CME Task Force Report

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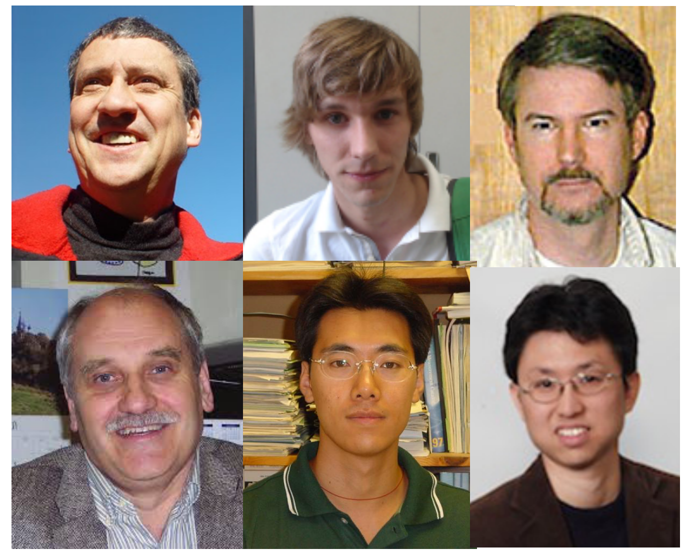
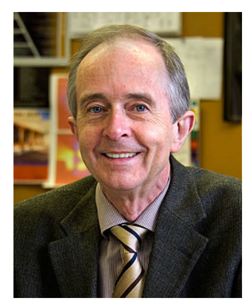


Ex Officio:

Berndt Mueller



Purpose and Background

Based on the suggestion of the 2015 RHIC Program Advisory Committee, Berndt Mueller formed this task force with the following charge:

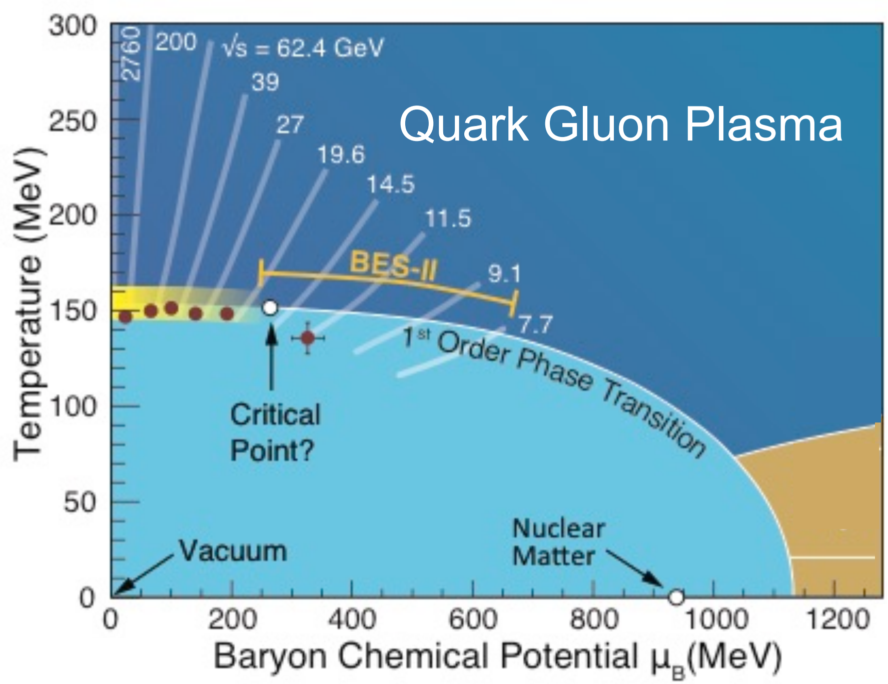
"Given the significant new advances since the original measurements, and given that the RHIC heavy ion program has a limited number of years remaining to make relevant measurements, it is now urgent to reevaluate the status of our understanding of the evidence for or against the observation of the chiral magnetic effect in heavy ion collisions and to identify specific crucial measurements that can help clarify whether strong parity violation has been observed in heavy ion collisions. The RHIC Program Advisory Committee has recommended the formation of a working group to

1) provide a critical assessment of the present state of understanding,
2) map out a strategy for how best to use the present suite of measurements (perhaps supplemented by other information that can be drawn from data already on-tape) to address open questions of interpretation, and
3) to investigate whether there are other measurements that can be performed at RHIC (such as running with nuclear isobars as suggested by STAR) to help resolve open questions."

NSAC Long Range Plan for Collective Dynamics

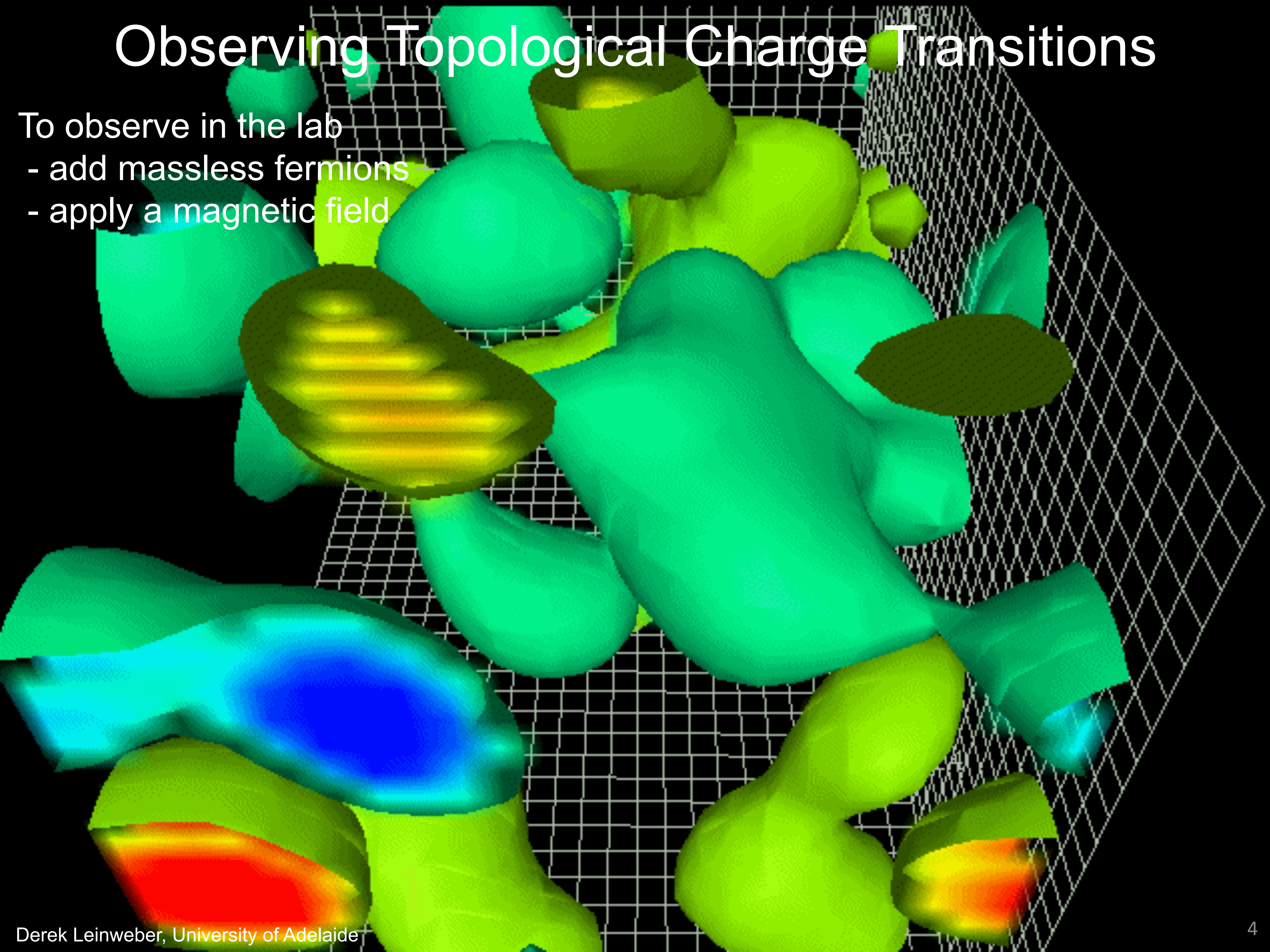
Emergence of near-perfect fluidity: characterization (η/s(T) for example) and understanding

Mapping the phase diagram: At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?



Can the same fluctuations that could have created the asymmetry between matter and anti-matter during the electro-weak phase transition be measured in the QGP phase in heavy ion collisions (chiral anamoly)?

Observing Topological Charge Transitions



To observe in the lab
- add massless fermions
- apply a magnetic field

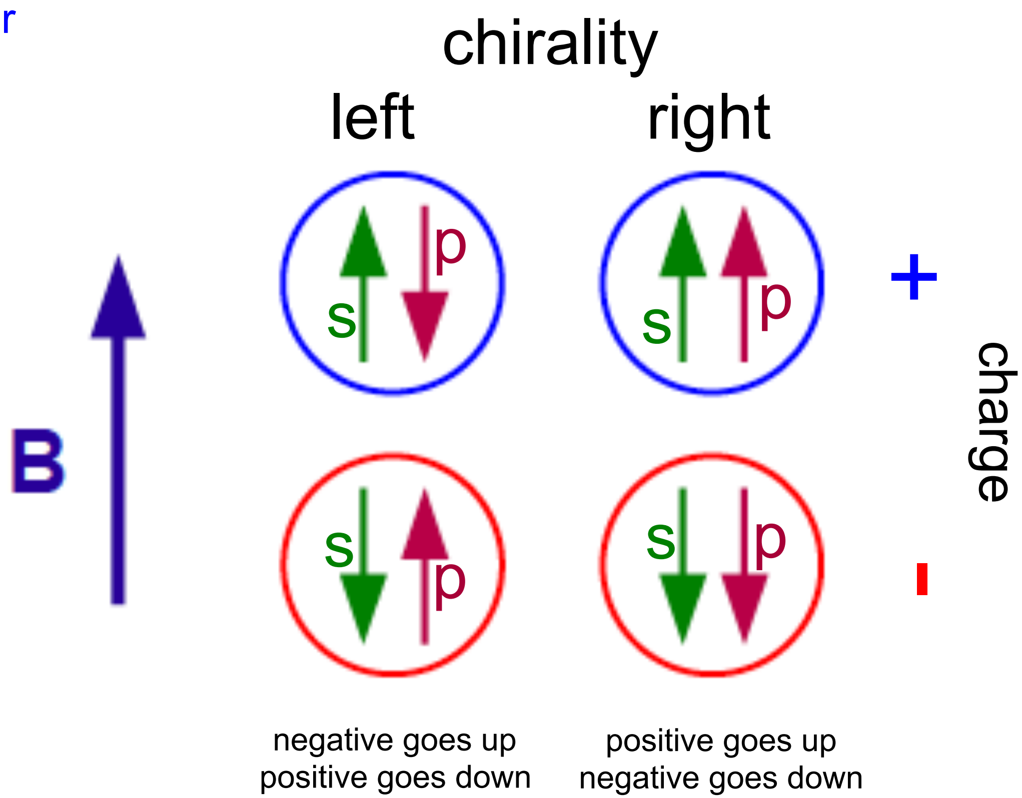
The Chiral Magnetic Effect

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

spin alignment in B-field:
opposite direction for opposite charges

handedness:
momentum and spin, aligned or anti-aligned



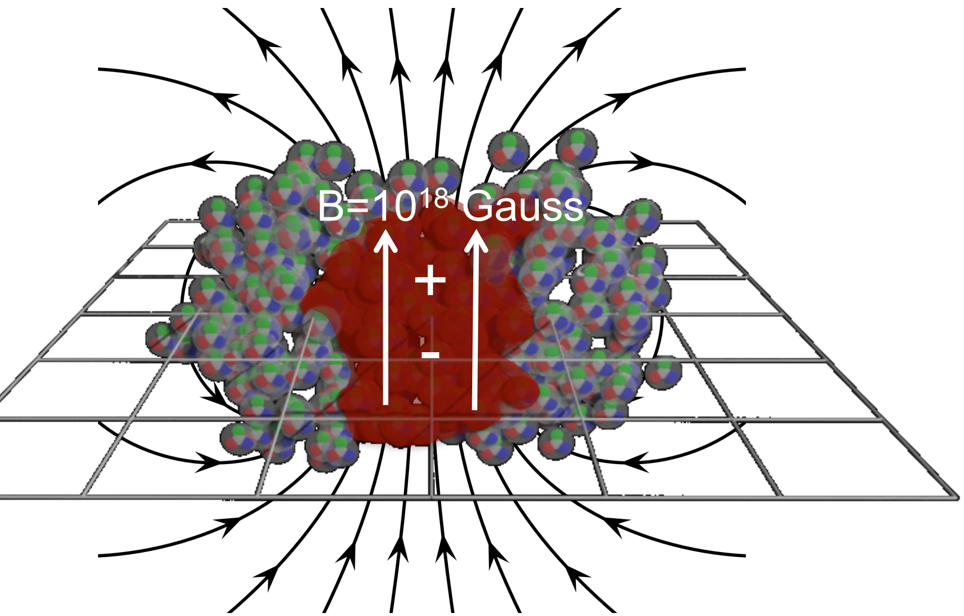
An excess of right or left handed quarks should lead to a current flow along the magnetic field

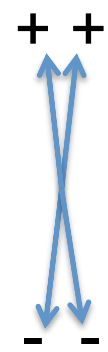
Measuring Topological Charge Transitions

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

charge separation





observable

$$\langle \cos(\varphi_{\pm} + \varphi_{\pm}) \rangle = -1$$

$$\langle \cos(\varphi_{\pm} + \varphi_{\mp}) \rangle = +1$$

in the lab frame we can measure

$$\gamma_{SS} = \langle \cos(\varphi_{\pm} + \varphi_{\pm} - 2\psi_{RP}) \rangle$$

$$\gamma_{OS} = \langle \cos(\varphi_{\pm} + \varphi_{\mp} - 2\psi_{RP}) \rangle$$

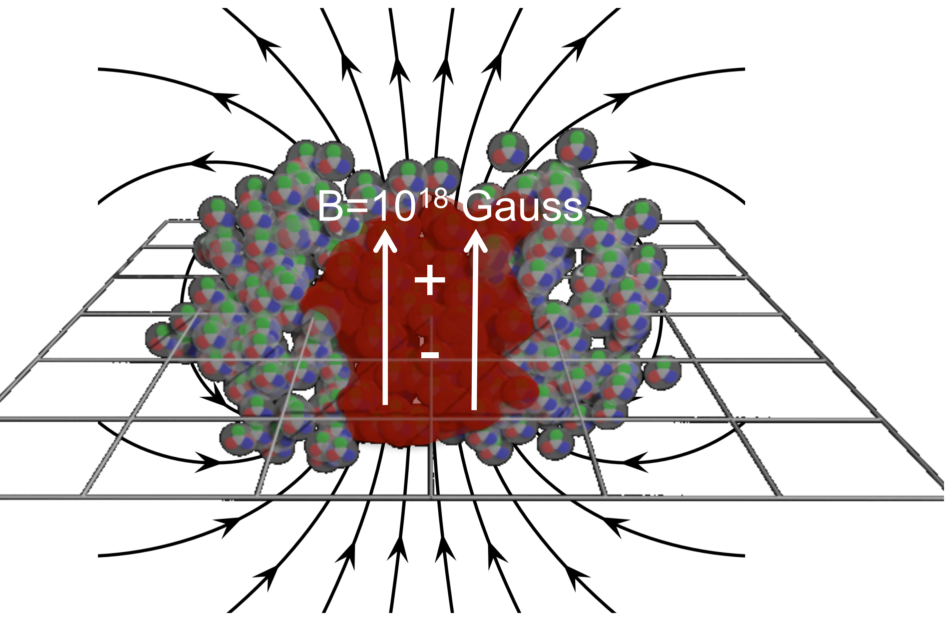
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

