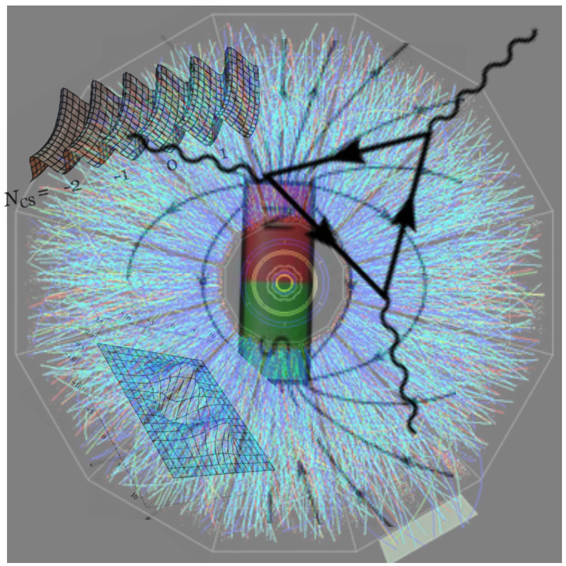
ECT* Workshop @ Trento   May. 10, 2018

Anomalous-Viscous Fluid Dynamics (AVFD)



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by U.S. NSF & DOE

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

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

arXiv:1611.04586

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

Yin Jiang(姜寅)[1] Shuzhe Shi(施舒哲)[2] Yi Yin(尹伊)[3] Jinfeng Liao(廖劲峰)[2,4;1)]

[1] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[2] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[3] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[4] Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan 430079, China

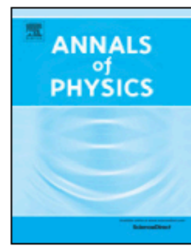
Annals of Physics 394 (2018) 50–72

Contents lists available at ScienceDirect

Annals of Physics

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

ELSEVIER



Anomalous chiral transport in heavy ion collisions from Anomalous-Viscous Fluid Dynamics

Check for updates

Shuzhe Shi [a,*], Yin Jiang [b,c], Elias Lilleskov [d,a], Jinfeng Liao [a,e,*]

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

D.E. Kharzeev [a,b], J. Liao [c,d,*], S.A. Voloshin [e], G. Wang [f]

[a] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA*
[b] *Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[c] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 727 E Third Street, Bloomington, IN 47405, USA*
[d] *RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA*
[e] *Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48201, USA*
[f] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*

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
- Isobaric Collisions
- Summary & Outlook

Introductory Discussions

Chiral Symmetry & SSB

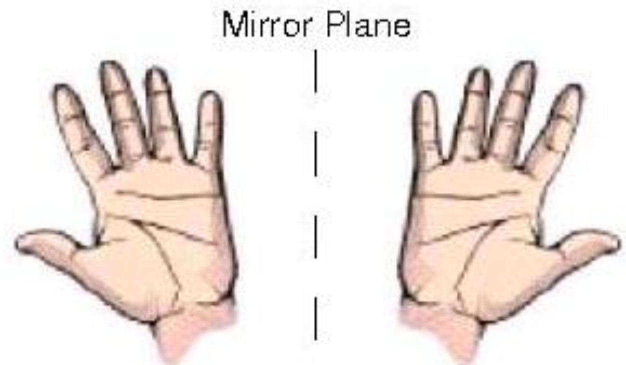
Classical symmetry:

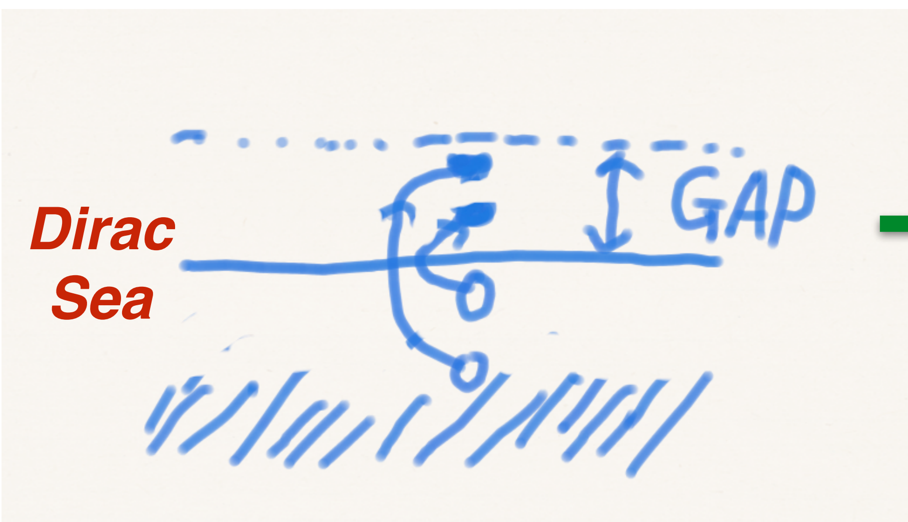
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

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





Dirac Sea

Constituent mass

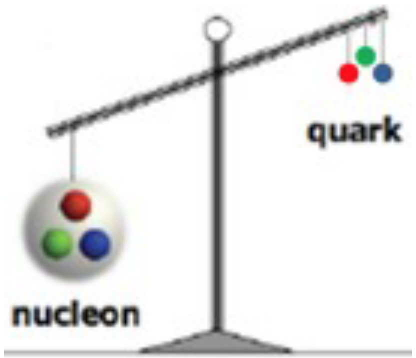
$$M = m - 2G\langle\bar{\psi}\psi\rangle$$

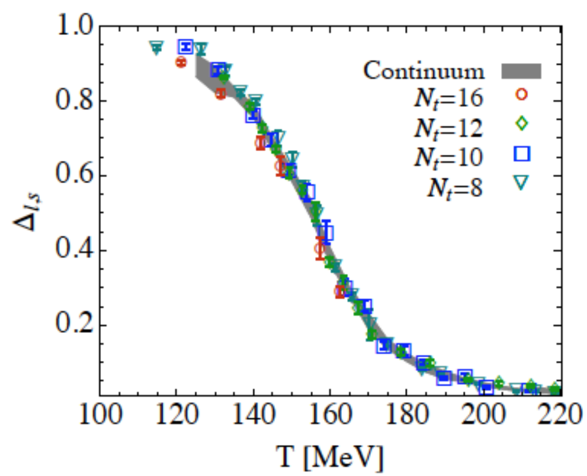
Lagrangian (SM) mass

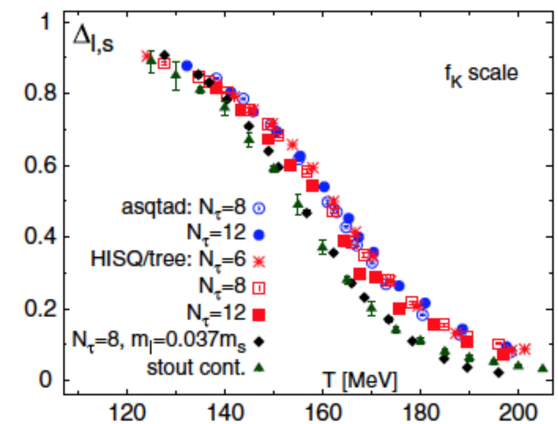
Axial symmetry is broken!

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?

Chiral Anomaly

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

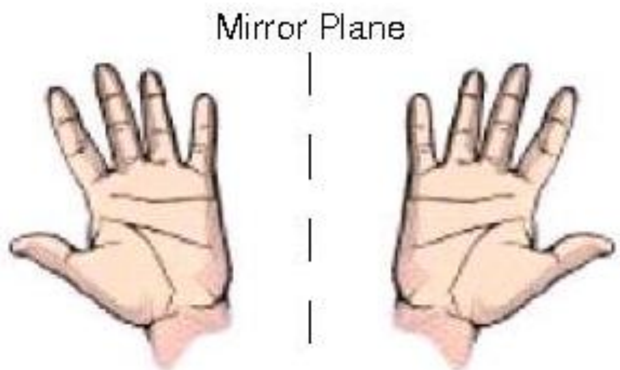
Classical symmetry:

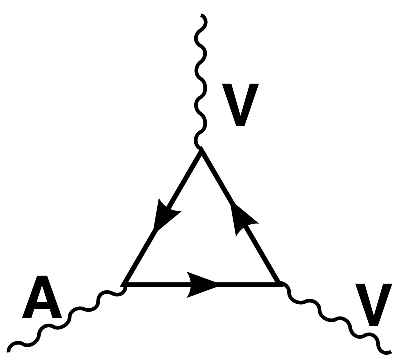
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

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





[e.g. pi0—> 2 gamma]

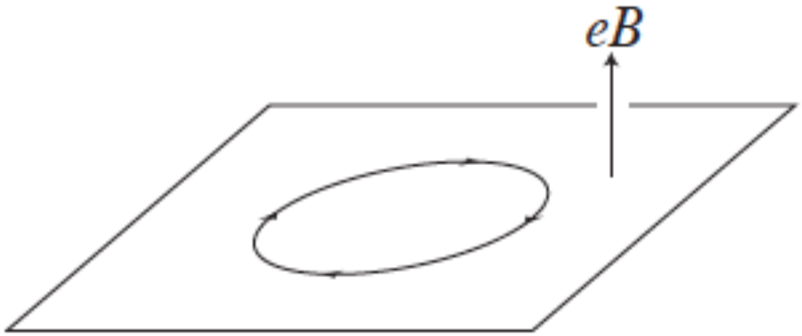
Broken at QM level:

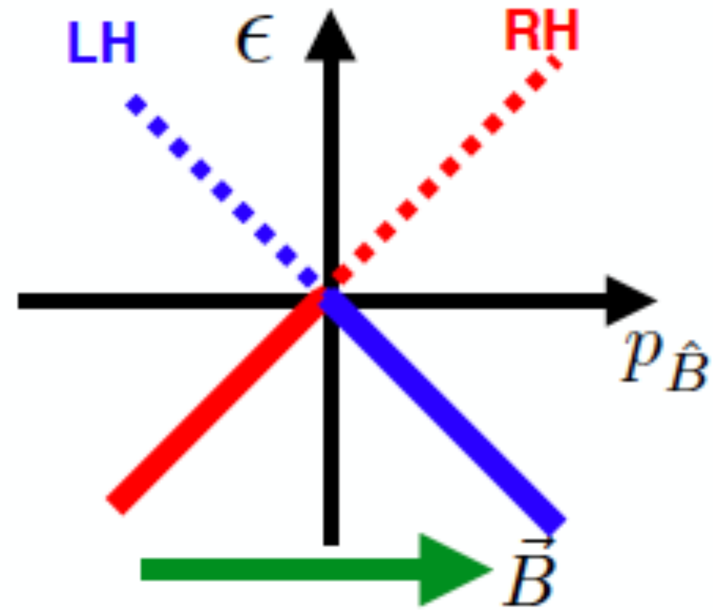
$$\partial_\mu J_5^\mu = C_A\vec{E}\cdot\vec{B}$$

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

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Landau Levels in Magnetic Field





$$E_n^2 = p_z^2 + 2nB$$

Lowest-Landau-Level (LLL):
LLL is chiral!

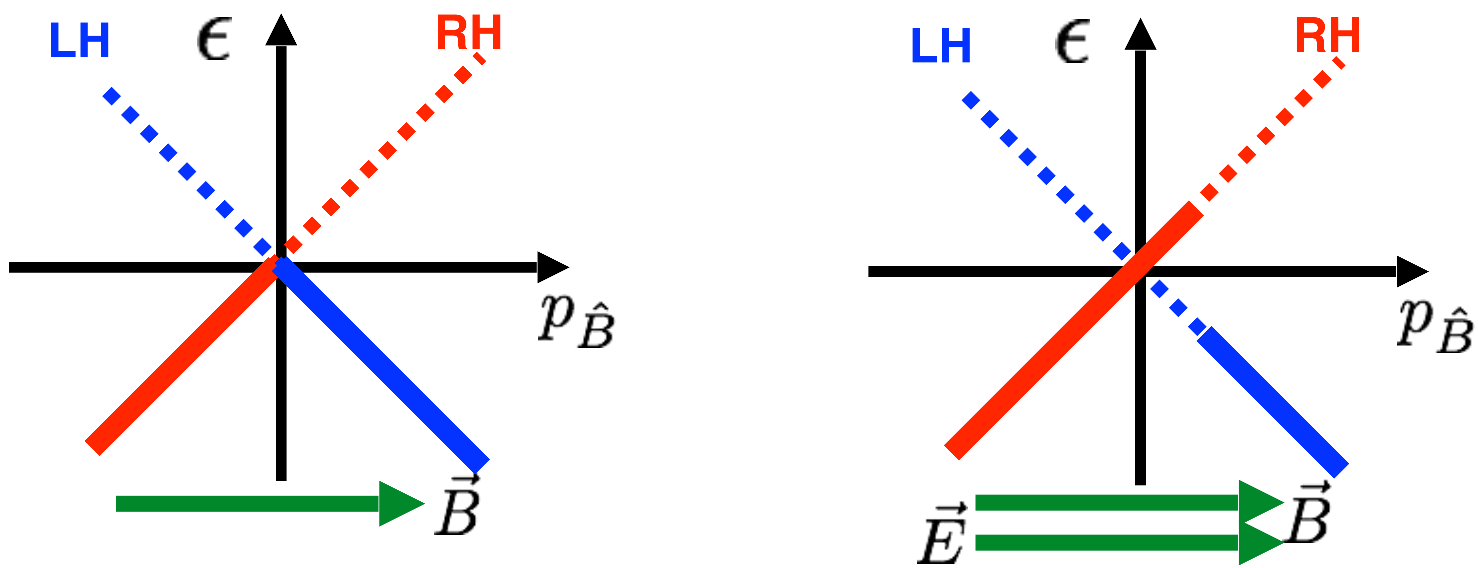
Chiral Anomaly

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

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

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

$$J_5^\mu = J_R^\mu - J_L^\mu$$



Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!

