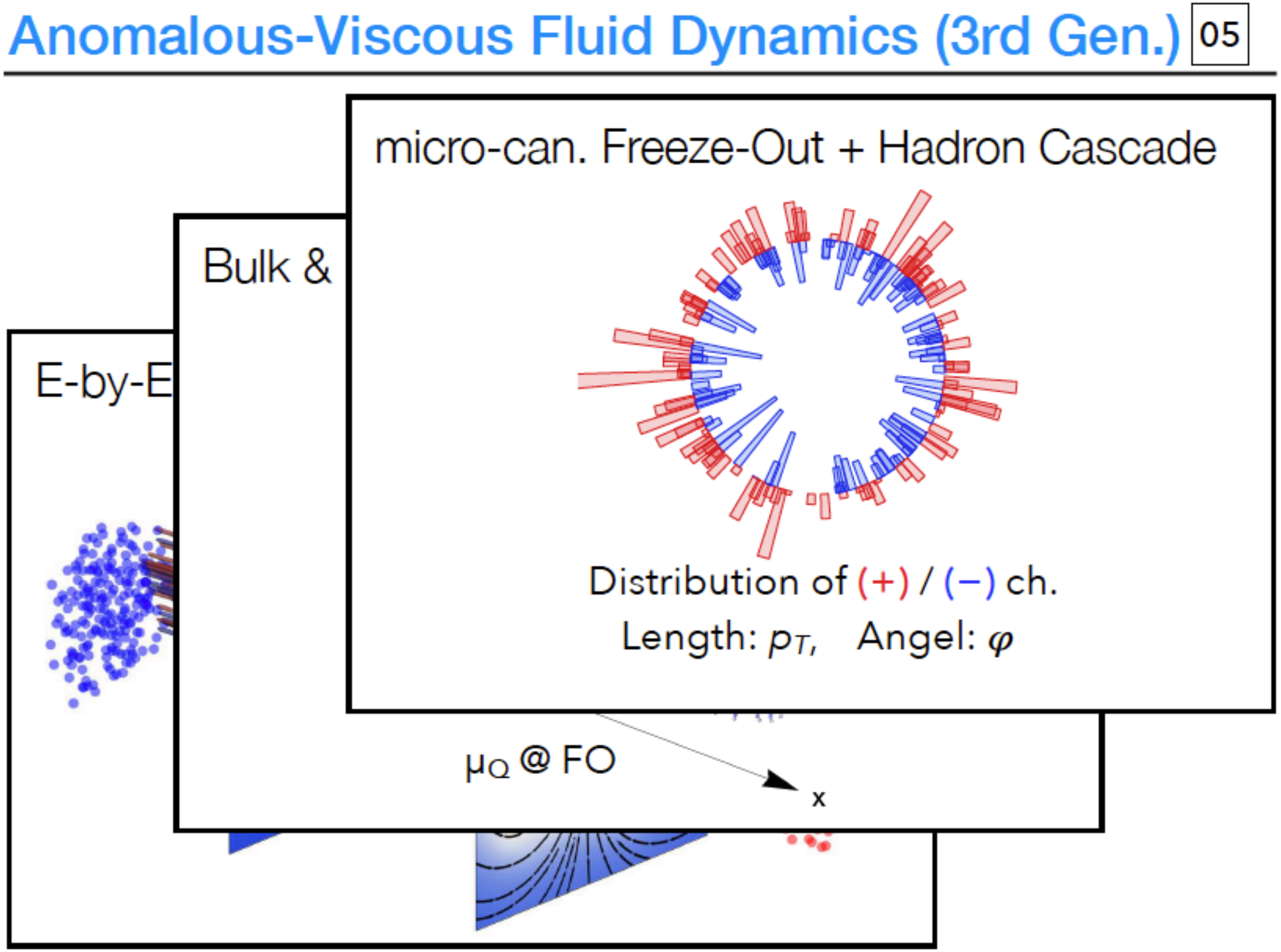
Unique feature of pure signal: independent of event shape

