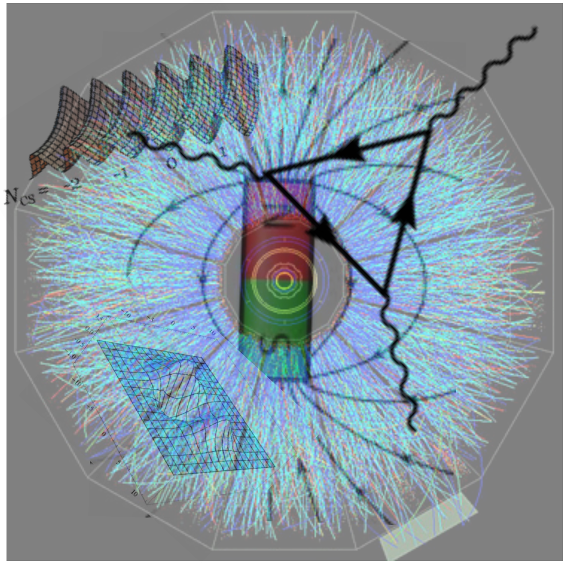
ECT* Workshop “Spin & Hydro” Oct. 8, 2020

Review of the Chiral Magnetic Effect



Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Outline

- *Brief Introduction*
- *Chirality*
- *Magnetic field*
- *Experimental status & isobar collisions*
- *Quantitative modeling*
- *Summary*

Disclaimer: not intended to be a comprehensive “review talk”

Exciting Progress: See Recent Reviews

Bzdak, Esumi, Koch, JL, Stephanov, Xu,
arXiv:1906.00936 [Phys. Rep. 853 (2020) 1-87].

Kharzeev, JL, Voloshin, Wang,
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050].

Becattini, Lisa, arXiv: 2003.03640, ARNPS2020

Fukushima, arXiv:1812.08886, PPNP2019.

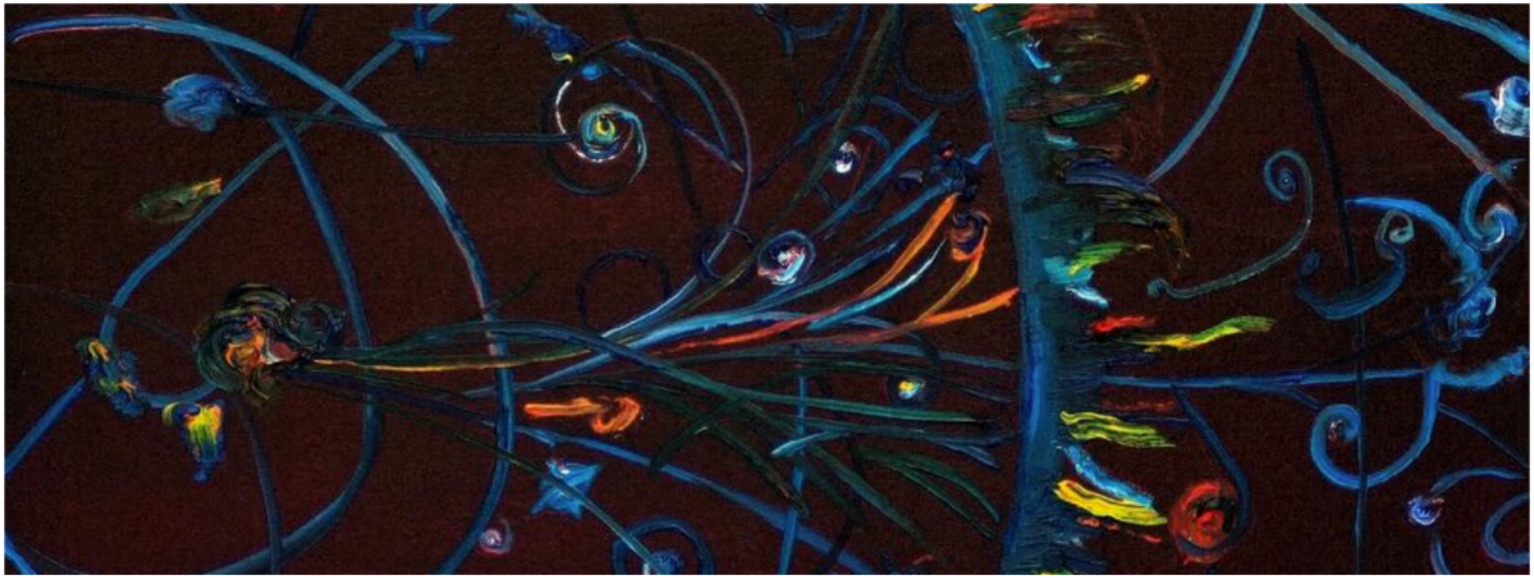
Florkowski, Kumar, Ryblewski, arXiv:1811.04409, PPNP2019.

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

Li, Wang, arXiv: 2002.10397, ARNPS2020

Zhao, Wang, arXiv:1906.11413, PPNP2019.

ONLINE | SPIN AND HYDRODYNAMICS IN RELATIVISTIC NUCLEAR COLLISIONS

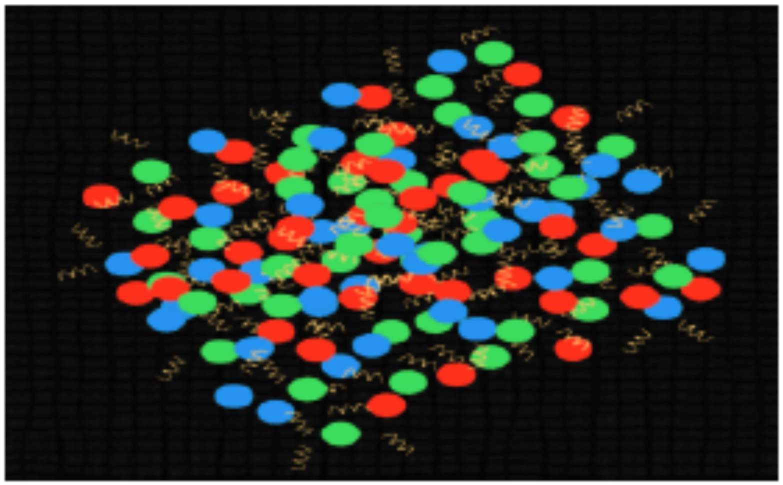


05 October 2020 — 16 October 2020 Virtual/Online

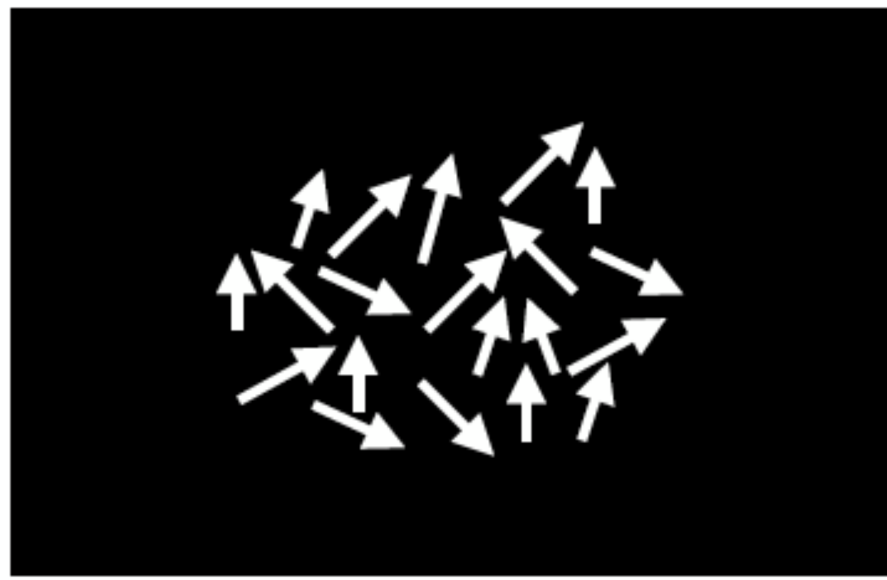
Spin + Hydro + Collisions

A New Paradigm: A Spin Fluid?!

A nearly perfect fluid (of energy-momentum)

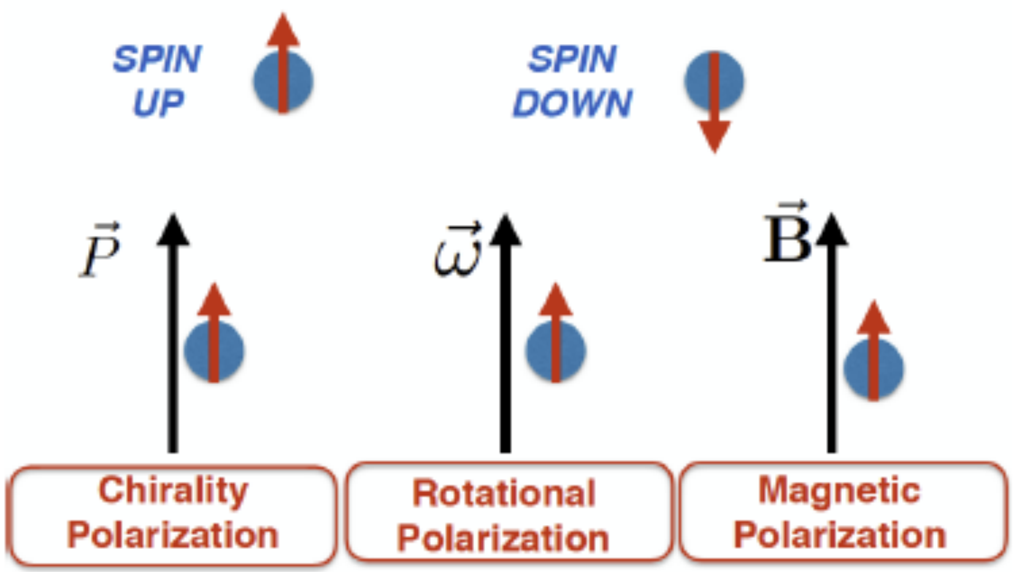


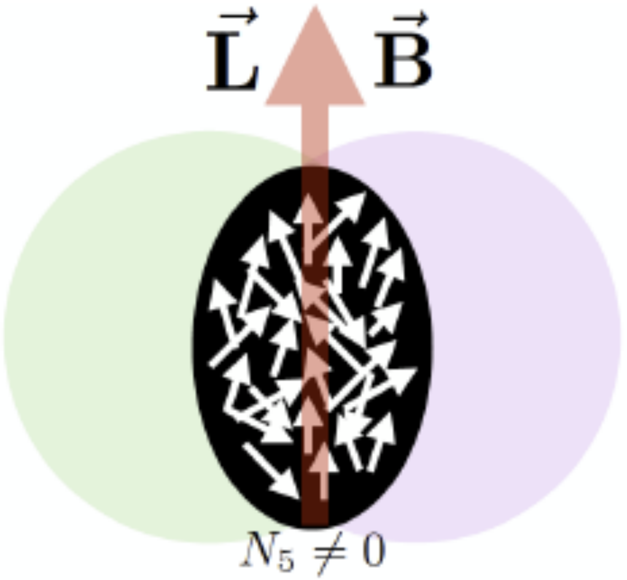
What happens to the spin DoF in the fluid???



Need probes to play with spin!

