Chiral Magnetic Effect: Status report and Holography

Karl Landsteiner

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

Campus Internacional excelencia UAM+CSIC

Phys. Rev. D. 104 (2021) 046009
2105.05855 [hep-ph]

With: J. Ghosh, S. Grieninger, S. Morales-Tejera

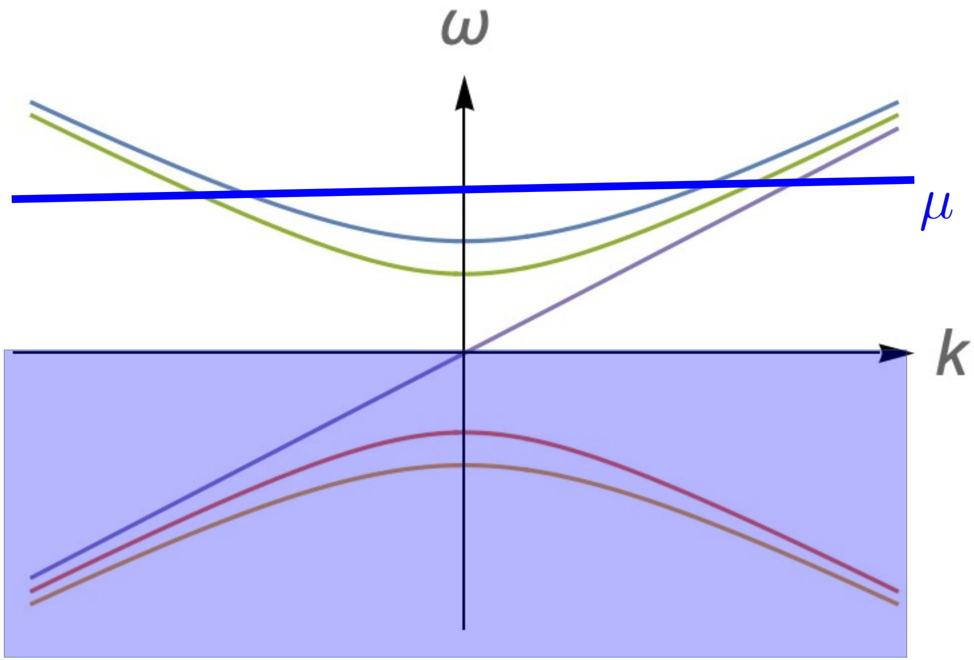
Tours, 01.June 2022

Outline

- Chiral Magnetic Effect
- CME in heavy ion collisions
- Out-of-equilibrium CME in Holography
  - Generic model properties
  - Matching to QCD
- Conclusions & Outlook

Chiral Magnetic Effect

Chiral fermion in (very strong) magnetic field:



Lowest Landau Level:

$$J = \frac{eB}{2\pi}\int_0^{\infty}\frac{dk}{2\pi}\left(n_F(\mu,T) - n_F(-\mu,T)\right) = \frac{\mu}{4\pi^2}eB$$

Higher Landau Levels:

$$J = \frac{eB}{2\pi}\int_{-\infty}^{+\infty}\frac{dk}{2\pi}\frac{\partial\epsilon}{\partial k}\left(n_F(\mu,T,k^2)\right) = 0$$

CME current stems from LLL only

Chiral Magnetic Effect

Higher “Zilch” currents: $$J^{(n)}_{0\ldots z} = \frac{eB}{2\pi}\int_0^\infty \frac{dk k^{n-1}}{2\pi}\left(n_F(\mu,T) + (-)^n n_F(-\mu,T)\right) =$$
$$= \frac{eB}{4\pi^2}T^n\left[Li_n(-e^{\mu/T}) + (-)^n Li_n(-e^{-\mu/T})\right]$$

Jonquiere inversion formula: $$Li_n(z) + (-)^n Li_n(1/z) = -\frac{(2\pi i)^n}{n}B_n\left(\frac{1}{2} + \frac{ln(-z)}{2\pi i}\right)$$

$\frac{\mu}{2\pi}$	CME
$\frac{\mu^2}{4\pi} + \frac{\pi T^2}{12}$	CME in Energycurrent, CVE in current
$\frac{\mu^3}{12\pi} + \frac{\pi T^2 \mu}{12}$	CME in 3-Zilch, CVE in Energycurrent
$\vdots$	

Chiral Anomalies

Relations to Hawking radiation

[Robinson, Wilczeck],
[Stone, Kim]
[Bonora,Cvitan, Pallua, Smolic]
..

CME @ HIC

Axial anomaly (QED): $\partial_\mu J_5^\mu = c\,\epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$

CME: $\vec{J} = 8c\,\mu_5 \vec{B}$

[Fukushima, Kharzeev,Warringa]
[Vilenkin] 1980
[Alekseev,Chaianov, Fröhlich]
[Giovaninni, Shaposhnikov],...

Equilibrium quantity, not the chiral charge !

Lifetime!