R-correlator shape



AVFD Framework

BEST: IU & McGill & LBNL



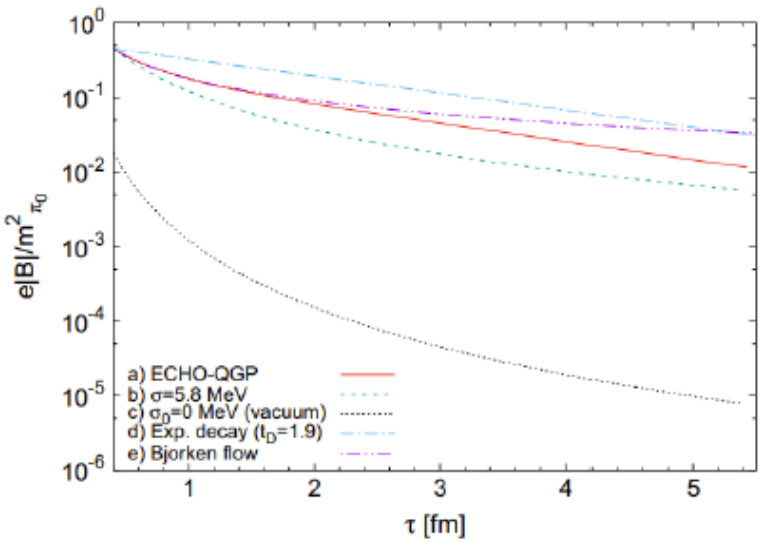
A major deliverable: Code package and key publication in preparation

[From talk by Shuzhe Shi]

Dynamical Magnetic Field

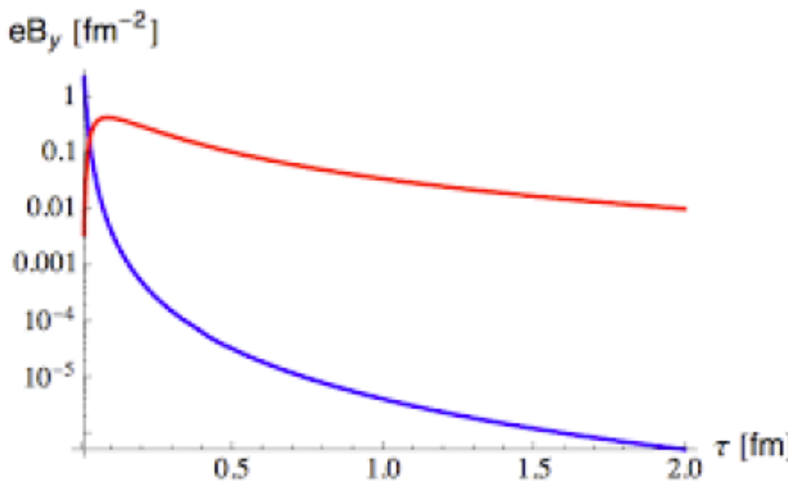
Two different regimes:

