Medium feedback effect on azimuthally fluctuating electromagnetic fields and observables in isobar collisions

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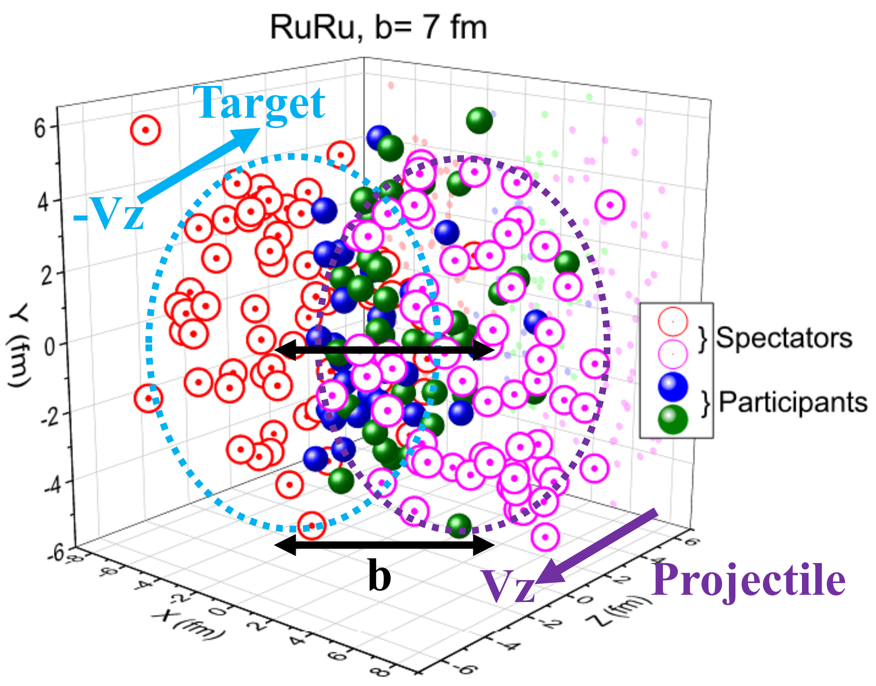
Outline

- Introduction & Motivation
- EM fields with and without medium feedback
- Numerical Results
- Summary

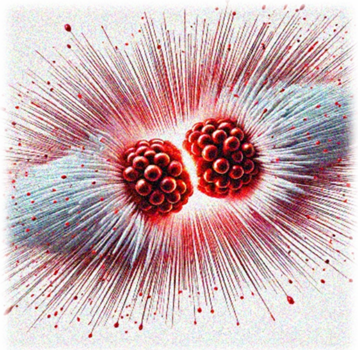
SIDDIQUE IRFAN, DOI: 10.1103/PhysRevC.109.034905 (2024)

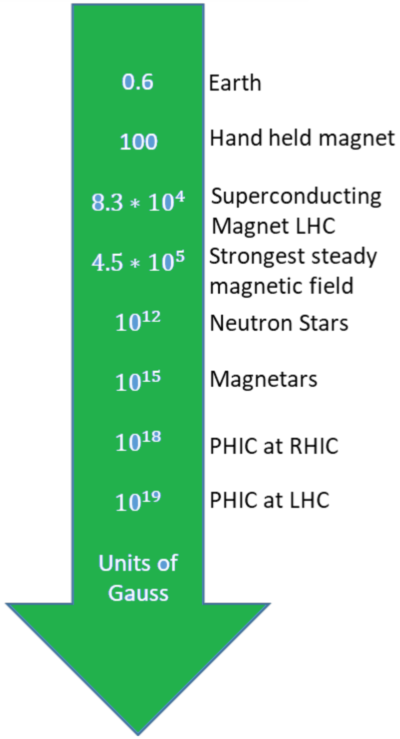
Magnetic field in HICs



x-axis impact parameter
z-axis beam direction

B Fields perpendicular to reaction plane

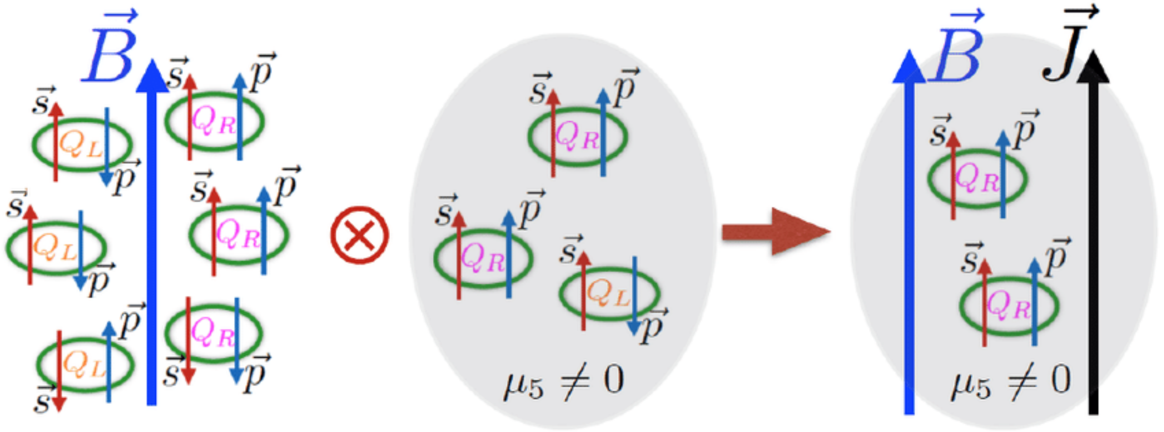




Extremely Strong magnetic fields

Chiral Magnetic Effect

- Strong magnetic field
- Non-zero chiral chemical potential
- Left handed quarks not equal to right handed quarks

