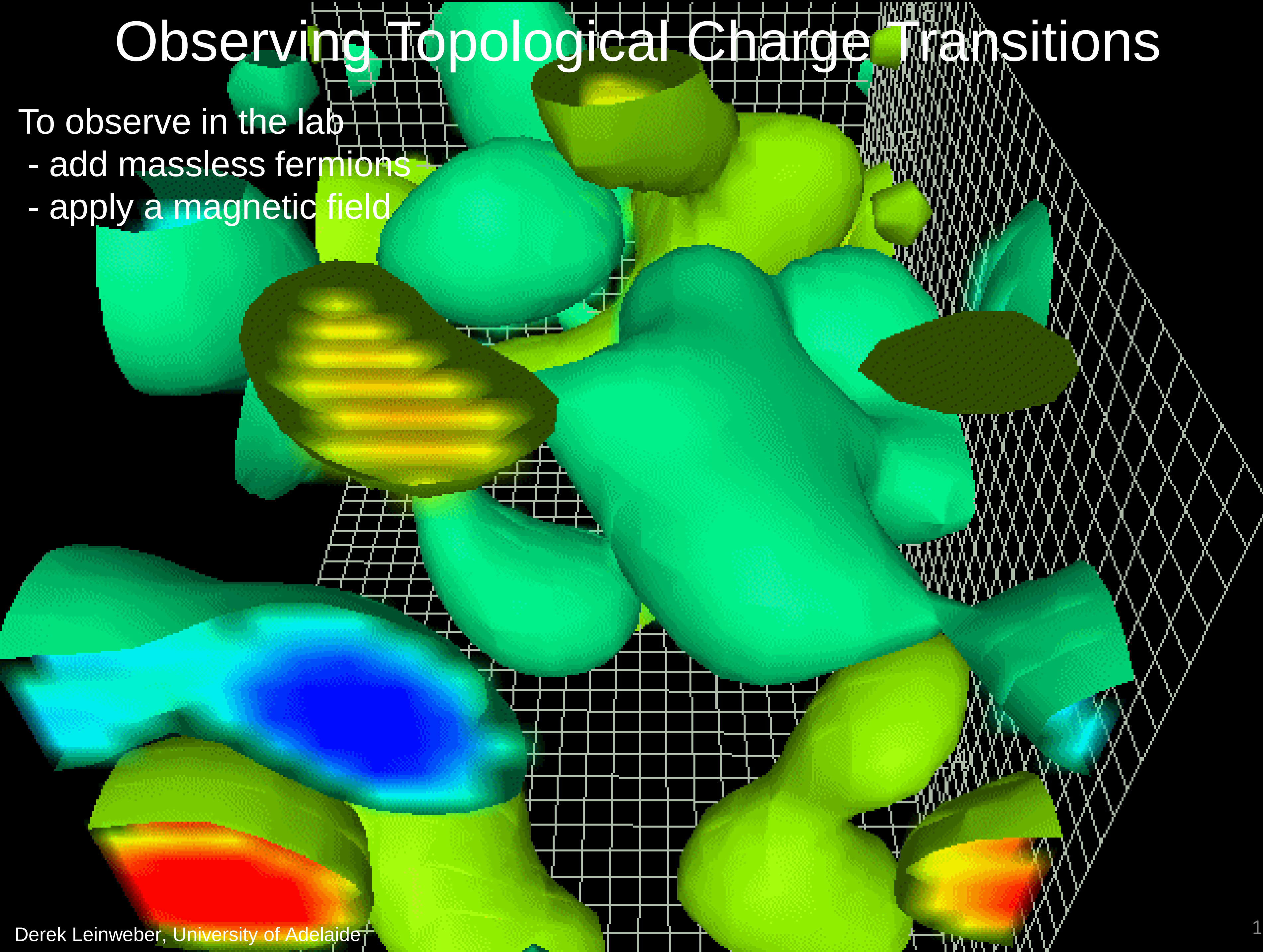
Observing Topological Charge Transitions

To observe in the lab

- add massless fermions
- apply a magnetic field

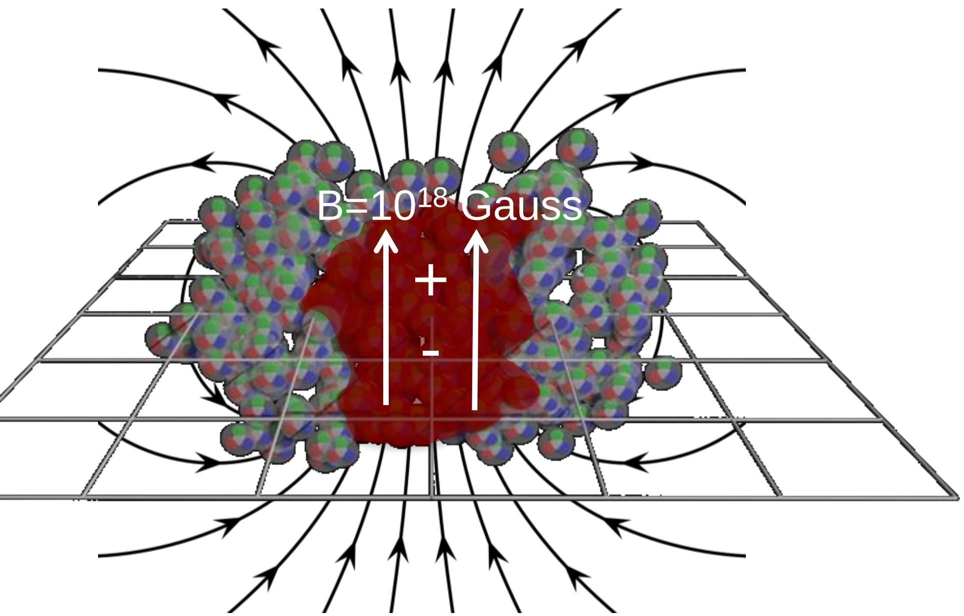


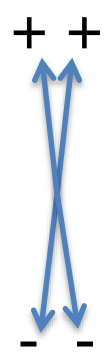
Measuring Topological Charge Transitions

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

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

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

in the lab frame we can measure

$$g_{SS} = \langle \cos(j_{\pm} + j_{\pm} - 2y_{RP}) \rangle$$

$$g_{OS} = \langle \cos(j_{\pm} + j_{\mp} - 2y_{RP}) \rangle$$

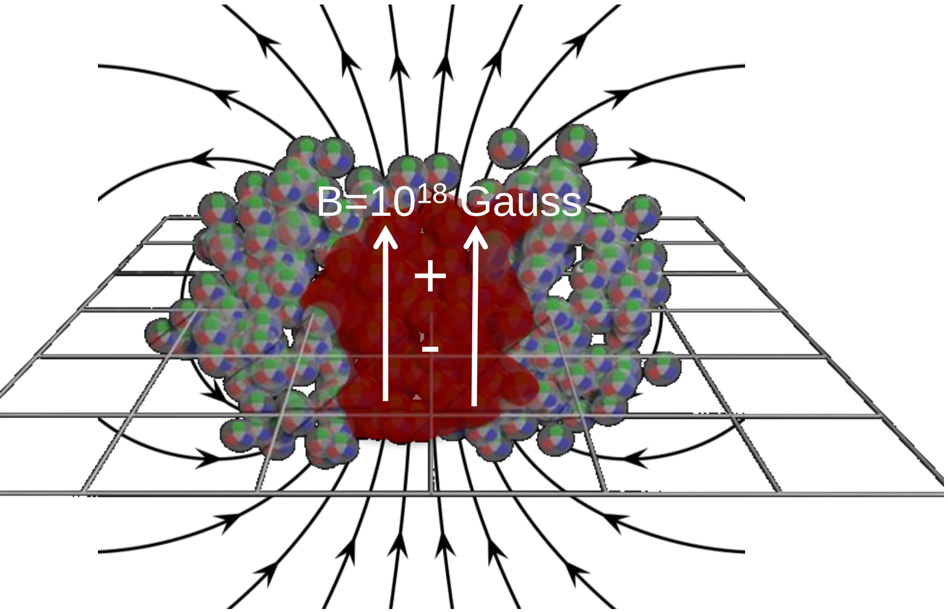
$$Dg = g_{OS} - g_{SS}$$

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

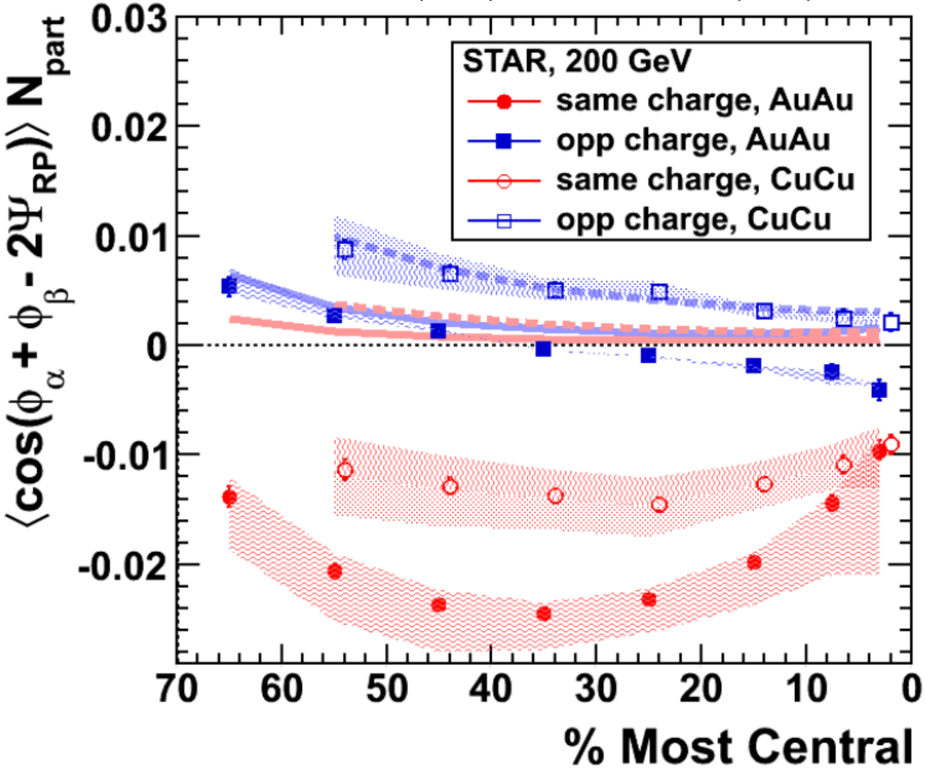
Measuring Topological Charge Transitions

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

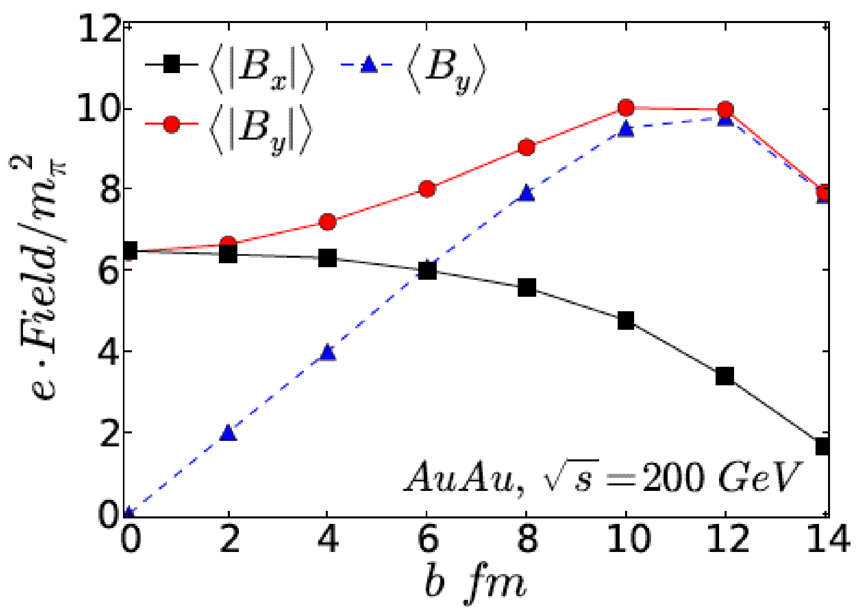


It was speculated that quenching and expansion dynamics suppress charge flow across the plane: requires more sophisticated modeling

