5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy-Ion Collisions

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

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BEST COLLABORATION

In collaboration with:
Yin Jiang, Hui Zhang, Elias Lilleskov,
Jinfeng Liao, Yi Yin, Defu Hou,

Chiral Magnetic Effect

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

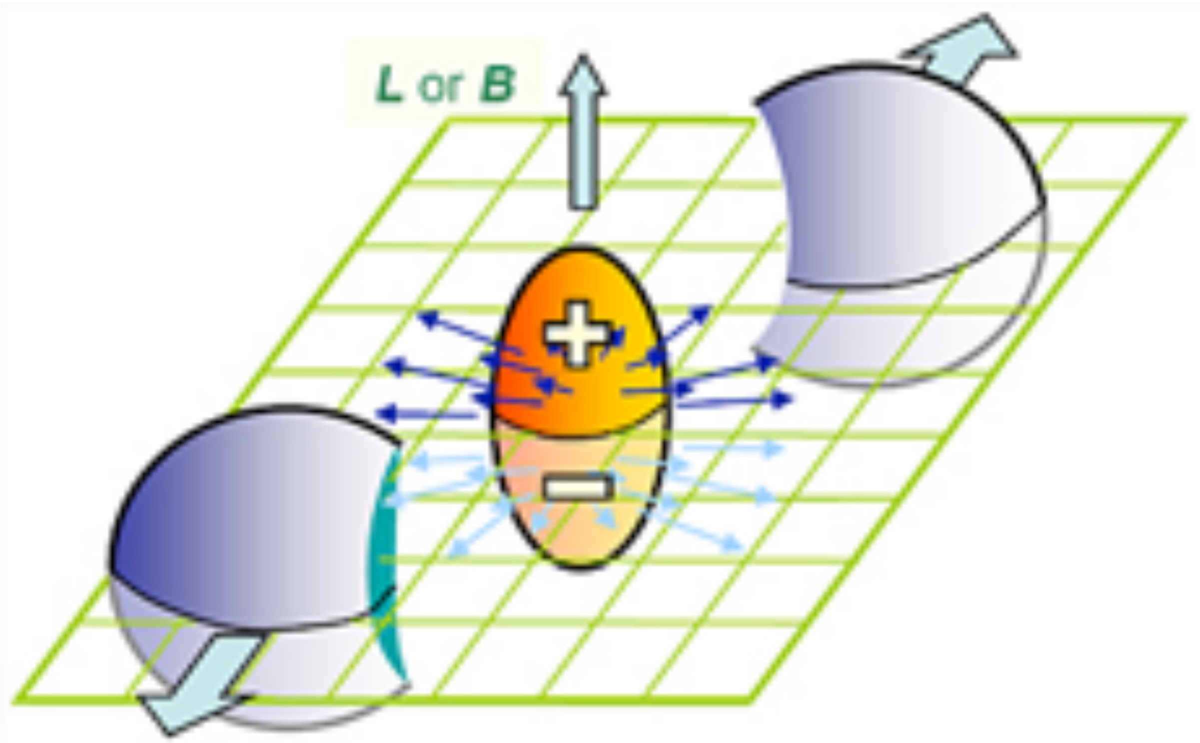
For right-handed particles w/ positive charge:

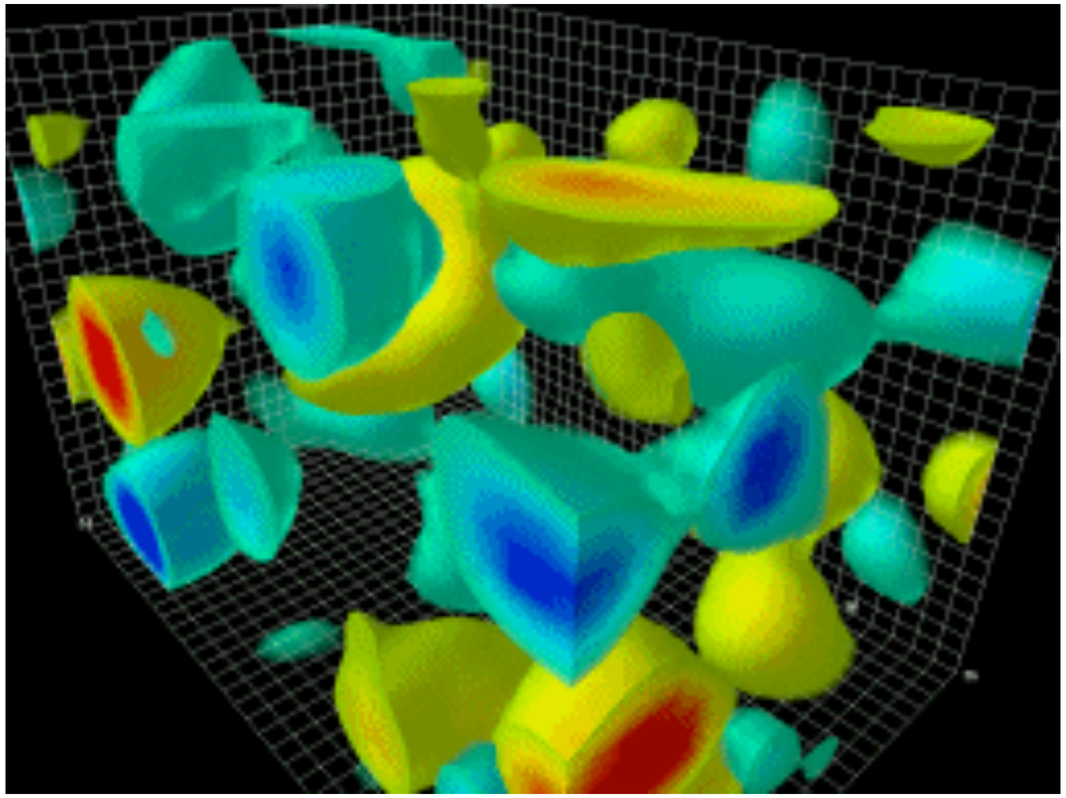
1. $\vec{p} \,//\, \vec{S} \,//\, \vec{\mu}$
2. Energy $= -\vec{\mu} \cdot \vec{B}$

⇒ lower energy if moving along B field direction

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

CME In Heavy-Ion Collisions





Magnetic Field

$\otimes$

Topology

$\otimes$ Chiral

$\otimes$ Anomaly

B ~ γ Z Q b / R^3

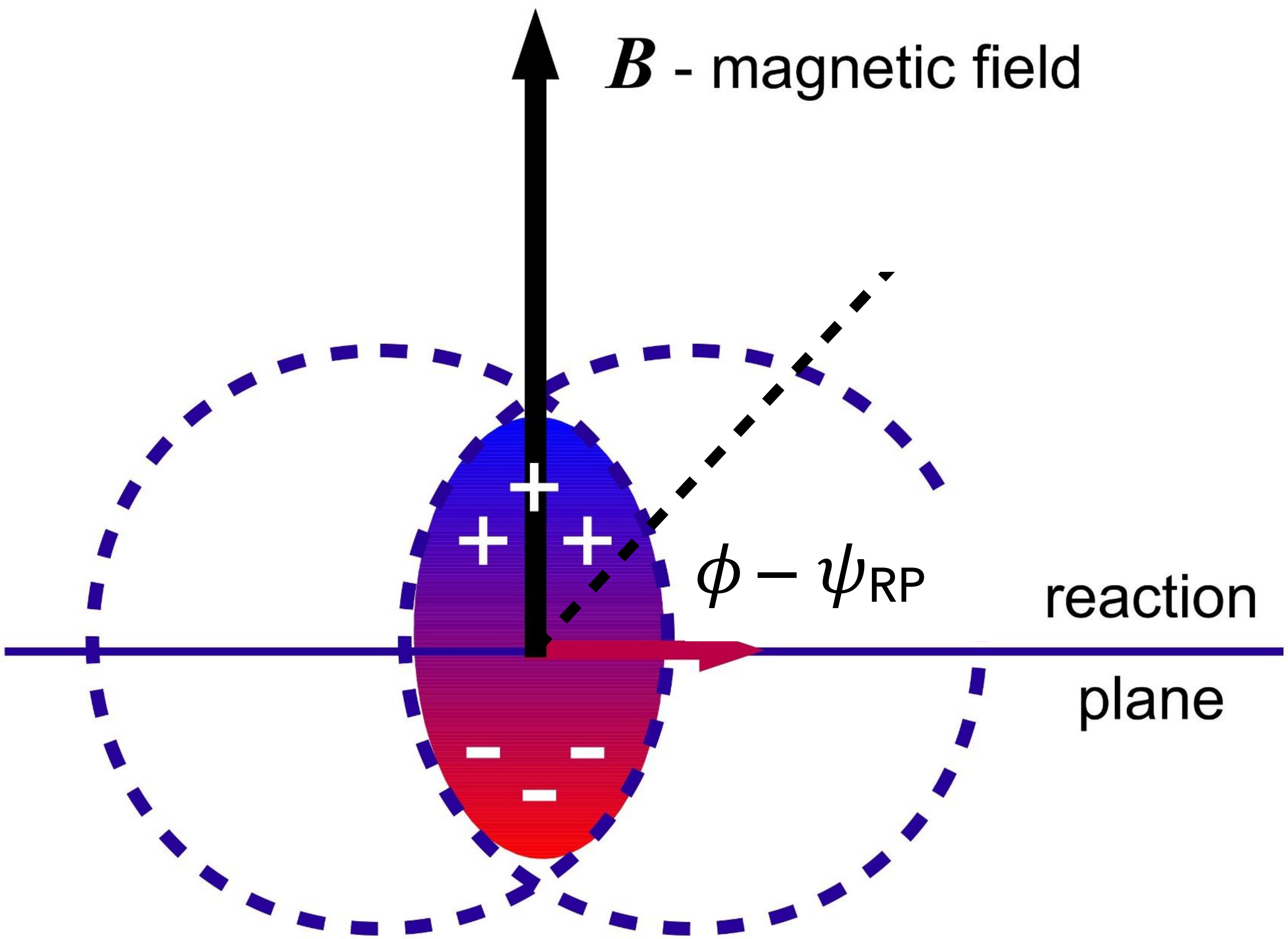
(10^{15} T @ 200 GeV Au-Au)

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

CME In Heavy-Ion Collisions

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

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



CME In Heavy-Ion Collisions

- B field $\otimes\ \mu_5 \ \Rightarrow$ current $\Rightarrow$ dipole (charge separation)

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

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

CME In Heavy-Ion Collisions

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

$$\delta_{bkg} = F$$

Bulk Background

CME In Heavy-Ion Collisions

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

$$\delta = F + H$$

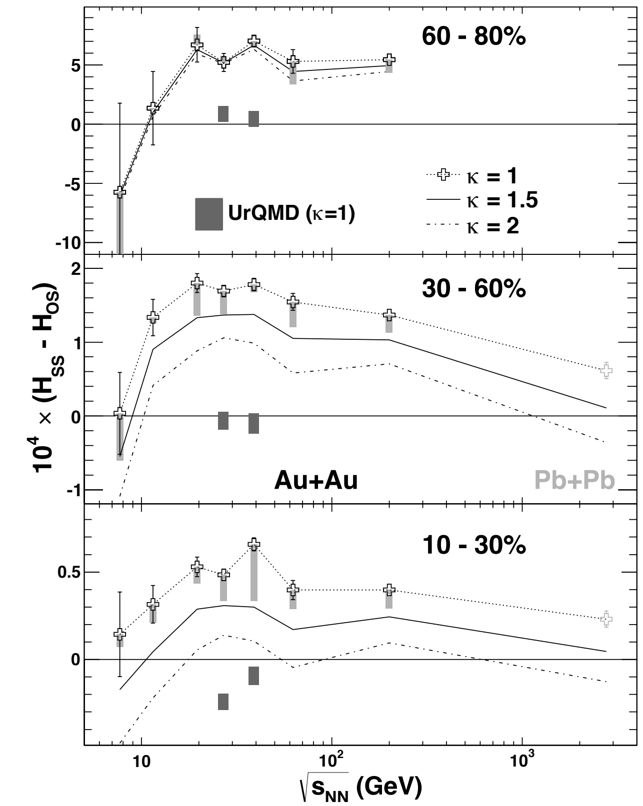
F: Bulk Background

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

CME In Heavy-Ion Collisions

axial & vector charge density

Anomalous
-**V**iscous
Fluid
Dynamics



initial condition

+

driving force

B field

→ dynamical evolution → final particle distribution

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

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

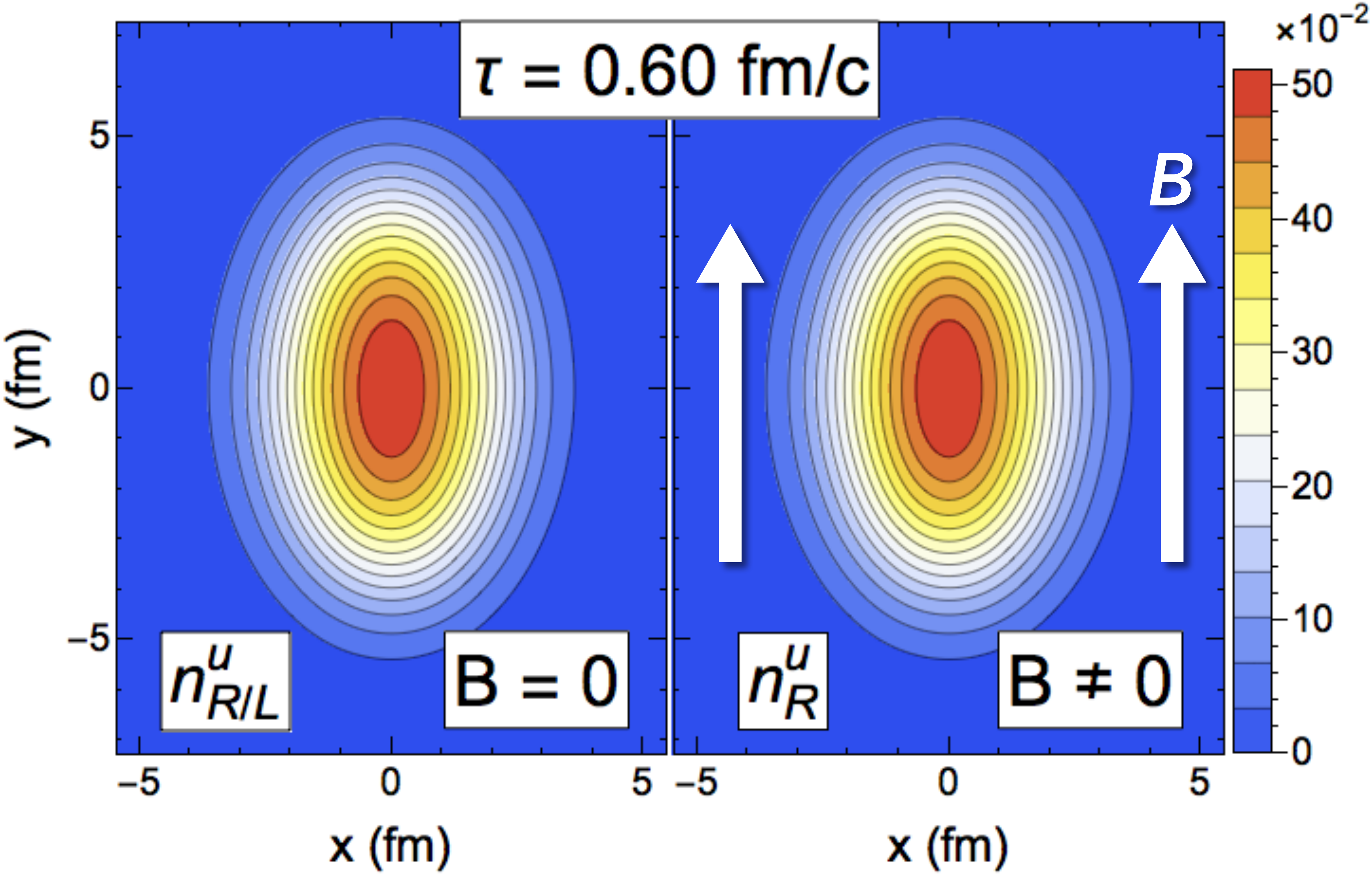
$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q\, E^\mu$$