Spin @ Chirality, Vorticity and Magnetic Field



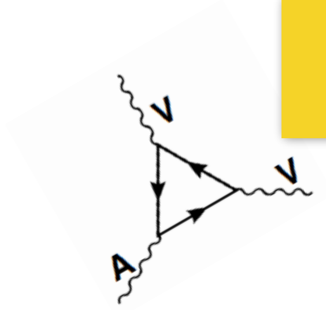


[arXiv:2004.00569]

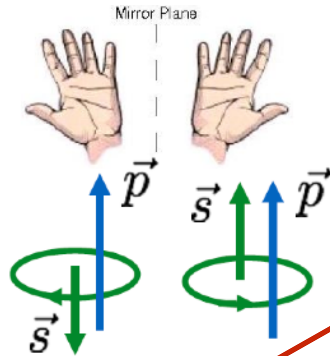
The interplay of spin with chirality/vorticity/magnetic field —> many novel phenomena

This talk will focus on one example:
Chiral Magnetic Effect (CME) in heavy ion collisions

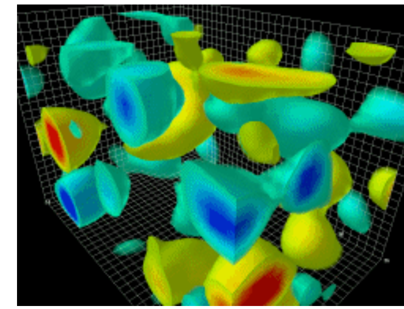
Chiral Magnetic Effect (CME)



Chirality & Anomaly

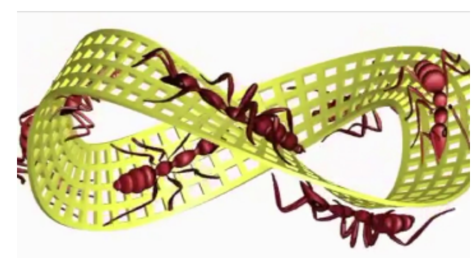


Chirality & Topology



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

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



Anomalous Electric Current

Magnetic Field

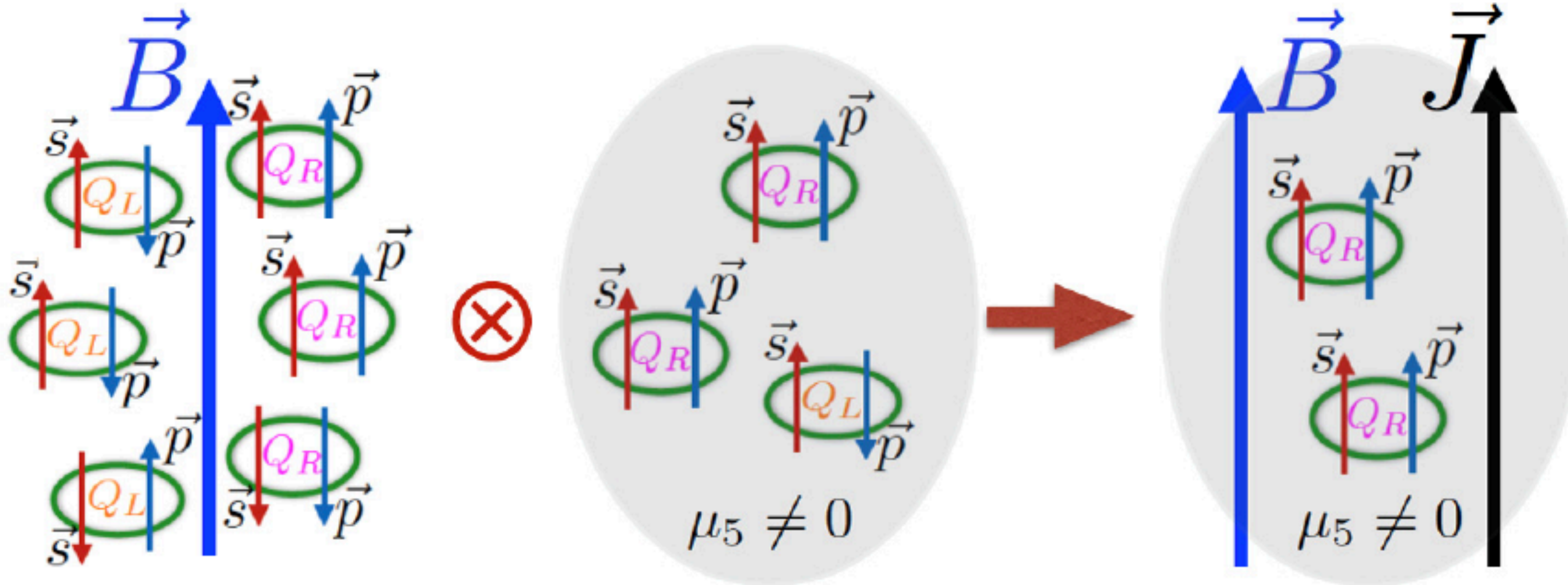
Q.M. Transport

CME <—> macroscopic chiral anomaly

CME: a new quantum, non-dissipative electricity

CME: strong interdisciplinary interests

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

Intuitive understanding of CME:

Magnetic Polarization —> correlation between micro. **SPIN & EXTERNAL FORCE** $\otimes$ **Chirality Polarization —>** correlation between directions of **SPIN & MOMENTUM**

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

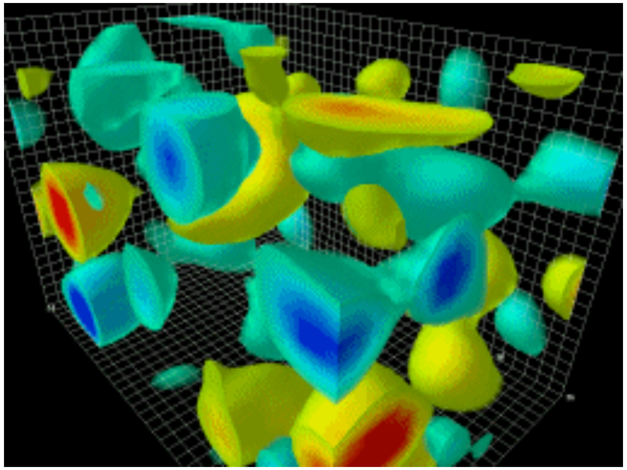
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

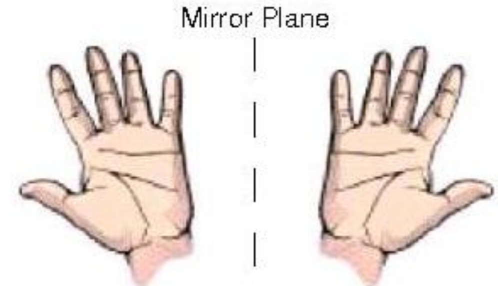
CME: Strong Interdisciplinary Interests

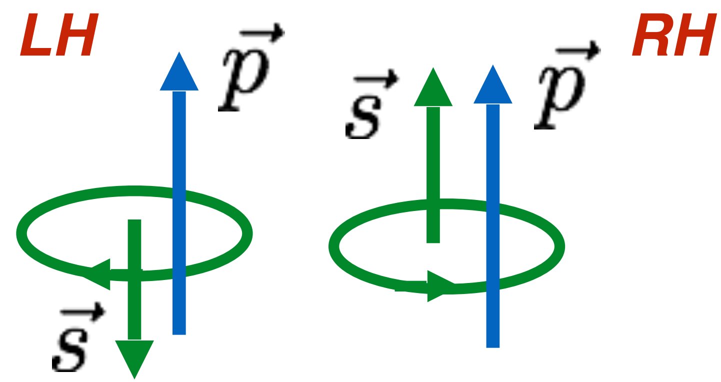
- *Condensed matter: CME in semimetals*
- *Astrophysics: leptons in supernova / compact star systems*
- *Cosmology: analogy beween Baryo-genesis and Chiro-genesis*
- *Plasma physics: MHD with CME & magnetic helicity*
- *Quantum information: devices based on CME*

Chirality

Chirality of the QGP







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

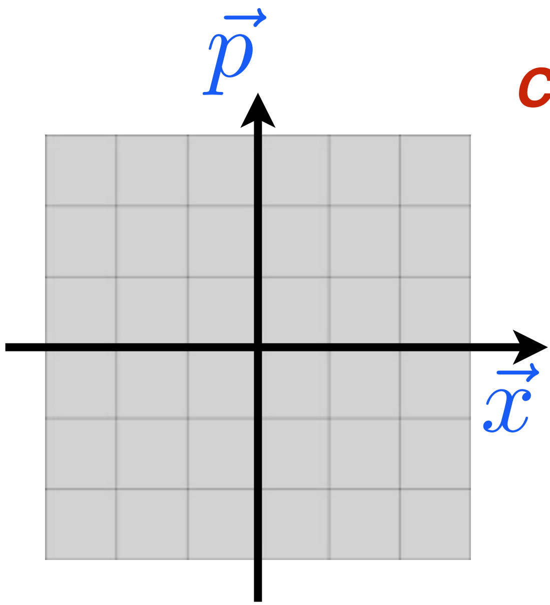
Topology <—> Chirality <—> CME

Kharzeev, 2004

Independent probe of axial charge could be very important
—> maybe connections to polarization/helicity measurements?!

See: talks by M. Buzzegoli, by Y. Sun, by Y. Ivanov

Chirality: A Many-Body Theory "Playground"



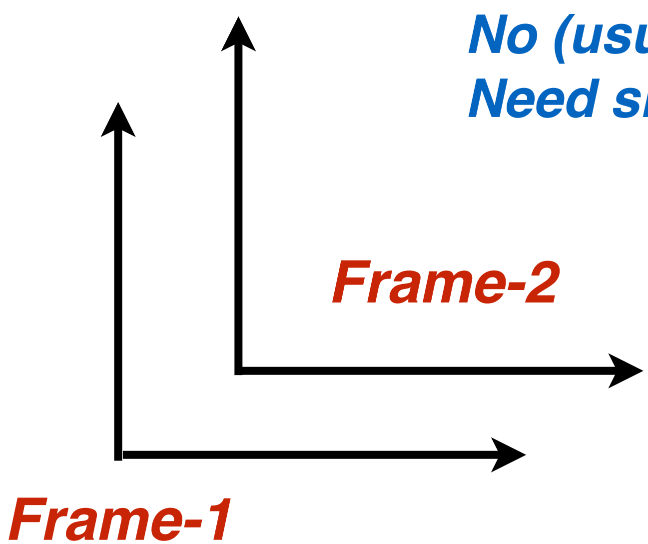
Chiral kinetic theory (with h-bar quantum effect)

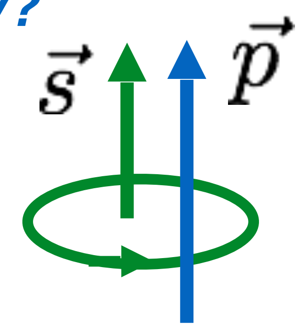
Son, Yamamoto, Chen, Stephanov, Yee, Yi, ...

$$\left[\partial_t + \dot{\vec{\mathbf{x}}} \cdot \vec{\nabla}_x + \dot{\vec{\mathbf{p}}} \cdot \vec{\nabla}_p\right] f_i(\vec{\mathbf{x}}, \vec{\mathbf{p}}, t) = C[f_i] \,,$$

$$\dot{\vec{\mathbf{x}}} = \frac{1}{\sqrt{G}}\left[\vec{\mathbf{v}}_p + q_i \vec{\mathbf{B}} \left(\vec{\mathbf{v}}_p \cdot \vec{\mathbf{b}}\right)\right] \,, \; \dot{\vec{\mathbf{p}}} = \frac{1}{\sqrt{G}}\left[q_i \vec{\mathbf{v}}_p \times \vec{\mathbf{B}}\right] .$$

However:
No (usual) Lorentz covariance — why?
Need side-jump — why?





A clash between spin, momentum & chirality!

Covariant Chiral Transport

This "non-covariance" issue is "troubling"
— in principle transport theory can be formulated entirely in a covariant way
— where and how the "non-invariance" arises?

Long history of covariant Wigner function formalism

Gyulassy, Vasak, Heinz, Zhuang, …… ~ 1990s

More recently in chiral transport context

Qun Wang & collaborators ~ 2012
Hidaka, Pu, Yang ~2016,2017,2018
Huang, Shi, Jiang, JL, Zhuang, 2018
Many more papers afterwards…

See: talks by Tinti, by Palermo, by S. Shi, by Z. Wang, by D. Yang, ……

Frame Dependence Issue

PHYSICAL REVIEW D **98**, 036010 (2018)

Complete and consistent chiral transport from Wigner function formalism

Anping Huang,[1] Shuzhe Shi,[2] Yin Jiang,[3] Jinfeng Liao,[2,*] and Pengfei Zhuang[1,†]
[1]*Physics Department, Tsinghua University, Beijing 100084, China*
[2]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*
[3]*School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*

Covariant chiral transport (with h-bar quantum effect)

— proper Wigner formalism treatment in massless case

— where and how the "Lorentz" issue arises

$$\mathcal{J}^{(1)}_{\mu,\chi} = \mathcal{H}_\mu \delta(p^2) + \chi Q \tilde{F}_{\mu\nu} p^\nu f^{(0)}_\chi \delta'(p^2).$$

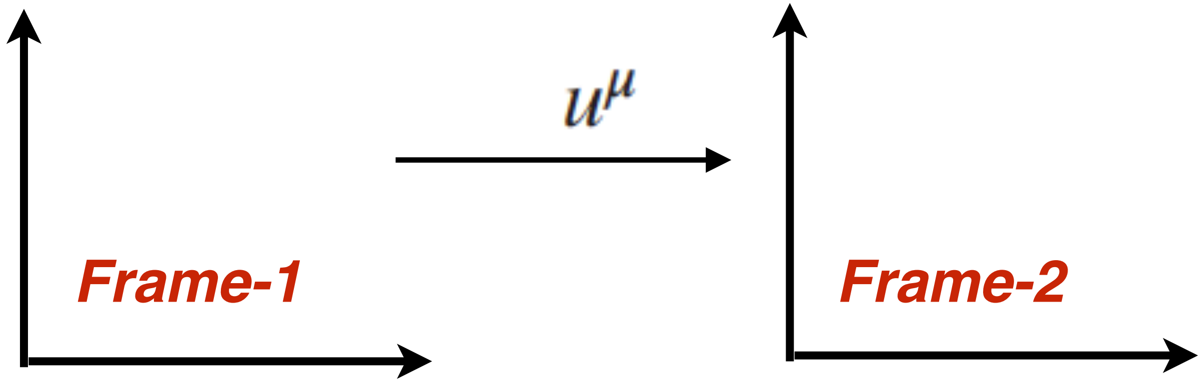
$$\mathcal{H}_\mu = p_\mu f^{(1)}_\chi + \mathcal{K}_\mu. \qquad \mathcal{K}_\mu = \frac{\chi}{2p\cdot n}\epsilon_{\mu\nu\lambda\rho} p^\nu n^\lambda (\nabla^\rho f^{(0)}_\chi)$$

But, to unambiguously define f_\chi^(1), we need to fix

$$\mathcal{K}_\mu \longrightarrow (0, \mathbf{K}) \qquad \mathbf{K}\cdot\mathbf{p} = 0.$$

This necessarily introduces frame dependence.