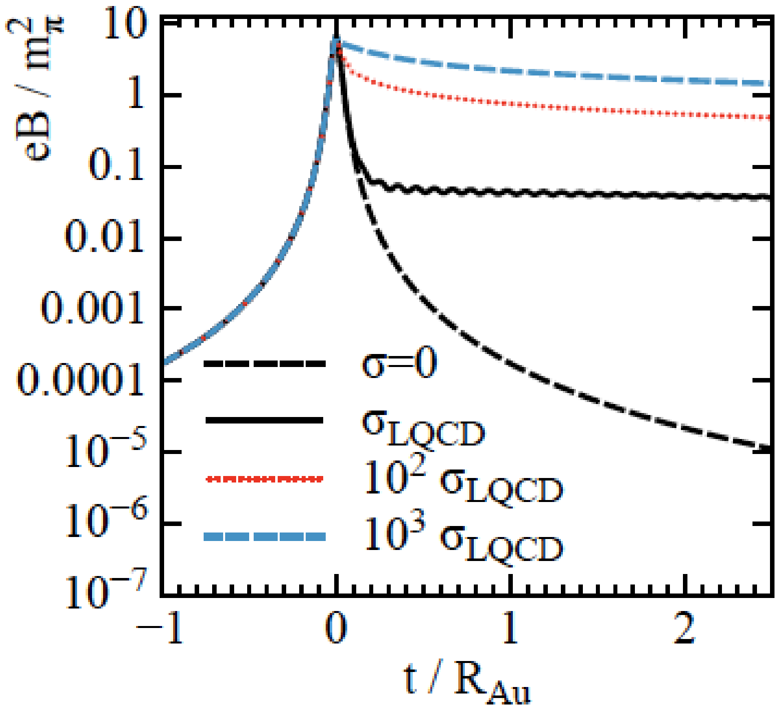
Assessment of Present Understanding

Solid predictions for CME are difficult

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



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

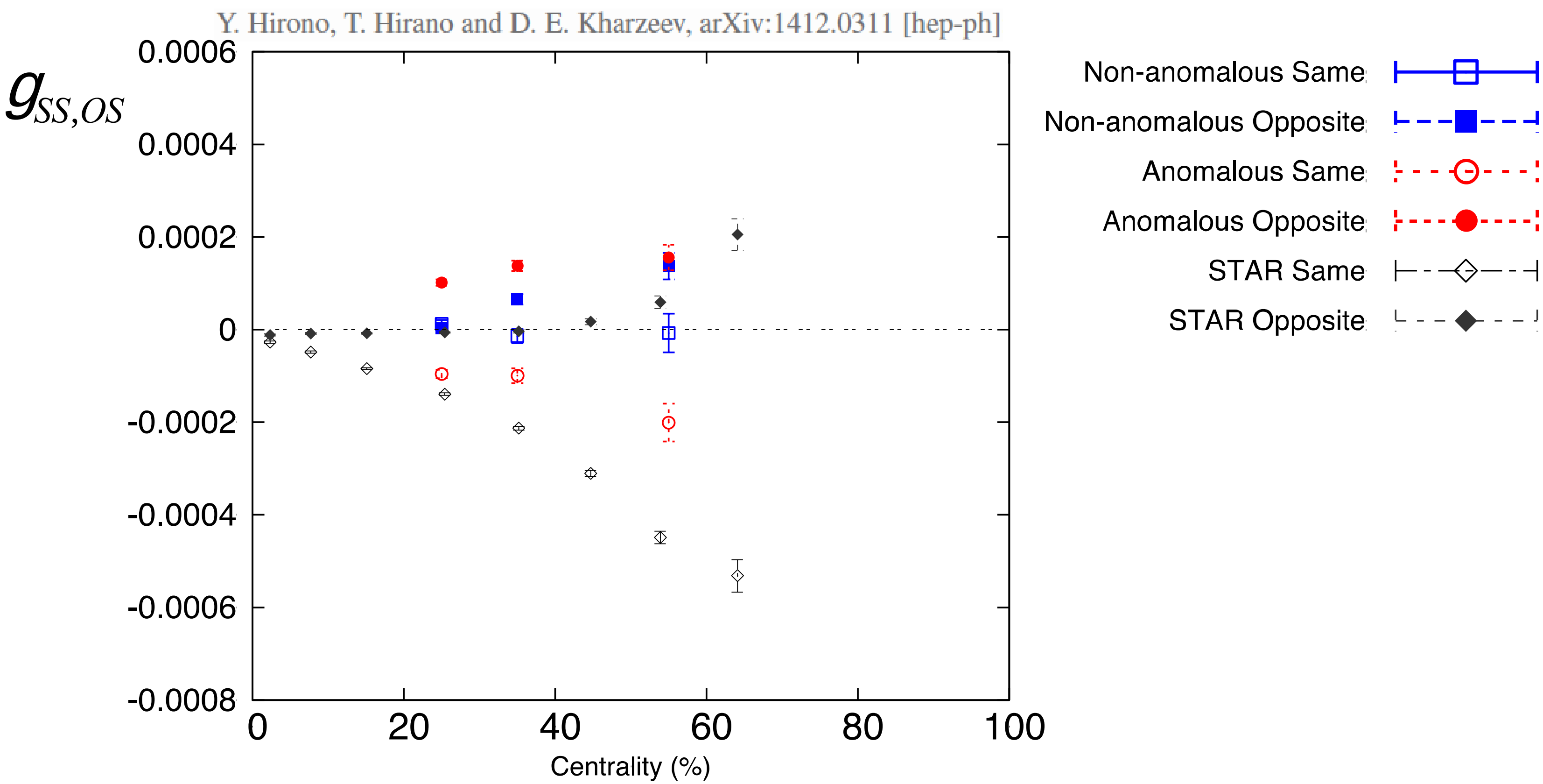


Magnetic field:

- effects of fluctuations are large
- alignment of B and flow axis is important
- lifetime still poorly understood

Assessment of Present Understanding

Solid predictions for CME are starting to come on shell



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

Assessment of Present Understanding

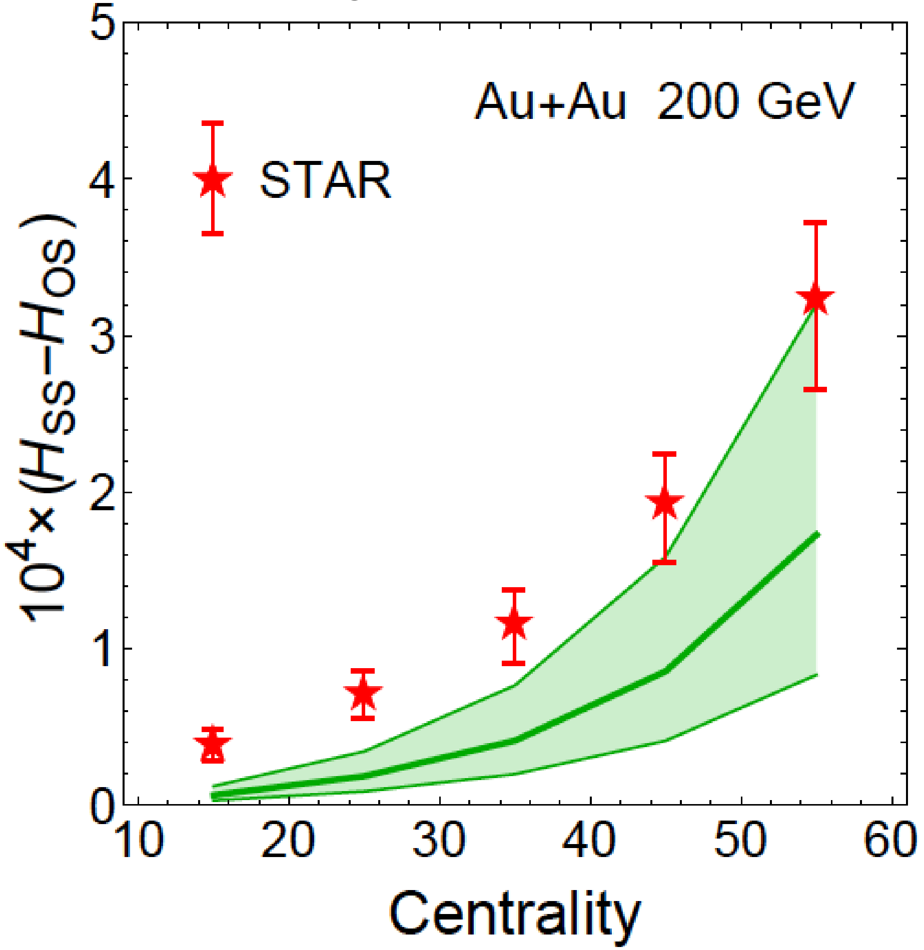
Solid predictions for CME are starting to come on shell

$$B = \frac{B_0}{1 + \left(\frac{\tau}{\tau_B}\right)}$$

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

$$< n_5 > \simeq \tau_{in} \frac{Q_s^4}{16\pi^2} \frac{\sqrt{N_{co.}}\,(\pi \rho^2)}{A}$$

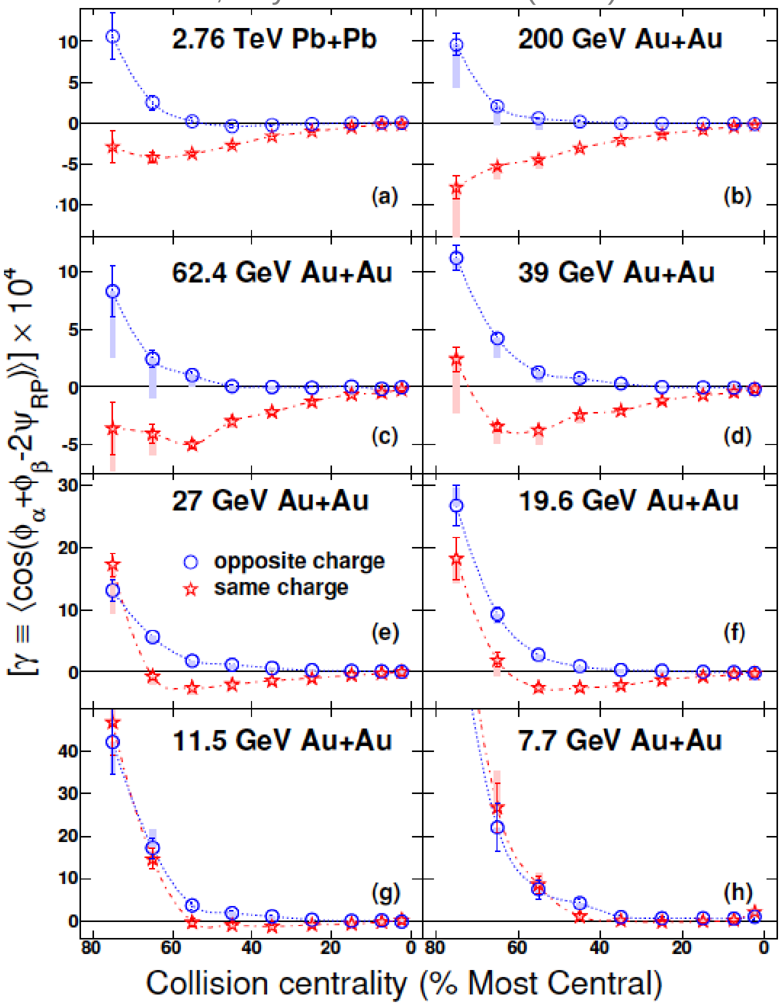
Jiang, Shi, Yin, Liao, 2016



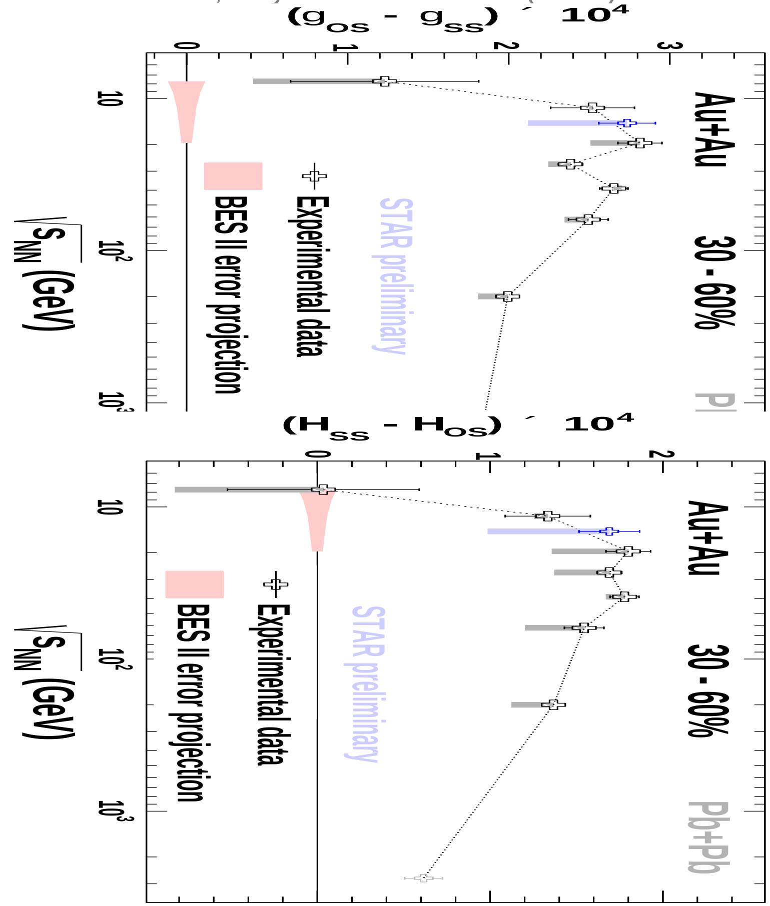
More realistic Magnetic Field still gives the right ball-park

Beam Energy Dependence

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



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



assuming factorization, background subtracted

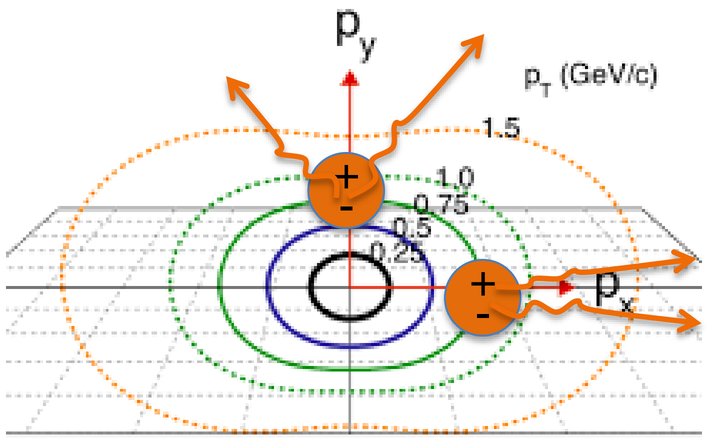
$$H = \frac{kv_2 d - g}{1 + kv_2}$$

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

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

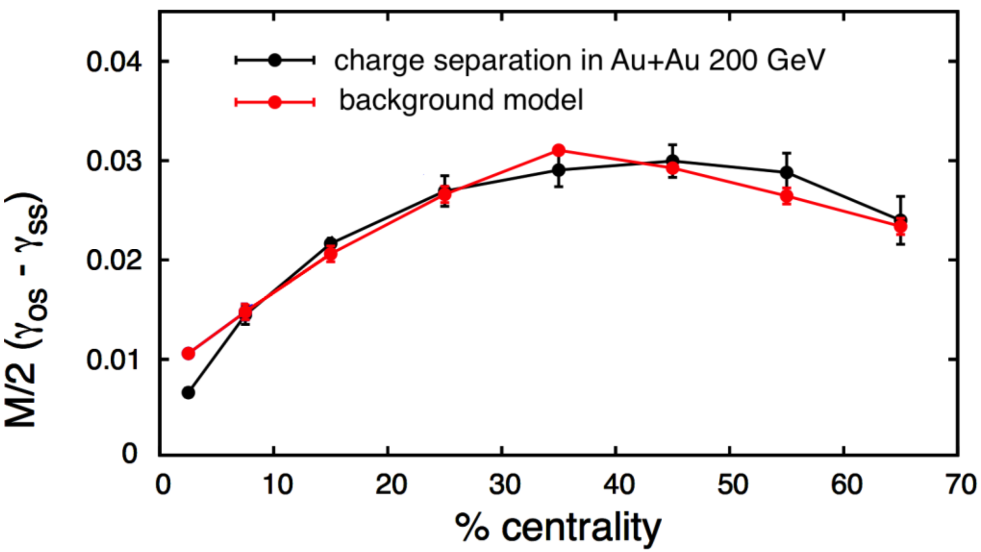
Questions of Interpretation Remain

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

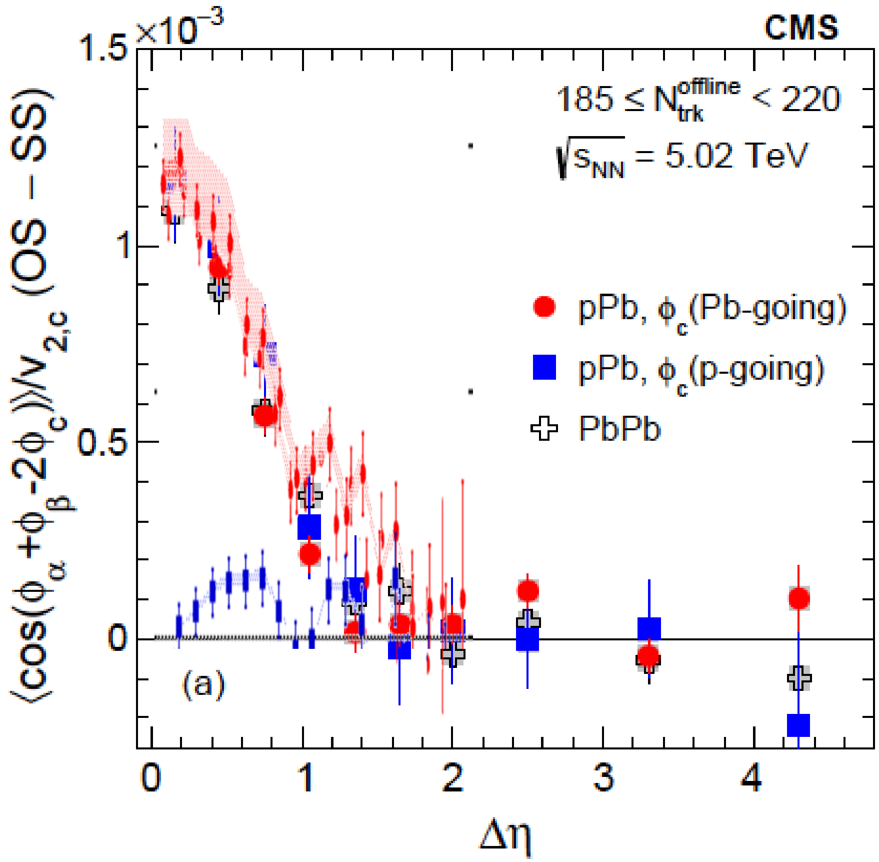
S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)

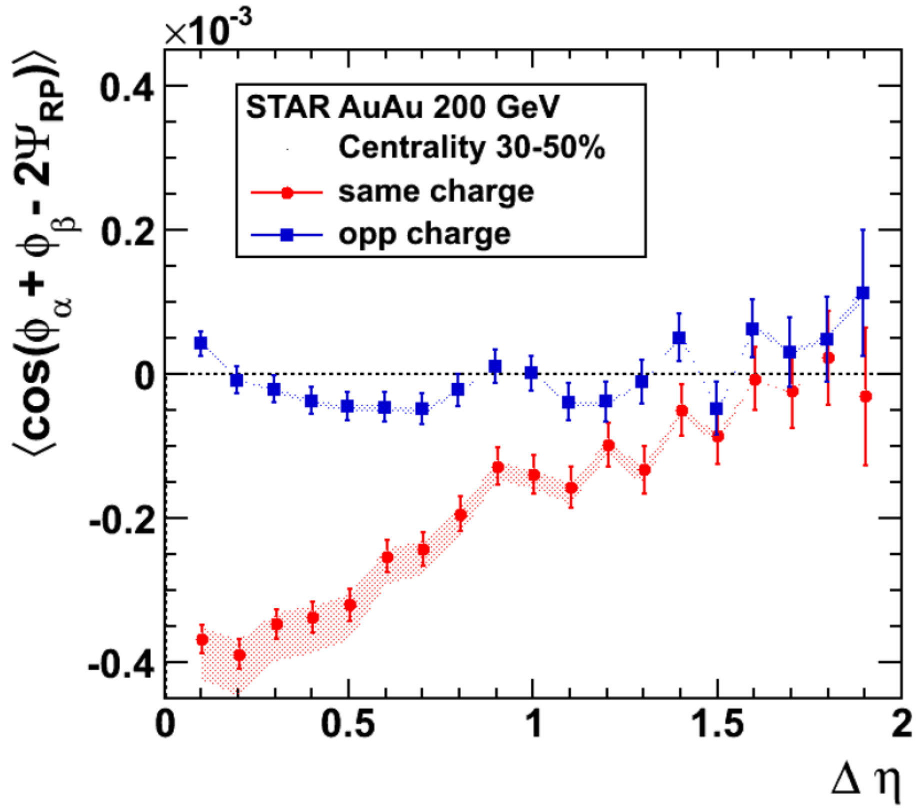


Difficult to draw definitive conclusions without better models, and an independent lever arm for magnetic field and v_2

Background estimates from p+Pb and Pb+Pb

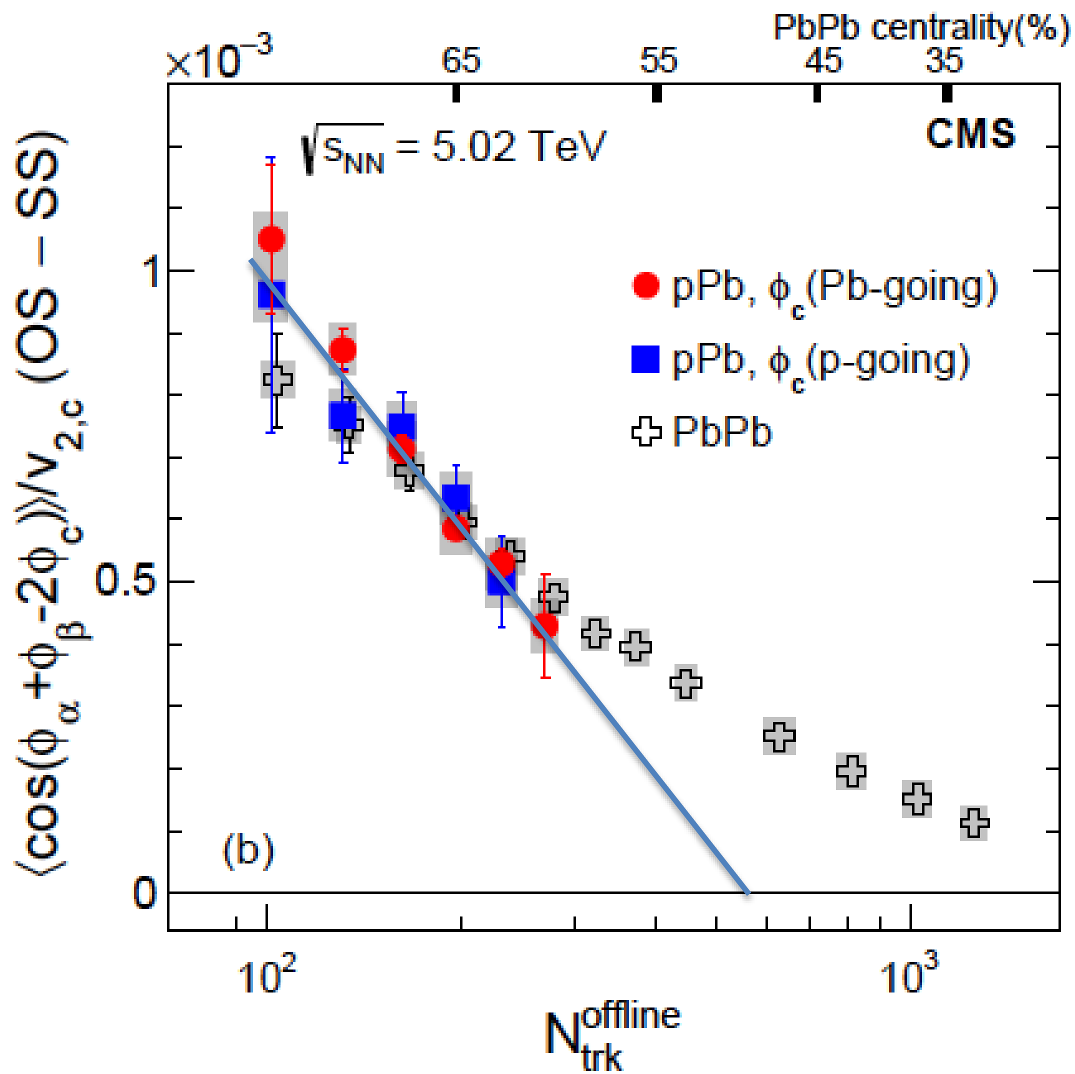
CMS analyzed a CME related observable in p+Pb





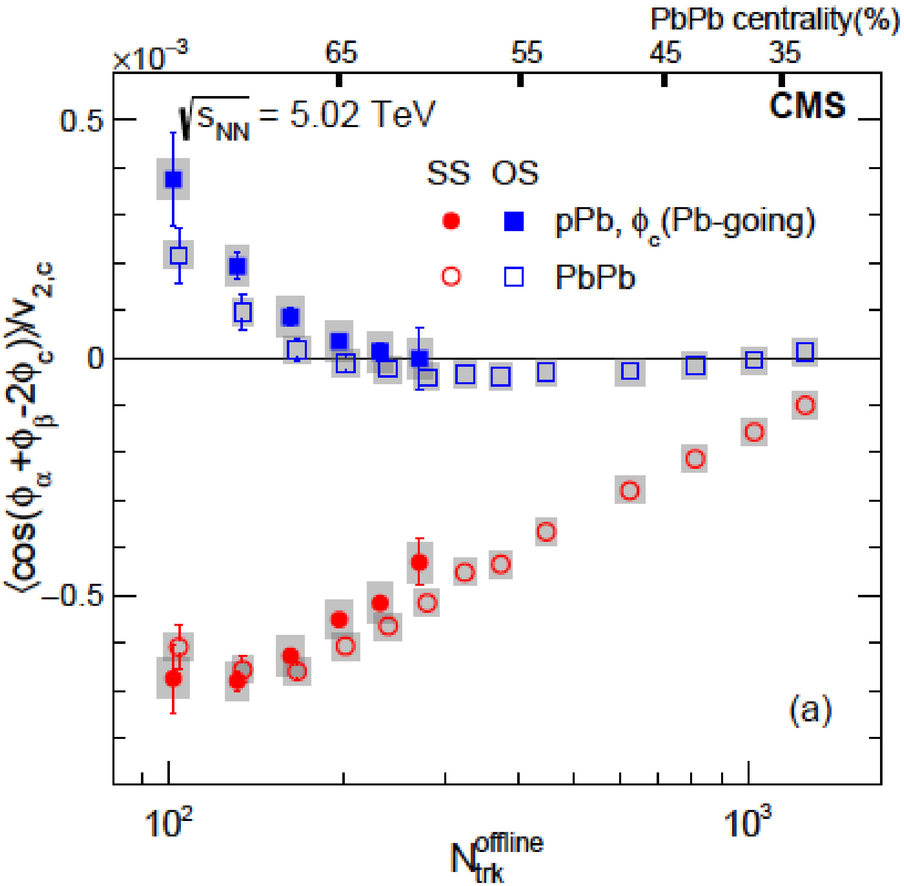
widths in p+Pb, peripheral Pb+Pb and Au+Au are all similar: final state effect?

CMS p+Pb and Pb+Pb

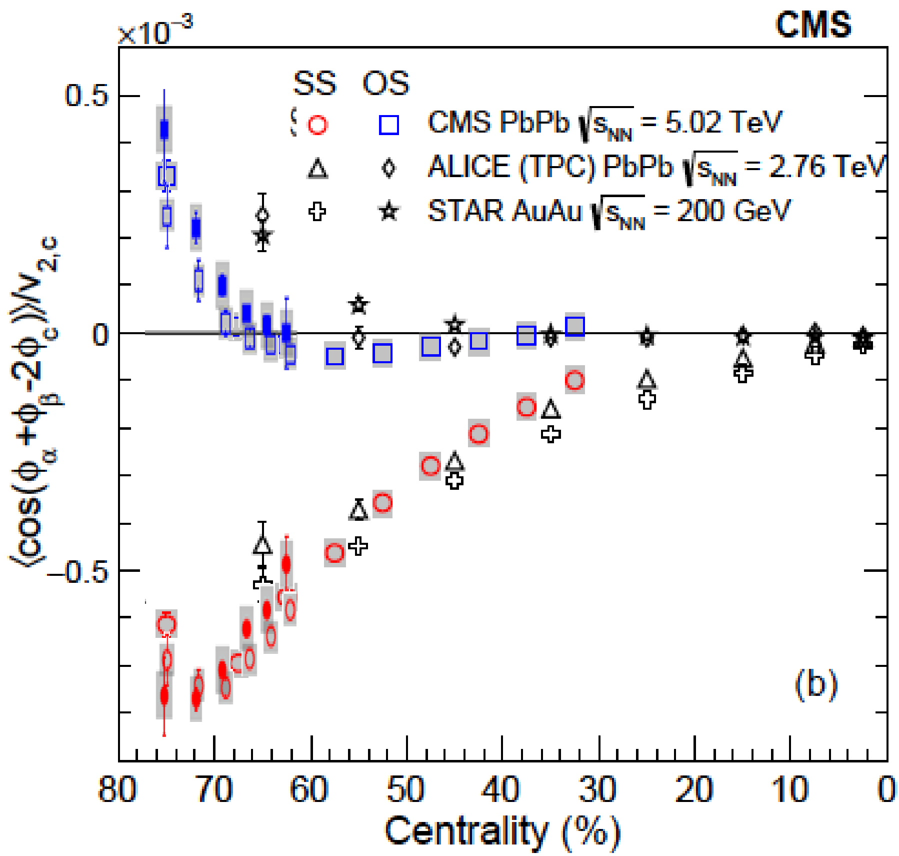


Universal curve? What does the trend look like going even more central? What happens if you scale out the trivial 1/N?

CMS p+Pb and Pb+Pb



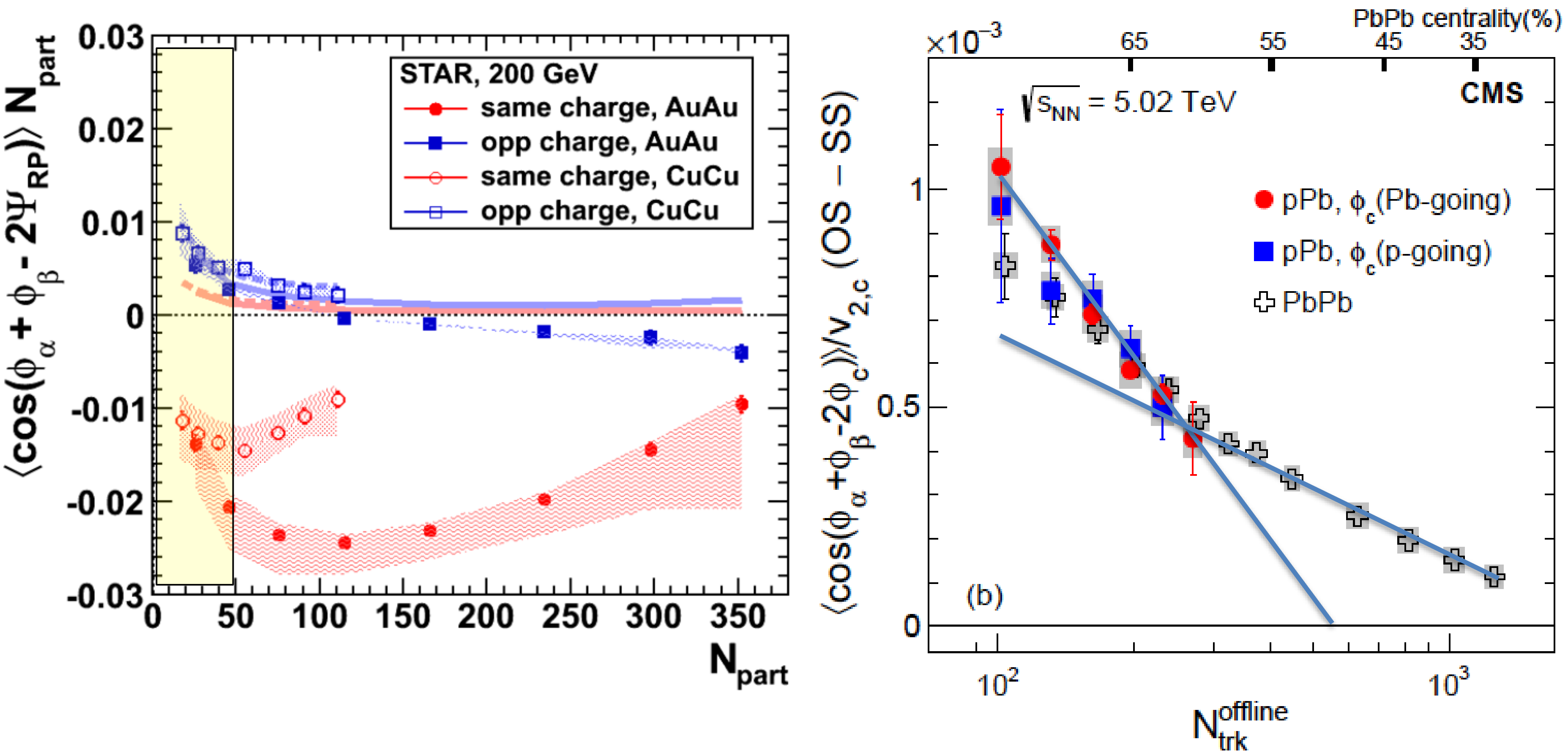
Comparing pPb and PbPb



Comparing PbPb and AuAu

Not much overlap between AuAu and pPb; pPb data covers a range previously assumed to be contaminated by background

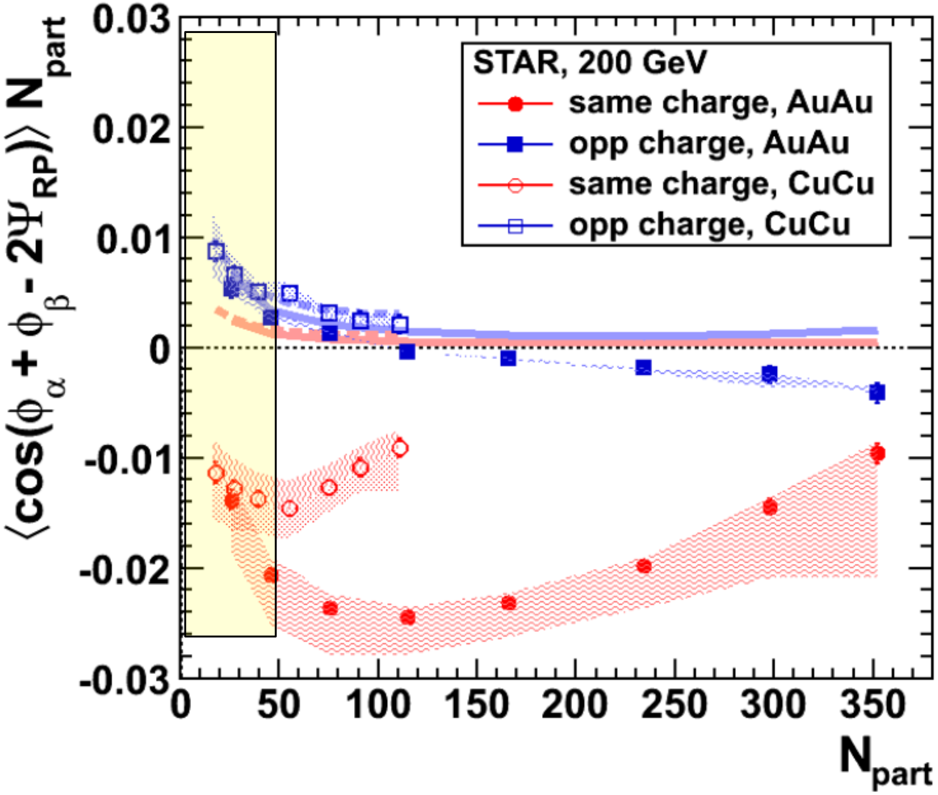
CMS p+Pb and Pb+Pb

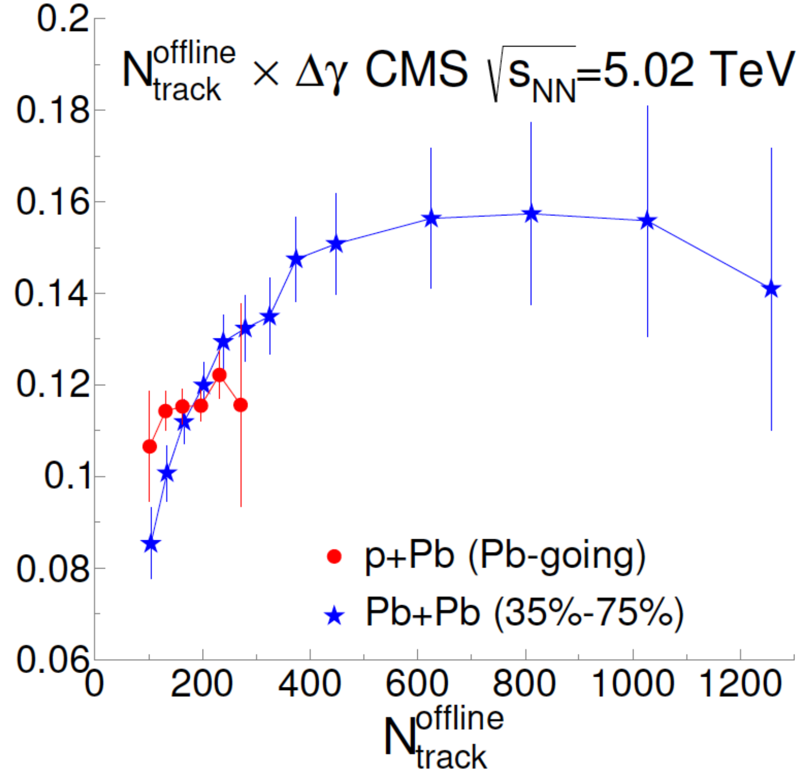


CMS results in context

Changes in physics can be obscured by 1/N trends

CMS p+Pb and Pb+Pb





CMS results in context

Changes in physics can be obscured by 1/N trends

Beam Energy Dependence

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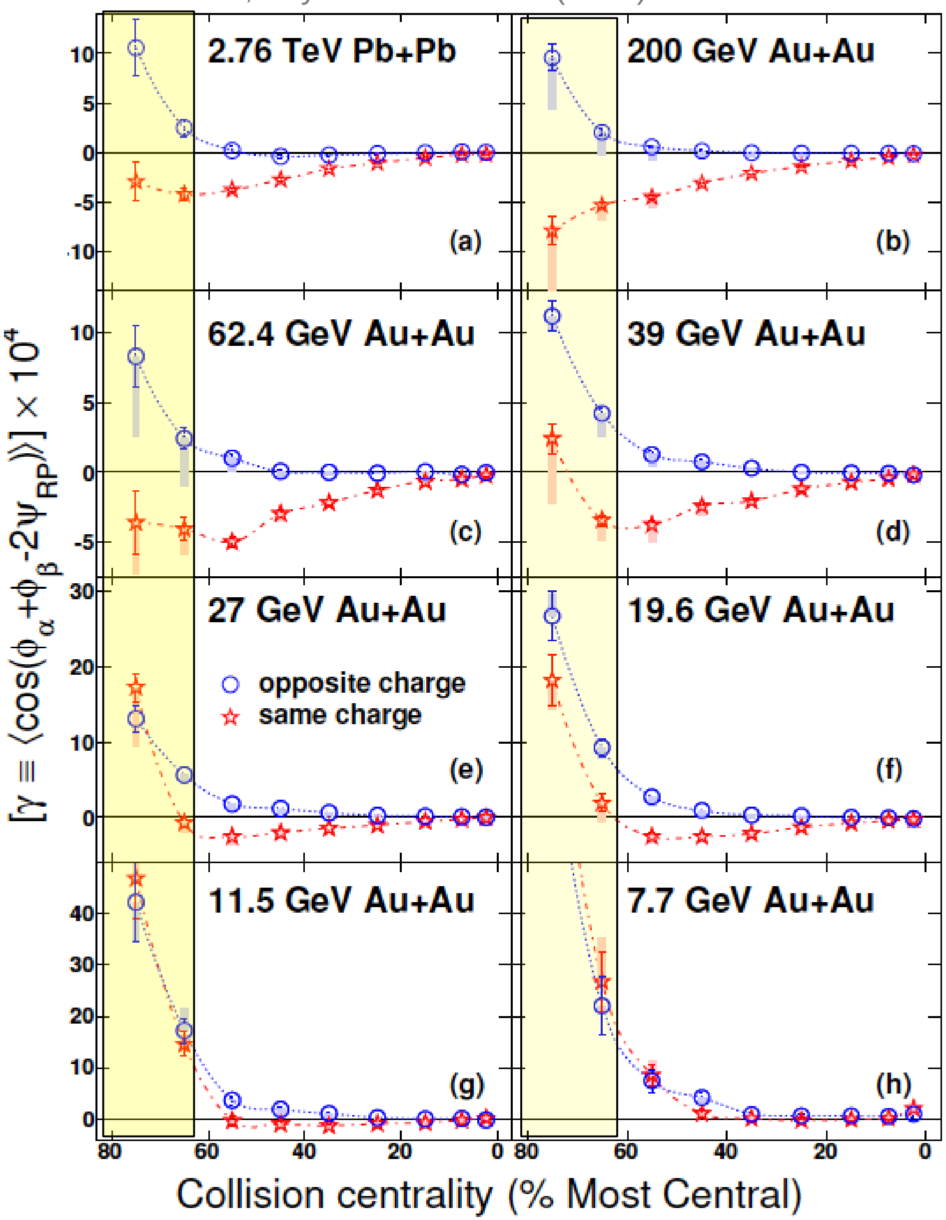
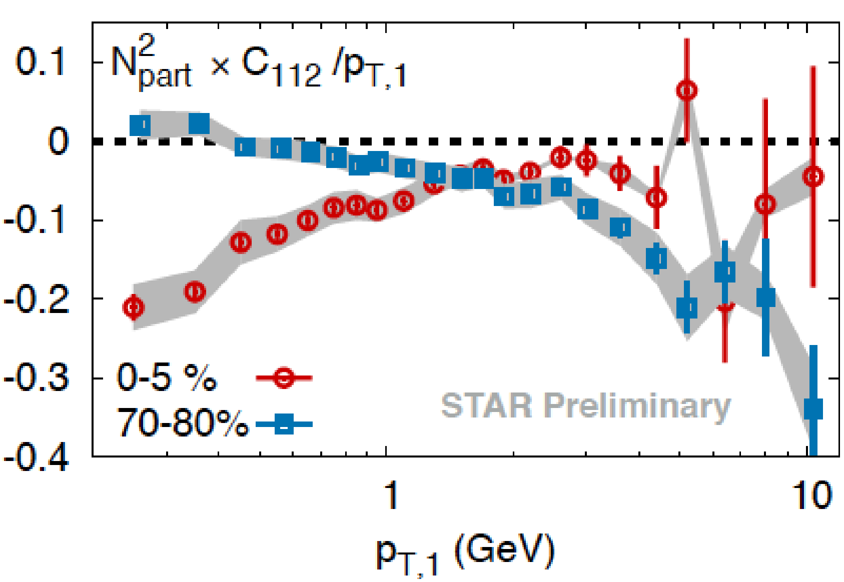


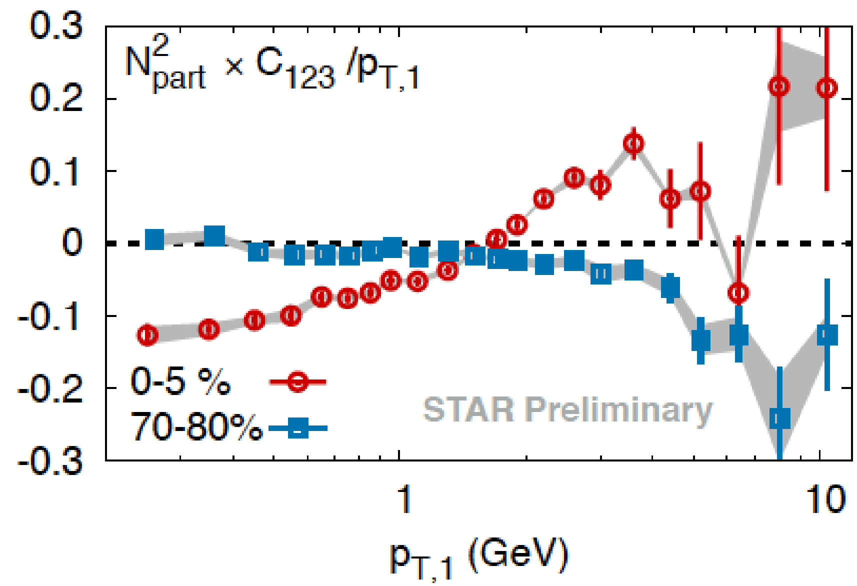
p+Pb results suggest peripheral data is dominated by background

If it's a hadronization or flow related background, why does it disappear at low energy?

What about central?

Central and Peripheral are VERY Different





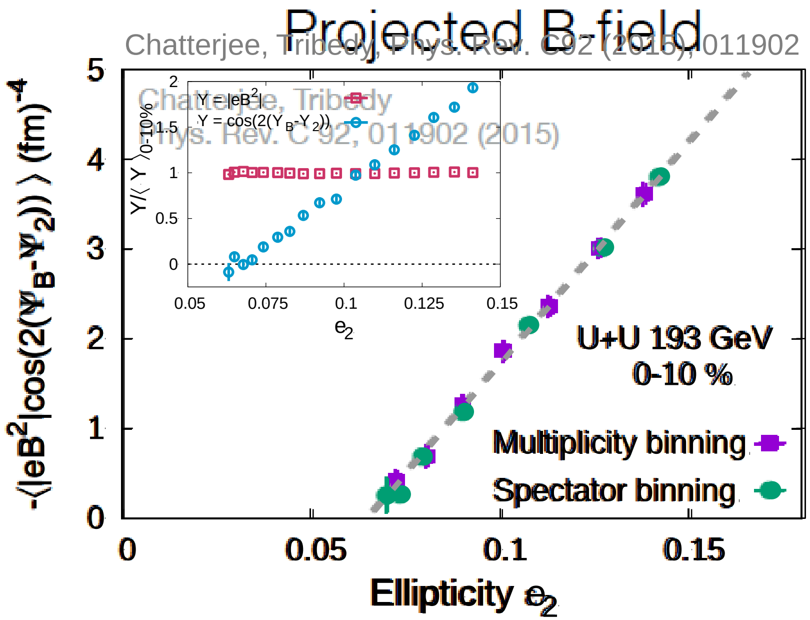
High p_T & peripheral events → momentum conservation from jets

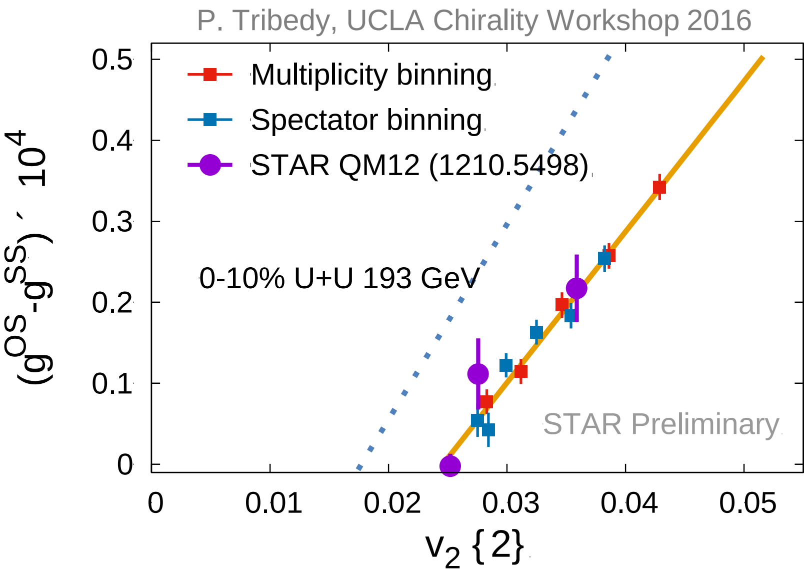
C_{112}, C_{123} → (-)

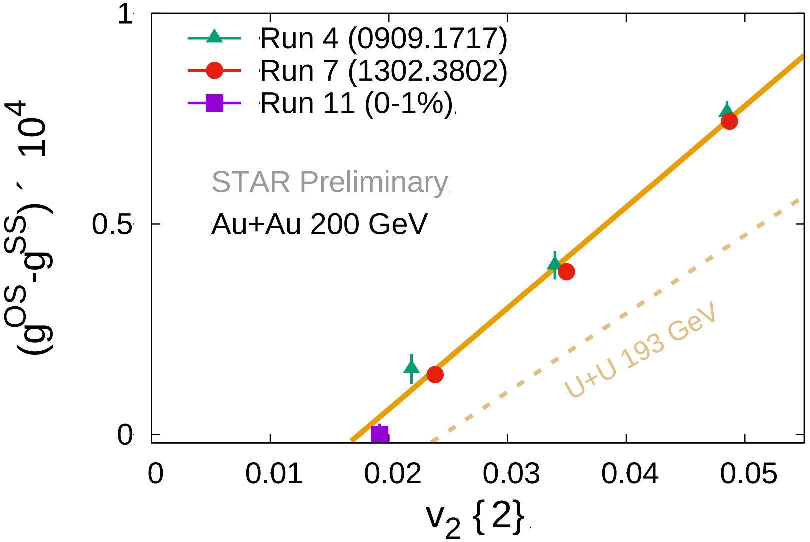
Correlations in central events look completely different from peripheral

Ultra-central Au+Au and U+U

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



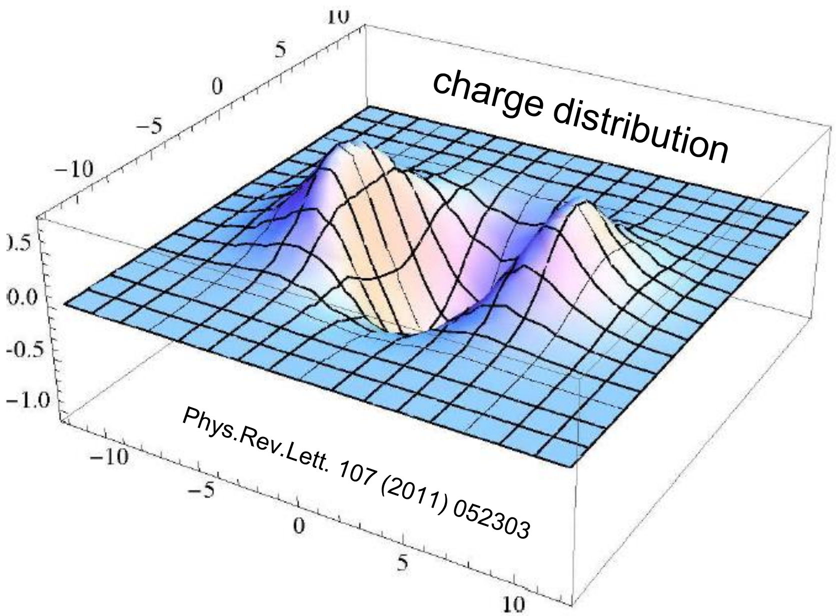




Chiral Magnetic Wave

Predicted Effect

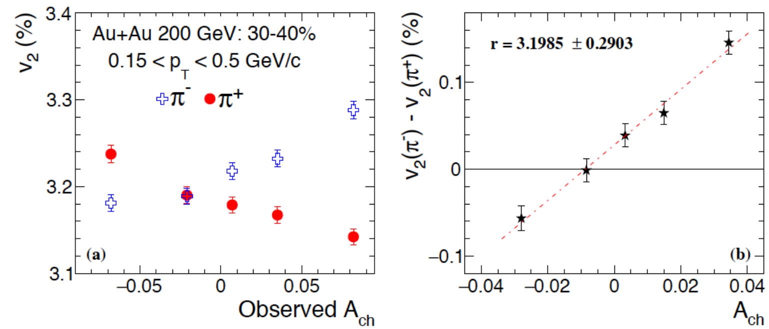
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B} \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$

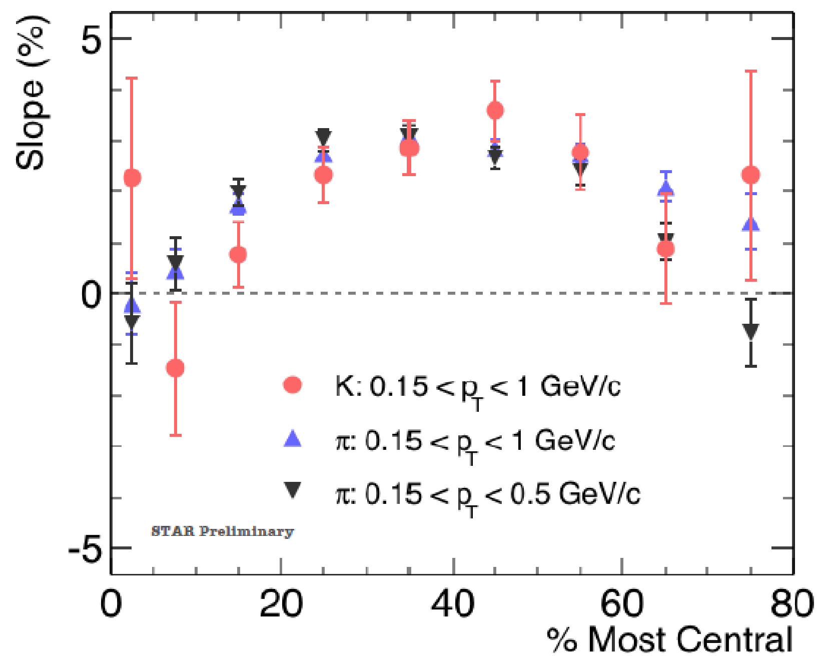


$$\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+) = r\ A_\pm$$

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

Confirmed in Data





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 (particularly in peripheral)*

On the other hand, a wide range of measurements including central U+U and those related to CMW and CVE 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?

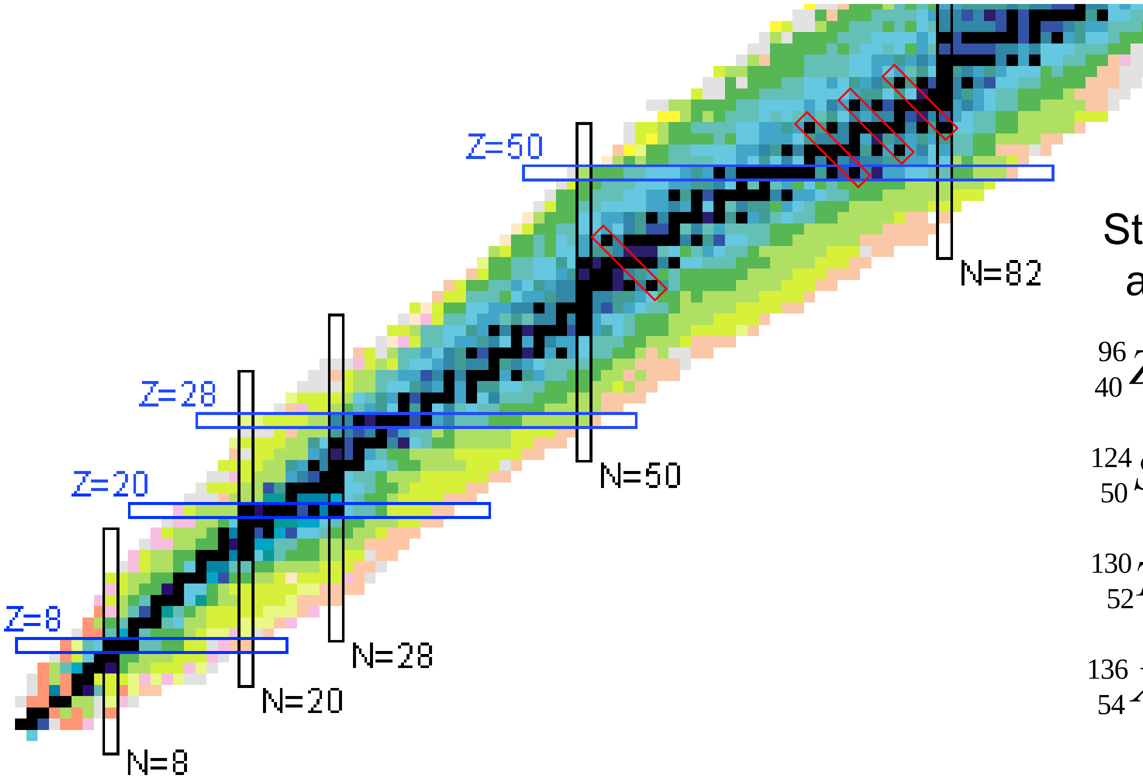
1) More analyses can be performed on current data sets
   -charge dependent <$\cos(m\varphi_1+n\varphi_2-(m+n)\varphi_3)$> measurements can be extended to higher m,n.
   -particularly in U+U, event shape engineering and geometry engineering using ZDC's can be and are being further explored
   -more identified 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

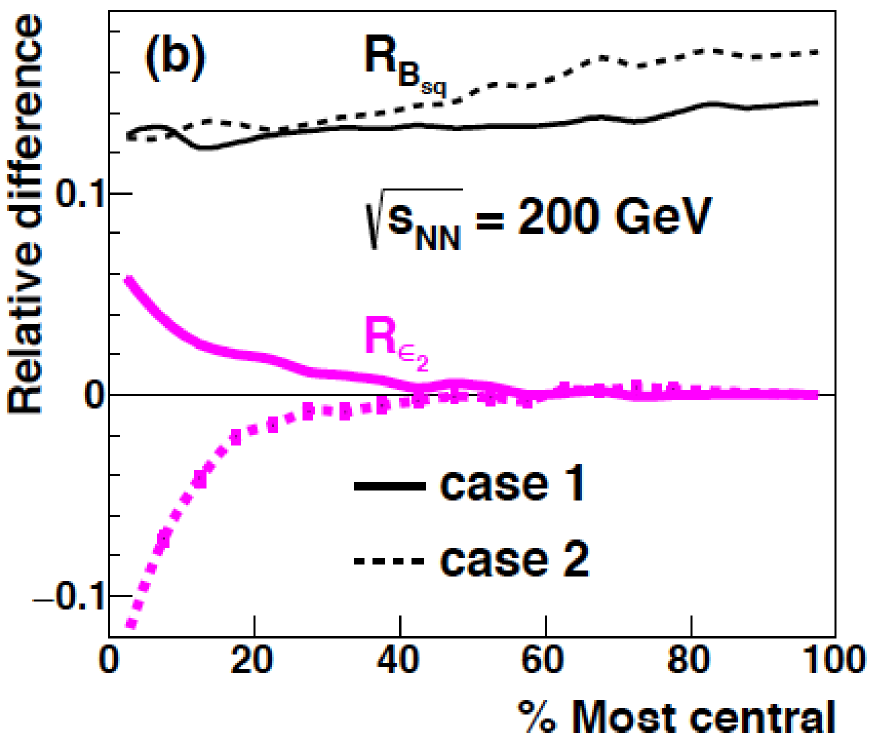
$b_2({}^{96}_{40}Zr) = 0.080$ (electron scattering)

$b_2({}^{96}_{40}Zr) = 0.217$ (model calculation)

$b_2({}^{96}_{44}Ru) = 0.158$ (electron scattering)

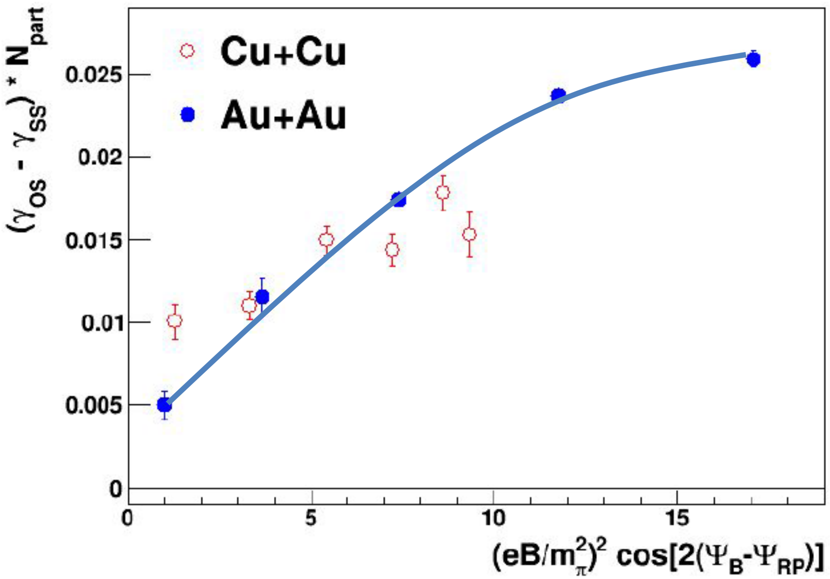
$b_2({}^{96}_{44}Ru) = 0.053$ (model calculation)

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



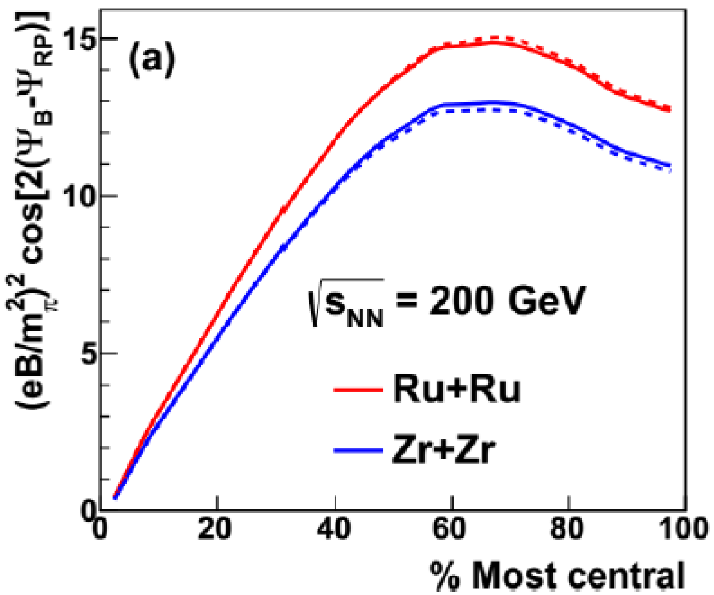
Evaluation of Running with Nuclear Isobars

How discerning will the measurements be?



parameterize observed charge separation vs CME expectation

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



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

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

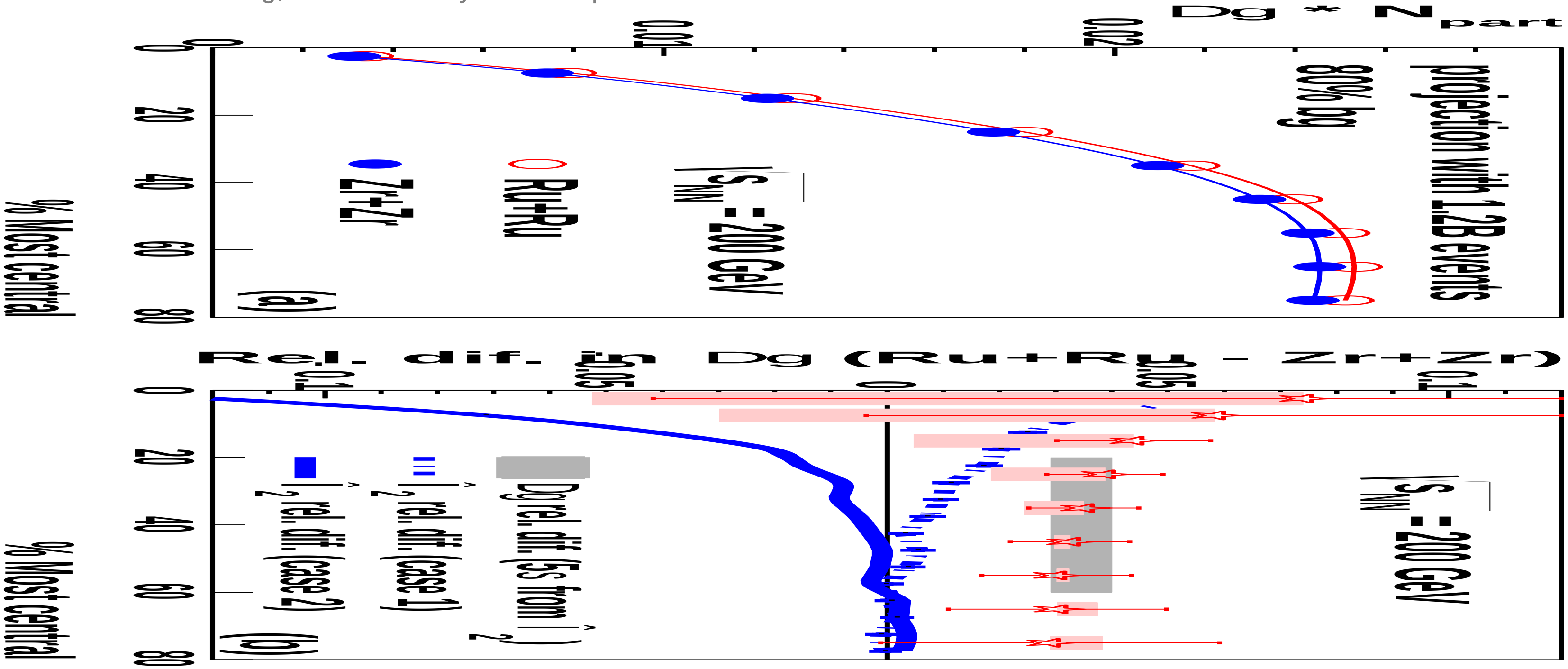
Evaluation of Running with Nuclear Isobars

How discerning will the measurements be?

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

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

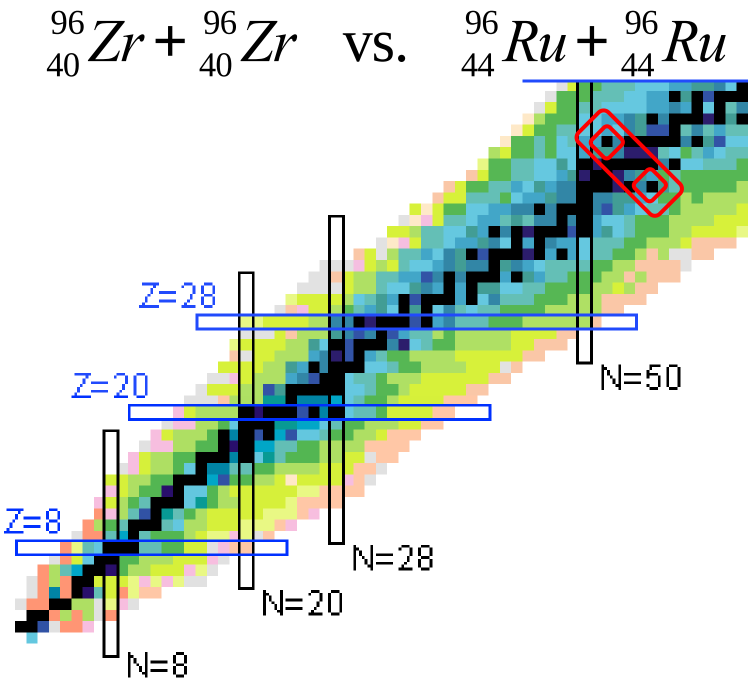
G. Wang, UCLA Chirality Workshop 2016

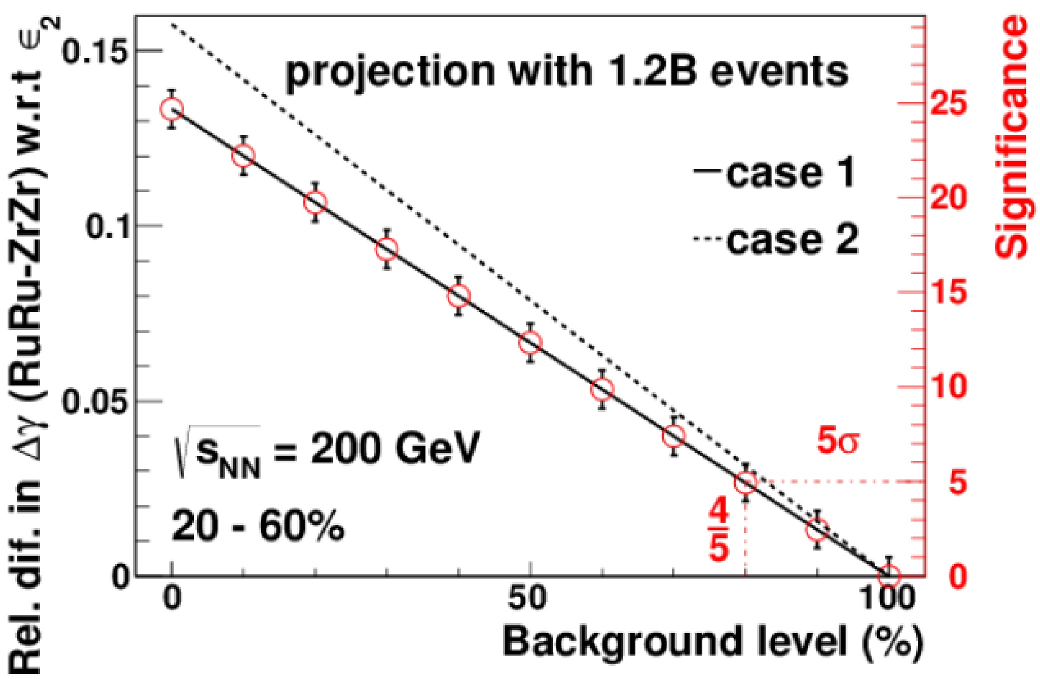


If magnetic field independent backgrounds make up less than 80% of the measured Δγ, the CME contribution will be determined with a significance better than 5σ

Probing Chiral Symmetry with Quantum Currents

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





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

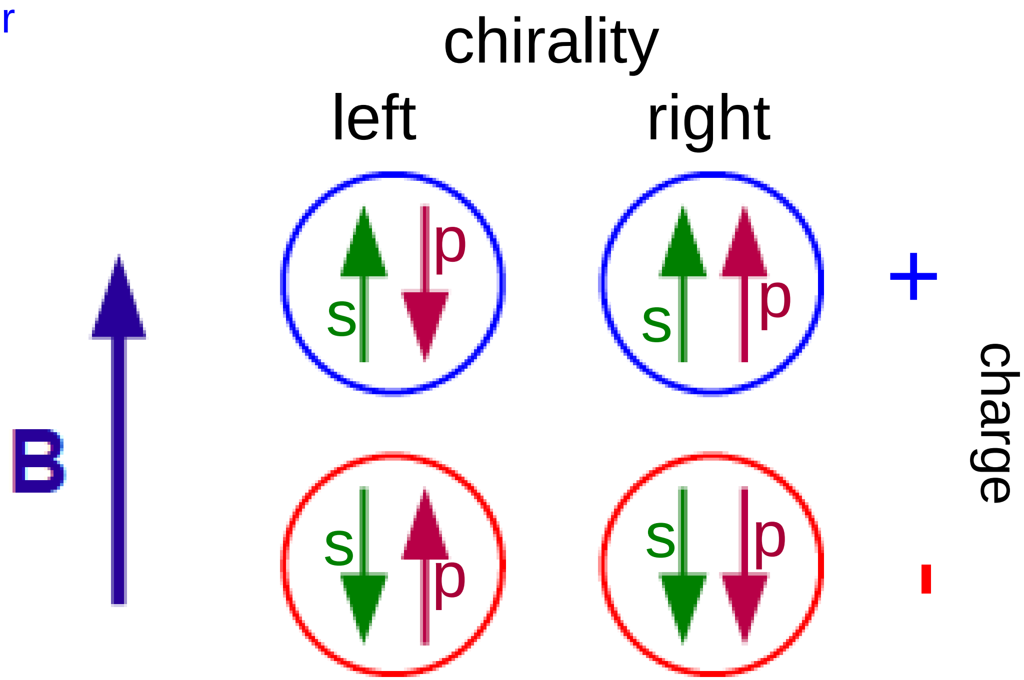
The Chiral Magnetic Effect

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



negative goes up
positive goes down

positive goes up
negative goes down

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

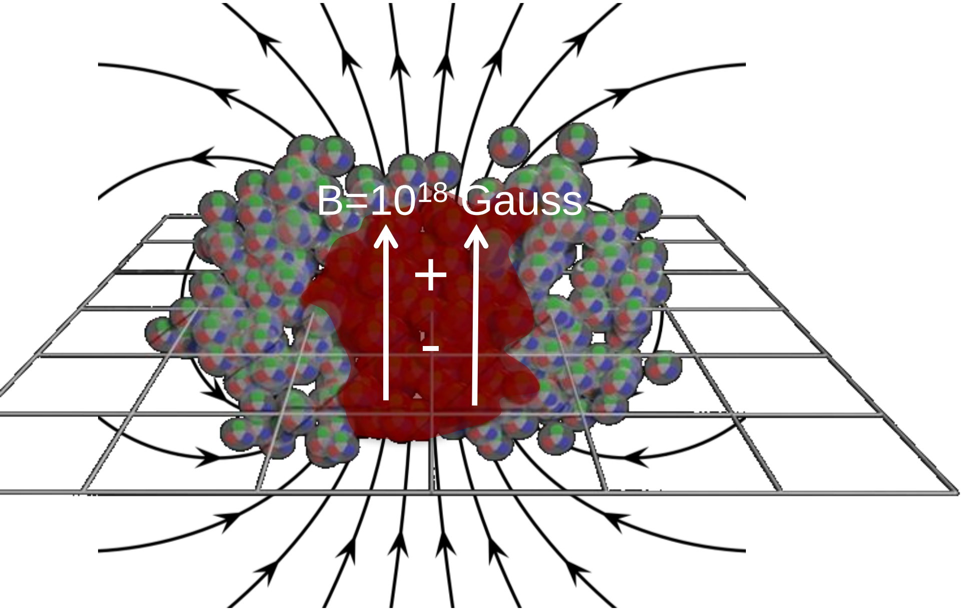
Probing Chiral Symmetry with Quantum Currents

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

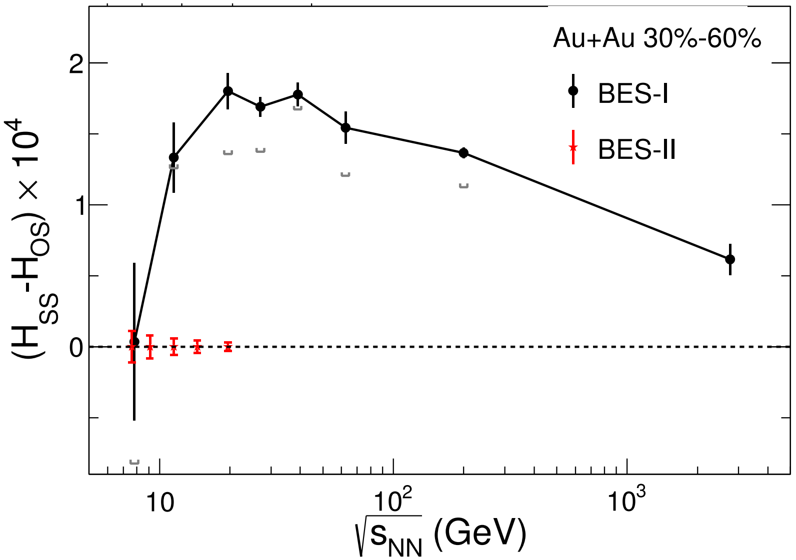
a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

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

charge separation



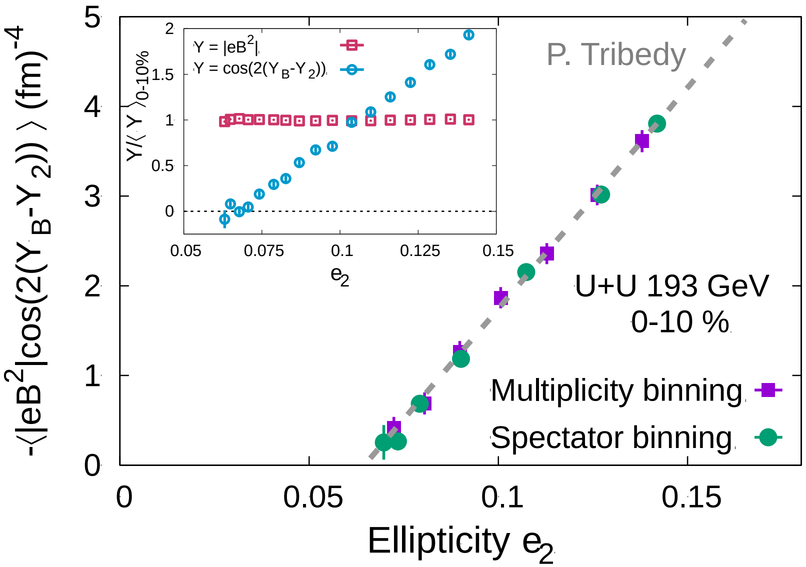
observed at all but the lowest energy

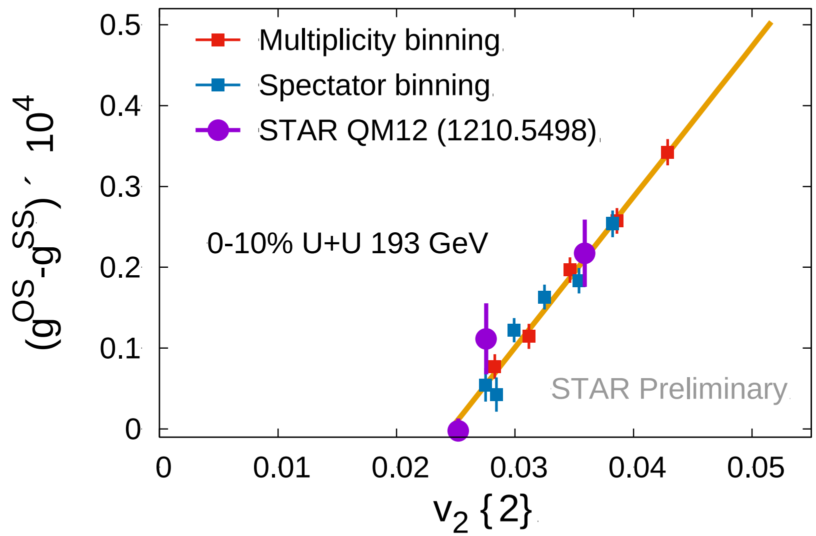


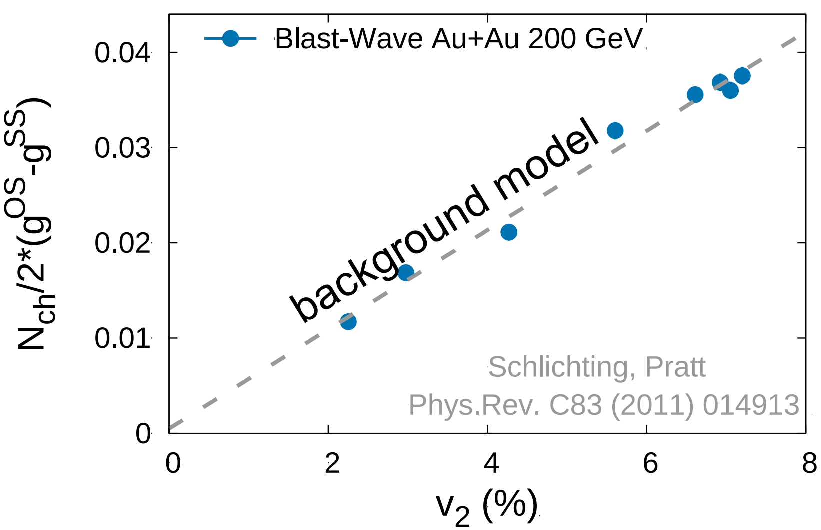
But models with magnetic field-independent backgrounds can also be tuned to reproduce the observed charge separation

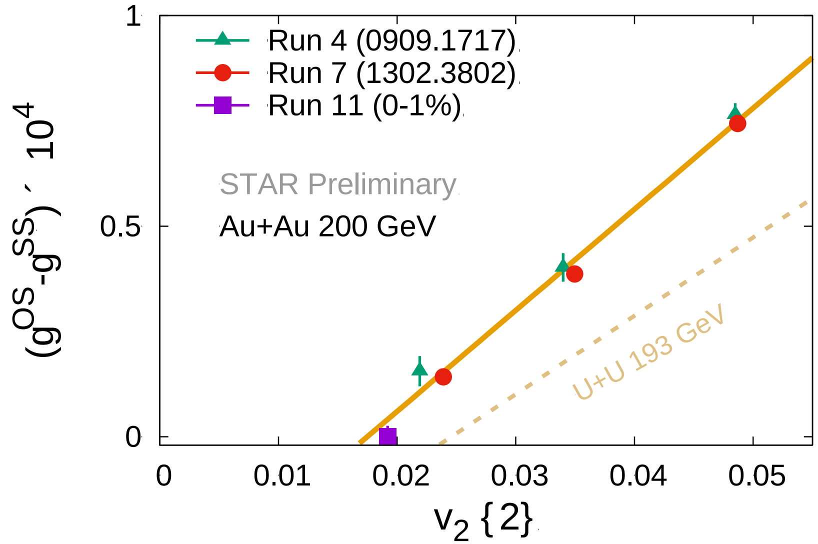
Ultra-central Au+Au and U+U

Charge separation follows projected B-Field, not v_2





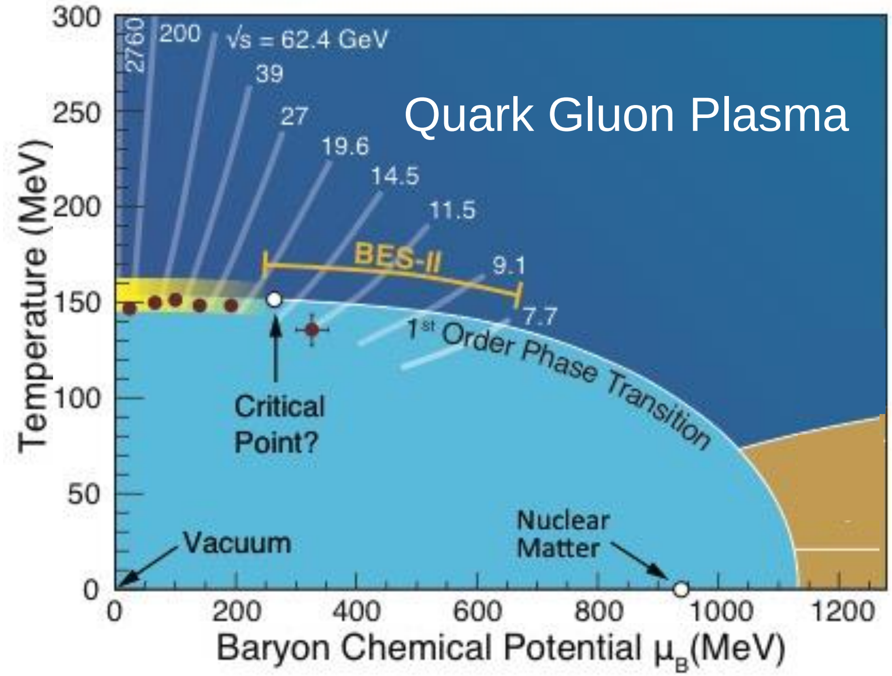




NSAC Long Range Plan for Collective Dynamics

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

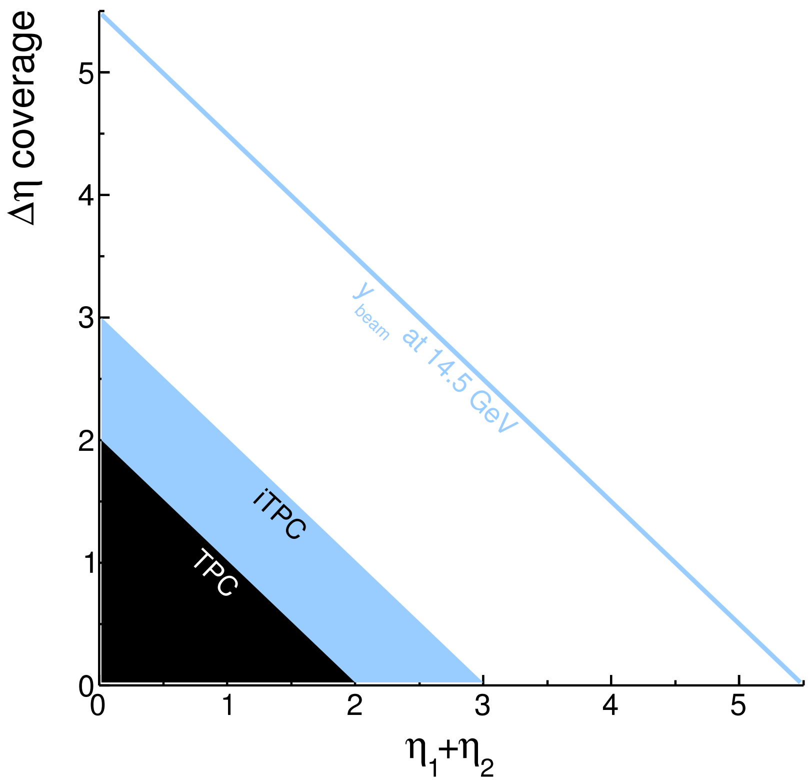
Mapping the phase diagram: At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?

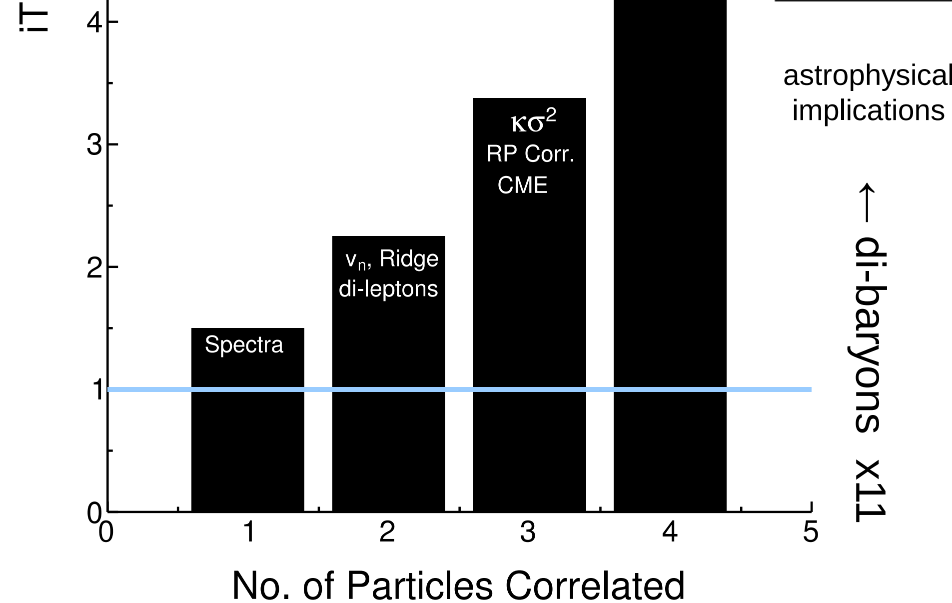


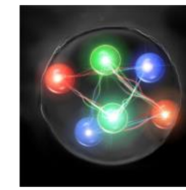
Can the same fluctuations that could have created the asymmetry between matter and anti-matter during the electro-weak phase transition be measured in the QGP phase in heavy ion collisions (chiral anamoly)?

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







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