Energy Dependence of the CME in Heavy Ion Collisions

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In collaboration with:
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Björn Schenke (BNL)

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Chiral Magnetic Effect in Heavy Ion Collisions

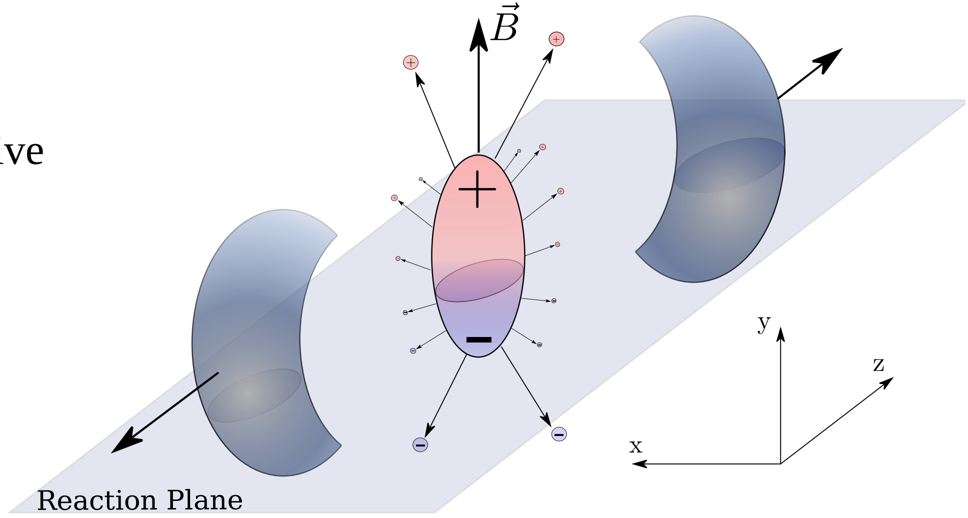
(CME) — the phenomenon of electric charge separation along the external magnetic field induced by the chirality imbalance. [Kharzeev, Prog. Part. Nucl. Phys., 2014]

Incoming nuclei generate enormous magnetic fields

Topological transitions in the QCD vacuum generate chiral imbalances

$$N_L - N_R = 2Q_w N_f \qquad Q_w \text{ -Winding number}$$

The orientation of the magnetic field aligns the spins of positive (negative) quarks parallel (anti-parallel) to $\vec{B}$ and hence generates an electric current



Energy dependence of the CME – Early thoughts

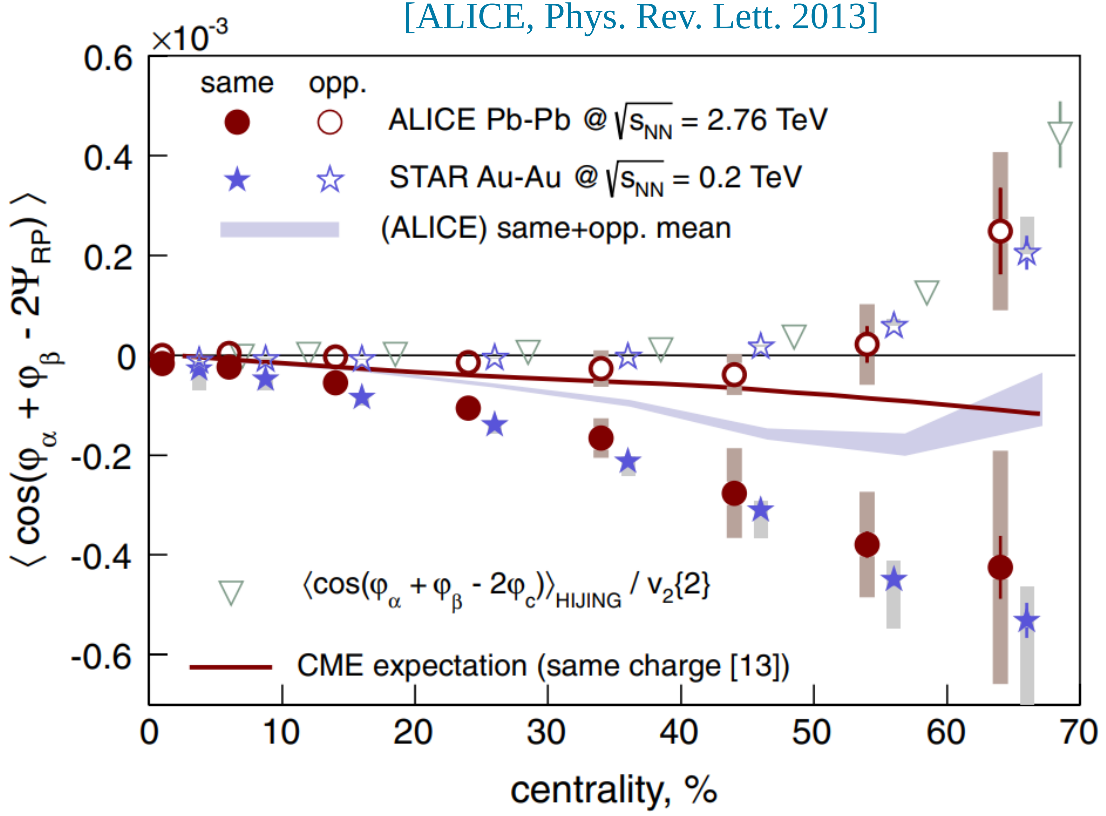
"We are very uncertain about the beam energy dependence, since our result will depend strongly on what we take as our initial time."
[Kharzeev, McLerran, Warringa, Nuc. Phys. A, 2008]

