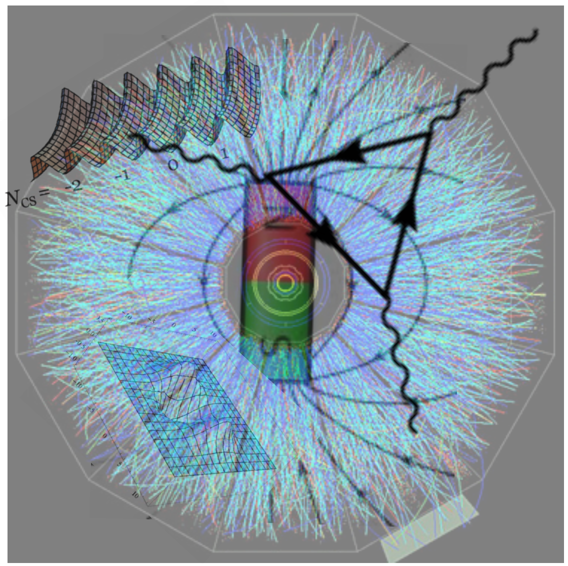
ATHIC2018 @ Hefei Nov. 3~6, 2018

Hydrodynamics with Anomaly Transport & CME in Isobaric Collisions



Jinfeng Liao

Indiana University / CCNU

Research Supported by U.S. NSF & DOE and by NSFC

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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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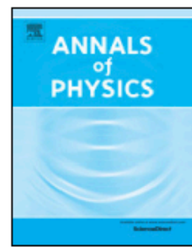

Anomalous chiral transport in heavy ion collisions from Anomalous-Viscous Fluid Dynamics

Check for updates

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

arXiv:1711.02496

Shuzhe Shi (McGill; PhD @ IUB)

Yin Jiang (Beihang), Yi Yin (MIT), Elias Lilleskov (REU)

The EBE-AVFD "Warriors"

XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2018)

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

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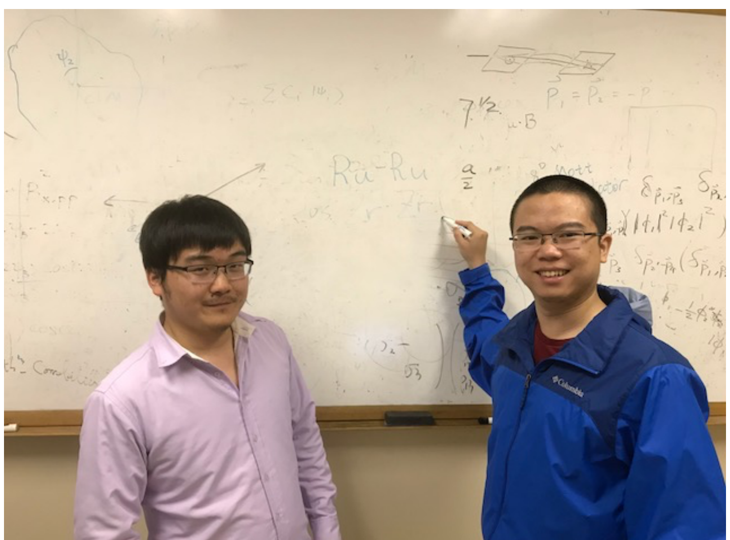
QM18 proceedings



Hui Zhang **Shuzhe Shi** **Defu Hou**

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

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Review

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

CrossMark

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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
- Predictions for CME in Isobaric Collisions
- Summary

Introductory Discussions

Chiral Symmetry & SSB

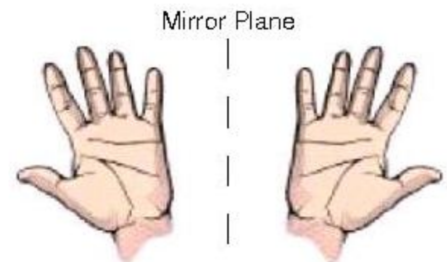
Classical symmetry:

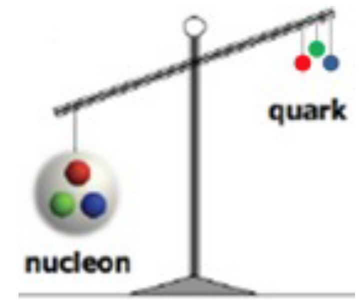
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

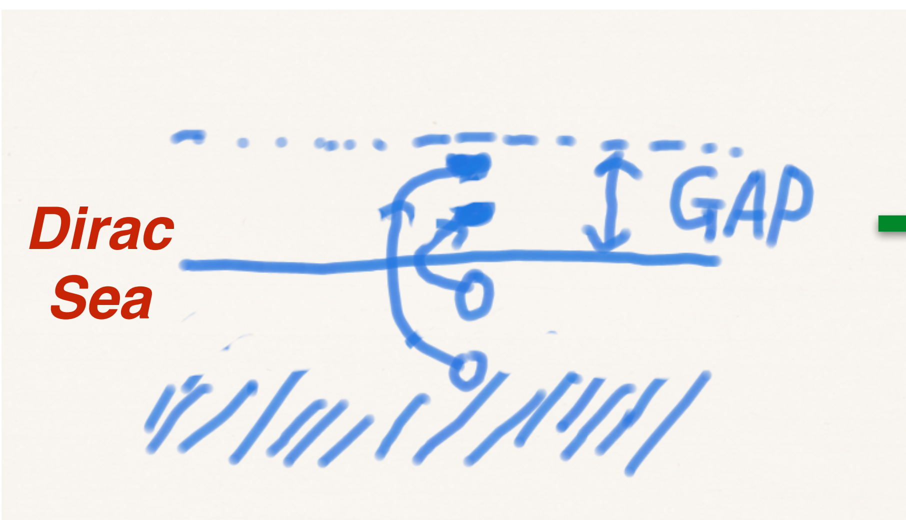
$$\mathcal{L} \to i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

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

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







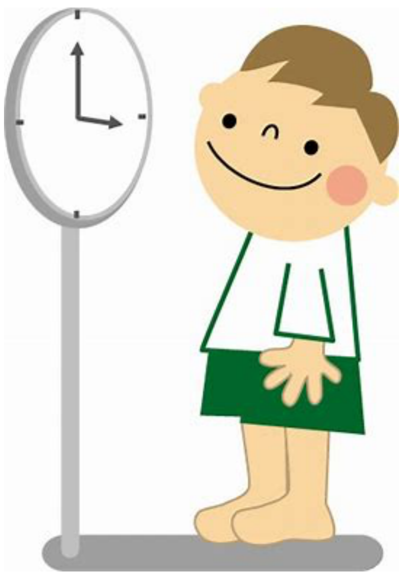
$$M = m - 2G\langle\bar{\psi}\psi\rangle$$

Constituent mass

Lagrangian (SM) mass

The "Origin of Mass"

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



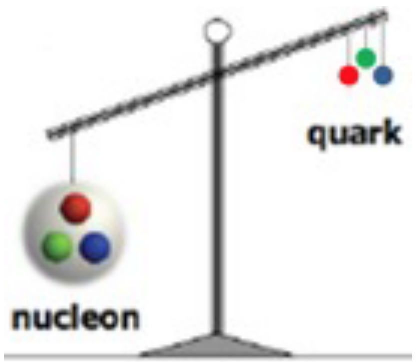
A typical person, say ~ 70 kg
** Reasonable estimate, dominantly H_2O ~ 10 protons + 8 neutrons ~ 28 u quarks + 26 d-quarks*

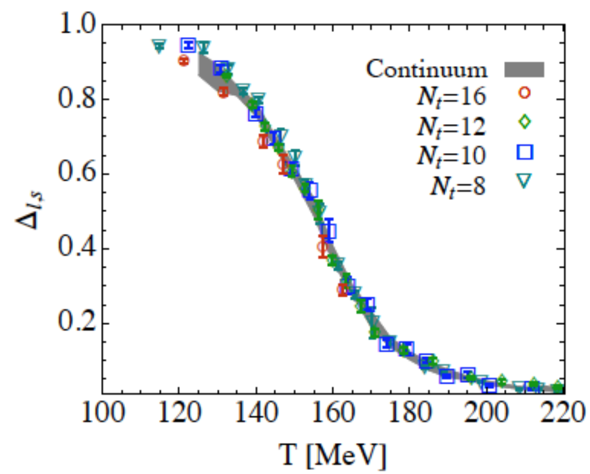
** Mass from Higgs: ~1.7kg (~2.4%)*
** Mass from QCD: ~ 68.3kg (~97.6%)*

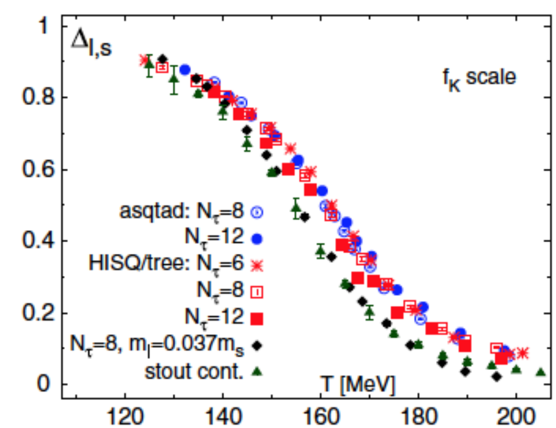
The QCD chiral symmetry is just of paramount importance!

QCD & Chiral Symmetry

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



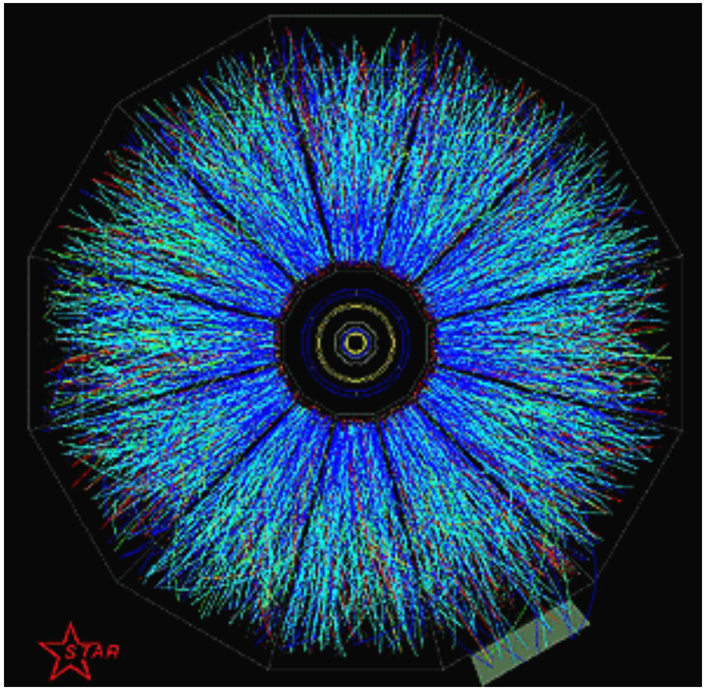




**** A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!***

Could we see direct experimental evidence for that?

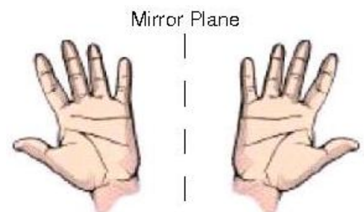
“Little Bang” in High Energy Nuclear Collision



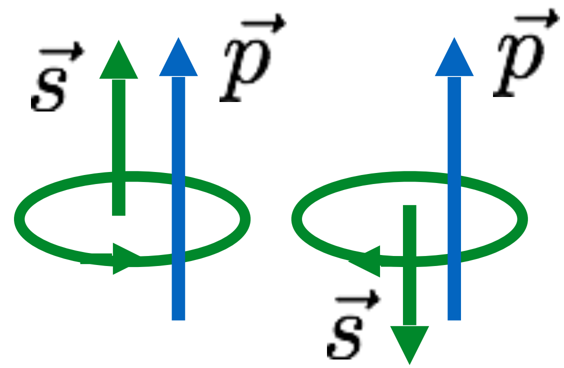
*** Quark-gluon plasma (QGP) is created in such collisions.**

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

*** Is chiral symmetry restored?**



CHIRAL FERMIONS



Chiral Anomaly

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

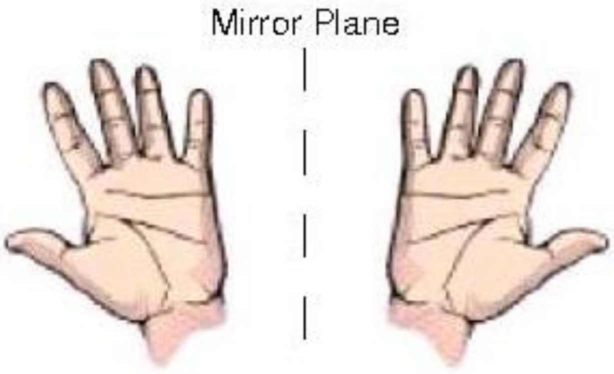
Classical symmetry:

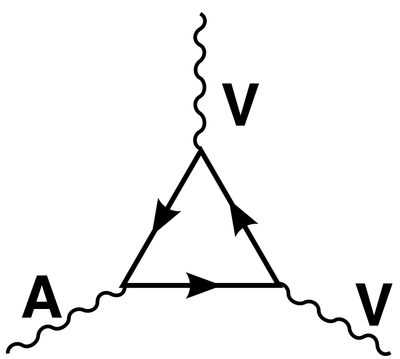
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

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





[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 (CME)

Chirality & Anomaly & Topology

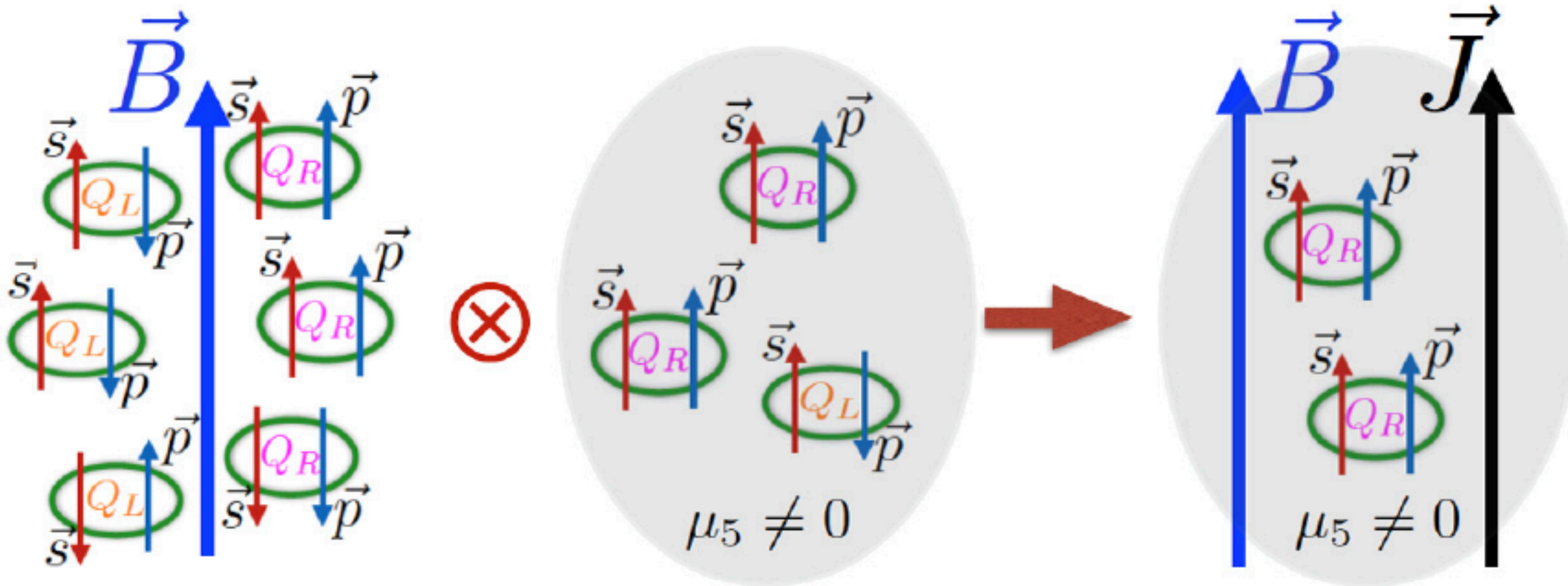
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current

Magnetic Field

Q.M. Transport

Intuitive Picture of CME



Intuitive understanding of CME:

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

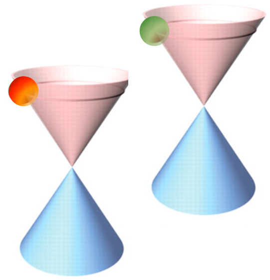
→ ***Transport current along magnetic field***

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

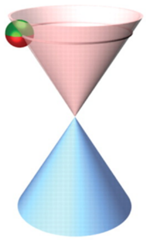
Searching for CME in Laboratories

CME was observed via negative magnetoresistance in semimetals.

Weyl semimetal
(non-degenerated bands)



Dirac semimetal
(doubly degenerated bands)

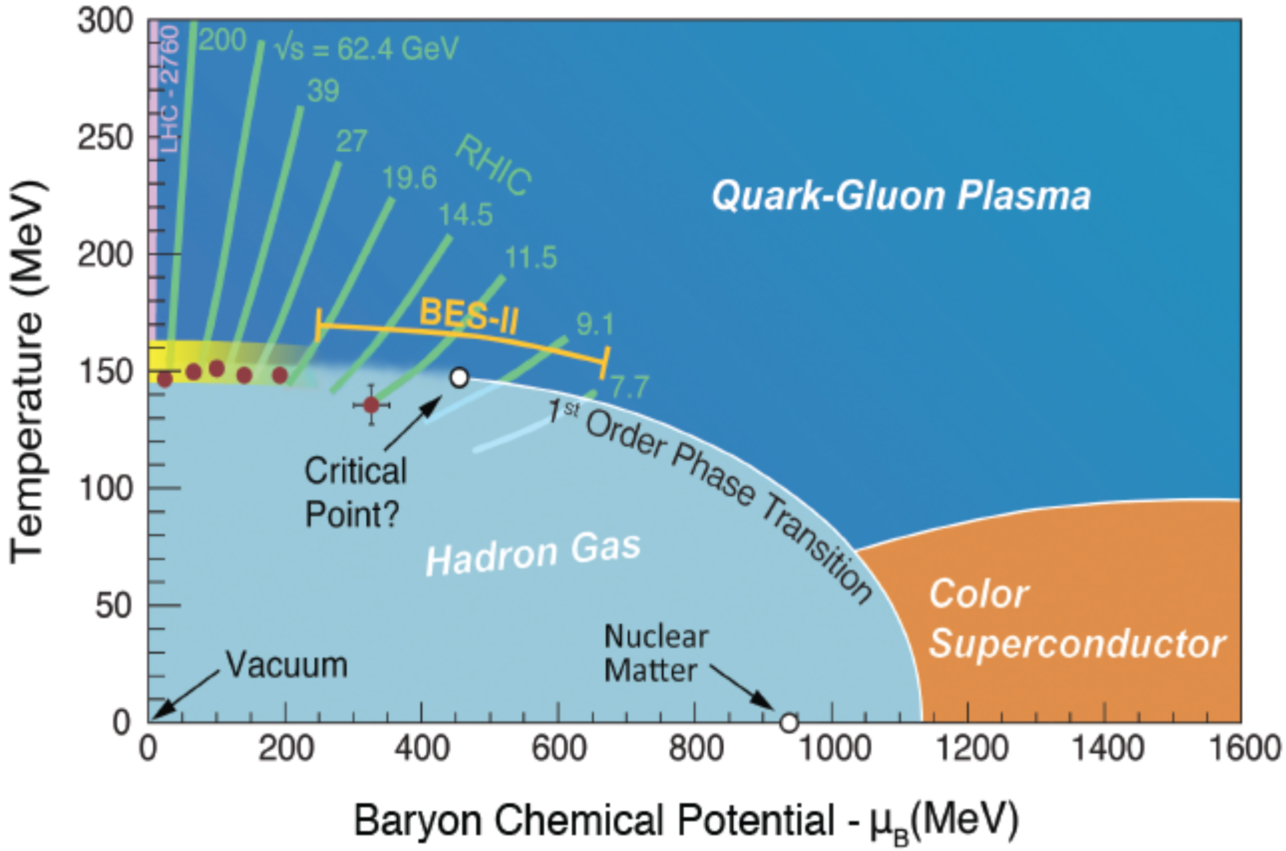


Observe CME for the subatomic chiral matter in heavy ion collisions?