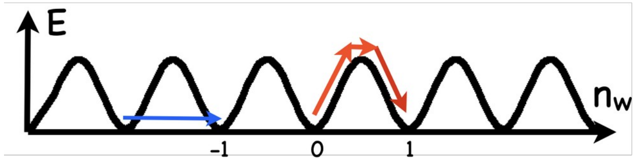
Theory subtelties:

[Rebhan, Schmitt, Stricker 0909.4782]
[Gynther, K.L., Pena-Benitez, Rebhan], 1005.2587
[K.L. 1610.04413]

CME @ HIC

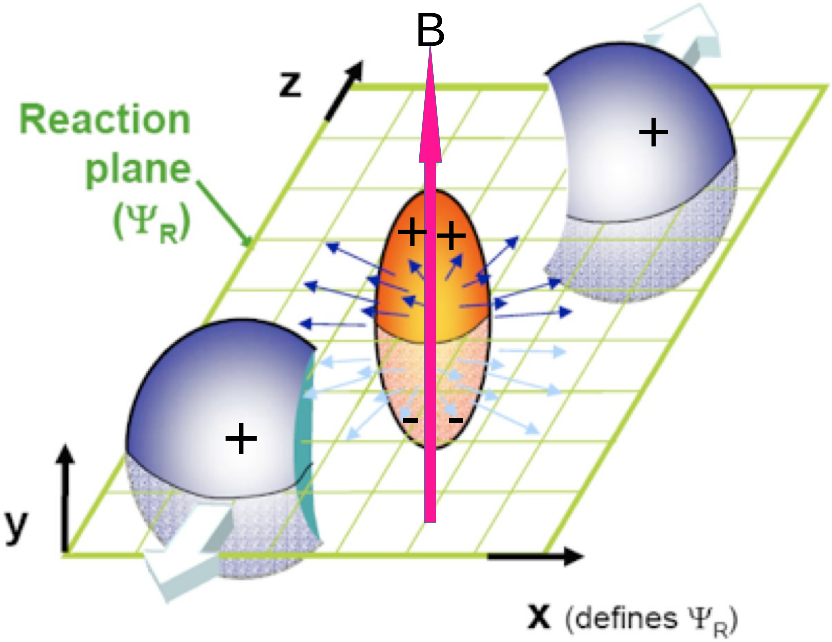
CME @ HIC

Quark Gluon Plasma:



$$\partial_\mu J^\mu_A = \frac{N_f}{32\pi^2}\epsilon^{\mu\nu\rho\lambda}G^a_{\mu\nu}G^a_{\rho\lambda}$$

[Kharzeev],
[Kharzeev, McLarren, Warringa] QCD out of equilibrium topological gluon field configurations



- QCD axial anomaly induces Q_5
- Spectators induce strong magnetic field
- CME leads to charge separation
- Strong non-equilibrium physics

- Resemblance to baryogenesis (Sakharov criteria, sphalerons, anomaly, out of equilibrium...)

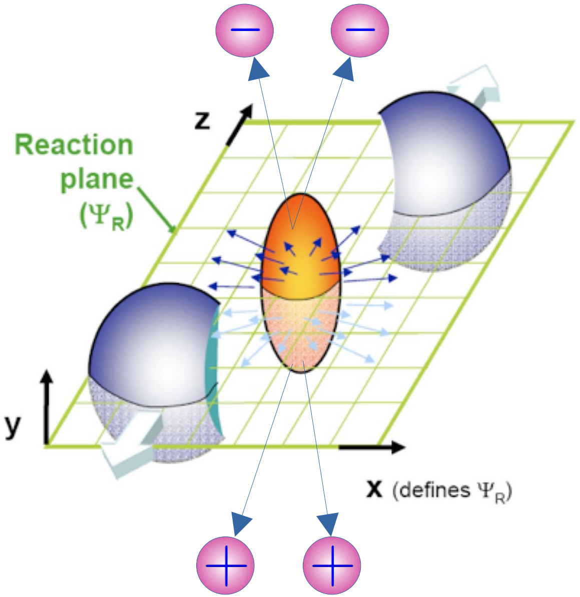
[Bödeker, Buchmüller: Rev. Mod. Phys. 93, 035004 (2021)]

CME @ HIC

How to measure CME?

$$\frac{dN}{Nd\phi} = 1 + 2v_1\cos(\phi - \psi_{RP}) + 2v_2\cos(2(\phi - \psi_{RP})) + 2a_{\pm}\sin(\phi - \psi_{RP}) + \ldots$$

P-odd CME $a_+ = -a_-$



CME signal averages out to zero over many collisions: $\langle a_{\pm} \rangle = 0$

Way out: "γ-correlator" $\gamma_{\alpha\beta} = \langle a_\alpha a_\beta \rangle$ – some background P-even

[Voloshin]

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

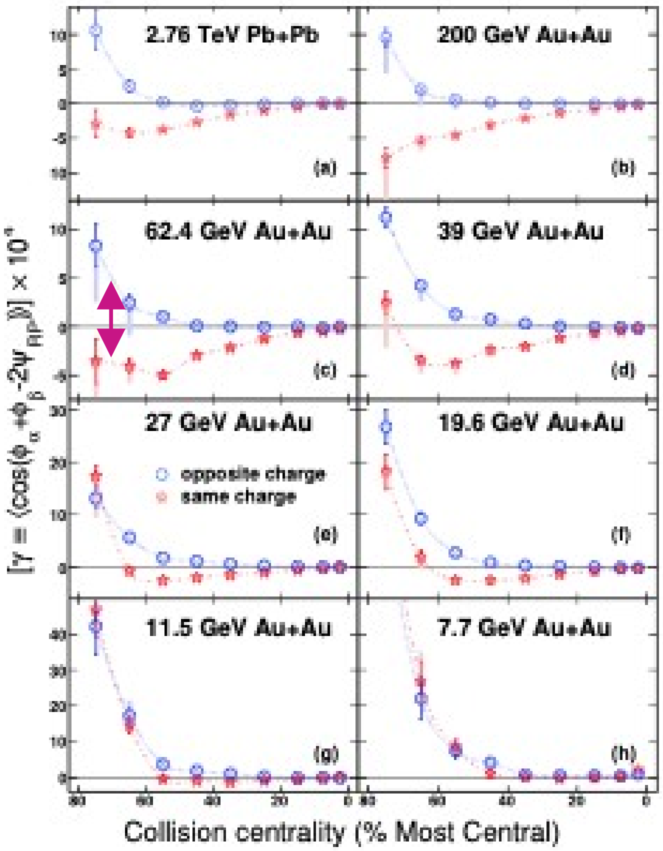
CME @ HIC

"same sign" vs. "opposite sign"   CME signal

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

But to soon to declare victory: signal is contaminated by significant backgrounds:

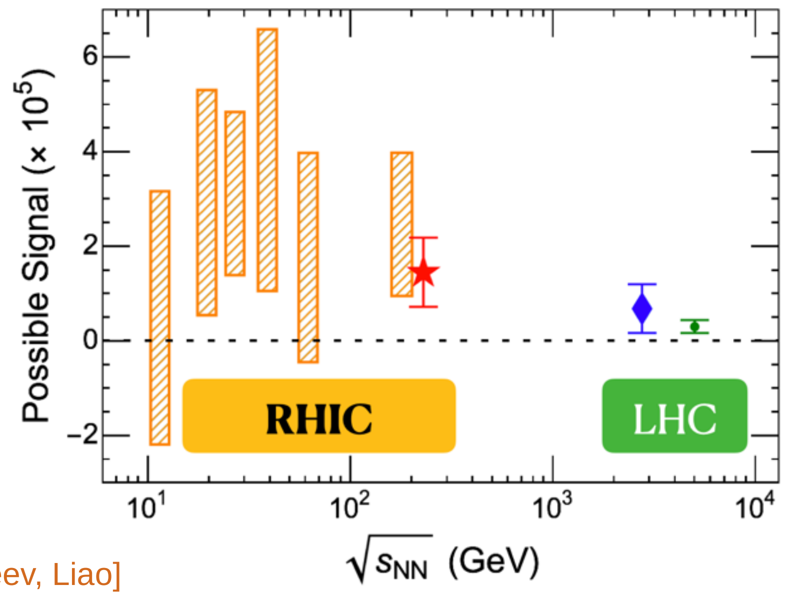
- "Local charge conservation"
- "Transverse momentum conservation"
- "Cluster decay"
- Signal present in p-A collisions



[Star Collaboration] Phys.Rev.Lett. 113 (2014) 052302

[Kharzeev, Liao, Voloshin, Wang] Prog.Part.Nucl.Phys. 88 (2016)

CME @ HIC



[Kharzeev, Liao]
Nature Reviews 3, pp.55–63 (2021)

"Caution must be taken .... Nevertheless, these experimental results, although far from being conclusive, are **strongly suggestive of a detectable CME signal, especially in the RHIC energy region**"

JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: June 5, 2020
REVISED: July 9, 2020
ACCEPTED: August 20, 2020
PUBLISHED: September 24, 2020

Constraining the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ and 5.02 TeV

ALICE
The ALICE collaboration

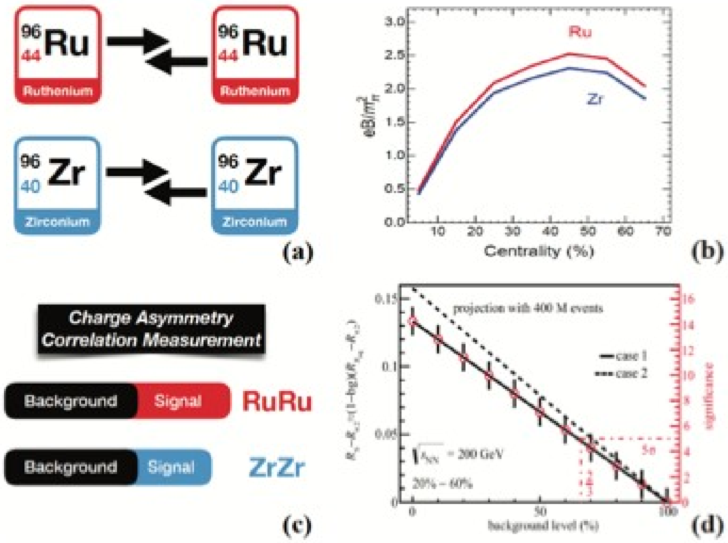
"..verify again that that background contributions dominate.."

CME @ HIC – Isobar run

Huge effort to get experimental grip on CME: new methods (“event shape engineering”), new improved correlators, ...

Most important: Isobar run @ RHIC in 2018

Expect ~20% higher CME signal in Ru



CME @ HIC – Isobar run

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{\rm NN}} = 200$ GeV by the STAR Collaboration at RHIC

M. S. Abdallah,[5] B. E. Aboona,[55] J. Adam,[6] L. Adamczyk,[2] J. R. Adams,[39] J. K. Adkins,[30] G. Agakishiev,[28] I. Aggarwal,[41] M. M. Aggarwal,[41] Z. Ahammed,[60] I. Alekseev,[3,35] D. M. Anderson,[55] A. Aparin,[28] E. C. Aschenauer,[6] M. U. Ashraf,[11] F. G. Atetalla,[29] A. Attri,[41] G. S. Averichev,[28] V. Bairathi,[53] W. Baker,[10]

arXiv:2109.00131 [nucl-ex]

Observables: $\gamma_{112} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$ Second order flow plane

