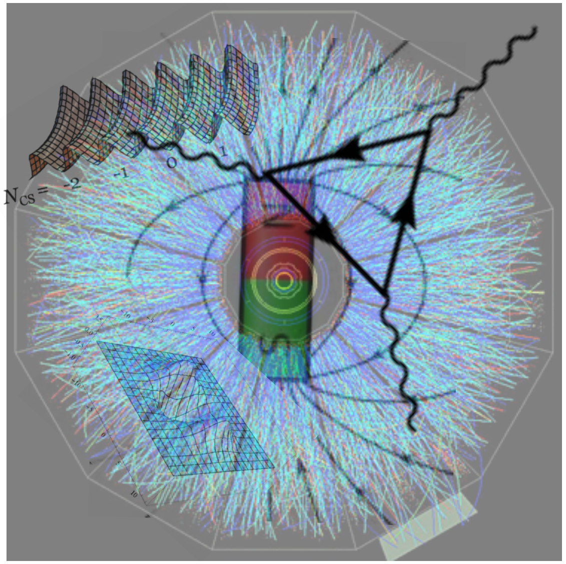
QM2018 @ Venice May. 13~19, 2018

Chiral Magnetic Effect in Isobaric Collisions from Anomalous-Viscous Fluid Dynamics (AVFD)



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by U.S. NSF & DOE and by the IAS of Indiana University

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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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Annals of Physics 394 (2018) 50–72

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ANNALS of PHYSICS

Check for updates

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

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

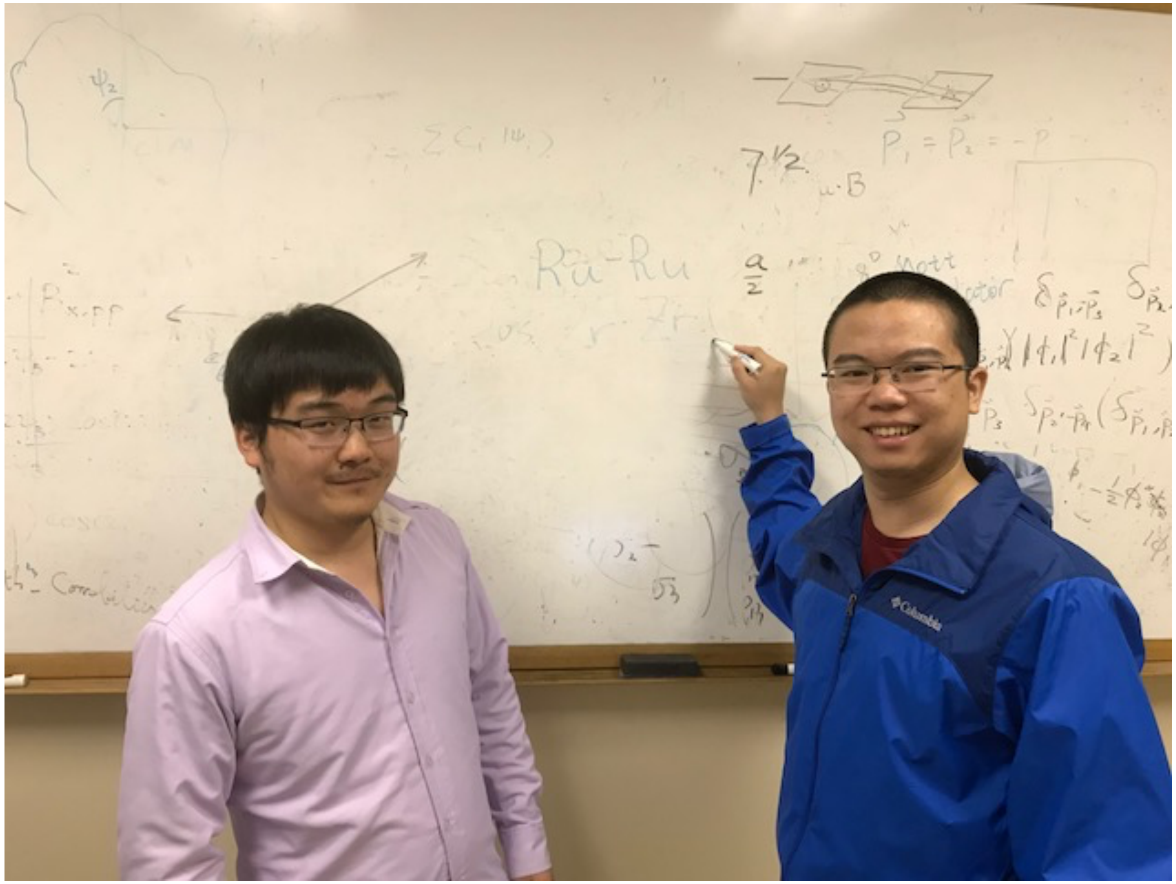
arXiv:1711.02496

Shuzhe Shi (PhD @ IUB)

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

Hui Zhang, Defu Hou (CCNU).

The AVFD “Warriors”



Hui Zhang **Shuzhe Shi**

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]].

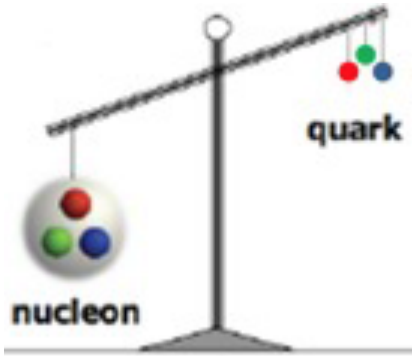
Outline

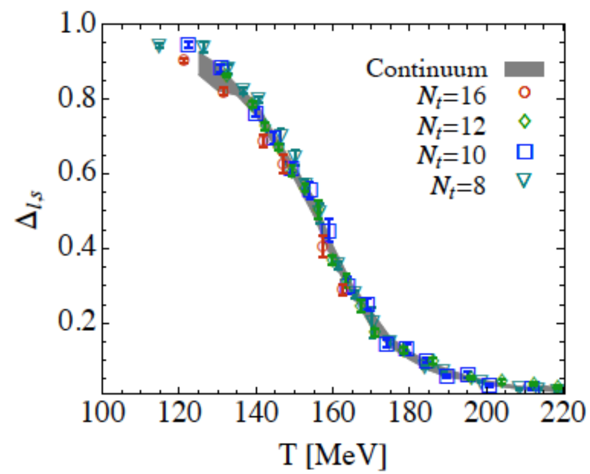
- Introductory Discussions
- The AVFD Framework
- AVFD Results for AuAu Collisions
- Searching for CME in Isobaric Collisions
- Summary

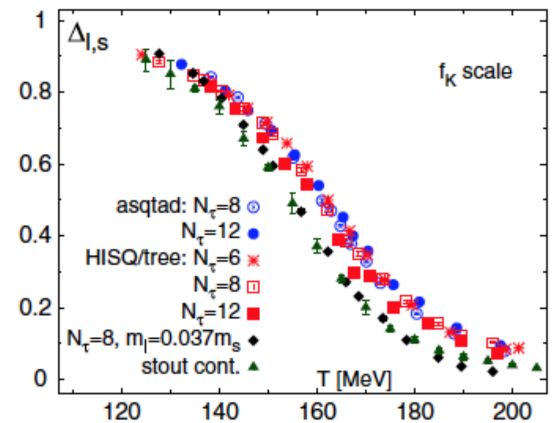
Introductory Discussions

QCD & Chiral Symmetry

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



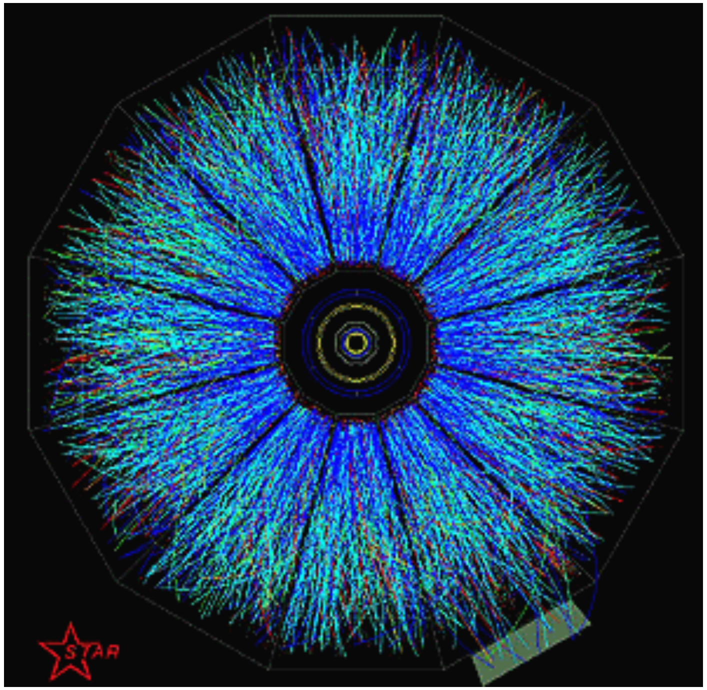


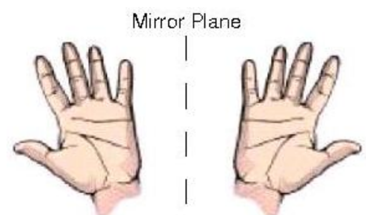


**** A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!***

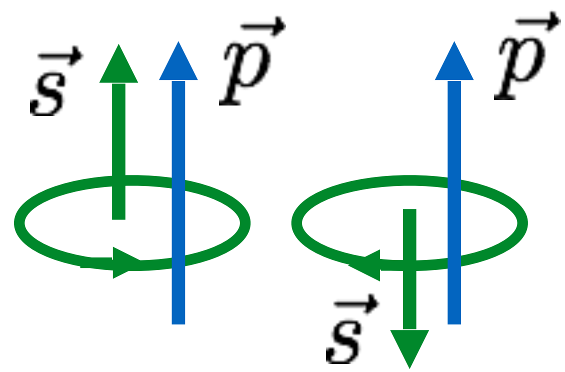
Could we see direct experimental evidence for that?

“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.

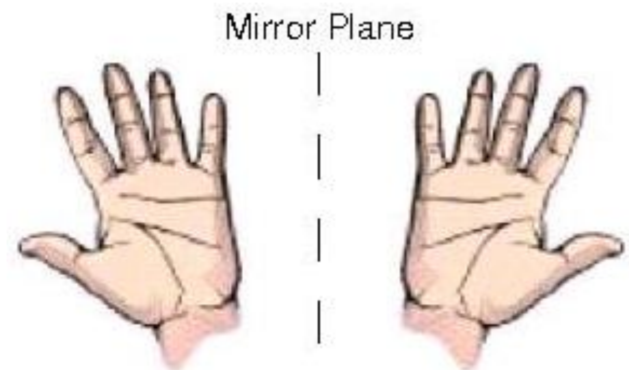
Classical symmetry:

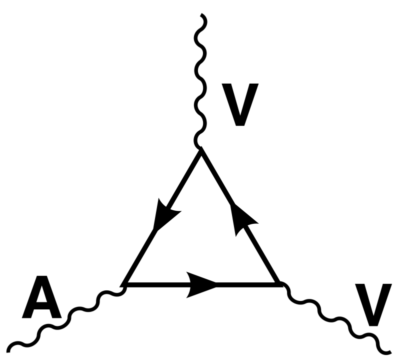
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

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





[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 (CME)