Topological charge fluctuates positive or negative, event-to-event or region-to-region: observe through angular correlations

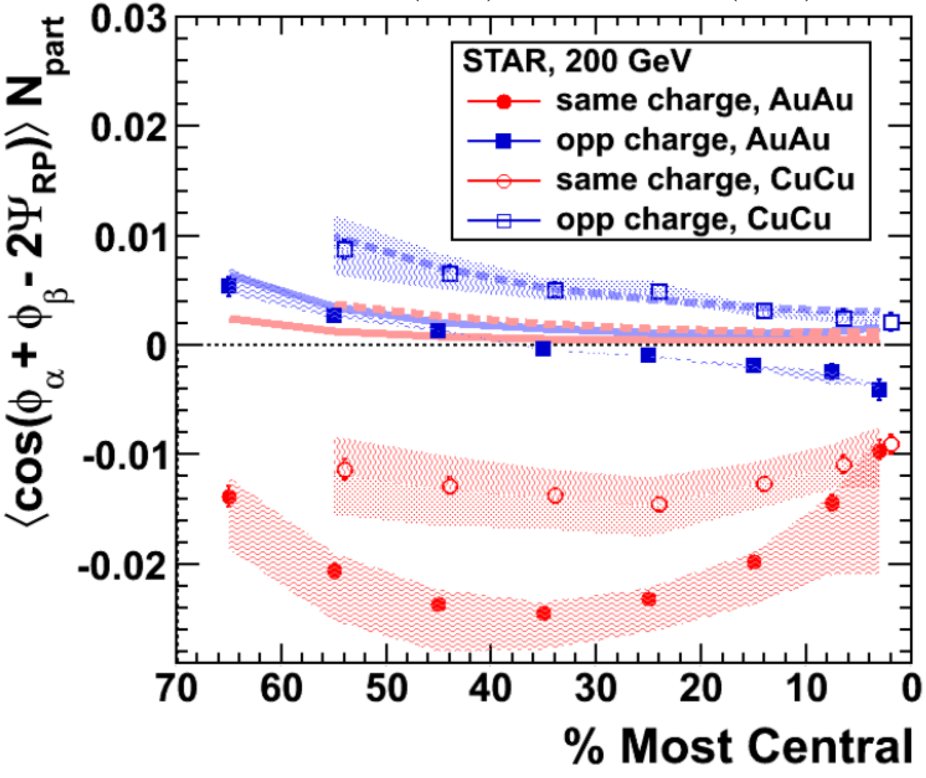
Measuring Topological Charge Transitions

Charge separation observed. But behavior is more complicated than initial cartoon: γ_{OS} is small and even sometimes the wrong sign

charge separation



STAR; PRL **103** (2009) 251601; PRC **81** (2010) 54908

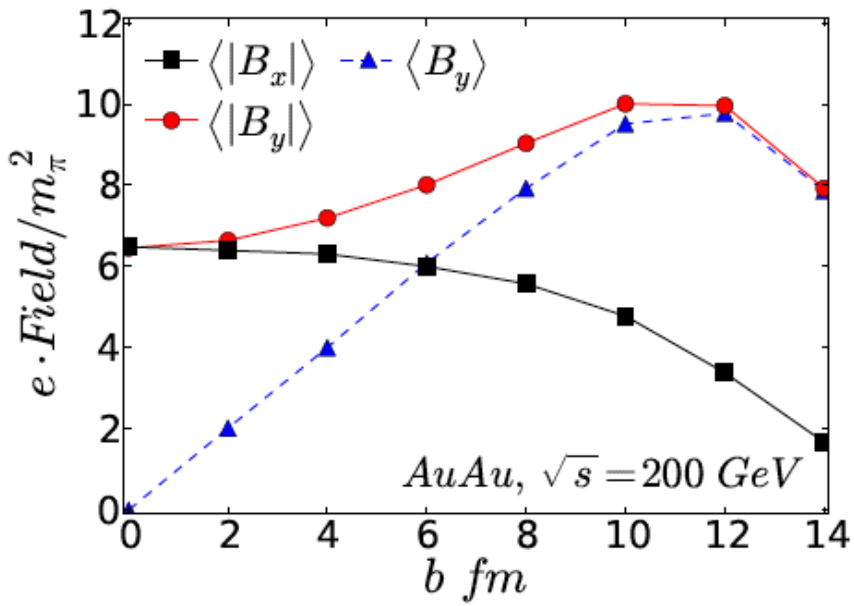


It was speculated that quenching and expansion dynamics suppress charge flow across the plane: requires more sophisticated modeling

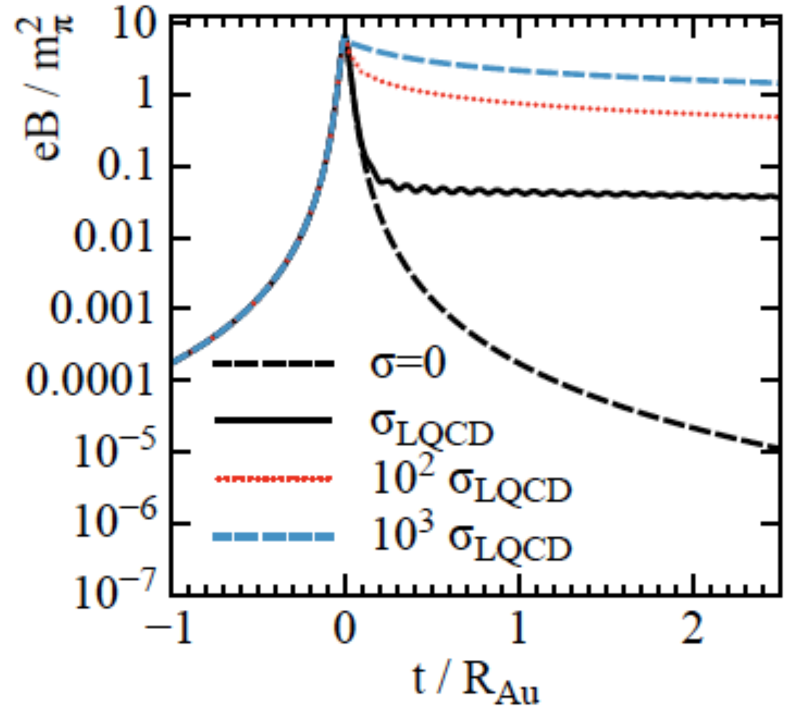
Assessment of Present Understanding

Solid predictions for CME are still difficult

Bzdak, Skokov, Phys.Lett. B710 (2012) 171-174



McLerran, Skokov, Nucl.Phys. A929 (2014) 184-190

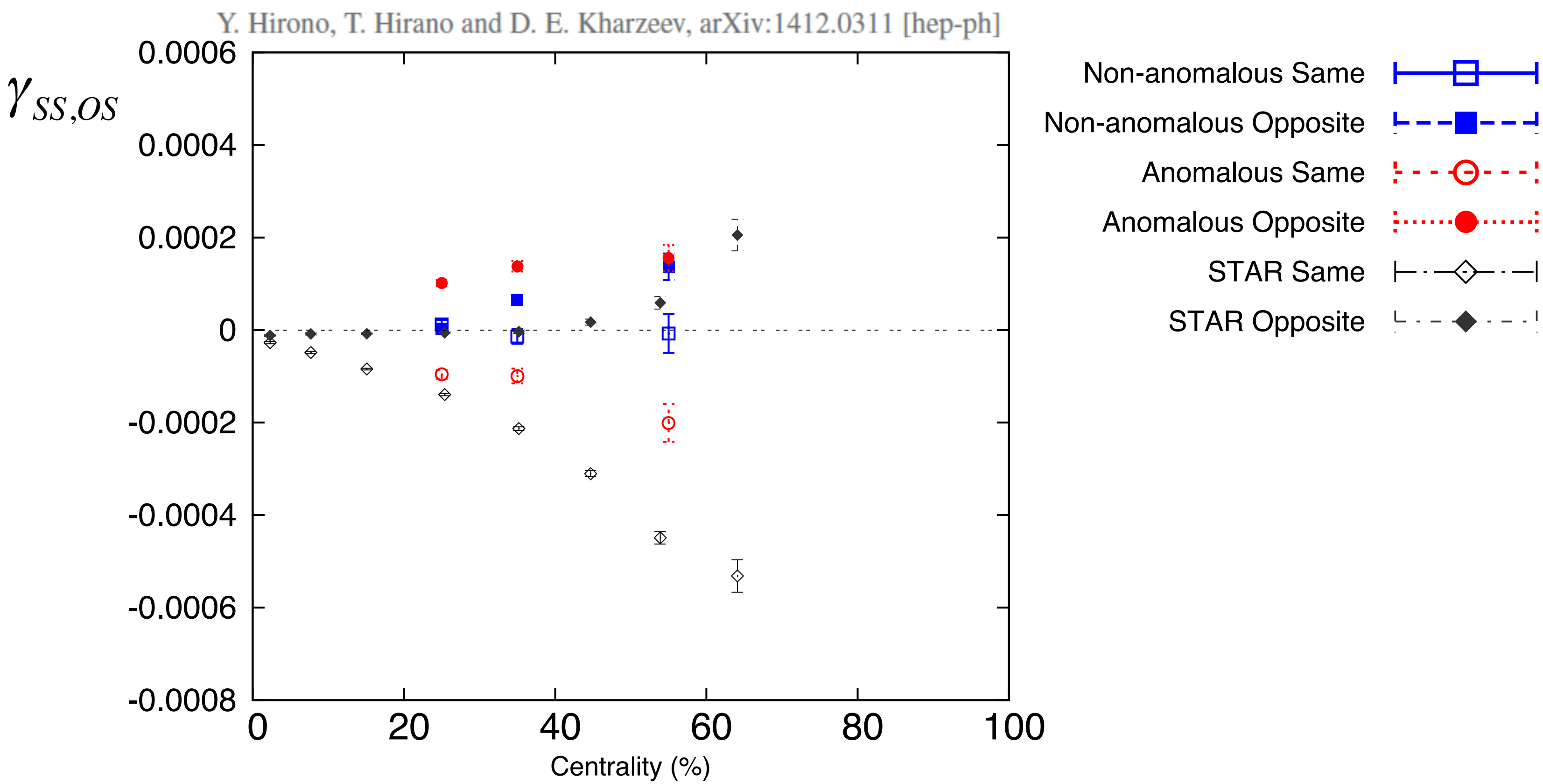


Magnetic field:

- effects of fluctuations are large
- lifetime still poorly understood

Assessment of Present Understanding

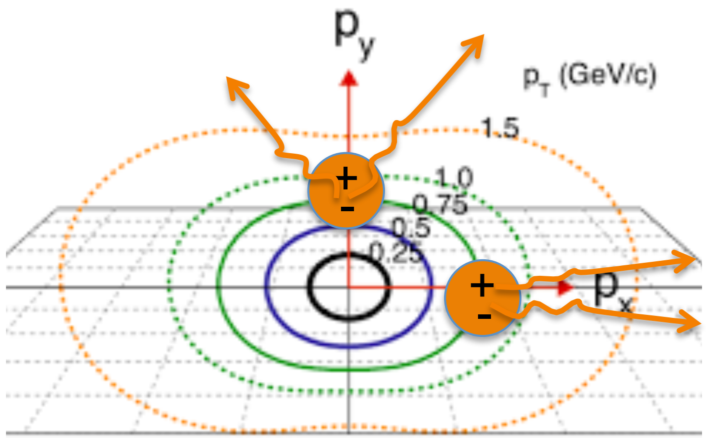
Solid predictions for CME are still difficult



Anomalous hydro calculations are needed (BEST Collaboration): initial work assuming constant magnetic field suggest correct order of magnitude

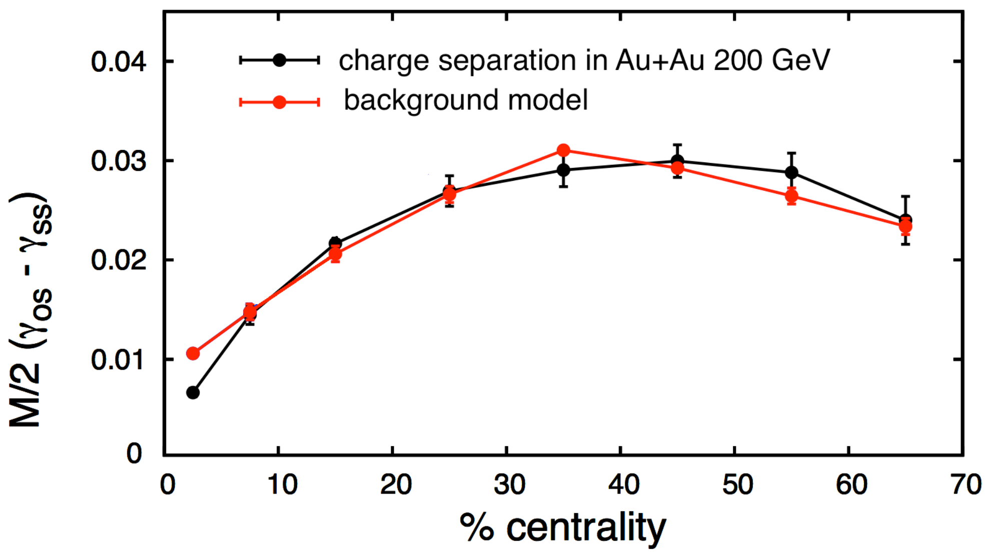
Questions of Interpretation Remain

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation



Flow boost collimates pairs more strongly in-plane than out of plane

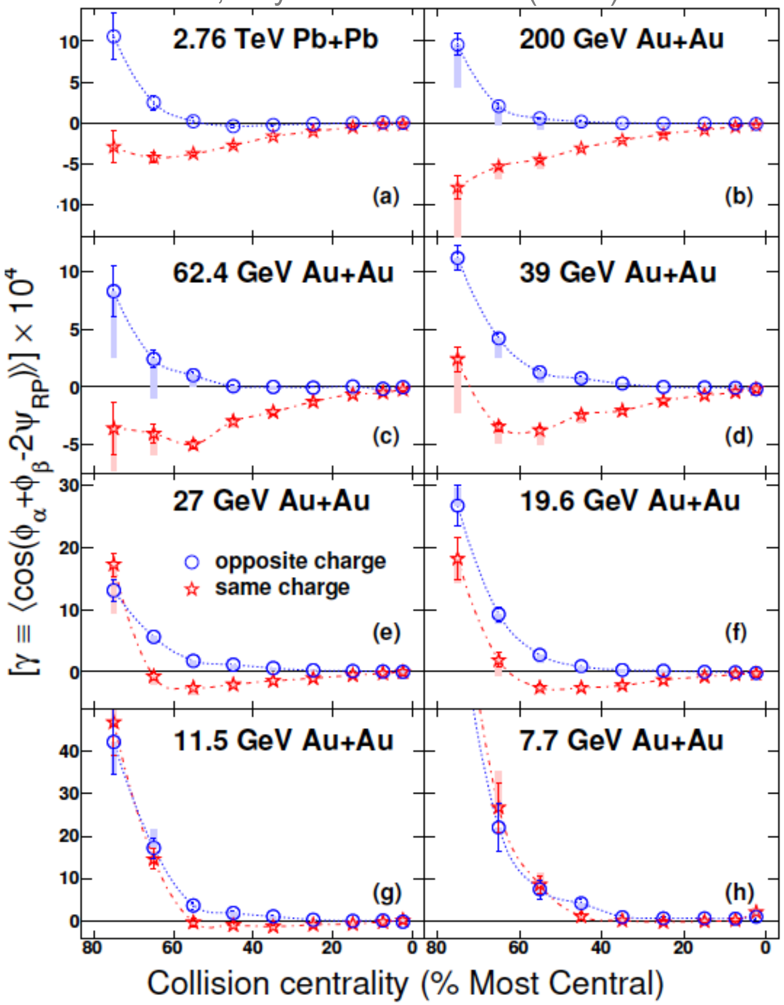
S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)