Frame Dependence Issue



$$p_\mu \xrightarrow{\text{Lorentz}} p'$$

$$\mathscr{K}_\mu = (0, \mathbf{K}) \qquad \mathscr{K}'' = (0, \mathbf{K}'')$$

$$\mathbf{K} \cdot \mathbf{p} = 0 \qquad \mathbf{K}'' \cdot p' = 0.$$

The K" in new frame is given in the old frame precisely by

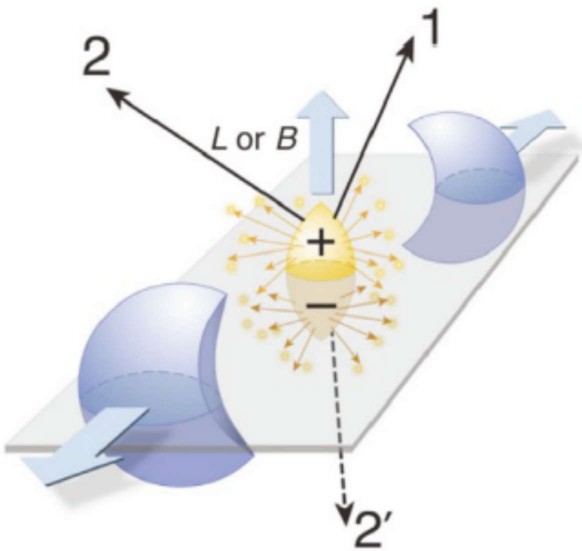
$$\mathscr{K}_\mu = \frac{\chi}{2p \cdot n} \epsilon_{\mu\nu\lambda\rho} p^\nu n^\lambda (\nabla^\rho f_\chi^{(0)})$$

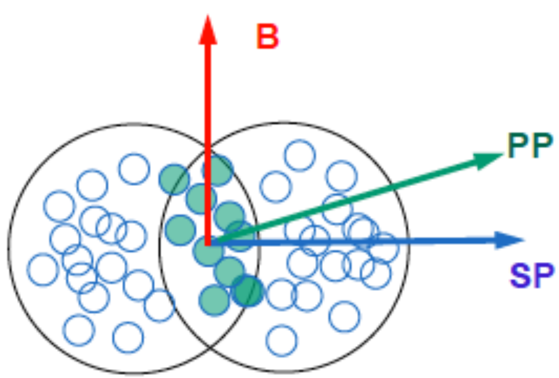
provided we identify: $n^\mu \rightarrow u^\mu$

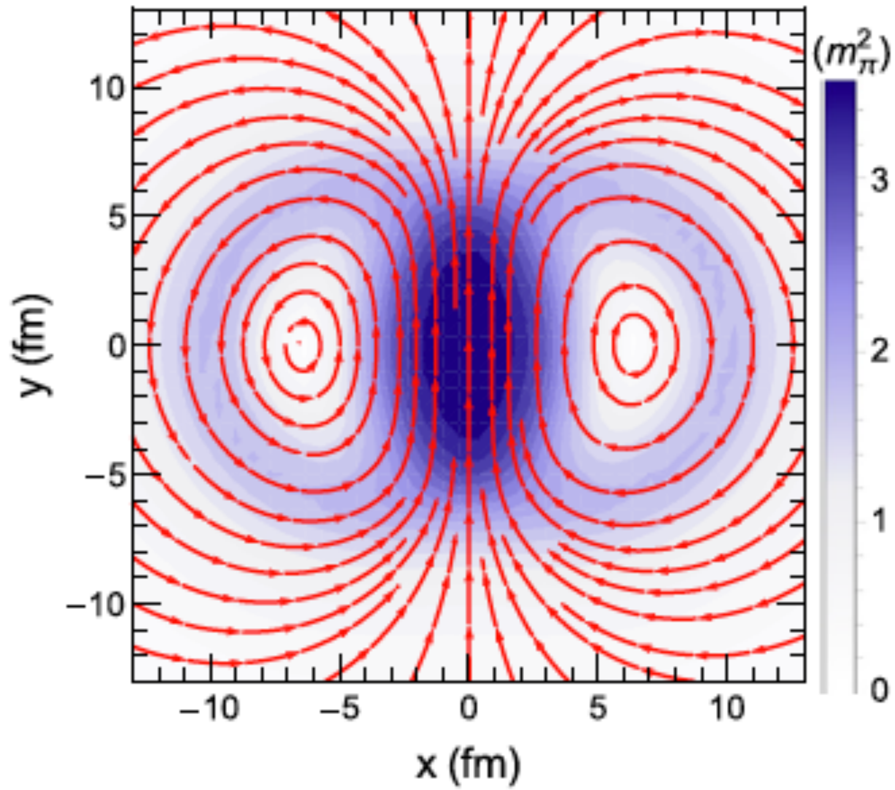
A clash between spin, momentum & chirality — identified & resolved

Magnetic Field

Strong (Initial) Magnetic Field in HIC





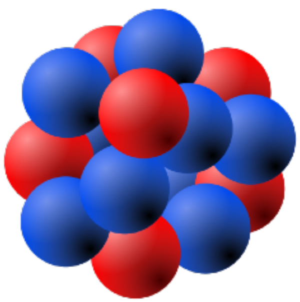


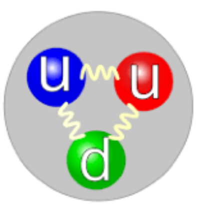
Two important issues:
Azimuthal fluctuations;
Time evolution

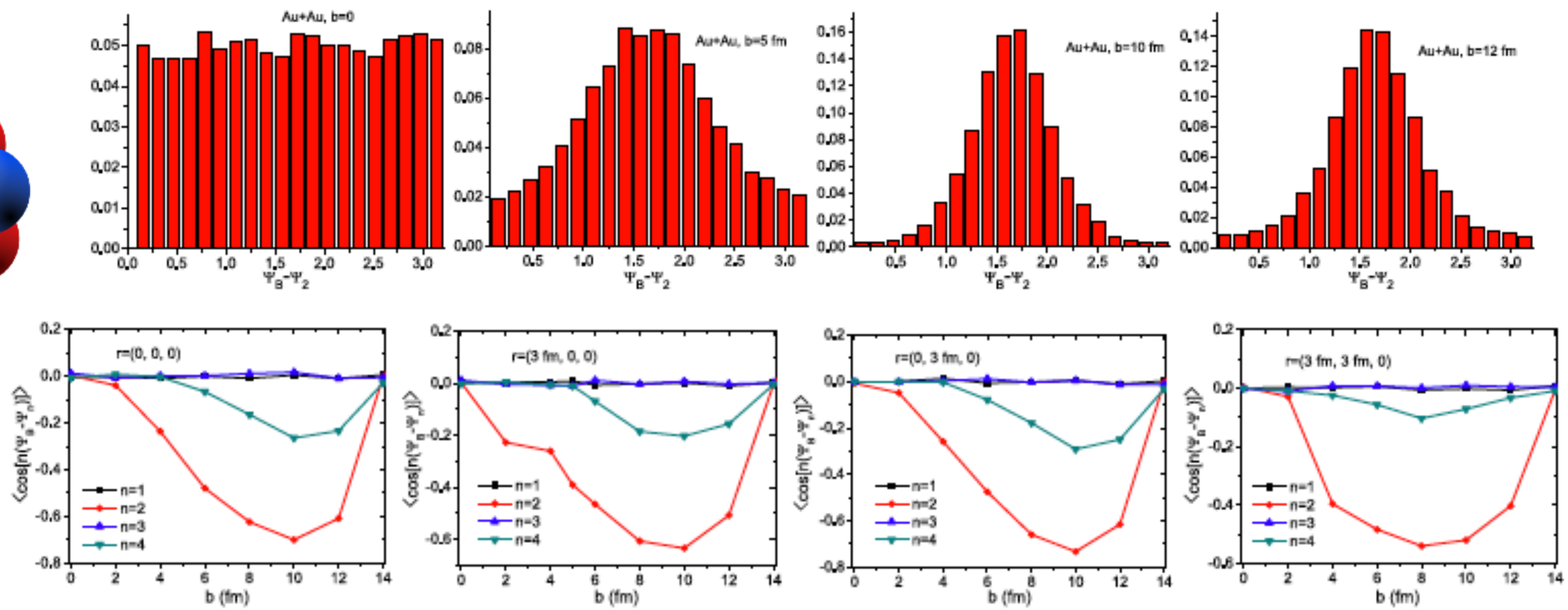
Azimuthally Fluctuating Magnetic Field

<u>Bloczynski, et al, arXiv:1209.6594[PLB]</u>

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***





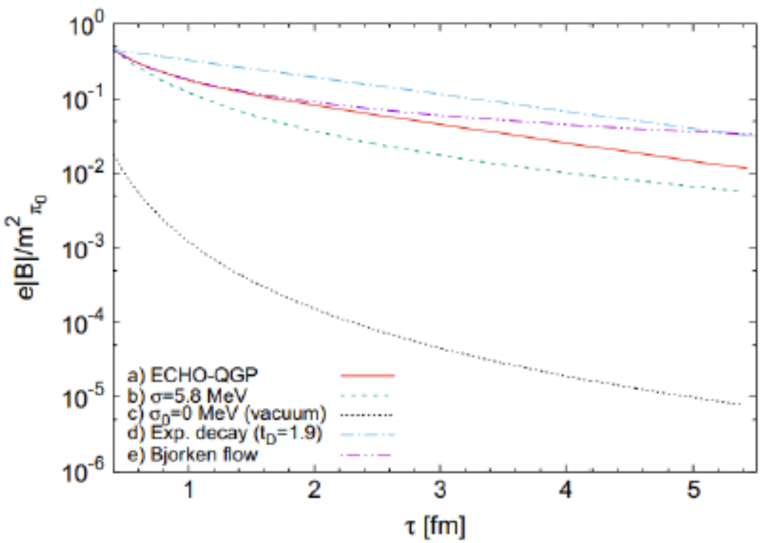


B field has different angular (de-)correlation with RP and with EP,
and is NOT correlated with triangular-EP
—— a valuable feature for validating B-field signal !!

