Impact of the characteristics of magnetic field on the CME and CMW measurements at RHIC

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References:
[1] Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma, Phys. Rev. C 99, 034903 (2019) [arXiv:1901.04151].
[2] Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma, https://doi.org/10.1016/j.physletb.2019.04.002 [arXiv:1901.04156].

Outline

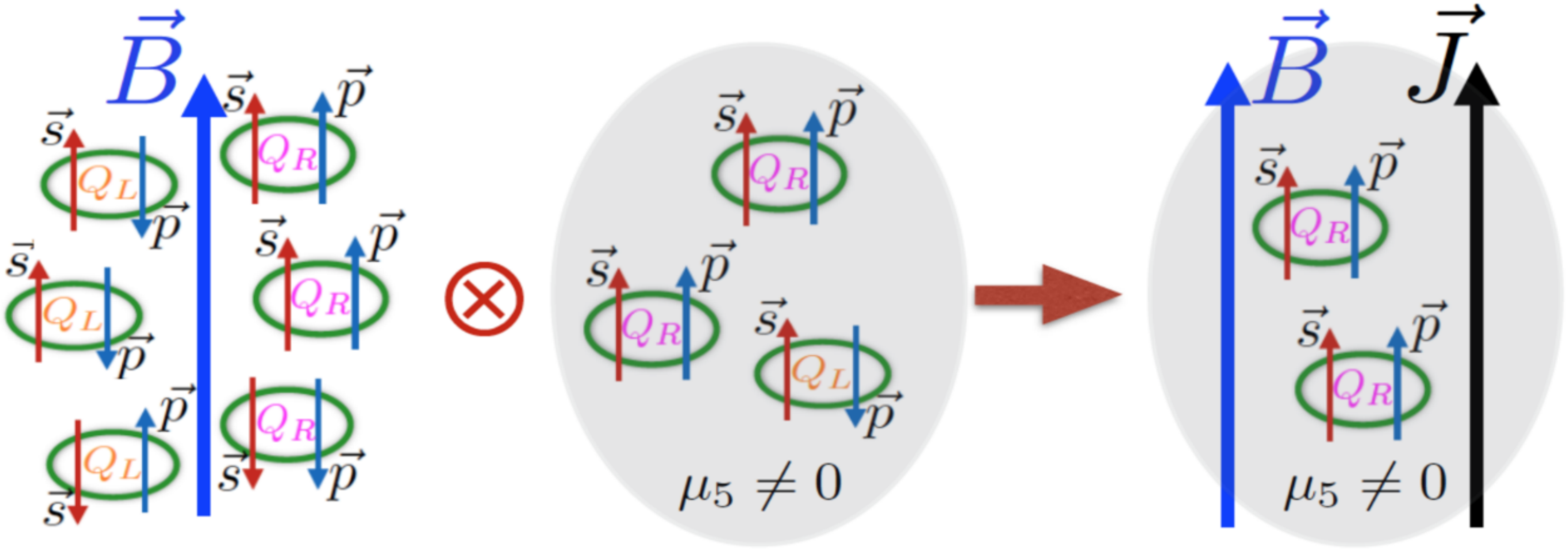
- ➢ **Introduction**
- ➢ **Results and Discussions**

(a) B and CME in isobaric collisions

(b) E·B and CMW in Au+Au collisions

- ➢ **Summary**

Chiral Magnetic Effect (CME)



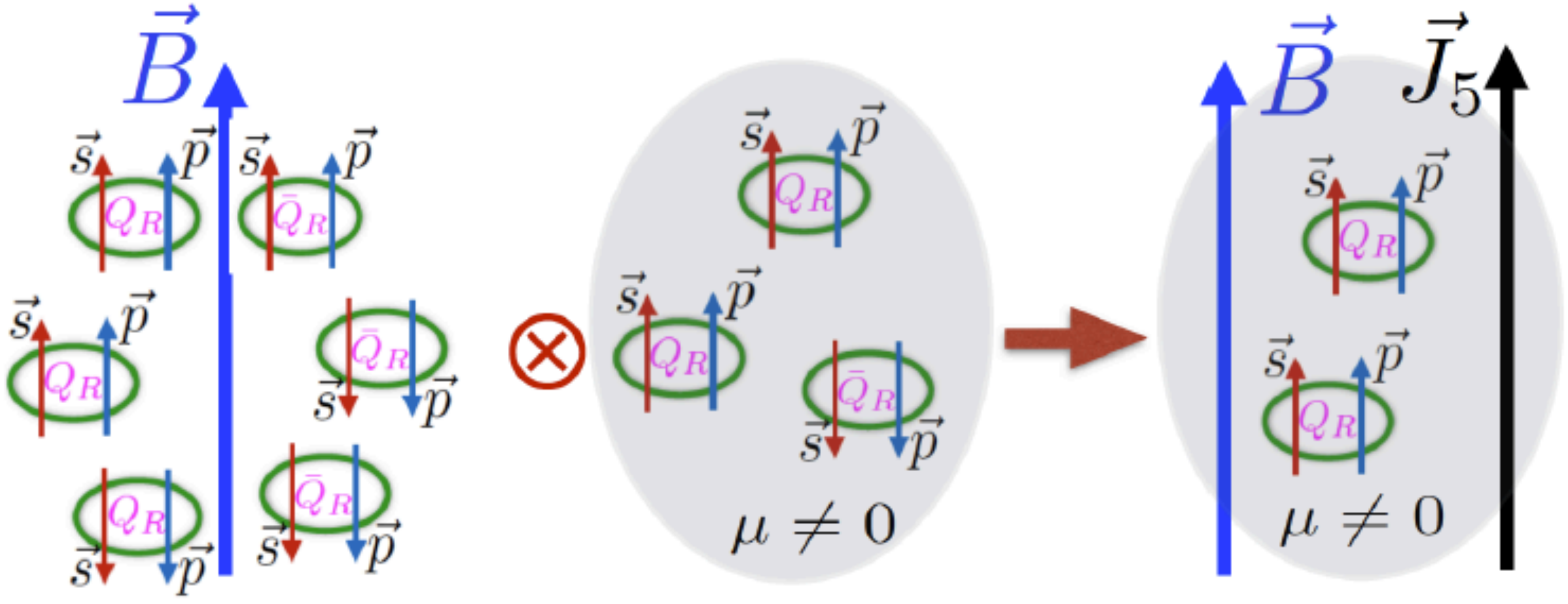
D.E. Kharzeev, J. Liao *et al* , PROG. PART. NUCL. PHYS. 88,1(2016)

The chiral anomaly creates differences in the number of left and right handed quarks. An excess of right or left handed quarks leads to a current flow along the magnetic field.

$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5\mathbf{B}$$

Charge separation signal: $\Delta\gamma \propto <\boxed{B^2}\boxed{\cos 2(\Psi_B - \Psi_{EP})}>$

Chiral Separation Effect (CSE)



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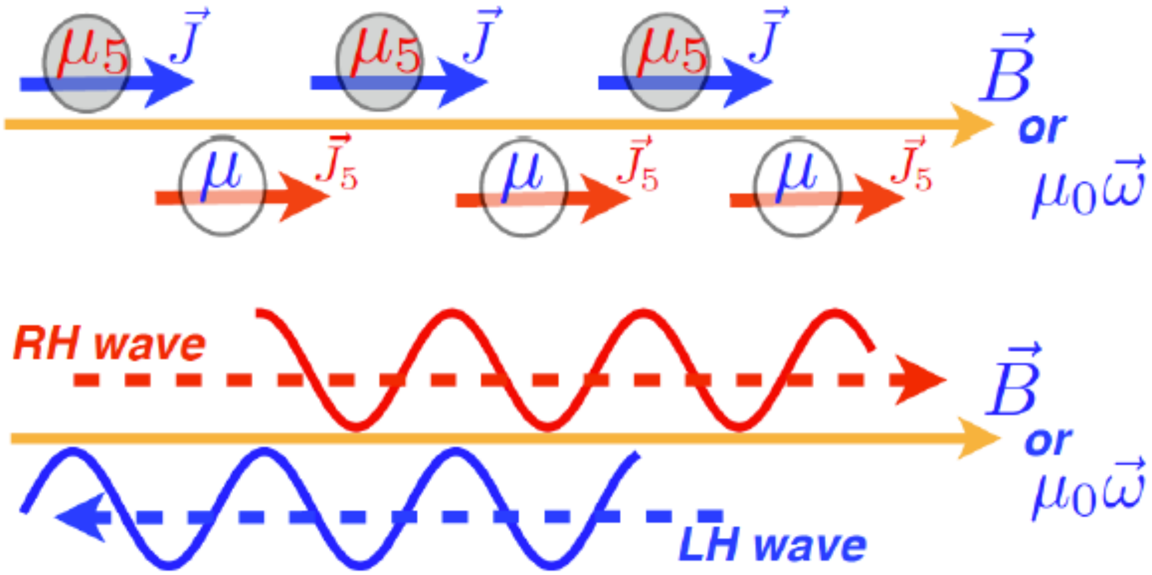
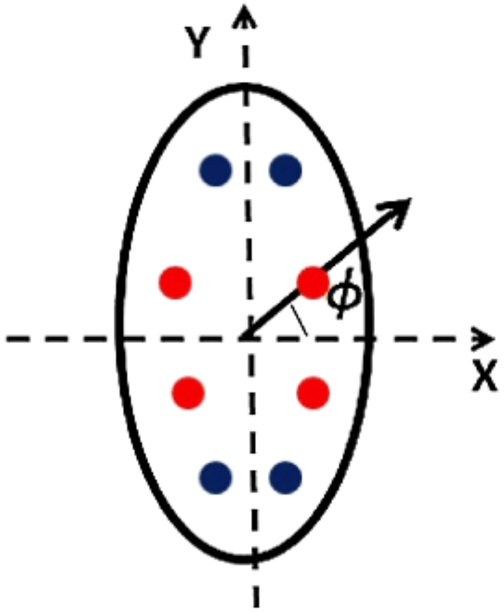
An axial current is generated along an external magnetic field, with its magnitude in proportion to the system's (nonzero) vector chemical potential as well as the magnetic field magnitude.