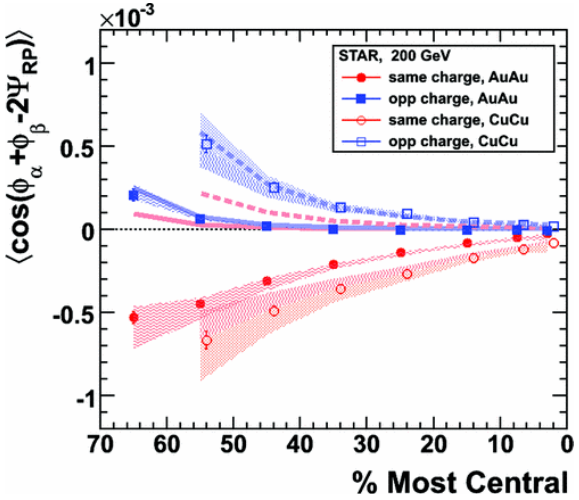


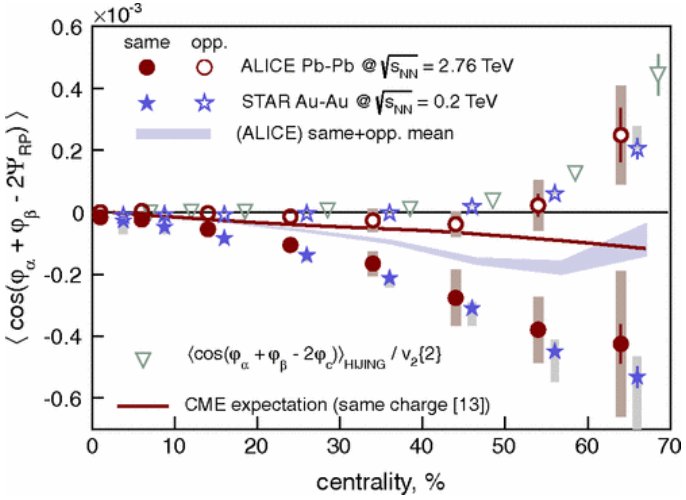
$$J_{CME} = \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}$$

- Influencing the dynamics of QGP
- CME etc
- Time evolution and spatial distribution etc.

- W.-T. Deng and X.-G. Huang, Phys. Rev. C 85, 044907 (2012), 1201.5108.
- J. Bloczynski, X.-G. Huang, X. Zhang, and J. Liao, Phys. Lett. B 718, 1529 (2013), 1209.6594.
- K. Hattori and X.-G. Huang, Nucl. Sci. Tech. 28, 26 (2017), 1609.00747.
- K. Tuchin, Phys. Rev. C 88, 024911 (2013), 1305.5806.

Experimental searches for CME





In early STAR and ALICE experiments, the charge separation effect was measured by measuring two particle azimuthal angle correlation. Results support CME but Highly contaminated signals

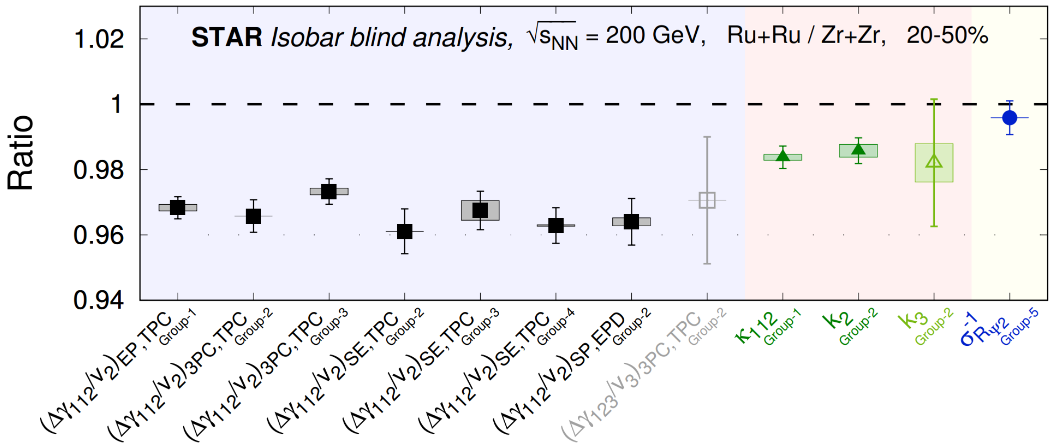
Extremely difficult to extract signal from background

- **Isobar collisions (Possible solution?)**

Pair invariant mass for Isolating the CMW from backgrounds: J. Zhao, H. Li, and F. Wang, Eur. Phys. J. C 79, 168 (2019).
and M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 106, 034908
Varying the chiral magnetic effect relative to flow in a single nucleus-nucleus collision: H.-J. Xu et al., Chin. Phys. C 42, 084103 (2018)
Introducing the initial charge separation proportional to magnetic field in a multiphase transport (AMPT) model and studying the effect of final state interactions on CME observables: W. T. Deng, X. G. Huang, G. L. Ma, and G. Wang, Phys. Rev. C 97, 044901 (2018).
Detecting CME signal, and predicting the correlation observables by using absolute difference between two isobars event with identical multiplicity and elliptic flow in anomalous-viscous fluid dynamics (AVFD) framework: S. Shi, H. Zhang, D. Hou, and J. Liao, Nucl. Phys. A 982, 539 (2019).
Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy ion collisions 10.1103/PhysRevC.81.054908
Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s}$=2.76 TeV 10.1103/PhysRevLett.110.012301

Isobar collisions $(Ru^{96}_{44} + Ru^{96}_{44}$ & $Zr^{96}_{40} + Zr^{96}_{40})$

The difference in number of protons can generate different magnitudes of electromagnetic fields and related induced effects, but the same mass number in two isobar systems are expected to generate the same background effect.



CME Signal ☹
Different background ☺

Significant differences in the multiplicity and flow harmonics are observed between the two systems in a given centrality, indicating that the magnitude of the CME background is different between the two species.

