Chiral Magnetic Effect from Event-by-Event Anomalous-Viscous Fluid Dynamics

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In collaboration with:
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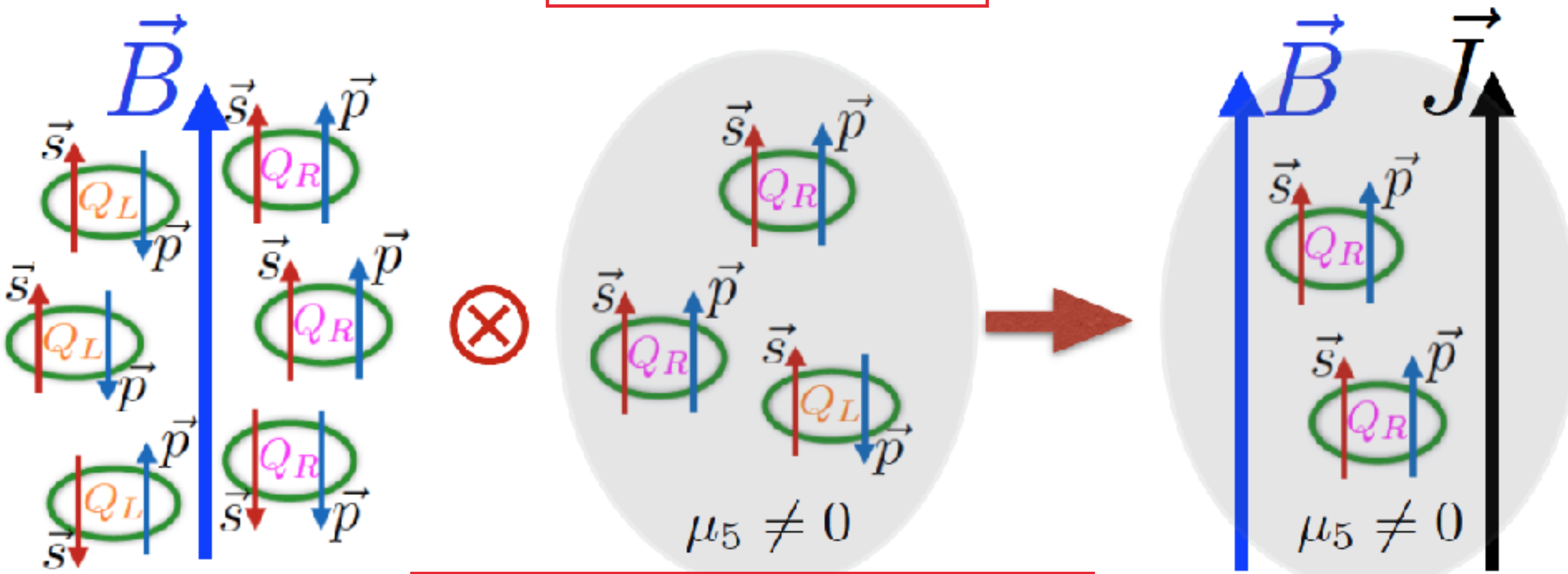
Outline

- Chiral Magnetic Effect (CME)
- How do we study CME quantitatively ← Anomalous-Viscous Fluid Dynamics
- Event-by-Event Simulations of CME in Au-Au Collisions
- Prediction of CME in IsoBaric Collisions

Chiral Magnetic Effect

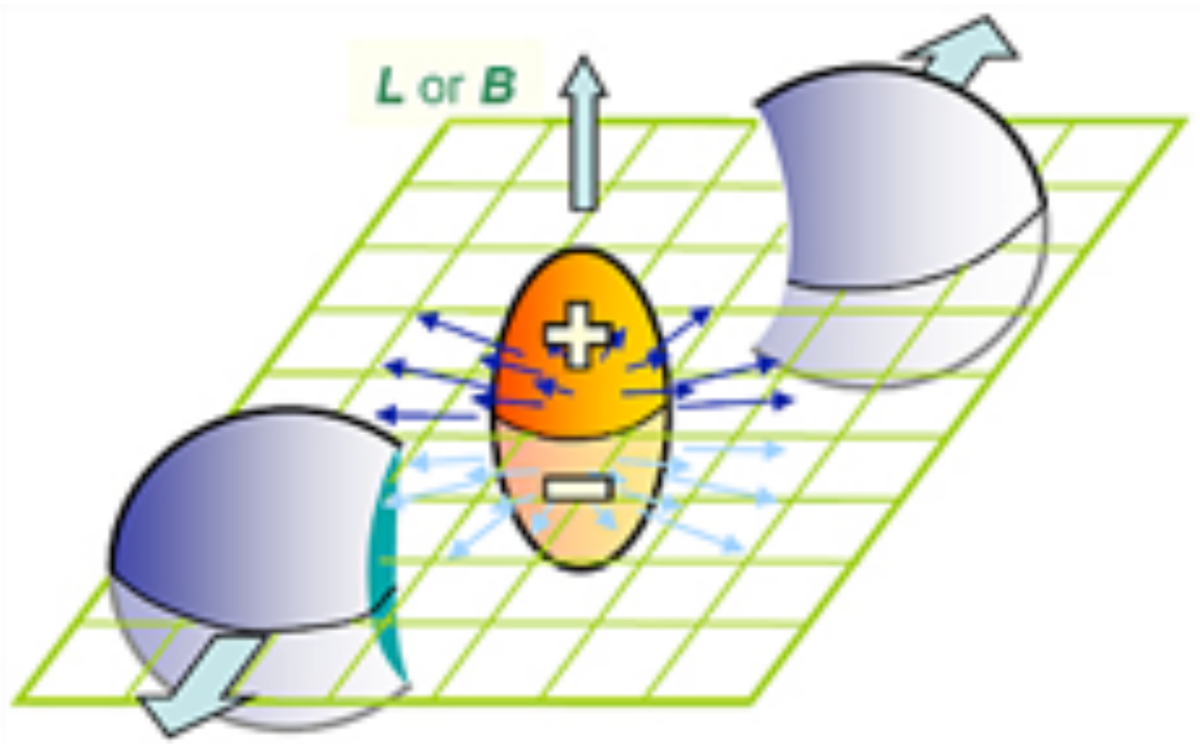
Chiral magnetic effect (CME) is the generation of electric current along an external magnetic field induced by chirality imbalance.

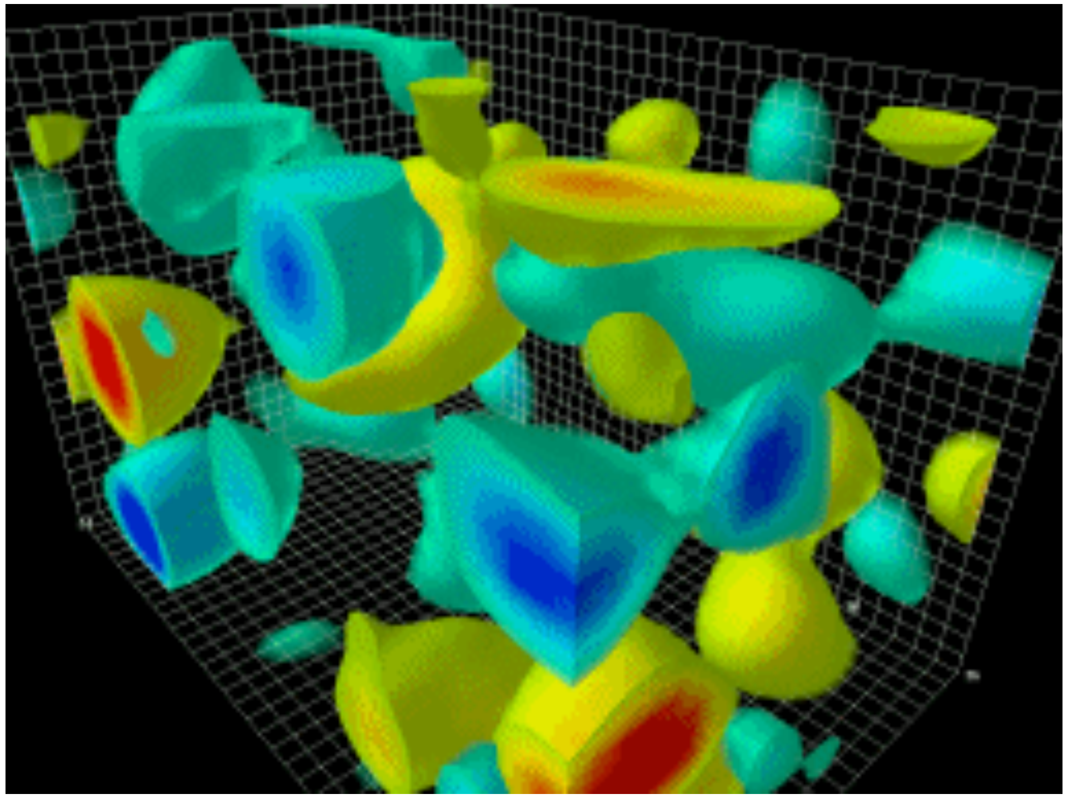
$$\boldsymbol{J} = \sigma_5\, \mu_5\, \boldsymbol{B}$$



$$\text{Energy} = -\mu \cdot \boldsymbol{B}$$

Chiral Magnetic Effect In Heavy-Ion Collisions





(B ~ 10^{15} T)
eB ~ 5 m_π^2
@ 200 GeV Au-Au

⊗

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 Collisions

- B field $\otimes$ μ_5 $\Rightarrow$ current $\Rightarrow$ dipole

Chiral Magnetic Effect In Heavy-Ion Collisions

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

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

Chiral Magnetic Effect In Heavy-Ion Collisions

- B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

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

- charge separation ⇒ charge dept. 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: $H = (a_{1\pm})^2$

Chiral Magnetic Effect In Heavy-Ion Collisions

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$$\gamma_{bkg} = \kappa\, v_2\, F$$

$$\delta_{bkg} = F$$

Bulk Background

Chiral Magnetic Effect In Heavy-Ion Collisions

- B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

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

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

$$\delta = F + H$$

F: Bulk Background

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

Chiral Magnetic Effect In He

- B field ⊗ μ_5 ⇒ current =

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

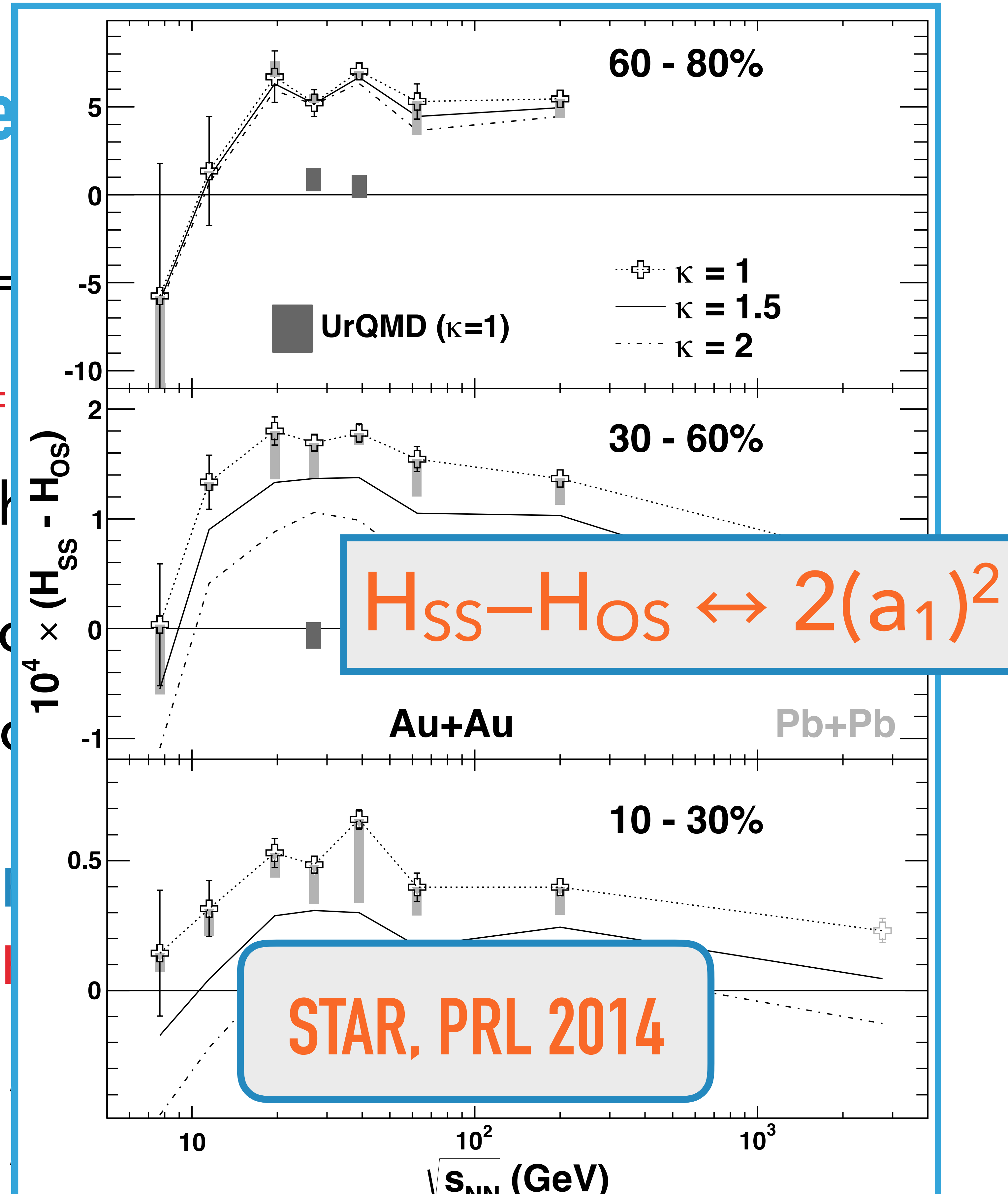
- charge separation ⇒ ch

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

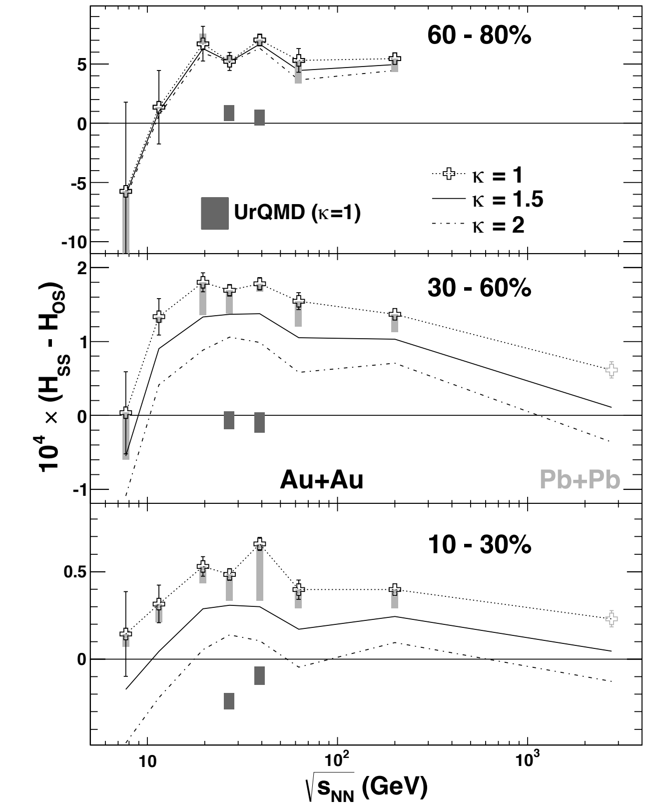
  $\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle c$