"Using the inverse saturation momentum for initial time, we can get a large dependence … the correlators are smaller at larger beam energies, we never expect them to become larger." [Kharzeev, McLerran, Warringa, Nuc. Phys. A, 2008]

It is speculated that there is no difference in top RHIC energies and LHC energies due to the universality of the fundamental physical process [Zhitnitsky, Nuc. Phys. A, 2011]

Energy dependence of the CME – LHC vs RHIC

[ALICE, Phys. Rev. Lett. 2013]



Surprisingly, for a collision of energy approximately 10 times larger, ALICE reports roughly the same signal

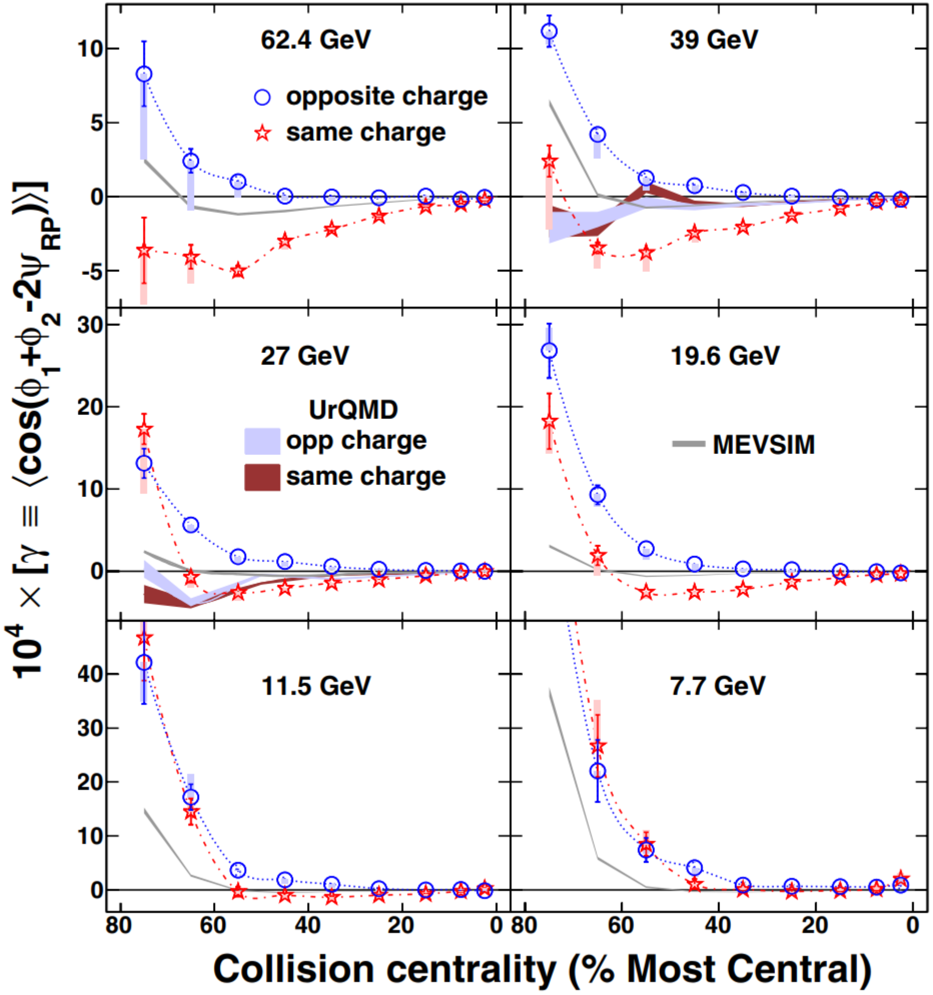
See Panos Christakoglou's talk for more on ALICE results 11/03/2021

Energy dependence of the CME – BES

Weak energy dependence is displayed with an effect decreasing towards lower energy

The signal is nearly gone by 7.7 GeV

“can be understood … if the formation of the quark-gluon plasma becomes less likely in peripheral collisions at low beam energies” [STAR, Phys. Rev. Lett. 2014]



[STAR, Phys. Rev. Lett. 2014]

There is still much to learn about the energy dependence of the CME in heavy ion collisions

