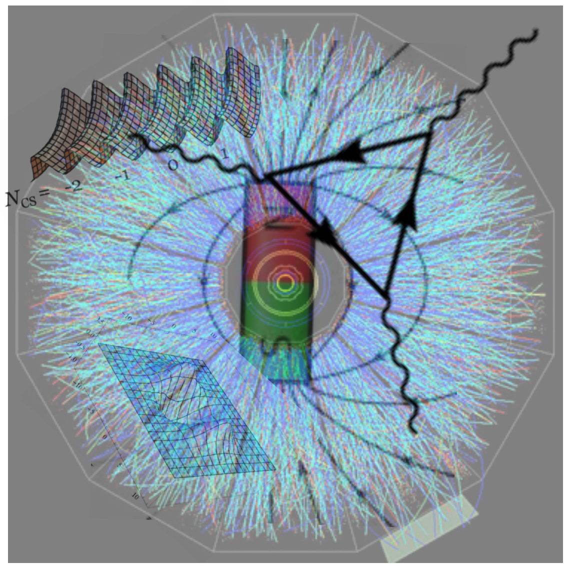
Chirality 2018 @ GGI, Florence Mar. 22, 2018

Anomalous-Viscous Fluid Dynamics (AVFD) For the Anomalous Chiral Transport in Heavy Ion Collisions



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by U.S. NSF & DOE

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BEST COLLABORATION

Chinese Physics C Vol. 42, No. 1 (2018) 011001

arXiv:1611.04586

Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics*

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Anomalous Chiral Transport in Heavy Ion Collisions from Anomalous-Viscous Fluid Dynamics

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arXiv:1711.02496

Shuzhe Shi (PhD @ IUB)

Other collaborators: Yin Jiang (Beihang), Yi Yin (MIT), Elias Lilleskov (REU);

Hui Zhang, Defu Hou (CCNU).

Exciting Progress: See Recent Reviews

Progress in Particle and Nuclear Physics 88 (2016) 1–28

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

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Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

Outline

- Introductory Discussions
- The AVFD Framework
- Quantitative Results from AVFD
- EBE-AVFD
- Summary & Outlook

Introductory Discussions

Chiral Symmetry & SSB

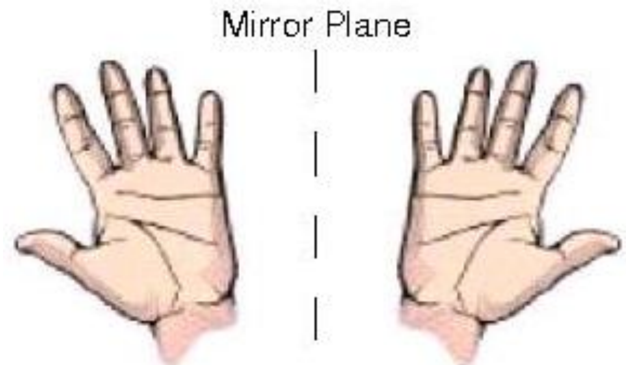
Classical symmetry:

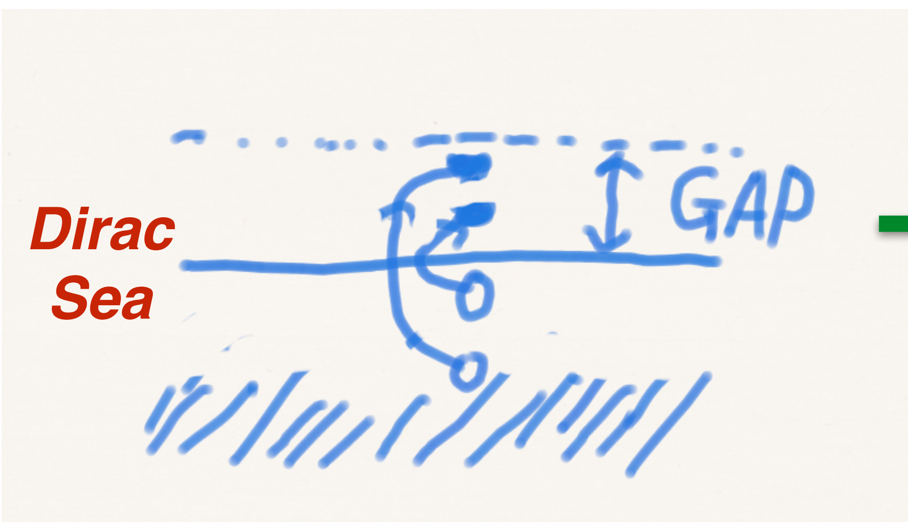
$$\mathcal{L} = i\bar{\Psi}\gamma^{\mu}\partial_{\mu}\Psi$$

$$\mathcal{L} \to i\bar{\Psi}_L\gamma^{\mu}\partial_{\mu}\Psi_L + i\bar{\Psi}_R\gamma^{\mu}\partial_{\mu}\Psi_R$$

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_{\mu}J_5^{\mu} = 0$$





Constituent mass

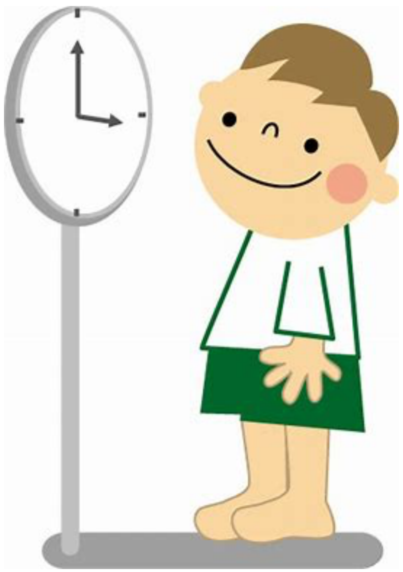
$$M = m - 2G\langle\bar{\psi}\psi\rangle$$

Lagrangian (SM) mass

Axial symmetry is broken!

The "Origin of Mass"

QCD interactions (via SSB) account for nearly all the visible mass in the Universe.



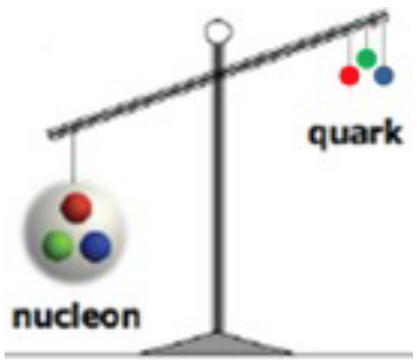
A typical person, say ~ 70 kg
** Reasonable estimate, dominantly H_2O ~ 10 protons + 8 neutrons ~ 28 u quarks + 26 d-quarks*

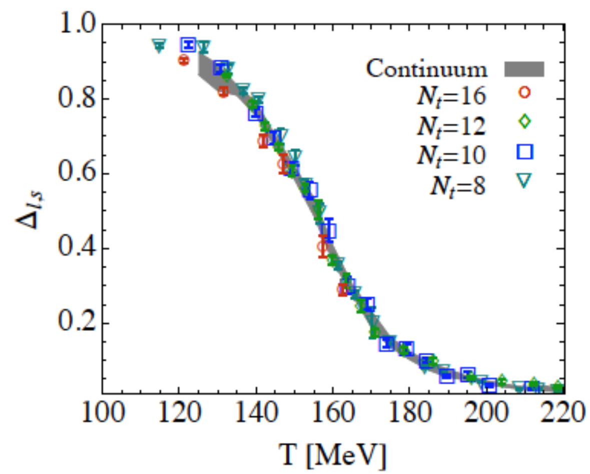
** Mass from Higgs: ~1.7kg (~2.4%)*
** Mass from QCD: ~ 68.3kg (~97.6%)*

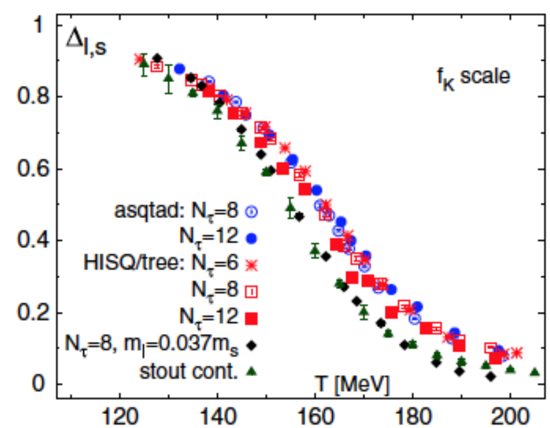
The QCD chiral symmetry is just of paramount importance!

QCD & Chiral Symmetry

**** Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.***



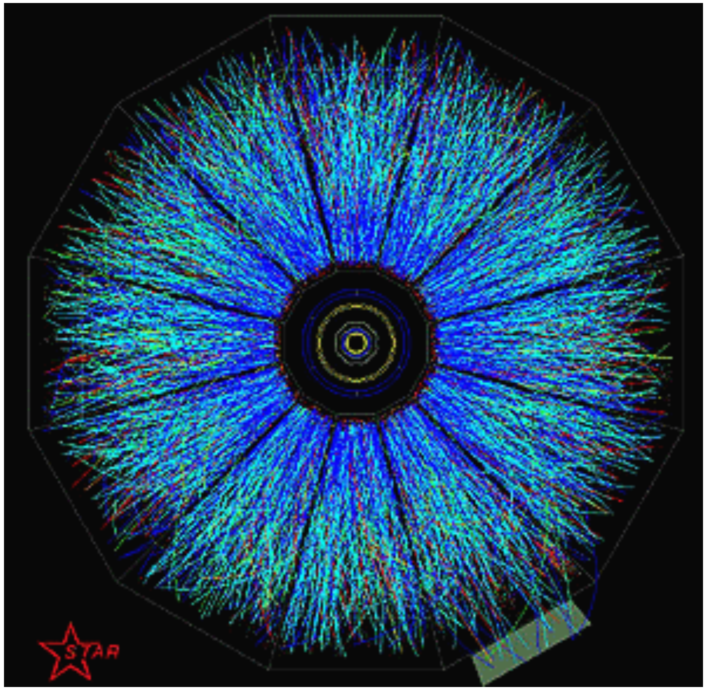


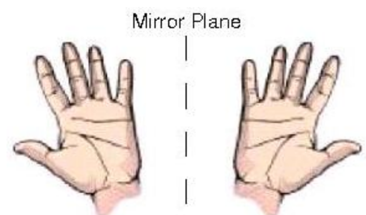


**** A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!***

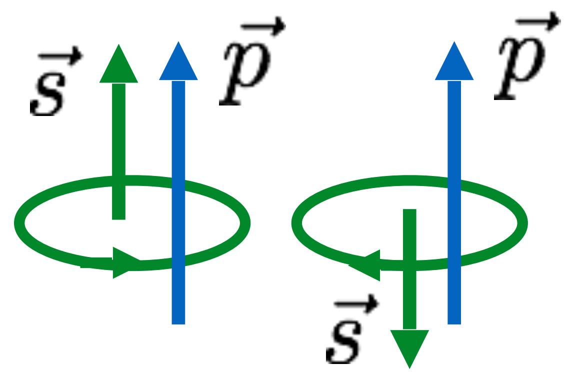
Could we see direct experimental evidence for that?

“Little Bang” in High Energy Nuclear Collision





CHIRAL FERMIONS



*** Quark-gluon plasma (QGP) is created in such collisions.**

*** It is PRIMORDIALLY HOT ~ trillion degrees ~ early universe.**

*** Is chiral symmetry restored?**

Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

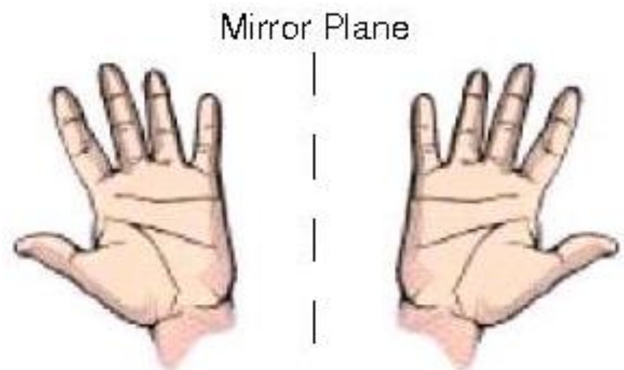
Classical symmetry:

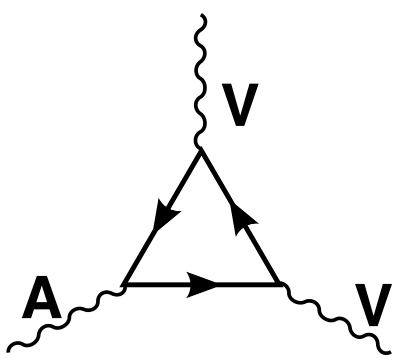
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

$$\mathcal{L} \to i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_\mu J_5^\mu = 0$$





[e.g. pi0—> 2 gamma]

Broken at QM level:

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

* C_A is universal anomaly coefficient

* Anomaly is intrinsically QUANTUM effect

The Chiral Magnetic Effect

Chirality & Anomaly & Topology

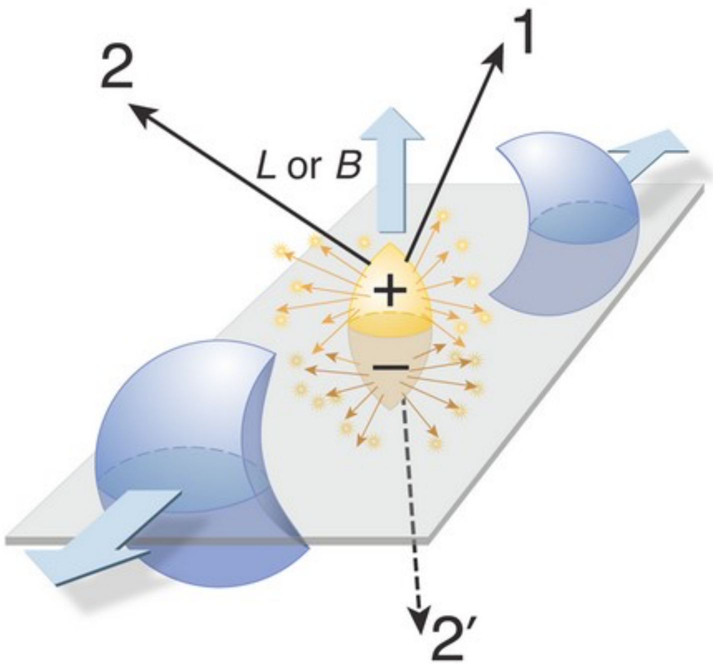
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