Chirality & Anomaly & Topology

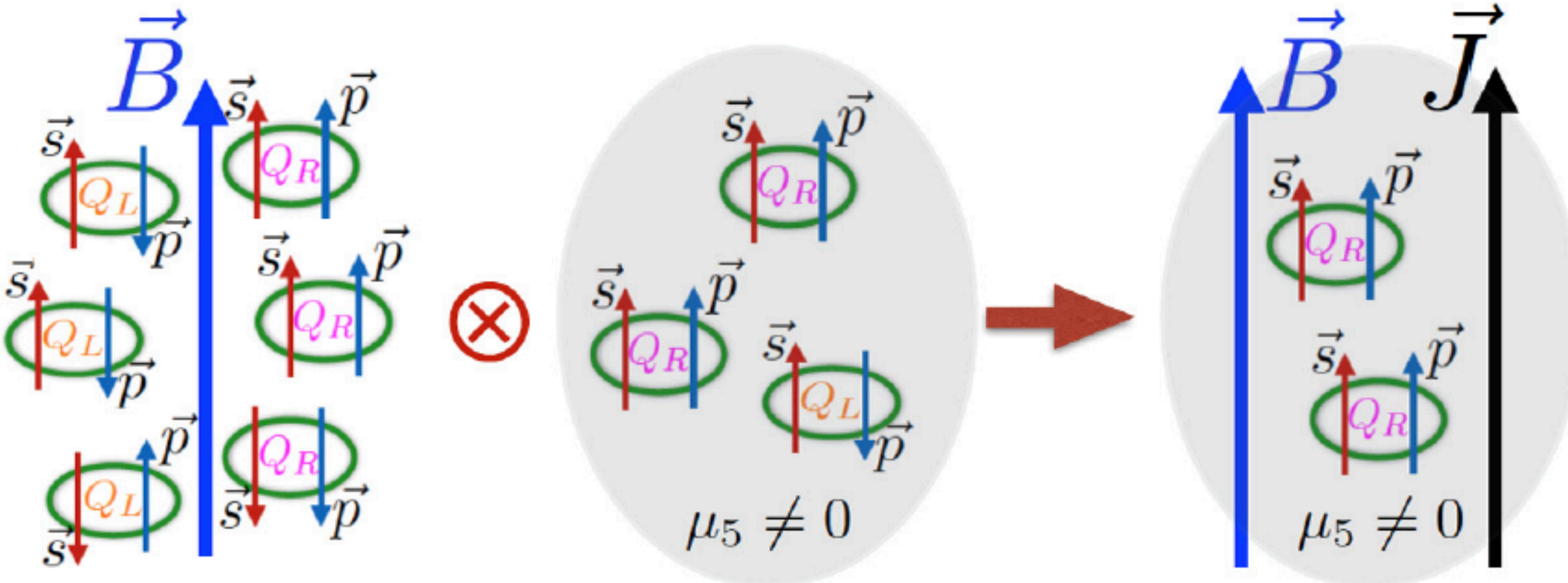
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current

Q.M. Transport

Magnetic Field

Intuitive Picture of CME



Intuitive understanding of CME:

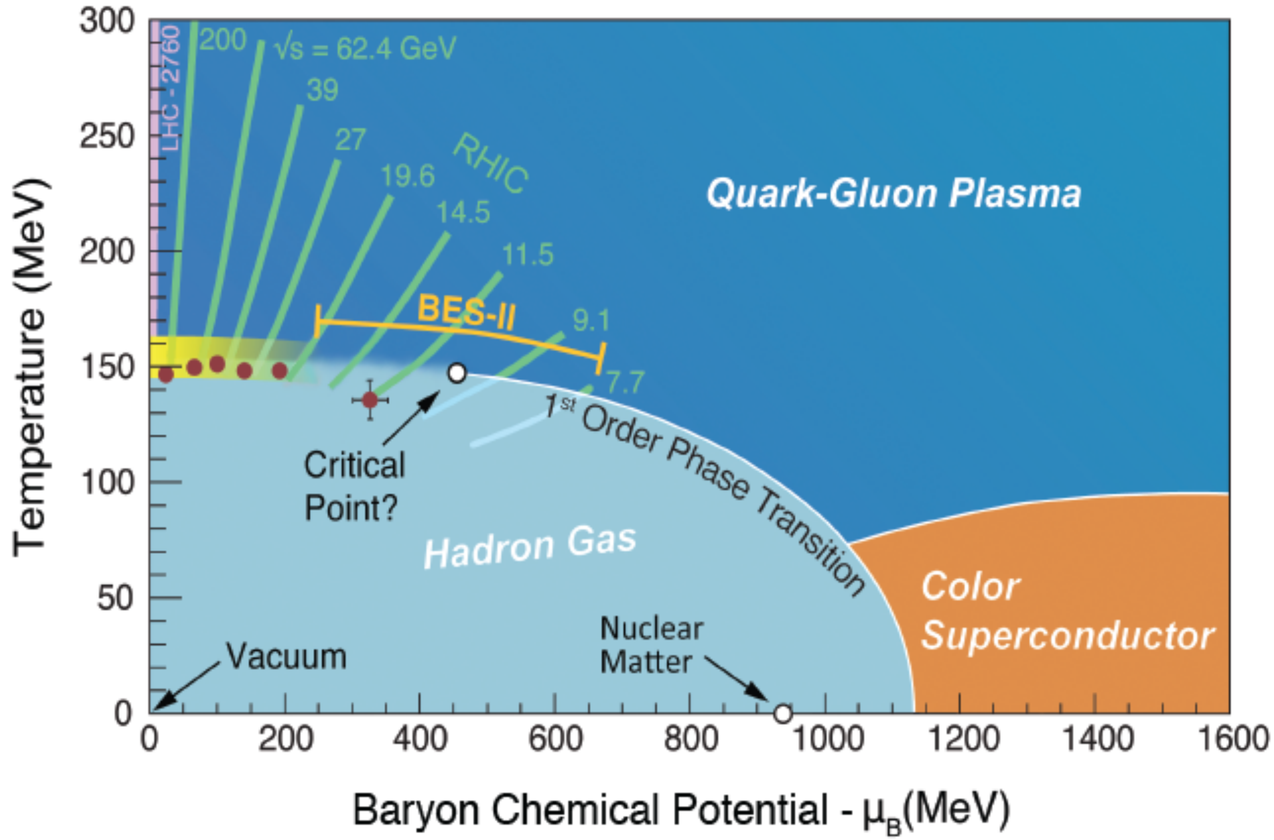
Magnetic polarization —> correlation between micro. SPIN & EXTERNAL FORCE $\otimes$ **Chiral imbalance —> correlation between directions of SPIN & MOMENTUM**

→ ***Transport current along magnetic field***

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

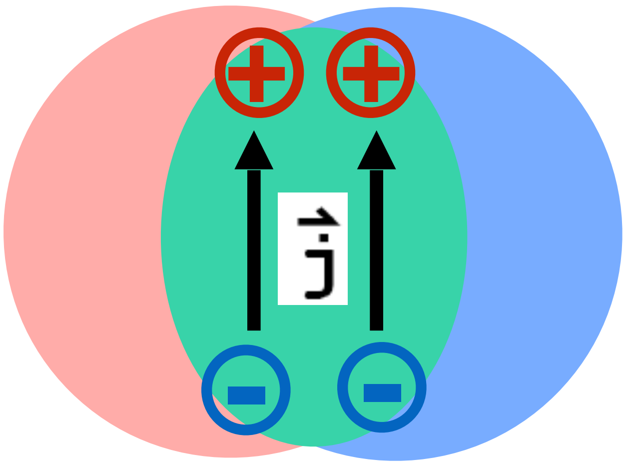
CME and Beam Energy Scan

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



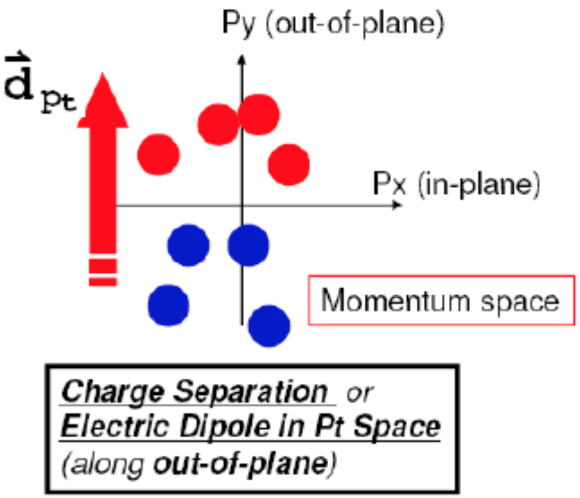
**** We'd like to see a chiral QGP above certain threshold energy via CME***
**** We'd like to see its turning off at low enough energy***

From CME Current to Charge Separation



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

strong radial blast:
position —> momentum



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

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

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

Very difficult measurement:
**** Zero average, only nonzero variance;***
**** Correlation measurement with significant backgrounds;***
**** Signal likely very small***

Experimental Observable

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

Voloshin, 2004

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

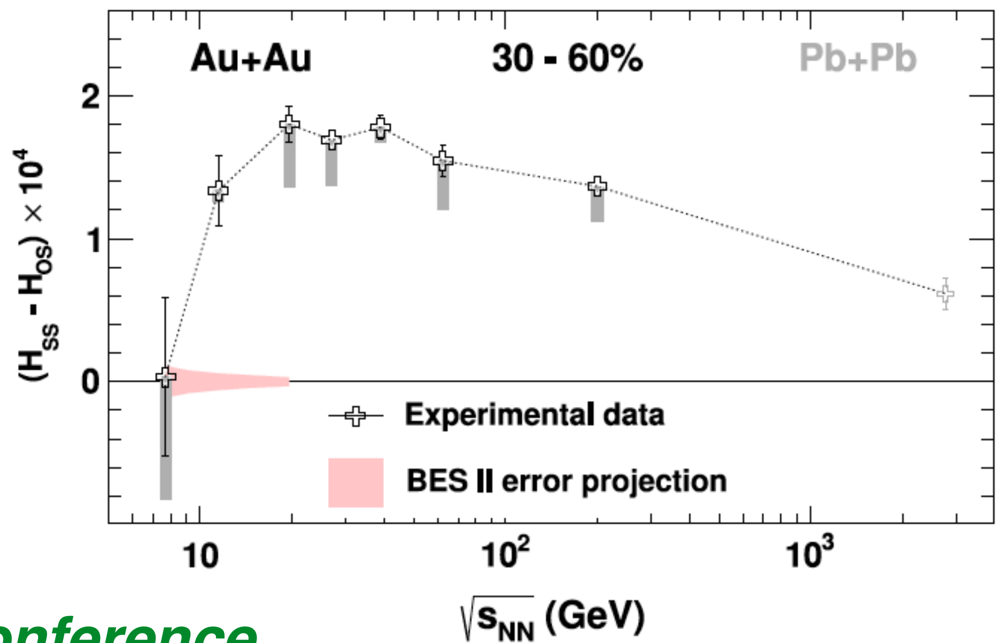
$$\delta = \langle \cos(\Delta\phi_i - \Delta\phi_j) \rangle = \langle \cos\Delta\phi_i \cos\Delta\phi_j \rangle + \langle \sin\Delta\phi_i \sin\Delta\phi_j \rangle$$

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

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

Bzdak, Koch, JL, 2012

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



Many interesting proposals of new observables!

See many other talks at this conference.

Summarizing Exp. Search Status

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

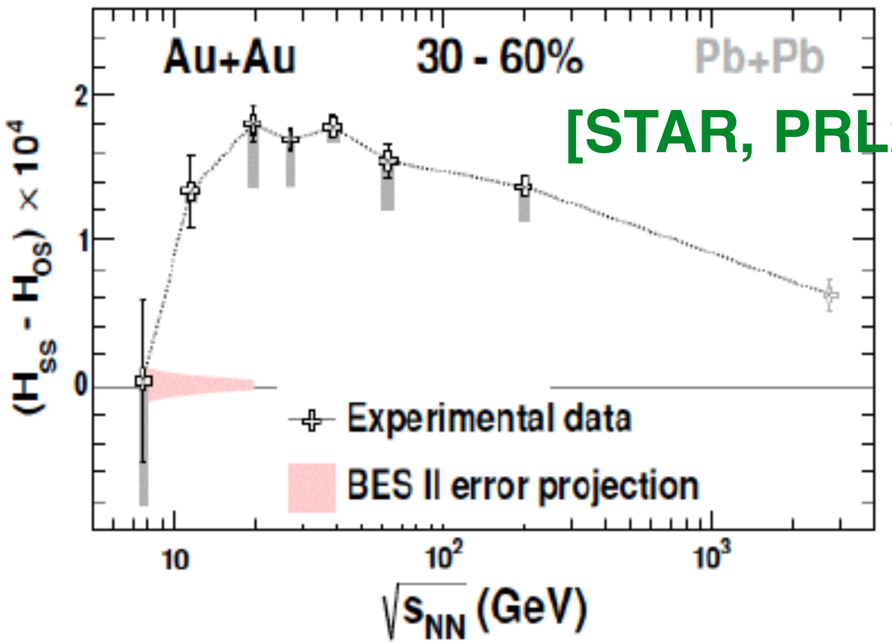
Vary v2 for fixed B:

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:



[STAR, PRL2014]

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

AVFD Framework

Fluid Dynamics 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!