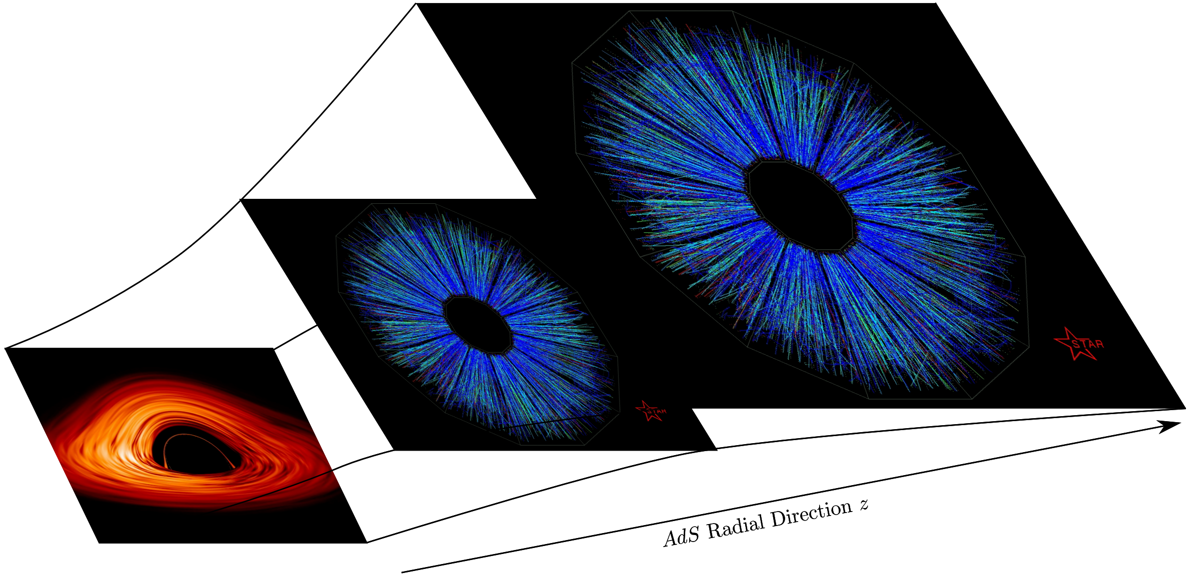
Can an increase in signal be achieved by lower energy collisions where the magnetic field lives longer?

BES-II (2019-2020): should we expect a pleasant surprise in the data for the CME?

[STAR, White paper, 2014]

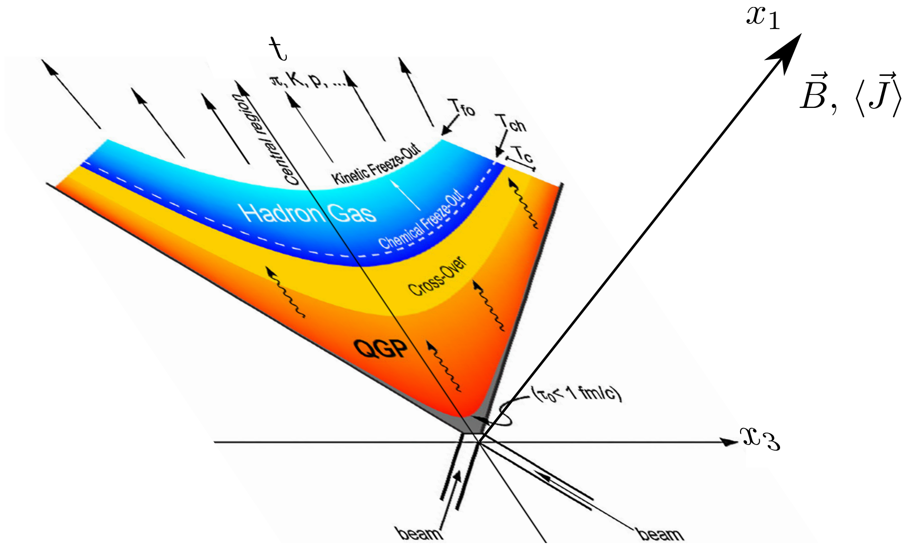
Goal

Use holography to create fully time dependent model of the energy dependence of the CME in SYM plasma



STAR Experiment: https://www.star.bnl.gov/public/tpc/photos/GeneralMisc/event.png
After decades of effort, scientists are finally seeing black holes- or are they? (2021). [Data set]. In AAAS Articles DO Group. American Association for the Advancement of Science (AAAS). https://doi.org/10.1126/science.abg4140

Desired Dual Description



[Braun-Munzinger, Dönigus, Nuc. Phys. A,2019]

[Cartwright, Kaminski, Schenke, to appear-2021]

–Boost invariant expanding SYM plasma

Note: Asymptotic to Bjorken flow

–Time dependent axial charge density $n_5(\tau)$

–Static magnetic field perpendicular to expansion

–Begins with non-zero dynamical anisotropy

Added benefit:

Includes initial far from equilibrium evolution

Holographic Model

See Karl Landsteiner's talk for more on this model 11/03/2021

See Matthias Kaminski's talk for more on holography and CME physics 11/04/2021

Einstein gravity coupled to $U(1)_V \times U(1)_A$ [Gosh, Grieninger, Landsteiner, Morales-Tejera, Phys. Rev. D, 2021]

$$S = \frac{1}{16\pi G_N} \int \mathrm{d}^5x\sqrt{-g}\left(R - 2\Lambda - \frac{L^2}{4}F_{\mu\nu}F^{\mu\nu} - \frac{L^2}{4}F^{(5)}_{\mu\nu}F^{\mu\nu}_{(5)} + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}A_\mu\left(3F_{\nu\rho}F_{\sigma\tau} + F^{(5)}_{\nu\rho}F^{(5)}_{\sigma\tau}\right)\right) + S_{ct}$$

The AdS/CFT Dictionary:

Metric ansatz	⟷	Dual Energy Momentum tensor
Axial gauge field ansatz	⟷	Dual axial current
Vector gauge field ansatz	⟷	Dual vector current

Metric ansatz

$$\begin{aligned}\mathrm{d}s^2 &= 2\mathrm{d}v(\mathrm{d}r - \frac{1}{2}A(v,r)\mathrm{d}v)\\ &+ S(v,r)^2 e^{H_1(v,r)}\mathrm{d}x_1^2\\ &+ S(v,r)^2 e^{H_2(v,r)}\mathrm{d}x_2^2\\ &+ S(v,r)^2 e^{-H_1(v,r)-H_2(v,r)}\mathrm{d}\xi^2\end{aligned}$$

ξ - Spacetime rapidity

Dual Energy Momentum tensor

$$\langle T^i_j\rangle \sim \mathrm{diag}(\epsilon(\tau), P_1(\tau), P_2(\tau), P_3(\tau))$$

$$\eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, \tau^2)$$

Axial gauge field ansatz

$$A_\mu = (-\phi(v,r), 0, 0, 0, 0)$$

Dual axial current

$$\langle J^i_{(5)}\rangle \sim (n_5(\tau), 0, 0, 0)$$

Vector gauge field ansatz

$$V_\mu = (0, -V_x(v,r), \frac{\xi}{2}B, -\frac{x_2}{2}B, 0)$$

Dual vector current

$$\langle J^i\rangle \sim (0, \tilde{V}_x(\tau), 0, 0)$$

Initial Data and Solutions

Field theory:

Initial time: τ_0

Initial axial charge density: $n_5(\tau_0)$

Initial vector current density: $\langle J^1 \rangle (\tau_0) = 0$

Initial energy density: $\epsilon(\tau_0)$

Parameters:

Anomaly coefficient: $\alpha = \alpha_{SUSY} = 1/\sqrt{3}$

Magnetic field: B

Evolution:

Evolve according to characteristic formulation
[Chesler, Yaffe, JHEP, 2014]
Written in Mathematica

Numerical scheme:
-Chebsyhev decomposition of radial dependence

-Combination of RK4 & 4th order Adams-Bashforth routine for stepping forward in time

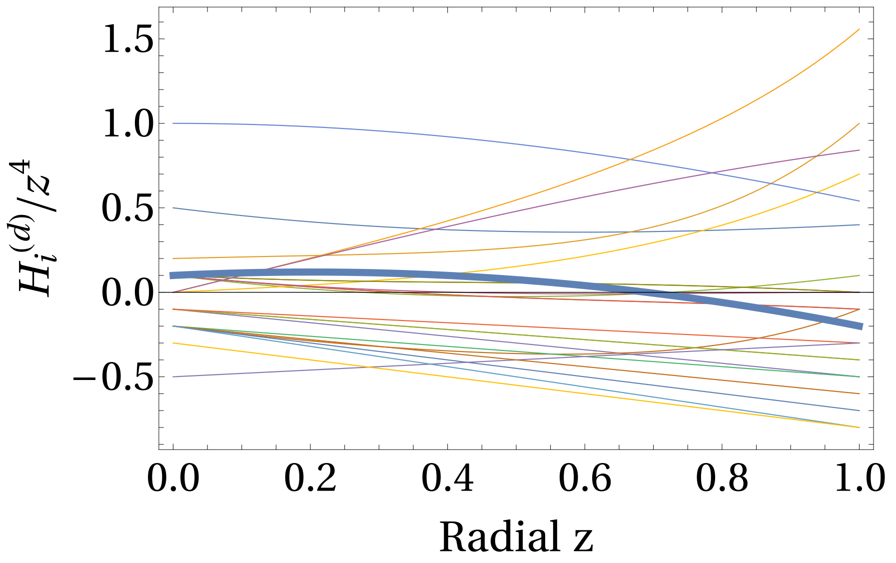
AdS bulk:

Spacetime ansiotropy: $H_1(v_0, r),\ H_2(v_0, r)$

Deviation from AdS $H_i = H_i^{(d)} - \frac{2}{3}\log(v+z)$

$$H_i^{(d)}(z)/z^4 = \Omega_1 \cos(\gamma_1 z) + \Omega_2 \tan(\gamma_2 z) + \Omega_3 \sin(\gamma_3 z) + \sum_{j=0}^{4} \beta_j z^j$$