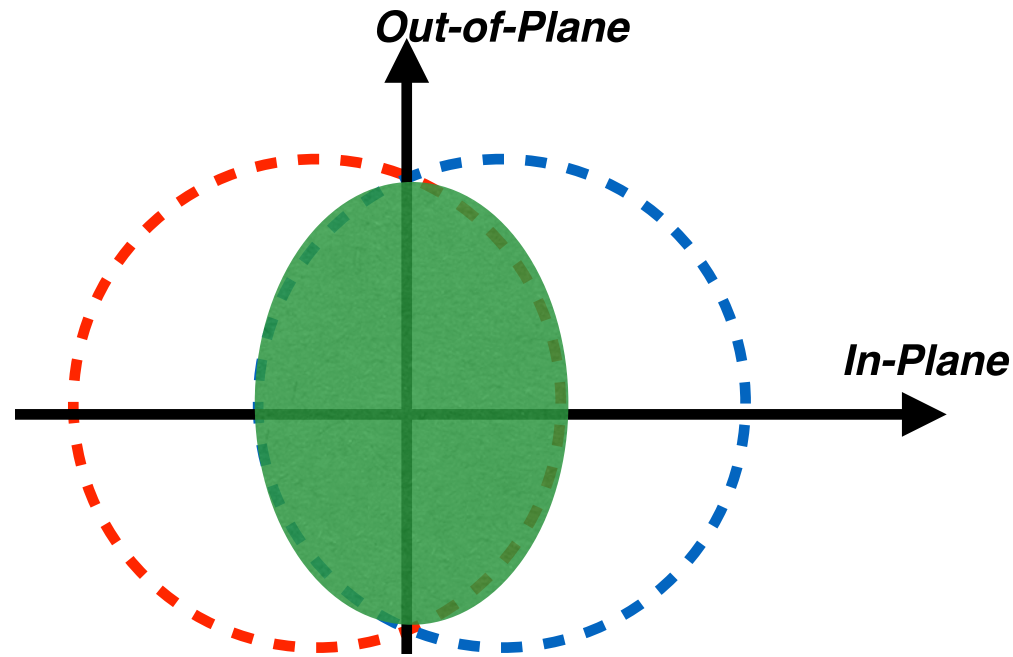
Electric Current

Magnetic Field

Q.M. Transport

New Phase & New Extreme Conditions

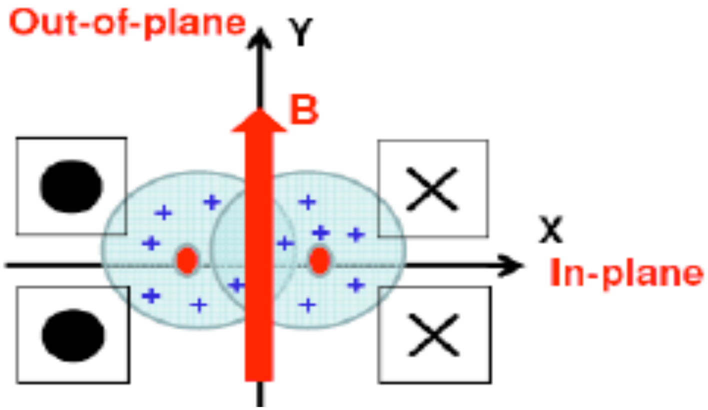


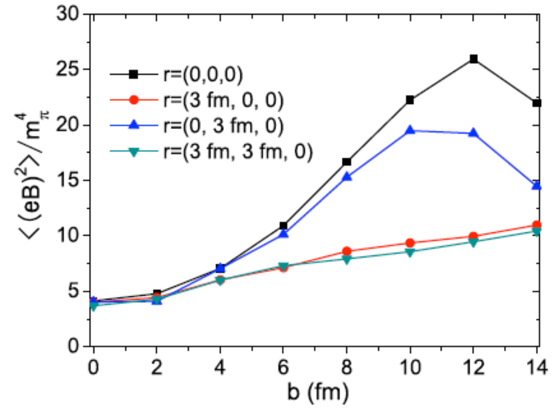


The quark-gluon plasma is a type of CHIRAL MATTER, with (approximately) chiral quarks.

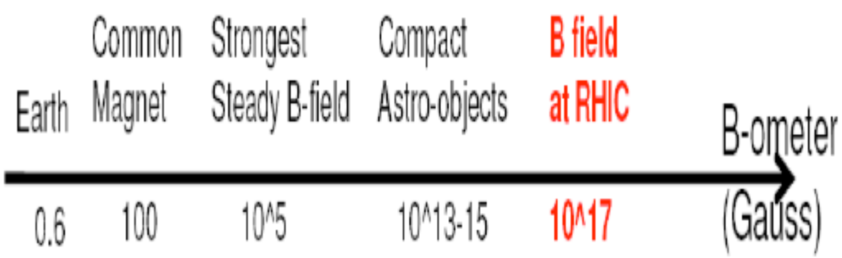
Heavy ion collision environment: extremely strong magnetic field and fluid rotation!

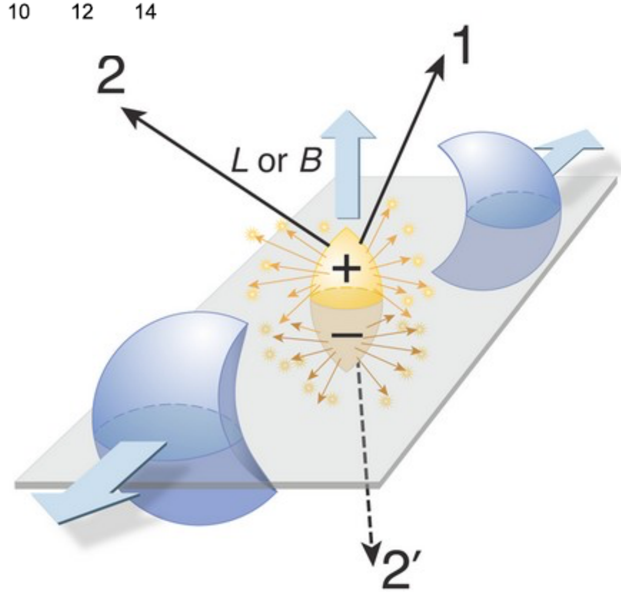
Strong EM Fields in Heavy Ion Collisions





$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$



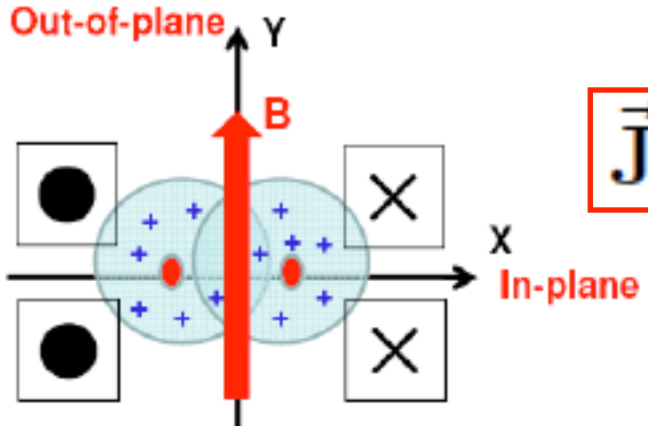


- Strongest B field (and strong E field as well) naturally arises!

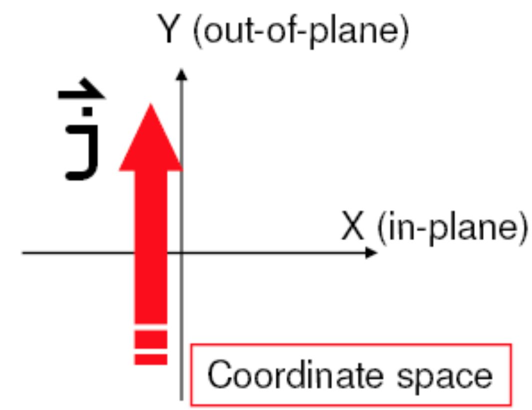
[Kharzeev,McLerran,Warringa; Tuichin; Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; ...]

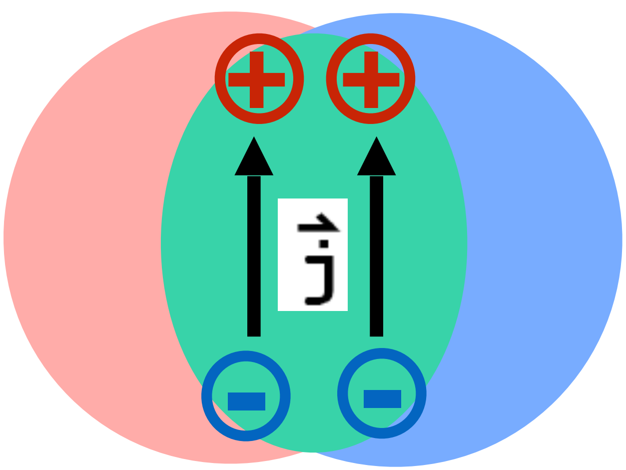
- "Out-of-plane" orientation (approximately)

From CME Current to Charge Separation

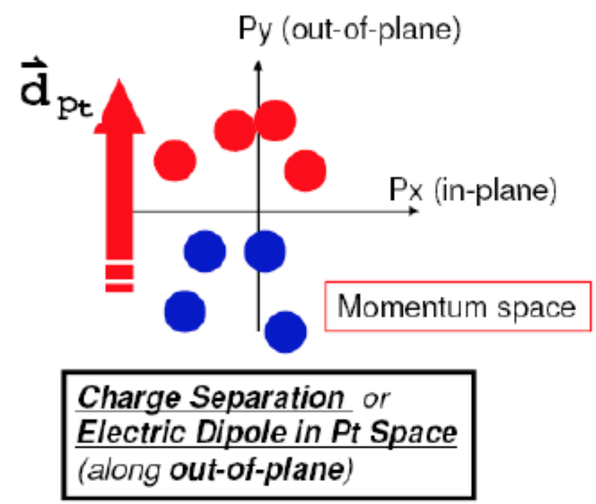


$$\boxed{\vec{J} = \sigma_5 \mu_5 \vec{B}}$$





strong radial blast:
position —> momentum



$$\boxed{\frac{dN_{\pm}}{d\phi} \propto \ldots + a_{\pm} \sin(\phi - \Psi_{RP})}$$

$$< a_{\pm} > \sim \pm < \mu_5 > B$$

[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

Experimental Observable

charge separation $\Rightarrow$ charge dept. two-particle correlation

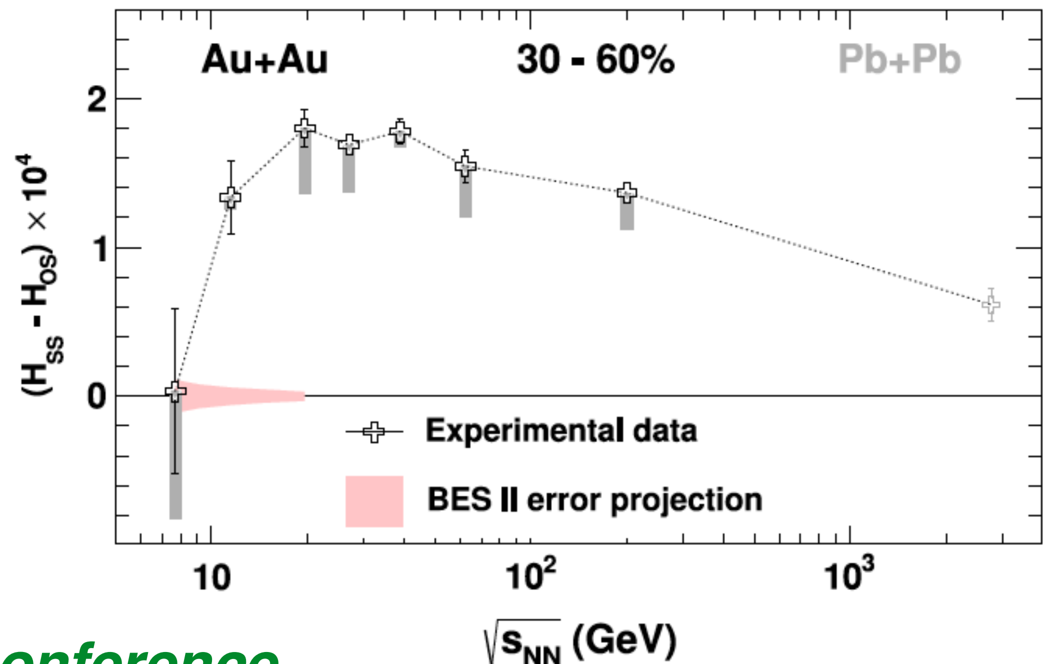
$$\gamma = \langle \cos(\Delta\phi_i + \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle - \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

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

$\gamma = \kappa\, v_2\, F - H$ F: Bulk Background

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

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



Many interesting proposals of new observables!

See many exp. talks at this conference.

Summarizing Exp. Search Status

Main challenge: flow-driven background v.s. CME signal

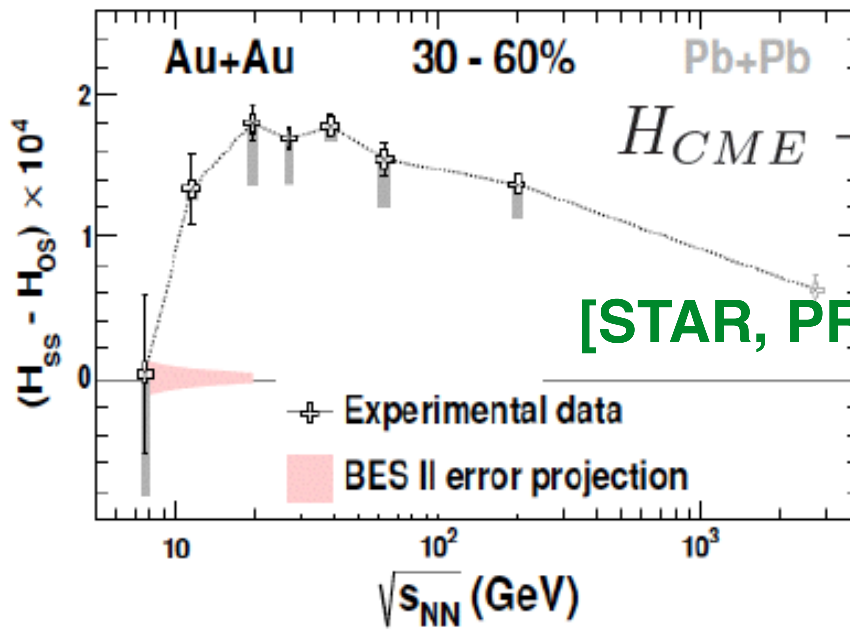
Vary v2 for fixed B:

AuAu v.s. UU;
Varying event-shape;
2-component subtraction.

