Quantifying Chiral Magnetic Effect from Anomalous-Viscous Fluid Dynamics

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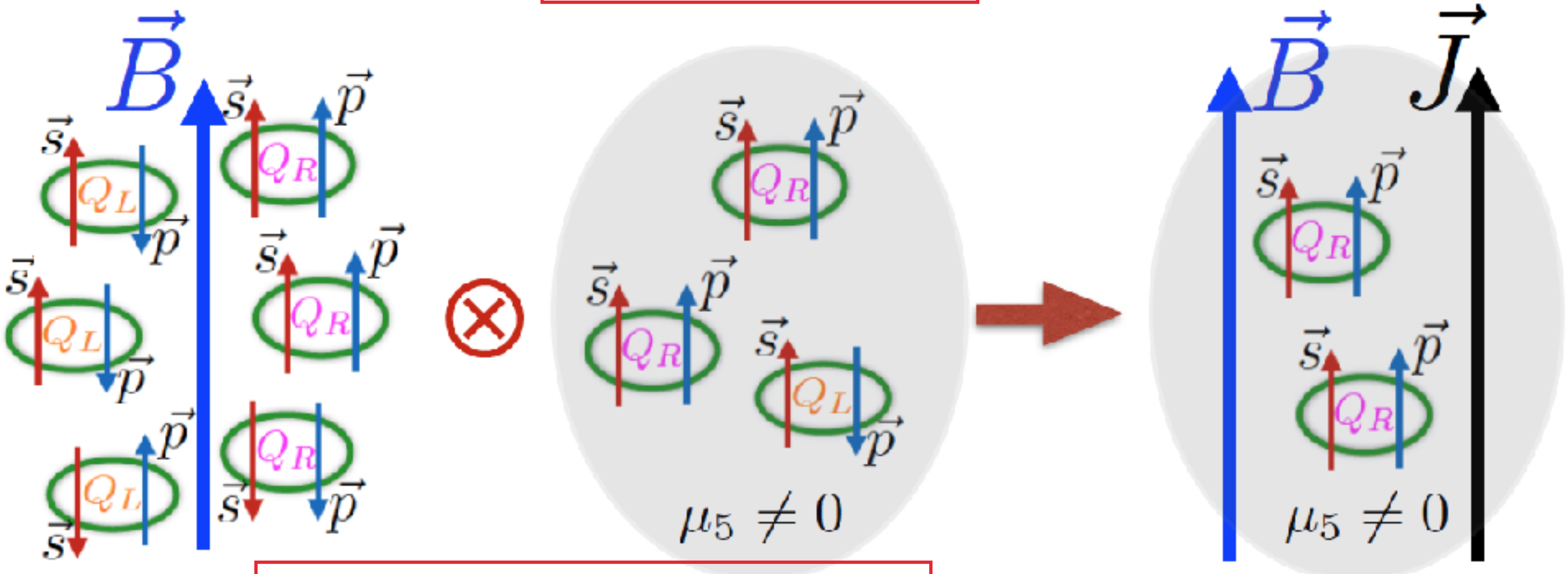
Outline

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

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

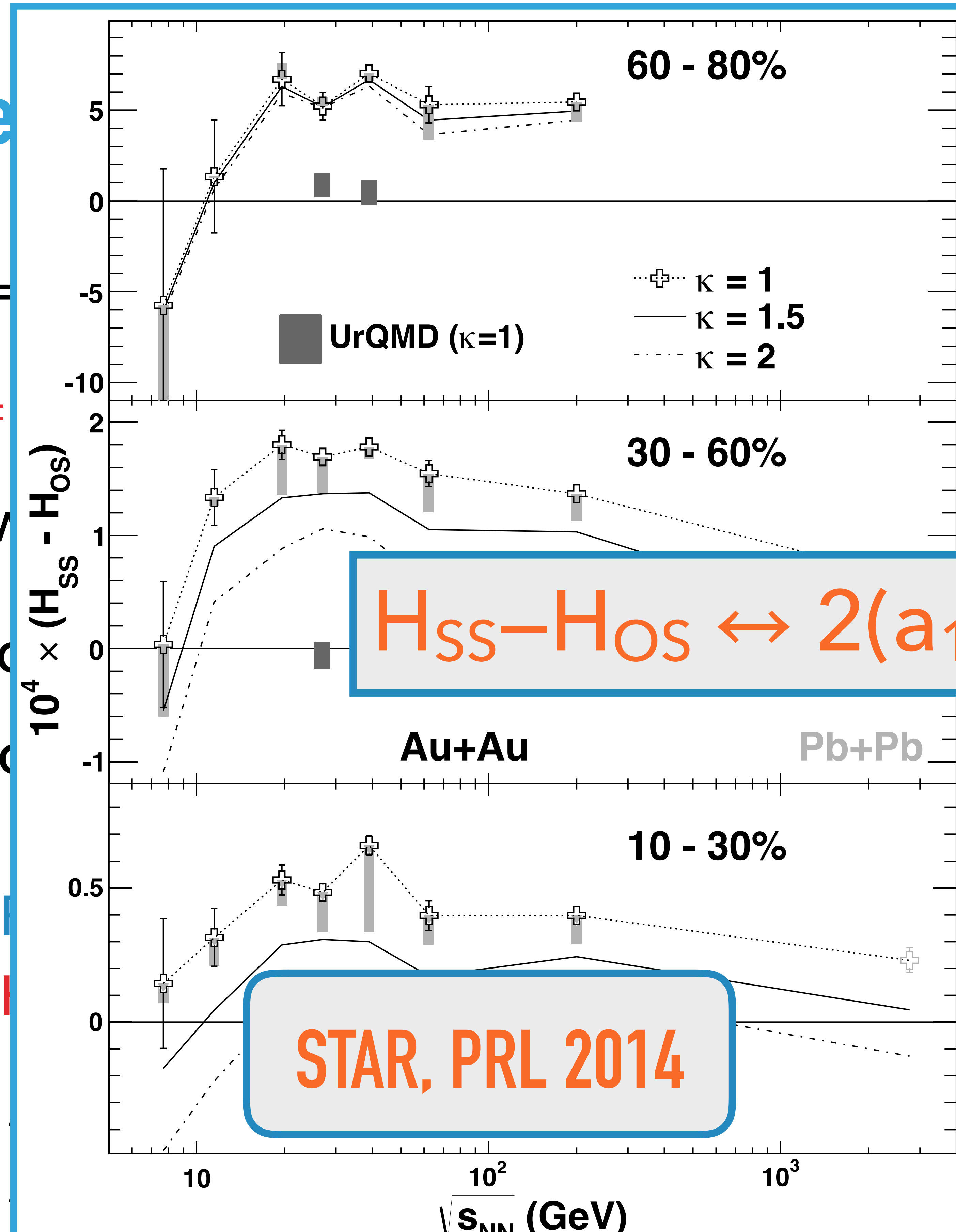
- charge separation ⇒ tw

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

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

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

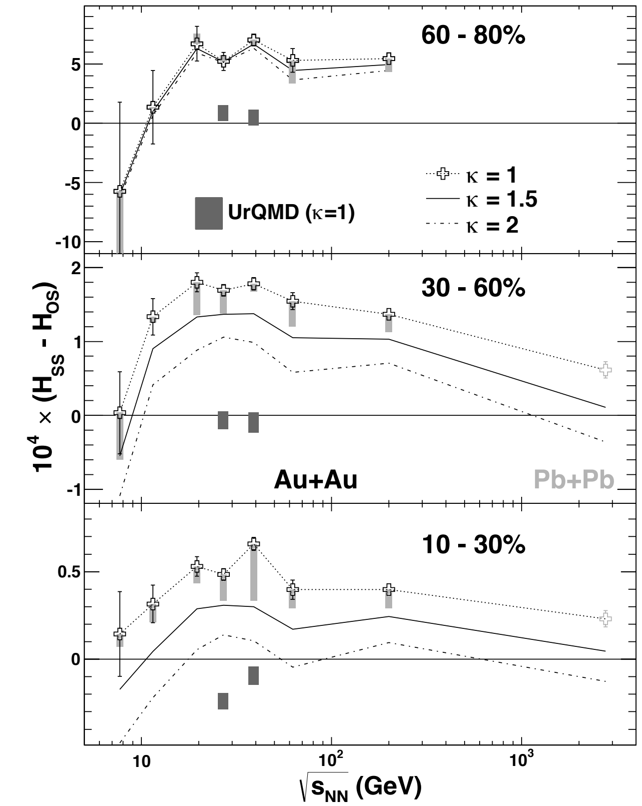
$\delta = F + H$



$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

STAR, PRL 2014

How Can We Calculate CME Quantitatively?