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

  $\delta = F + H$ H



How Can We Calculate CME Quantitatively?



axial & vector charge density

initial condition

+

driving force

B field

→

Anomalous-Viscous Fluid Dynamics

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

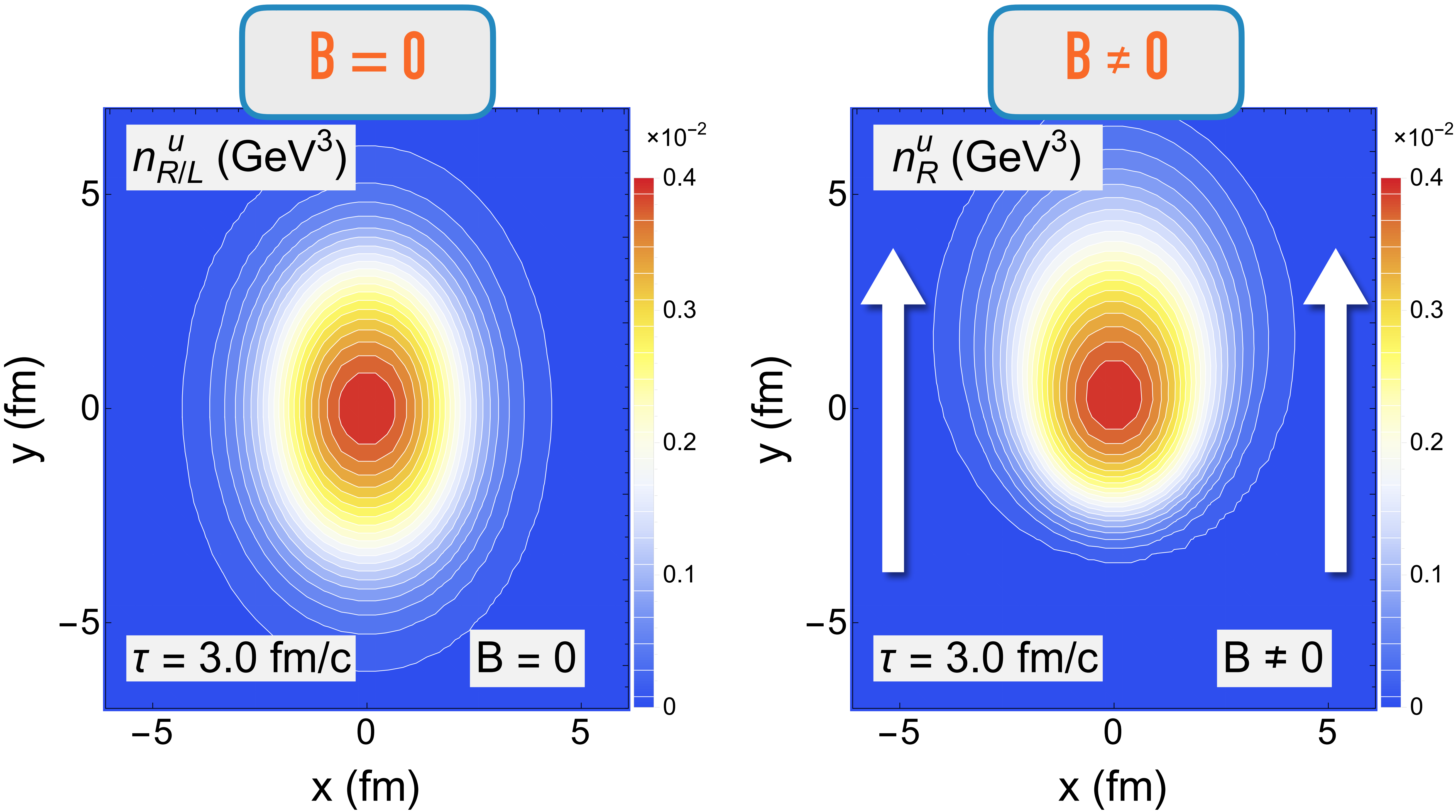
Viscous Effect

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

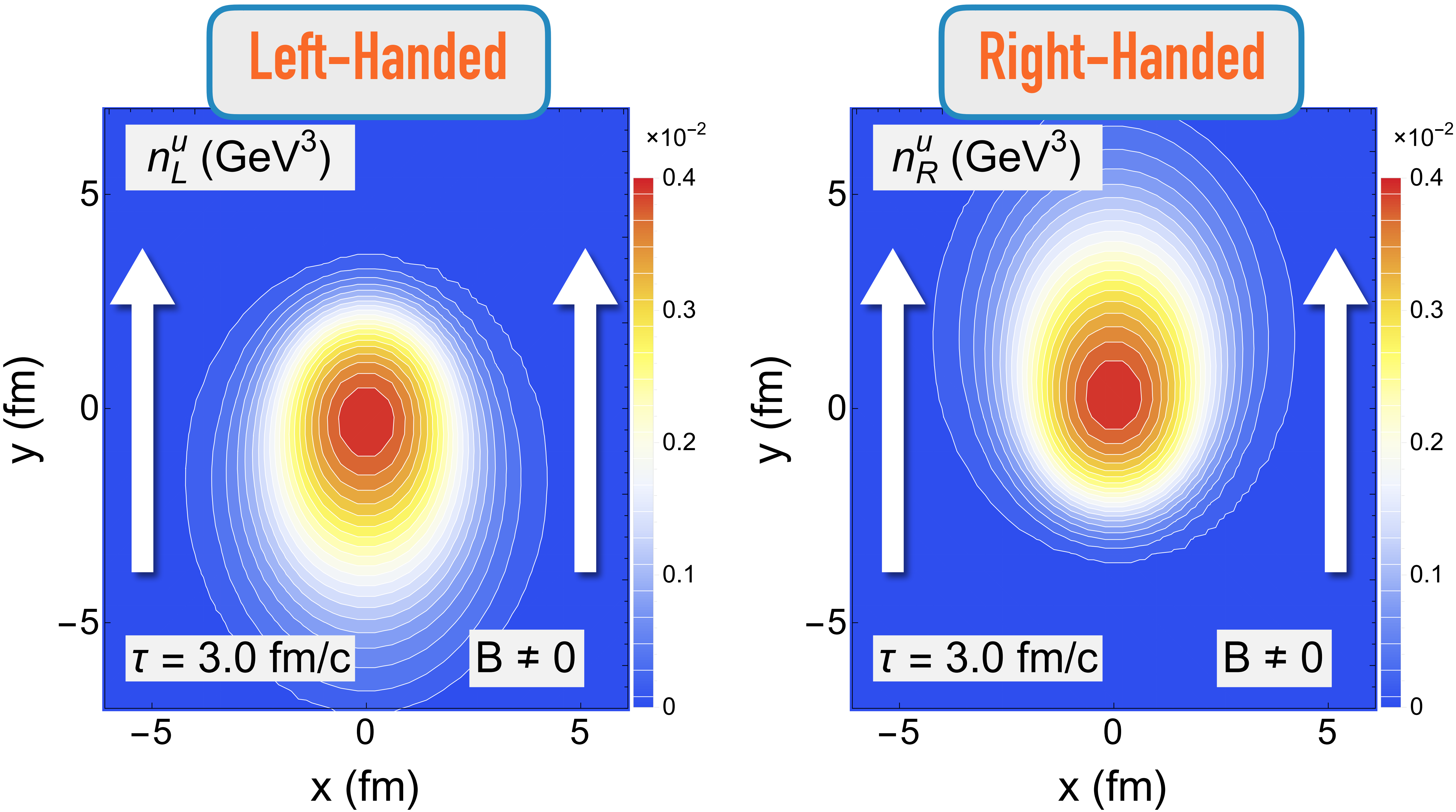
$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q\, E^\mu$$