MHD regime:
need LARGE conductivity



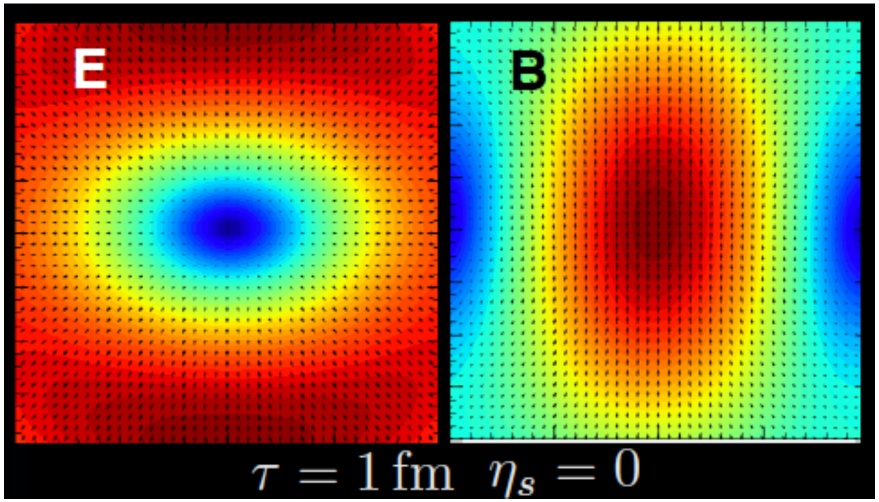
ECHO-QGP based calculations

Linear regime:
B field has little feedback to bulk evolution

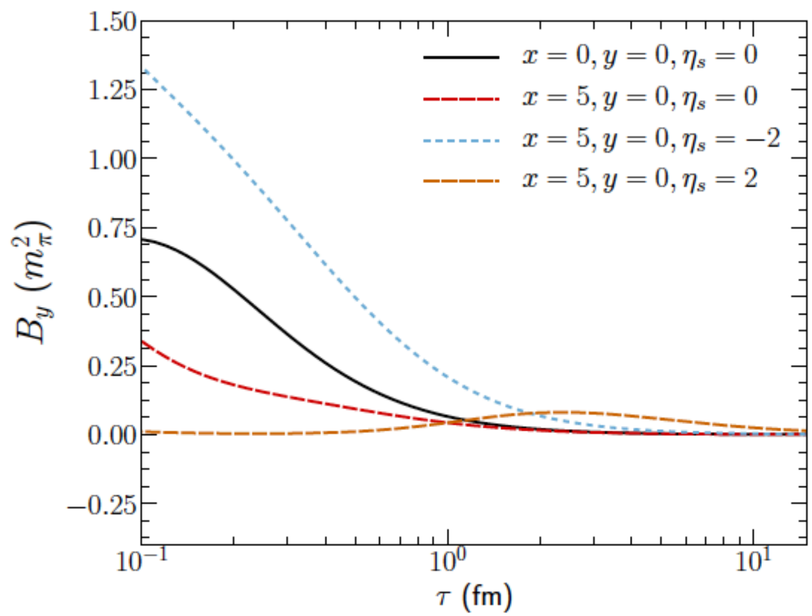


Solving Maxwell equations (robustly) in rapidly evolving medium

Dynamical Magnetic Fields



BEST: BNL& Wayne State & SBU & MIT



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

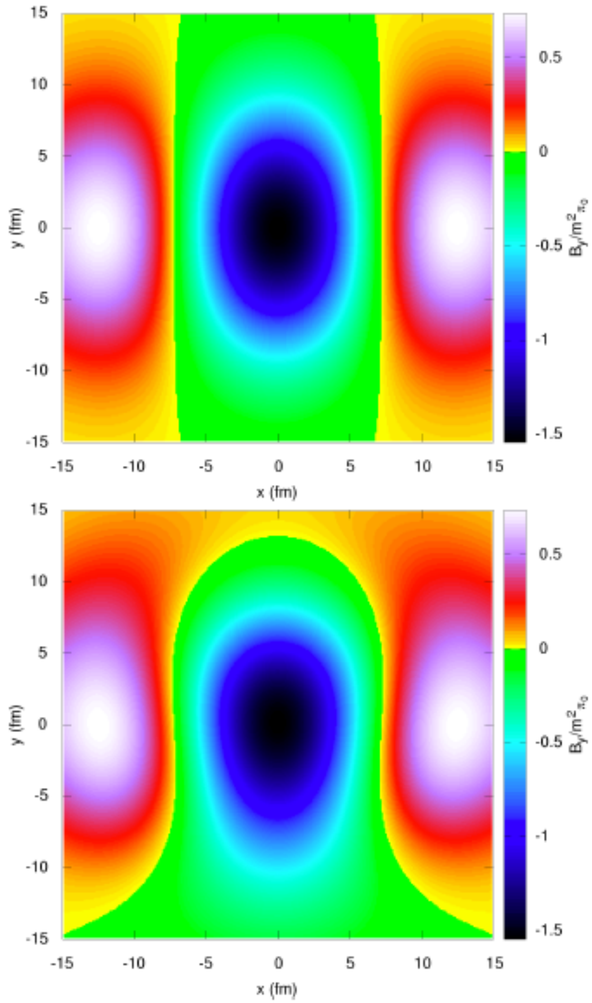
Code package available:

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

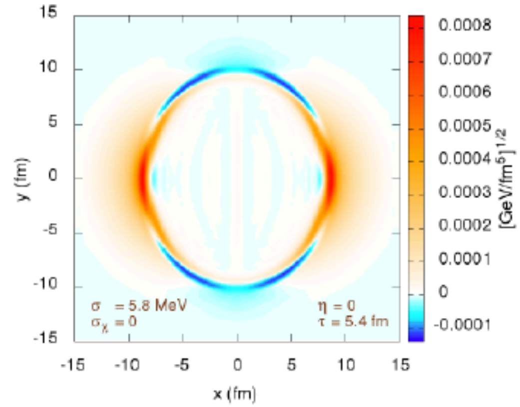
[Kharzeev, Rajagopal,Shen, et al, PRC2018]

Pro: B field in realistic fluid; Con: unrealistic assumption

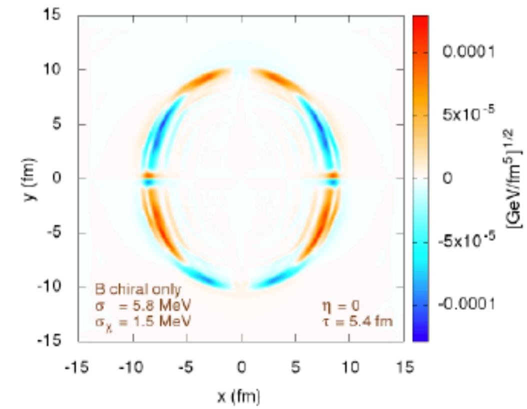
Dynamical Magnetic Field



No CME



CME



Inclusion of chiral magnetic conducting contributions

Interesting observables on charge dependent flow

[Kharzeev & Collaborators, 1908.07605 EPJC2020]

BEST: SBU & BNL

Dynamical Magnetic Field

A more realistic approach: B field and currents as "ripples" on top of bulk — good for high energy