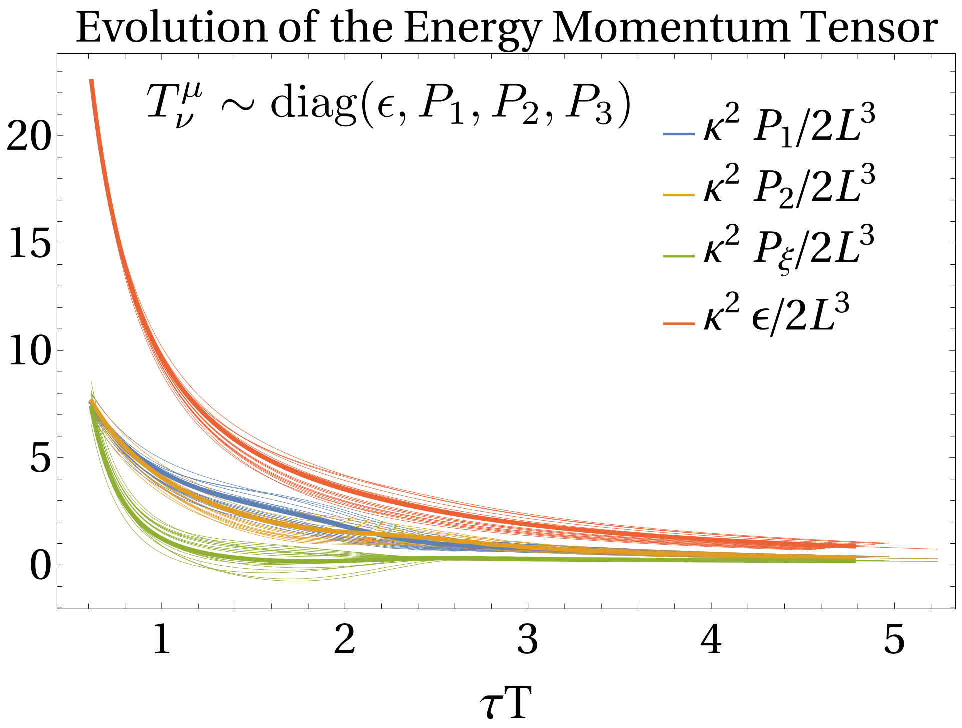
[Rougemont et. al., arXiv:2105.02378]

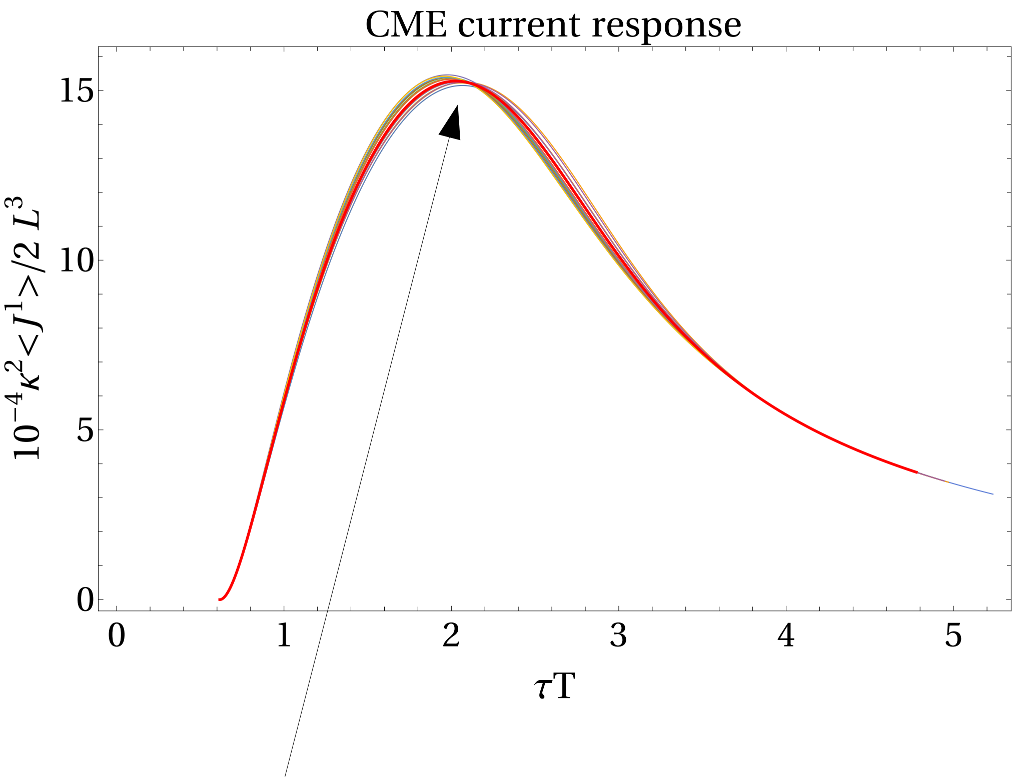


Note: Highlighted curve will serve as a representative curve in coming slides

Evolution of Energy Momentum and Vector Current

22 initial conditions are displayed at fixed $\epsilon(\tau_0),\ n_5(\tau_0),\ B$