on top of 2+1D VISHNU —– OSU Group

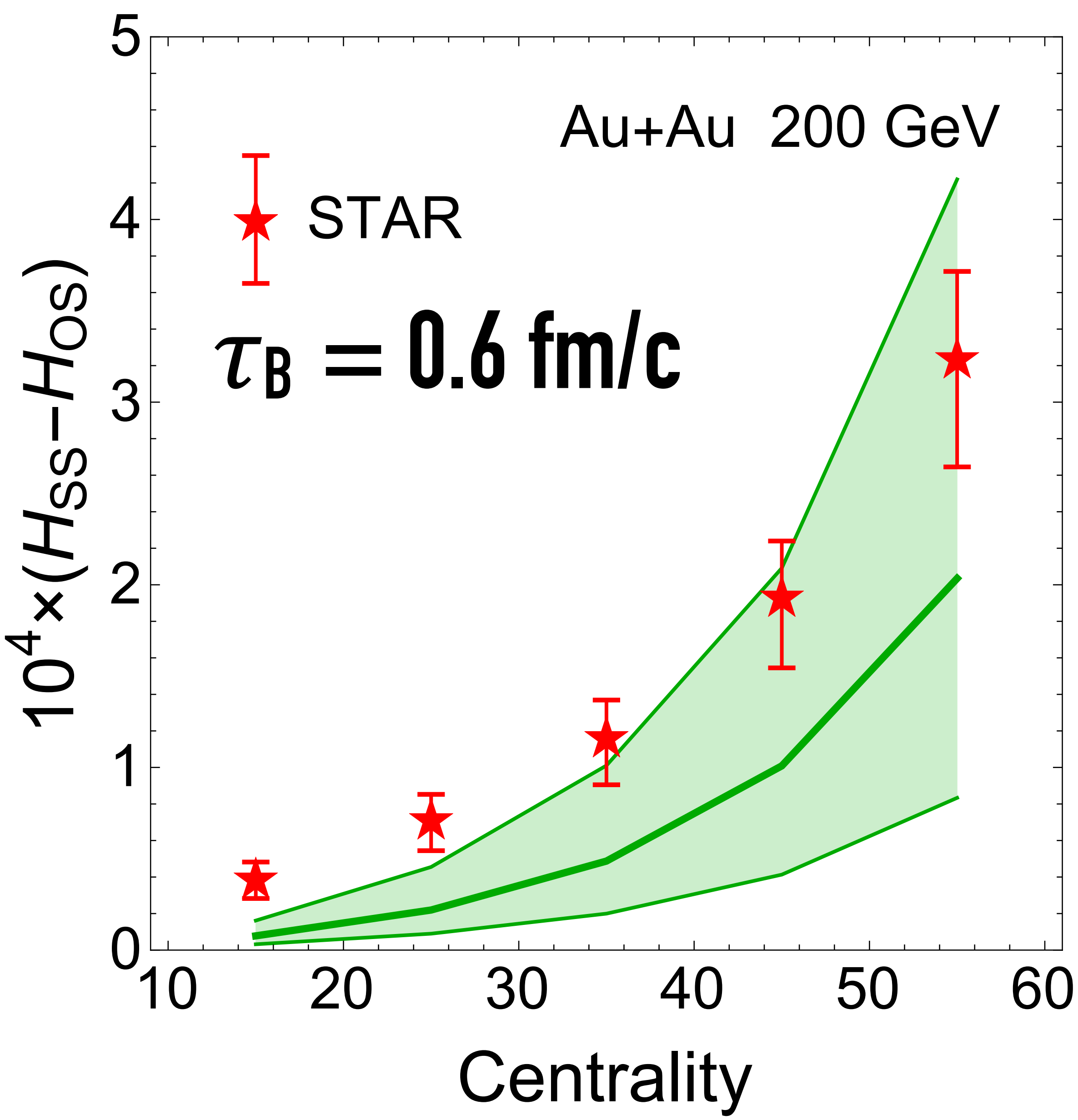
Evolution of Quark Number Density



Evolution of Quark Number Density



CME from Smooth AVFD simulation



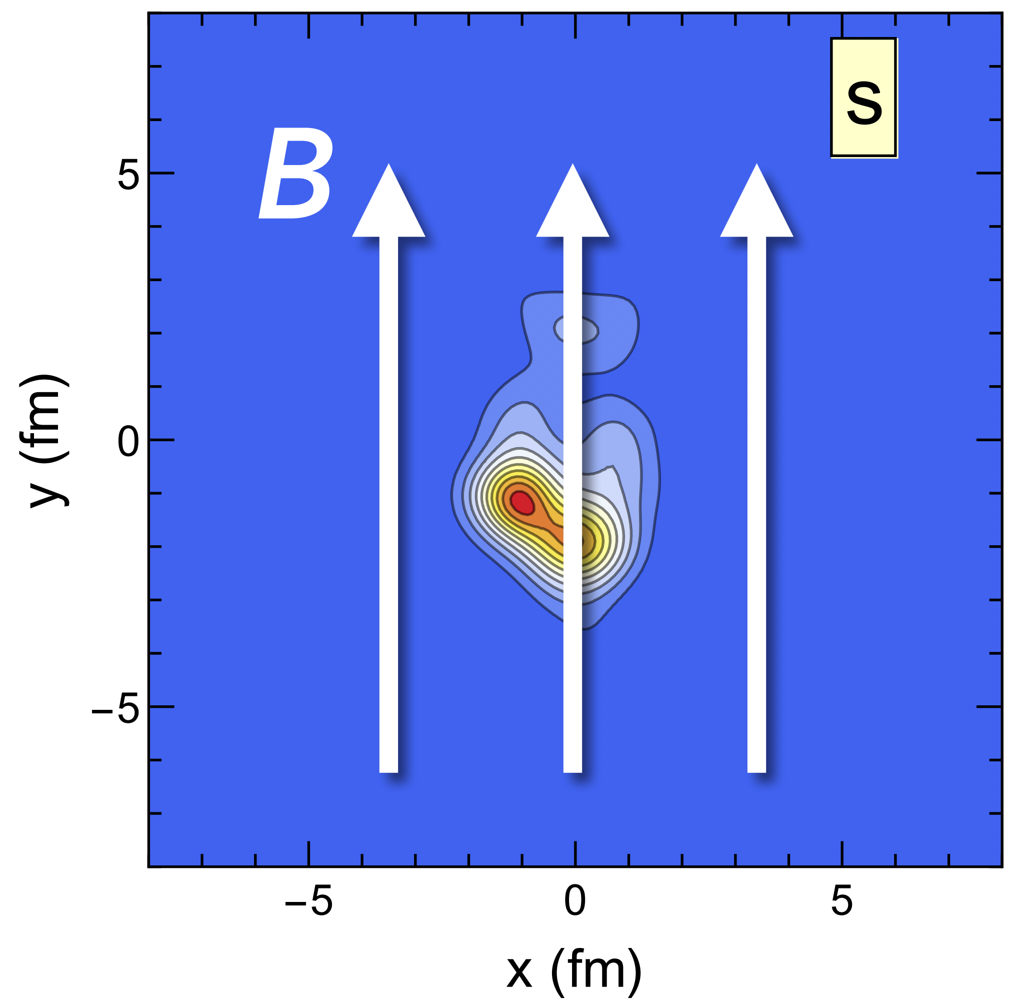
Implementing with best estimated n_A & τ_B

Good agreement for magnitude & centrality trend

Y.Jiang, SS, Y.Yin & J.Liao, arXiv:1611.04586

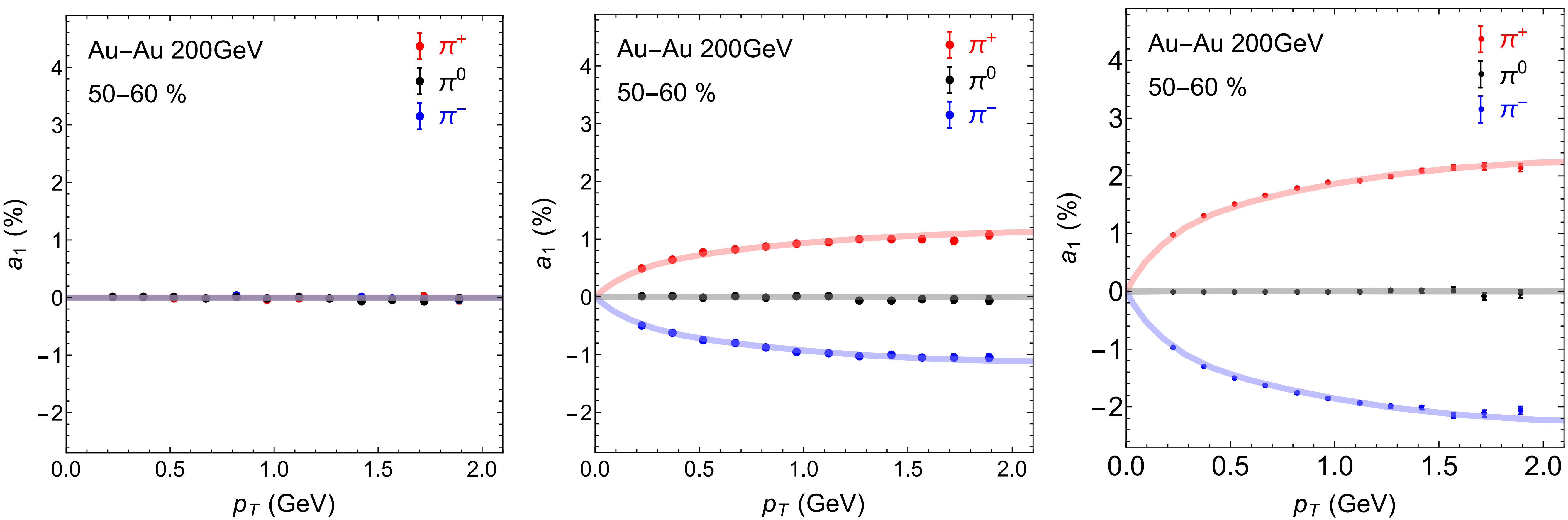
Event-by-Event AVFD simulation

- Fluctuations! Fluctuations! Fluctuations!
    - Initial Conditions
    - Statistic @ Freeze-out
    - Hadron Cascade



Event-by-Event vs. Smooth AVFD

Au-Au @ 200GeV
50-60%



n_A/s=0.0

n_A/s=0.1

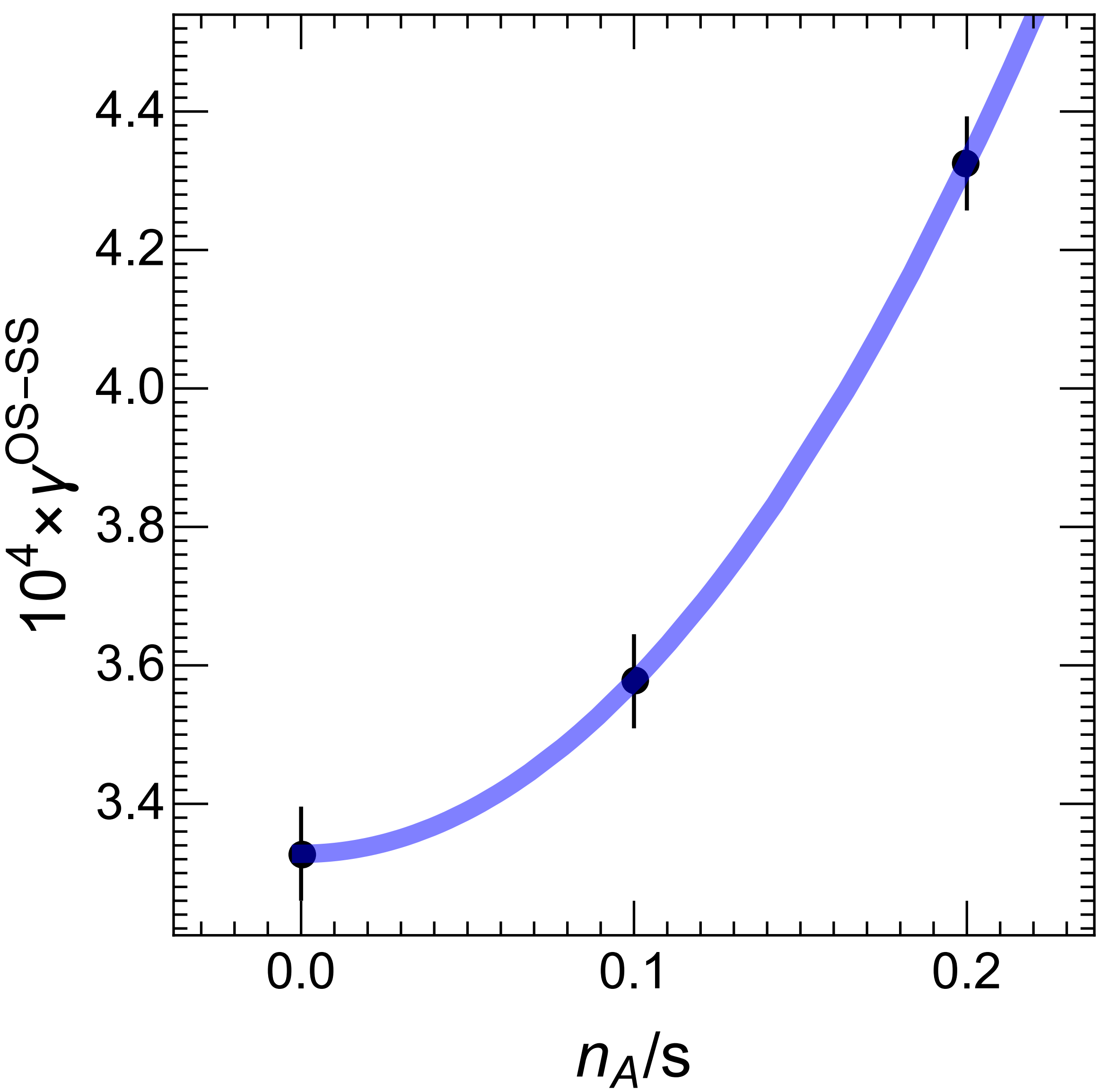
n_A/s=0.2

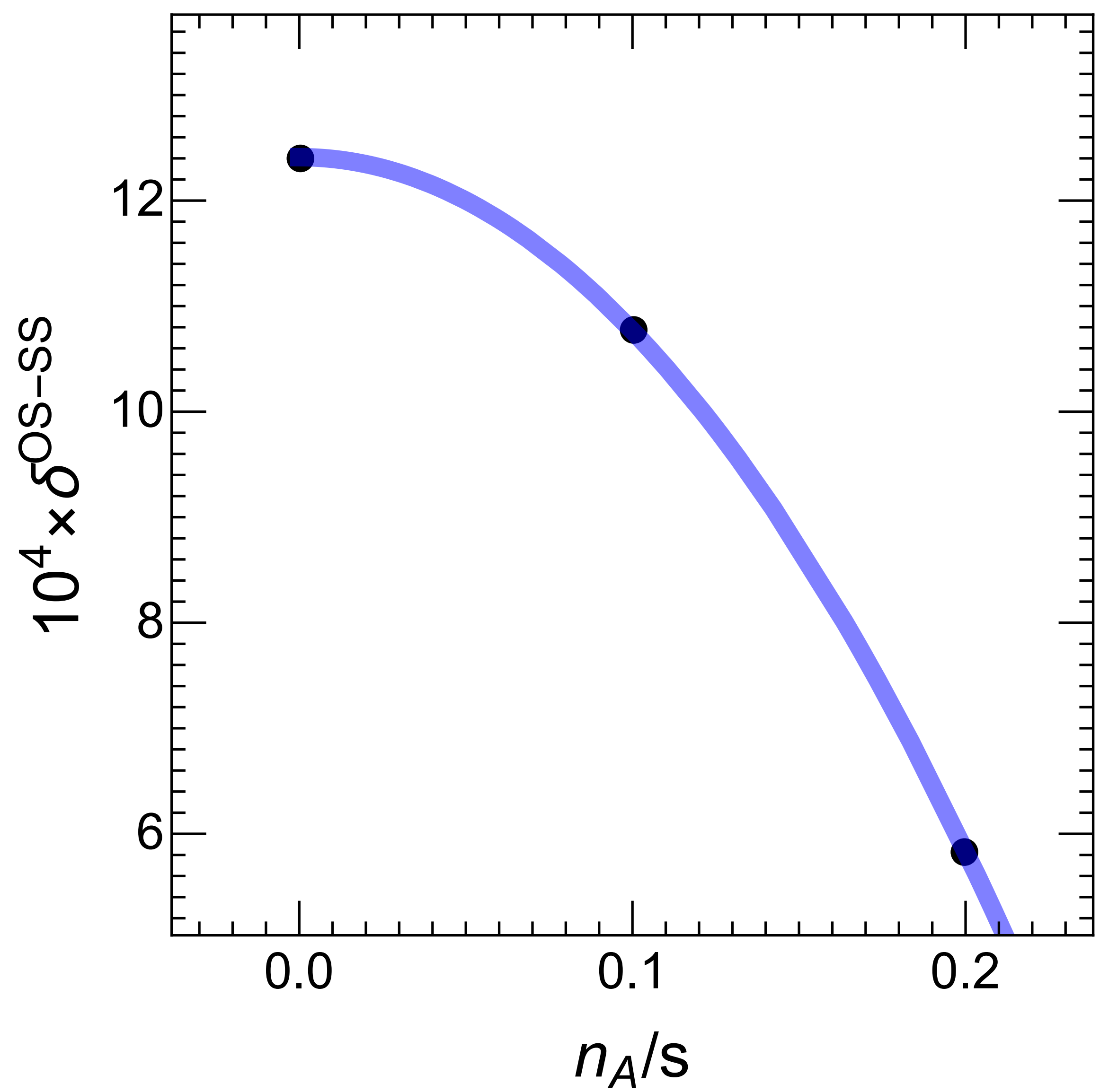
chirality imbalance

Au-Au @ 200GeV

50-60%

Event-by-Event: Correlators



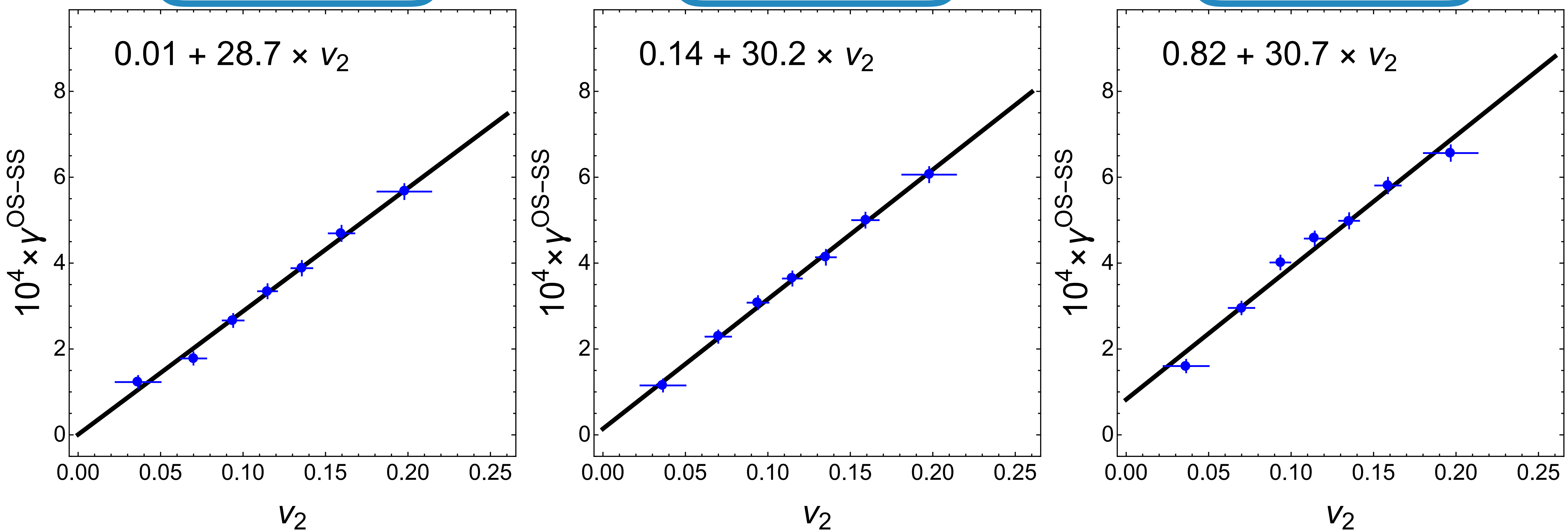


Au-Au @ 200GeV

50-60%

Event-by-Event: v_2-γ Correlation

$n_A/s=0.0$ $n_A/s=0.1$ $n_A/s=0.2$



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

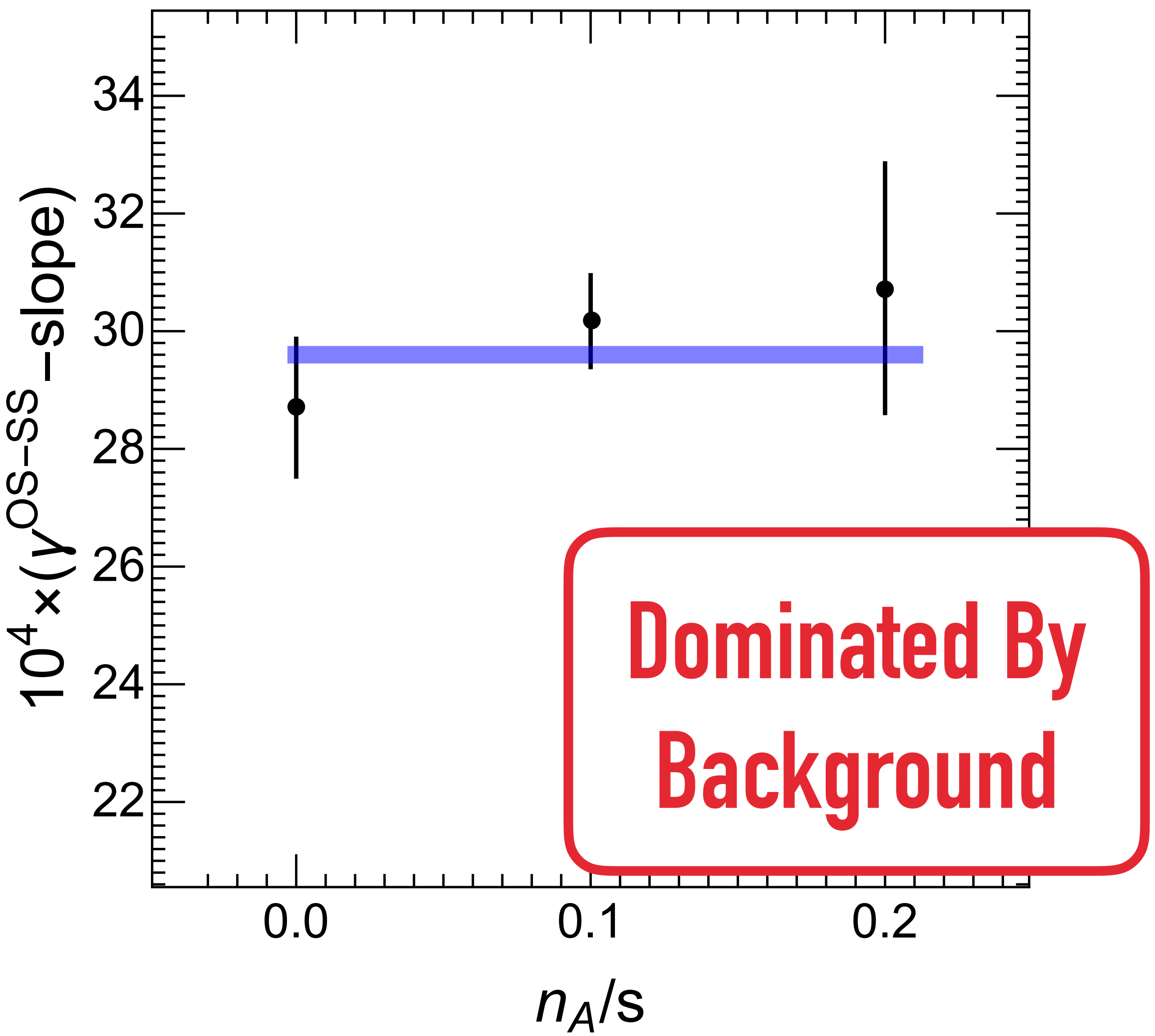
Au-Au @ 200GeV

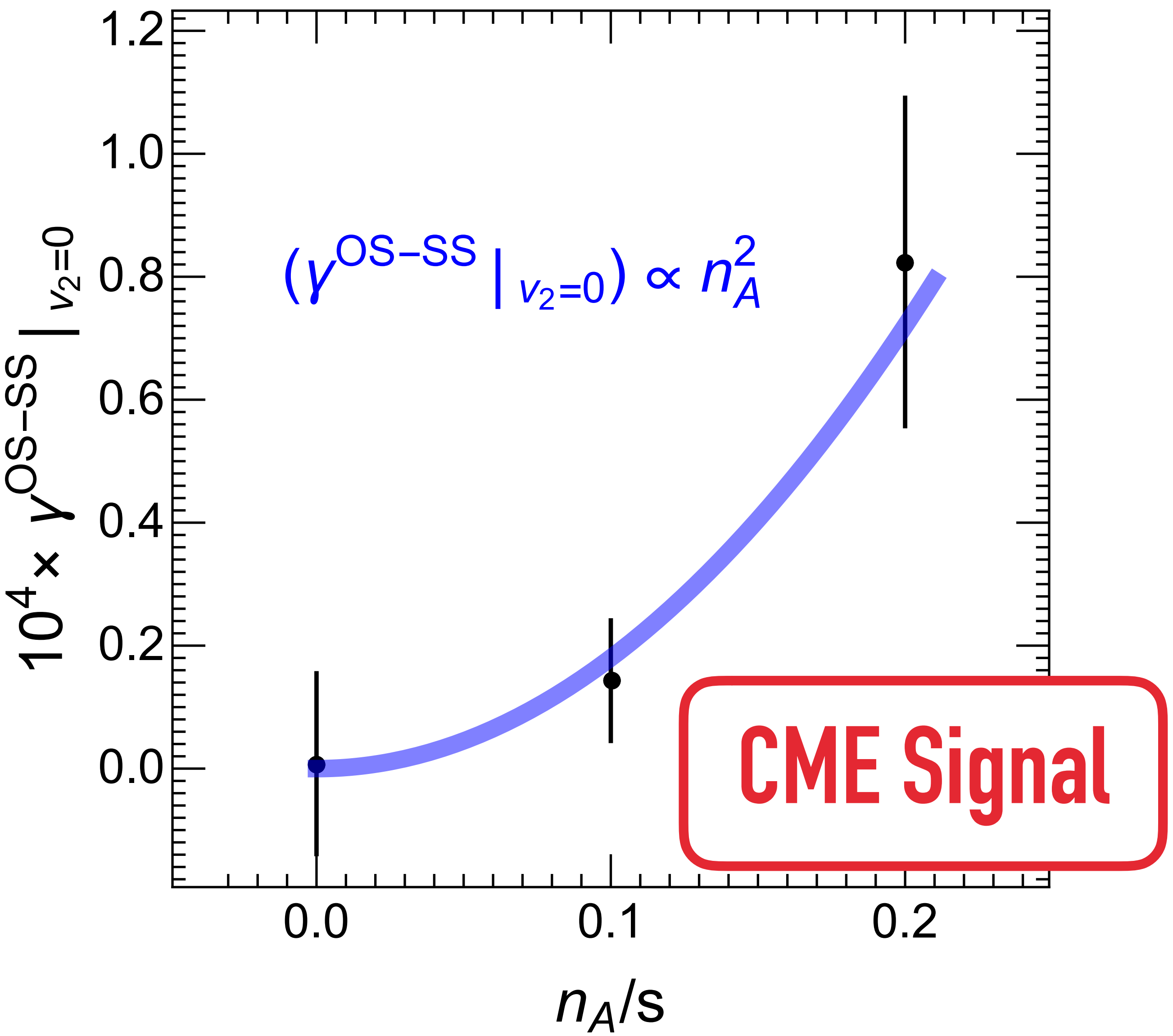
50-60%

Event-by-Event: v_2-γ Correlation

slope

intercept $\propto n_A^2$

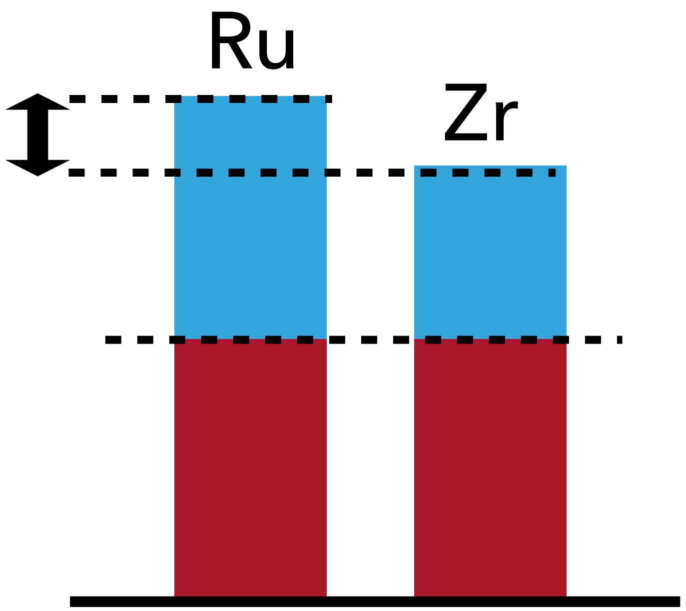




Test of CME — Isobaric Collisions @ RHIC

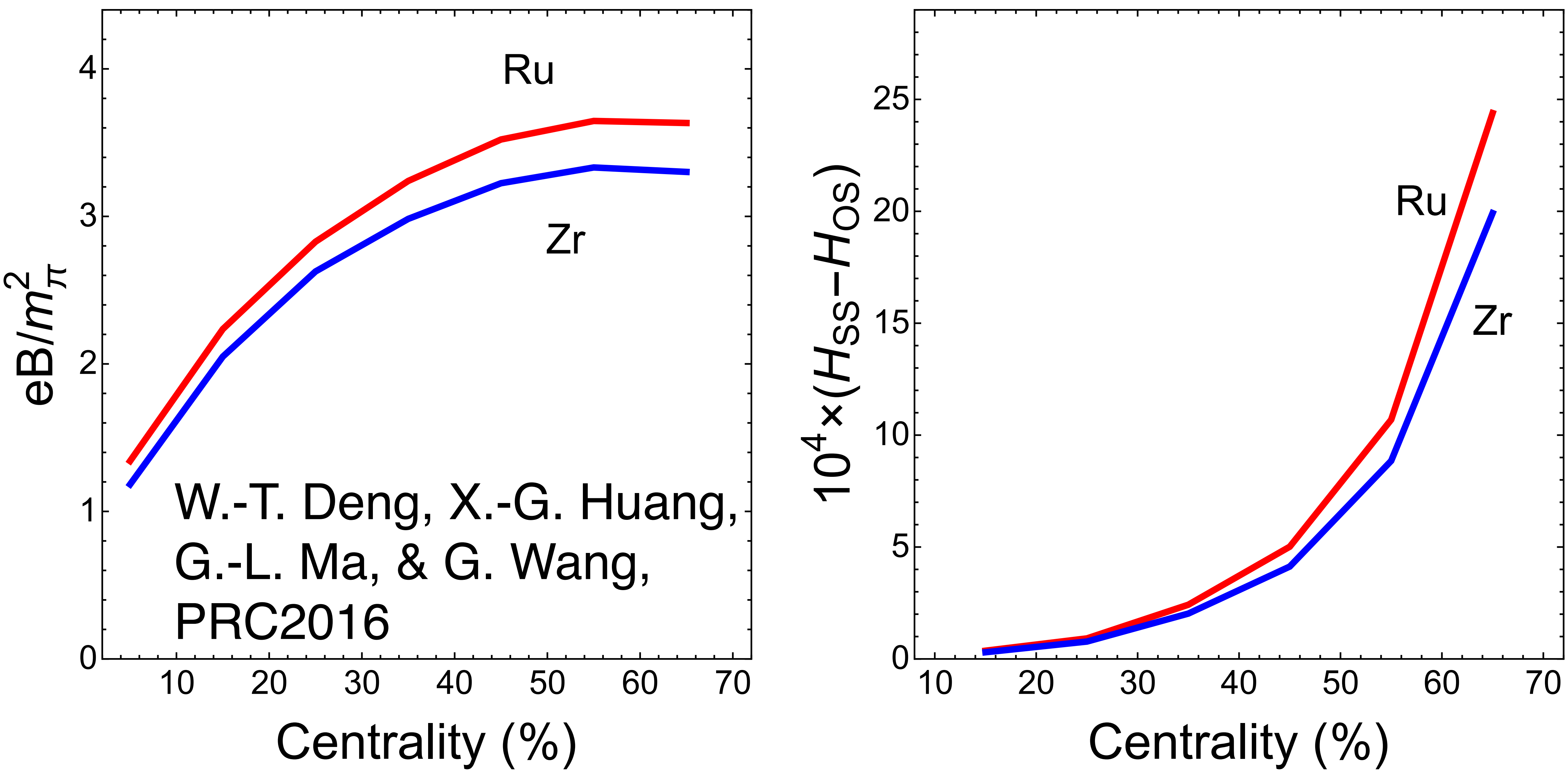
Different Proton # → Different CME!

Same Baryon # → Same Background



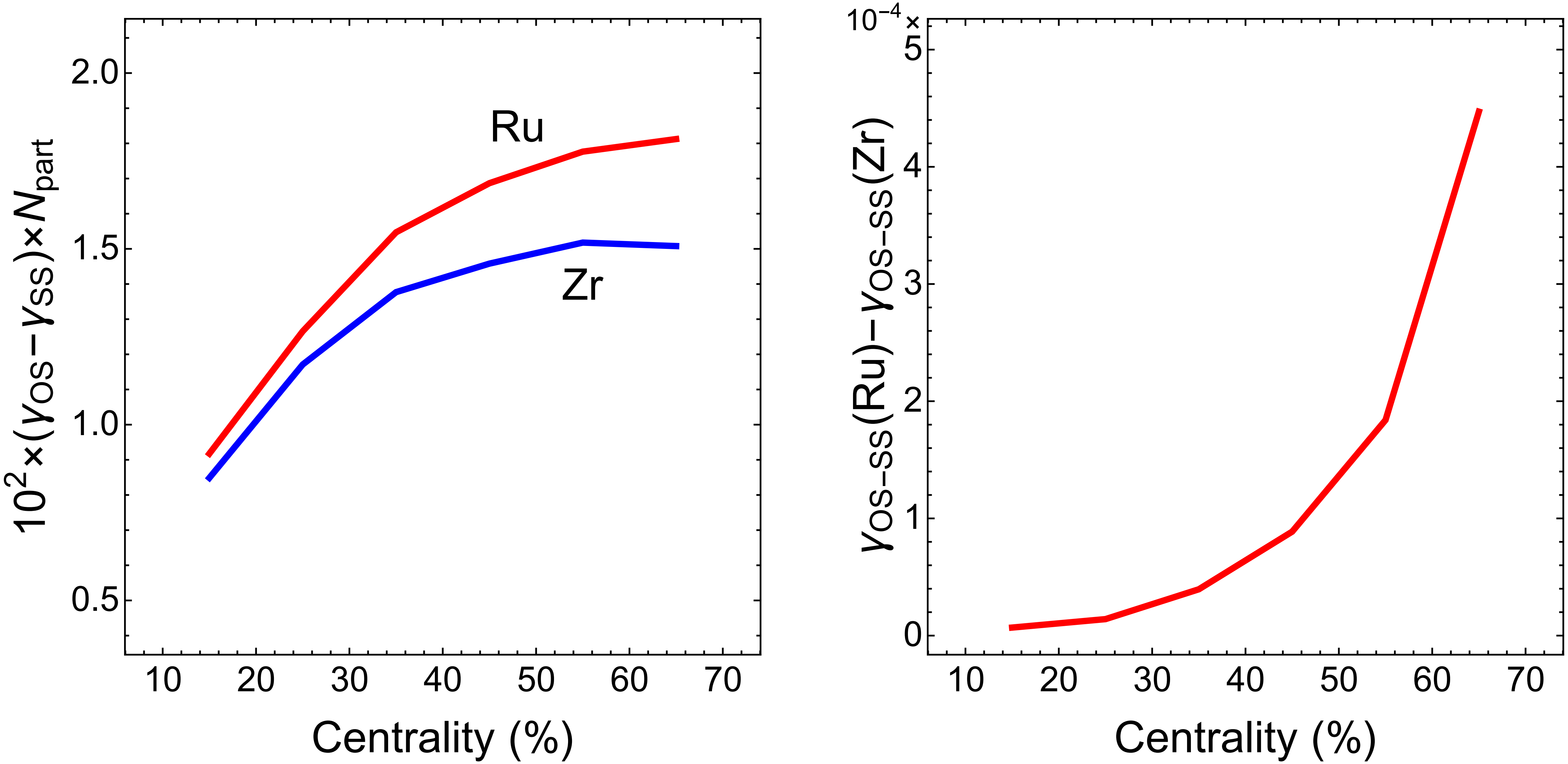
[Liwen Wen, WED] — Experimental Preview

IsoBar CME from smooth AVFD simulation



IsoBar CME from smooth AVFD simulation

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



SS, Y.Jiang, E.Lilleskov, & J.Liao, in final preparation

Summary

- Smooth AVFD + Best estimated n_A & τ_B ⇒ good agreement with Au-Au experiments.
- Event-by-Event AVFD ⇒ intercept of v_2-γ correlation tells CME signal from background.
- IsoBar Program shall be a crucial test of CME.
- in EbE simulation: Transverse Momentum Conservation, Local Charge Conservation …

Other Talks About Chiral Effects @ CPOD 2017

[WEN, Liwen WED 9:00]
Searches for Chiral Effects and Prospects for Isobaric Collisions at STAR/RHIC

[SCHLICHTING, Soeren WED 9:30]
Chiral magnetic effect and anomalous transport in real time

[HIRONO, Yuji WED 10:00]
Properties of chiral magnetohydrodynamics

[UPSAL, Isaac WED 11:00]
Global polarization of Lambda hyperons in Au+Au Collisions at RHIC

[WANG, Qun WED 11:30]
Global Lambda polarization in heavy-ion collisions

[SORIN, Alexander WED 12:00]
Vorticity and polarization in baryon-rich matter

[TU, Zhoudunming WED 14:00]
Studies of charge-dependent azimuthal correlations in search for the chiral magnetic effect in pPb and PbPb collisions at CMS

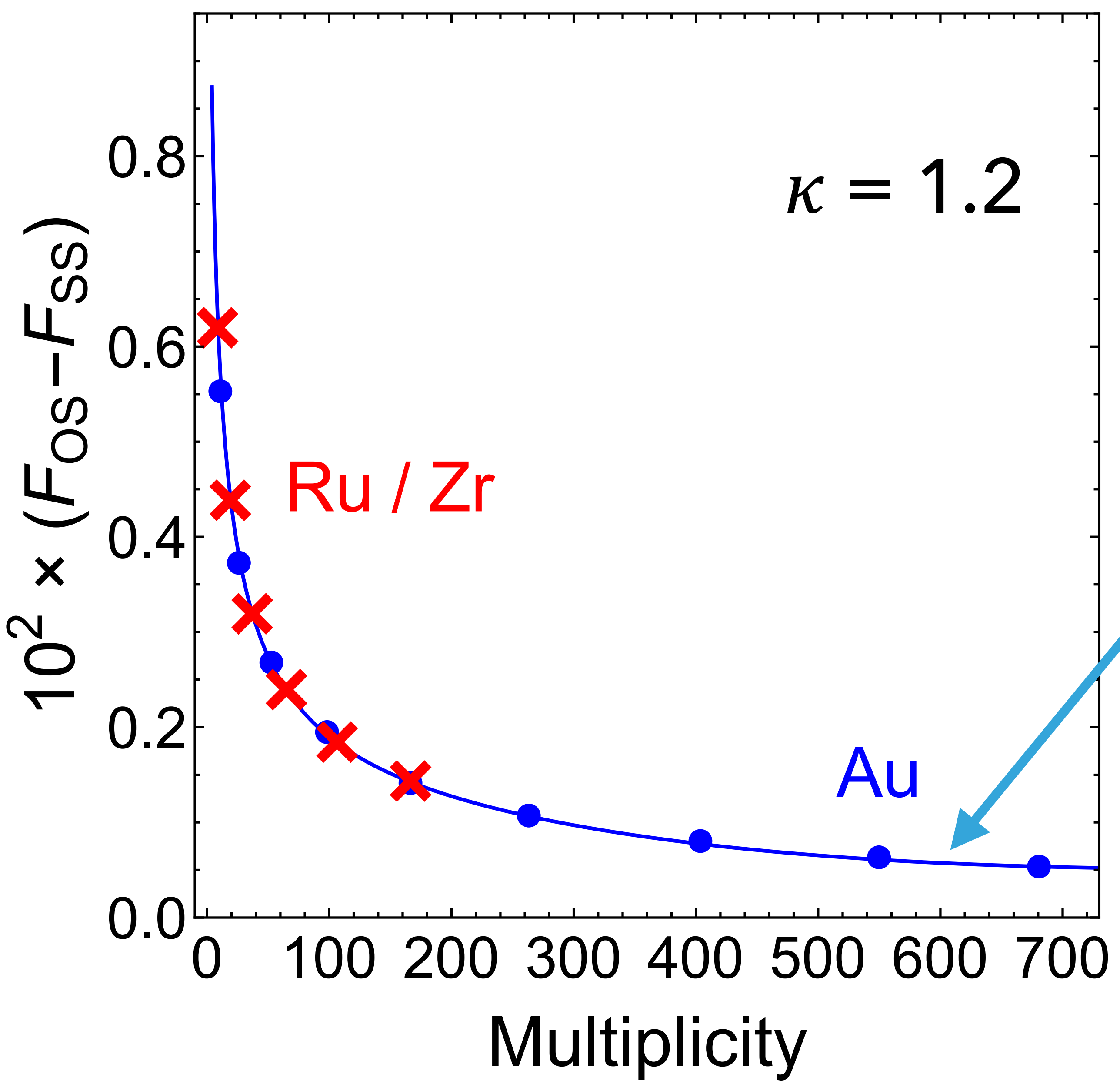
[YEE, Ho-Ung WED 14:30]
Anatomy of Chiral Magnetic Effect In and Out of Equilibrium

[VENUGOPALAN, Raju WED 15:00]
World-line approach to chiral kinetic theory

THANK YOU!

BACKUP SLIDES

Estimation Of IsoBar Bulk Background



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

Fitting Formular:

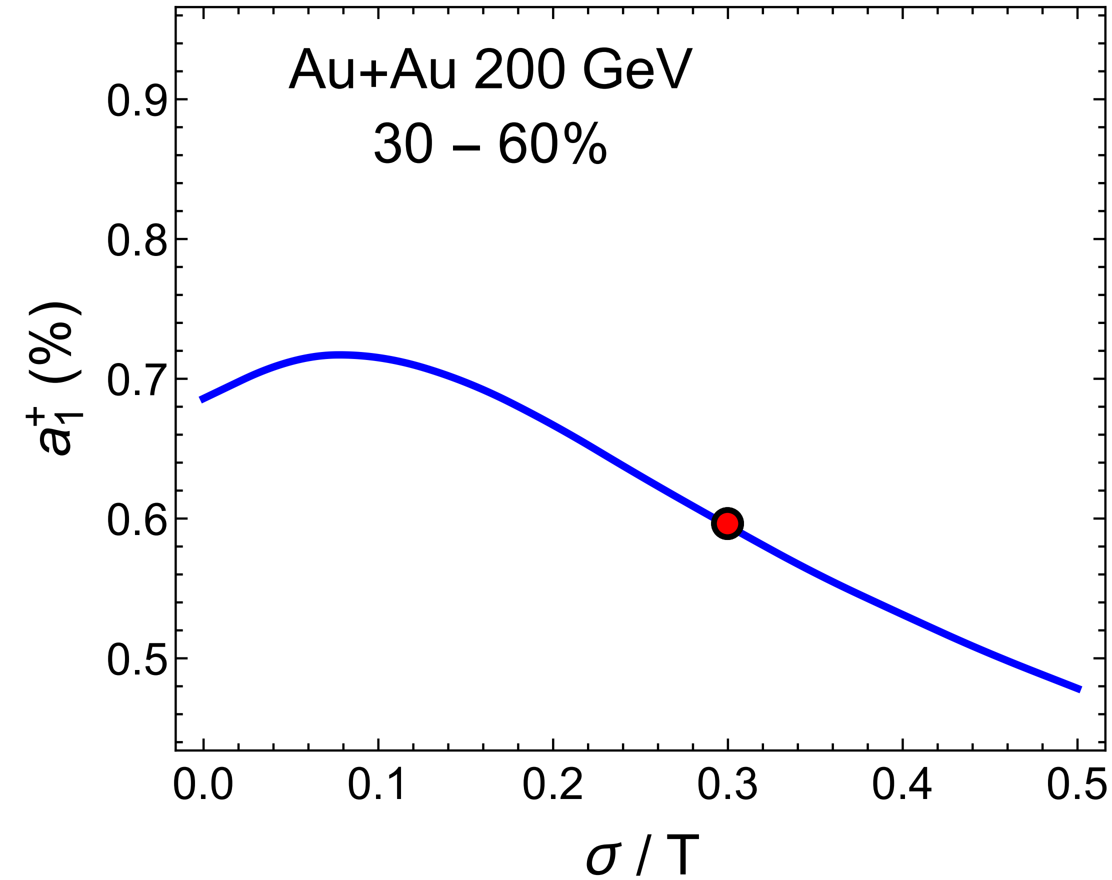
$$F(x) = \frac{1 + a_1\, x + a_2\, x^2}{b_1\, x + b_2\, x^2}$$

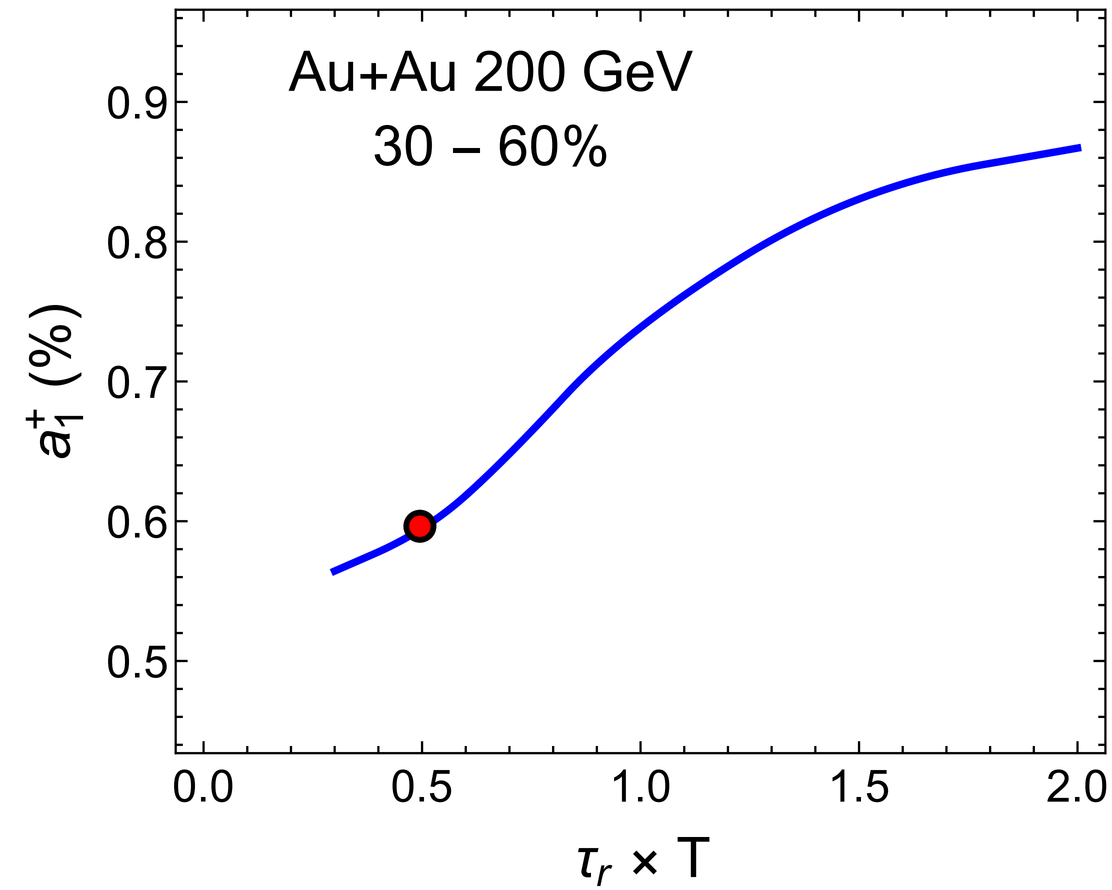
Effect of Viscous Transportation

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

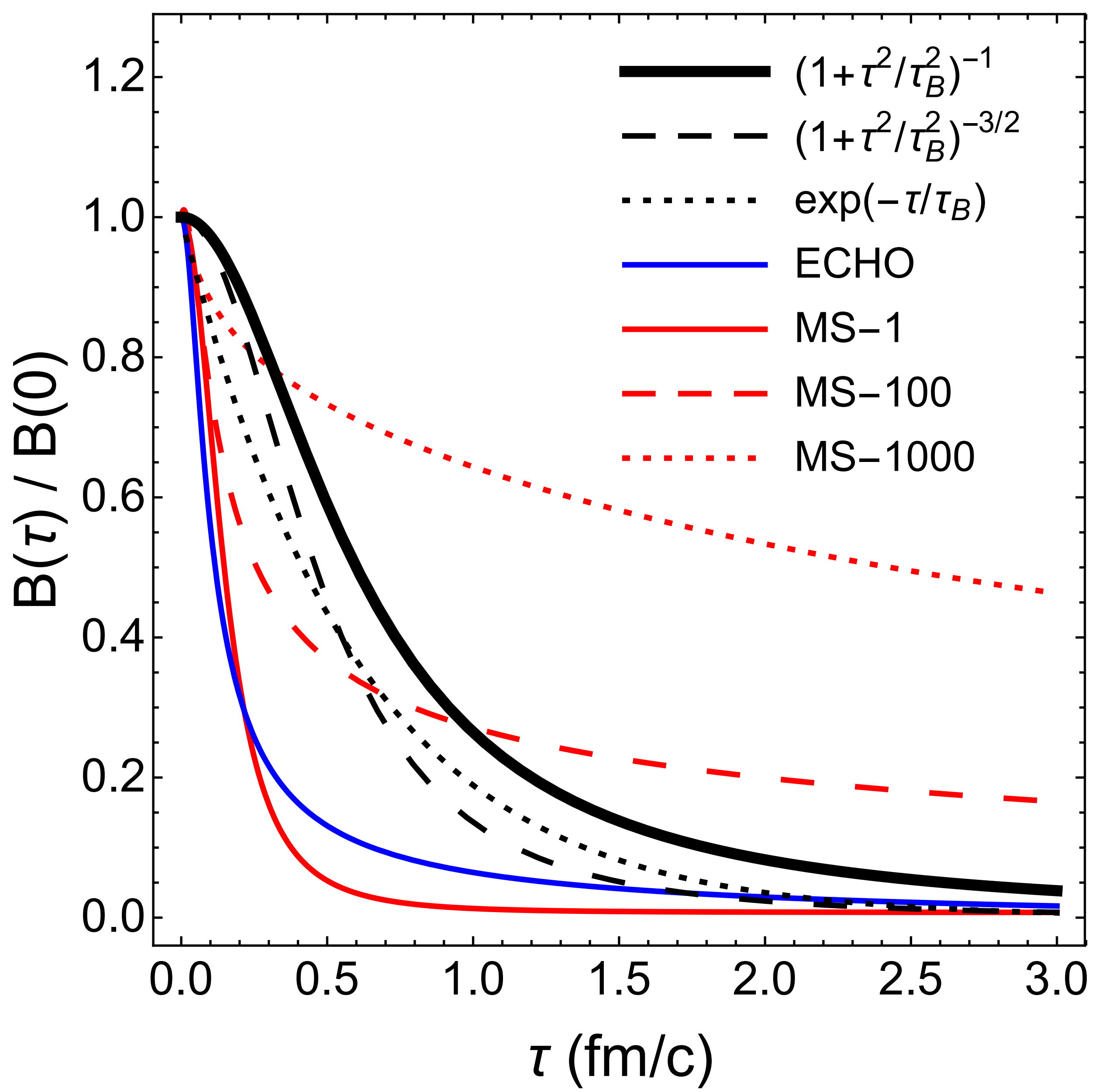
$$\nu_{NS}{}^{\mu} = \frac{\sigma}{2} T \Delta^{\mu\nu}\, \partial_{\nu} \frac{\mu}{T} + \frac{\sigma}{2} q\, E^{\mu}$$

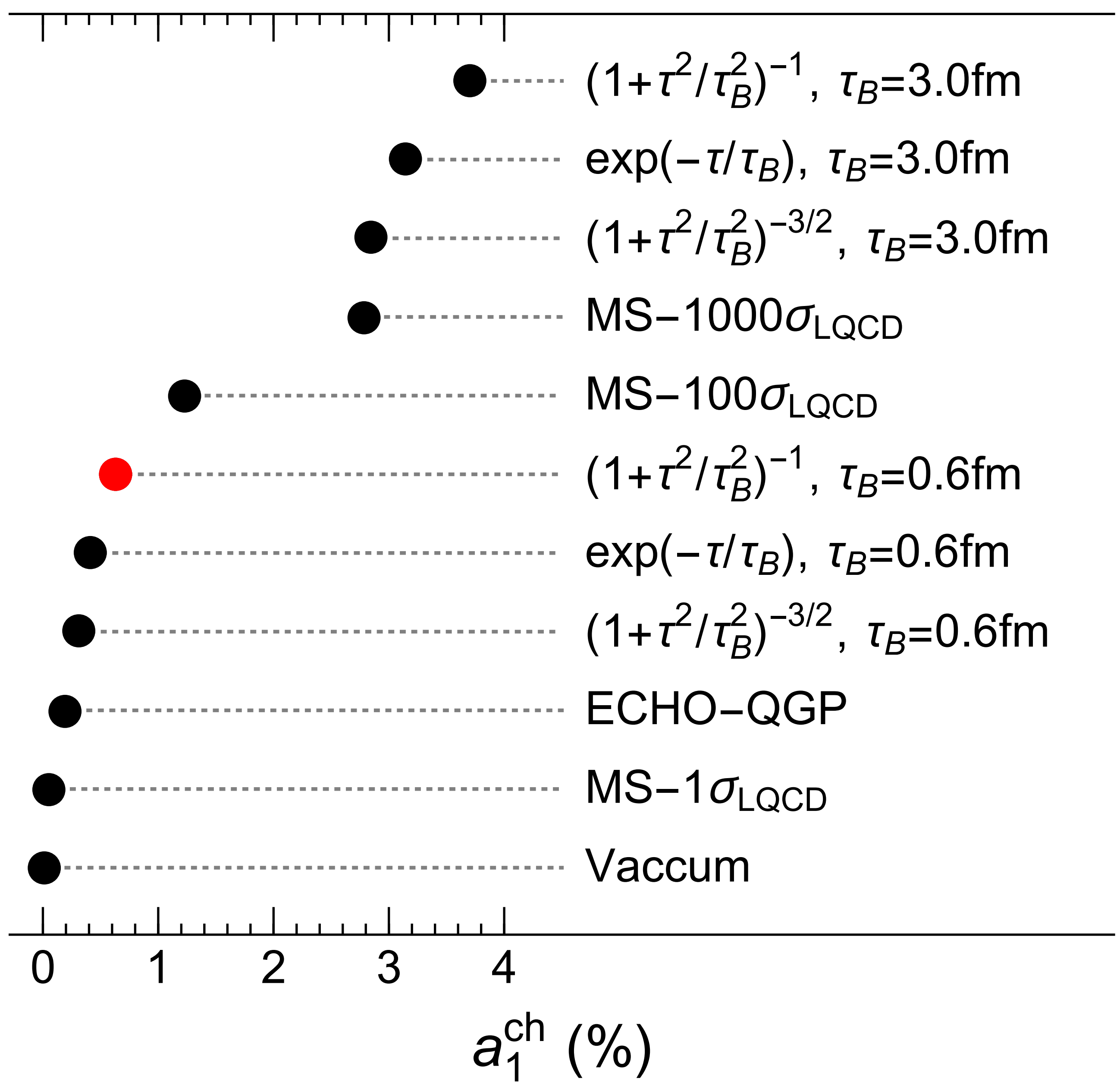
- Viscous transportation has sizable (~30%) effect on charge separation.
- "Canonic" parameters are employed.



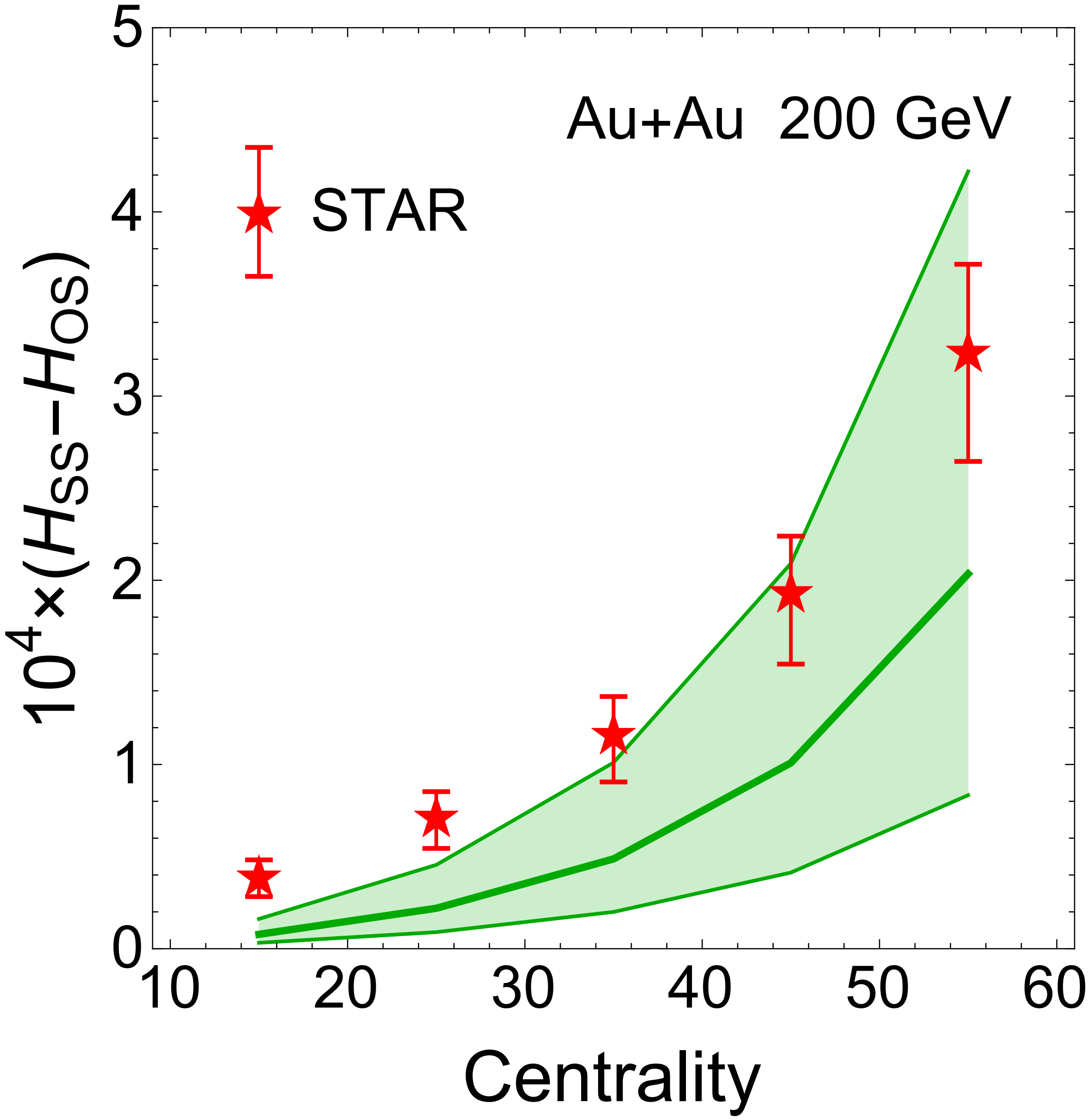


Dependence on the Magnetic Field





CME in Au-Au Collisions

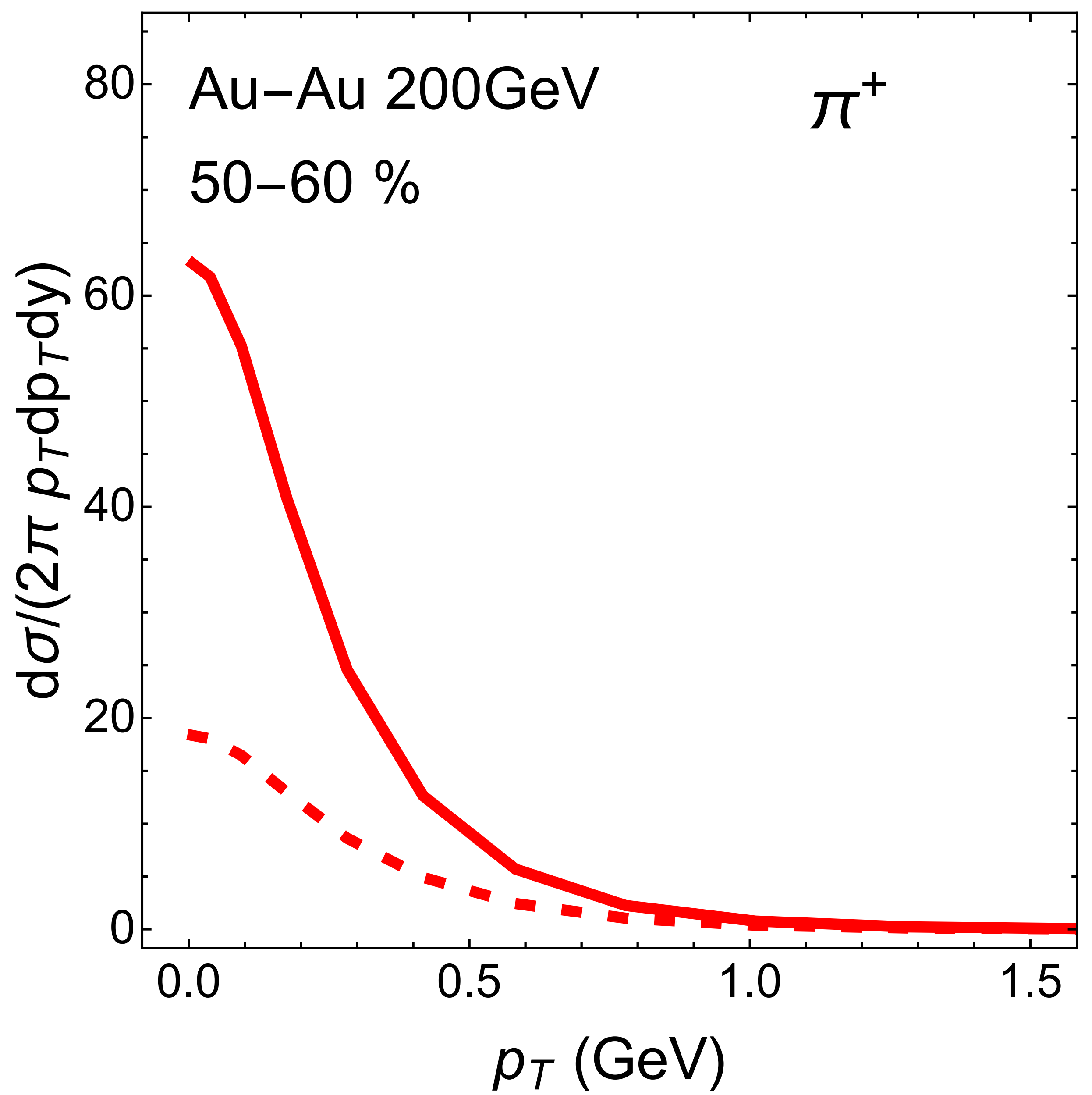


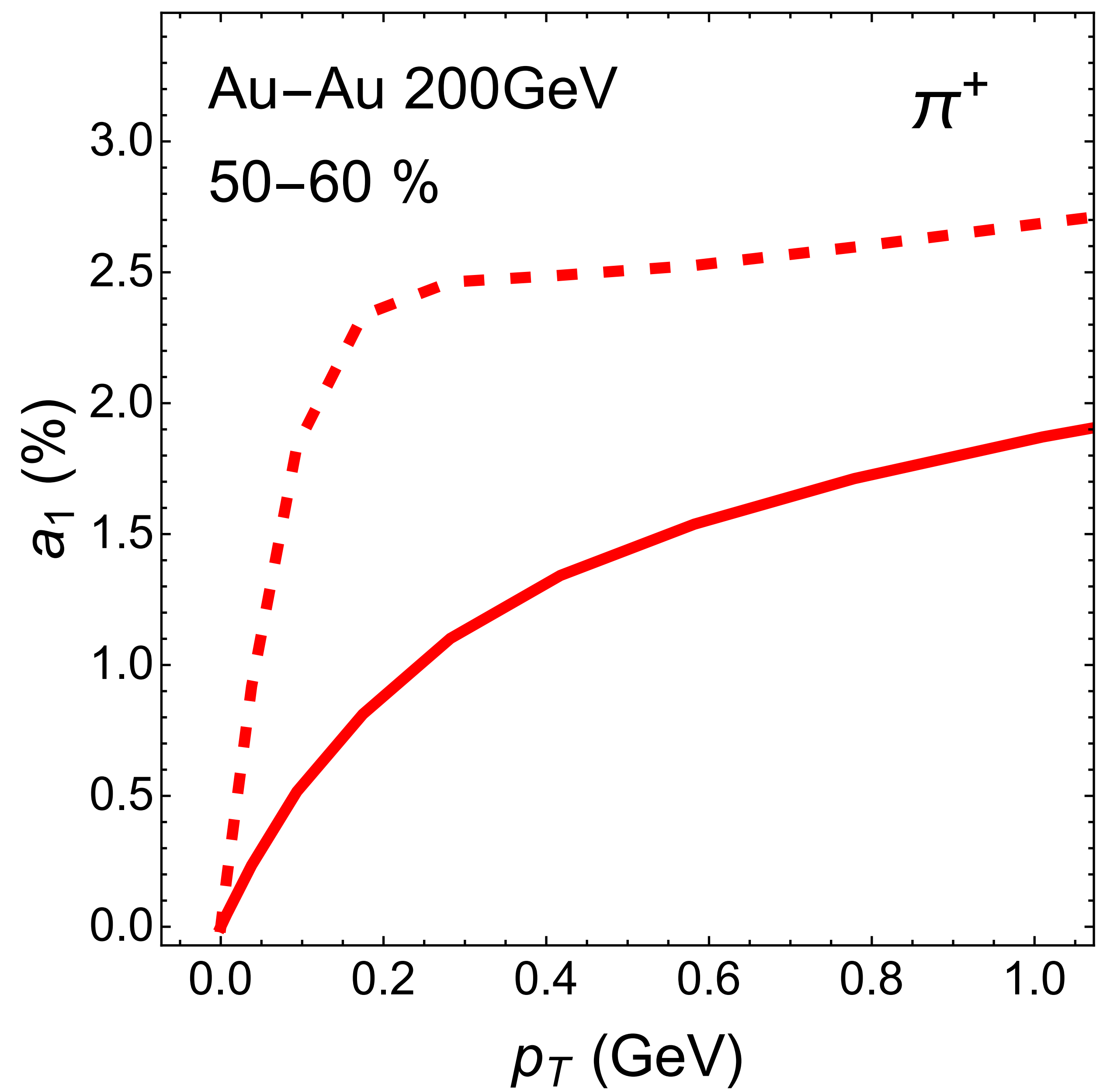
$$B = \frac{B_0}{1+(\tau/\tau_B)^2} \quad \tau_B = 0.6\ \mathrm{fm/c}$$

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

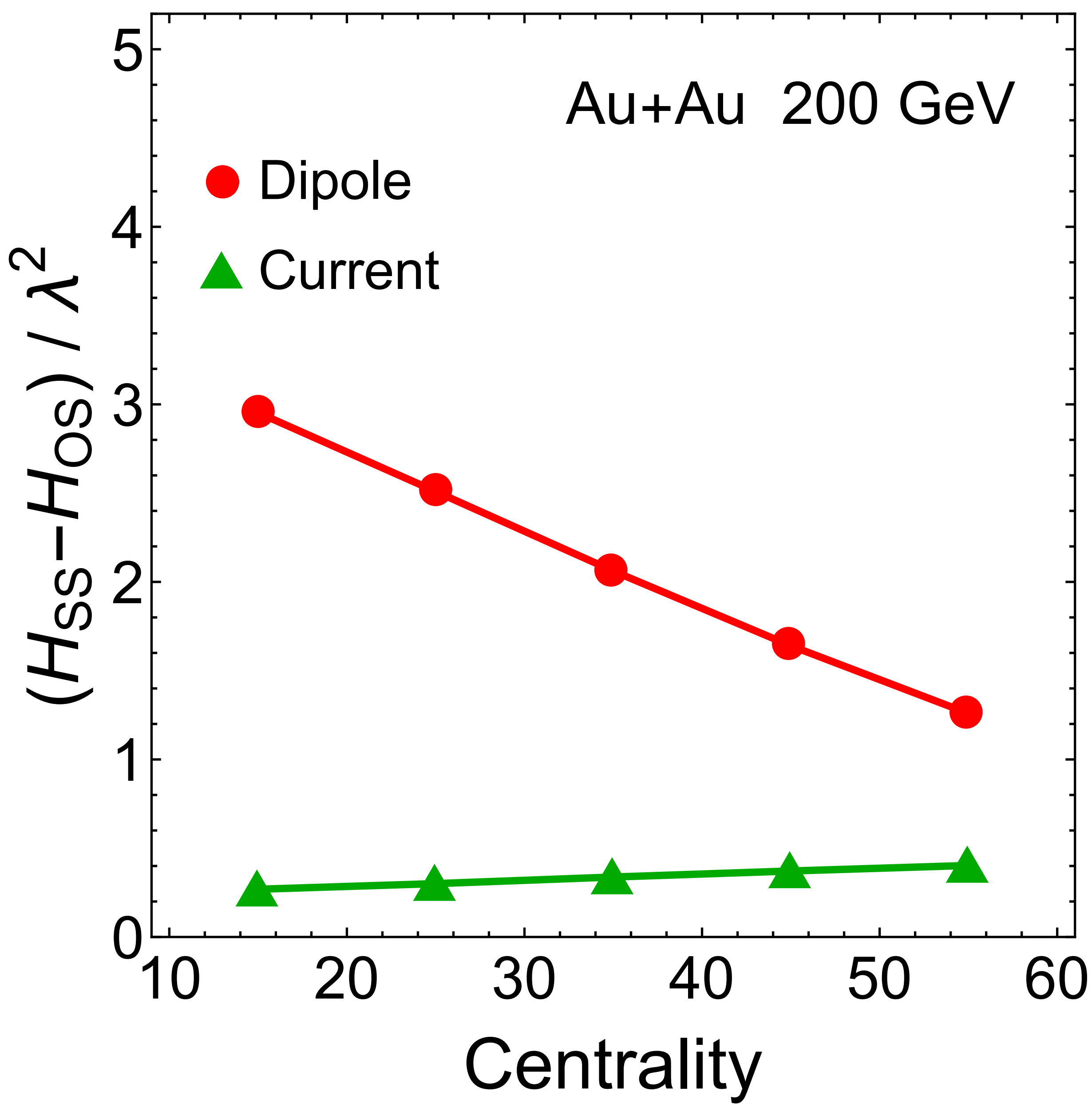
Contribution of Decay from Resonances

solid: decay of resonances included
dashed: only thermal production





Pre-Thermal Anomalous Dipole/Current?