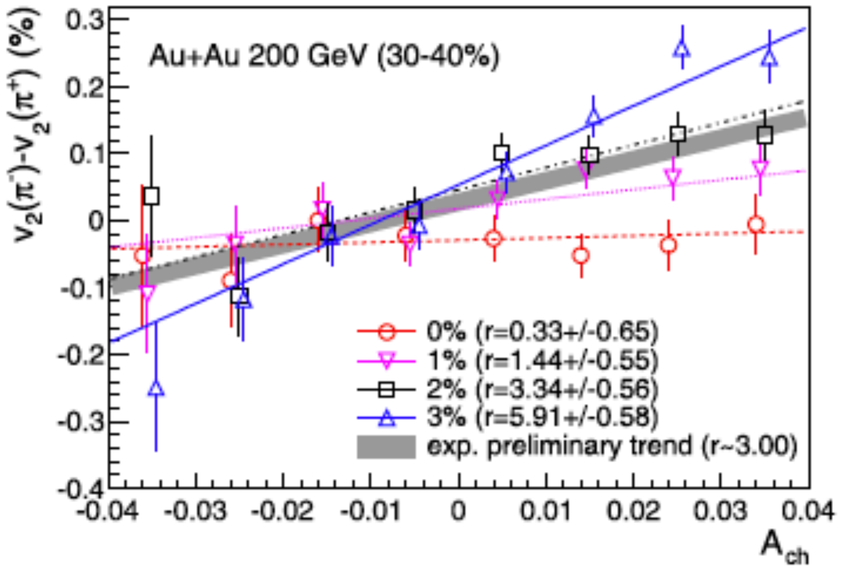
$$\mathbf{J}_5 = \frac{Qe}{2\pi^2}\mu \ \mathbf{B}$$

CSE signal:???

Chiral Magnetic Wave (CMW)







D.E. Kharzeev, J. Liao *et al* , PROG. PART. NUCL. PHYS. 88,1(2016)

G.-L. Ma, Phys. Lett. B 735, 383 (2014)

The interplay of CME and CSE lead to a collective wave mode, i.e. chiral magnetic wave. It results in a electric quadrupole which further lead to charge-dependent elliptic flow through final state interactions

$$\textbf{CME:}\quad \mathbf{J}=\frac{Qe}{2\pi^2}\mu_5\mathbf{B} \quad \rightleftharpoons \quad \textbf{CSE:}\quad \mathbf{J}_5=\frac{Qe}{2\pi^2}\mu\,\mathbf{B}$$

CMW (CME+CSE) signal: v2 splitting of positive and negative charged particles (slope para. *r*)

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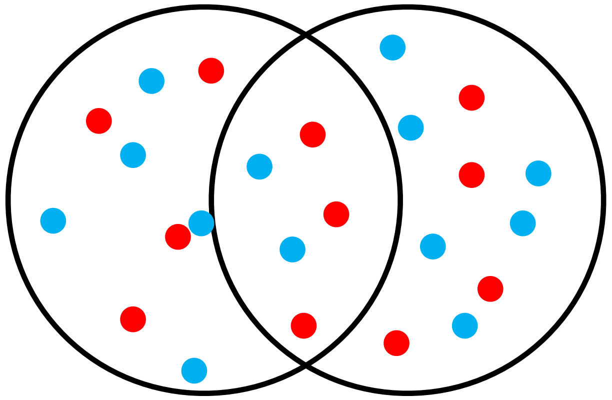
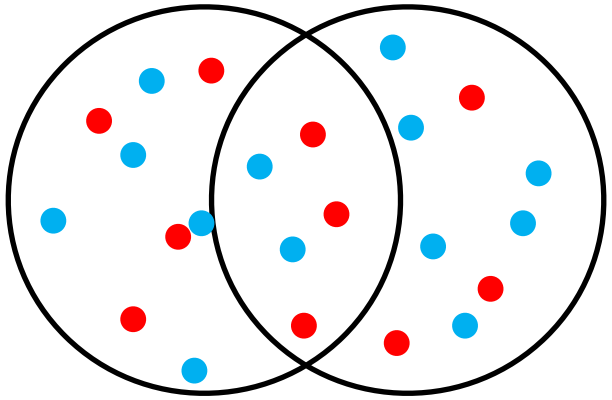
Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma, Phys. Rev. C 99, 034903 (2019) [arXiv:1901.04151].

Using Isobaric Collisions for CME Search

$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5 \boxed{\mathbf{B}}$$



$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$



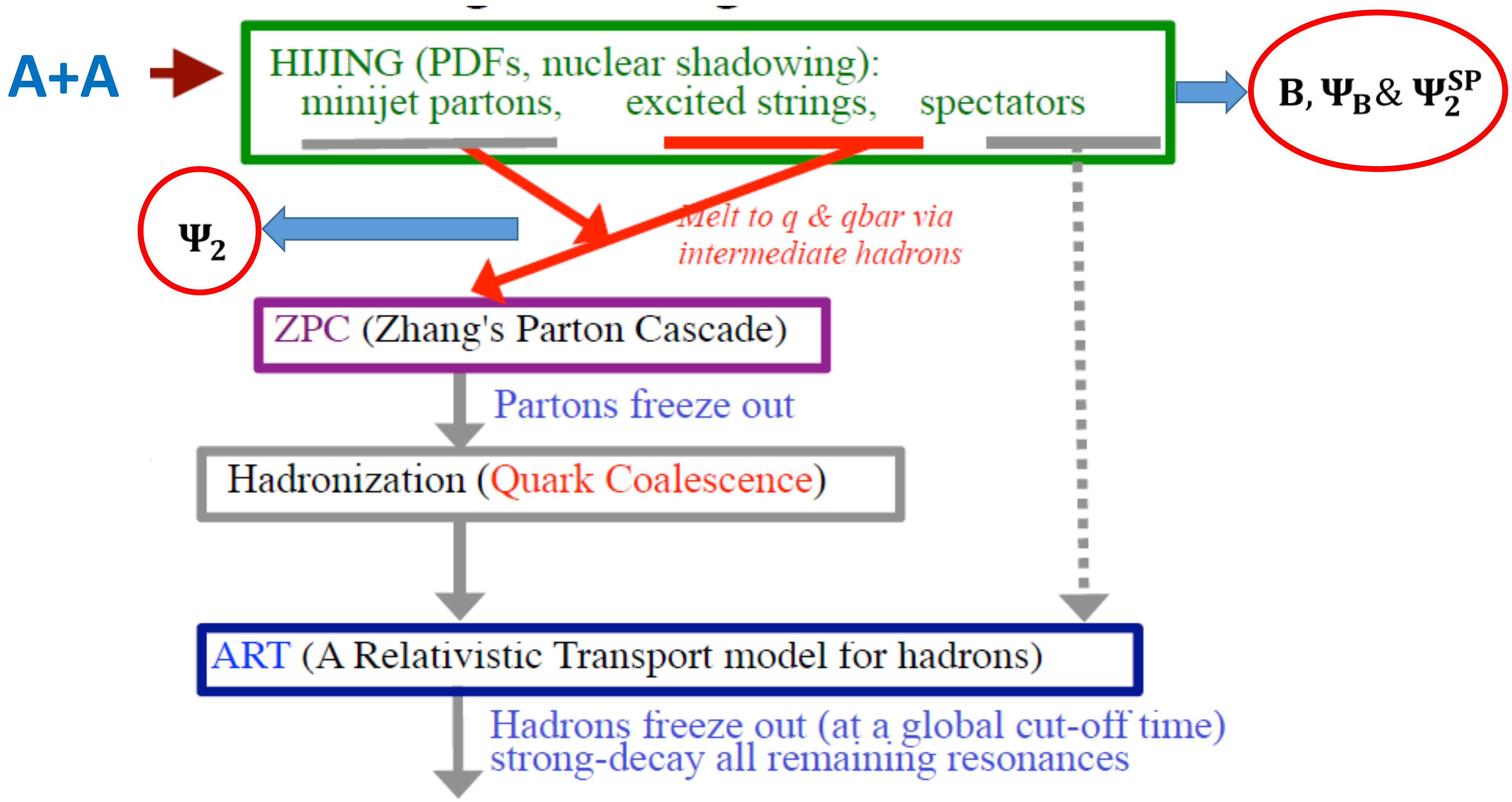
$^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$

Identical nucleon number → Identical background

Different proton number → Different magnetic field

String-melting AMPT model

Zi-Wei Lin, Che Ming Ko *et al*, PHYSICAL REVIEW C 72, 064901 (2005)



A+A

HIJING (PDFs, nuclear shadowing):
minijet partons, excited strings, spectators

B, Ψ_B & Ψ_2^{SP}

Ψ_2

Melt to q & qbar via intermediate hadrons

ZPC (Zhang's Parton Cascade)

Partons freeze out

Hadronization (Quark Coalescence)

ART (A Relativistic Transport model for hadrons)

Hadrons freeze out (at a global cut-off time)
strong-decay all remaining resonances