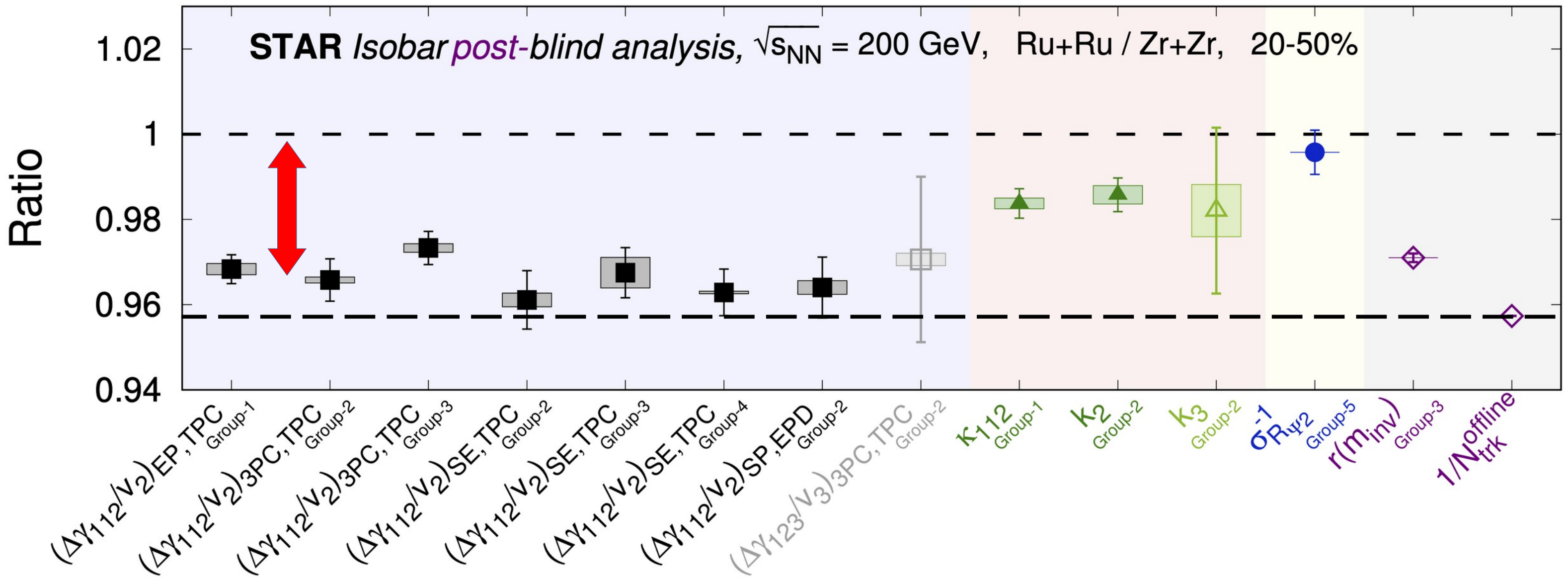
$$\gamma_{123} = \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$ Third harmonic plane

$$\delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle \qquad \kappa_{112} = \frac{\Delta\gamma_{112}}{v_2 \Delta\delta}$$ Non-flow background (LCC & TMC)

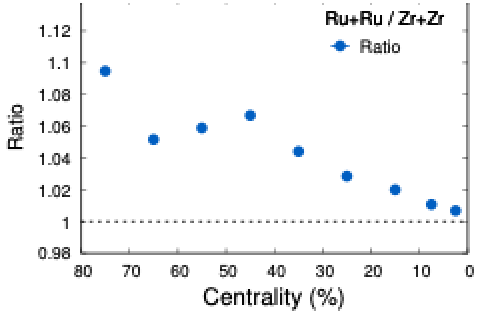
Signals:

$$\frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > 1 \;\; ; \;\; \frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > \frac{(\Delta\gamma_{123}/v_2)^{Ru+Ru}}{(\Delta\gamma_{123}/v_2)^{Zr+Zr}} \;\; ; \;\; \frac{(\Delta\kappa_{112})^{Ru+Ru}}{(\Delta\kappa_{112})^{Zr+Zr}} > 1$$

CME @ HIC – Isobar run



It's the multiplicities, ...



$$\frac{(\Delta\gamma_{112}/v_2)^{Ru+Ru}}{(\Delta\gamma_{112}/v_2)^{Zr+Zr}} > \frac{N^{Zr+Zr}}{N^{Ru+Ru}}$$

CME @ HIC

arXiv.org > nucl-th > arXiv:1608.00982

Nuclear Theory

[Submitted on 2 Aug 2016 (v1), last revised 12 Aug 2016 (this version, v2)]

Chiral Magnetic Effect Task Force Report

Vladimir Skokov, Paul Sorensen, Volker Koch, Soeren Schlichting, Jim Thomas, Sergei Voloshin, Gang Wang, Ho-Ung Yee

II. THEORY UNCERTAINTIES

As discussed in Sect. I, the QCD plasma created in high energy nucleus-nucleus collisions

A) the initial distribution of axial charges,

B) the evolution of the magnetic field,

C) the dynamics of the CME during the pre-equilibrium stage,

D) the uncertainties in the hadronic phase and the freeze-out.

CME @ HIC

$$\vec{J} = 8c\,\mu_5\,\vec{B}$$

Question: How long does it take to build up the CME current if one starts out with J=0 ?

- Quark Gluon Plasma: strongly coupled liquid
- One of the success stories of holography
- Especially successful for CME, CVE

→ Shear viscosity: $\frac{\eta}{s} = \frac{1}{4\pi}$ [Policastro, Son, Starinets]

→ Equilibration, isotropisation times: $\tau \approx 0.5 fm/c$ [Chesler, Yaffe]