Vary B for fixed v2:

Isobaric collisions with
RuRu v.s. ZrZr

Our best guess for now:



$H_{CME} \to 2a_1^2$

[STAR, PRL2014]

Encouraging experimental evidence for CME in QGP
— can we quantitatively compute CME signal?

Many interesting proposals of new observables!

See many exp. talks at this conference.

Toward Quantitative Era of CME Study

- *Modeling CME &CMW with transport model (AMPT):*
  SINAP group; TAMU group; …

- *Modeling CME with chiral kinetic theory:*
  Tsinghua-IU group; TAMU group; …

- *Dynamical magneto-hydro: Florence-Frankfurt group;*
  BNL-SBU group; Tokyo group; …

- *Axial charge dynamics: SYSU group; BNL-SBU group*
  Tsinghua-IU group; …

- *Fluid dynamical description:*
  IU group; BNL-SBU group; …

The rest of this talk will focus on the approach based on a new kind of fluid dynamics simulations: Anomalous-Viscous Fluid Dynamics (AVFD)

The AVFD Framework

From Micro. Laws To Macro. Phenomena

Micro. Laws:

Symmetry;
Lagrangian;
Conservation laws;
……

↔

Macro. Phenomena:

Thermodynamics;
Phase transitions;
Transport;
Hydrodynamics;
……

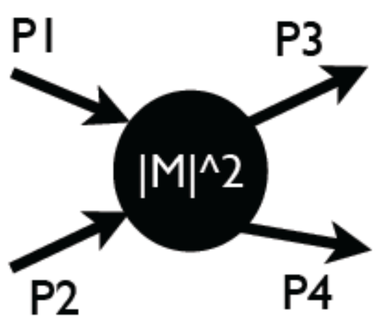
Would chiral anomaly, usually considered at microscopic level, manifest itself MACROSCOPICALLY in a many-body system of chiral fermions? If so, how?

Many-body physics of chiral anomaly:
General interest and broad impact!
e.g. semimetals, neutrinos in supernovae,
Compact stars, cosmology, plasma physics, …

Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	**energy and momentum conserved**	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	**charge conserved**	$\partial_\mu J^{\mu} = 0$

$$\mathcal{L} \rightarrow \mathcal{L}$$



Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^\mu = 0$

WHAT ABOU "HALF"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

Hydrodynamics That Knows Left & Right

conservation law:

$$\partial_\mu J^\mu = 0 \longrightarrow \partial_\mu J^\mu = C E^\mu B_\mu$$

constituent relation:

$$J^\mu = n u^\mu + \nu^\mu$$

$$\partial_\mu s^\mu \geq 0$$

$$\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu$$

[Son, Surowka, 2009;…]

CVE CME

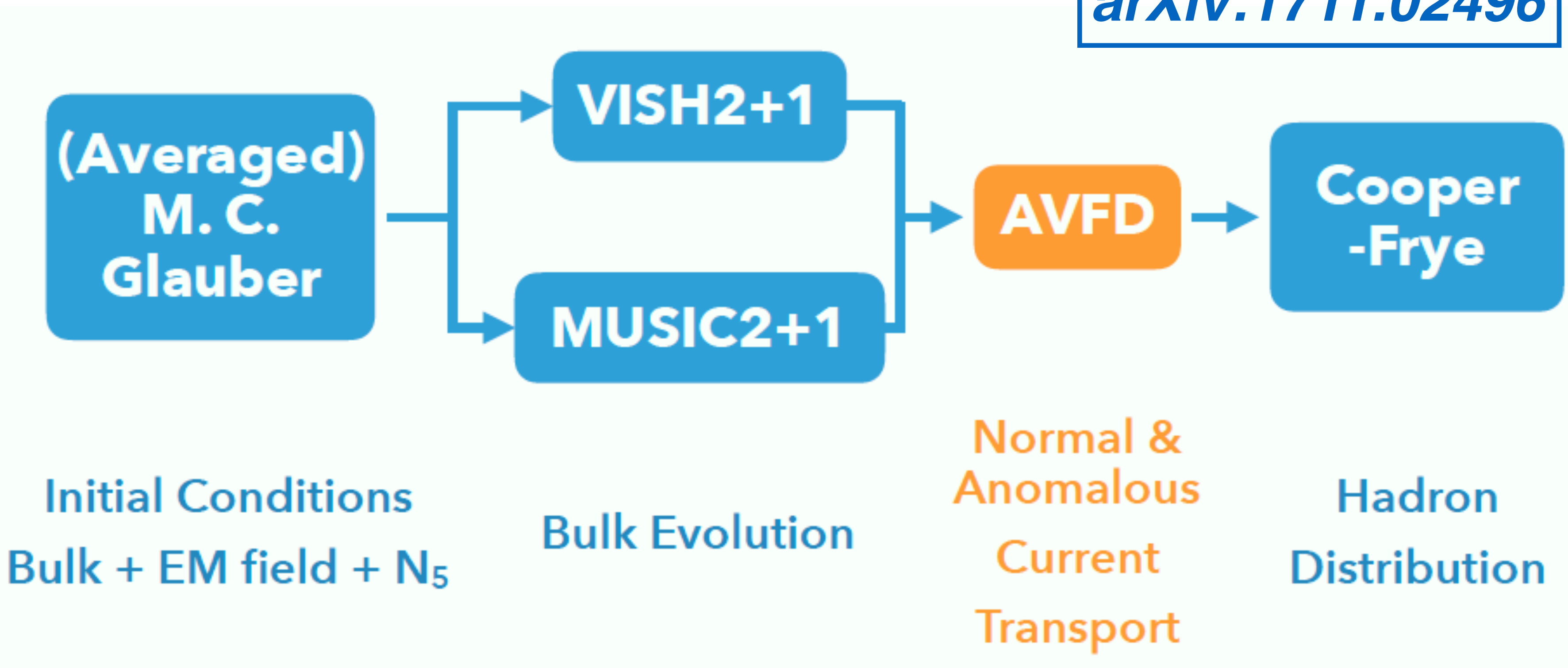
Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

It would be remarkable to actually "see" this new hydrodynamics at work in real world materials!

The AVFD Framework

arXiv:1611.04586

arXiv:1711.02496



AVFD:
Anomalous-Viscous Fluid Dynamics

The AVFD Framework

Anomalous-Viscous Fluid Dynamics

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

CME

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

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

Viscous Effect

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

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

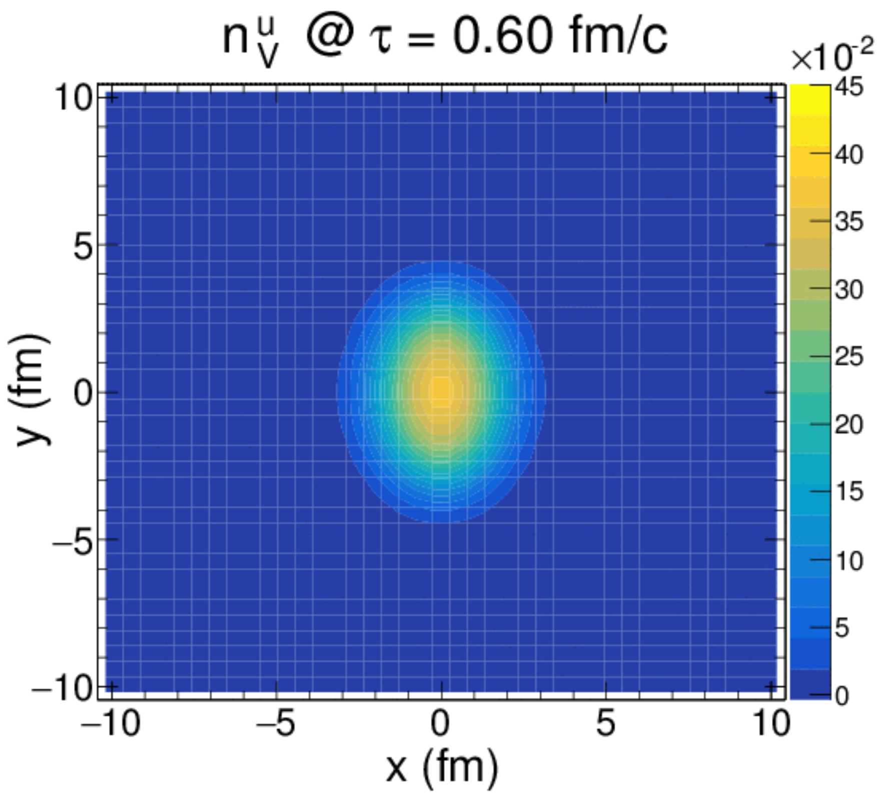
on top of VISH2+1D –– OSU Group

[We now also have MUSIC-AVFD!]

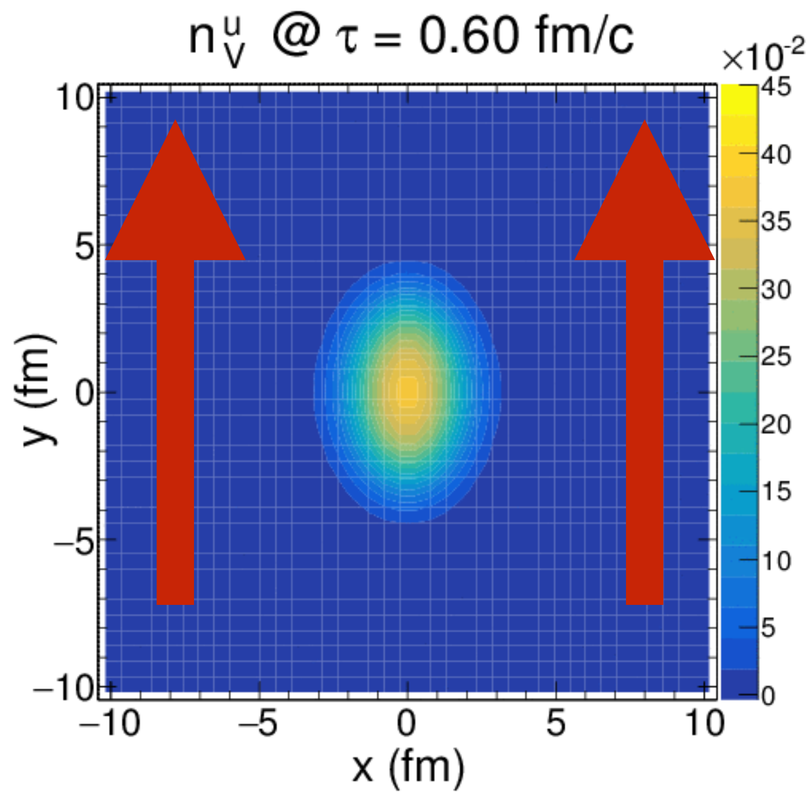
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

Zero B Field



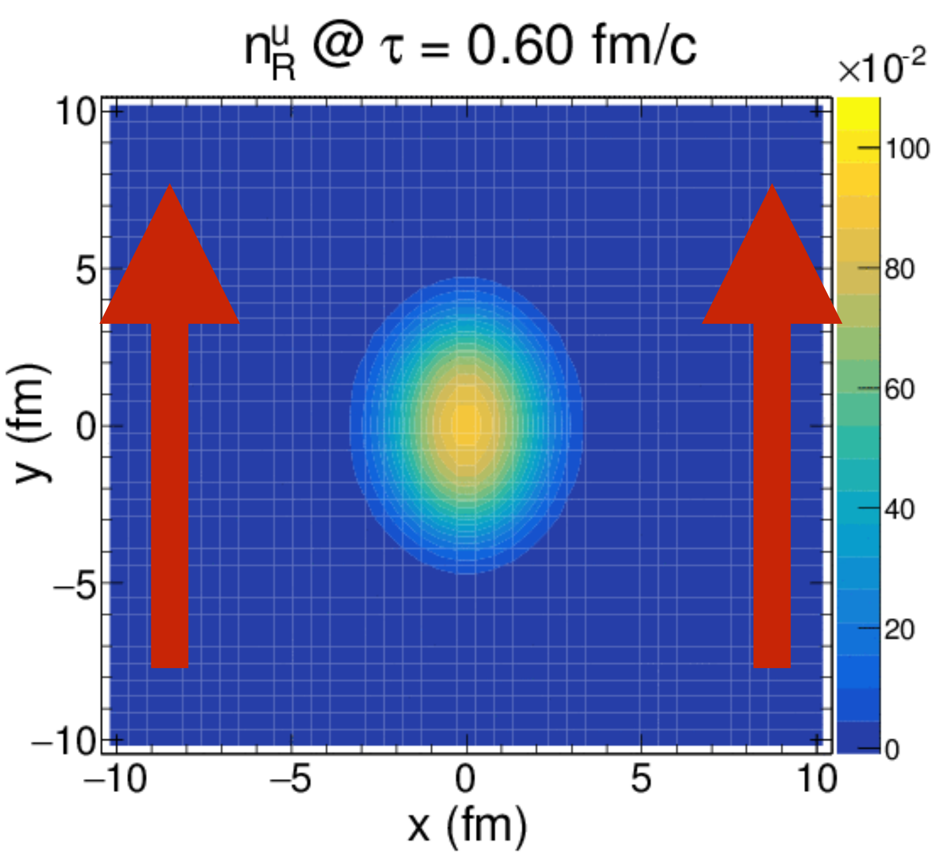
Nonzero B Field



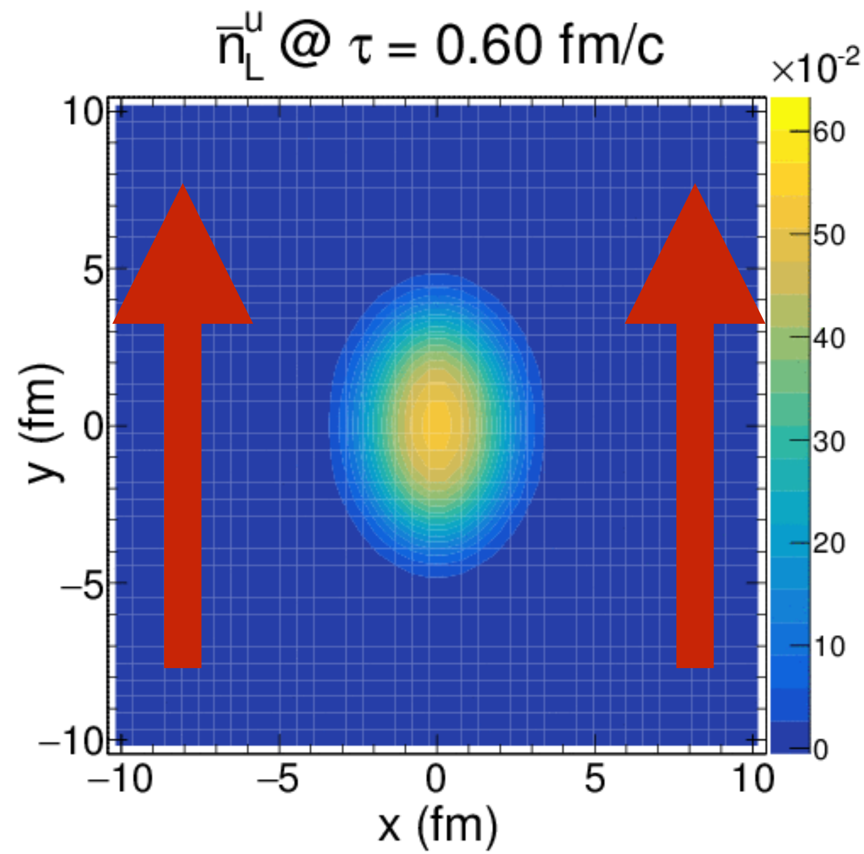
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