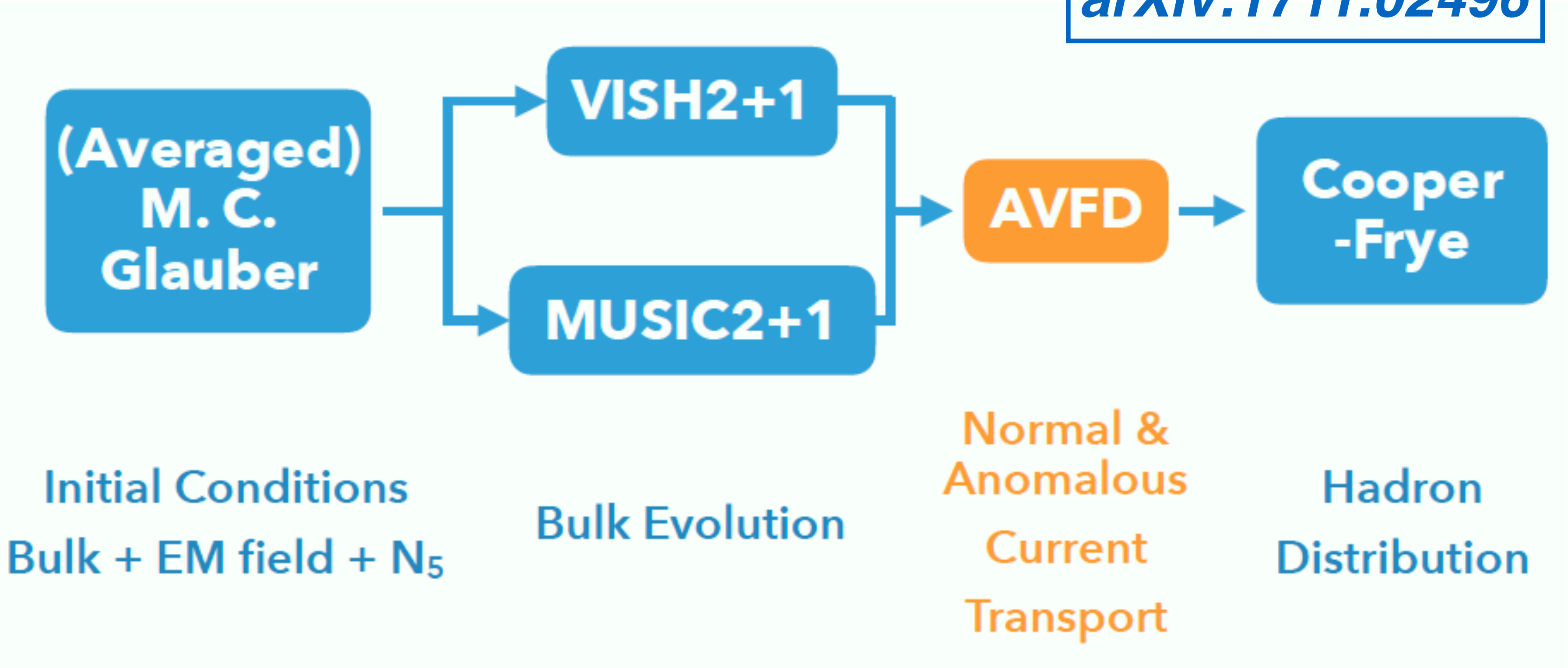
It would be remarkable to actually "see" this new hydrodynamics at work in real world materials!

The AVFD Framework

The AVFD Framework

arXiv:1611.04586

arXiv:1711.02496



AVFD:
Anomalous-Viscous Fluid Dynamics

The AVFD Framework

Anomalous-Viscous Fluid Dynamics

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

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

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

CME

Viscous Effect

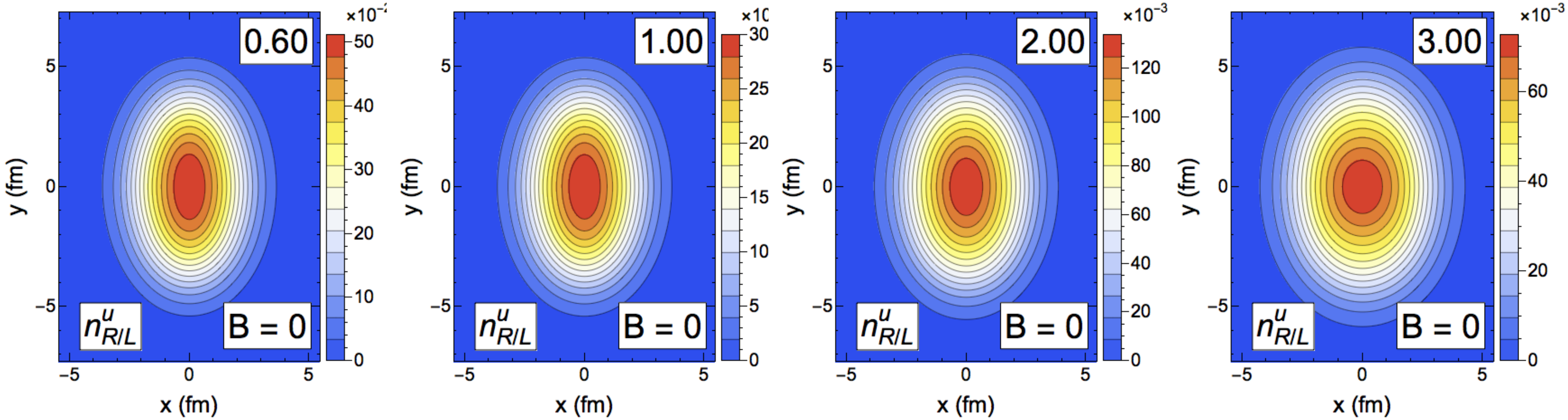
$$\Delta^\mu{}_\nu\, \mathrm{d}\, \nu_{R,L}{}^\nu = - \frac{1}{\tau_{rlx}} (\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

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

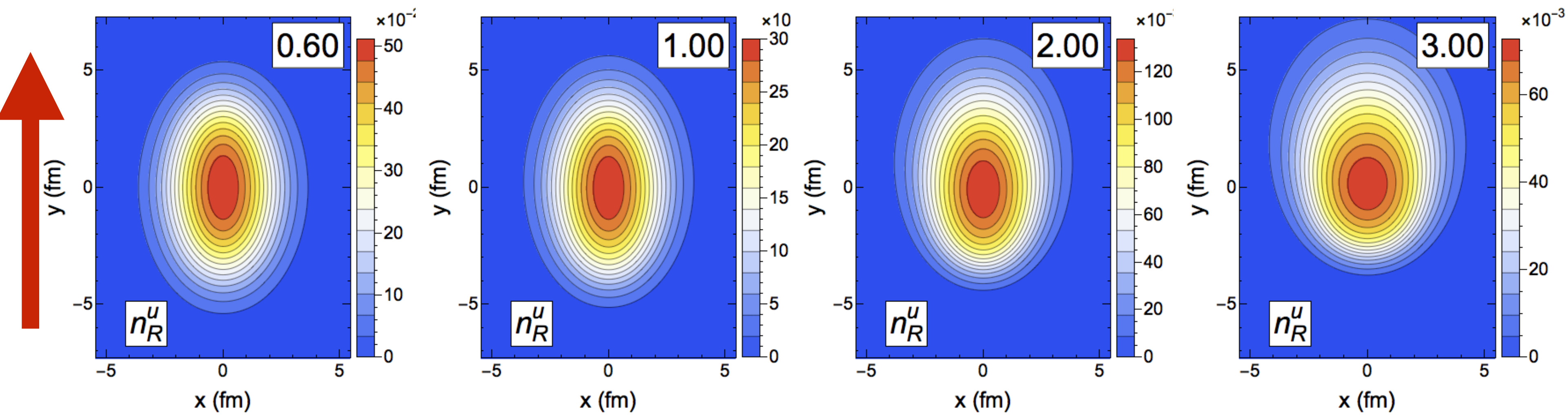
on top of VISH2+1D –– OSU Group

[We now also have MUSIC-AVFD!]

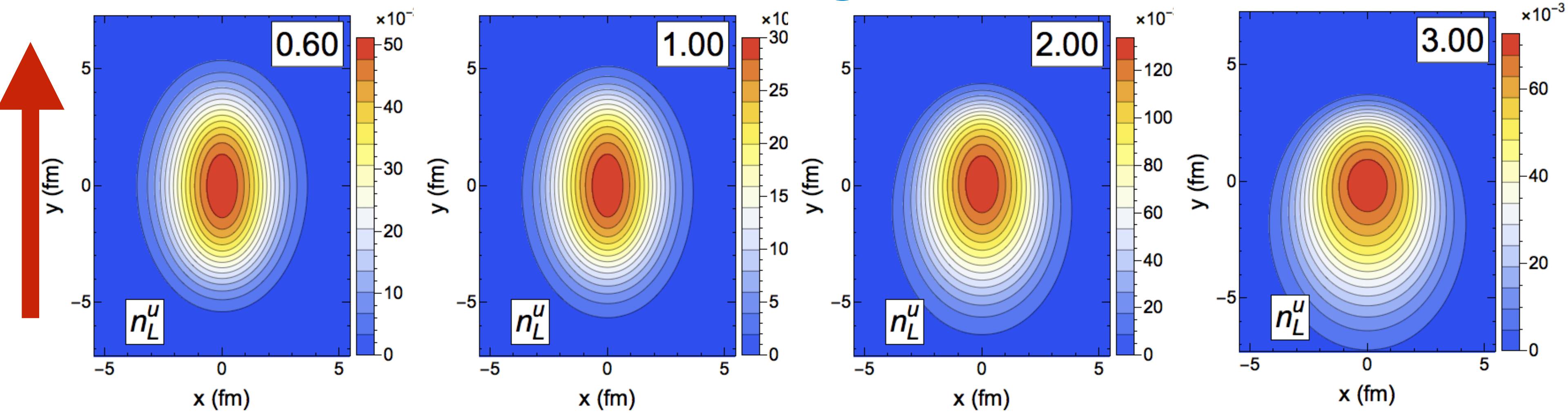
Demonstrating the AVFD



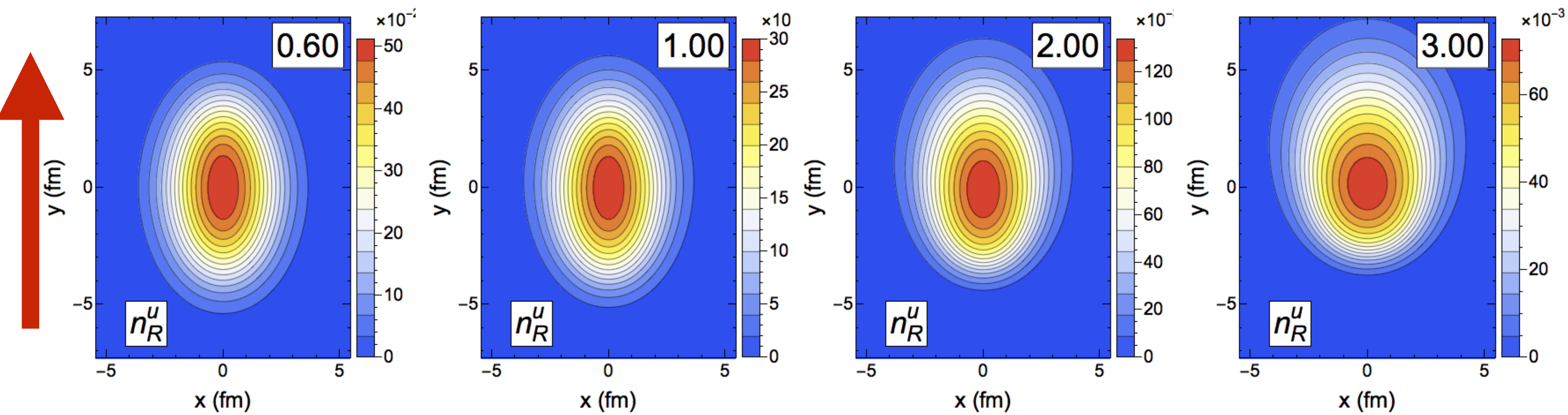
Upper: NO magnetic field
Lower: with B field (along y+ direction)