1) ***(nearly) chiral quarks***
2) ***chirality imbalance***
3) ***strong magnetic field***

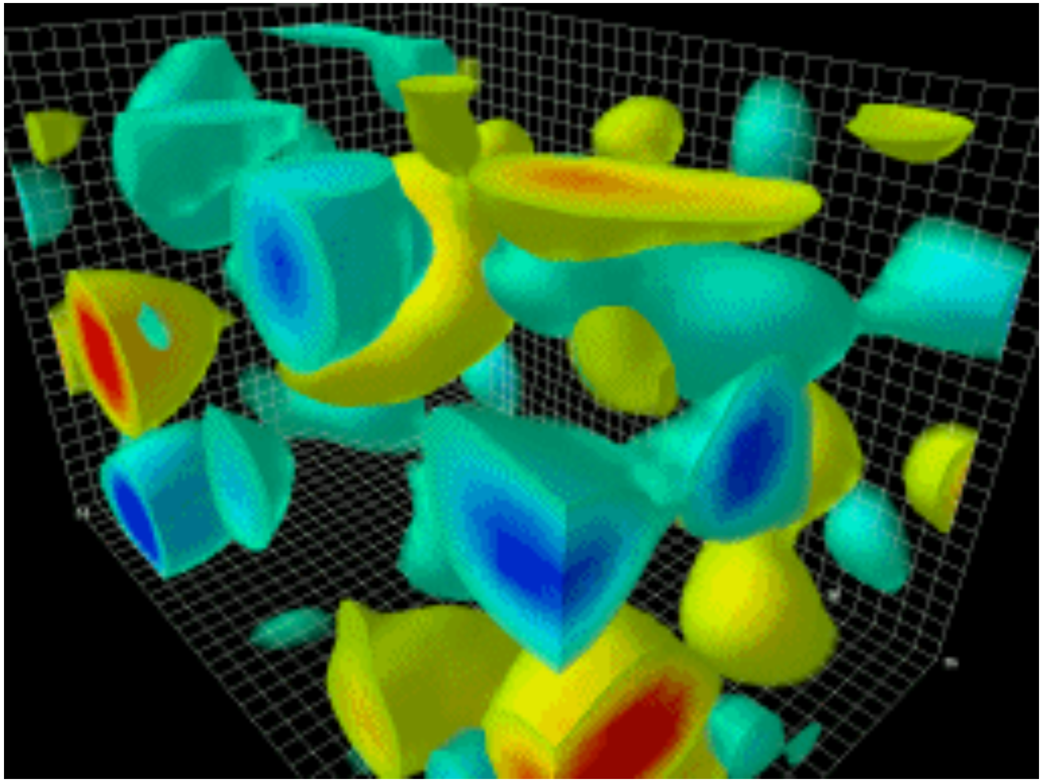
CME and Beam Energy Scan

Restoration of chiral symmetry only at high enough beam energy —> beam energy dependence is crucial!



**** 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 Gluon Topology to Quark Chirality



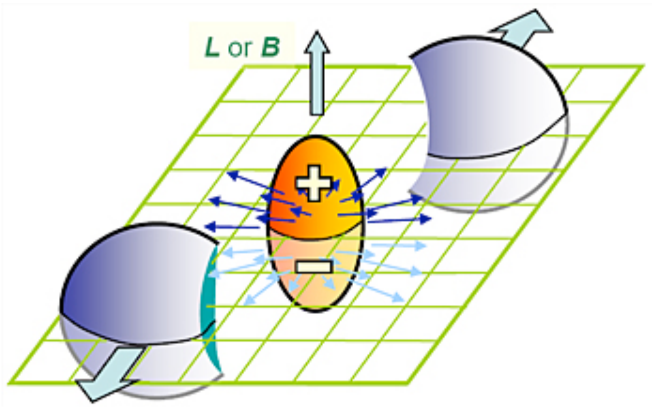
$$Q_w = \frac{1}{32\pi^2} \int d^4x \, (gG_a^{\mu\nu}) \cdot (g\tilde{G}^a_{\mu\nu})$$

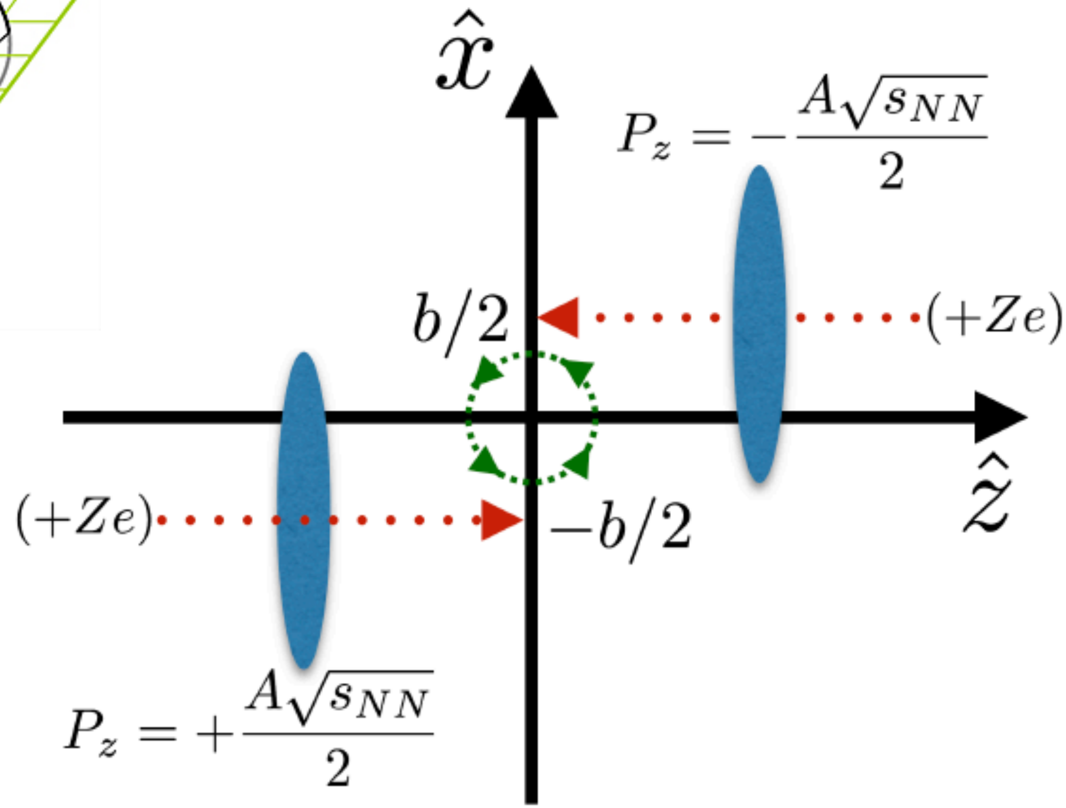
$$N_5(t \to +\infty) - N_5(t \to -\infty) = \frac{g^2}{16\pi^2} \int dt d^3\mathbf{r} \, G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

QCD anomaly: gluon topology —> chirality imbalance

$$N_R - N_L = N_5 = 2Q_w$$

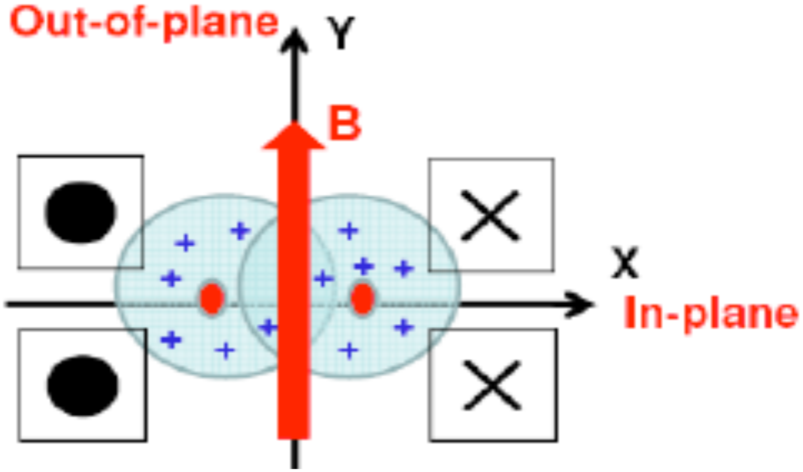
Strong Electromagnetic Fields



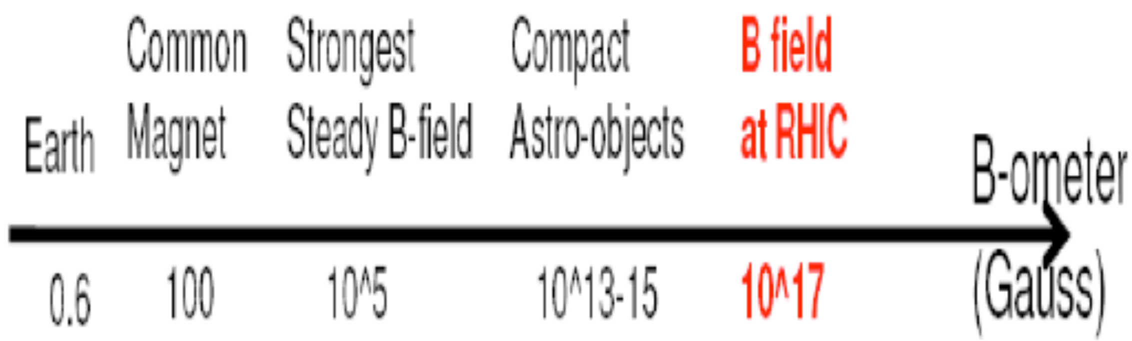


Large angular momentum together with large (+Ze) nuclear charge —> strong magnetic field!

Strong Electromagnetic Fields



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



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

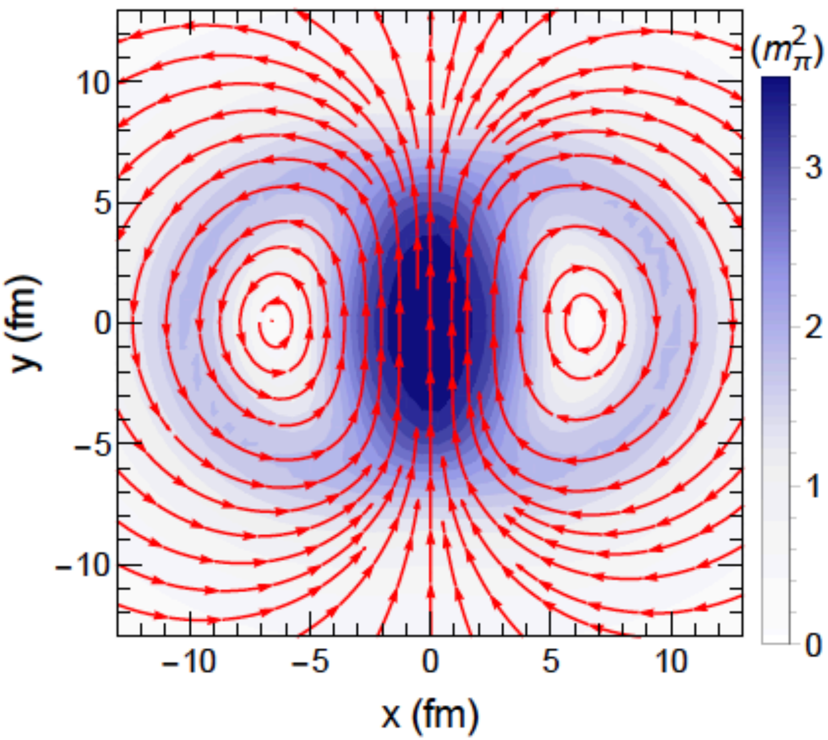
[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Skokov-McLerran; Tuchin; ...]

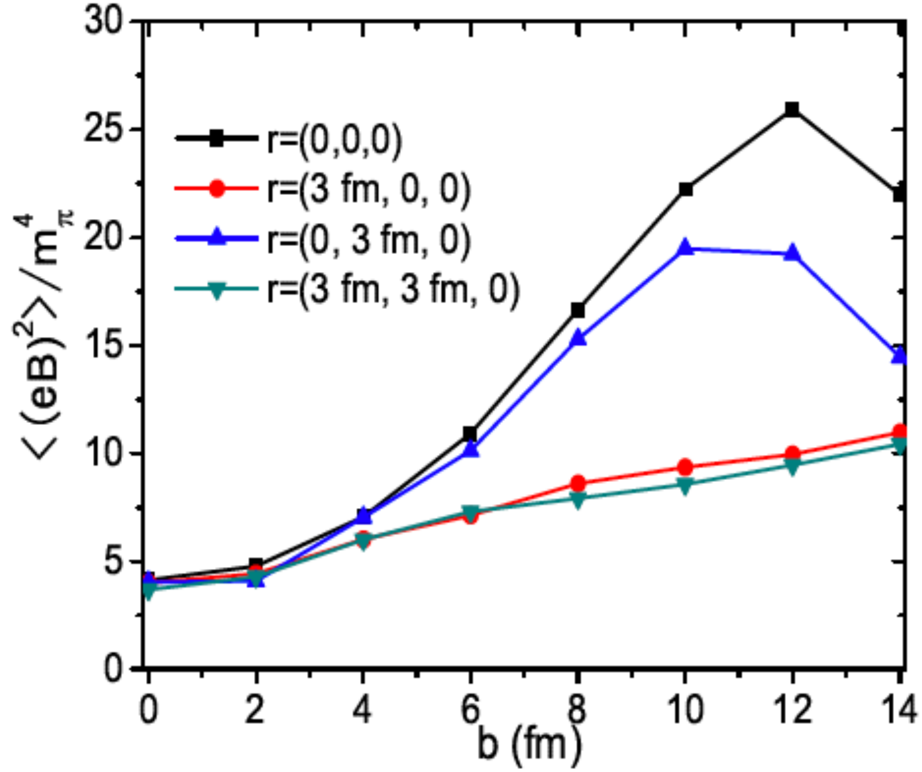
- "Out-of-plane" orientation (approximately)

[Bloczynski-Huang-Zhang-Liao]

Strong Electromagnetic Fields

Huang, Liao, et al PLB2012

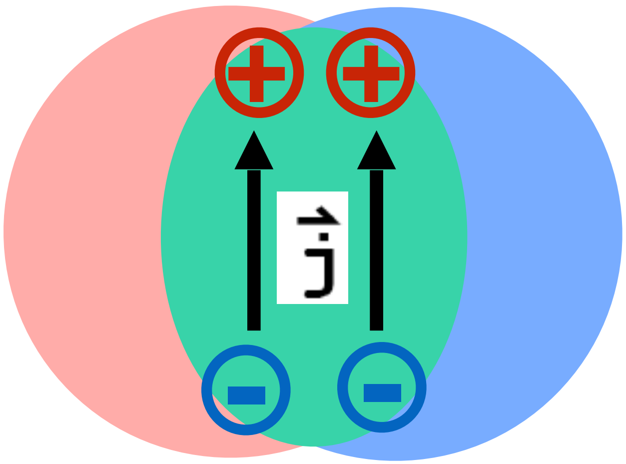




Quantitative simulations confirm the existence of such extreme fields!