Final particle
spectra

Geometry Configuration of Isobaric Collisions

Woods-Saxon form of spatial distribution of nucleons:

$$\rho(r,\theta) = \rho_0/(1+exp((r-R_0-\beta_2 R_0 Y_2^0(\theta))/a))$$

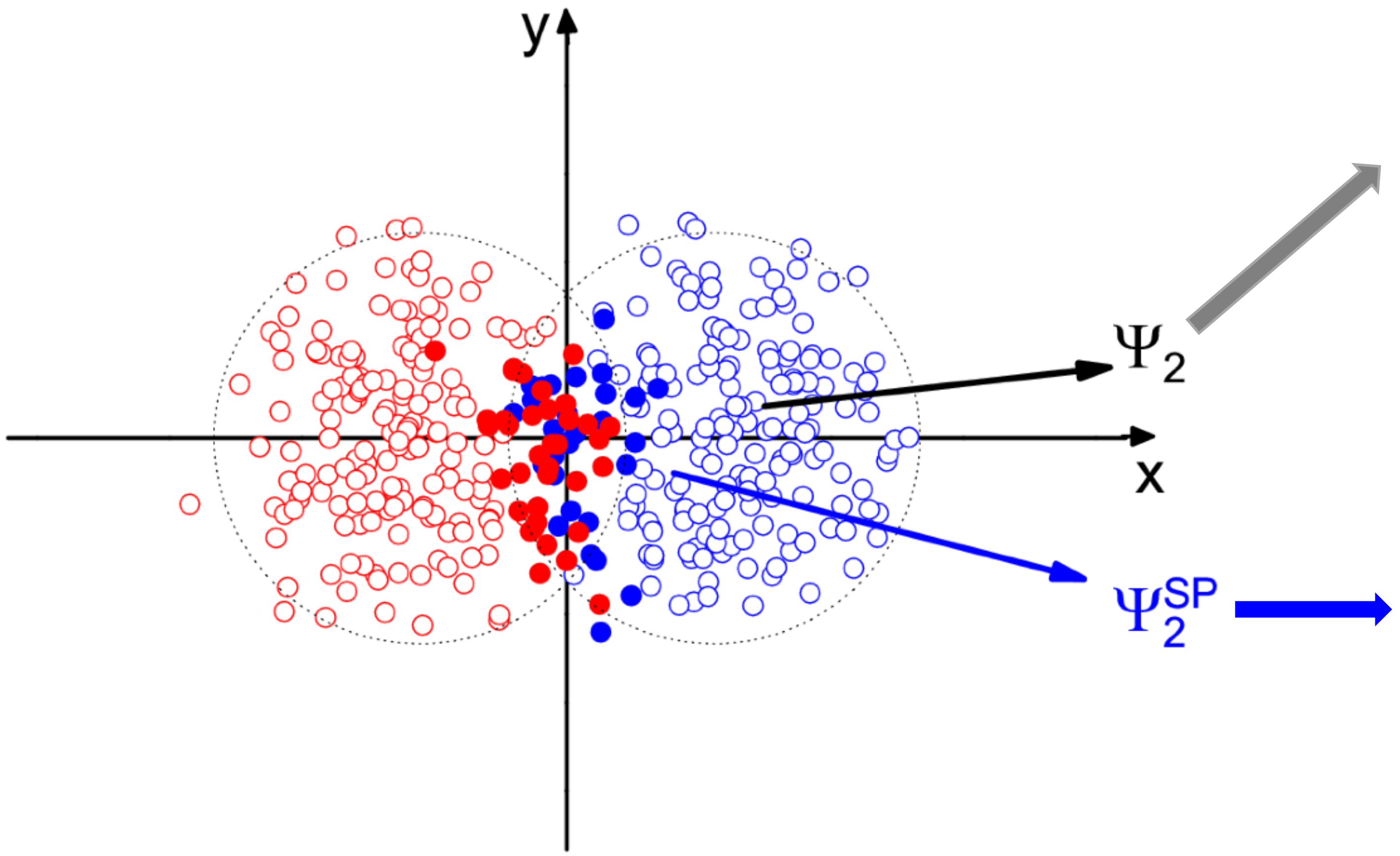
Case 1	R_0	a	β_2	β_4
Ru96	5.13	0.46	0.13	0.00
Zr96	5.06	0.46	0.06	0.00
Case 2	**R_0**	**a**	**β_2**	**β_4**
Ru96	5.13	0.46	0.03	0.00
Zr96	5.06	0.46	0.18	0.00

Relative ratio (RR): $R_Q = \frac{2(Q^{Ru}-Q^{Zr})}{Q^{Ru}+Q^{Zr}}$

e.g. for case 1, $R_{\beta_2} = \frac{2(0.13-0.06)}{0.13+0.06} = 0.33$; for case 2, $R_{\beta_2} = \frac{2(0.03-0.18)}{0.03+0.18} = -1.43$

Q can represent $|B|$, $\cos 2(\Psi_B - \Psi_2)$, $B^2 \cos 2(\Psi_B - \Psi_2)$, $\cos 2(\Psi_B - \Psi_2^{SP})$ and $B^2 \cos 2(\Psi_B - \Psi_2^{SP})$.

Calculation Method of Ψ_2 & Ψ_2^{SP}



In model,

$$\Psi_2 = \frac{1}{2}[arctan\frac{\langle r_p^2 sin(2\phi_p)\rangle}{\langle r_p^2 cos(2\phi_p)\rangle} + \pi]$$

X. L. Zhao, Y. G. Ma, G. L. Ma, PRC 97, 024910 (2018)

Ψ_2 is participant plane which is constructed by initial geometry of partons.

$$\Psi_2^{SP} = \frac{1}{2}arctan\frac{\langle r_s^2 sin(2\phi_s)\rangle}{\langle r_s^2 cos(2\phi_s)\rangle}$$

Sandeep Chatterjee *et al,* PRC 92, 011902(R) (2015)

Ψ_2^{SP} is spectator plane which is constructed by spectator neutrons from one projectile.

In experiment, Ψ_2 is the 2nd-harmonic event plane measured by the TPC, and Ψ_2^{SP} is assessed by spectator neutrons measured by ZDC.

Jie Zhao *et al*, arXiv:1807.05083; Hao-Jie Xu *et al*, arXiv:1710.07265; Sergei A. Voloshin, arXiv:1805.05300

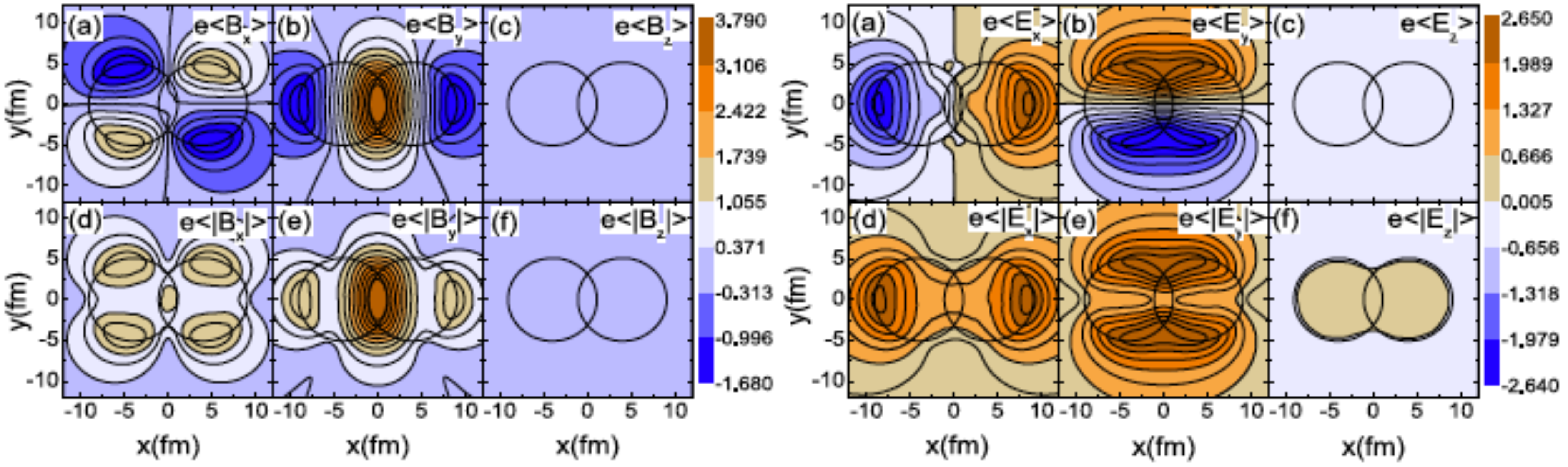
Spatial Distributions of Electromagnetic Fields

From Lienard-Wiechert potential:

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n\mathbf{v}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$$