Right-Handed Density



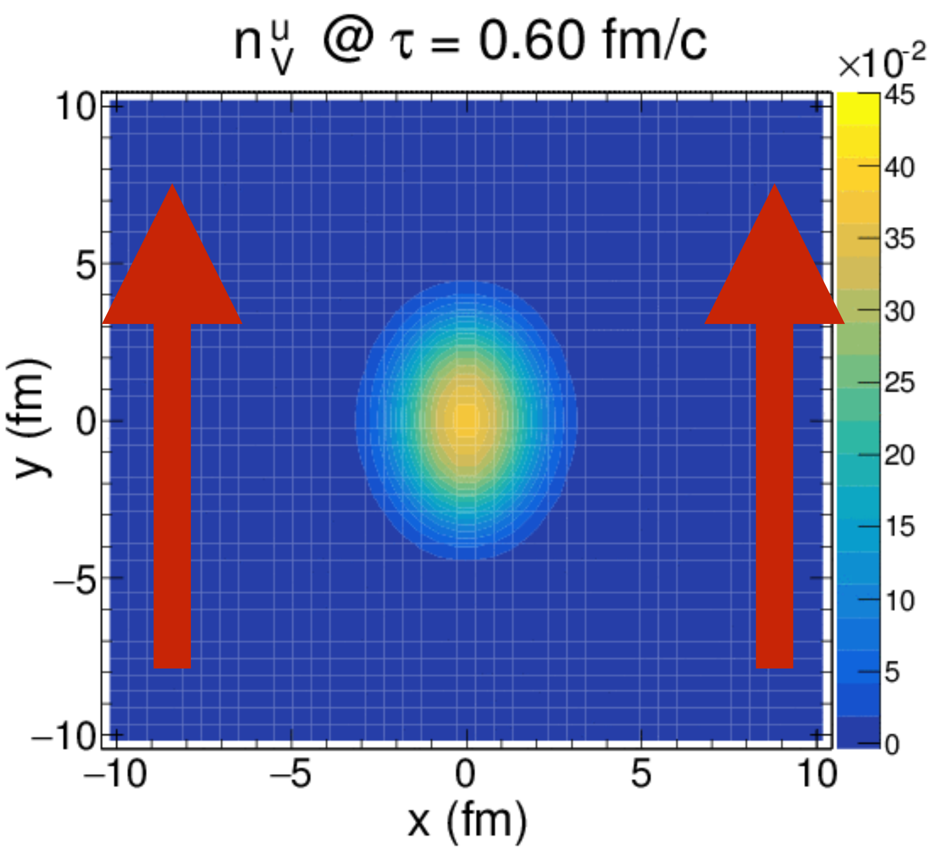
Left-Handed Density



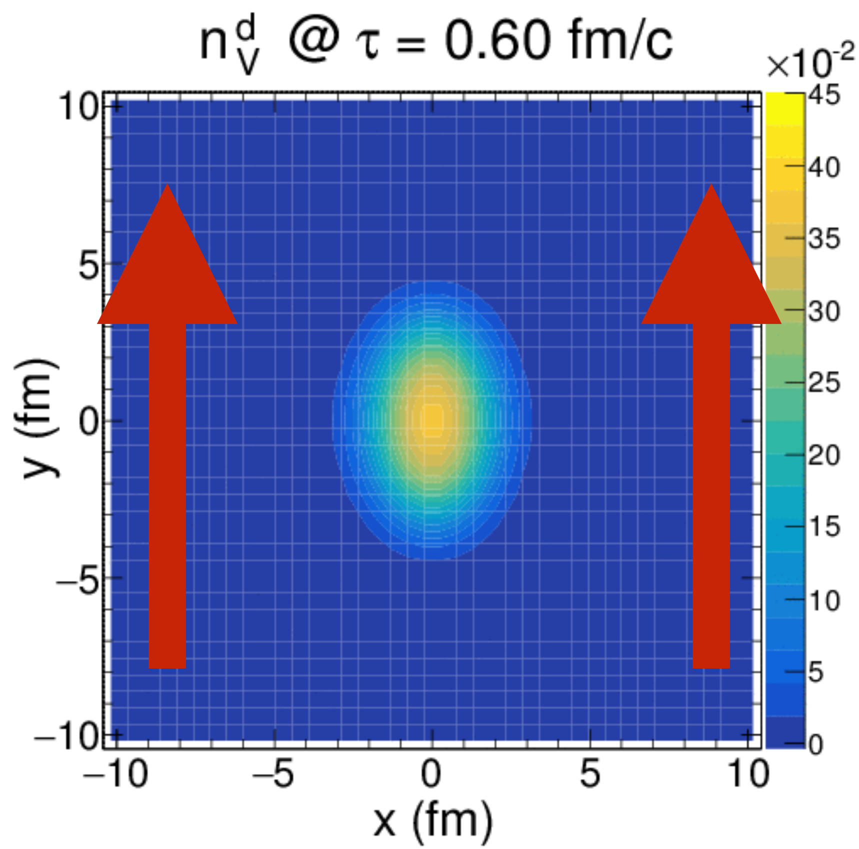
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

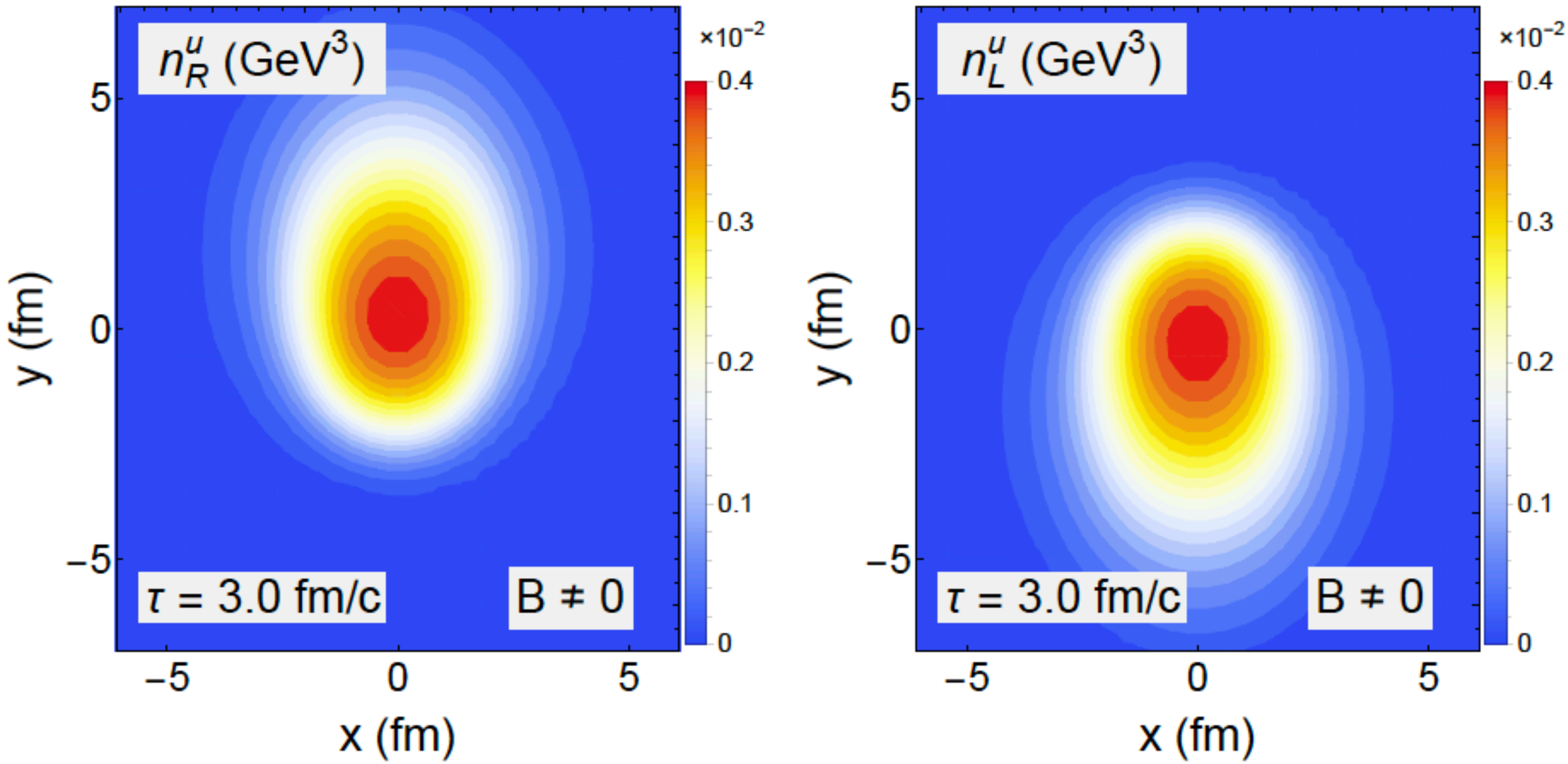
U Flavor Density



D Flavor Density



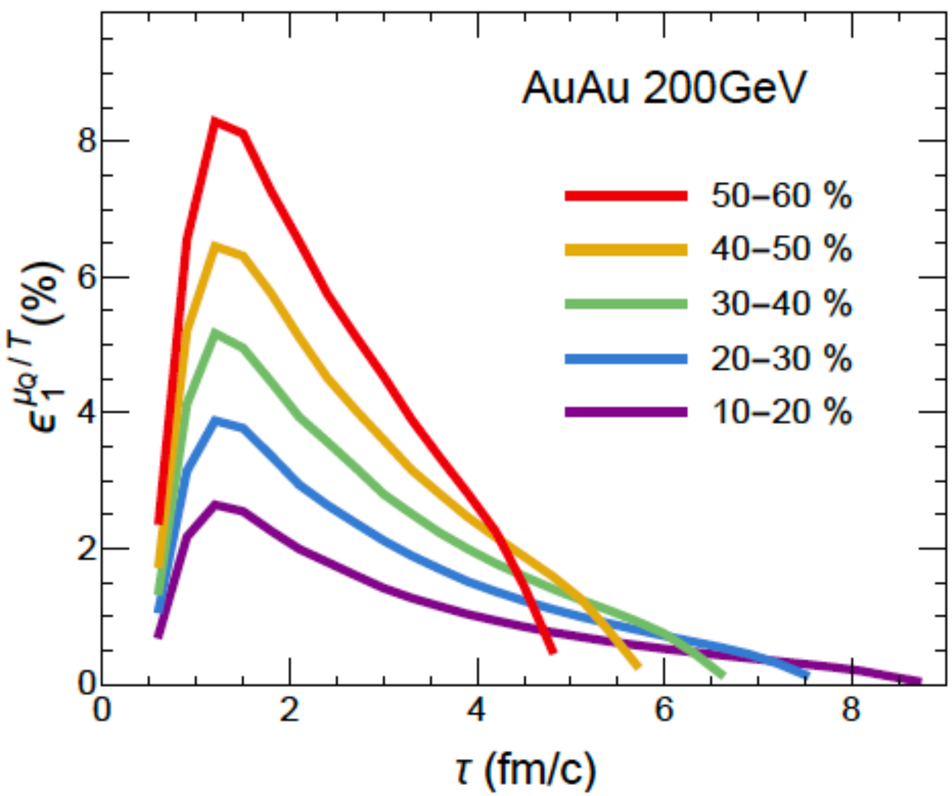
The Charge Separation from AVFD



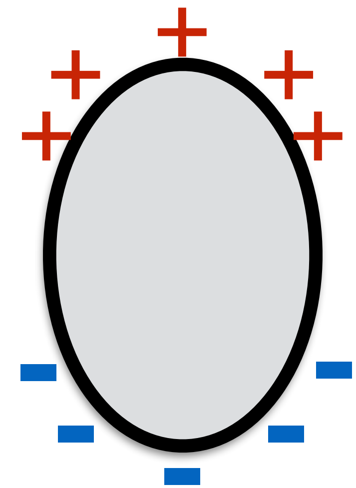
B field $\otimes\ \mu_5 \ \Rightarrow$ current $\Rightarrow$ dipole (charge separation)

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

The Charge Separation from AVFD



$$E\frac{dN}{d^3p}(x^\mu, p^\mu) = \frac{g}{(2\pi)^3}\int_{\Sigma_{\rm fo}} p^\mu d^3\sigma_\mu f(x,p)$$