The Chiral Magnetic Effect

Chirality & Anomaly & Topology

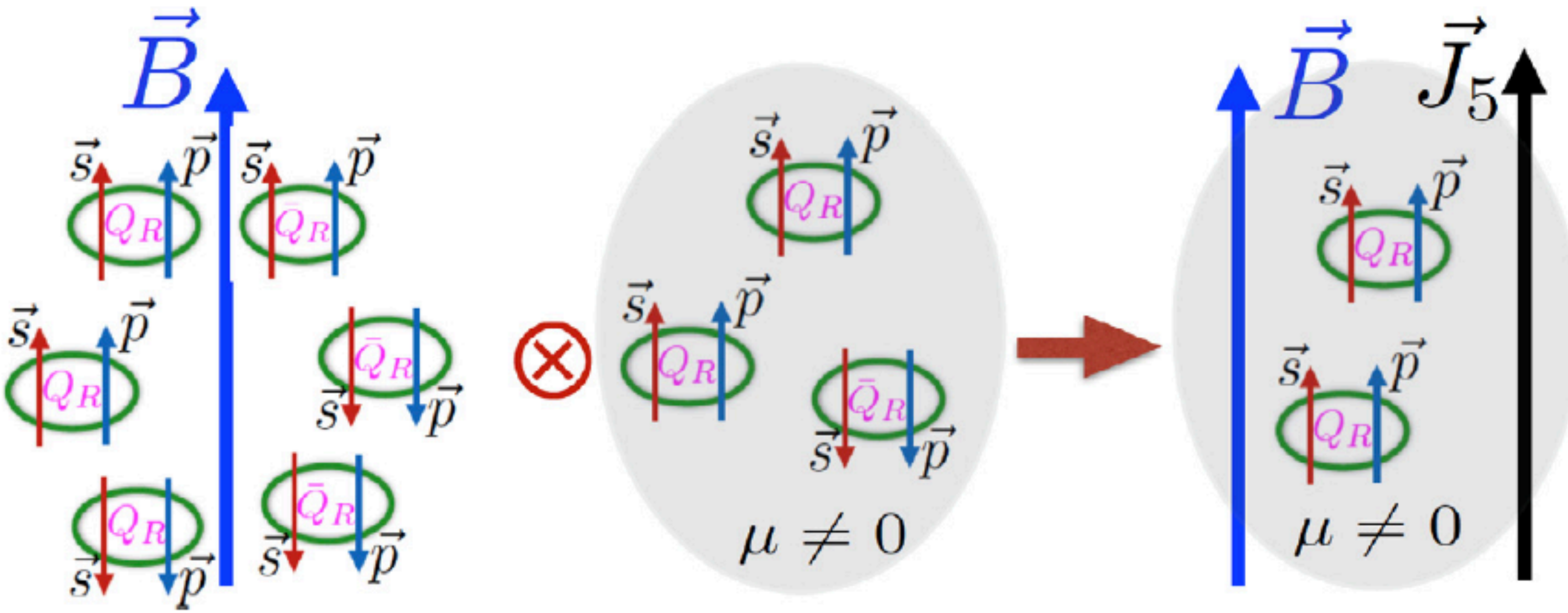
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current

Magnetic Field

Q.M. Transport

Intuitive Picture of CME



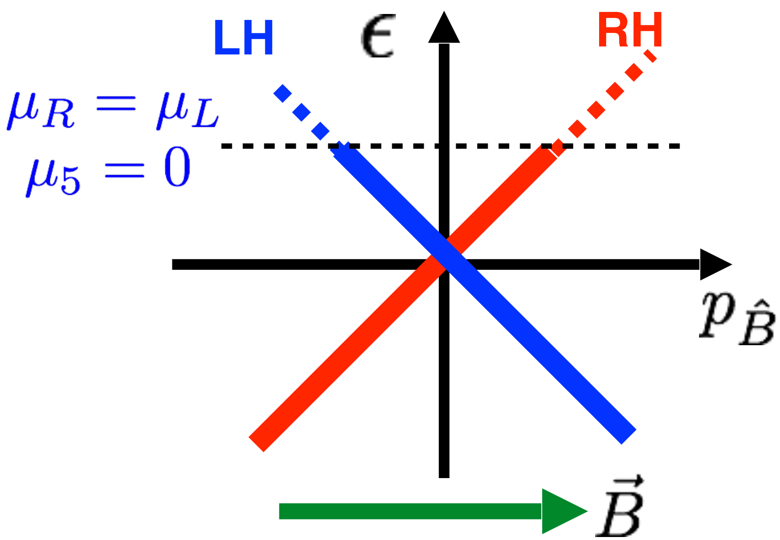
Intuitive understanding of CME:

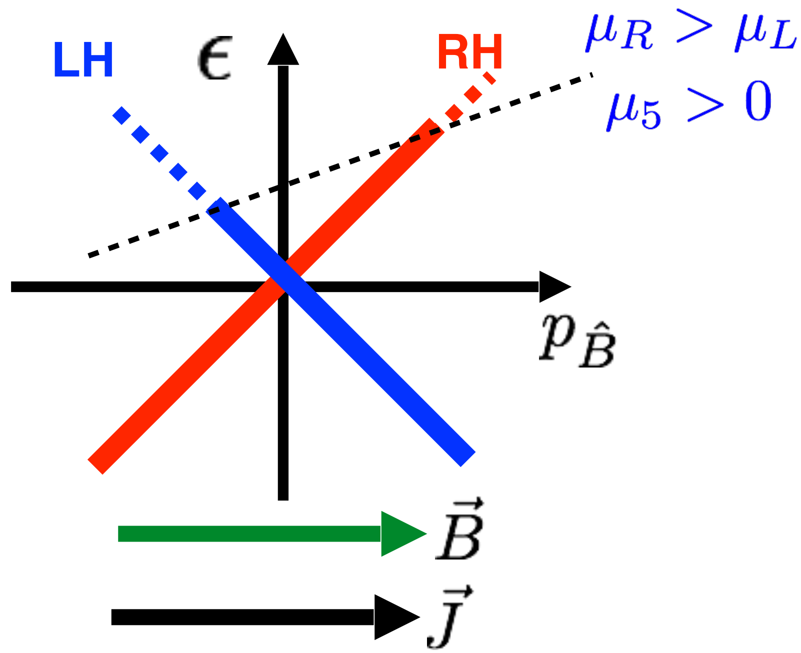
Magnetic polarization —> correlation between micro. SPIN & EXTERNAL FORCE $\otimes$ **Chiral imbalance —> correlation between directions of SPIN & MOMENTUM**

Transport current along magnetic field

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

From Anomaly to CME





One may recognize deep connection between CME & anomaly.

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

$$\updownarrow$$

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

The CME conductivity is

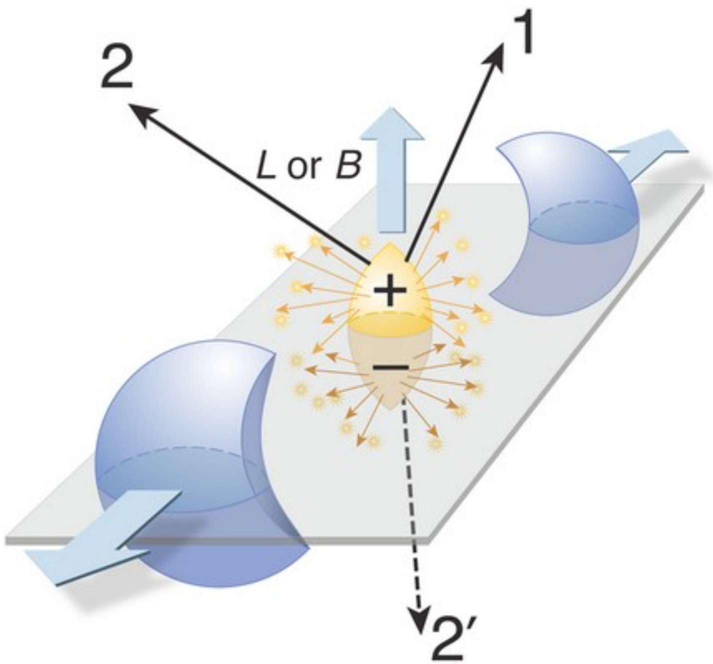
**** fixed entirely by quantum anomaly***

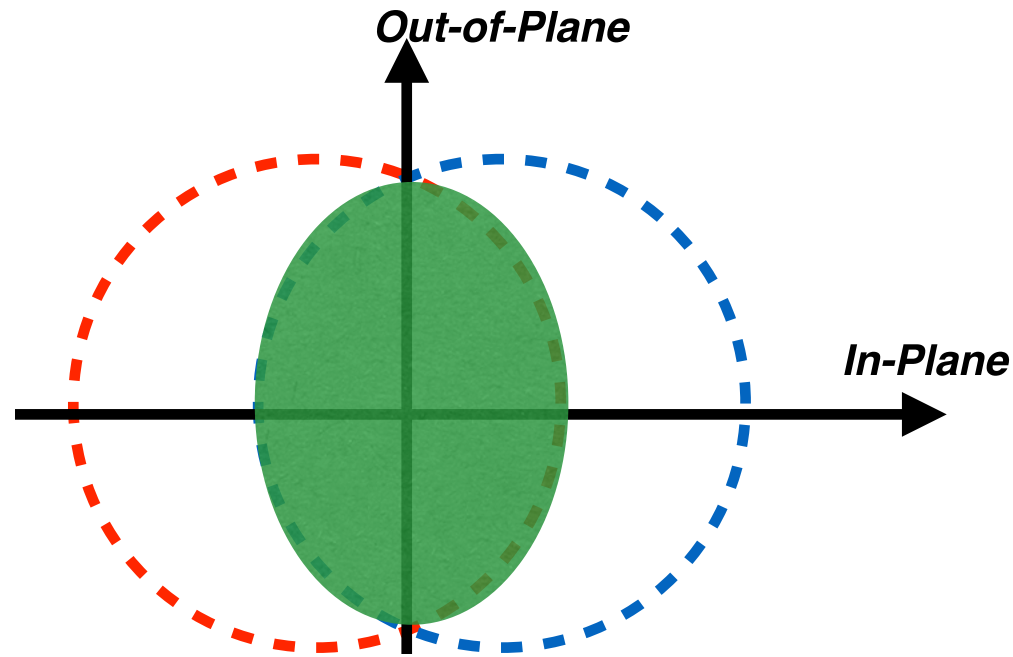
**** T-even, non-dissipative***

**** universal from weak to strong coupling***

We need to modify hydrodynamics!

New Phase & New Extreme Conditions

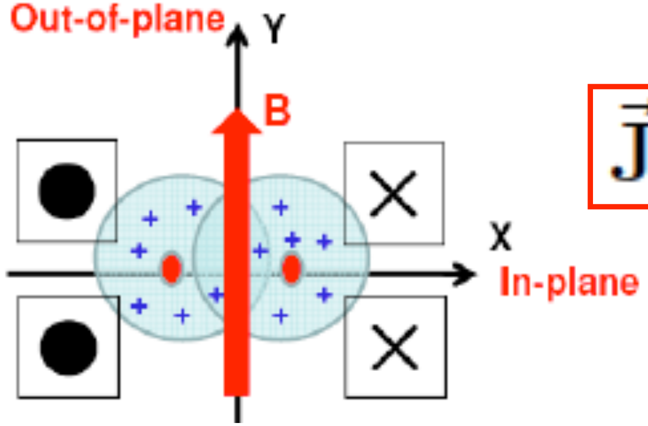




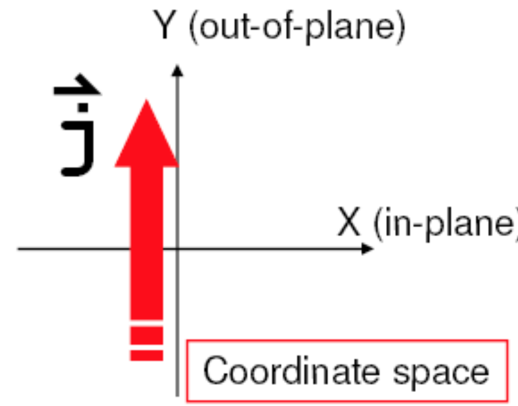
The quark-gluon plasma is a type of CHIRAL MATTER, with (approximately) chiral quarks.

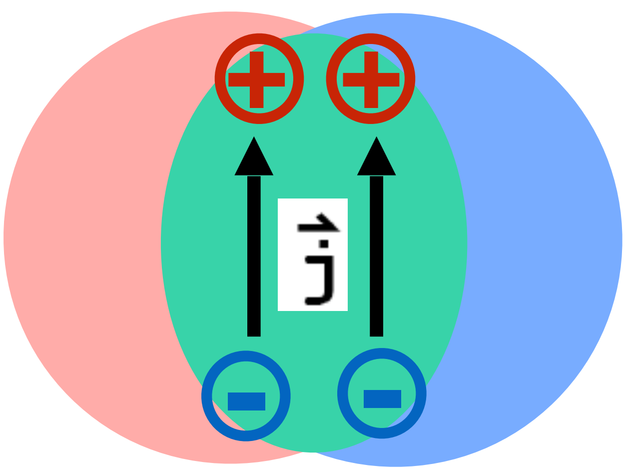
Heavy ion collision environment: extremely strong magnetic field and fluid rotation!

From CME Current to Charge Separation

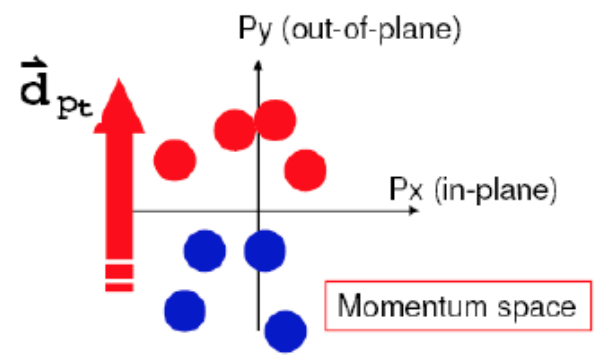


$$\boxed{\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}}$$





strong radial blast:
position —> momentum



Charge Separation *or*
Electric Dipole in Pt Space
(along ***out-of-plane****)*

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

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

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

Summarizing Exp. Search Status

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

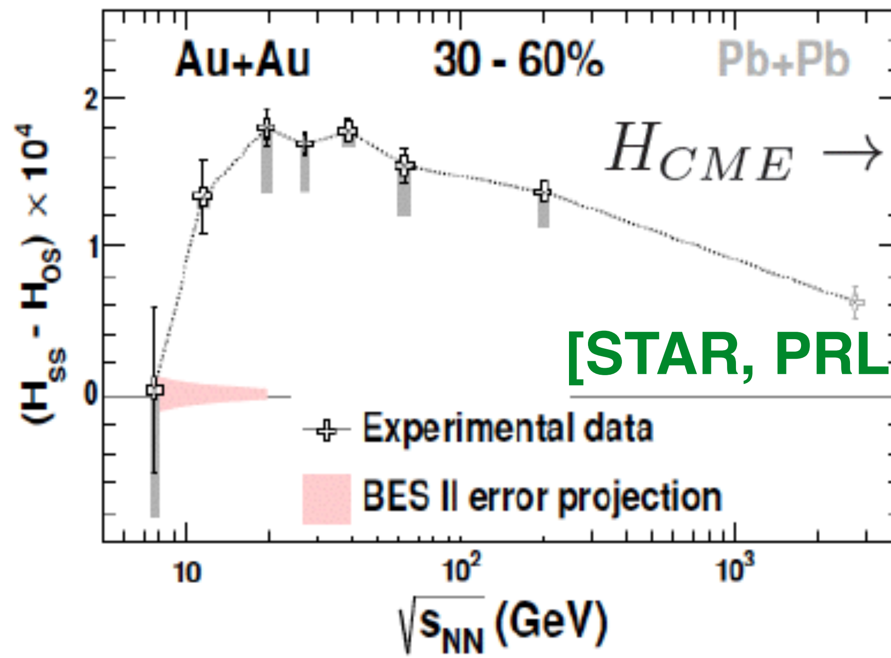
Vary v2 for fixed B:

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?