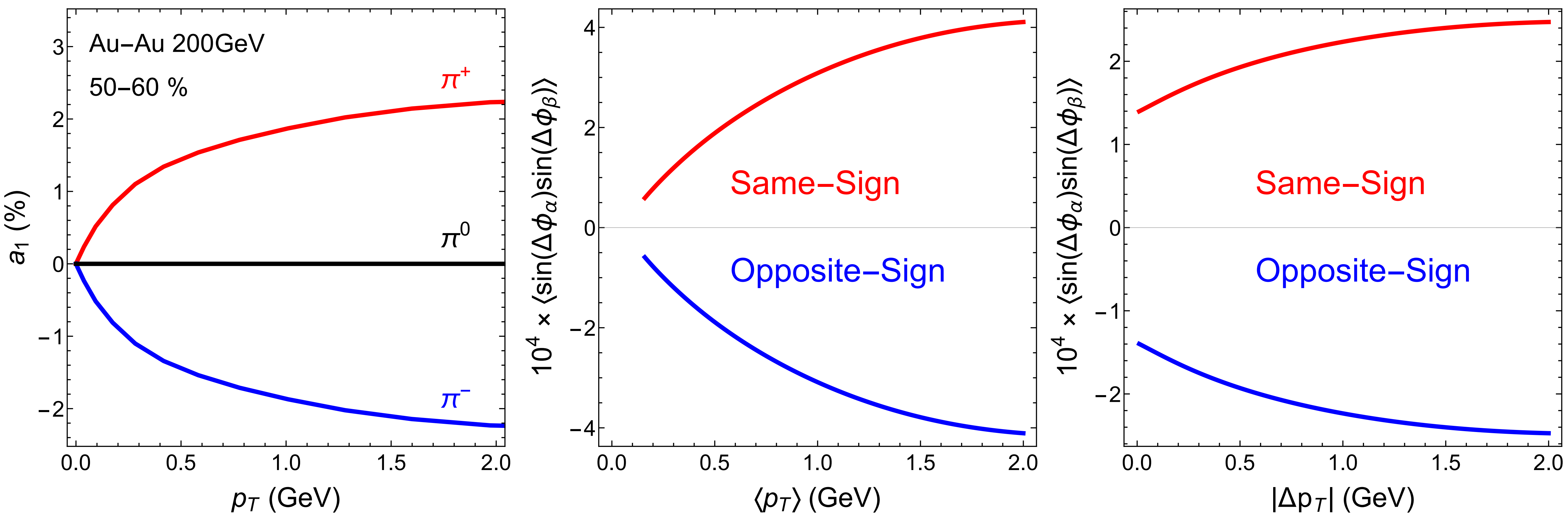


B (τ>0.6fm) = 0

$$J^\mu(\tau=\tau_0) \;=\; \lambda_J \times (C_A\,\mu_A\,B^\mu)$$

pre-thermal anomalous dipole/current are possible candidate for charge separation.

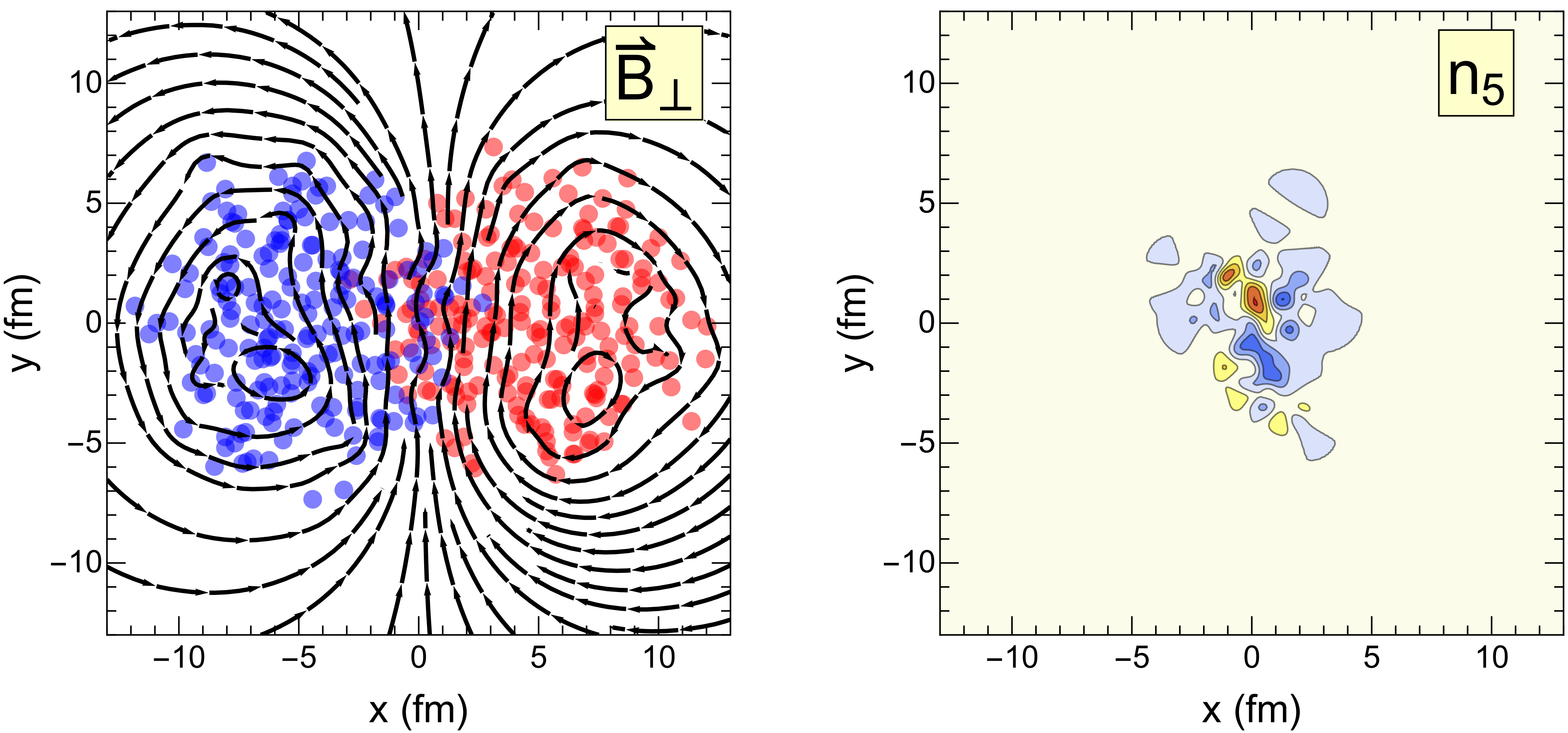
pT-Differential Correlation from Smooth CME



Outlook - Fluctuating B-Field & n_A

Au-Au @ 200GeV

50-60%



Outlook – Fluctuating B-Field & n_A

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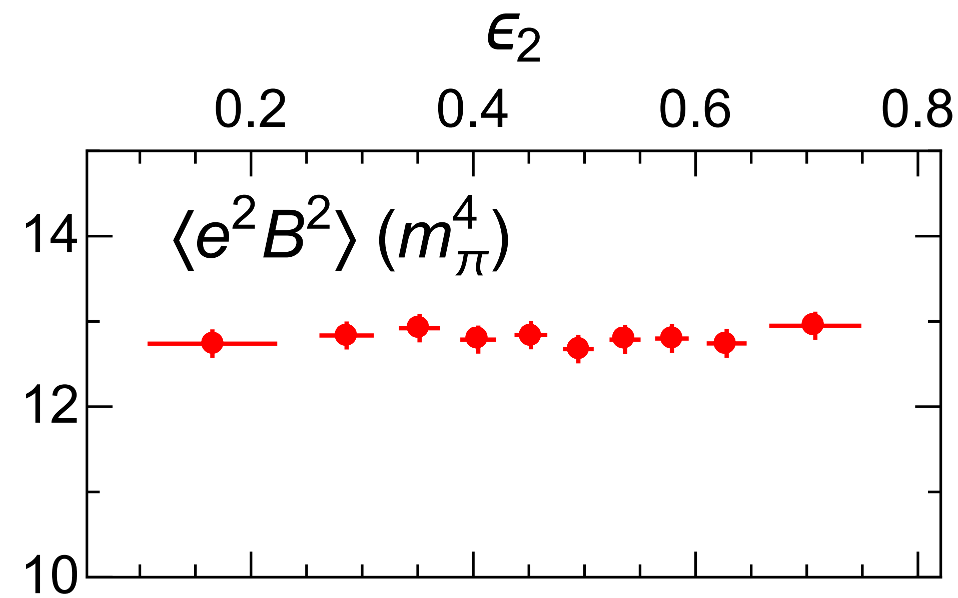
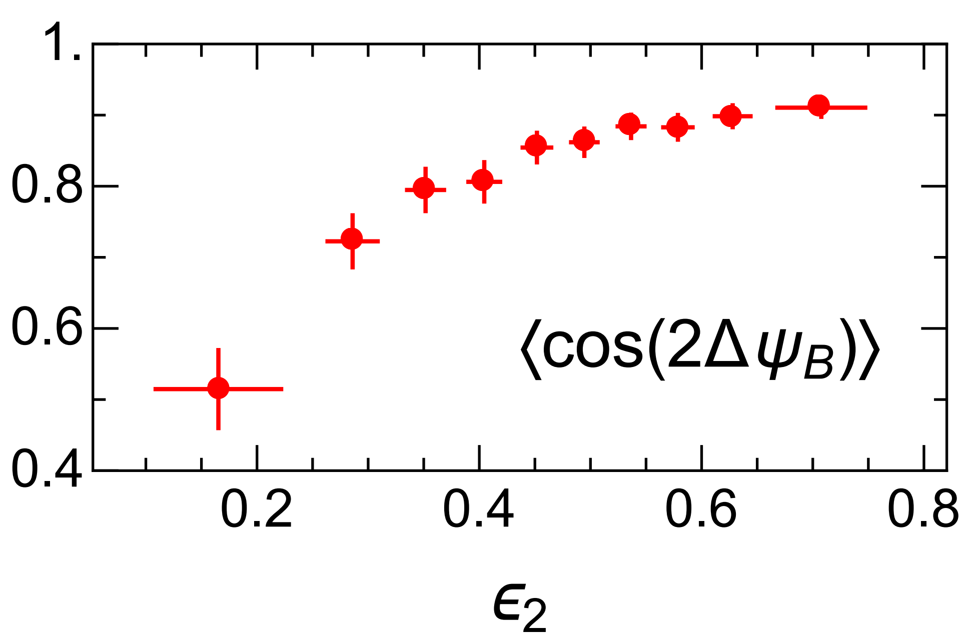
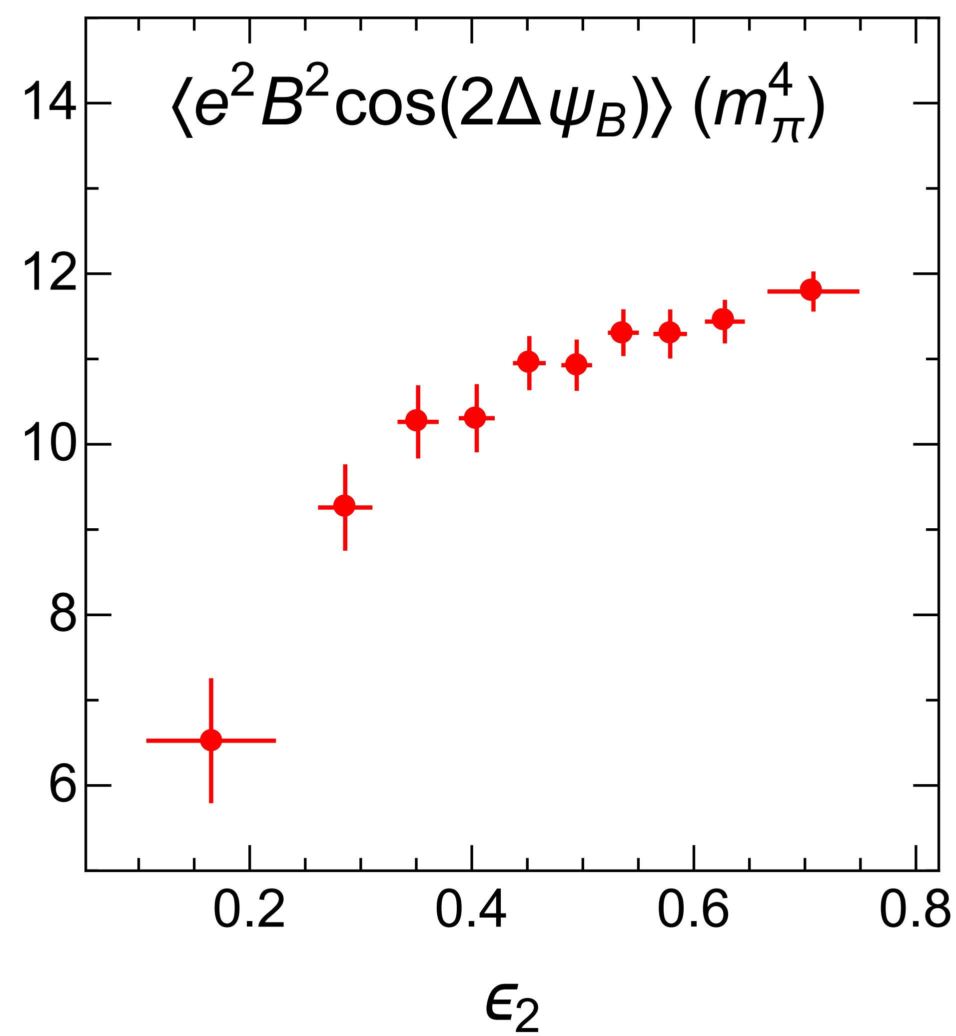


$\otimes$



$\Rightarrow$



$$\Delta\Psi_B \equiv \Psi_B - \Psi_{IC.EP} - \pi/2$$