Dynamical Magnetic Field

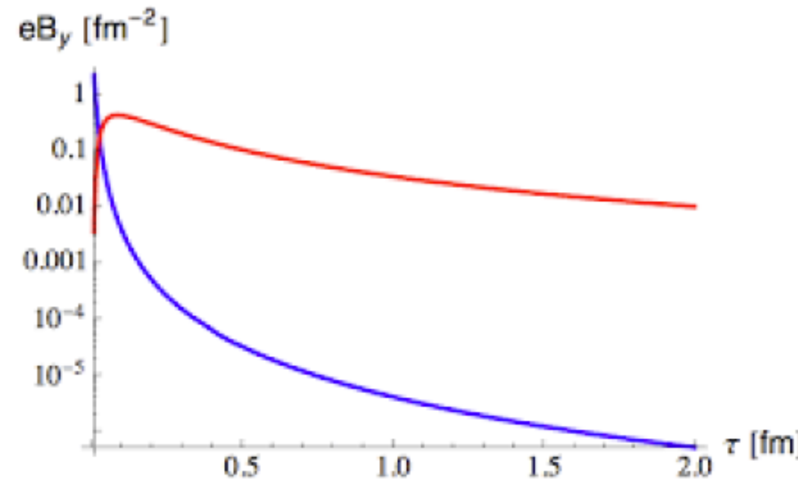
Two different regimes:

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

See: talks by Inghirami, by Hattori
Many earlier works, e.g.: Skokov-McLerran; Tuchin; Deng, Huang; ……

Go Beyond Ideal MHD

Theoretical development of magneto-hydro dynamic framework

Second-order equations of motion for dissipative currents

CRC-TR 211

Bulk viscous pressure

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \ell_{\Pi V}\nabla_\mu V_f^\mu - \tau_{\Pi V} V_f^\mu \dot{u}_\mu - \delta_{\Pi\Pi}\Pi\theta - \lambda_{\Pi V} V_f^\mu \nabla_\mu \alpha_0 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} - \delta_{\Pi VE}\, \mathfrak{q} E_\mu V_f^\mu$$

where

$$\dot{u}^\mu = \frac{1}{\varepsilon_0 + P_0}\left[\nabla^\mu P_0 - \Delta^\mu_\nu \partial_\kappa \pi^{\kappa\nu} - \Pi \dot{u}^\mu + \nabla^\mu \Pi + n_{f0}\, \mathfrak{q} E^\mu + \epsilon^{\mu\nu\alpha\beta} u_\alpha \mathfrak{q} B_\beta V_{f,\nu}\right]$$

Particle diffusion current

$$\begin{aligned}\tau_V \dot{V}_f^{\langle\mu\rangle} + V_f^\mu = {} & \kappa\nabla^\mu\alpha_0 - \tau_V V_{f,\nu}\omega^{\nu\mu} - \delta_{VV} V_f^\mu \theta - \ell_{V\Pi}\nabla^\mu\Pi + \ell_{V\pi}\Delta^{\mu\nu}\nabla_\lambda \pi^\lambda_\nu \\ & + \tau_{V\Pi}\Pi\dot{u}^\mu - \tau_{V\pi}\pi^{\mu\nu}\dot{u}_\nu - \lambda_{VV} V_{f,\nu}\sigma^{\mu\nu} + \lambda_{V\Pi}\Pi\nabla^\mu\alpha_0 - \lambda_{V\pi}\pi^{\mu\nu}\nabla_\nu\alpha_0 \\ & + \delta_{VE}\, \mathfrak{q} E^\mu + \delta_{V\Pi E}\, \mathfrak{q} E^\mu \Pi + \delta_{V\pi E}\, \mathfrak{q} E_\nu \pi^{\mu\nu} + \delta_{VB}\, \epsilon^{\mu\nu\alpha\beta} u_\alpha \mathfrak{q} B_\beta V_{f,\nu}\end{aligned}$$

Shear-stress tensor

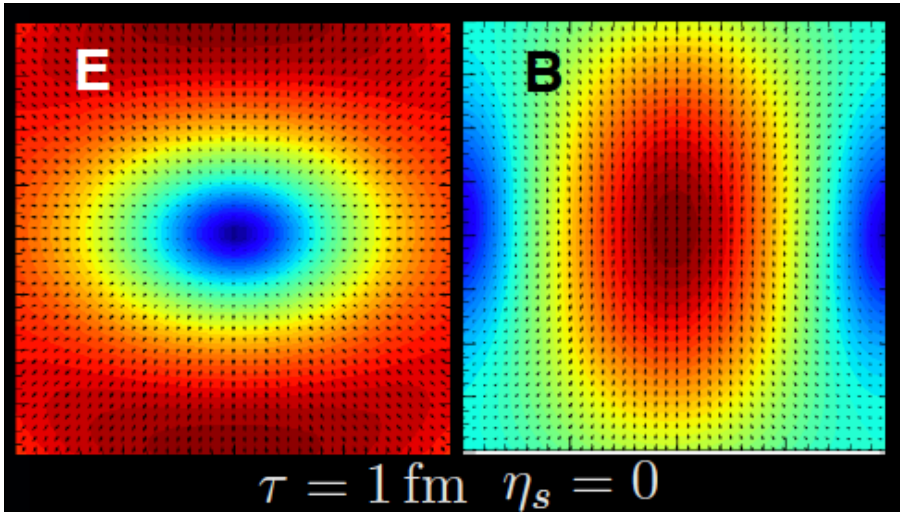
$$\begin{aligned}\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = {} & 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma_\lambda^{\nu\rangle} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} \\ & - \tau_{\pi V} V_f^{\langle\mu}\dot{u}^{\nu\rangle} + \ell_{\pi V}\nabla^{\langle\mu} V_f^{\nu\rangle} + \lambda_{\pi V} V_f^{\langle\mu}\nabla^{\nu\rangle}\alpha_0 \\ & + \delta_{\pi VE}\, \mathfrak{q} E^{\langle\mu} V_f^{\nu\rangle} + \delta_{\pi B}\, \epsilon^{\alpha\beta\rho\sigma} u_\rho \mathfrak{q} B_\sigma \Delta^{\mu\nu}_{\alpha\kappa}\pi^\kappa_\beta\end{aligned}$$

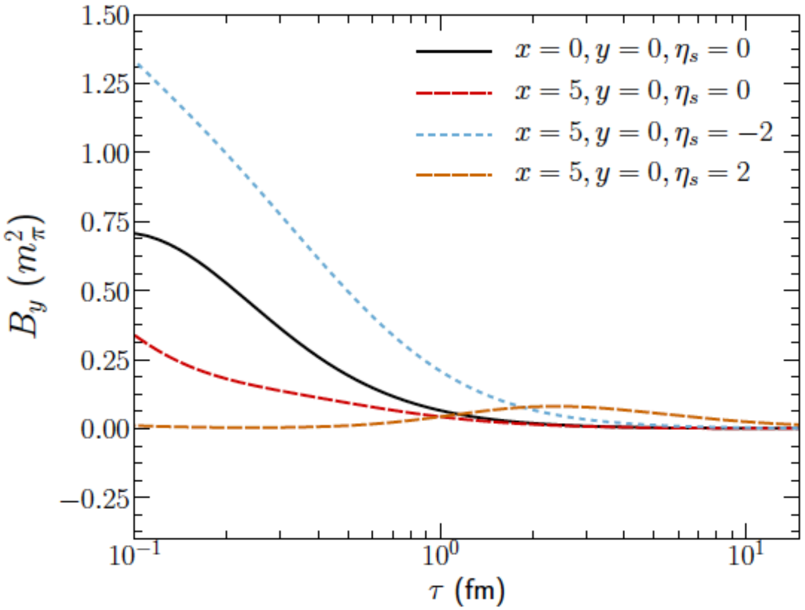
Dirk H. Rischke | Dissipative MHD | 12 / 18

Rischke, et al, arXiv: 1804.05210; 1902.01699; [see more refs therein]

See also works by Kharzeev et al; by Son; by Kovtun; etc

Dynamical Magnetic Fields



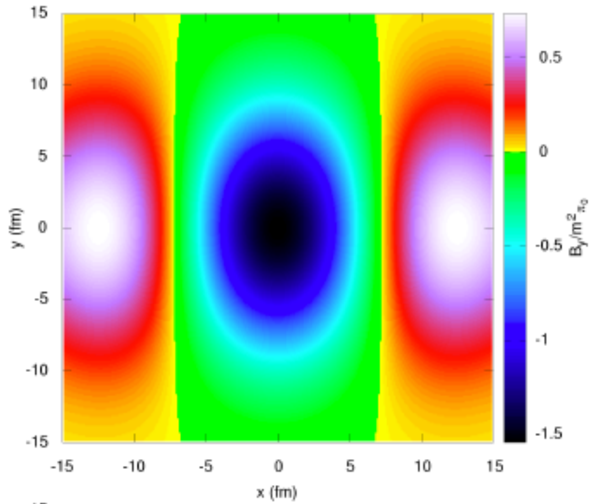


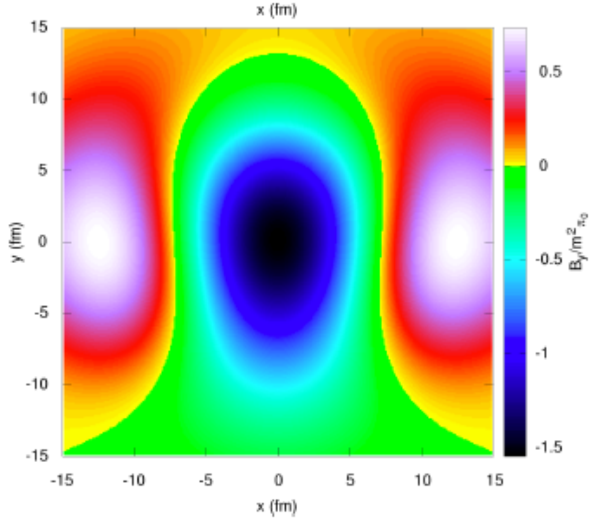
Based on analytic solution (Q. Wang et al) assuming medium from infinitely past to infinitely future; Code package available: ***https://bitbucket.org/bestcollaboration/heavy-ion-em-fields***

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

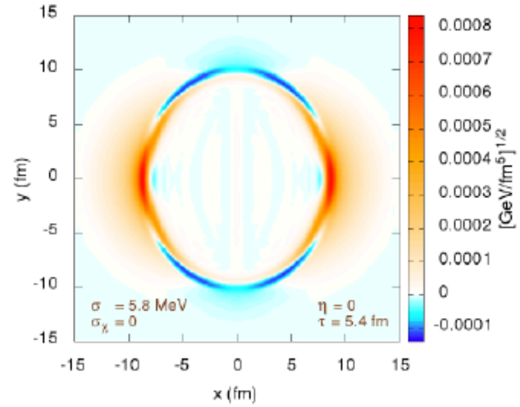
Pro: B field in realistic fluid; Con: unrealistic assumption

Dynamical Magnetic Field

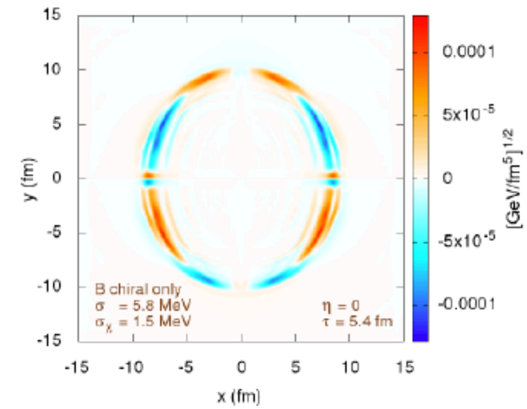




No CME



CME



Inclusion of chiral magnetic conducting contributions

Interesting observables on charge dependent flow

[Kharzeev & Collaborators, 1908.07605 EPJC2020]