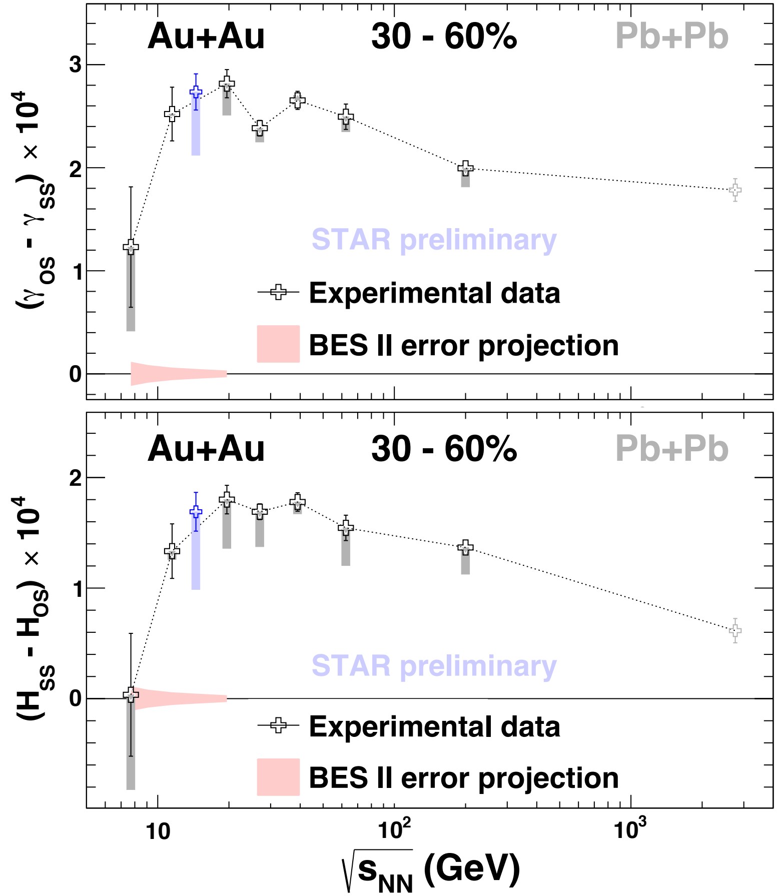
Difficult to draw definitive conclusions without better models, and an independent lever arm for magnetic field and v_2

Beam Energy Dependence

STAR, Phys. Rev. Lett. **113** (2014) 52302



STAR, Phys. Rev. Lett. **113** (2014) 52302



assuming factorization, background subtracted

$$H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$$

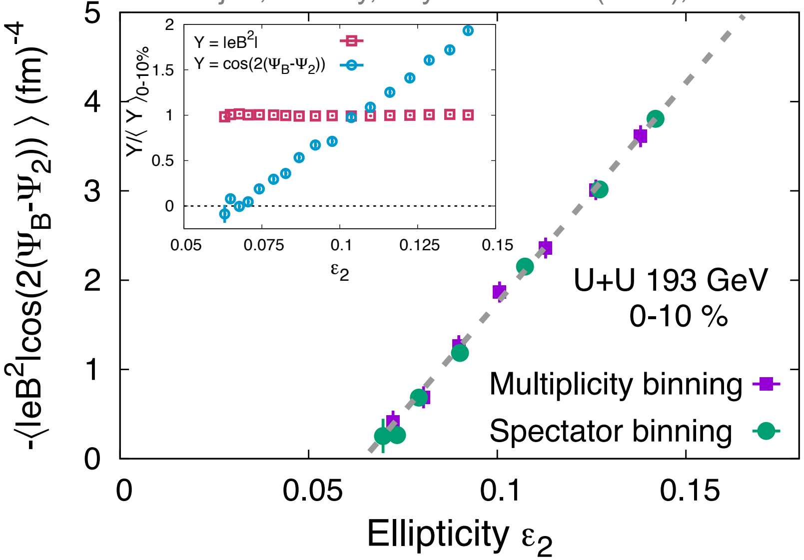
Bzdak, Koch and Liao, Lect. Notes Phys. 871, 503

Significant charge separation observed at all but the lowest energy: Consistent with evidence for QGP

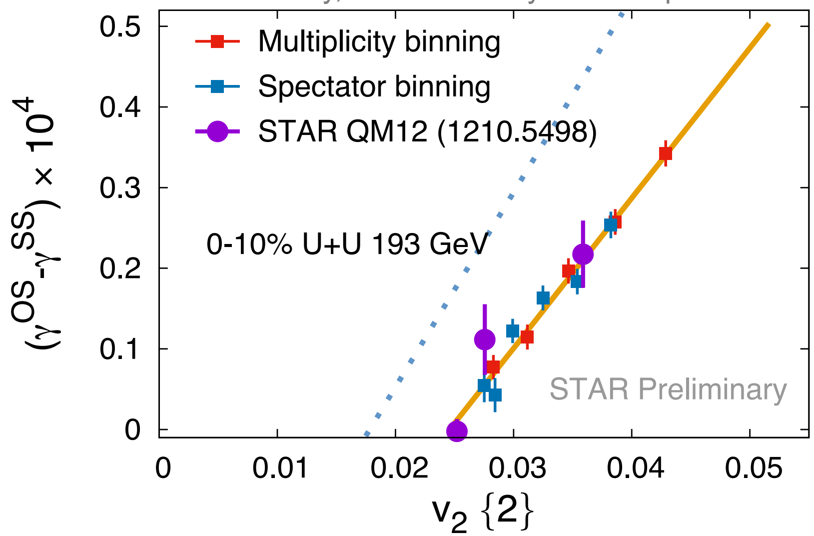
Ultra-central Au+Au and U+U

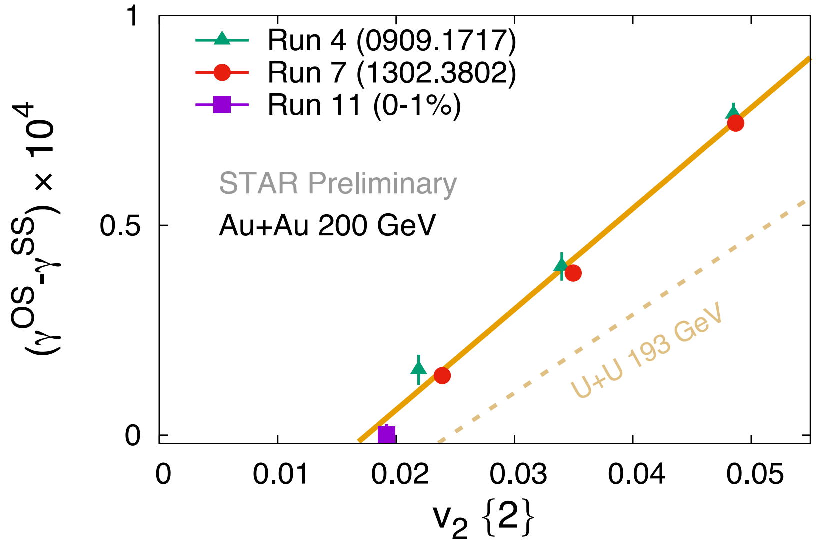
Charge separation in central collisions follows projected B-Field, not v_2

Chatterjee, Tribedy, Phys. Rev. C92 (2015), 011902



P. Tribedy, UCLA Chirality Workshop 2016

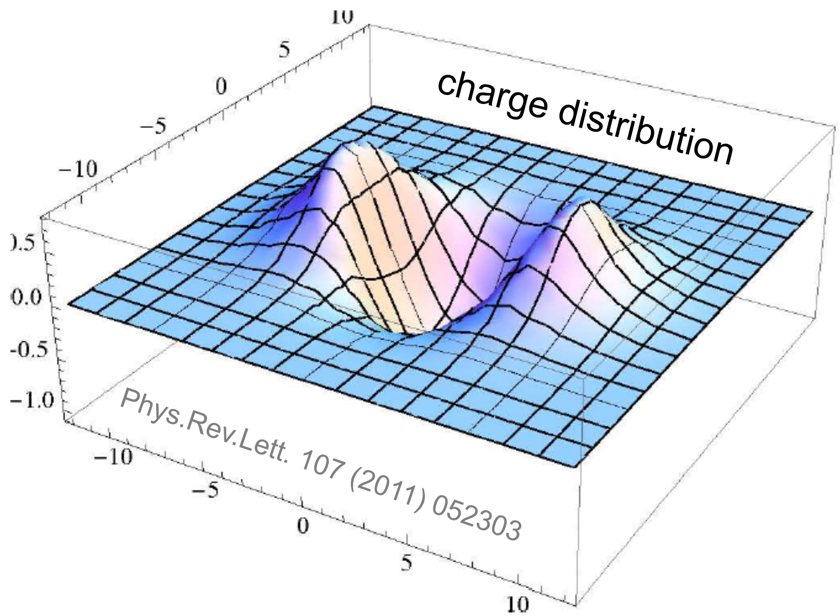




Chiral Magnetic Wave

Predicted Effect

$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B} \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$

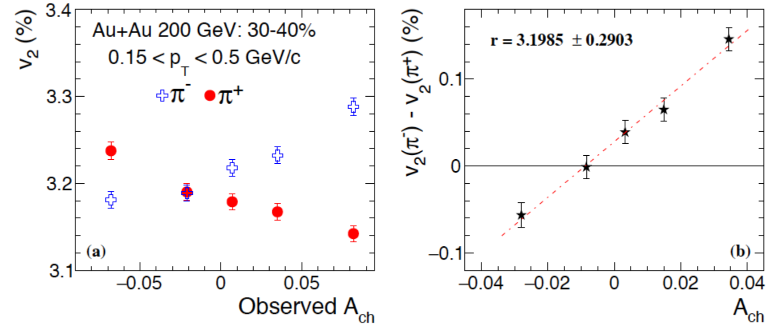


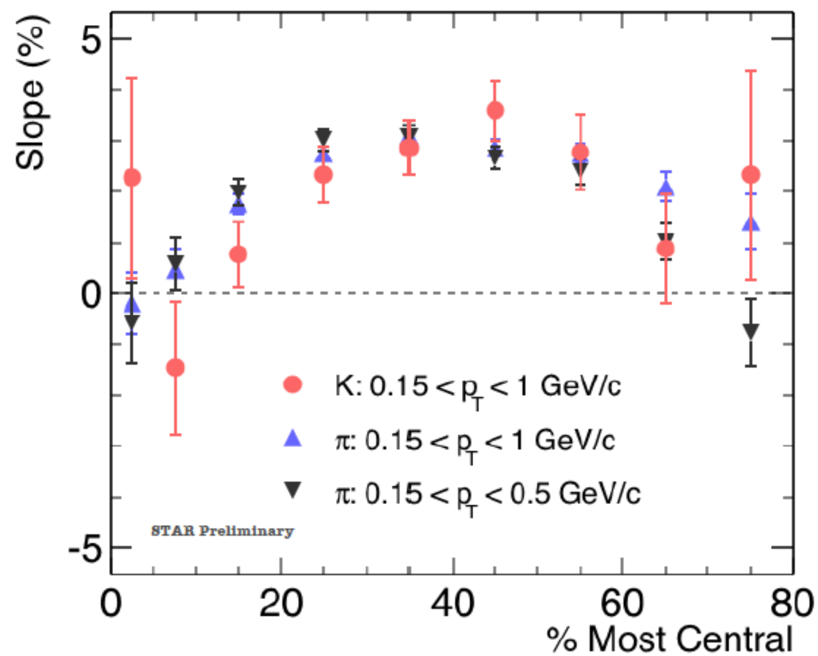
$$\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+) = r\, A_\pm$$

$$A_\pm \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

Confirmed in Data

STAR, Phys. Rev. Lett. **114** (2015) 252302





Assessment of Present Understanding

Uncertainties (particularly in the size and duration of the B-field and the unknown sphaleron rate) lead to orders-of-magnitude uncertainty in expectations for charge separation from CME

Several measurements and model calculations are suggestive of large contributions from background: *measurements could be entirely from background*

On the other hand, a wide range of measurements including those related to CMW, Chiral Vortical Effect (no B-field dependence), and central U+U collisions continue to accumulate that fall in line with basic expectations

Given this, progress seems to require

- -continued advances in anomalous hydro models to assess expectations
- -a better understanding of the magnitude and duration of the B-field
- -a way to determine what portion of the signal is related to the B-field

Strategy to Address Questions of Interpretation

What can and should be done?