axial (& vector) charge density

initial condition

+

driving force

B field

Anomalous
-**V**iscous
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

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

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

on top of 2+1D `VISHNew` –– OSU Group

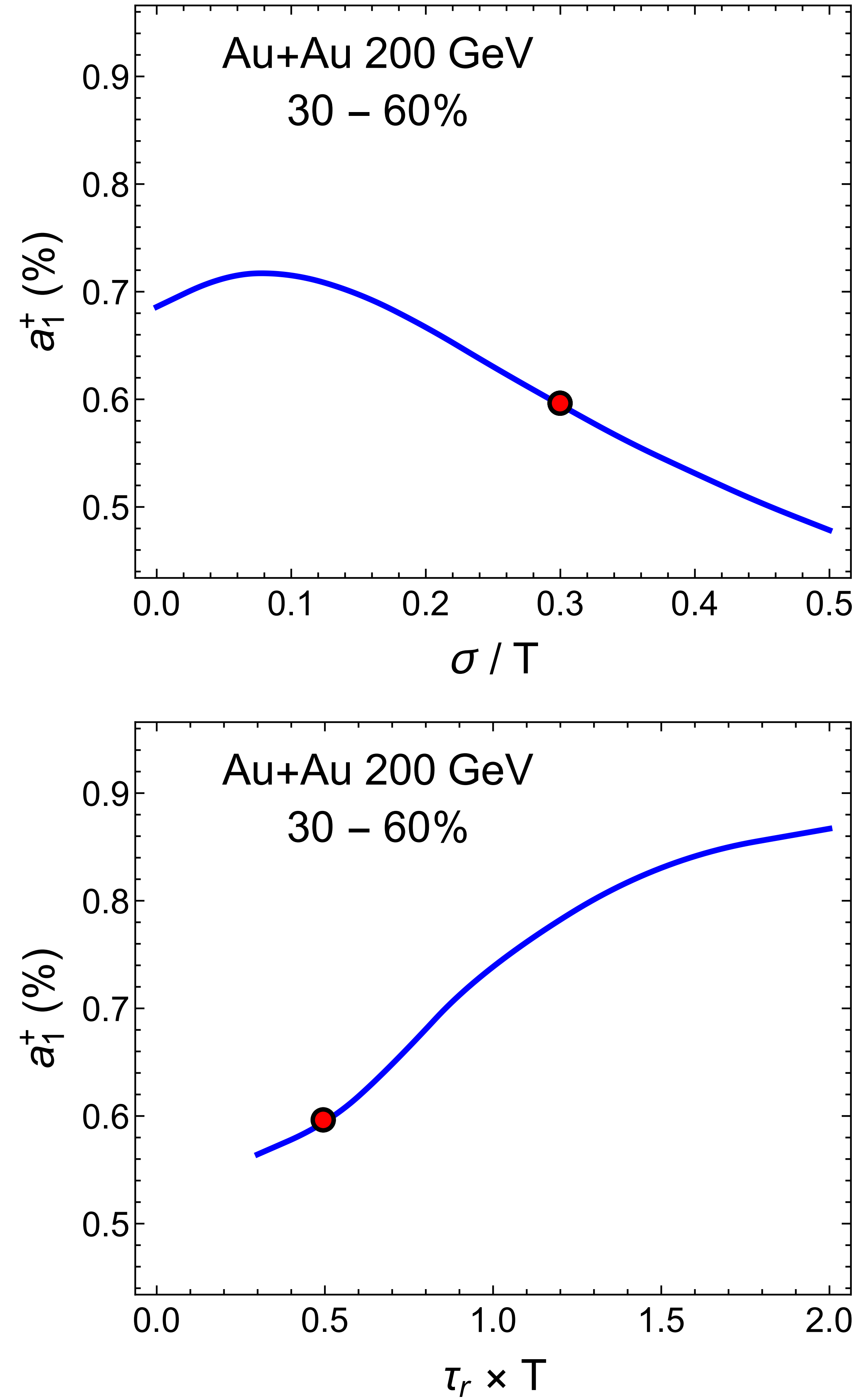
$$D_\mu T^{\mu\nu} = 0$$

Effect of Viscous Transportation

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

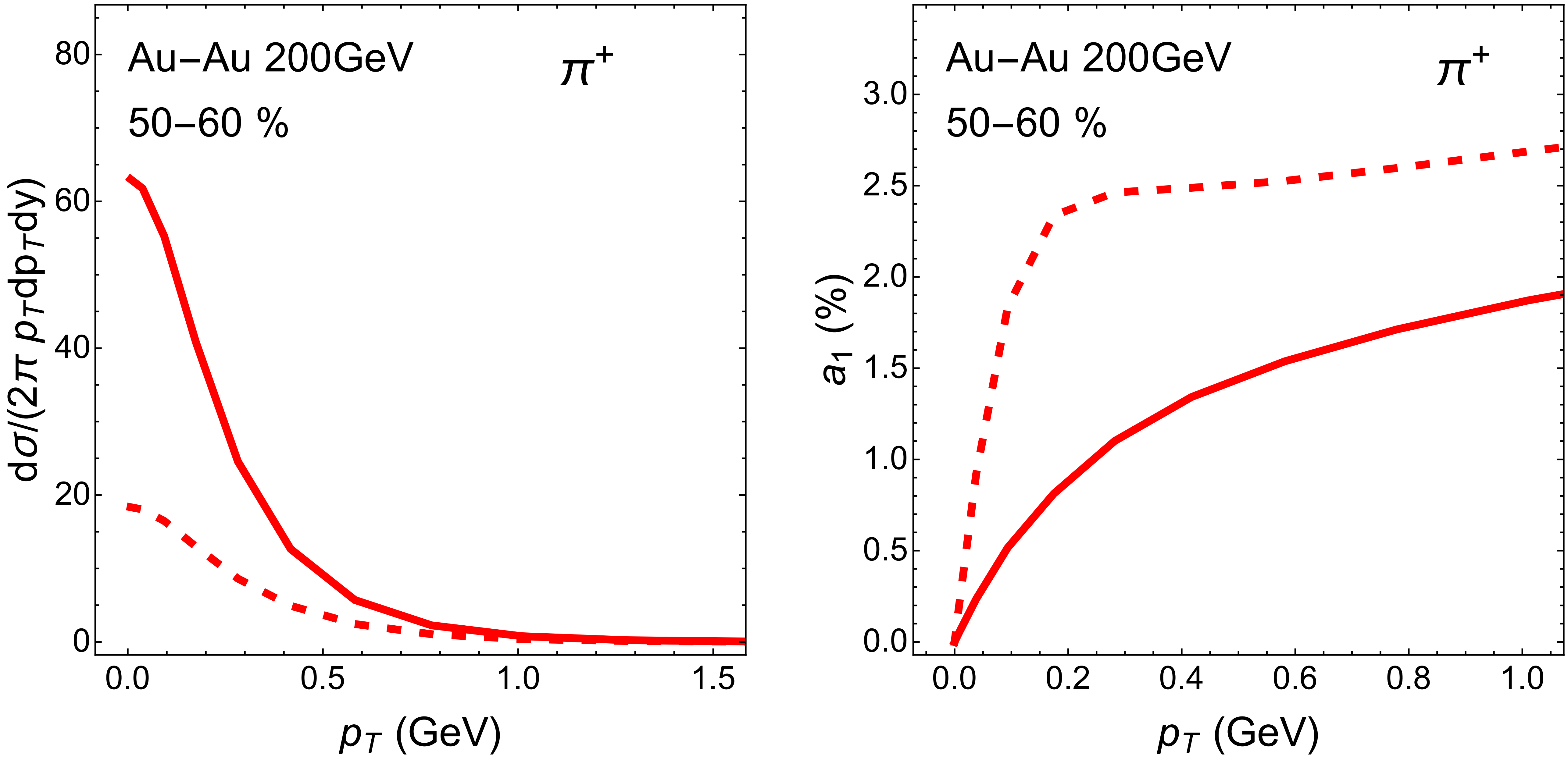
$$\nu_{NS}{}^{\mu} = \frac{\sigma}{2} T \Delta^{\mu\nu}\, \partial_{\nu} \frac{\mu}{T} + \frac{\sigma}{2} q\, E^{\mu}$$

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

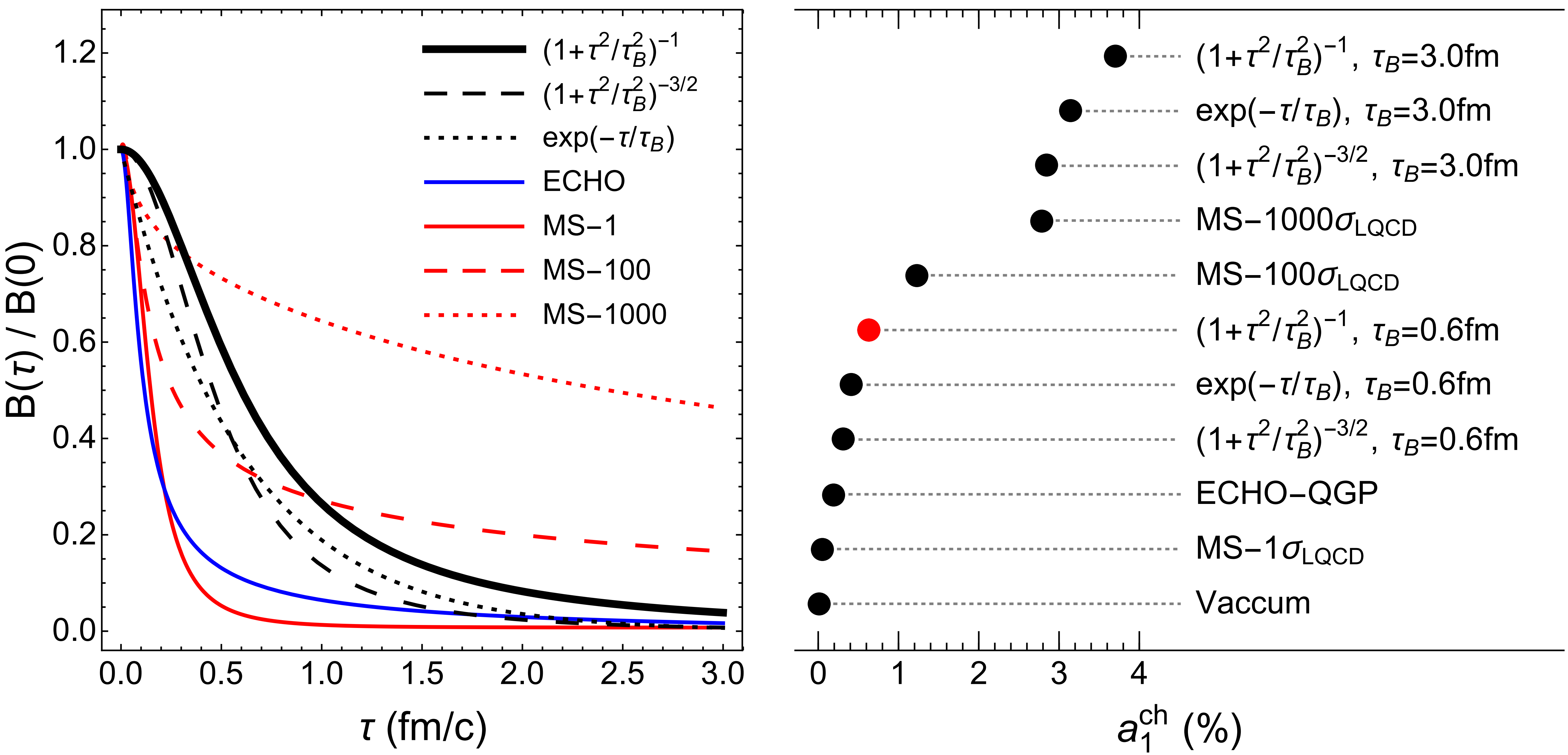


Contribution of Decay from Resonances

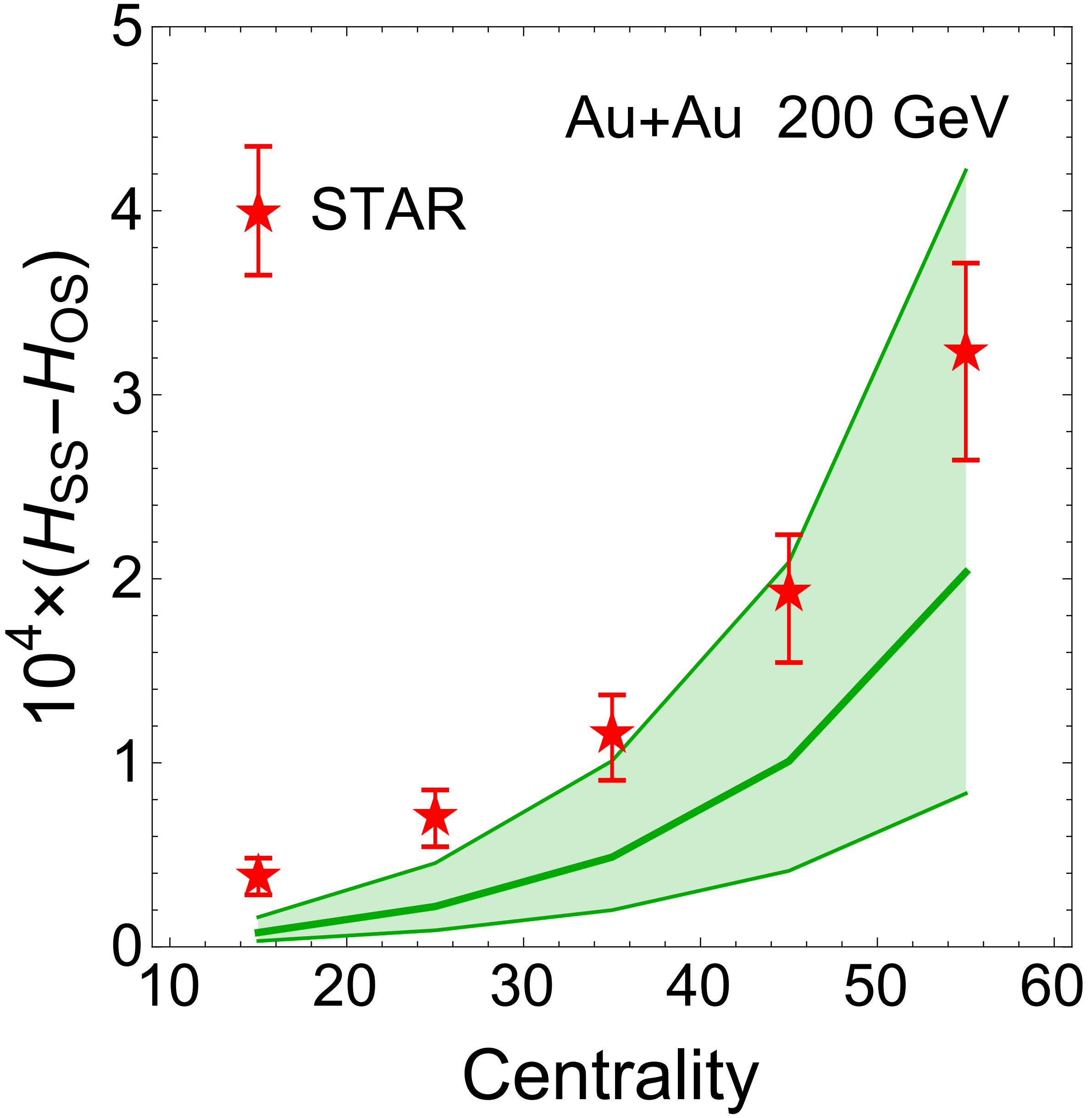
solid: decay of resonances included
dashed: only thermal production