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: $\widetilde{E}^i = F_M^{i0}, \quad \widetilde{B}^i = \widetilde{F}_M^{i0}.$

$$\hat{D}_\mu F_M^{\mu\nu} = J^\nu$$

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

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

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

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

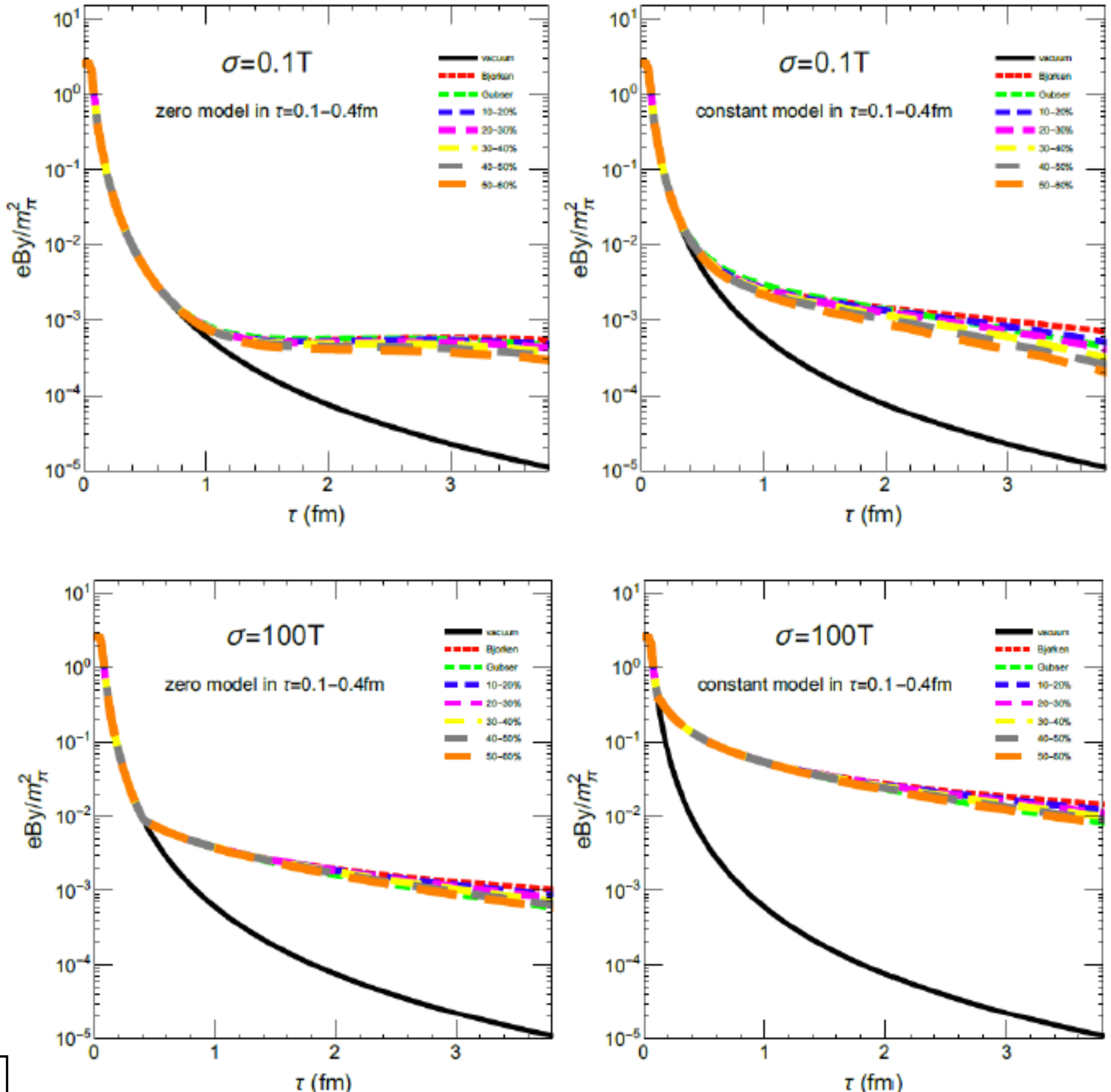
Our code is robust and tested with Bjorken, Gubser, and MUSIC.

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

Longitudinal expansion very important; Transverse expansion not as important.

[Anping Huang, Shuzhe Shi, Kharzeev, JL, et al, to appear]

Dynamical Magnetic Field



Roughly sigma_QCD @ 1~2 Tc

Roughly sigma_QED

Dynamical Magnetic Field

Take-away messages:

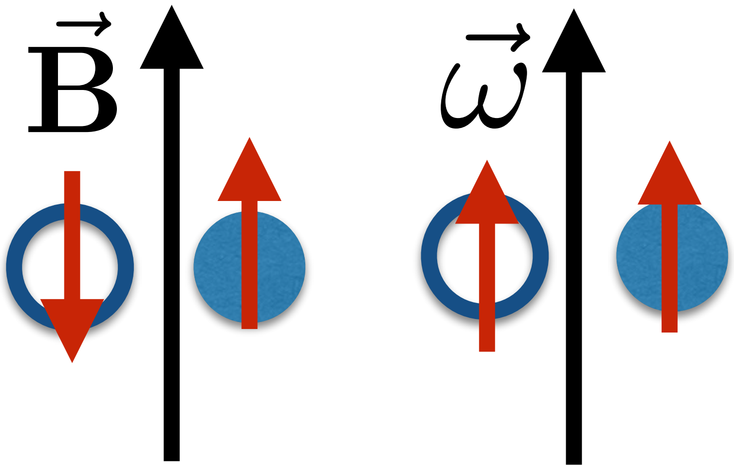
- ***Really we just need a bit medium help within ~ 1 fm/c***
- ***Pre-hydro "conductivity" is crucial***
- ***sigma_QCD at high T end, ~ 3Tc, is crucial too***
- ***Machinery is ready, now need physics inputs (conductivity)***
- ***Integration with AVFD underway (~ near future)***
- ***Useful applications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

[Anping Huang, Shuzhe Shi, Kharzeev, JL, et al, to appear]

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

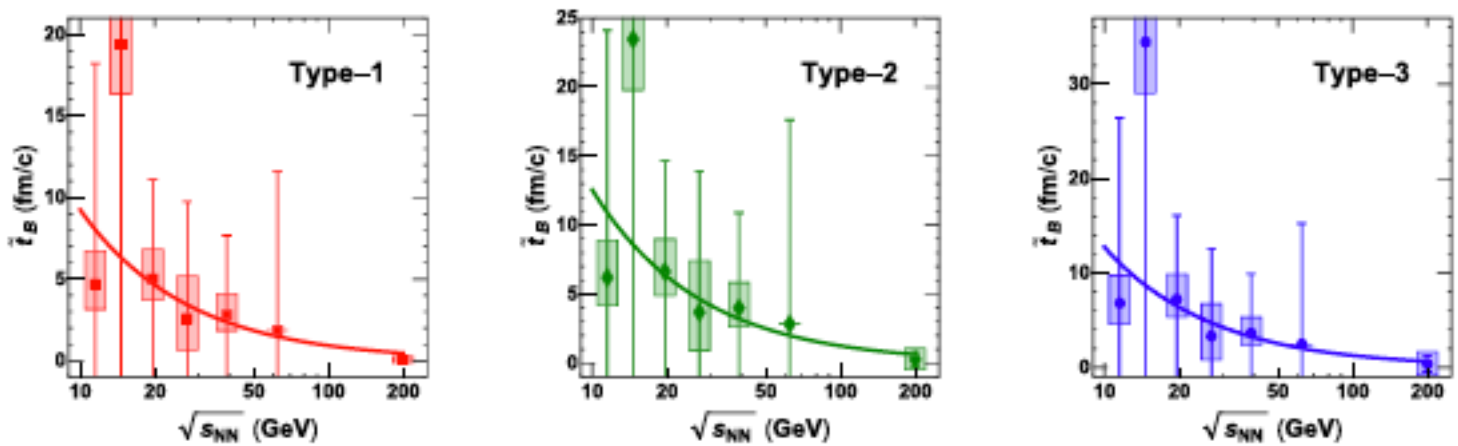


Mueller & Schaefer, arXiv:1806.10907

[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

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

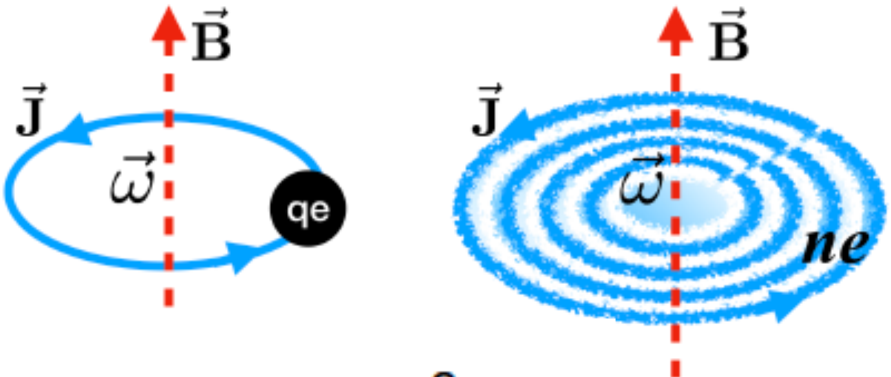
Yu Guo, et al, arXiv:1905.12613 [PLB2019]



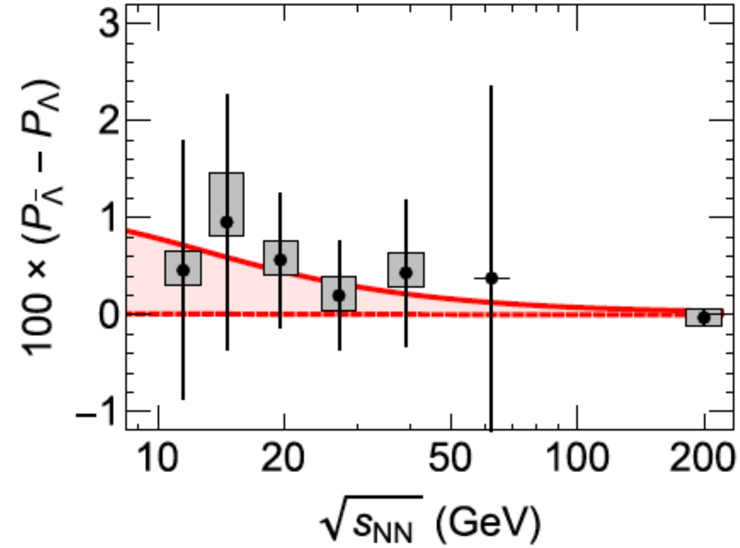
$$\tilde{t}_B = \frac{A}{\sqrt{s_{NN}}} \quad \text{with} \quad A = 115 \pm 16 \ \text{GeV} \cdot \text{fm/c}$$

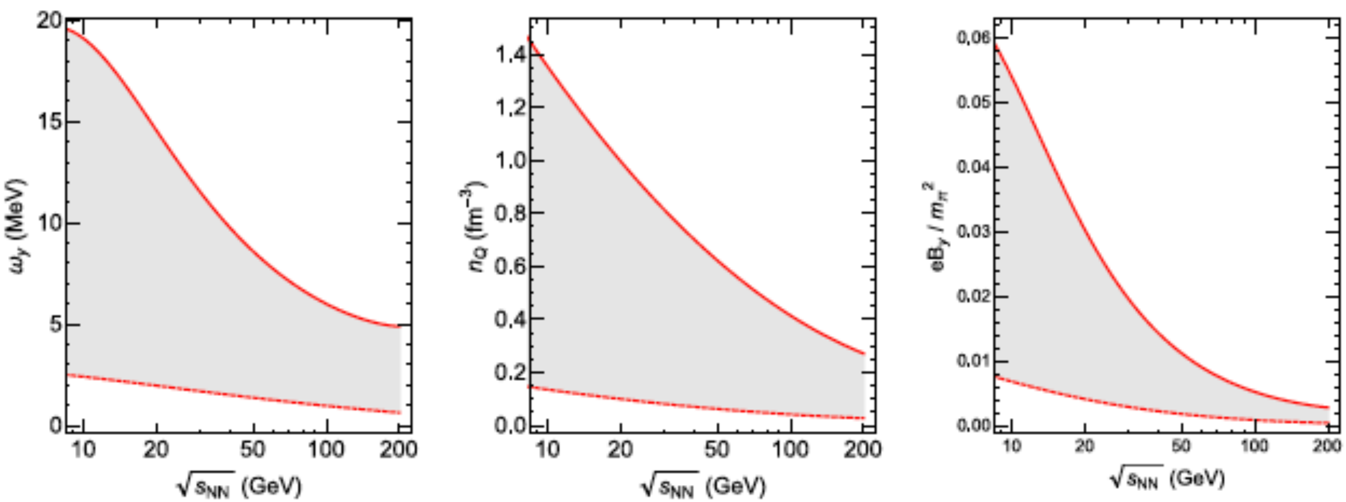
~ 5 times the vacuum lifetime

New Mechanism of B-Field at BES Energies



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





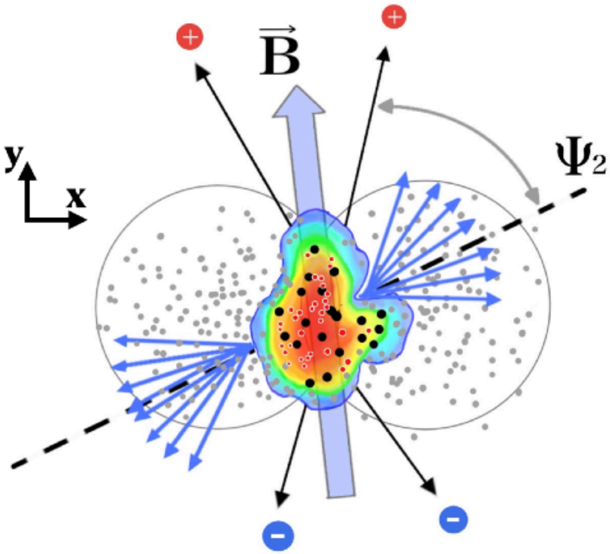
Important at low beam energy!