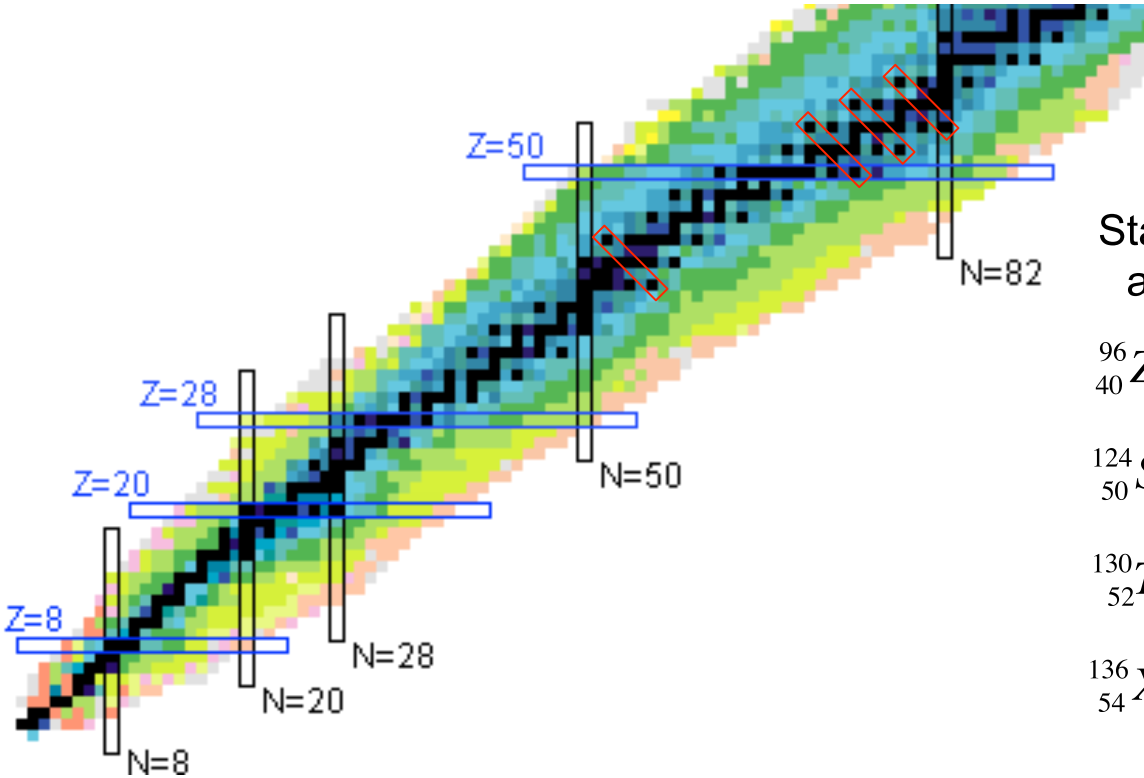
1) More analyses can be performed on current data sets
   -charge dependent $\langle \cos(m\varphi_1+n\varphi_2-(m+n)\varphi_3) \rangle$ measurements can be extended to higher m,n.
   -particularly in U+U, event shape engineering and geometry engineering using ZDC's can be and are being further explored
   -more identified particle measurements
   -more differential studies and cross correlations between observables…
   **caveats* new analyses should be shown to be interpretable, better than previous methods, and/or to provide truly new information. Conclusions based on semi-qualitative arguments should be avoided.*

2) Are theory/model advances likely to lead to a resolution?
   These are essential but given the complexity of the problem, it seems unclear that theory alone will resolve the questions

3) Is there new data that could be collected to help?
   -BES-II (2019-2020)
   -Nuclear isobars (see following slides)

Evaluation of Running with Nuclear Isobars

Isobars: nuclei with the same mass number but different charges



Stable isobar pairs with ΔZ=4
and natural abundance > 0

${}^{96}_{40}Zr + {}^{96}_{40}Zr$	vs.	${}^{96}_{44}Ru + {}^{96}_{44}Ru$	preferred by CAD
${}^{124}_{50}Sn + {}^{124}_{50}Sn$	vs.	${}^{124}_{54}Xe + {}^{124}_{54}Xe$	not promising
${}^{130}_{52}Te + {}^{130}_{52}Te$	vs.	${}^{130}_{56}Ba + {}^{130}_{56}Ba$	still possible
${}^{136}_{54}Xe + {}^{136}_{54}Xe$	vs.	${}^{136}_{58}Ce + {}^{136}_{58}Ce$	not promising

Would make it possible to change the B-field about 10% while most other variables are fixed. But,

- how well do we understand the magnetic field?
- how well do we understand the effect of the nuclear geometry?
- will the measurements be discerning enough?

Evaluation of Running with Nuclear Isobars

Calculations and measurements of deformations disagree

$\beta_2({}^{96}_{40}Zr) = 0.080$ (electron scattering) $\beta_2({}^{96}_{44}Ru) = 0.158$ (electron scattering)

$\beta_2({}^{96}_{40}Zr) = 0.217$ (model calculation) $\beta_2({}^{96}_{44}Ru) = 0.053$ (model calculation)

It's not even clear which nucleus is most deformed!

Shou, Ma, Sorensen, Tang, Videbaek, Wang, Phys. Lett. B 749, 215

			R0	a (d)	β2	β4
Zr96	Set 1	old	5.0212	0.574	0.08	/
		new	5.07	0.48	0.06	
	Set 2	old	5.0212	0.574	0.217	0.01
		new	5.05	0.45	0.18	0.01
Ru96	Set 1	old	5.0845	0.567	0.1579	/
		new	5.14	0.46	0.13	
	Set 2	old	5.0845	0.567	0.053	0.009
		new	5.13	0.45	~0.03*	0.009

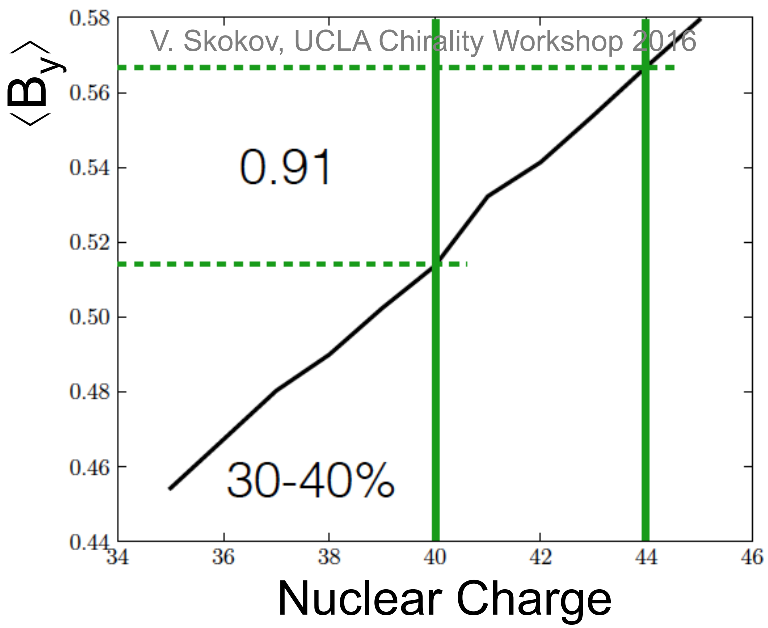
Note: for deformed nuclei and finite sized nucleons, parameters can't be blindly plugged in to Woods-Saxon distribution

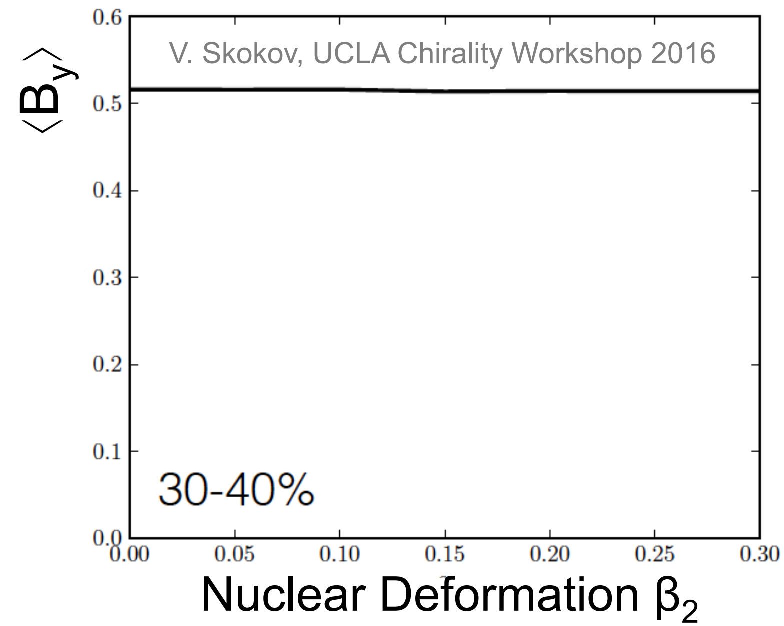
There is some uncertainty even if we agree on a β_2

Evaluation of Running with Nuclear Isobars

Magnetic Field Calculations Revisited:

-B-field integrated over 1 fm spot centered at most dense region
-Centrality intervals based on number of produced particles
-B-field calculated at t=0 for point like protons





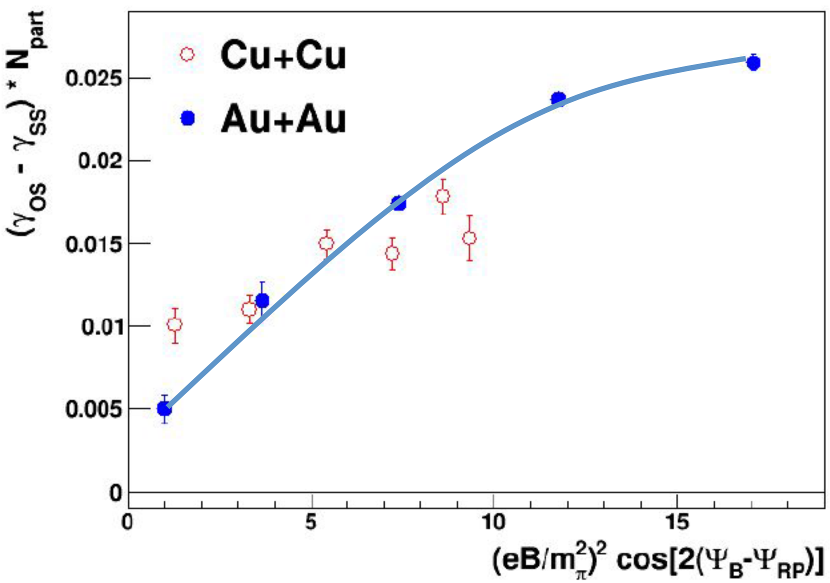
The strength of the field remains proportional to Z

For centralities of interest, strength independent of β_2:
a weak dependence is found when considering fluctuations

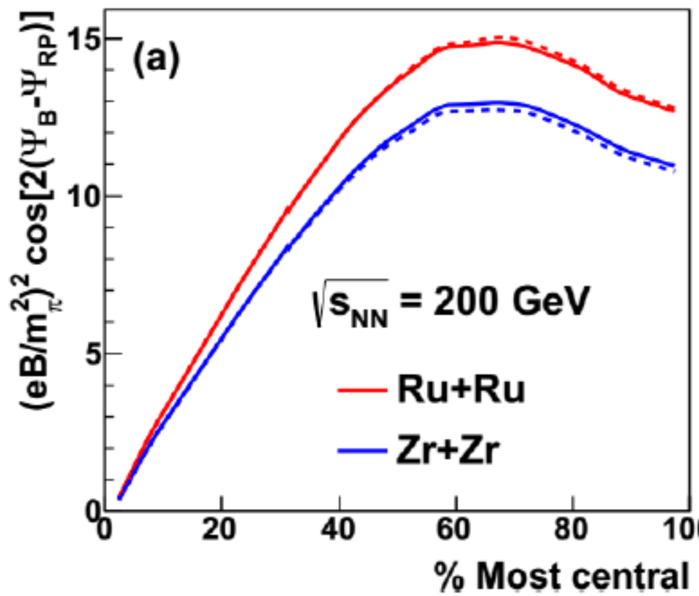
Evaluation of Running with Nuclear Isobars

How discerning will the measurements be?

Calculations: X.-G. Huang and W.-T. Deng



parameterize observed charge separation vs CME expectation



Use parameterization to convert CME calculation for Ru and Zr into expected signal

dashed: Woods-Saxon case 1
solid: Woods-Saxon case 2

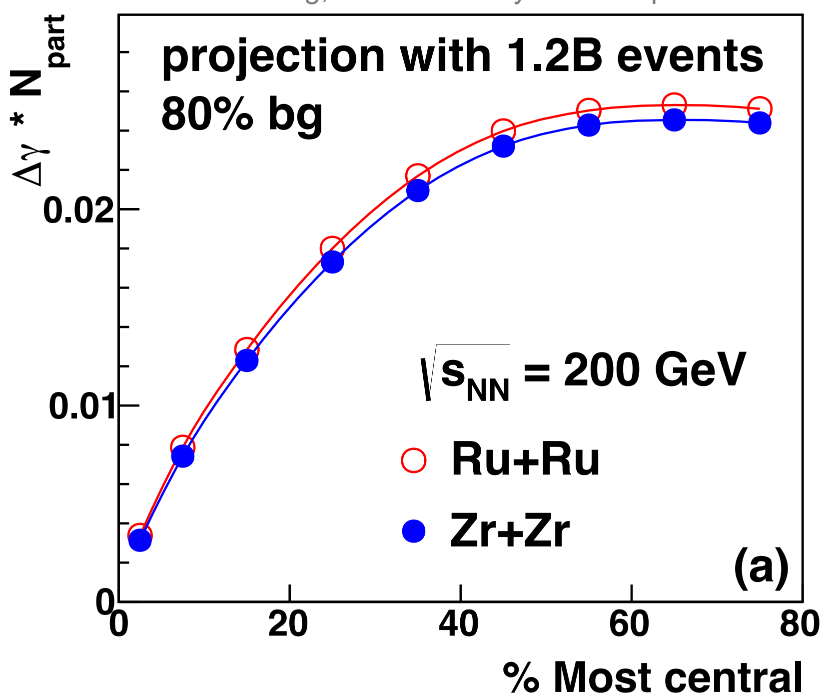
note: charge separation from CME is expected to go as $\langle (eB)^2 \cos[2(\psi_B-\psi_{RP})] \rangle$

Evaluation of Running with Nuclear Isobars

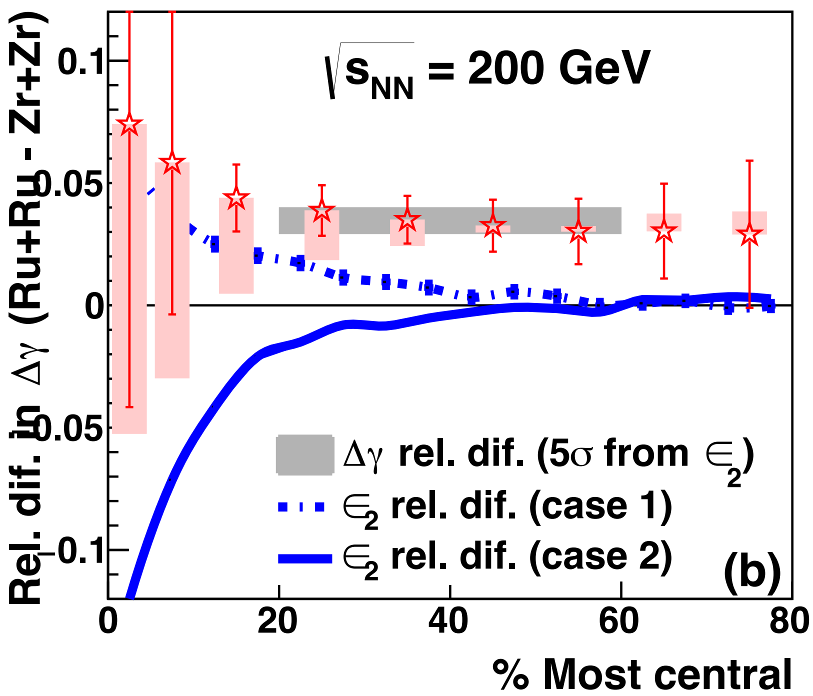
How discerning will the measurements be?

expected signal from parameterization and model calculations (80% background)