Dependence on the Magnetic Field



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

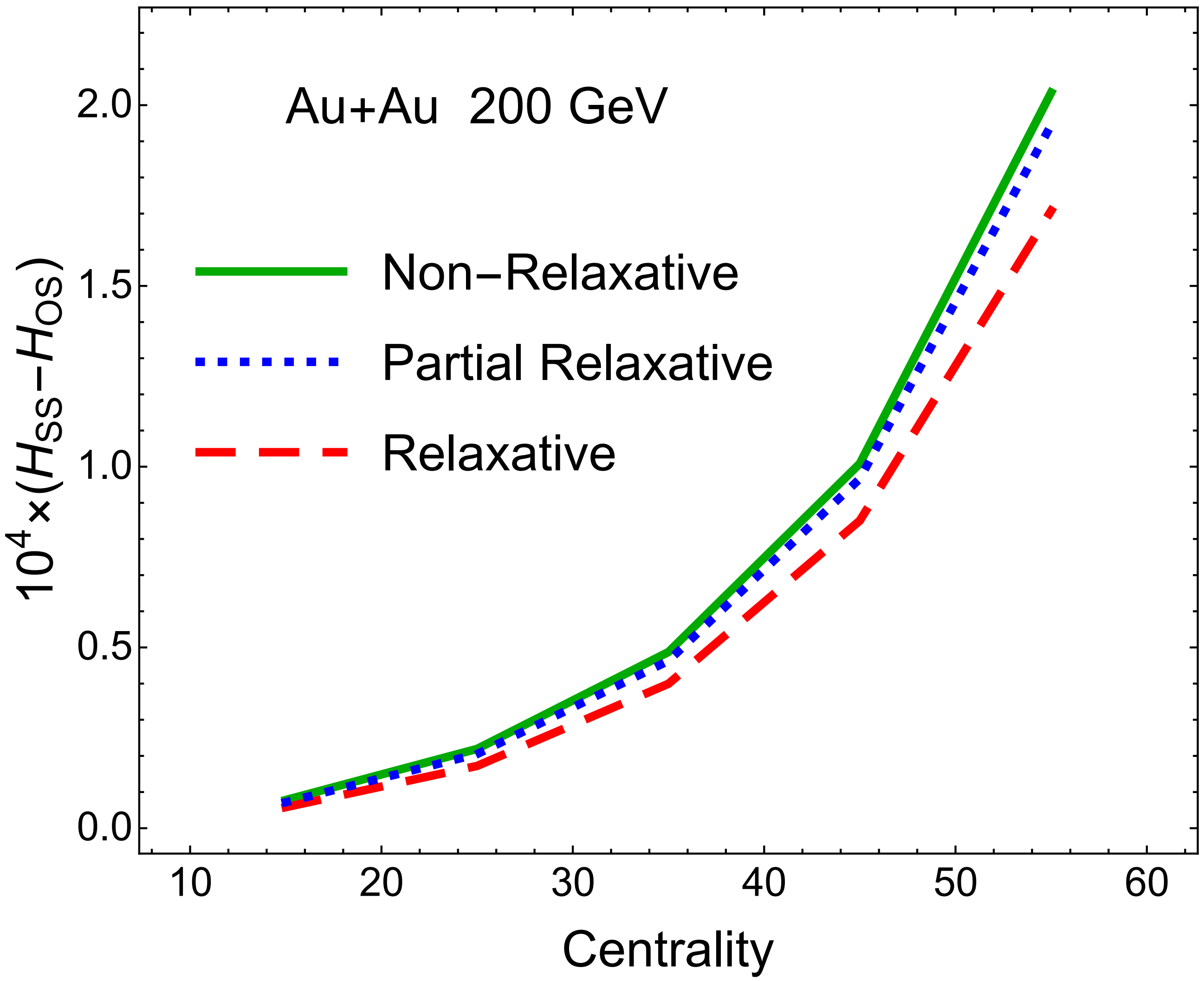
Y.Jiang, SS, Y.Yin & J.Liao, arXiv:1611.04586

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

Relaxation Effect on CME Current?

$$J_{R/L}{}^{\mu} = n_{R/L}\, u^{\mu} + \nu_{R/L}{}^{\mu} \pm \frac{N_c q}{4\pi^2}\, \mu_{R/L}\, B^{\mu}$$

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



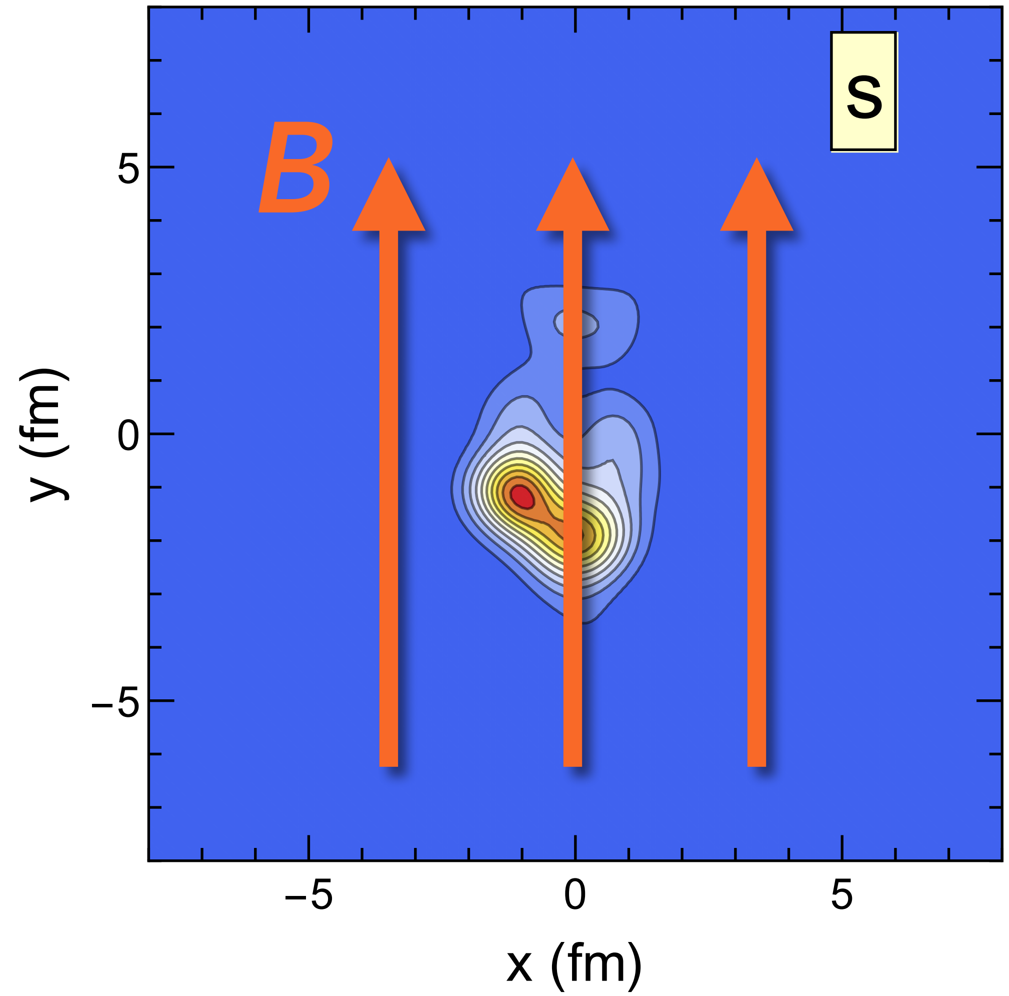
V.S.

$$J_{R/L}{}^{\mu} = n_{R/L}\, u^{\mu} + \nu_{R/L}{}^{\mu}$$

$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu} \pm \frac{N_c q}{4\pi^2}\, \mu_{R/L}\, B^{\mu})$$

CME from Event-by-Event Simulation

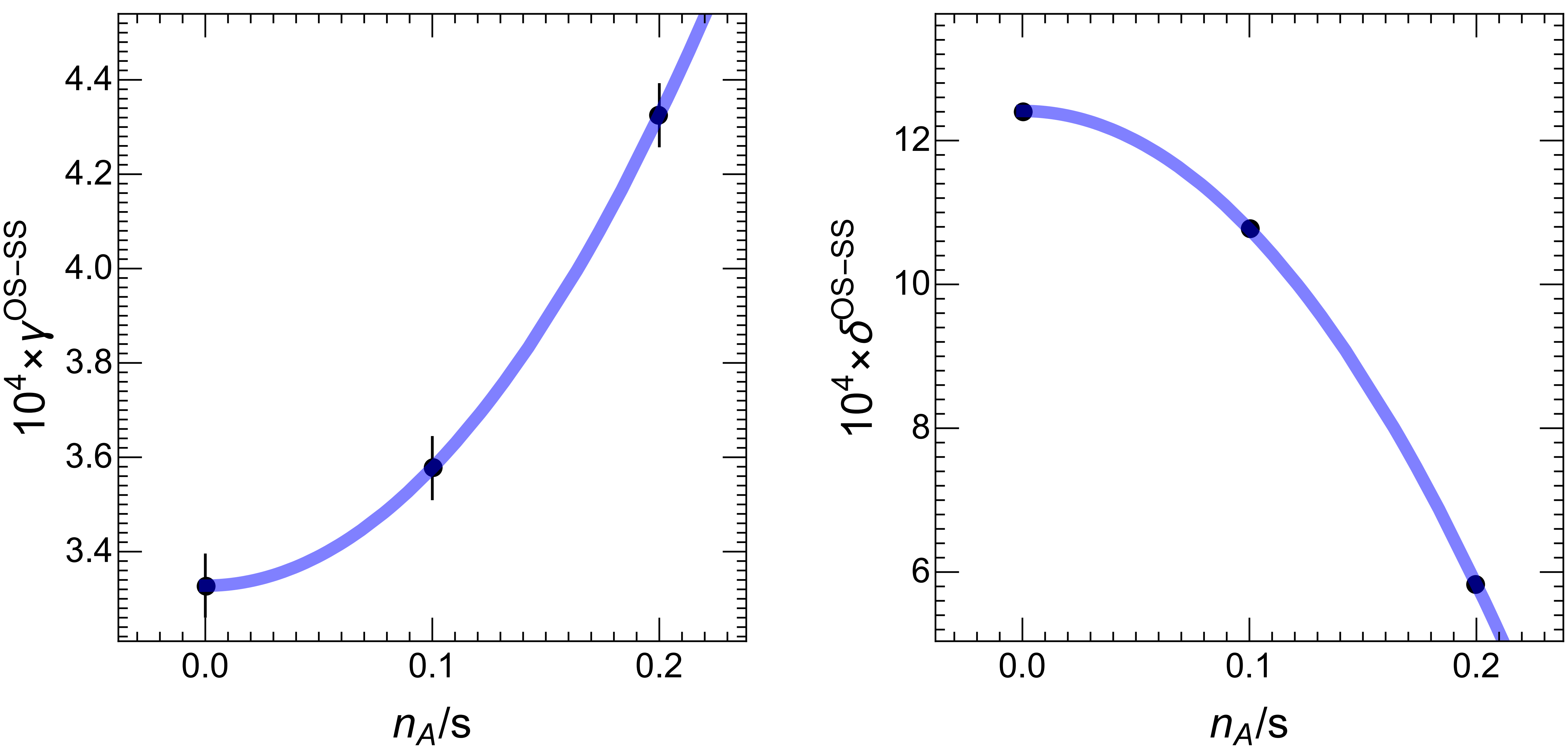
- Fluctuations! Fluctuations! Fluctuations!
    - Initial Conditions
    - Statistic @ Freeze-out
    - Hadron Cascade



Event-by-Event: Correlators

Au-Au @ 200GeV

50-60%



Au-Au @ 200GeV

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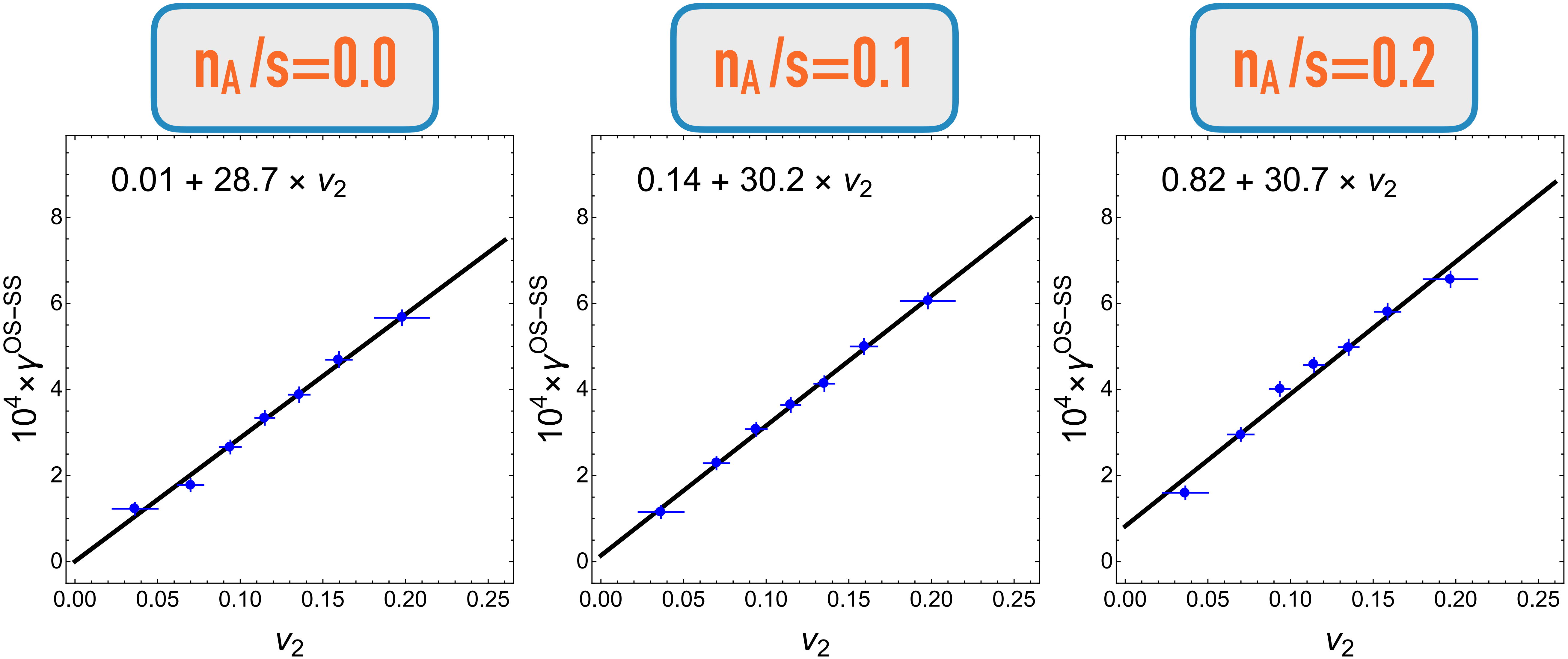
Event-by-Event: v_2 Dependence