The Maxwell equation in Milne space: $\widetilde{E}^i = F^{i0}_M, \quad \widetilde{B}^i = \widetilde{F}^{i0}_M.$

$$\hat{D}_\mu F^{\mu\nu}_M = J^\nu.$$

$$\partial_x \widetilde{E}_x + \partial_y \widetilde{E}_y + \partial_\eta \widetilde{E}_z = J_\tau,$$
$$\partial_\tau(\tau\,\widetilde{E}_x) = \partial_y(\tau^2 \widetilde{B}_z) - \partial_\eta \widetilde{B}_y - \tau\,J_x,$$
$$\partial_\tau(\tau\,\widetilde{E}_y) = -\partial_x(\tau^2 \widetilde{B}_z) + \partial_\eta \widetilde{B}_x - \tau\,J_y,$$
$$\partial_\tau(\tau\,\widetilde{E}_z) = \partial_x \widetilde{B}_y - \partial_y \widetilde{B}_x - \tau\,J_\eta.$$

$$\hat{D}_\mu \widetilde{F}^{\mu\nu}_M = 0$$

$$\partial_x \widetilde{B}_x + \partial_y \widetilde{B}_y + \partial_\eta \widetilde{B}_z = 0,$$
$$\partial_\tau(\tau\,\widetilde{B}_x) = -\partial_y(\tau^2 \widetilde{E}_z) + \partial_\eta \widetilde{E}_y,$$
$$\partial_\tau(\tau\,\widetilde{B}_y) = \partial_x(\tau^2 \widetilde{E}_z) - \partial_\eta \widetilde{E}_x,$$
$$\partial_\tau(\tau\,\widetilde{B}_z) = -\partial_x \widetilde{E}_y + \partial_y \widetilde{E}_x.$$

$$J^\mu = n u^\mu_M + d^\mu + \sigma\,F^{\mu\nu}_M u_\nu + \sigma_\chi \widetilde{F}^{\mu\nu}_M u_\nu,$$
$$J_\tau = n u_\tau + d_\tau + \sigma\left(\widetilde{E}_x u_x + \widetilde{E}_y u_y + \tau^2 \widetilde{E}_z u_\eta\right) + \sigma_\chi\left(\widetilde{B}_x u_x + \widetilde{B}_y u_y + \tau^2 \widetilde{B}_z u_\eta\right),$$
$$J_x = n u_x + d_x + \sigma\left(\widetilde{E}_x u_\tau + \tau \widetilde{B}_z u_y - \tau \widetilde{B}_y u_\eta\right) + \sigma_\chi\left(\widetilde{B}_x u_\tau - \tau \widetilde{E}_z u_y + \tau \widetilde{E}_y u_\eta\right),$$
$$J_y = n u_y + d_y + \sigma\left(\widetilde{E}_y u_\tau - \tau \widetilde{B}_z u_x + \tau \widetilde{B}_x u_\eta\right) + \sigma_\chi\left(\widetilde{B}_y u_\tau + \tau \widetilde{E}_z u_x - \tau \widetilde{E}_x u_\eta\right),$$
$$J_\eta = n u_\eta + d_\eta + \sigma\left(\widetilde{E}_z u_\tau + \frac{\widetilde{B}_y}{\tau} u_x - \frac{\widetilde{B}_x}{\tau} u_y\right) + \sigma_\chi\left(\widetilde{B}_z u_\tau - \frac{\widetilde{E}_y}{\tau} u_x + \frac{\widetilde{E}_x}{\tau} u_y\right).$$

Our code is robust and tested with Bjorken, Gubser, and MUSIC.

