Quantifying Chiral Magnetic Effect in IsoBaric Collisions at RHIC

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Y.Jiang, SS, Y.Yin & J.Liao, arXiv:1611.04586
SS. Y.Jiang, E.Lilleskov, Y.Yin & J.Liao, arXiv:1704.05531
SS. Y.Jiang, E.Lilleskov & J.Liao, in final preparation

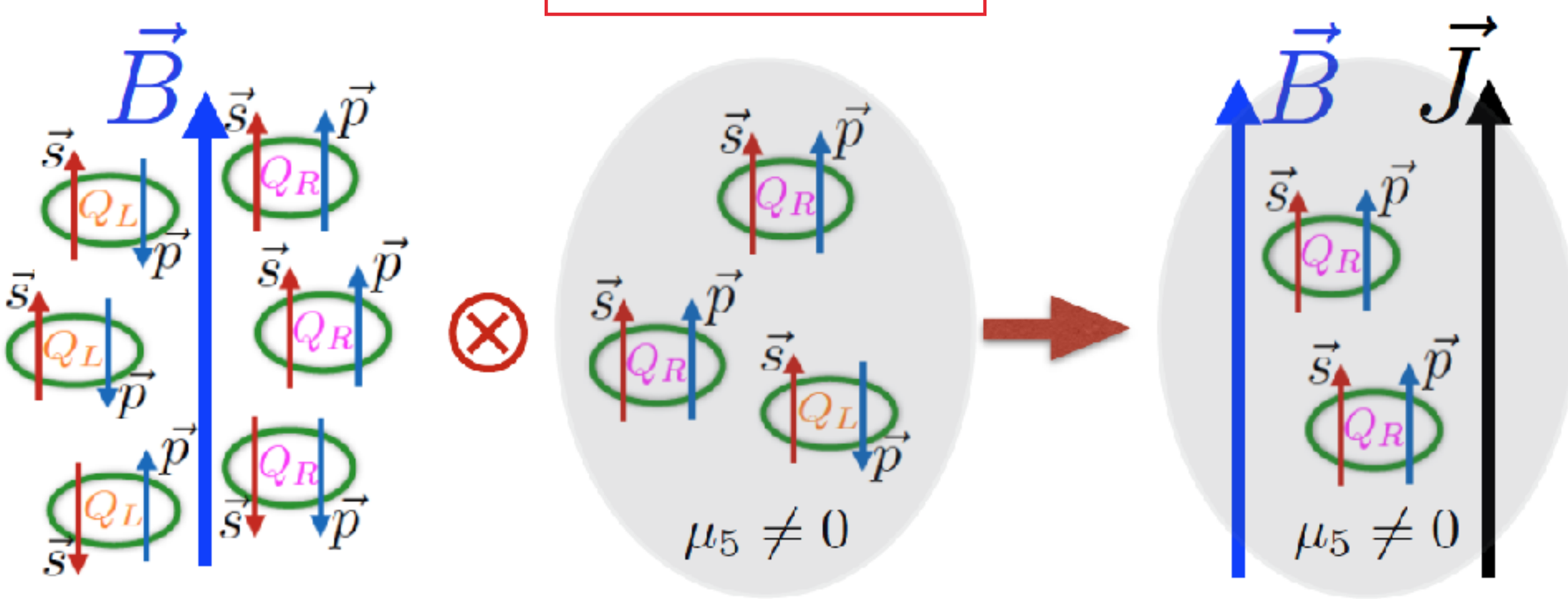
Outline

- Chiral Magnetic Effect (CME)
- How do we study CME quantitatively ← Anomalous-Viscous Fluid Dynamics
- CME from Anomalous-Viscous Fluid Dynamics
  - Au-Au Collisions
  - Isobaric Collisions

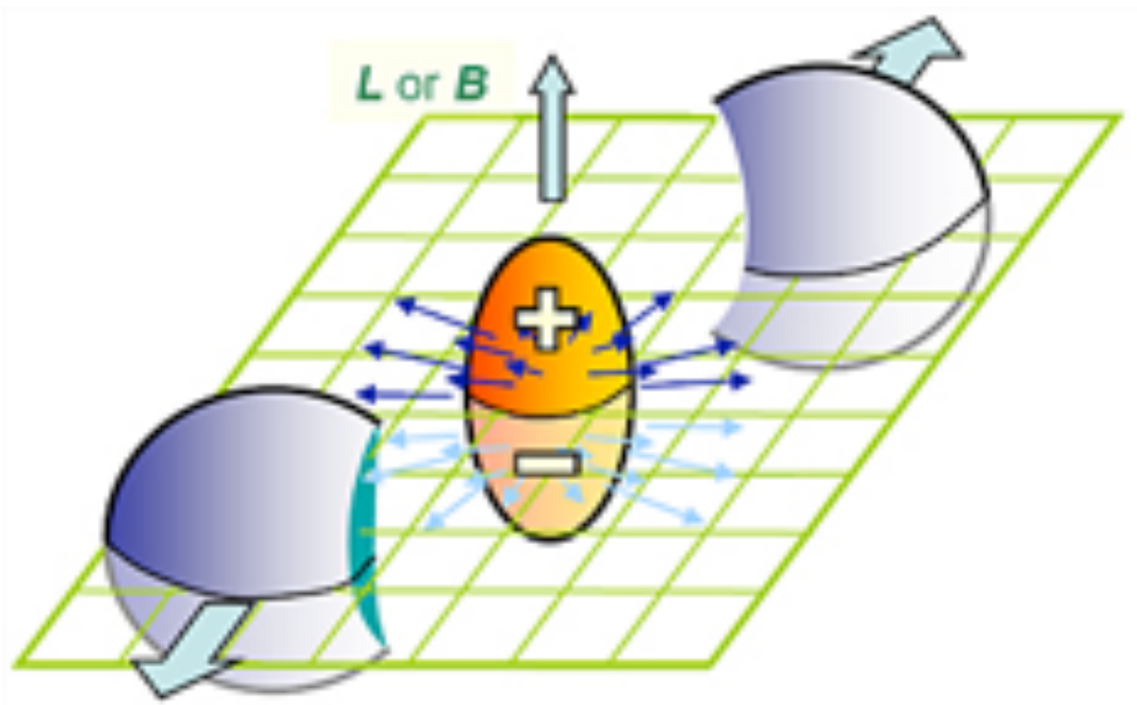
Chiral Magnetic Effect

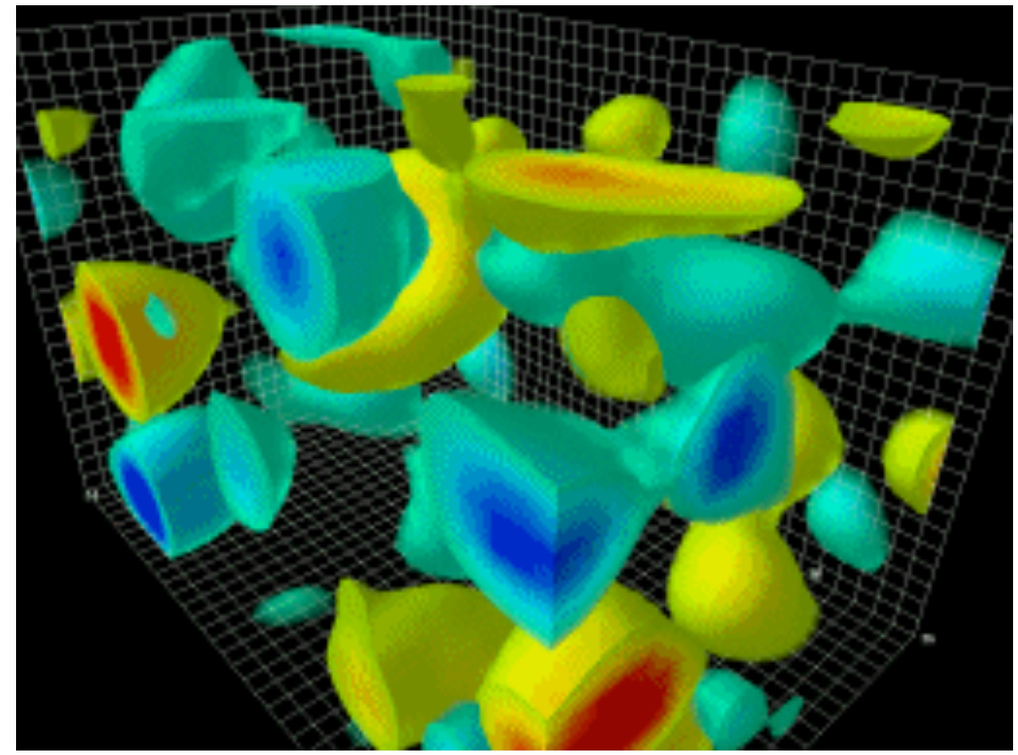
Chiral magnetic effect (CME) is the generation of electric current along an external magnetic field induced by chirality imbalance.