CME response is roughly independent of choices of spacetime anisotropy

CME signal dependence on the energy – I

Match parameters to QCD:

–Set $L = 1\mathrm{fm}$

–Fixes κ

$$T(\tau) = \Lambda^{8/3}\left(\frac{1}{\tau}\right)^{4/3} - \frac{2\Lambda^2}{(3\pi)\tau^2} + O\left(\tau^{-7/3}\right)$$

–Extract Λ from late time data

–Use scaling symmetry to set overall scale

Program:

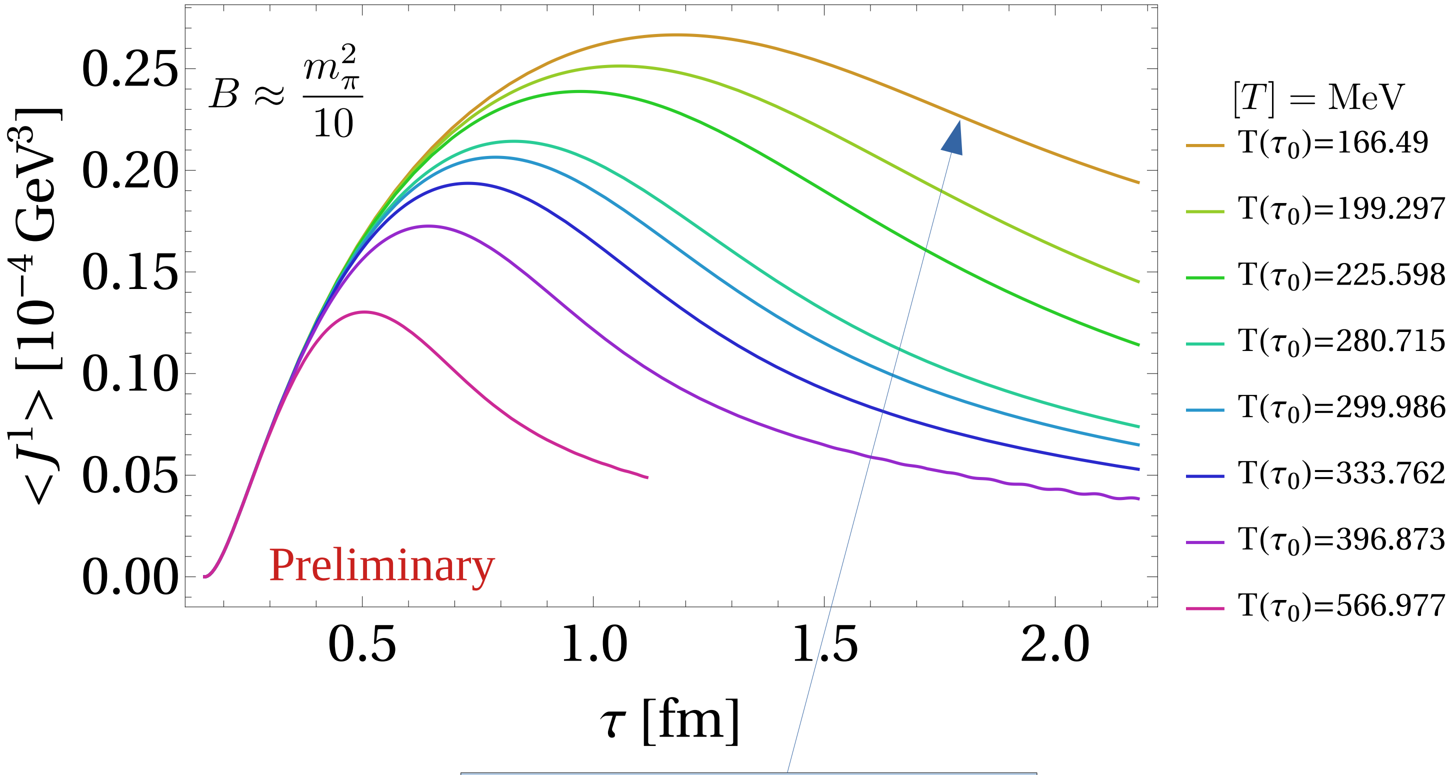
–Fix spacetime anisotropy function to characteristic form