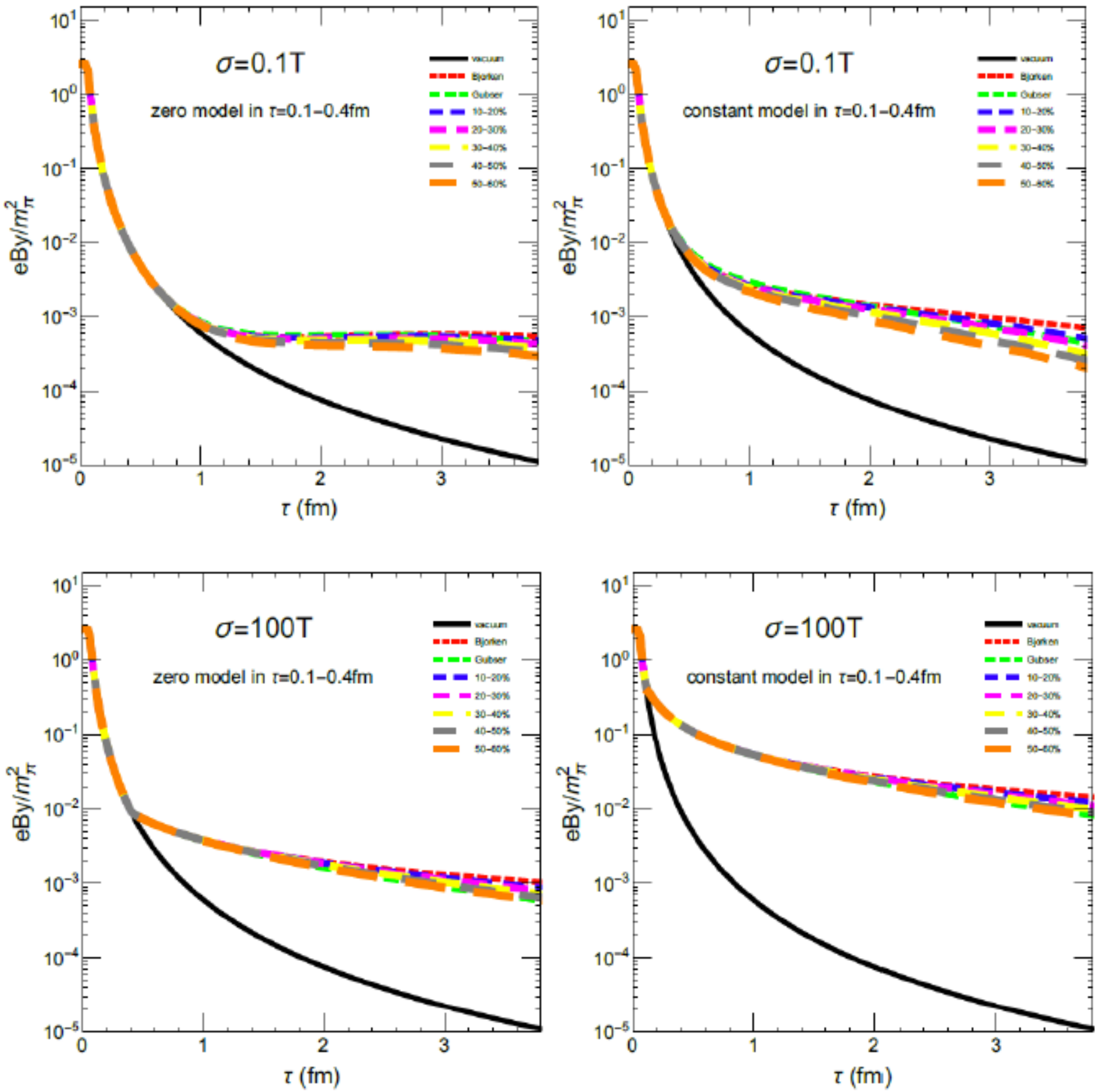
Vacuum (pre-collision) —> pre-hydro stage —> hydro stage

Longitudinal expansion very important; Transverse expansion not important.

BEST: IU & SBU/BNL & McGill

[From talk by Anping Huang]

Dynamical Magnetic Field



Roughly sigma_QCD @ 1~2 Tc

Roughly sigma_QED

BEST: IU & SBU/BNL & McGill

[From talk by Anping Huang]

Dynamical Magnetic Field

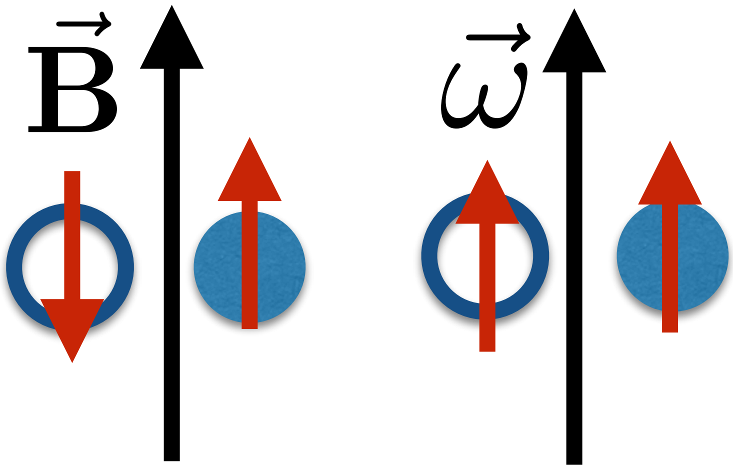
Take-away messages:

- ***Really we just need a bit medium help within ~ 1 fm/c***
- ***Pre-hydro conductivity is crucial***
- ***sigma_QCD at high T end, ~ 3Tc, is crucial too***
- ***Machinery is ready, now need physics inputs (conductivity)***
- ***Integration with AVFD underway (~ half year)***
- ***Useful applications to other B field effects***

