# Quantifying Chiral Magnetic Effect from Anomalous-Viscous Fluid Dynamics

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Quark Matter 2017

# Outline

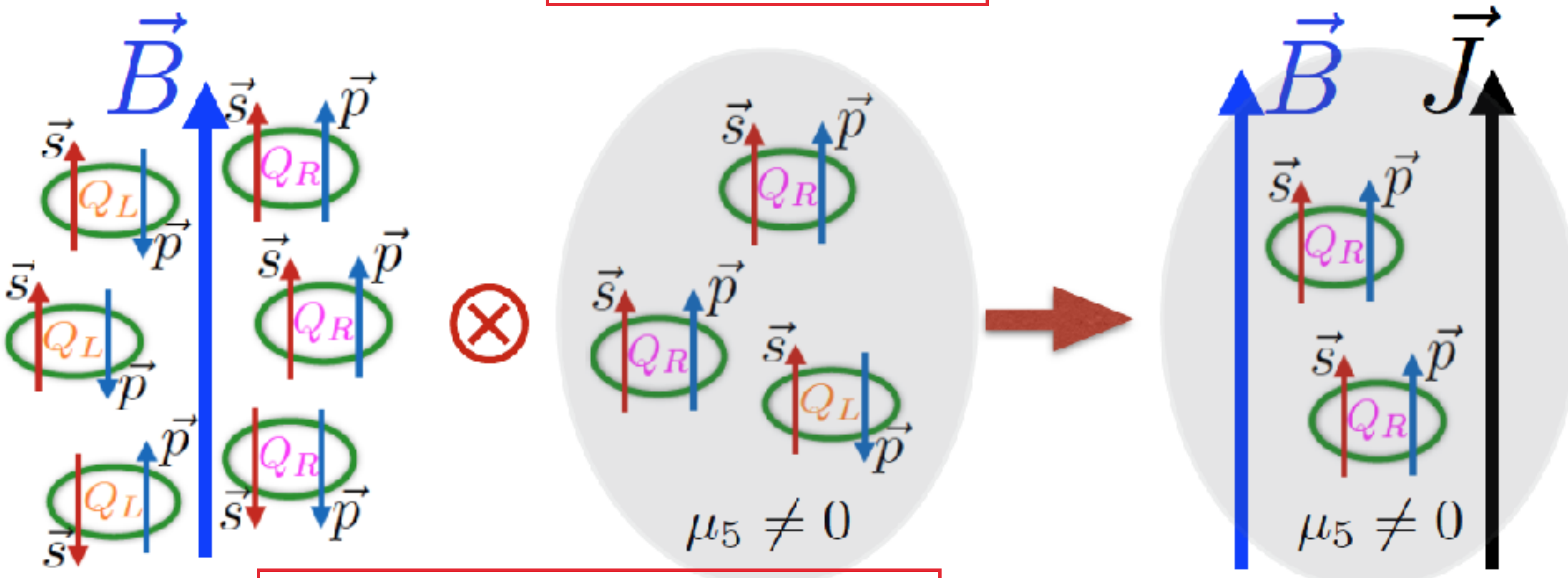
- Chiral Magnetic Effect (CME)
- How do we study CME quantitatively ← Anomalous-Viscous Fluid Dynamics
- CME from Anomalous-Viscous Fluid Dynamics
  - Au-Au Collisions
  - Isobaric Collisions
  - Event-by-Event Simulations

# Chiral Magnetic Effect

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

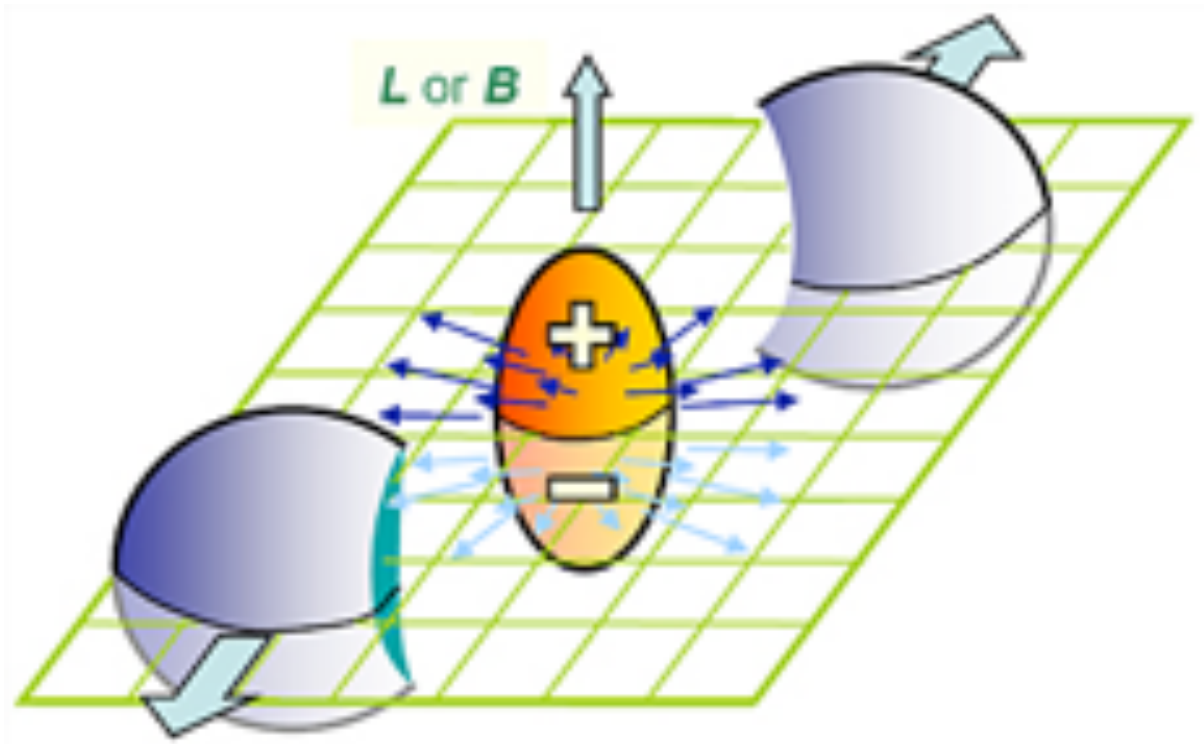
WIKIPEDIA
The Free Encyclopedia

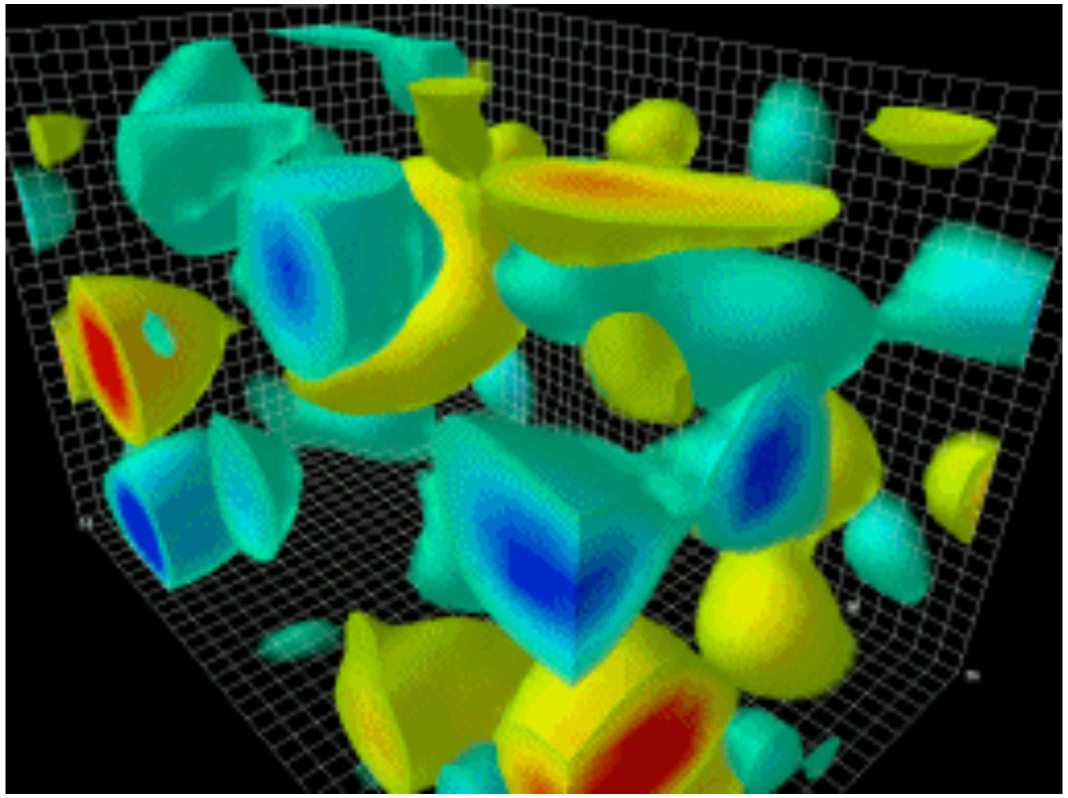
$$\boldsymbol{J} = \sigma_5\, \mu_5\, \boldsymbol{B}$$




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

# Chiral Magnetic Effect In Heavy-Ion Collisions



eB ~ 5 $m_\pi^2$
@ 200 GeV

$\otimes$

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 Collisions

- B field ⊗ $\mu_A$ ⇒ current ⇒ dipole (charge separation)