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

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

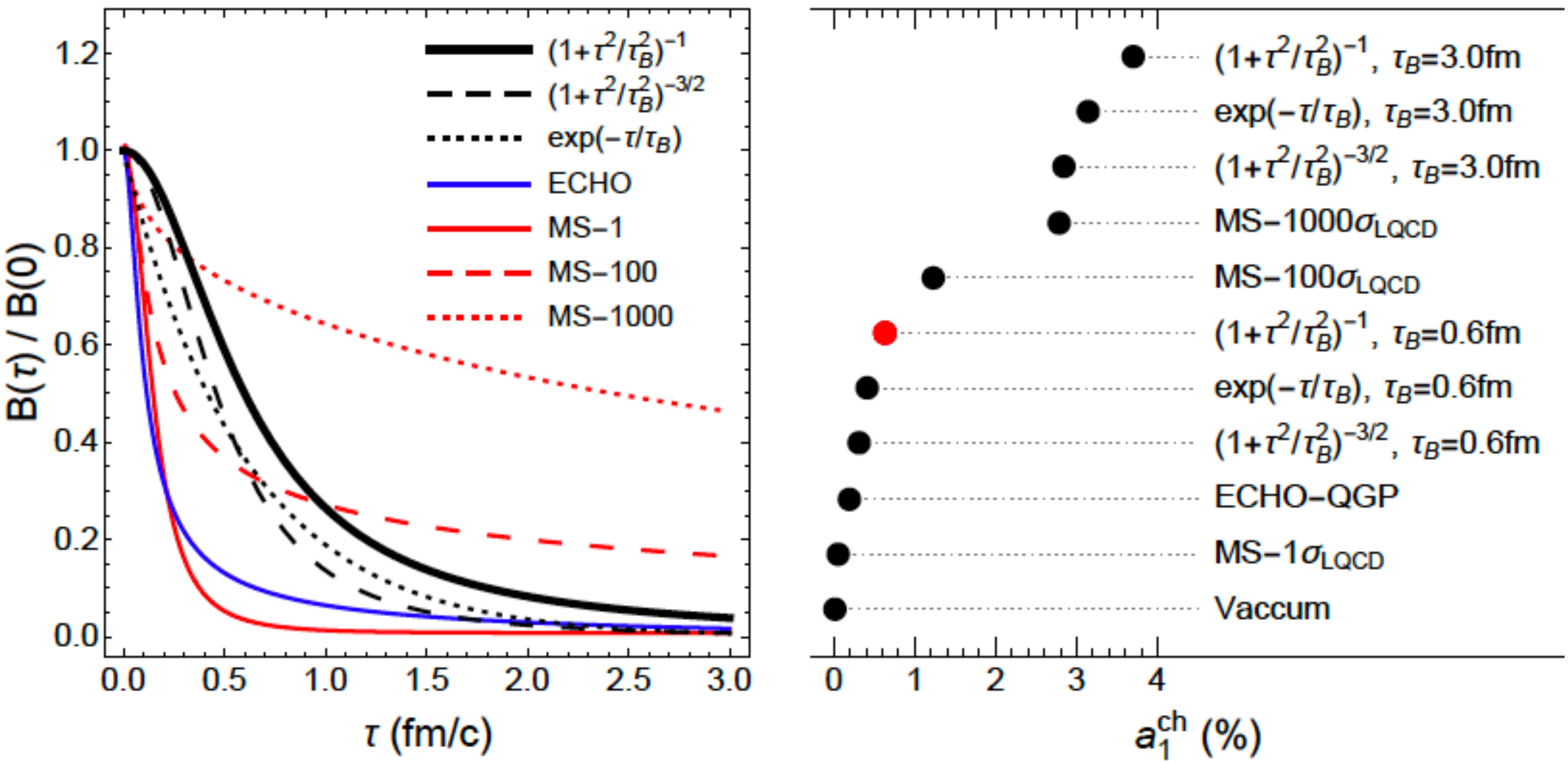
$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

Detailed Results from AVFD

arXiv:1611.04586

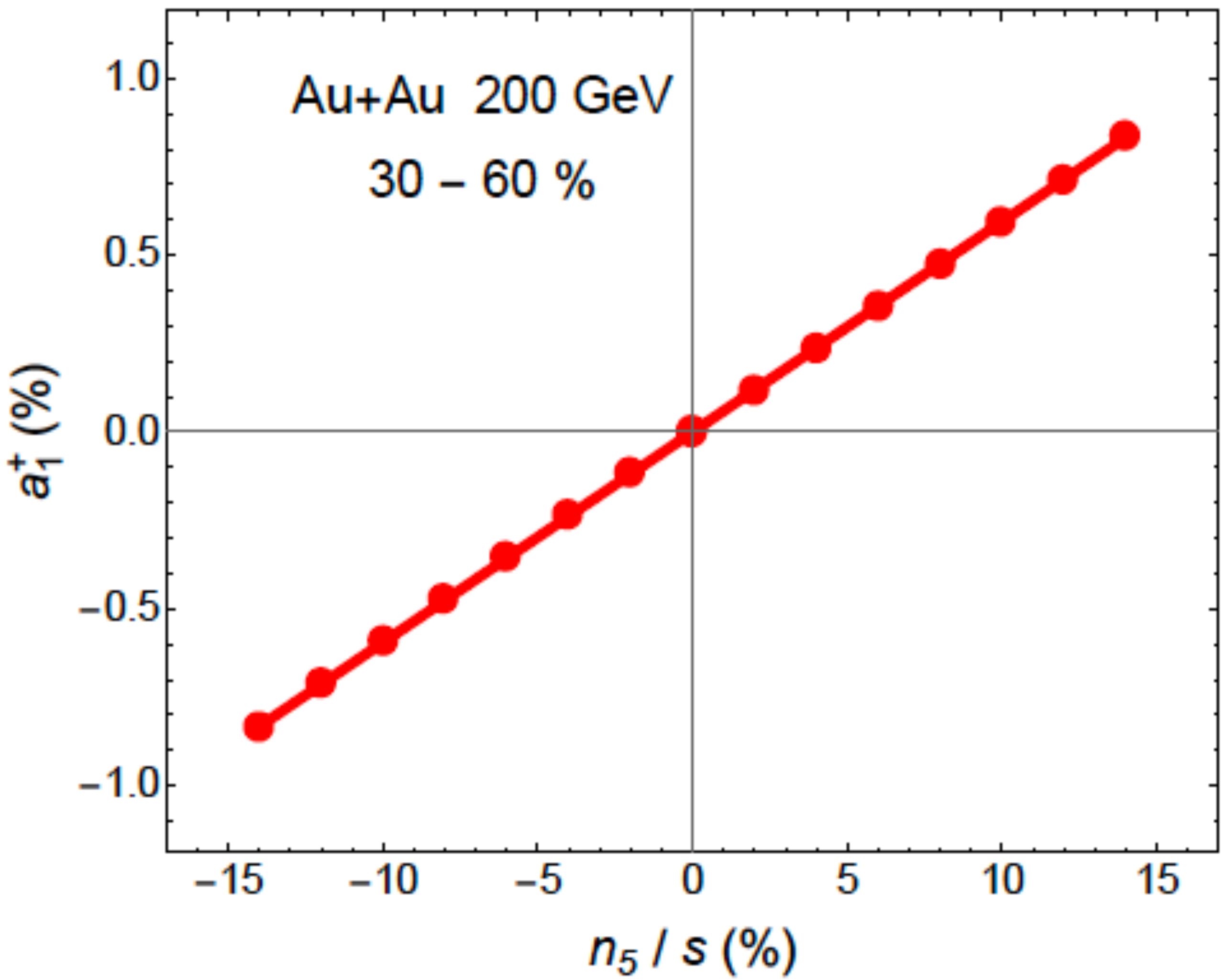
arXiv:1711.02496

The Influence of the Magnetic Field



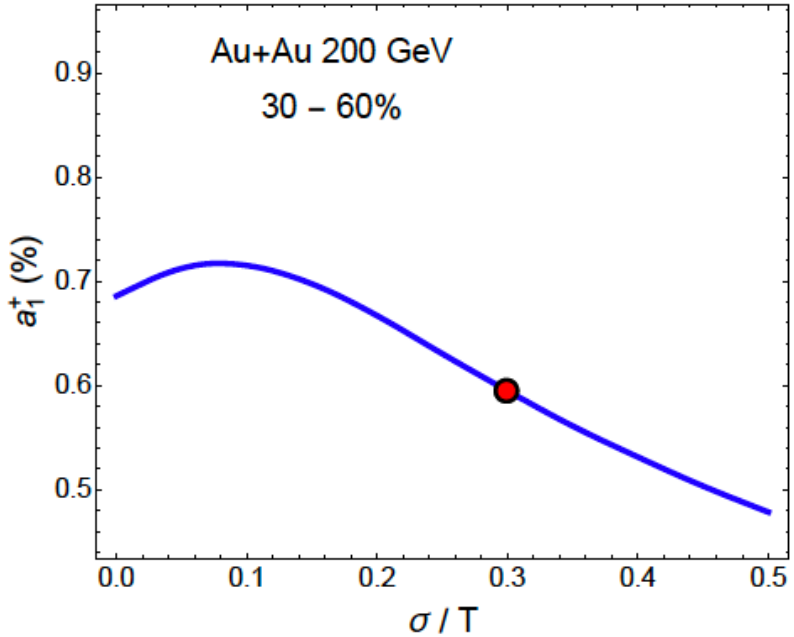
Strong influence by B field evolution;
Significant theoretical uncertainty!

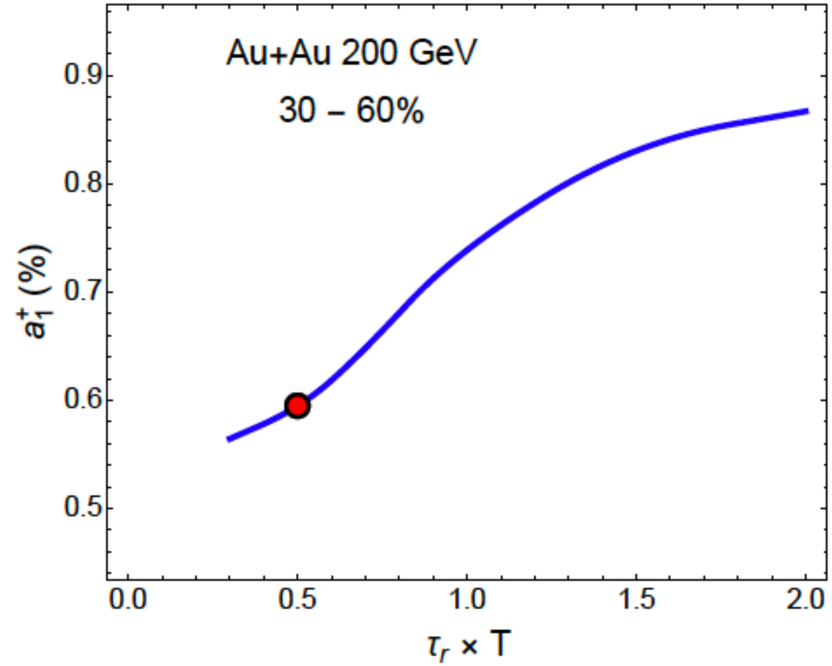
The Axial Charge Initial Condition



Very sensitive to initial axial charge;
Significant theoretical uncertainty!

The Influence of the Viscous Transport



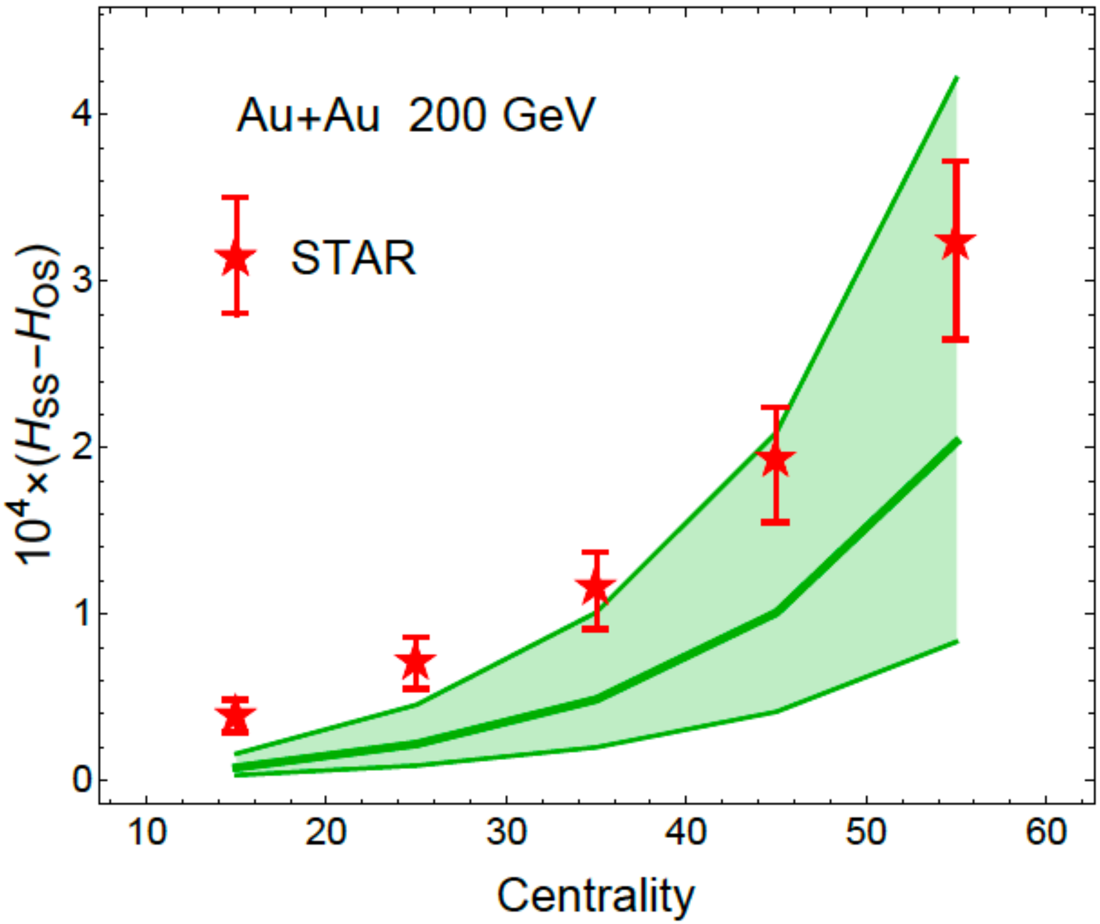


$$\Delta^{\mu}{}_{\nu}\, \mathrm{d}\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}\left(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu}\right)$$

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

First calibration for the influence of the viscous transport on charge separation signal!