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

CME: Exp. Status

Looking for CME Signals in Nuclear Collisions

CME transport induces a charge dipole distribution along magnetic field direction in the QGP fluid.

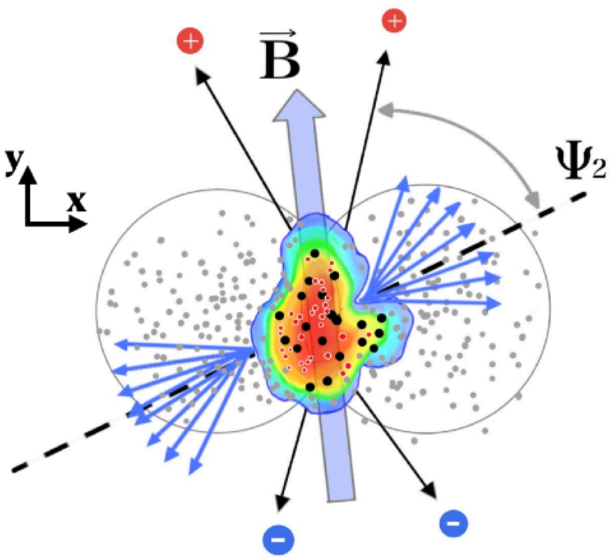


A specific emission pattern of charged particles along B field: Same-sign hadrons emitted preferably side-by-side; Opposite-sign hadrons emitted preferably back-to-back.

A number of experimental observables were designed: gamma & delta correlators; kappa parameter; event-shape & invariant mass dependence; EP versus RP versus triangular plane; R correlator; charged balance function.

Looking for CME Signals in Nuclear Collisions

- *First measurement ~ 2009 by STAR;*
- *Efforts in past decades by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5020GeV beam energies*
- *Various colliding systems pA, dA, CuCu, AuAu, UU, PbPb*



Signal ~ B field strength

B field strength ~ elliptic shape

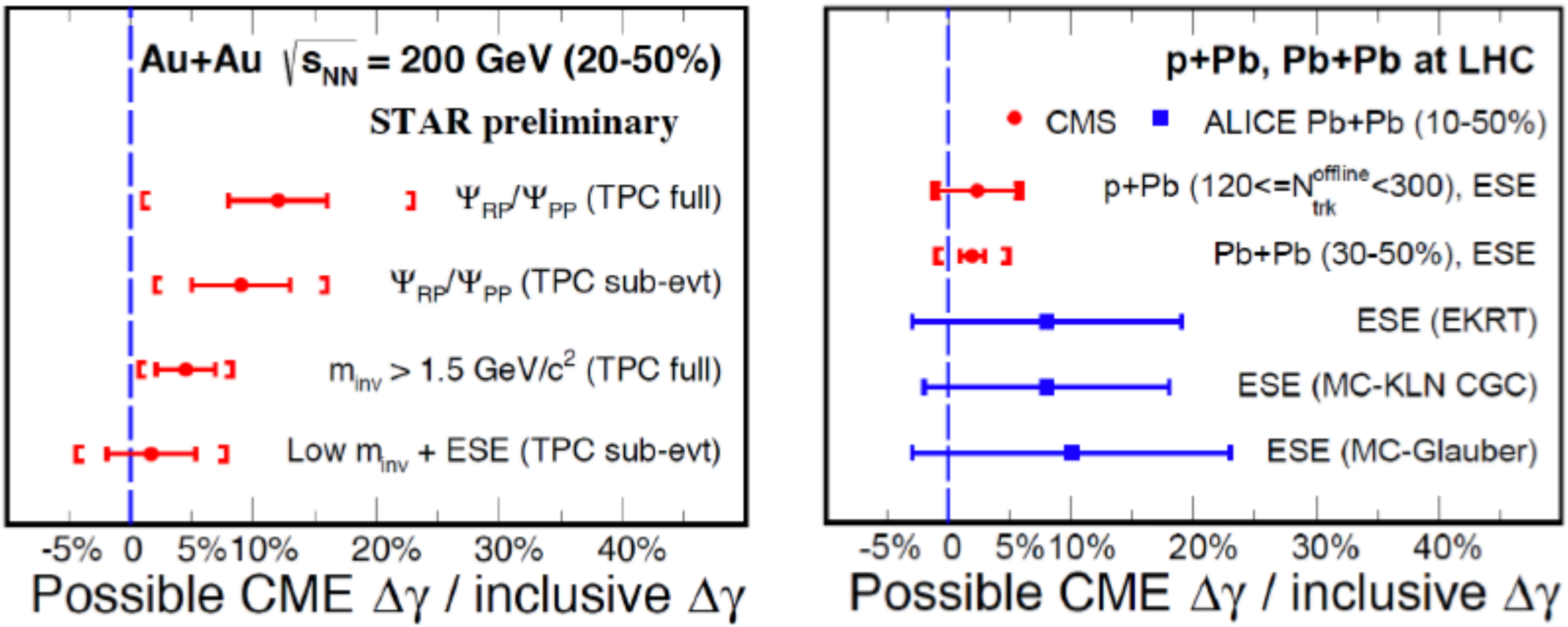
Elliptic shape ~ elliptic flow

Elliptic flow ~ background correlations

It proves to be a very difficult search:
Small signal contaminated by strong backgrounds!

Exp. Search for CME (early 2019)

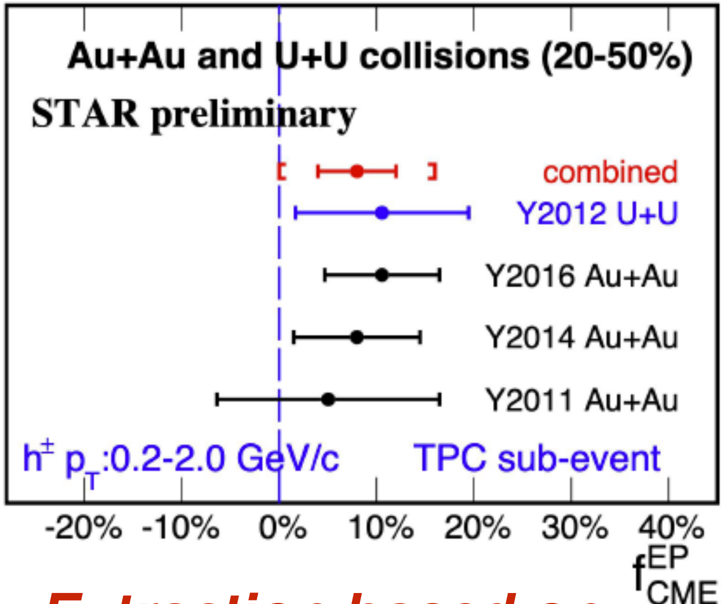
Most measurements based on:
gamma correlator + certain procedure to fight backgrounds



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.

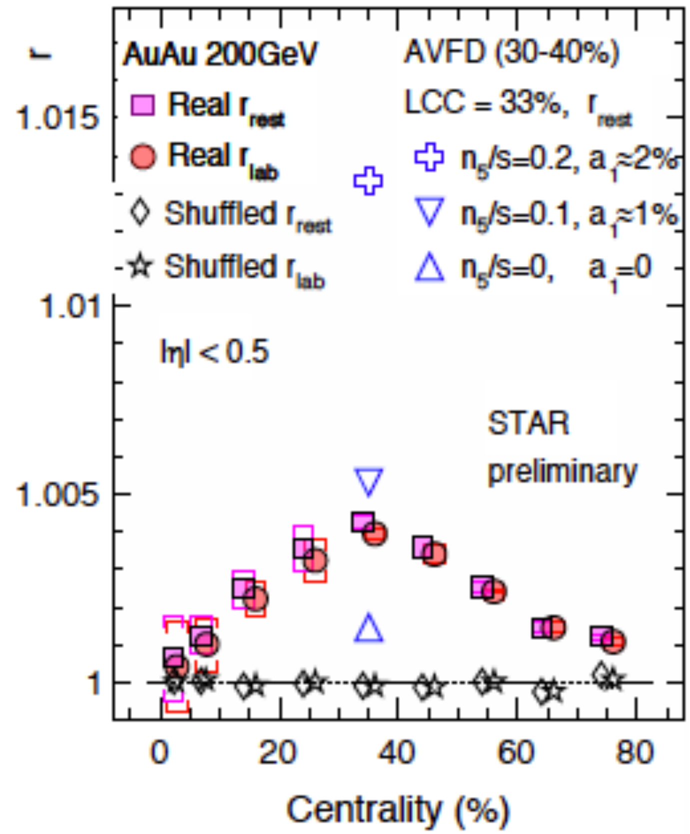
Chiral Magnetic Effect: Exp. Status



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

the combined result is $(8 \pm 4 \pm 8)\%$

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



Charged balance function: supportive for nonzero signal!

Challenge: observable sensitivity!

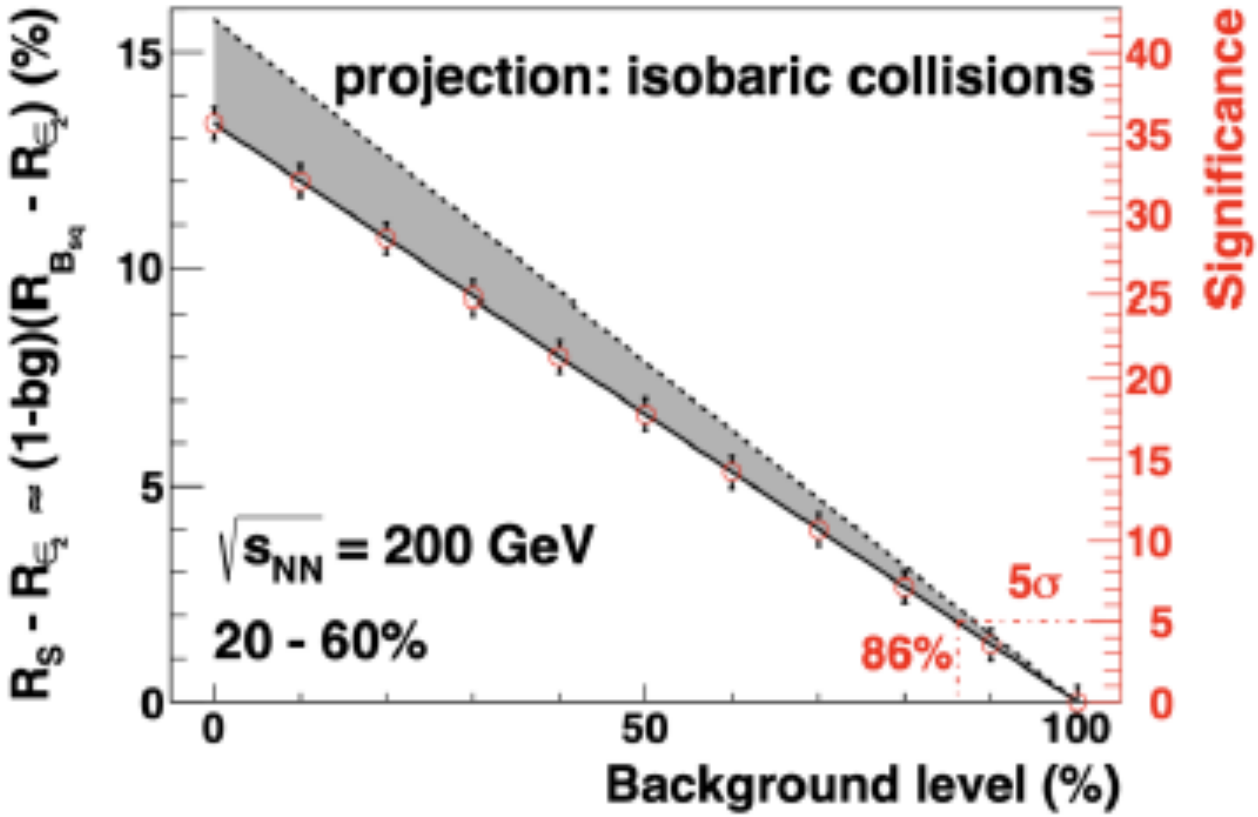
Talks @ QM19 by M. Lisa; Z. Xu; J. Zhao; Y. Lin