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

- charge separation ⇒ two particle correlation

  $$\gamma = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle = \kappa\, v_2\, F - H$$

  $$\delta = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle = F + H$$

  F: Bulk Background

  H: Possible CME Signal

# Chiral Magnetic Effect In He

- B field ⊗ $\mu_A$ ⇒ current =

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

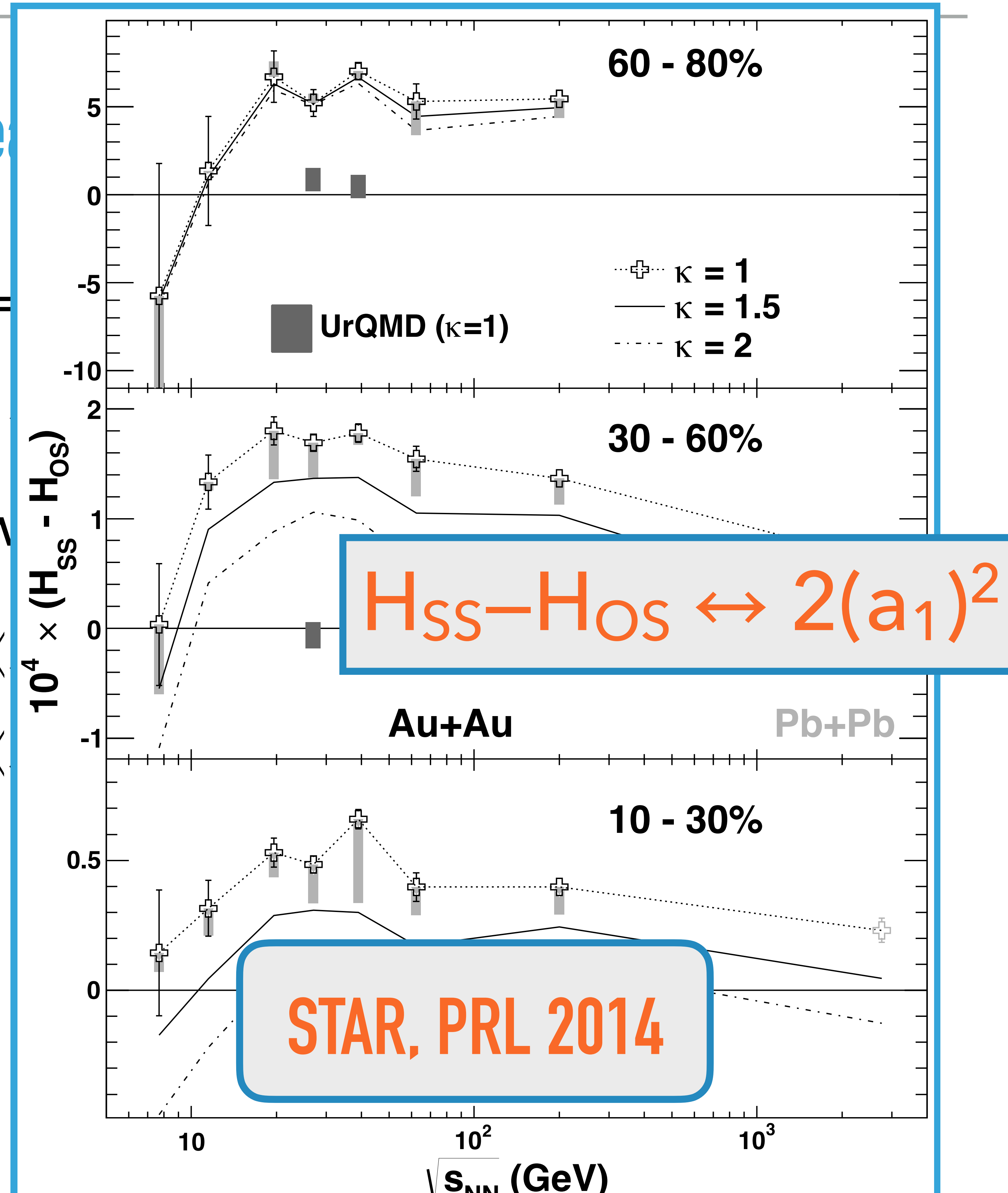
- charge separation ⇒ tw

  $\gamma = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle$

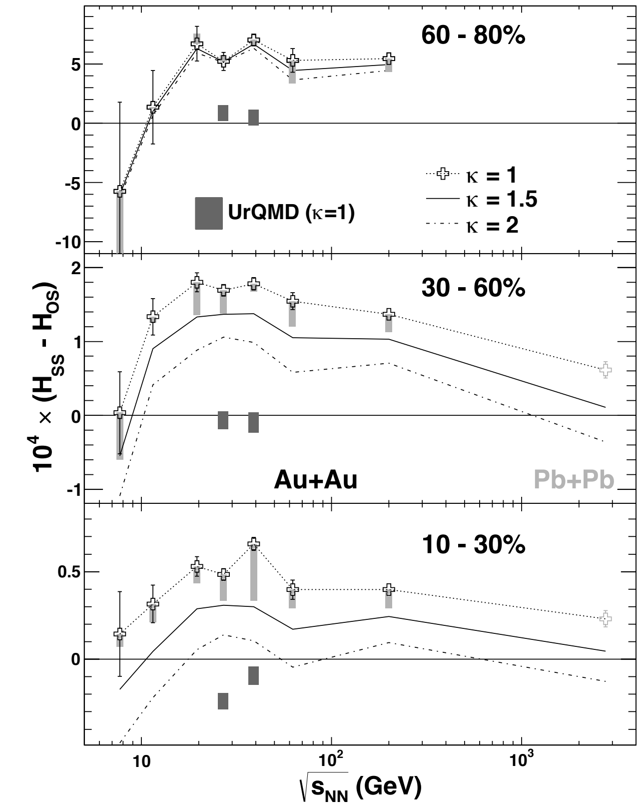
  $\delta = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle$

