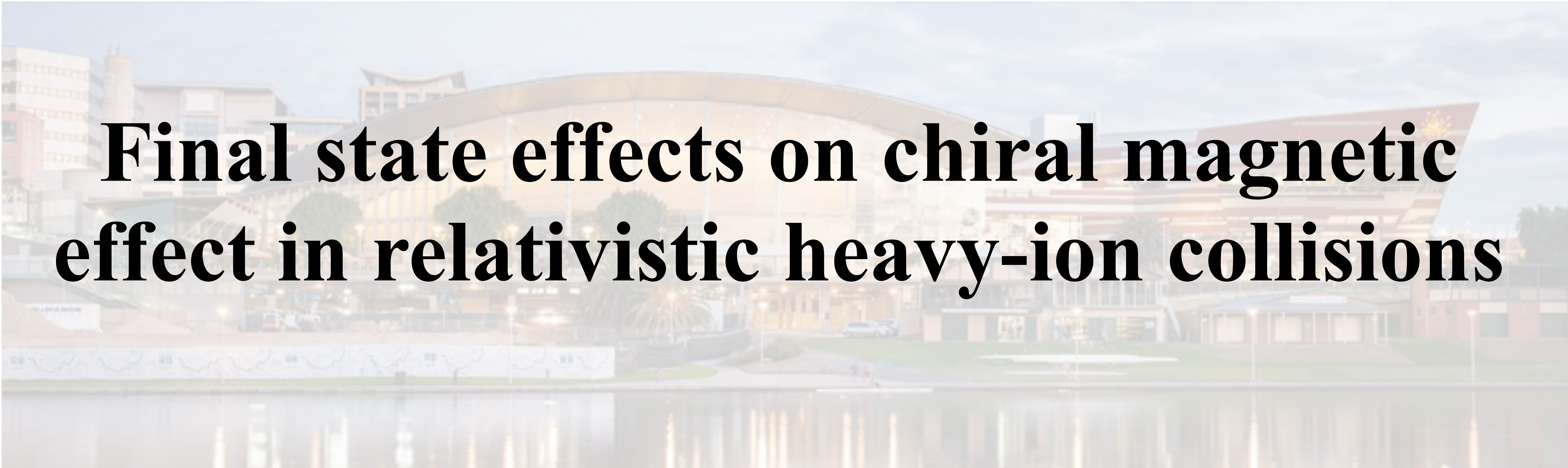

Final state effects on chiral magnetic effect in relativistic heavy-ion collisions

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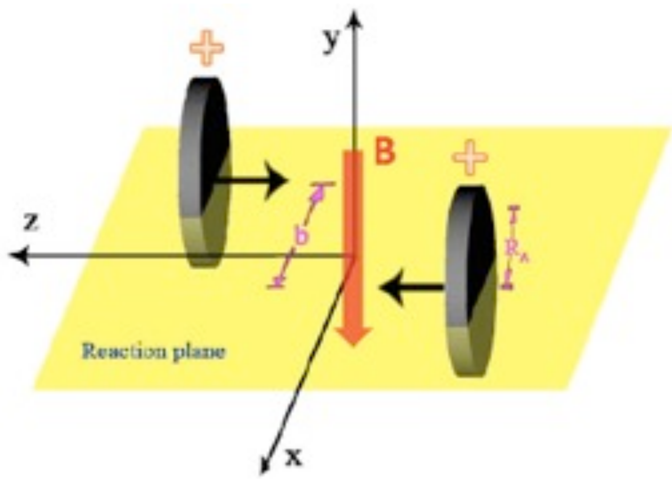
Outline

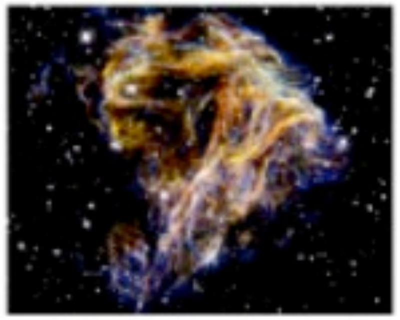
- Motivation
- The AMPT model and its results
- Predictions on CME in isobar collisions
- Summary

Strong B field in HIC



The B field at the colliding time, $t = 0$. Biot-Savart law

$$-eB_y \sim 2 \times \gamma \frac{e^2}{4\pi} Z v_z \left(\frac{2}{b}\right)^2 \approx 40 m_\pi^2 \sim 10^{19}\text{Gauss}$$

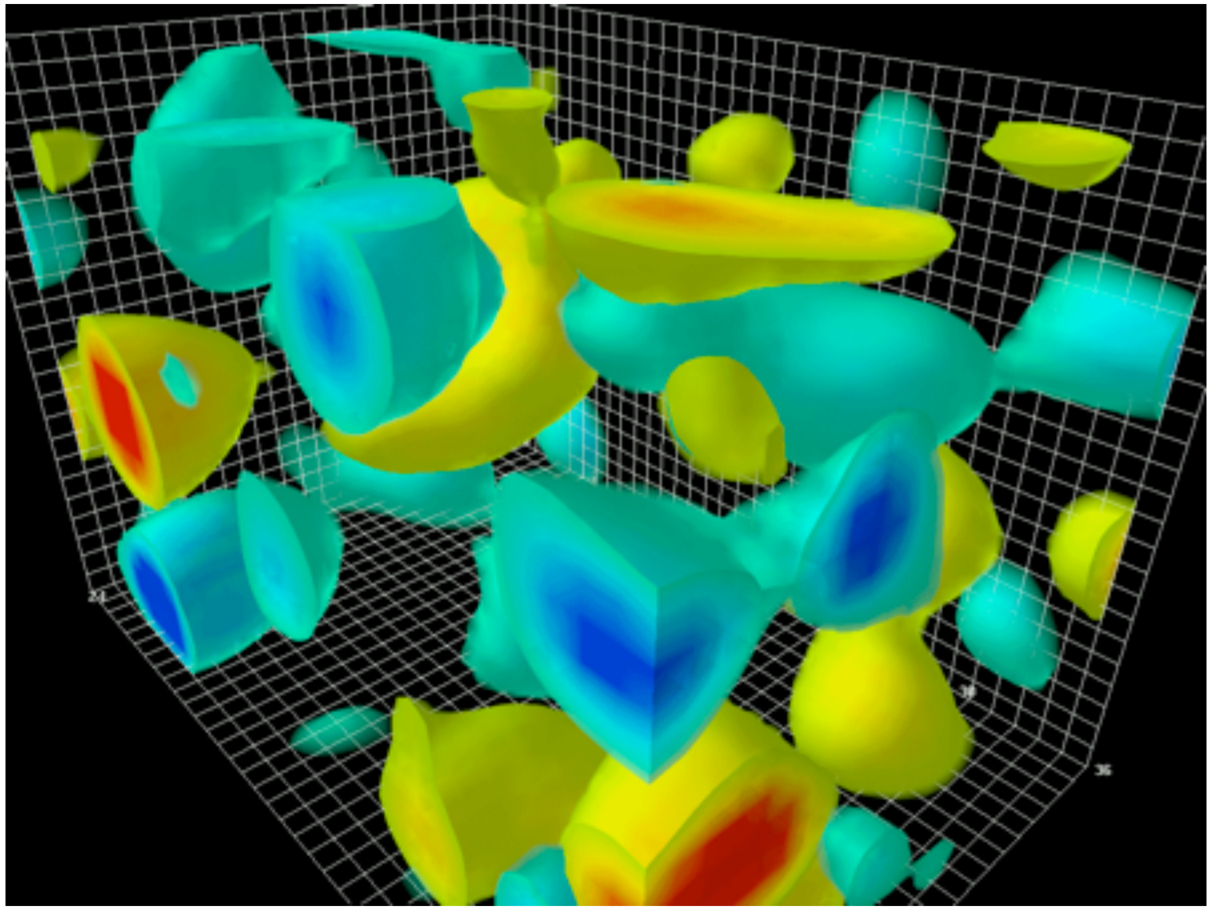


The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

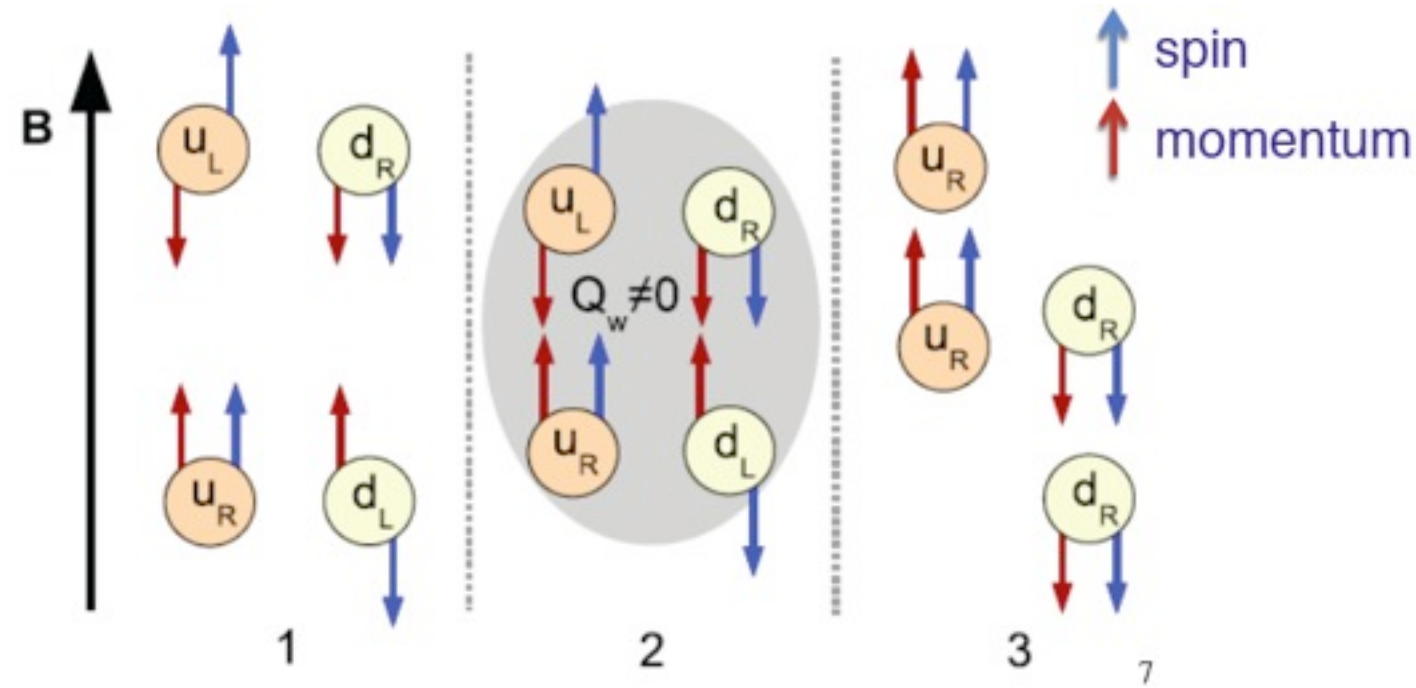
http://solomon.as.utexas.edu/~duncan/magnetar.html