G. Wang, UCLA Chirality Workshop 2016



assume Δγ ∝ x*background+(x-1)*CME for x=0.8

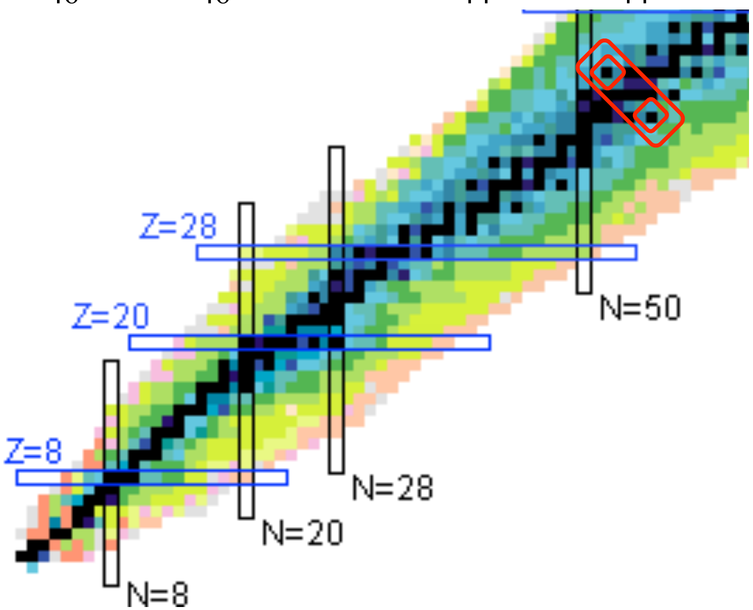


If magnetic field independent backgrounds make up less than 80% of the measured Δγ, the CME contribution will be determined with a significance better than 5σ

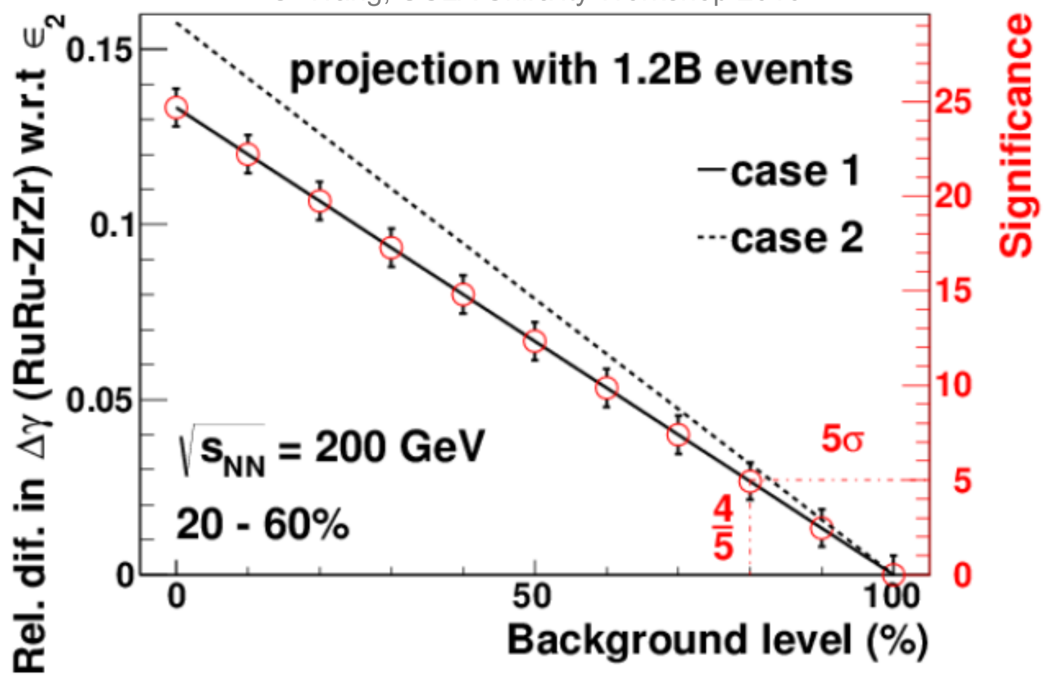
Probing Chiral Symmetry with Quantum Currents

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$$^{96}_{40}Zr + ^{96}_{40}Zr \quad \text{vs.} \quad ^{96}_{44}Ru + ^{96}_{44}Ru$$



G. Wang, UCLA Chirality Workshop 2016



Isobar collisions in 2018 can tell us what percent of the charge separation is due to CME to within +/- 6% of the current signal

Conclusions

Large uncertainties in interpretation exist: *Current CME measurements could be entirely from background*

There remain analyses to be done that are likely to provide some help in clarifying the relevance of CME but, *none so far have proven to be decisive*

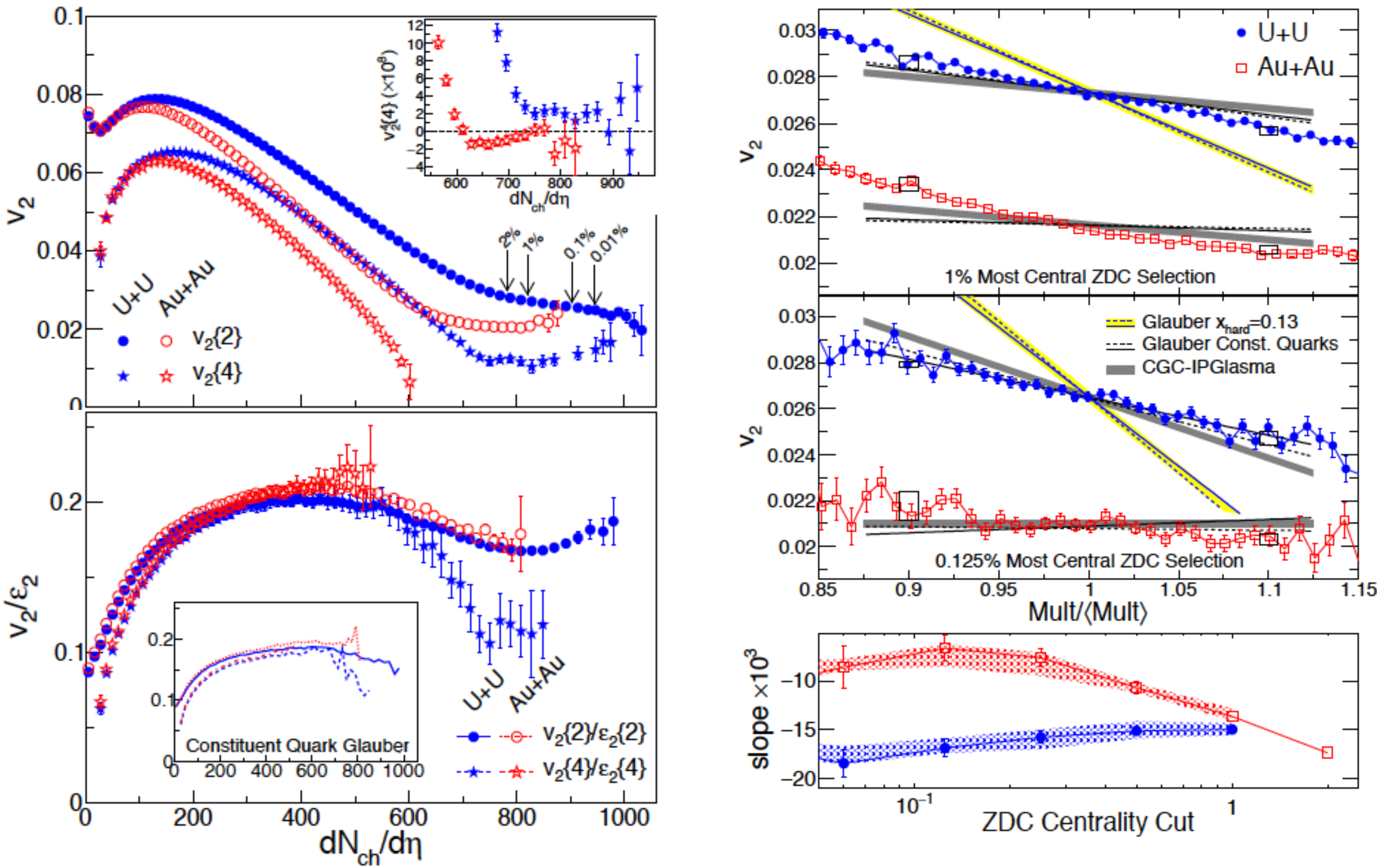
Reliable handles on the effect of the B-field may prove crucial

Along with the sphaleron transition rate, uncertainty in the duration of the B-field will probably remain one of the key challenges to reliable predictions for the CME effect

So far, the isobar program looks promising: as long as the isotopes can be acquired there seem to be no show-stoppers: *note proposed statistics are sufficient for CME but not CMW studies*

Thanks

Uranium: High Level of Coherence



Phys. Rev. Lett. **115** (2015) 222301

Notes…

Baysian analysis of multi-parameter simulations compared to charge separation data? Determine B-field and sph. transition rate instead of EOS and see if the results are physically reasonable? Are anomalous hydro models up to the task?

We can drown the field in data: pid, pt, eta, harmonics, centrality, charge, energy etc. Does anyone know what to do with the data? Requires concerted modeling efforts…

Studies of the B-Field can be a rich new subfield with diverse physics implications. Consider heavy-ion collisions as a tool to create the largest fields in nature. RHIC can pioneer this topic, potentially defining a new direction in nuclear physics.

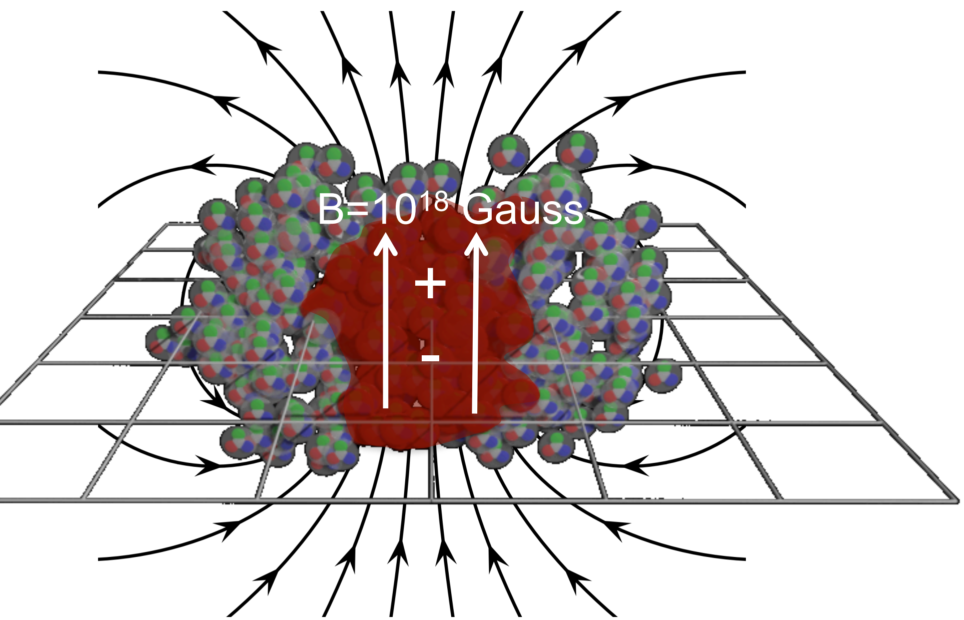
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

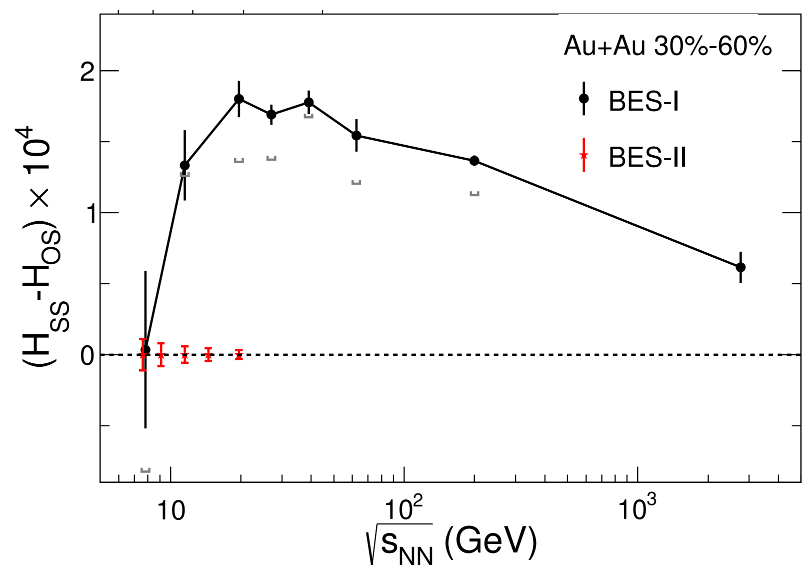
a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

In a chirally symmetric QGP, this imbalance can create charge separation along the magnetic field

charge separation



observed at all but the lowest energy



But models with magnetic field-independent backgrounds can also be tuned to reproduce the observed charge separation

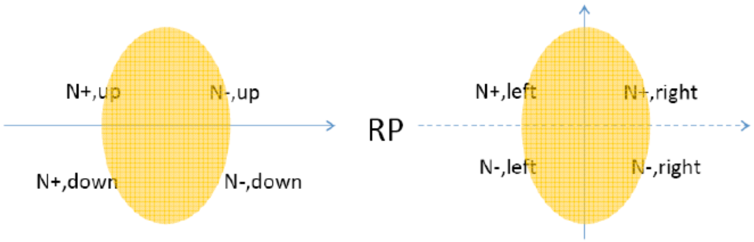
Assessment of Present Understanding

Three requirements for the Chiral Magnetic effect

1) Large B-fields
   - can MHD stretch the field out over time?
   - what fraction of quarks fall into the L=0 Landau level?
2) Chiral symmetry restoration
   - When do quarks form?
   - When is equilibrium achieved?
3) Topological charge changing transitions
   - What is the rate and how does it change with density?

Do 1, 2, and 3 all happen simultaneously such that we should expect to see a signal of CME in heavy ion collisions?