$$\boldsymbol{J} = \sigma_5 \, \mu_5 \, \boldsymbol{B}$$



Chiral Magnetic Effect In Heavy Ion Collision





$eB \sim 5\ m_\pi^2$

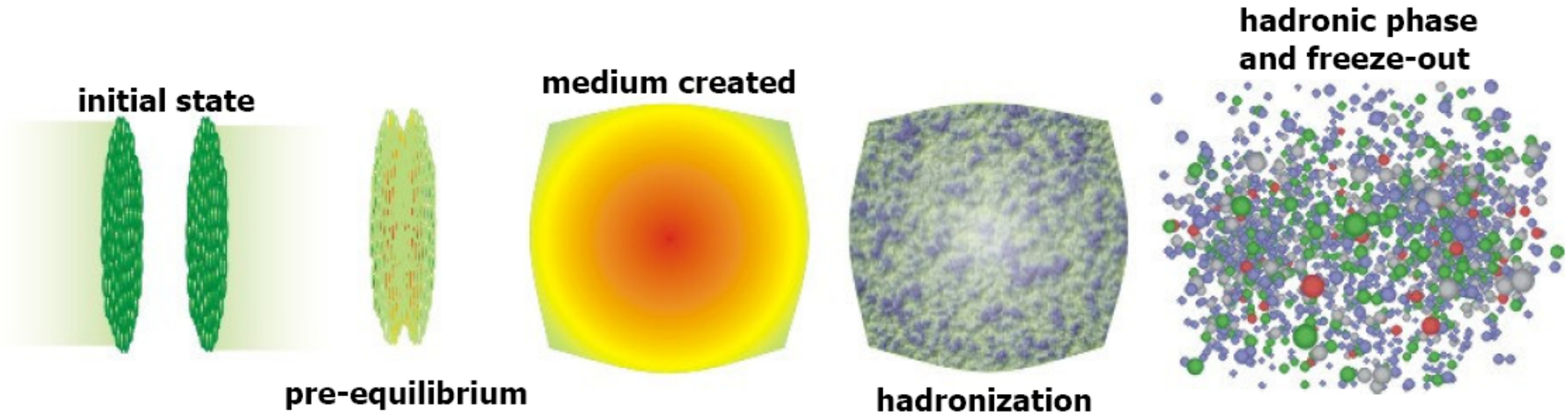
$(B \sim 10^{15}\ T)$

$\otimes$

QCD Vacuum

$$Q_w = \frac{g^2}{32\pi^2} \int d^4x\, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

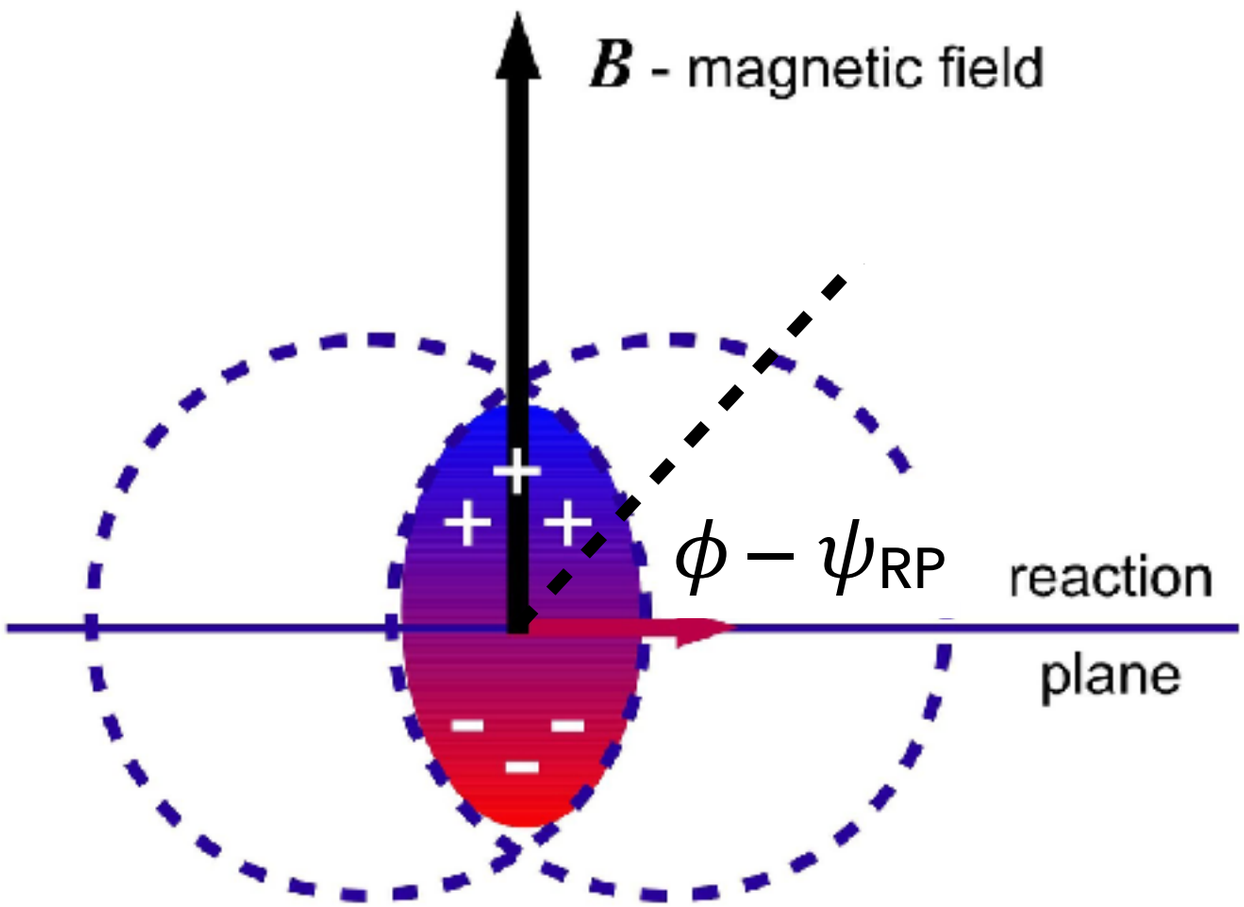
Chiral Magnetic Effect In Heavy Ion Collision



Chiral Magnetic Effect In Heavy Ion Collision

- B field $\otimes$ μ_5 $\Rightarrow$ current $\Rightarrow$ dipole (charge separation)

$$dN_{\pm}/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$



$\langle \mu_5 \rangle = 0 \;\Rightarrow\; \langle a_1 \rangle = 0$

Chiral Magnetic Effect In Heavy Ion Collision

- B field $\otimes$ μ_5 $\Rightarrow$ current $\Rightarrow$ dipole (charge separation)

$$dN_{\pm}/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$

- charge separation $\Rightarrow$ two particle correlation

$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

CME: $(a_{1\pm})^2$

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$$\gamma = \kappa\, v_2\, F - H$$