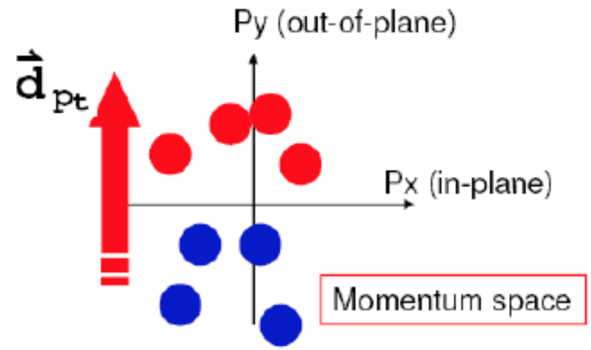
[STAR measurements of di-electron — direct hint?! PRL2018]

From CME Current to Charge Separation



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

strong radial blast:
position —> momentum



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

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

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

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

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

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

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

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

$$\delta = F + H$$

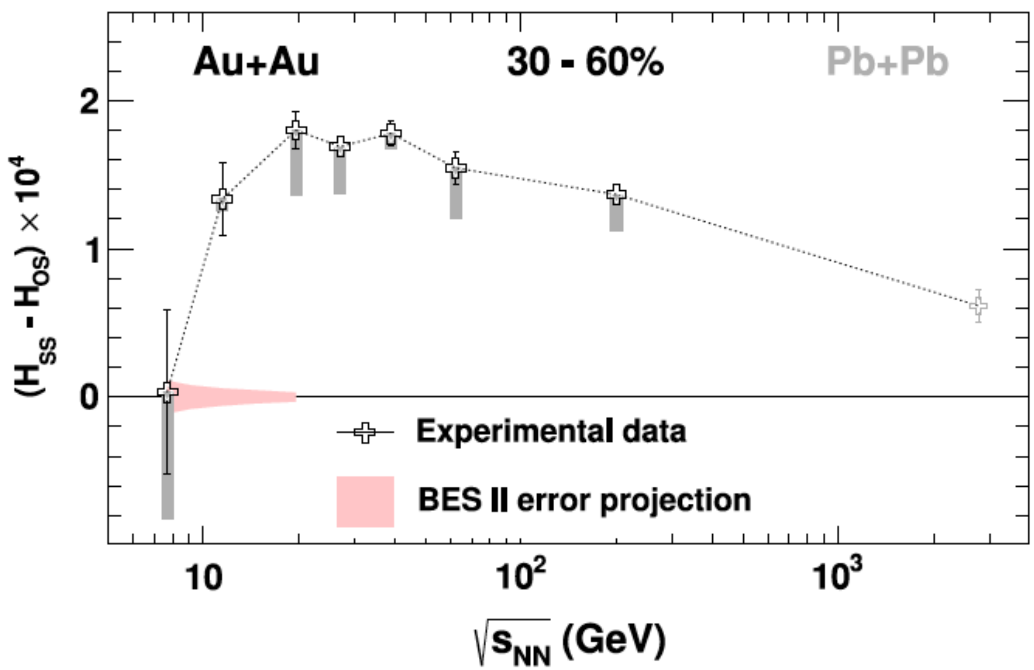
F: Bulk Background

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

Bzdak, Koch, JL, 2012

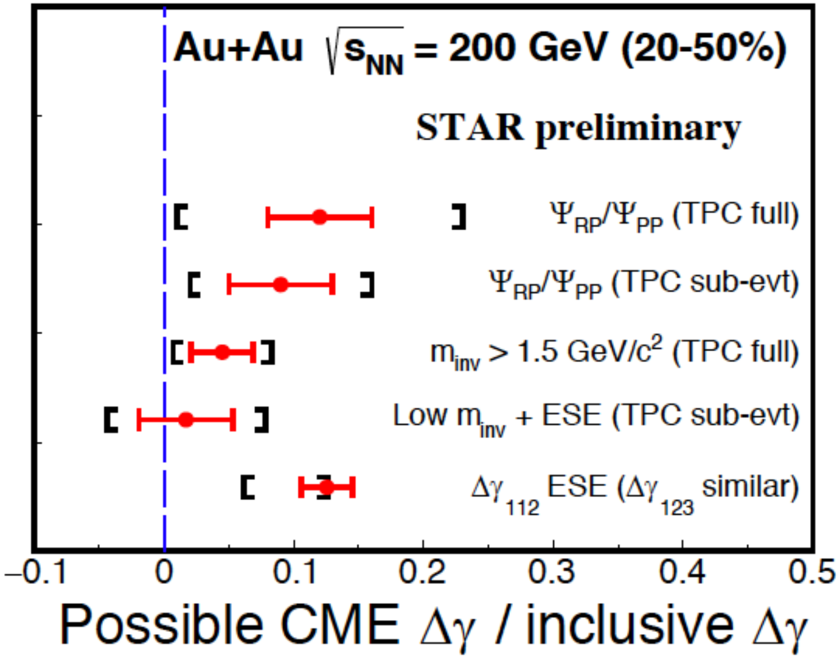
$$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$$

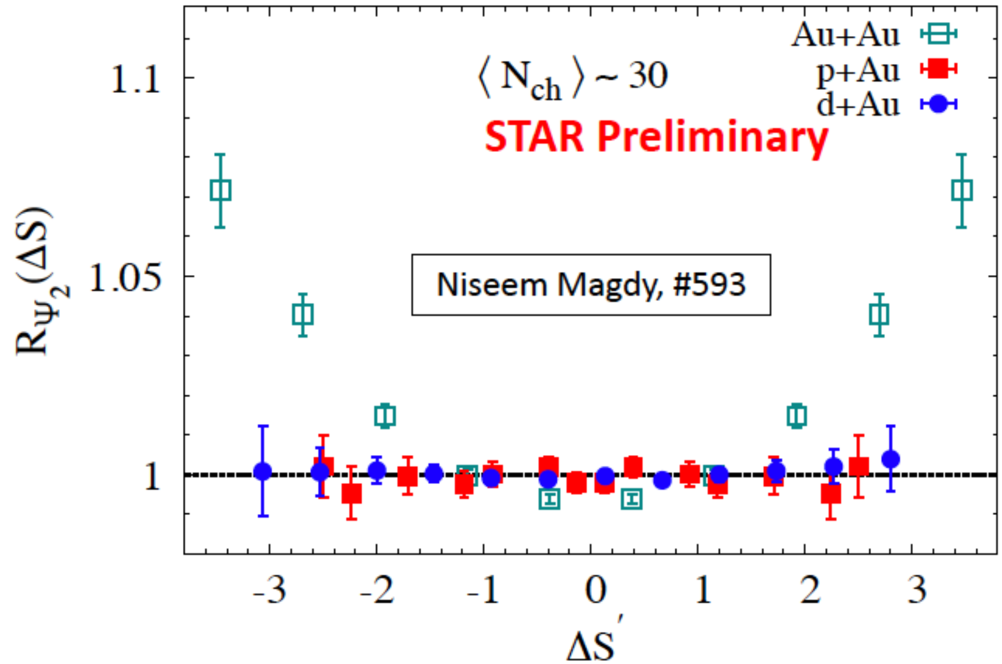
Many interesting proposals of new observables!



STAR PRL2014

Recent Exp. Search Status





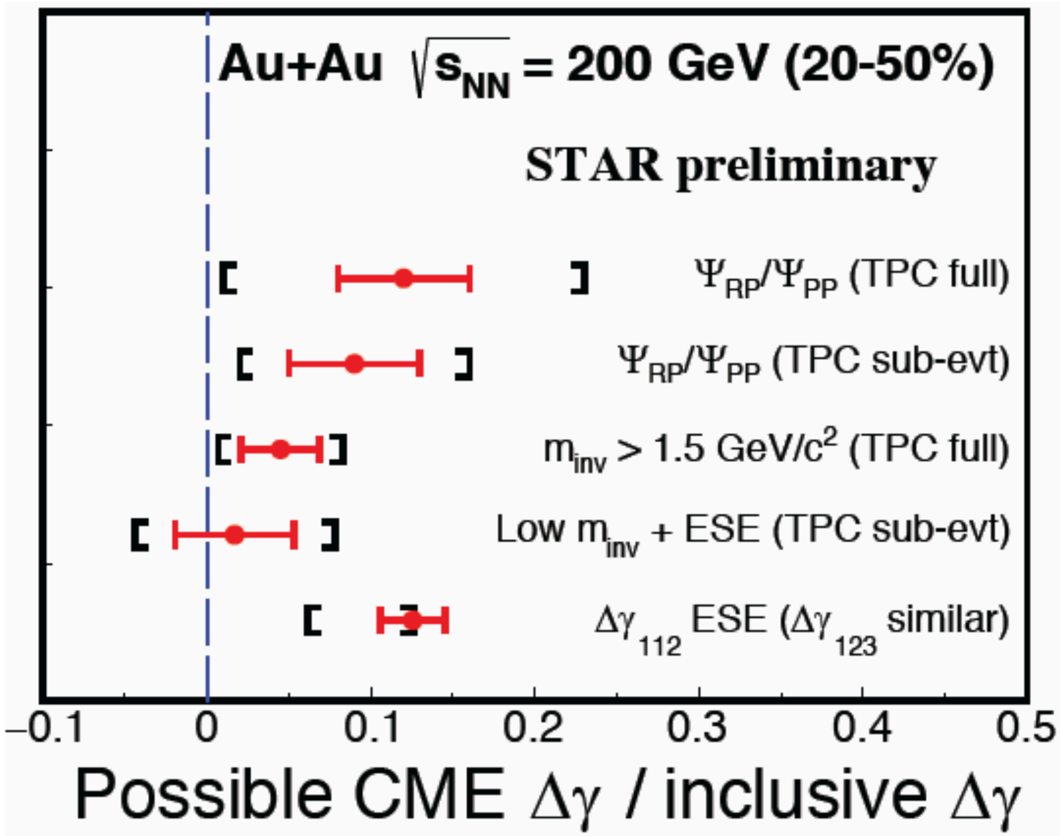
[From Z. Ye, STAR Summary Talk @ QM2018]

ALICE @ LHC 2.76TeV: signal level possibly about 8~10%

CMS @ LHC 5.02TeV: signal level no more than 4%

The trend with beam energy seems in line with expectation!

MORE Consistent with Being NONZERO?!



A "naive" statistical interpretation: (8.5 +/- 1.2) % .

It is MORE consistent with being NONZERO @ 200GeV!

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

AVFD Framework

[Not discussed here: calculations based on transport framework, e.g. works by X. Huang, G. Ma, Y. Ma, J. Xu, C.M. Ko, ……]

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!

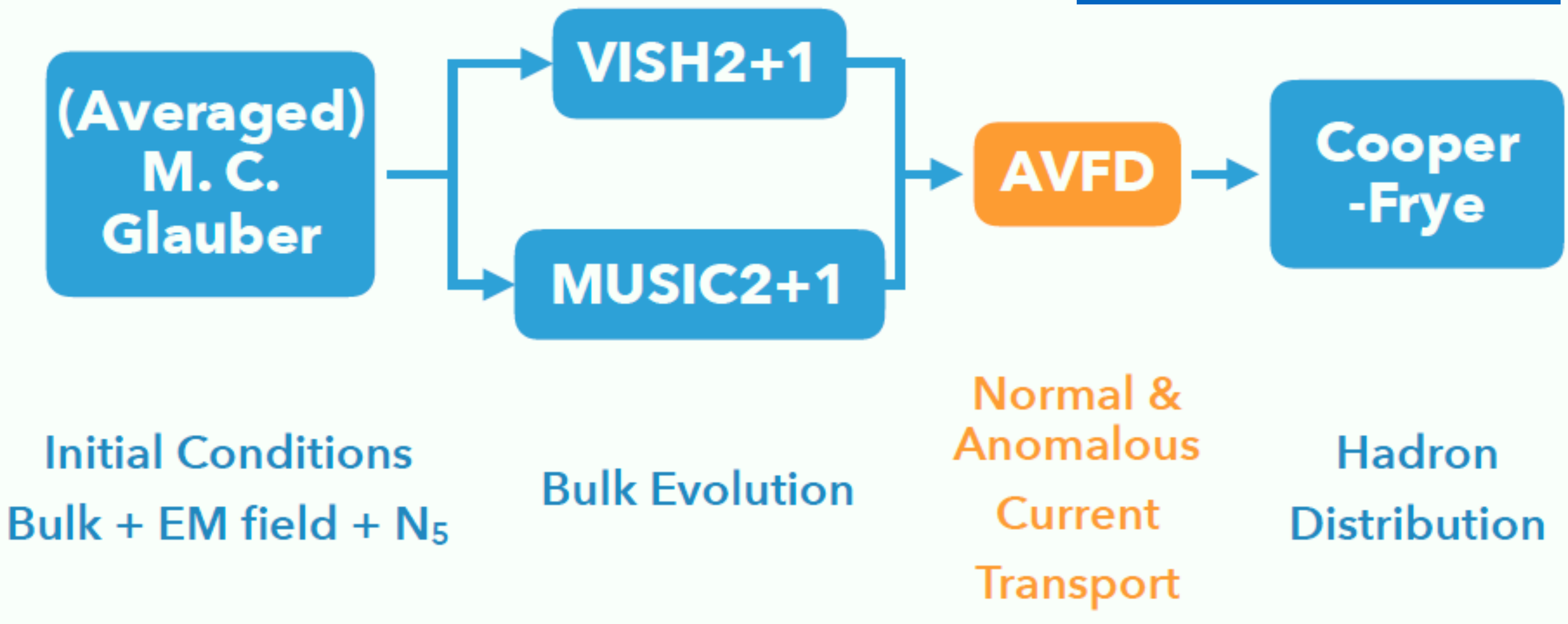
It would be remarkable to actually "see" this new hydrodynamics at work in real world materials!

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

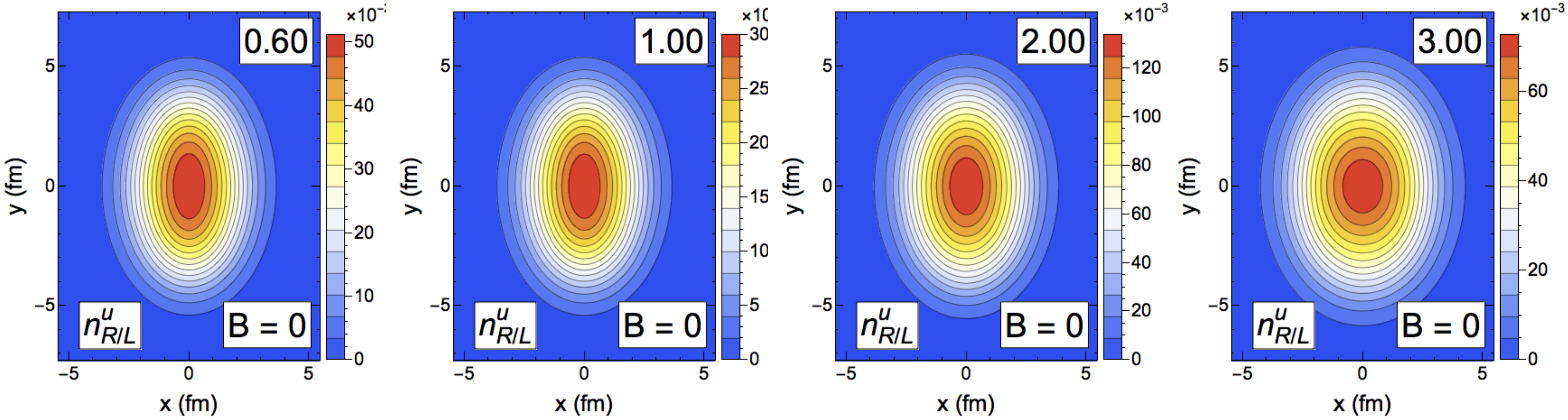
$$\Delta^\mu{}_\nu \, d\, \nu_{R,L}^\nu = -\frac{1}{\tau_{rlx}}(\nu_{R,L}^\mu - \nu_{NS}^\mu)$$

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

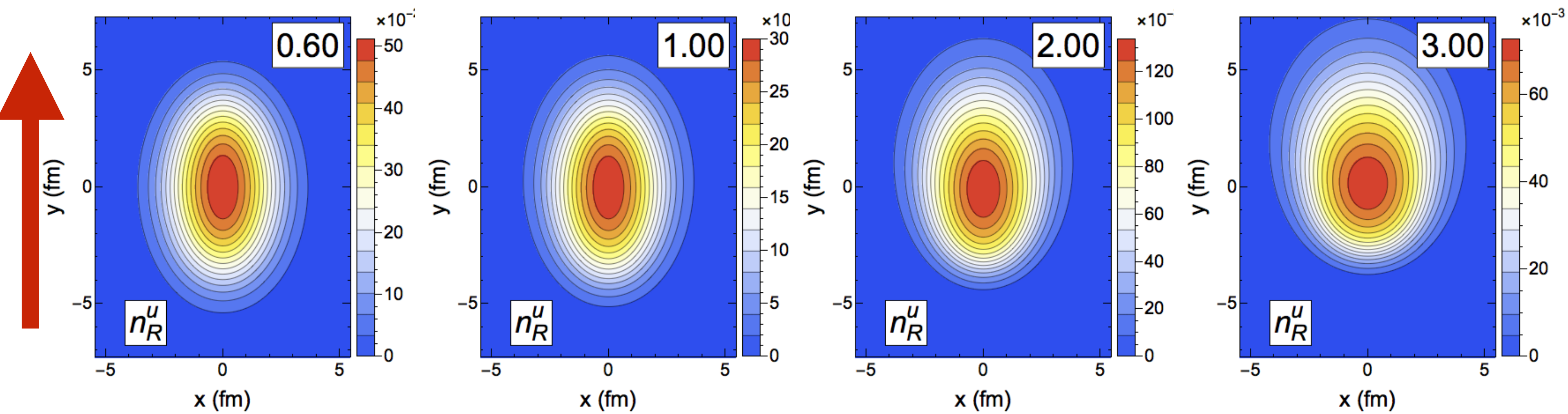
on top of VISH2+1D –– OSU Group

[We now also have MUSIC-AVFD!]

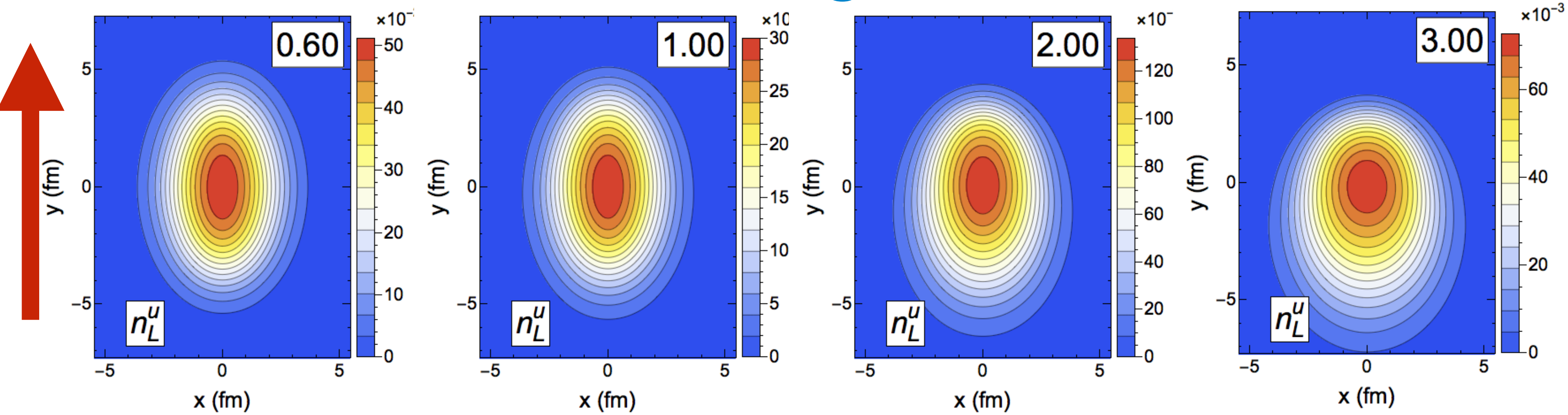
Demonstrating the AVFD



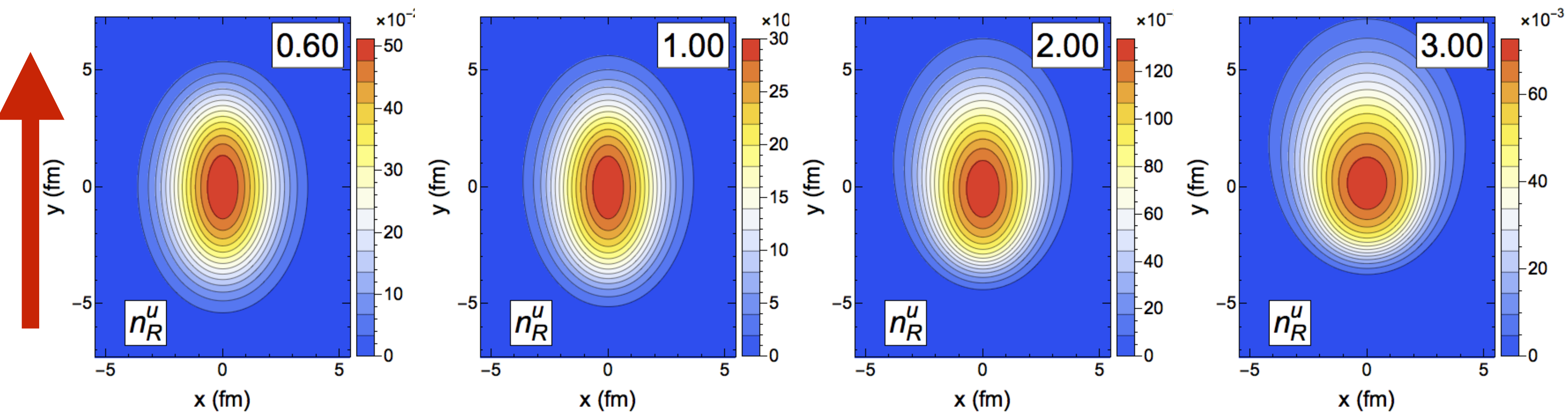
Upper: NO magnetic field
Lower: with B field (along y+ direction)