–Scan over different initial energy densities

–Hold fixed at the initial time $n_5(\tau_0)$

–Estimate for Ru+Ru/Zr+Zr at $200\mathrm{GeV}$

$$n_5(\tau_0) = 0.0014\mathrm{GeV}^3$$



CME signal is enhanced for decreasing initial energy

CME signal dependence on the energy – II

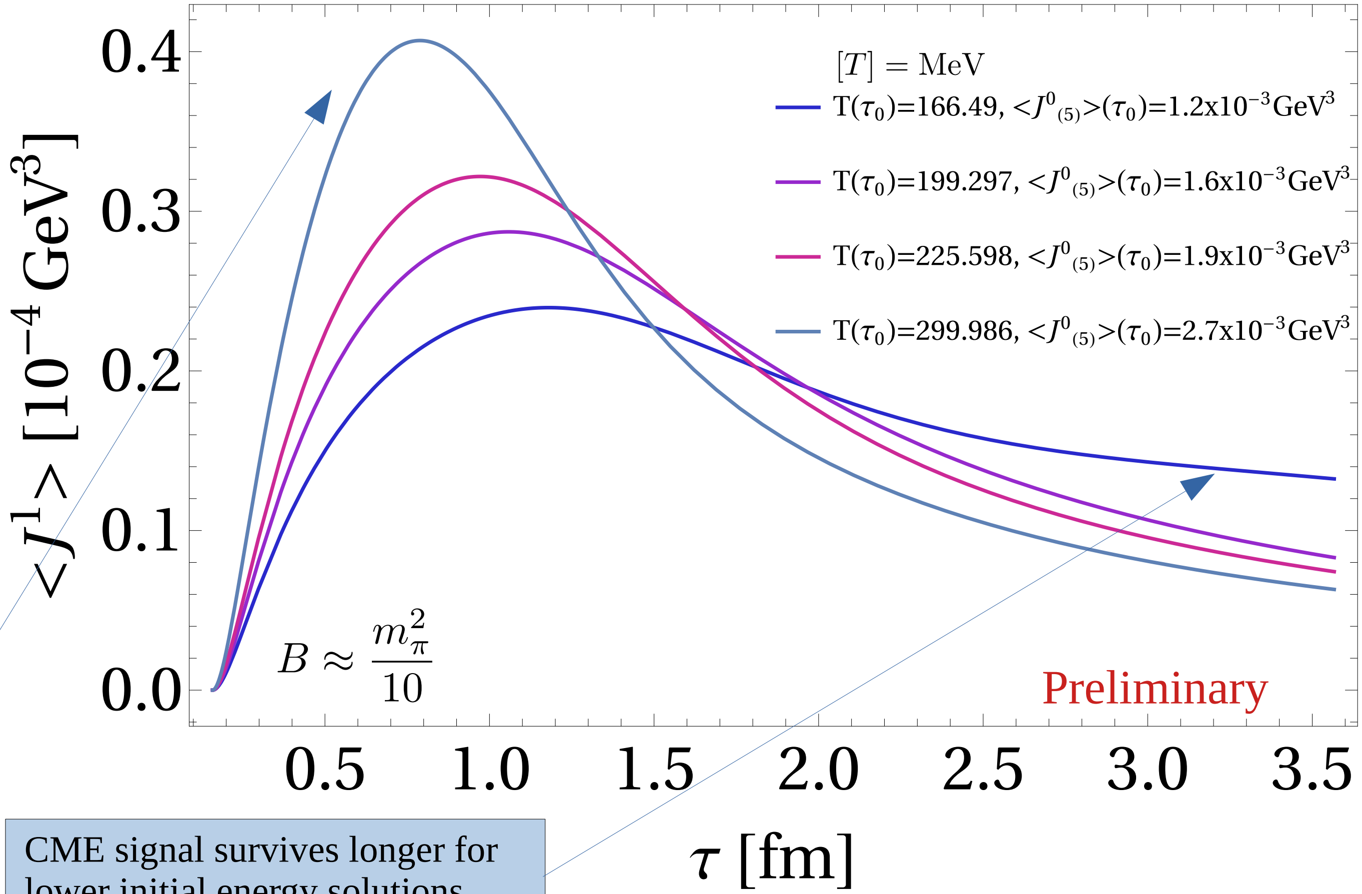
Axial charge density depends on energy of the collision [Sun, Ko,Phys. Rev. C, 2018]

$$\sqrt{N_5} \approx \frac{2\tau_0 \pi \rho_{\rm tube} Q_s^4 \sqrt{N_{\rm coll}}}{16\pi^2}$$

Program:

–Fix spacetime anisotropy function to characteristic form

–Scan over different initial energy densities with corresponding axial charge densities



Higher initial energy solutions quickly reach peak value

CME signal survives longer for lower initial energy solutions

Discussion and Conclusions

Will appear on the arXiv very soon

-There is still much to learn about chiral magnetic physics

-We use holography to generate a time dependent model of the CME which includes:

–Longitudinal expansion

–Initial far from equilibrium evolution

–Asymptotic to Bjorken flow

–Static magnetic field

–Time dependent axial charge density $n_5(\tau)$

Varying $\epsilon(\tau_0)$	CME response is enhanced for decreasing initial energy density
Varying $\epsilon(\tau_0),\, n_5(\tau_0, \epsilon(\tau_0))$	Late time CME response is enhanced for decreasing initial energy density
Varying $\epsilon(\tau_0),\, n_5(\tau_0, \epsilon(\tau_0))\,, B(\epsilon(\tau_0))$	CME response is enhanced for increasing initial energy density

-Much to improve upon:

–Time dependent magnetic field

–Radial/directed flow in the transverse plane, higher harmonics

–Non homogeneous axial charge density

Thank you! Any Questions?