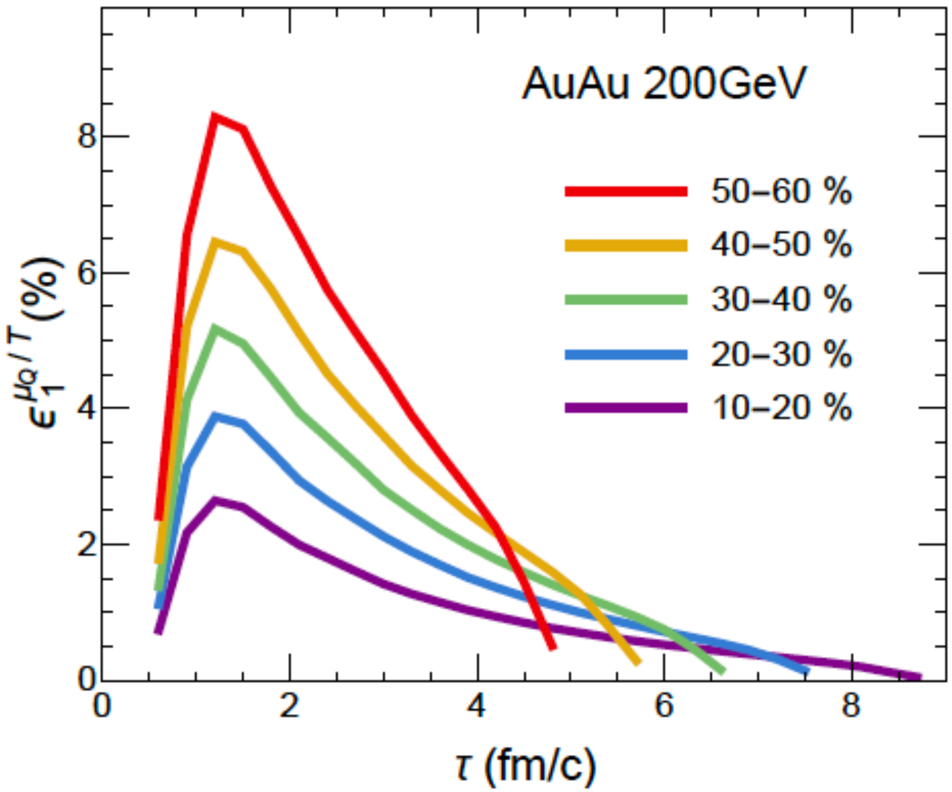
Demonstrating the AVFD



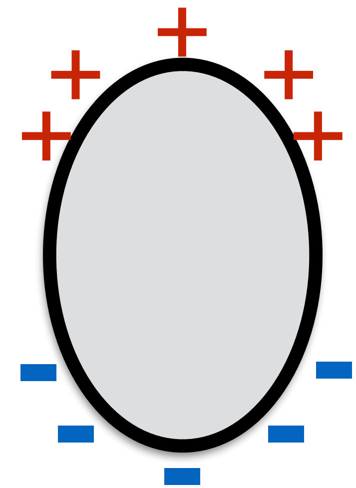
Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)



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)

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

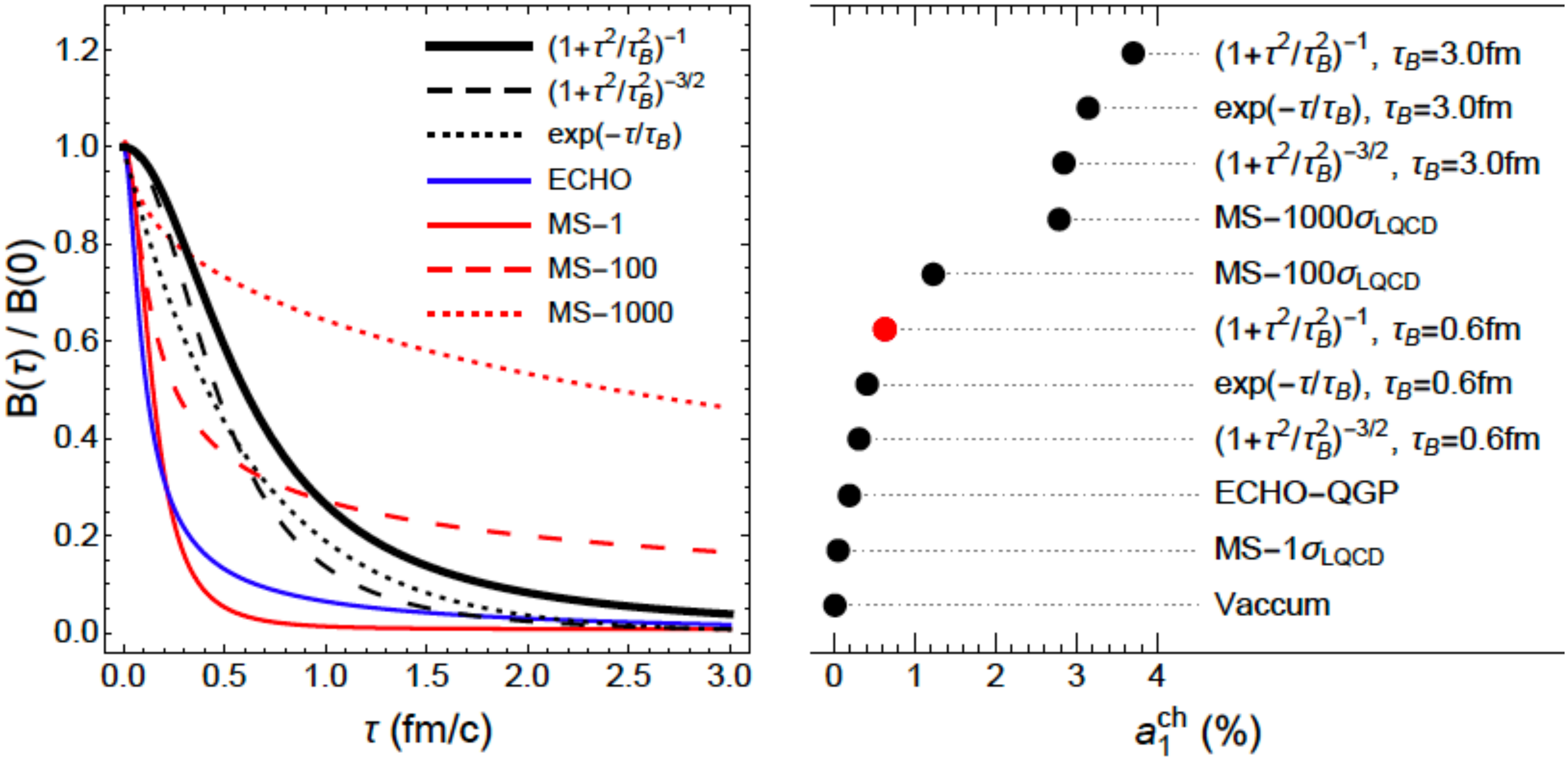
$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

AVFD Results for AuAu Collisions

arXiv:1611.04586

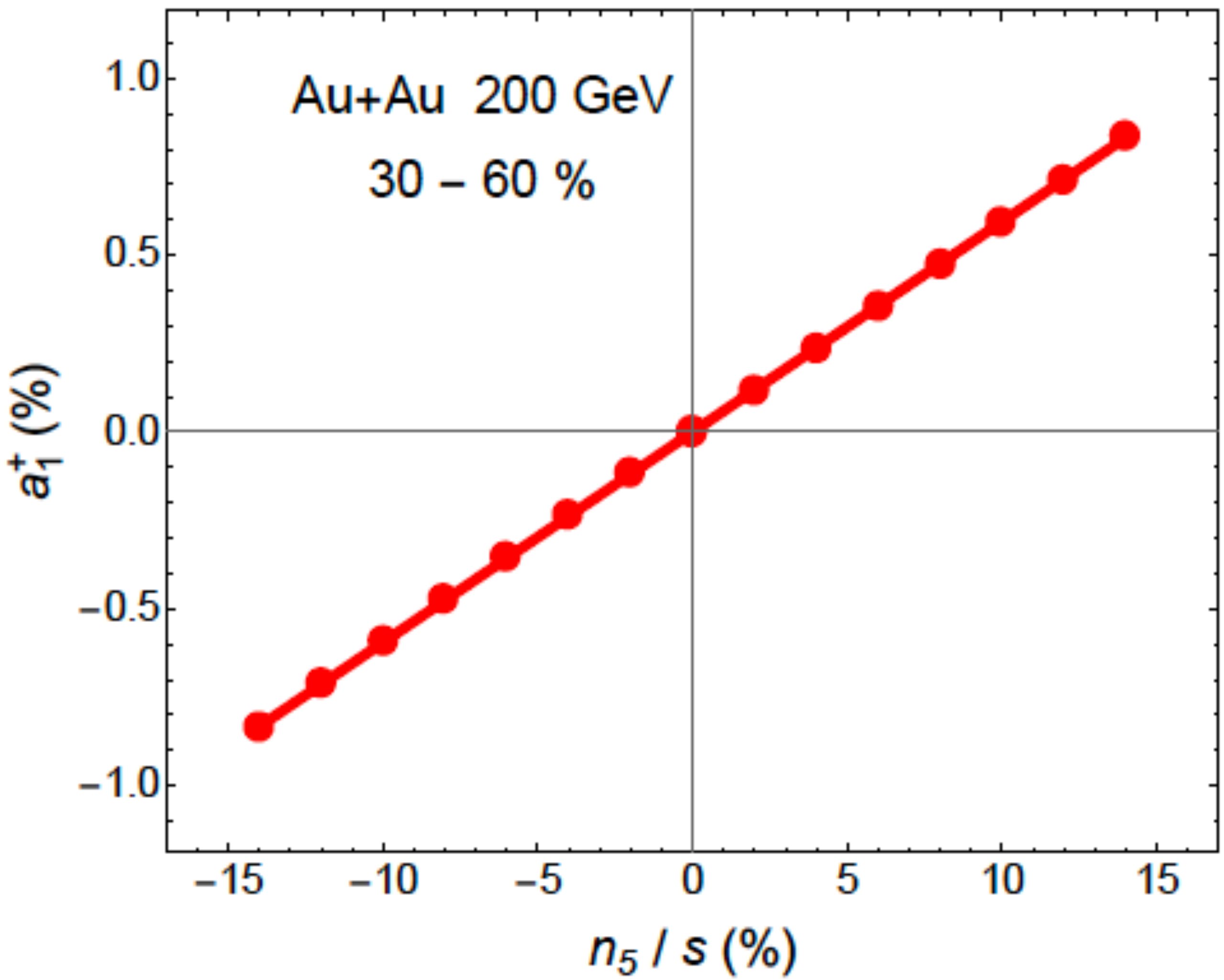
arXiv:1711.02496

The Influence of the Magnetic Field



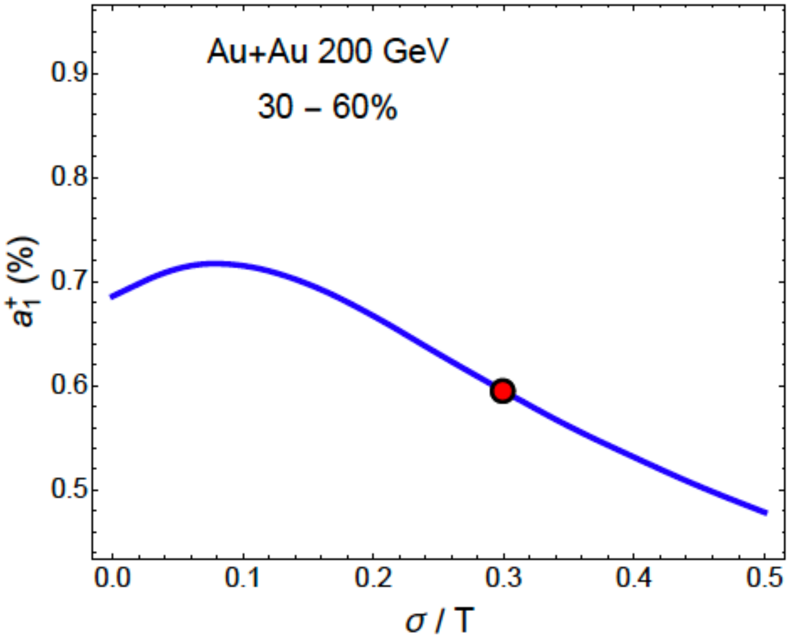
Strong influence by B field evolution;
Significant theoretical uncertainty!