Chiral Magnetic Effect

D. Leinweber



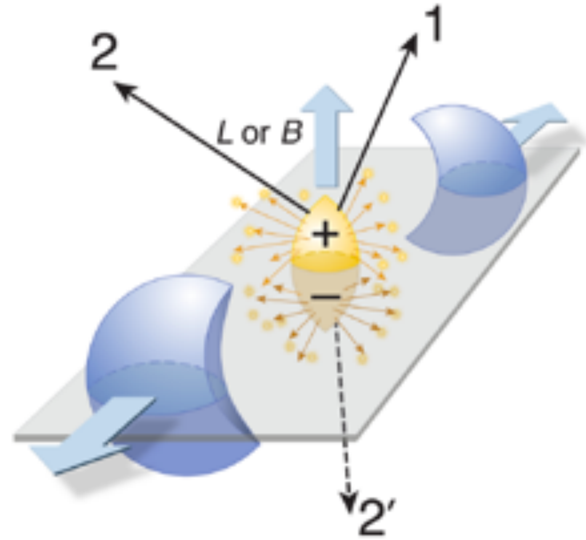
DE Kharzeev(2008)



$$\vec{j} \propto (N_L - N_R)\,\vec{B} \propto \mu_5 \vec{B}$$

- CME: Initial fluctuations of topological charge in QCD vacuum → P and CP odd metastable domains → Charge separation in the direction of magnetic field
- CME indicates that parity is locally violated in strong interactions, which shows us the vacuum nature and QCD electromagnetics.

CME exp. probe: charge azimuthal correlator

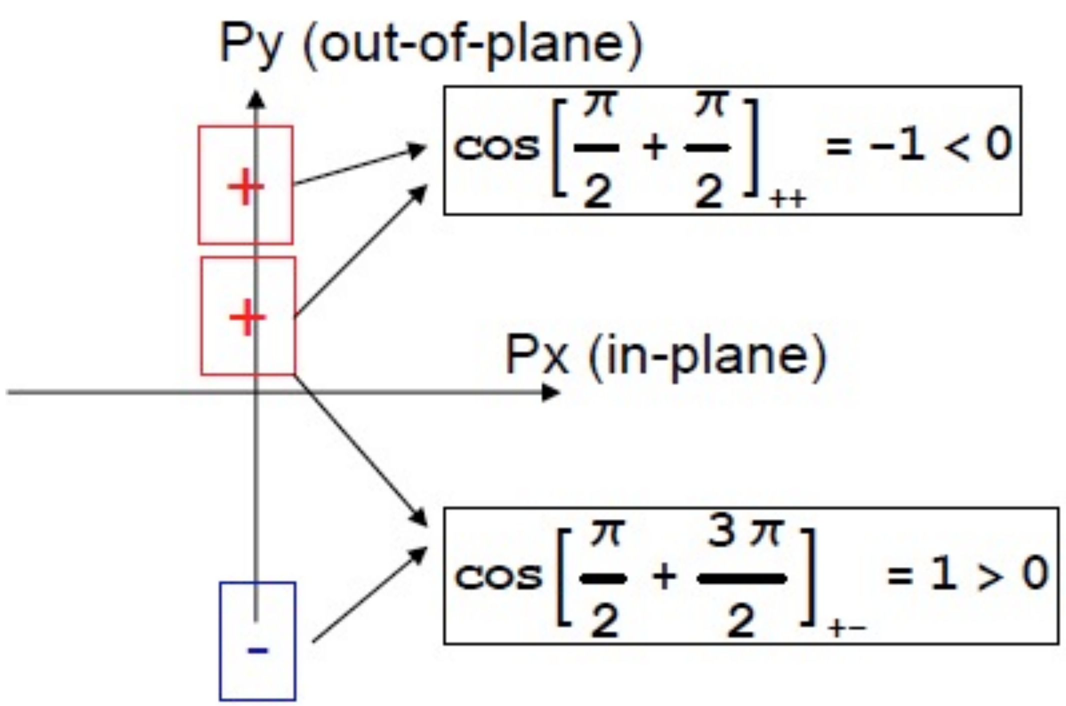


$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle = [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

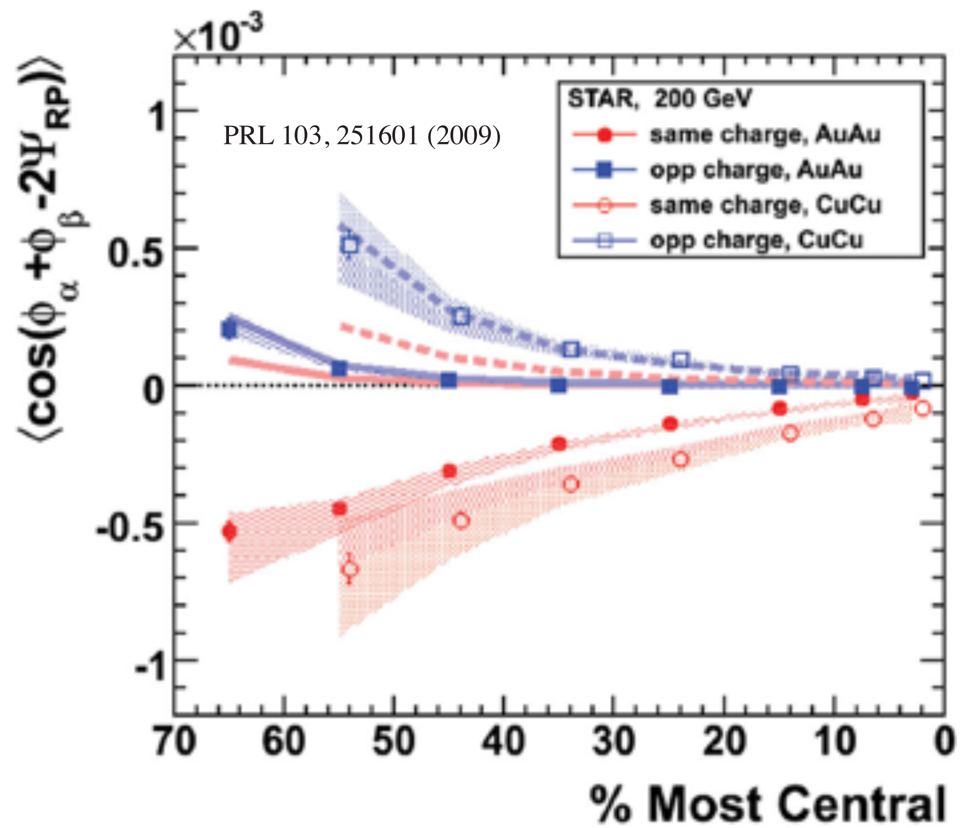
Non-flow/non-parity effects: largely cancel out