AVFD Predictions v.s Experimental Data



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

$$\tau_B = 0.6\text{fm/c}$$

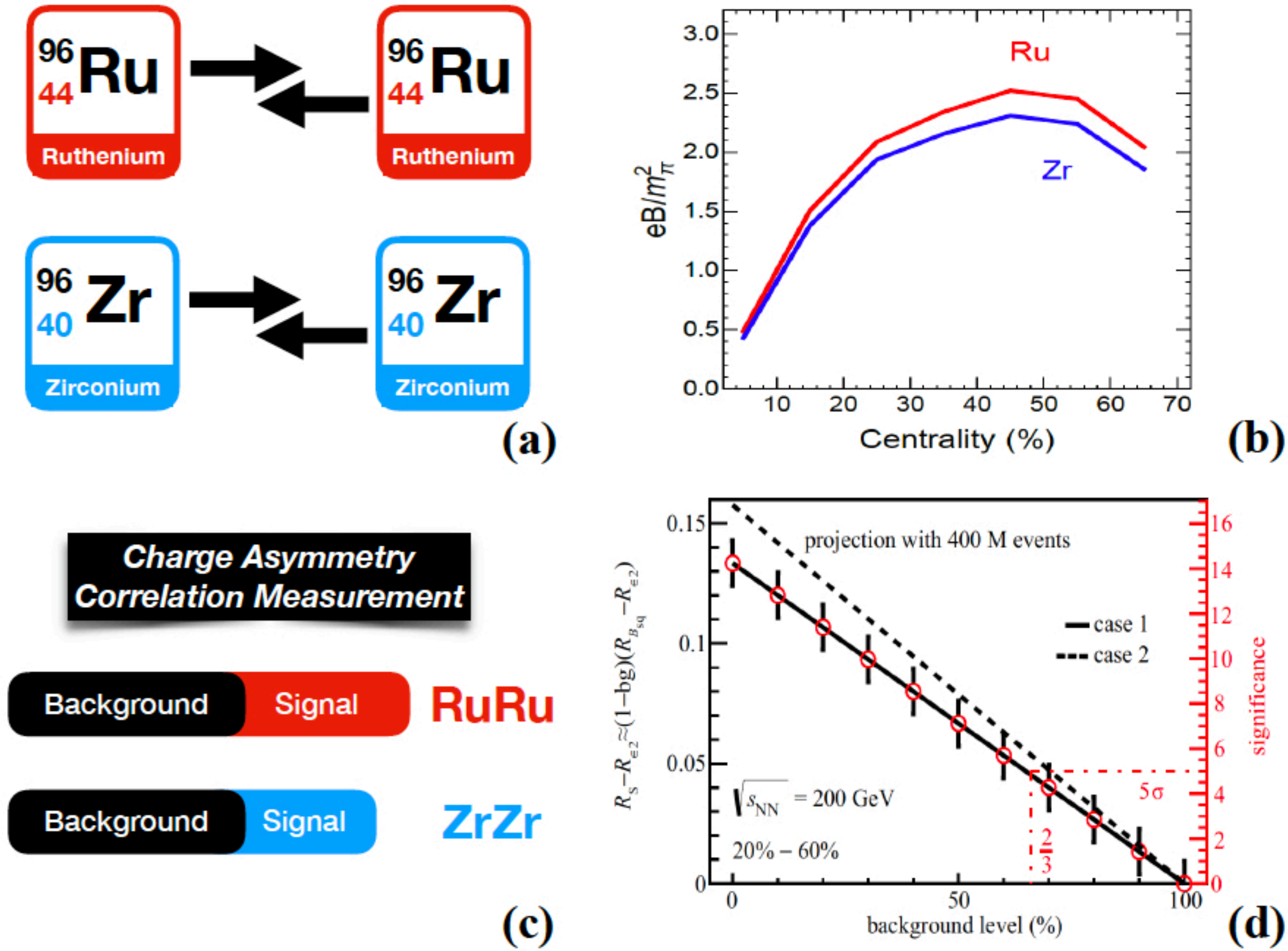
$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4\,(\pi\rho_{tube}^2\tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\,A_{overlap}}$$

Nice agreement; But read them in perspective!

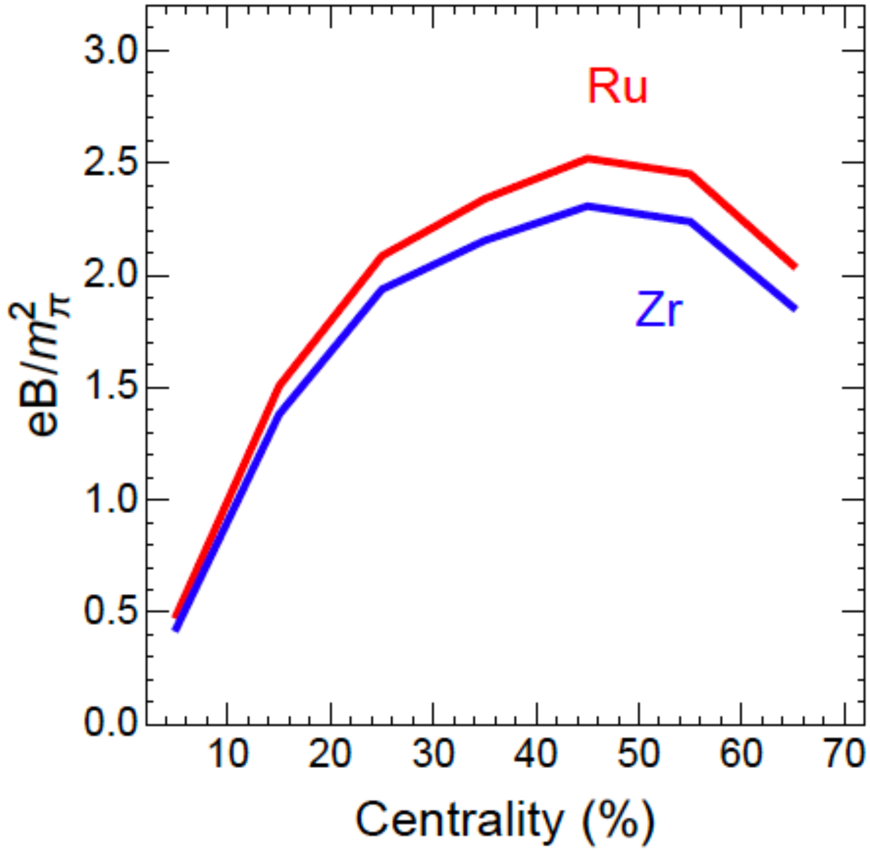
centrality bin	10-20%	20-30%	30-40%	40-50%	50-60%
$eB_0(m_\pi^2)$	2.34	3.10	3.62	4.01	4.19
n_5/s	0.065	0.078	0.095	0.119	0.155

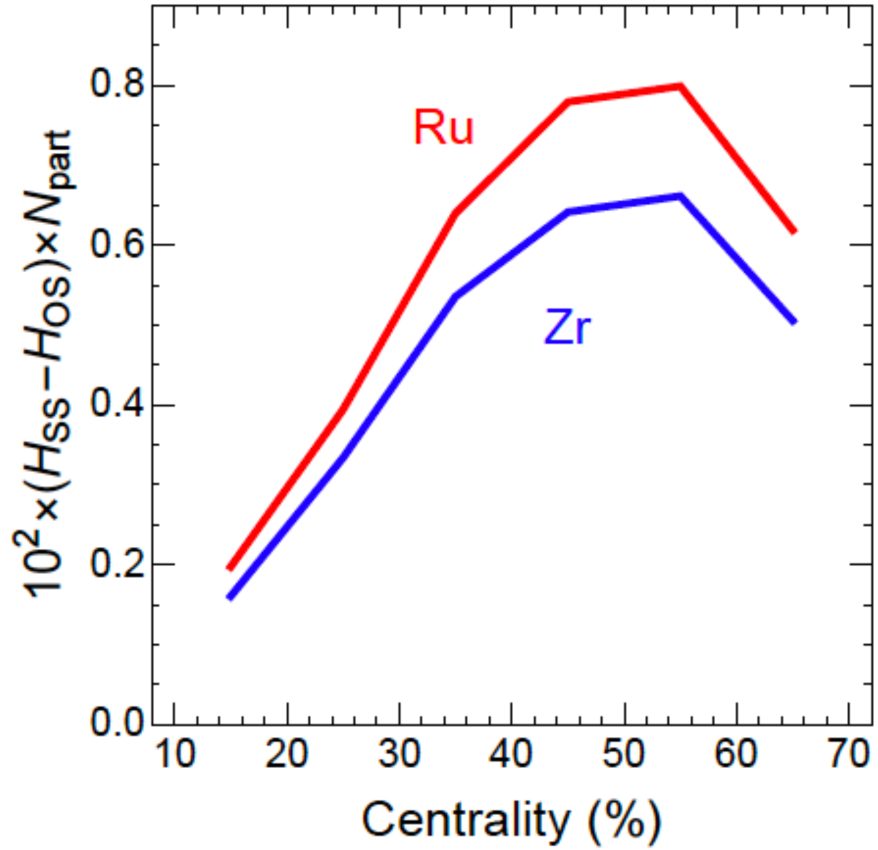
Table 1. Centrality dependence of magnetic field peak strength and the initial chirality imbalance. The n_5/s shown here is obtained with a saturation scale $Q_s^2 = 1.25\text{GeV}^2$.

Using Isobaric Collisions for CME Search



The Magnetic Fields and Signals of Isobars





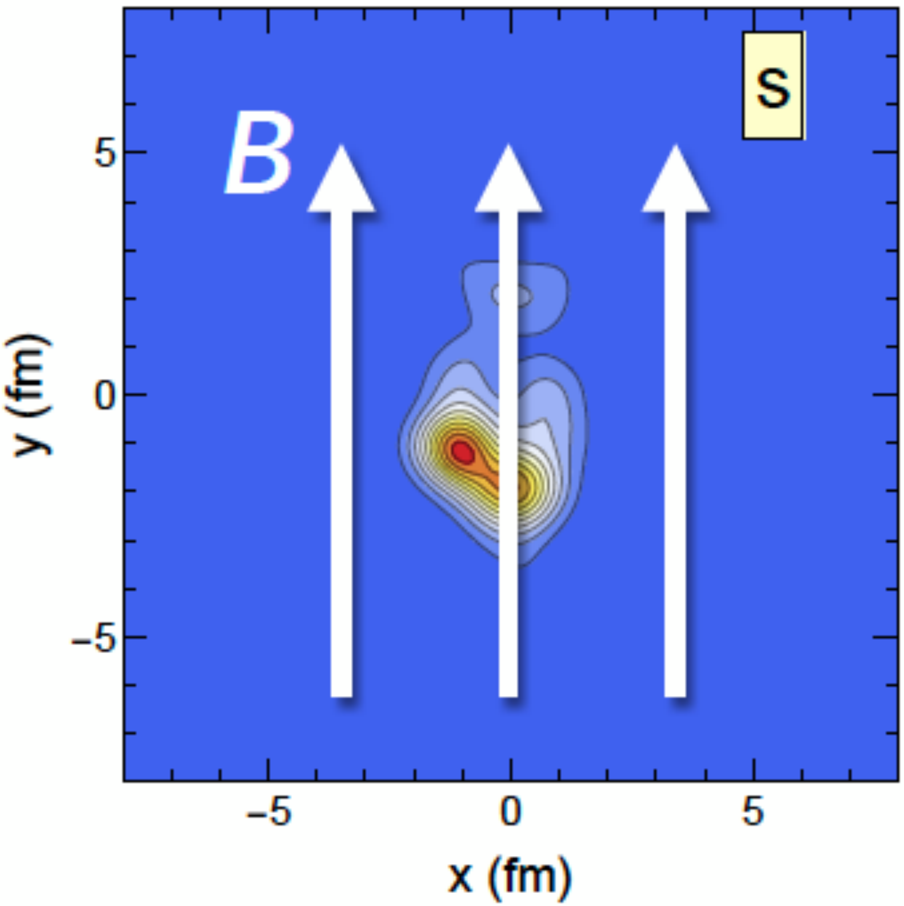
Note: B field projected onto participant plane!

Expected variation of signal, 10~20%

EBE-AVFD

Shuzhe Shi, JL, in preparation.

Toward Event-by-Event Simulations

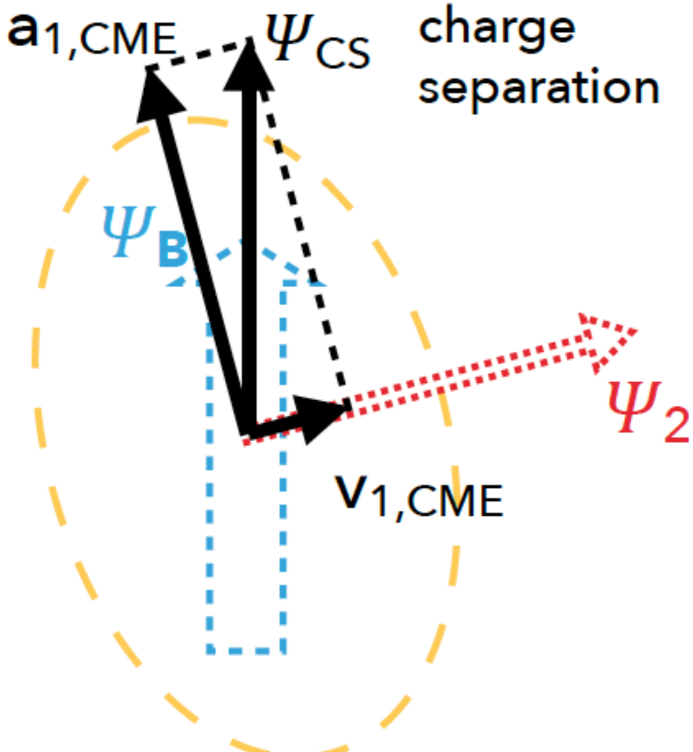


Include EBE fluctuations:

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

Important for better understanding:
**** Interplay between signal and BKG;***
**** Experimental analysis methods***

Fluctuations and Angular De-Correlation



Angular de-correlation between B field and geometry is very important!