$$\delta = F + H$$

F: Bulk Background

H: Possible Pure CME Signal = $(a_{1,CME})^2$

$\kappa = 1 \sim 2$

$\kappa = 1.2$ From AMPT Simulation

Chiral Magnetic Effect In He

- B field ⊗ μ_5 ⇒ current =

$$dN_{\pm}/d\phi \propto 1 + 2\, a_{1\pm}$$

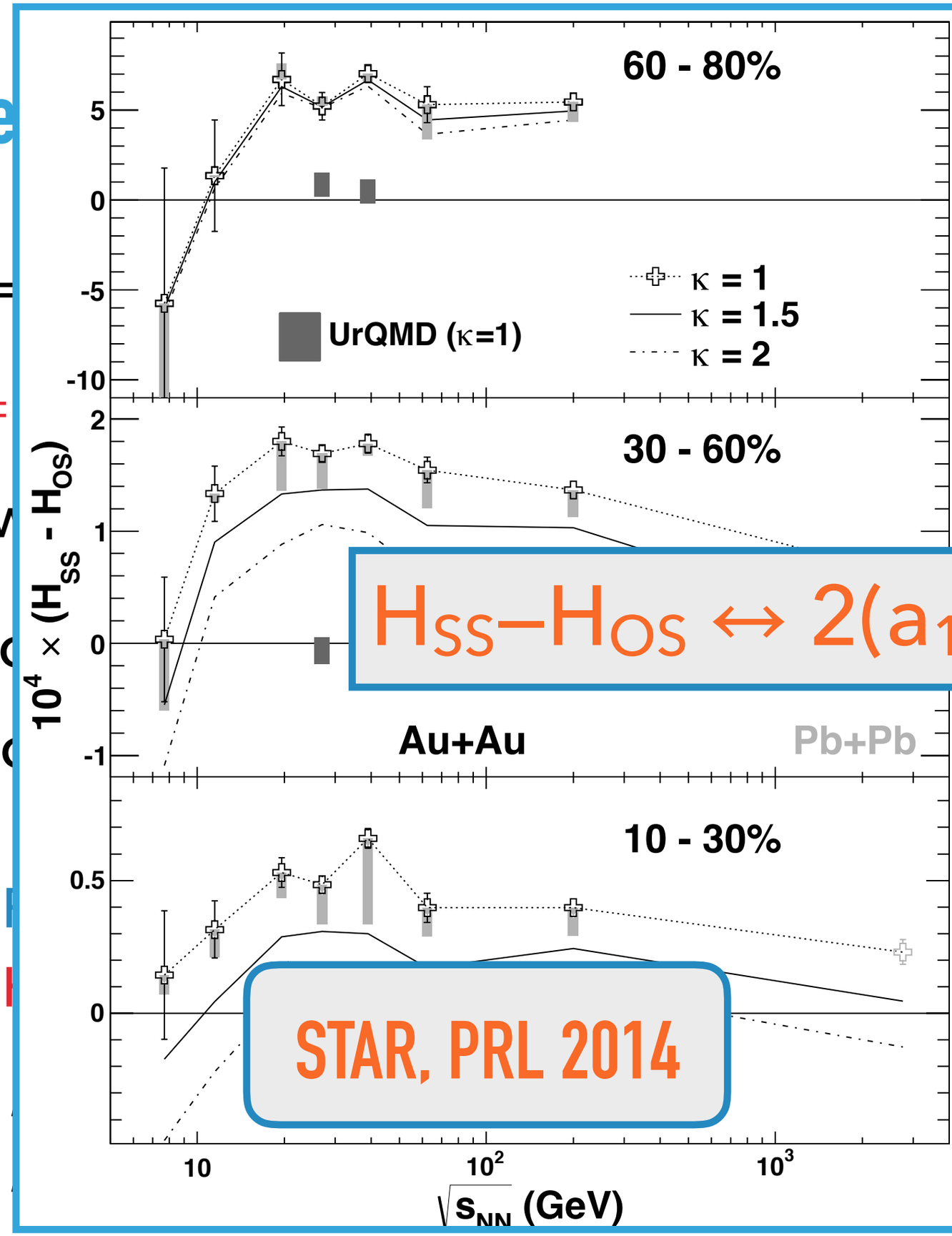
- charge separation ⇒ tw

$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle = \langle c$$

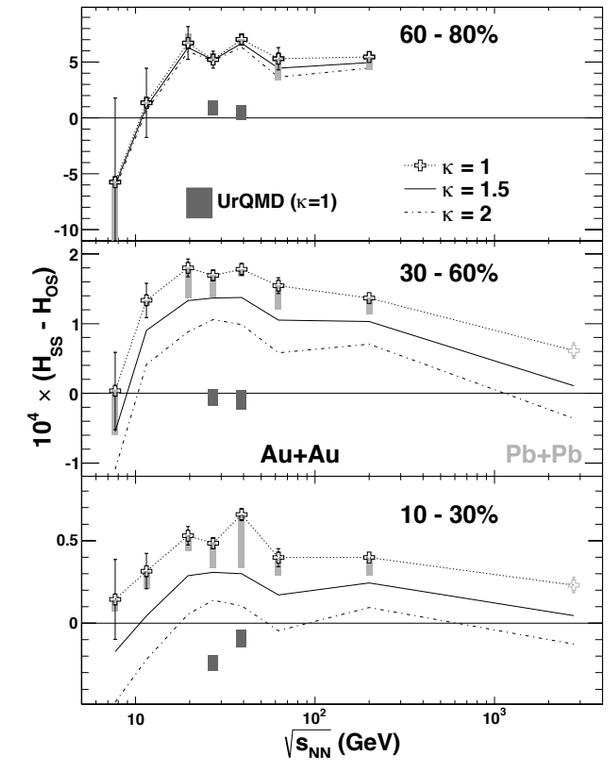
$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle c$$

$$\gamma = \kappa\, v_2\, F - H$$

$$\delta = F + H$$



How Can We Calculate CME Quantitatively?



axial (& vector) charge density

Anomalous
-**V**iscous
Fluid
Dynamics

initial condition

+

driving force

B field

dynamical evolution

final particle distribution

M.Hongo, Y.Hirono, T.Hirano, 2013;
H.-U.Yee, Y.Yin, 2014;
Y.Hirono, T.Hirano, D.Kharzeev, 2014;
Y.Yin, J.Liao, 2016;

Anomalous-Viscous Fluid Dynamics

$$D_\mu J_R{}^\mu = +\frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L{}^\mu = -\frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R{}^\mu = n_R\, u^\mu + \nu_R{}^\mu + \frac{N_c q}{4\pi^2}\, \mu_R\, B^\mu$$

$$J_L{}^\mu = n_L\, u^\mu + \nu_L{}^\mu - \frac{N_c q}{4\pi^2}\, \mu_L\, B^\mu$$

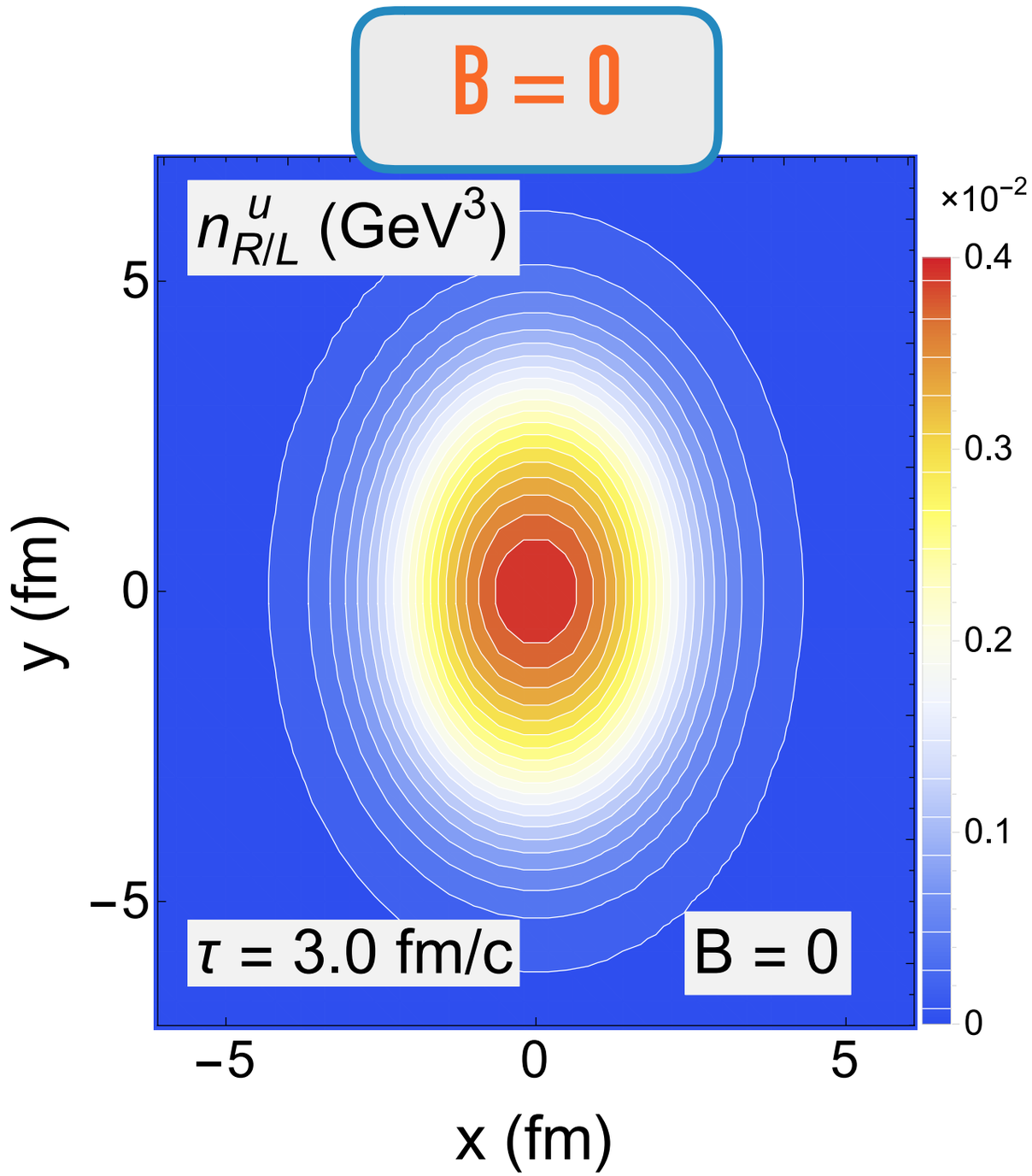
CME

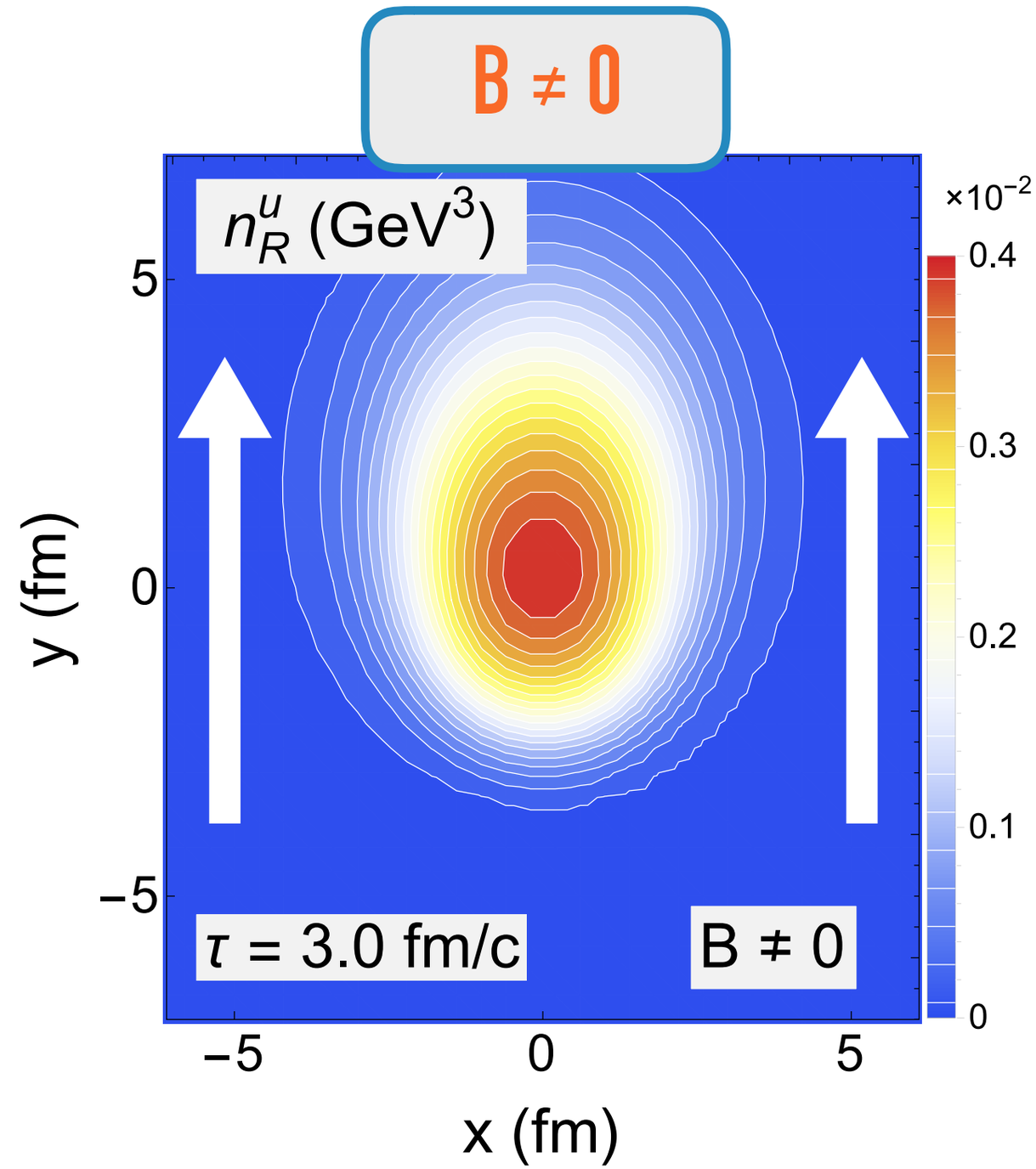
$$\Delta^\mu{}_\nu\, \mathrm{d}\, \nu_{R,L}{}^\nu = -\frac{1}{\tau_{rlx}} (\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