Appendix: CME signal dependence on the energy – III

Pushing to the extreme

Magnetic field strength also depends on the collision energy as well as on the particular nuclei [Sun, Ko,Phys. Rev. C, 2018]

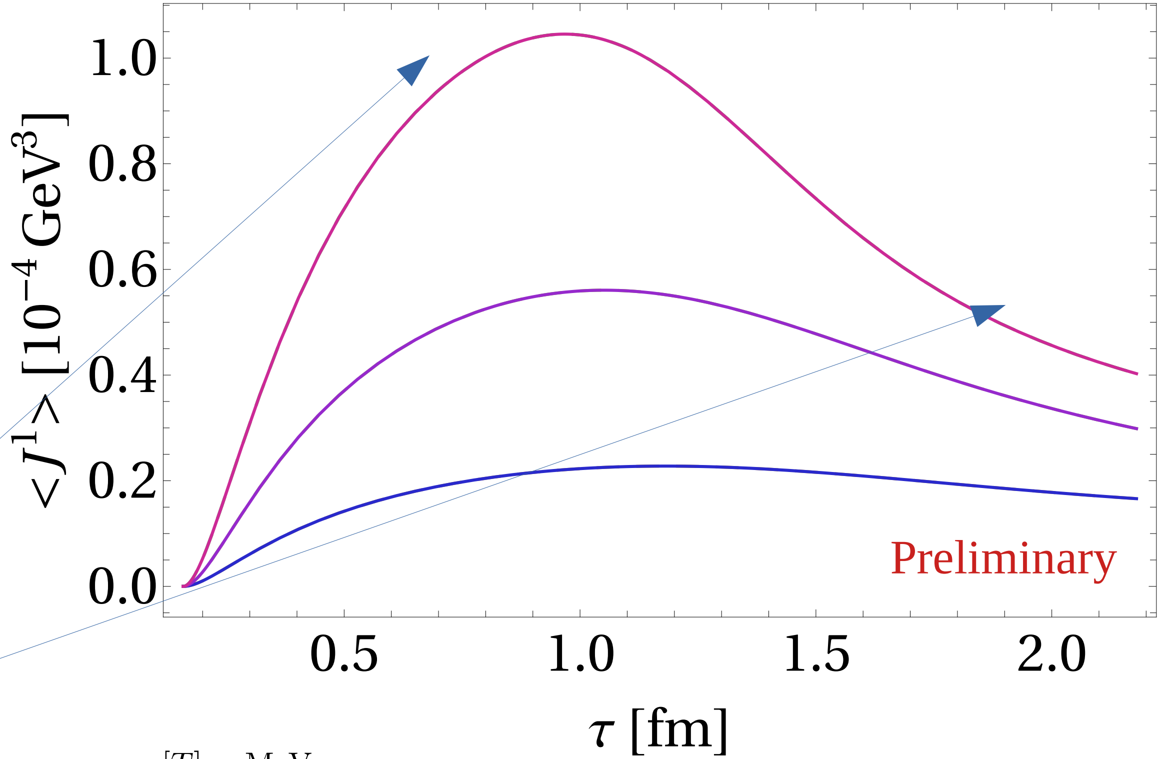
$$\frac{eB_{RHIC}}{eB_{LHC}} = \frac{1}{2}\frac{\gamma_{LHC}}{\gamma_{RHIC}}\left(\frac{Q_s^{RHIC}}{Q_s^{LHC}}\right)^2$$

Program:

–Fix spacetime anisotropy function to characteristic form

–Scan over different initial energy densities with corresponding axial charge densities along with matching peak magnetic field strength

CME signal is enhanced for increasing initial energy



$[T] = \mathrm{MeV}$

- $T(\tau_0)$=166.49, $<J^0{}_{(5)}>(\tau_0)$=1.2x10^{-3}GeV^3, B=0.095mπ^2 $t_B = 6.05\mathrm{fm}$
- $T(\tau_0)$=199.297, $<J^0{}_{(5)}>(\tau_0)$=1.6x10^{-3}GeV^3, B=0.195mπ^2 $t_B = 2.94\mathrm{fm}$
- $T(\tau_0)$=225.598, $<J^0{}_{(5)}>(\tau_0)$=1.9x10^{-3}GeV^3, B=0.32mπ^2 $t_B = 1.79\mathrm{fm}$

Note: Naive estimate of characteristic time scale of the magnetic field [Guo et. al. Phys. Lett. B 2019]

$$t_B \sim \frac{115\mathrm{GeVfm}}{\sqrt{s}}$$