$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$$

b = 8 fm

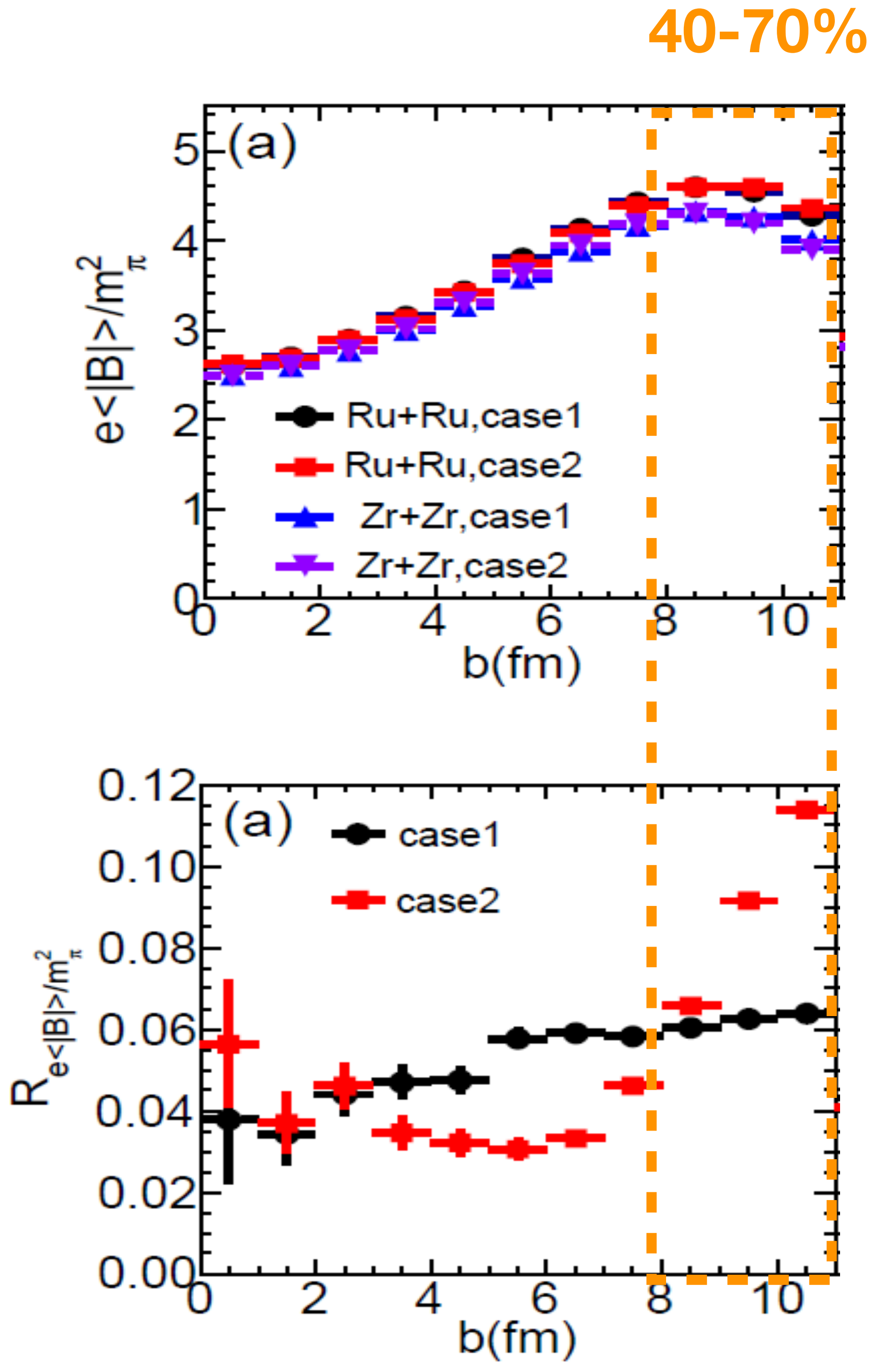


The distributions of RuRu collisions for case 1.

$\mathbf{r} = (0,0,0)$ & $\mathrm{t} = 0$

Charge separation signal: $\Delta\gamma \propto <\boxed{B^2}\boxed{\cos 2(\Psi_B - \Psi_{EP})}>$

|B|

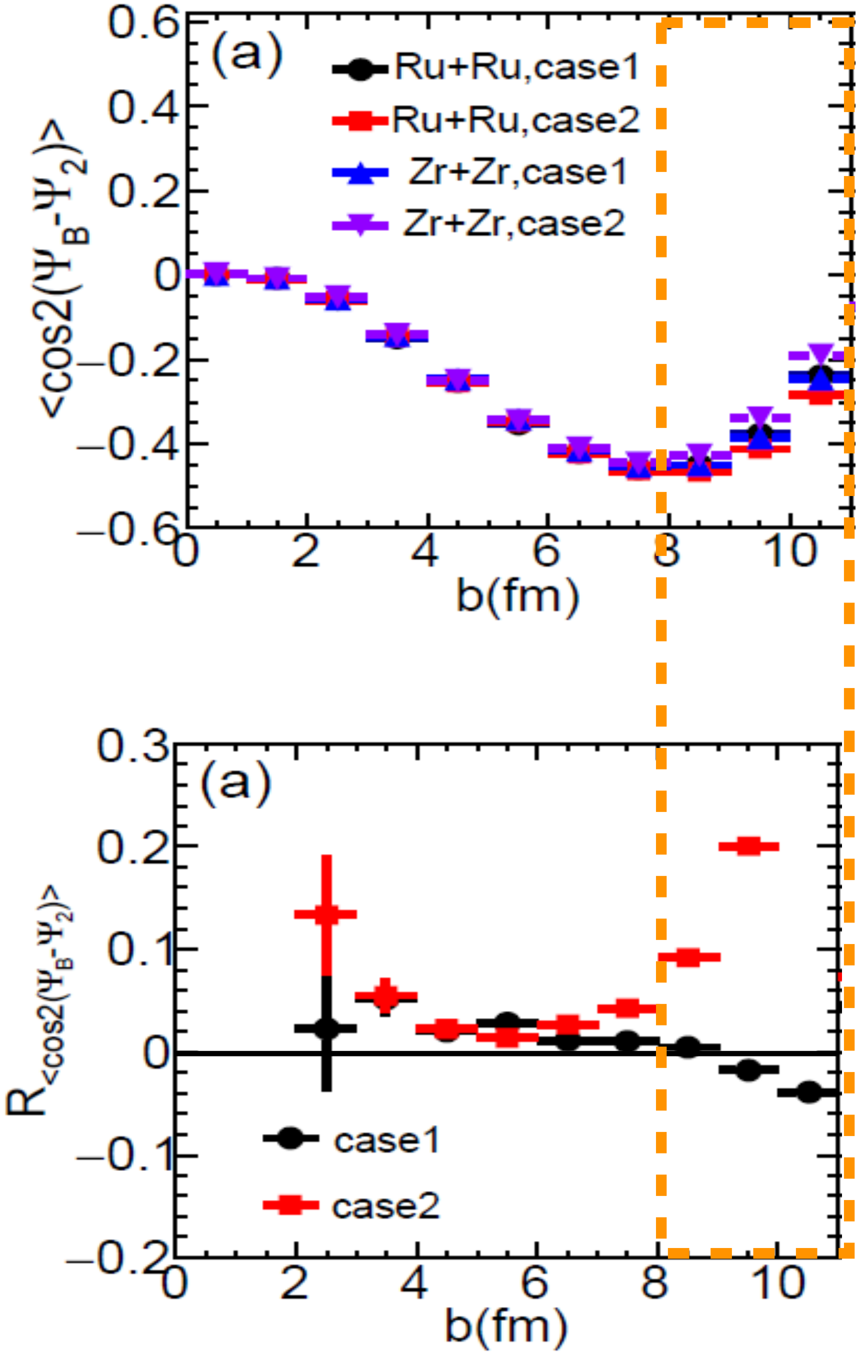


- ➢ |B|_{Ru} > |B|_{Zr}

- ➢ For case 1, RR is about 4% - 6%.
- ➢ For case 2, RR is about 4% - 12%.
- ➢ Deformation info. causes difference