on top of 2+1D VISHNU —— OSU Group

$$D_\mu T^{\mu\nu} = 0$$

Evolution of Quark Number Density





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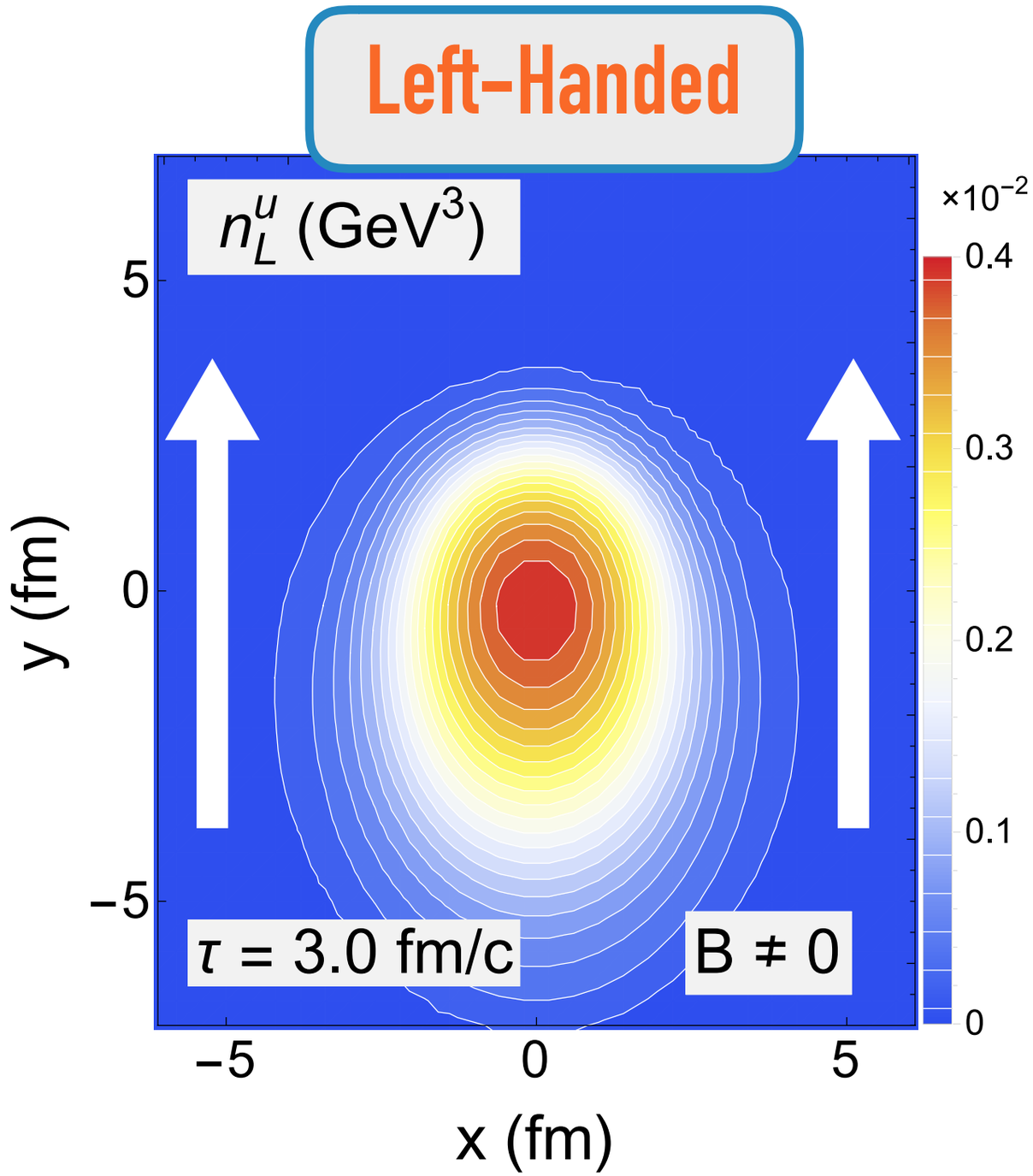
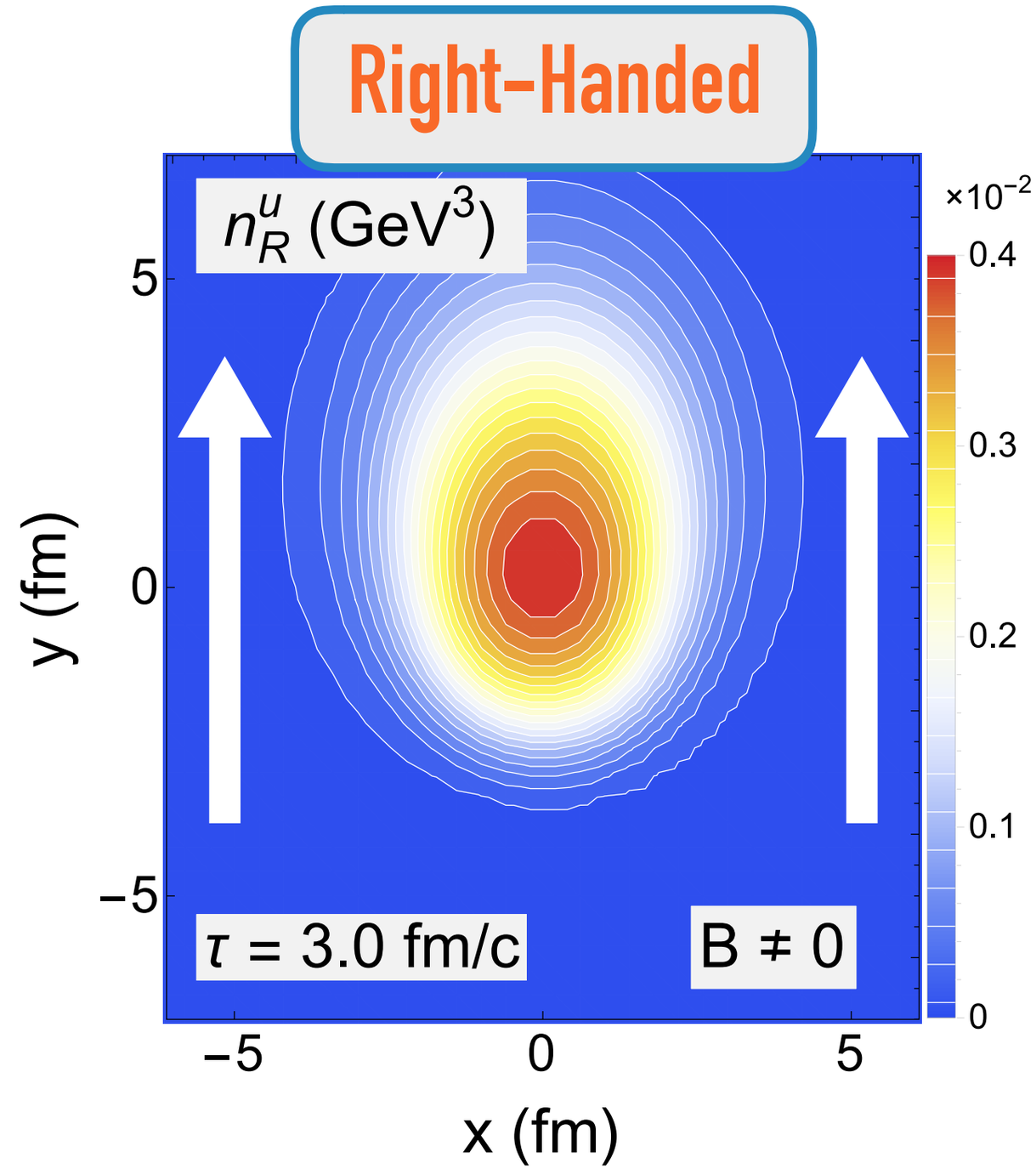
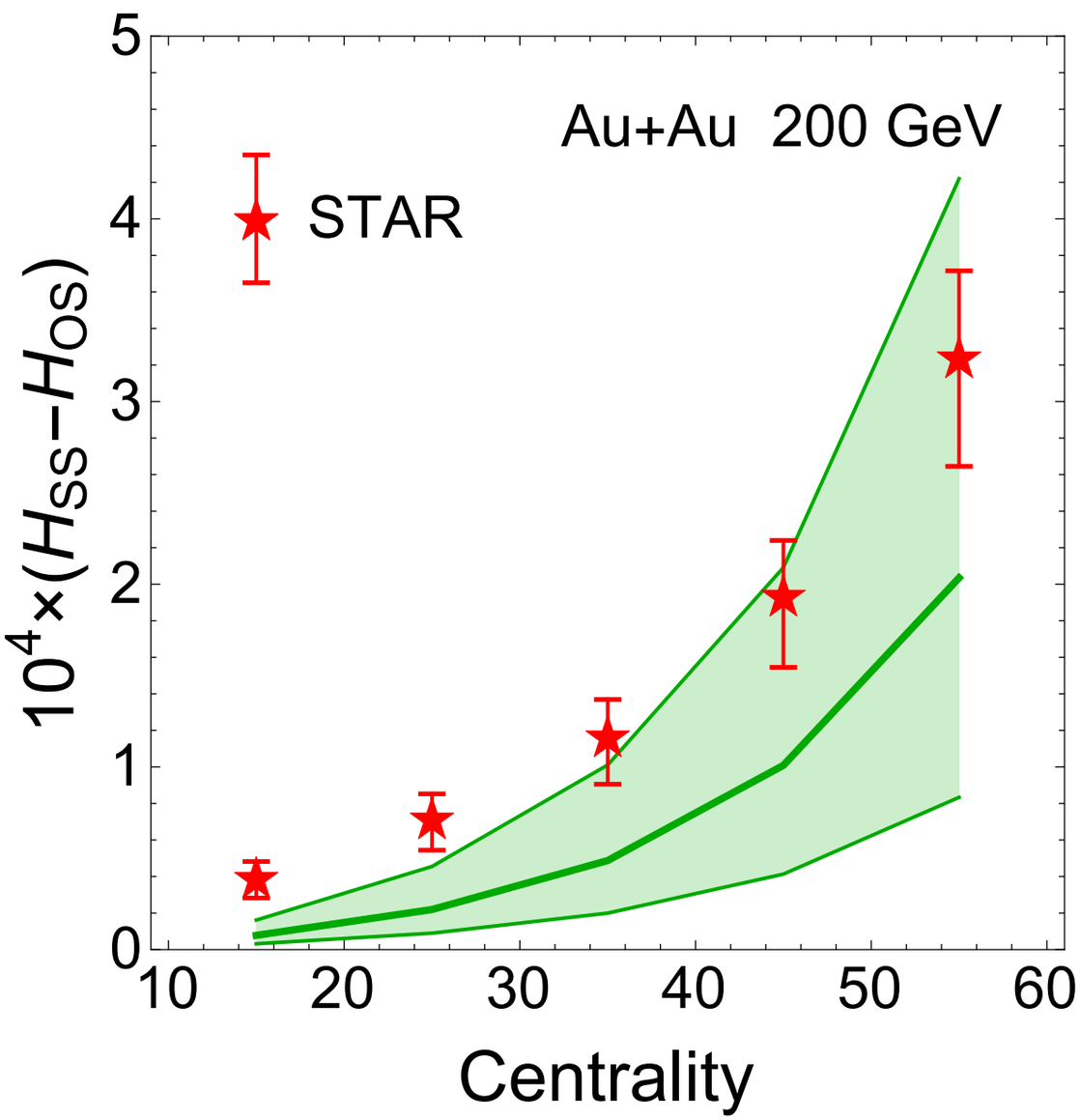