  F: Bulk Background

  H: Possible CME Signal



# How Can We Calculate CME Quantitatively?




axial (& vector) charge density

Anomalous
-Viscous
Fluid
Dynamics

initial condition → dynamical evolution → final particle distribution

+

driving force

B field

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

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

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

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

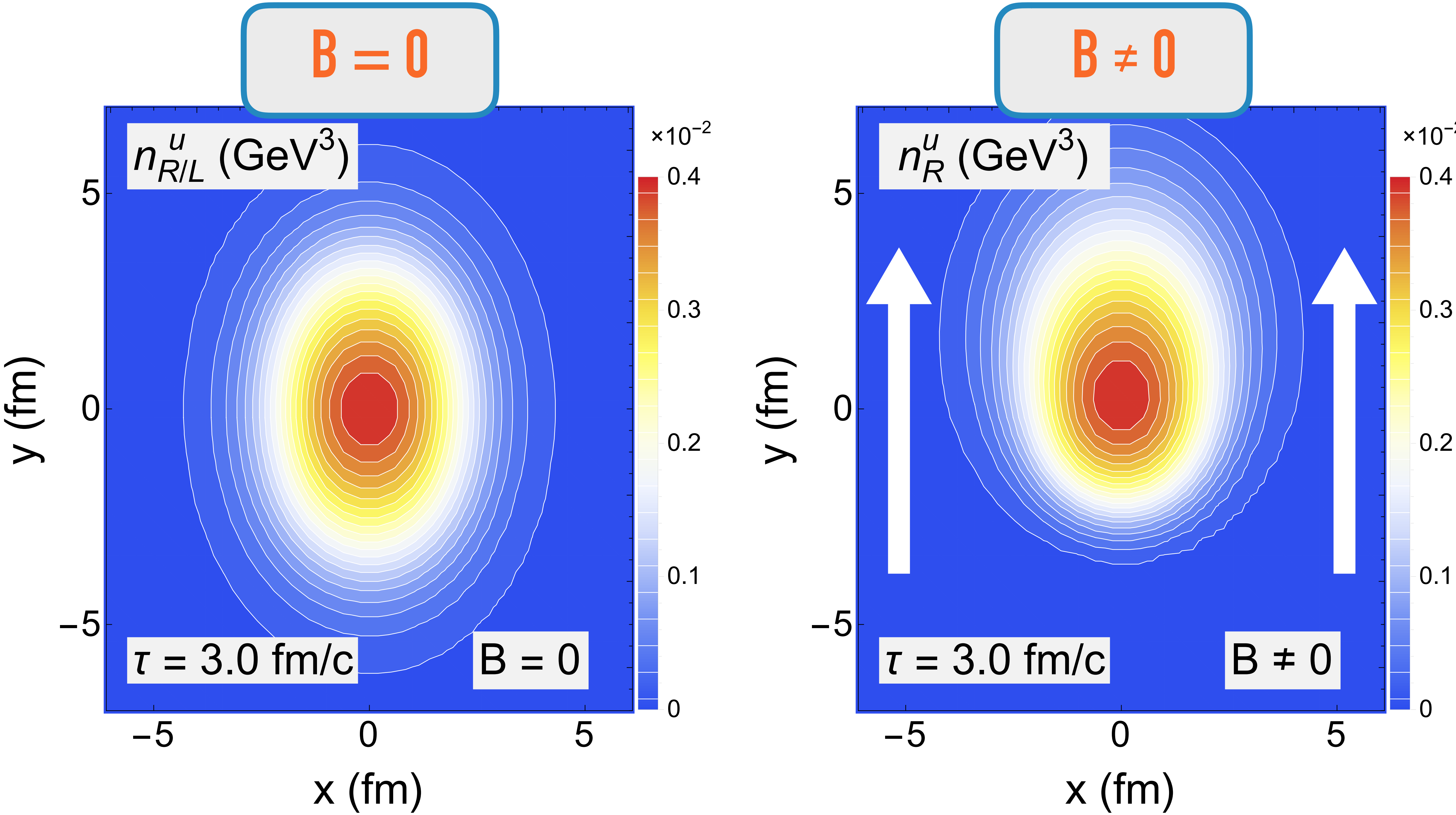
CME

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

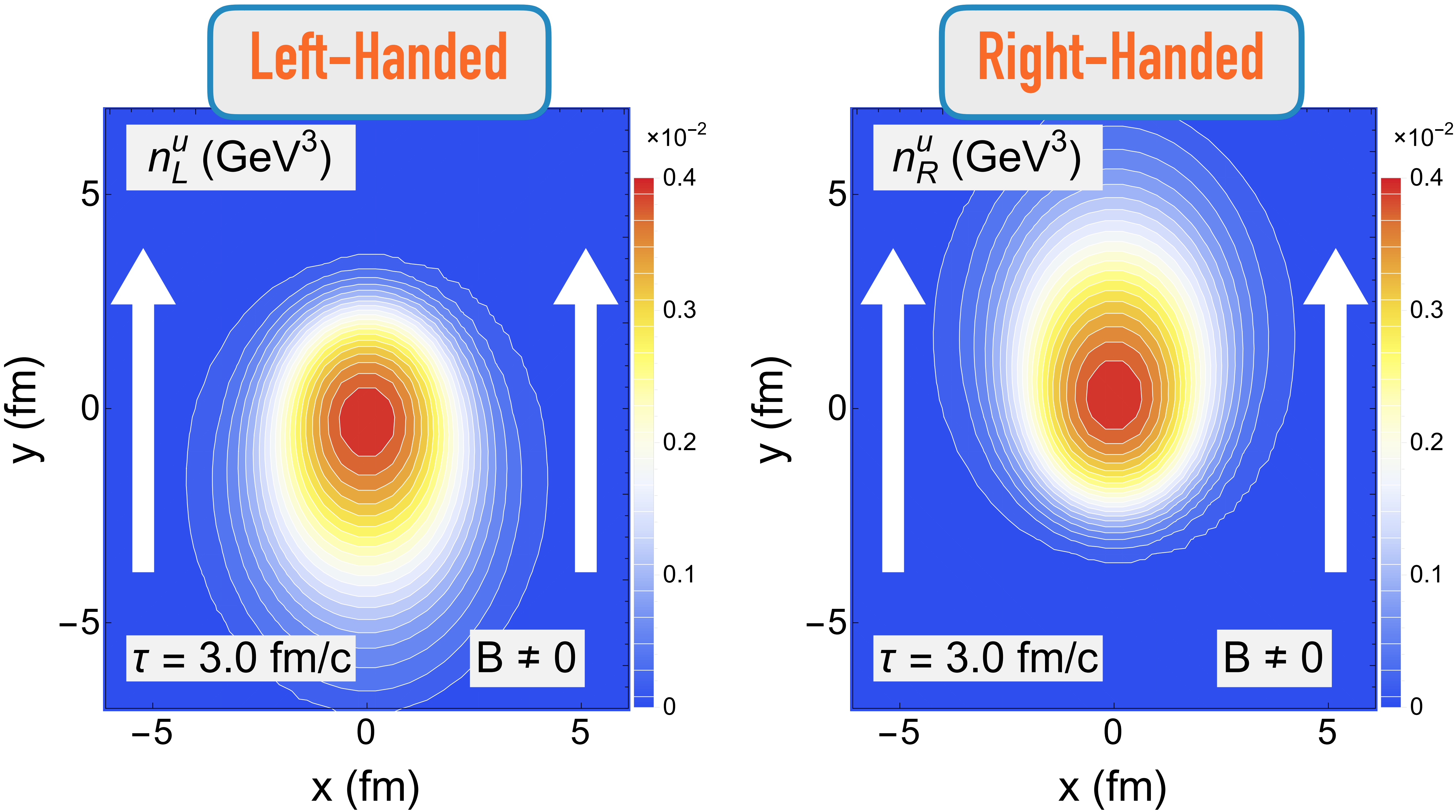
on top of 2+1D `VISHNew` –– OSU Group

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

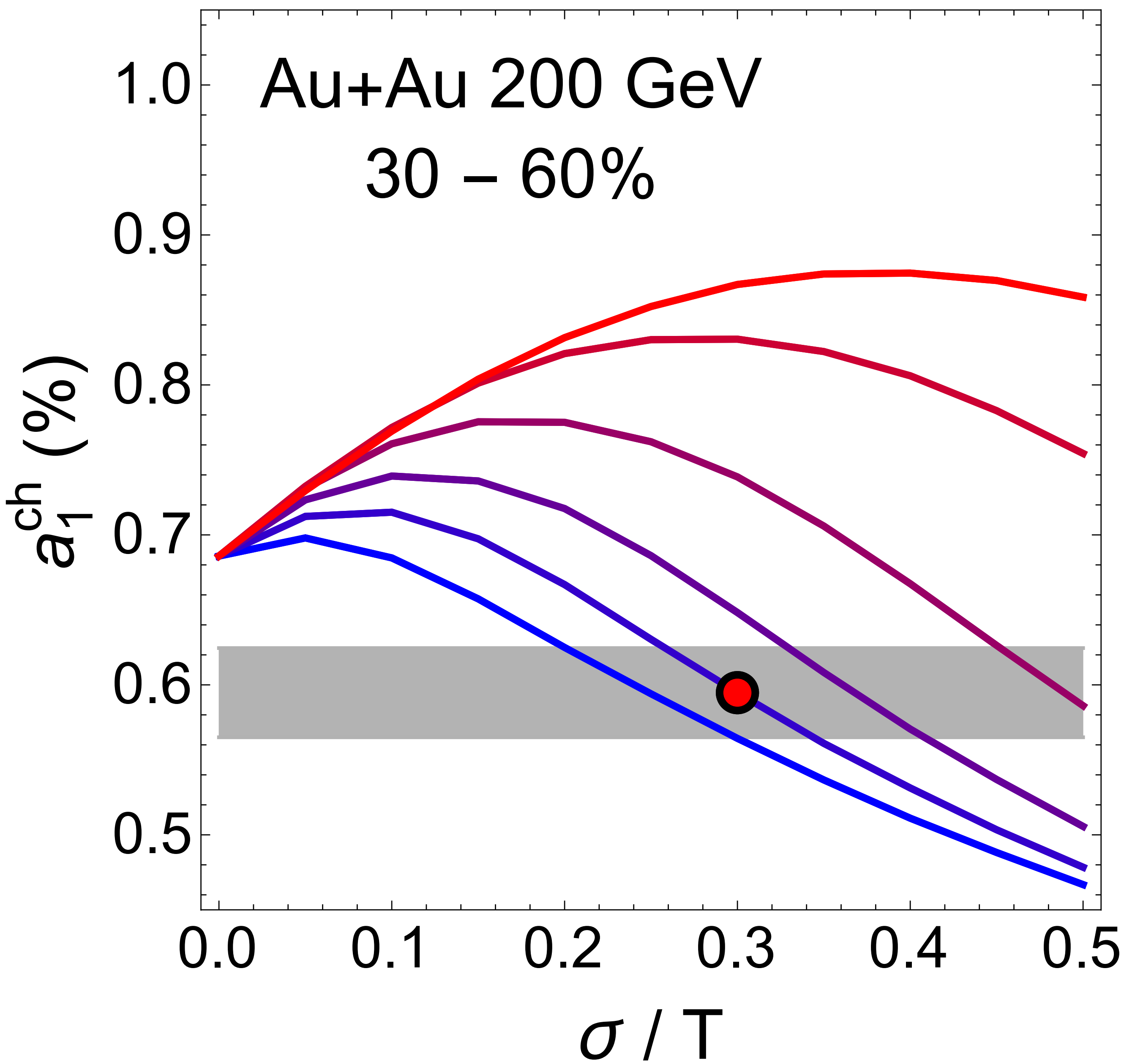
# Evolution of Quark Number Density



# Evolution of Quark Number Density



# Effect of Viscous Transportation




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

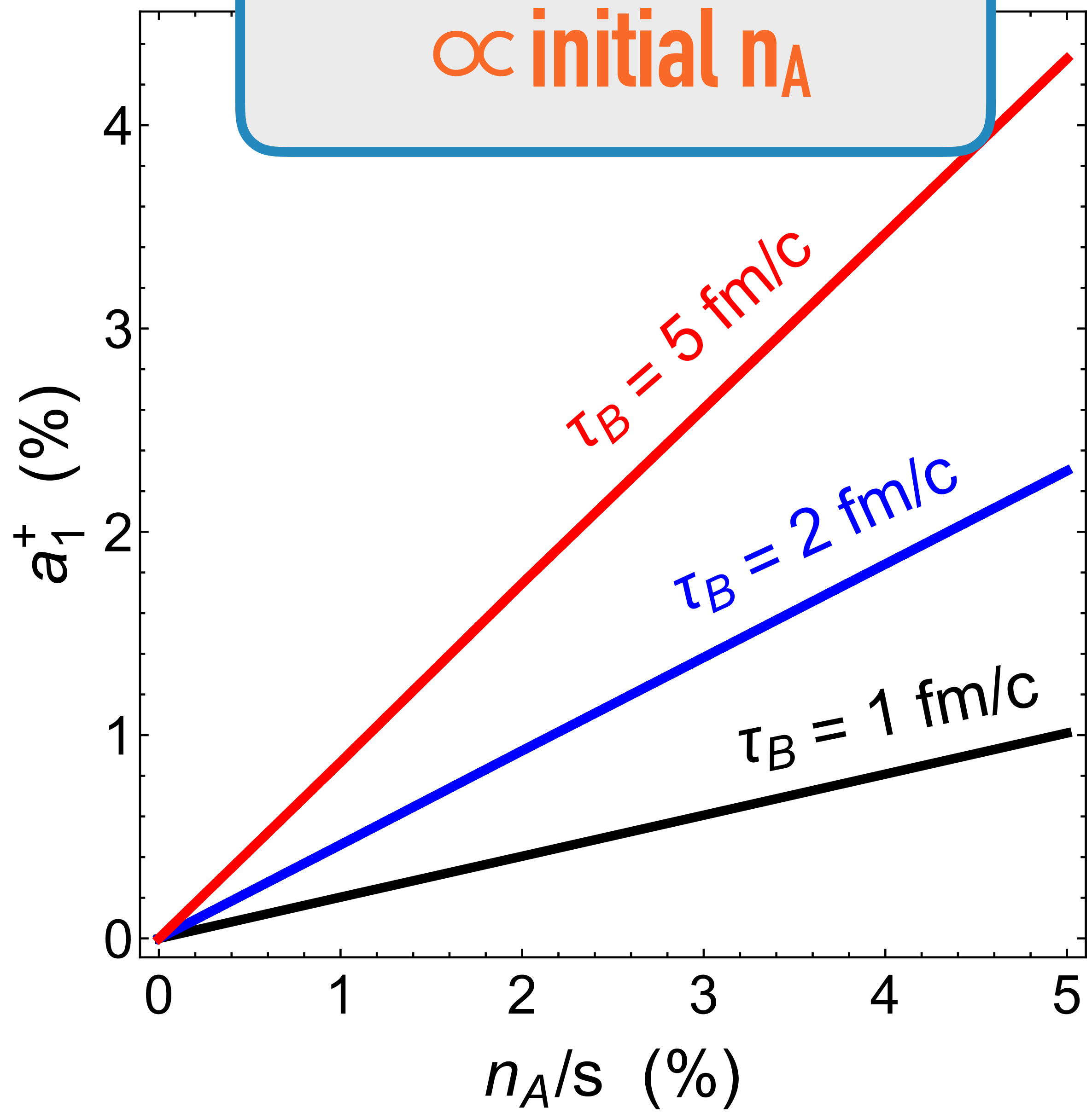
$$\nu_{NS}{}^{\mu} = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_{\nu} \frac{\mu}{T} + \frac{\sigma}{2} q E^{\mu}$$