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

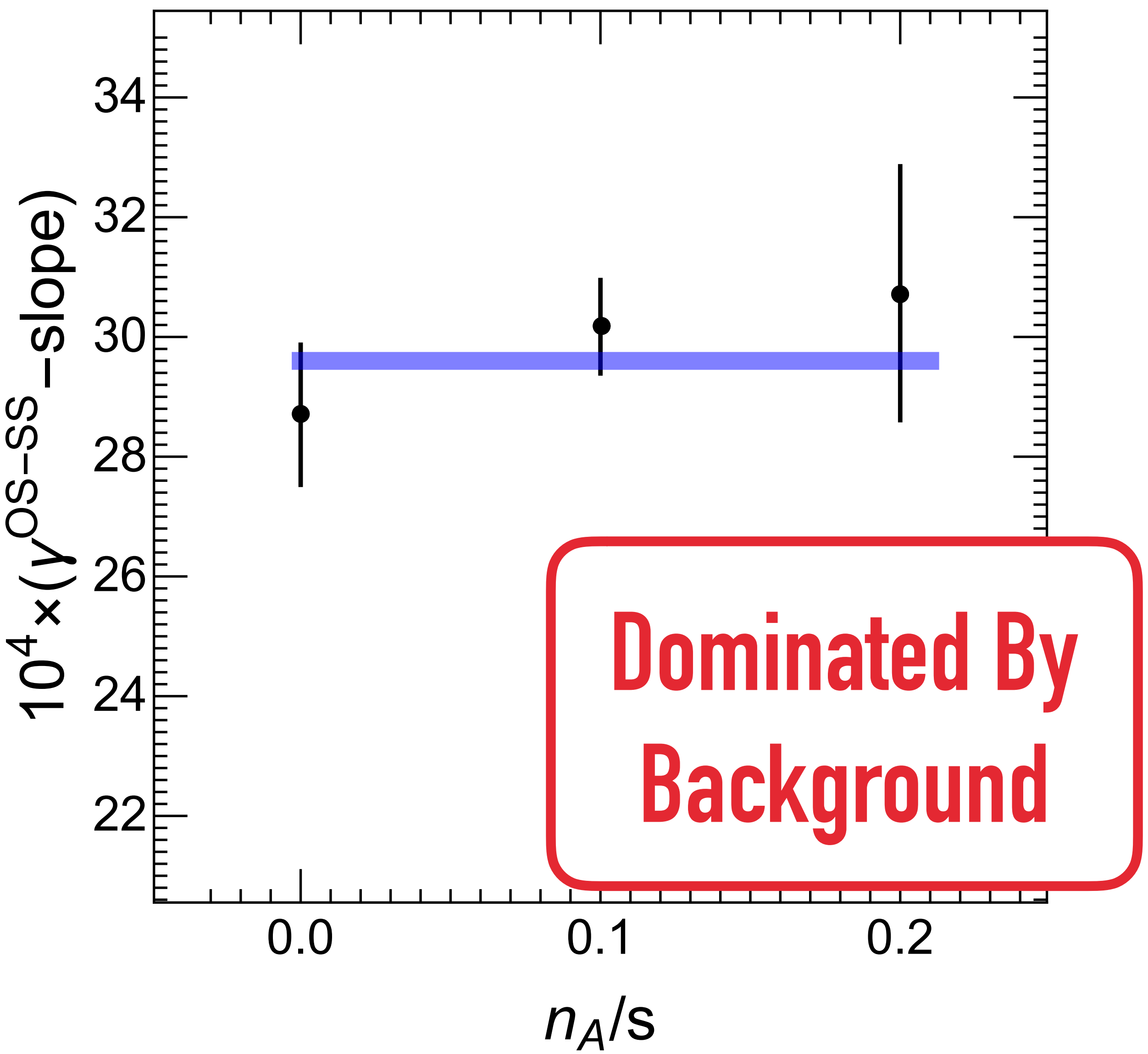
Au-Au @ 200GeV

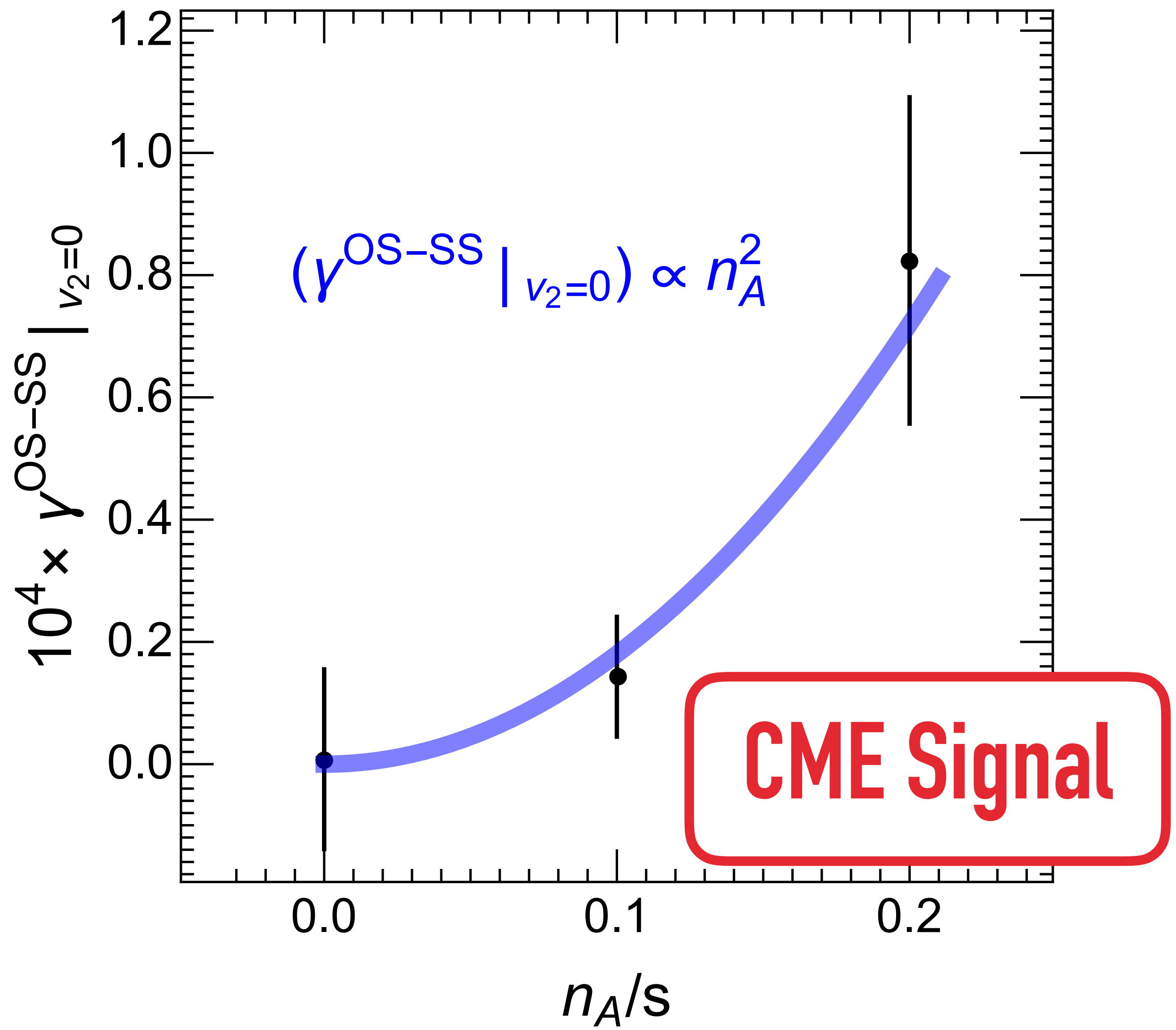
50-60%

Event-by-Event: v_2 Dependence

slope

intercept $\propto n_A^2$





Test of CME — Isobaric Collisions @ RHIC

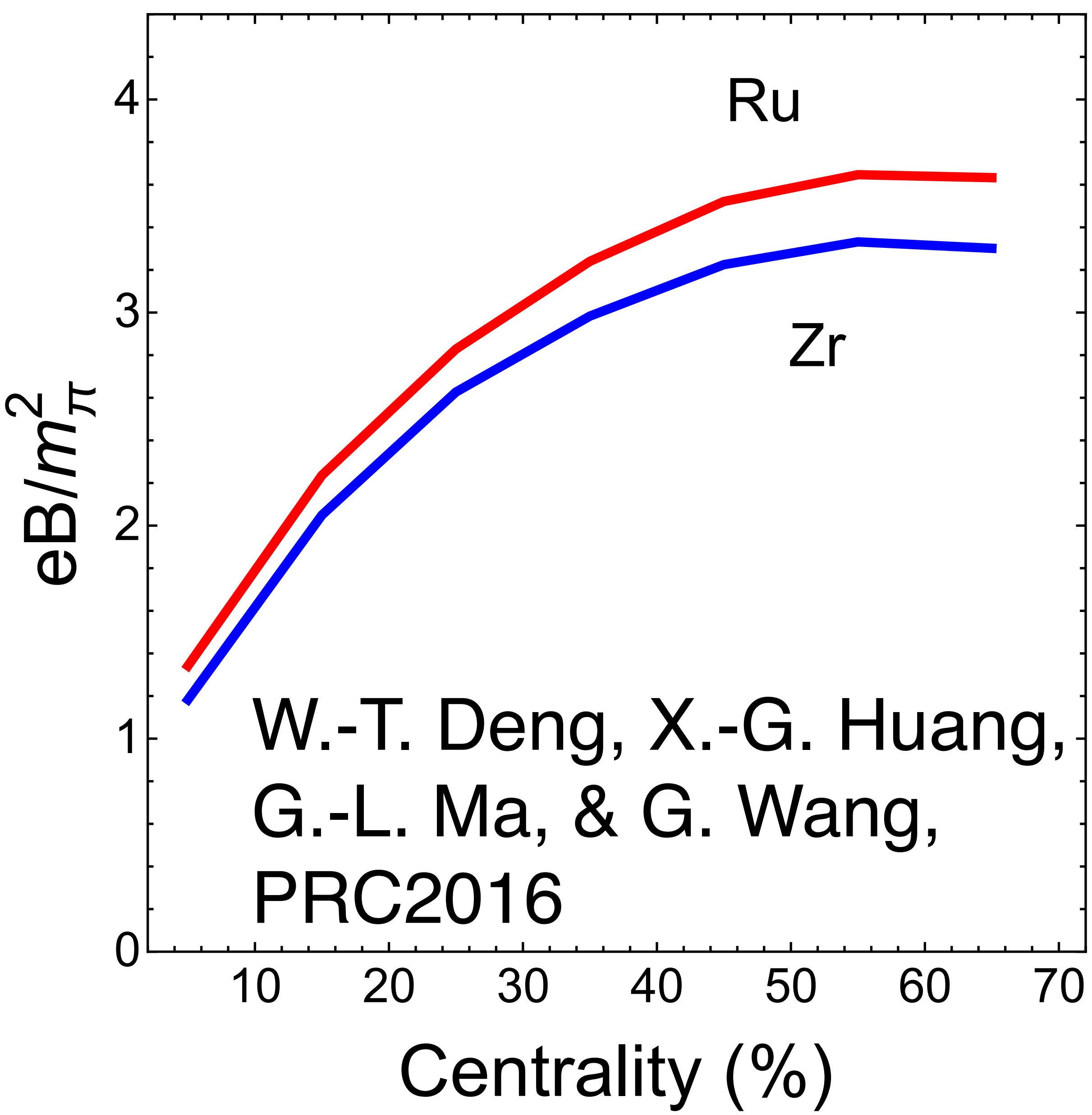
$^{96}_{44}$Ruthenium

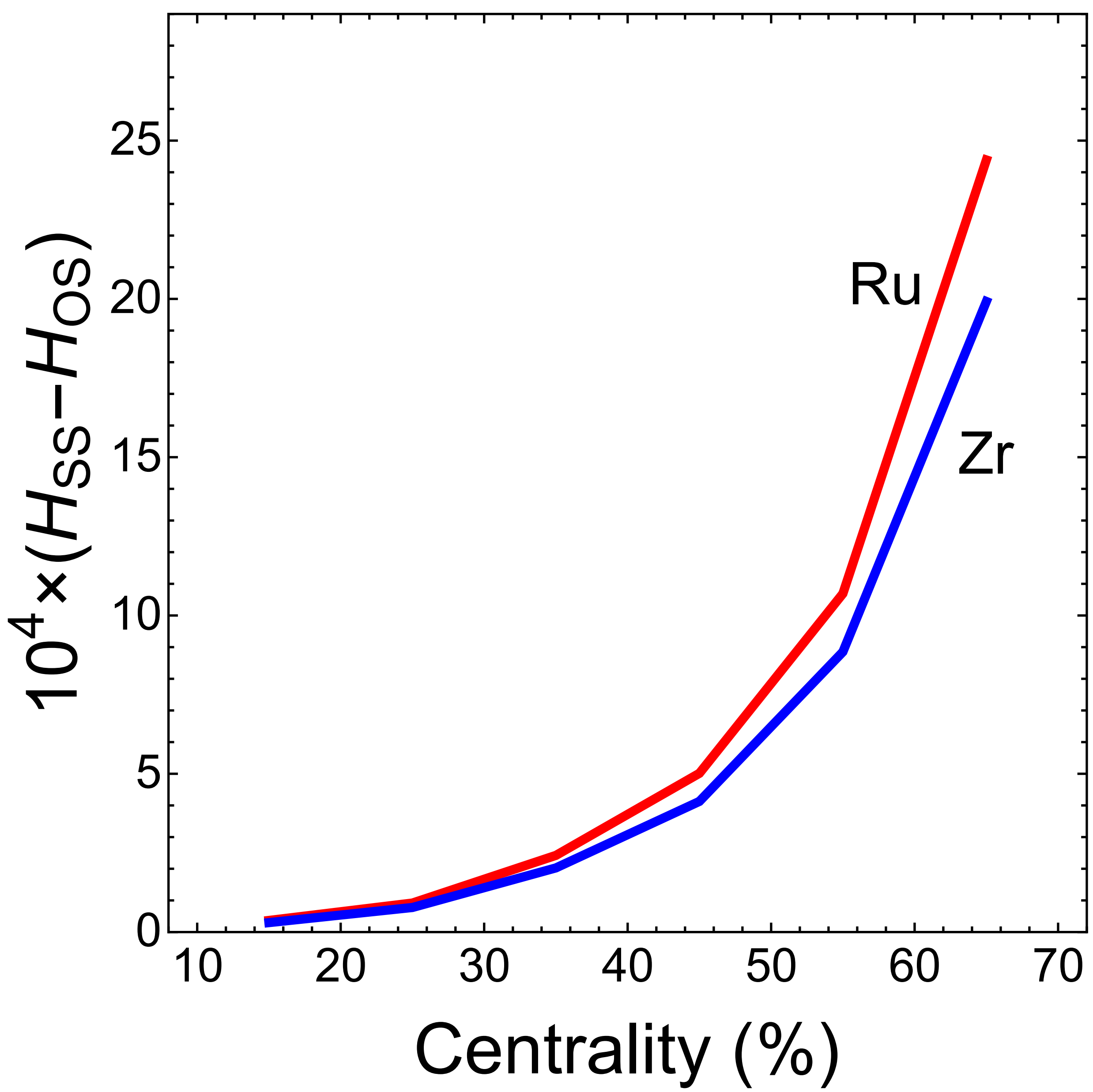
$^{96}_{40}$Zirconium

Same Baryon # → Similar Bulk Background

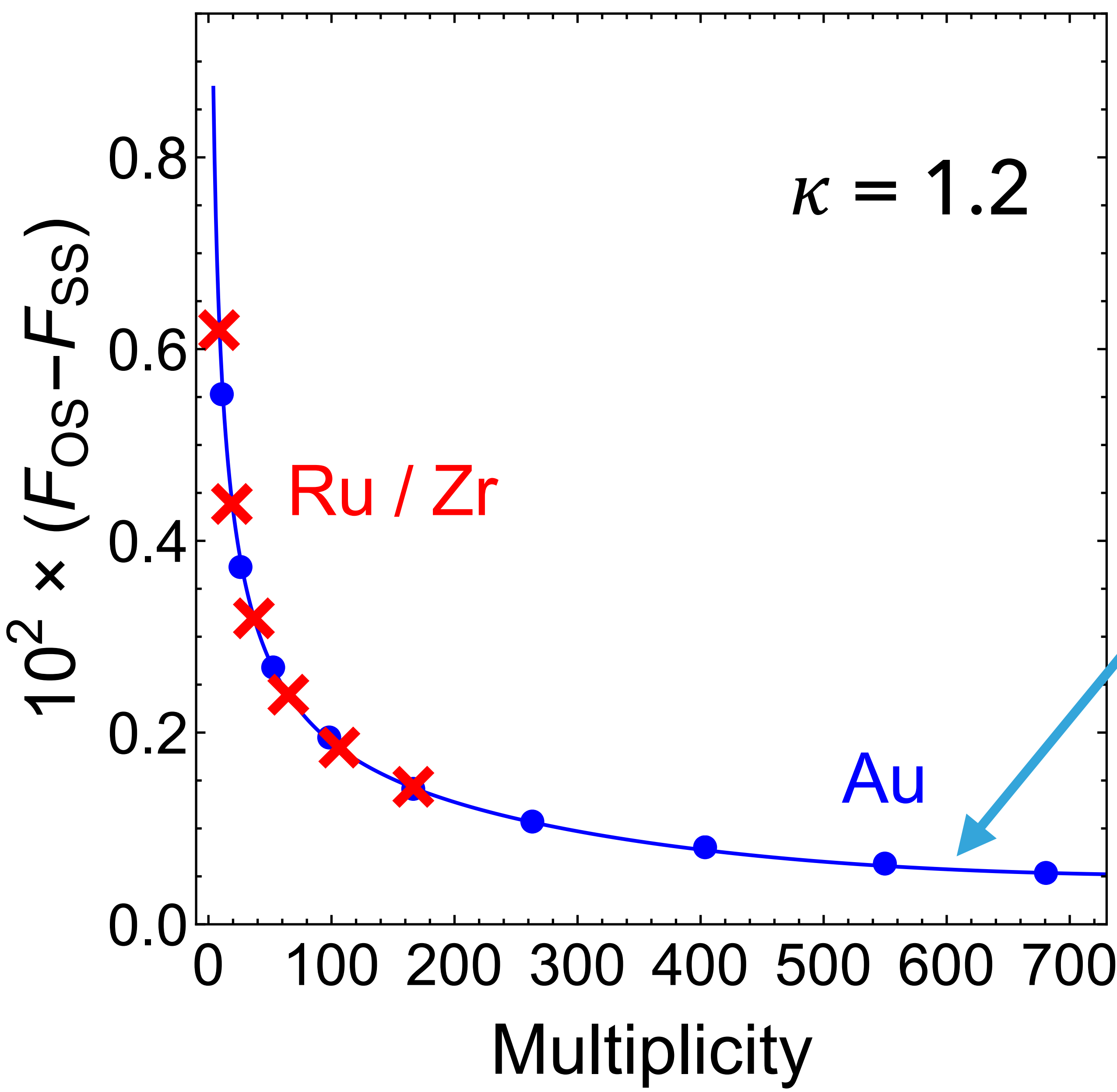
Different Proton # → Different CME!

Test of CME — Isobaric Collisions @ RHIC





Estimation Of Bulk Background

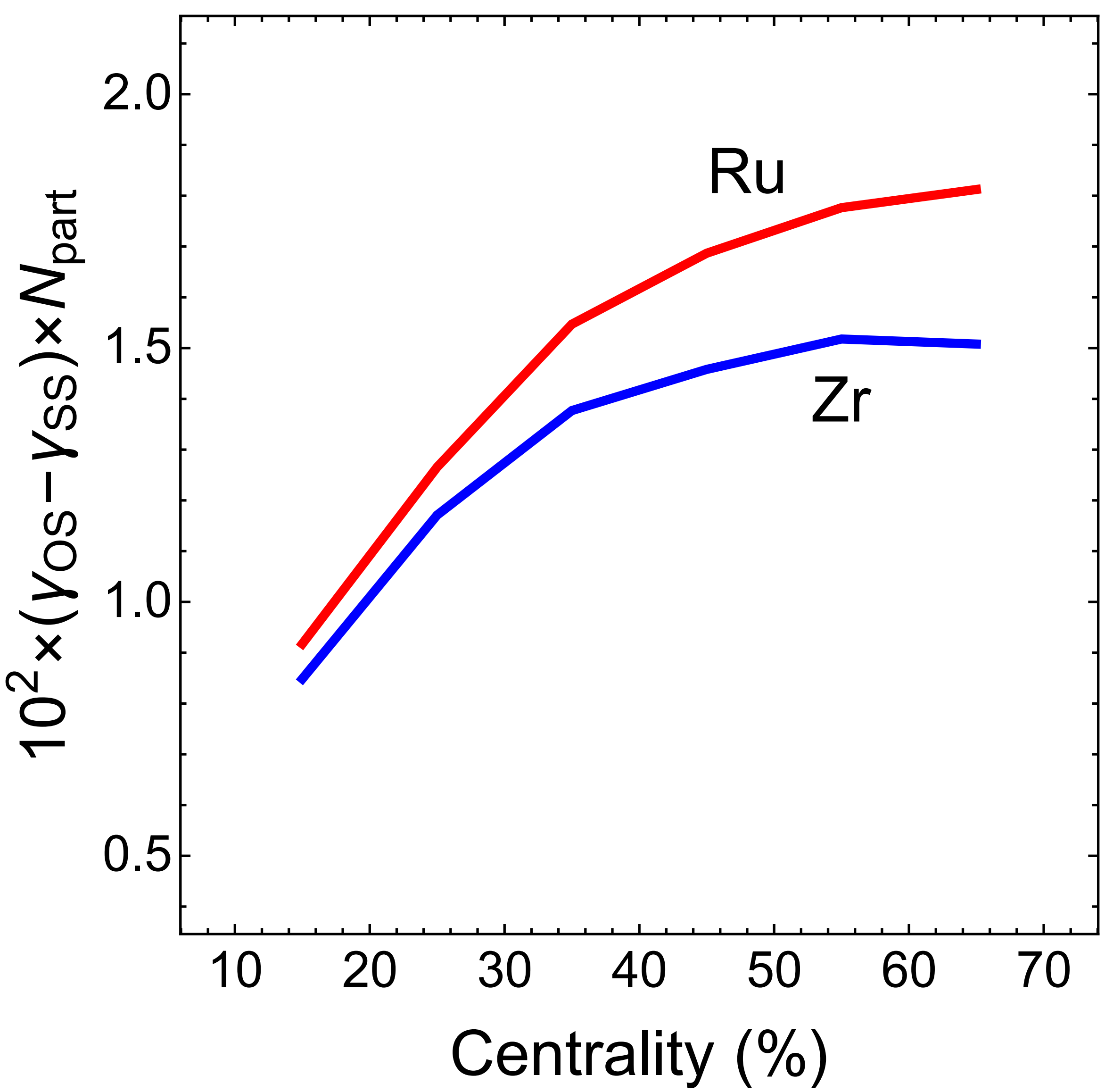


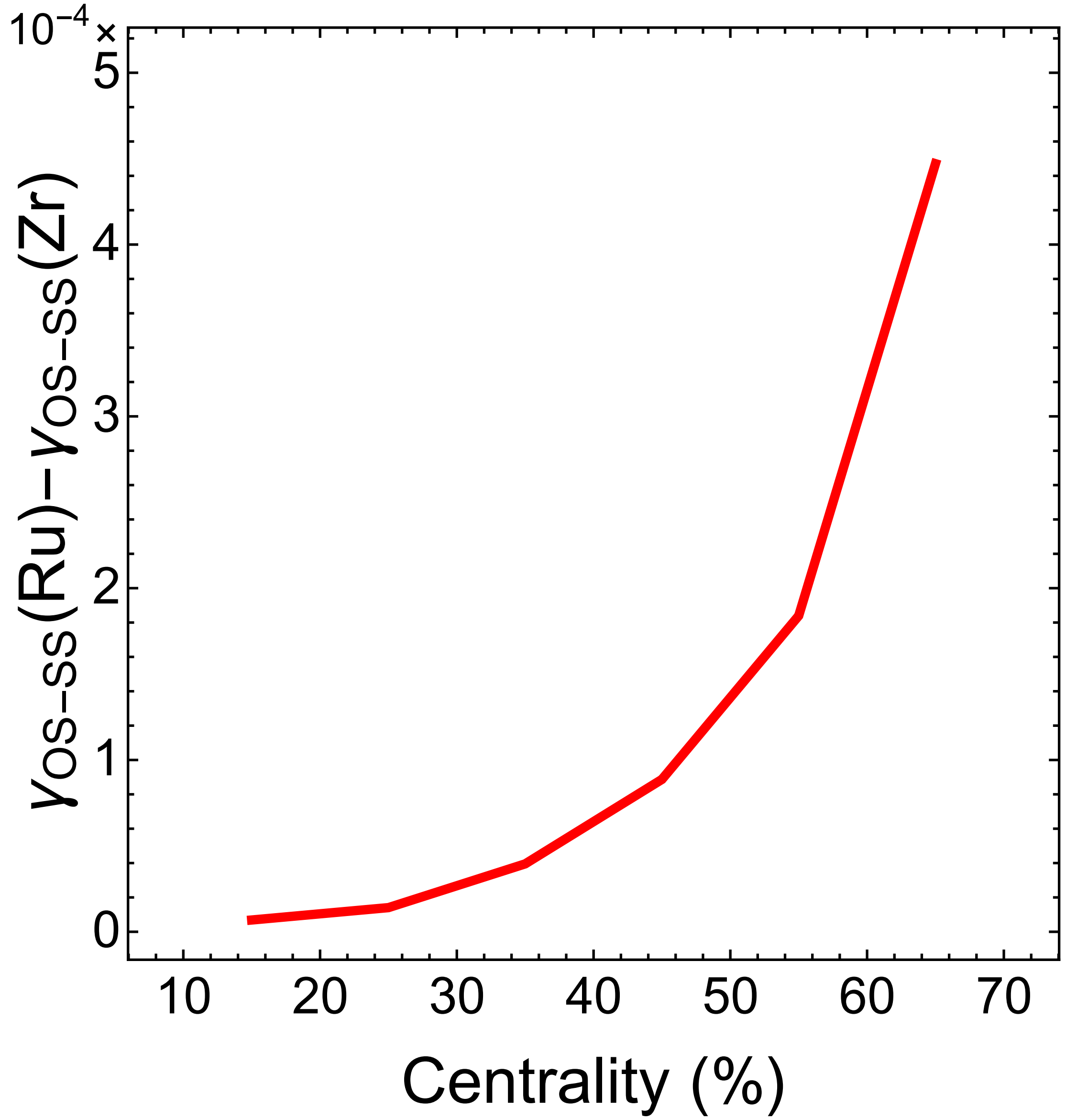
$$\gamma = \kappa\, v_2\, \mathbf{F} - \mathbf{H}$$