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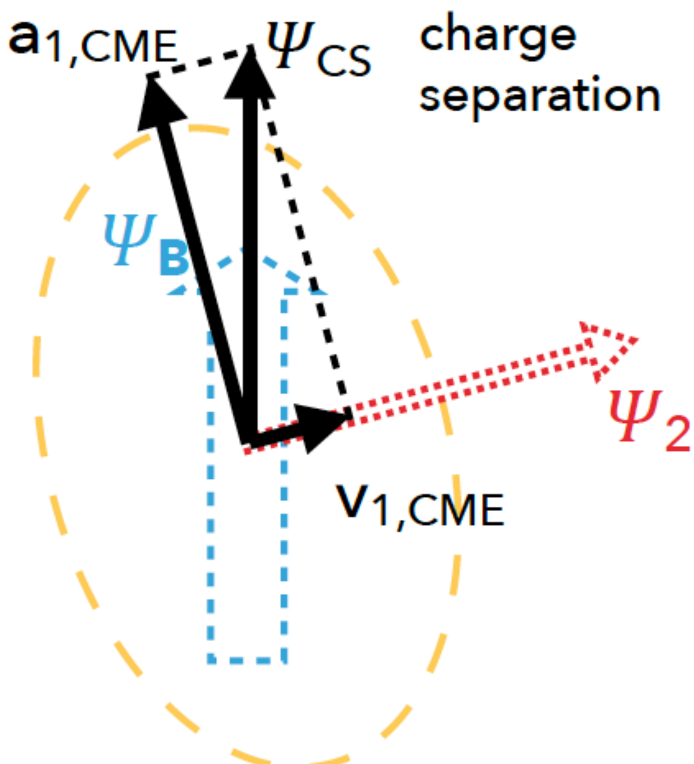
Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

John Bloczynski [a], Xu-Guang Huang [a,*], Xilin Zhang [a], Jinfeng Liao [a,b]

Fluctuations and Angular De-Correlation



** CME signal totally independent of v2?*

NO!

** For event-shape engineering, B field is approximately constant across different shapes within same centrality?*

NO!

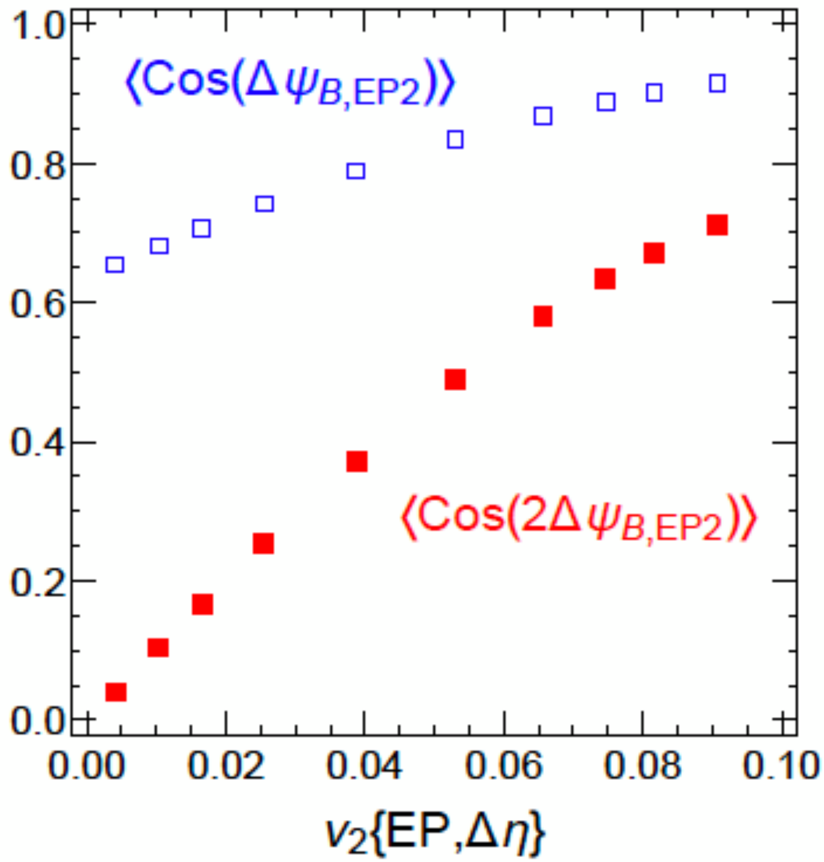
** In small systems / central collisions, no B field effect at all?*

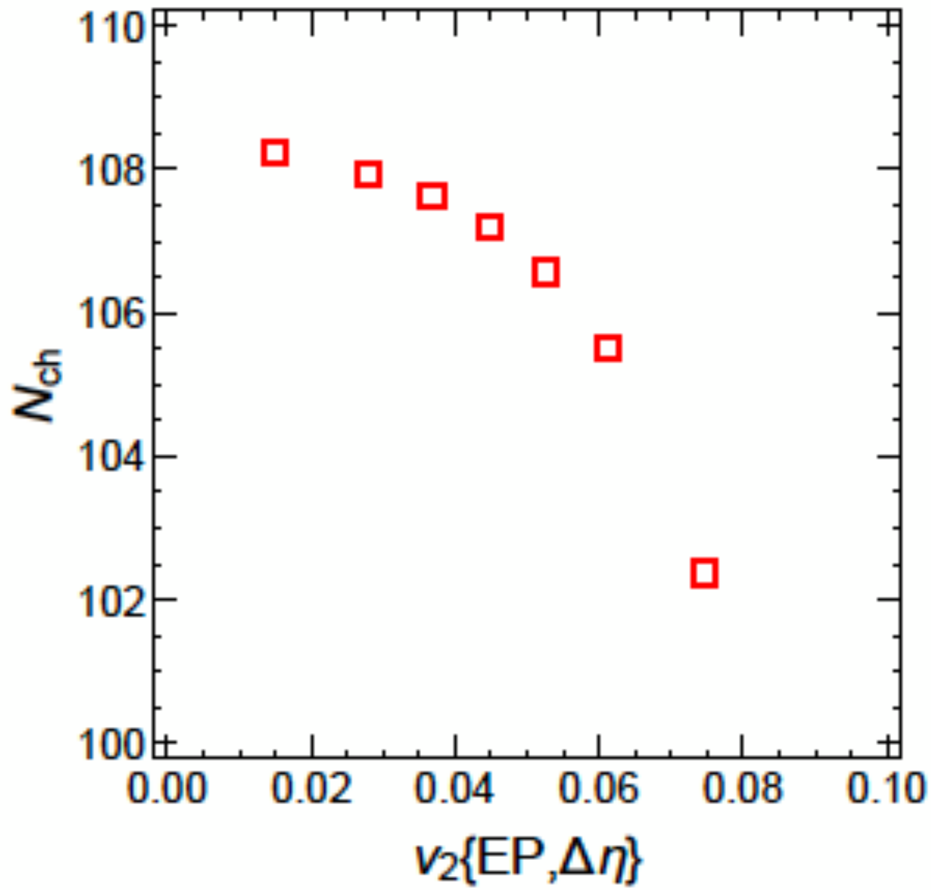
NO!

Unfortunately, signal and BKG entangle more deeply than we'd hope. Both theorists and experimentalists need to be very careful!

Binning Events Could Be Tricky!

Au-Au @ 200GeV 50-60%

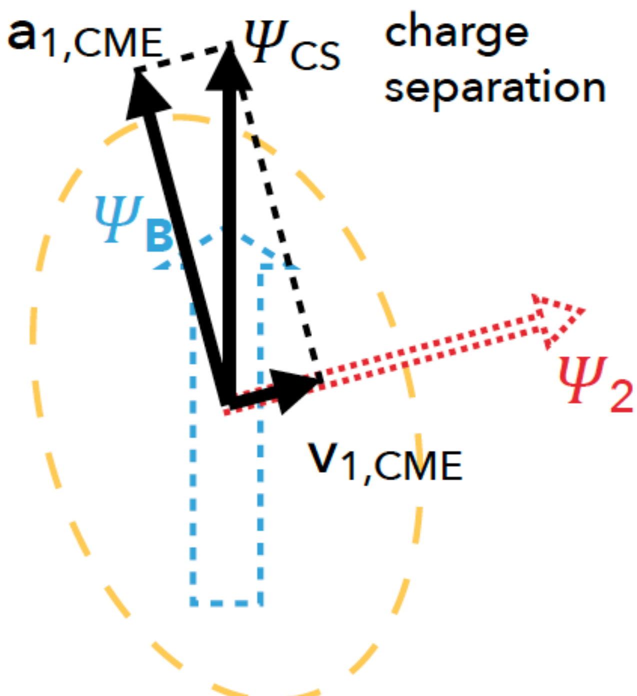


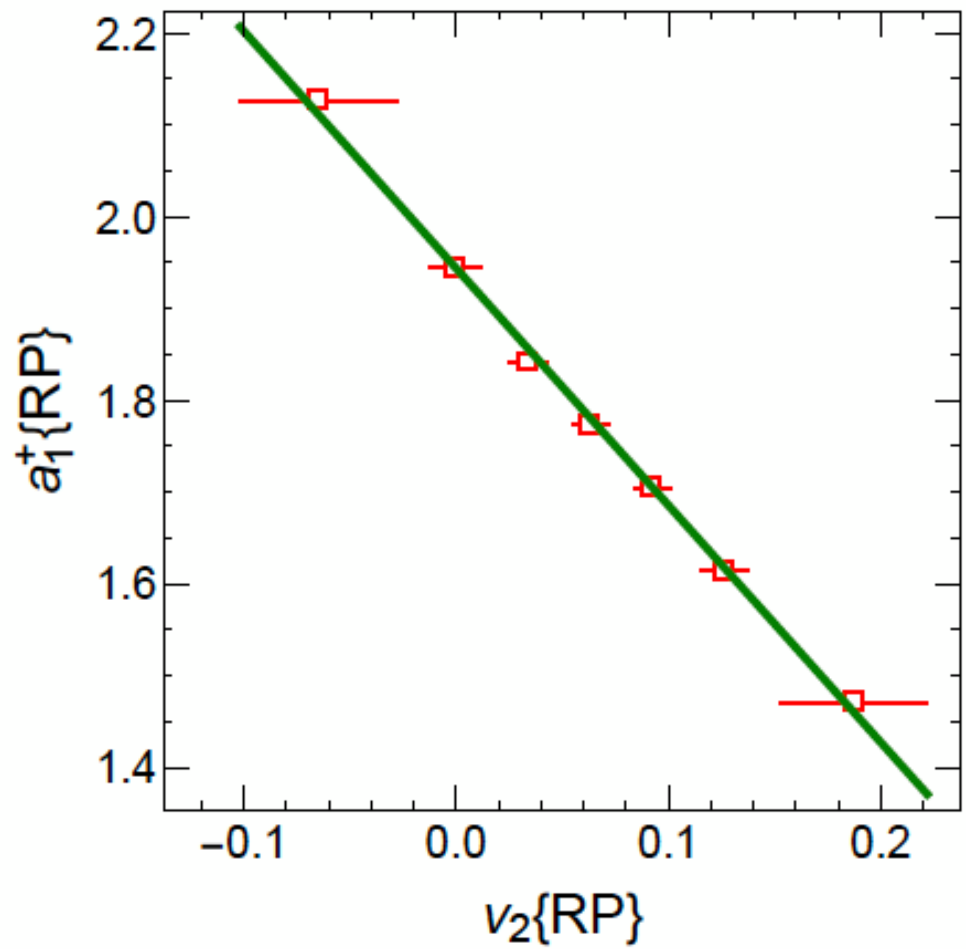


The multiplicity and B-EP de-correlation change with event shape!