New Opportunity: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC

Very successful data taking @ 2018 Run

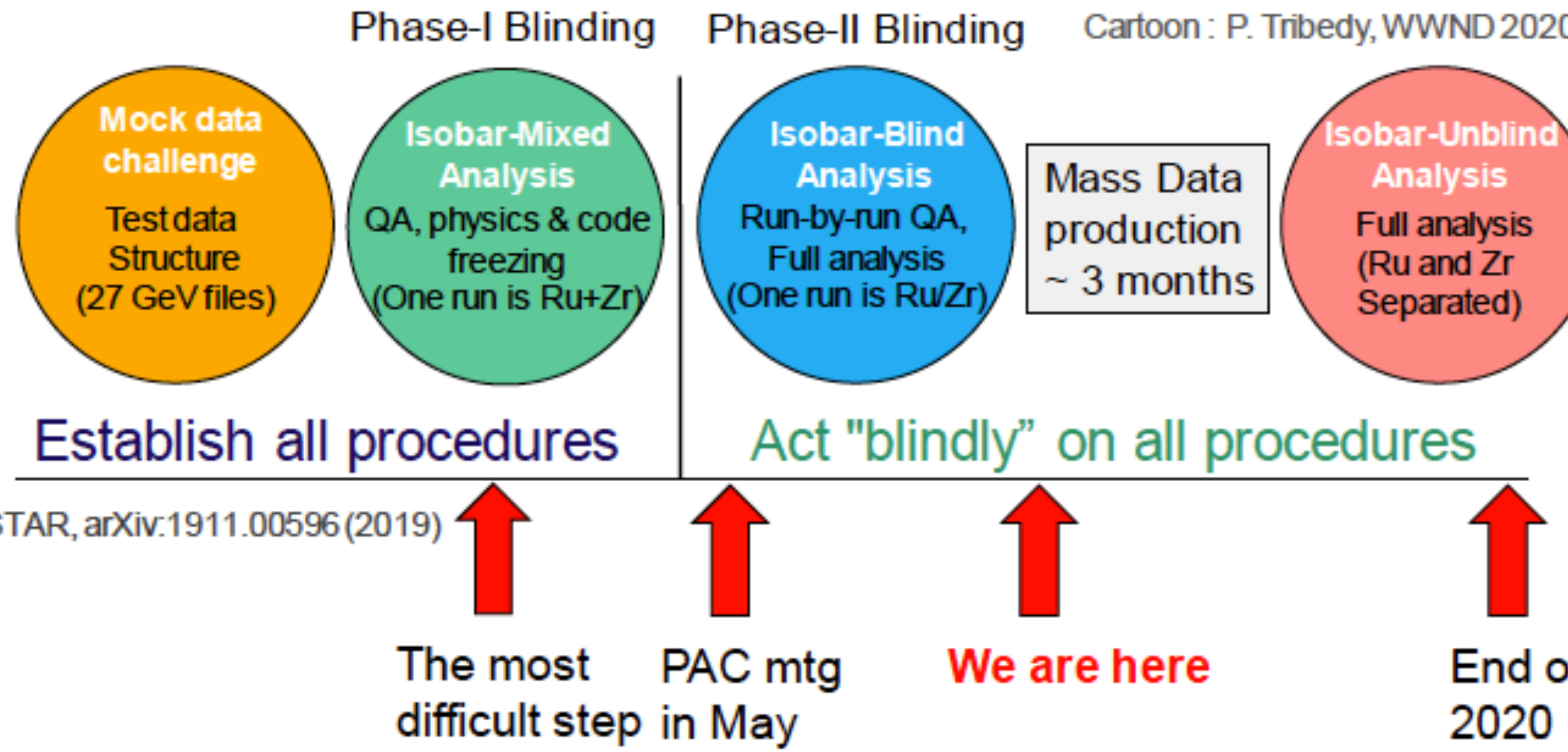
Very Successful Isobar Run



Anticipated significance with 2.5 B good evts.
5σ difference in $\Delta\gamma$ if bkg. is at ~86% level.

Latest update from A. Tang and G. Wang

Analysis Work Underway!

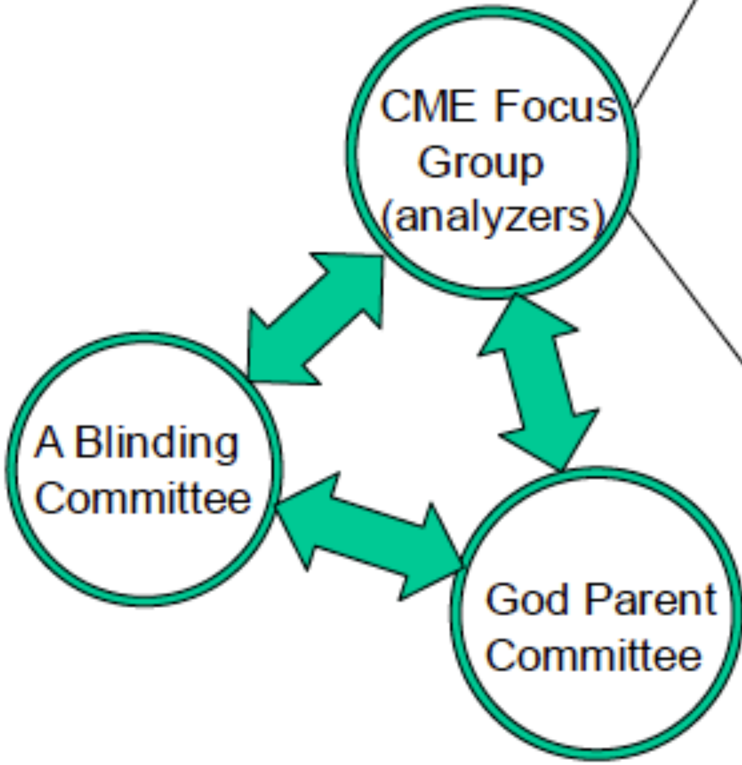


- Program Advisory Committee Recommendation:
  - The PAC strongly recommends that any STAR publication regarding CME observables should contain the result after unblinding and without any additional corrections applied after unblinding that are deemed necessary by STAR. If such additional corrections are needed, then a paper containing both the unblinded and post-unblinded results should be published for reference in papers reporting the isobar data.

From A. Tang (Sep 2020 status)

Analysis Work Underway!

A large, collective effort



Blind analyses (5 groups):

- $\Delta\gamma$, $\Delta\delta$, and κ.
- $\Delta\gamma$, $\Delta\delta$, $\Delta\gamma(\Delta\eta)$.
- $\Delta\gamma$ in PP/SP, $\Delta\gamma(M_{inv})$.
- $\Delta\gamma$ in PP/SP.
- R(ΔS) Correlator.

No-Blind analysis (1 group):

- Signed Balance Function.

Challenges :

- Coordination and synchronization. (among groups, as well as between groups and committees).
- Unify procedures in common.
- Identify run-by-run abnormalities before hand without actual seeing them.

  ......

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC, Wayne State

See backup slides for key observables.

From A. Tang

Analysis Work Underway!

Case for CME :

$\Delta\gamma/v_2$ (Ru / Zr) > 1

$\Delta\gamma_{112}/v_2$(Ru / Zr) > $\Delta\gamma_{123}/v_3$(Ru / Zr)

κ (Ru / Zr) > 1

$\Delta\gamma^{\mathrm{Ru}} - a'r'\Delta\gamma^{\mathrm{Zr}} > 0$

$\Delta\gamma$ and its derivatives

R (Ru / Zr) concave shape

Correlation shape

$\mathrm{f}_{\mathrm{CME}}^{\mathrm{Ru+Ru}} > \mathrm{f}_{\mathrm{CME}}^{\mathrm{Zr+Zr}} > 0$

SP & PP + $\Delta\gamma$

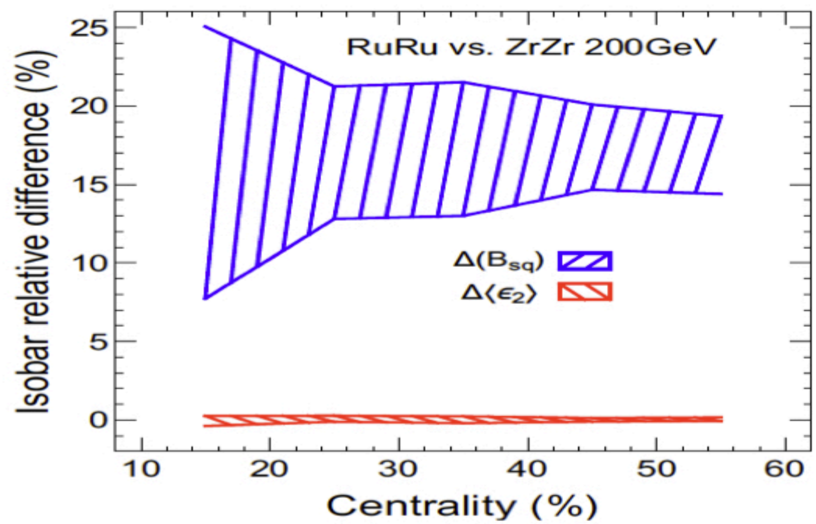
From A. Tang

What We Really Need

#1 step: a statistically significant-enough departure from pure background scenario
— — where we can take full advantage of isobar contrast!

Important: to ensure identical isobar bulk properties!

Charge Asymmetry Correlation Measurement



Strategies to overcome the issue:
— apply joint multiplicity—ellipticity cut for event samples
— stay at the relatively peripheral region

arXiv: 1910.14010

Quantitative Modeling of CME in Heavy Ion Collisions

The experimental status cries for a detailed dynamical modeling

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

Modeling CME: Integration into Bulk Evolution

** Approach based on fluid dynamics (AVFD)*

— our focus here

** Approach based on transport models.*

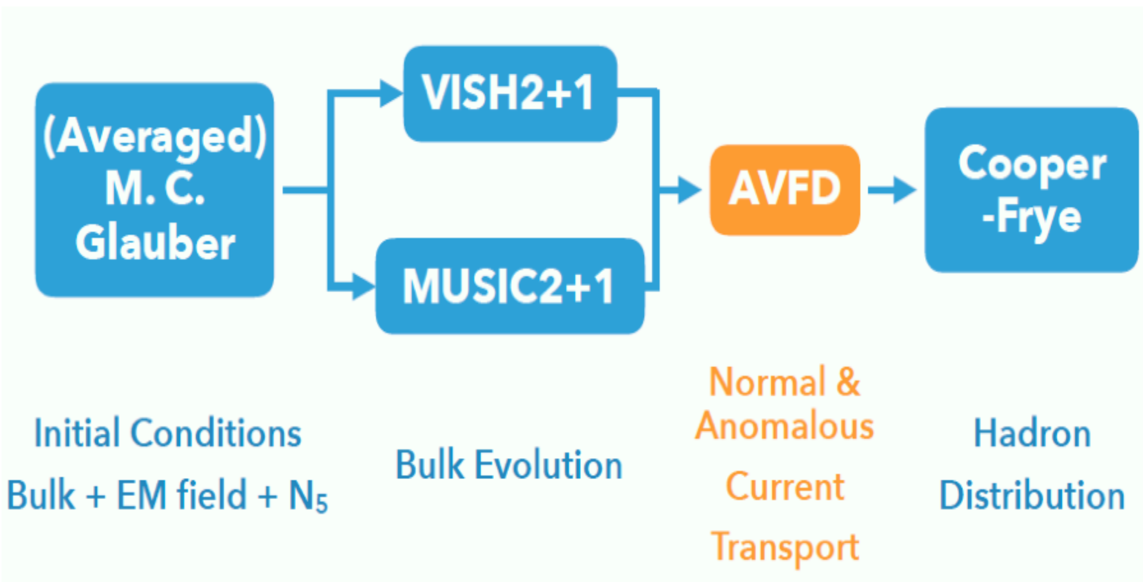
— AMPT based
(Guoliang Ma, Yugang Ma, and collaborators)
[NO dynamically generated anomalous transport]

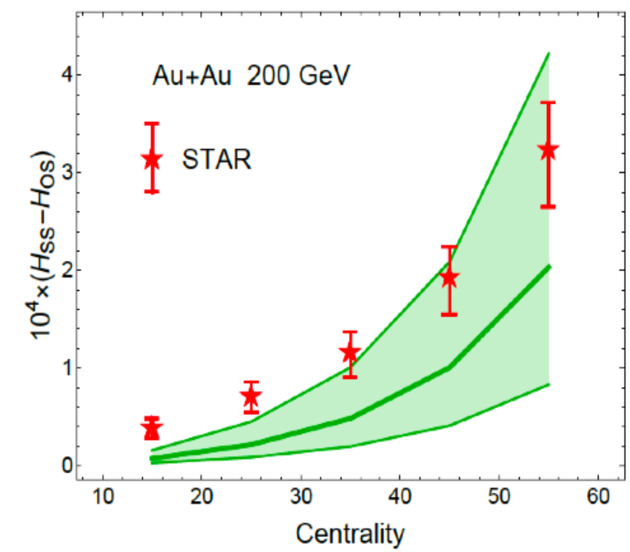
— Chiral kinetic transport based <u>*Talk by Y. Sun*</u>
(Che-ming Ko and collaborators)
[realistic heavy ion environment?]