- ❖ Search for the chiral magnetic effect with isobar collisions at $\sqrt{s}$=200 GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider 10.1103/PhysRevC.105.014901
- ❖ CME search at STAR: 10.1051/epjconf/202225913013

Electromagnetic Fields in HICs

- **Without medium feedback:**
  - Use of Event generator/ transport model
  - Use Lienard-Wiechert potential

$$\boldsymbol{E} = \frac{e}{4\pi}\sum_n \frac{(1-v_n^2)\boldsymbol{R}_n}{(\boldsymbol{R}_n^2 - (\boldsymbol{R}_n \times \boldsymbol{v}_n)^2)^{3/2}}$$

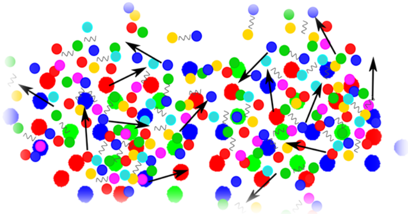
$$\boldsymbol{B} = \frac{e}{4\pi}\sum_n \frac{(1-v_n^2)(\boldsymbol{v}_n \times \boldsymbol{R}_n)}{(\boldsymbol{R}_n^2 - (\boldsymbol{R}_n \times \boldsymbol{v}_n)^2)^{3/2}}$$

Here $\boldsymbol{R}_n = \boldsymbol{x} - \boldsymbol{x}_n$ is the relative position vector between the field point $\boldsymbol{x}$ and the source point $\boldsymbol{x}_n$

  - Over estimate or underestimate

- W.-T. Deng and X.-G. Huang, Phys. Rev. C 85, 044907 (2012), 1201.5108.
- J. Bloczynski, X.-G. Huang, X. Zhang, and J. Liao, Phys. Lett. B 718, 1529 (2013), 1209.6594.
- K. Hattori and X.-G. Huang, Nucl. Sci. Tech. 28, 26 (2017), 1609.00747.

- **With medium feedback (σ & σ_χ):**



QGP

$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$
$$\boldsymbol{\nabla} \cdot \boldsymbol{E} = \rho/\epsilon$$
$$\boldsymbol{\nabla} \times \boldsymbol{E} = -\partial_t \boldsymbol{B}$$
$$\boldsymbol{\nabla} \times \boldsymbol{B} = \partial_t \boldsymbol{E} + \boldsymbol{j}_{ext} + \sigma \boldsymbol{E} + \sigma_\chi \boldsymbol{B}$$

Maxwell Eqs.

Finite σ **&** σ_χ electric and chiral magnetic conductivities

- K. Tuchin, Phys. Rev. C 88, 024911 (2013), 1305.5806.
- LI H, LI SHENG X, WANG Q. DOI:10.1103/physrevc.94.044903

Numerical Setup

Isobar Nuclei $(Ru^{96}_{44} + Ru^{96}_{44}$ & $Zr^{96}_{40} + Zr^{96}_{40})$

Woods-Saxon distribution for Ru and Zr

$$\rho = \frac{\rho_0}{1 + exp\left[\frac{r - R(1 + \beta_2 Y_{20} + \beta_4 Y_{40})}{a}\right]}$$

β_i deformation parameter

$Y_i(\theta)$ spherical harmonic functions

a surface thickness parameter

$\sigma = 5.8$ MeV

$\sigma_\chi = 1.5$ MeV

Deformed Nuclei Case			
	R_0	a	β_2
Ru	5.085	0.46	0.158
Zr	5.020	0.46	0.08
Halotype Nuclei Case			
Ru, n	5.085	0.523	0
Ru, p	5.085	0.523	0
Zr, n	5.021	0.592	0
Zr, p	5.021	0.523	0