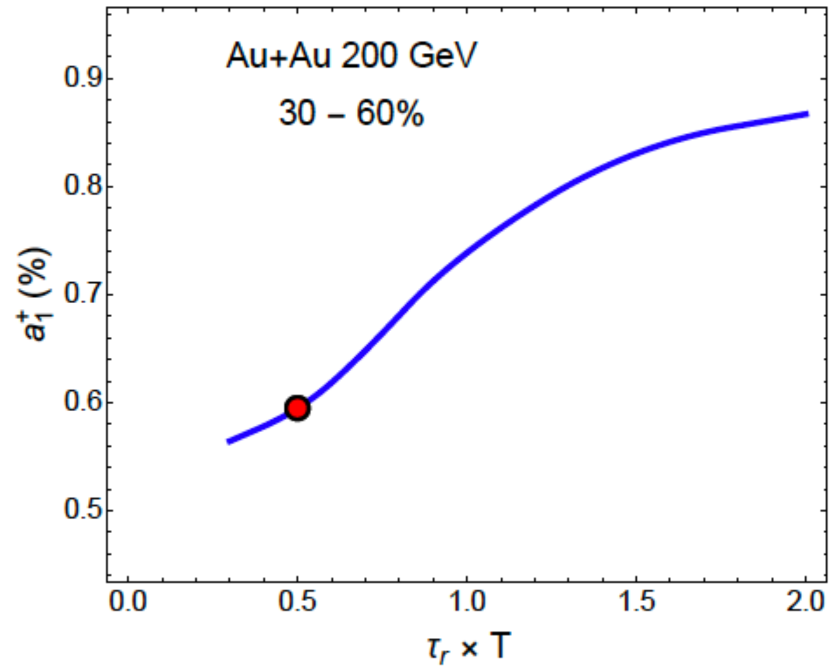
The Axial Charge Initial Condition



Very sensitive to initial axial charge;
Significant theoretical uncertainty!

The Influence of the Viscous Transport



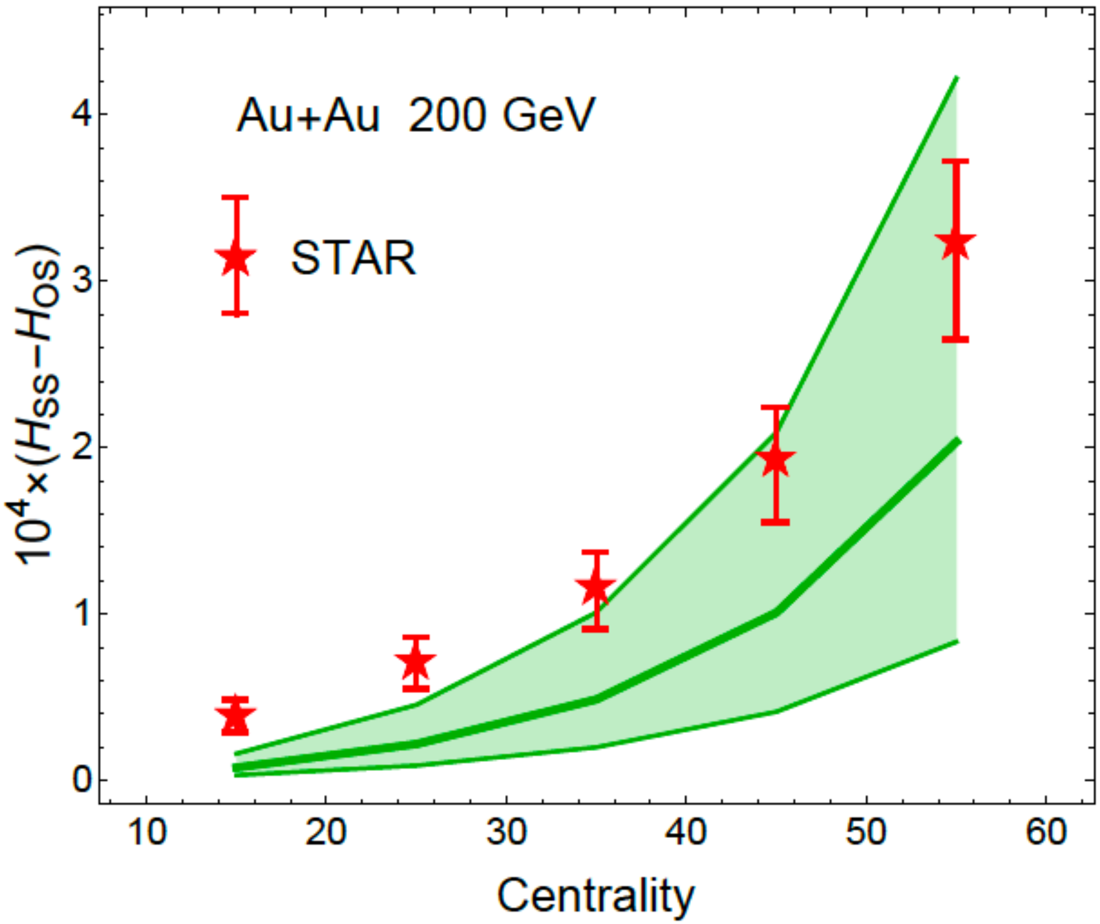


$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}\left(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu}\right)$$

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

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

AVFD Predictions v.s Experimental Data



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

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

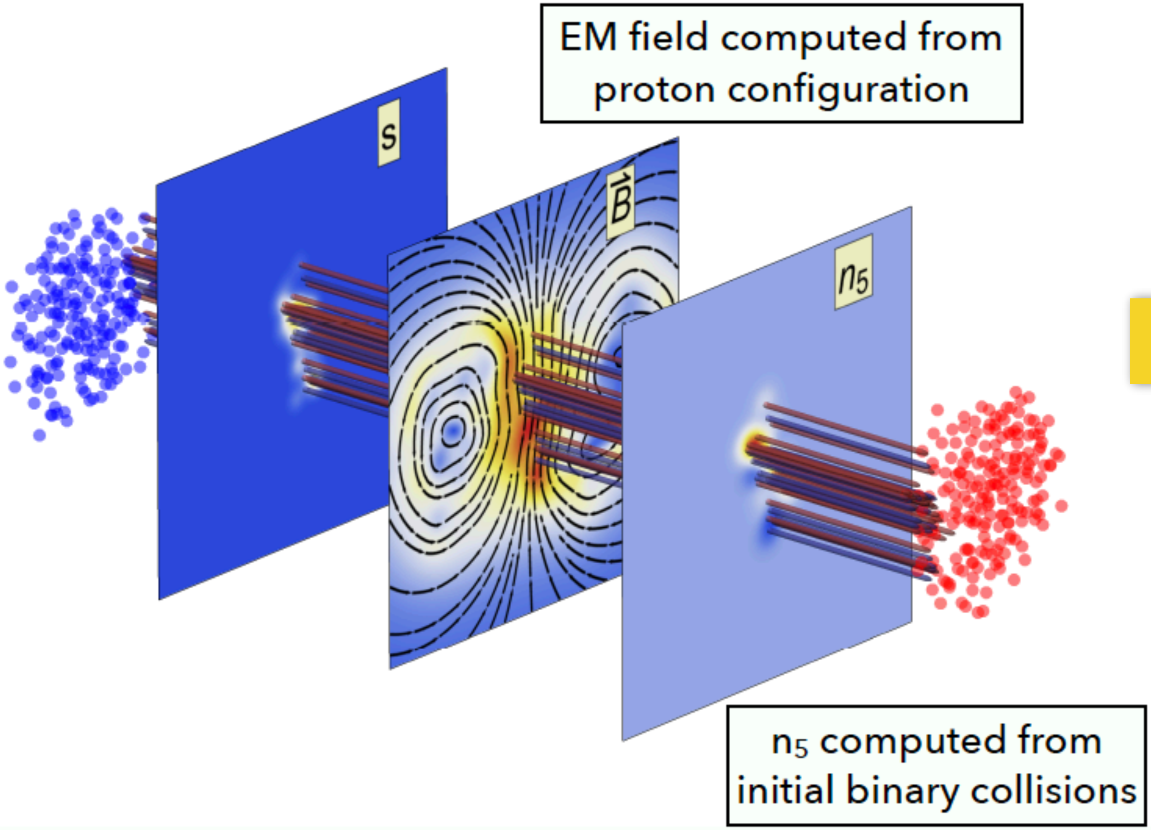
$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4\,(\pi \rho_{tube}^2 \tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\, A_{overlap}}$$

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 $Q_s^2 = 1.25\text{GeV}^2$.