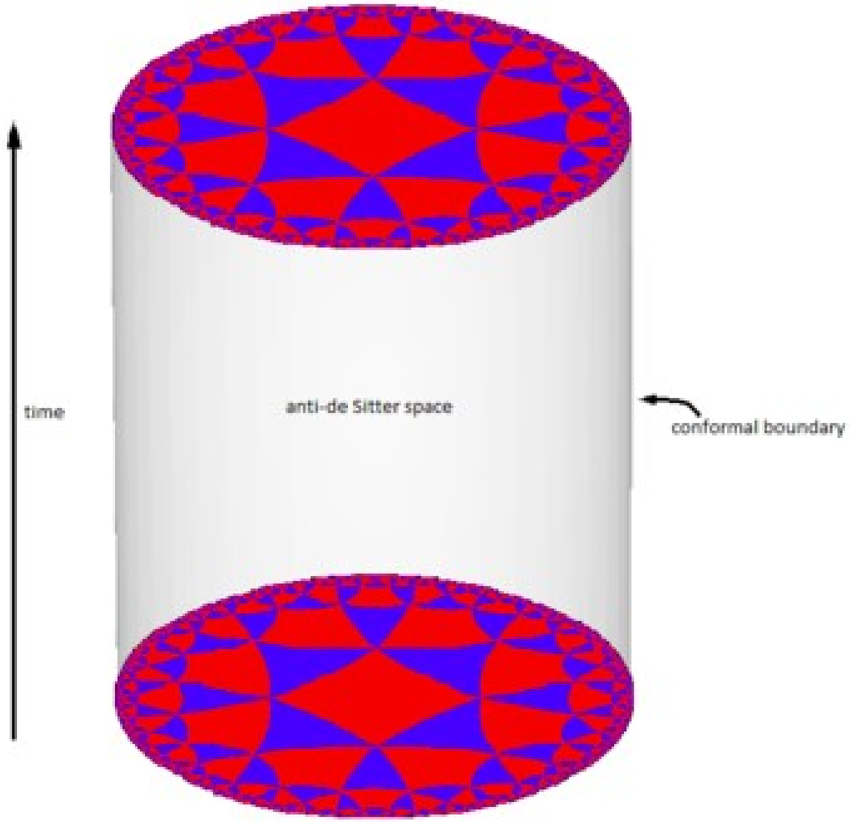
[Newman], [Yee], [Erdmenger, Kaminski, Haack, Yarom], [Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka] [Rebhan, Schmitt, Stricker], [Gynther, K.L., Pena-Benitez, Rebhan], [K.L., Megias, Melgar, Pena-Benitez], [Ammon, Grieninger, Hernandez, Kaminski, Koirala, Leiber ,Wu], ...

→ Investigate this question in a holographic setup

[Lin, Yee], [Ammon, Grieninger, Jimenez-Alba, Malcedo, Melgar],[K.L., Lopez, Milans del Bosch], [Fernandez-Pendas, K.L.], [Morales-Tejera, K.L.], [Cartwright]

Quantum simulation approach 2D model: [Kharzeev, Kikuchi]

Holography



Gravity in asymptotically AdS = QFT

Holographic Dictionary	
Metric	Energy Momentum Tensor
Gauge field	Conserved current = symmetry
Scalar field	Scalar operator
Boundary value	**Coupling**
Black Hole	**Temperature**

Holography

Holographic bottom-up approach: chose symmetries, simplest Lagrangian

$$S = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R + \frac{12}{L^2} - \frac{1}{4}F_V^2 - \frac{1}{4}F_A^2 + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\lambda\sigma}A_\mu\left(F^V_{\nu\rho}F^V_{\lambda\sigma} + \frac{1}{3}F^A_{\nu\rho}F^A_{\lambda\sigma}\right)\right]$$

Ansatz: $$ds^2 = -f(v,u)dv^2 - \frac{2L^2}{u^2}dvdu + \frac{2}{u^2}h(v,u)dvdz + \Sigma(v,u)^2\left[e^{\xi(v,u)}(dx^2+dy^2) + e^{-2\xi(v,u)}dz^2\right]$$

$$V_\mu = (0,0,-y\,B/2, x\,B/2, V_z(v,u)) \quad , \quad A_\mu = (-Q_A(v,u),0,0,0,0)$$

Asympotic expansion:

$$Q_5(v,u) = \frac{u^2}{2}q_5 + \mathcal{O}(u^3)\,,$$
$$V_z(v,u) = u^2\,V_2(v) + \mathcal{O}(u^3)\,,$$
$$\Sigma(v,u) = \frac{1}{u} + \lambda(v) + \mathcal{O}(u^5)\,,$$
$$\xi(v,u) = u^4\left(\xi_4(v) - \frac{B^2}{12}\log(u)\right) + \mathcal{O}(u^5)\,,$$
$$f(v,u) = \left(\frac{1}{u} + \lambda(v)\right)^2 + u^2\left(f_2 + \frac{B^2}{6}\log(u)\right) - 2\dot{\lambda}(v) + \mathcal{O}(u^3)\,.$$

Operators:

$$J_z = \frac{1}{\kappa^2}V_2(v)$$
$$J^0_5 = \frac{1}{2\kappa^2}q_5$$
$$T^v{}_v = \frac{1}{4\kappa^2}\left[6f_2 - B^2\log(\mu L)\right]$$
$$T^x{}_x = T^y{}_y = -\frac{1}{8\kappa^2}\left[B^2 + 4f_2 - 16\xi_4(v) - 2B^2\log(\mu L)\right]$$
$$T^z{}_z = -\frac{1}{4\kappa^2}\left[2f_2 + 16\xi_4(v) + B^2\log(\mu L)\right]$$

Holography

Initial state:

- Static, non-expanding, infinite plasma
- Chiral charge density uniform and constant in time
- Magnetic field is uniform and constant in time
- Energy density is uniform and constant in time
- Dynamical pressure anisotropy vanishes $\xi = 0$
- CME current is absent $V_z = 0$

Final state:

- Dynamical pressure anisotropy determined by magnetic field
- CME current has approached equilibrium expression

Compare to:

[Chesler, Yaffe] 2010 "Isotropization" , no magnetic field

[Fuini, Yaffe] 2016 Magnetic field, no chiral charge, no CME

Holography

Numerical Methods:

- Pseudo-spectral methods
- Chebyshev Polynomials
- Chebyshev-Lobatto grid $x_n = \cos(n\pi/N)$
- Keep apparent horizon fixed $\lambda(v)$
- Subtract logs for better convergence
- Time evolution 4th order Runge-Kutta

[Chesler, Yaffe] JHEP 07 (2014) 086

Implementation:

- Mathematica (original code, somewhat slow)
- julia

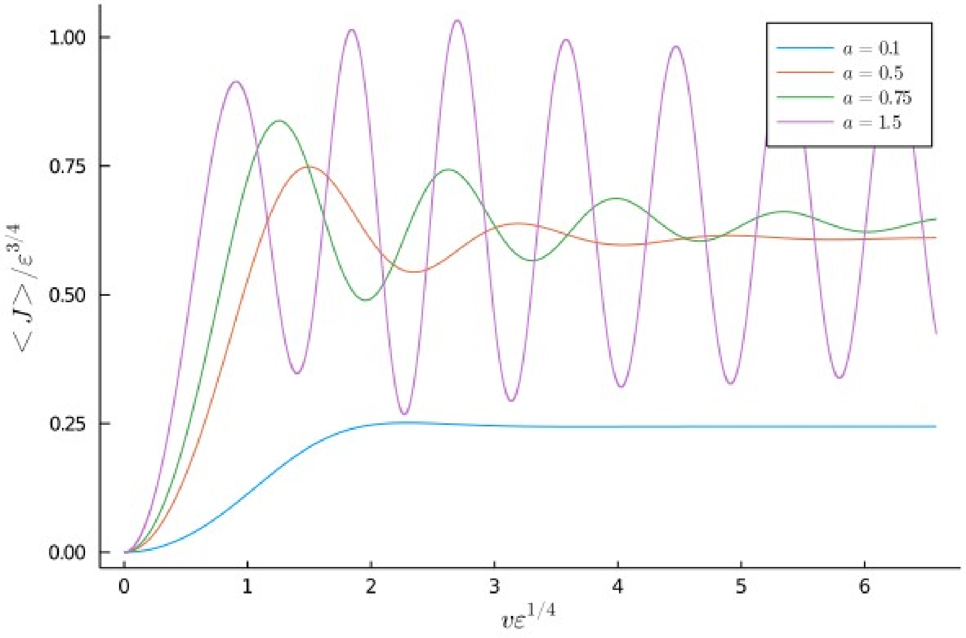
Renormalization scale:

- Numerics $\mu = 1/L$
- Physics $\mu = \sqrt{B}$

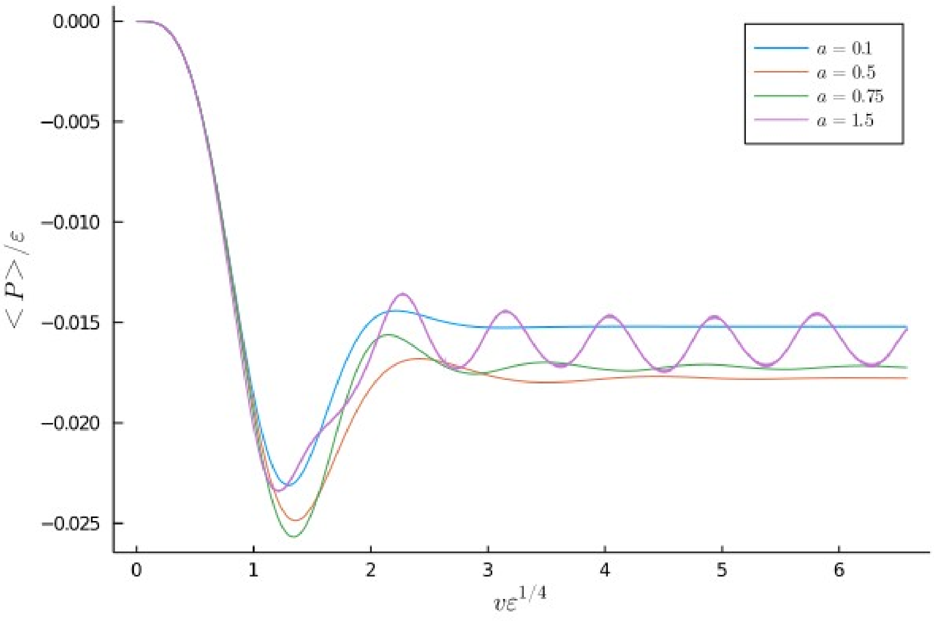
$$\frac{\epsilon_B}{B^2} = \frac{\epsilon_L}{B^2} + \frac{1}{4}\log(BL^2)$$

Holography

Anomaly dependence: $q_5 = 1.5$, $B = 2$



Current



Pressure anisotropy

Holography

Trying to connect to the real world (aka wading knee-deep in the swampland...)

➔ Gravitational coupling: match to entropy

$$s_{BH} = \frac{4\pi^2 T^3}{2\kappa^2} \qquad s_{SB} = 4\left(\nu_b + \frac{7}{4}\nu_f\right)\frac{\pi^2 T^3}{90}$$

$$s_{BH} = \frac{3}{4} s_{SB} \qquad \Longrightarrow \quad \kappa^2 \approx 12.5$$

➔ Chern Simons coupling: match to anomaly

$$\frac{\alpha}{2\kappa^2} = \mathcal{A}_{QCD} = \frac{1}{8\pi^2} \qquad \Longrightarrow \alpha \approx 0.316$$