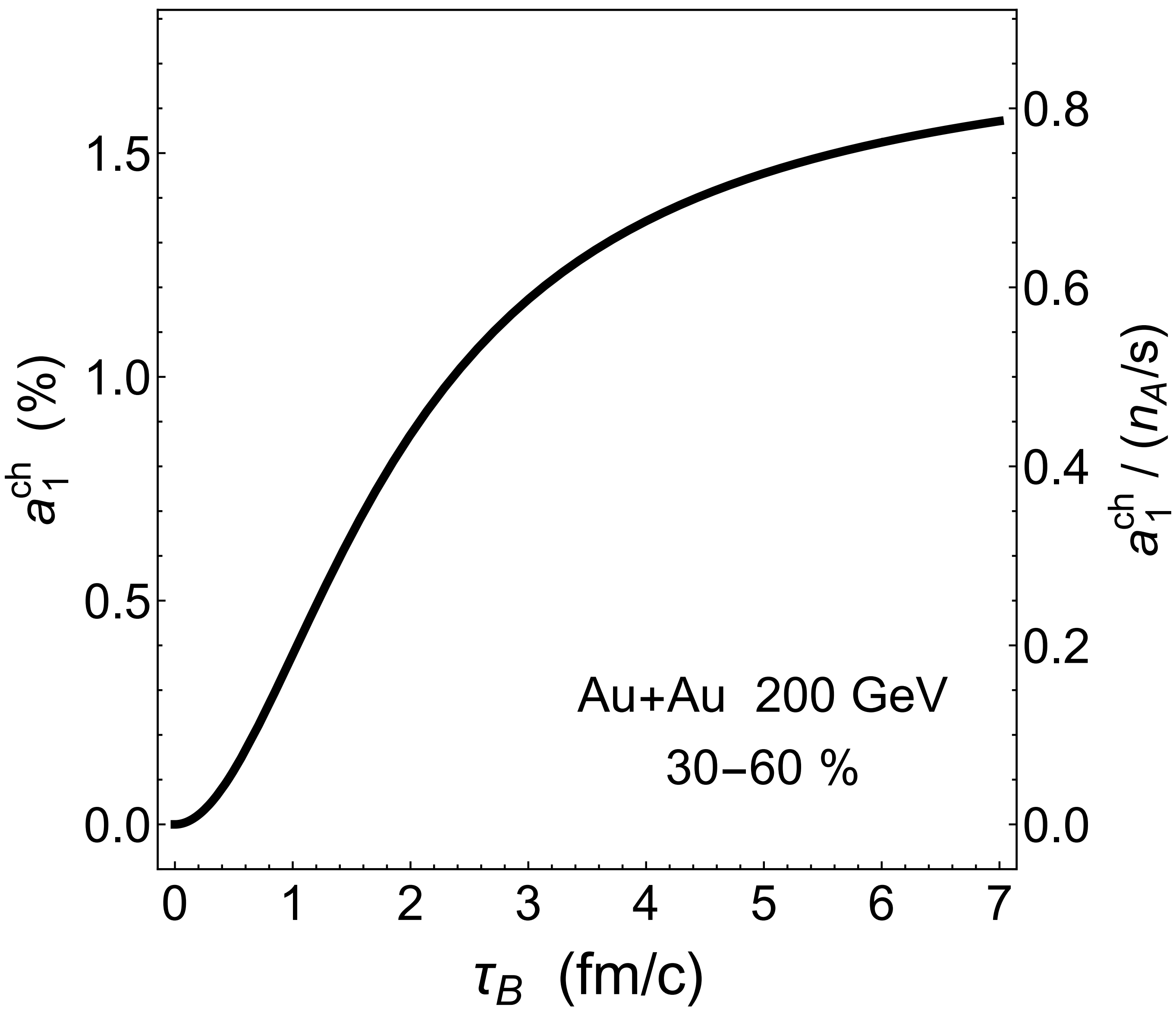
- Viscous transportation has sizable (~30%) effect on charge separation.
- "Canonic" parameters are employed.

# Dependence on { Initial Axial Charge Density $n_A$ / B Field Lifetime $\tau_B$

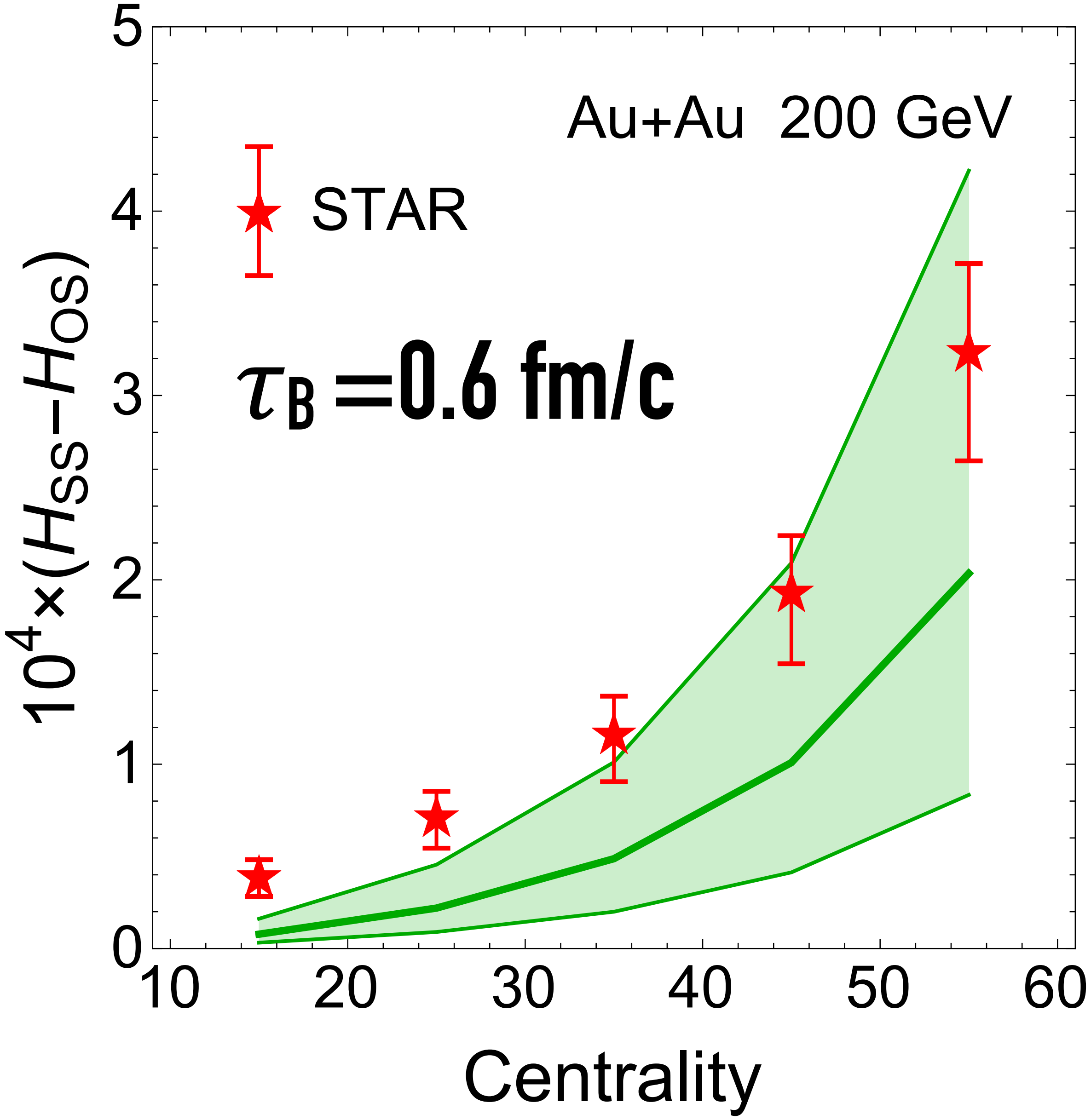
**Charge separation $\propto$ initial $n_A$**