as the linear perturbation on top of

2+1D VISHNU/MUSIC Hydro background

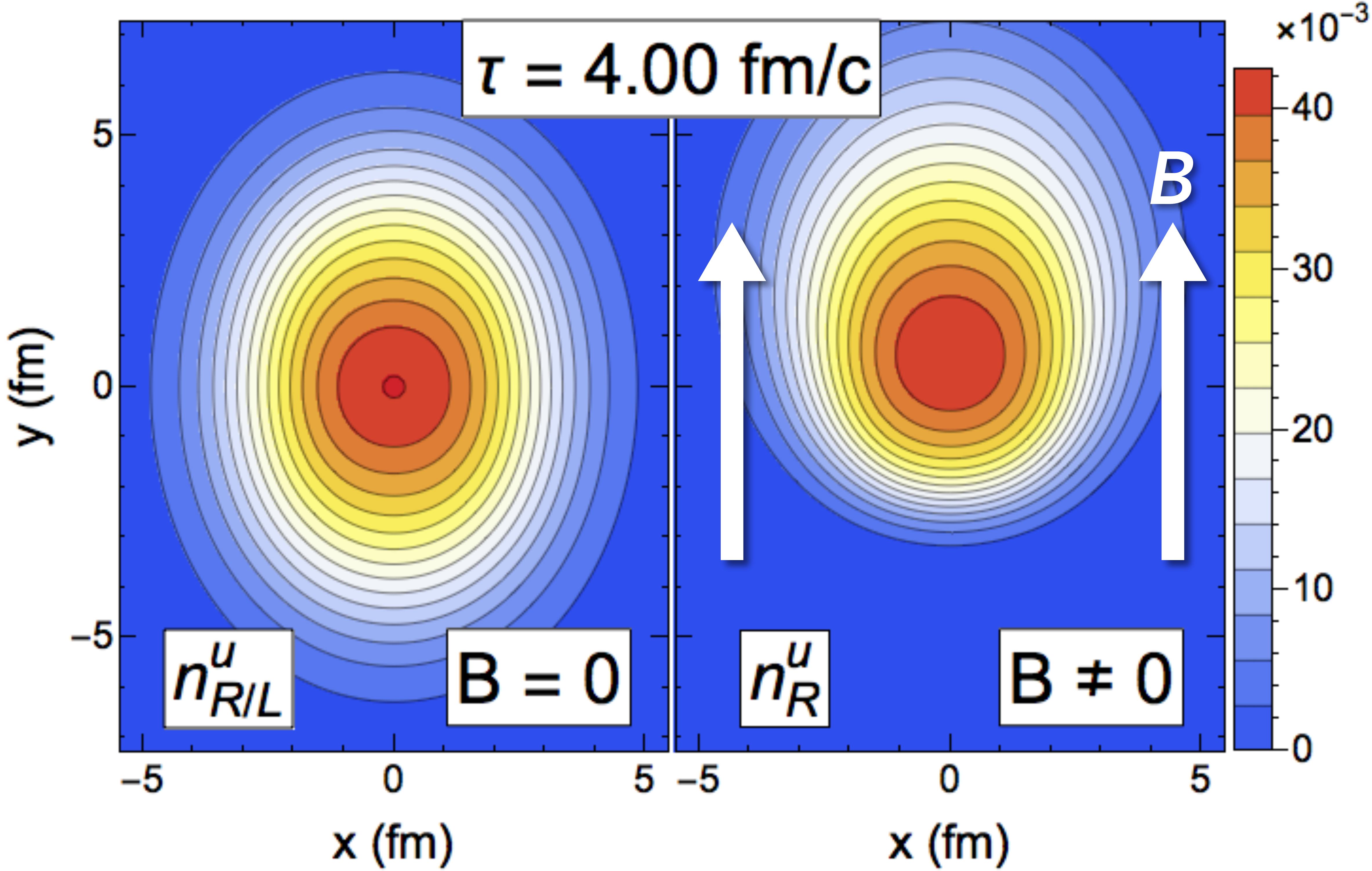
Evolution of Quark Number Density

w/ vs. w/o magnetic field



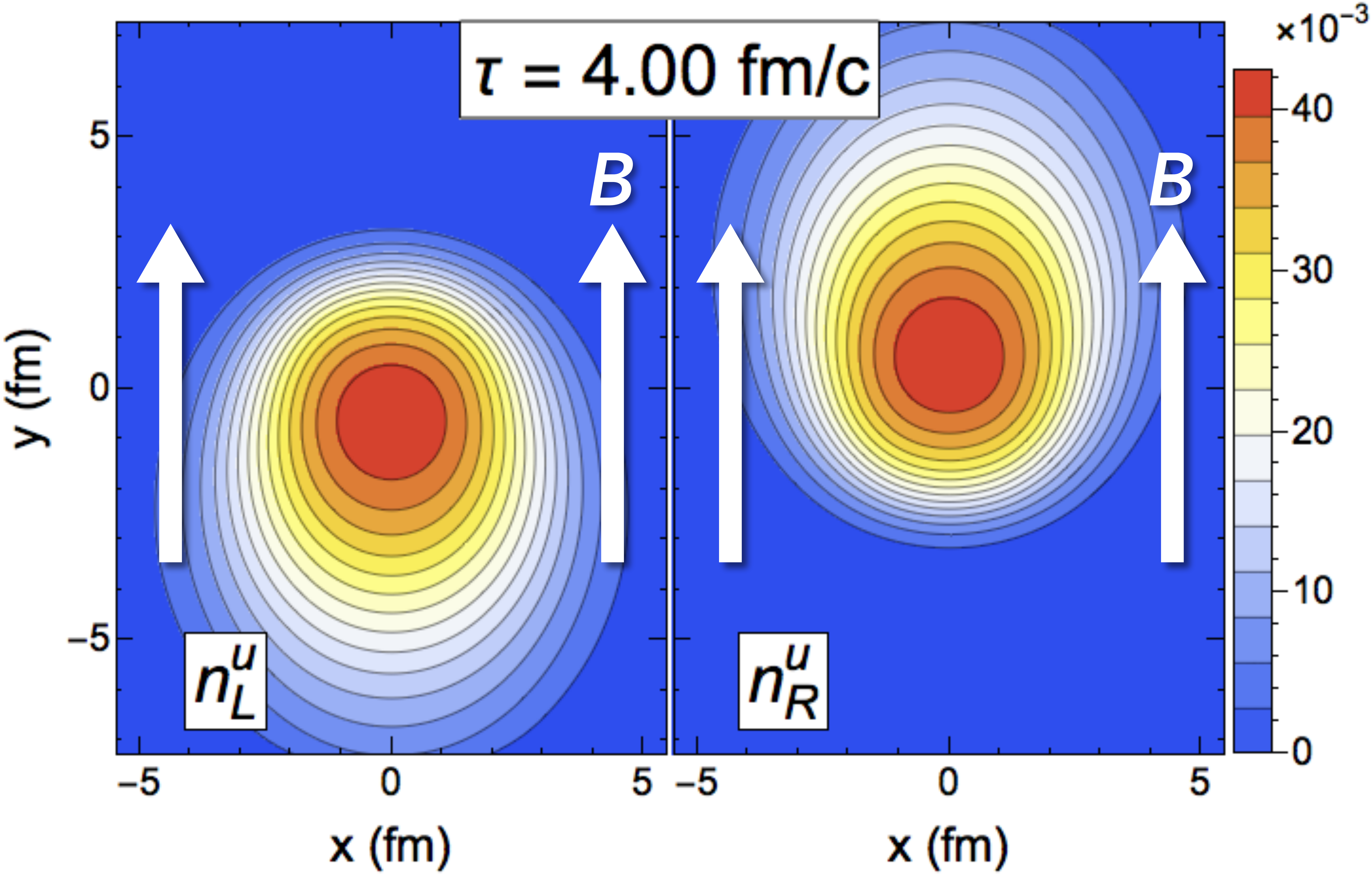
Evolution of Quark Number Density

w/ vs. w/o magnetic field



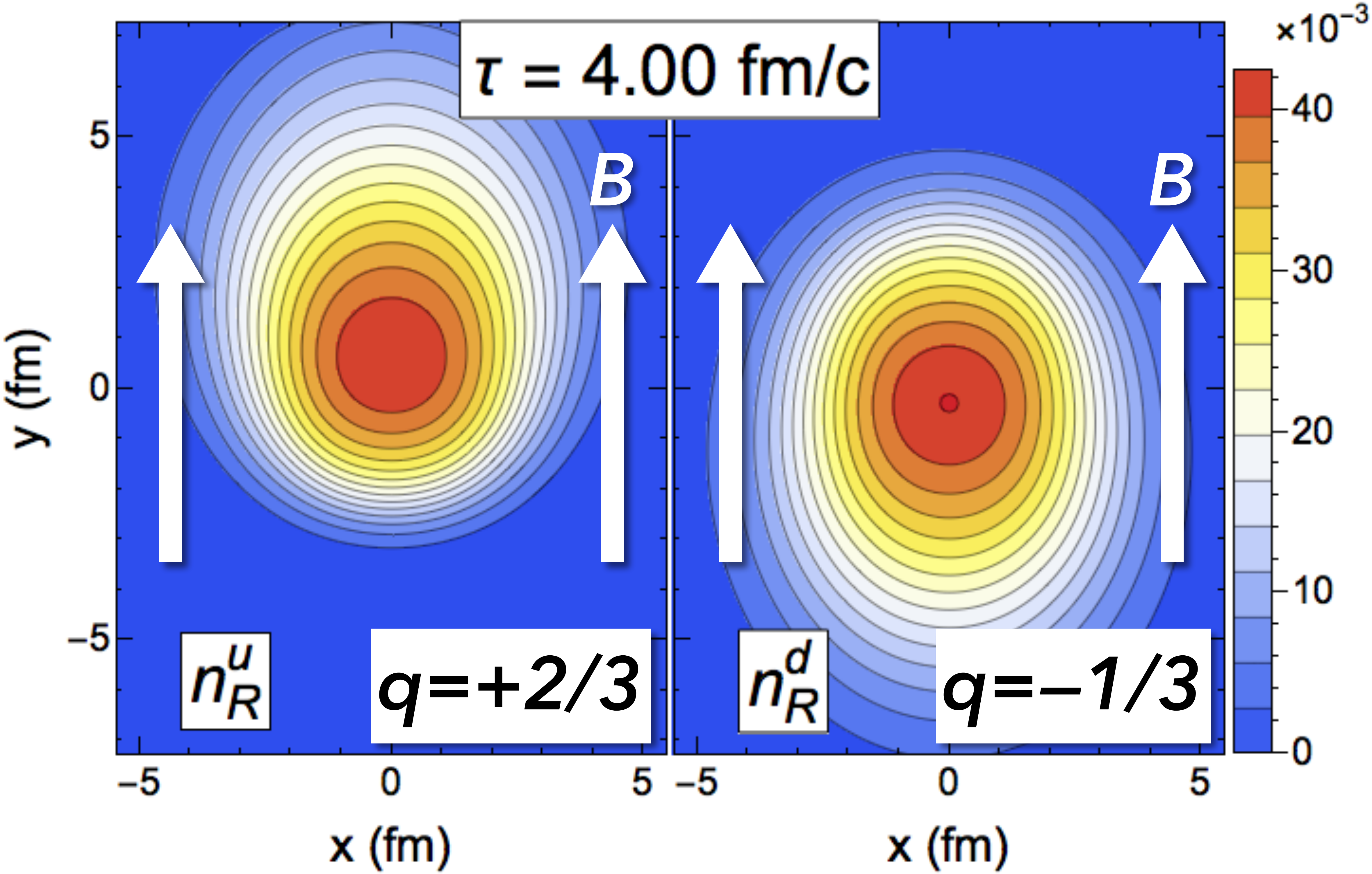
Evolution of Quark Number Density

Left- vs. Right-Handed

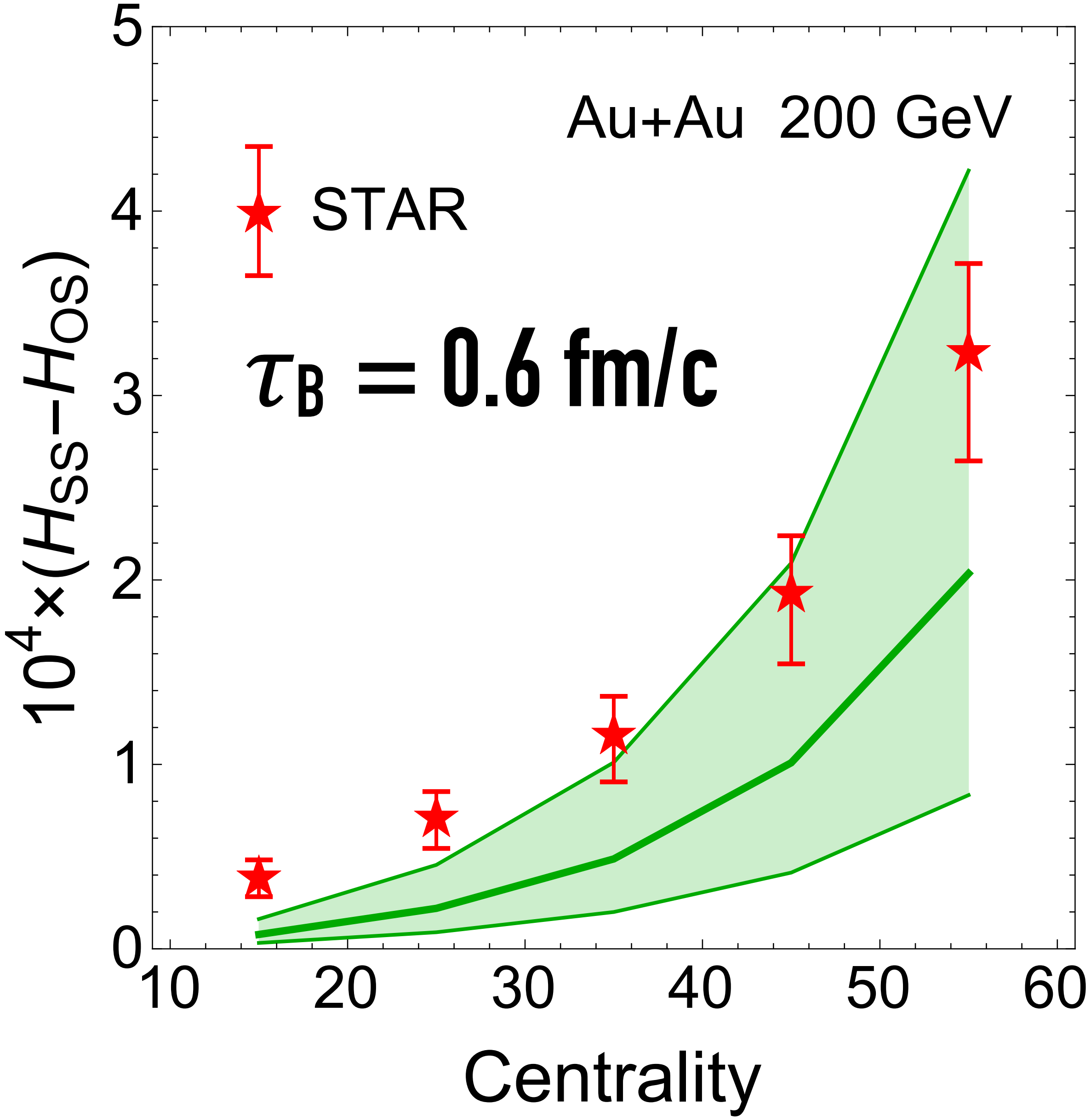


Evolution of Quark Number Density

u- vs. *d*- Quarks



CME from Smooth AVFD simulation



Implementing with best estimated n_A

& with $\tau_B = 0.6$ fm/c

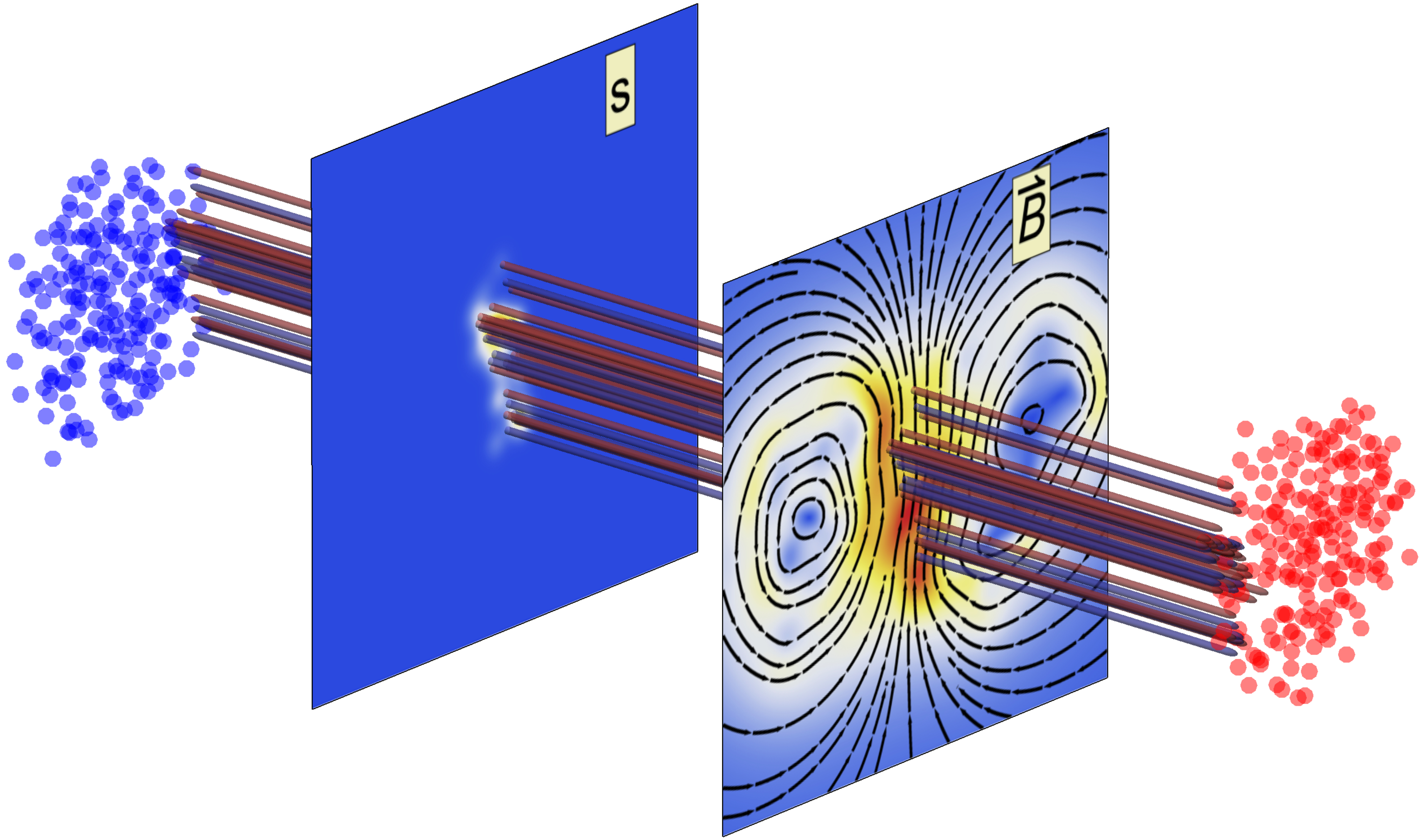
Good agreement for magnitude & centrality trend

Y.Jiang, SS, Y.Yin & J.Liao, **Chin. Phys. C (2018)**

SS, Y.Jiang, E.Lilleskov & J.Liao, **Annals Phys. (2018)**

Influence from Event-by-Event Fluctuation

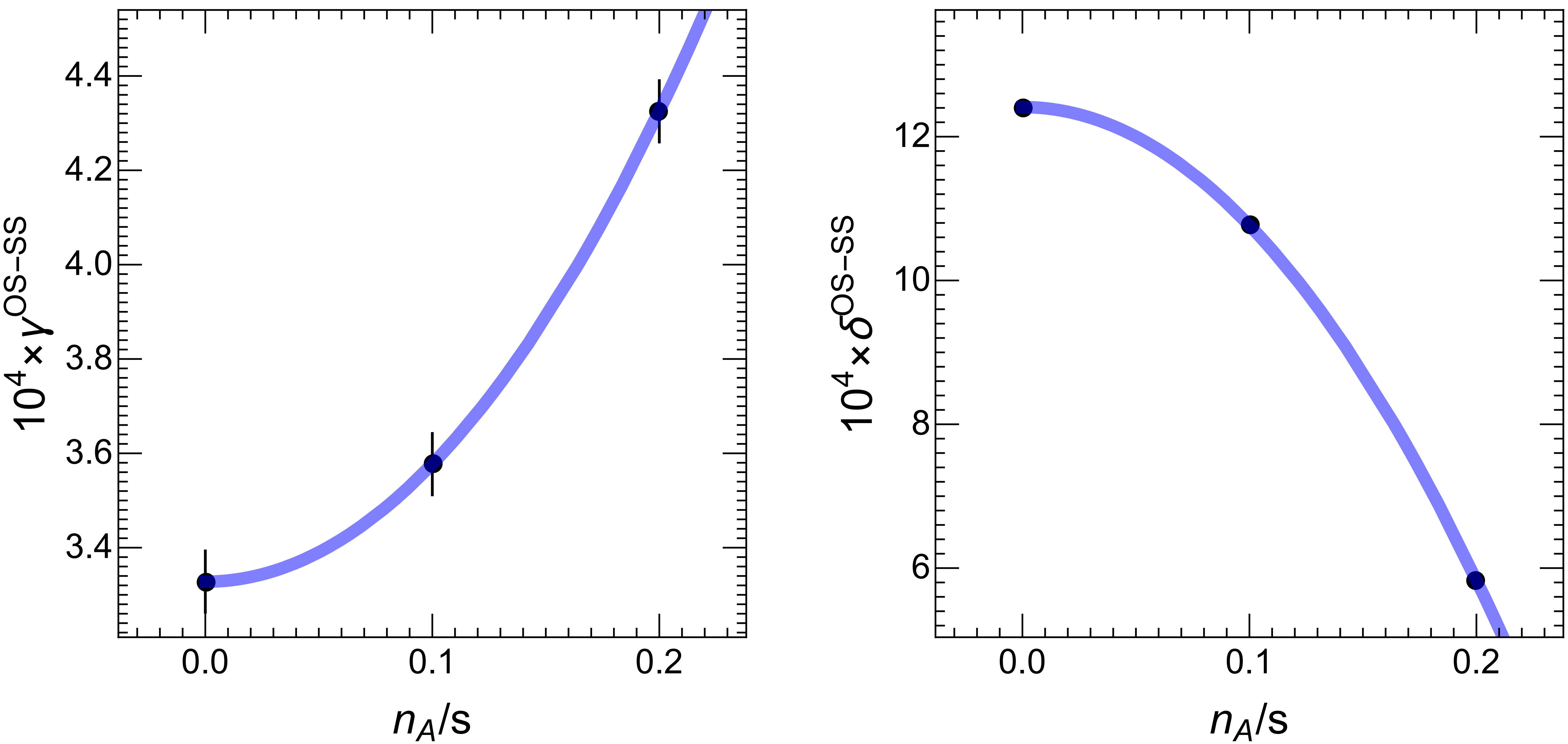
- Fluctuations !!!
  - Initial Conditions
  - Hadron Scattering & Resonance Decay



Event-by-Event: Correlators

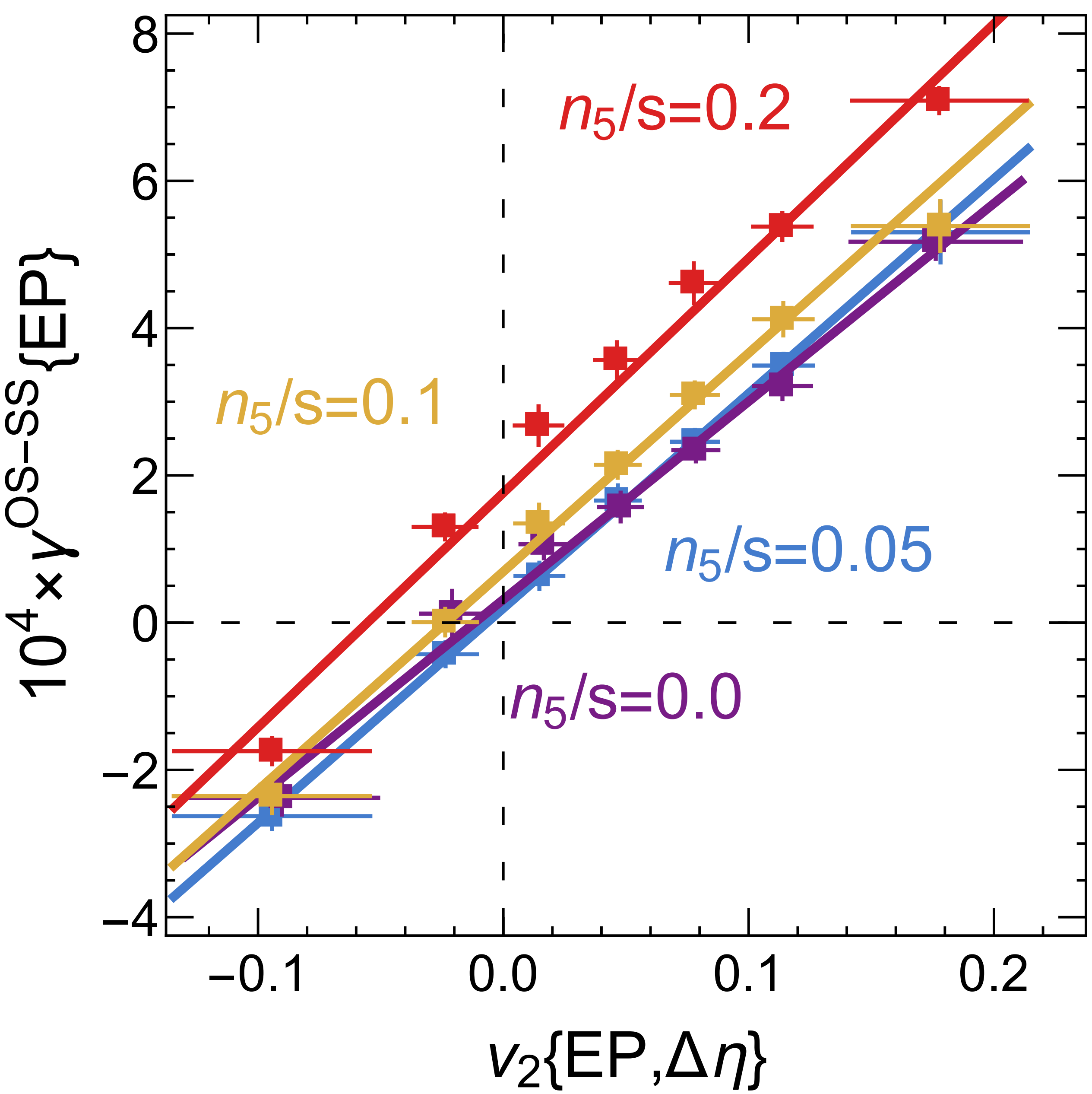
Au-Au @ 200GeV

50-60%



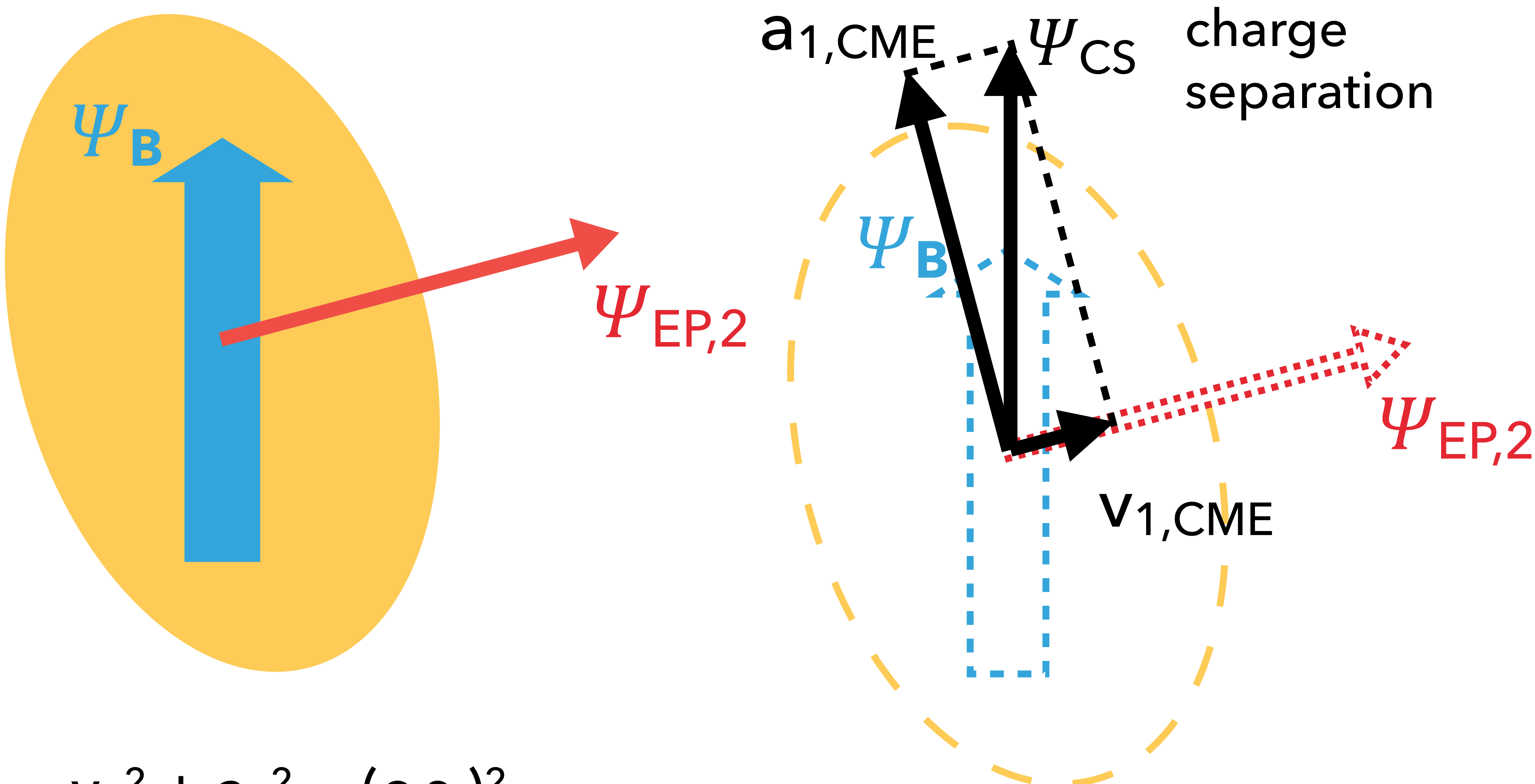
Event-Shape Engineering Method?

$$\gamma = \kappa\, v_2\, F_{BKG} - H_{CME}$$



- intercept reflects CME
- subtleties due to Event Plane de-correlation

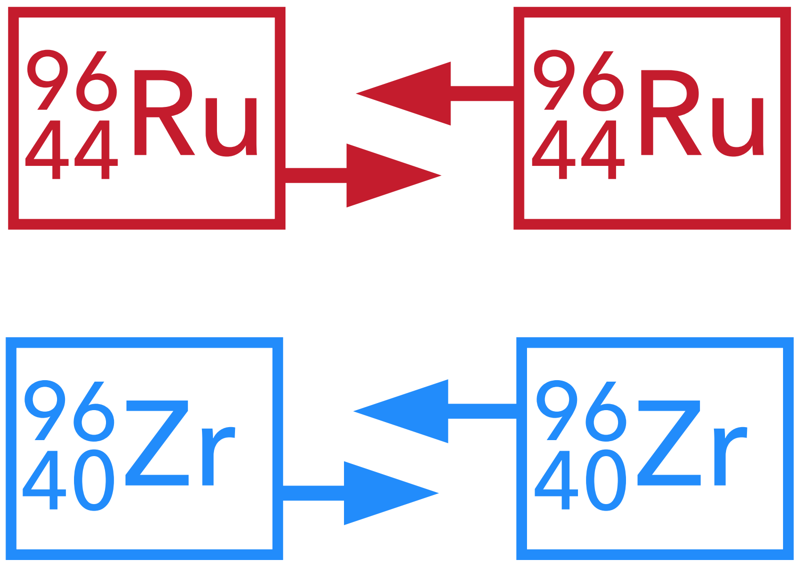
Event-Plane De-Correlation?

