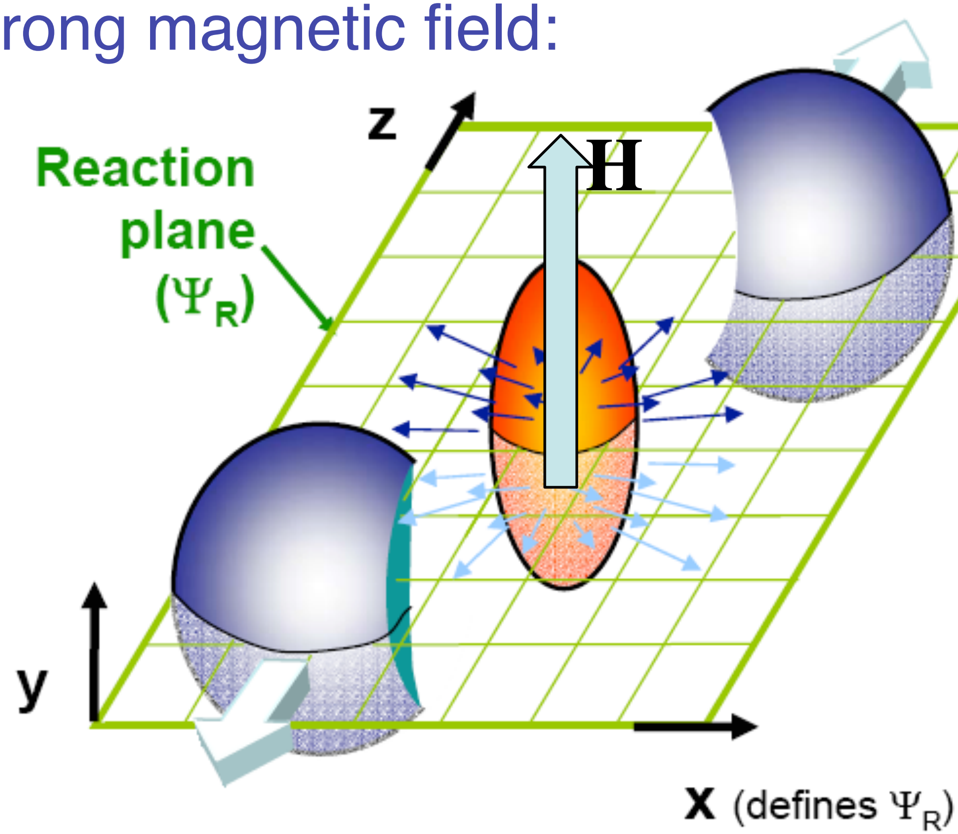
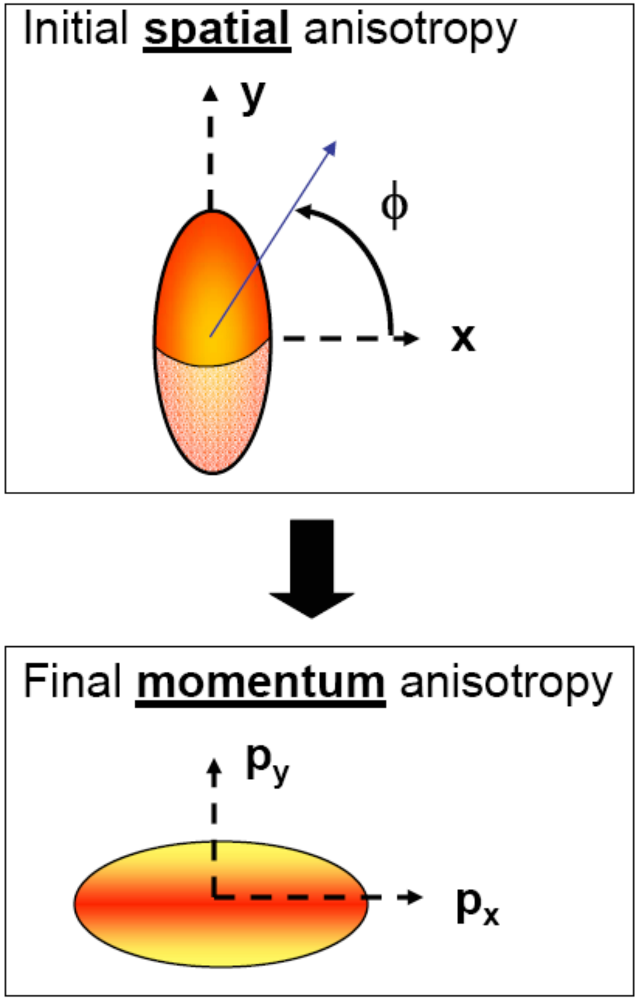
# Is there a way to observe CME in nuclear collisions at RHIC?

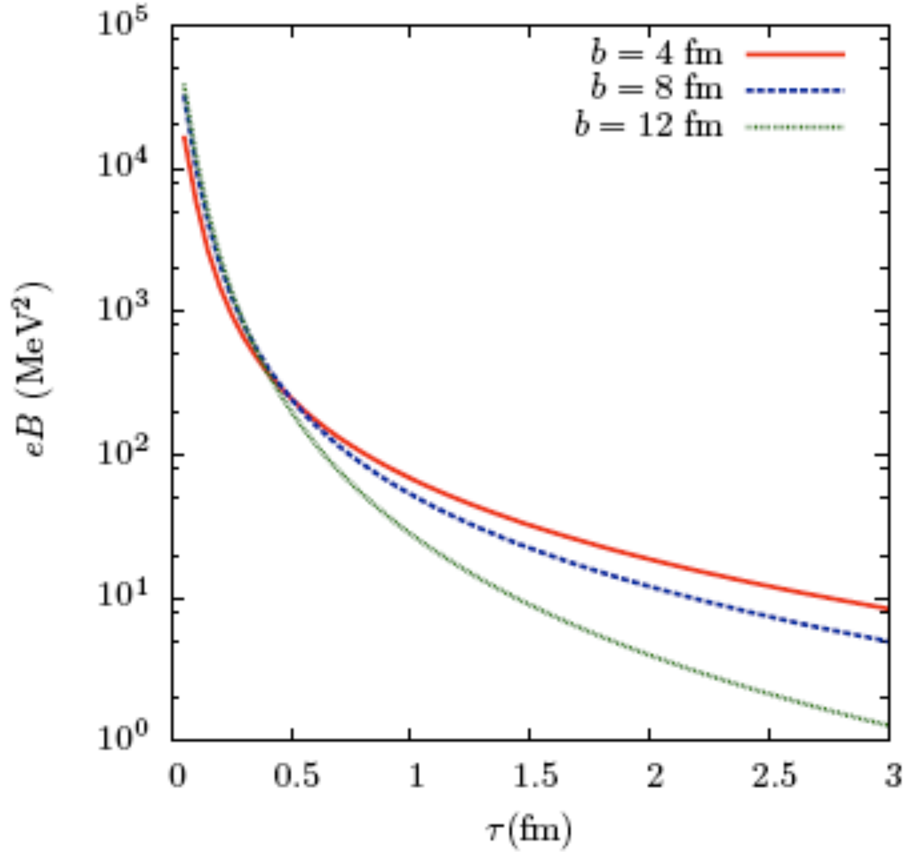
Relativistic ions create a strong magnetic field:




DK, McLerran, Warringa '07



# Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory



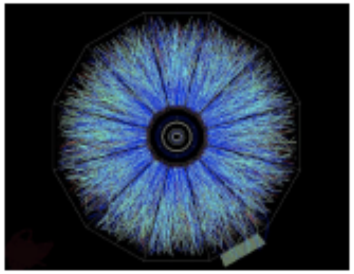

DK, McLerran, Warringa, Nucl Phys A803(2008)227

Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

# Comparison of magnetic fields

| | |
|---|---|
| The Earths magnetic field | 0.6 Gauss |
| A common, hand-held magnet | 100 Gauss |
| The strongest steady magnetic fields achieved so far in the laboratory | $4.5 \times 10^5$ Gauss |
| The strongest man-made fields ever achieved, if only briefly | $10^7$ Gauss |
| Typical surface, polar magnetic fields of radio pulsars | $10^{13}$ Gauss |
| Surface field of Magnetars | $10^{15}$ Gauss |

http://solomon.as.utexas.edu/~duncan/magnetar.html



Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

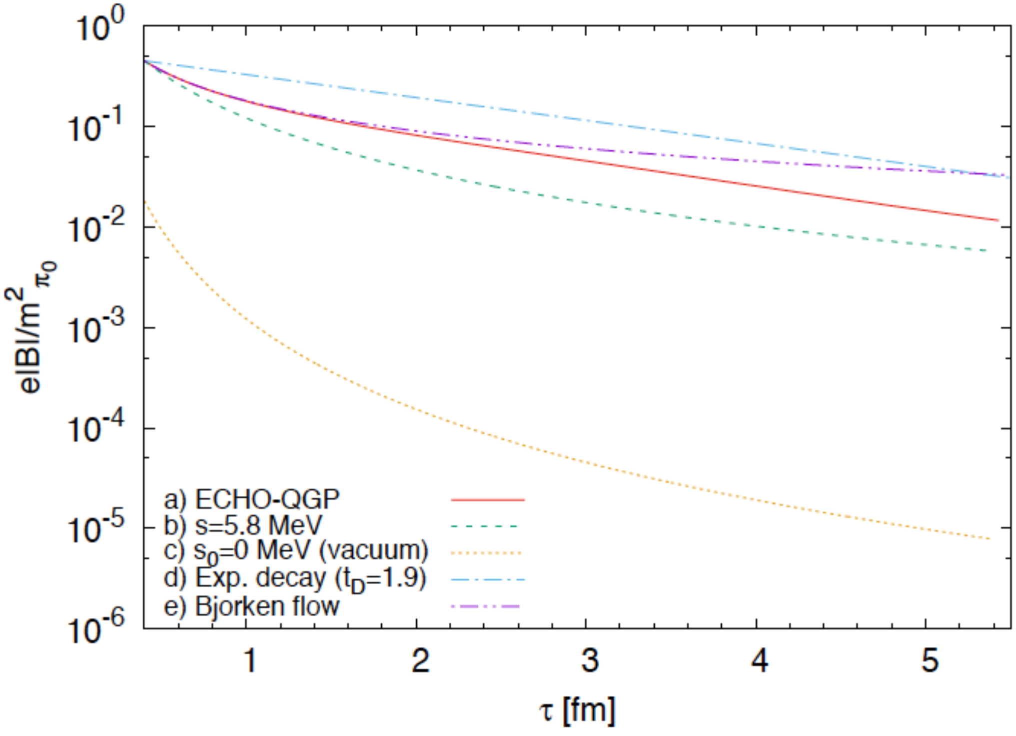
$$eB(\tau=0.2\,\mathrm{fm}) = 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

# Evolution of magnetic field in full ideal MHD

**Numerical magneto-hydrodynamics for relativistic nuclear collisions**

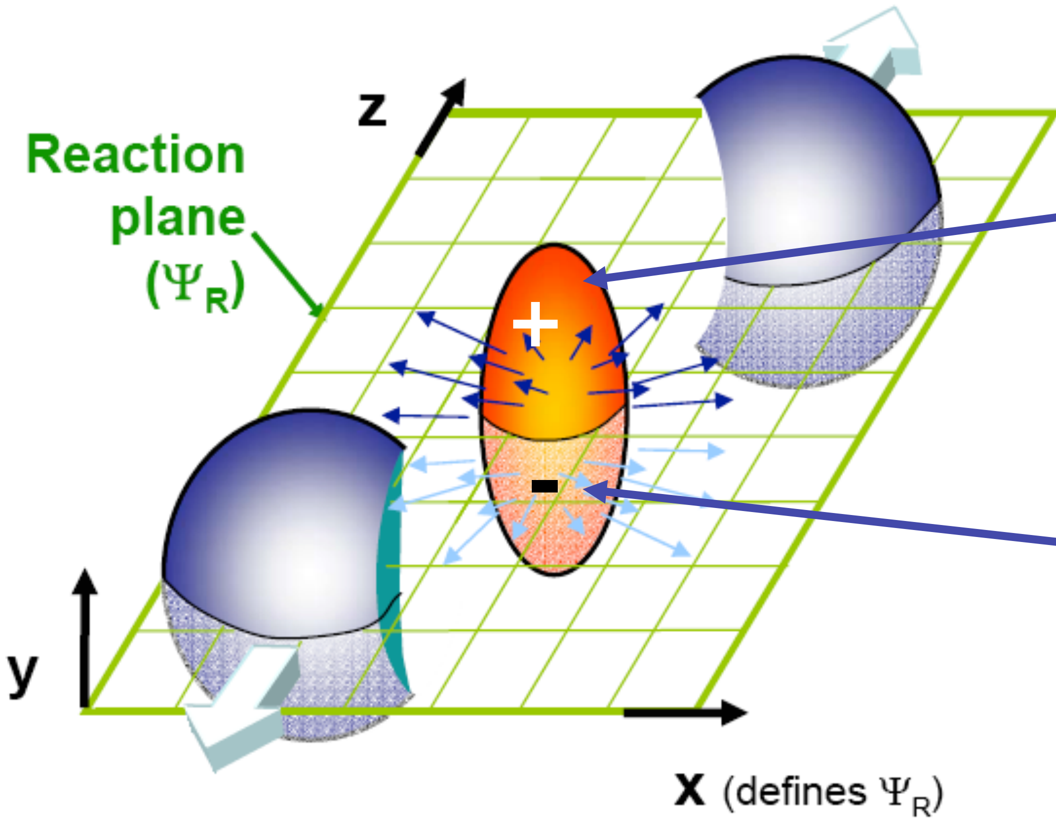
Gabriele Inghirami,[1,2,3,4,*] Luca Del Zanna,[5,6,7] Andrea Beraudo,[8]
Mohsen Haddadi Moghaddam,[9,8] Francesco Becattini,[5,6] and Marcus Bleicher[1,2,3,4]

arxiv:1609.03042



# Charge asymmetry w.r.t. reaction plane as a signature of chirality imbalance

Electric dipole moment due to chiral imbalance




excess of positive charge

excess of negative charge

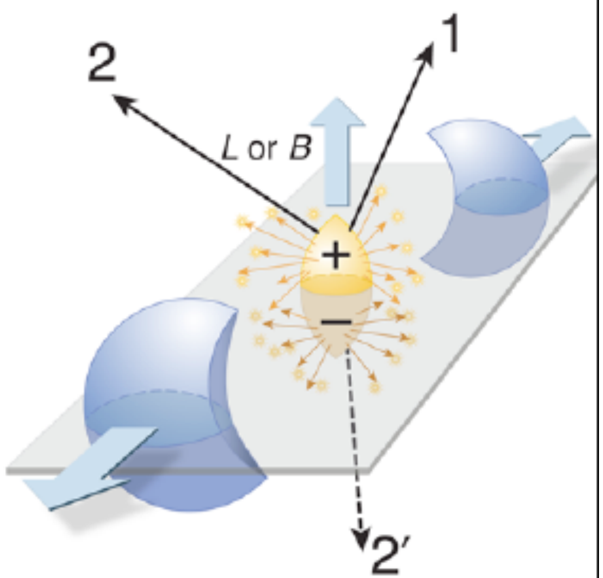
$$\Theta \rightarrow \Theta(x,t)$$

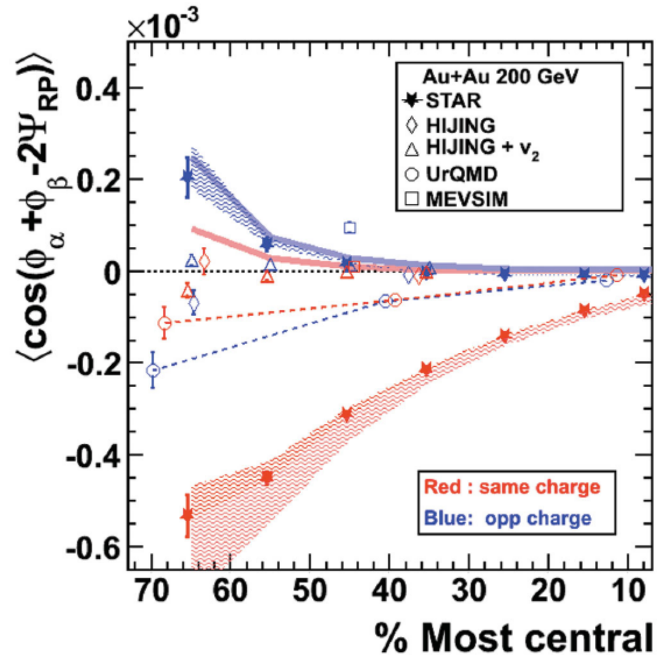
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

Selected for a Viewpoint in *Physics*
PRL **103**, 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

# Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)




S.Voloshin '04

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP})\rangle = \langle \cos\Delta\phi_\alpha \, \cos\Delta\phi_\beta\rangle - \langle \sin\Delta\phi_\alpha \, \sin\Delta\phi_\beta\rangle$$

$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{\rm IN}] - [\langle a_\alpha a_\beta\rangle + B_{\rm OUT}] \approx -\langle a_\alpha a_\beta\rangle + [B_{\rm IN} - B_{\rm OUT}],$$

**NB: P-even quantity (strength of P-odd fluctuations) – subject to large background contributions**

# Observation of charge-dependent azimuthal correlations in pPb collisions and its implication for the search for the chiral magnetic effect

arxiv:1610.00263

The CMS Collaboration*

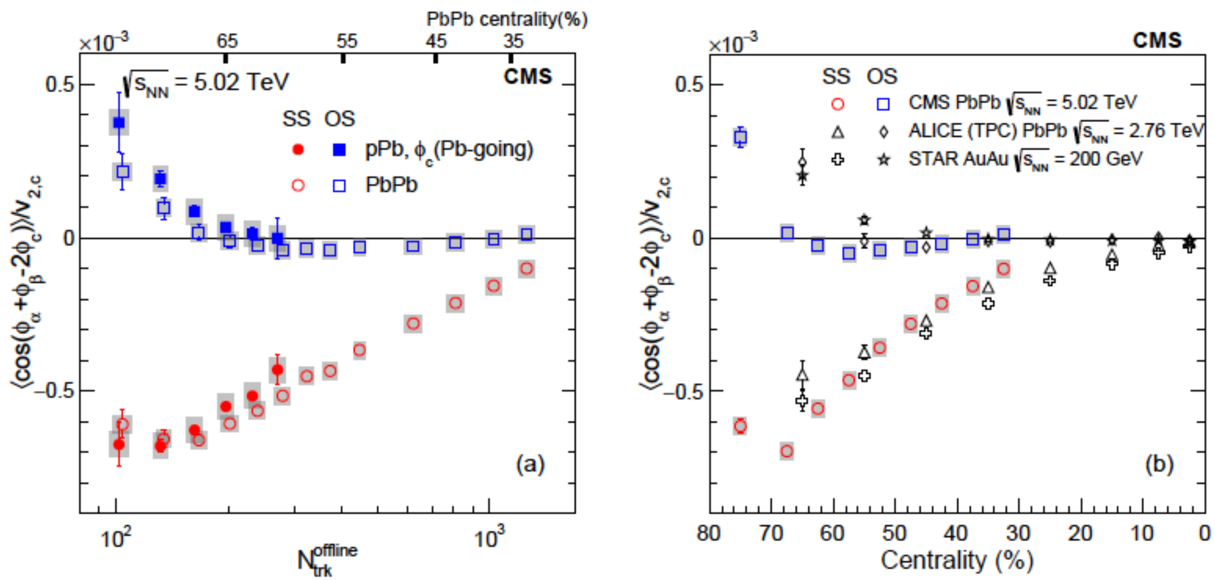



Figure 2: In (a), the same sign (SS) and opposite sign (OS) three-particle correlator averaged over $|\eta_\alpha - \eta_\beta| < 1.6$ as a function of $N_{trk}^{offline}$ in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown. In (b), the same correlation as a function of centrality is presented in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from CMS, at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE, and in AuAu collisions at $\sqrt{s_{NN}} = 0.2$ TeV from STAR. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

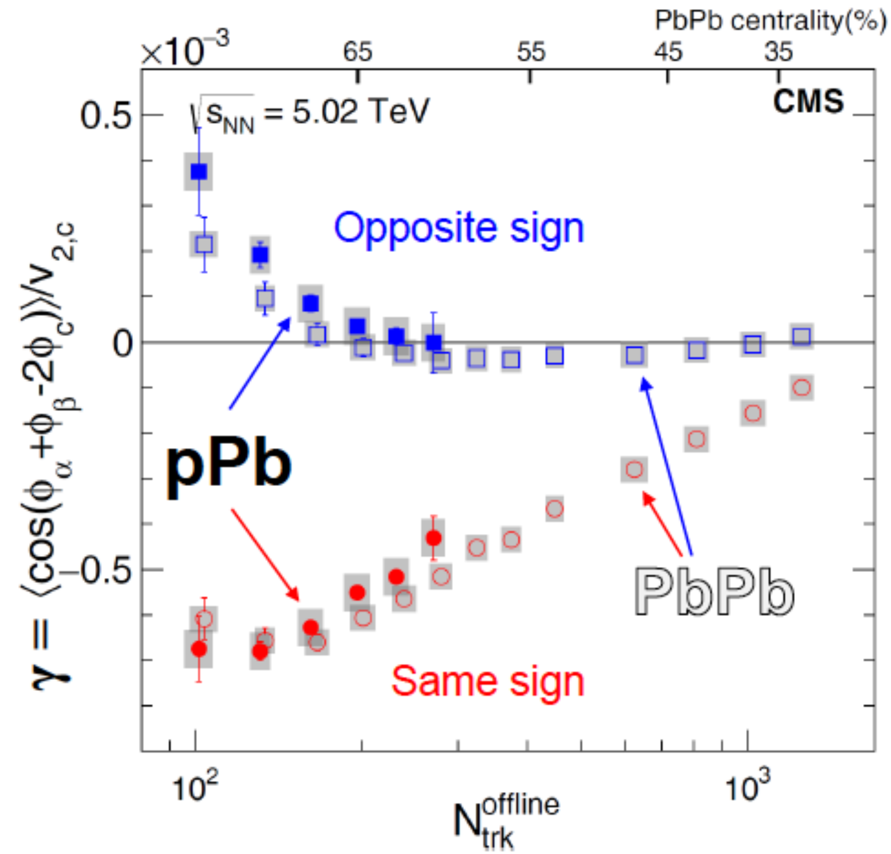
Background everywhere? (dAu at RHIC!)

Magnetic field in pA?

# CMS: Surprising scaling of pA and AA results at different energies?

arXiv: 1610.00263
Submitted to PRL

**Charge Separation Signal $\gamma$**




PbPb and **pPb** with the same event multiplicity are **similar…!**

**Challenge to CME interpretation!**

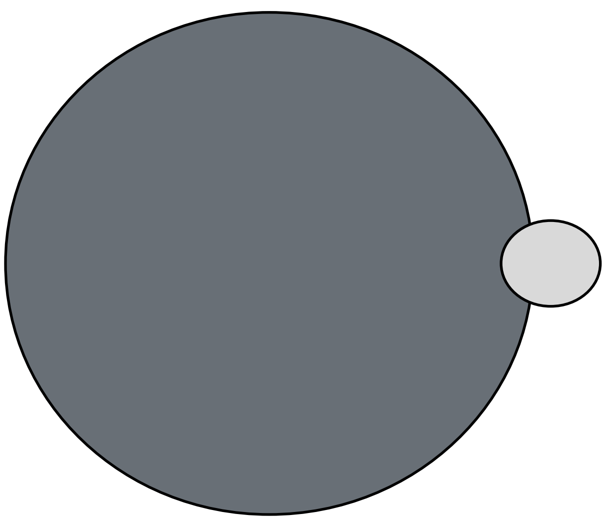
Zhoudunming Tu (Talk)

But: different dependence on rapidity difference between α and β

Some comments:

1. The scaling is a challenge to both CME and background interpretations, since background scales as $v_2/N$, and $v_2$ is different (~ 30%?) in pA and AA at the same multiplicity. Even more challenging for RHIC vs LHC comparison.

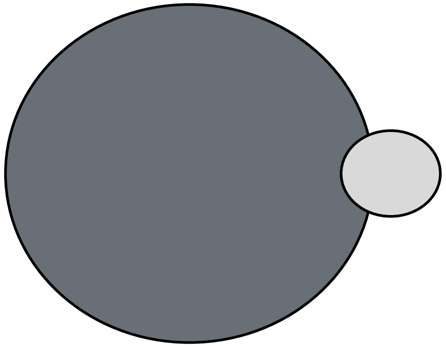
2. In pA, one expects much weakened, but <u>non-zero</u> correlations between magnetic field B and reaction plane due to the gradient of nuclear density. For a black disk:



This configuration yields B orthogonal to the reaction plane;

Its contribution is suppressed by

$(R_N/R_A)^2$



This configuration yields
B orthogonal to the reaction plane (RP);
Its contribution is suppressed by
$(R_N/R_A)^2$

The proton is always much smaller than the nucleus… or is it?

The proton size grows with energy:

$$R_p^2(s) = R_p^2(s_0) + \alpha'_P \ln(s/s_0)$$

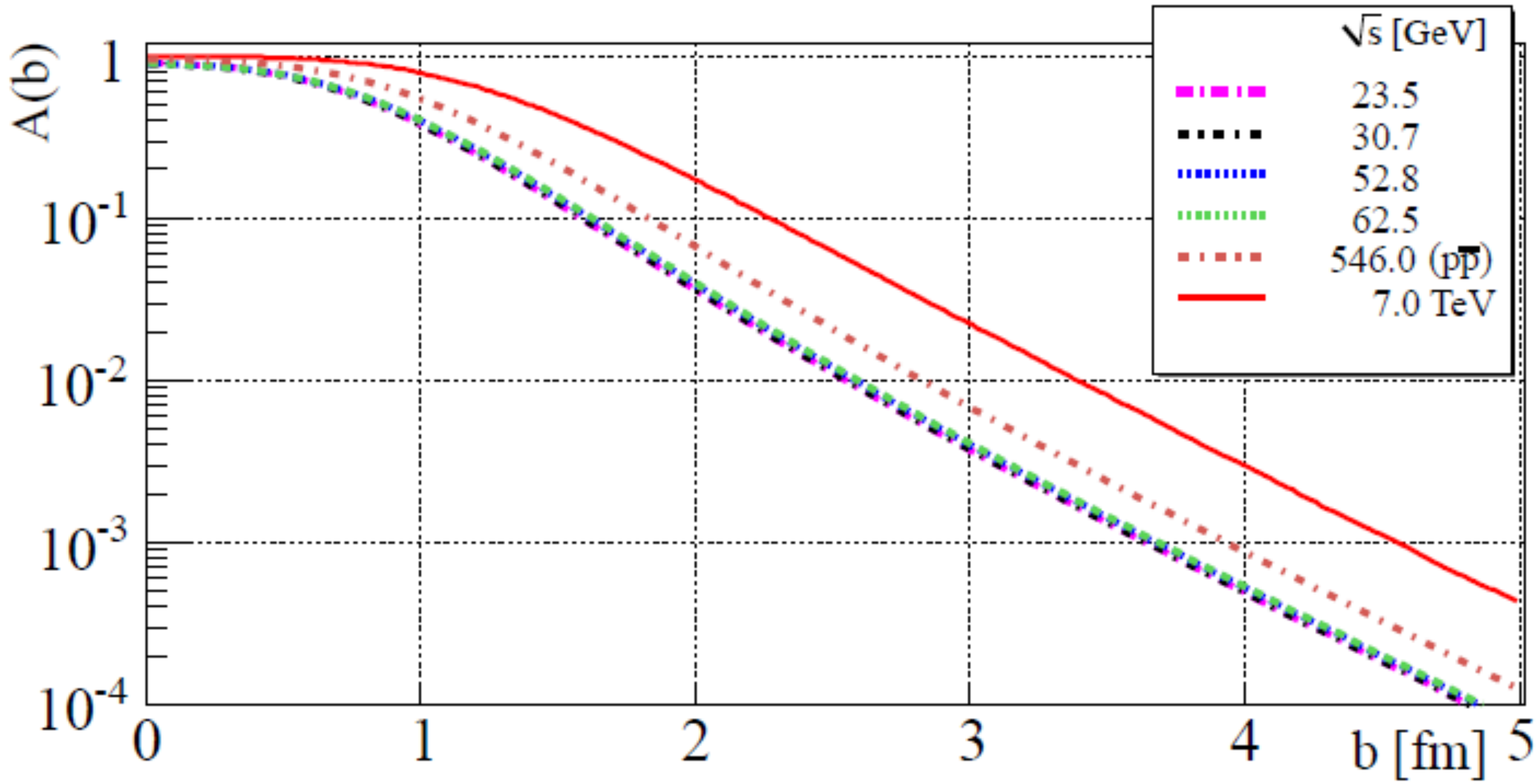
Gribov diffusion; Shrinkage of diffraction peak. Even at LHC, still a relatively modest size growth [TOTEM: non-linear dependence]

But: the second term is due to the number of parton splittings – in high multiplicity N events, can expect larger than average size of the proton,

$$R_p^2(s;N) = \bar{R}_p^2(s)\ \frac{N}{\bar{N}}$$

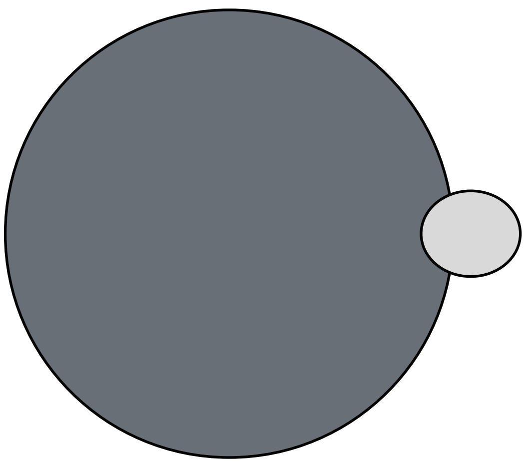
Can this effect give a sizeable correlation between B and RP?

# The growth of the proton size at high energies

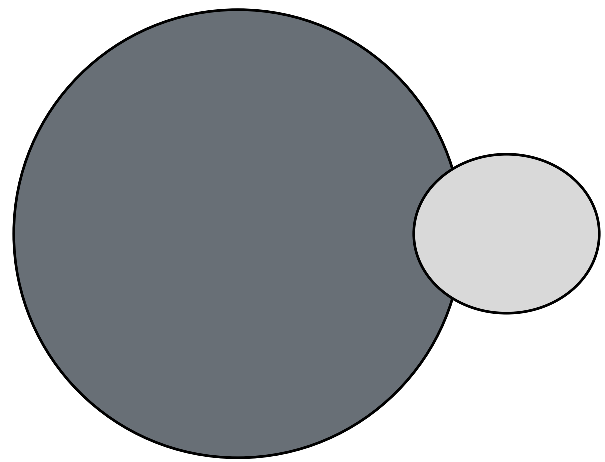



TOTEM Collaboration

Average Multiplicity:



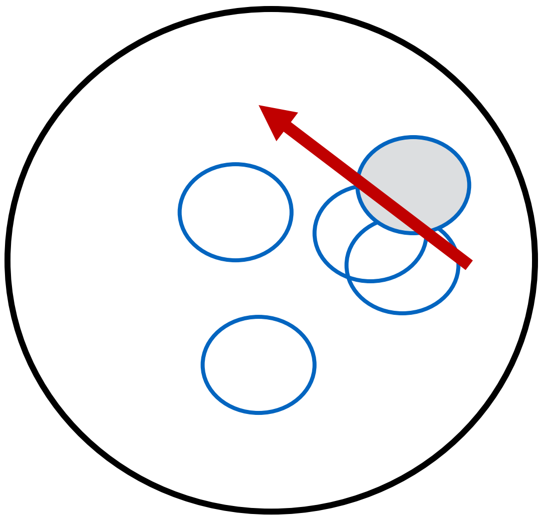
High Multiplicity:



$$R_p^2(s;N) = \bar{R}_p^2(s)\ \frac{N}{\bar{N}}$$

Can this effect give a sizeable correlation between B and RP?

3. Even in pA collisions, **vorticity** has to be correlated with the reconstructed reaction plane:



Perhaps, the **Chiral Vortical Effect** (CVE)?

Can this be studied in **high multiplicity pp collisions**? (small B, high vorticity, can check scaling expected for background vs CVE)

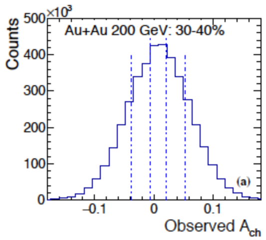
Is there a different observable with a controlled initial state?

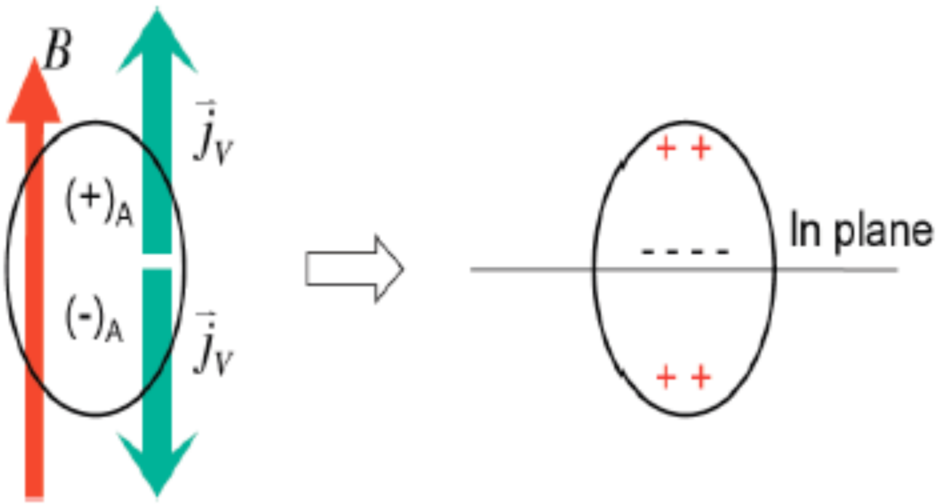
# The Chiral Magnetic Wave: controlling the initial state

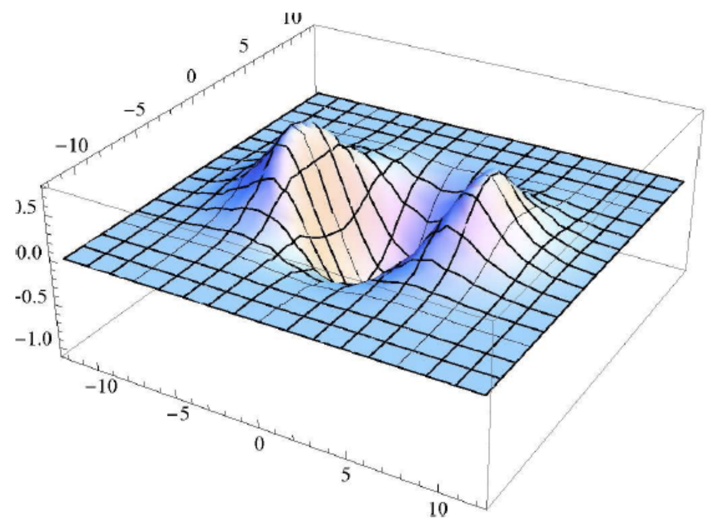
Finite baryon density + CMW = electric quadrupole moment of QGP

Signature - difference of elliptic flows of positive and negative pions determined by total charge asymmetry of the event A:

at A>0, $v_2(-) > v_2(+)$;   at A<0, $v_2(+) > v_2(-)$



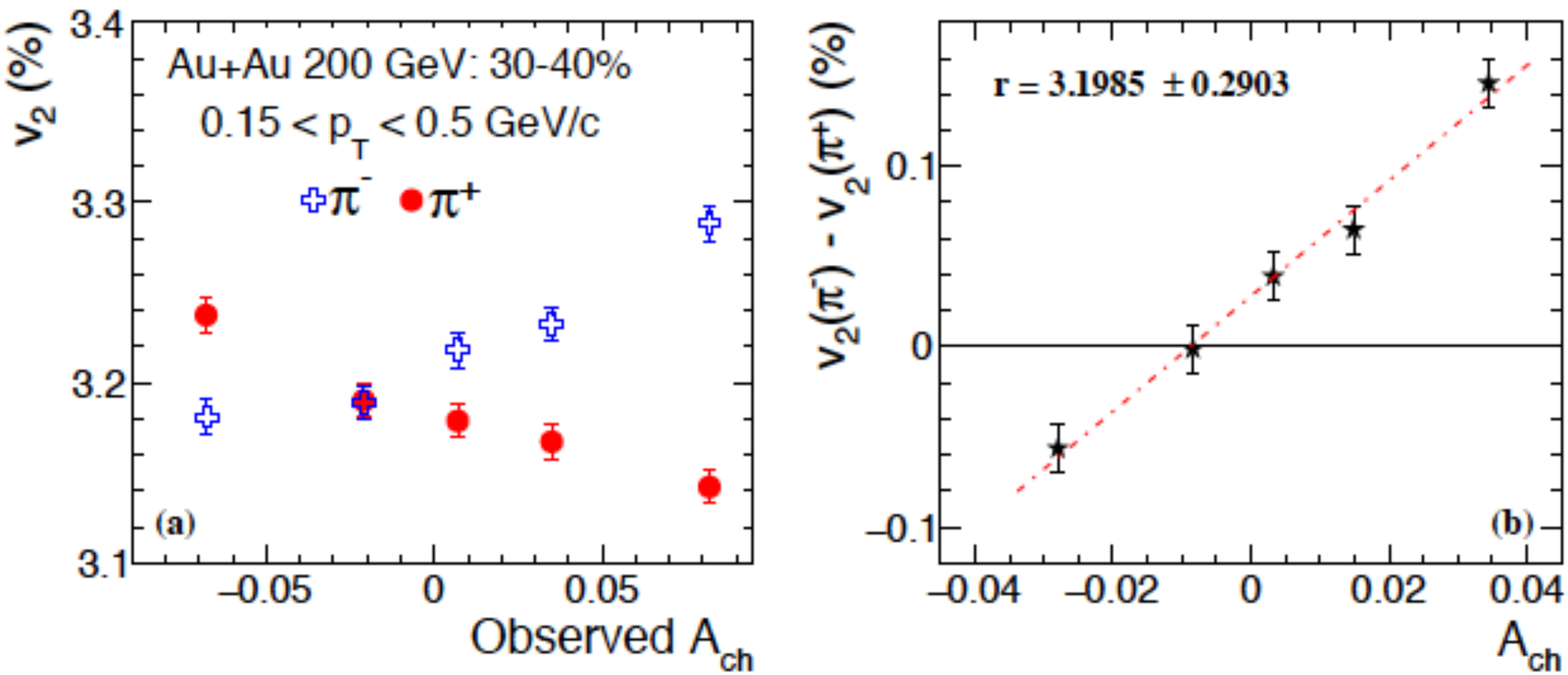
$$v_2^- - v_2^+ = C + 2(\frac{q_e}{\bar{\rho}_e})A_\pm$$

$$A_\pm = (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

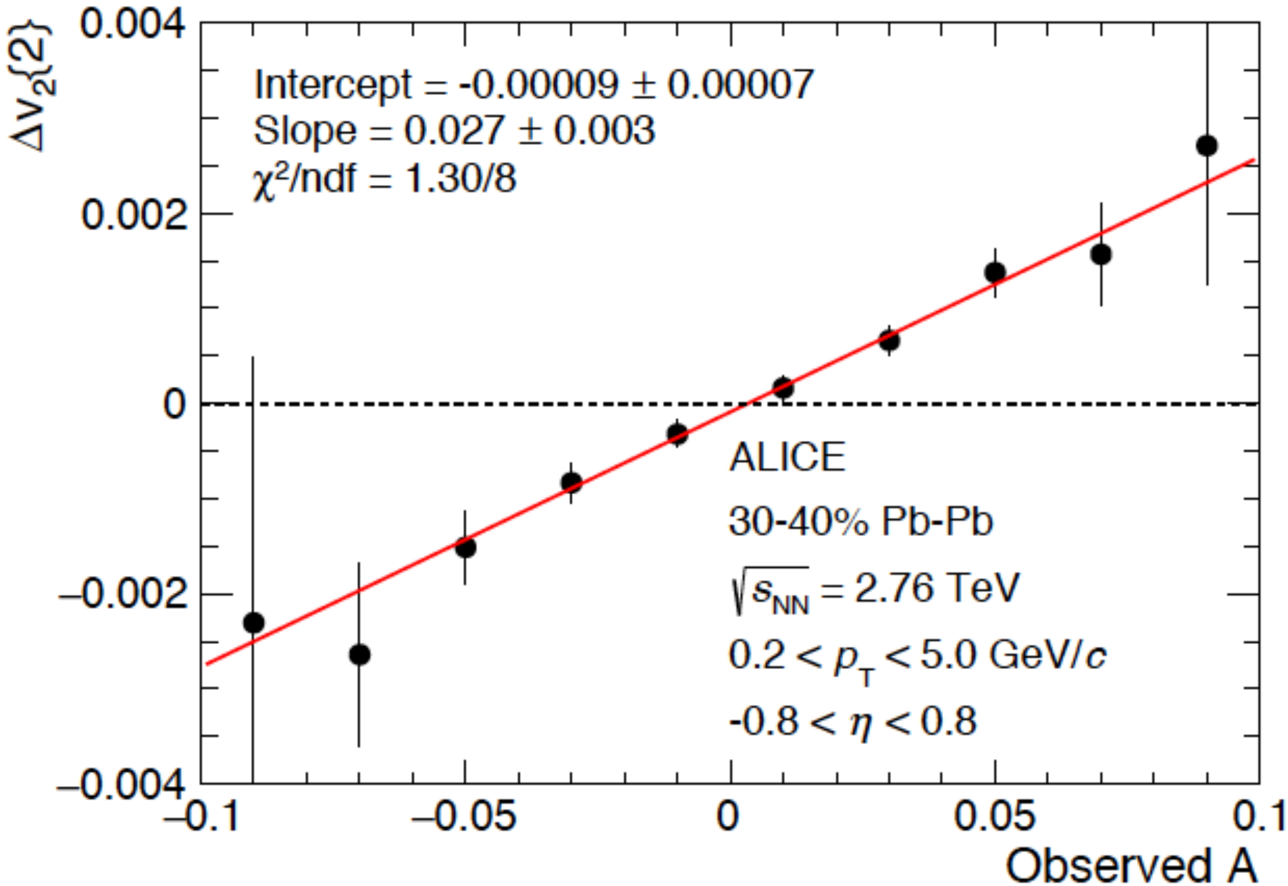
Y.Burnier, DK, J.Liao, H.Yee, PRL 2011

Observation of charge asymmetry dependence of pion elliptic flow and the possible chiral magnetic wave in heavy-ion collisions

(STAR Collaboration) arXiv:1504.02175



# ALICE Coll. at the LHC




ALICE Coll, Phys. Rev. C93 (2016) 044903

# Chiral Magnetic Effect Task Force Report

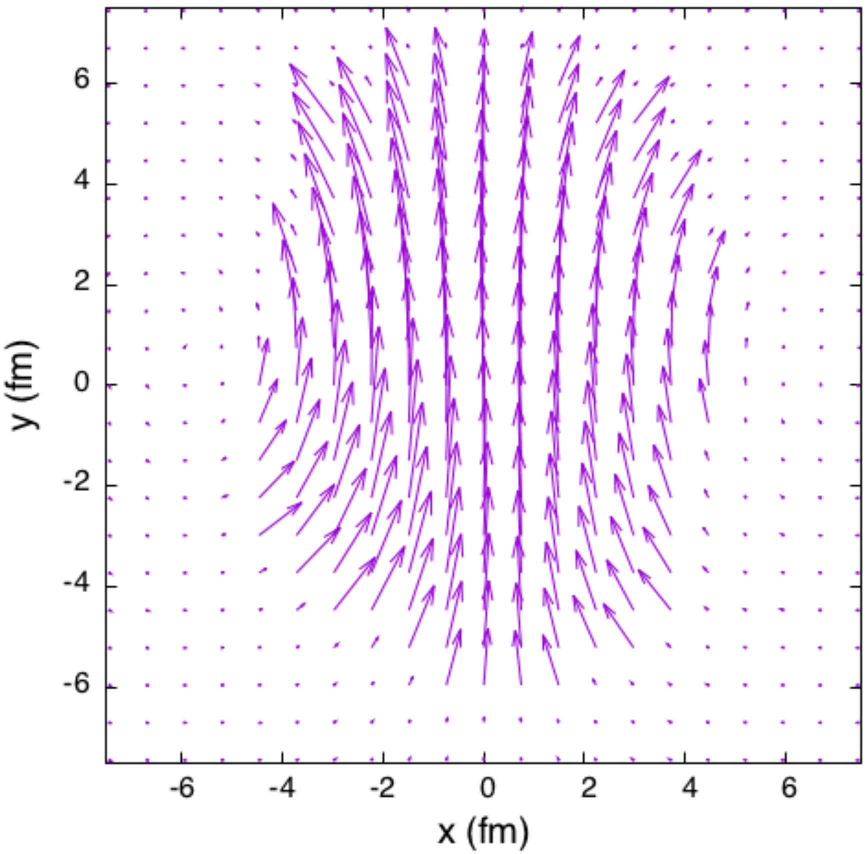
Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

arxiv:1608.00982

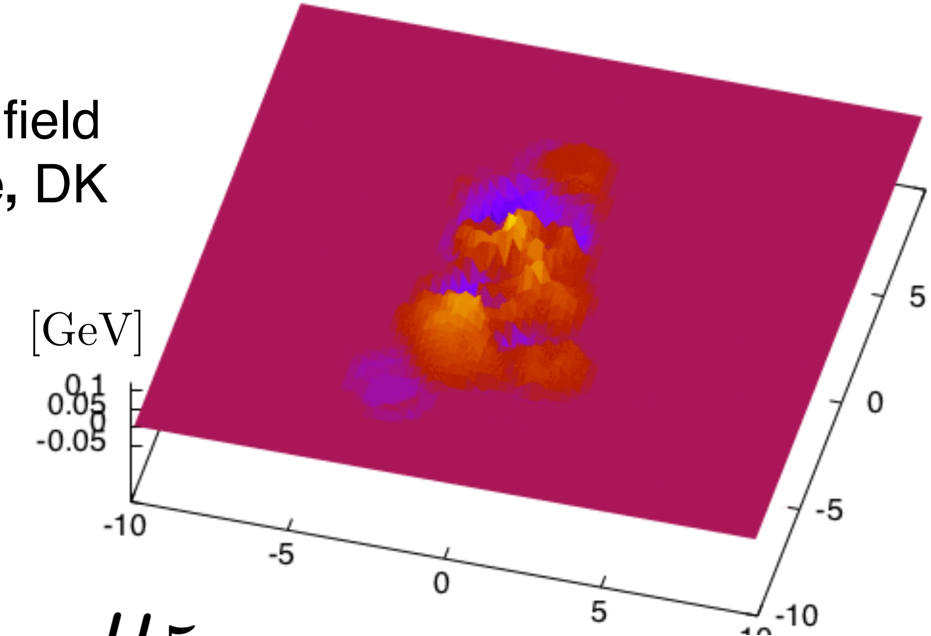
The unique identification of the chiral magnetic effect in heavy-ion collisions would represent one of the highlights of the RHIC physics program and would provide a lasting legacy for the field. The current plan for completing the RHIC mission envisions a second phase of RHIC. **We have specifically investigated the case for colliding nuclear isobars (nuclei with the same mass but different charge) and find the case compelling. We recommend that a program of nuclear isobar collisions to isolate the chiral magnetic effect from background sources be placed as a high priority item in the strategy for completing the RHIC mission.**

Approved dedicated 2018 CME run at RHIC with
Zr (Z=40), Ru (Z=44) isobars

CMHD with dynamical MHD magnetic field from ECHO-QGP: **Y. Hirono, M. Mace,** DK



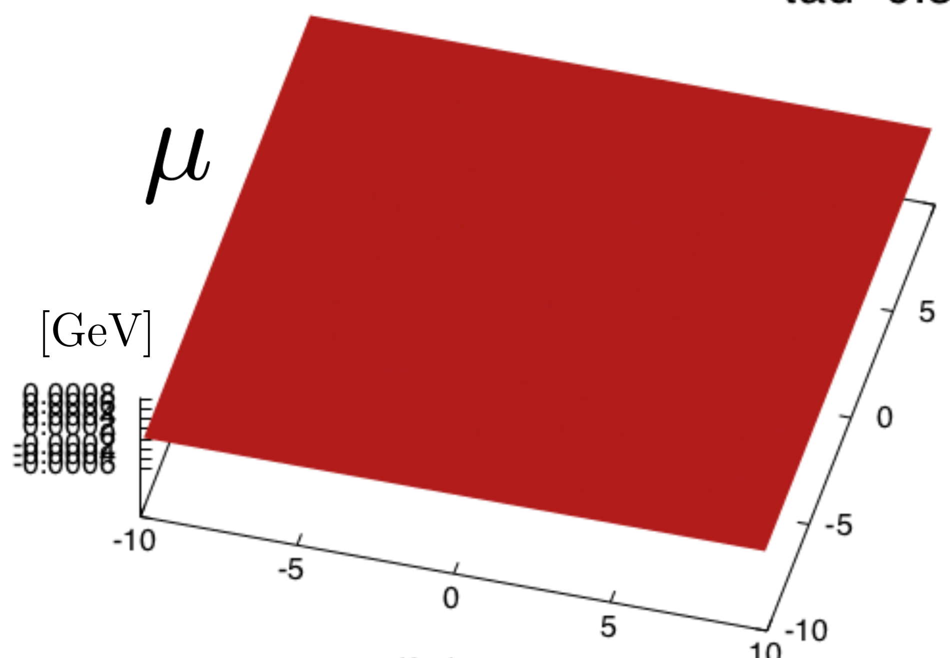

B field evolution
in transverse plane




$\mu_5$

tau=0.5

$\mu$



# Anomalous viscous hydrodynamics

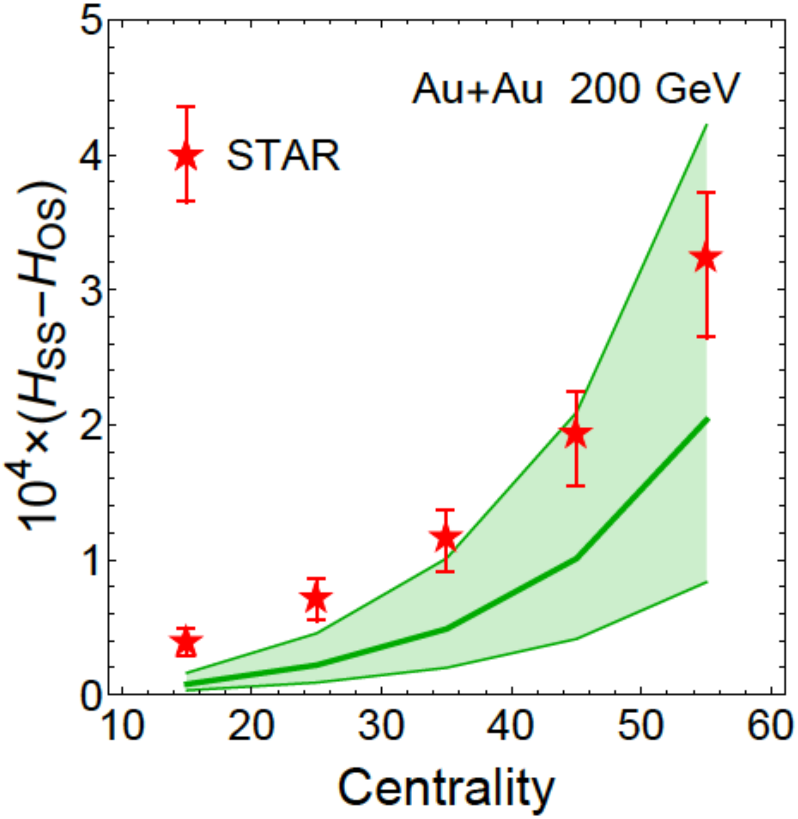



FIG. 3: (color online) The azimuthal correlation observable $(H_{SS} - H_{OS})$ for various centrality, computed from AVFD simulations and compared with STAR data [20], with the green band spanning the range of key parameter from $Q_s^2 = 1\mathrm{GeV}^2$ (bottom edge) to $Q_s^2 = 1.5\mathrm{GeV}^2$ (top edge).

Anomalous currents as perturbations on top of "conventional" (2+1)D VISHNU viscous hydrodynamics; background magnetic field.

Y.Jiang, S.Shi, Y.Yin, J.Liao, Arxiv:1611.04586