$$B = \frac{B_0}{1+(\tau/\tau_B)^2}$$



# Comparison with Experimental Data




Implementing with best estimated $n_A$ & $\tau_B$

Good agreement for magnitude & centrality trend

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

# Test of CME — Isobaric Collisions @ RHIC

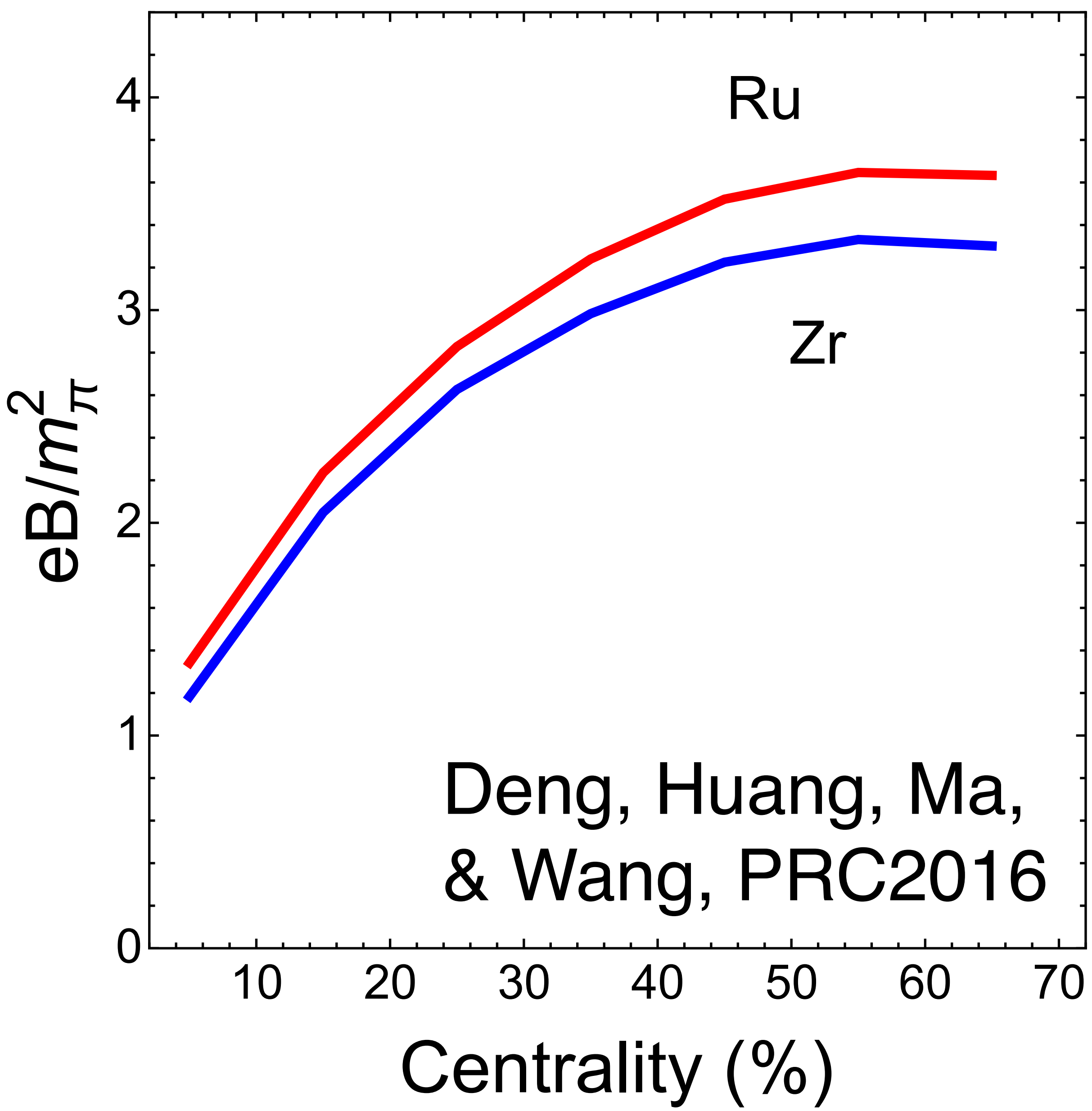
$^{96}_{44}$Ruthenium

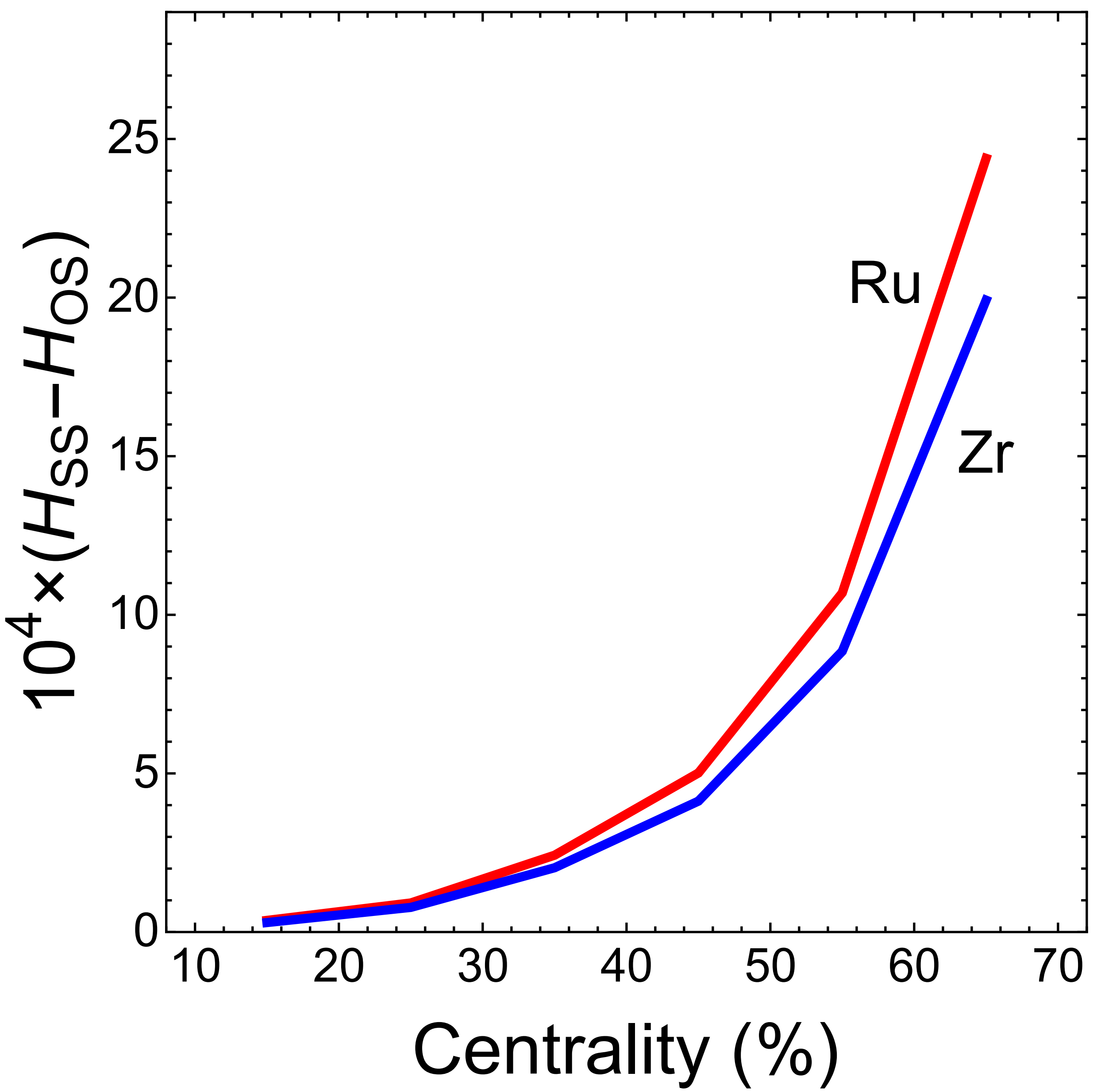
$^{96}_{40}$Zirconium

Same Baryon # ⟶ Similar Bulk Background

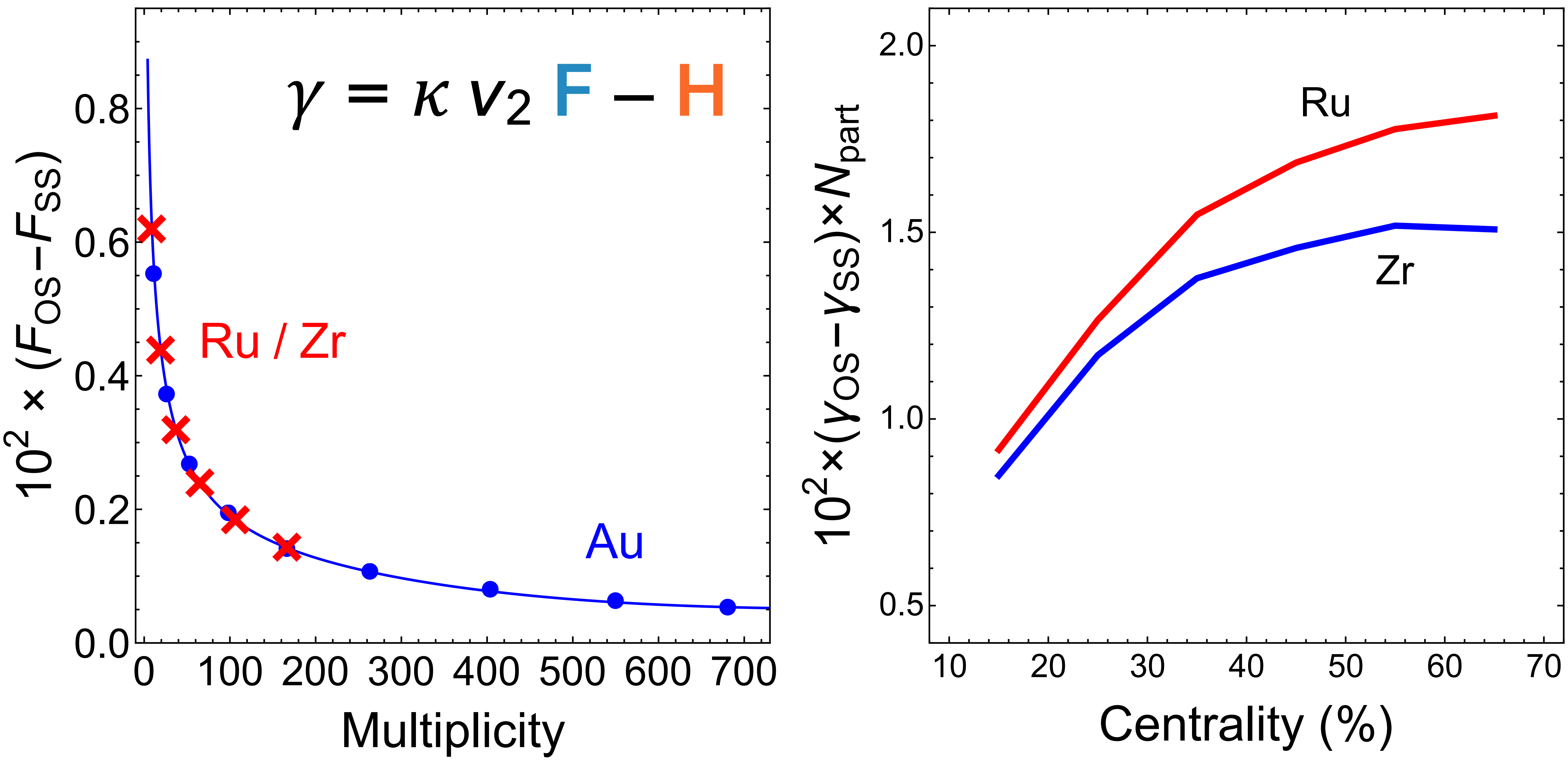
Different Proton # ⟶ Different CME!