Event-By-Event AVFD

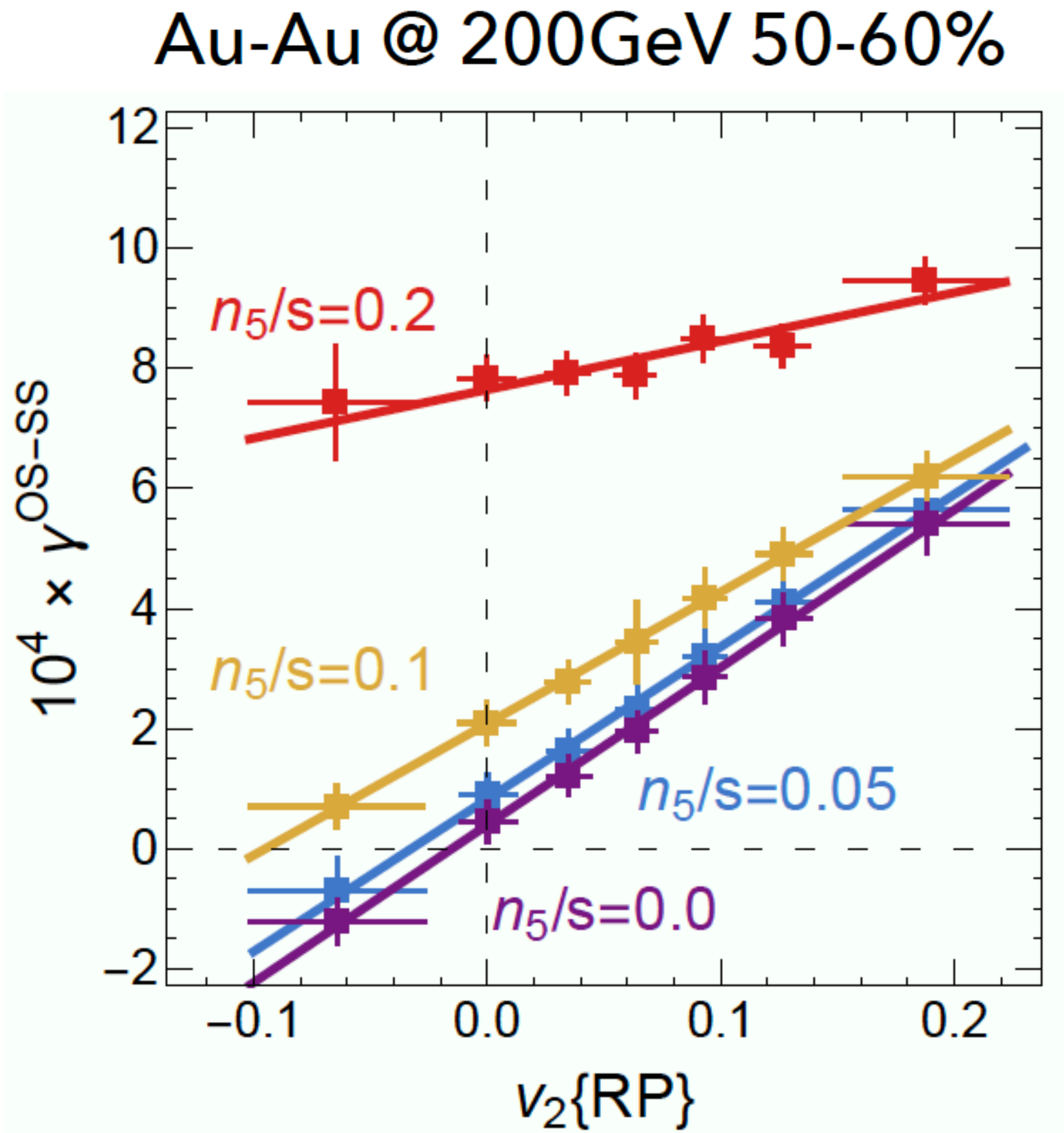


Include EBE fluctuations:

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

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

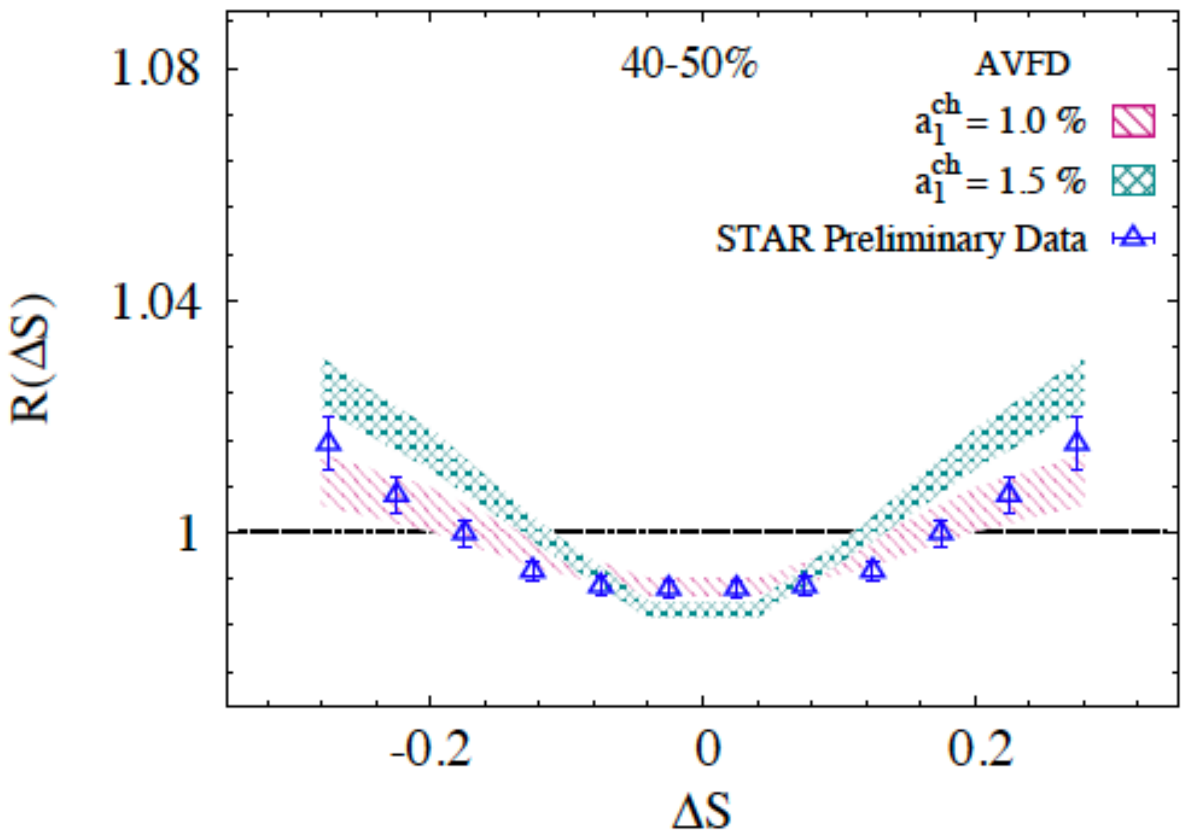
EBE-AVFD for Event-Shape Engineering



The intercept is very sensitive to the CME contribution!

Slope depends on CME too: naive subtraction may not be good.

EBE-AVFD for R-Correlator

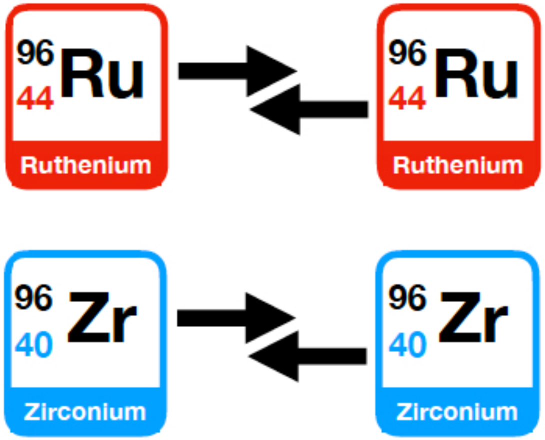


Magdy, Lacey, et al, arXiv:1710.01717; arXiv:1803.02416

R-correlator sensitively responds to CME contribution.

Searching for CME in Isobaric Collisions (Newest results!)

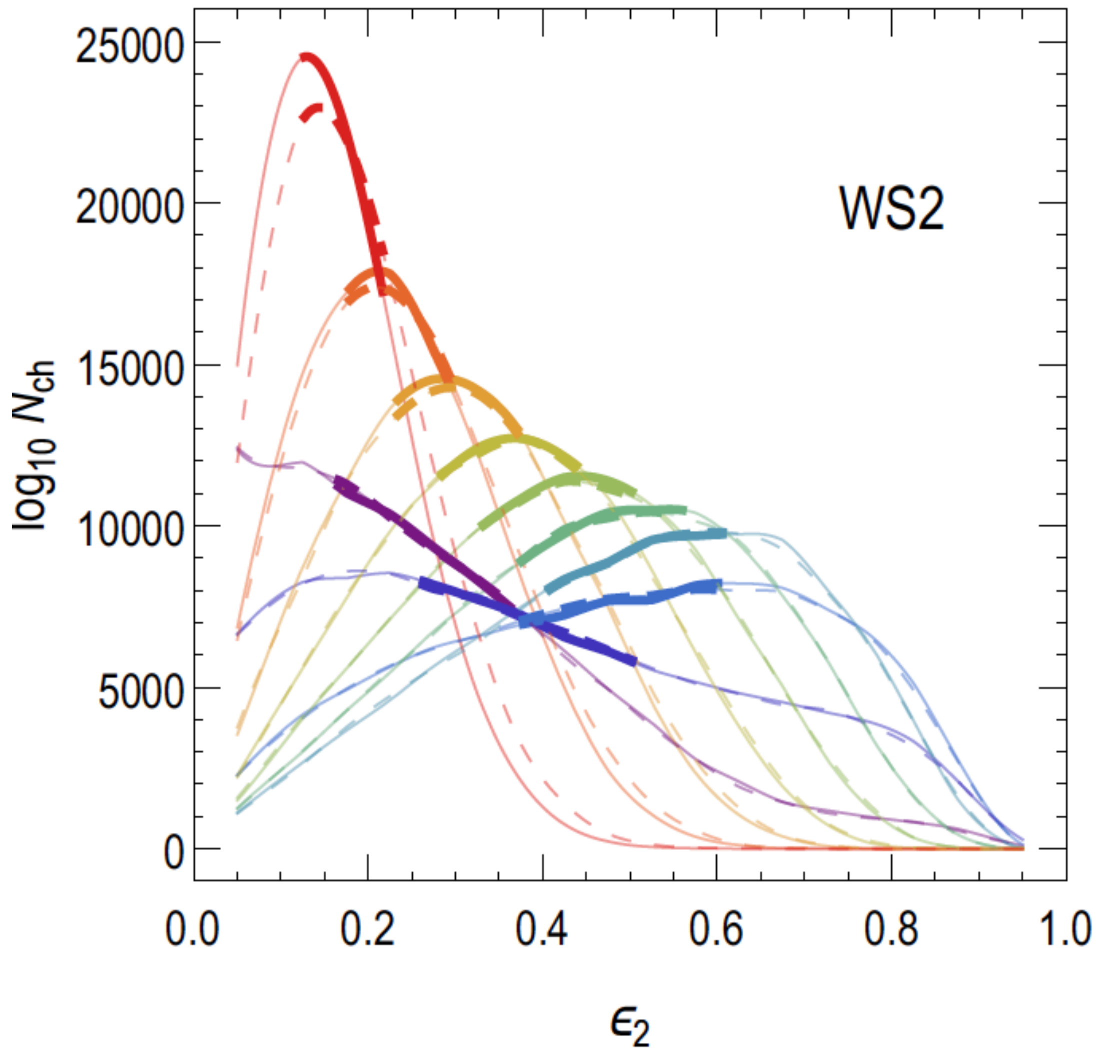
Using Isobaric Collisions for CME Search



Key idea: contrasting two systems with identical bulk, varied magnetic fields.