The AVFD Framework

From Micro. Laws To Macro. Phenomena

Micro. Laws:

Symmetry;
Lagrangian;
Conservation laws;
……

$\Longleftrightarrow$

Macro. Phenomena:

Thermodynamics;
Phase transitions;
Transport;
Hydrodynamics;
……

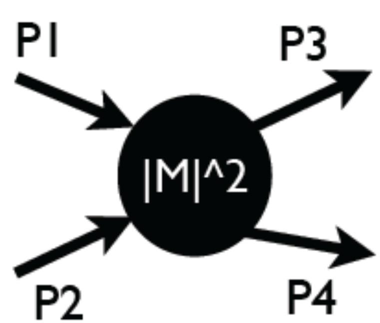
Would chiral anomaly, usually considered at microscopic level, manifest itself MACROSCOPICALLY in a many-body system of chiral fermions? If so, how?

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	$\partial_\mu J^\mu = 0$

$$\mathcal{L} \to \mathcal{L}$$



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

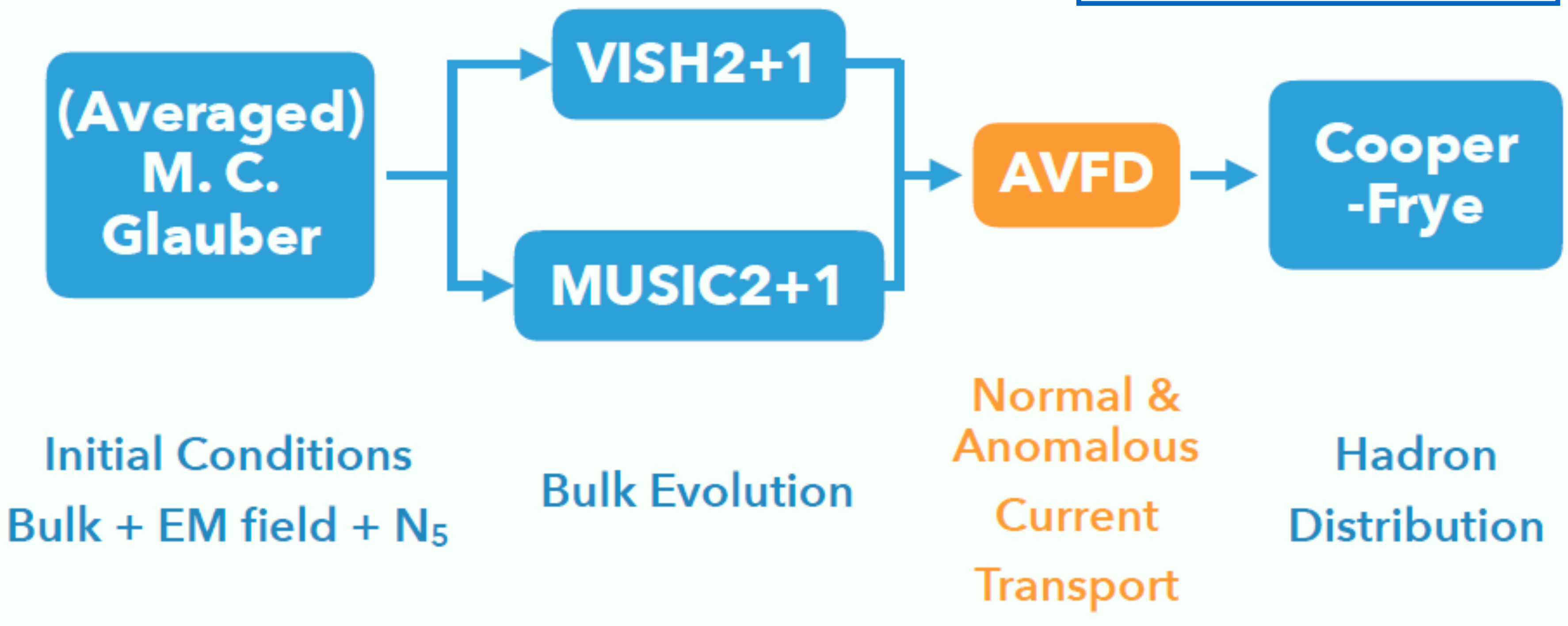
Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

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

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

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

Viscous Effect

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

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

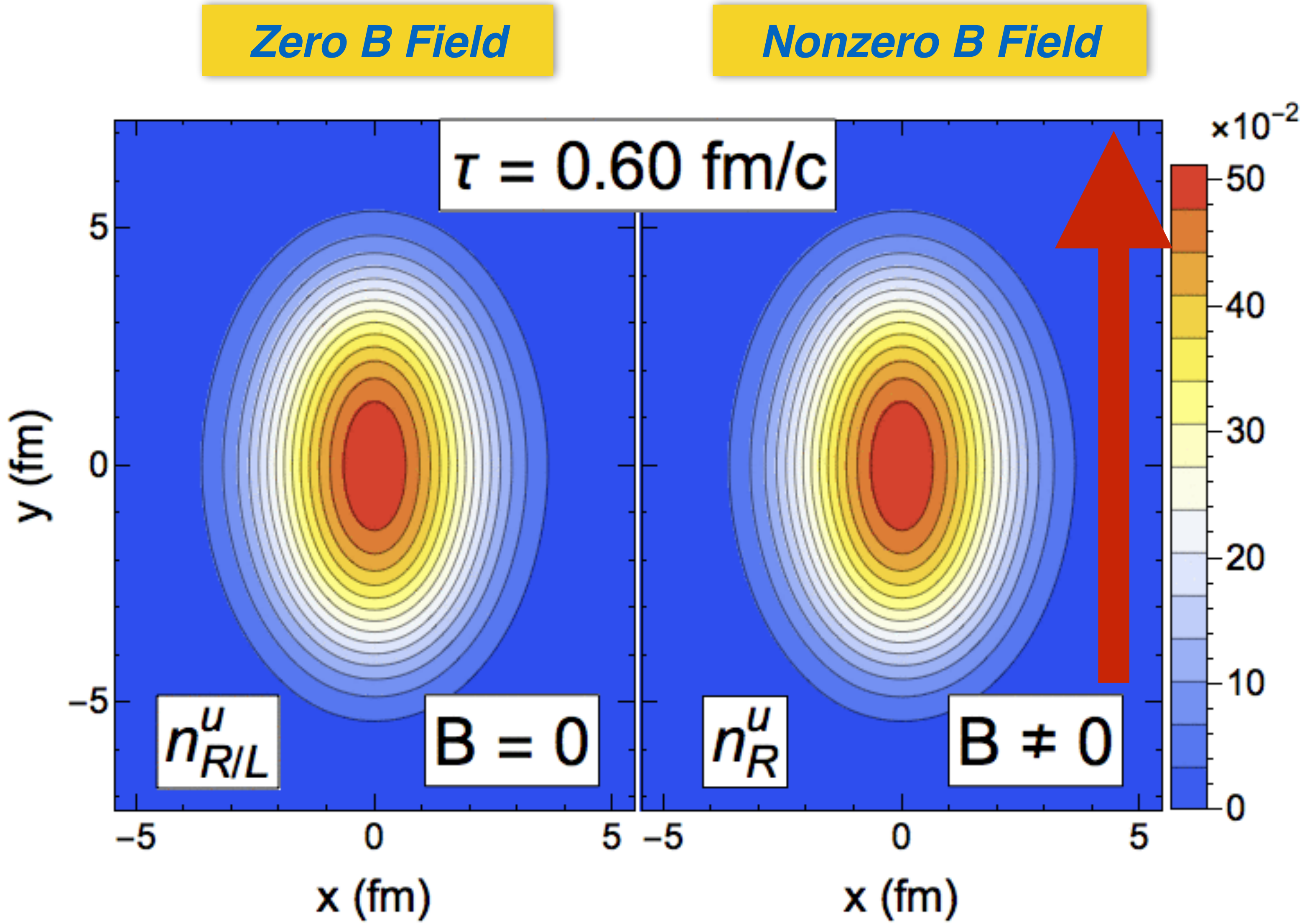
on top of VISH2+1D –– OSU Group

[We now also have MUSIC-AVFD!]

The AVFD Framework

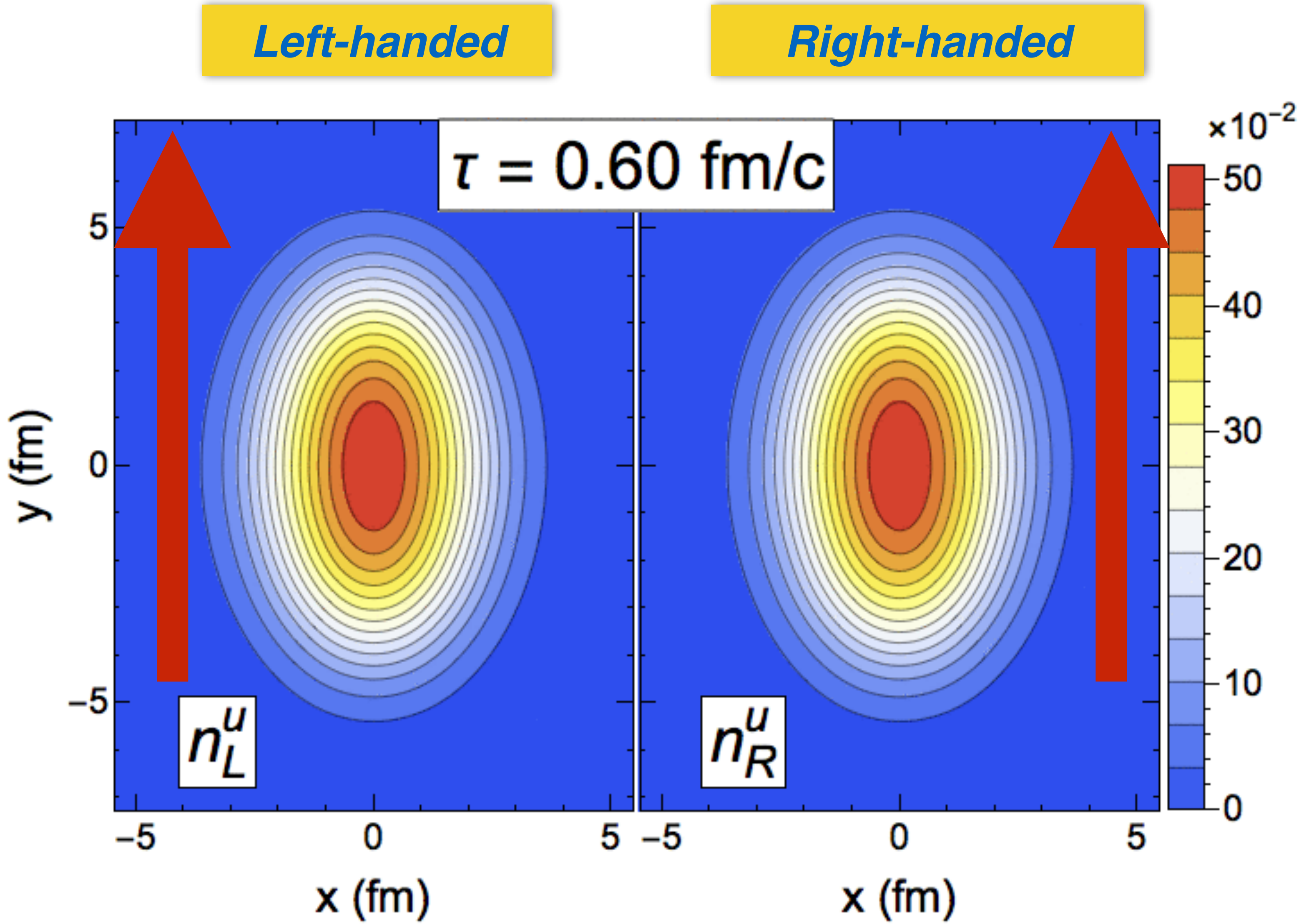
The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]