# Test of CME —— Isobaric Collisions @ RHIC



# Test of CME —— Isobaric Collisions @ RHIC

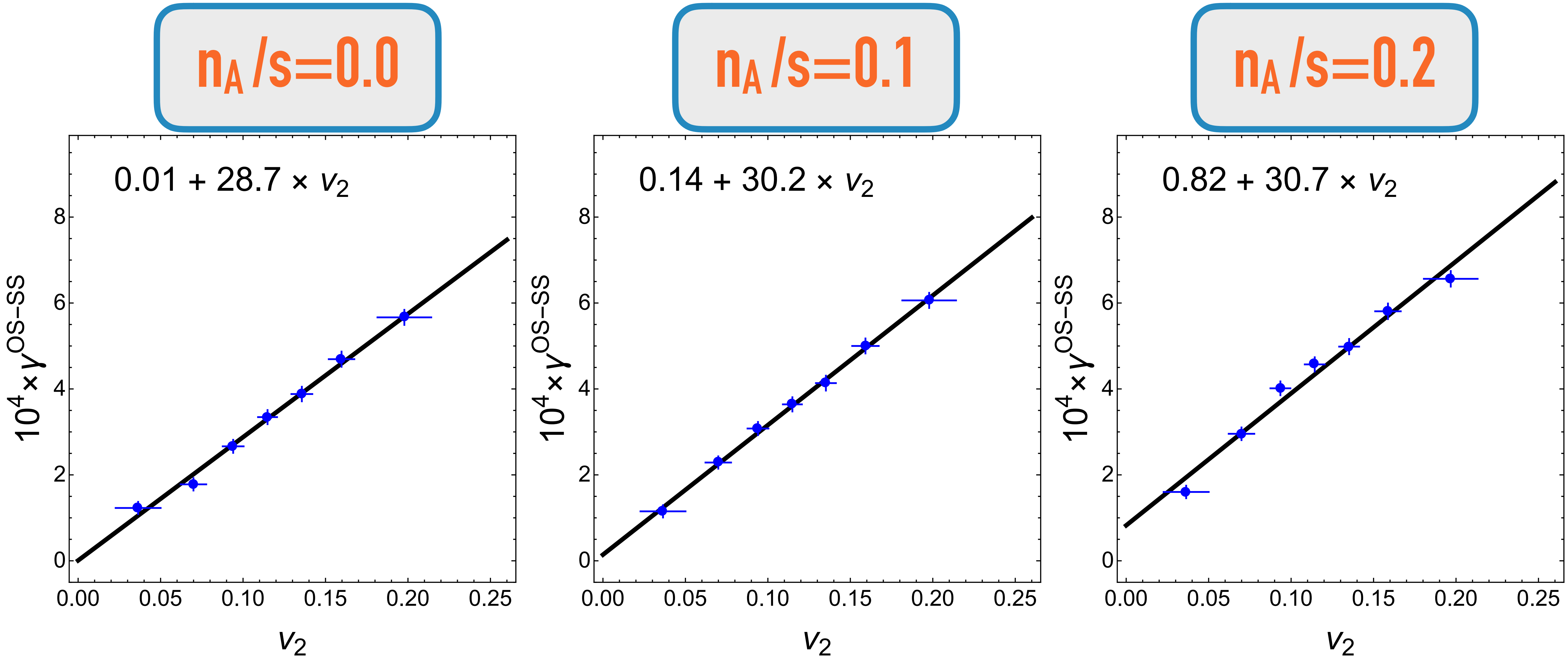



collaborating with E.Lilleskov, Y.Jiang & J. Liao

# CME from event-by-event simulation

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

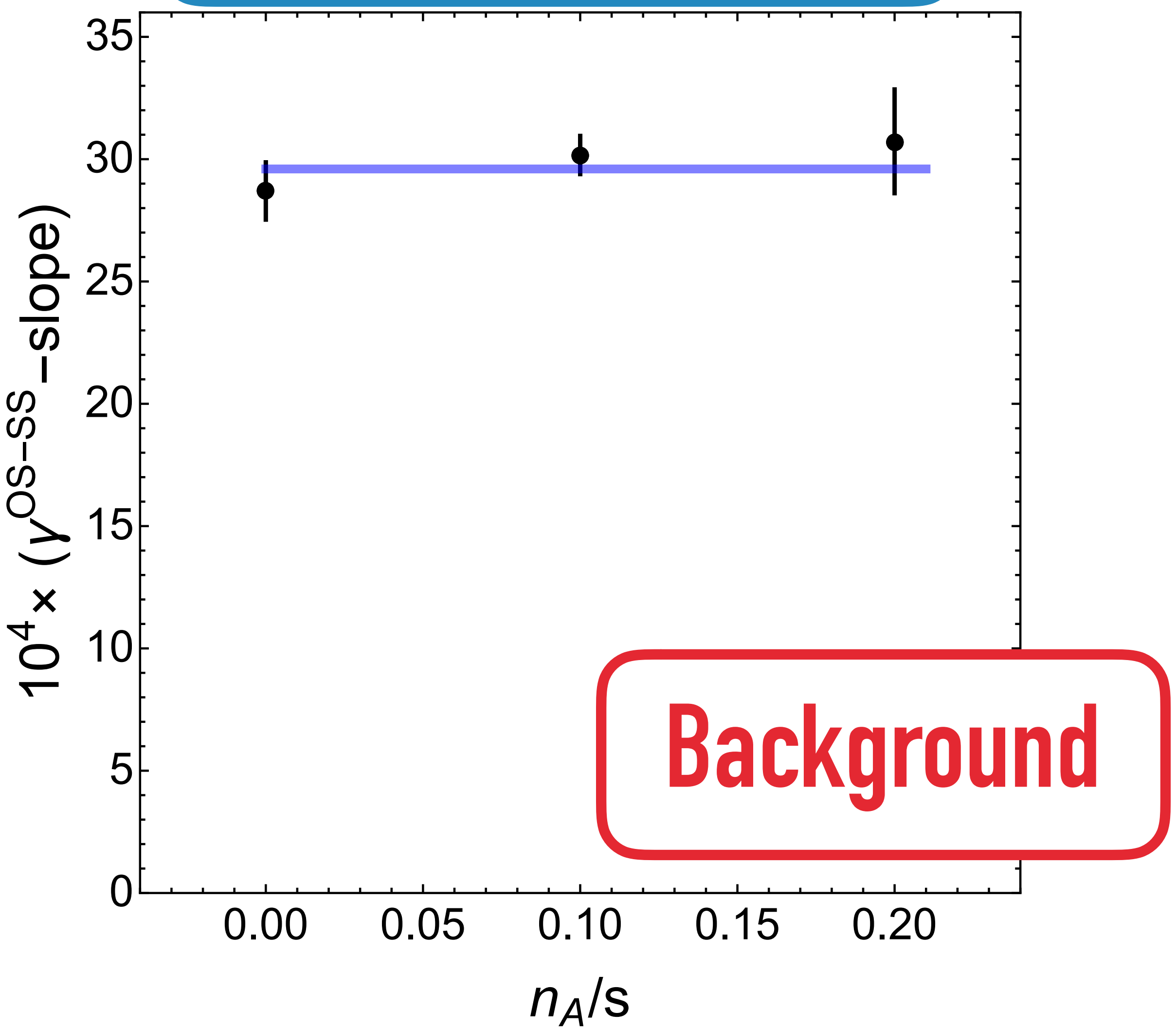
# CME from event-by-event simulation



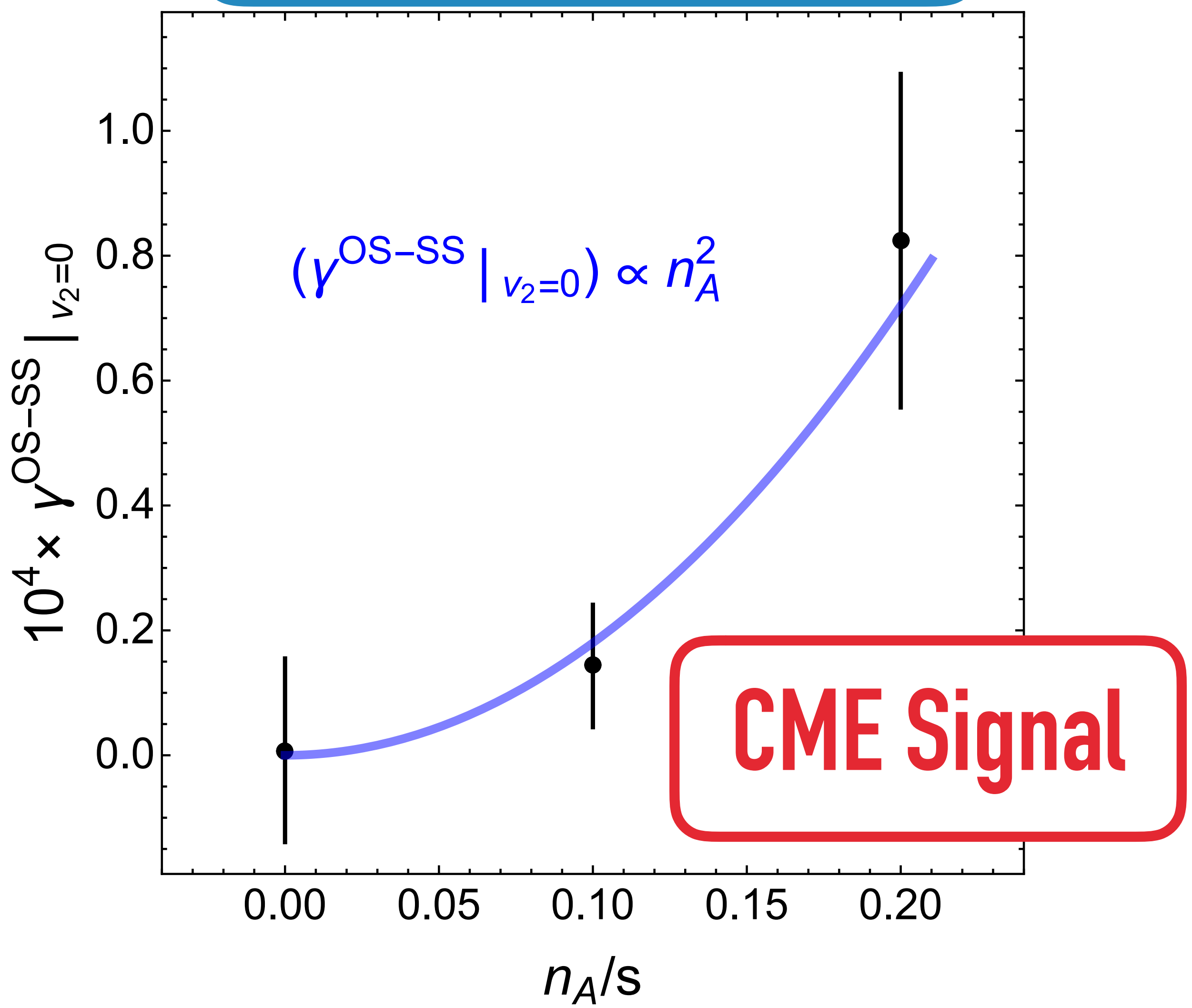

$$\gamma = \kappa\, v_2\, F - H$$

# CME from event-by-event simulation

slope ∝̸ $n_A$




intercept ∝ $n_A{}^2$




in collaborating with Y.Jiang & J. Liao

# Summary & Outlook

- AVFD framework is developed to quantitatively study CME.
- Best estimated $n_A$ & $\tau_B$ ⇒ good agreement with experiment.
- CME in isobaric collisions ($^{96}$Ru $-$$^{96}$Ru v.s.$^{96}$Zr $-$$^{96}$Zr) studied.
- event-by-event simulation
- TMC, LLC … in EbE simulation