CME in Au-Au Collisions



$$B = \frac{B_0}{1+(\tau/\tau_B)^2} \qquad \tau_B = 0.6 \text{ fm/c}$$

$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4 \, (\pi \, \rho_{tube}^2 \, \tau_0) \sqrt{N_{coll}}}{16\pi^2 \, A_{overlap}}$$

Good agreement for magnitude & centrality trend

Crucial Test of CME — Isobaric Collisions

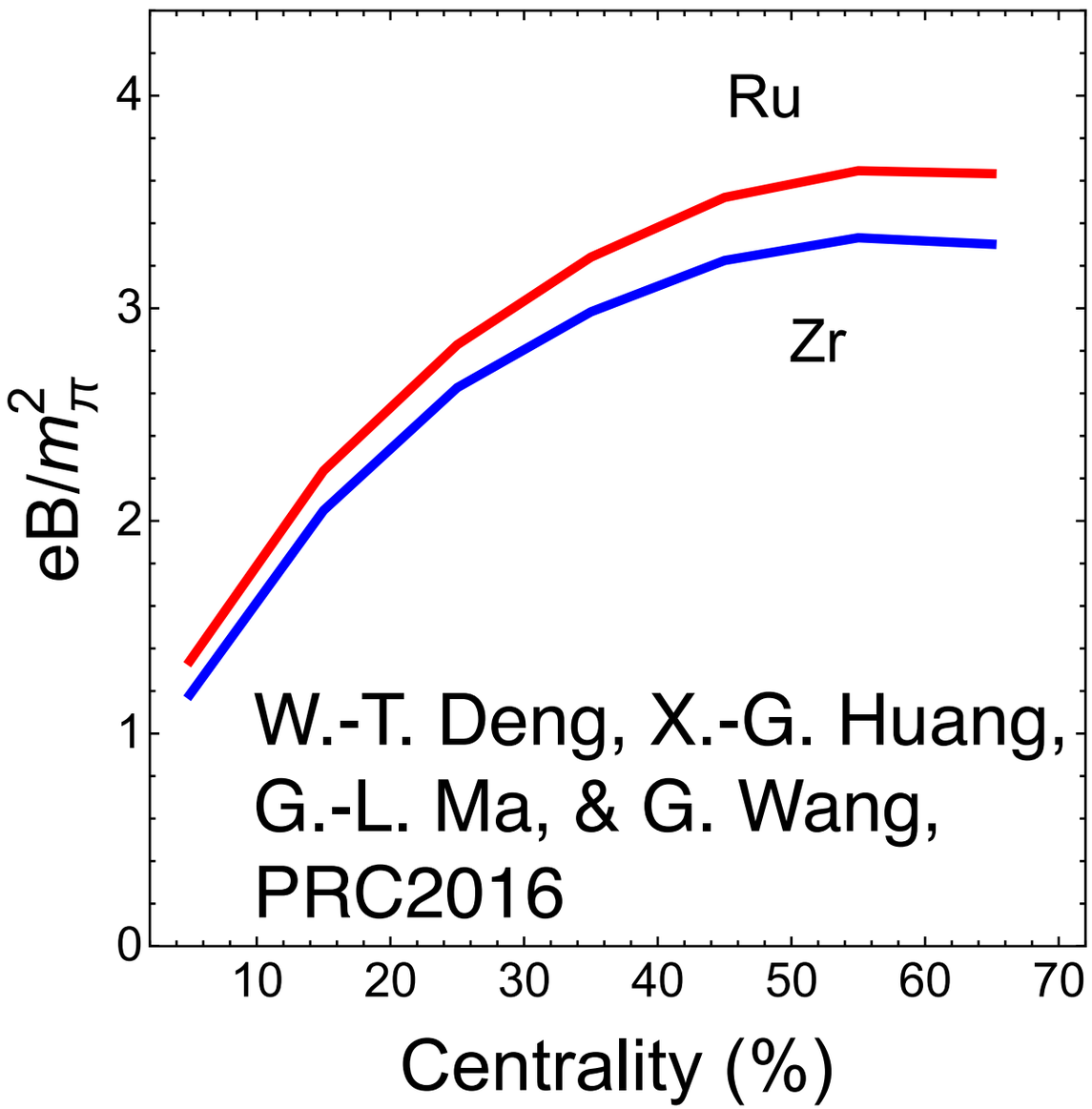