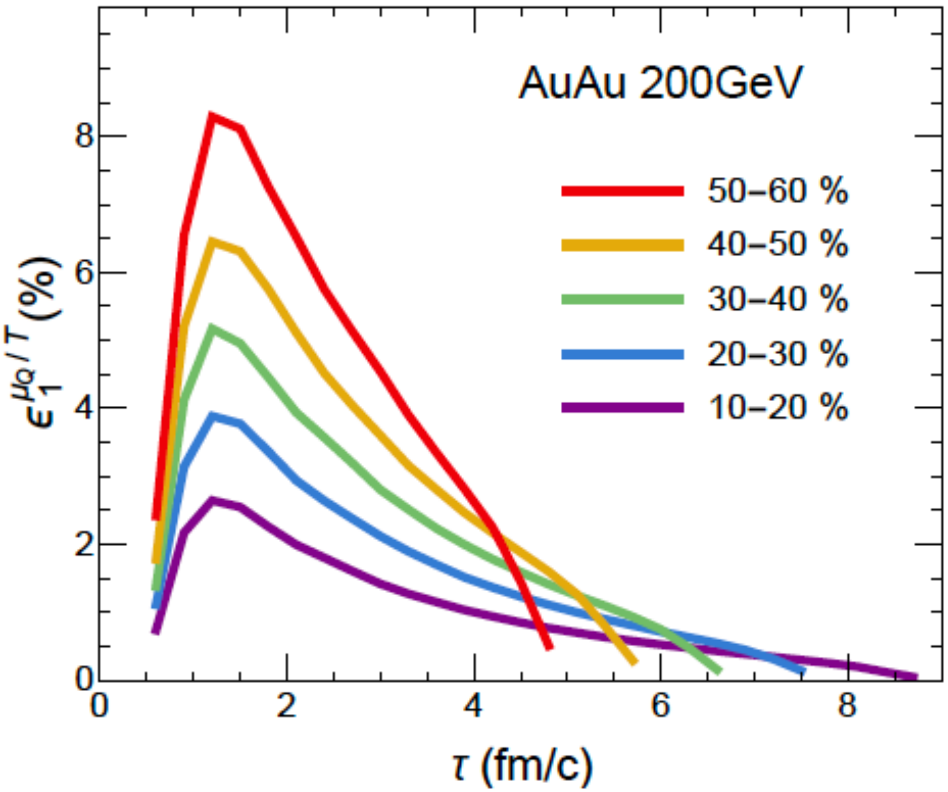
Demonstrating the AVFD



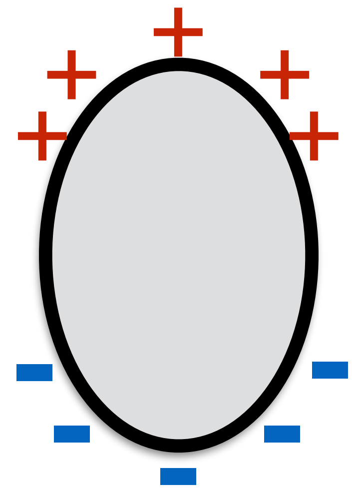
Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)



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)

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

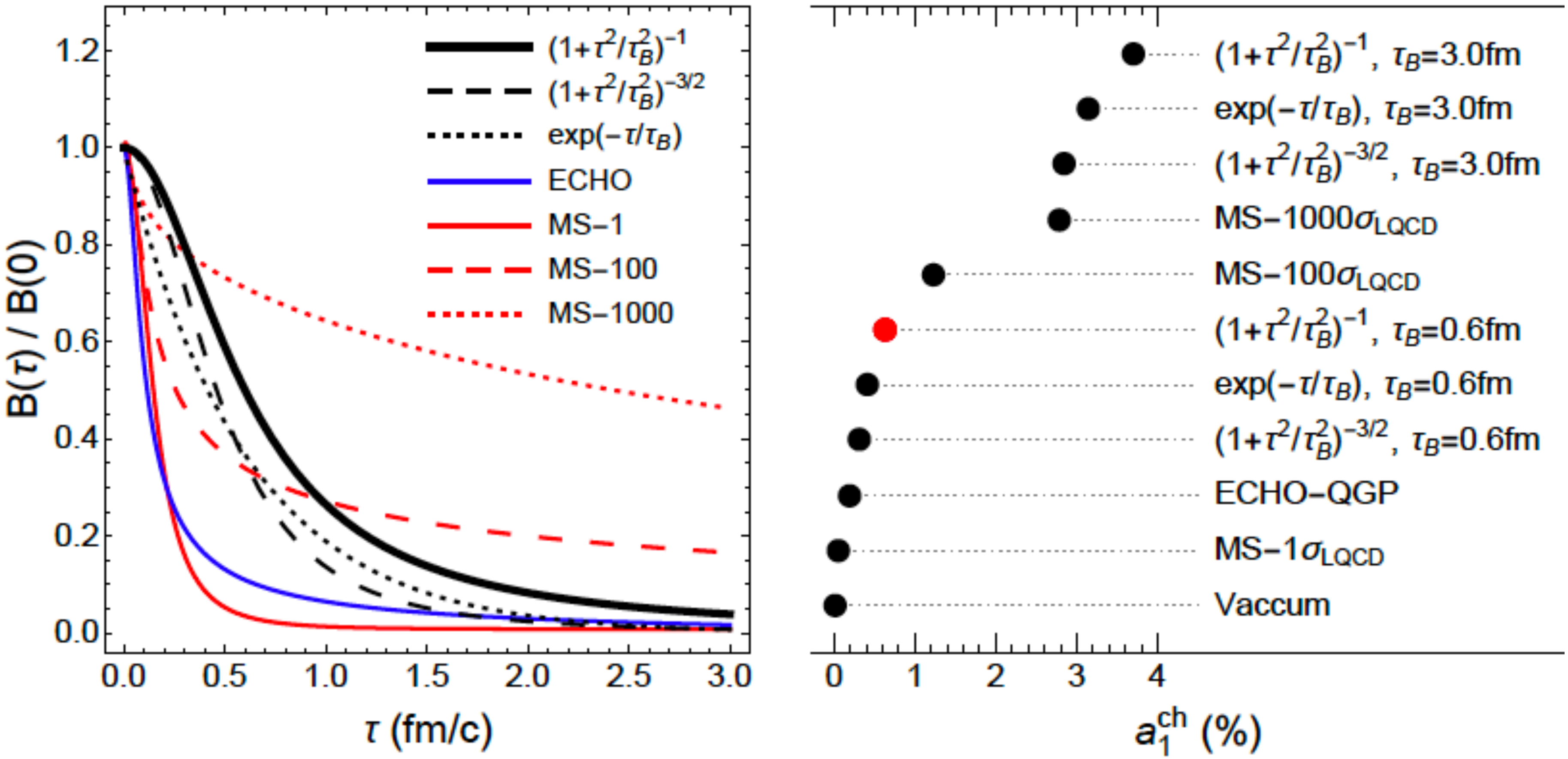
$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$

AVFD Results for AuAu Collisions

We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

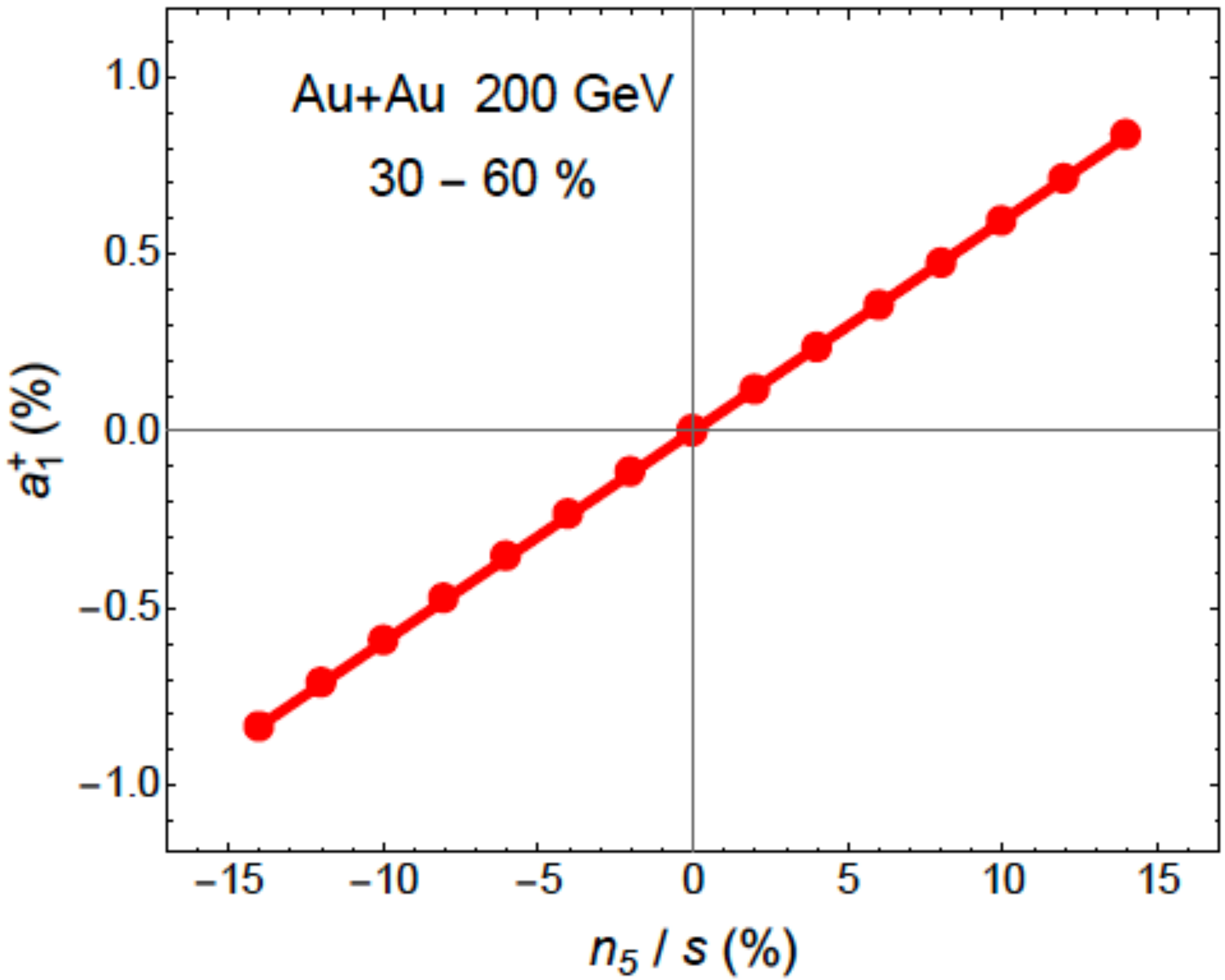
arXiv:1611.04586 ***arXiv:1711.02496***

The Influence of the Magnetic Field



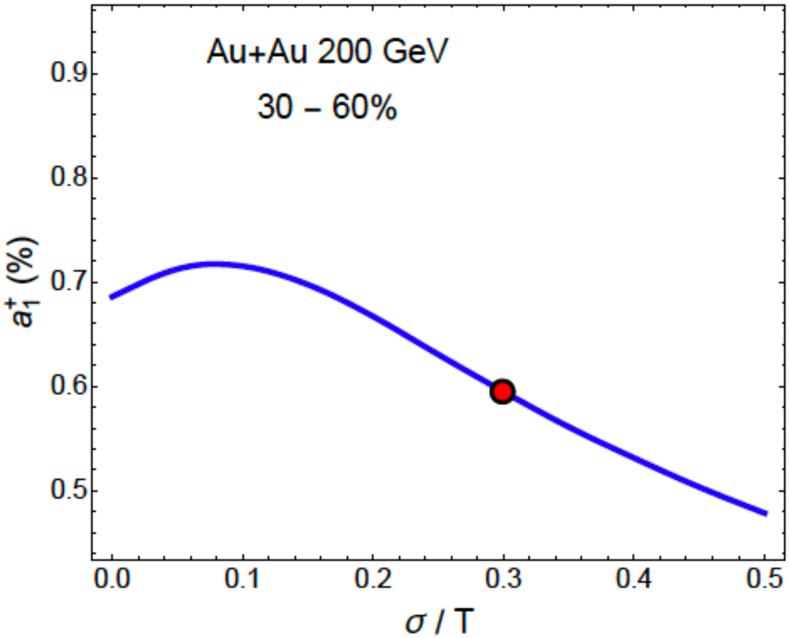
Strong influence by B field evolution;
Significant theoretical uncertainty!

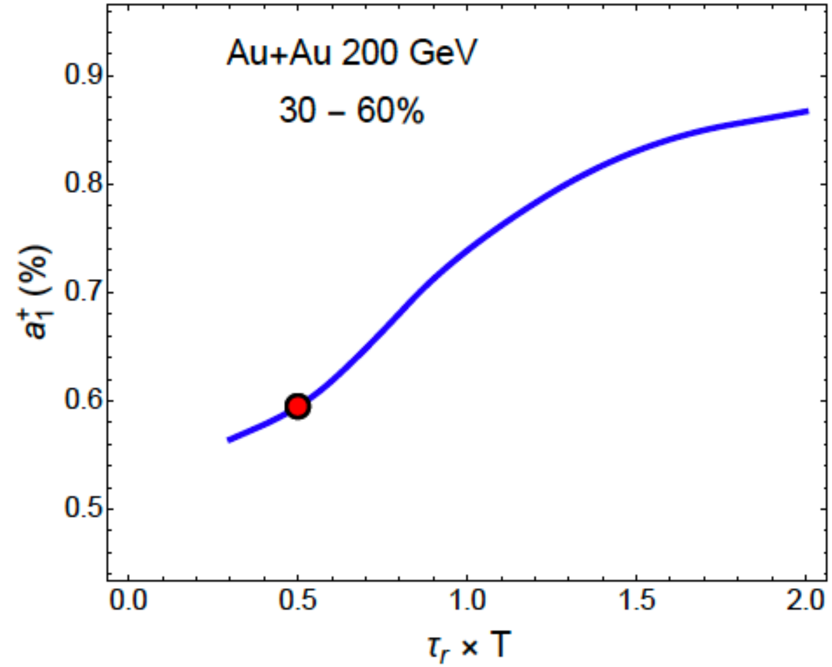
The Axial Charge Initial Condition



Very sensitive to initial axial charge;
Significant theoretical uncertainty!

The Influence of the Viscous Transport



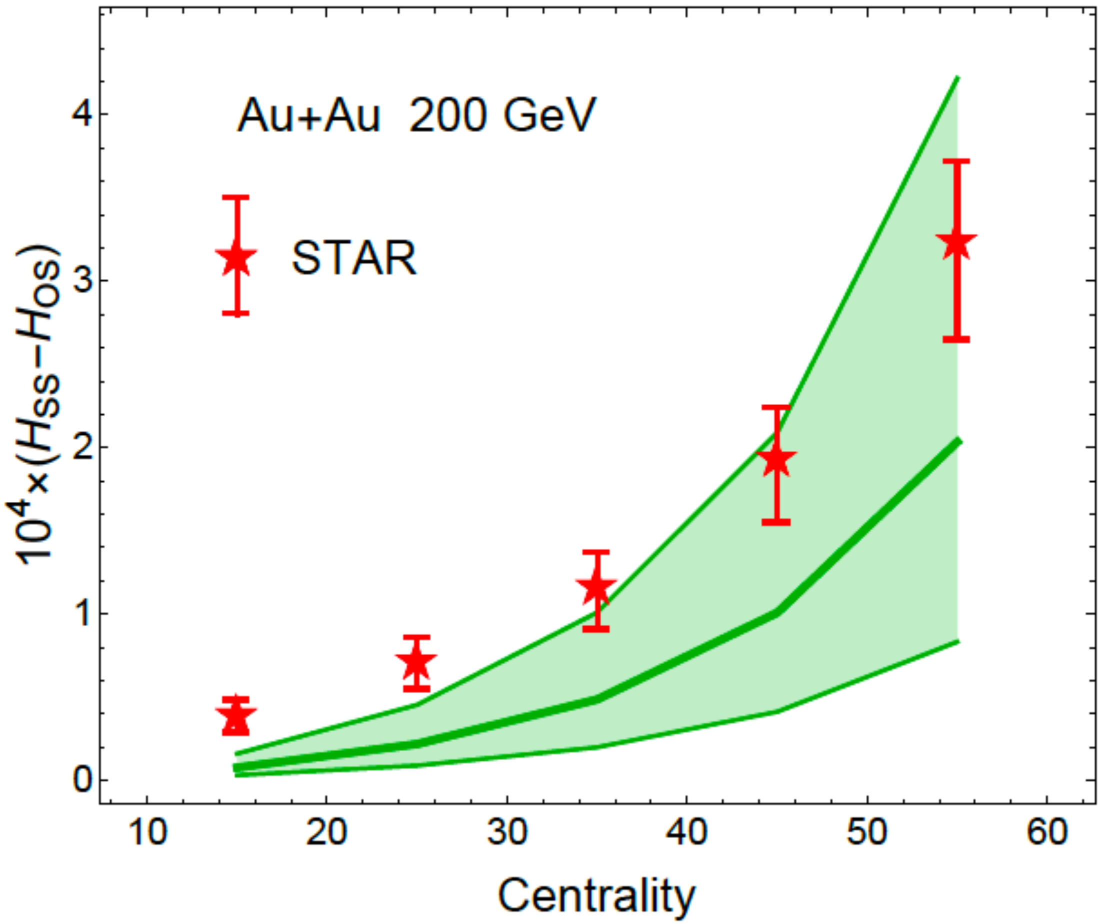


$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}\left(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu}\right)$$

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

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

AVFD Predictions v.s Experimental Data



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

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

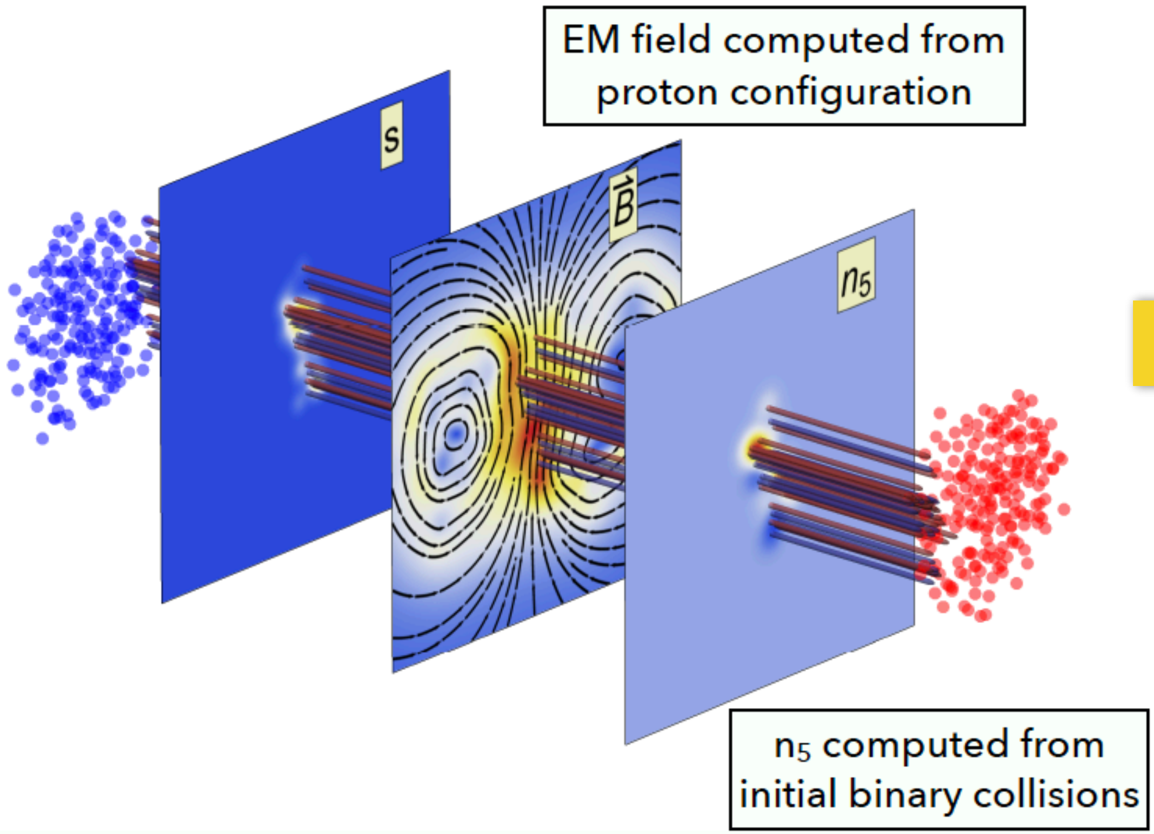
$$\sqrt{\langle n_5^2\rangle} \simeq \frac{Q_s^4\,(\pi\rho_{tube}^2\tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\,A_{overlap}}$$

Good agreement !