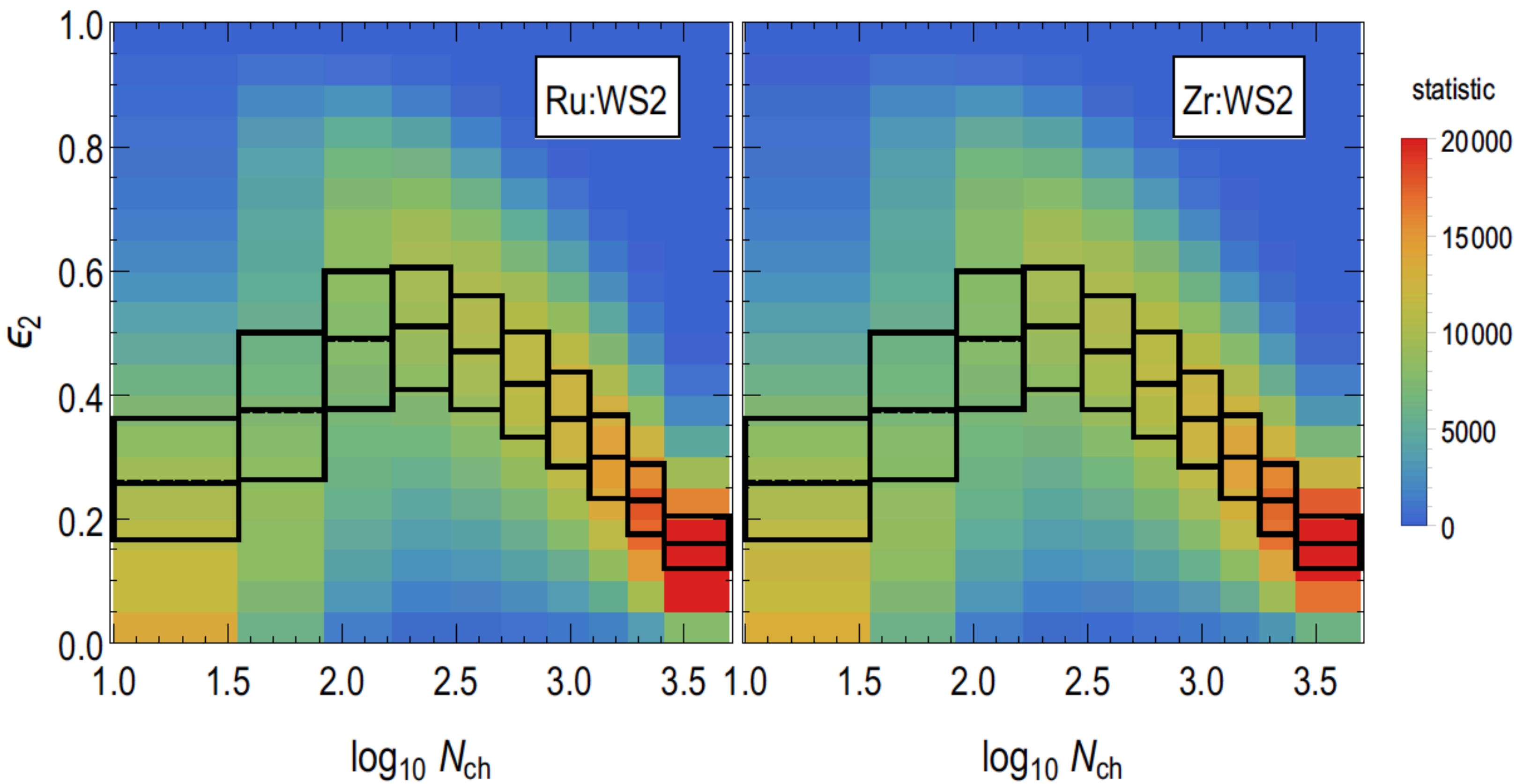
Charge Asymmetry Correlation Measurement

How to Choose Identical Systems?



Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

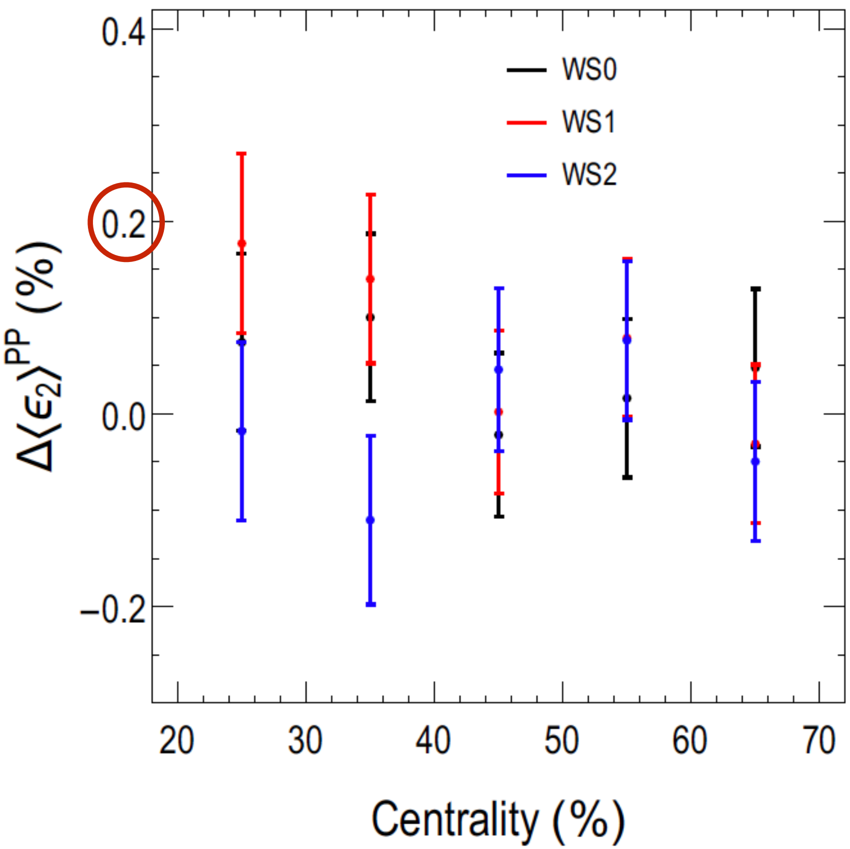
How to Choose Identical Systems?



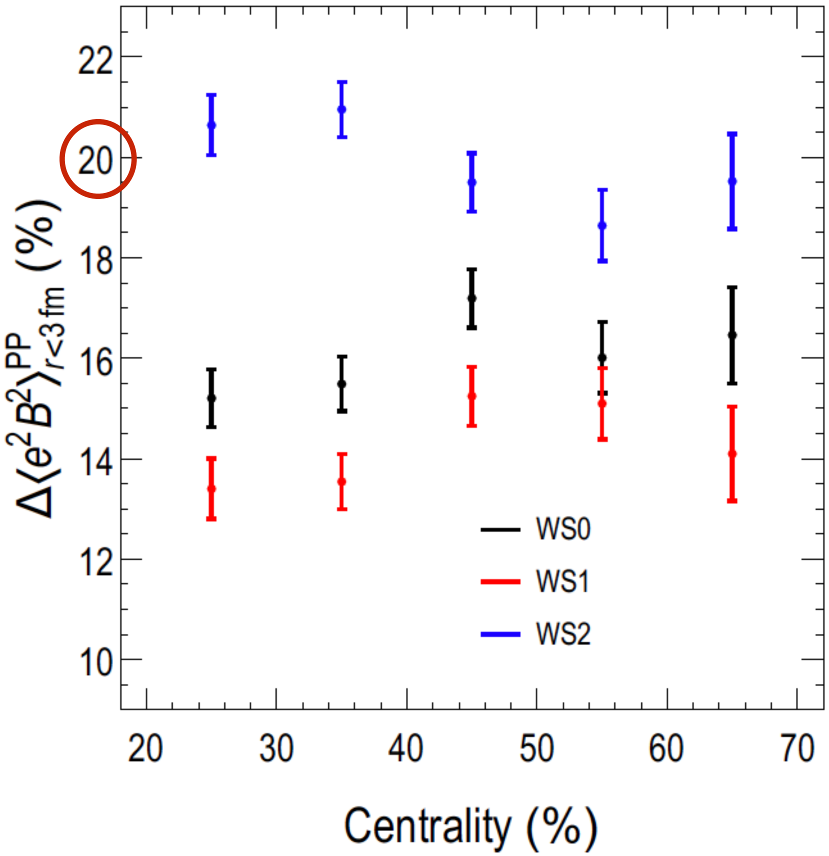
Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

How to Choose Identical Systems?

Eccentricity is guaranteed the same!

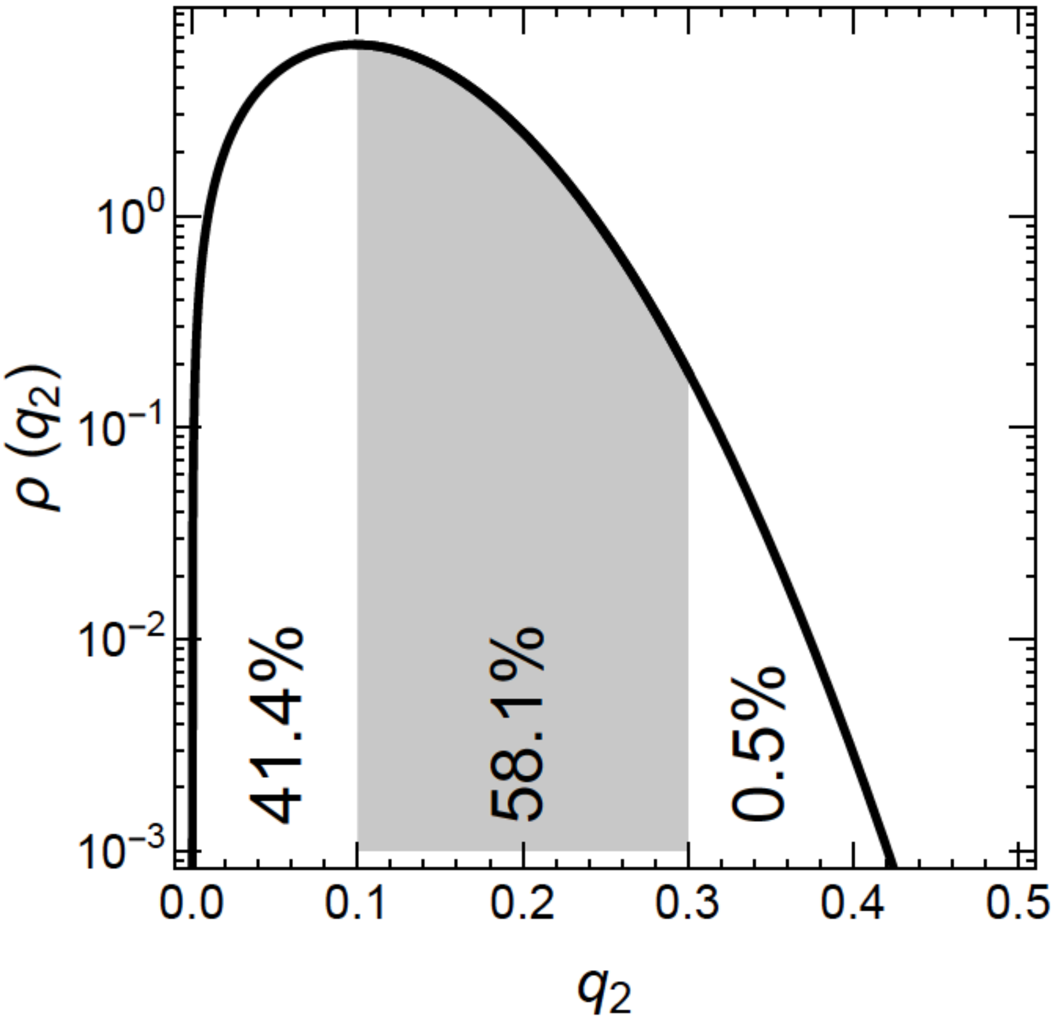


B field differs by 12~20% !



After joint-cut:
Vanishing difference in eccentricity,
Sizable difference in magnetic fields!!!