$^{96}_{44}$Ruthenium

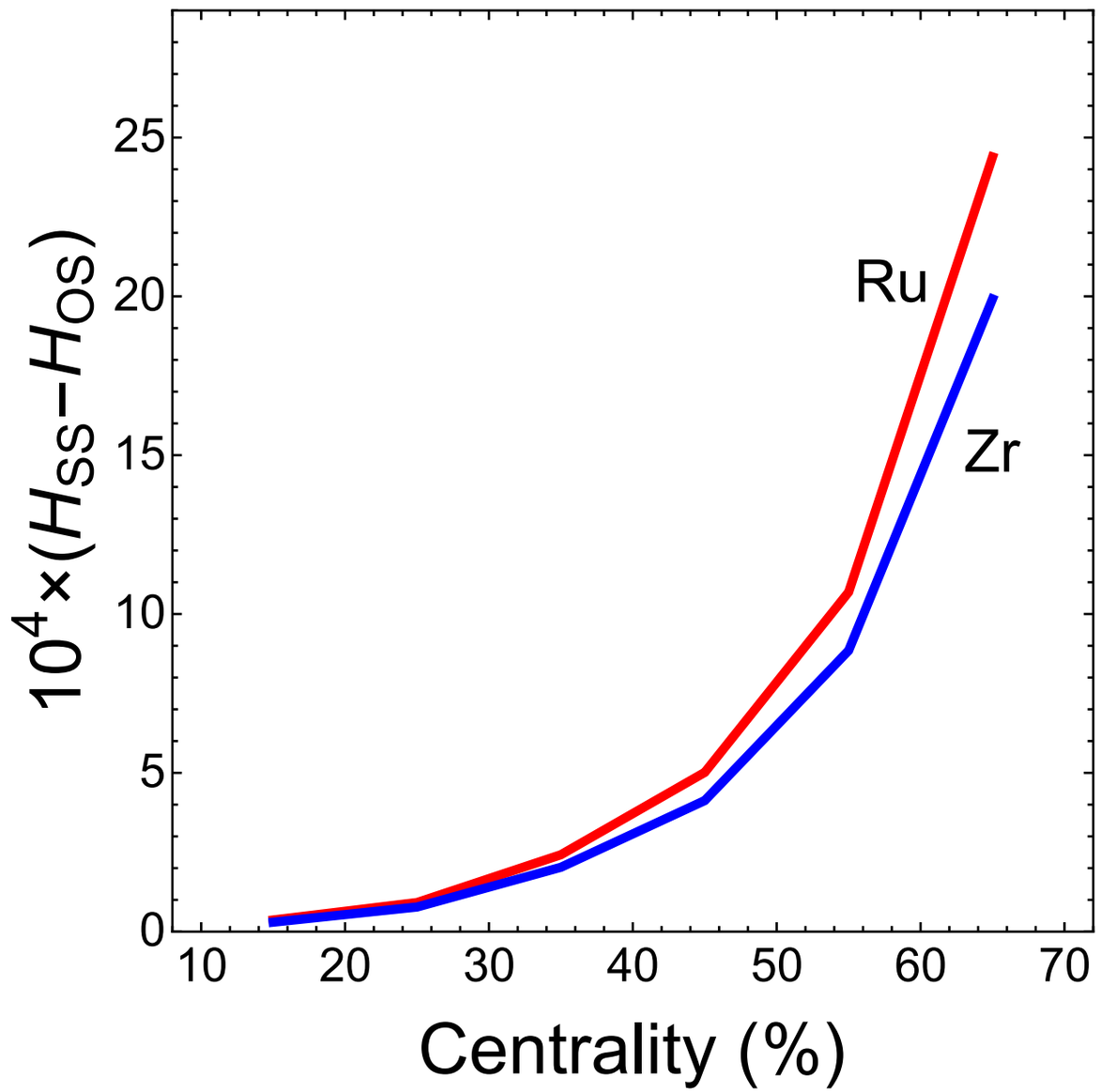
$^{96}_{40}$Zirconium

Same Baryon # → Similar Bulk Background

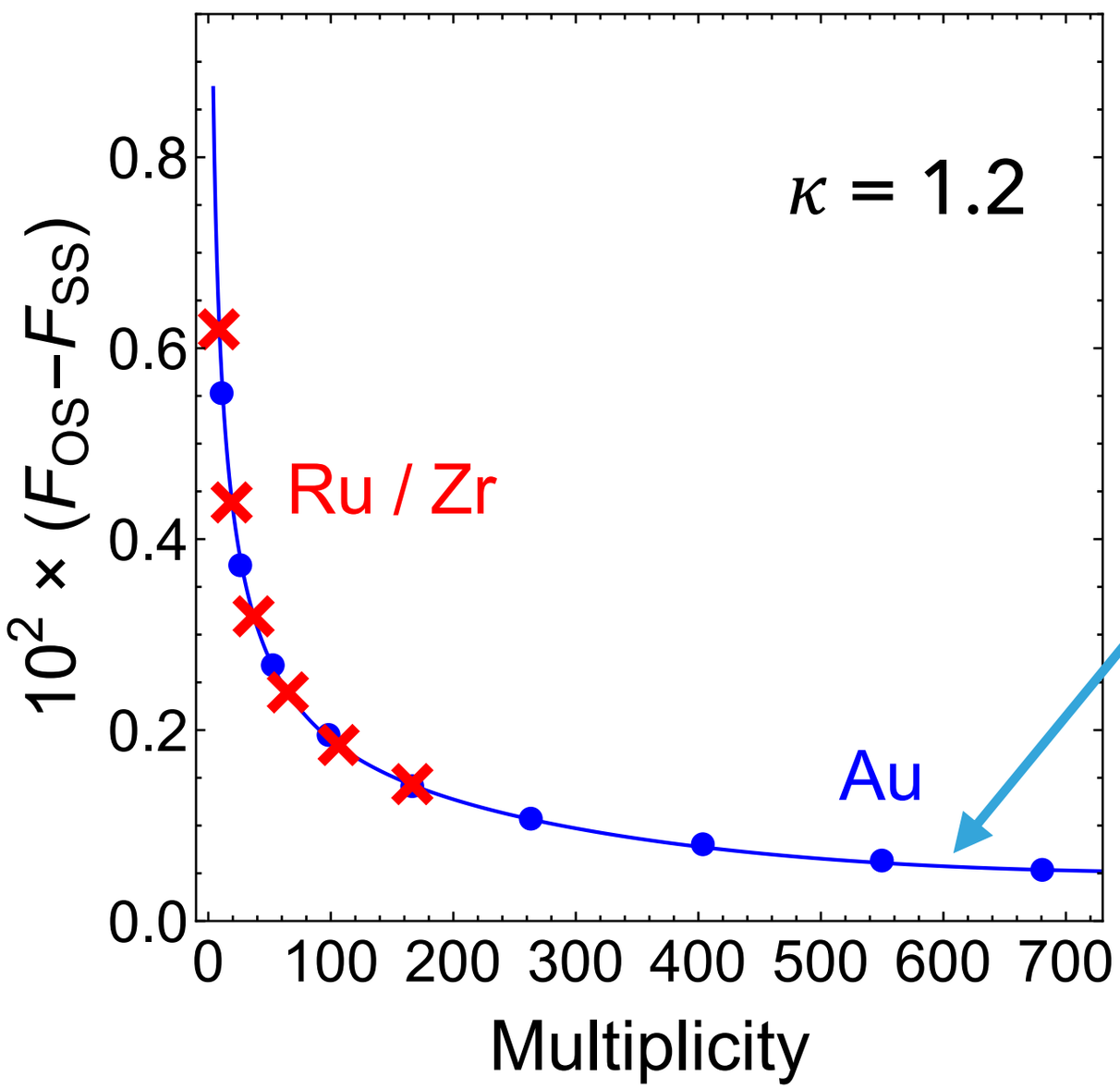
Different Proton # → Different CME!

Test of CME — Isobaric Collisions @ RHIC





Estimation Of Bulk Background

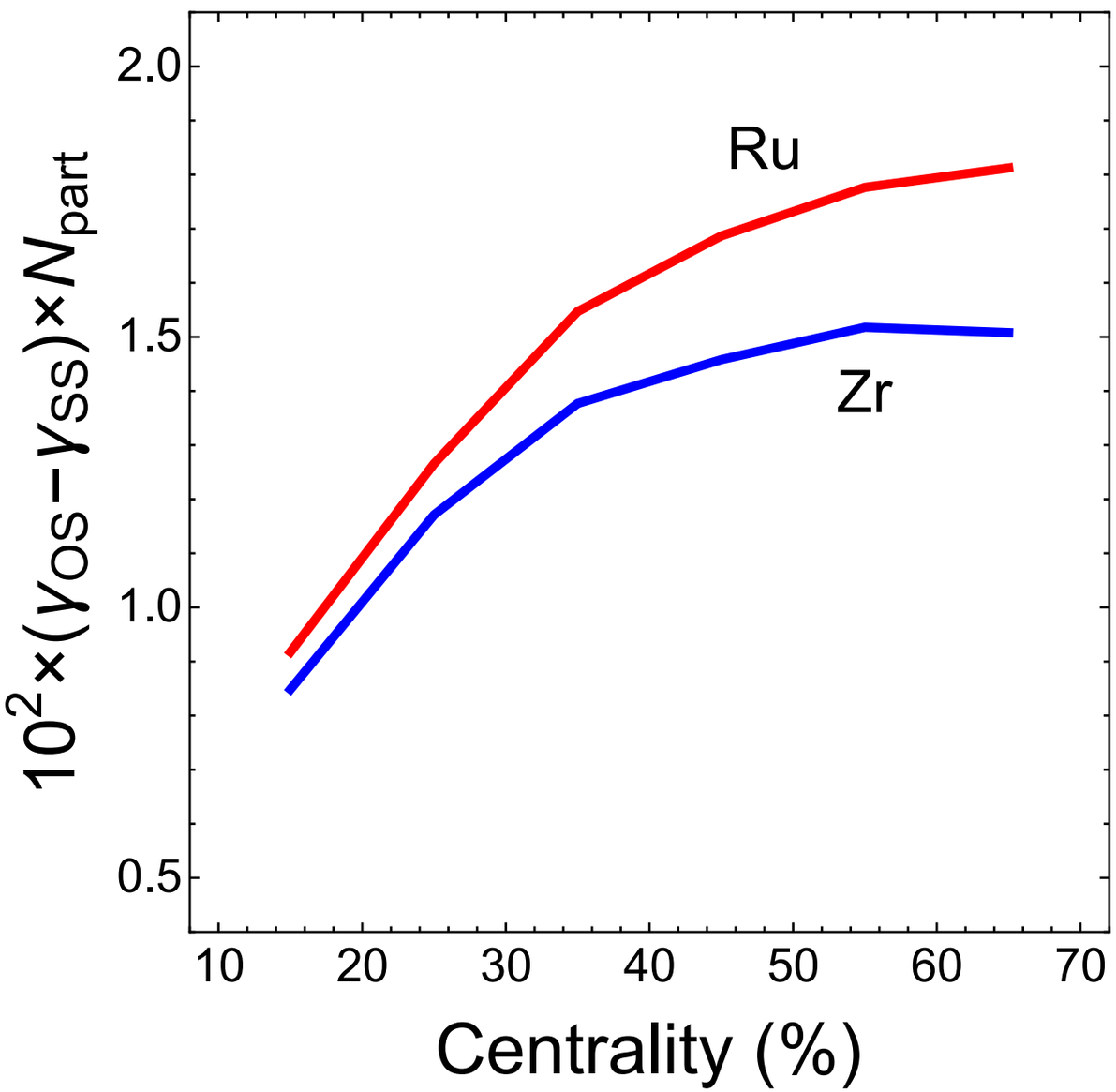


$$\gamma = \kappa\, v_2\, F - H$$

Fitting Formular:

$$F(x) = \frac{1 + a_1 x + a_2 x^2}{b_1 x + b_2 x^2}$$

CME Signal + Estimated Background



$\gamma_{\text{os-ss}}(\text{Ru}) - \gamma_{\text{os-ss}}(\text{Zr})$

20-30%: 1×10^{-5}

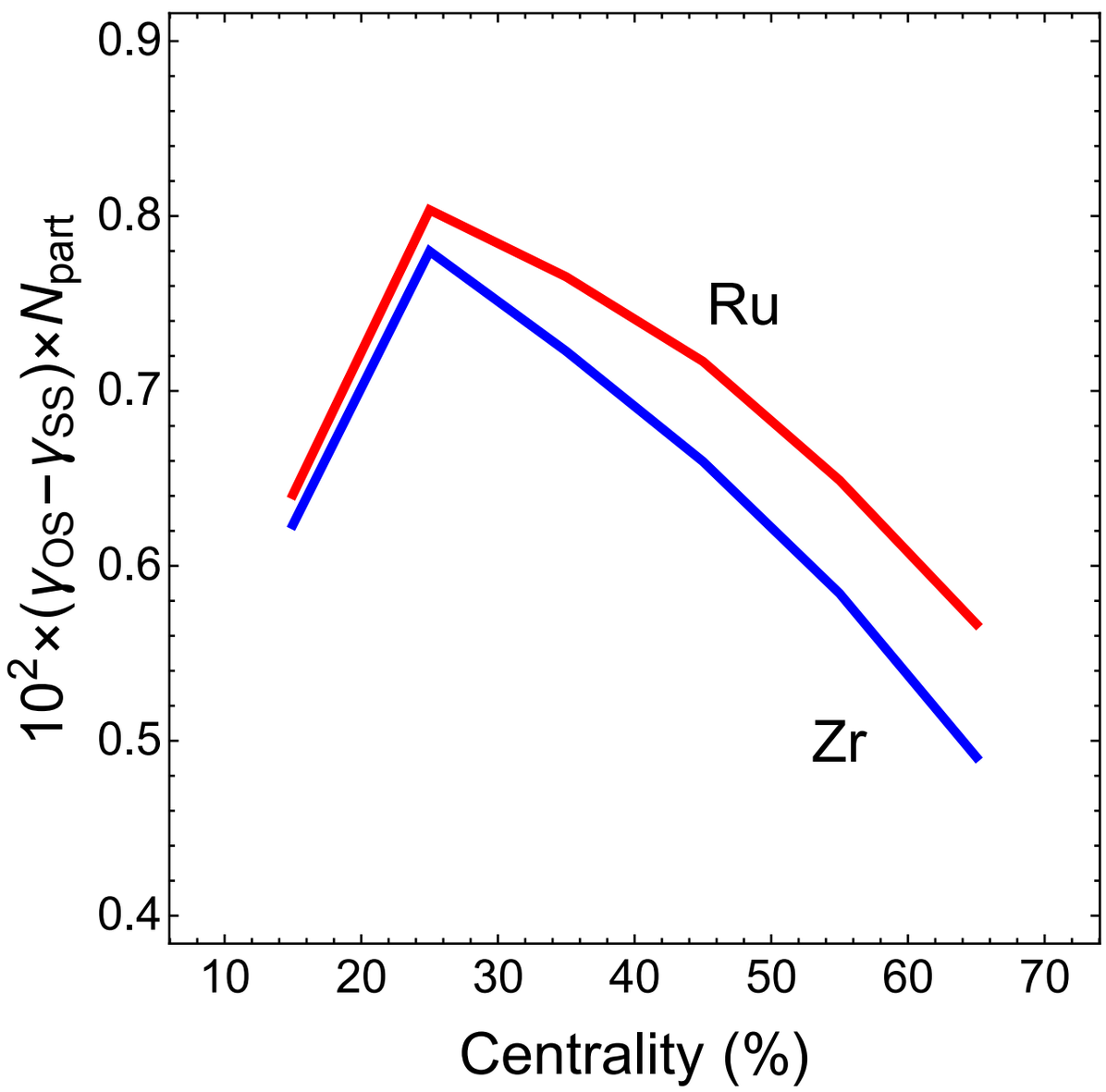
40-50%: 8×10^{-5}

60-70%: 4×10^{-4}

$$\gamma = \kappa\, v_2\, \mathsf{F} - \mathsf{H}$$

If Less CME?

Taking $n_5 \rightarrow n_5/2$



$\gamma_{os\text{-}ss}(Ru) - \gamma_{os\text{-}ss}(Zr)$

20-30%: 3×10^{-6}

40-50%: 2×10^{-5}

60-70%: 1×10^{-4}

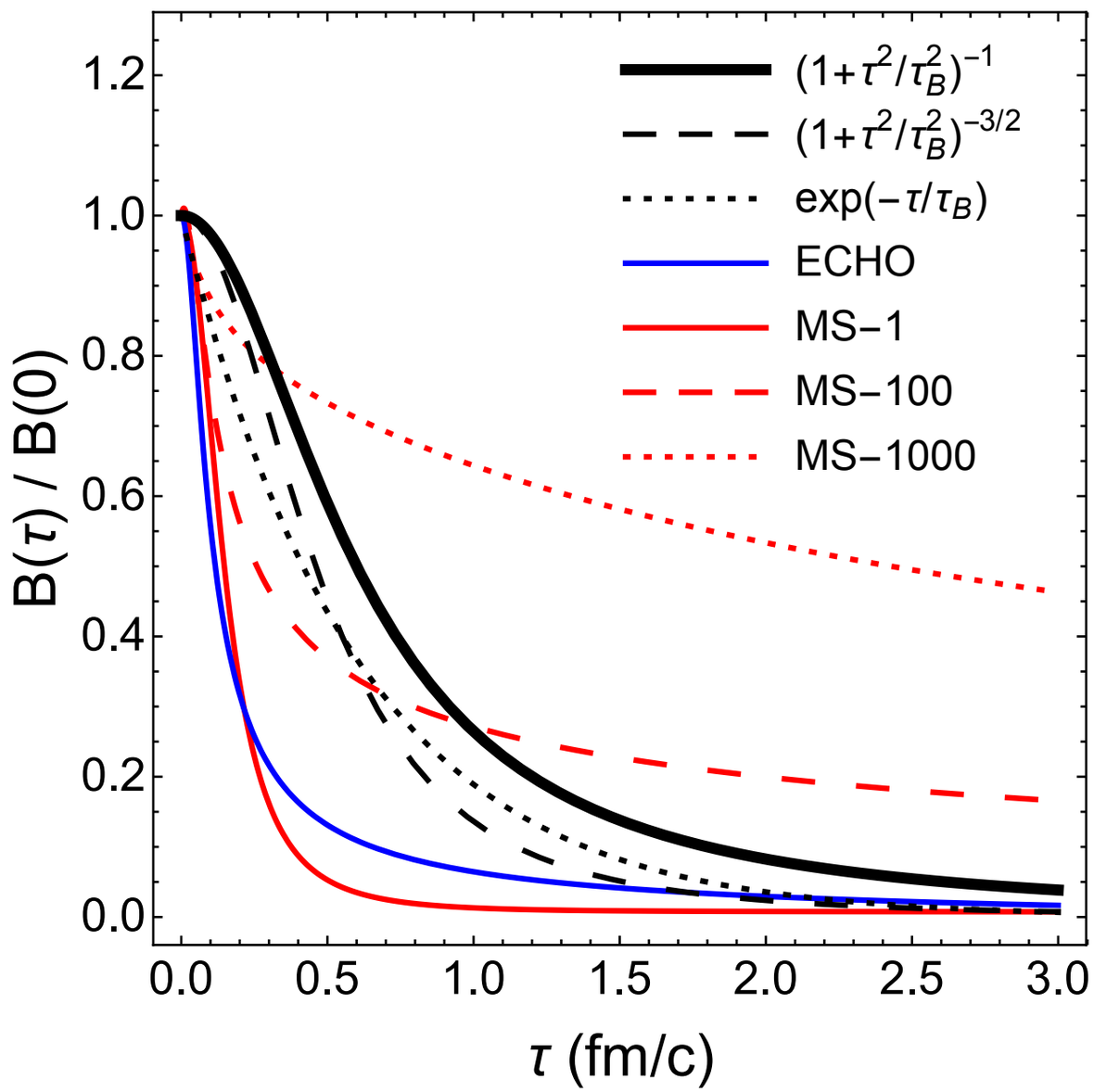
$n_5 \rightarrow n_5/2 \quad \Rightarrow \quad \Delta\gamma \rightarrow \Delta\gamma/4$