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

Event-By-Event AVFD



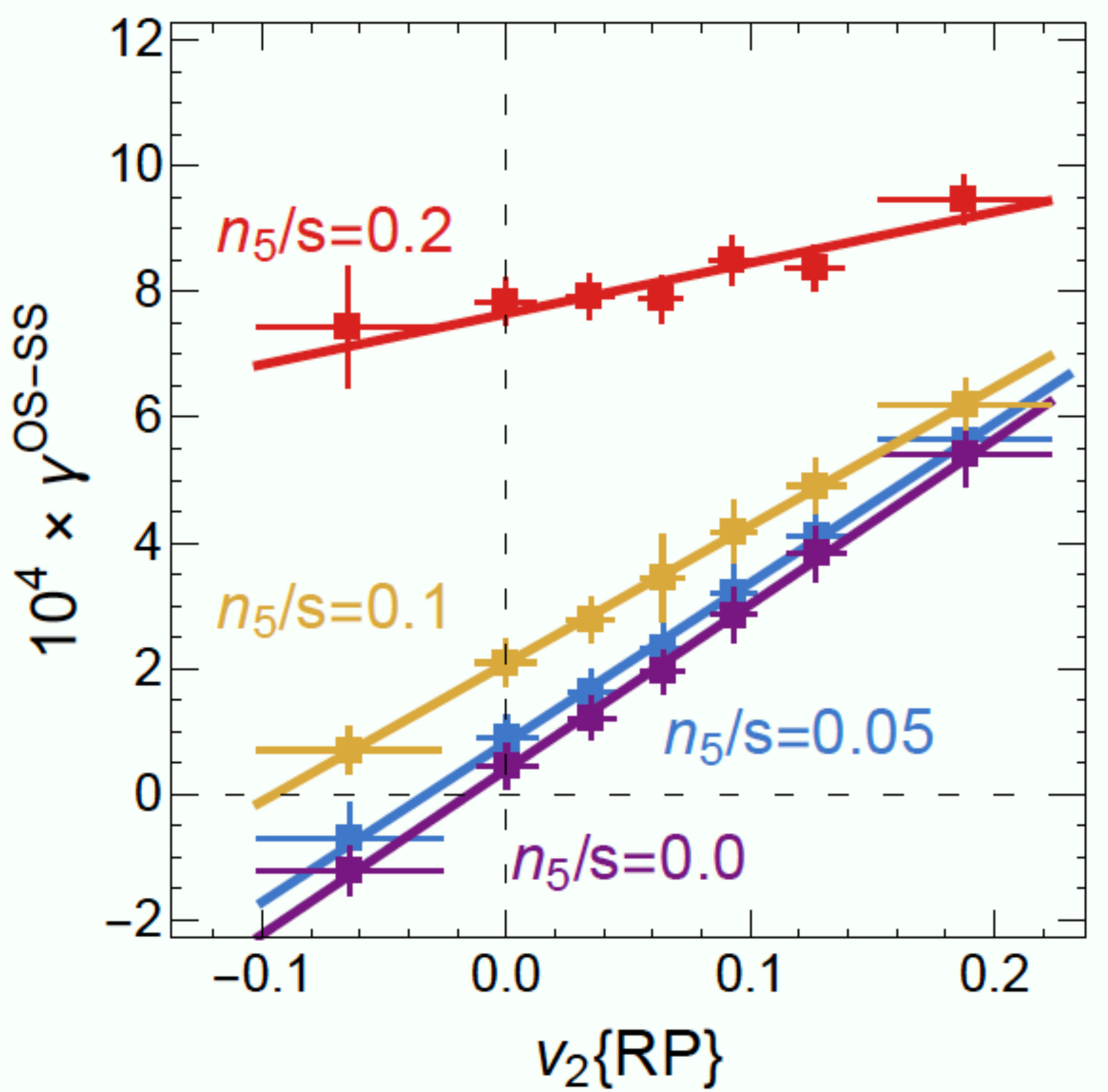
Include EBE fluctuations:

- 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

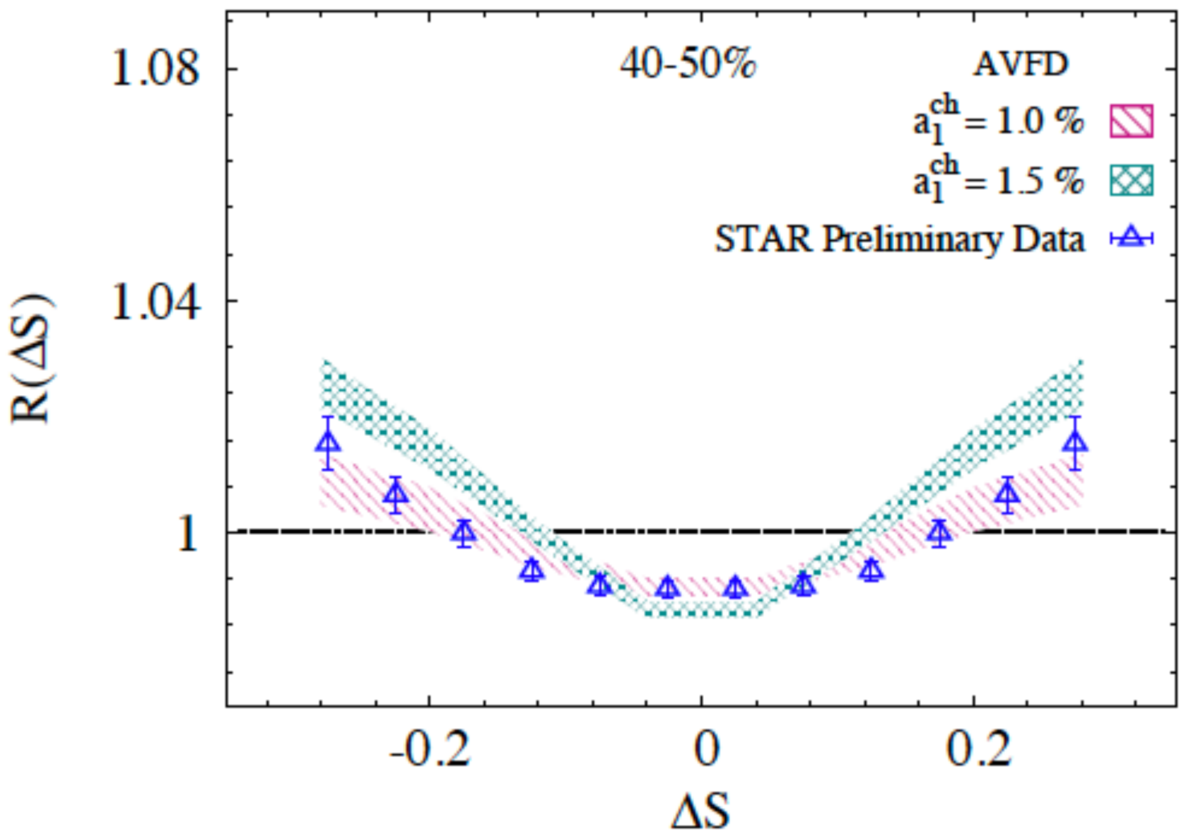
Au-Au @ 200GeV 50-60%



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



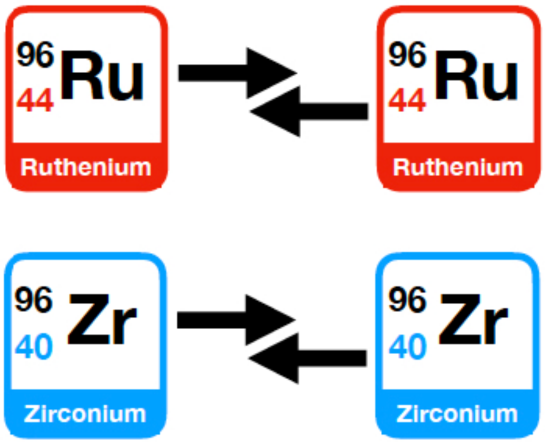
Magdy, Lacey, et al, arXiv:1710.01717; arXiv:1803.02416

R-correlator sensitively responds to CME contribution.

EBE-AVFD Predictions for CME in Isobaric Collisions (Newest results!)

Shi, Zhang, Hou, JL, in final preparation, to appear soon;
Shi, Zhang, Hou, JL, contribution in QM18 proceedings.

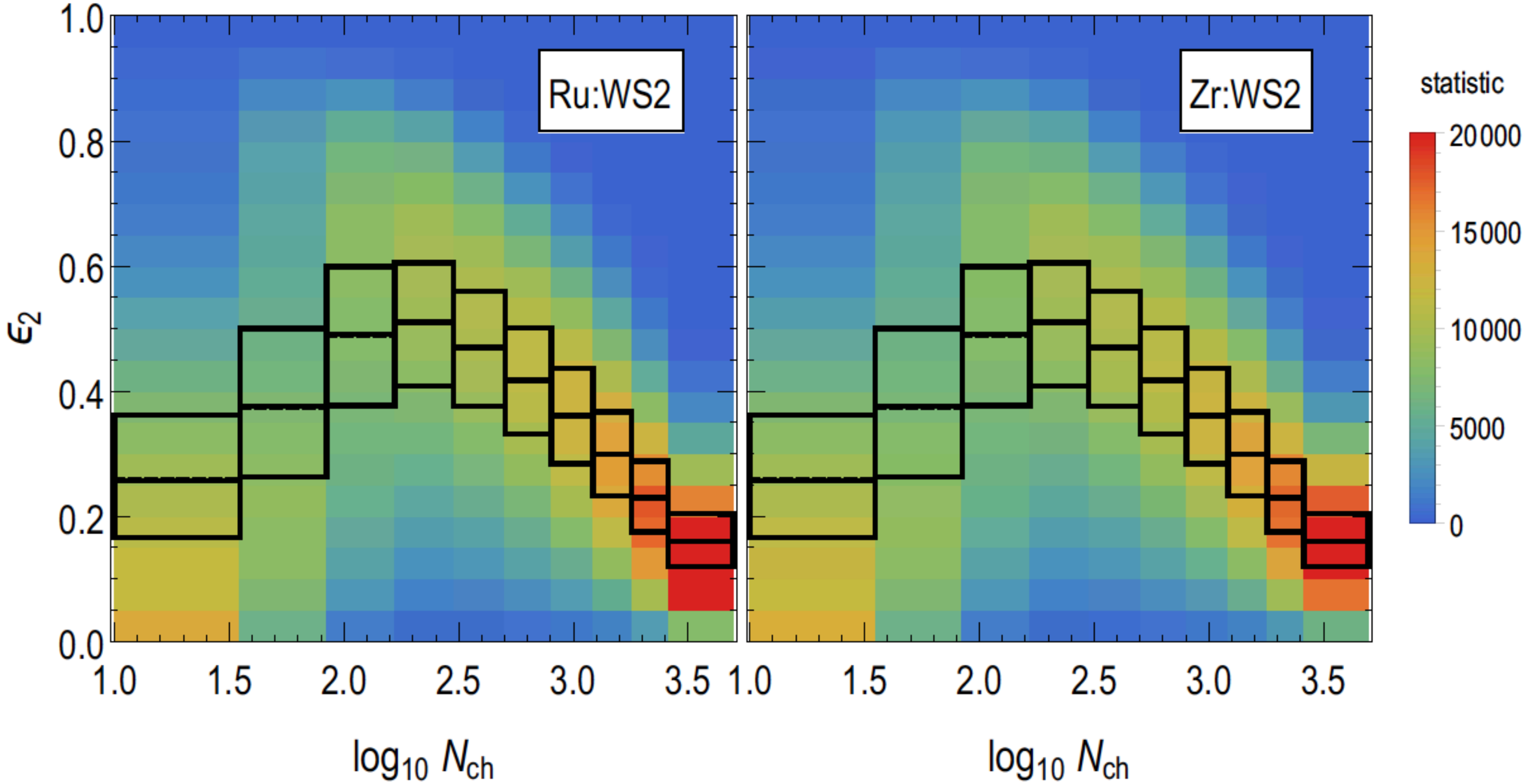
Using Isobaric Collisions for CME Search



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

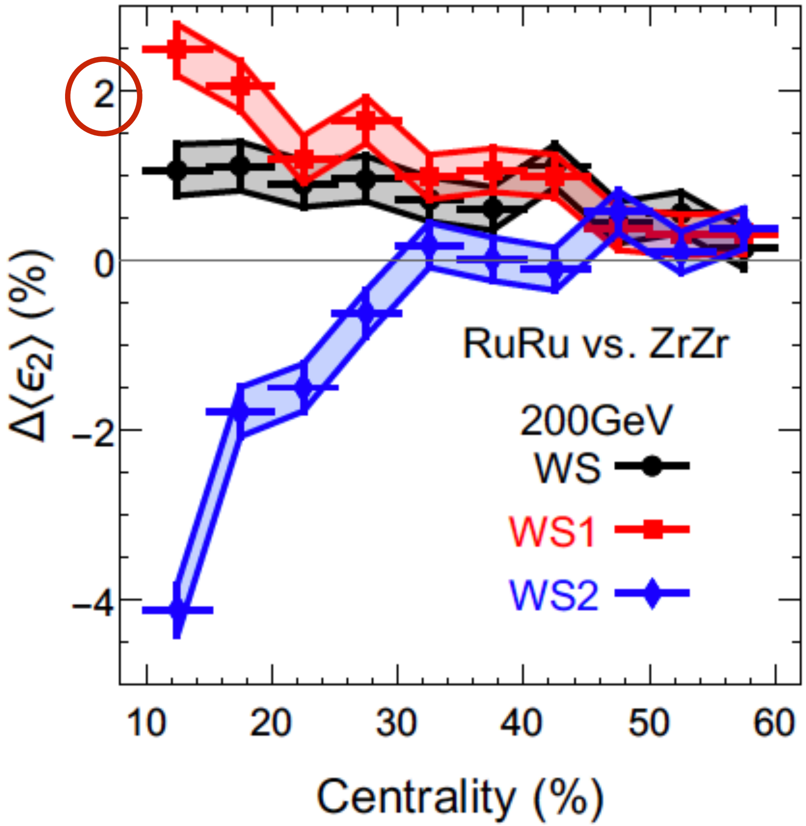
Charge Asymmetry Correlation Measurement

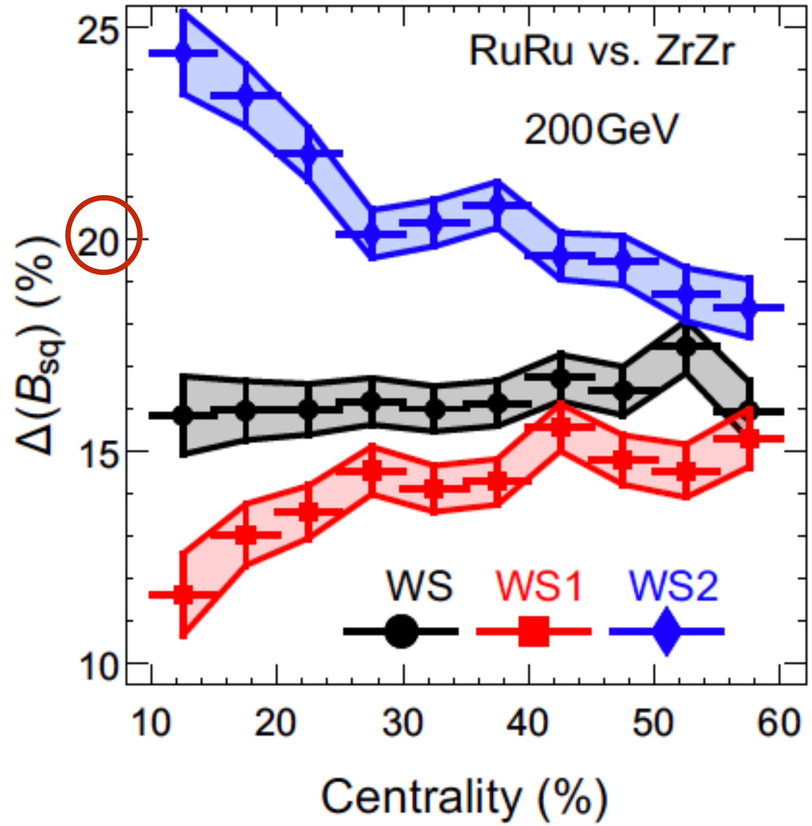
How to Choose Identical Systems?



Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

How to Choose Identical Systems?