Alternative Measures



$$A_{\pm,UD} = \frac{N_{\pm,up} - N_{\pm,down}}{N_{\pm,up} + N_{\pm,down}} \qquad A_{\pm,LR} = \frac{N_{\pm,left} - N_{\pm,right}}{N_{\pm,left} + N_{\pm,right}}$$

Quan Wang

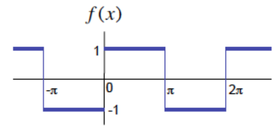
Then form the quantity

$$\frac{\langle A_{+,UD} A_{-,UD} \rangle}{\langle A_{+,LR} A_{-,LR} \rangle} - 1$$

How is it related to <cos(a+b-2Ψ)>

The A terms can be written as square waves

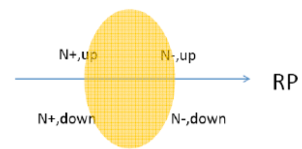
$$f(x) = \begin{cases} +1 & 0 < x < \pi \\ -1 & \pi < x < 2\pi \end{cases}$$



$$A_{+,UD} = \frac{N_{+,up} - N_{+,down}}{N_{+,up} + N_{+,down}} = \frac{\sum_i^{N_+} f(\phi_{+,i} - \psi)}{N_+}$$

For left vs right, we shift phase by π/2

$$A_{+,LR} = \frac{N_{+,left} - N_{+,right}}{N_{+,left} + N_{+,right}} = \frac{\sum_i^{N_+} f(\phi_{+,i} - \psi + \frac{\pi}{2})}{N_+}$$



Now we take the product of these quantities

$$A_{+,UD} = \frac{N_{+,up} - N_{+,down}}{N_{+,up} + N_{+,down}} = \frac{4}{\pi N_+} \sum_i^{N_+} \sum_{n=0}^{\infty} \frac{\sin[(2n+1)(\phi_{+,i} - \psi)]}{2n+1}$$

$$A_{+,LR} = \frac{N_{+,left} - N_{+,right}}{N_{+,left} + N_{+,right}} = \frac{4}{\pi N_+} \sum_i^{N_+} \sum_{n=0}^{\infty} \frac{\cos[(2n+1)(\phi_{+,i} - \psi)]}{2n+1}$$

We end up with very familiar terms (aa=<sinsin> and vv=<coscos>)

$$\langle A_{+,UD} A_{-,UD} \rangle = \left(\frac{4}{\pi}\right)^2 \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{a_{2n+1}^{+} a_{2m+1}^{-}}{(2n+1)(2m+1)}$$

$$\langle A_{+,LR} A_{-,LR} \rangle = \left(\frac{4}{\pi}\right)^2 \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{v_{2n+1}^{+} v_{2n+1}^{-}}{(2n+1)(2m+1)}$$

$$\begin{aligned} \cos(\alpha + \beta - 2\psi) &= \cos(\alpha - \psi + \beta - \psi) \\ &= \cos(\alpha - \psi)\cos(\beta - \psi) - \sin(\alpha - \psi)\sin(\beta - \psi) \\ &= v_1^\alpha v_1^\beta - a_1^\alpha a_1^\beta \end{aligned}$$

The asymmetry can be written as

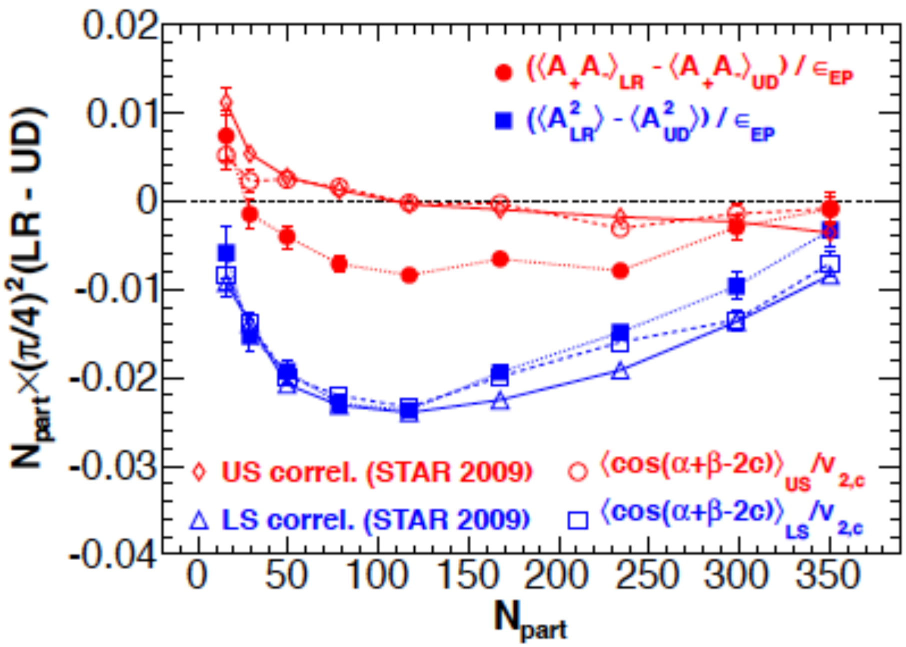
$$\frac{\langle A_{+,UD} A_{-,UD} \rangle}{\langle A_{+,LR} A_{-,LR} \rangle} - 1 = \frac{a_1^\alpha a_1^\beta + \frac{a_1^\alpha a_3^\beta}{3} + \frac{a_1^\alpha a_5^\beta}{5} + \ldots + \frac{a_3^\alpha a_1^\beta}{3} + \frac{a_3^\alpha a_3^\beta}{9} + \ldots}{v_1^\alpha v_1^- + \frac{v_1^\alpha v_3^\beta}{3} + \frac{v_1^\alpha v_5^\beta}{5} + \ldots + \frac{v_3^\alpha v_1^\beta}{3} + \frac{v_3^\alpha v_3^\beta}{9} + \ldots} - 1$$

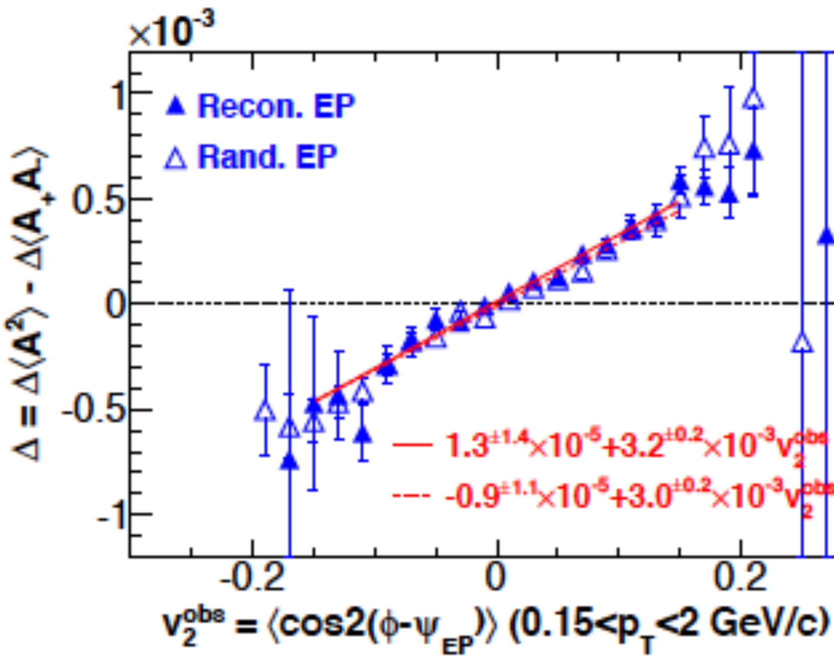
$$= \frac{a_1^\alpha a_1^\beta + \delta aa}{v_1^\alpha v_1^\beta + \delta vv} - 1$$

$$\approx \boxed{\frac{a_1^\alpha a_1^\beta}{v_1^\alpha v_1^\beta} - 1} + \frac{\delta aa}{v_1^\alpha v_1^\beta} - \frac{\delta vv}{v_1^\alpha v_1^\beta}\left(\frac{a_1^\alpha a_1^\beta}{v_1^\alpha v_1^\beta} + \frac{\delta aa}{v_1^\alpha v_1^\beta}\right)$$

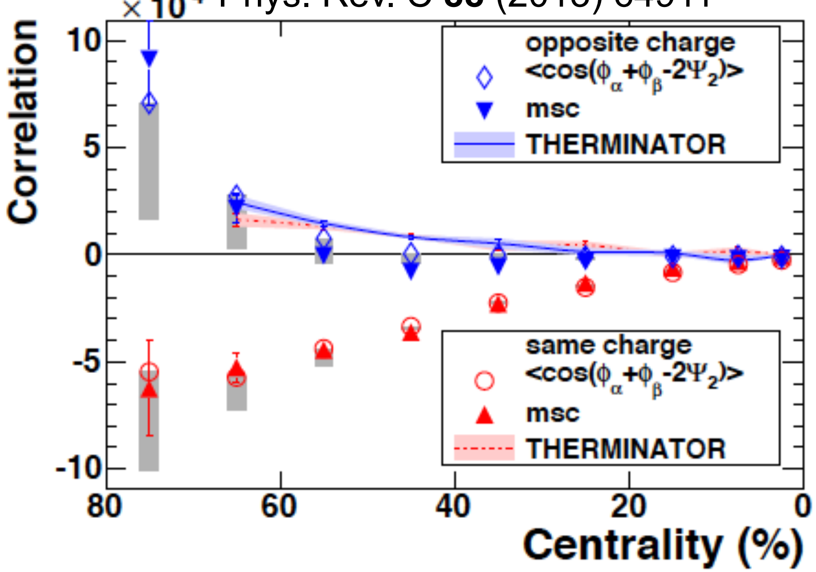
$$= \frac{-\cos(\alpha + \beta - 2\psi)}{v_1^\alpha v_1^\beta} + \frac{\delta aa}{v_1^\alpha v_1^\beta} - \frac{\delta vv}{v_1^\alpha v_1^\beta}\left(\frac{a_1^\alpha a_1^\beta}{v_1^\alpha v_1^\beta} + \frac{\delta aa}{v_1^\alpha v_1^\beta}\right)$$

Alternative Measures

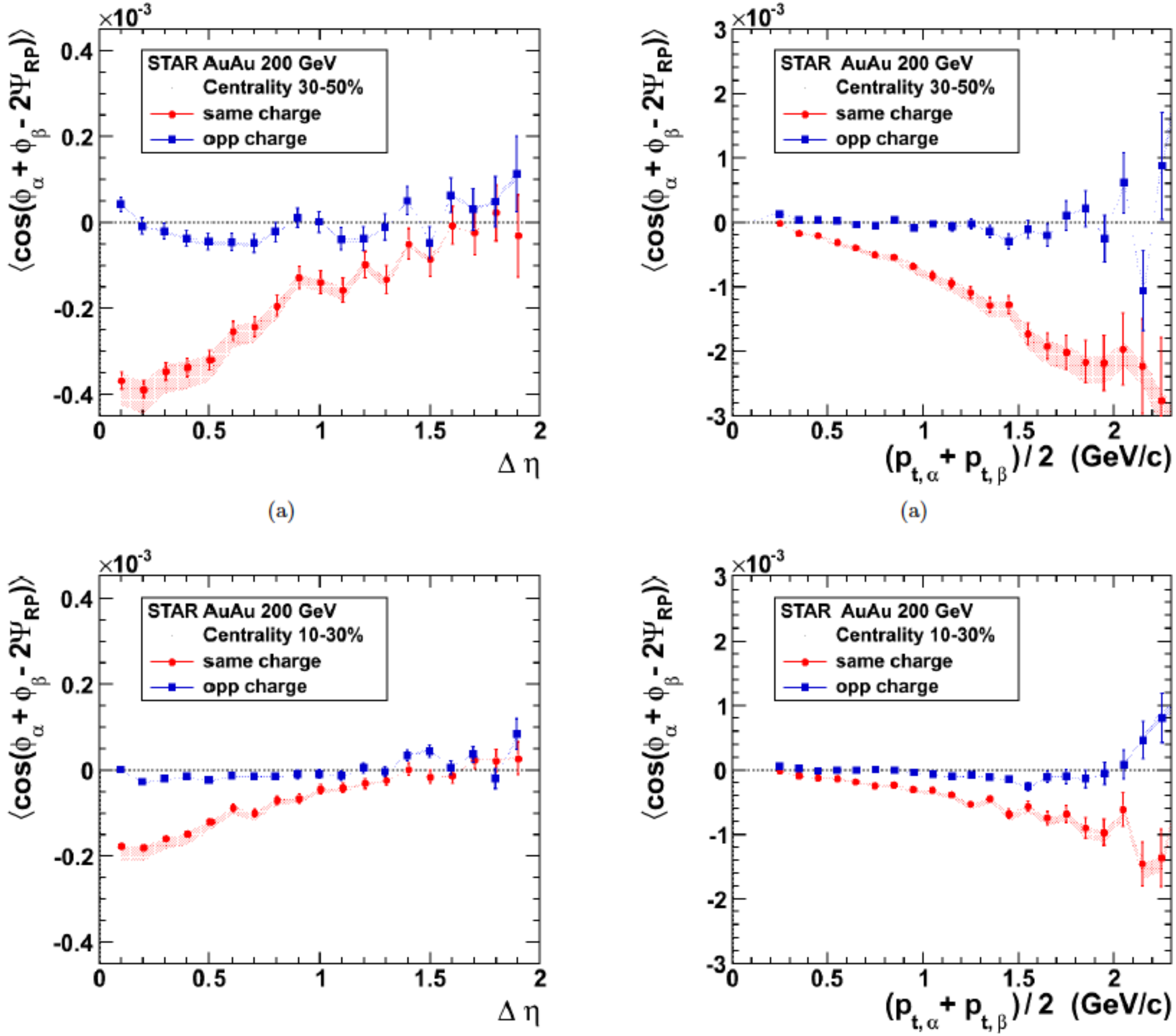




Phys. Rev. C **88** (2013) 64911



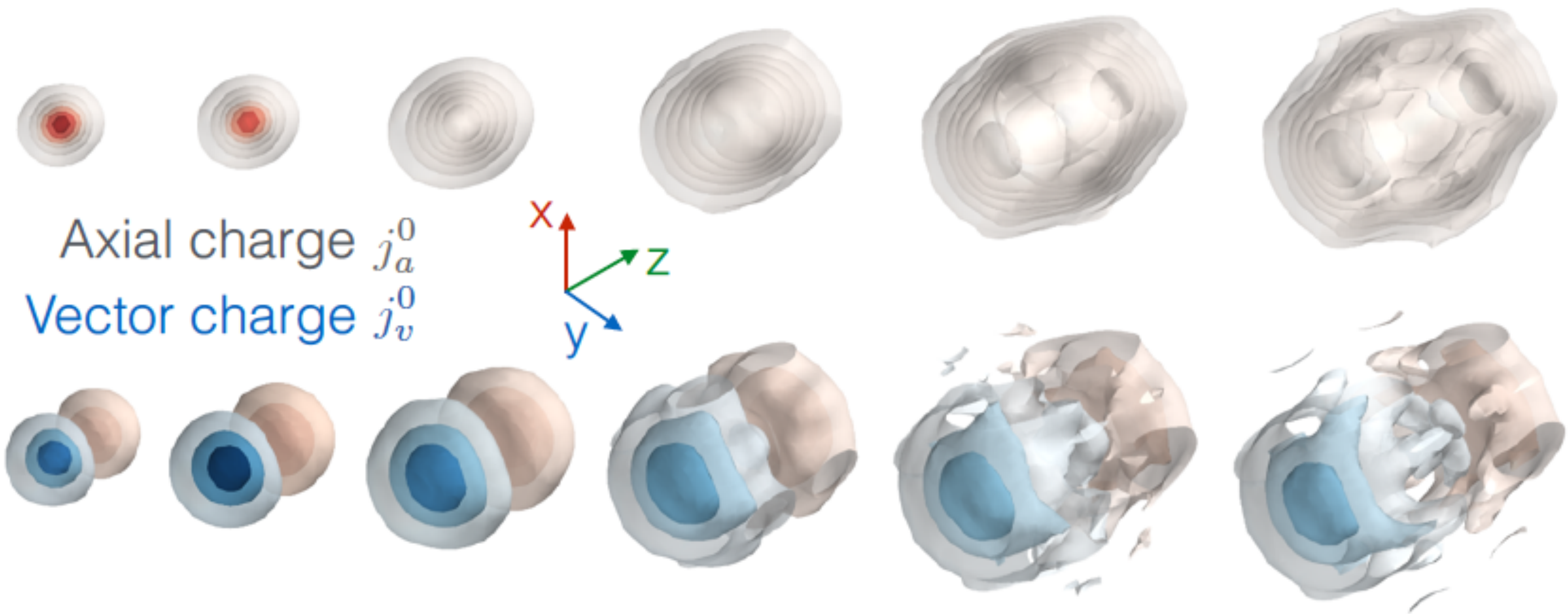
Back Up



STAR AuAu 200 GeV
Centrality 30-50%
same charge
opp charge
Centrality 10-30%
$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$
$\times 10^{-3}$
$\Delta\eta$
$(p_{t,\alpha} + p_{t,\beta})/2$ (GeV/c)
(a)
(a)