Fitting Formular:

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

CME for Isobaric Collisions





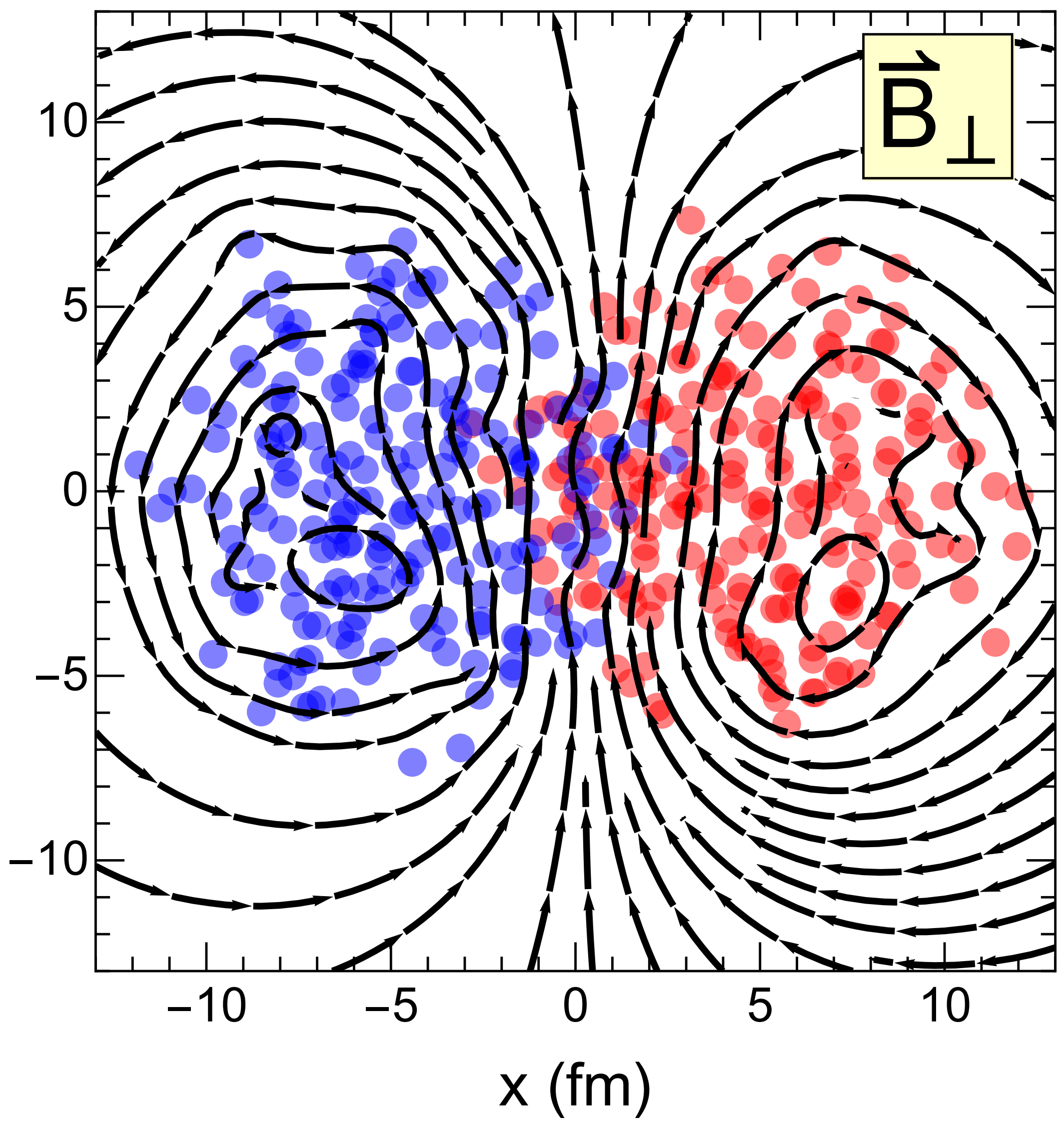
Summary & Outlook

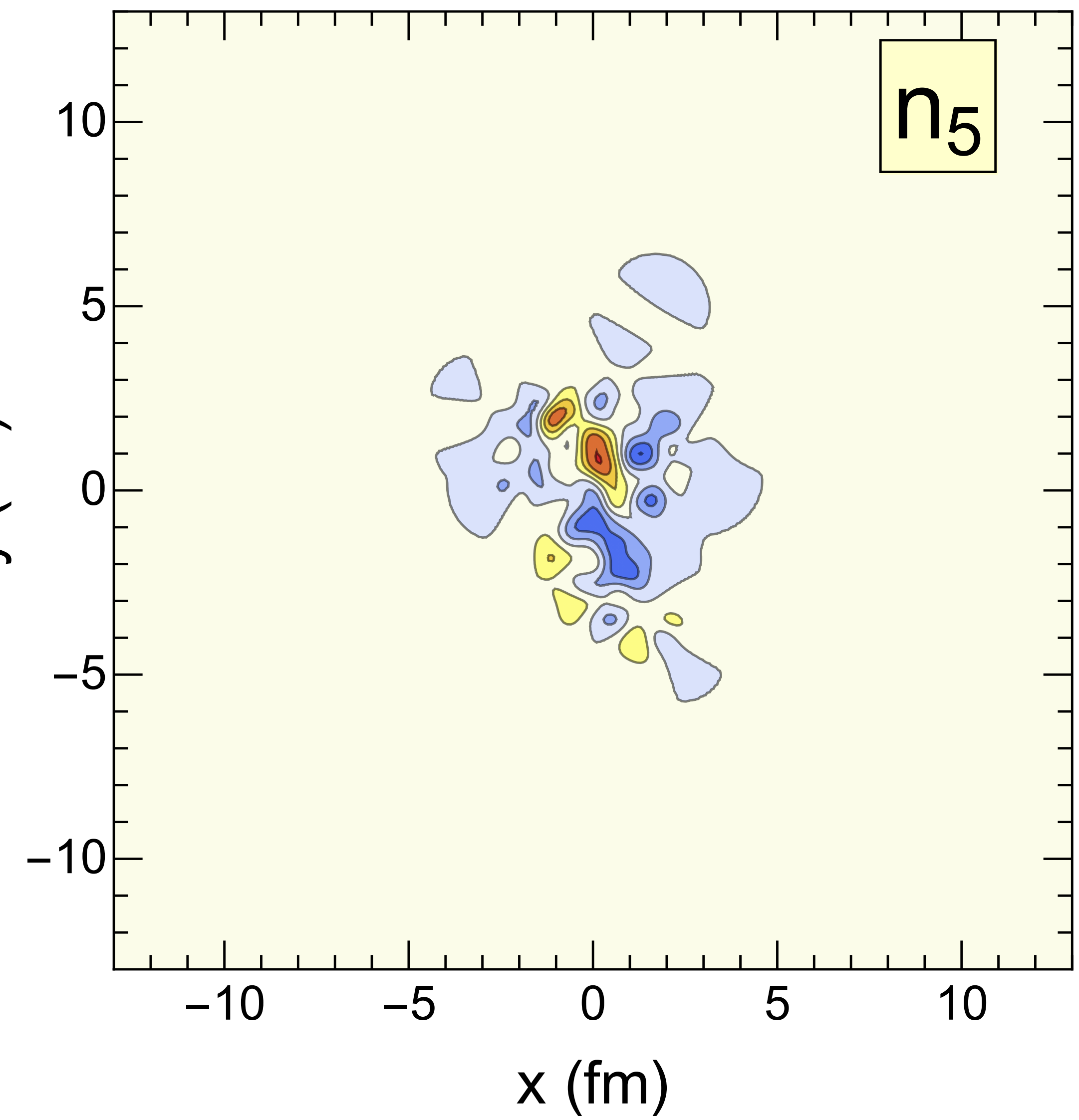
- Smooth AVFD + Best estimated n_A & τ_B ⇒ good agreement with experiment of Au-Au Collisions.
- Event-by-Event AVFD ⇒ intercept of γ-correlator versus v_2 tells CME signal from background.
- Transverse Momentum Conservation, Local Charge Conservation … in EbE simulation

Outlook - Fluctuating B-Field & n_A

Au-Au @ 200GeV

50-60%





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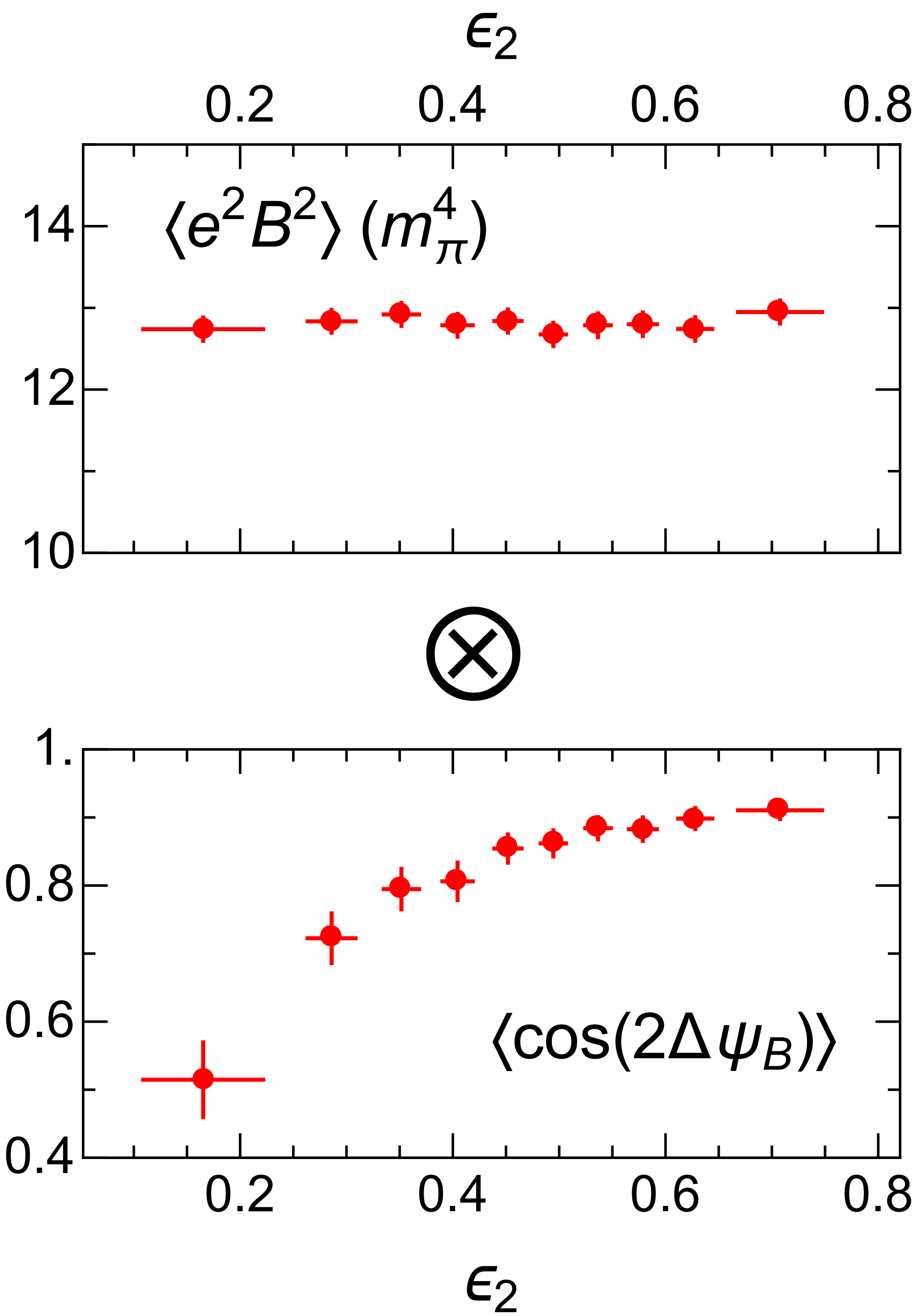
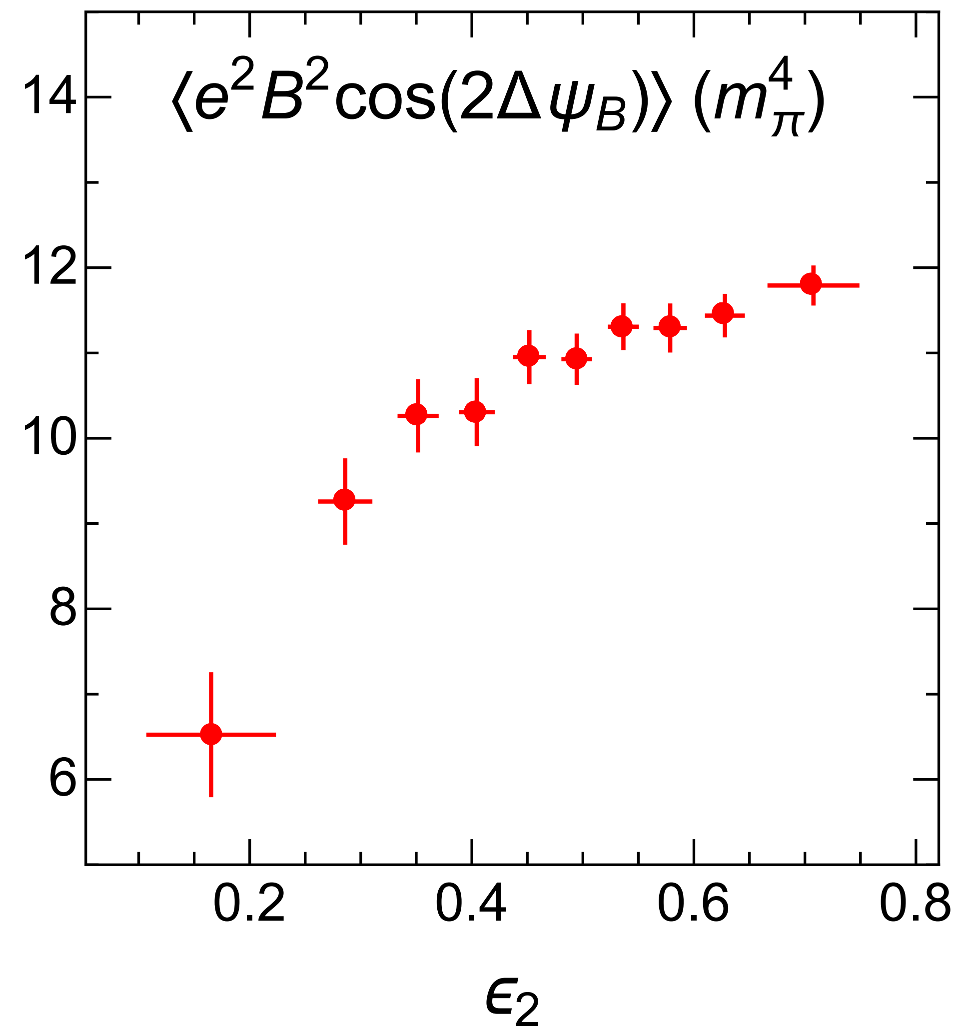


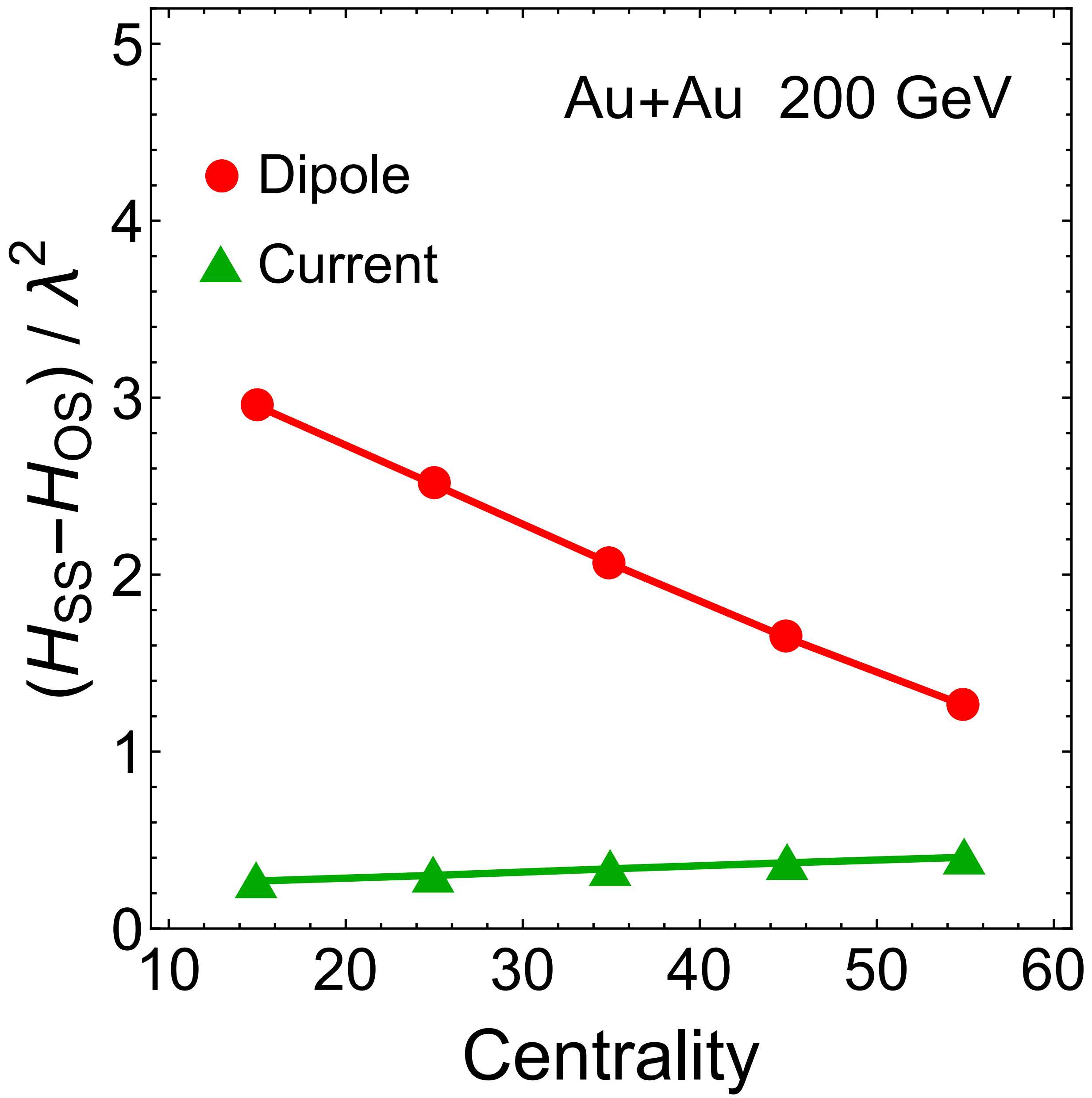
$\Rightarrow$



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

THANK YOU!

BACKUP — Pre-Thermal Anomalous Dipole/Current?

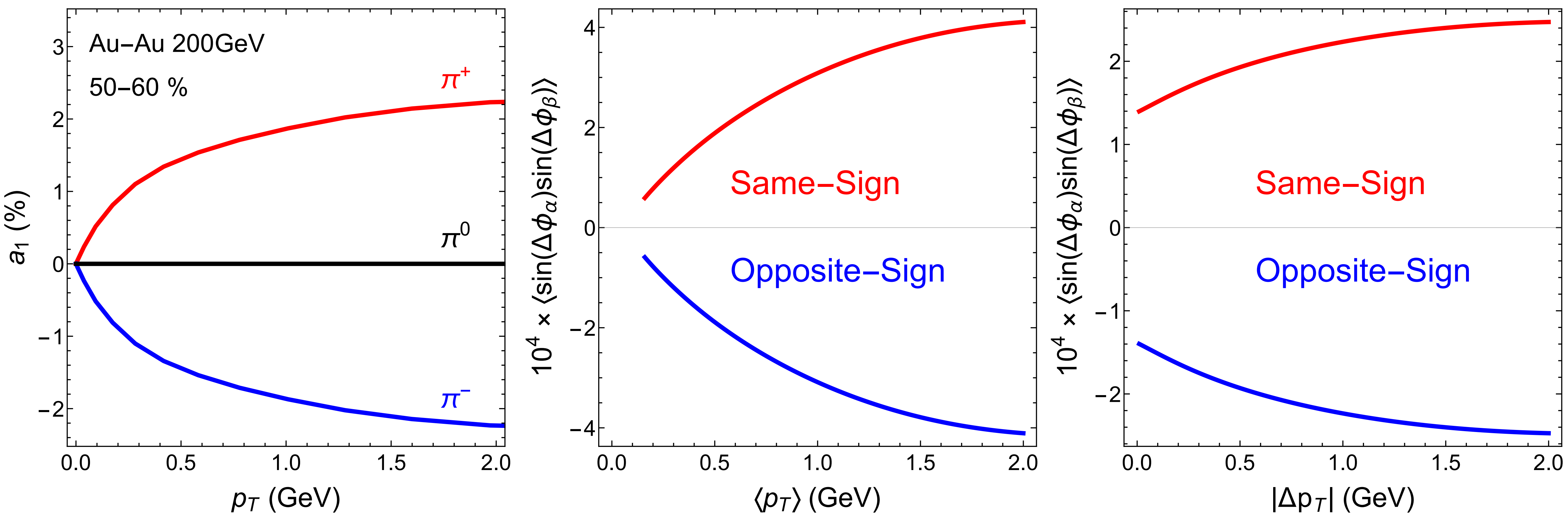


B (τ>0.6fm) = 0

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

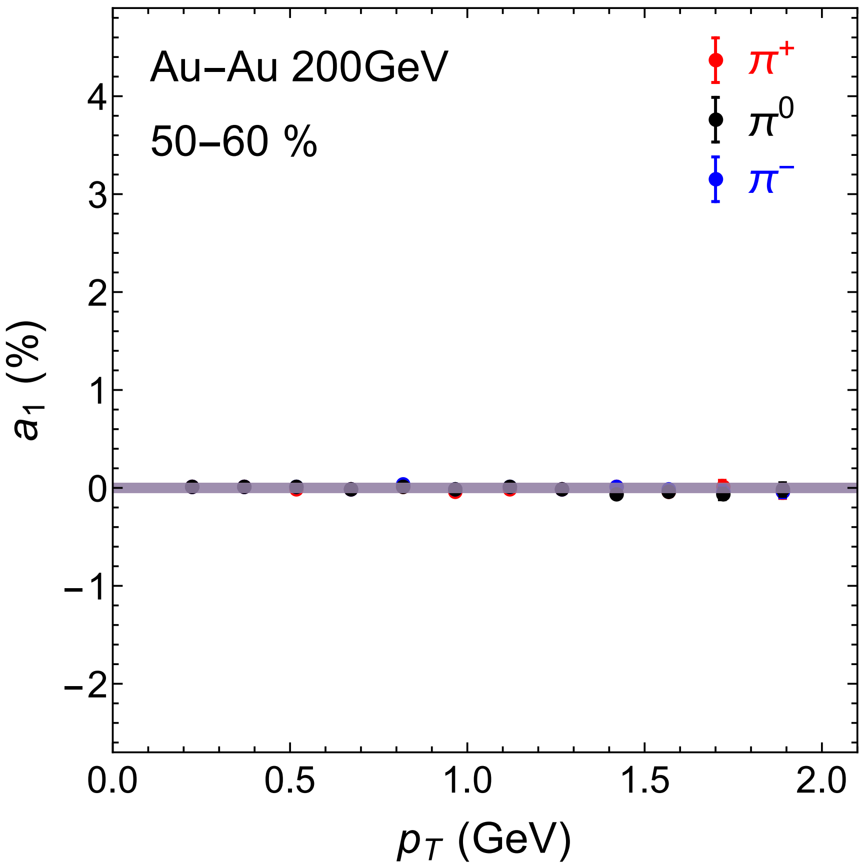
pre-thermal anomalous dipole/current are possible candidate for charge separation.