Directed flow: vanishes if measured in a symmetric rapidity range

P-even quantity: still sensitive to charge separation

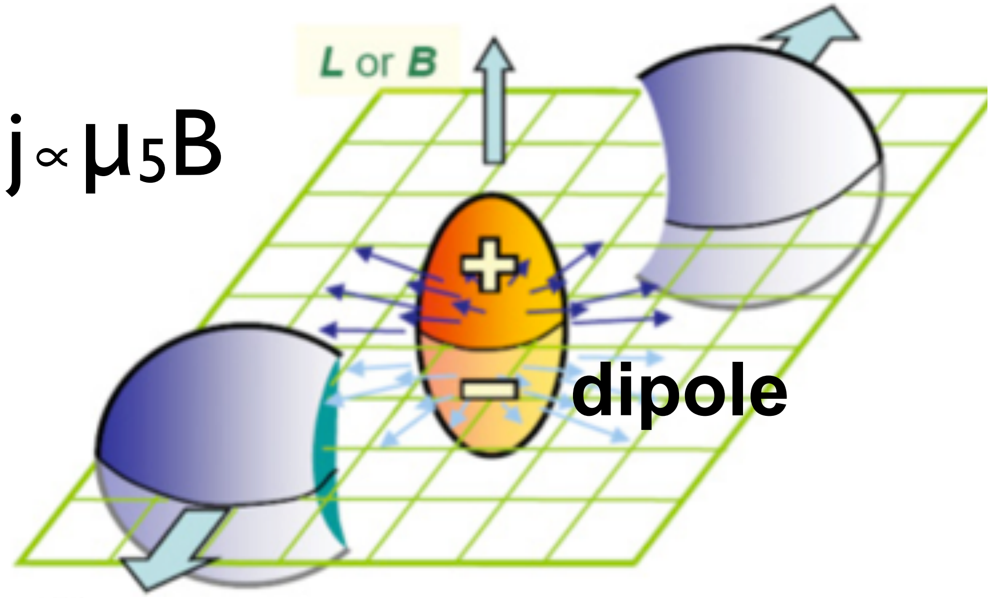


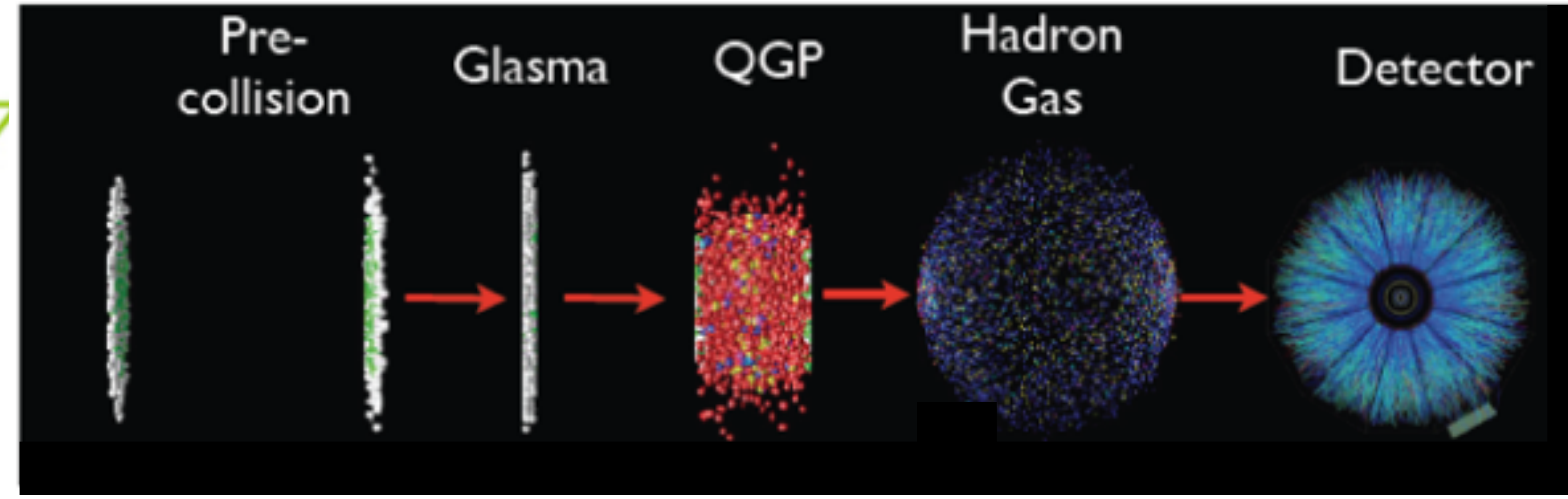
CME expectation

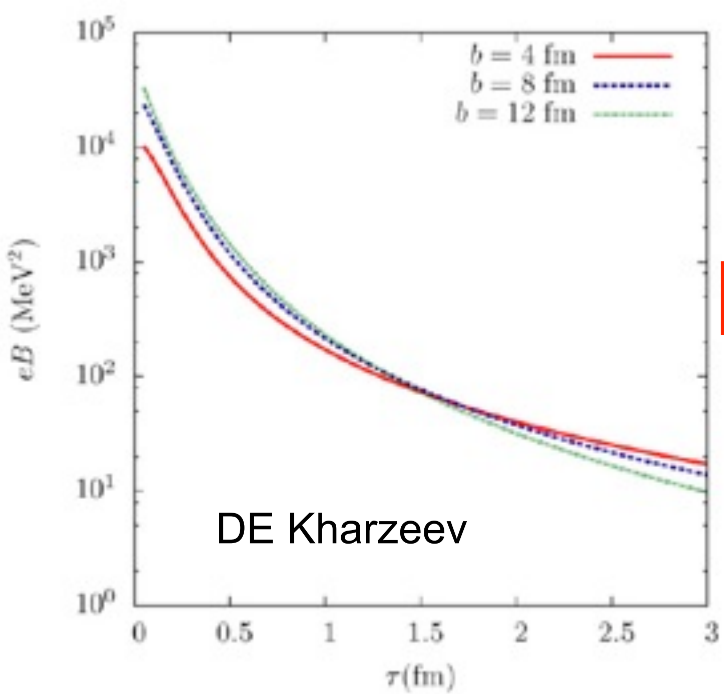


- The STAR data are consistent with the CME expectation. → Charges are distributed asymmetrically w.r.t reaction plane, i.e. dipole charge separation.

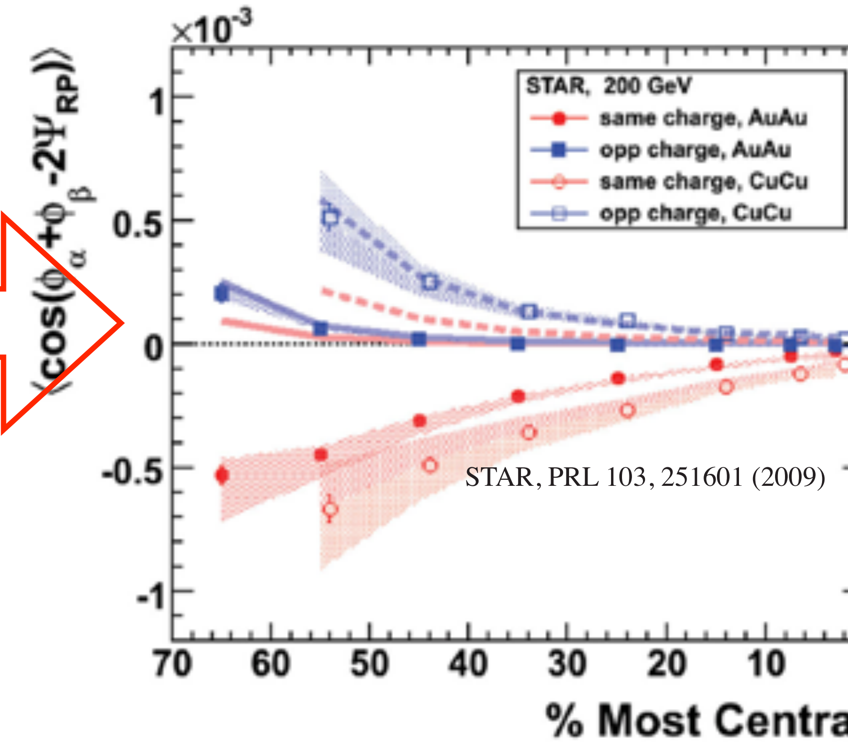
Can CME signal survive from final interactions?







final interaction effects

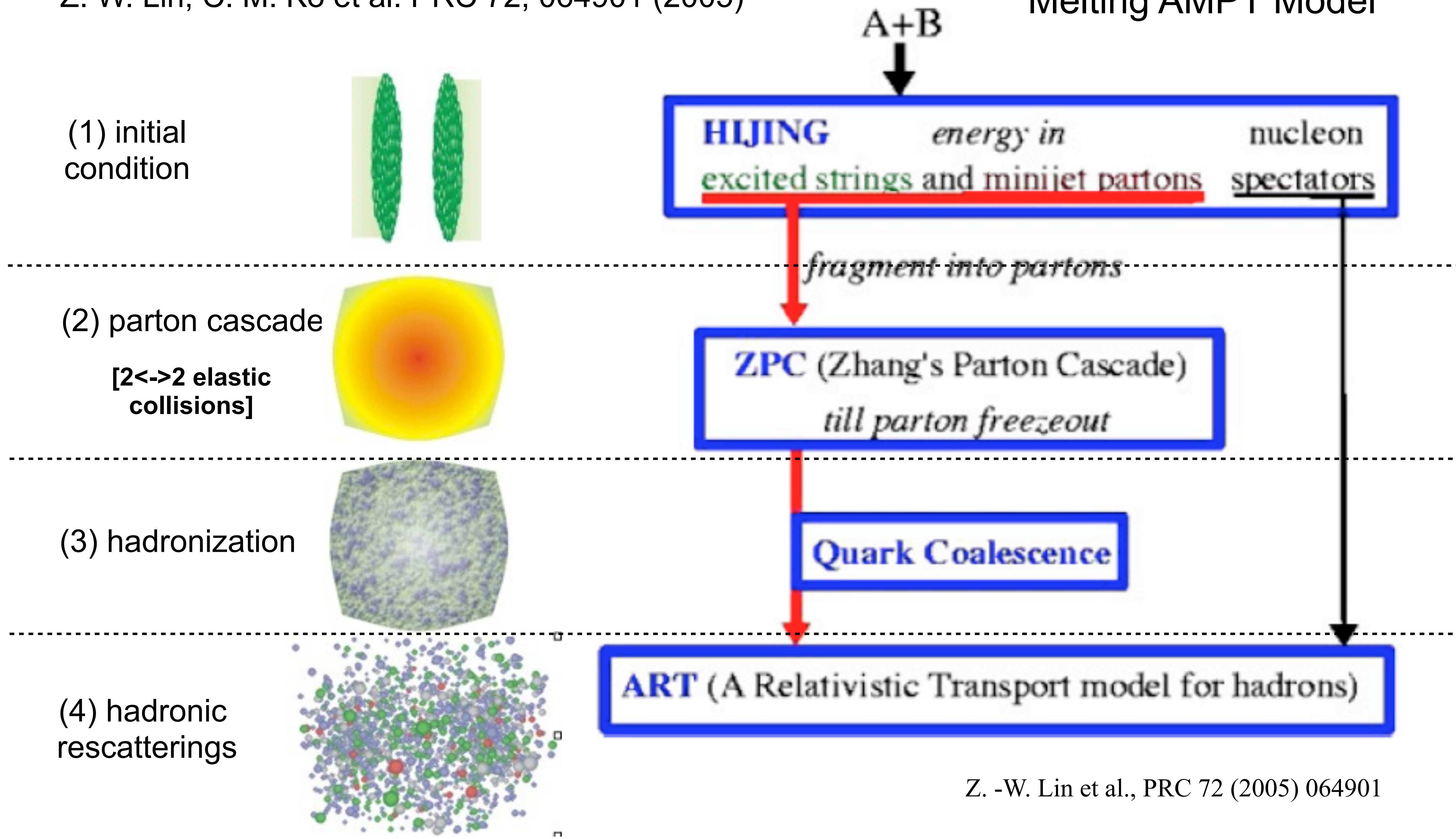


- The lifetime of B field is short. →The CME is an initial effect.
- Final state interaction effects on the CME is important.

A multiphase transport (AMPT) model

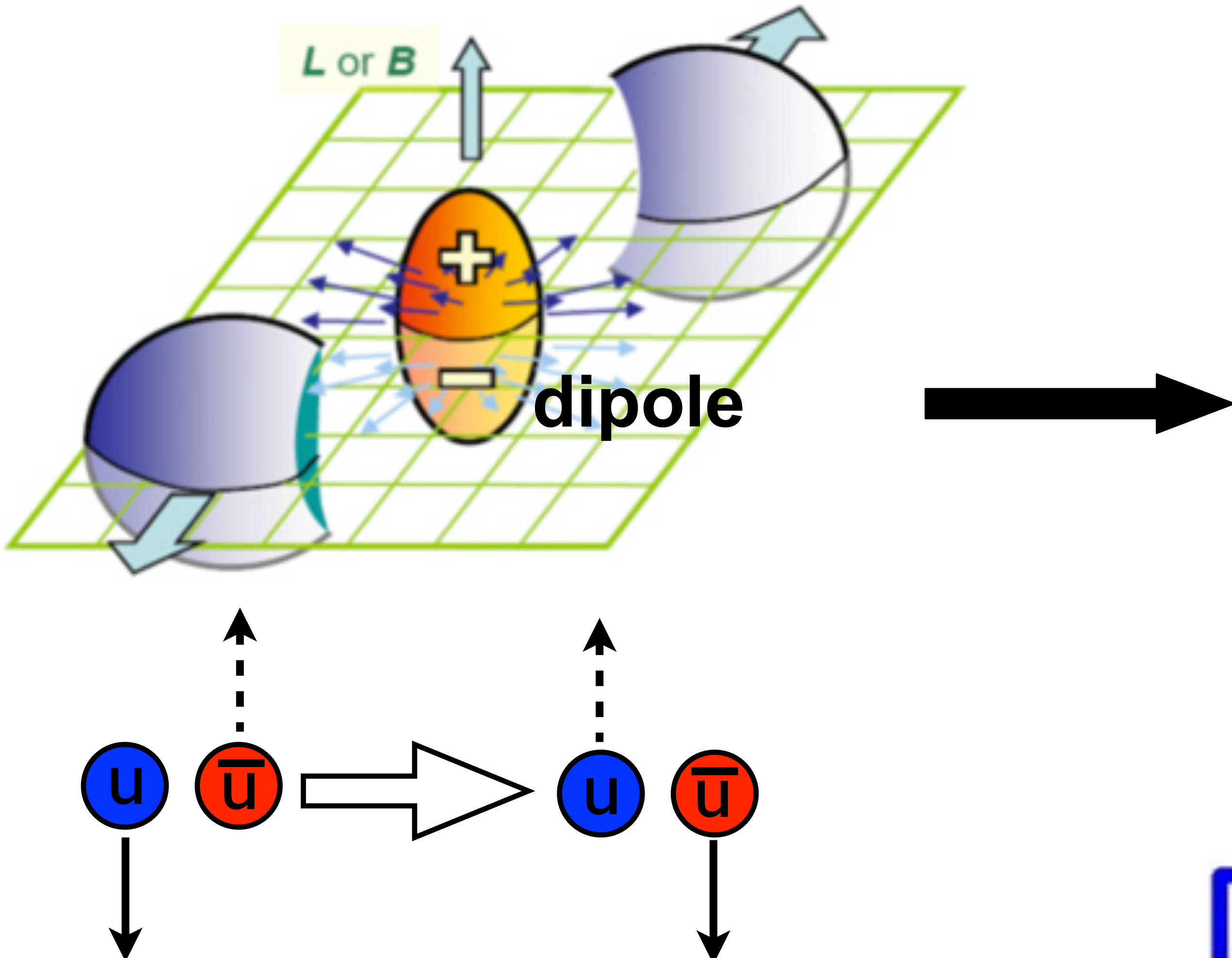
Z. W. Lin, C. M. Ko et al. PRC 72, 064901 (2005)