Connecting B Field with Global Polarization

Use phenomenology to constrain B-field lifetime:
t_B about 0.5~1 fm/c at RHIC

STAR talk
by J. Adams

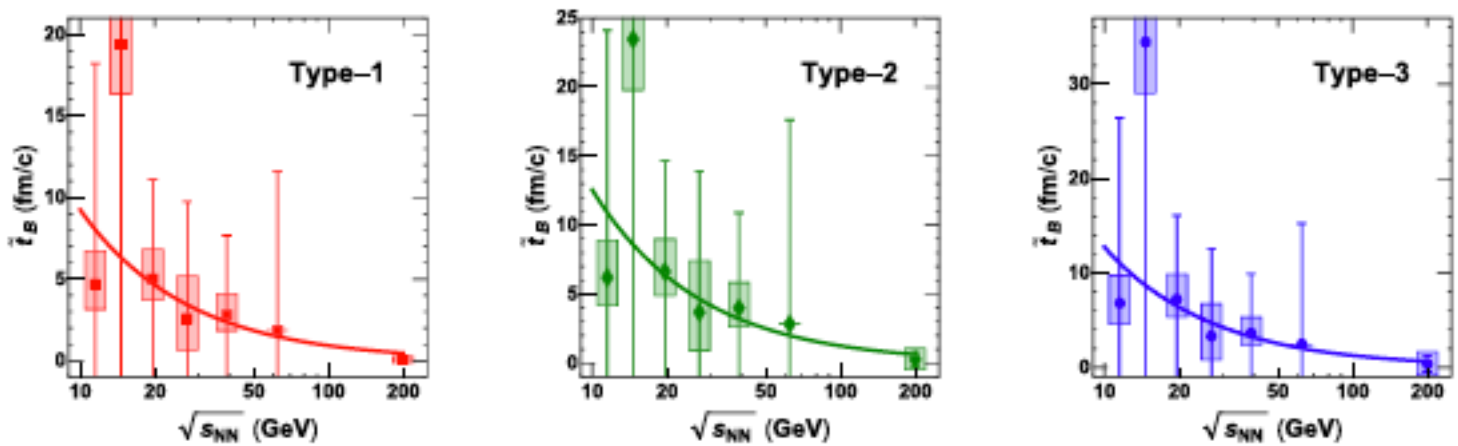


Mueller & Schaefer, arXiv:1806.10907

[22]. The lifetime of the quark-gluon plasma in a 200 GeV Au + Au collision is $t_s \approx 5$ fm/c [23]. Using the just derived limit $eB(t_s) < 0.0027 m_\pi^2$ on the magnetic field at hadronization, we then obtain

$$\tau_B = t_s (B_0/B(t_s))^{-1} \approx 1 \text{ fm}/c, \qquad (23)$$

Yu Guo, et al, arXiv:1905.12613 [PLB2019]