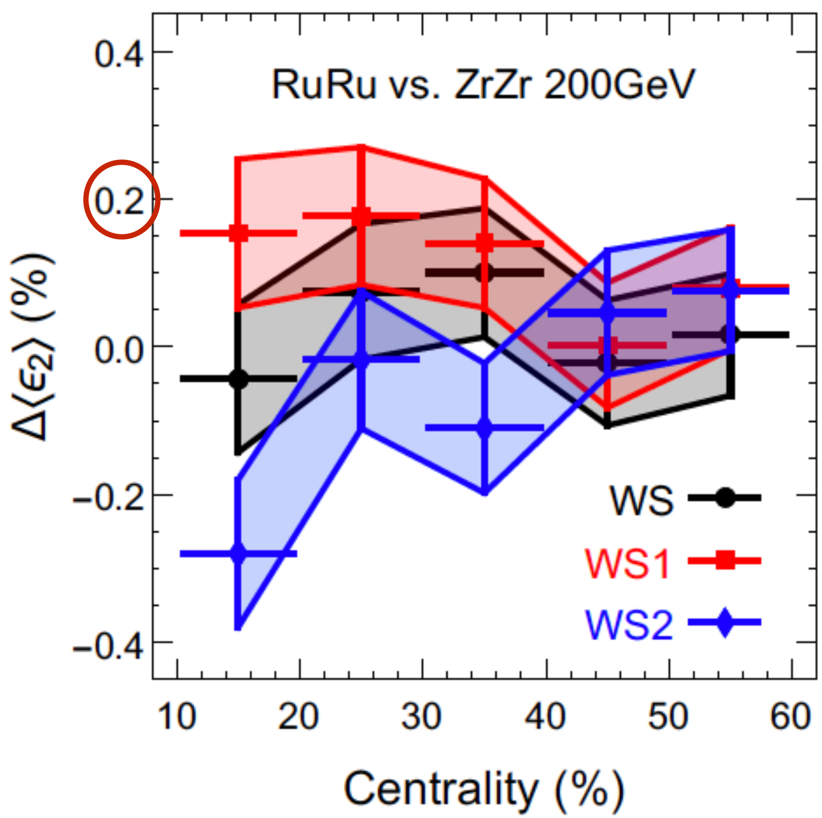




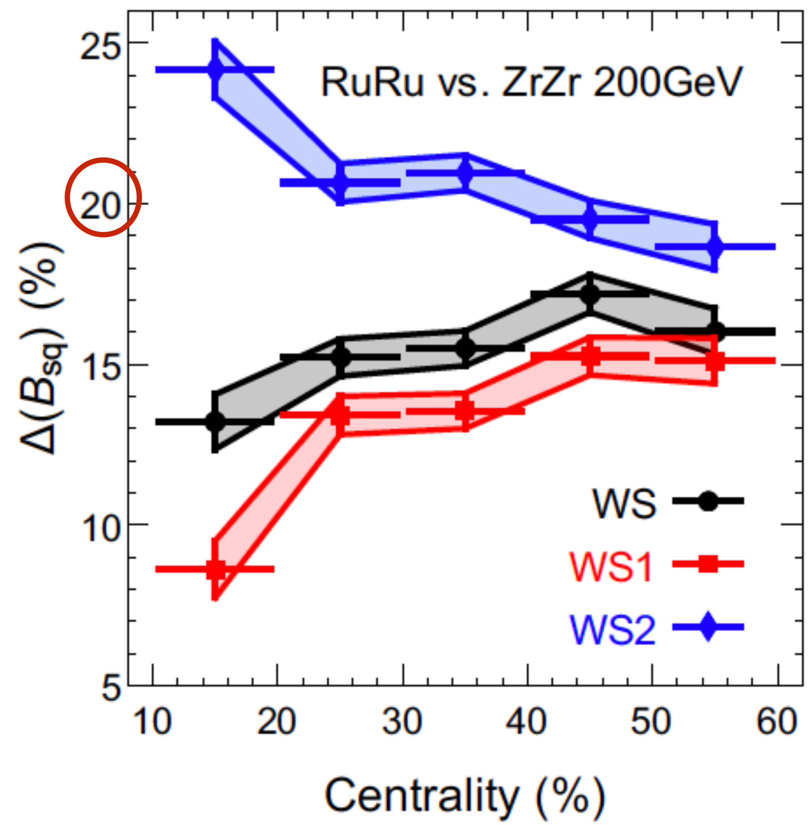
Conventional centrality bin (without joint-cut):
A few percent level of difference in bulk geometry

How to Choose Identical Systems?

Eccentricity is guaranteed the same!

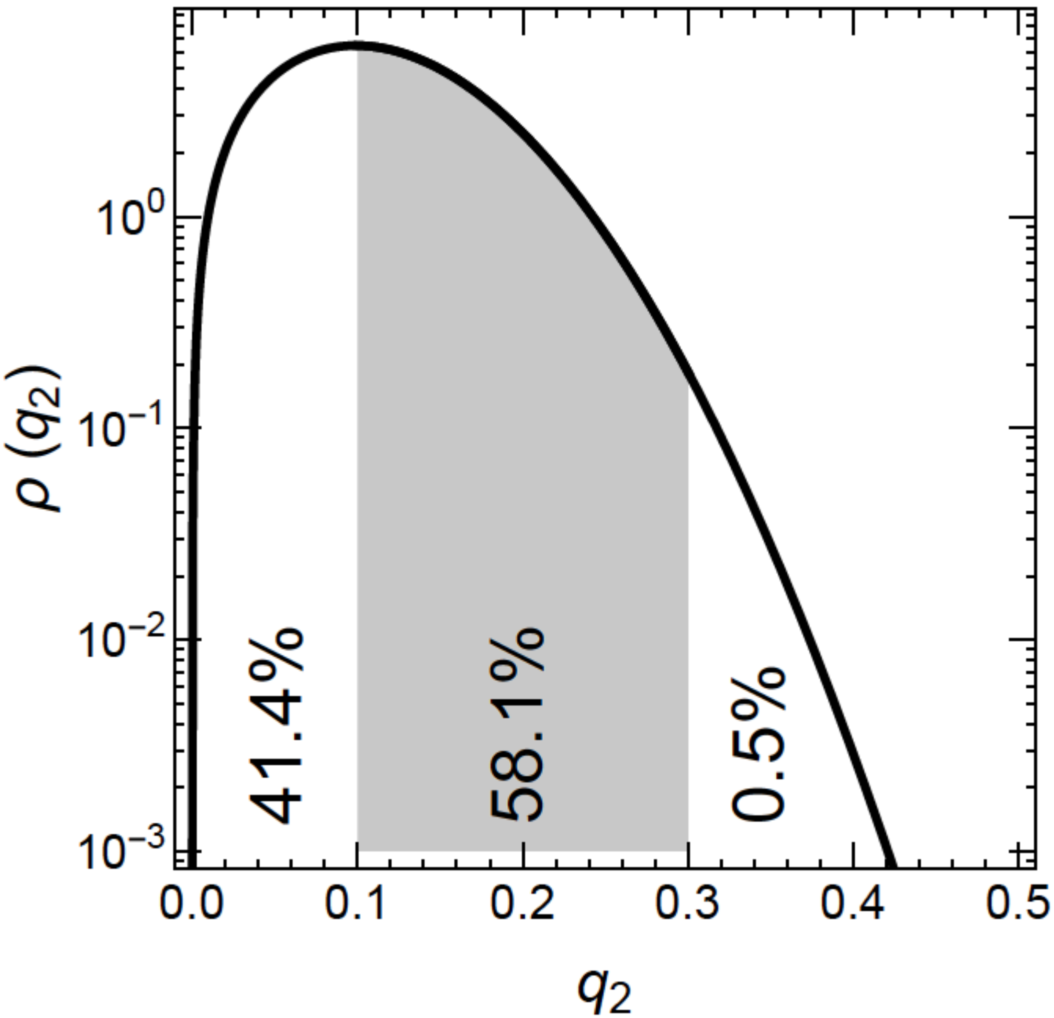


B field differs by 12~20% !



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

Analyzing Actual EBE-AVFD Events for Isobars

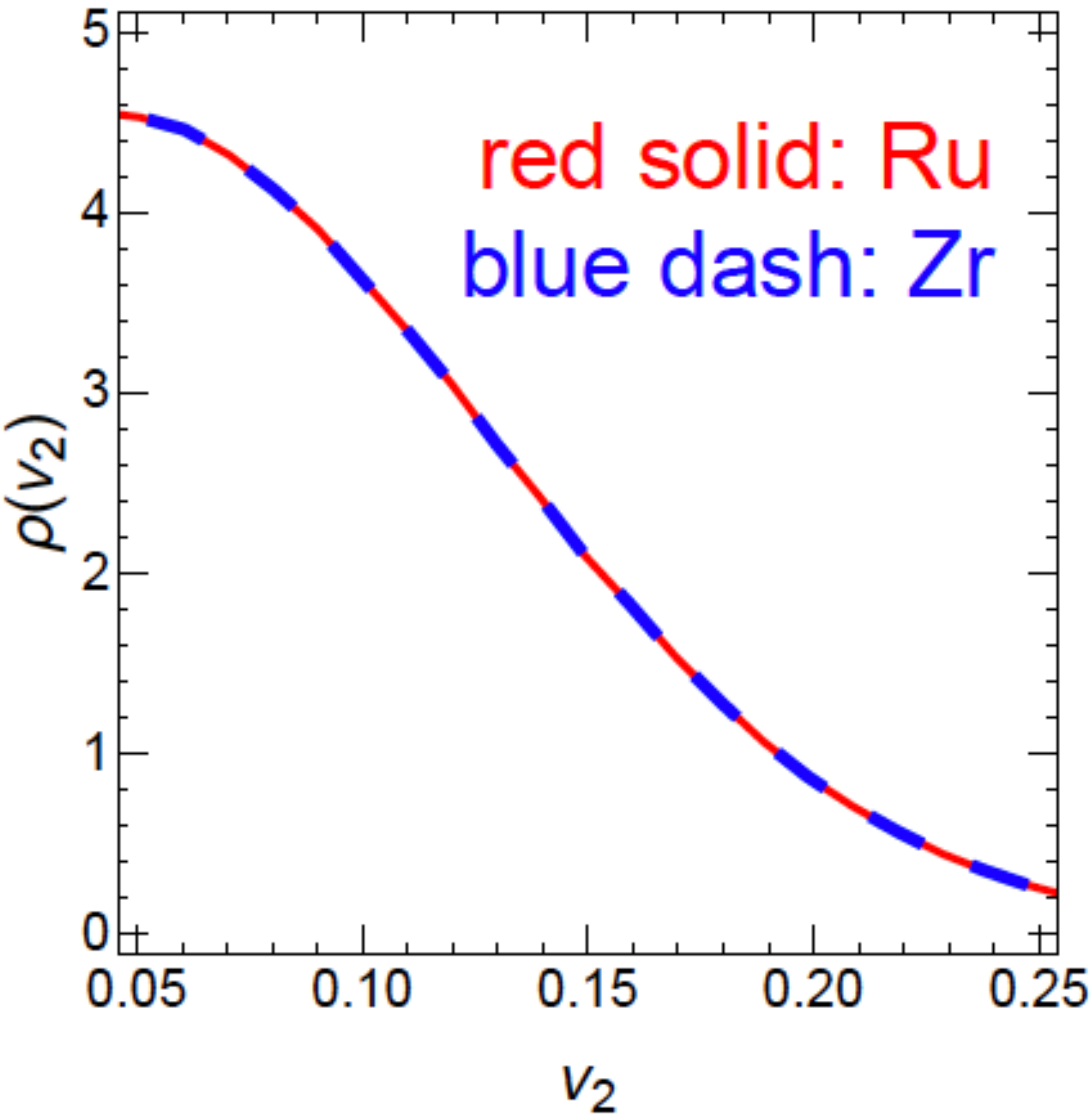


100M EBE-AVFD events: Subject to joint-cut

$64 < N_{ch, |y|<1} < 96$

$0.1 < q_2 < 0.3$

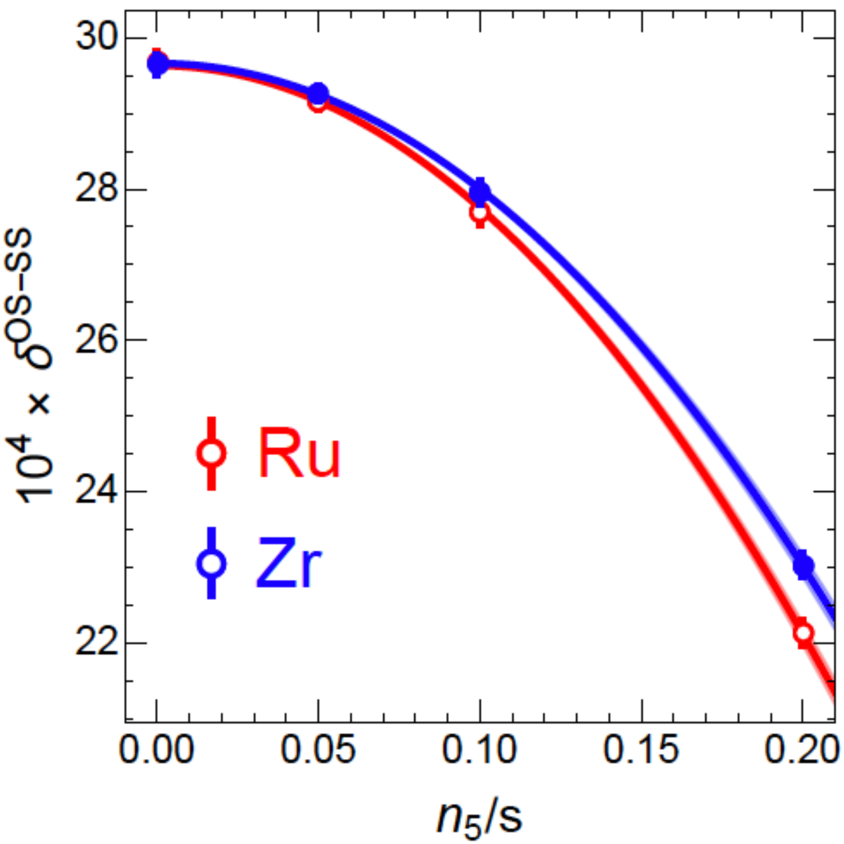
Analyzing Actual EBE-AVFD Events for Isobars

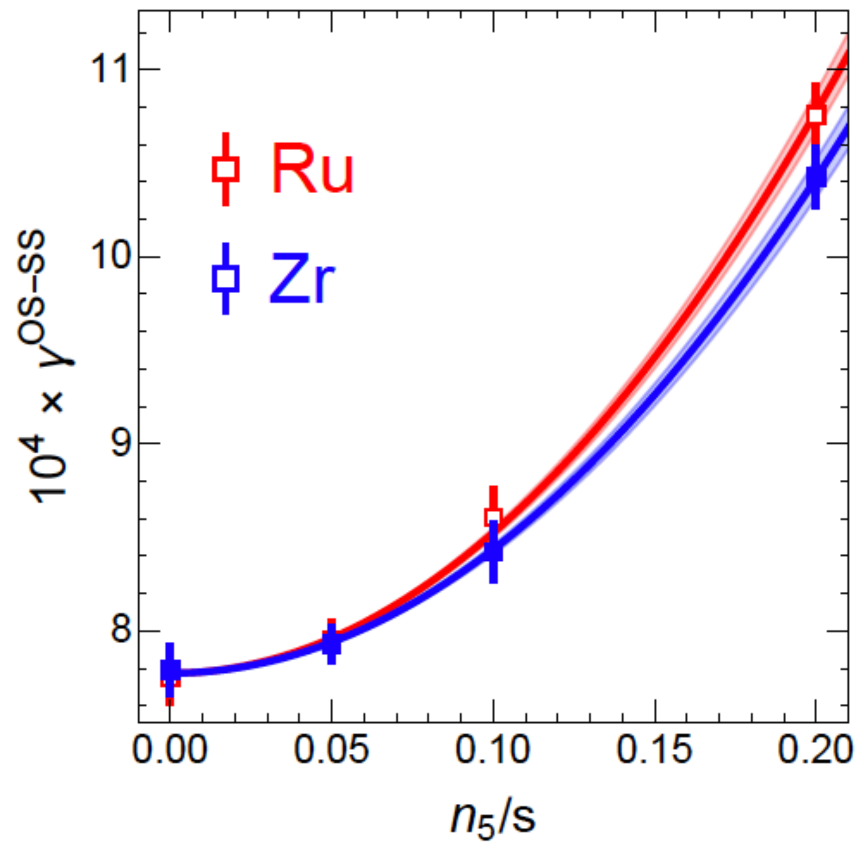


Post-selection double-check: Identical v2 !

Getting two identical sample of isobar events for contrast

Correlation Observables of Isobars from AVFD



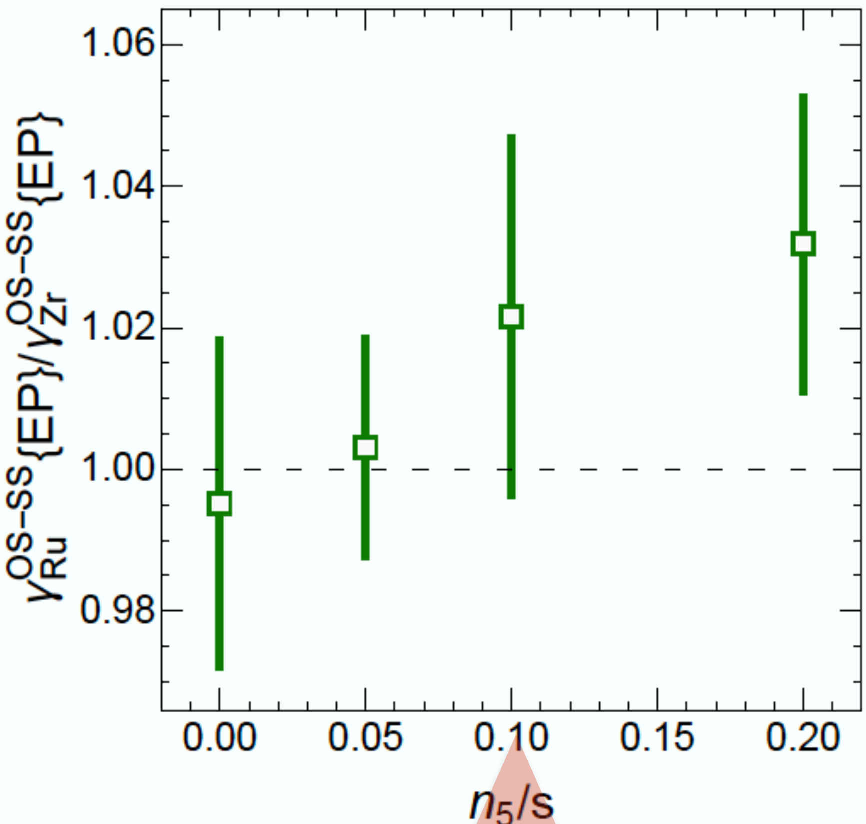


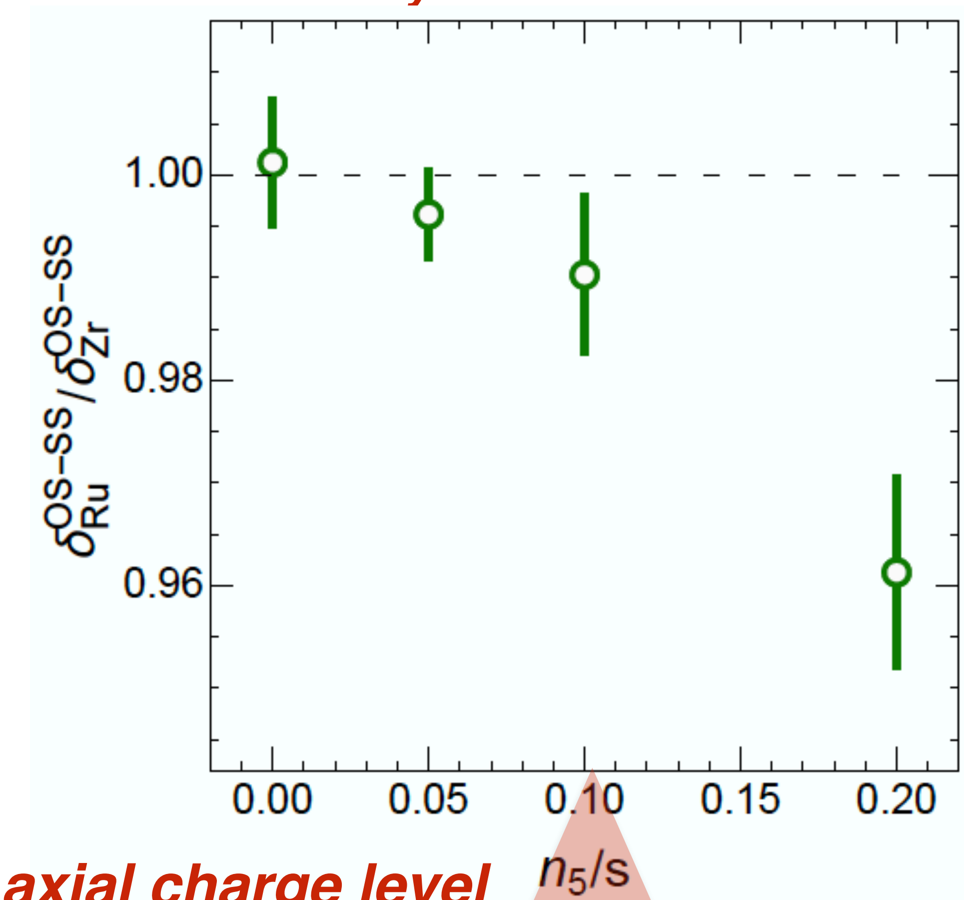
Difference in correlations is very sensitive to CME contribution!