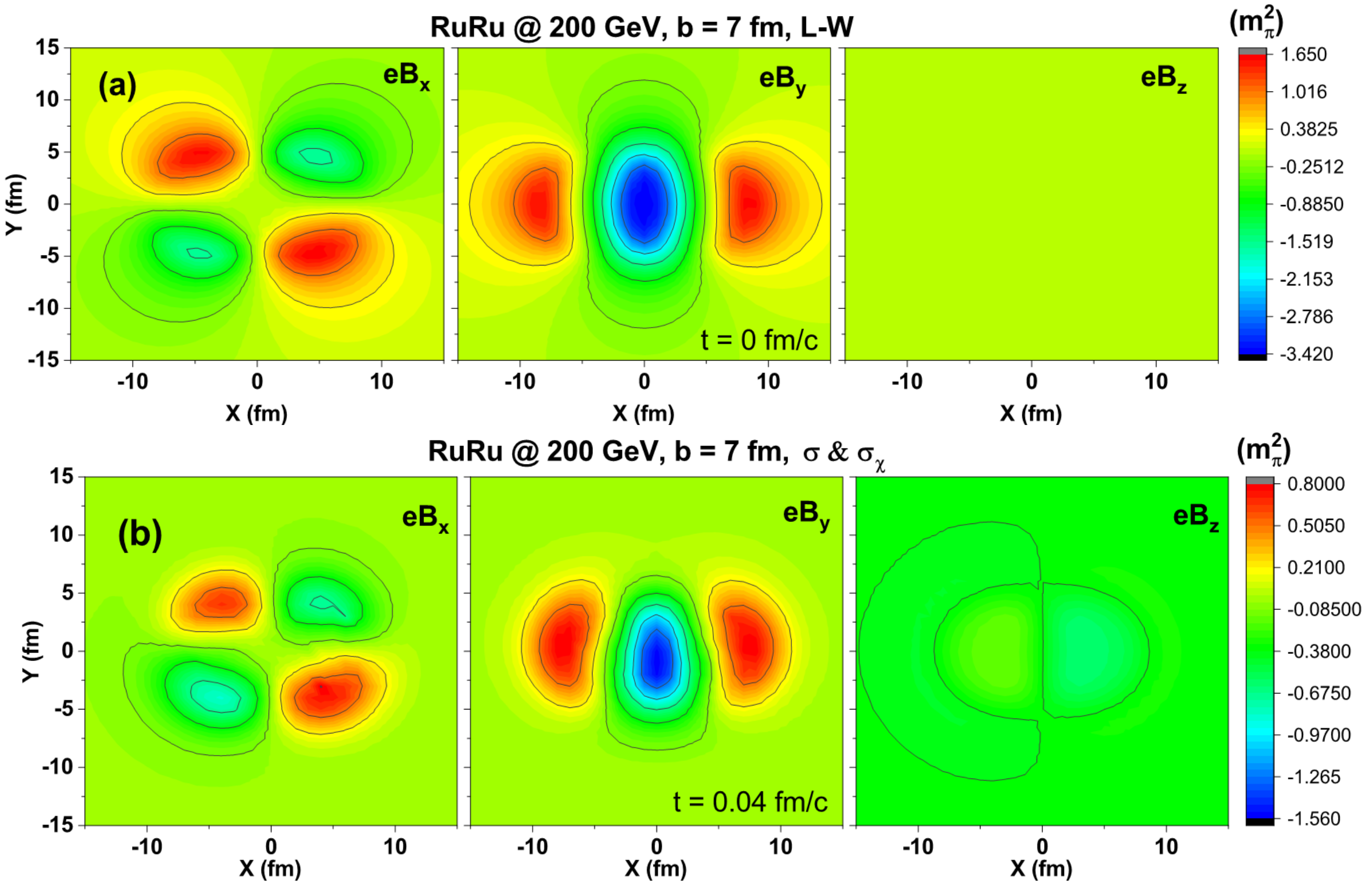
Woods-Saxon parameters for Ru and Zr

MCGlauber model

- B. Pritychenko, M. Birch, B. Singh, and M. Horoi, arXiv:1312.5975.
- Q. Y. Shou *et al.*, arXiv:1409.8375.
- H.-j. Xu, H. Li, X. Wang, C. Shen, and F. Wang, arXiv:2103.05595.
- X.-L. Zhao and G.-L. Ma, arXiv:2203.15214

EM Fields in HICs

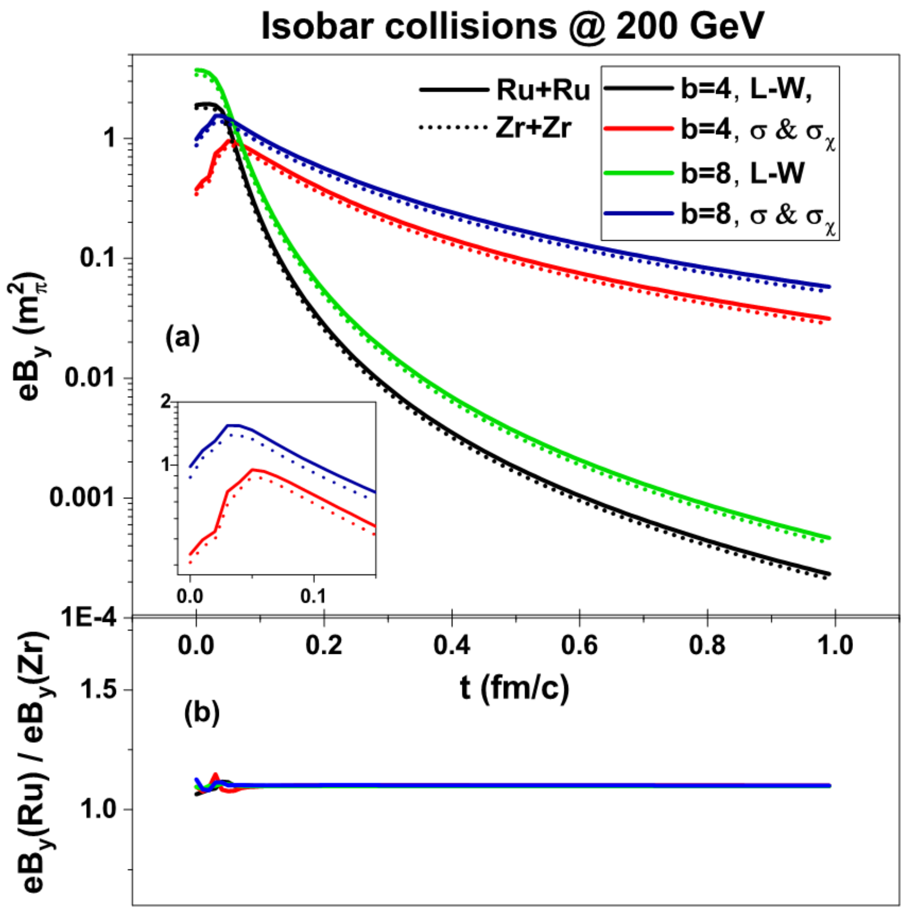
Spatial Distribution



- Inhomogeneous
- L-W symmetrical
- With σ & σ_χ partially symmetric

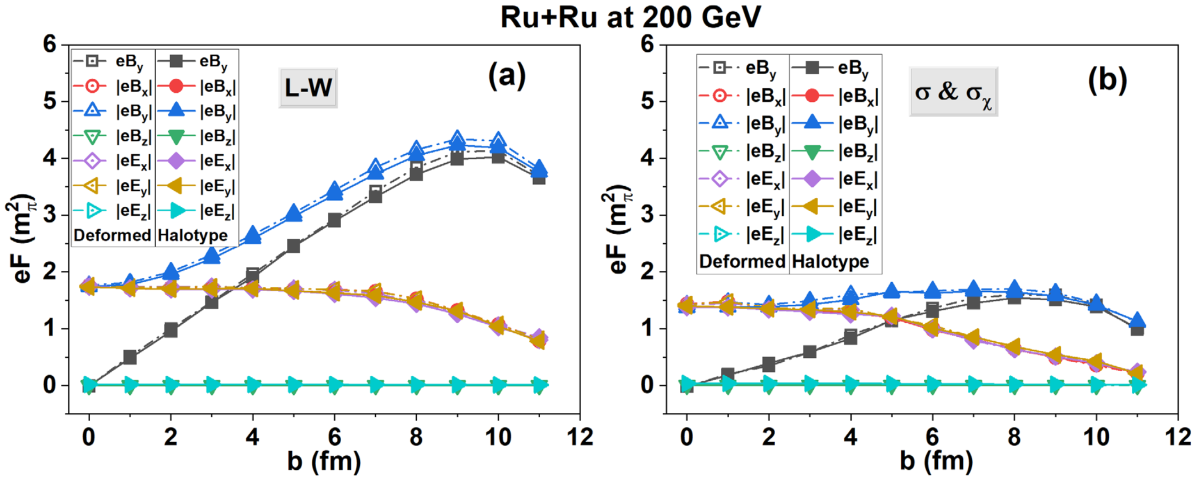
- Asymmetry due to non vanishing radial component in the presence of σ_χ.

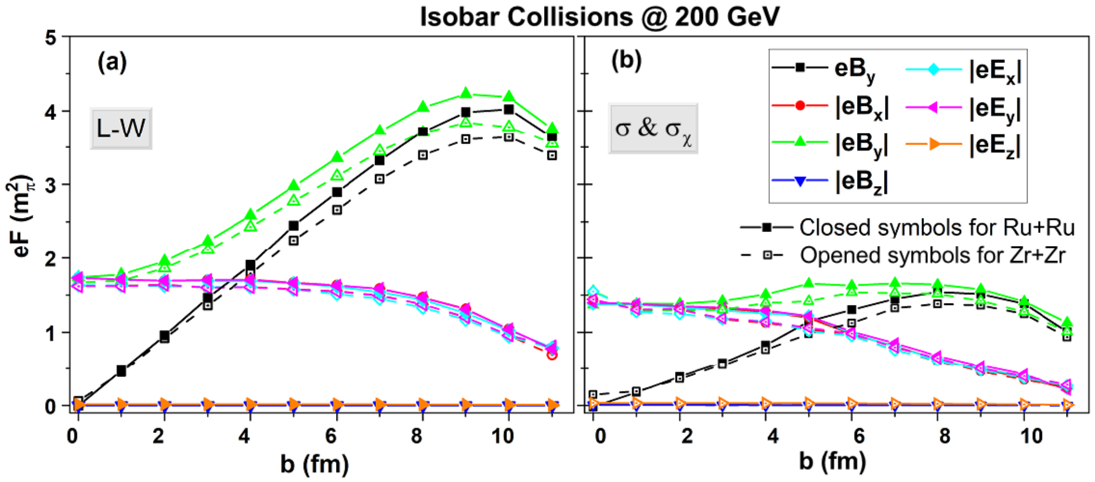
Time-Evolution



- Without medium feedback decays very fast.
- With medium feedback decays much slower.
- Ratio ~ 10%

Impact parameter dependence





Nuclear profile comparison

Ru vs Zr

Compared at $t = t_Q$ (peak value time)

$$e\mathbf{F}_{Au} > e\mathbf{F}_{Ru} > e\mathbf{F}_{Zr}$$

$$|eB_x| \approx |eE_x| \approx |eE_y|$$

$$eF_z \ll eF_{x,y} \sim 0$$

- A. Bzdak and V. Skokov, Phys. Lett. B **710**, 171 (2012).
- W.-T. Deng and X.-G. Huang, Phys. Rev. C **85**, 044907 (2012).
- V. Voronyuk, et. al., Phys. Rev. C **83**, 054911 (2011).
- V. Skokov, A. Y. Illarionov, and V. Toneev, Int. J. Mod. Phys. A **24**, 5925 (2009)
- J. Bloczynski, X.-G. Huang, X. Zhang, and J. Liao, Phys. Lett. B **718**, 1529 (2013)
- K. Hattori and X. G. Huang, Nucl. Sci. Tech. **28**, 26 (2017).
- V. Roy, S. Pu, L. Rezzolla, and D. Rischke, Phys. Lett. B **750**, 45 (2015).
- S. Pu, V. Roy, L. Rezzolla, and D. H. Rischke, Phys. Rev. D **93**, 074022 (2016).
- L. Yan and X. G. Huang, Phys. Rev. D **107**, 094028 (2023).

Effects on correlation

According to the expectations from CME, the difference between the correlation of opposite charge pairs and same charge pairs is expected to be directly proportional to the strength of the squared magnetic field and $\cos 2(\Psi_B - \Psi_2)$,

$$\Delta\gamma = \gamma_{opposite} - \gamma_{same} \propto (\mathrm{eB})^2 \cos 2(\Psi_B - \Psi_2)$$

Quantitative contribution to B-induced effect

Where Ψ_B represents the azimuthal angle of the magnetic field and Ψ_2 represents the second harmonic participant plane

$$\Psi_n = \frac{\mathrm{atan2}(\langle r_p^2 \sin(n\phi_p)\rangle, \langle r_p^2 \cos(n\phi_p)\rangle + \pi)}{n}$$

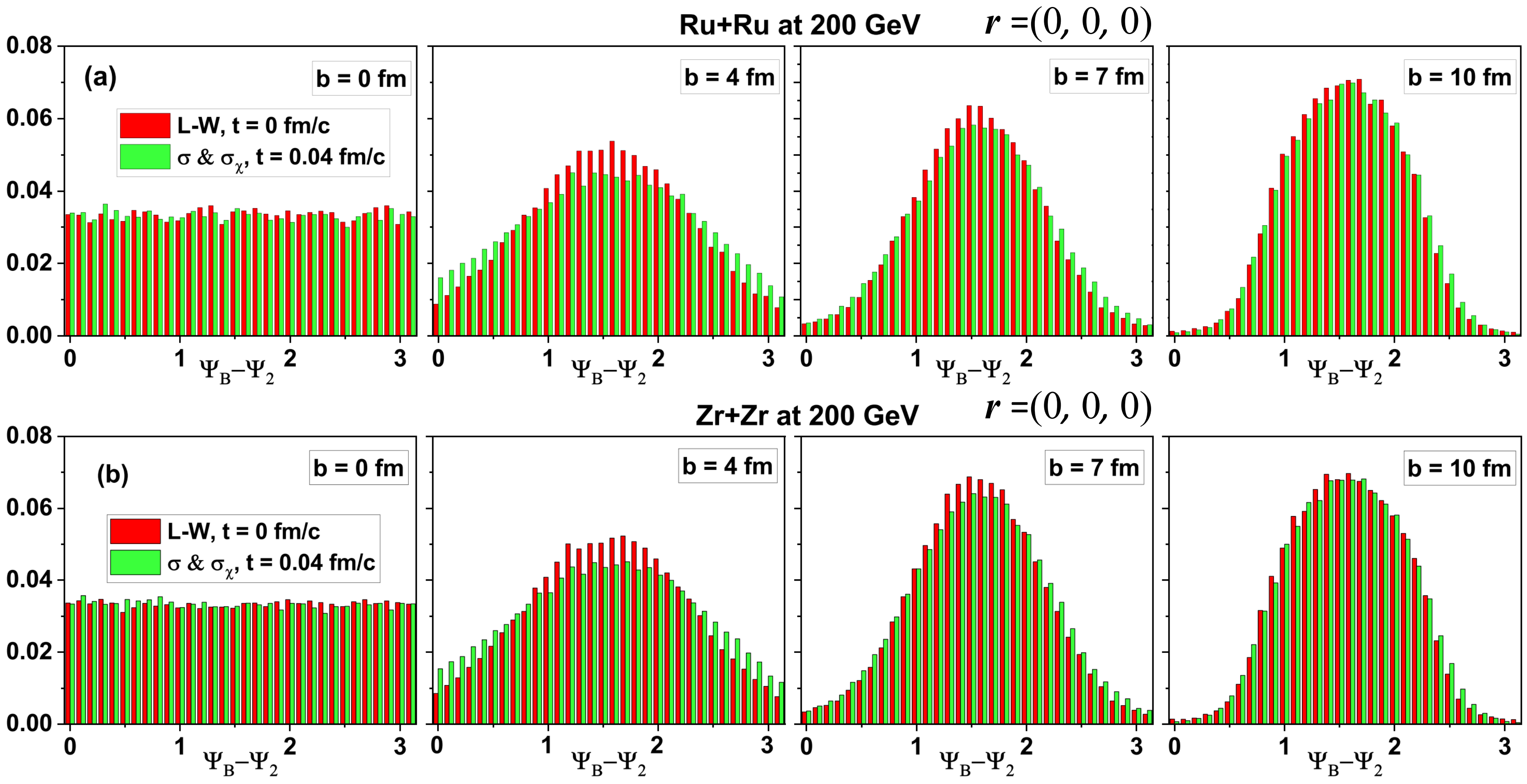
$$X_c = 2\frac{c^{Ru} - c^{Zr}}{c^{Ru} + c^{Zr}}$$, Relative Ratios

For similarity or dissimilarity

- J. Bloczynski, X.-G. Huang, X. Zhang, and J. Liao, Phys. Lett. B **718**, 1529 (2013), arXiv:1209.6594.
- J. Bloczynski, X.-G. Huang, X. Zhang, and J. Liao, Nucl. Phys. A **939**, 85 (2015), arXiv:1311.5451.
- S. Chatterjee and P. Tribedy, Phys. Rev. C **92**, 011902 (2015), arXiv:1412.5103.
- X.-L. Zhao, G.-L. Ma, and Y.-G. Ma, Phys. Rev. C **99**, 034903 (2019), arXiv:1901.04151.

Correlations between magnetic field and participant plane

Histogram $\Psi_B - \Psi_2$



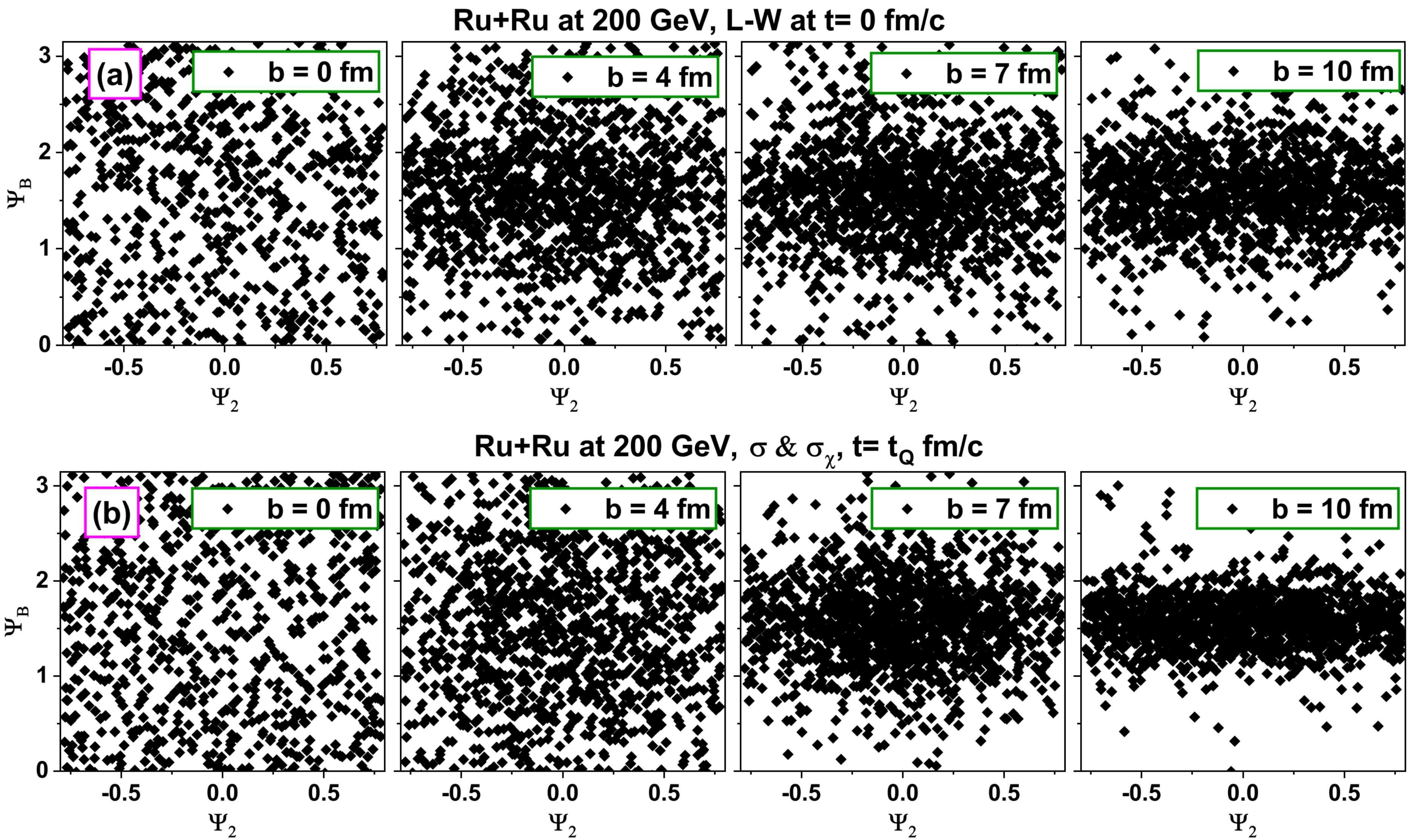
b = 0 fm ✗ no correlation

b > 0 fm ✓ correlation

- Fluctuates strongly in azimuthal direction
- b > 0 fm the concentration of distributions at $(\Psi_B, \Psi_2) = (\pi/2, 0)$ indicating correlation

Correlations

2D distribution plot for Ψ_B and Ψ_2

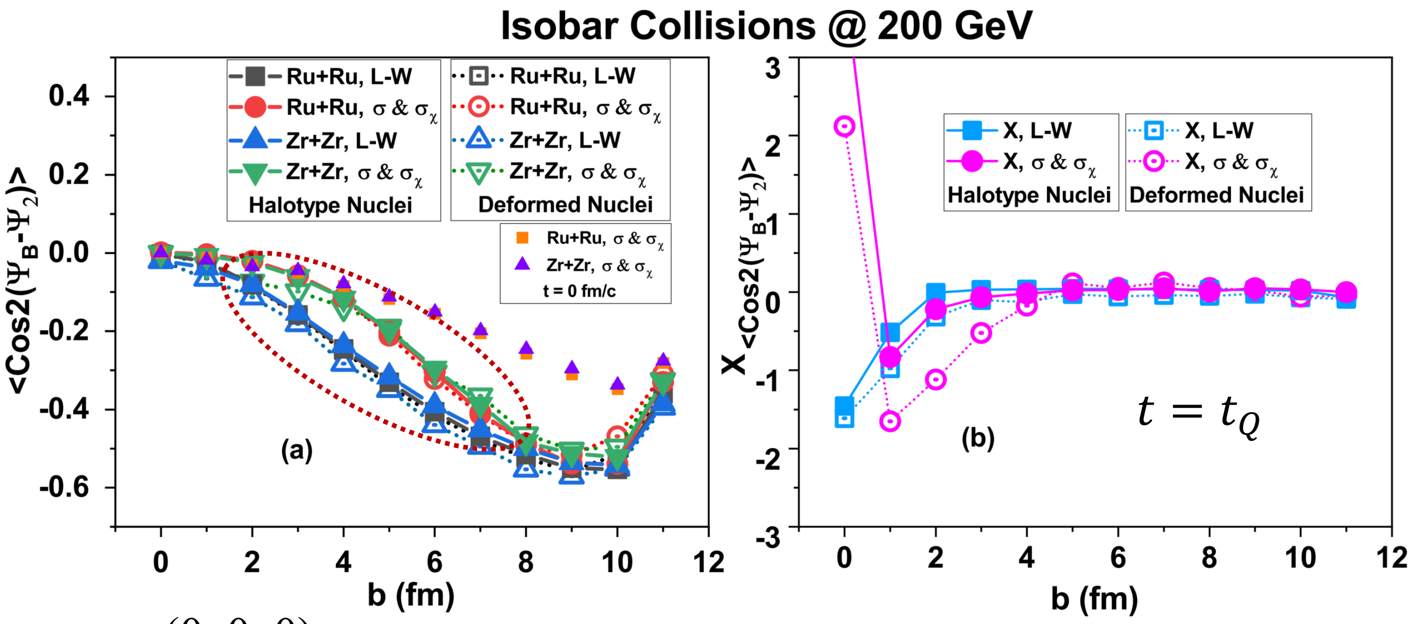


b = 0 fm ✗ no correlation

b > 0 fm ✓ correlation

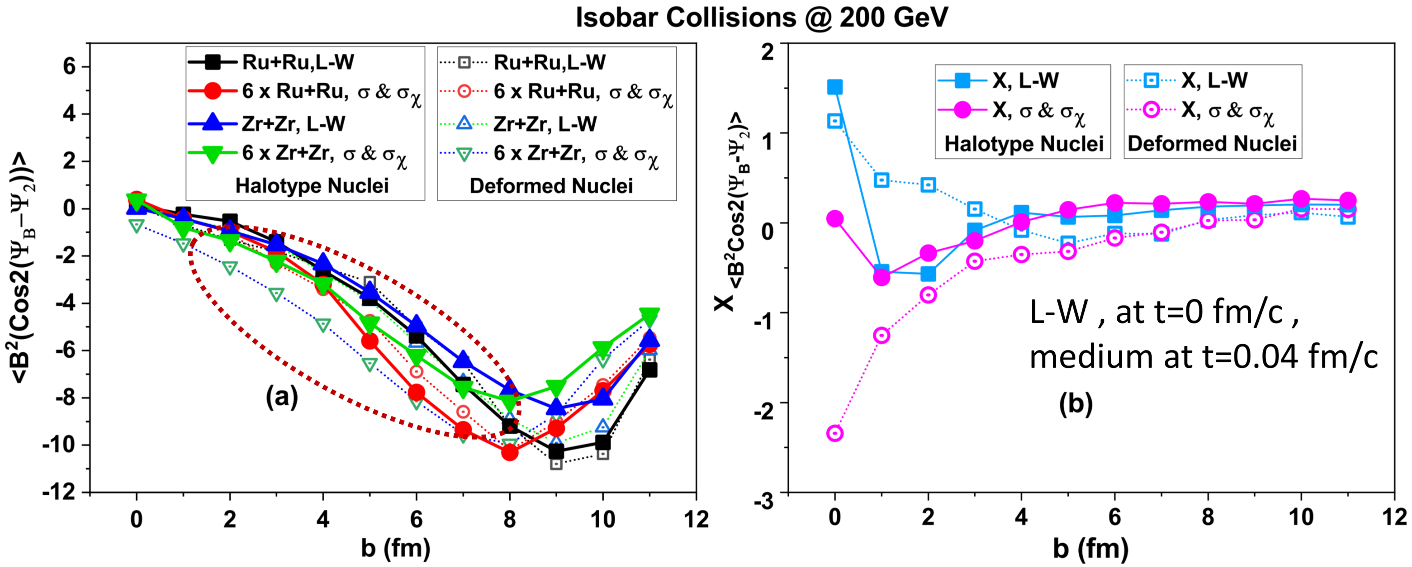
Correlations

1. $\cos2(\Psi_B - \Psi_2)$



r =(0, 0, 0)

2. $(\mathrm{eB})^2\cos2(\Psi_B - \Psi_2)$



Inherits influence from both strength of magnetic field and $\cos2(\Psi_B - \Psi_2)$

3. $\left\langle (\mathbf{eB})^2 \cos 2(\Psi_B - \Psi_2) \right\rangle_t$

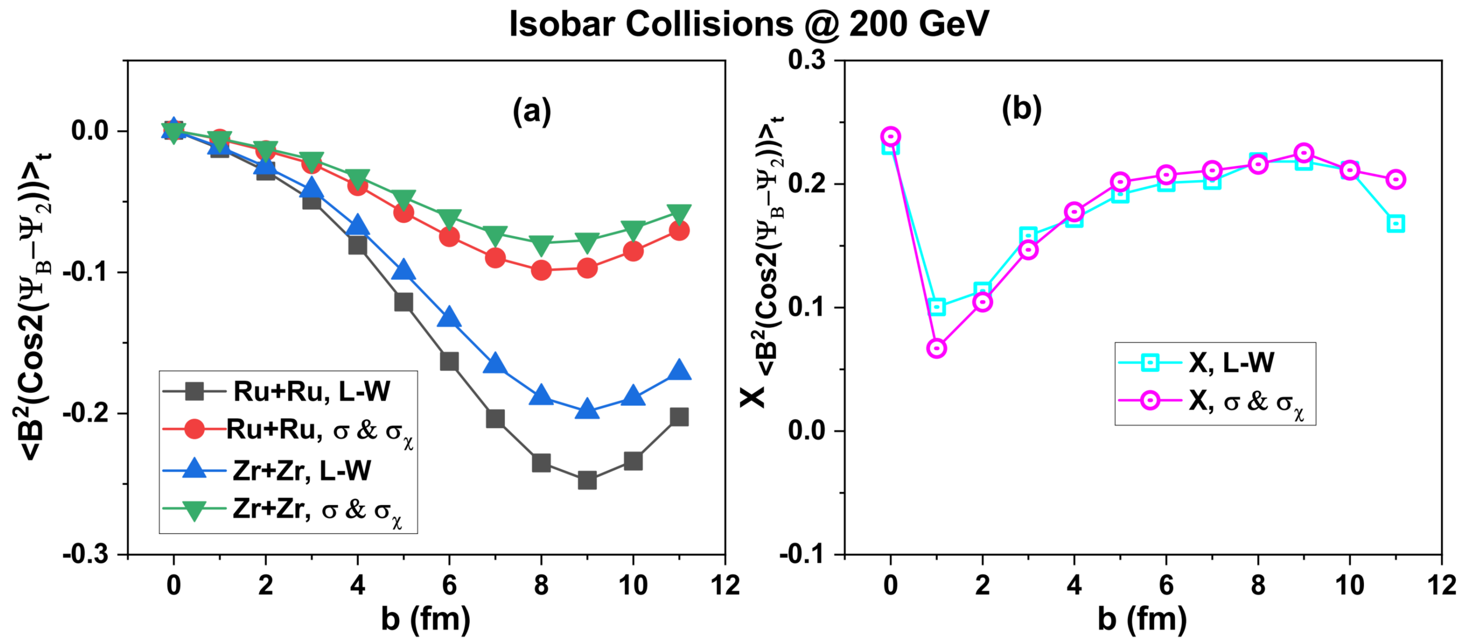
$$\langle \mathbf{G} \rangle_t(x) \equiv \frac{\int \mathbf{G}(t,x)\,dt}{\int dt} \qquad \therefore\ \mathbf{G} \equiv (\mathbf{eF})^2 \cos 2(\Psi_F - \Psi_2)$$

F is **B** or **E**

Averaged correlation

EM fields behavior varies with respect to both time and space, so their impact on physical observables should be at average level in lifespan of quark and nuclear matter. To quantify the average effects of correlators on physical observables time-averaged correlation can be defined

$$\langle \mathbf{G} \rangle_t(x) \equiv \frac{\sum_i \mathbf{G}(t_i,x)\,\Delta t_i}{\sum_i \Delta t_i}$$



Summary

Effects of the electric (σ) and chiral magnetic (σ) conductivities on the space and time evolution of the electromagnetic fields.
Partially asymmetric spatial distribution as compared to conductivity free system.
Decay in the presence of conductivities is much slower as compared to zero conductivity system.
Studied effect on magnetic field related correlations which reflect information about field related effects.