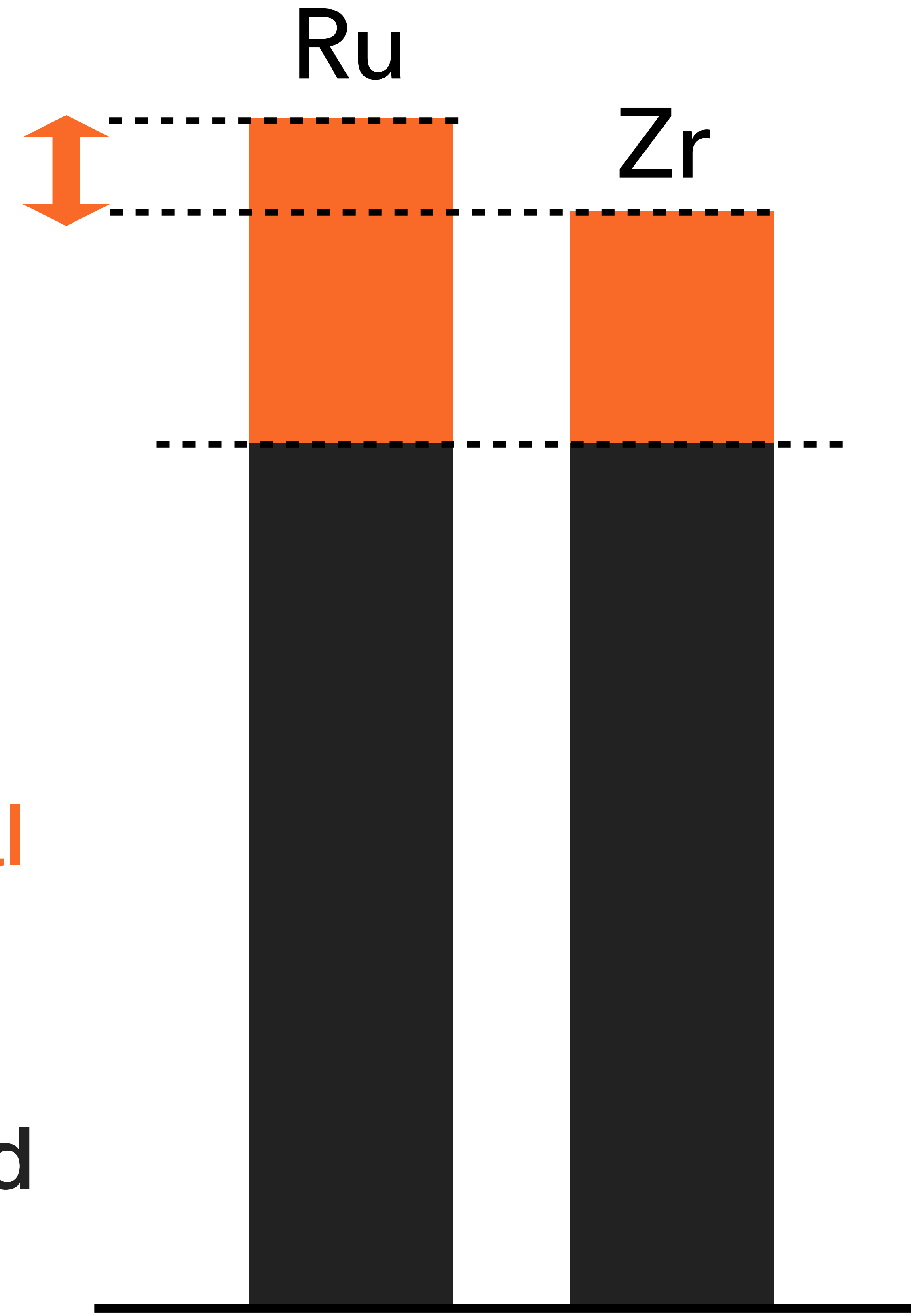


$$\delta_{CME} = v_1^2 + a_1^2 = (c.s.)^2$$
$$\gamma_{CME} = v_1^2 - a_1^2 = (c.s.)^2 \cos(2\Psi_{CS} - 2\Psi_2) \approx (c.s.)^2 \cos(2\Psi_B - 2\Psi_2)$$

- γ_{CME} picks up a factor, related to de-correlation
- different v_2-bins correspond to different de-correlation factors

Decisive Test of CME — Isobaric Collisions





Different Proton # → Different CME Signal

Same Baryon # → ? Same Background

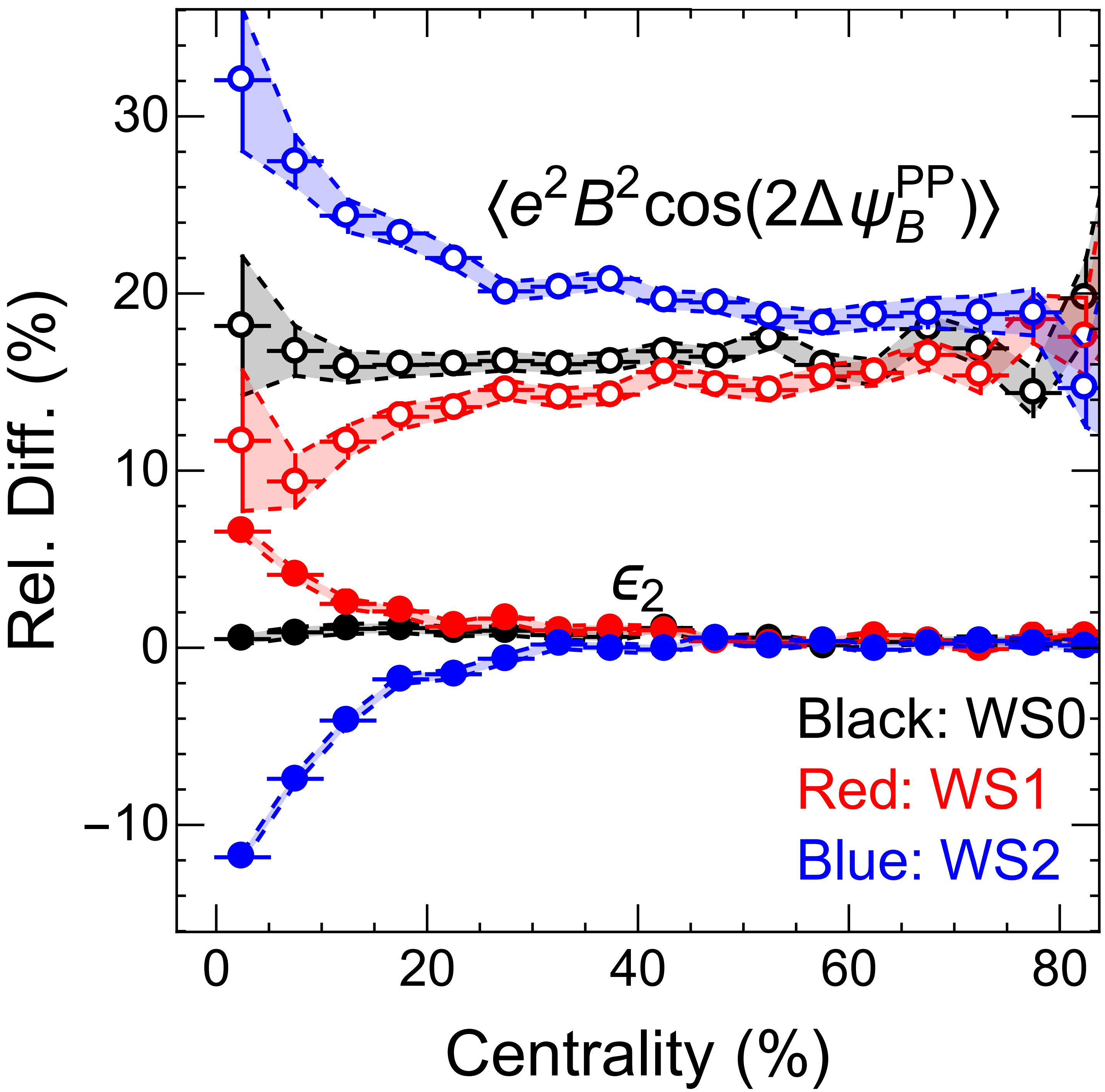
Non-CME Background

Different deformation schemes:

black - no deformation (both are spheric)

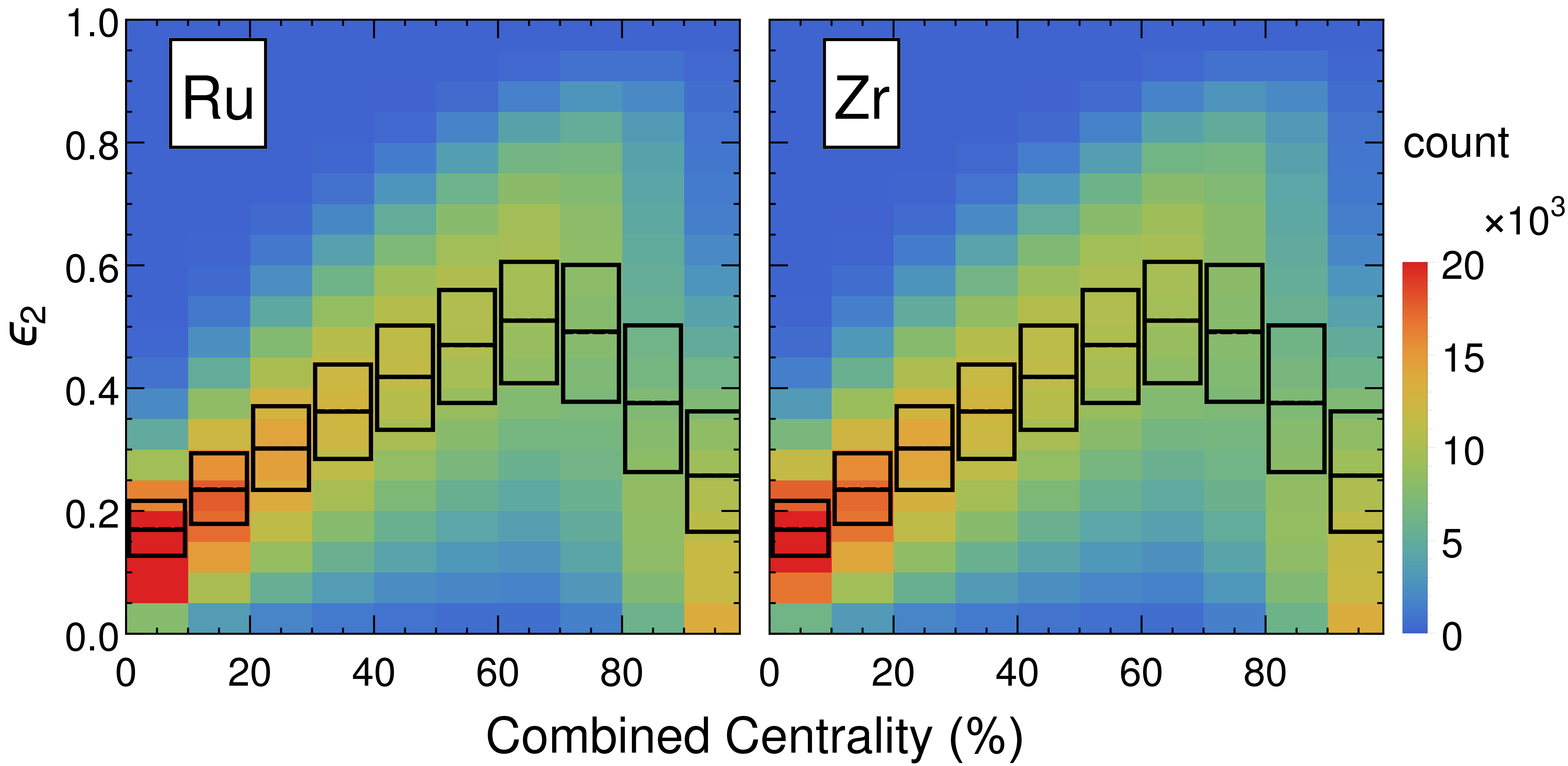
red - Ru is more deformed

blue - Zr is more deformed



Several percent relative difference in ellipticity

CME in IsoBar System



Joint cut of **Multiplicity⊗Eccentricity** ⇒ same background!

CME in IsoBar System

Different deformation schemes:

black - no deformation (both are spheric)

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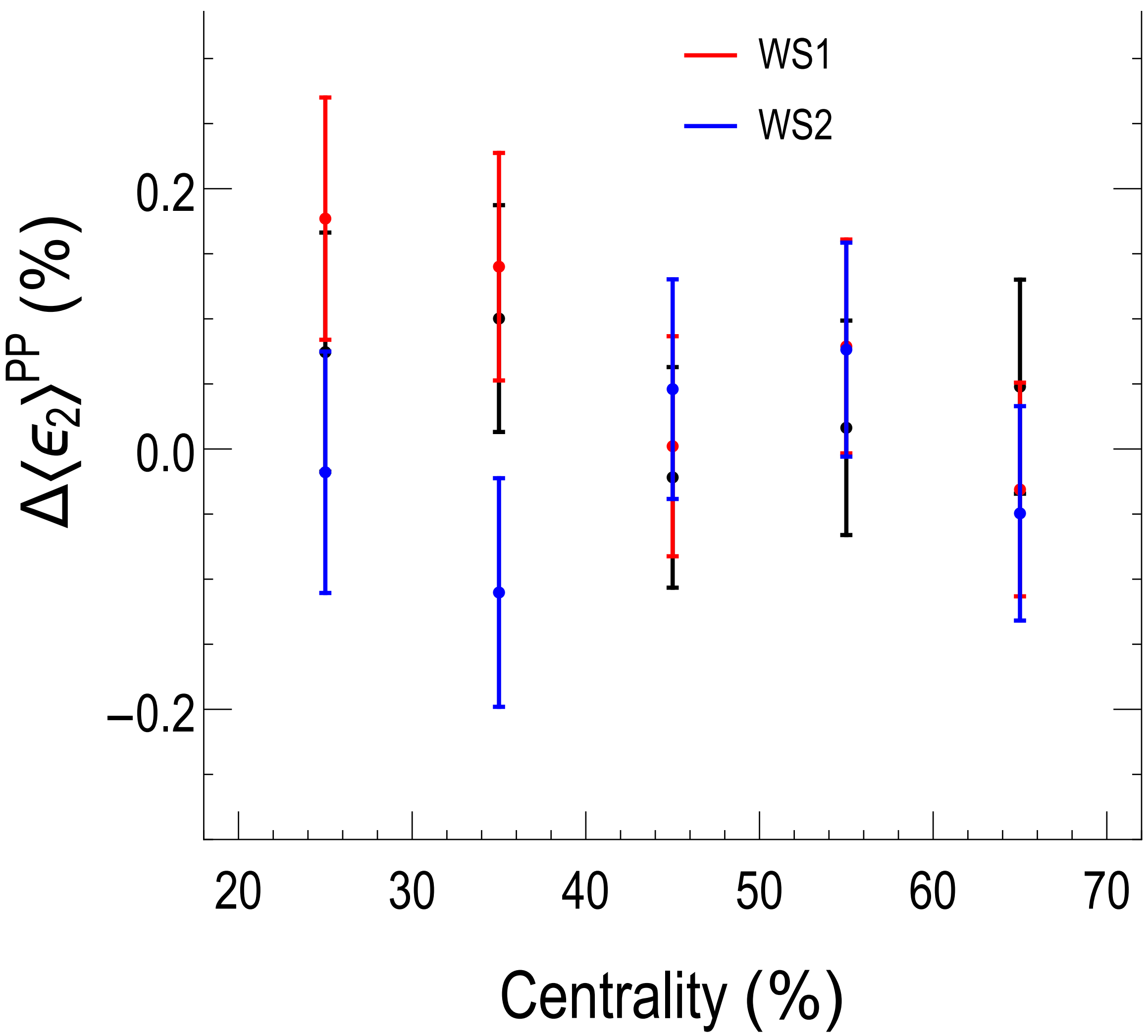
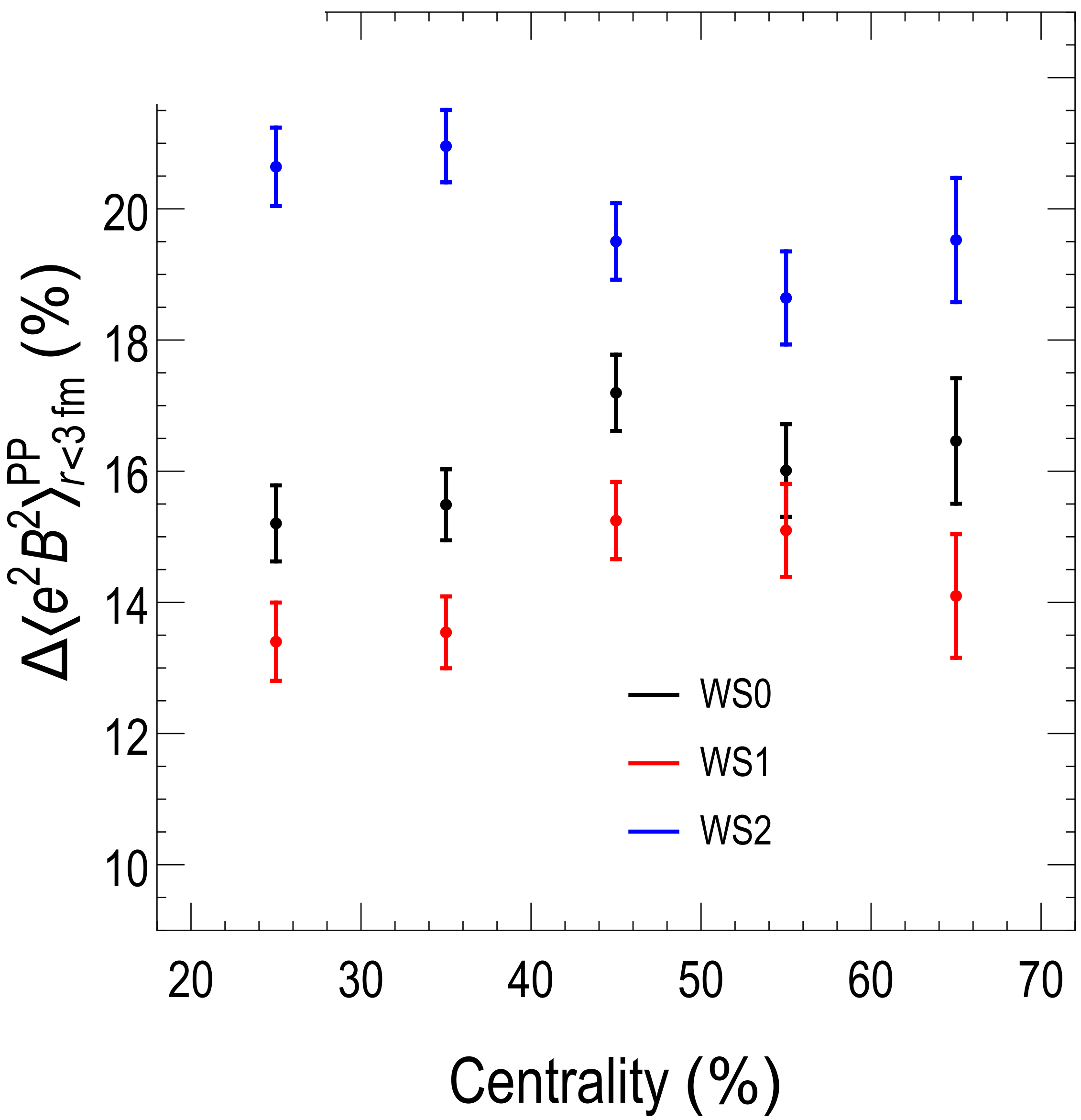




|background difference| < 0.5%

|signal difference| ~ 15%

CME in IsoBar System

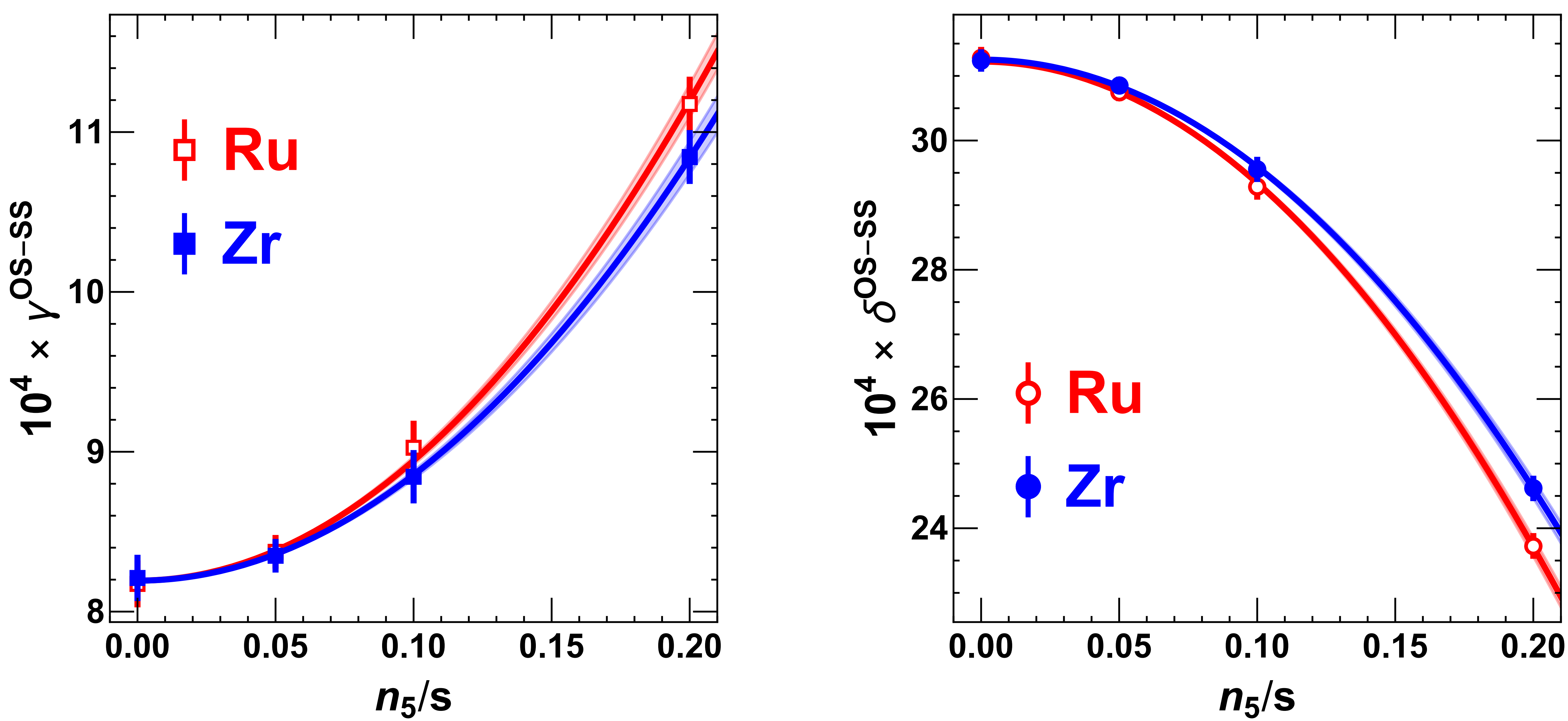
$-1 < \eta < 1$

$64 < N_{ch} < 96$

$0.05 < v_2^{ref} < 0.25$

Statistics: 10^7 events in AVFD simulation

~ 3×10^8 events in experiment



in collaboration with H.Zhang, J.Liao & D.Hou, **in final preparation**

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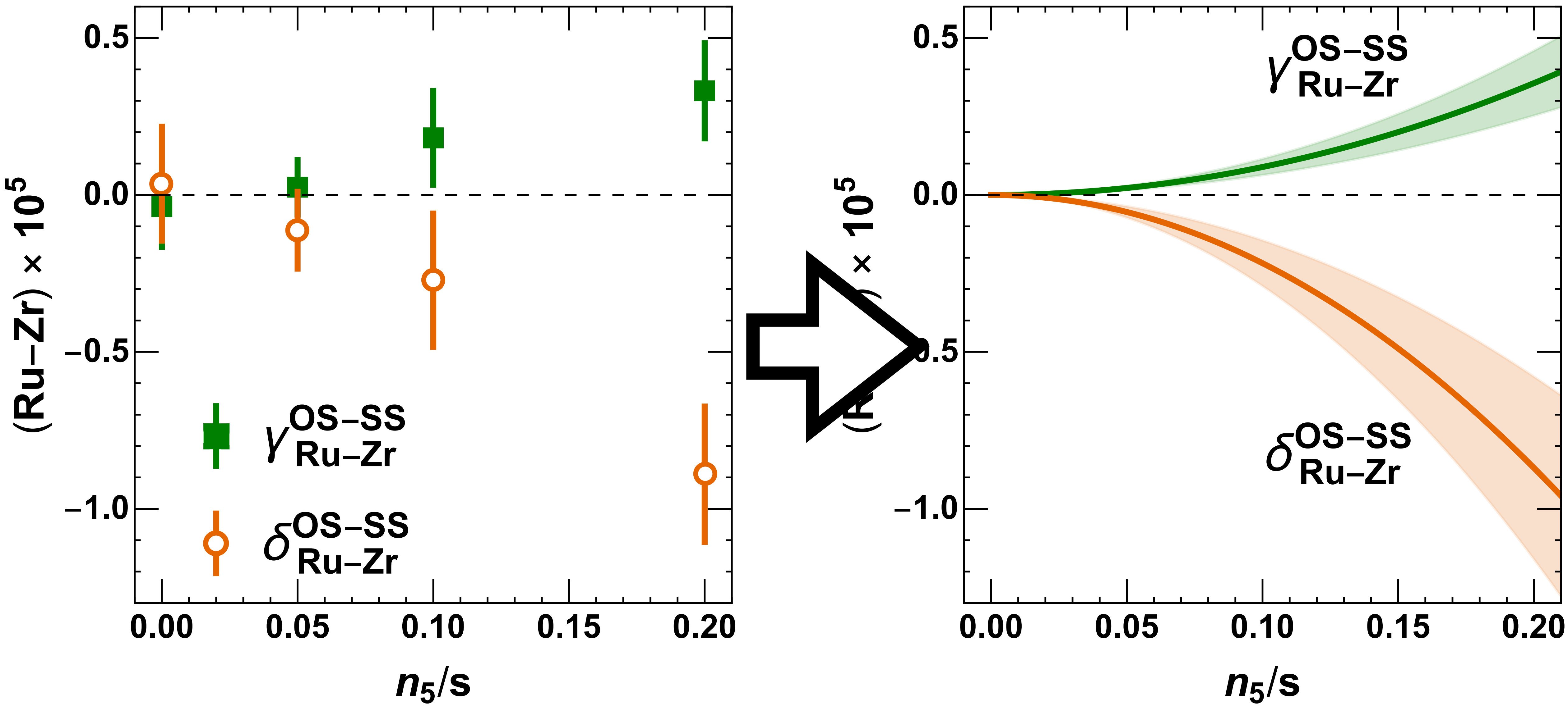

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Summary & Outlook

EBE-AVFD for the Isobars:

1) (N_{ch} , v_2) joint-cut eliminates difference in non-CME bkg.

2) Absolute differences in correlators are very **sensitive to CME**!

3) Decisive probe of topological charge transition

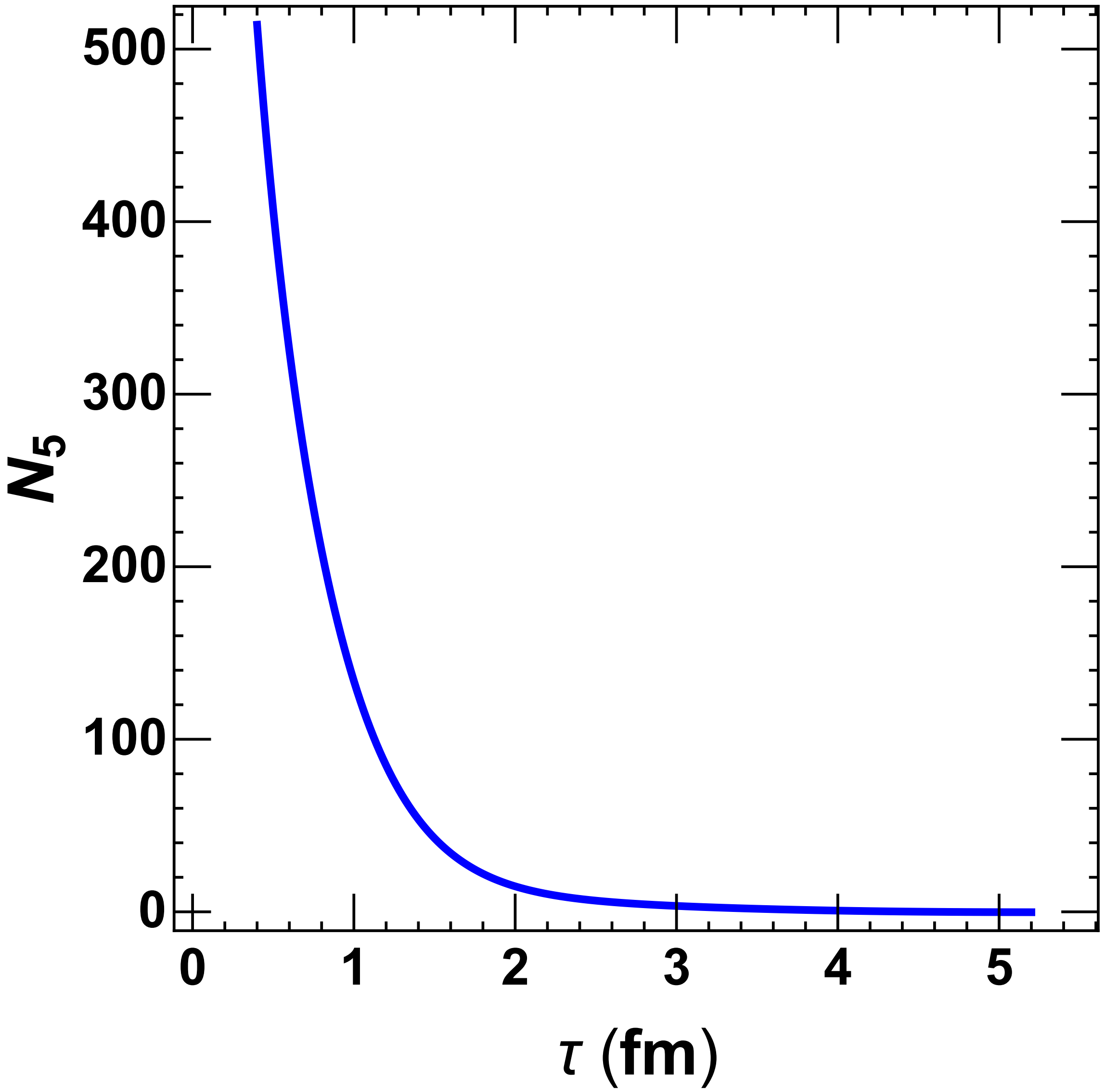
Further Development of the AVFD framework:

1) Damping of axial charge

2) More realistic background (Local Charge Conservation)

3) 3+1Hydro with non-trivial vorticity and rapidity dependence

Damping of Axial Charge



$$D_\mu J_5^\mu = -\frac{n_5}{\tau_{\rm CS}}$$

$$\tau_{\rm CS} = \frac{\chi T}{30\alpha_s^4 T^4 + 0.013 m_{\rm quark}^2 T^2}$$

For more details about damping, see *Shu Lin*'s talk on Thursday

in collaboration with A.Huang, S.Lin, J.Liao, X.Zhu & L.He, **in progress**

Implementing LCC

take neutral systems (μ = 0) as example

In the current particle sampler,
two ways to sample particles in a single FOHS cell:

(a) grand-canonical ensamble (both N_{net}, E fluctuate)
N_{pos} ~ Poisson Distribution with mean $\langle N \rangle = N_{thermal}$
N_{neg} ~ Poisson Distribution with mean $\langle N \rangle = N_{thermal}$
N_{pos} and N_{neg} are not necessarily the same

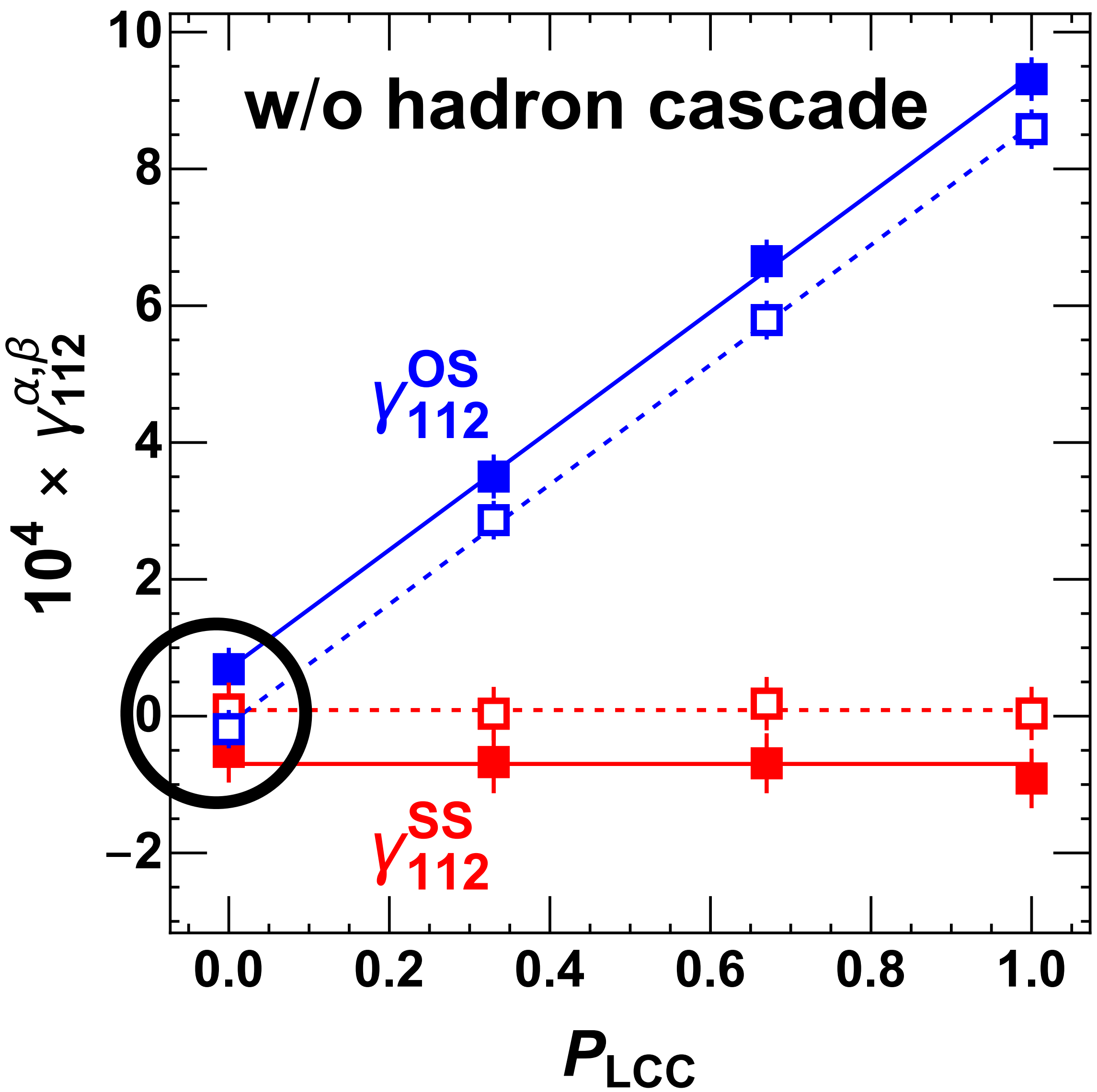
(b) canonical ensamble (N_{net} conserved, E fluctuates)
N_{pos} ~ Poisson Distribution with mean $\langle N \rangle = N_{thermal}$
$N_{neg} = N_{pos}$ B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378

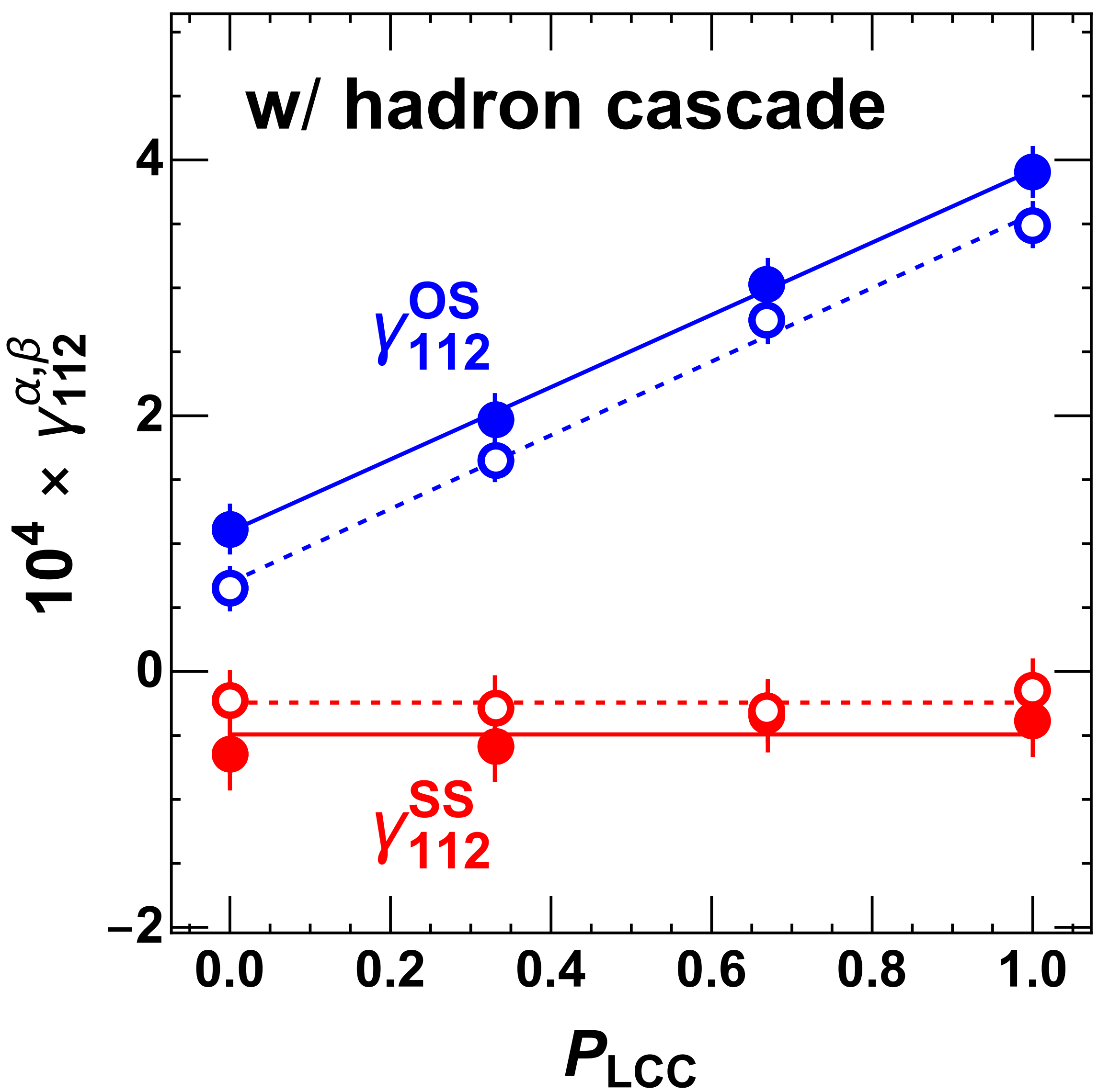
A hybrid approach?

c) for every cell, randomly choose (a) or (b), according to given acceptance probability P_{LCC} being a parameter ∊ [0,1].

Correlators with LCC

solid: w/ CME
dash: w/o CME





$$\gamma_{112} = \langle \cos(\phi_i+\phi_j-2\psi_{EP}) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

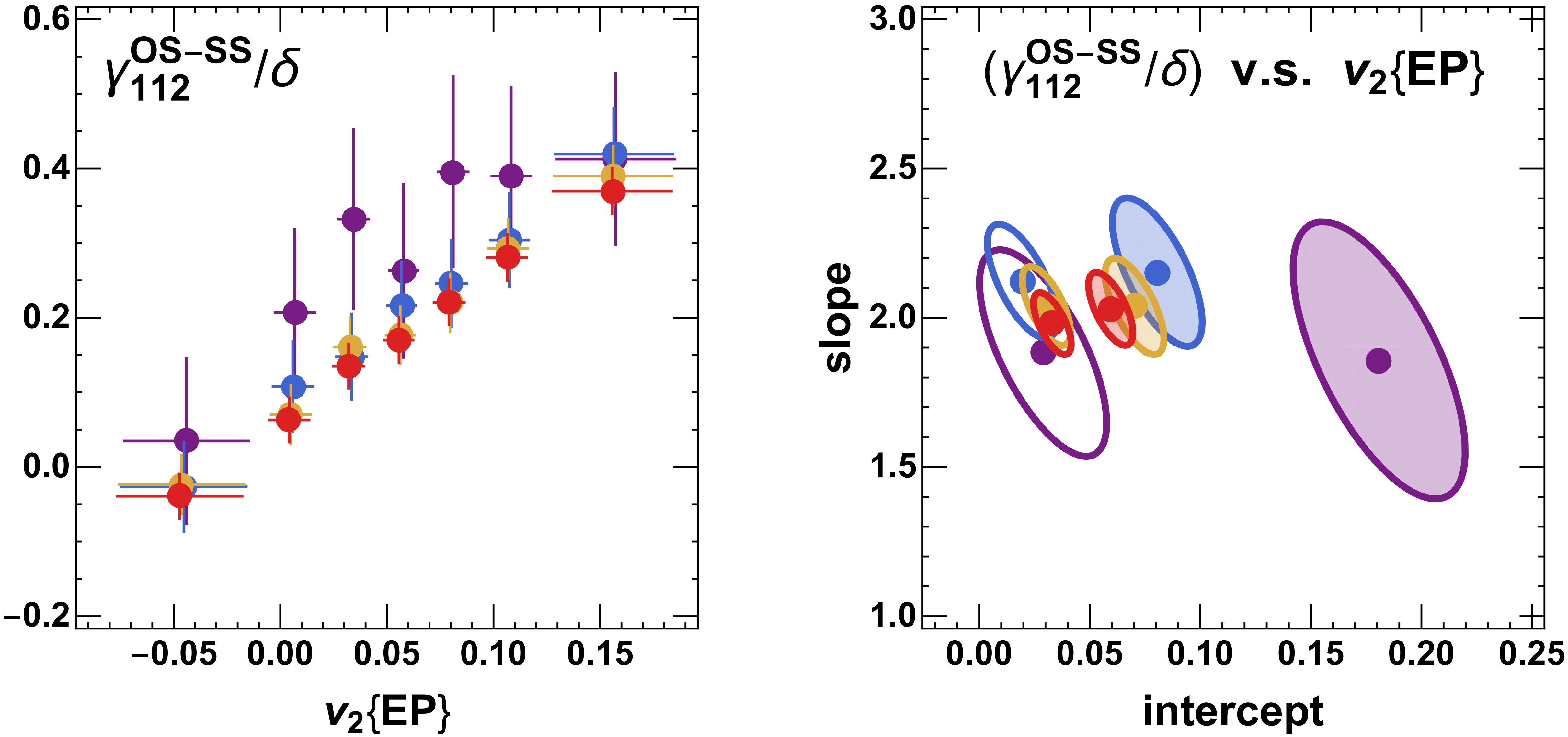
Event-Shape Engineering (with LCC)

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

$\delta = F + H$

filled: w/ CME
open: w/o CME

P_{LCC} = 0.00, 0.33, 0.67, 1.00



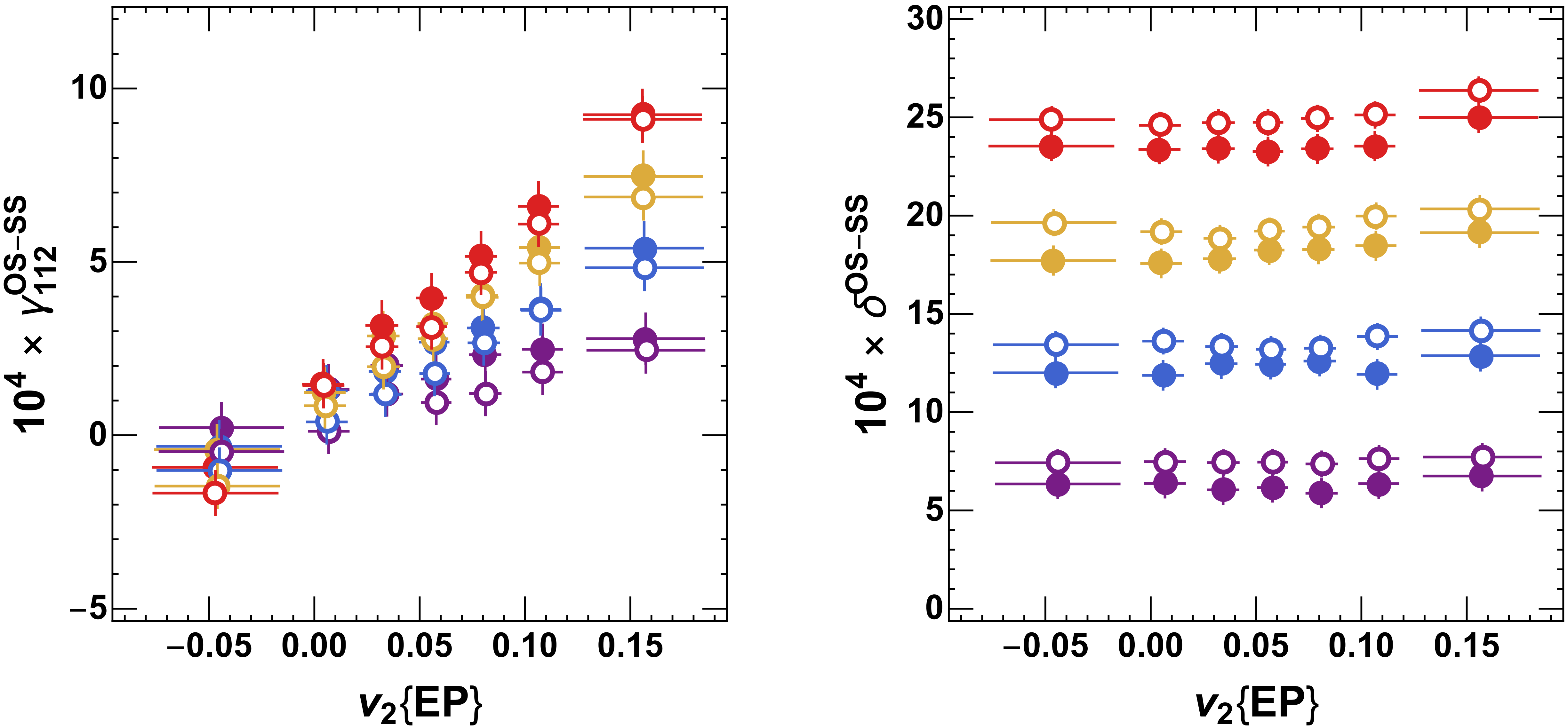
THANK YOU!

BACKUP SLIDES

Correlators with LCC

filled: w/ CME
open: w/o CME

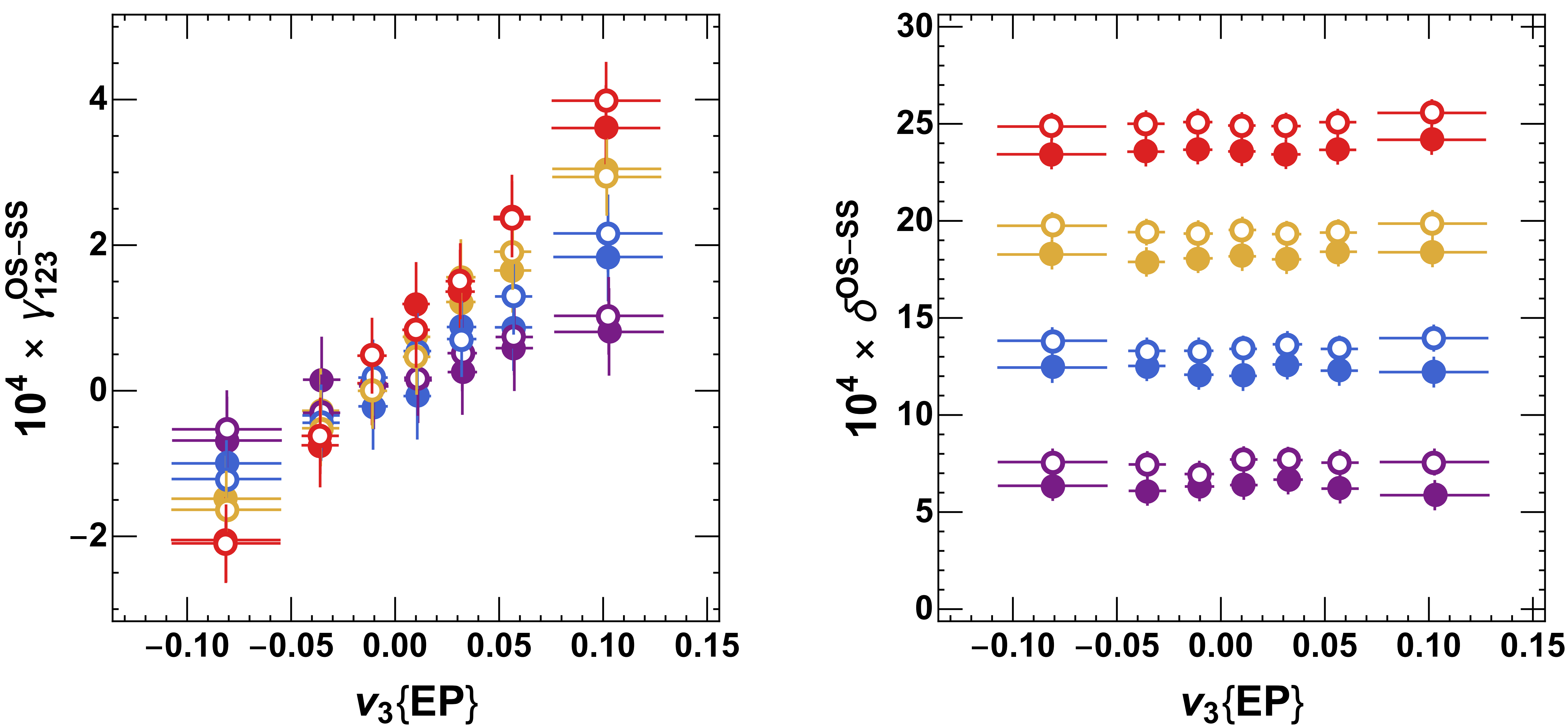
P_{LCC} = 0.00, 0.33, 0.67, 1.00



Correlators with LCC

filled: w/ CME
open: w/o CME

P_{LCC} = 0.00, 0.33, 0.67, 1.00



$$\gamma_{123} = \langle \cos(\phi_i + 2\phi_j - 3\psi_{EP,3}) \rangle = \langle \cos\Delta\phi_i \cos 2\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin 2\Delta\phi_j \rangle$$

Event-Shape Engineering (with LCC)

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

$\delta = F + H$

filled: w/ CME
open: w/o CME

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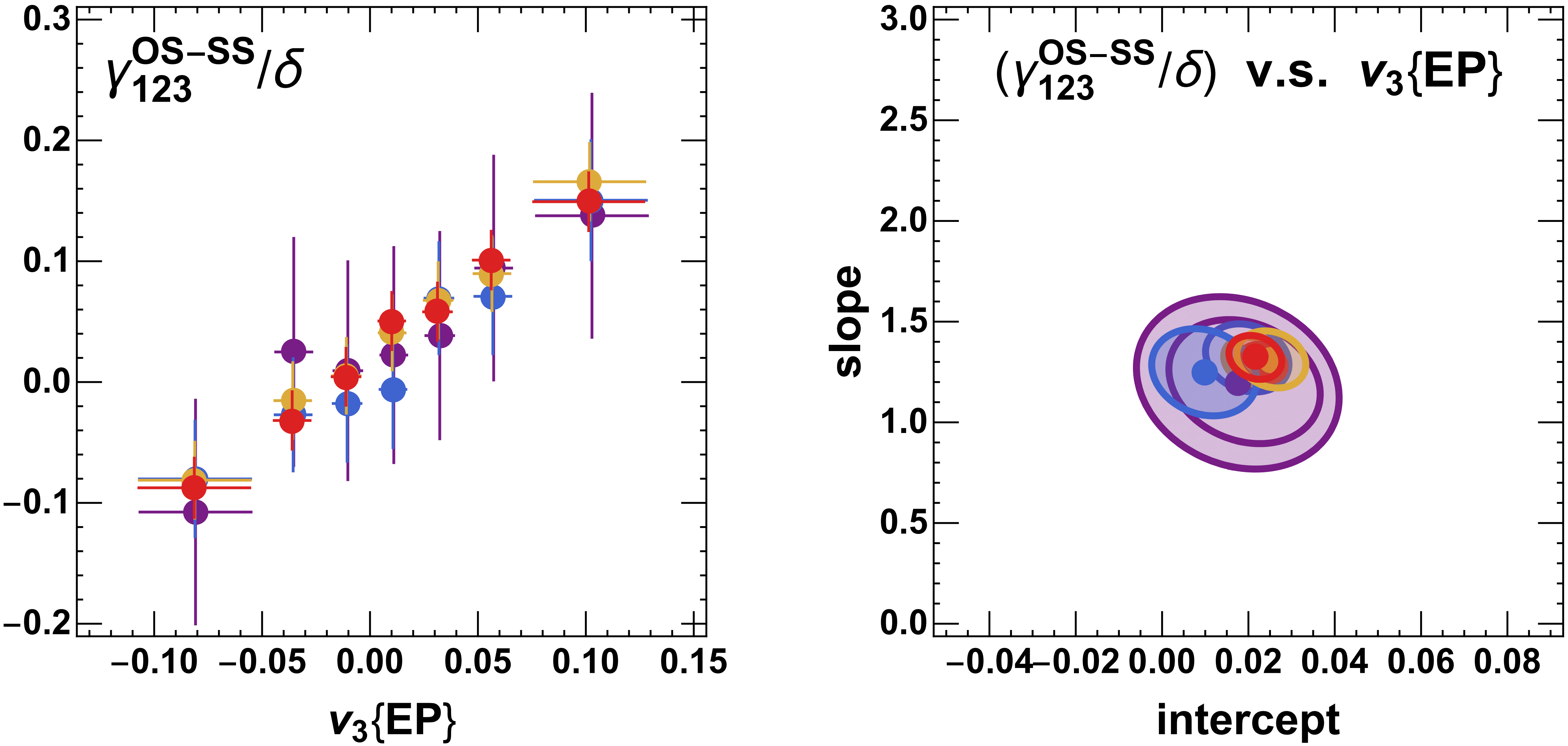
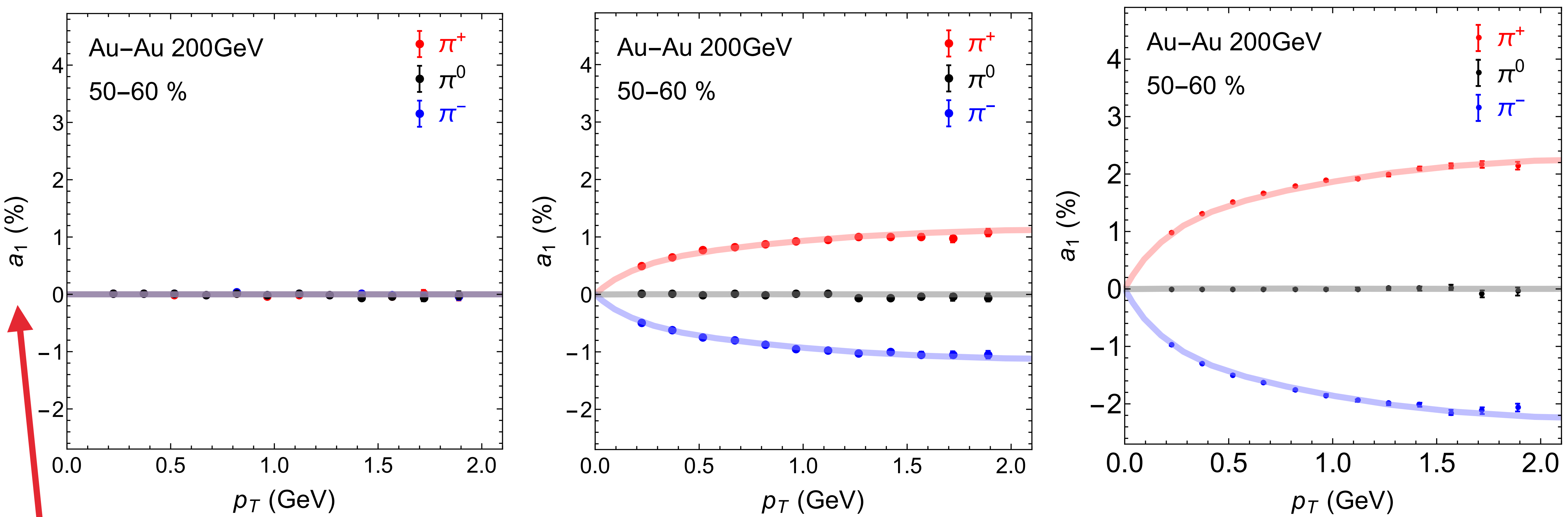


CME: Event-Averaged v.s. Event-by-Event

dots: E-by-E
curves: smooth

Au-Au @ 200GeV
50-60%



n_A/s=0.0

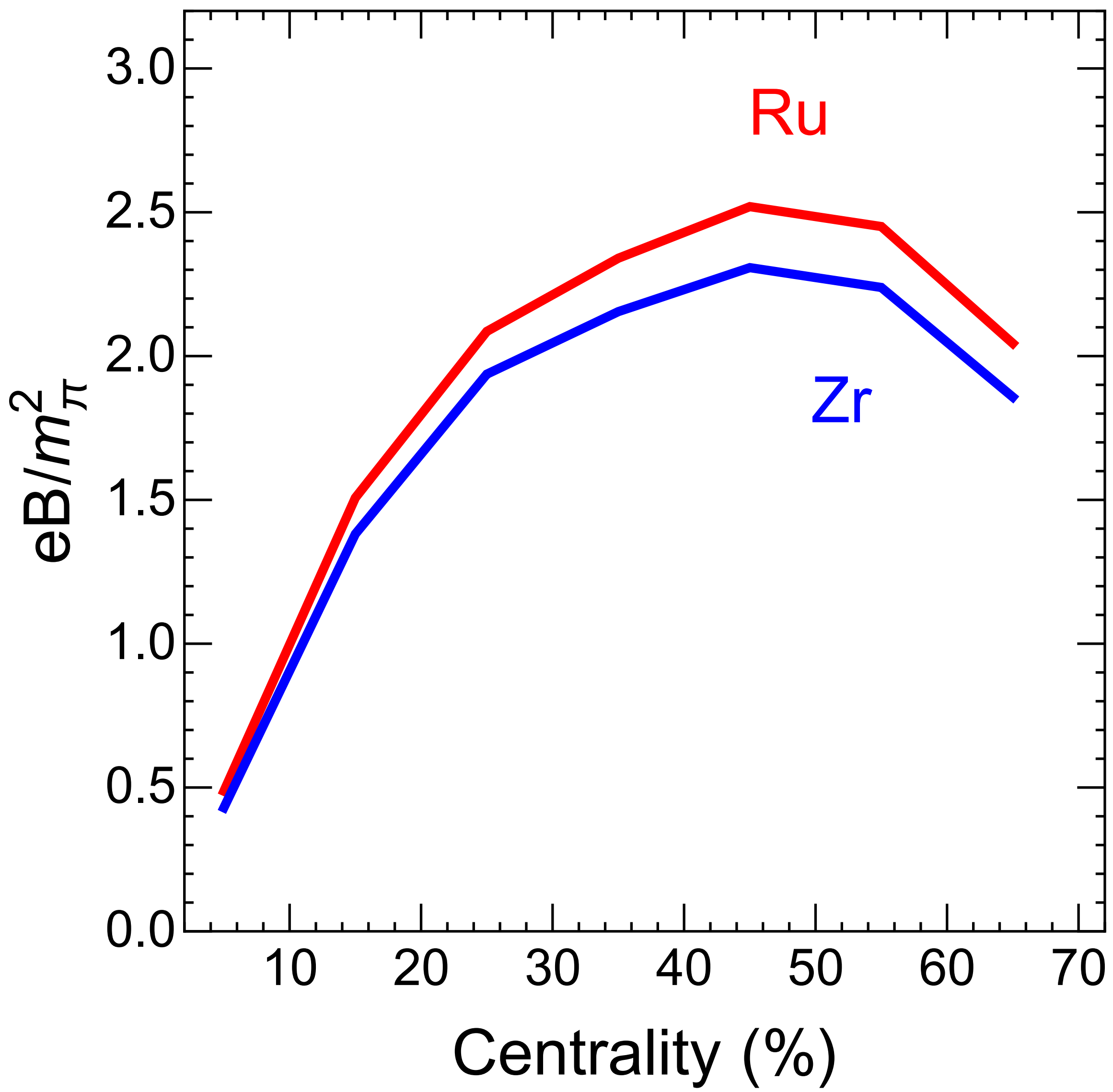
n_A/s=0.1

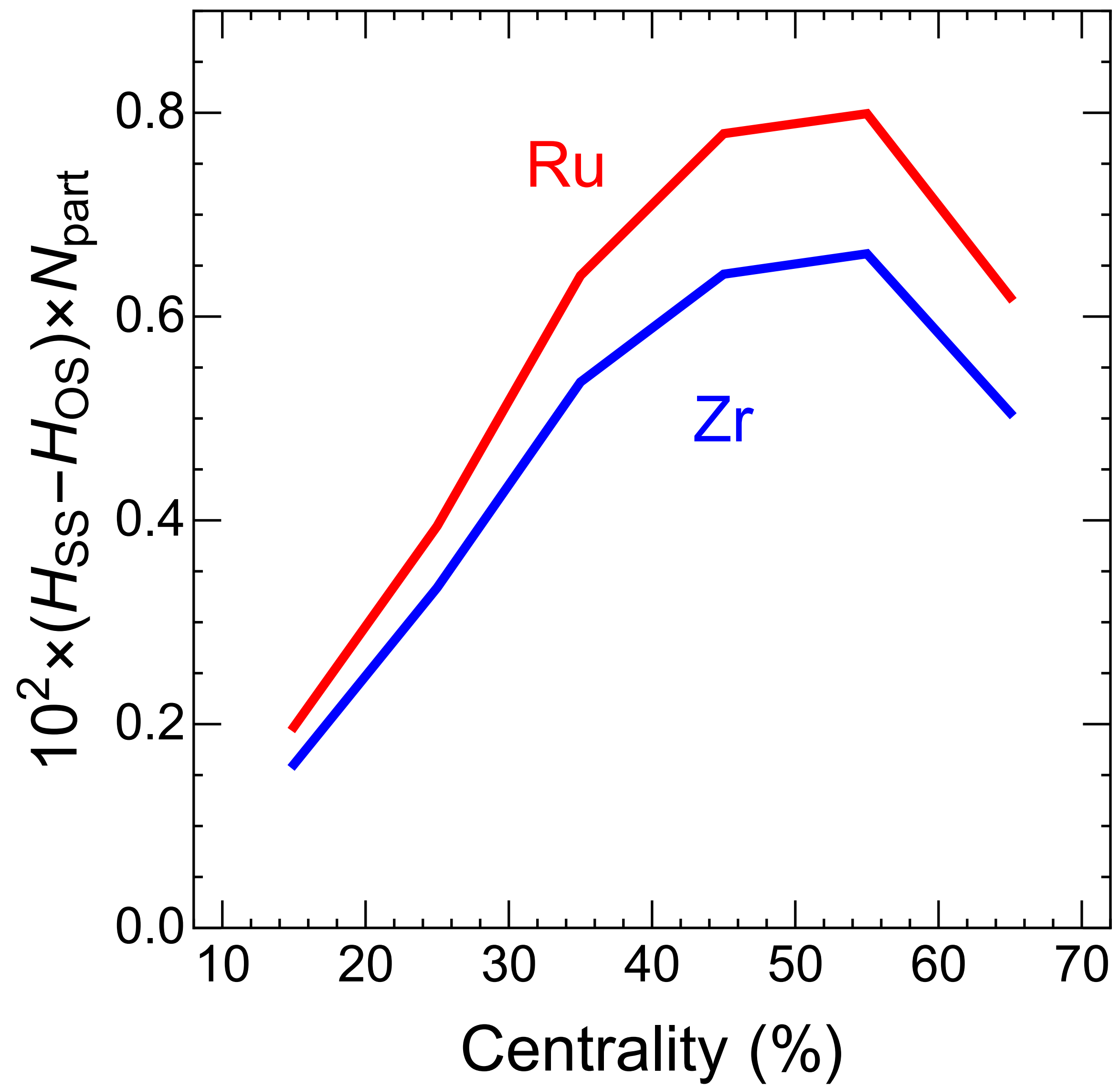
n_A/s=0.2

CME charge separation

chirality imbalance

IsoBar CME from smooth AVFD simulation



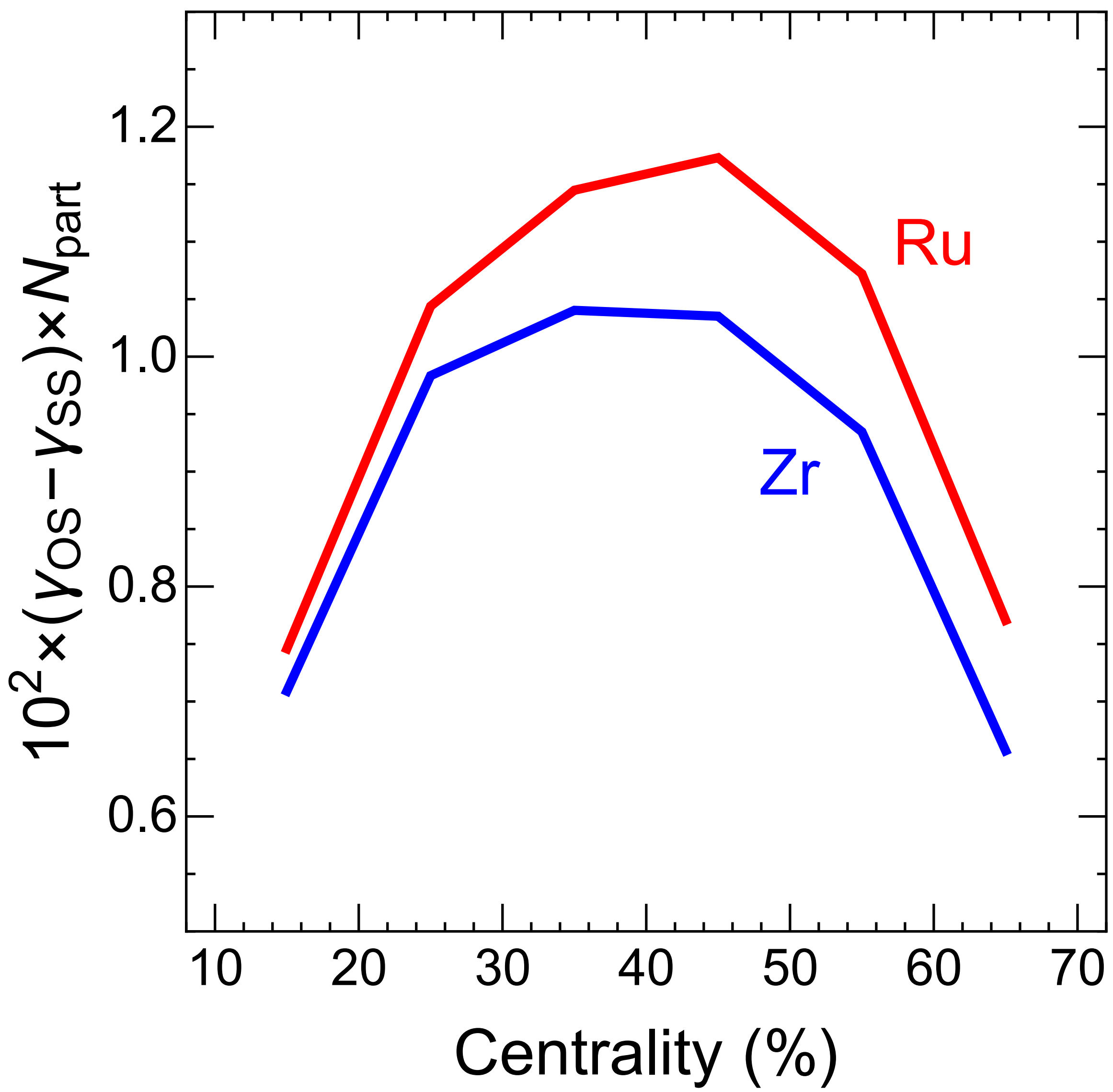


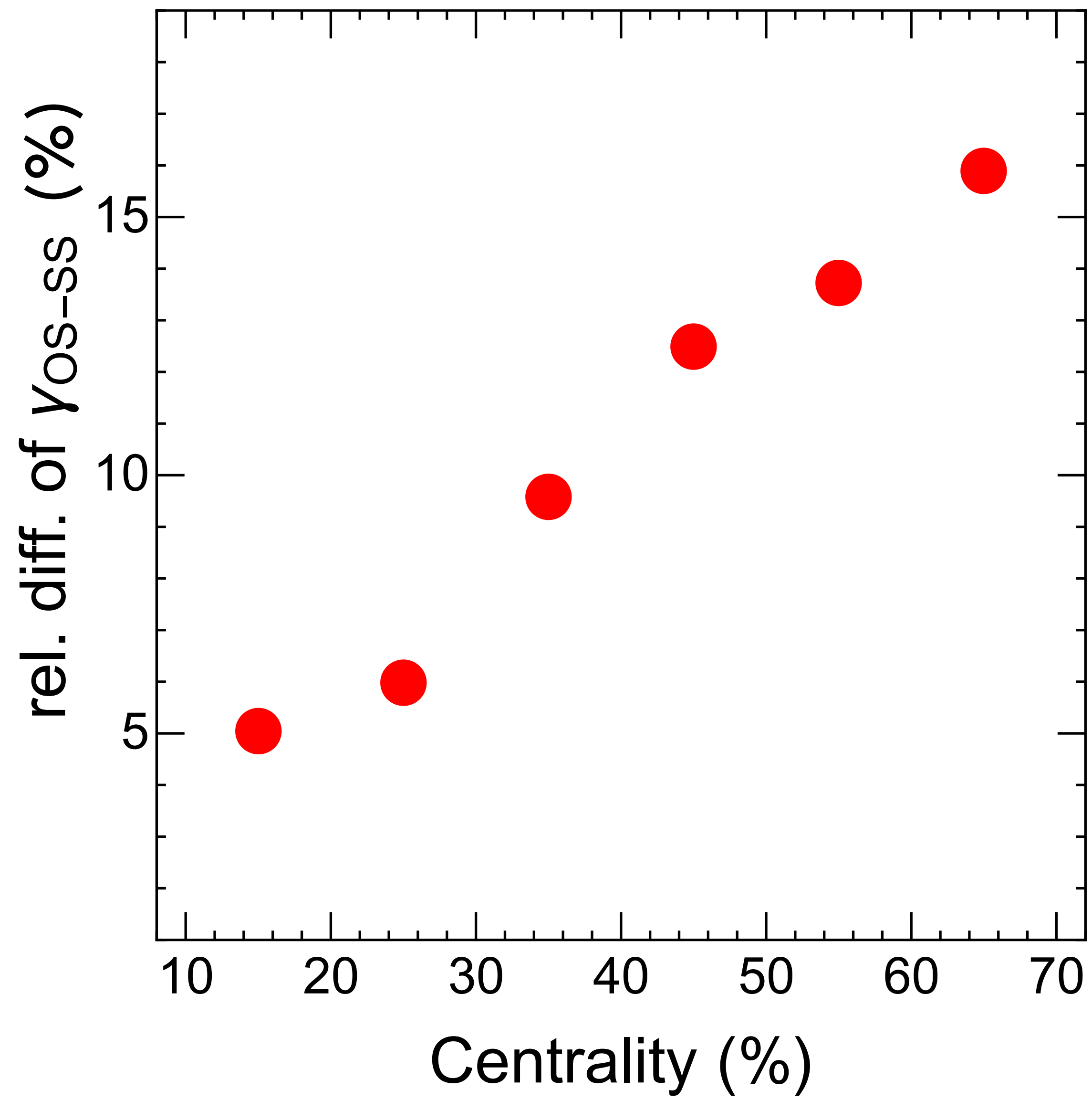
B field projected w.r.t. Participant Plane

SS, Y.Jiang, E.Lilleskov & J.Liao, **Annals Phys. (2018)**

IsoBar CME from smooth AVFD simulation

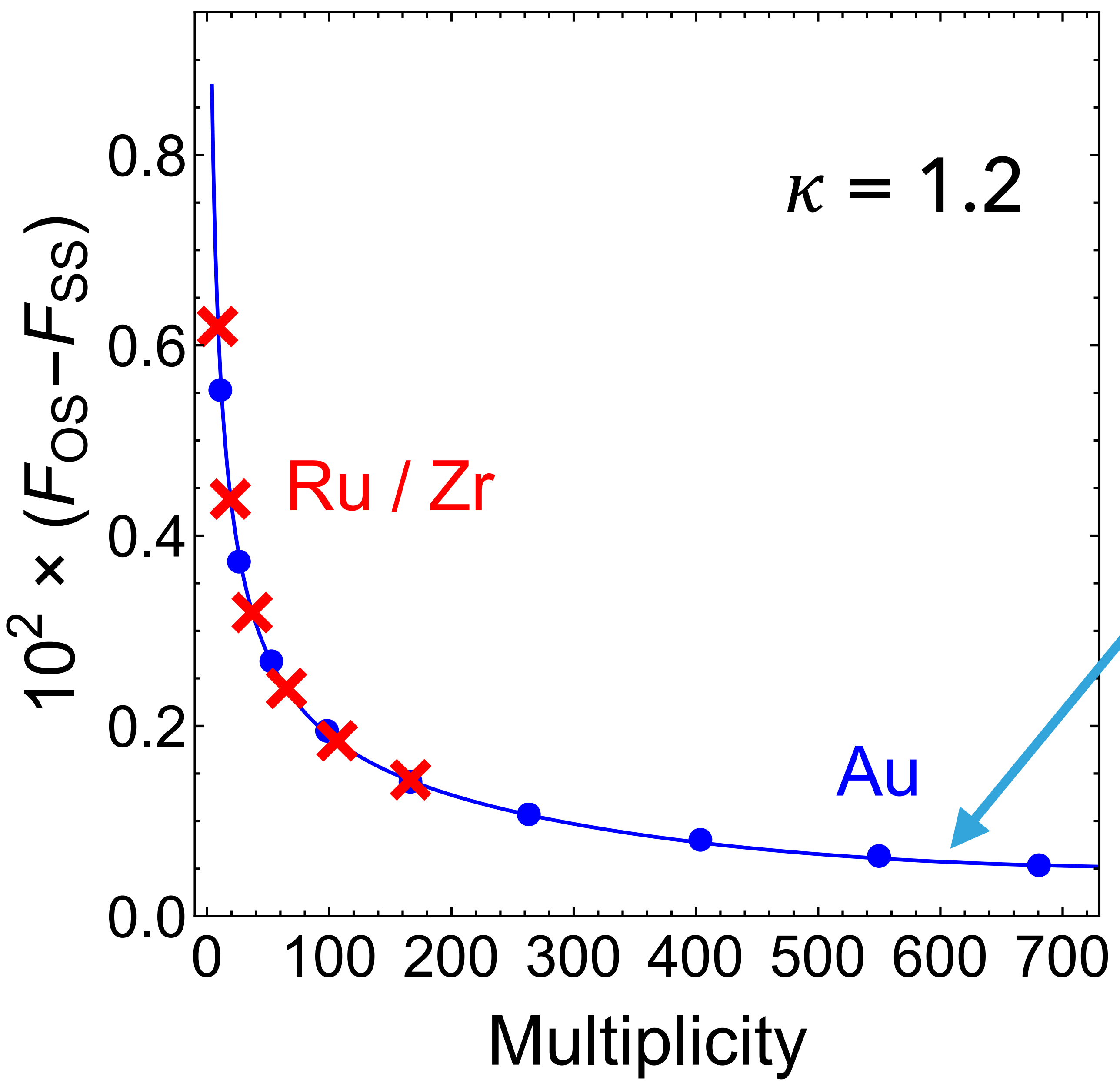
$$\gamma = \kappa\, v_2\, F - H$$





SS, Y.Jiang, E.Lilleskov & J.Liao, **Annals Phys. (2018)**

Estimation Of IsoBar Bulk Background



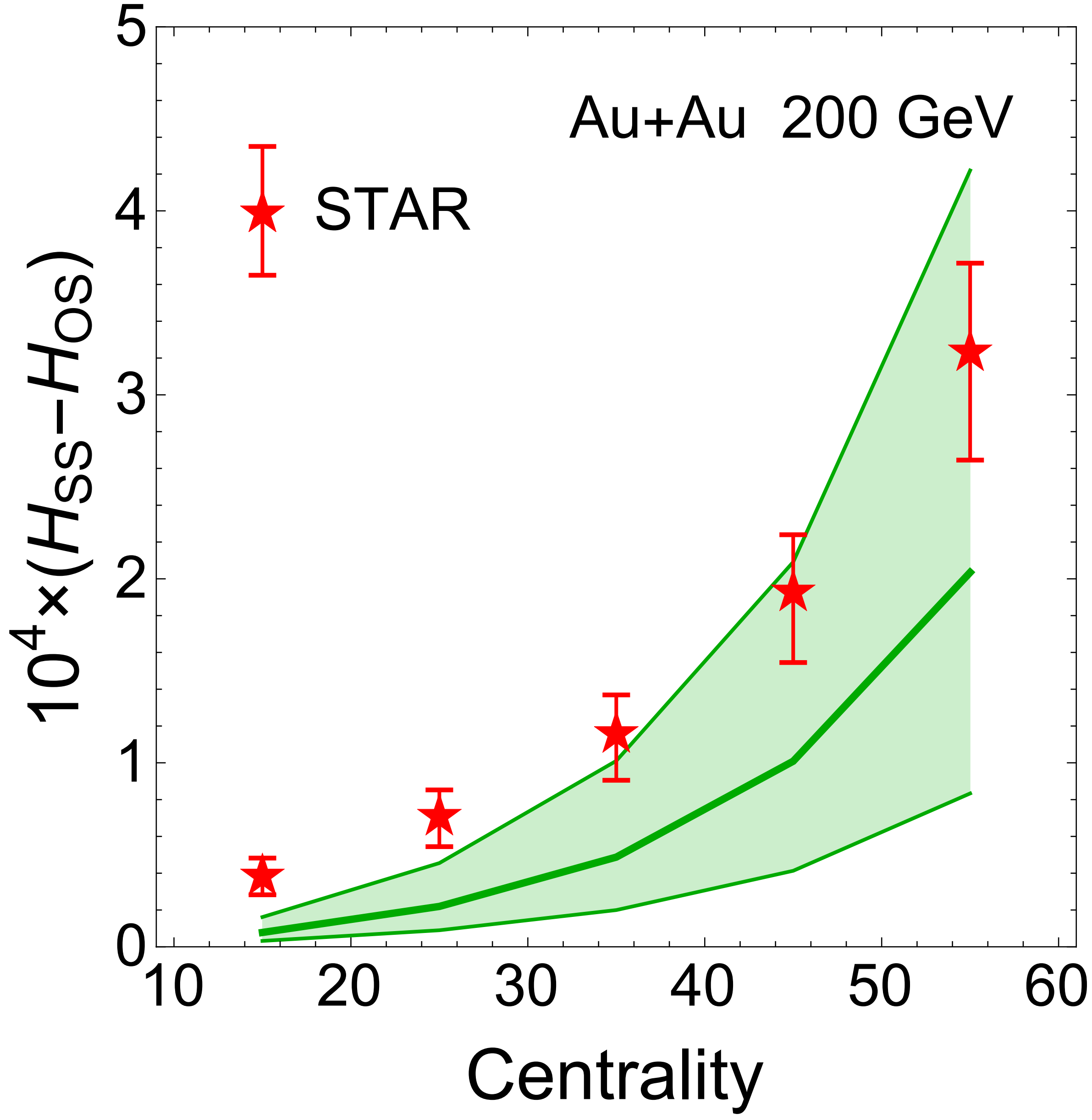
$$\gamma = \kappa \, v_2 \, \mathbf{F} - \mathbf{H}$$

Fitting Formular:

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

SS, Y.Jiang, E.Lilleskov & J.Liao, **Annals Phys. (2018)**

CME in Au-Au Collisions



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

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

SS, Y.Jiang, E.Lilleskov & J.Liao, **Annals Phys. (2018)**