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, Zhang, Hou, …, JL: CPC42(2018)011001; Annals of Physics 394(2018)50; ; arXiv:1910.14010]

AVFD Framework

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] ***[shared with STAR for observable studies]***

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

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

3rd generation: ***[final code package to be made public in the near future]***

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

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

Consistency is checked across generations.

Shuzhe Shi [McGill]

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)

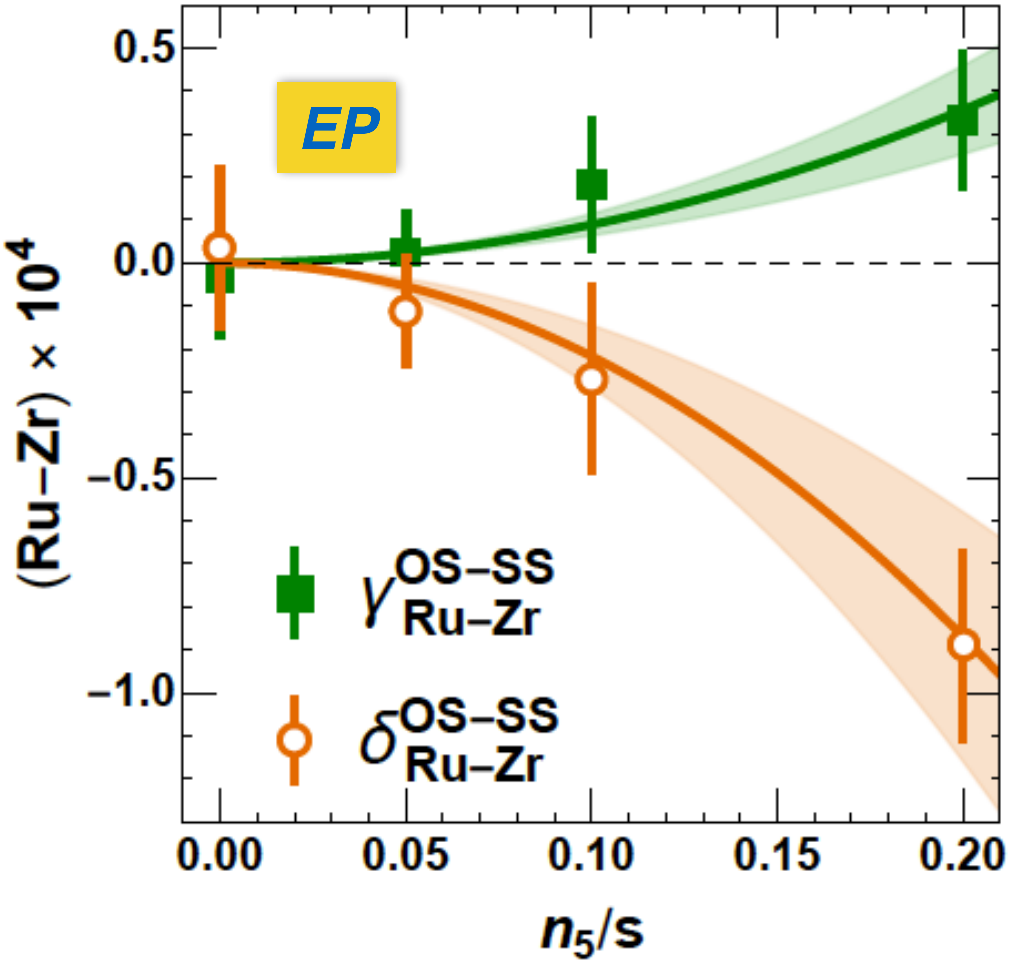
LCC (0->weak->strong)

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!]

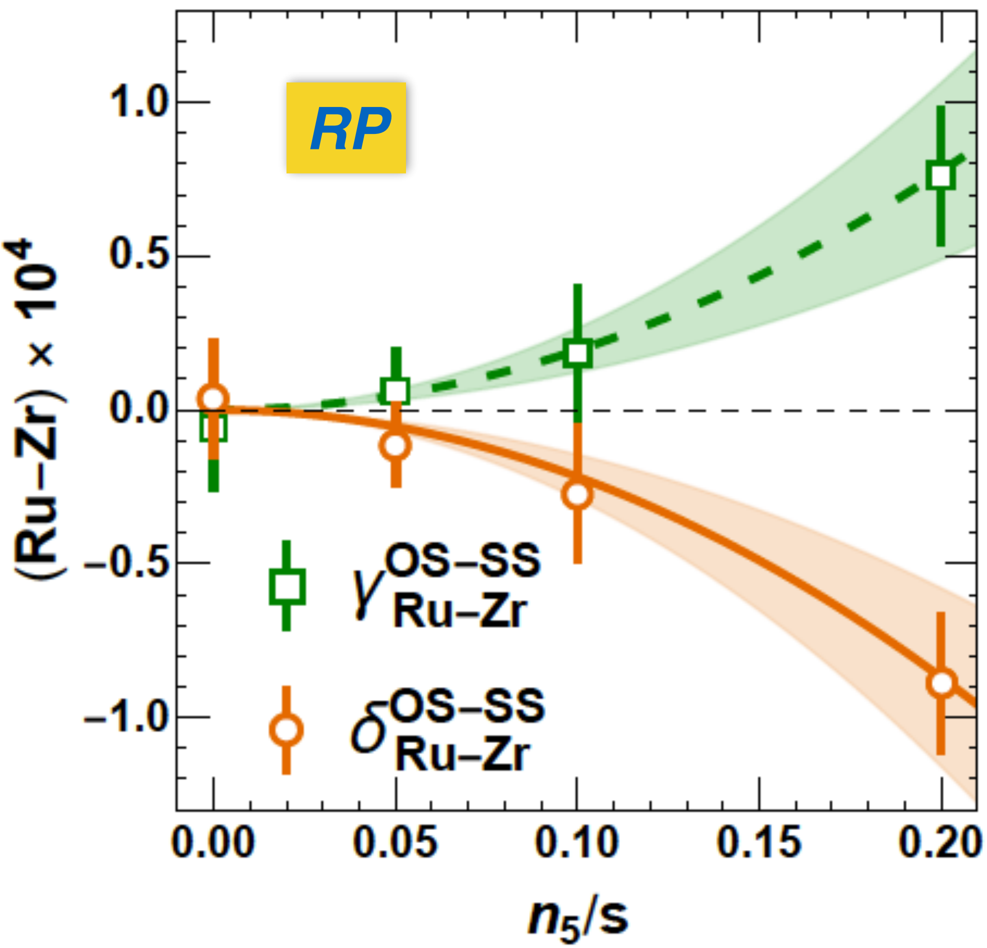
$$\zeta^{EP}_{isobar} \equiv \frac{\gamma^{OS-SS}_{Ru-Zr}\Big|_{EP}}{\delta^{OS-SS}_{Ru-Zr}\Big|_{EP}} \simeq -(0.41 \pm 0.27)$$

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 —>>

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

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

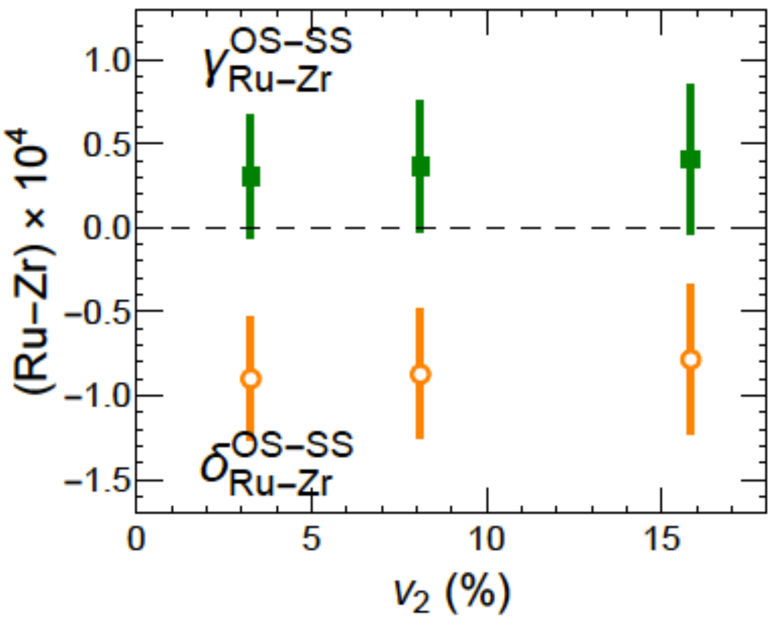
Use gamma and delta together to remove uncertainty! [unique feature of pure signal!]

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

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

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

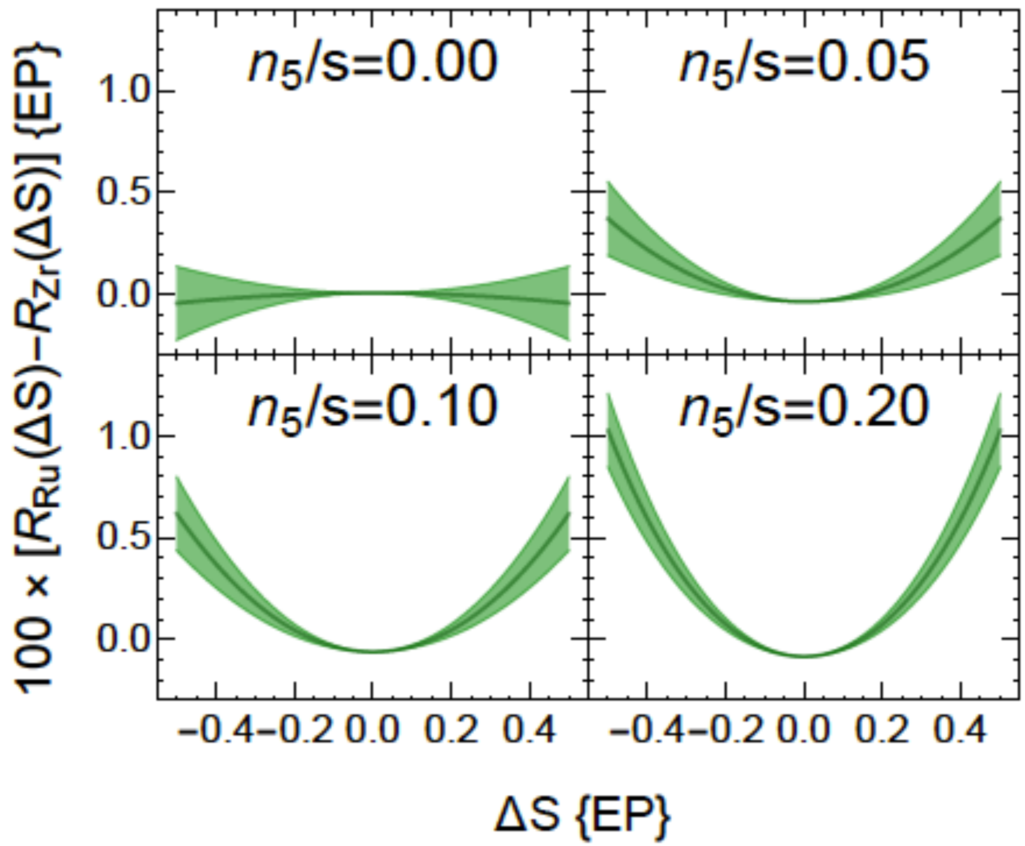
AVFD Predictions for Isobars



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

Unique feature of pure signal: independent of event shape

R-correlator shape



SUMMARY

Summary/Outlook

— *Fascinating physics of spin under chirality, vorticity and magnetic field*

— *A "spin fluid" in relativistic nuclear collision as the ideal laboratory for studying such physics*

— *Chirality leads to interesting phenomena, including CME*

— *Dynamical magnetic field evolution is challenging, but we are getting there*

— *Positive hints of CME signals but not conclusive yet due to large backgrounds: strong exp./th. efforts underway*

Stay tuned for exciting(?!) news
from isobar collisions, in just a few months!