Both gamma and delta are important to look at!

Correlation Observables of Isobars from AVFD

Exp. statistics are expected to shrink error bar by a factor of ~10

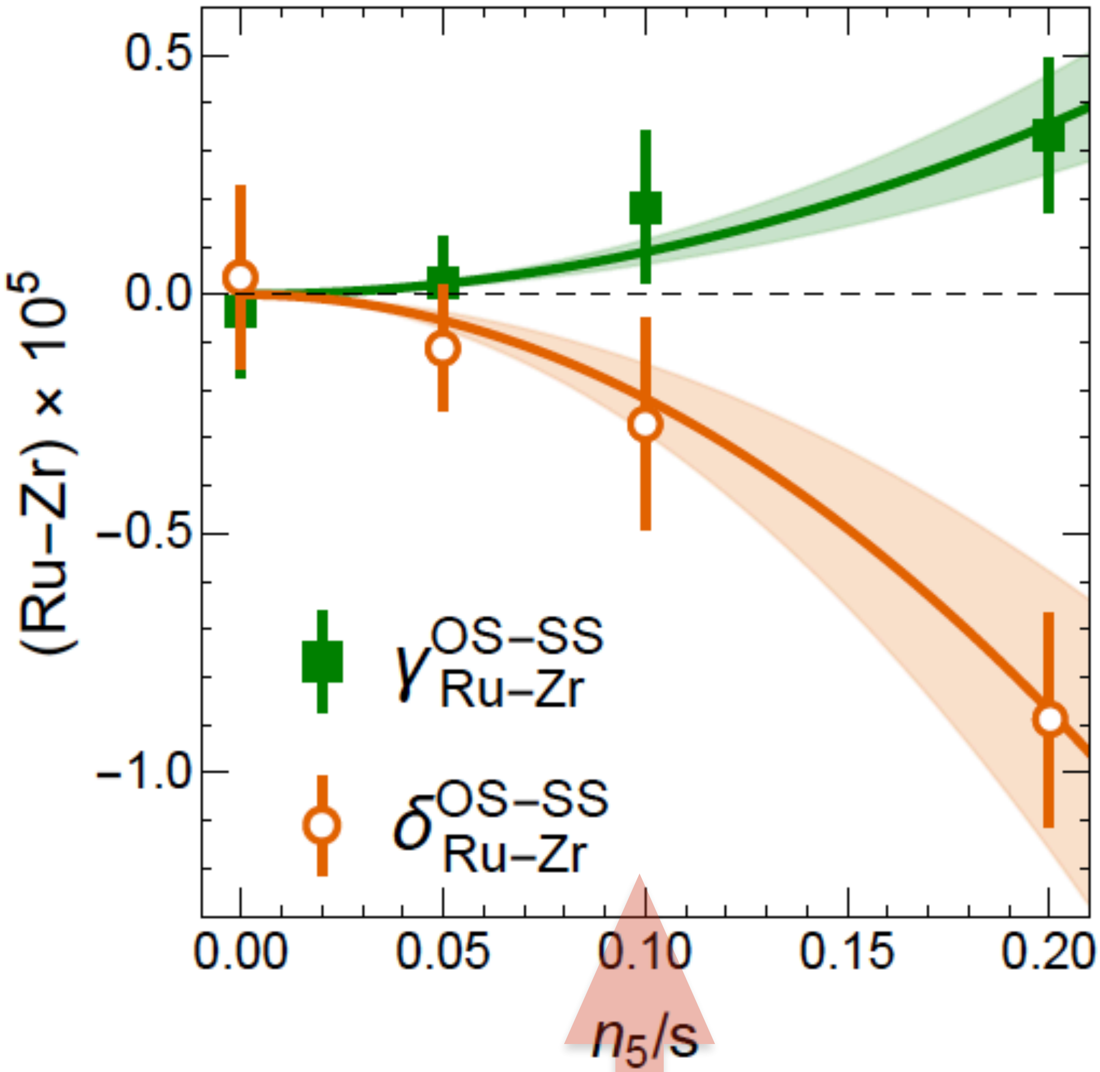




Projected axial charge level based on comparison AuAu data

Both gamma and delta are important to look at!

Absolute Difference between Isobars from AVFD



Exp. statistics are expected to shrink error bar by a factor of ~10

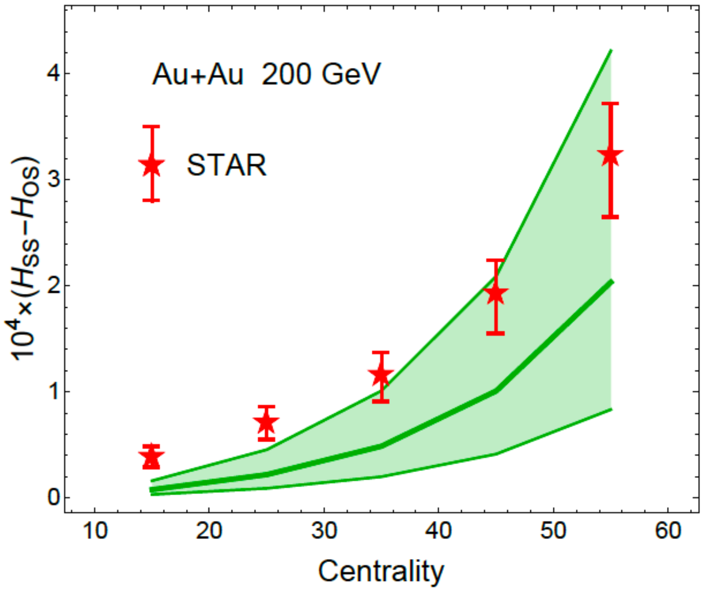
The absolute difference between isobars, after identical multiplicity + elliptic flow cuts: very sensitive and clean probe of CME signal !

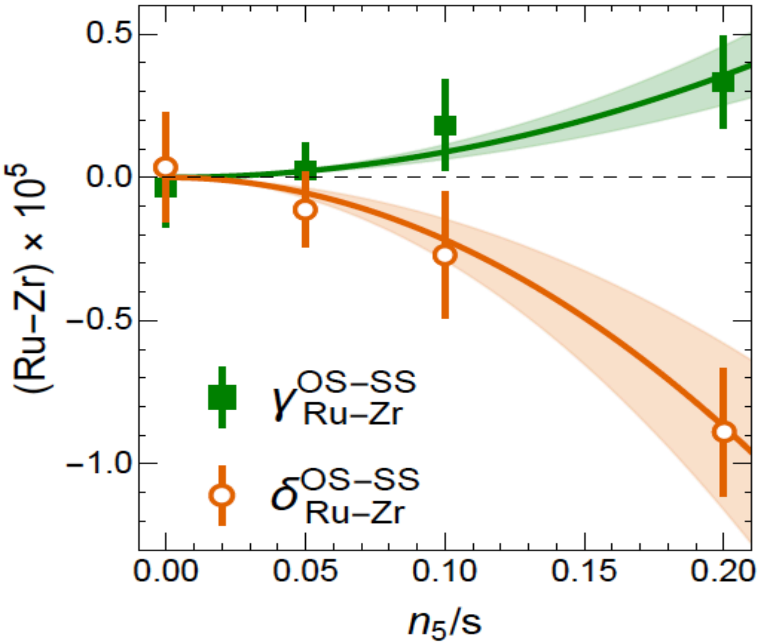
Projected axial charge level based on comparison AuAu data

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:

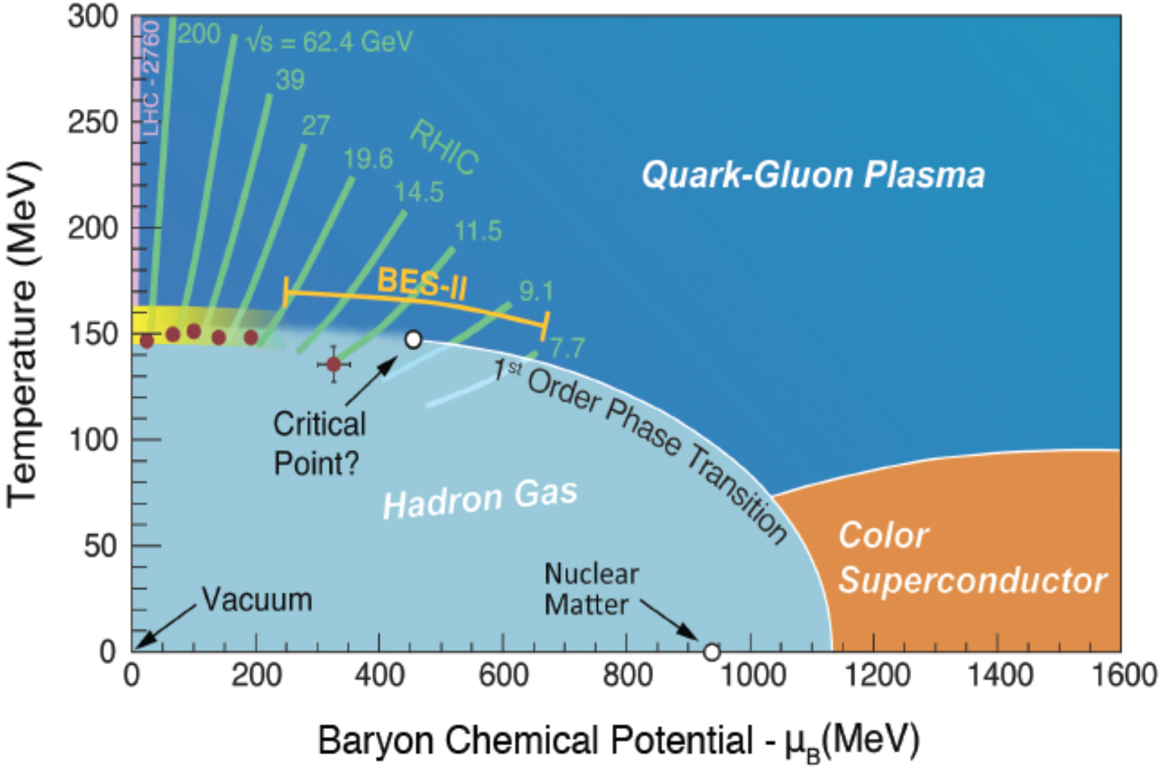
1) Event selection for truly identical bulk!

2) Both gamma & delta needed!

2) Absolute difference in correlations sensitive to CME!

Mapping Out the Phases of QCD Matter

**** Establishing a chiral QGP at higher energy via anomalous chiral effects***
**** IF hints of CME at 200GeV —> Isobar exp. at BES energies is crucial!***



BEST
COLLABORATION

Stay tuned for exciting news in the near future!

Beam Energy Scan Theory (BEST) Collaboration:
BNL, IU, LBNL, McGill U, Michigan State U, MIT, NCSU, OSU, Stony Brook U, U Chicago, U Conn, U Huston, UIC

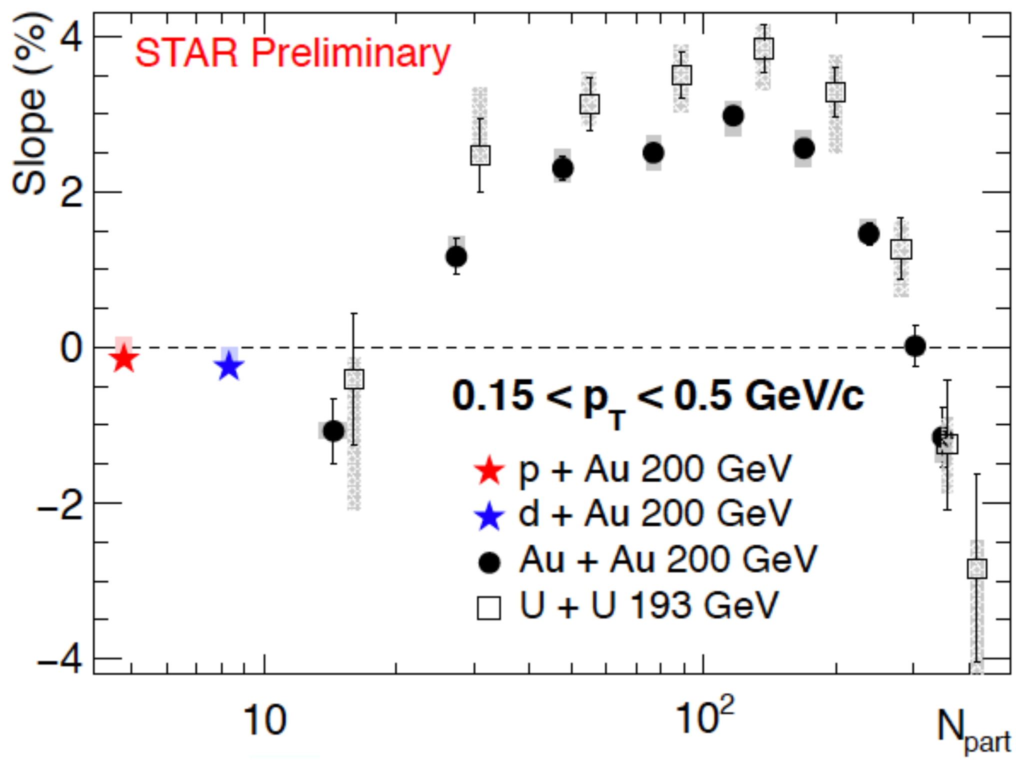
Backup Slides

CMW Induced Flow Splitting

CMW —> charge quadrupole of QGP —> elliptic flow splitting

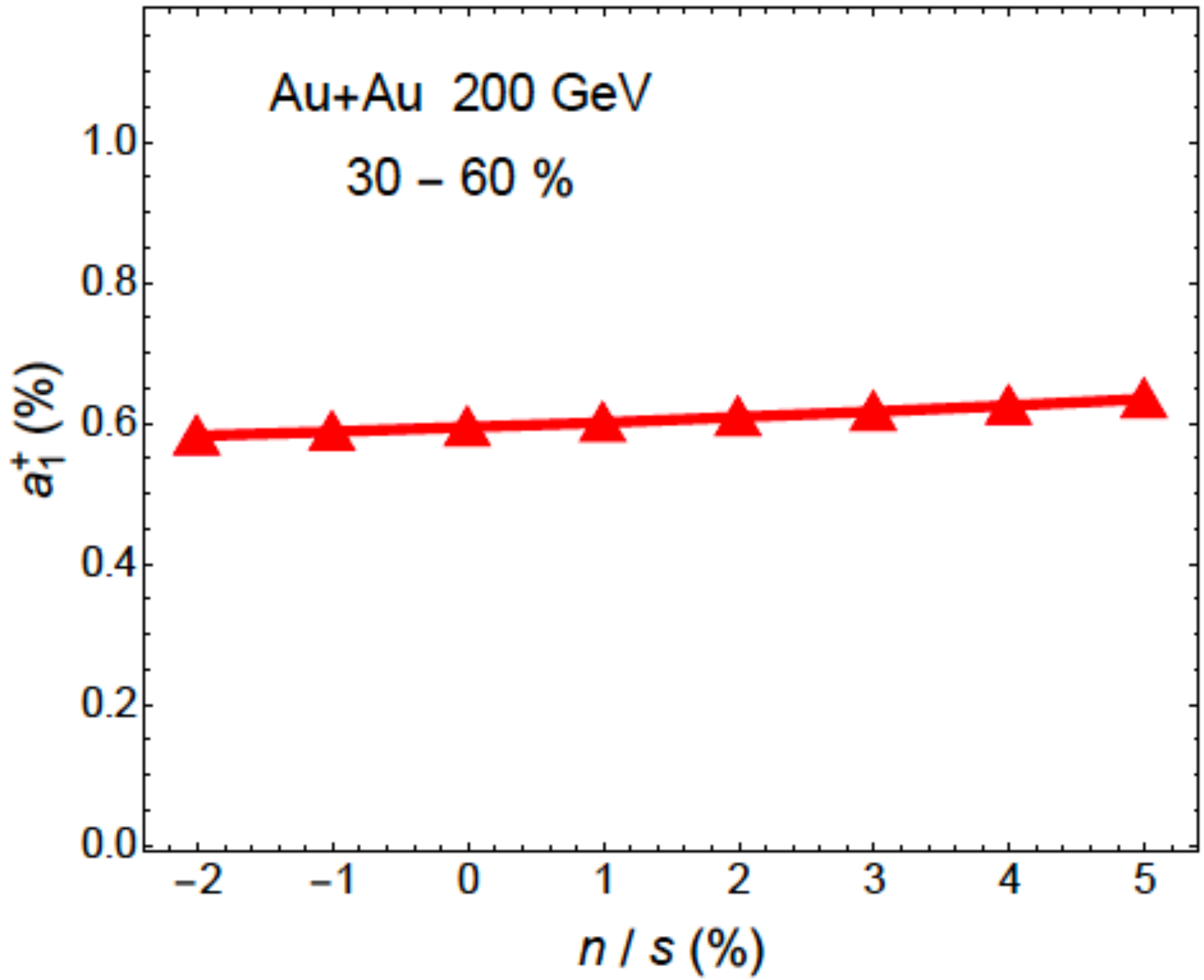
[Burnier, Kharzeev, JL, Yee, PRL2011; and arXiv: 1208.2537]