BACKUP — pT-Differential Correlation from Smooth CME

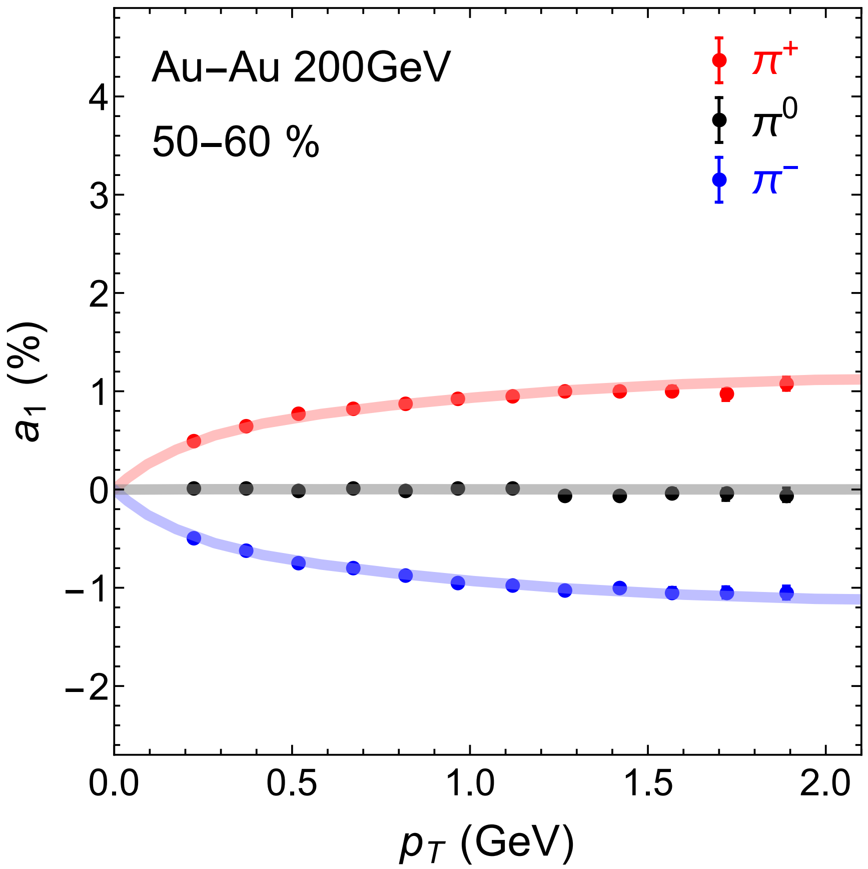


E.-b-E. vs Smooth Hydro

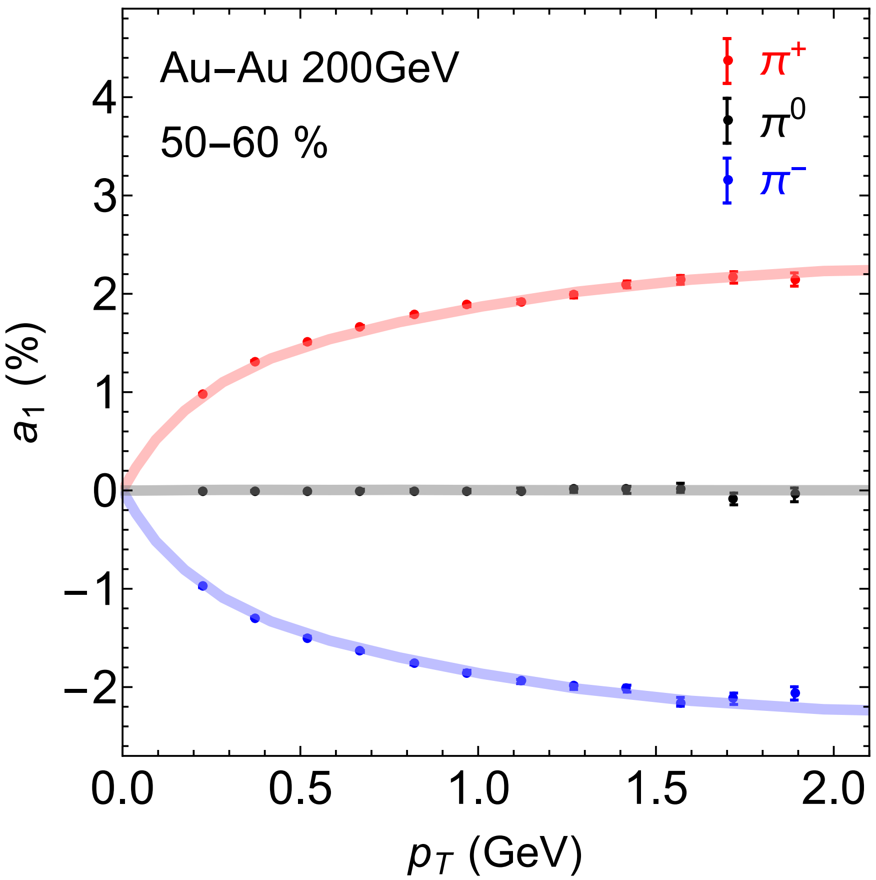
Au-Au @ 200GeV
50-60%



n_A/s=0.0



n_A/s=0.1

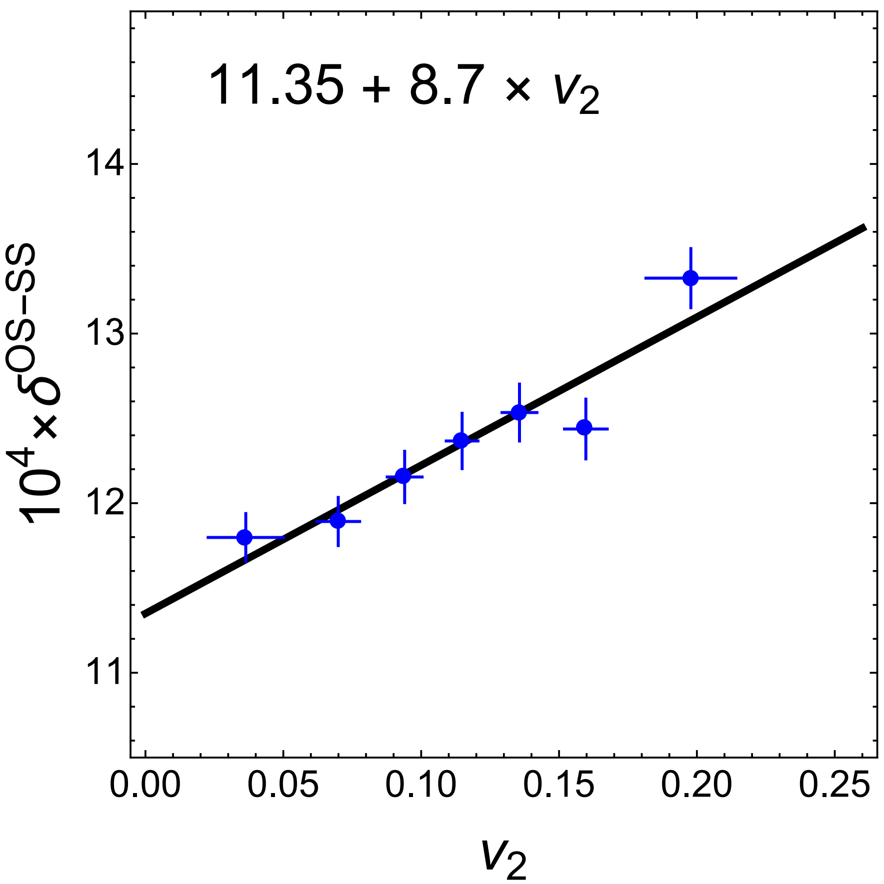


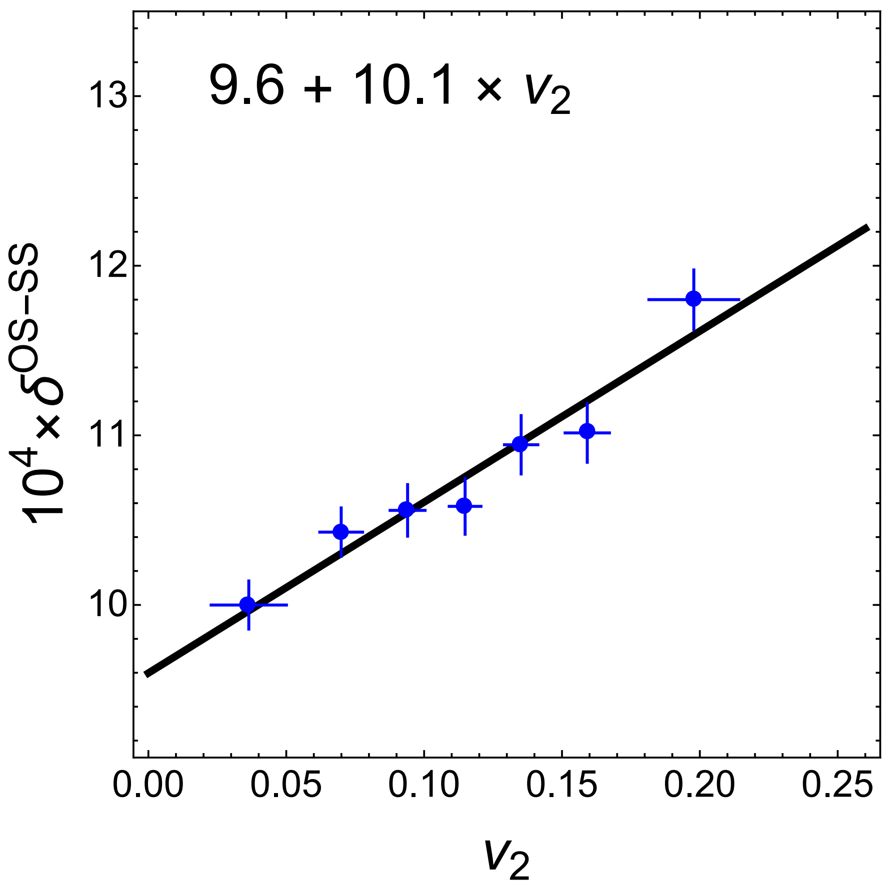
n_A/s=0.2

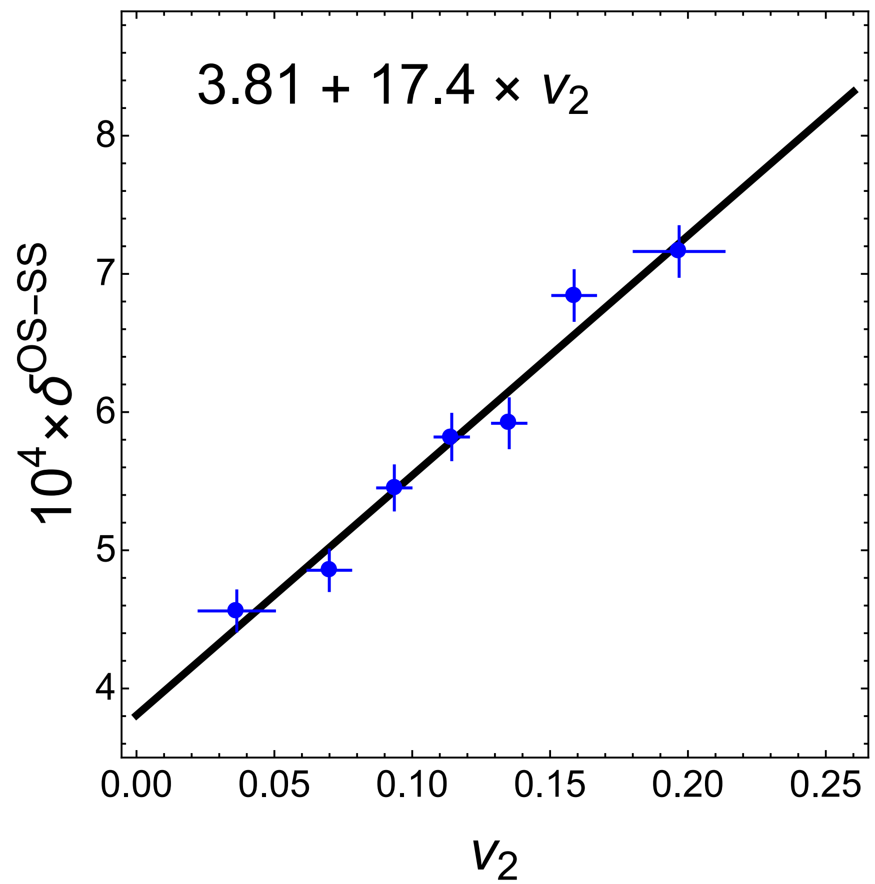
δ-Correlator Event-by-Event simulation

Au-Au @ 200GeV

50-60%







n_A/s=0.0

n_A/s=0.1

n_A/s=0.2