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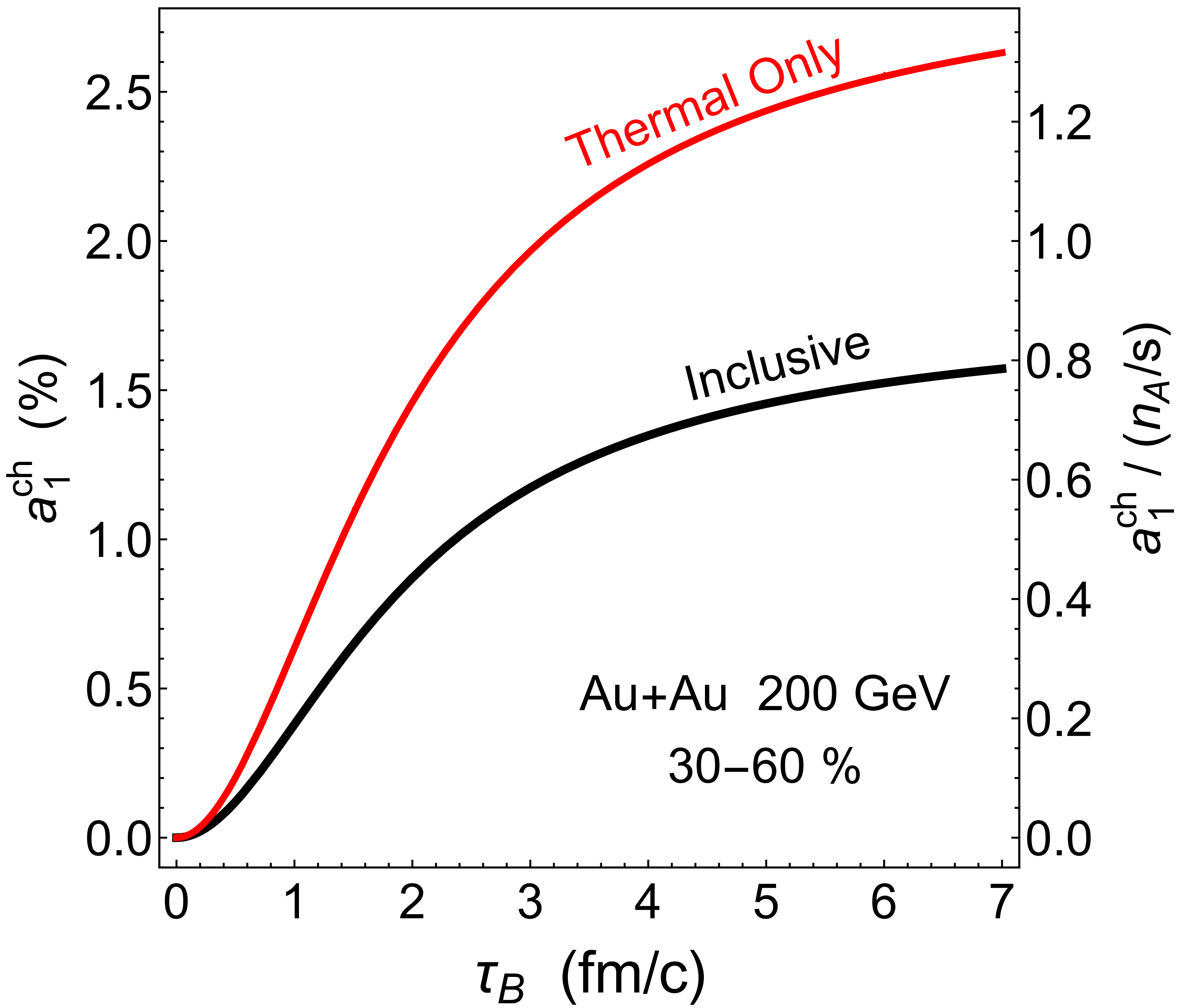
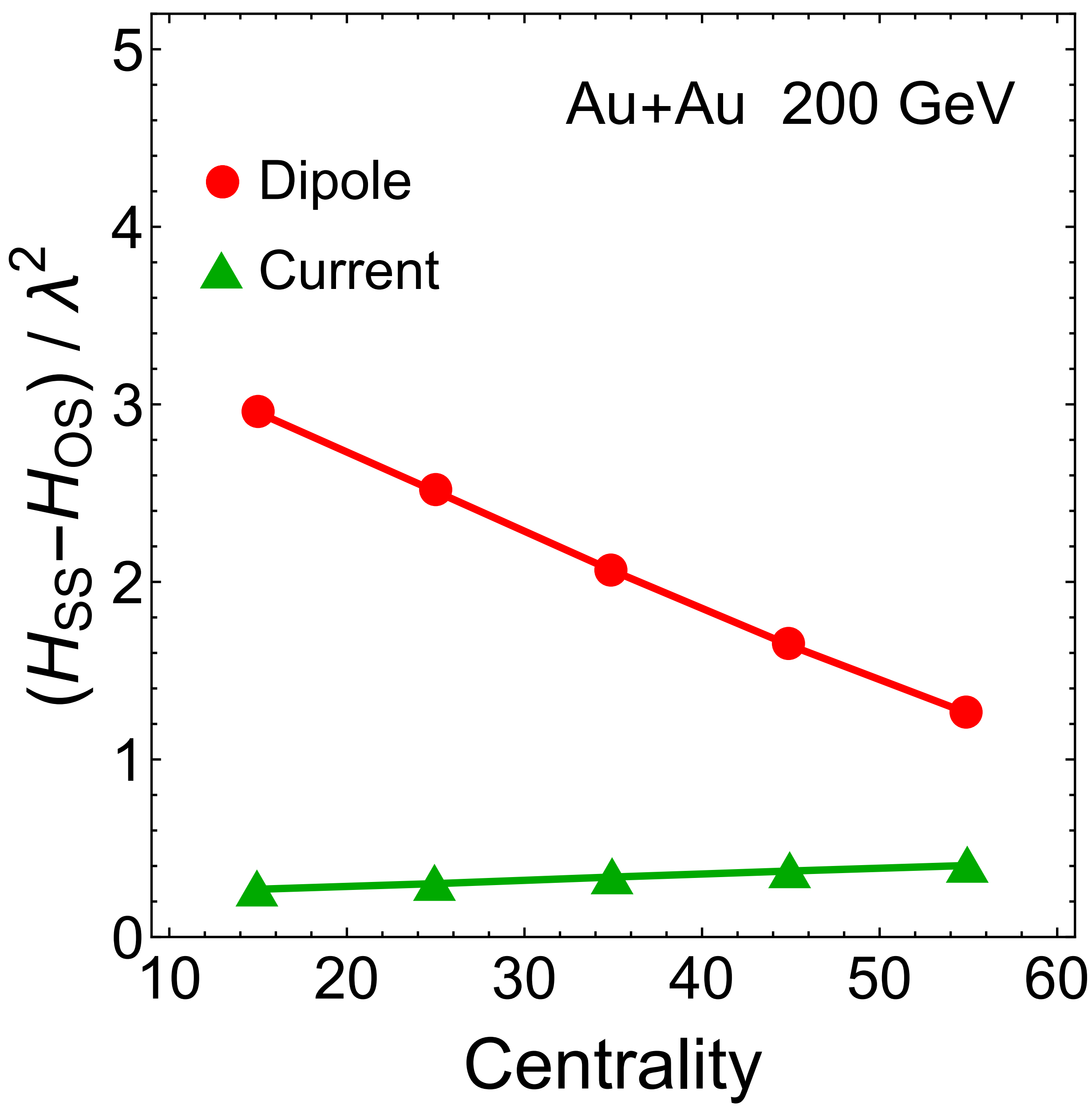
# THANK YOU!