Melting AMPT Model

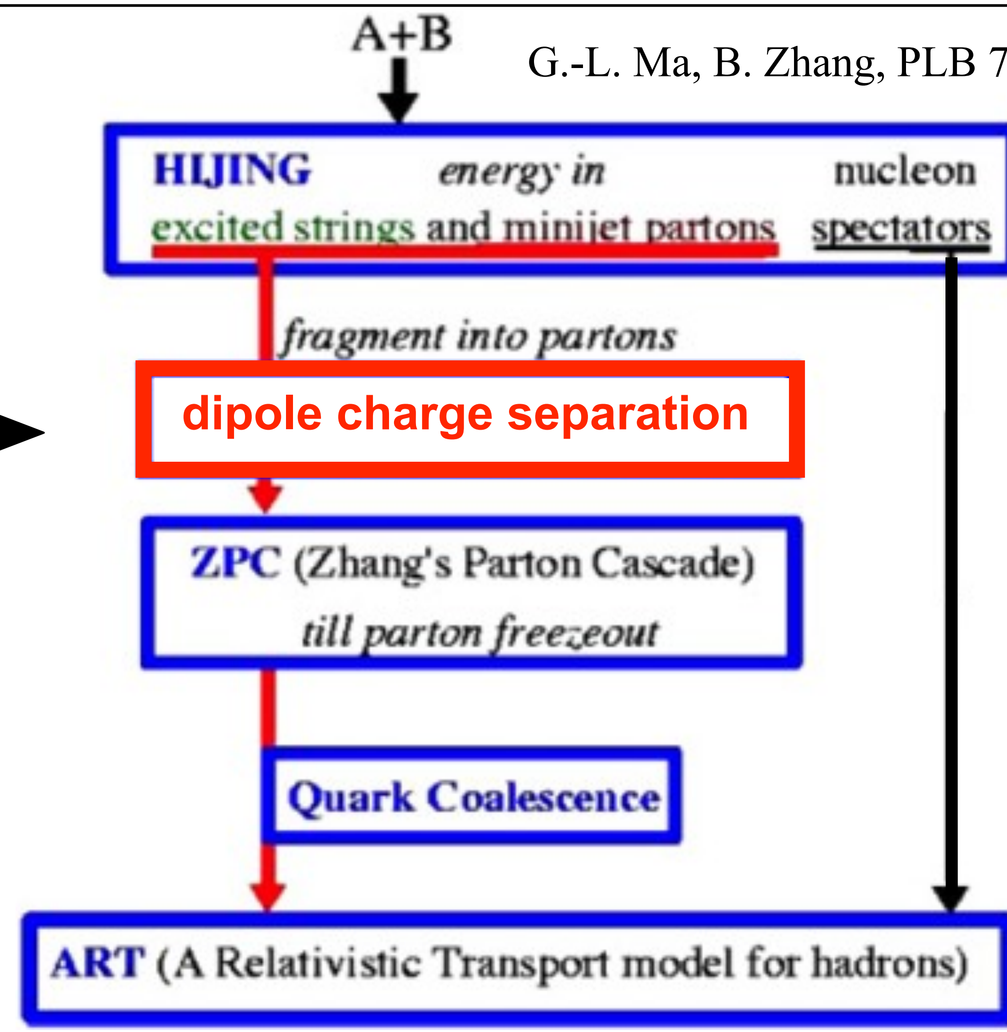


- Only resonance decays are employed to ensure charge conservation for now.

AMPT model with CME-like charge separation



G.-L. Ma, B. Zhang, PLB 700 (2011) 39



$f\% = (N^{+}_{upward} - N^{+}_{downward})/(N^{+}_{upward} + N^{+}_{downward})$

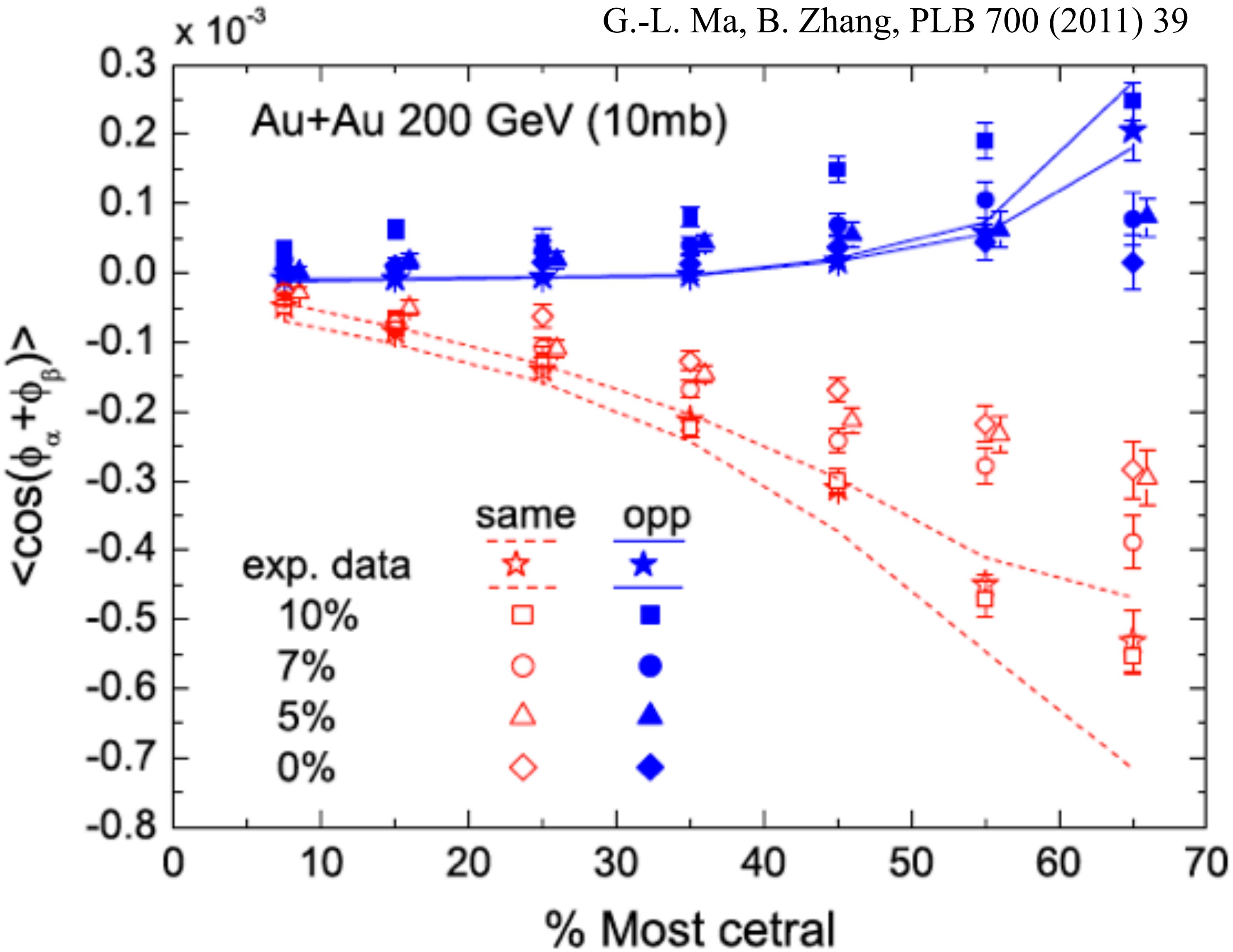
● **We include initial dipole charge separation mechanism into AMPT model.**

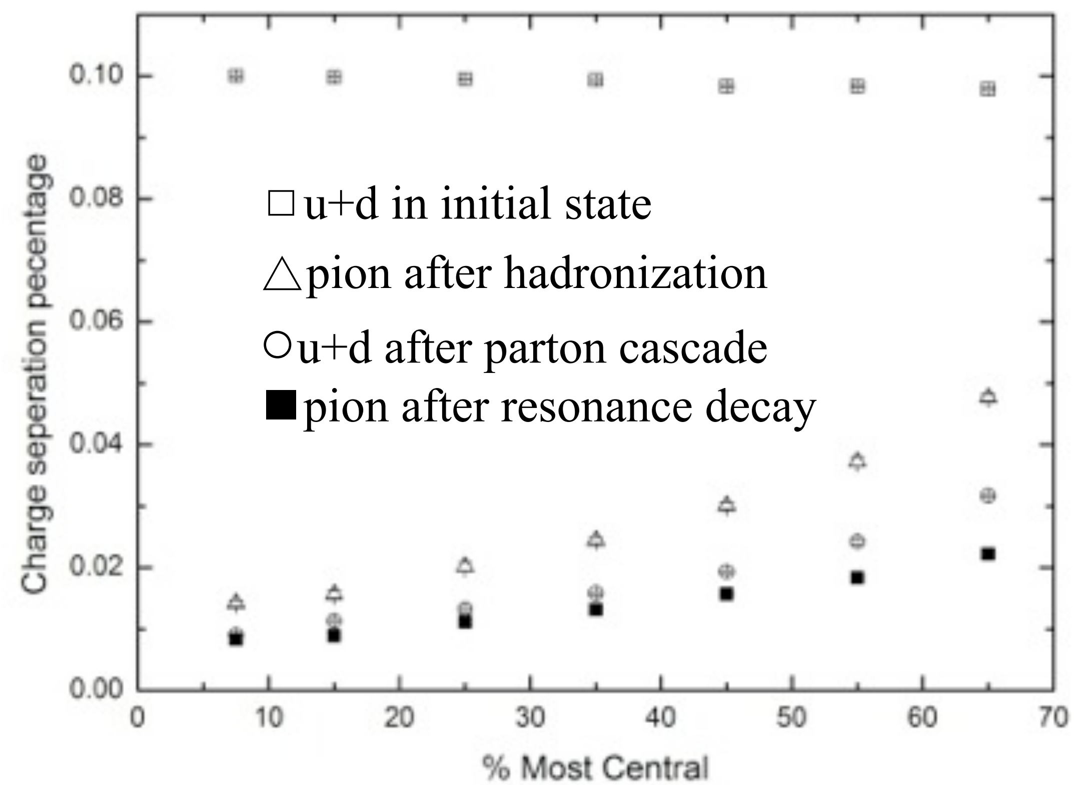
We switch the p_y values of a percentage of the downward moving u quarks with those of the upward moving u-bar quarks, and likewise for d-bar and d quarks, where the percentage is a relative ratio with respect to the total number of quarks.