EBE-AVFD Results

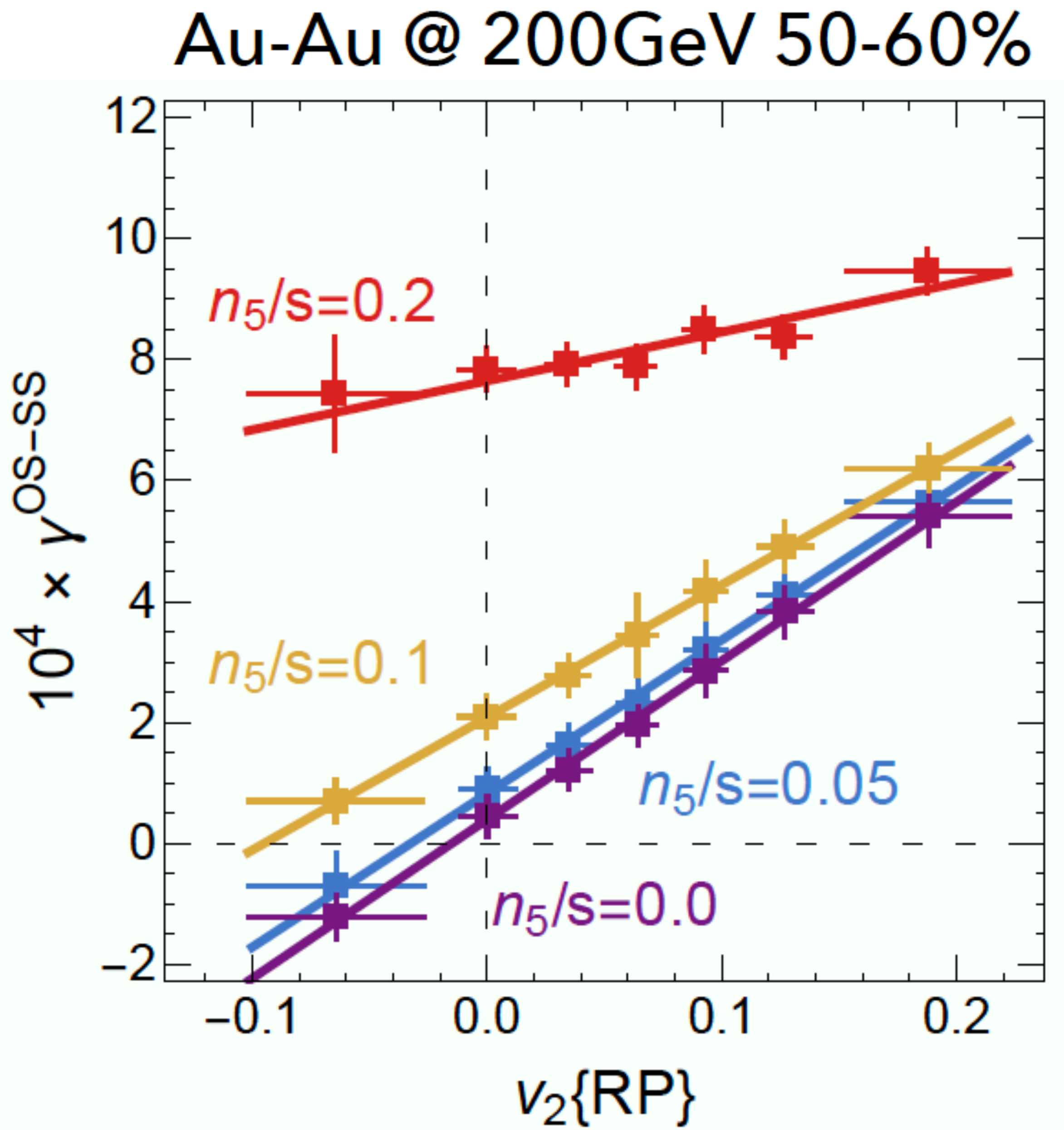
Au-Au @ 200GeV 50-60%



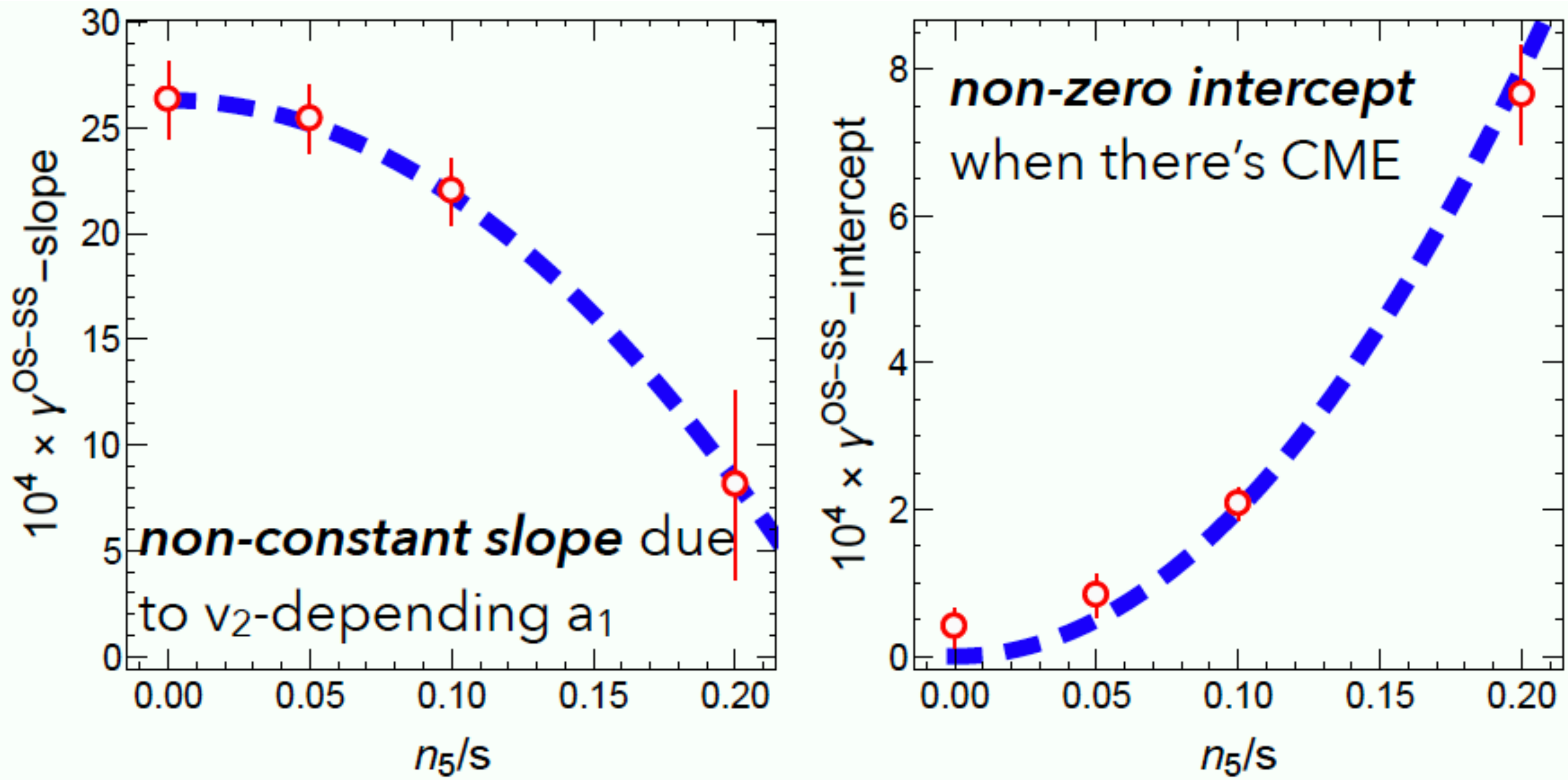


The CME signal is also correlated with event shape !

EBE-AVFD Results: Gamma(1,1,2)



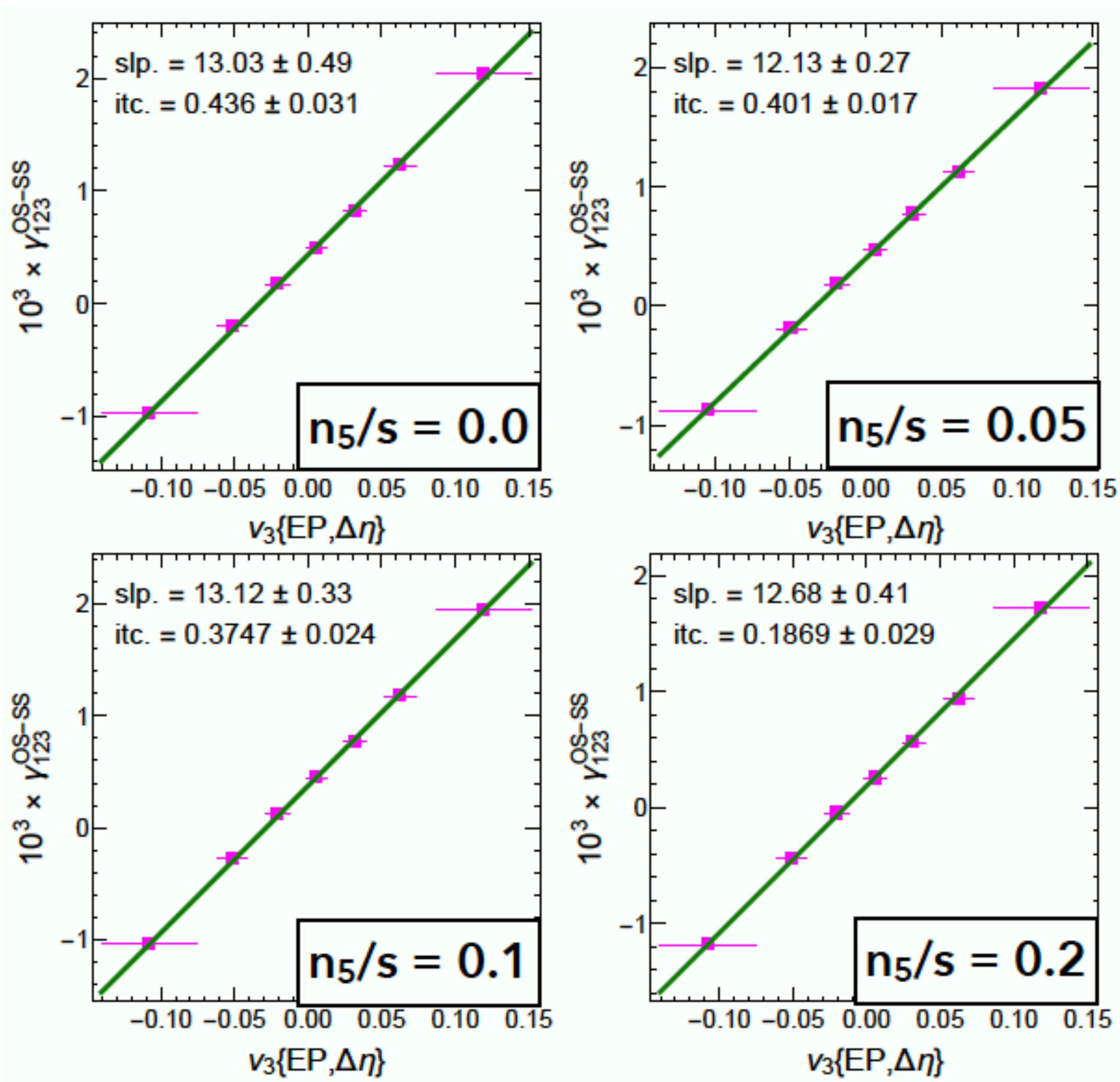
EBE-AVFD Results: Slope & Intercept



The intercept is SENSITIVE to CME signal !

The slope contains both BKG and signal !

EBE-AVFD Results: Gamma(1,2,3)

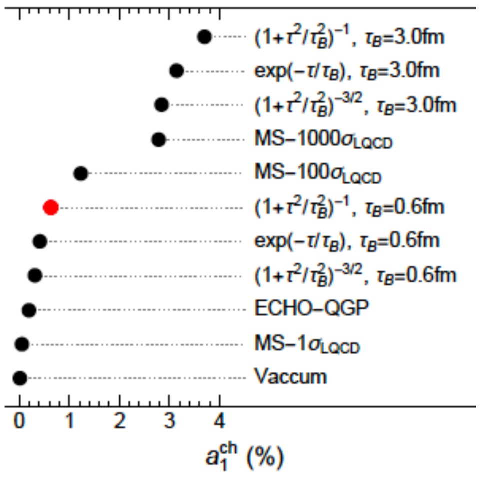


Good linear dependence;

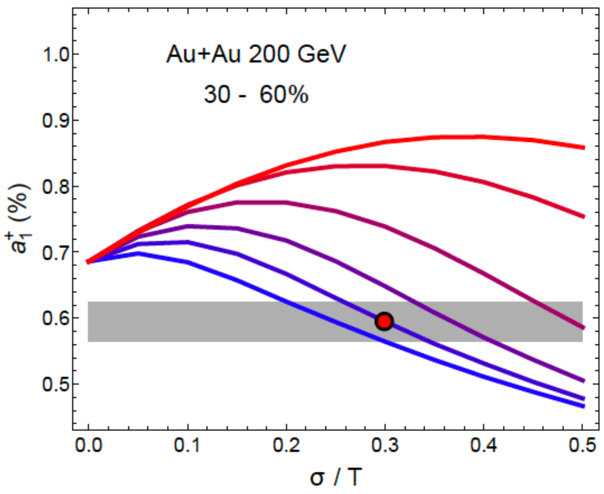
The slope is insensitive to CME signal.

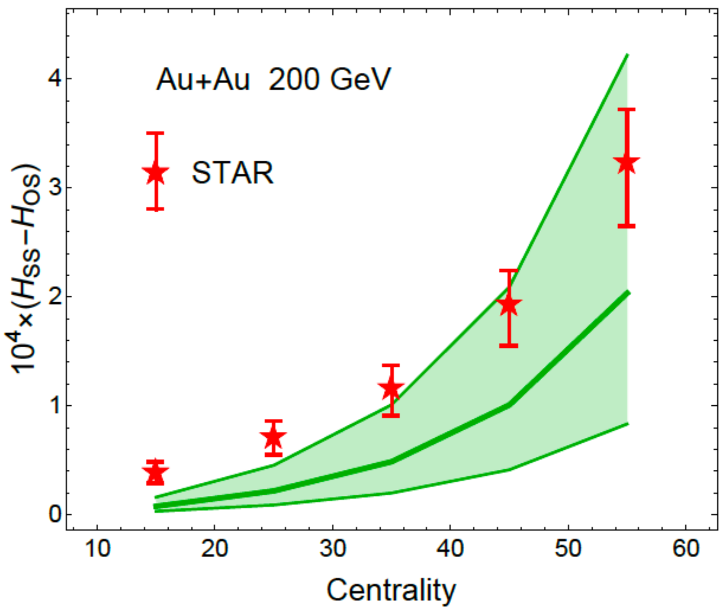
Summary & Outlook

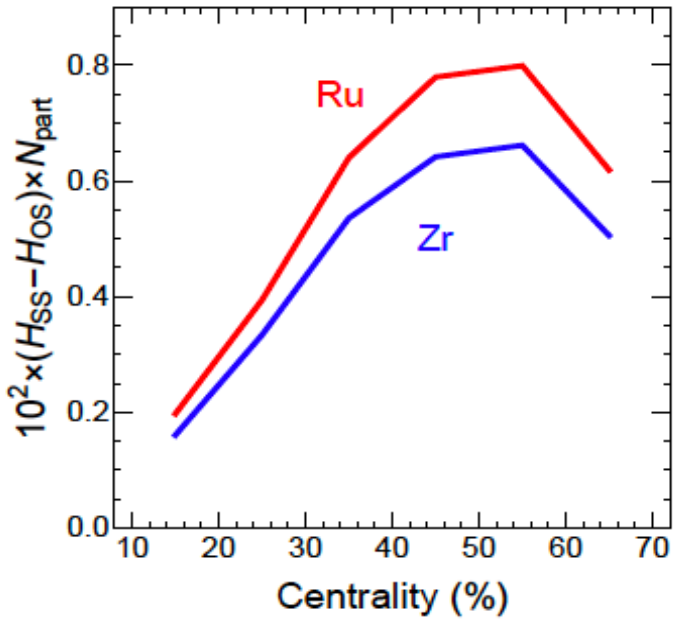
Summary



AVFD:
A versatile tool
for an era of
quantitative study
of CME in
heavy ion collisions







Toward Full-Fledged EBE-AVFD: Stay Tuned!