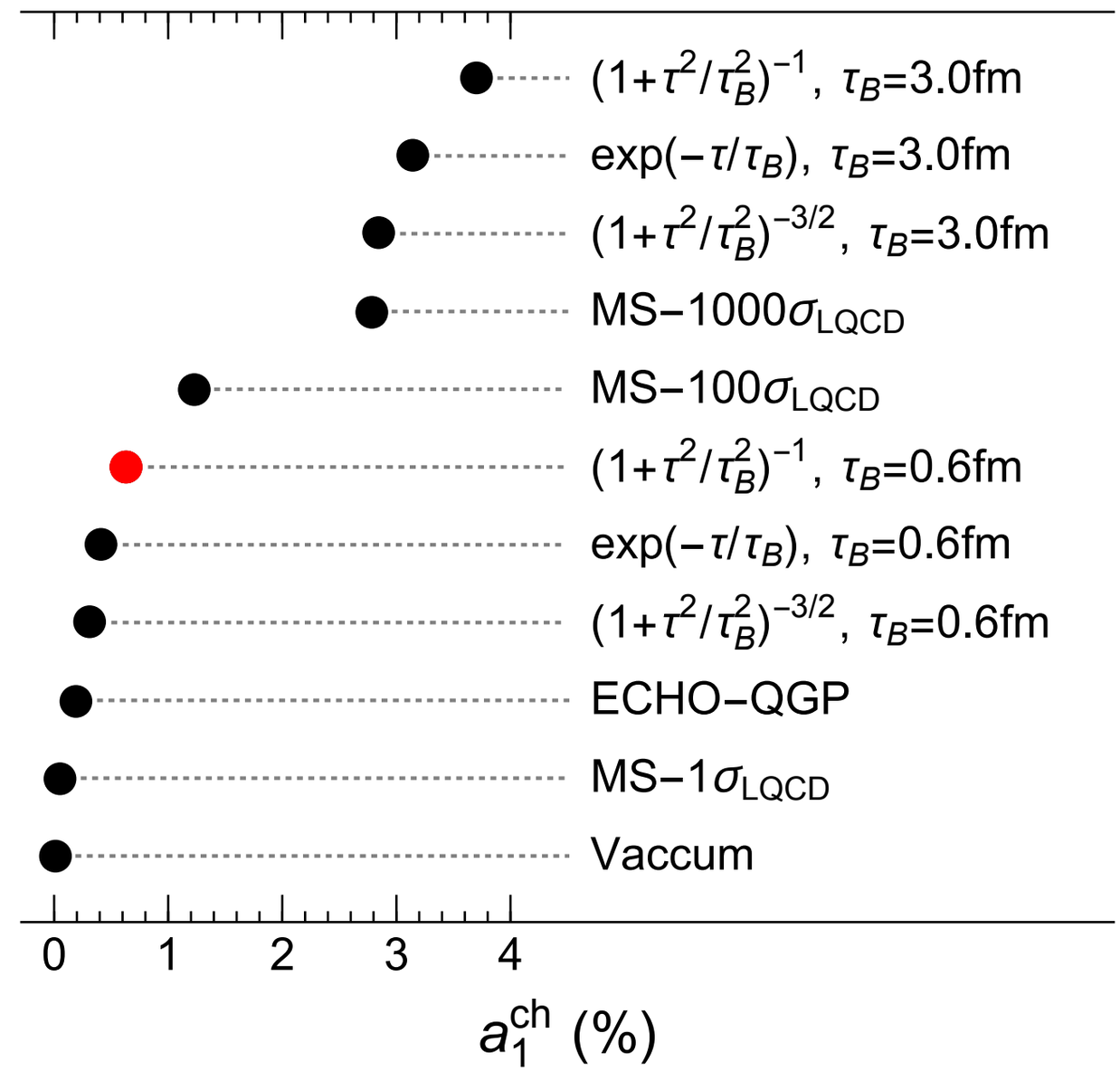
Summary & Outlook

- AVFD framework is developed to quantitatively study Chiral Effects in QGP.
- CME in Au-Au collisions & isobaric collisions (^{96}Ru –^{96}Ru v.s.^{96}Zr –^{96}Zr) studied.
- If our understanding about CME in Au-Au collision is correct, the IsoBar program should be able to disentangle the CME signal from bulk backgrounds.

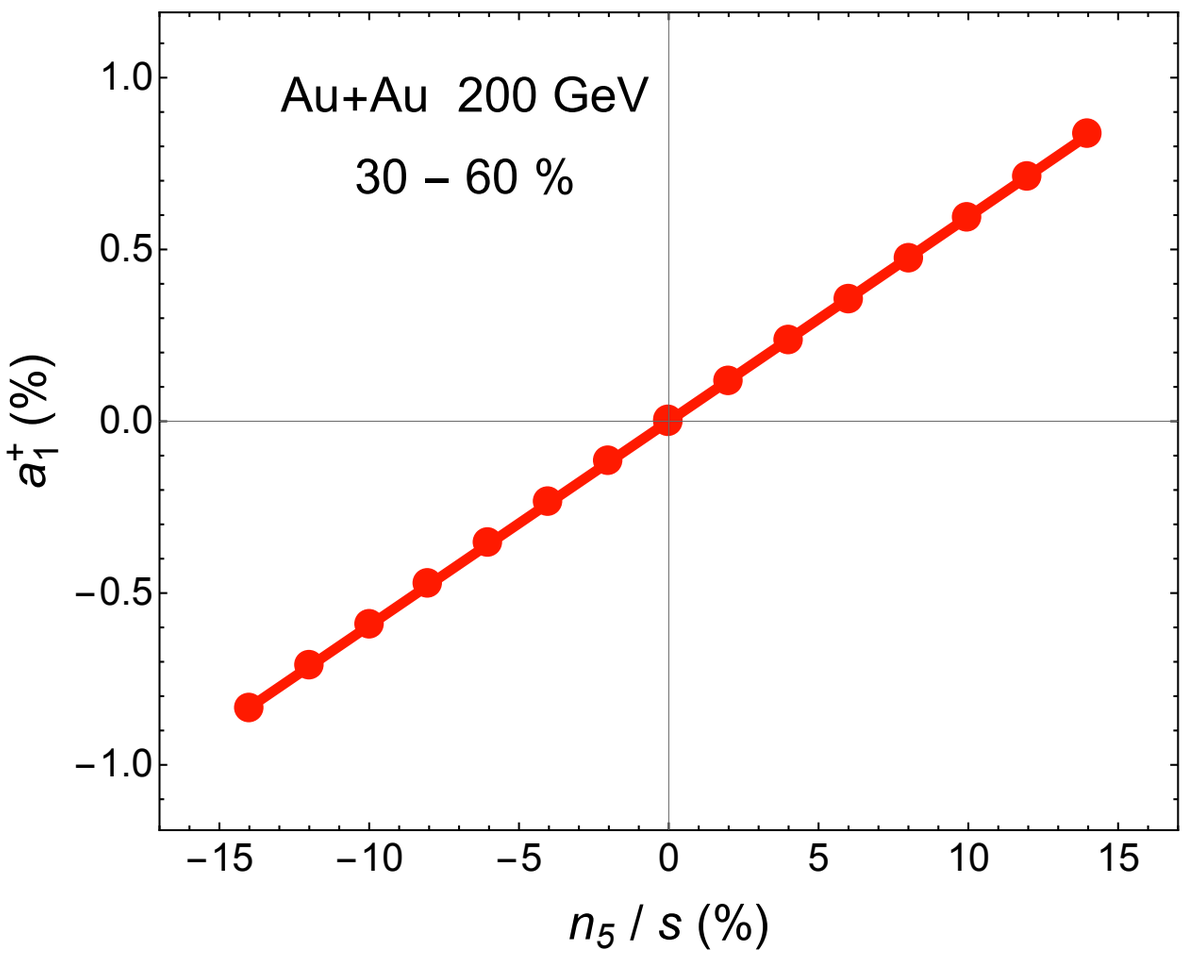
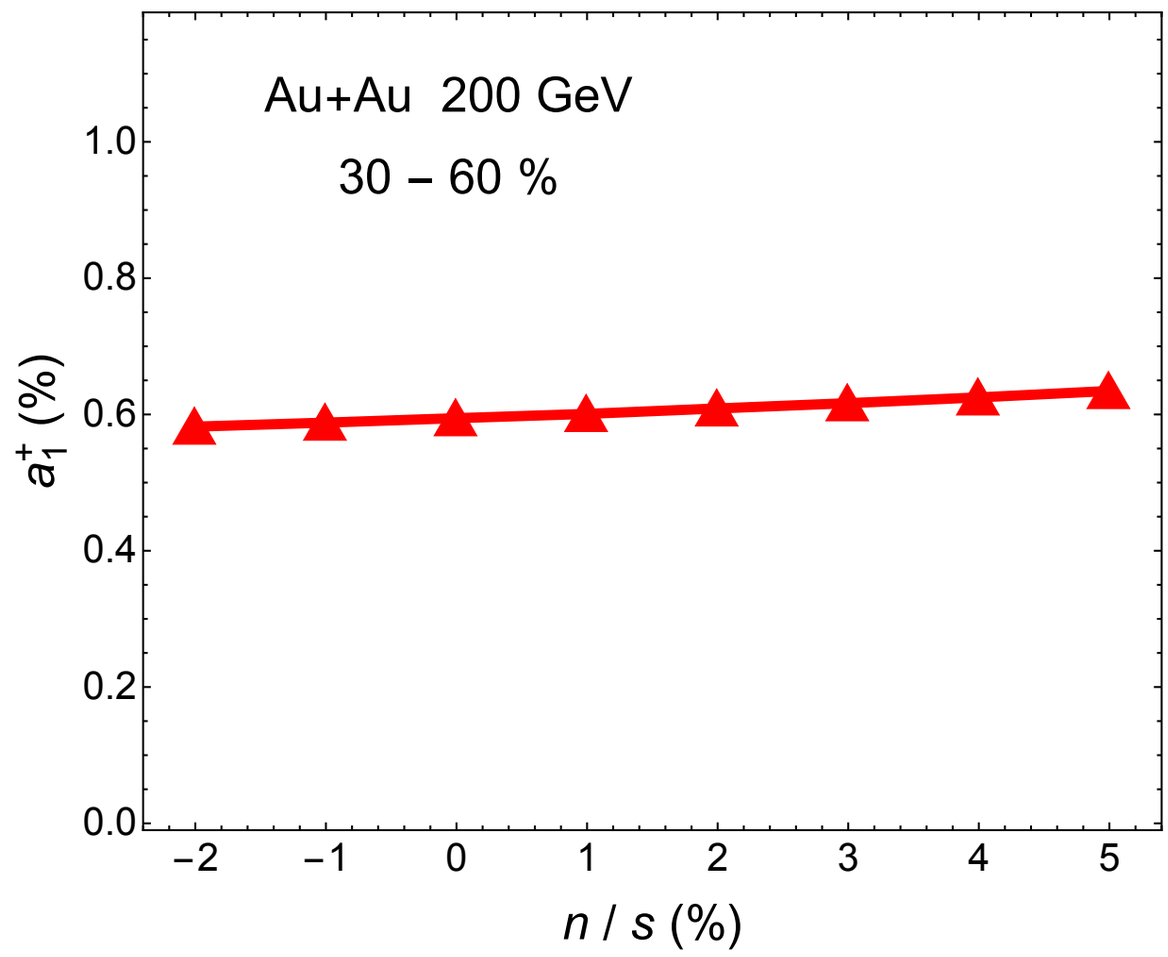
THANK YOU!

Dependence on the Magnetic Field





Dependence on { Initial Axial Charge Density n_A / Initial Vector Charge Density n_V

Charge separation $\propto$ initial n_A

Charge separation $\not\propto$ initial n_V