The AVFD At Work

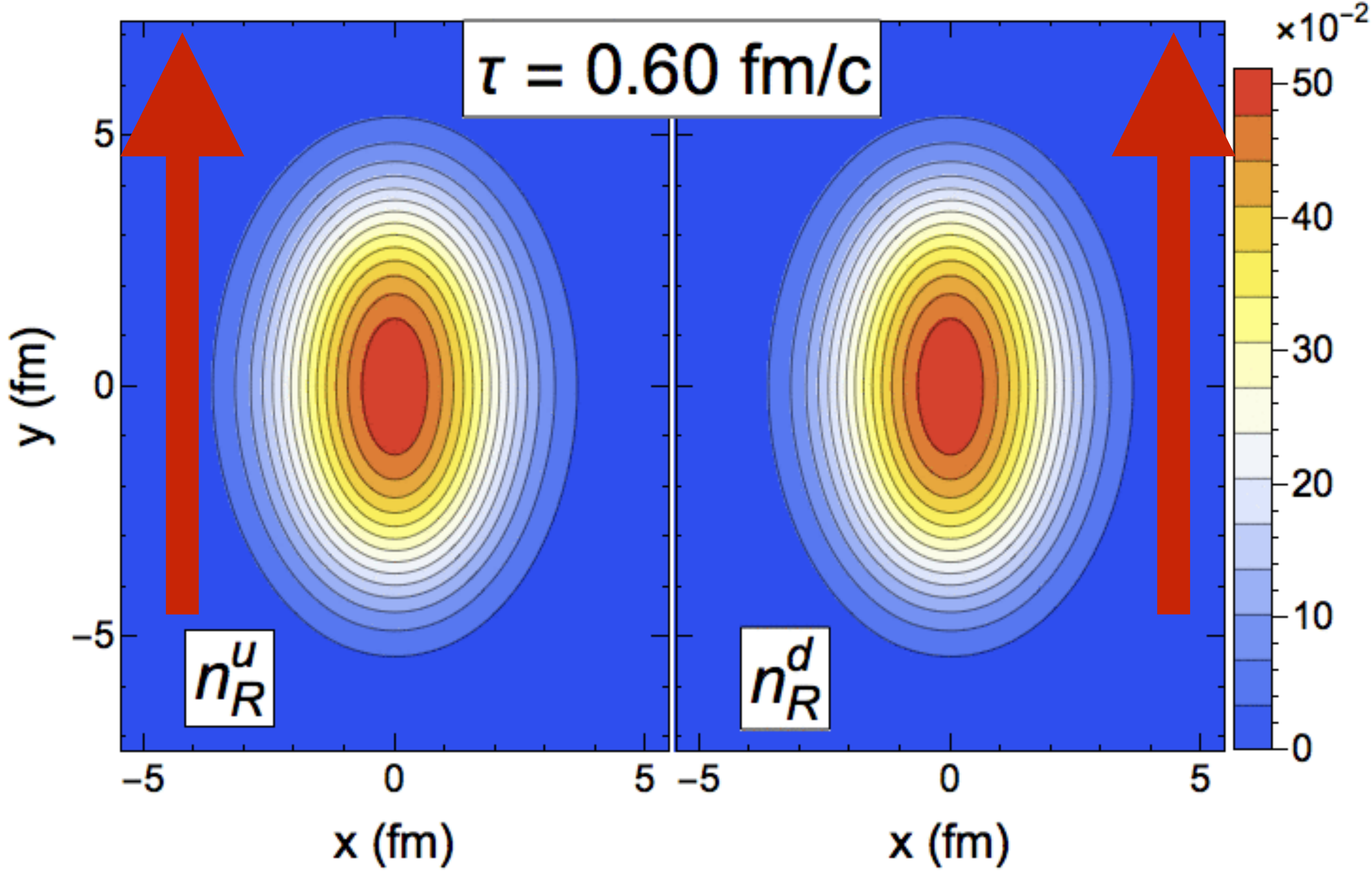
[arXiv:1611.04586; arXiv:1711.02496]



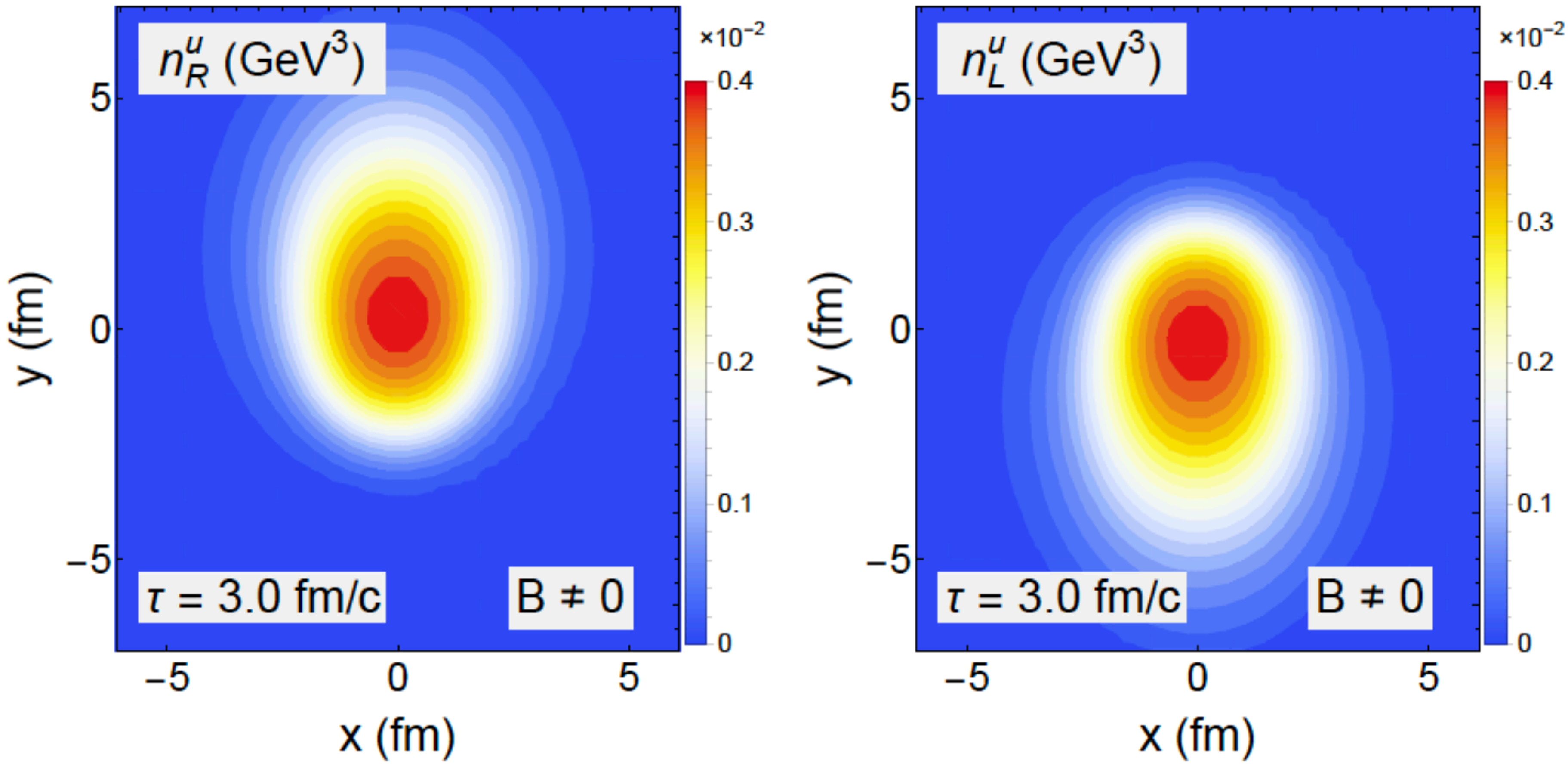
The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]

u-flavor *D-flavor*



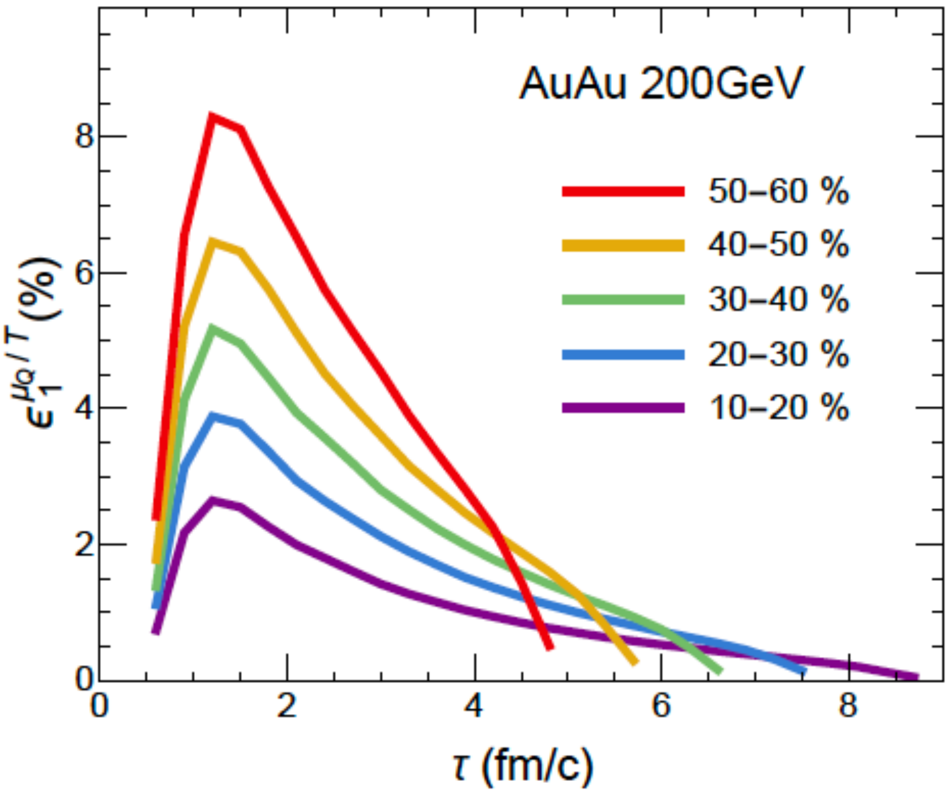
The Charge Separation from AVFD



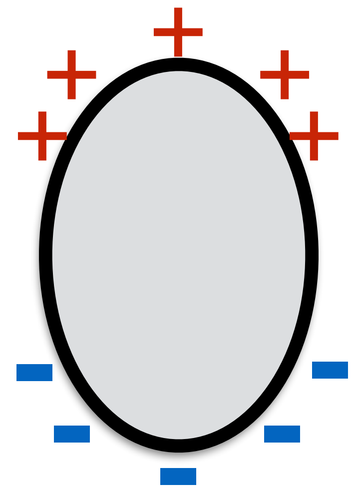
B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

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

The Charge Separation from AVFD



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



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

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

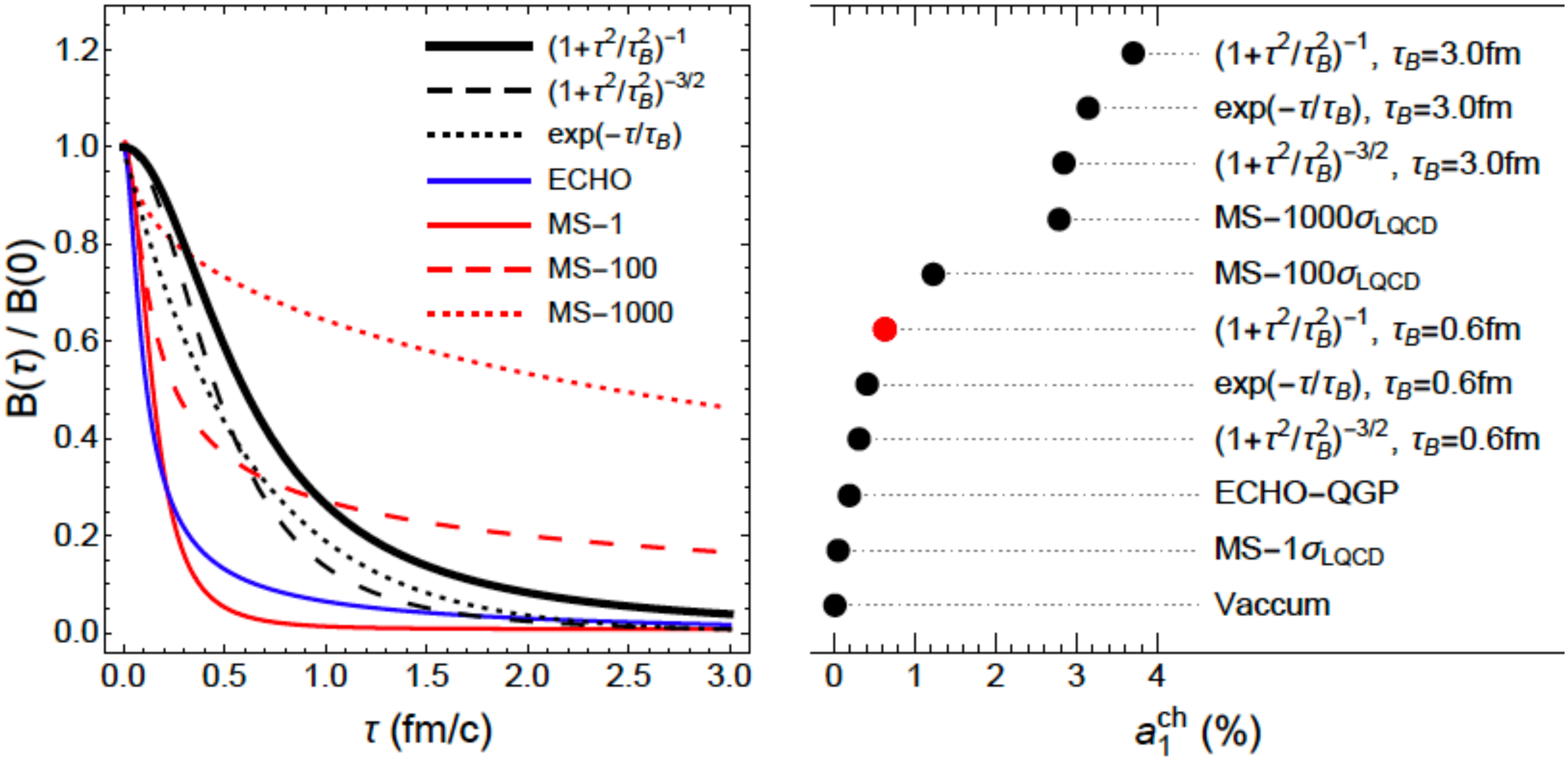
$$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$$