# BACKUP — Contribution of Decay from Resonances



# BACKUP — Pre-Thermal Anomalous Dipole/Current?

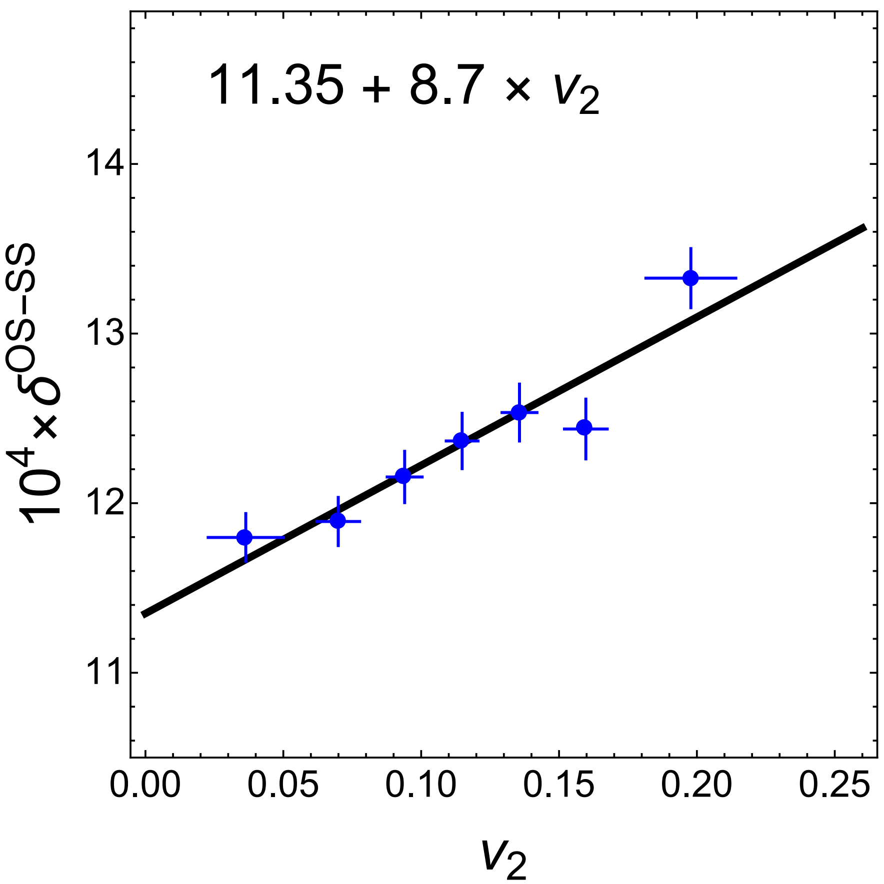


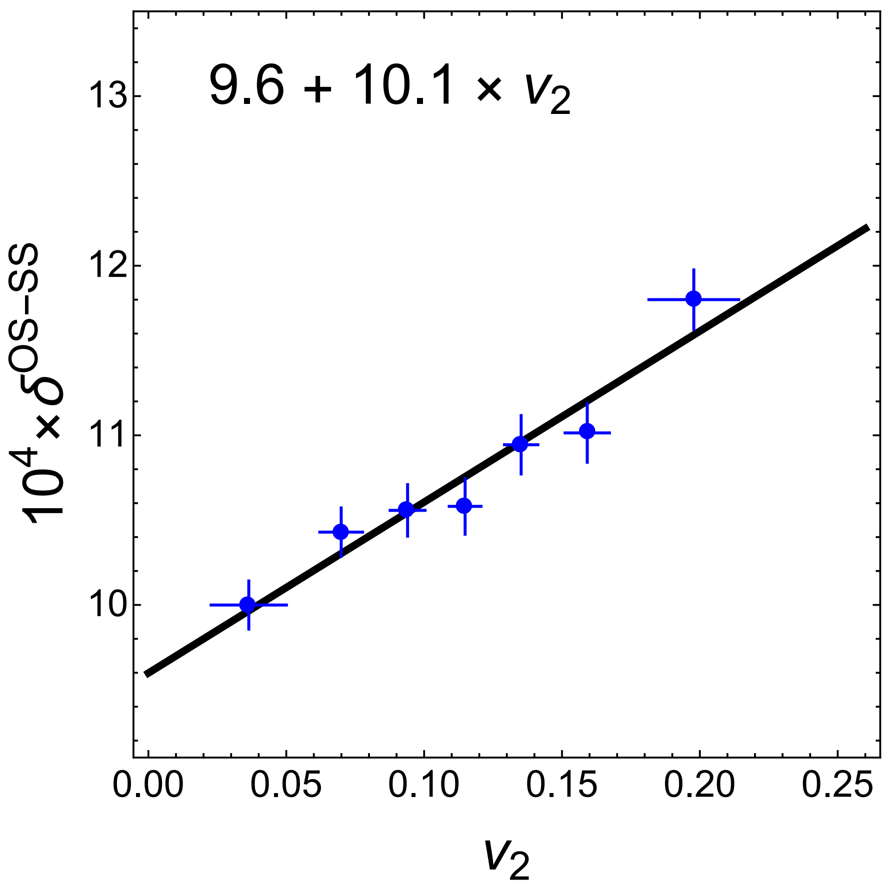

B ($\tau$>0.6fm) = 0

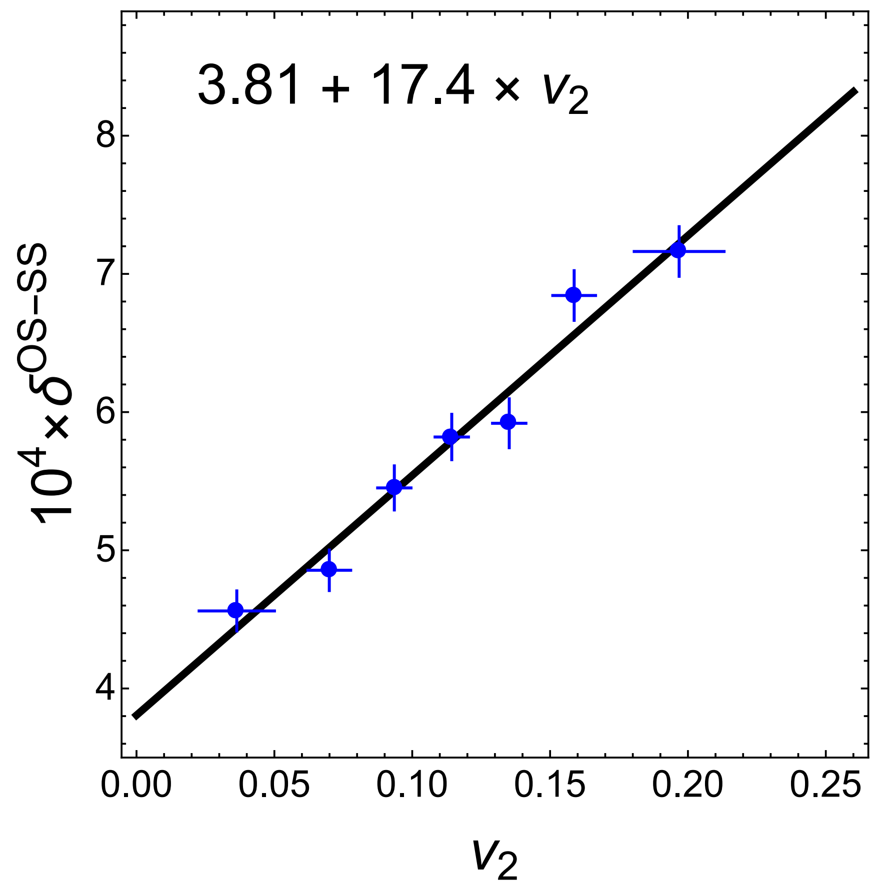
$$J^\mu(\tau=\tau_0) = \lambda_J \times (C_A \mu_A B^\mu)$$

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

# BACKUP — CME from event-by-event simulation



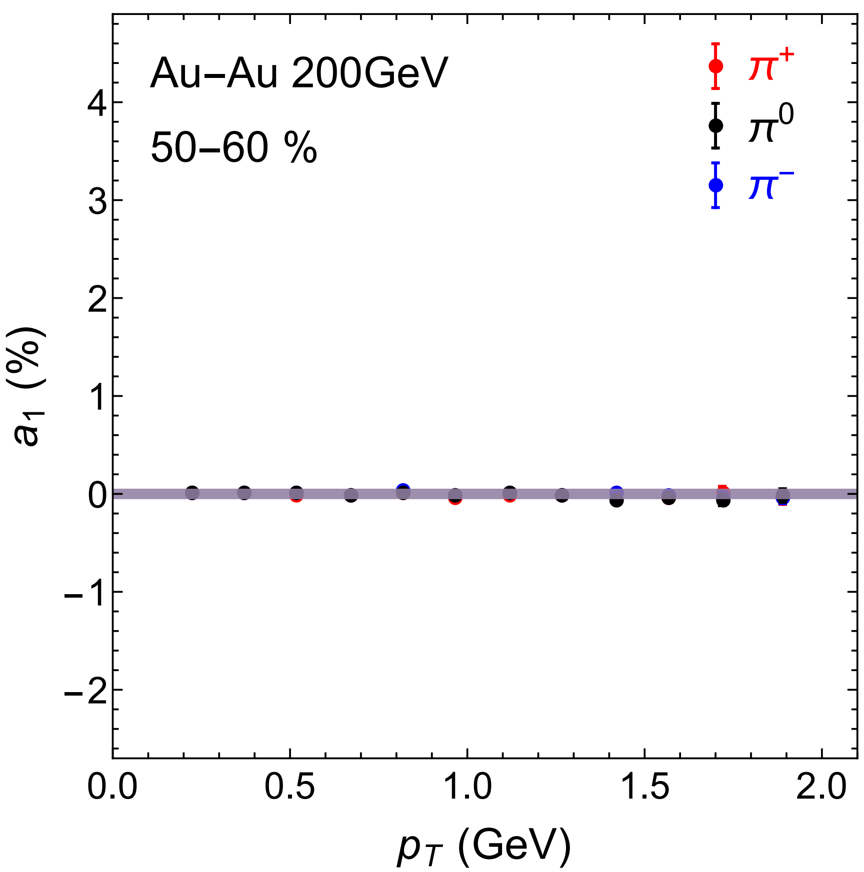




$n_A/s$=0.0

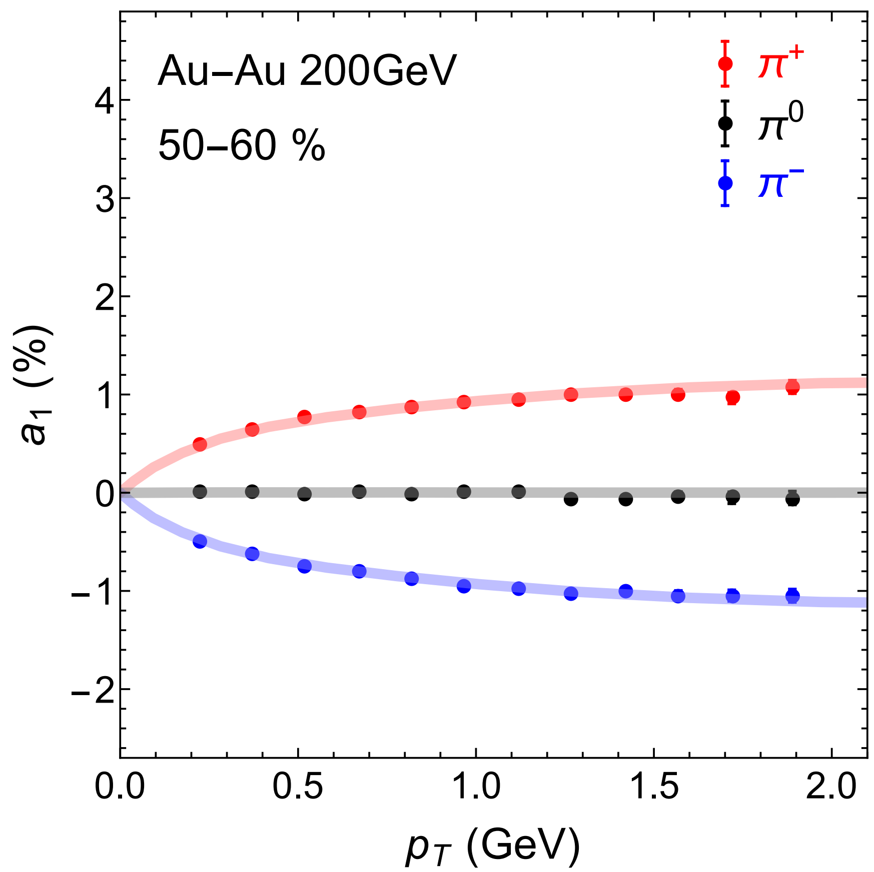
$n_A/s$=0.1

$n_A/s$=0.2

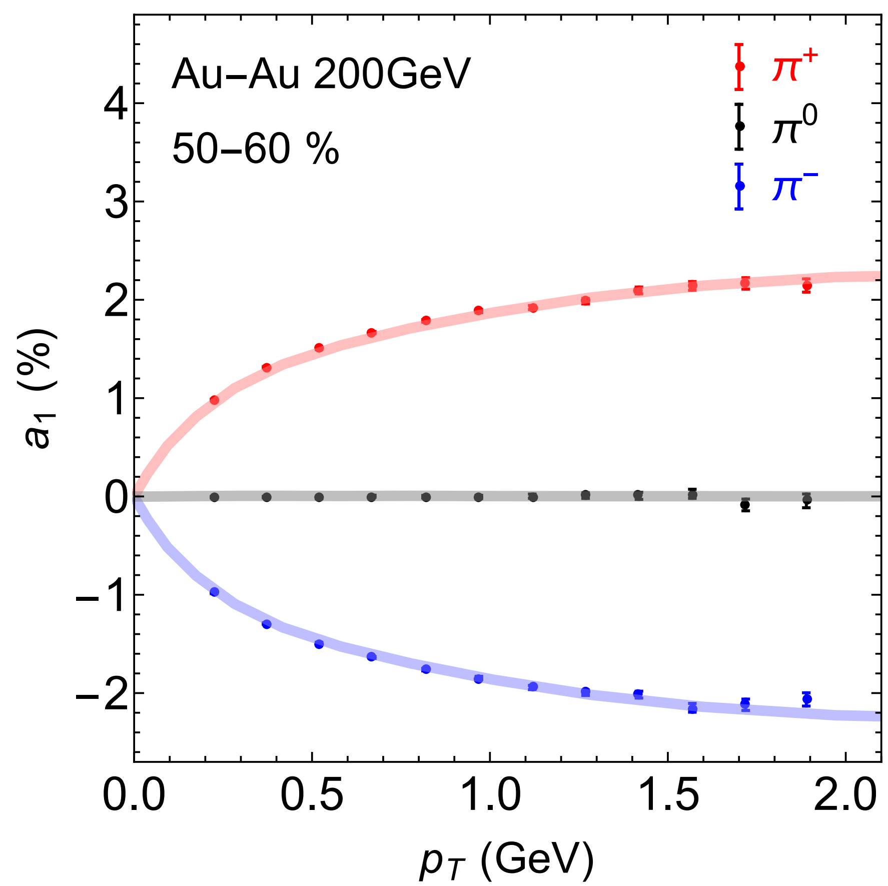
# BACKUP — EbE vs Smooth Hydro




$n_A/s$=0.0




$n_A/s$=0.1




$n_A/s$=0.2