$$R_Q = \frac{2(Q^{Ru} - Q^{Zr})}{Q^{Ru} + Q^{Zr}}$$

$\cos 2(\Psi_B - \Psi_2)$



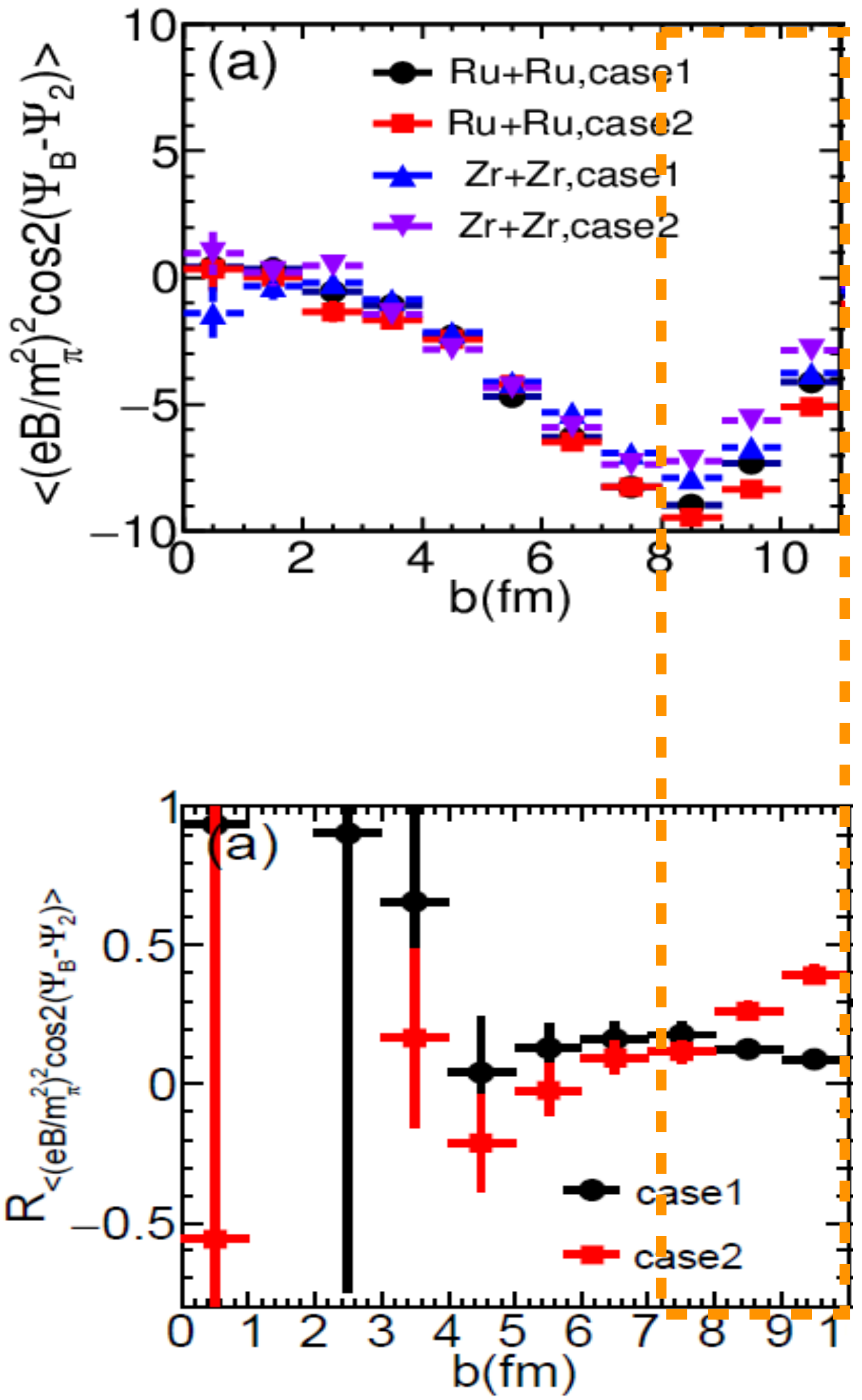
- The maximum of $\cos 2(\Psi_B - \Psi_2)$ is about -0.5.
- In central and mid-central collisions, $\cos 2(\Psi_B - \Psi_2)$ are similar in the four cases but different in peripheral collisions.

- **In mid-central collisions, RR are similar for case 1 and 2.**
- **In peripheral collisions, RR are different.**

A bad news for looking for CME!

$$R_Q = \frac{2(Q^{Ru} - Q^{Zr})}{Q^{Ru} + Q^{Zr}}$$

$B^2\cos2(\Psi_B-\Psi_2)$



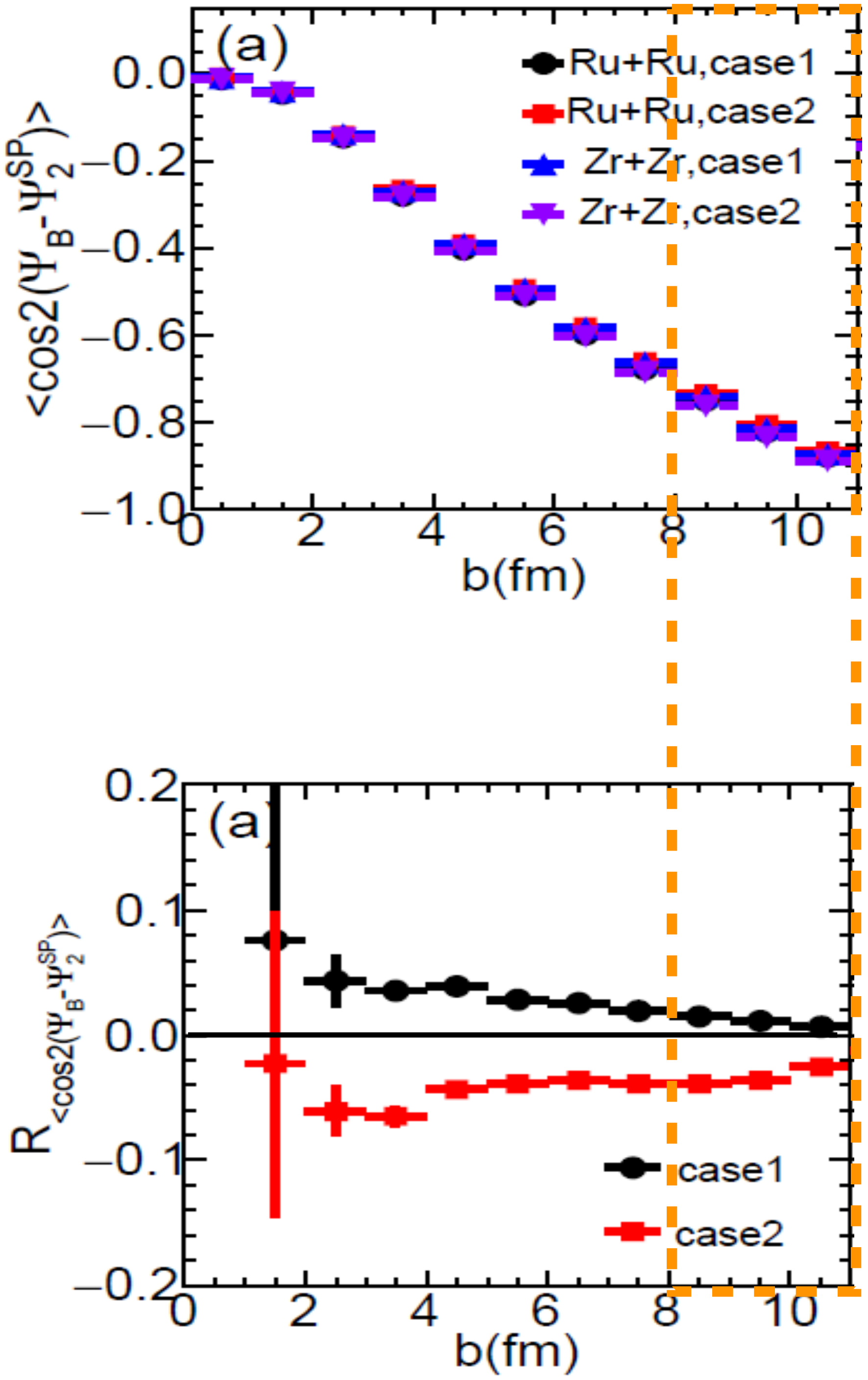
- ➢ The maximum of $B^2\cos2(\Psi_B-\Psi_2)$ is about -10.
- ➢ In central and mid-central collisions, $B^2\cos2(\Psi_B-\Psi_2)$ are similar in the four cases but different in peripheral collisions.

- ➢ RR of $B^2\cos2(\Psi_B-\Psi_2)$ are similar to RR of $\cos2(\Psi_B-\Psi_2)$.

contaminated by deformation

$$R_Q=\frac{2(Q^{Ru}-Q^{Zr})}{Q^{Ru}+Q^{Zr}}$$

$\cos 2(\Psi_B - \Psi_2^{SP})$



- $\cos 2(\Psi_B - \Psi_2^{SP})$ are around two times larger than $\cos 2(\Psi_B - \Psi_2)$.
- In peripheral collisions, this correlation $\cos 2\left(\Psi_B - \Psi_2^{SP}\right) = -0.9$.

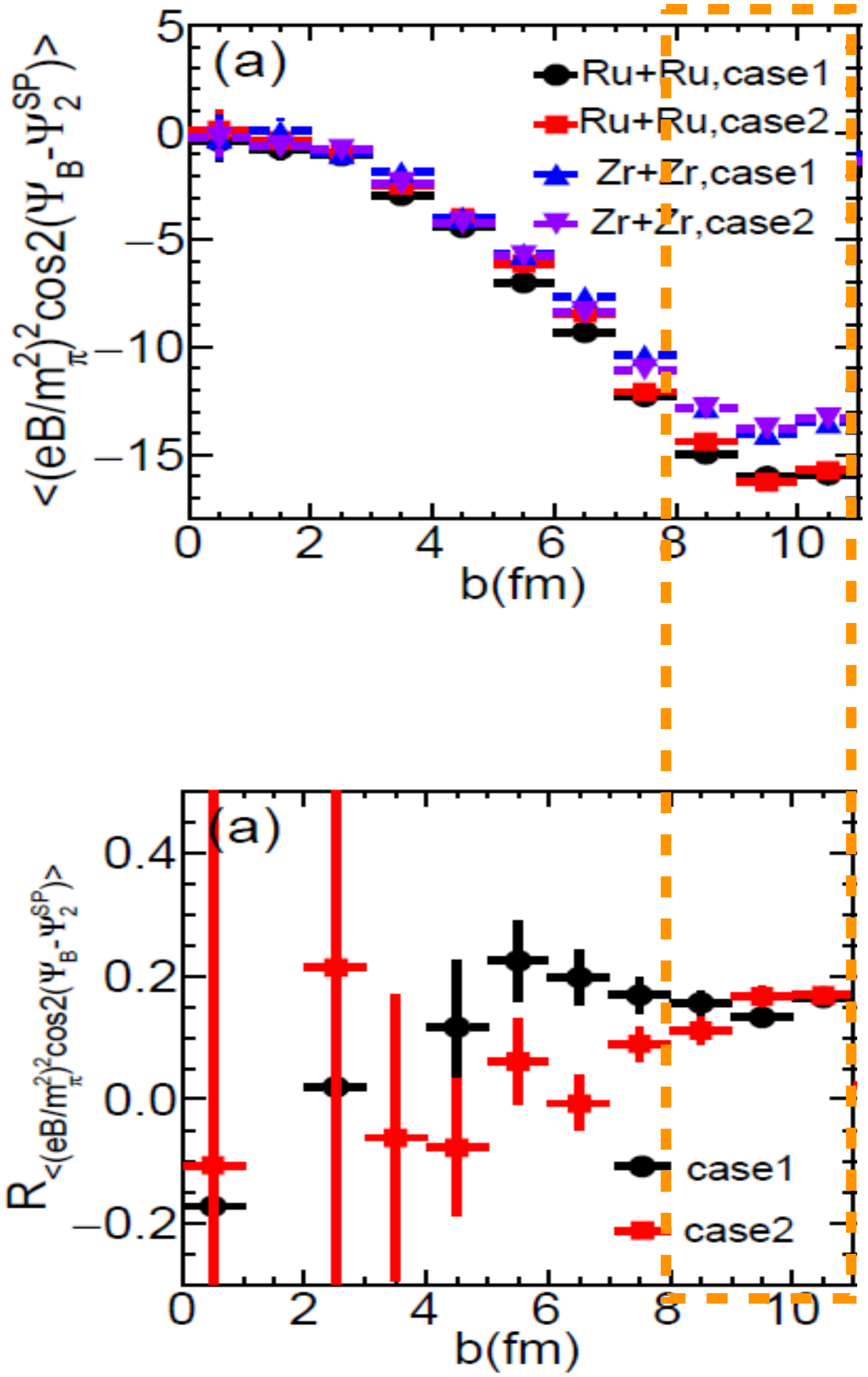
Ψ_2^{SP} has stronger correlation with Ψ_B than Ψ_2.