Detailed Results from AVFD

arXiv:1611.04586

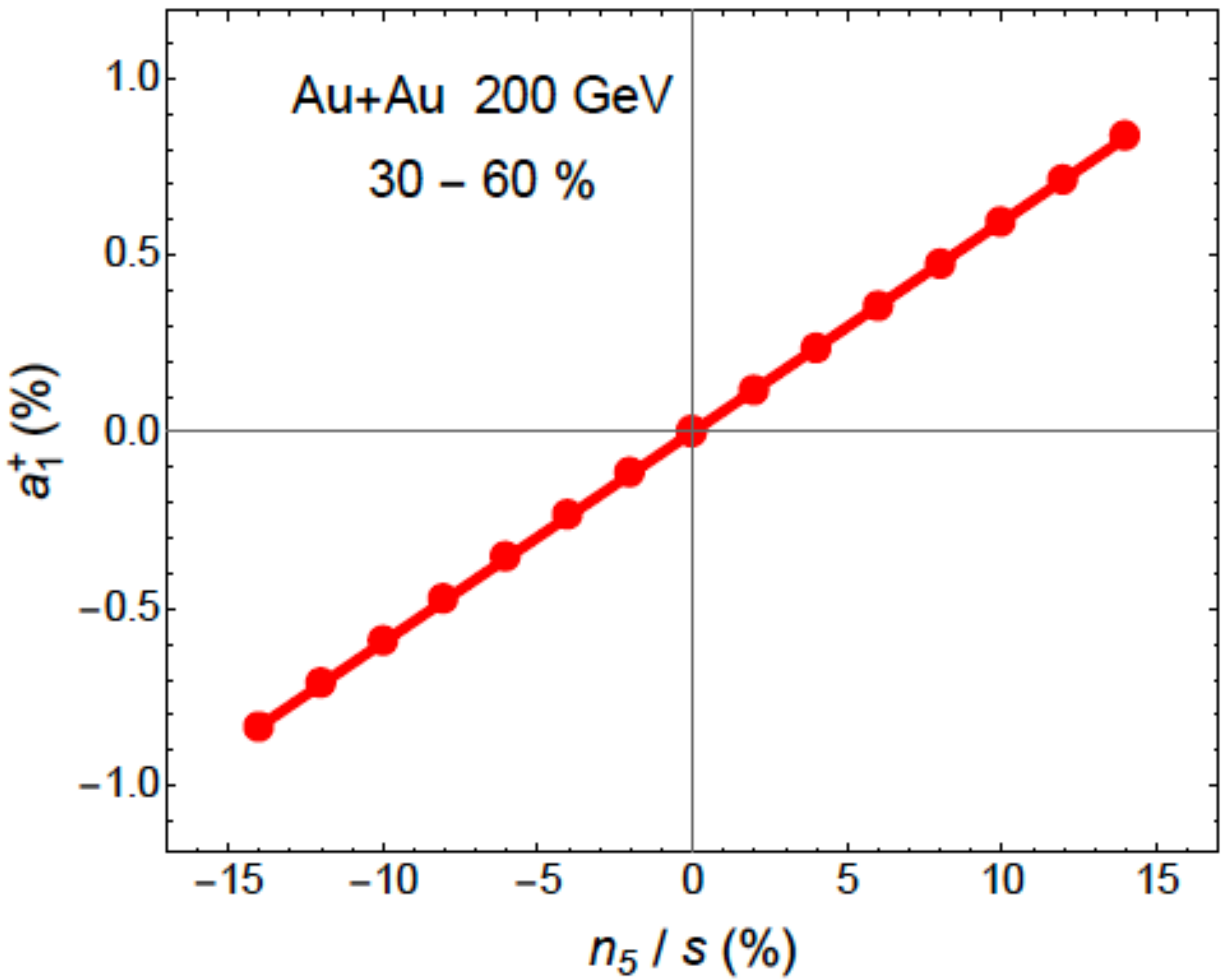
arXiv:1711.02496

The Influence of the Magnetic Field



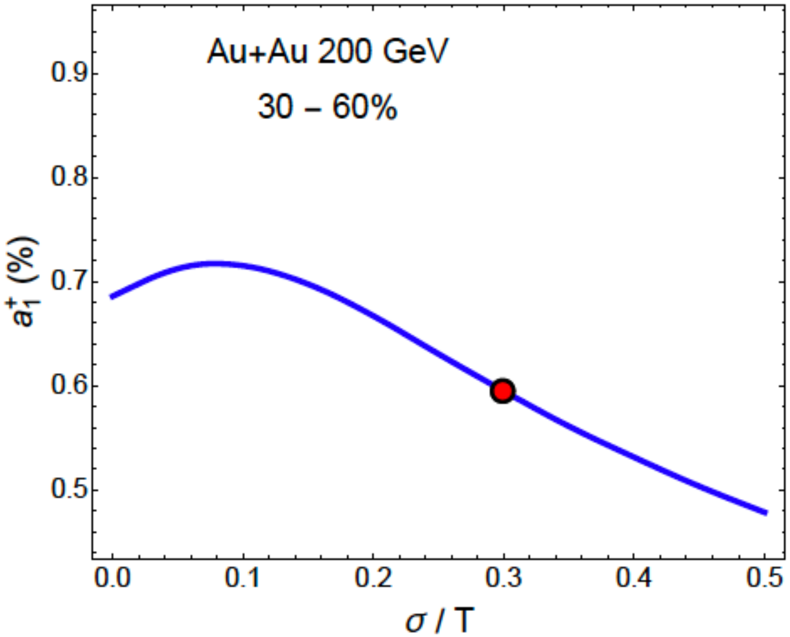
Strong influence by B field evolution;
Significant theoretical uncertainty!

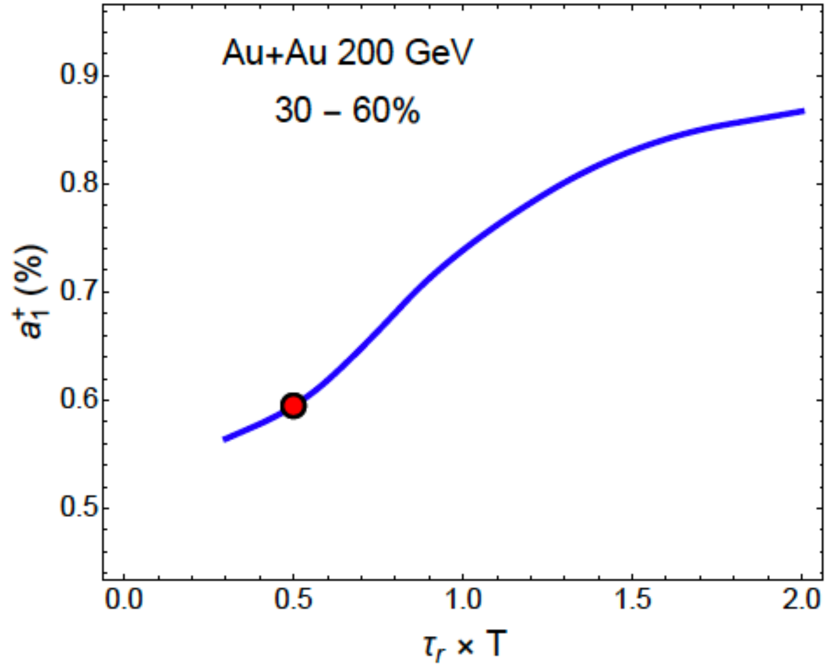
The Axial Charge Initial Condition



Very sensitive to initial axial charge;
Significant theoretical uncertainty!

The Influence of the Viscous Transport



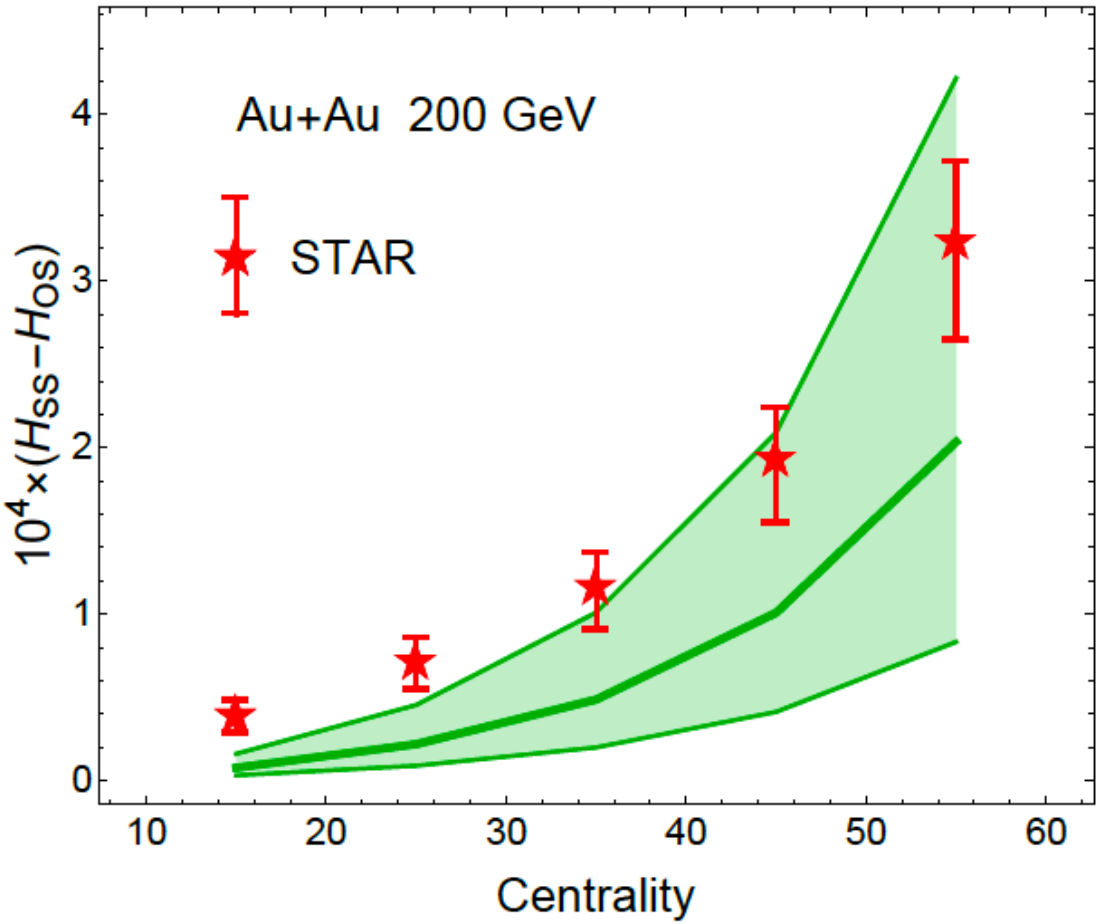


$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}\left(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu}\right)$$

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

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

AVFD Predictions v.s Experimental Data



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

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

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

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

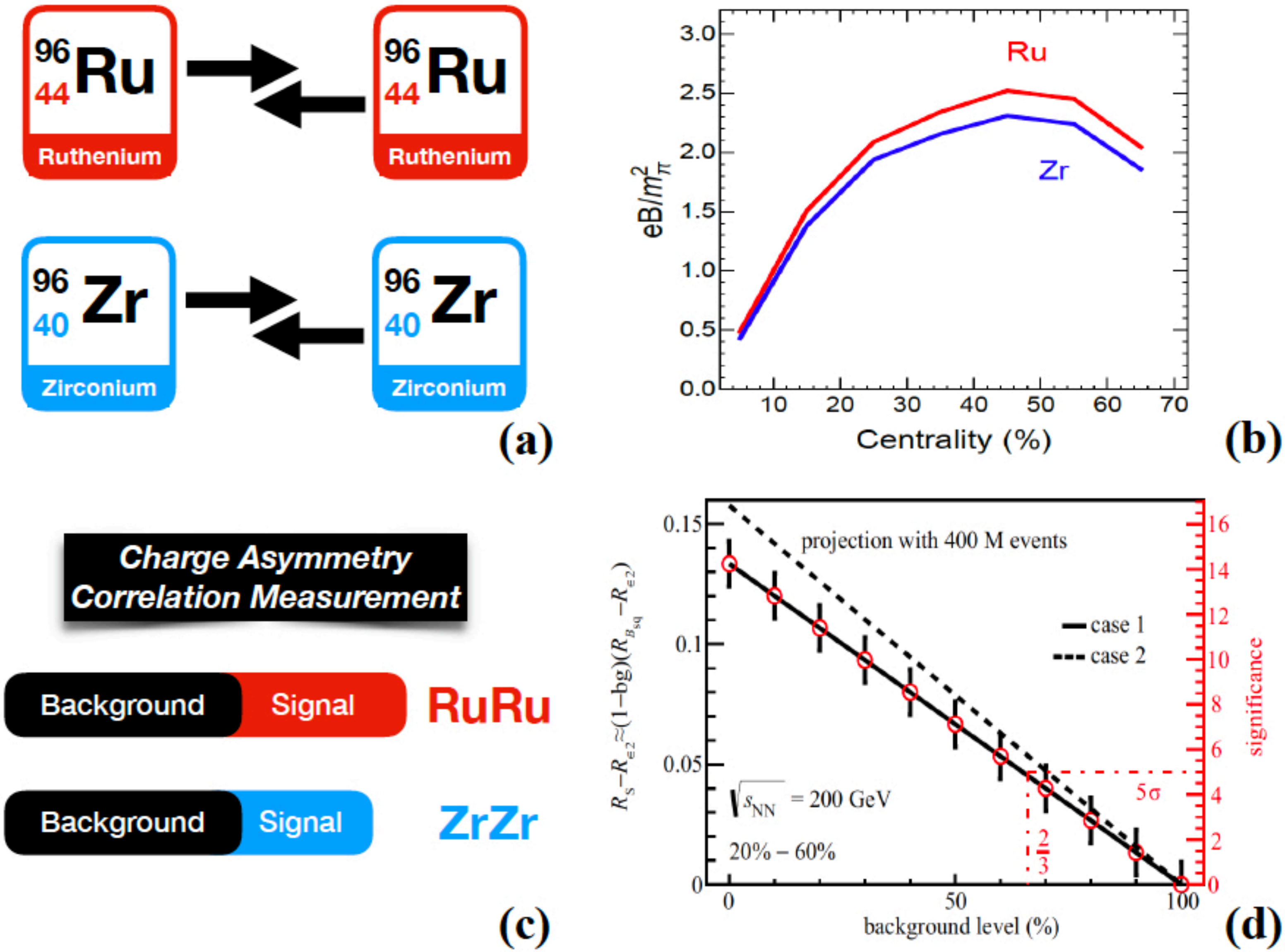
Table 1. Centrality dependence of magnetic field peak strength and the initial chirality imbalance. The n_5/s shown here is obtained with a saturation scale $Q_s^2 = 1.25\mathrm{GeV}^2$.