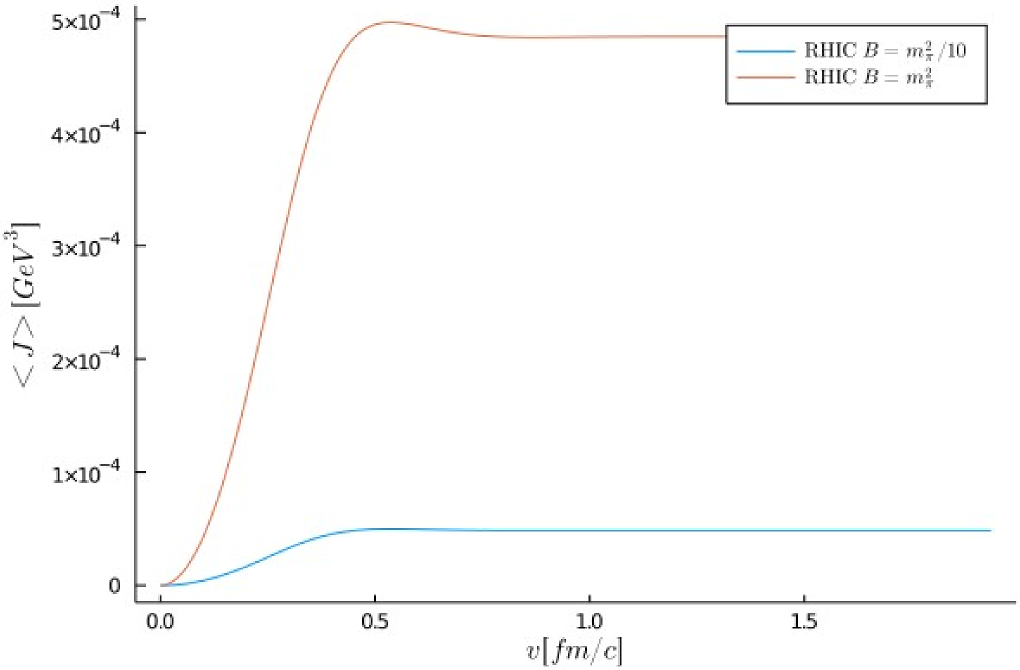
Holography

Physical parameters:

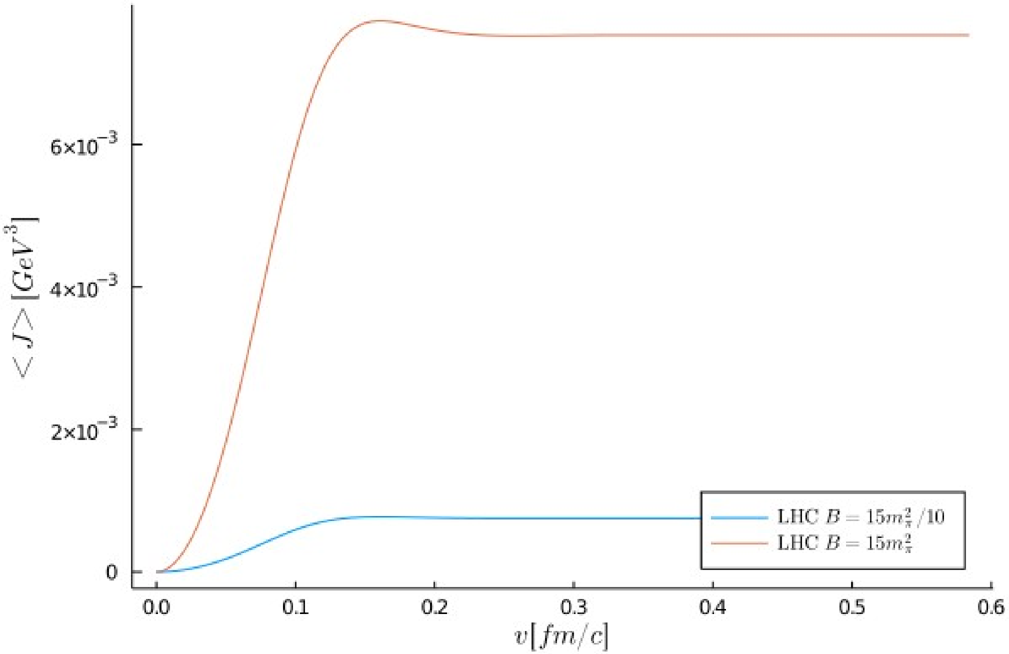
	"RHIC"	"LHC"
T	300MeV	1000MeV
μ_5	10 (100) MeV	10 (100) MeV
B	1 (0.1) m_π^2	15 (1.5) m_π^2

Holography

CME current



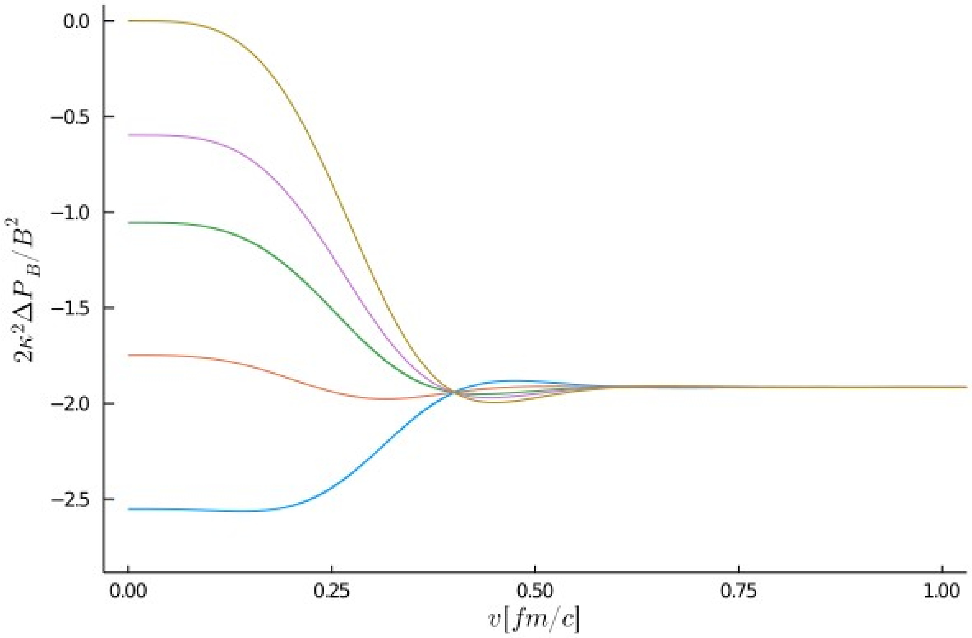
RHIC



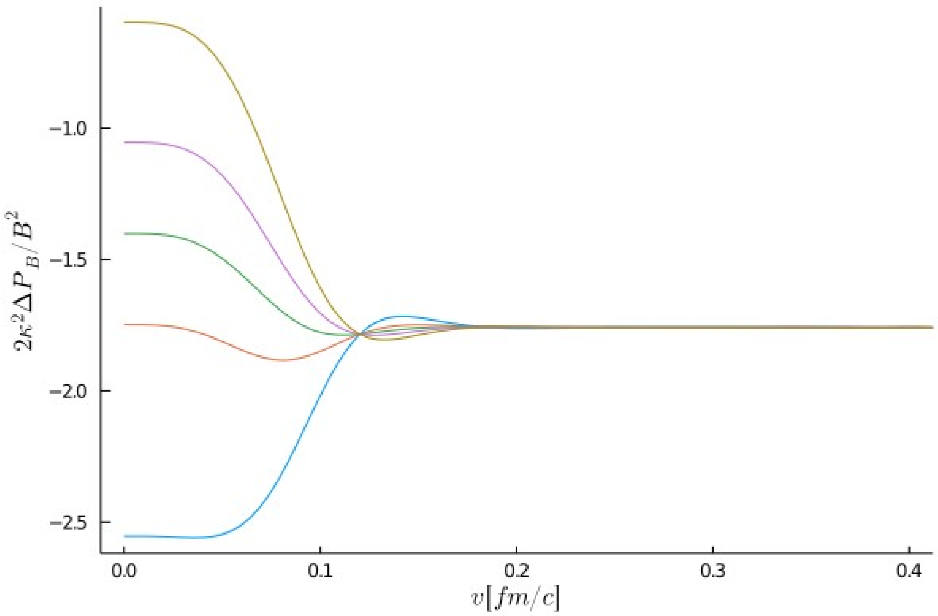
LHC

Holography

Pressure anisotropy (large B)



RHIC



LHC

$$2\kappa^2 \frac{\Delta P_B}{B^2} = 12\,\frac{\xi_4(v)}{B^2} + \frac{1}{2}\,\log(BL^2) - \frac{1}{4}$$

$$4\kappa^2 \frac{\epsilon_B}{B^2} = 6\,\frac{f_2}{B^2} - \frac{1}{2}\log(BL^2)$$

Holography

- No oscillations !
- Equilibration time: within 10% of final value [Chesler, Yaffe]

RHIC $B = m_\pi^2$					
δP_i	-2.55	-1.75	-1.05	-0.60	0.00
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.383	0.418	0.334	0.344	0.350
RHIC $B = 0.1 m_\pi^2$					
δP_i	-3.70	-2.90	-2.55	-2.21	-1.75
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.383	0.418	0.310	0.334	0.344

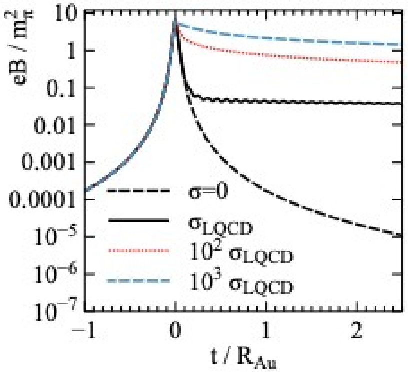
LHC $B = 15\, m_\pi^2$					
δP_i	-2.55	-1.75	-1.40	-1.05	-0.60
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.114	0.187	0.085	0.098	0.103
LHC $B = 1.5\, m_\pi^2$					
δP_i	-3.70	-2.90	-2.55	-2.21	-1.75
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.114	0.187	0.085	0.098	0.103

Compare to
- Without anomaly [Chesler, Yaffe]: τ ~0.5 fm/c
- Experimental estimate [U. Heinz]: τ~0.3 fm/c

Holography

Lifetime of magnetic field

- Highly uncertain
- Rapid decay in vacuum
- Medium effects can prolong lifetime considerably
- Many different estimates in literature



[McLerran, Skokov]] Nucl.Phys.A 929 (2014) 184

Latest available estimate: [Guo, Feng, Liao, Shi] Phys.Lett.B 798 (2019) 134929

$$\tau_B = \frac{117}{\sqrt{s}} GeV\, fm/c$$

$\tau_B^{RHIC} \approx 0.6 fm/c$ $\tau_B^{LHC} \approx 0.02 fm/c$

Holography

BUT:

- Main improvement: expansion
- Main new assumption: $B \propto \frac{1}{\tau}$

Summary and Outlook

- ***Results on isobar collisions are out and confusing!***
- ***Need for much better understanding of theory and data***
- ***Holography allows to address important issues for CME@HIC***
- ***Even simple models give interesting results***
- ***Many model improvements are possible***

  (Dynamical B-field, finite axial lifetime, …)
- ***AdS4CME collaboration*** https://ads4cme.wixsite.com/ads4cme

THANKS!