$$v_2^- - v_2^+ = r_e\, A$$



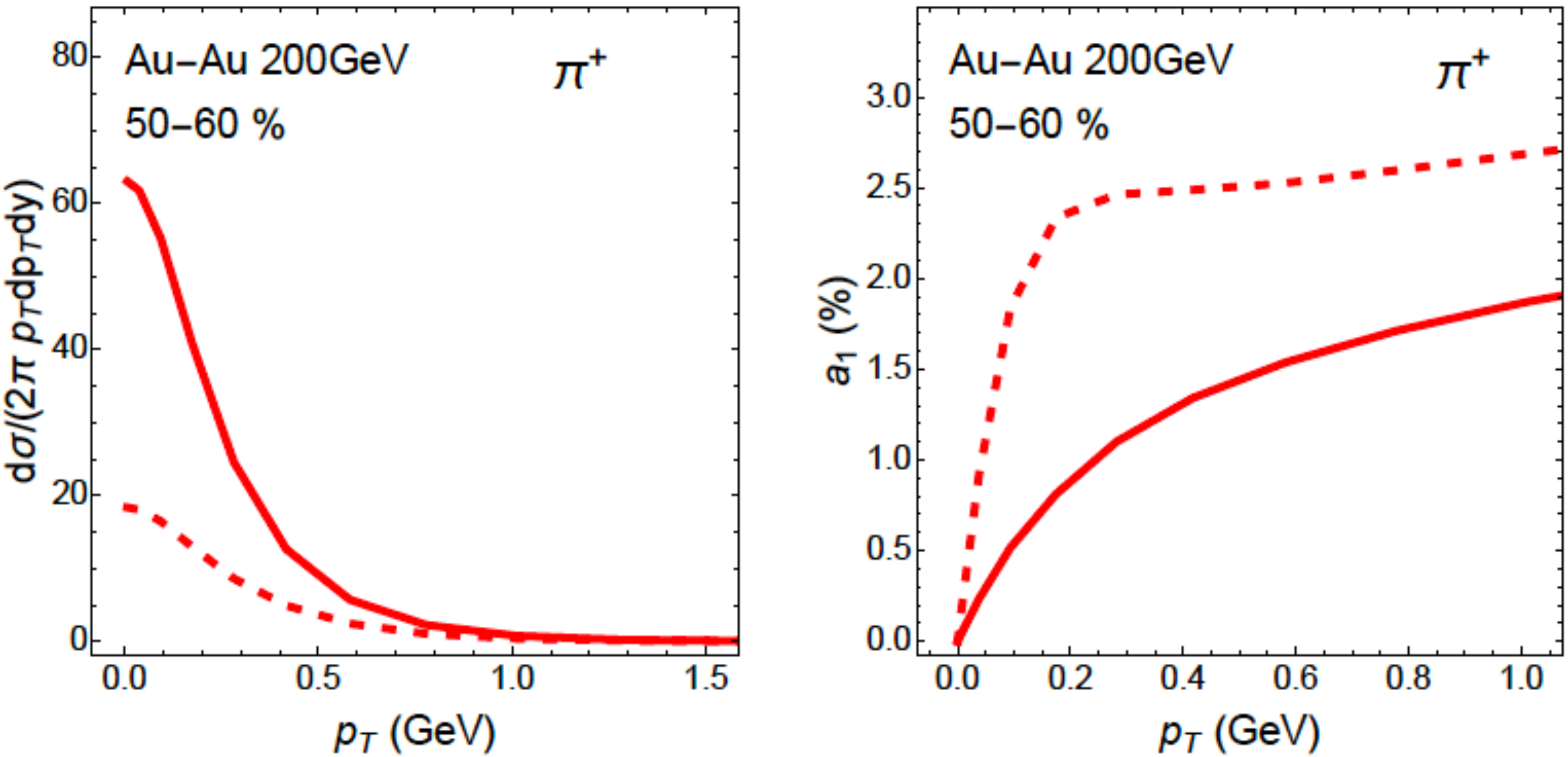
[STAR, QM2018]

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!

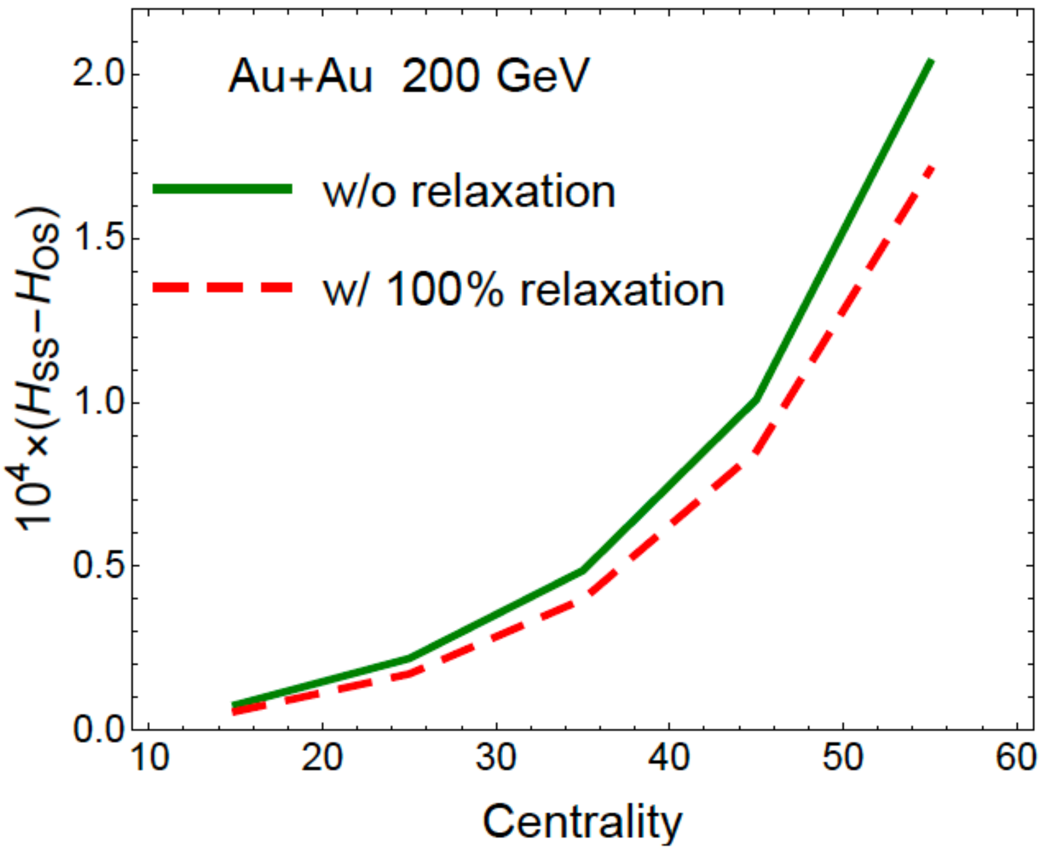
Relaxation Effect for the CME Current ??

$$\hat{D}_\mu J^\mu_{\chi,f} = \chi \frac{N_c Q_f^2}{4\pi^2} E_\mu B^\mu$$

$$J^\mu_{\chi,f} = n_{\chi,f}\, u^\mu + \nu^\mu_{\chi,f}$$

$$\Delta^\mu{}_\nu \hat{d}\left(\nu^\nu_{\chi,f}\right) = -\frac{1}{\tau_r}\left[\left(\nu^\mu_{\chi,f}\right) - \left(\nu^\mu_{\chi,f}\right)_{NS}\right]$$

$$\left(\nu^\mu_{\chi,f}\right)_{NS} = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu\left(\frac{\mu_{\chi,f}}{T}\right) + \frac{\sigma}{2} Q_f E^\mu + \chi \frac{N_c Q_f}{4\pi^2}\mu_{\chi,f} B^\mu$$



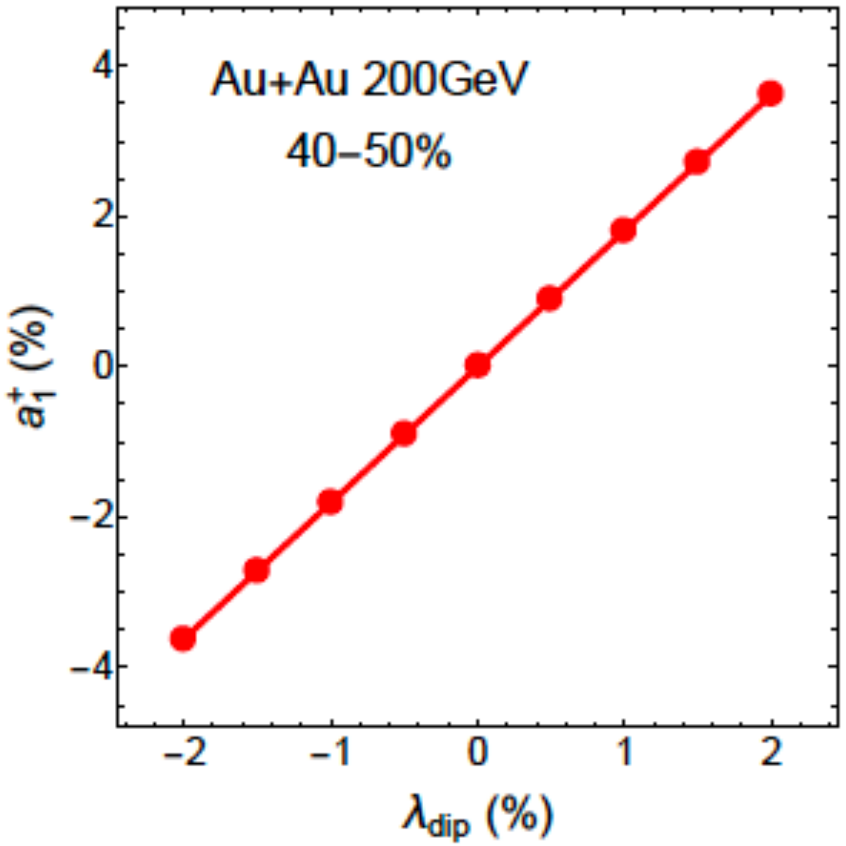
Pre-Hydro CME ??

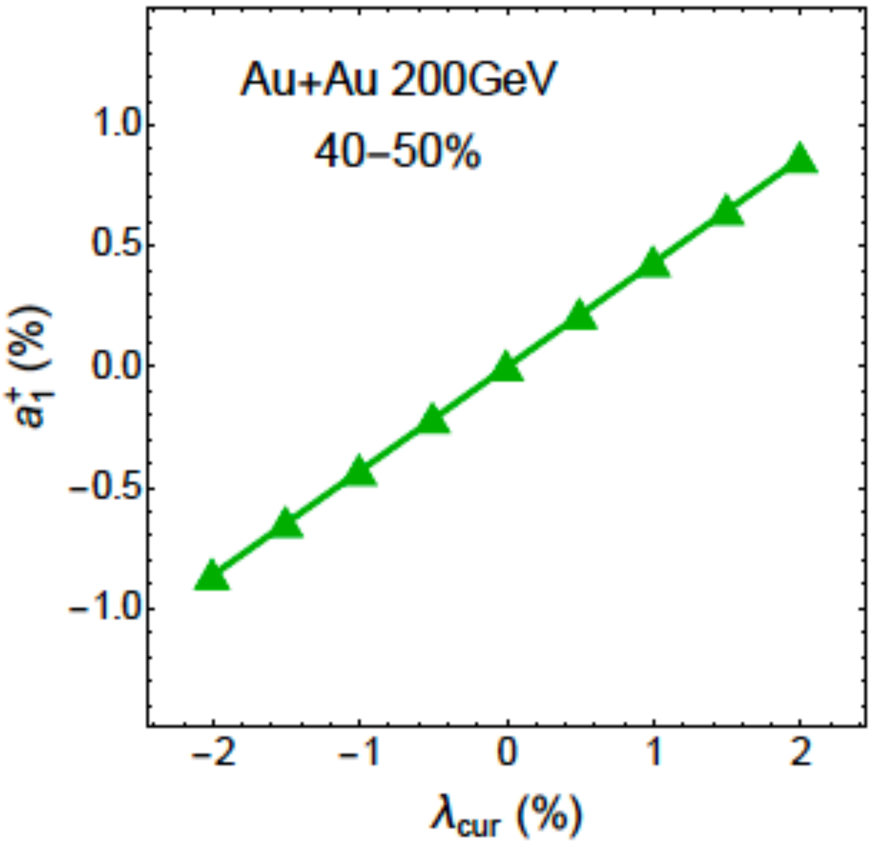
$$n_{\mathrm{ini},f} = (\lambda_{0,f} + \lambda_{\mathrm{dip},f} \sin\phi)\, s_0.$$

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

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

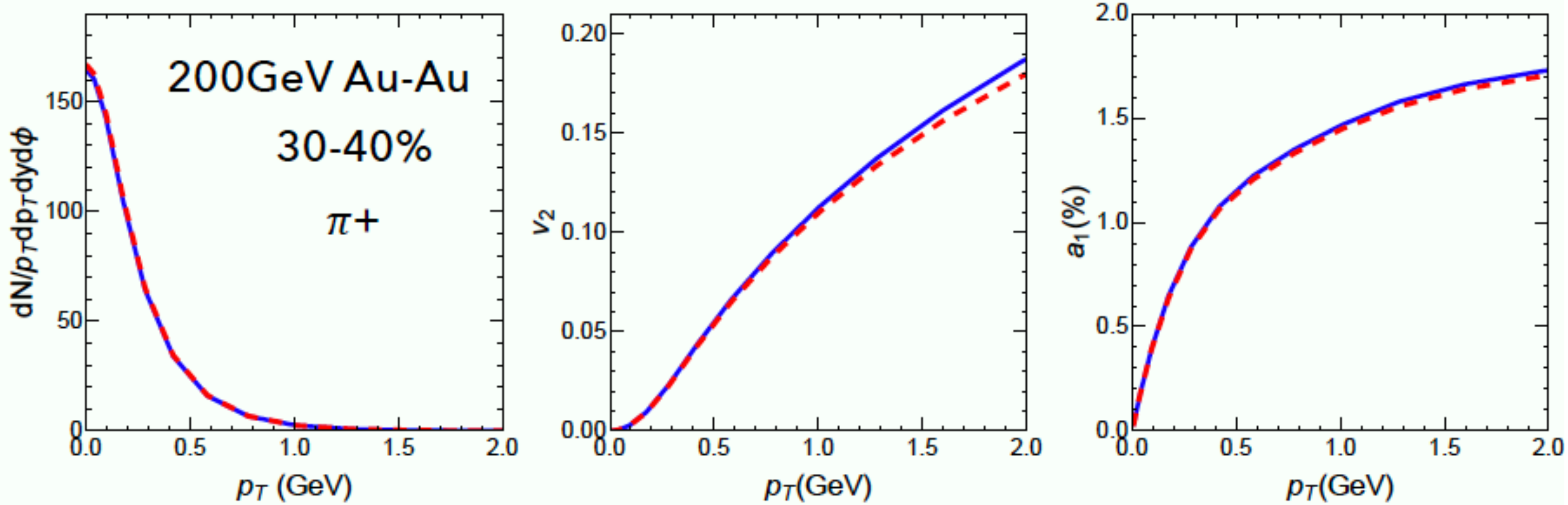
$$\lambda_{\mathrm{cur}} \equiv \lambda_{\mathrm{cur},u} = -2\lambda_{\mathrm{cur},d}.$$





MUSIC-AVFD

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

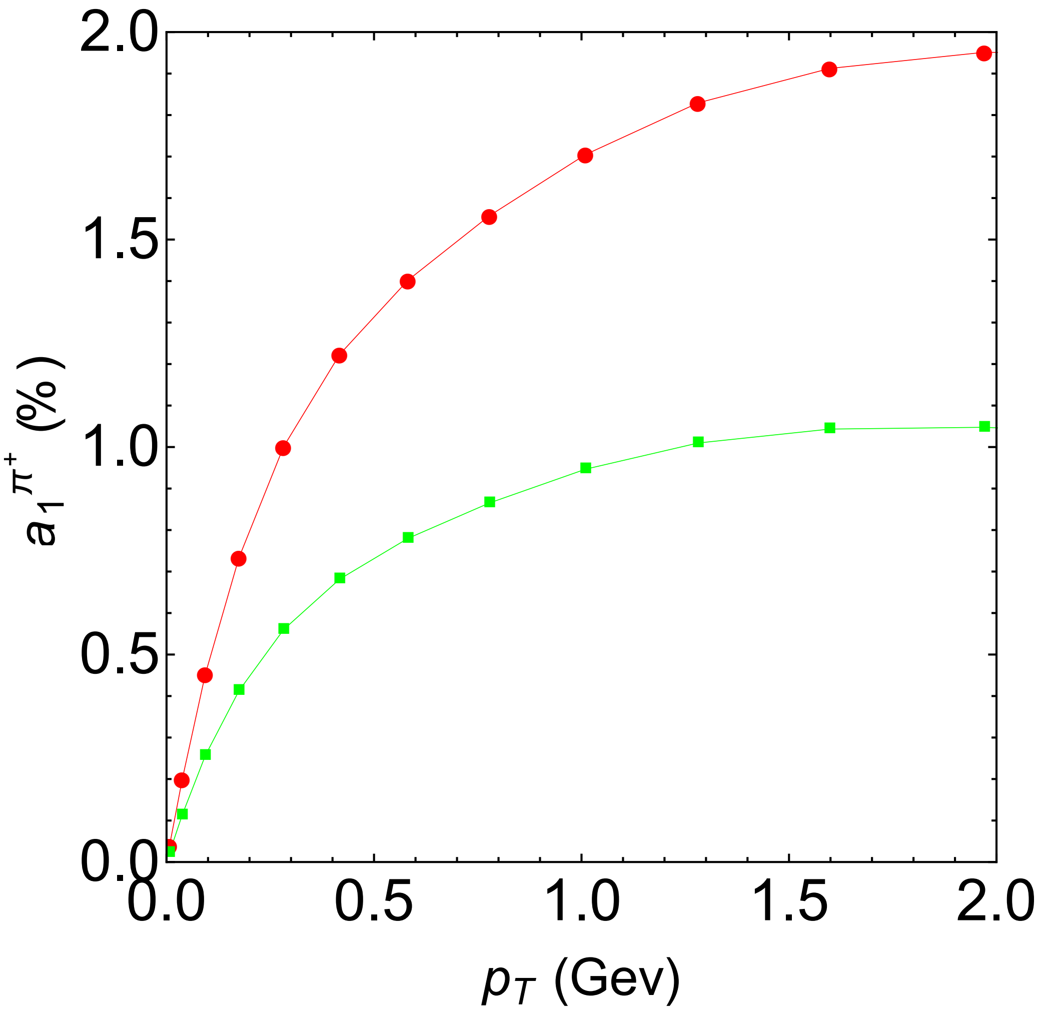


Blue = MUSIC(2+1) + AVFD

Red = VISH(2+1) + AVFD

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

Axial Charge Relaxation



The axial charge non-conservation is important and can be quantified in AVFD.