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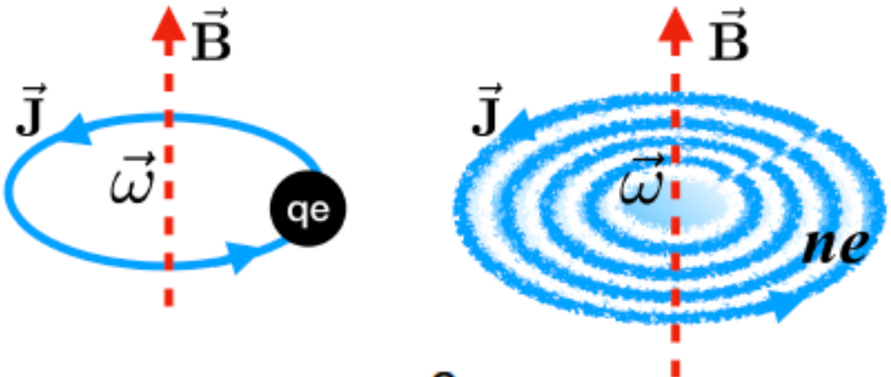
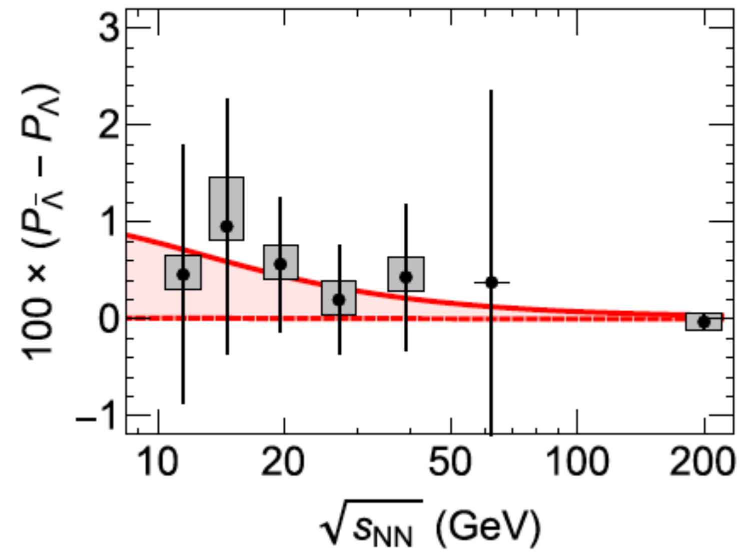
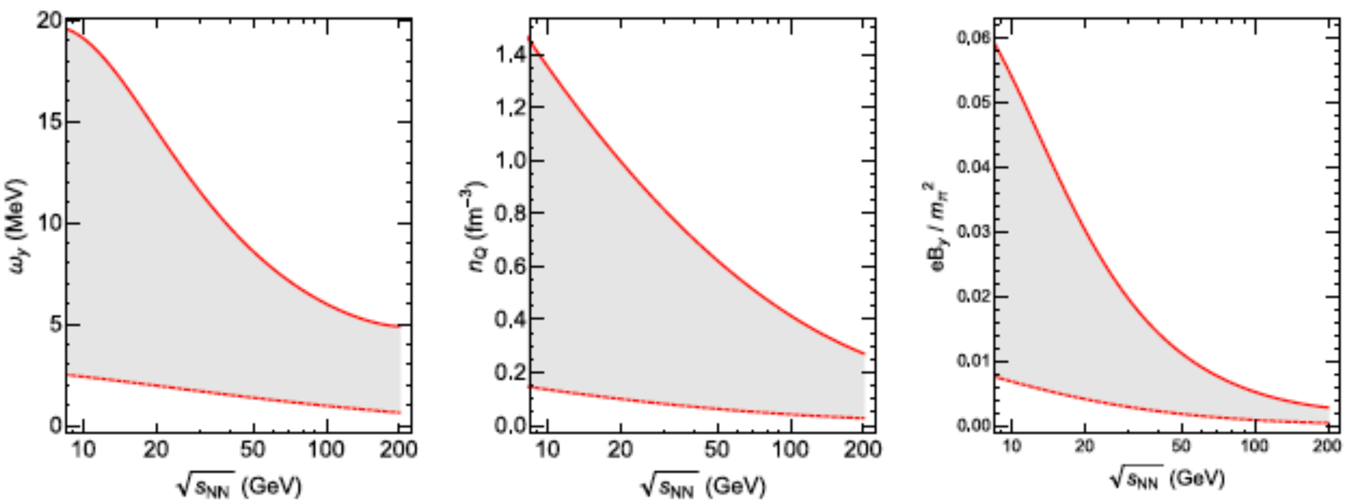
$$\tilde{t}_B = \frac{A}{\sqrt{s_{NN}}} \quad \text{with} \quad A = 115 \pm 16 \text{ GeV} \cdot \text{fm/c}$$

New Mechanism of B-Field at BES Energies



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





Important at low beam energy!

Xingyu Guo, et al, arXiv:1904.04704 [Sci. Rep. 2020]

BEST: IU

AVFD with Axial Charge Stochastic Dynamics

Anomalous-Viscous Fluid Dynamics

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

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

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

CME

Viscous Effect

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

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

$$\begin{cases} \partial_t n_5 + \nabla\cdot \mathbf{j}_5 = -2q, \\ \mathbf{j}_5 = -D\nabla n_5 + \xi, \\ q = \dfrac{n_5}{2\tau_{CS}} + \xi_q, \end{cases}$$

thermal fluctuation

topological fluctuation

dissipation

$$\partial_t N_5 = -\frac{N_5}{\tau_{cs}}$$

New AVFD with axial charge dynamics:

$$\hat{D}_\mu J^\mu_{f,5} = \frac{N_c Q_f^2}{2\pi^2} E\cdot B - \left(\frac{n_{f,5}}{\tau_{cs}} + 2\xi_q\right)$$

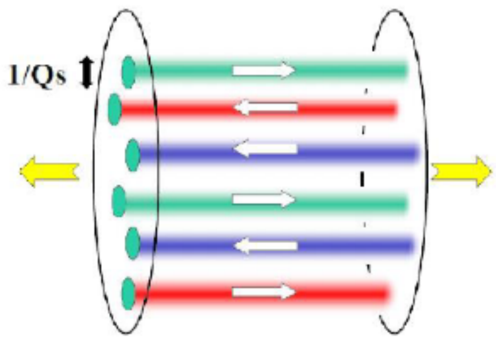
$$= \frac{N_c Q_f^2}{2\pi^2} E\cdot B - \frac{n_{f,5} - \theta(n_{f,5})\bar{n}_{f,5}}{\tau_{cs}}.$$

$$< N_5^2 > \approx \chi T V, \quad \bar{n}_{f,5} = \frac{\bar{n}_5}{N_f},$$

$$\bar{n}_{f,5} = \frac{\chi_f T}{N_f V}, \quad V = \tau * d\eta * A.$$

[Work in progress: A. Huang, S. Shi, S. Lin, JL, …]