Isobaric Collisions

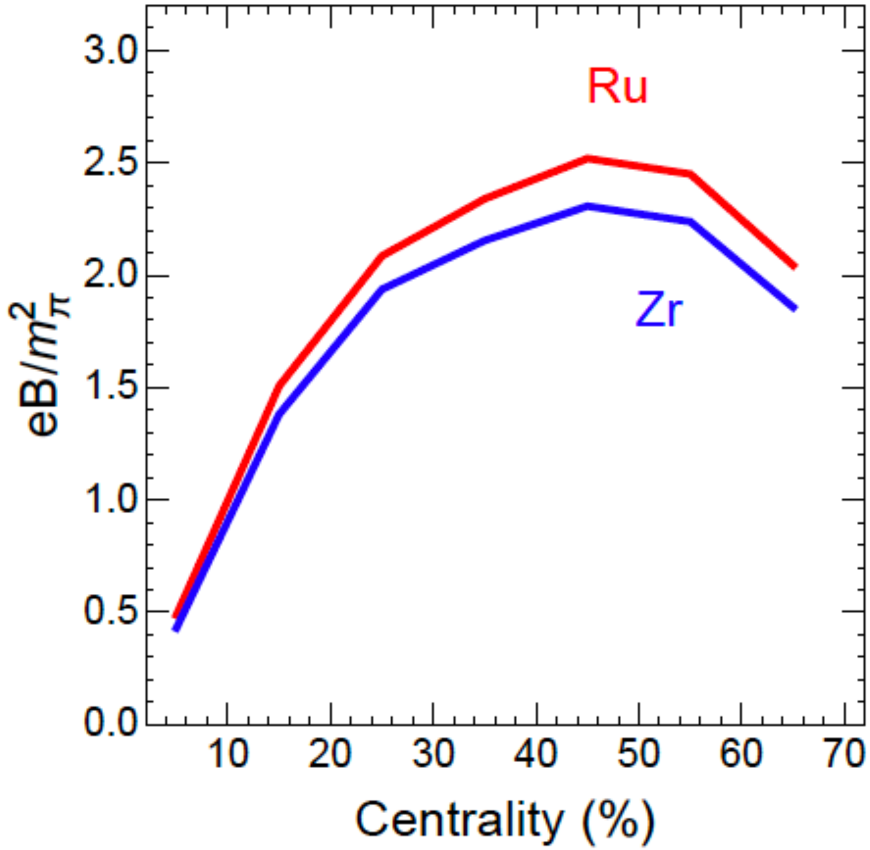
arXiv:1611.04586

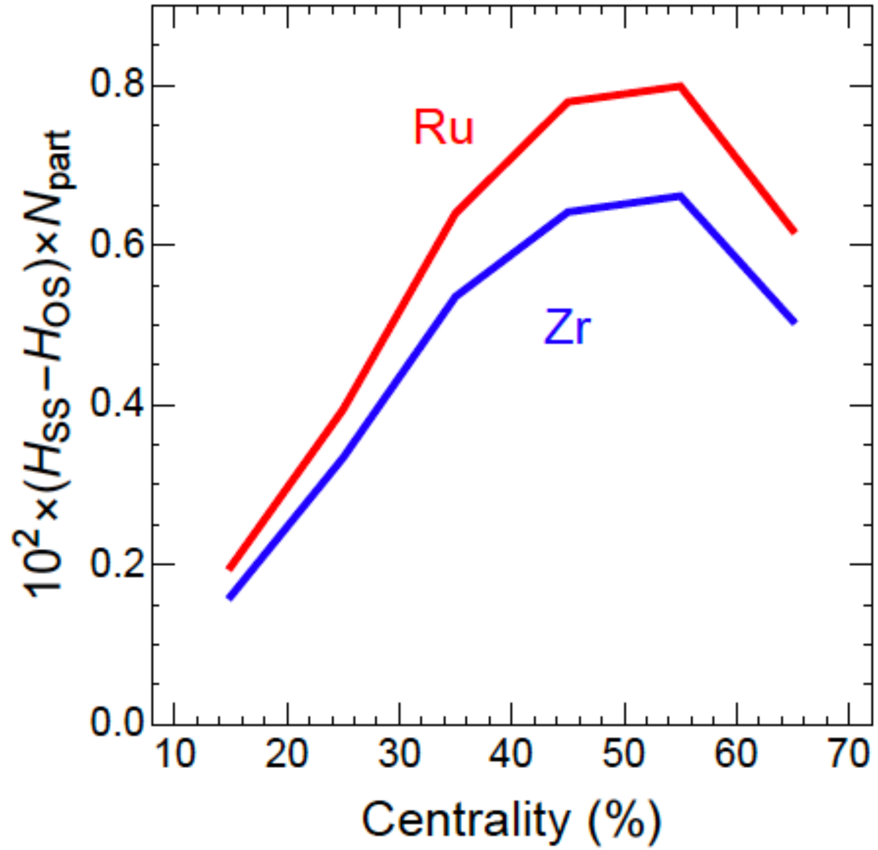
arXiv:1711.02496

Using Isobaric Collisions for CME Search



The Magnetic Fields and Signals of Isobars



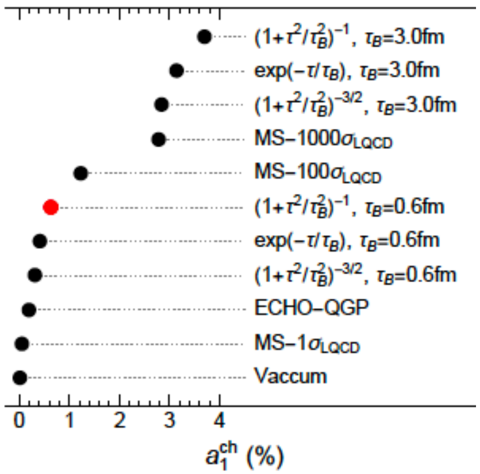


Note: B field projected onto participant plane!

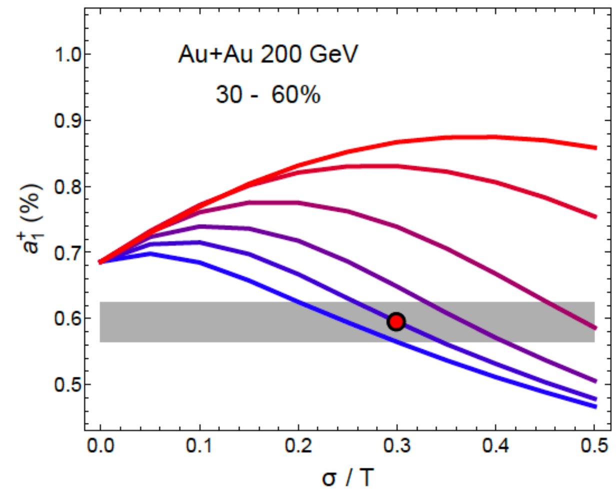
Expected variation of signal, 10~20%

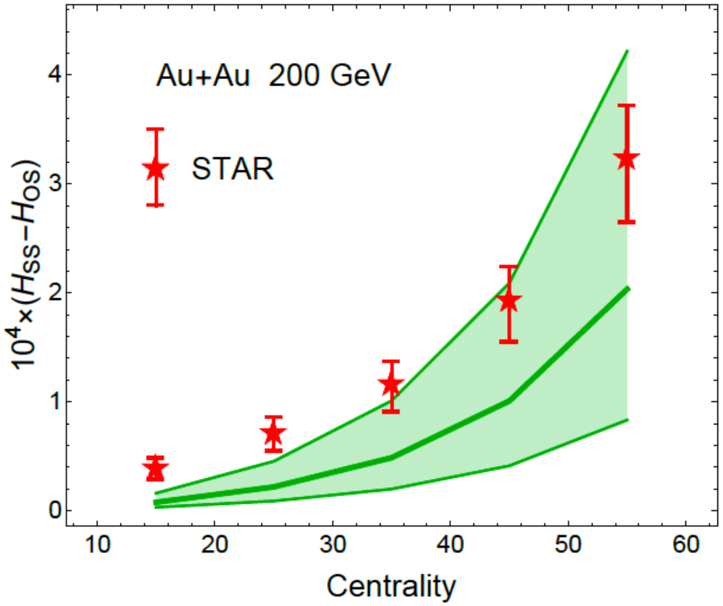
Summary & Outlook

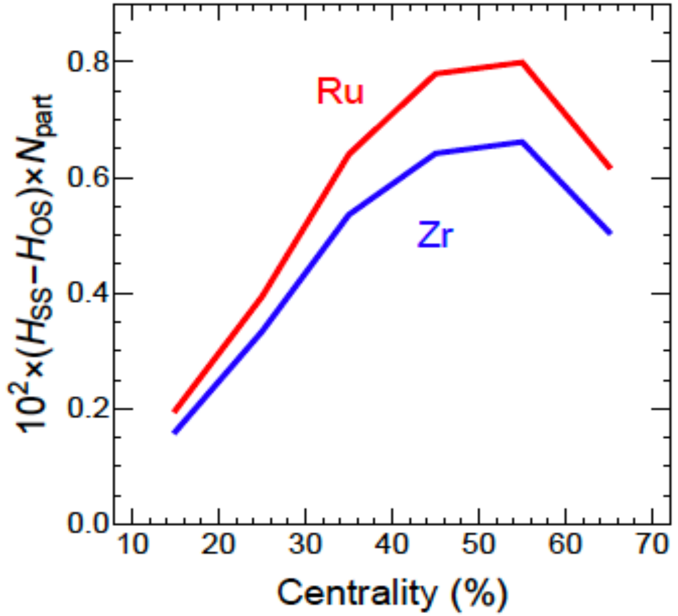
Summary



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

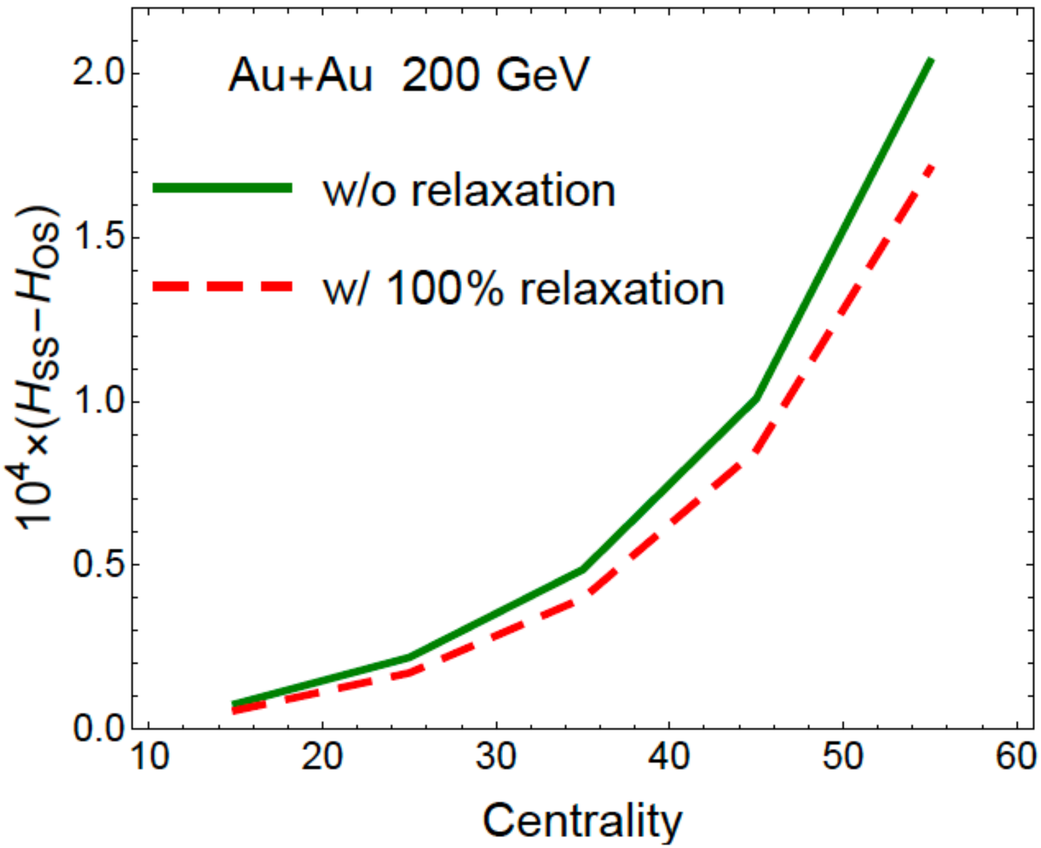






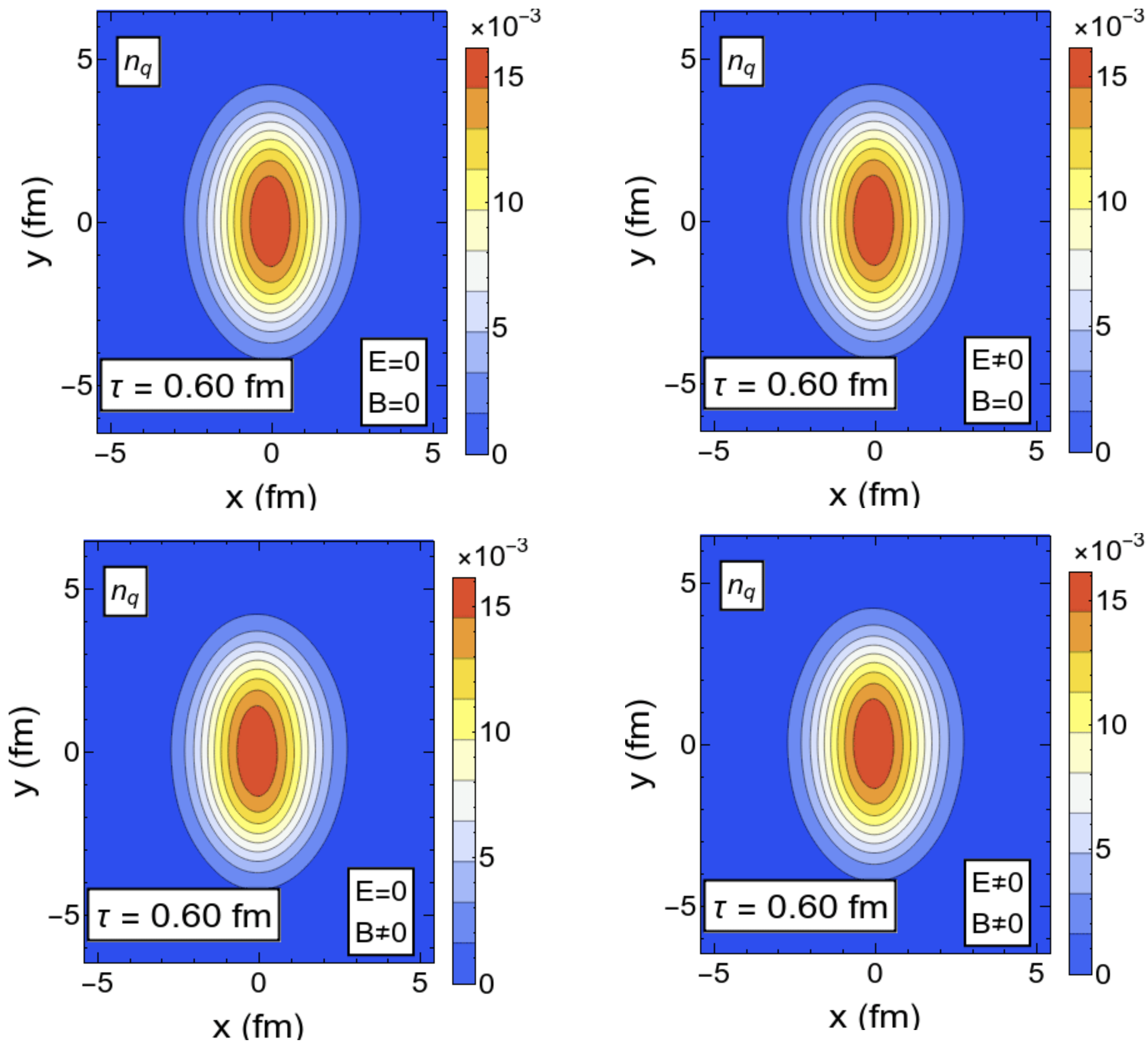
Relaxation of Anomalous Current ?