Back Up

Recent real-time lattice simulation:
(Mueller-Schlichting-Sharma)



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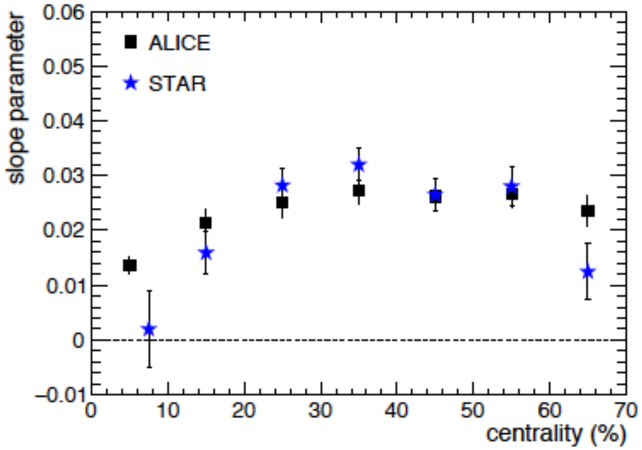
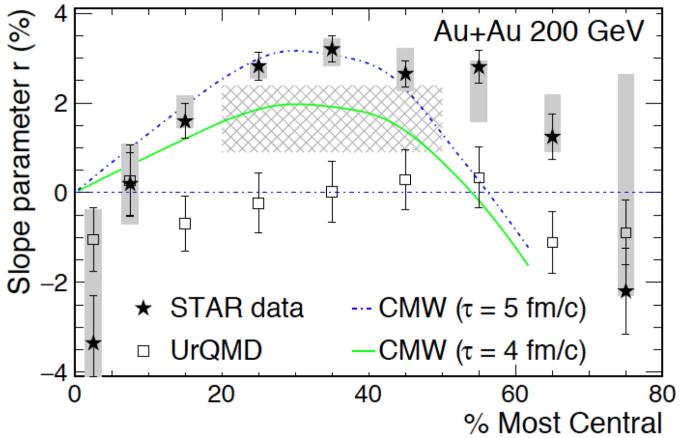
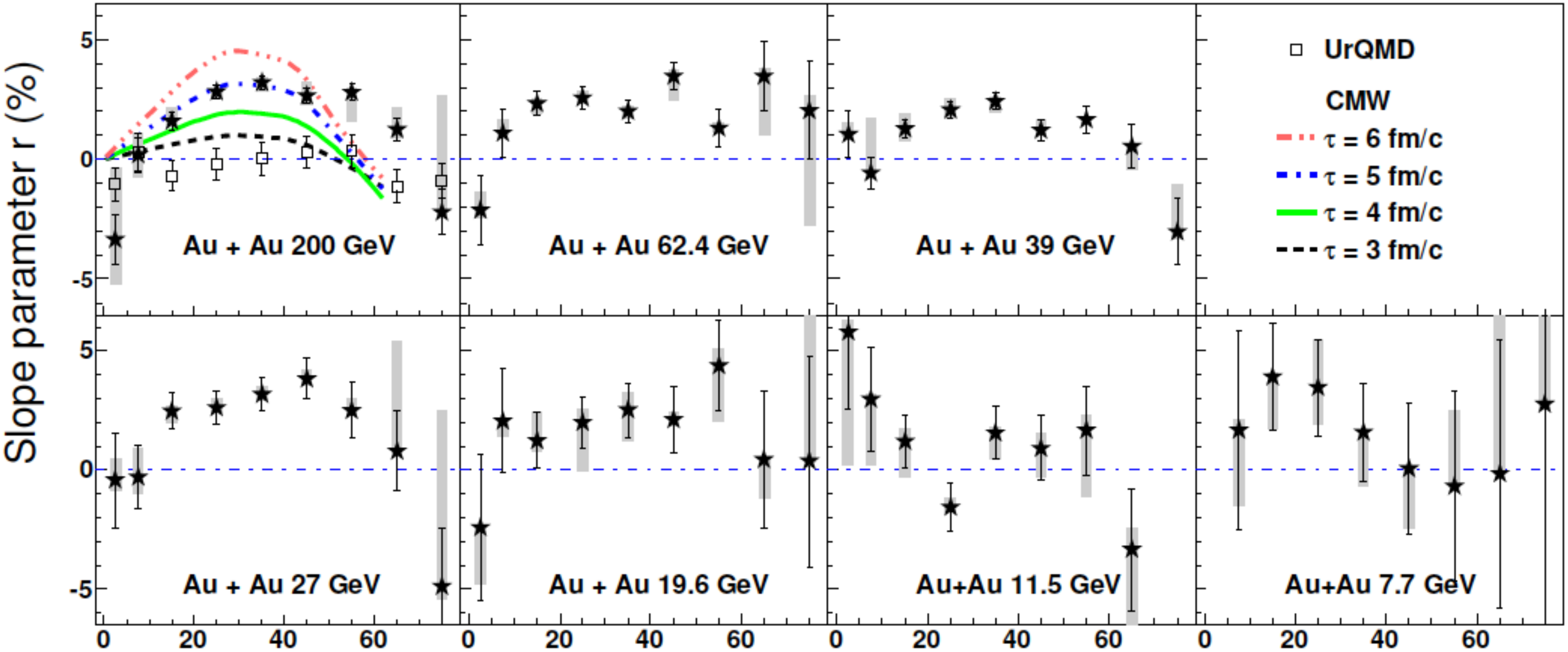


slope parameter
ALICE
STAR
centrality (%)

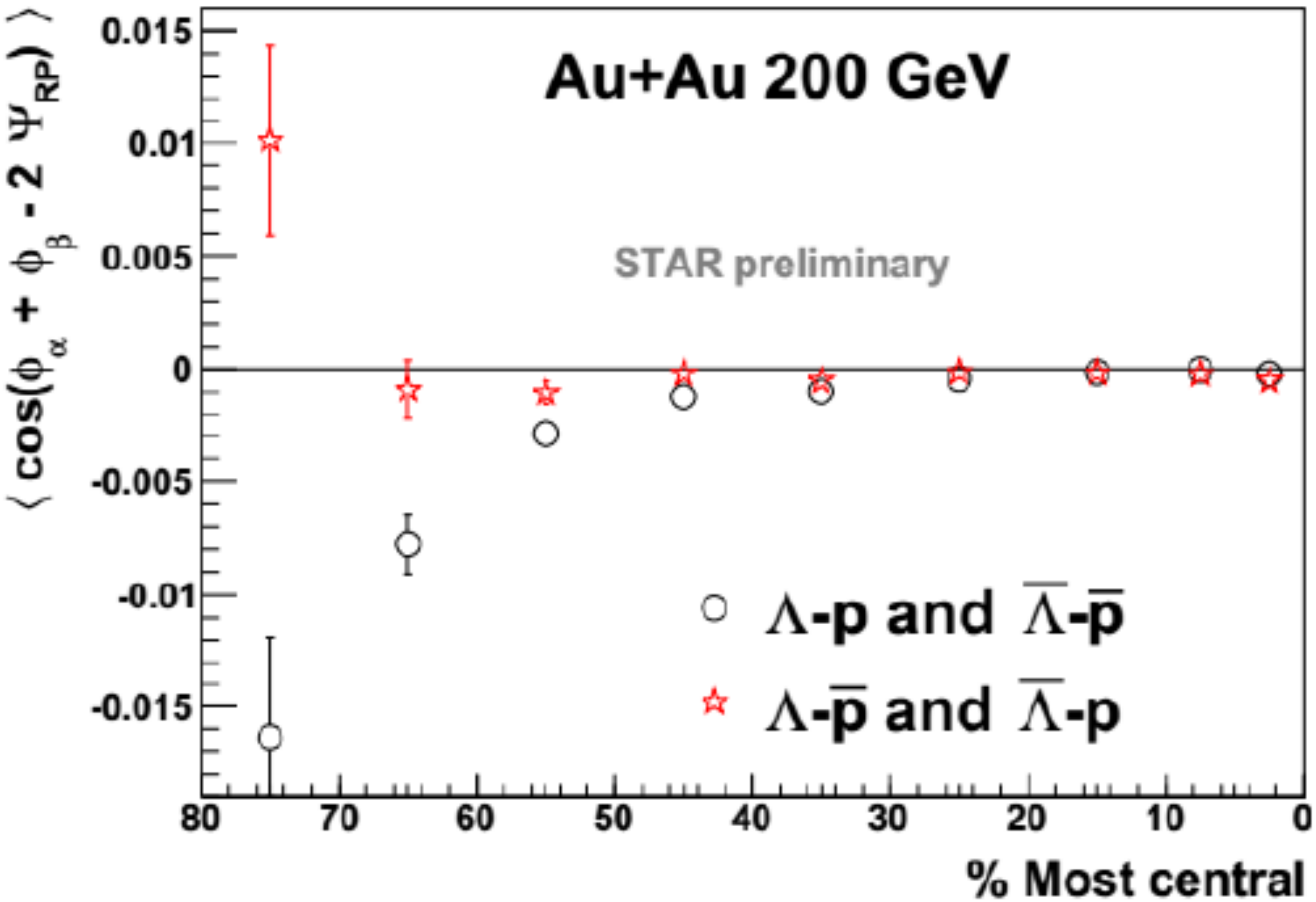


Slope parameter r (%)
Au+Au 200 GeV
STAR data
UrQMD
CMW (τ = 5 fm/c)
CMW (τ = 4 fm/c)
% Most Central

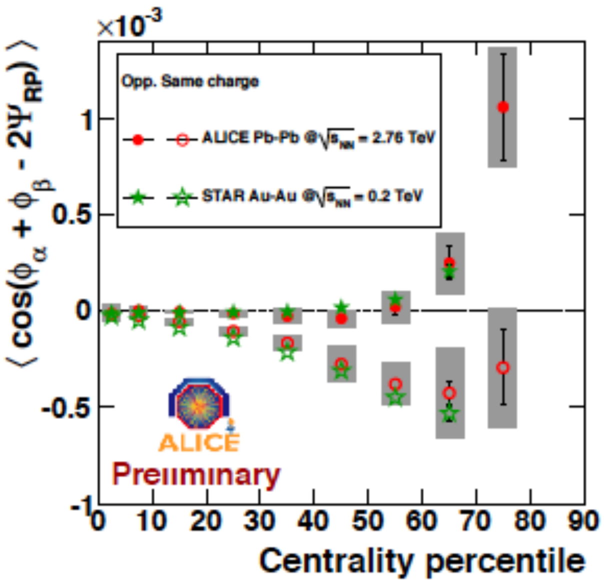


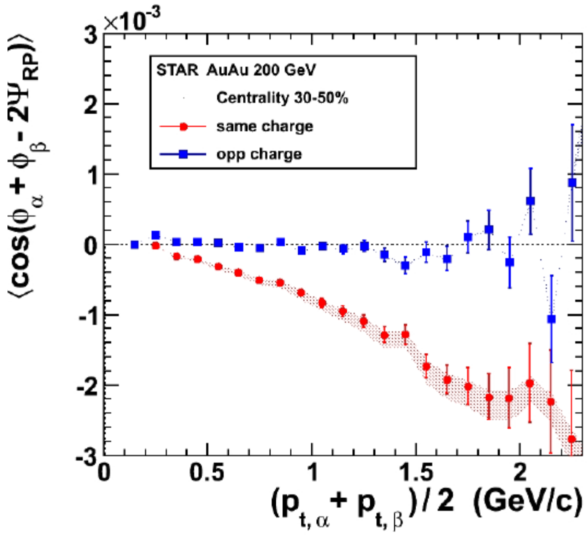
Slope parameter r (%)
Au + Au 200 GeV
Au + Au 62.4 GeV
Au + Au 39 GeV
UrQMD
CMW
τ = 6 fm/c
τ = 5 fm/c
τ = 4 fm/c
τ = 3 fm/c
Au + Au 27 GeV
Au + Au 19.6 GeV
Au+Au 11.5 GeV
Au+Au 7.7 GeV

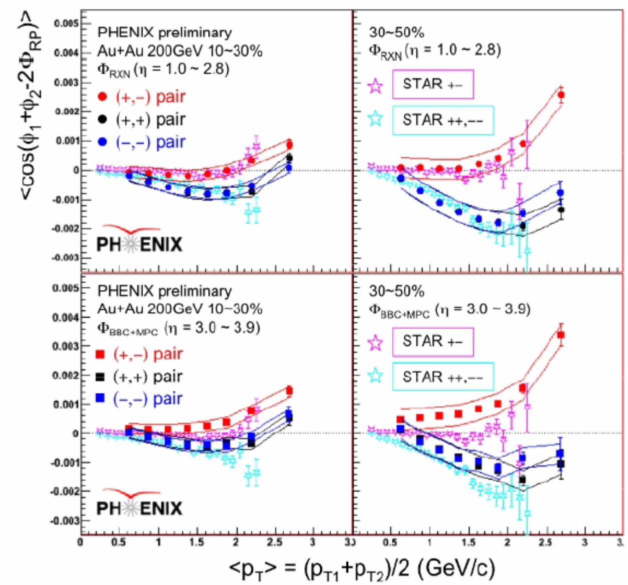
Back Up


Au+Au 200 GeV
STAR preliminary
$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
80
70
60
50
40
30
20
10
0
% Most central
Λ-p and $\bar{\Lambda}$-$\bar{p}$
Λ-$\bar{p}$ and $\bar{\Lambda}$-p

Back Up

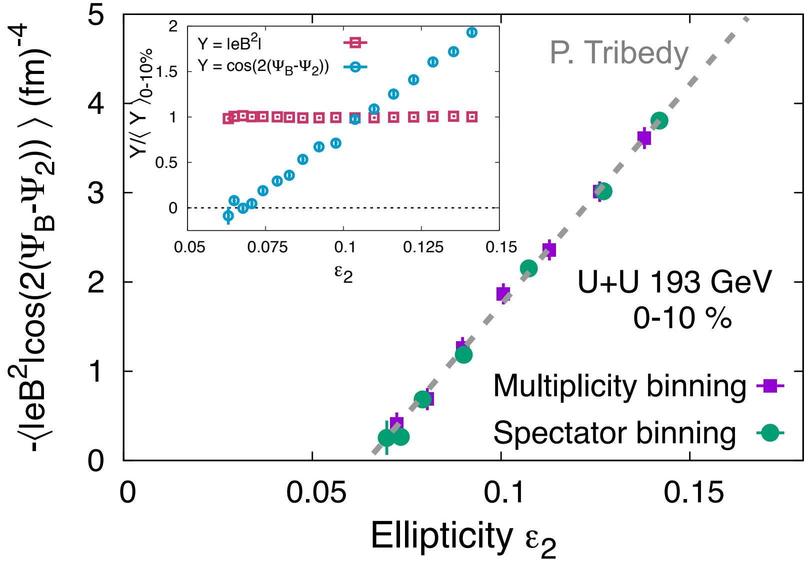

×10-3
Opp. Same charge
ALICE Pb-Pb @√sNN = 2.76 TeV
STAR Au-Au @√sNN = 0.2 TeV
ALICE
Preliminary
Centrality percentile
⟨cos(φα + φβ - 2ΨRP)⟩