- RR of $\cos 2(\Psi_B - \Psi_2^{SP})$ for the two cases are close to zero in peripheral collisions.

A good news for looking for CME!

$$R_Q = \frac{2(Q^{Ru} - Q^{Zr})}{Q^{Ru} + Q^{Zr}}$$

$B^2\cos2(\Psi_B-\Psi_2^{SP})$



CME observable Δγ:

- $B^2\cos2(\Psi_B-\Psi_2^{SP}) > B^2\cos2(\Psi_B-\Psi_2)$.

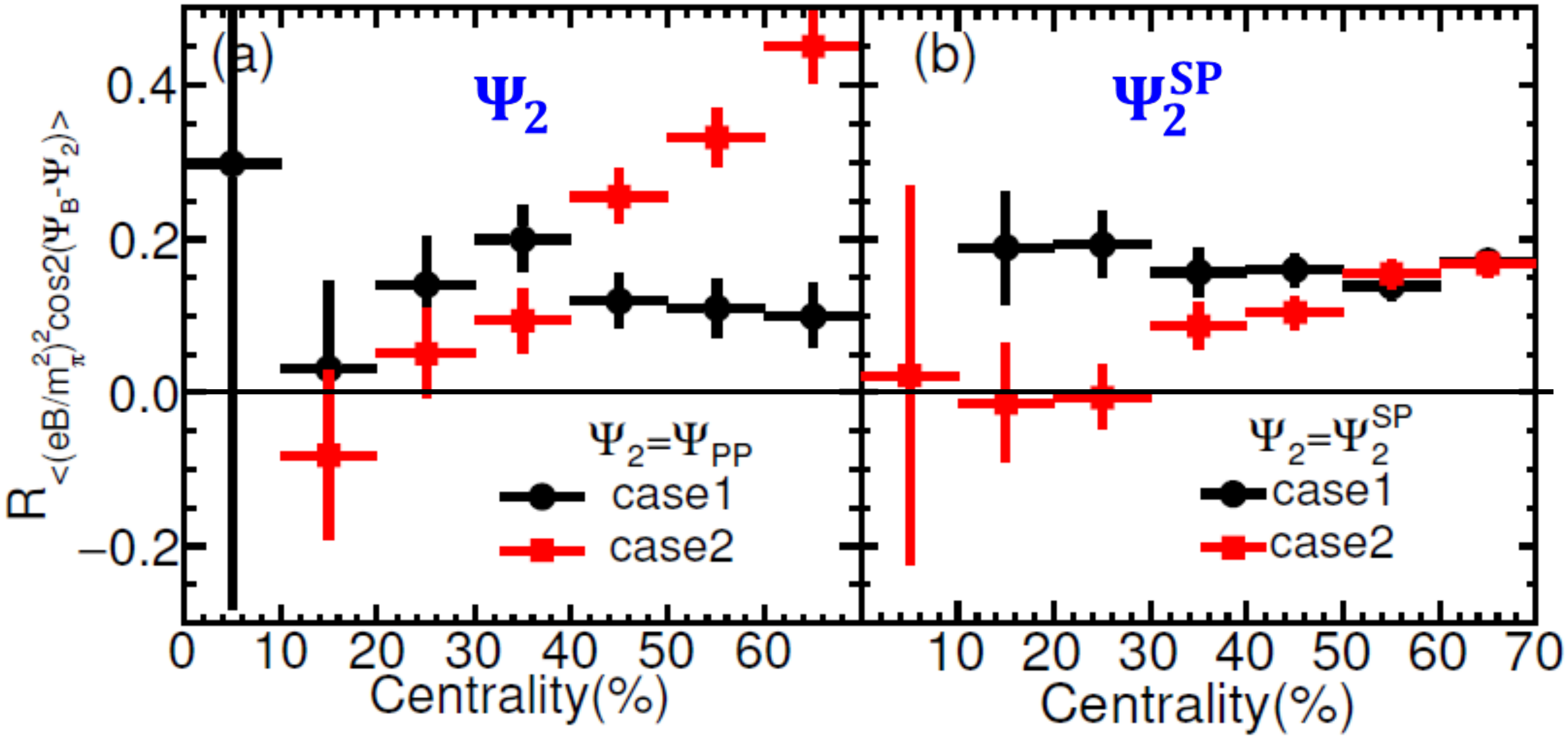
~15 **~10**

- **For case 1, RR is near 15%.**
- **For case 2, RR increases from 0 to 15% from central to peripheral events.**

Less contaminated by deformation in peripheral events

$$R_Q = \frac{2(Q^{Ru}-Q^{Zr})}{Q^{Ru}+Q^{Zr}}$$

Ψ_2 VS Ψ_2^{SP}



- For case 1, RR of $B^2\cos2(\Psi_B-\Psi_2)$ and $B^2\cos2(\Psi_B-\Psi_2^{SP})$ are similar.
- For case 2, RR of Ψ_2 is larger than RR of Ψ_2^{SP}.
- Ψ_2^{SP} is expected to reflect much cleaner information about the CME signal.

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XL Zhao, GL Ma, YG Ma, https://doi.org/10.1016/j.physletb.2019.04.002 [arXiv:1901.04156].

Chiral anomaly μ_5 sources

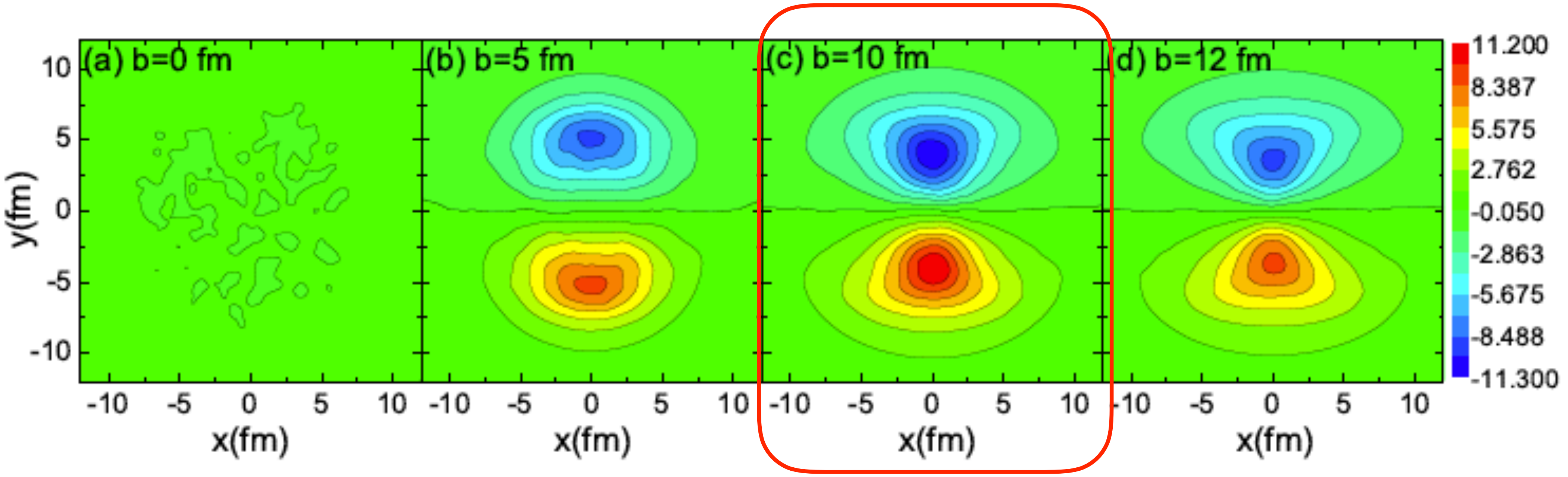
$$\partial_\mu J_5^\mu = 2im\bar{\psi}\gamma^5\psi - \frac{e^2}{16\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} - \frac{g^2}{16\pi^2}tr\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}$$

- **QED anomaly effects**: Fermi surface balance in the Dirac sea; neutral pion condensation; Dirac semimetal experiments etc.
- ***QED anomaly in heavy-ion collisions?***

$$\mathbf{E}\cdot\mathbf{B} = E_xB_x + E_yB_y + E_zB_z\,.$$

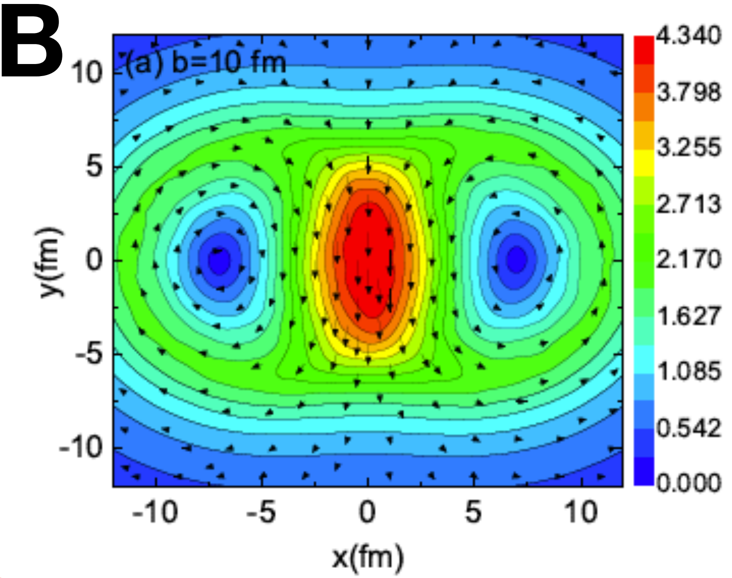
E·B in Au+Au 200GeV

E·B

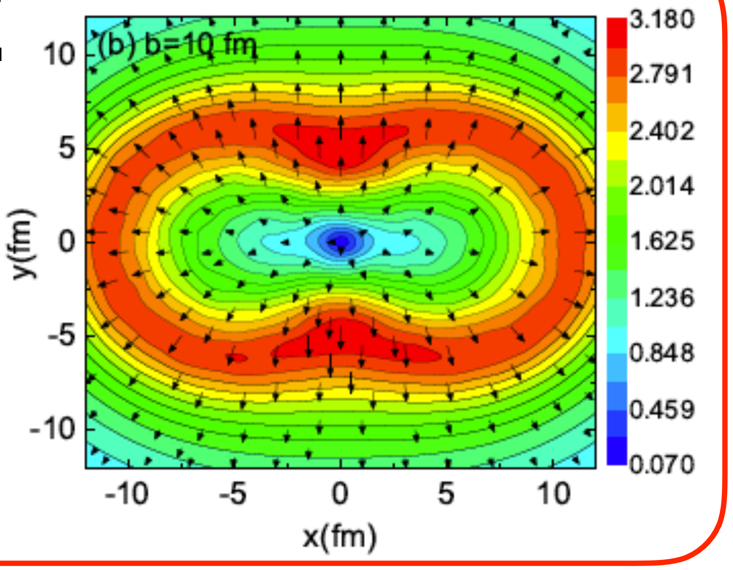


b=10 fm

B



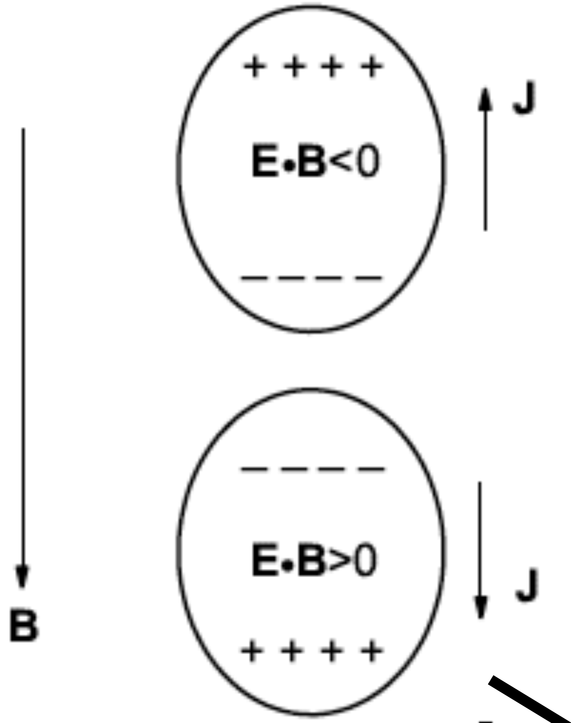
E



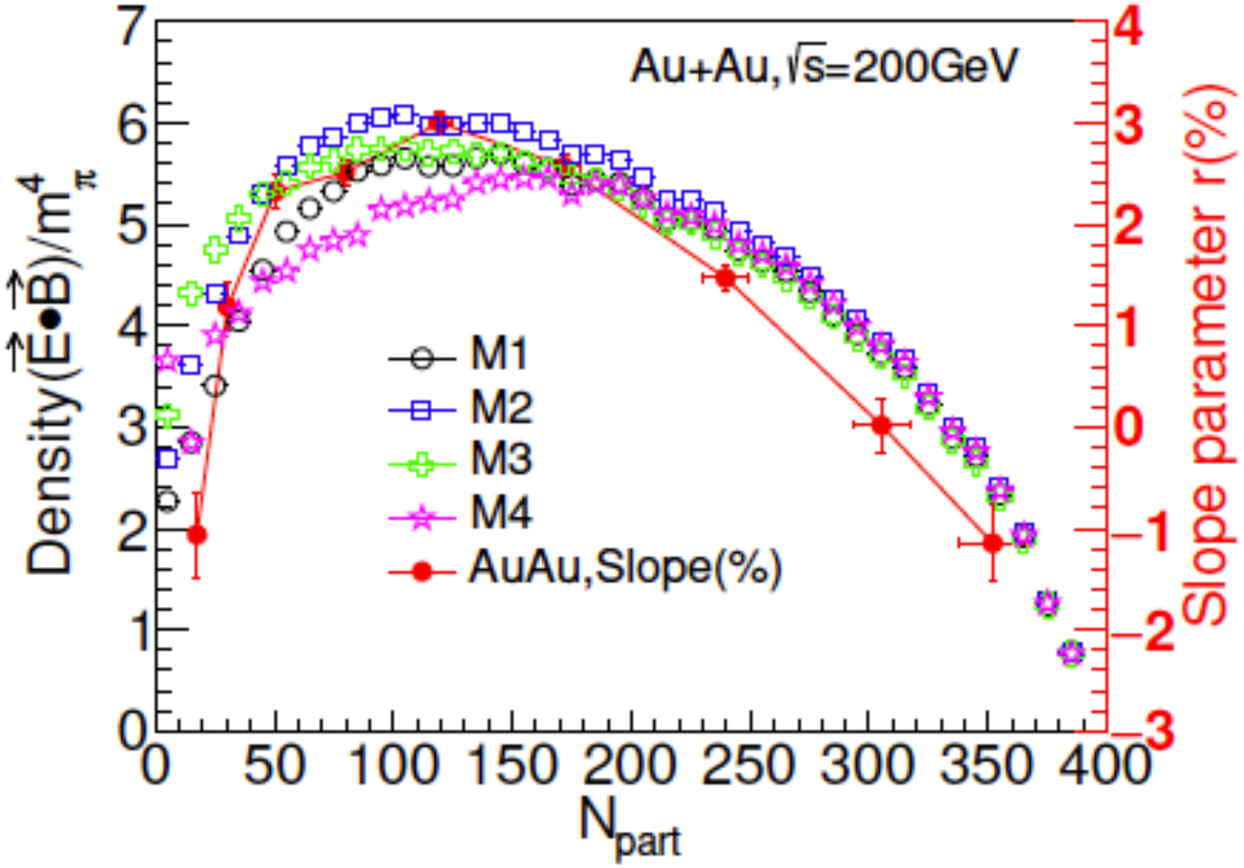
- **A dipolar distribution of E·B is observed in noncentral Au+Au collisions.**

From E·B dipole to electric quadrupole

$$\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5\mathbf{B}$$



$$\xcancel{\mathbf{J}_5 = \frac{Qe}{2\pi^2}\mu\,\mathbf{B}}$$

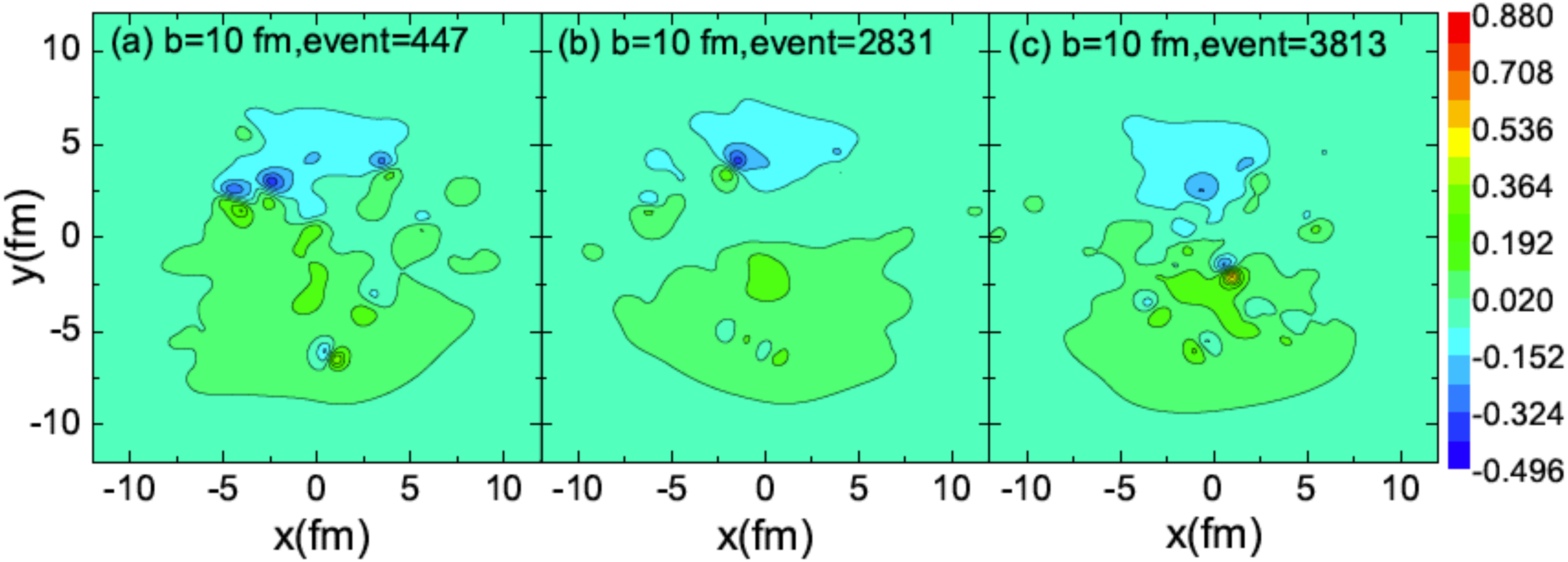


- A dipolar E·B in a magnetic field can lead to a electric quadrupole with the help of CME.

- No formation of CMW here

- The density of E·B is consistent with the centrality dependence of the slope para. r by STAR

Event-by-event E·B in Au+Au



- **A dipolar E·B holds on event-by-event basis.**
- **Our new mechanism does not need the CSE (μ-dependent) ➠different energy dependence from the CMW-driven one**

Summary

➢ B and CME in isobaric collisions

(a) Deformation difference causes some effects.

(b) $\Psi 2^{SP}$ has stronger correlation with ΨB than Ψ2

➠$\Delta\gamma$ w.r.t $\Psi 2^{SP}$ reflects much cleaner information about the CME signal

➢ E·B and CMW in Au+Au

(a) A dipolar E·B is observed in noncentral Au+Au collisions.

(b) It can result in a electric quadrupole without CMW ➠ a new interpretation to the slope r measured by STAR.

(c) Source for other chiral anomalous effects?

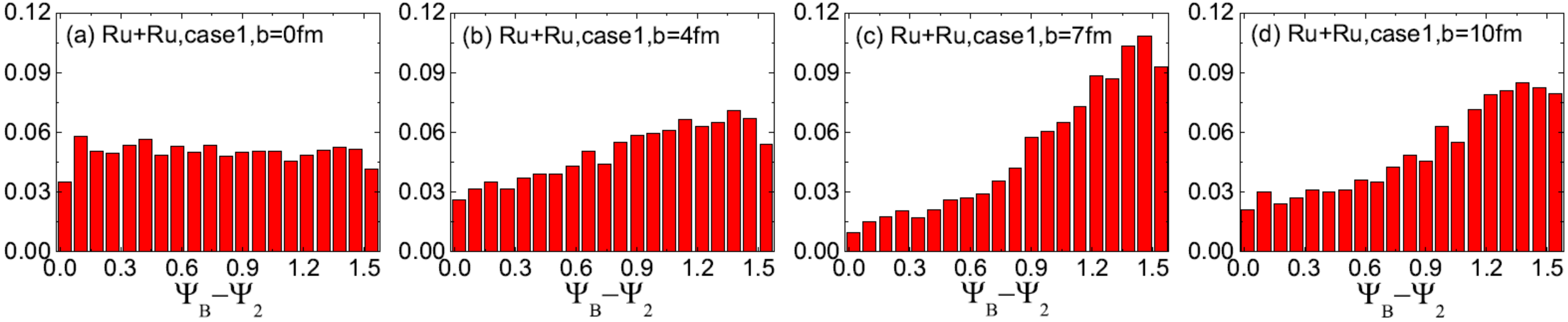
Thank you for your attention!

Backup

Centrality cuts for Ru+Ru and Zr+Zr

Centrality	b_{min} (fm)	b_{max} (fm)
0-10%	0	3.9
10-20%	3.9	5.5
20-30%	5.5	6.8
30-40%	6.8	7.8
40-50%	7.8	8.8
50-60%	8.8	9.6
60-70%	9.6	10.3

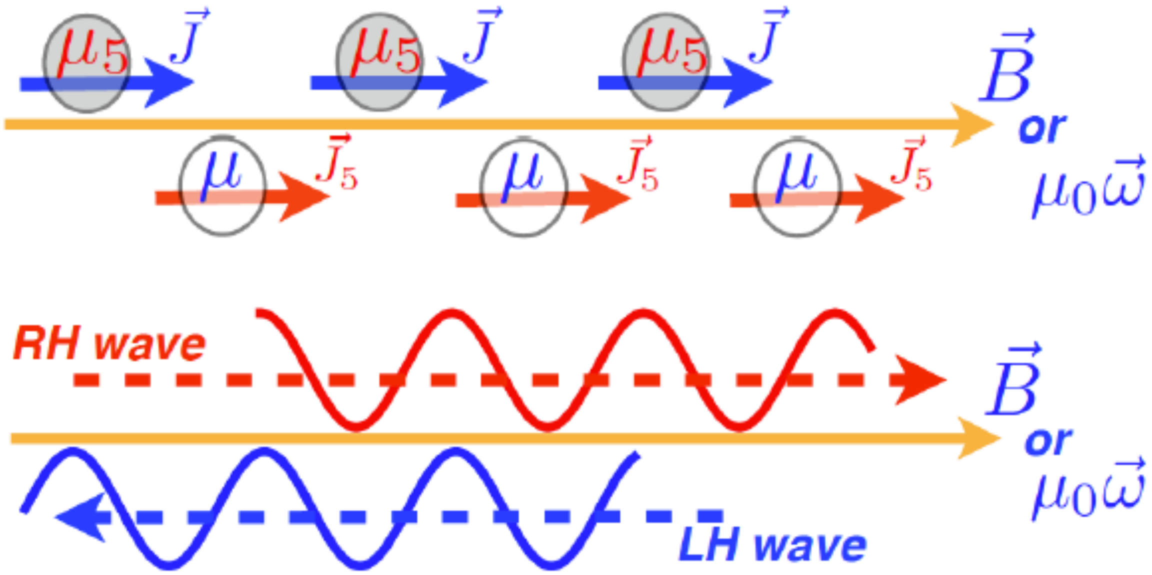
Distributions of $\Psi_B - \Psi_2$

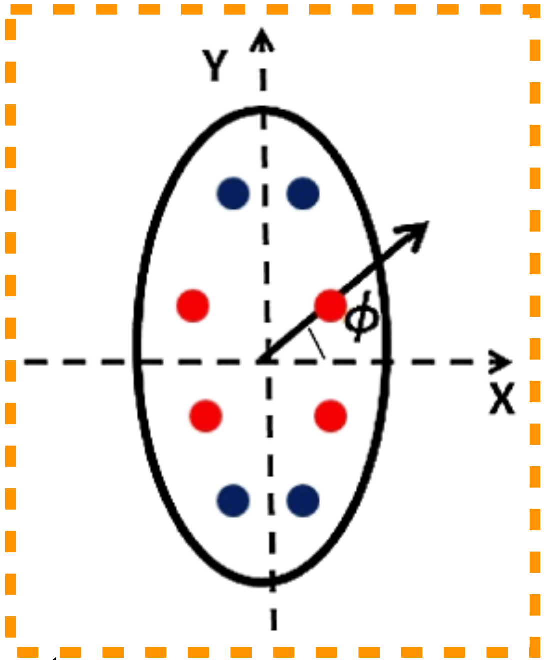


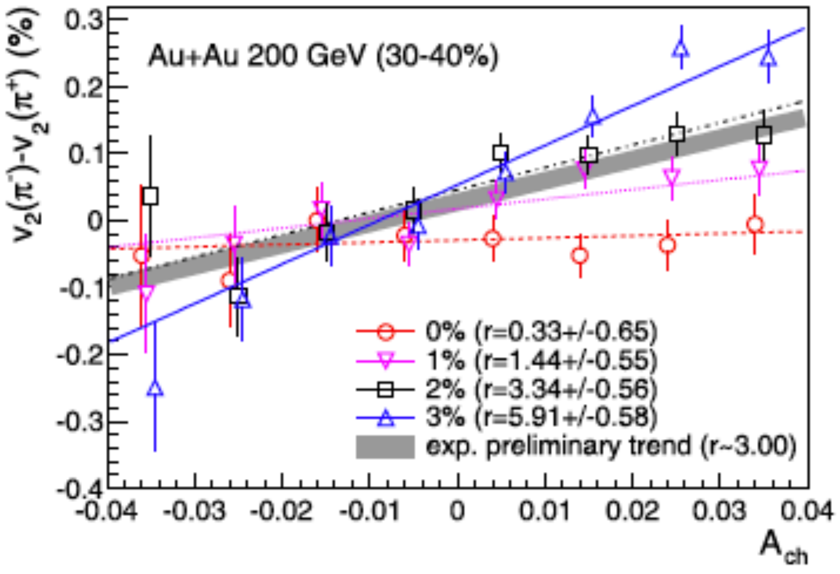
uncorrelated correlated strongly correlated correlated

most central mid-central peripheral

Chiral Magnetic Wave (CMW)







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