$$\hat{D}_\mu J^\mu_{\chi,f} = \chi \frac{N_c Q_f^2}{4\pi^2} E_\mu B^\mu$$
$$J^\mu_{\chi,f} = n_{\chi,f}\, u^\mu + \nu^\mu_{\chi,f}$$
$$\Delta^\mu{}_\nu \hat{d}\left(\nu^\nu_{\chi,f}\right) = -\frac{1}{\tau_r}\left[\left(\nu^\mu_{\chi,f}\right) - \left(\nu^\mu_{\chi,f}\right)_{NS}\right]$$
$$\left(\nu^\mu_{\chi,f}\right)_{NS} = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu\left(\frac{\mu_{\chi,f}}{T}\right) + \frac{\sigma}{2} Q_f E^\mu + \chi \frac{N_c Q_f}{4\pi^2}\mu_{\chi,f} B^\mu$$



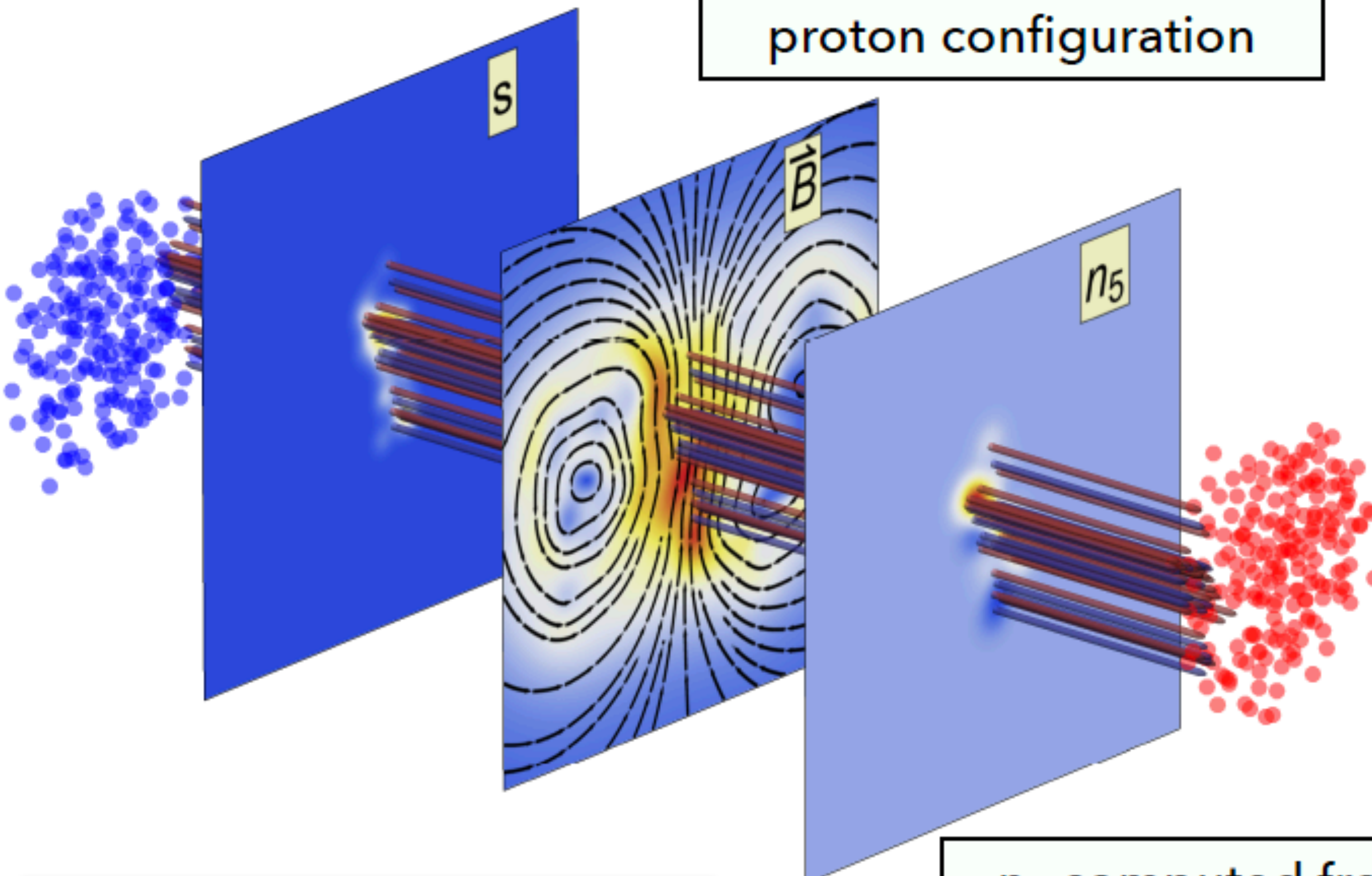
Also exploring effects from axial fluctuations/ dissipations

Electric Field Induced Transport



Interesting to explore E/B induced transport in CuAu collisions

Toward EBE-AVFD: Stay Tuned!



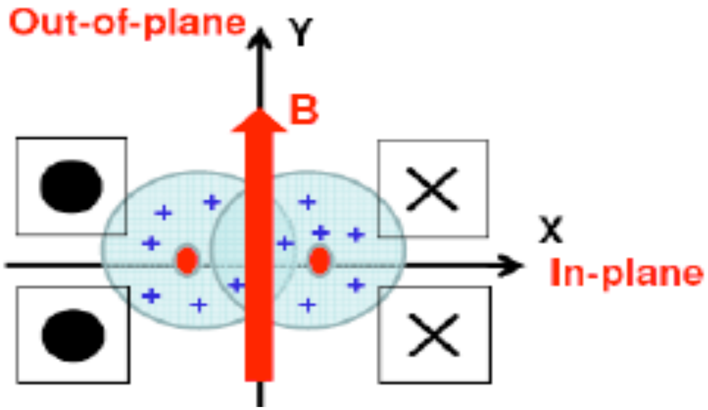
EM field computed from proton configuration

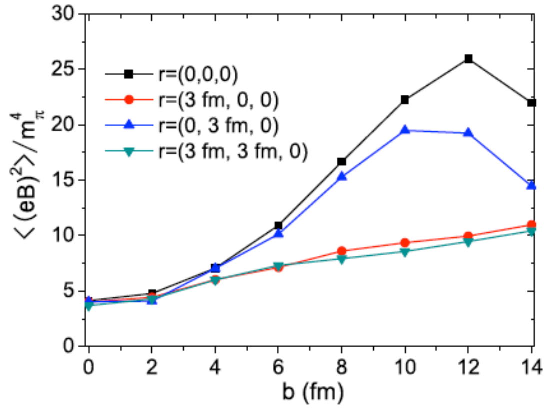
n_5 computed from initial binary collisions

See QM18 talk at Venice!

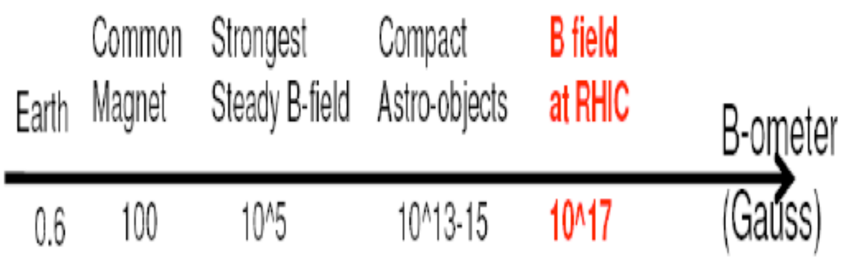
Backup Slides

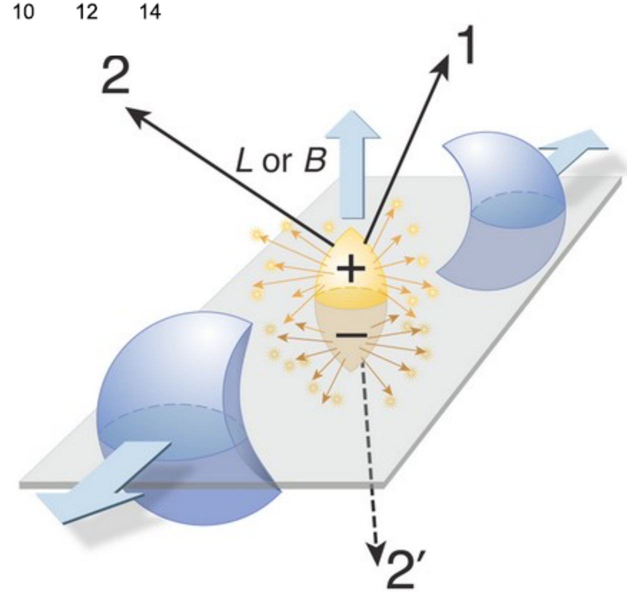
Strong EM Fields in Heavy Ion Collisions





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





- 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)

Experimental Observable

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

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

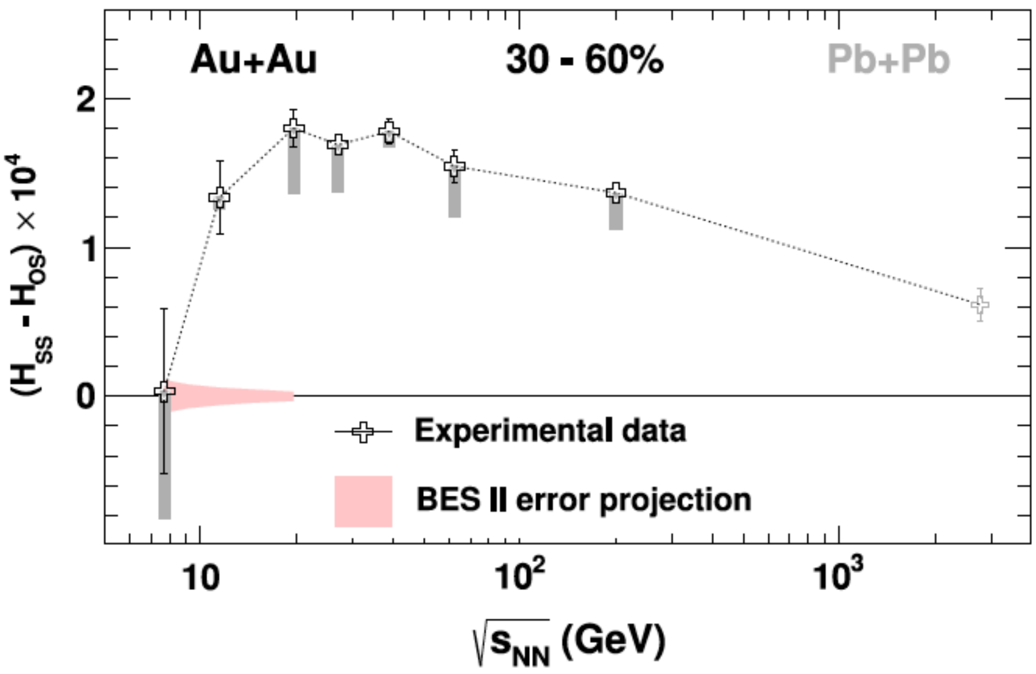
$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

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

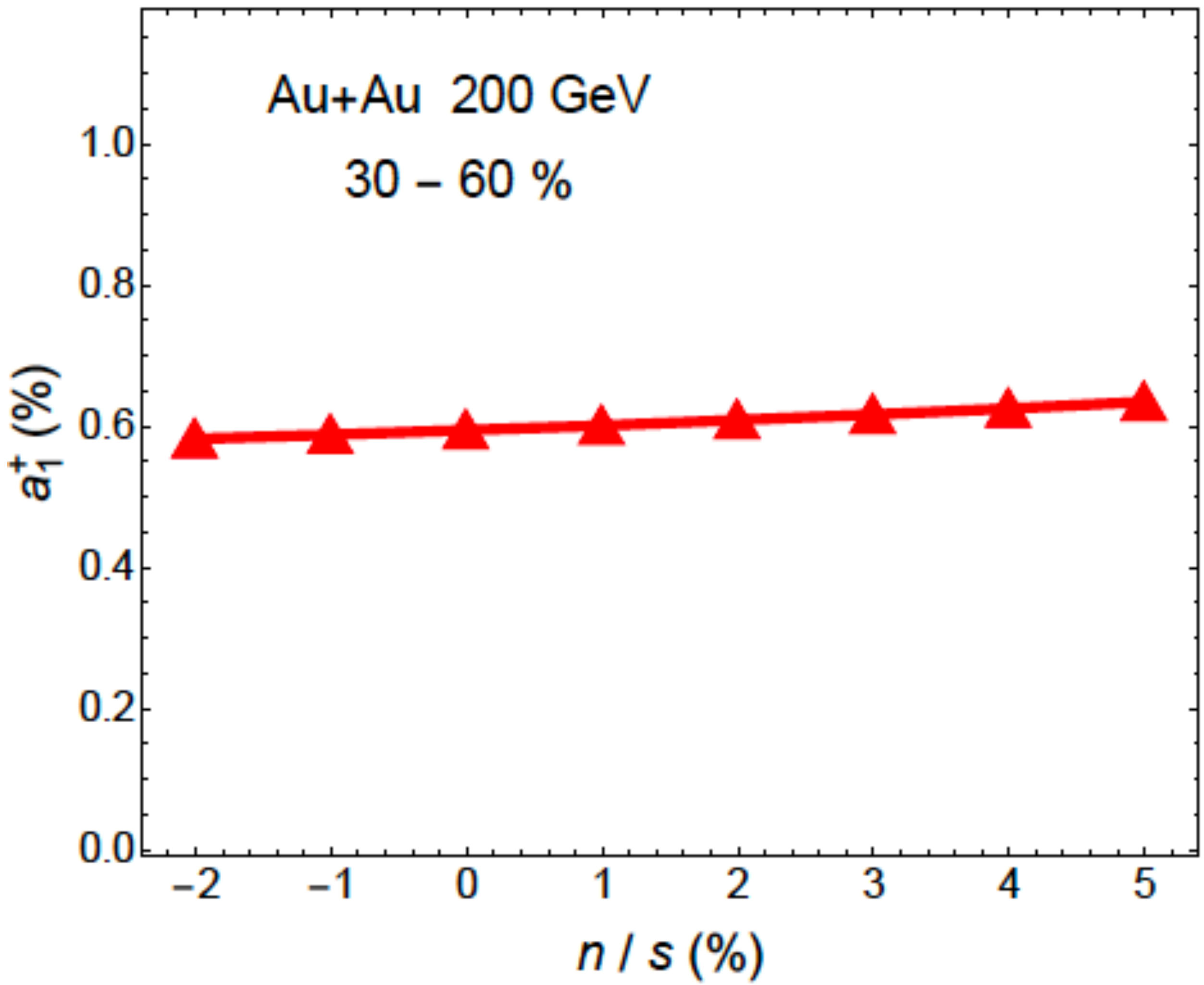
$\delta = F + H$ H: Possible Pure CME Signal = $(a_{1,CME})^2$

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

Many interesting proposals of new observables!