● **We focus on final state effects on the charge separation, including parton cascade, hadronization, resonance decays after $\vec{B}$ and $\vec{E}$ vanish quickly.**

AMPT results on <cos(φα+φβ)> in Au+Au

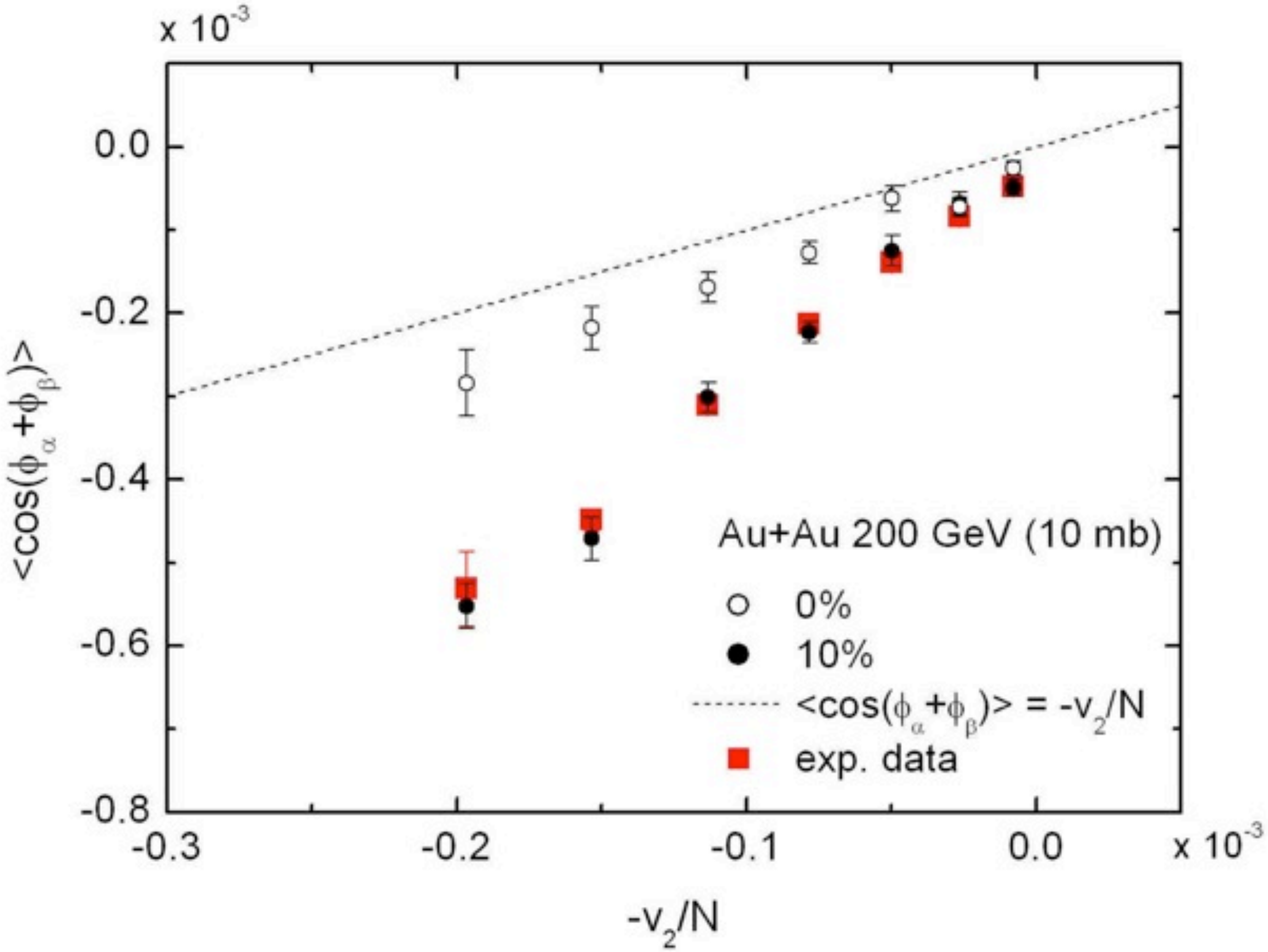
G.-L. Ma, B. Zhang, PLB 700 (2011) 39





- An initial charge separation ~10% can describe same-charge data in the presence of strong final state interactions.
- But ~10% only can describe opposite-charge correlation for 60-70%.
- From a percentage of charge separation of 10% in the beginning →1-2% percentage at the end.

CME vs trans. mom. conservation



- The AMPT result without CME is very close to the expectation of trans. mom. conservation [dashed: $<\cos(\varphi_\alpha+\varphi_\beta)>=-v_2/N$].

- TMC can partly account for data, and an initial 10% dipole charge separation are needed.**=> CME+TMC (+LCC)~ experimental data**

isobar collisions : a new probe to test CME

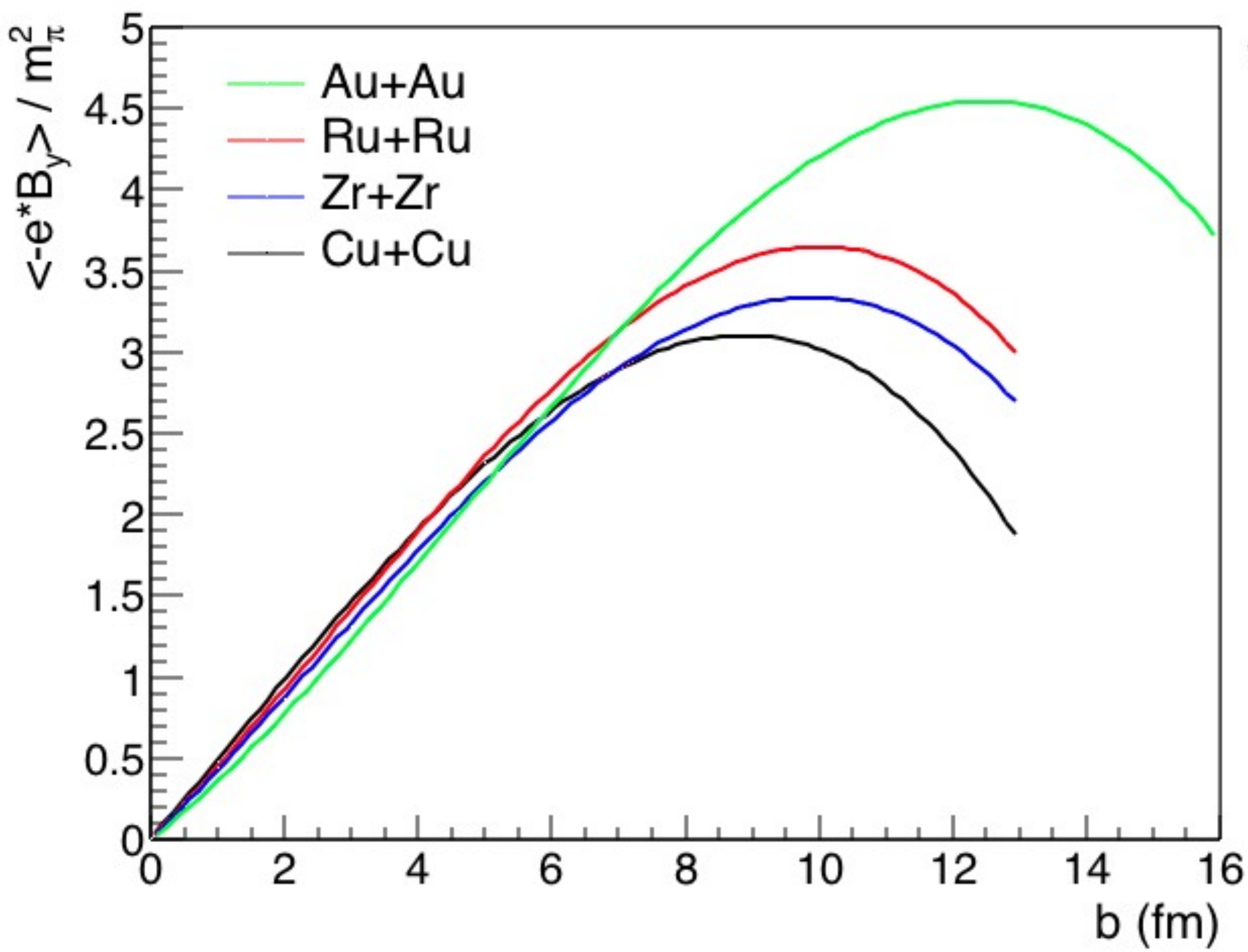
— $^{96}_{40}$Zirconium vs $^{96}_{44}$Ruthenium

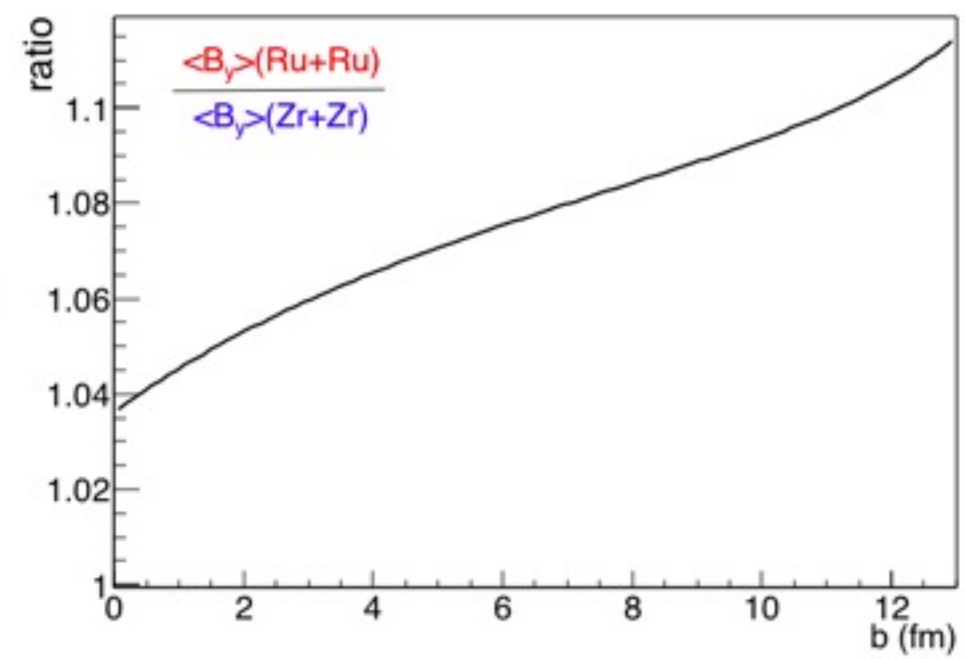
Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