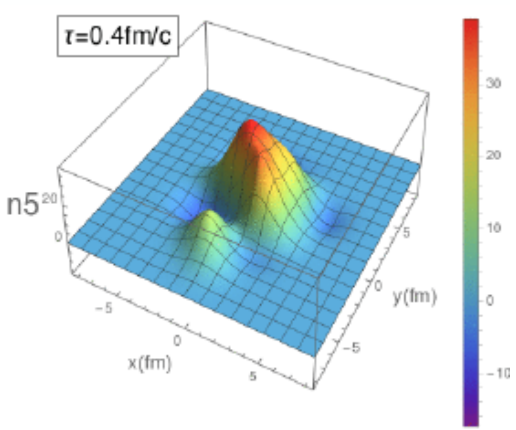
Axial Charge I.C. & Stochastic Dynamics



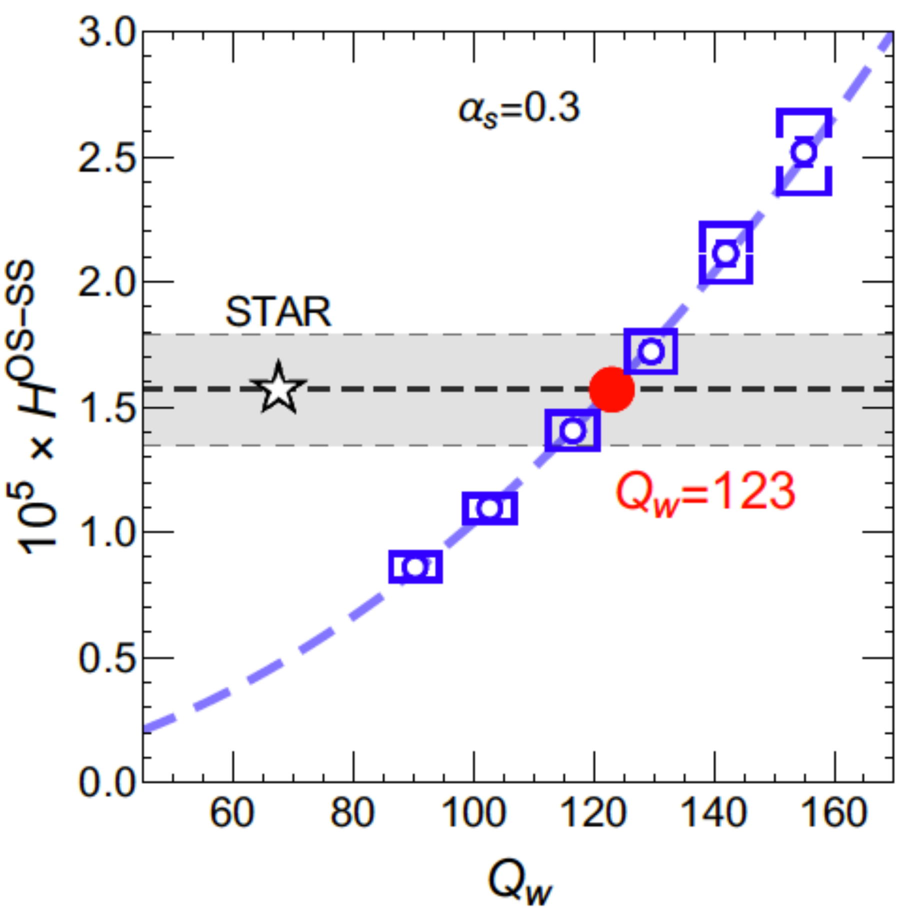
THE early motivation for CME was to pinpoint and count such P & CP odd domains from gluon topological fluctuations!

[Dima, Raju, Rob, Larry, …]

Lumpy initial conditions



$$n_{5,i}(\tau,x,y,\eta) = (\pm)\cdot\lambda\frac{Qs^2}{8\pi^2}\tau\,\frac{1}{2\sigma^2}e^{-\frac{(\mathbf{x}-\mathbf{x}_i)^2}{2\sigma^2}}$$



First quantitative extraction of its kind!

Outlook & Discussions

Realistic Goals in the Next 1~2 Years: Synergy

– *Integration of axial initial conditions + axial dynamics*

– *Implementing dynamical B field into AVFD*

– *Adding background correlations (mainly calibrating LCC)*

– *Full scale EBE simulations & predictions*

Collaborative efforts:
IU, McGill, Stony Brook, BNL, LBNL, …

Deliverable:
Final results for CME observables in AuAu/CuCu and isobaric collisions (BEST/CME-WG publications)

EBE-MUSIC/AVFD-Particlization-SMASH Code;