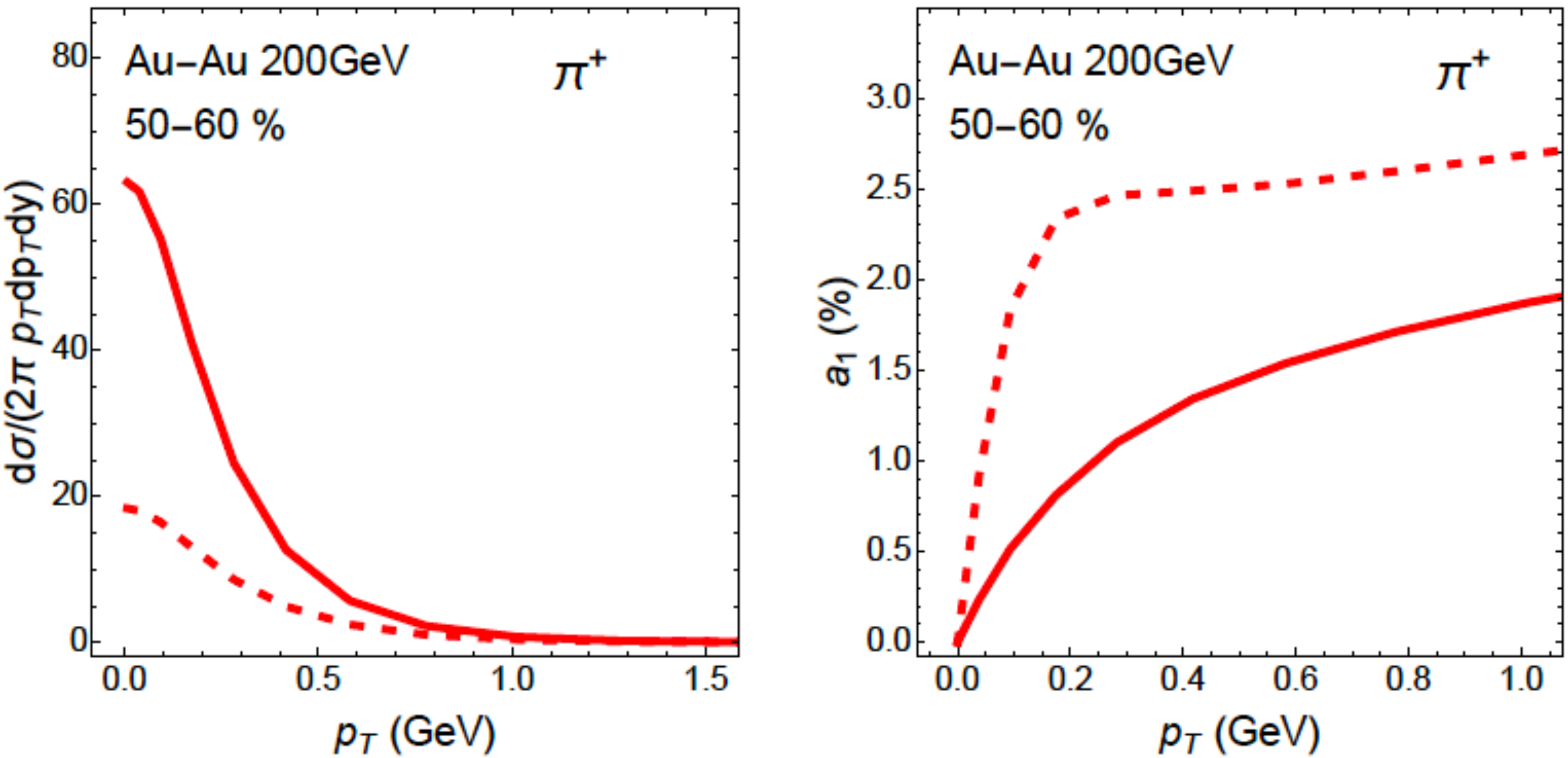


The Vector Charge Initial Condition



Insensitive to nonzero vector charge density

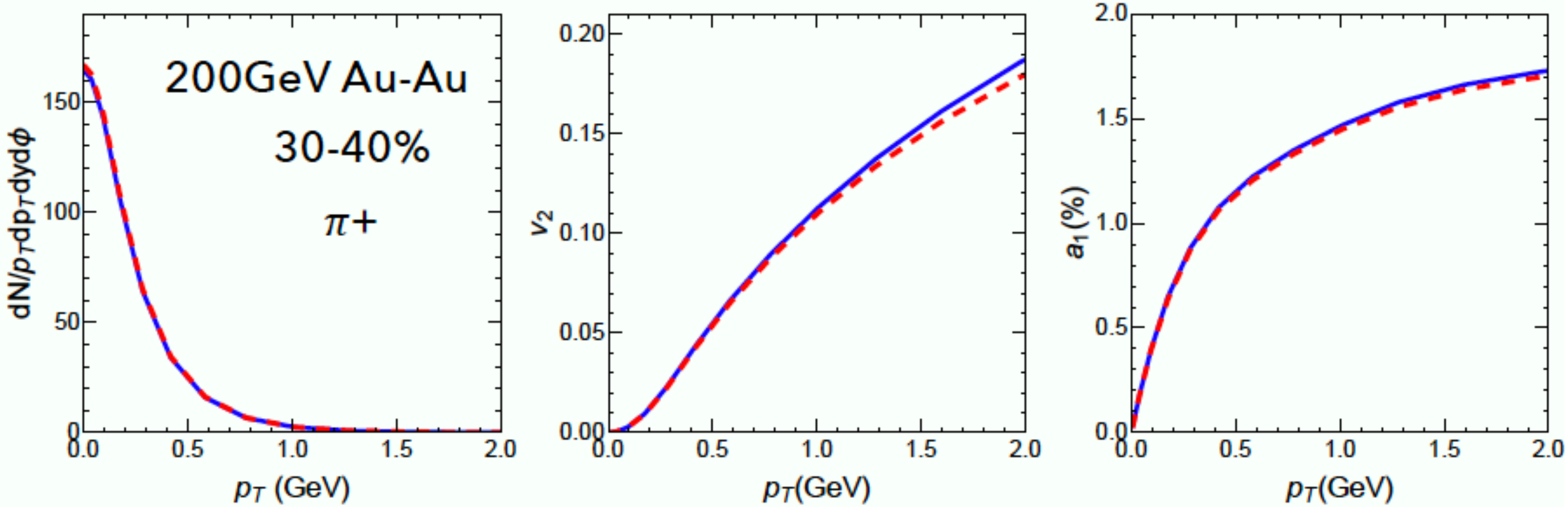
The Influence of the Resonance Decays



Considerable impact from resonance decays;
Must be included for quantitative results!

Toward MUSIC-AVFD

MUSIC(2+1) + AVFD versus VISH(2+1) + AVFD



Blue = MUSIC(2+1) + AVFD

Red = VISH(2+1) + AVFD

match with each other
(with the same set-up)

Special thanks to: MUSIC by McGill-BNL Group

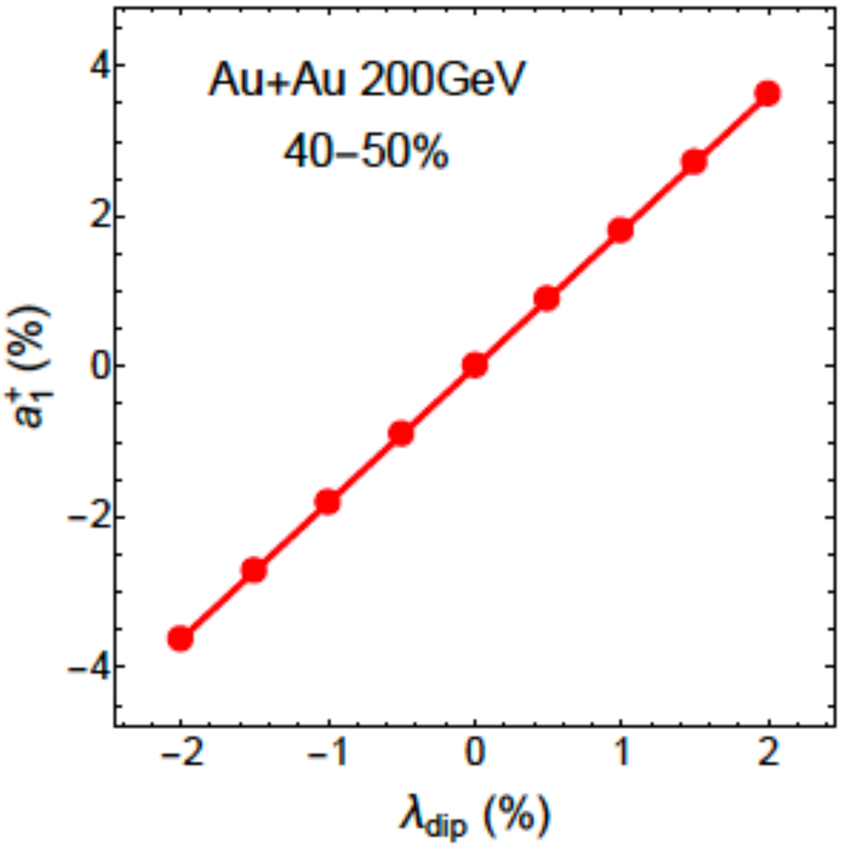
Pre-Hydro CME ??

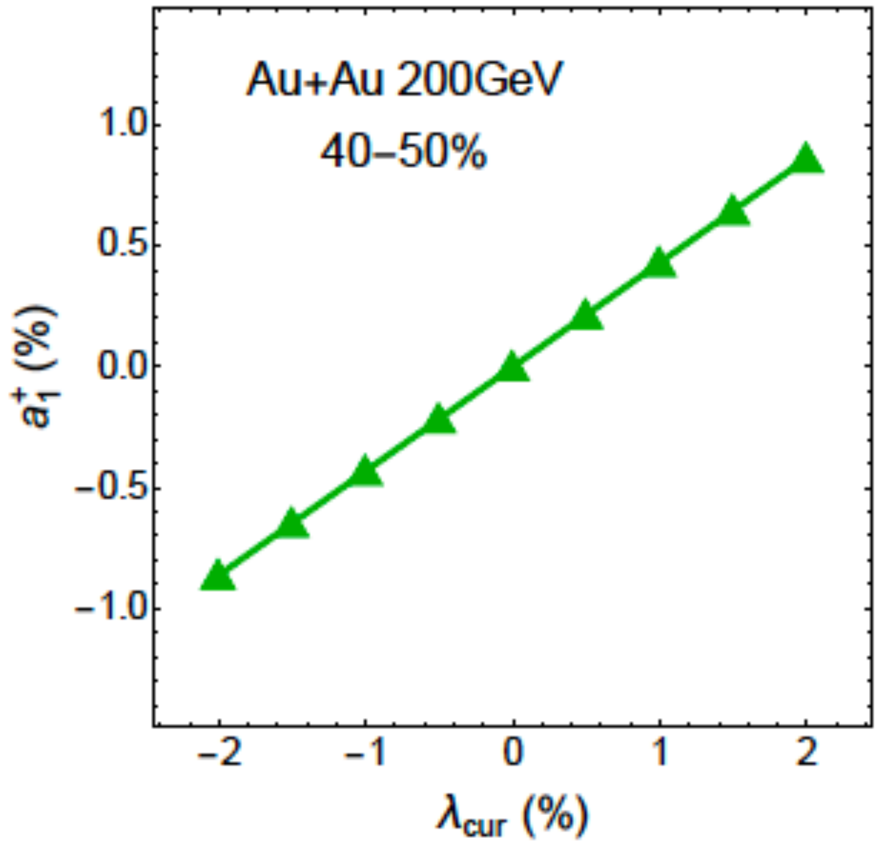
$$n_{\mathrm{ini},f} = (\lambda_{0,f} + \lambda_{\mathrm{dip},f} \sin\phi)\, s_0.$$

$$\lambda_{\mathrm{dip}} \equiv \lambda_{\mathrm{dip},u} = -2\lambda_{\mathrm{dip},d},$$

$$\nu_f|_{\tau=\tau_0} = J_{\mathrm{ini},f} = \lambda_{\mathrm{cur},f}\, s_0\, \hat{y},$$

$$\lambda_{\mathrm{cur}} \equiv \lambda_{\mathrm{cur},u} = -2\lambda_{\mathrm{cur},d}.$$





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