Analyzing actual EBE-AVFD for Isobars

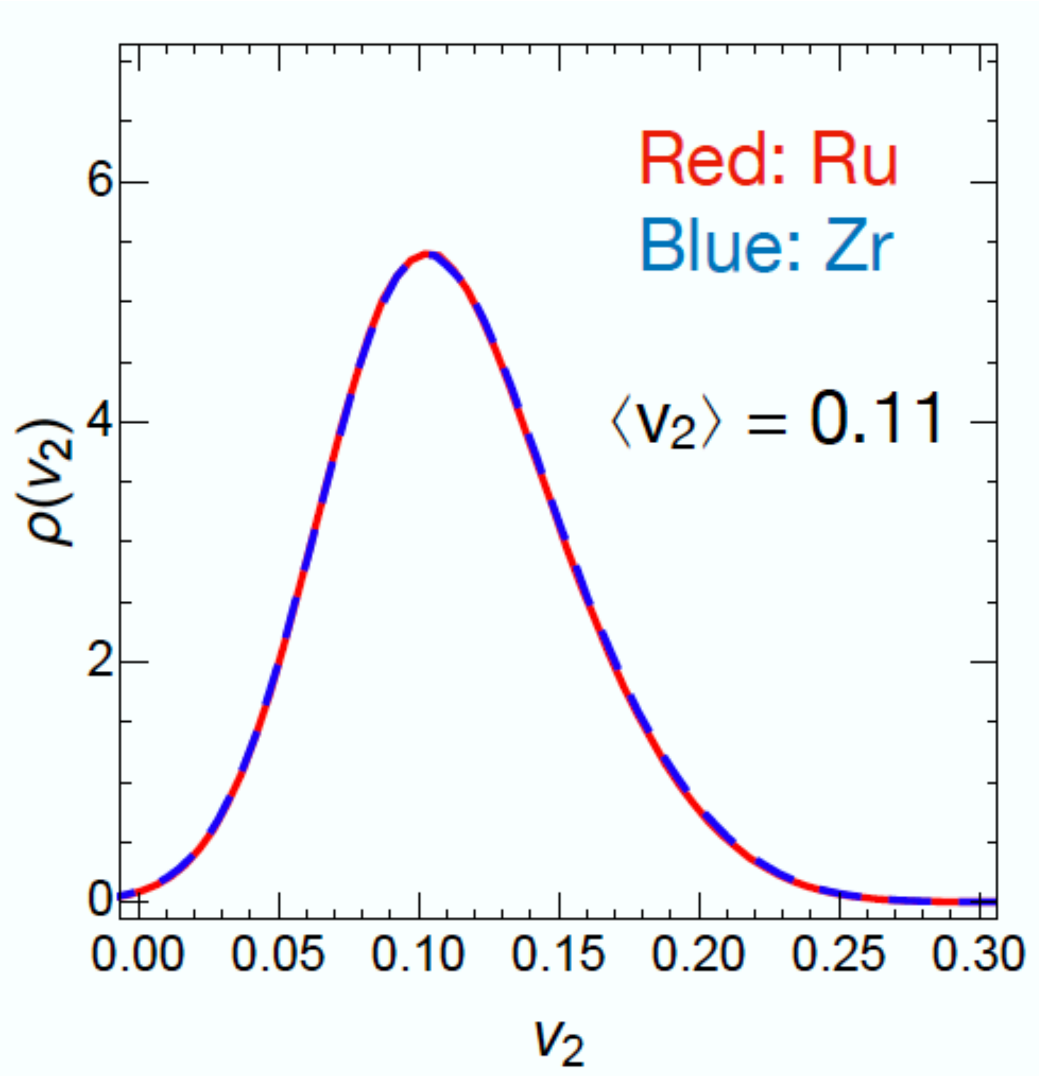


100M EBE-AVFD events: Subject to joint-cut

$32 < N_{ch,\,|y|<0.5} < 48$

$0.1 < q_2 < 0.3$

Analyzing actual EBE-AVFD for Isobars

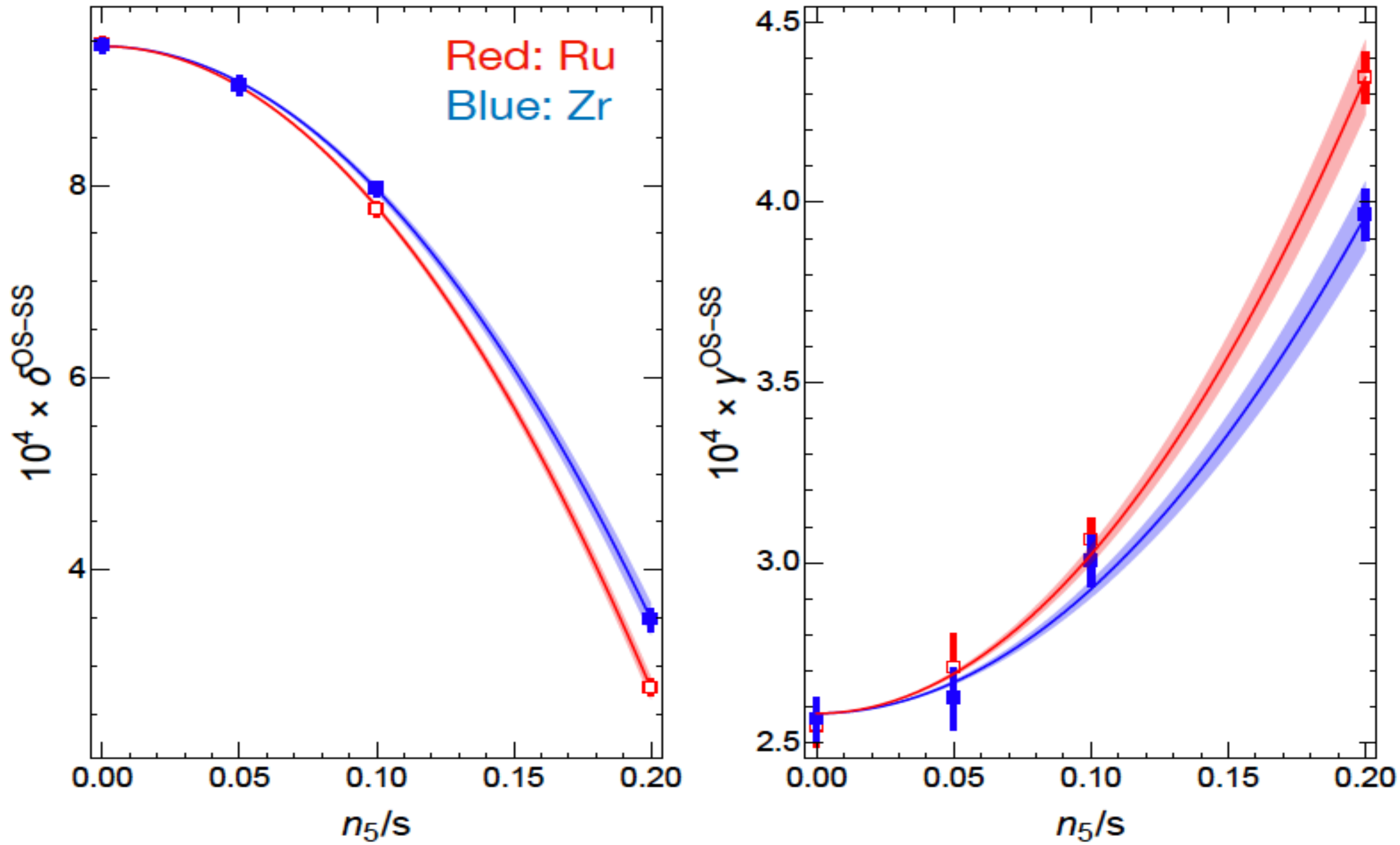


Post-selection double-check: Identical v2 !

Getting two identical sample of isobar events for contrast

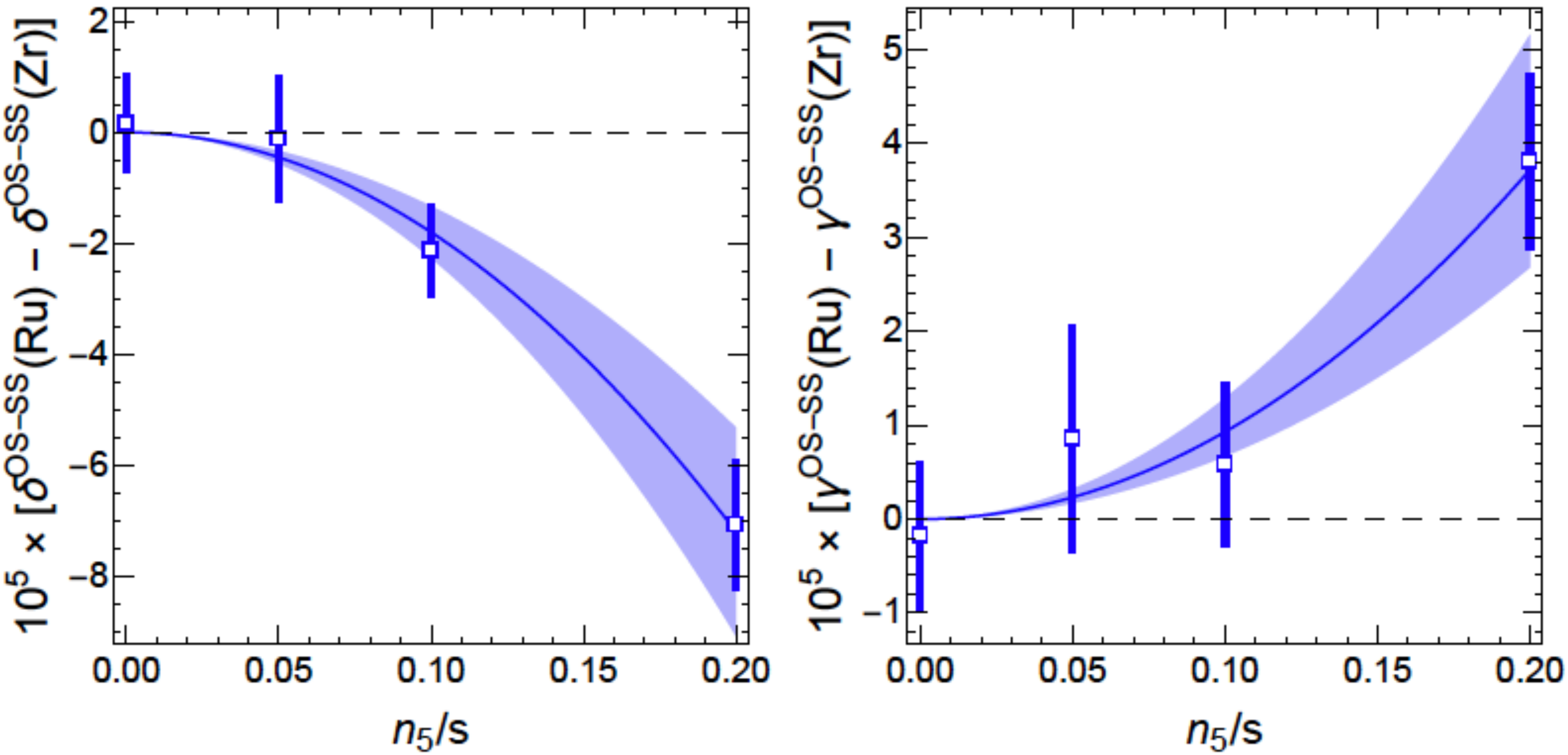
Correlations of Isobars

Points: EBE-AVFD simulation events after cut (~6M events each);
Curve: quadratic fitting, a + b * (n_5)^2 (as expected from CME)



Clear difference in correlations!
Very sensitive to CME contribution!

Absolute Difference between Isobars

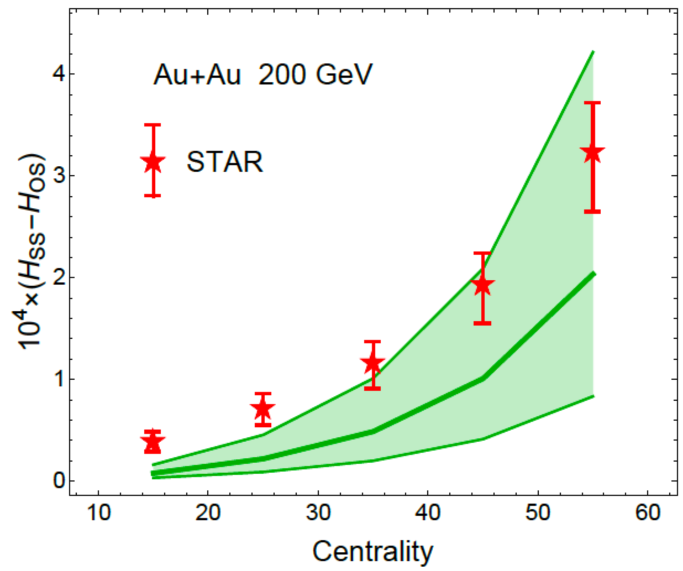


The absolute difference between isobars,
after identical multiplicity+elliptic flow cuts,
will provide the most sensitive and clean probe of CME signal.

Summary & Outlook

Summary

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



EBE-AVFD for the Isobars:
1) Event selection for truly identical bulk;
2) Absolute difference in correlations very sensitive to CME!