	$^{96}_{44}$Ru+$^{96}_{44}$Ru vs $^{96}_{40}$Zr+$^{96}_{40}$Zr
Flow	~
CME	>
CMW	>

•**RHIC plans to collide isobars (96Zr+96Zr and 96Ru+96Ru) at 200 GeV in Run-18 (2017-2018).**

b-dependent Magnetic field



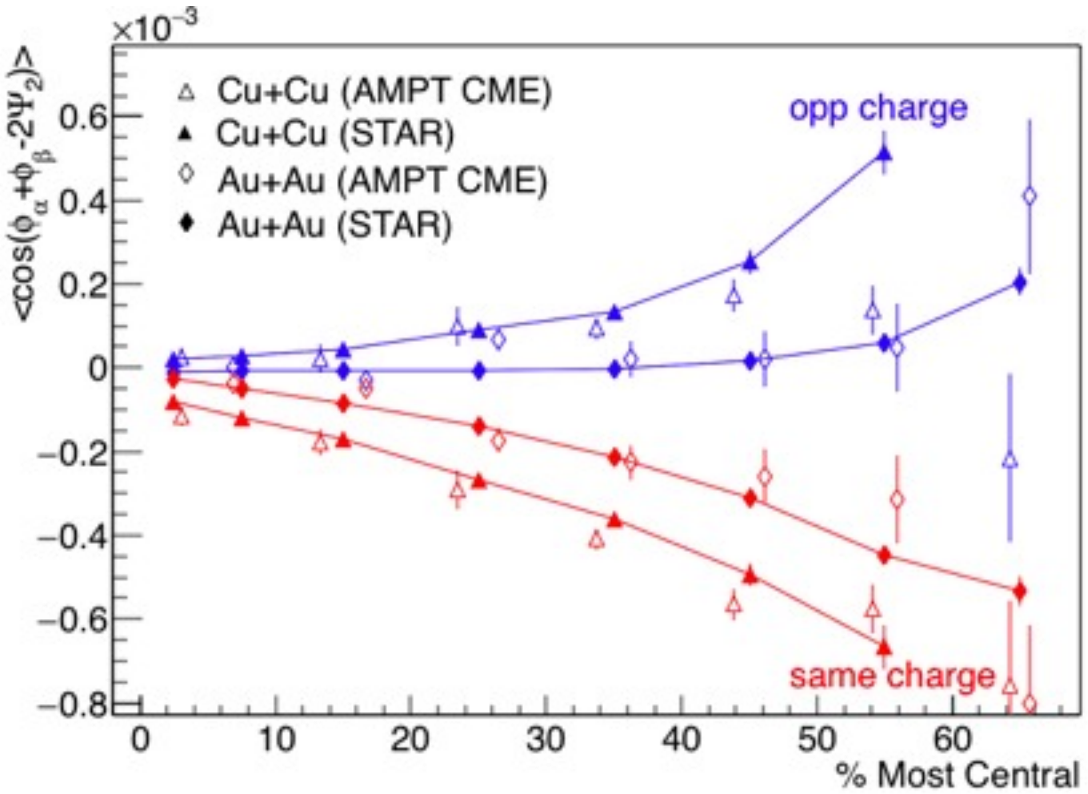


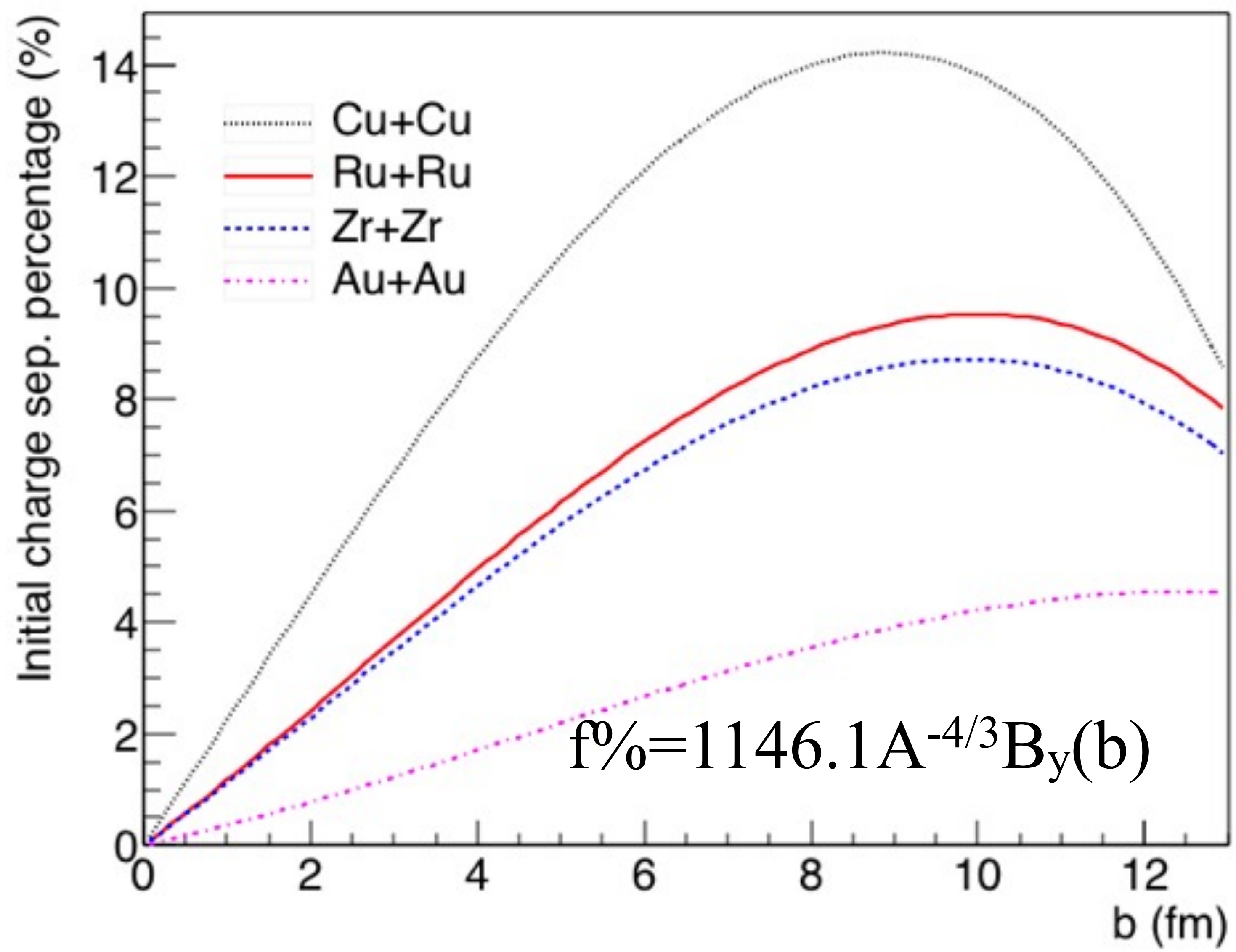
Lienard-Wiechert potentials:

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

- b dependence of averaged $<B_y>$ for Ru+Ru and Zr+Zr, and other systems.
- $<B_y>$(Ru+Ru) is larger than $<B_y>$(Zr+Zr) by 10% at large b.

b-dependent initial charge sep. percent

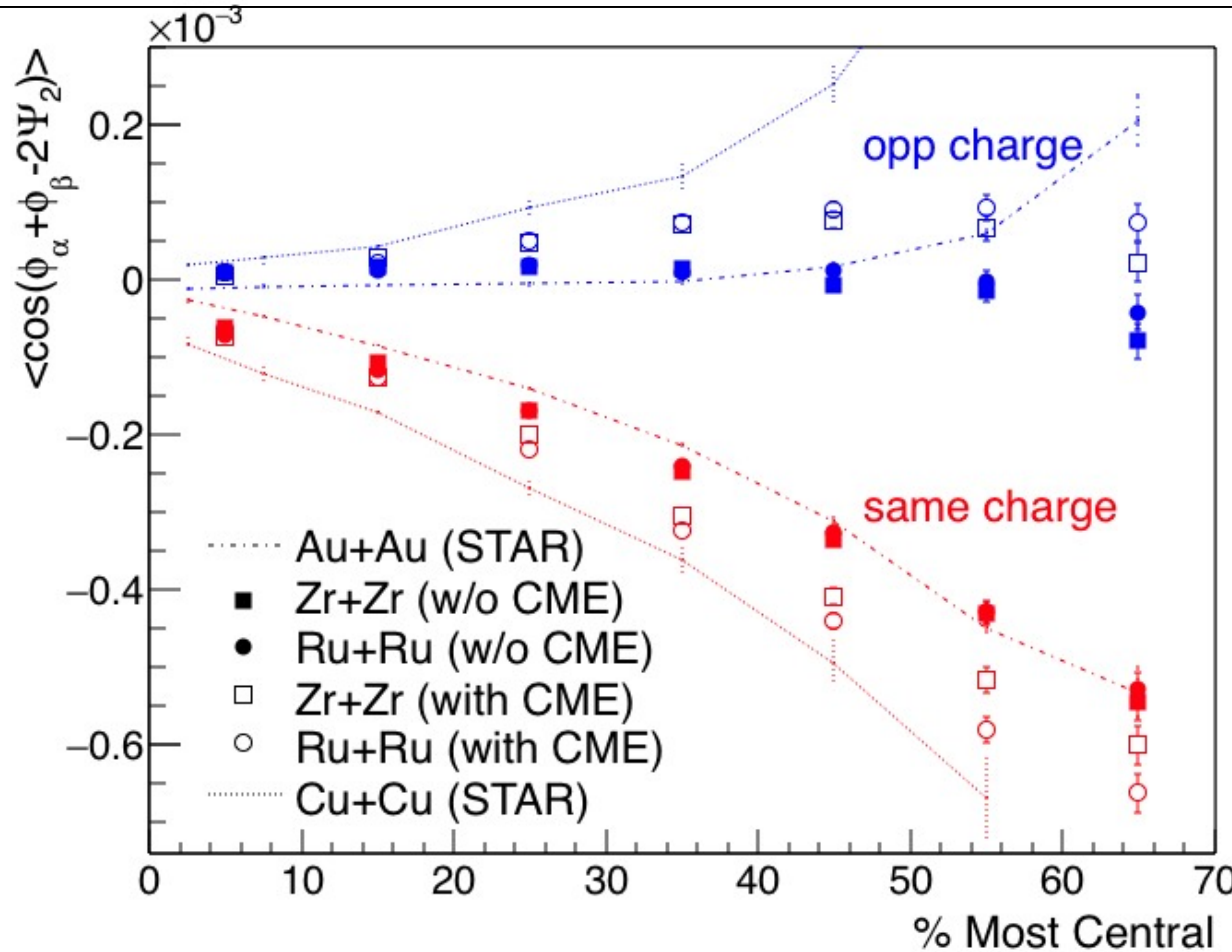




$f\% = (N^{+}_{upward} - N^{+}_{downward})/(N^{+}_{upward} + N^{+}_{downward}) \sim J\pi R^2/N_{mult} \sim A^{-4/3}B_y$

- We apply **$f\% = 1146.1A^{-4/3}B_y(b)$** to introduce the initial charge separation into Ru+Ru and Zr+Zr, by fitting the STAR data of Au+Au and Cu+Cu.

AMPT results on <cos(ϕa+ϕβ-2ψ2)> in isobar collisions



- If CME, a magnitude ordering that Au+Au < Zr+Zr < Ru+Ru < Cu+Cu.
- The CME difference due to different B fields between Zr+Zr and Ru+Ru can be seen, even with considering FSI effects.

Summary

- The initial CME results from QCD vacuum fluctuations+large B field.

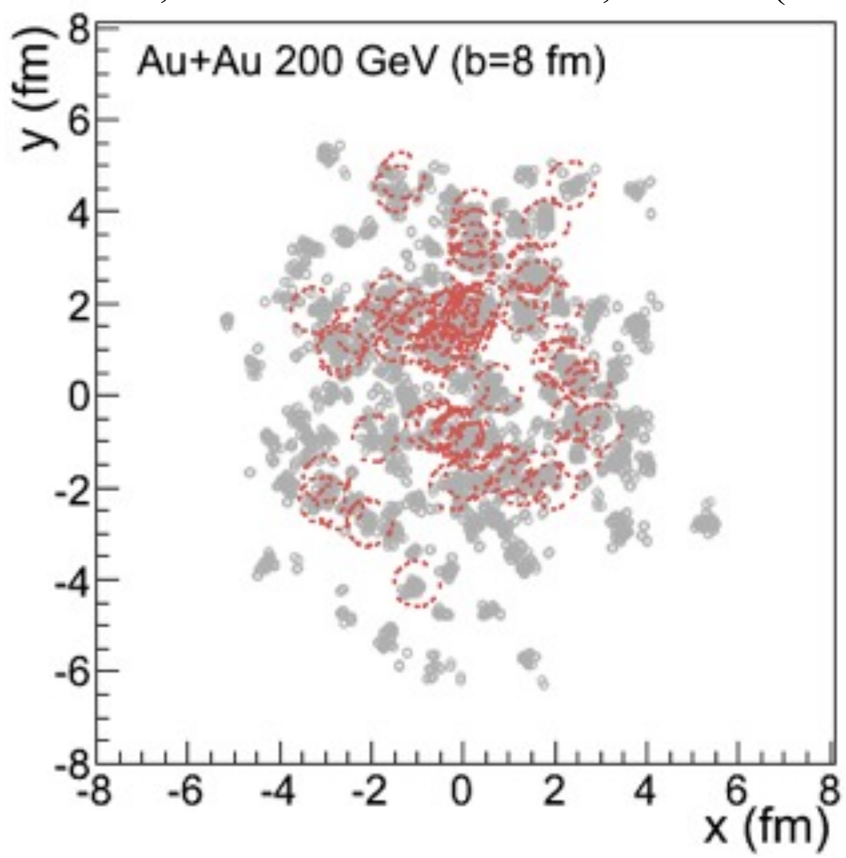
- Final state interactions reduce the CME signal, so the percentage of initial CME charge separation should be larger than that without FSI.

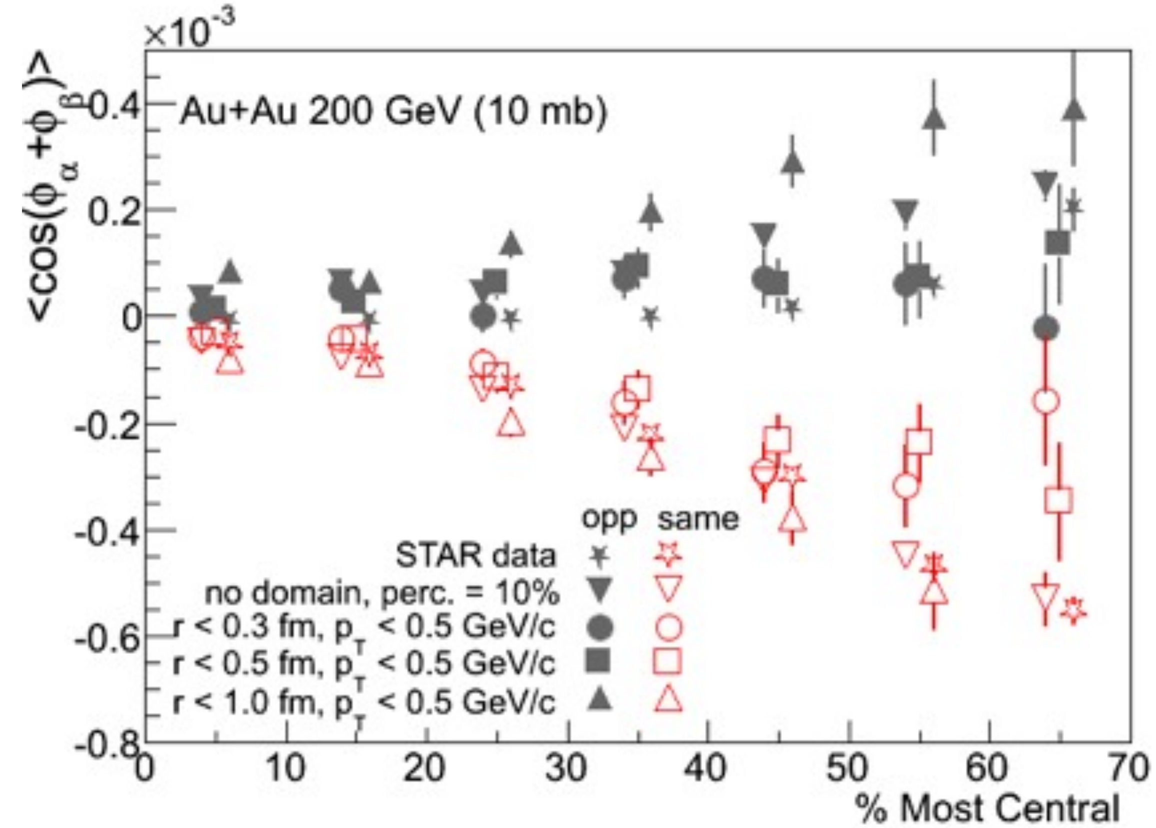
- Isobaric collisions will be a good test to directly see CME difference due to different B fields.

Thanks for your attention!

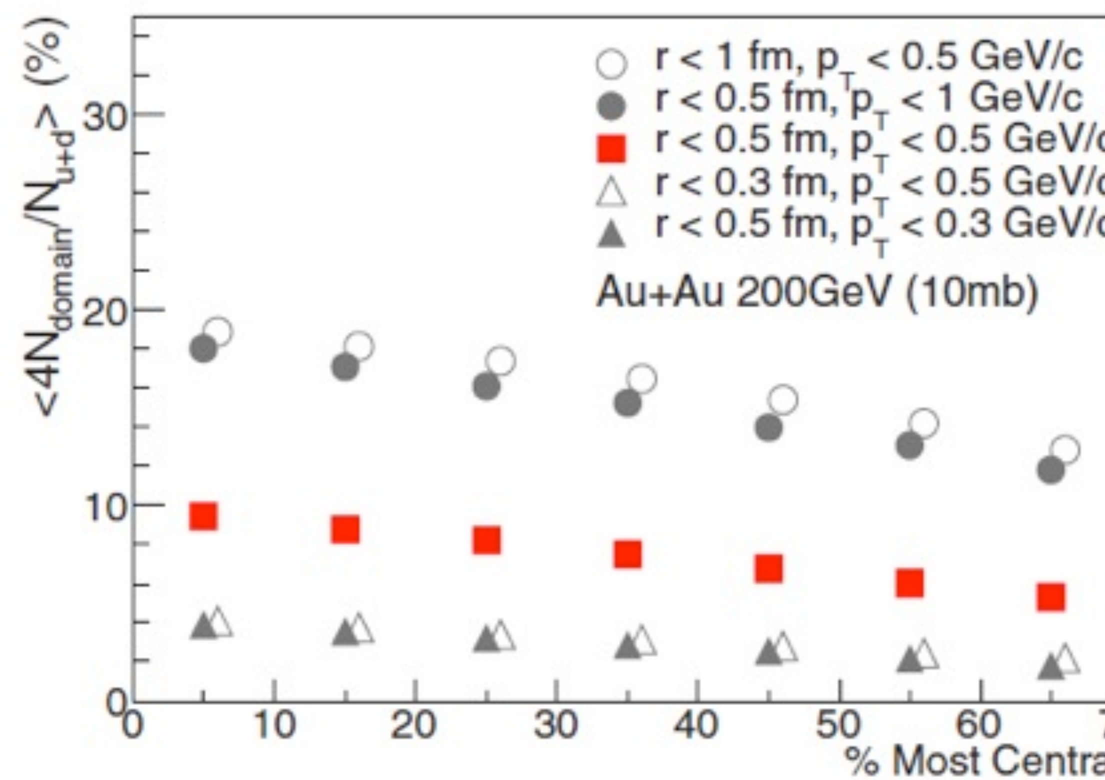
$\langle\cos(\varphi_\alpha+\varphi_\beta)\rangle$ from AMPT with local CME

Q. -Y. Shou, G.-L. Ma and Y. -G. Ma, PRC 90 (2014) 047901

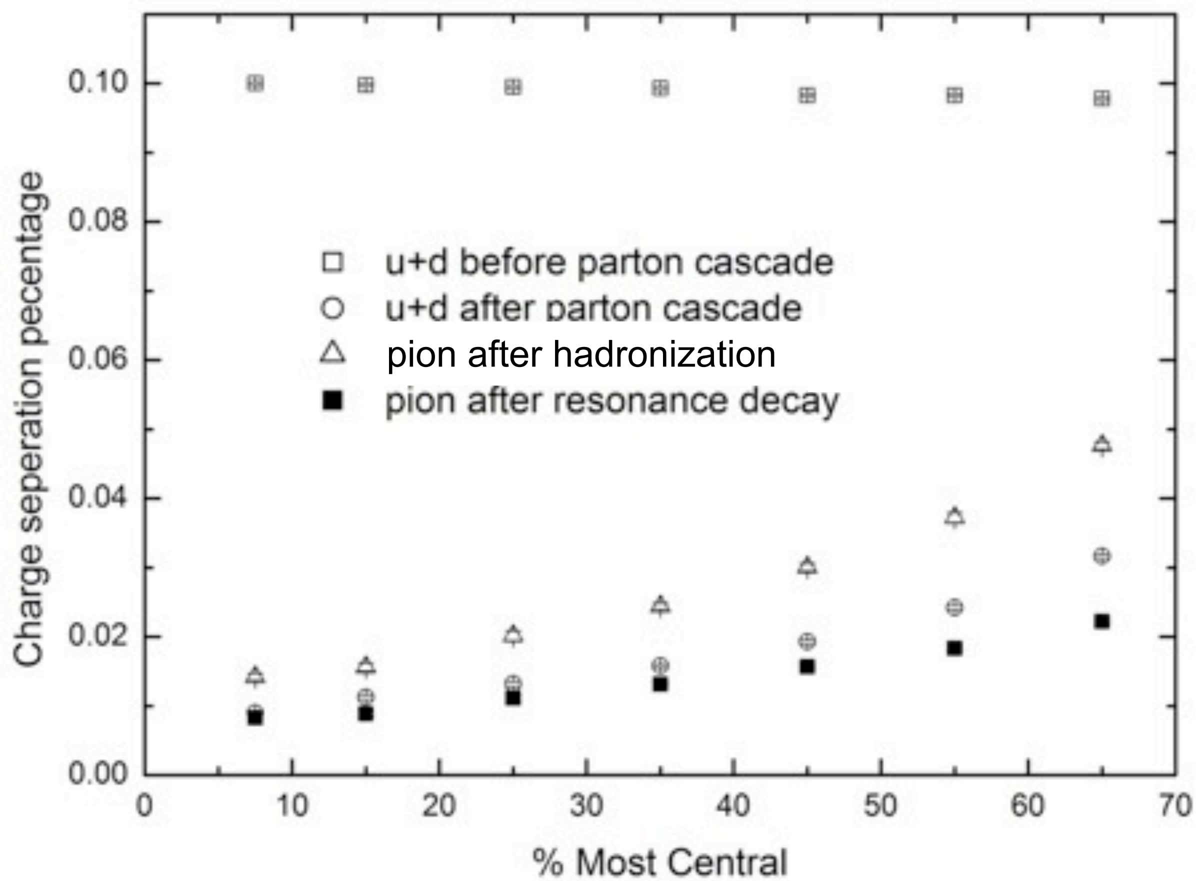


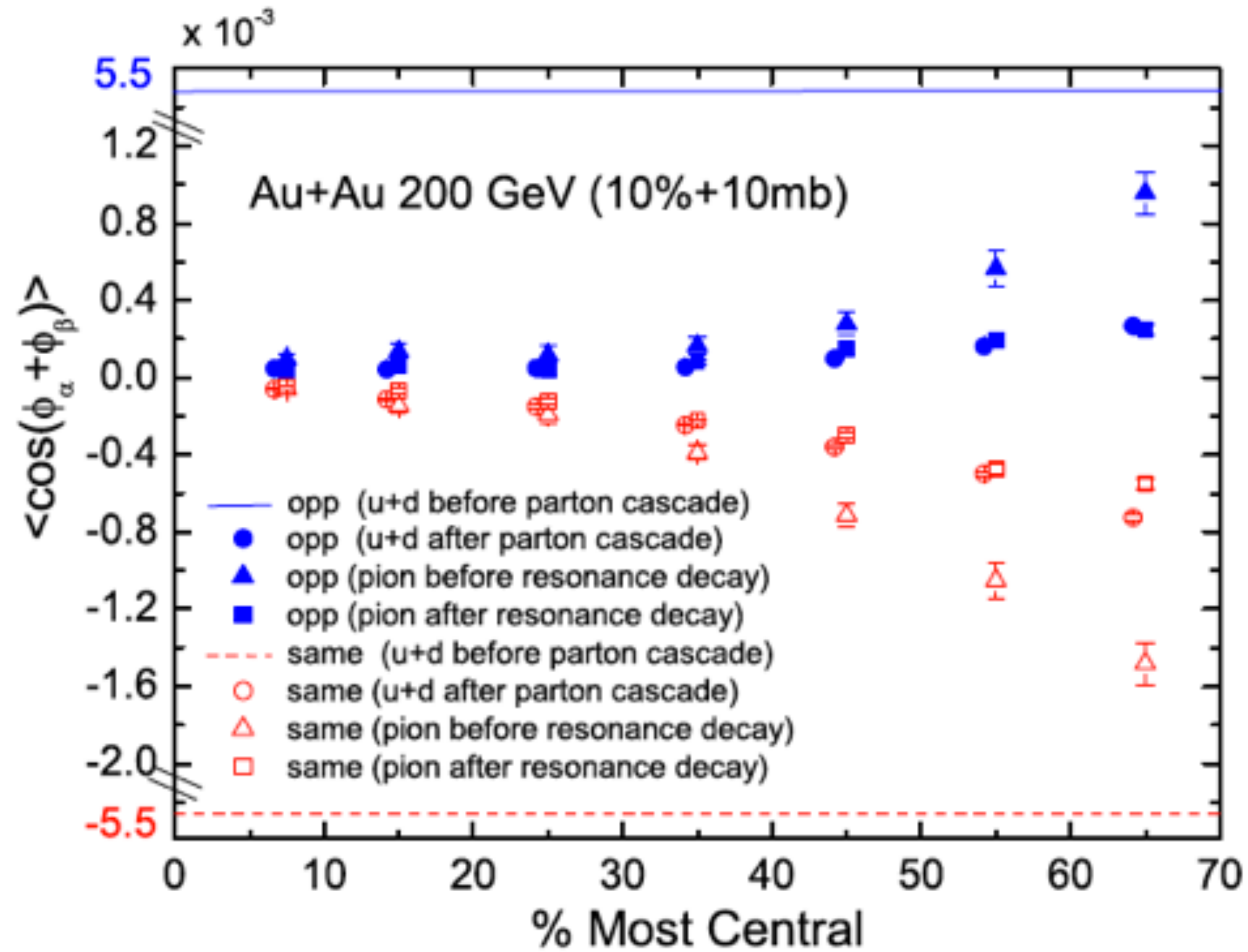


- A domain-based charge separation better describe the STAR data.
- The domain rate is consistent with the charge separation percentage in the global case.



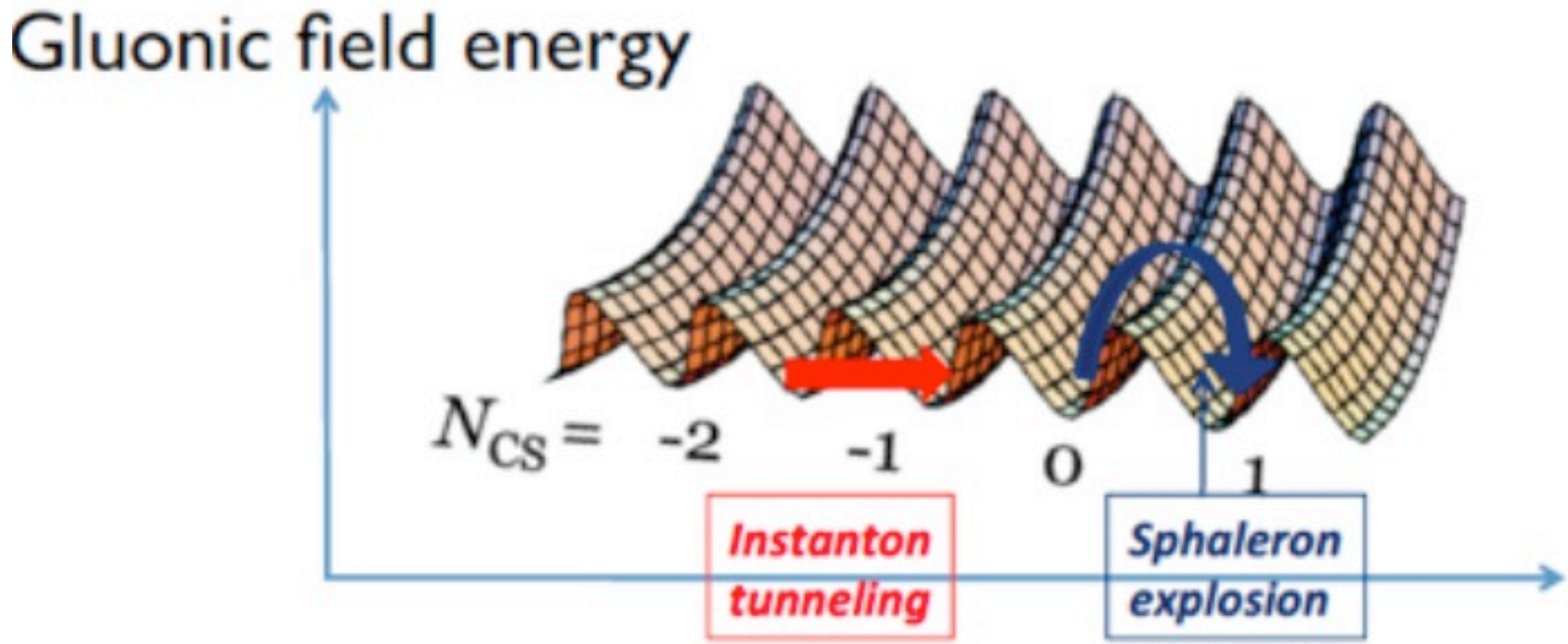
Final state effects on <cos($\varphi_\alpha+\varphi_\beta$)>





- Parton cascade reduces charge separation significantly.
- Coalescence recovers some charge separation in part because it reduces the number of particles after combining quarks into hadrons.
- Resonance decays reduce charge separation, where local charge conservation washes out the magnitude of opposite-charge correlation.

Topological structure of QCD vacuum



$$N_{CS} = \frac{1}{16\pi^2}\int d^3x\epsilon^{ijk}\left(A_i^a\partial_j A_k^a + \frac{1}{3}\epsilon^{abc}A_i^a A_j^b A_k^c\right)$$

$$\boxed{Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F_{\mu\nu}^a \tilde{F}_a^{\mu\nu}} \sim \vec{E}^a \cdot \vec{B}^a$$

P & CP ODD