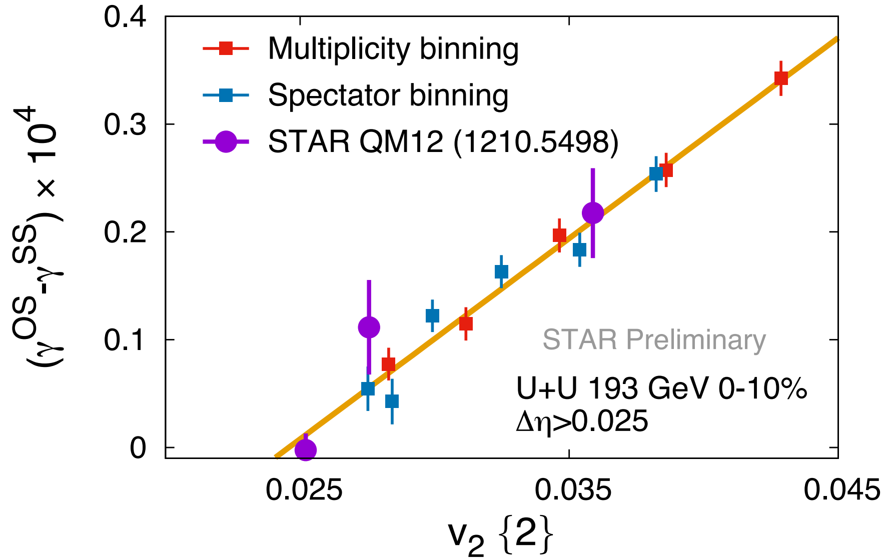

×10-3
STAR AuAu 200 GeV
Centrality 30-50%
same charge
opp charge
⟨cos(φα + φβ - 2ΨRP)⟩
(pt,α + pt,β) / 2 (GeV/c)

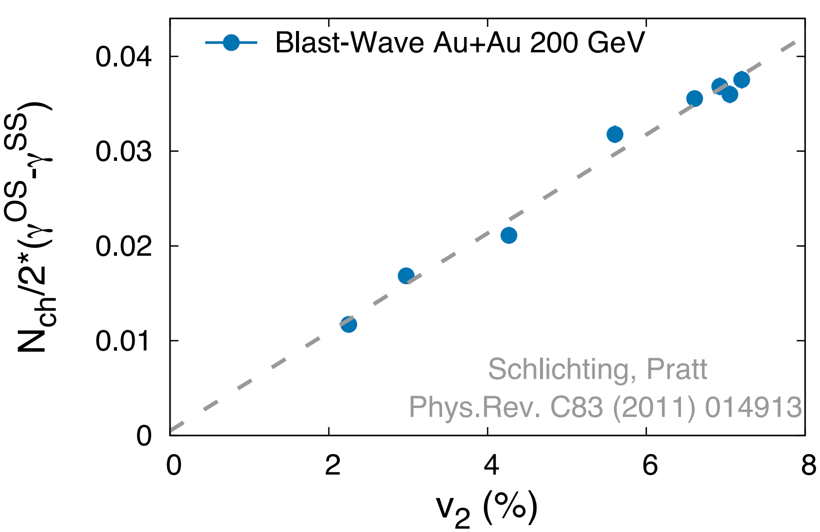

PHENIX preliminary
Au+Au 200GeV 10~30%
(+,-) pair
(+,+) pair
(-,-) pair
30~50%
STAR +-
STAR ++,--
PHENIX
<cos(φ1+φ2-2ΦRP)>
<pT> = (pT1+pT2)/2 (GeV/c)

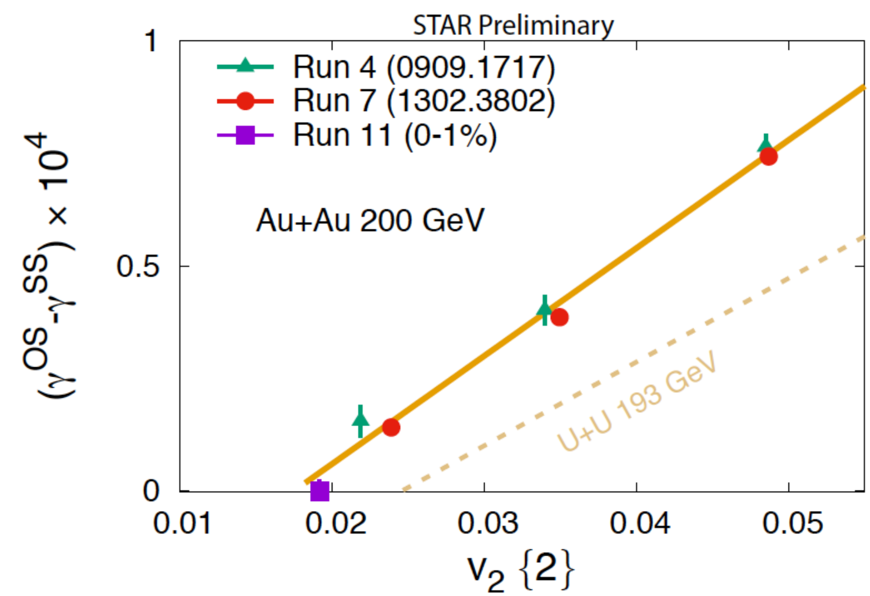
Ultra-central Au+Au and U+U

Charge separation follows projected B-Field, not v_2



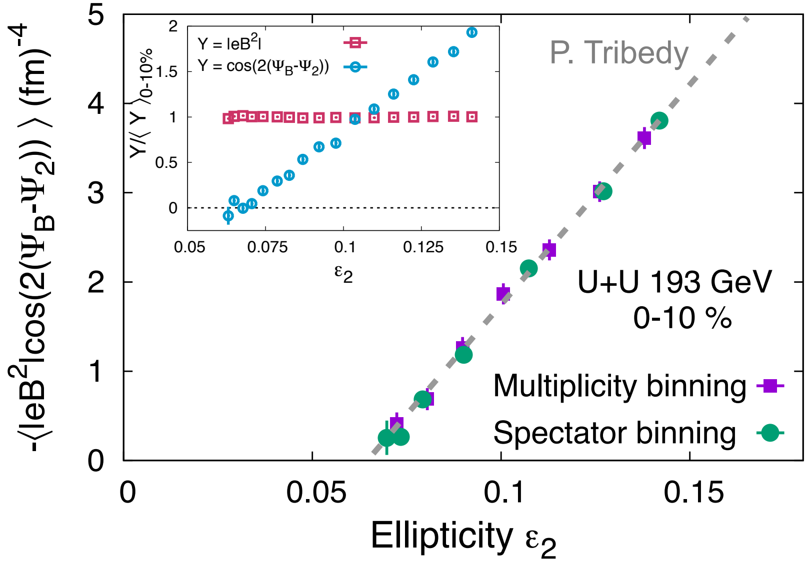


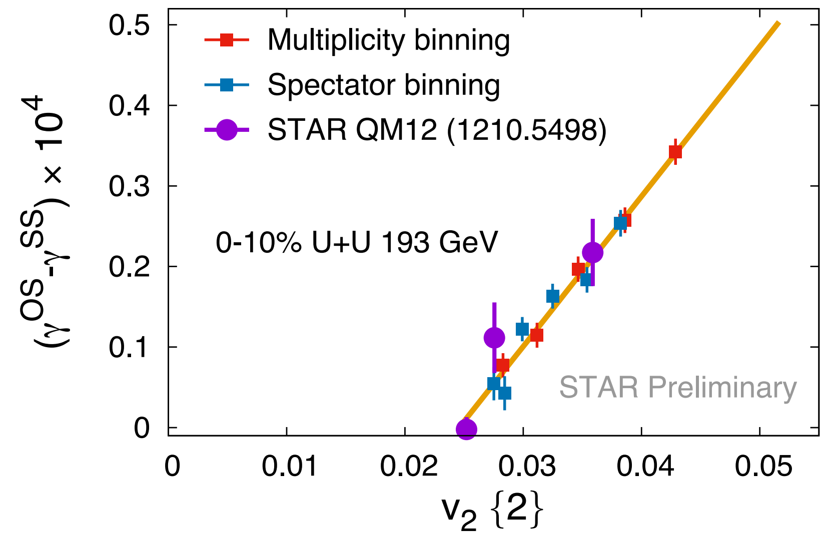


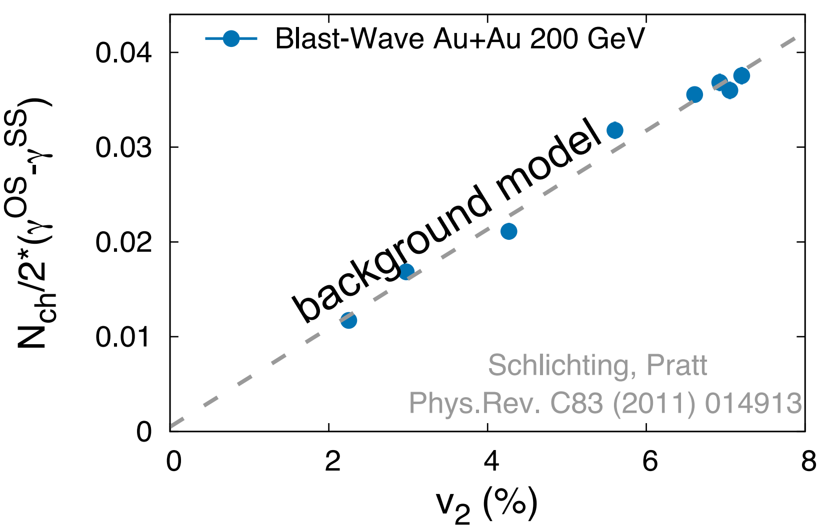


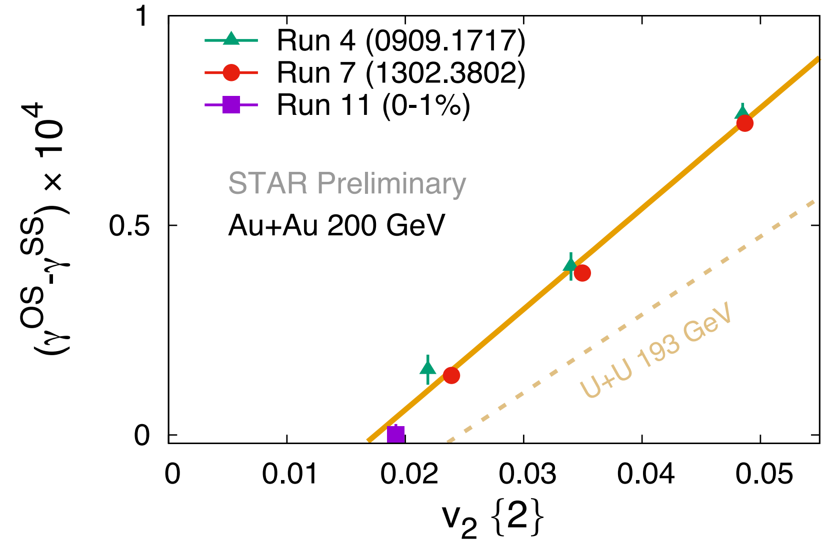
Ultra-central Au+Au and U+U

Charge separation follows projected B-Field, not v_2



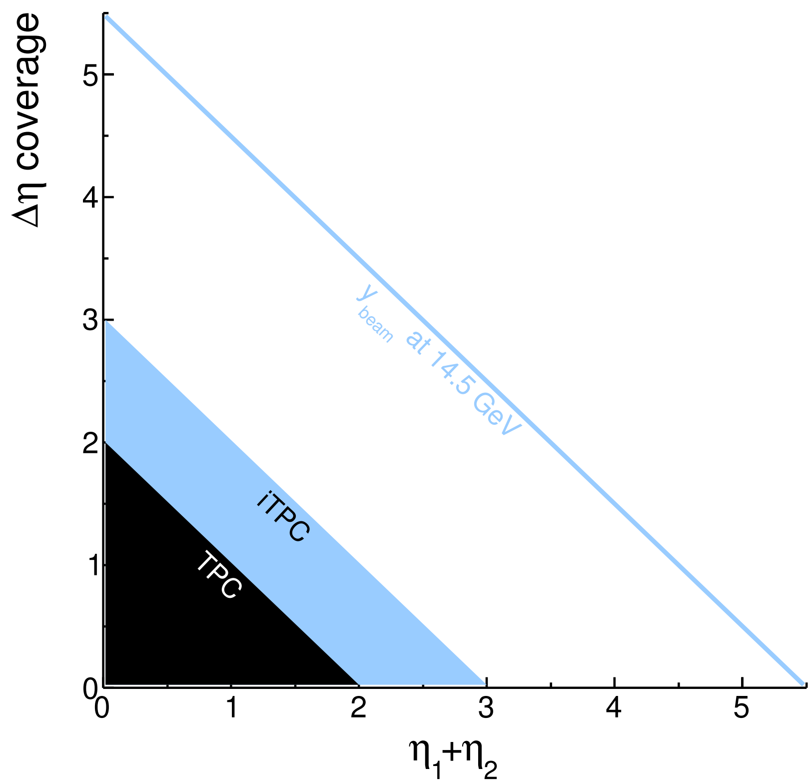


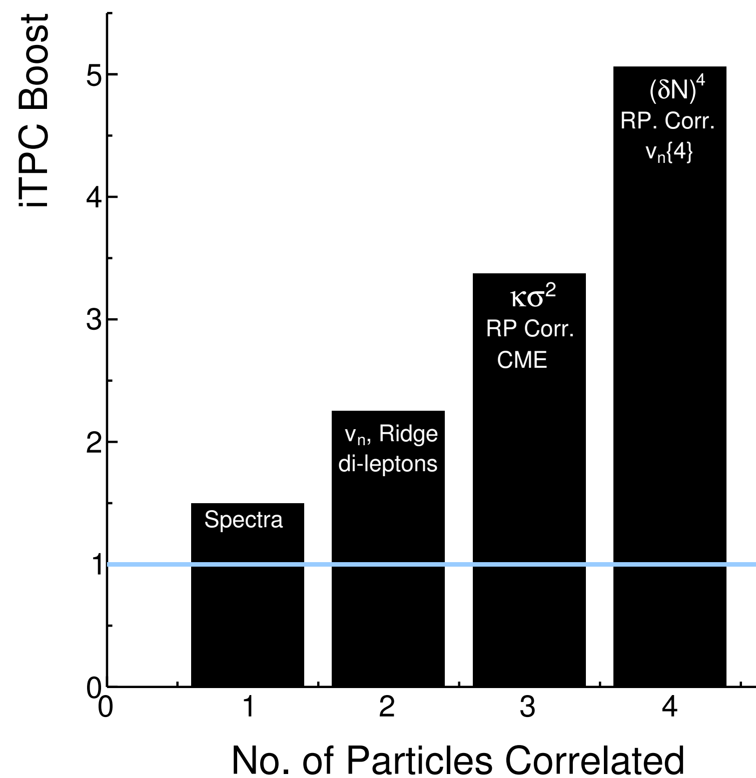


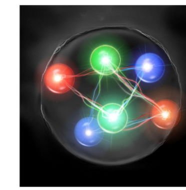


RHIC Run Plan

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au







astrophysical implications

By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX