Probes of Anomalous Chiral Effects

Sergei A. Voloshin Wayne State University

- What is it? Why is that important? Why heavy ions?
- Methods/approaches/techniques
  - "gamma" correlator (CME, CVE)
  - v_2 vs A and 3-particle correlator (CMW)
- First measurements (CME, CMW)
- Background correlations and what we can do with them
  - higher harmonics
  - U+U, isobar collisions
  - "cross" comparison and other observables
- EM fields studies
- Where we are. Presentations at this QM. What might be next

Many references, including to other reviews can be found in:
D. Kharzeev, J. Liao, S. Voloshin and G. Wang, Prog. Nucl. Phys. **88**, 1 (2016)

Quark Matter 2017

Chirality. Chiral anomaly

$$\psi_{R/L} = \frac{1}{2}(1 \pm \gamma_5)\psi$$

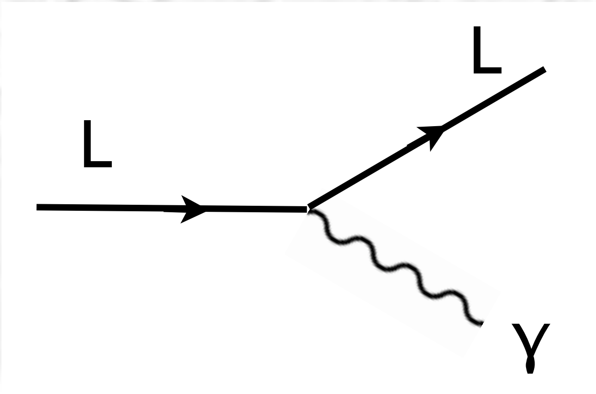
For massless fermions:

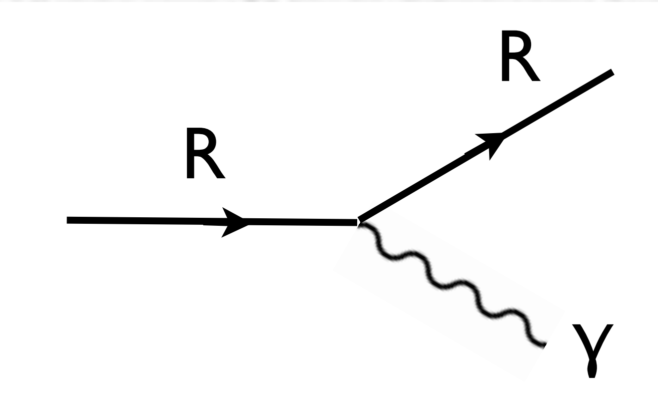
RH - spin along the momentum
LH - spin opposite the momentum

$$J_5^\mu = J_R^\mu - J_L^\mu \qquad J_\mu = J_R^\mu + J_L^\mu$$

$$\mathcal{L} = \bar{\psi}_R(i\partial_\mu - eA_\mu)\gamma^\mu\psi_R + [R \to L]$$

Chirality does not change when quarks interacts with photons or gluons.





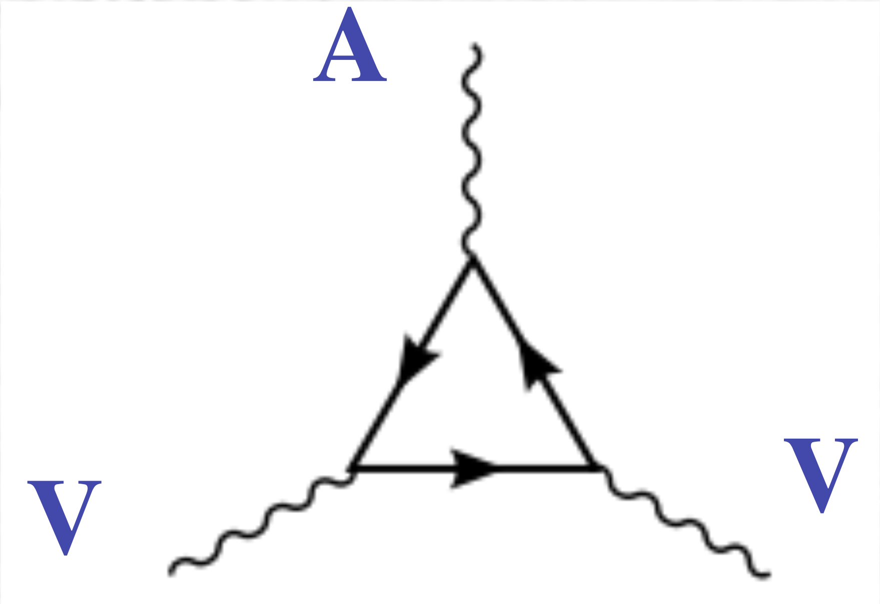
Quantum anomaly — symmetry of the Lagrangian is broken at quantum level

Chirality is not conserved due to anomalies

$$\partial_\mu J_5^\mu = C_A E_\mu B^\mu$$

$$dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}$$

$$\mu_5 \propto Q_5 = n_R - n_L$$



Chiral Magnetic Effect

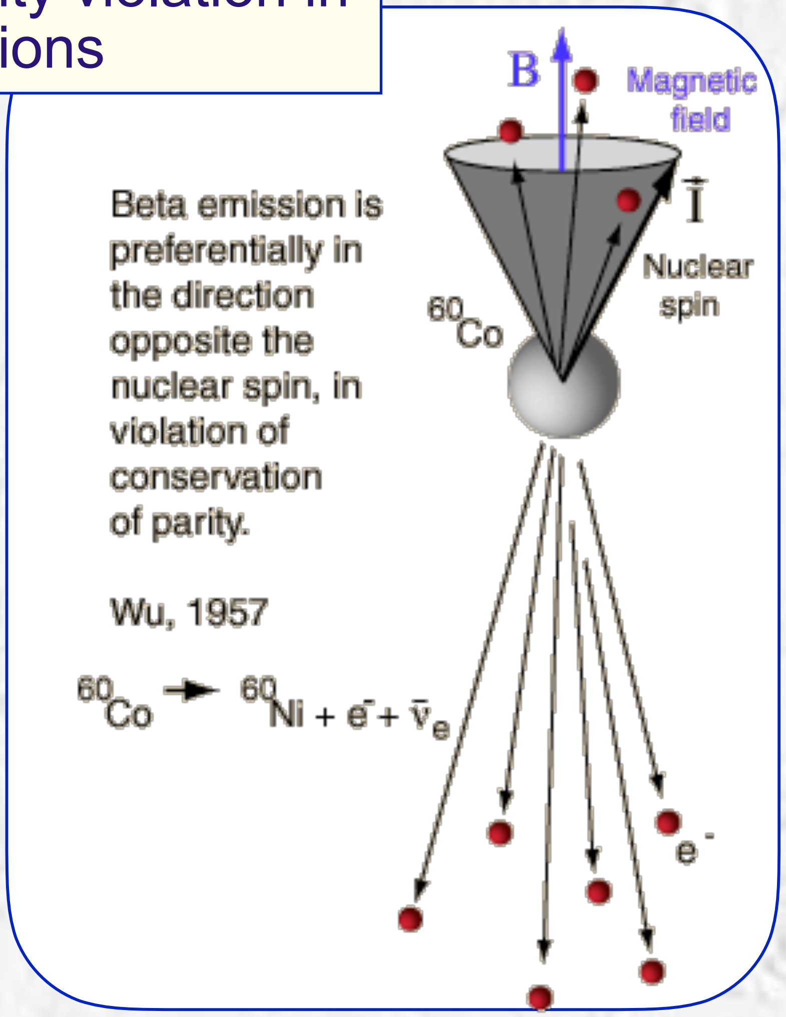
CME - induction of the electric current along the magnetic field

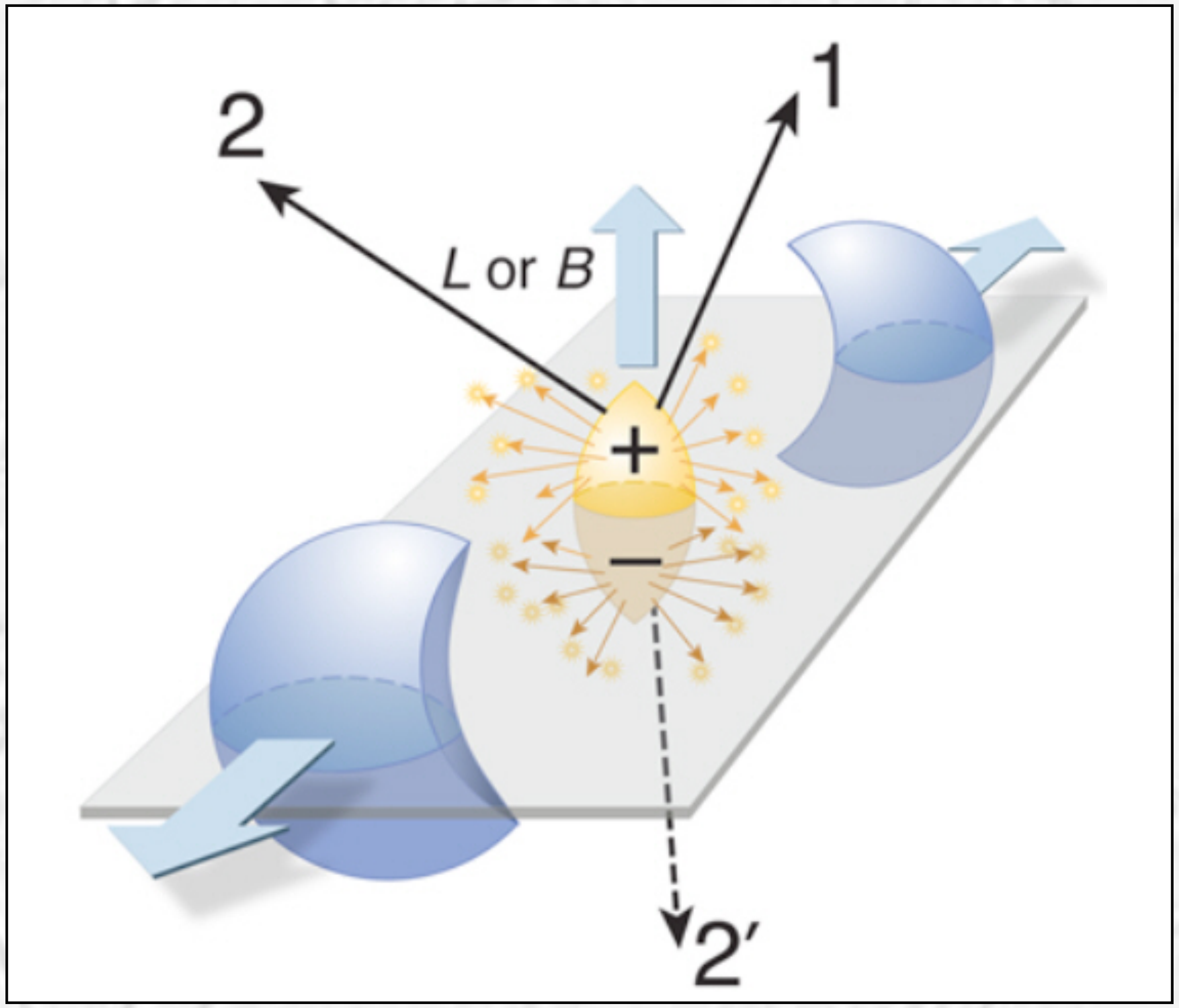
$$\mathbf{J} = \sigma_5 \mathbf{B}$$

Charge separation in the magnetic field direction violates parity

The direction fluctuates event-by-event

Similar to parity violation in weak interactions





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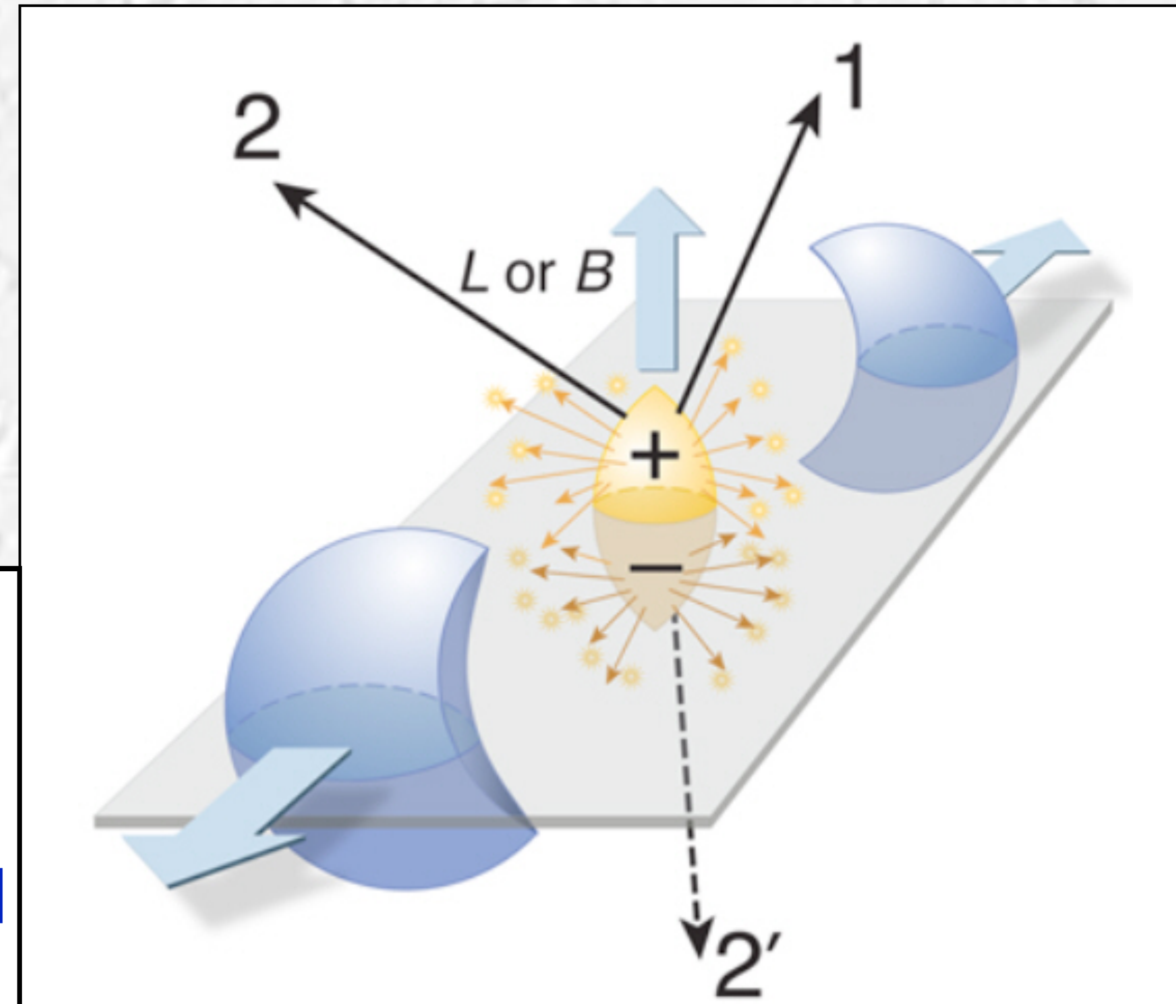


No entropy production from T-even anomalous terms

DK and H.-U. Yee, 1105.6360

Slide taken from D. Kharzeev

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

P-odd T-odd

P-even T-odd

P-odd

P-odd effect!

T-even

Non-dissipative current!

cf Ohmic conductivity:

$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

23

(time-reversible - no arrow of time, no entropy production)

Anomalous chiral effects

Chiral Magnetic effect (CME) - separation of the electric charge along **B**

$$\mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}$$

Chiral Vortical effect (CVE) - separation of the baryon charge along vorticity

$$\mathbf{J} = \frac{1}{\pi^2}\mu_5(\mu\boldsymbol{\omega})$$

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \mathbf{v}$$

Chiral Separation Effect (CSE) - separation of the axial charge along the magnetic field

$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}$$

Chiral Electric Separation Effect (CESE) - separation of the axial charge along the electric field

In common: chiral anomalous transport determined by the chiral (axial) quantum anomaly

	Magnetic field	Vorticity
Vector current	$\frac{\mu_A}{2\pi^2}$	$\frac{\mu\mu_A}{2\pi^2}$
Axial current	$\frac{\mu}{2\pi^2}$	$\frac{\mu^2+\mu_A^2}{4\pi^2}+\frac{T^2}{12}$

Coefficients are fixed by the axial anomaly, no corrections

Chiral Magnetic Wave

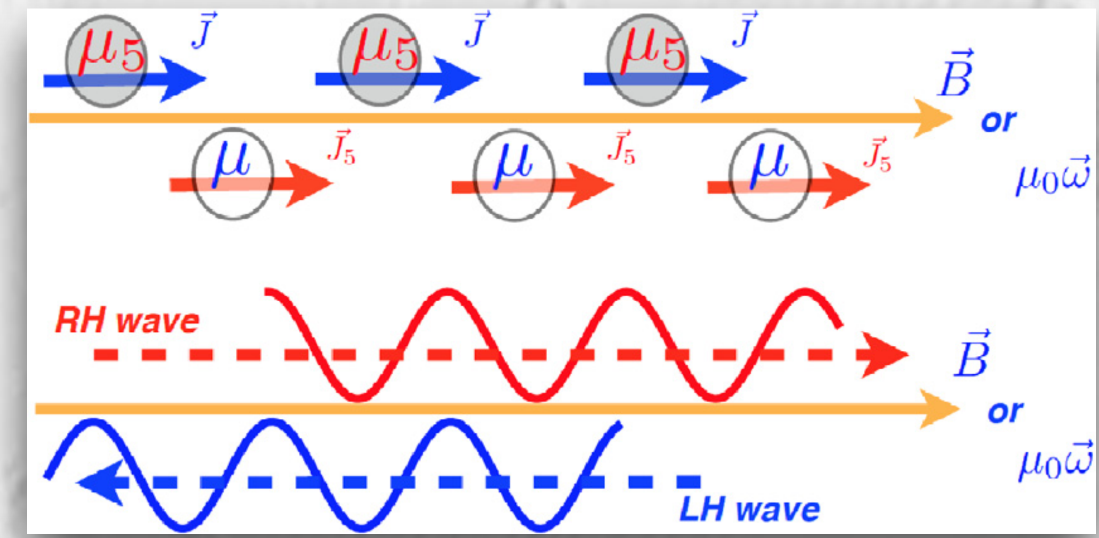
Yannis Burnier,[1] Dmitri E. Kharzeev,[1,2] Jinfeng Liao,[2] and Ho-Ung Yee[1]

PRL **107,** 052303 (2011)

$$\boxed{\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}}$$

$$\boxed{\mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}}$$

D.E. Kharzeev et al. / Progress in Particle and Nuclear Physics 88 (2016) 1–28



g. 5. (Color online) Illustration of the chiral magnetic wave and the chiral vortical wave.

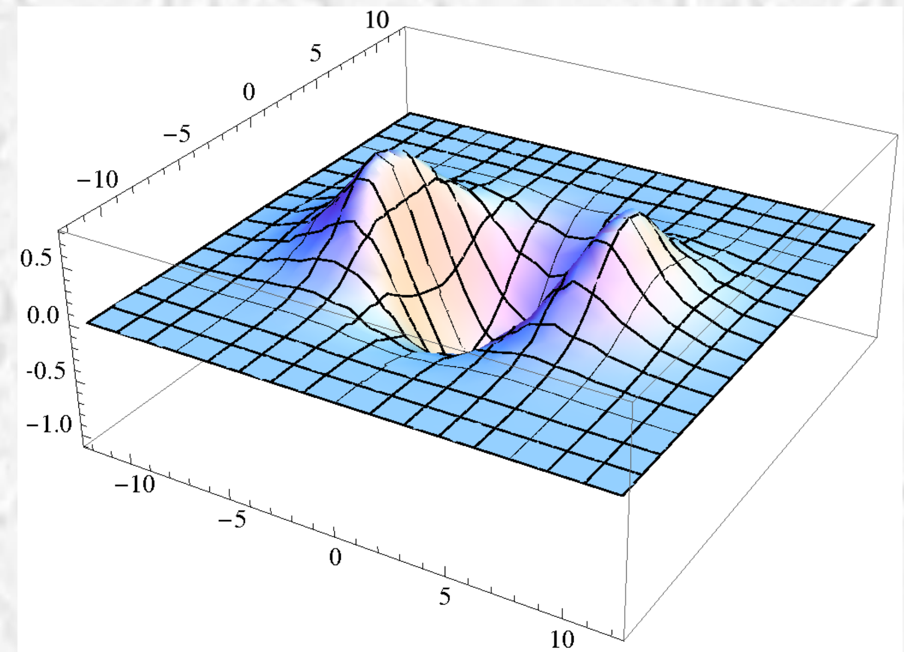
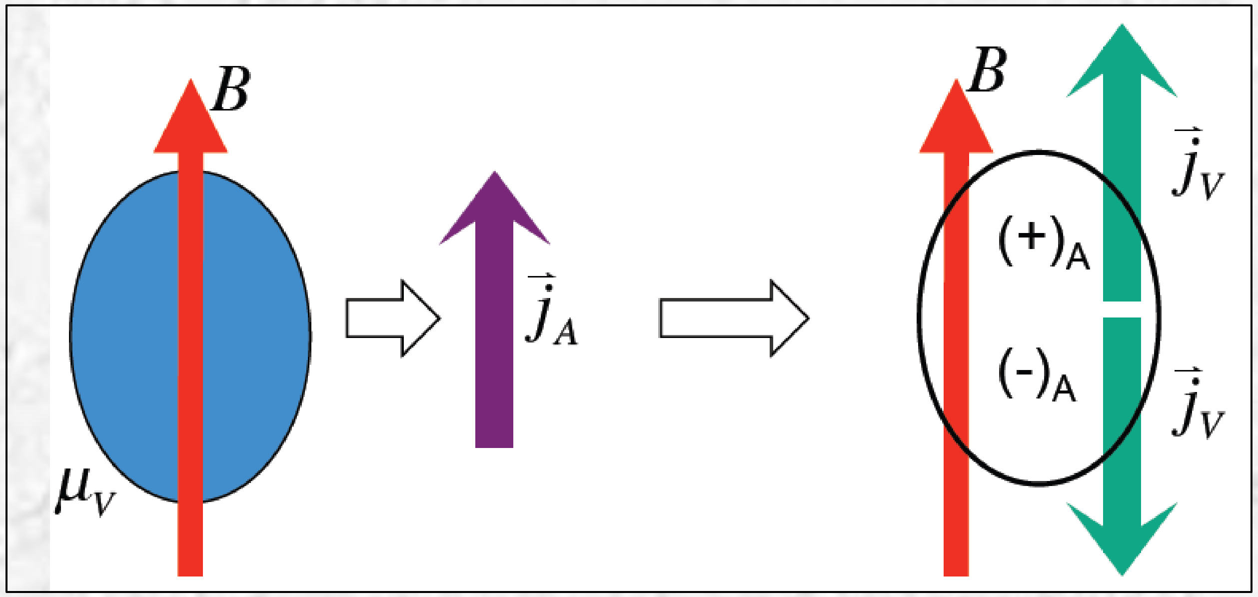


FIG. 2 (color online). Electric charge density in the transverse plane (background subtracted, see text). Same parameters as in Fig. 1.



CME "components"

Chirality imbalance
+
Magnetic field

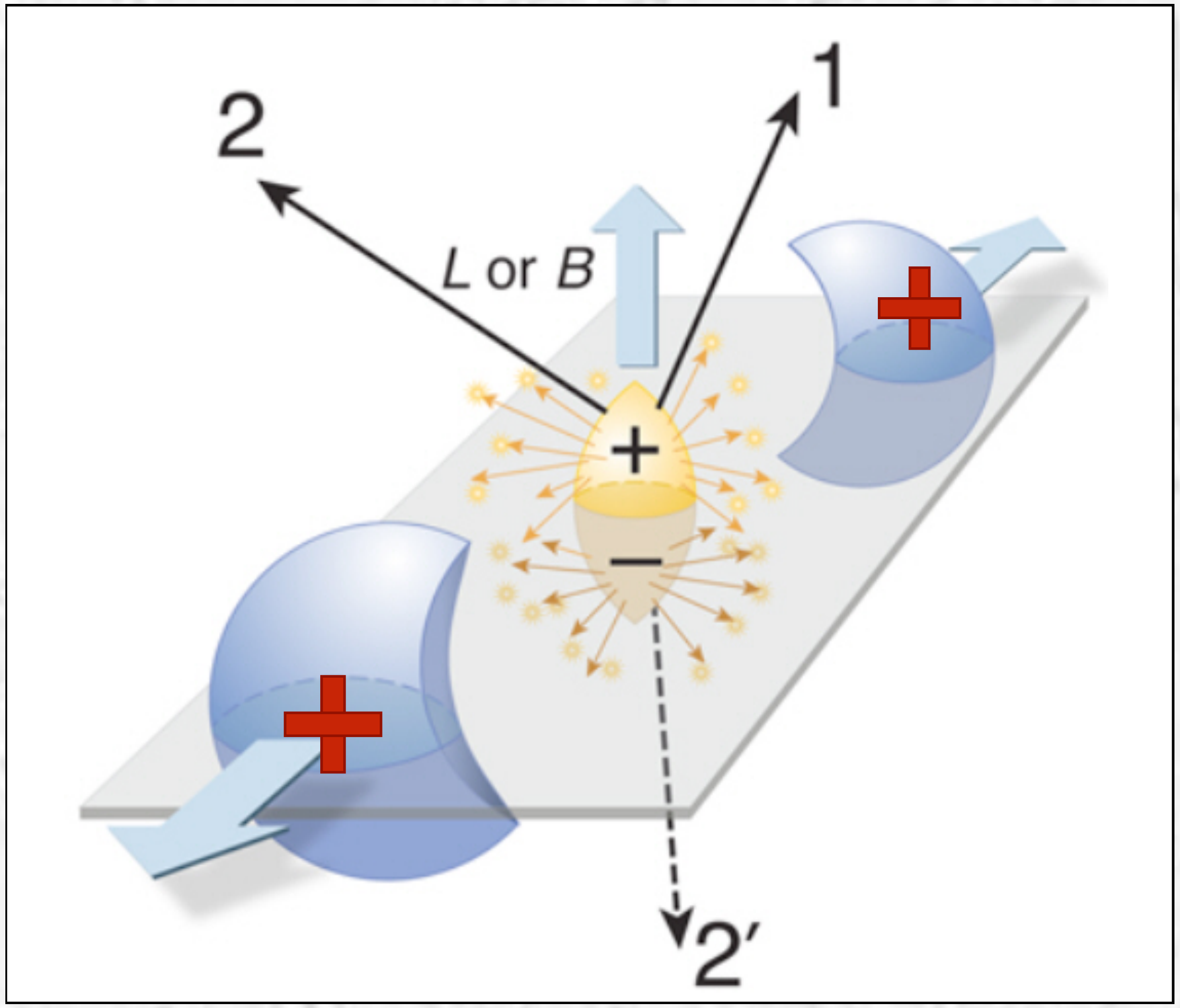
$$\mu_5 \sim \vec{E}\vec{B}\ t$$

Anomalous transport,
Electric current along magnetic filed

$$\mathbf{J} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B}$$

Radial flow

Charge separation along **B** direction



Spectator directed flow determine the direction of **B**

S. A. Voloshin and T. Niida, Ultrarelativistic nuclear collisions: Direction of spectator flow Phys. Rev. C **94**, 021901 (R) (2016).

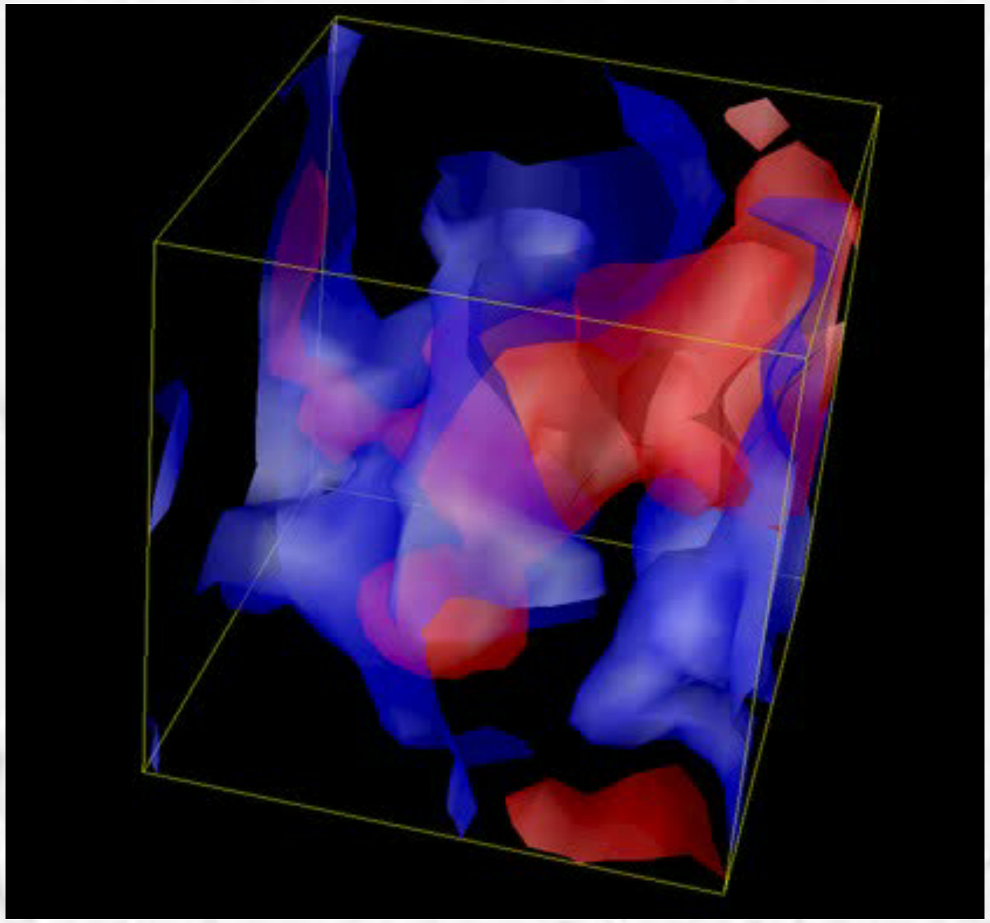
$$\frac{dN_\pm}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + \ldots$$
$$+ 2a_{1,\pm} \sin(\Delta\phi) + \ldots ; \qquad \Delta\phi = \phi - \Psi_{RP}$$

CME - observations

Lattice QCD

Condensed matter

"Numerical evidence for chiral magnetic effect in lattice gauge theory", P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov, ArXiv 0907.0494; PRD

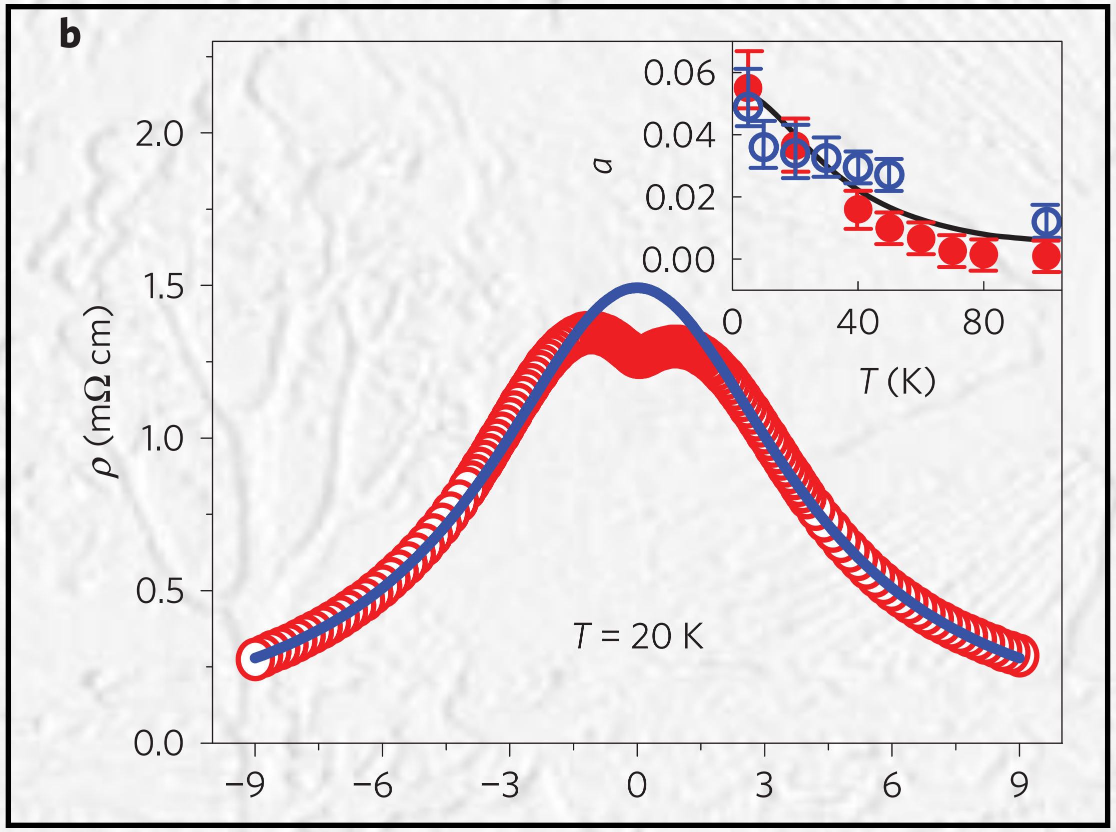


nature physics | LETTERS

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

Chiral magnetic effect in $ZrTe_5$

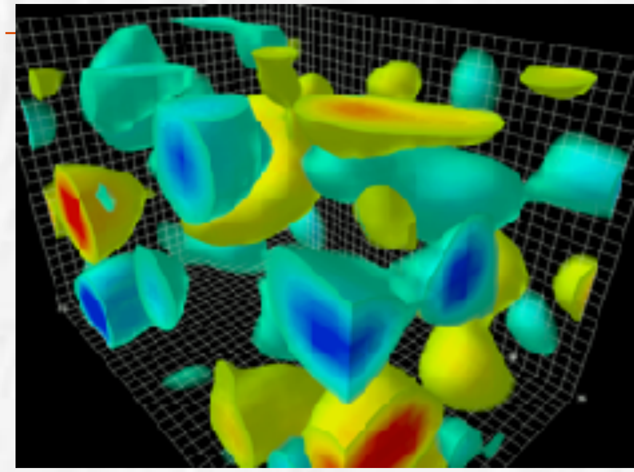
Qiang Li[1*], Dmitri E. Kharzeev[2,3*], Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1*]



And many other publications, both on LQCD calculations, as well as on the observation of the effect in condensed matter

$$\mathbf{J}_{\mathrm{CME}} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B} \qquad \mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\mathbf{E}\cdot\mathbf{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_V$$

Initial chirality imbalance, $n_R \neq n_L$

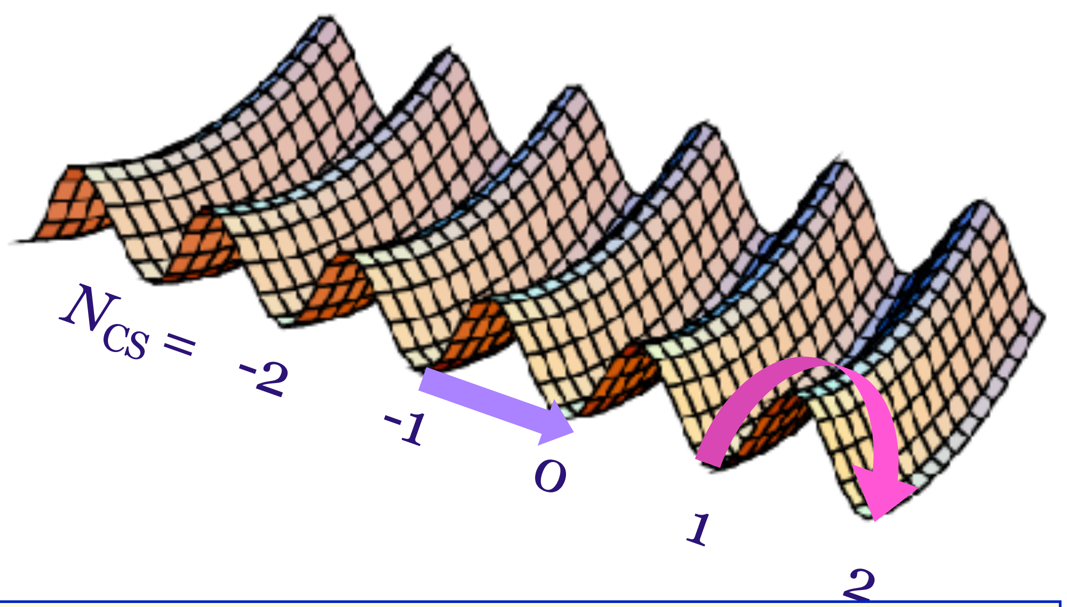


$$\boxed{dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}}$$

Topological transitions

Glasma

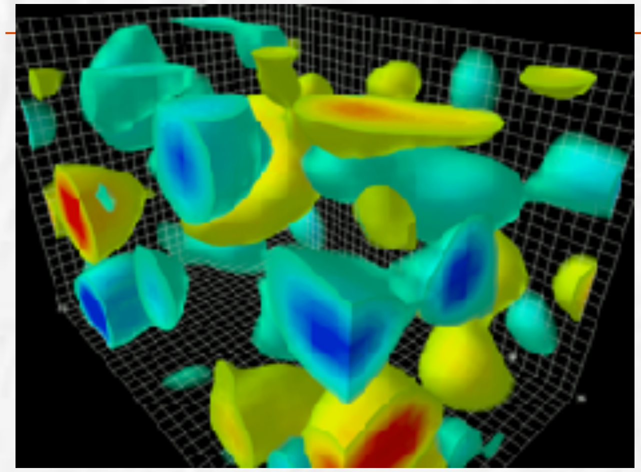
$$\boxed{2Q_T = n_R - n_L}$$



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

Quark interactions with topologically non-trivial gluonic configurations - instantons, sphalerons, etc., the same physics as that of the chiral symmetry breaking.

Initial chirality imbalance, $n_R \neq n_L$



$$dQ_5/dt \propto \mathbf{E}\cdot\mathbf{B}$$

Topological transitions

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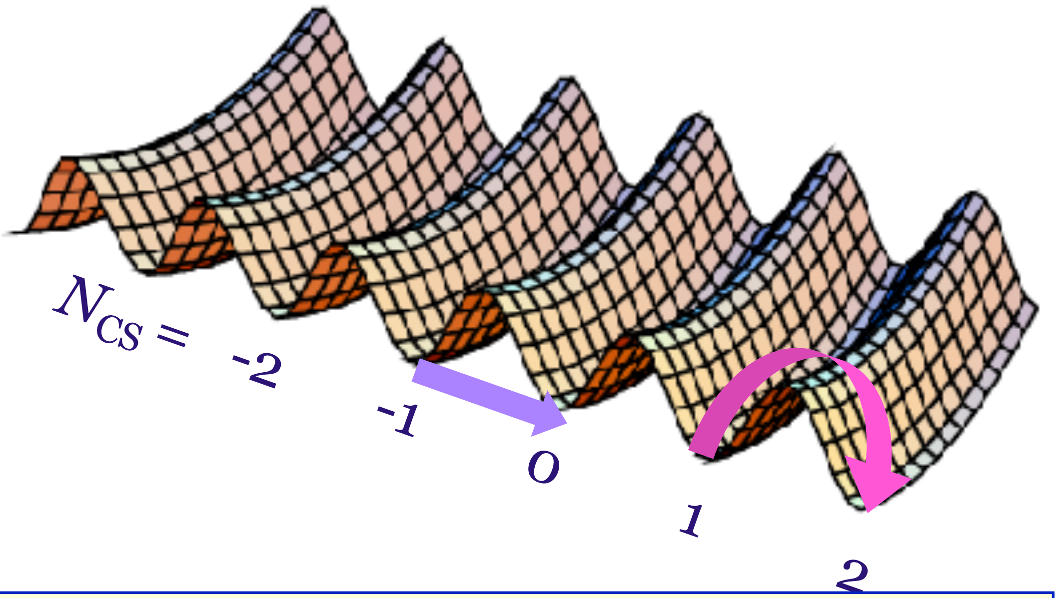
$$2Q_T = n_R - n_L$$



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

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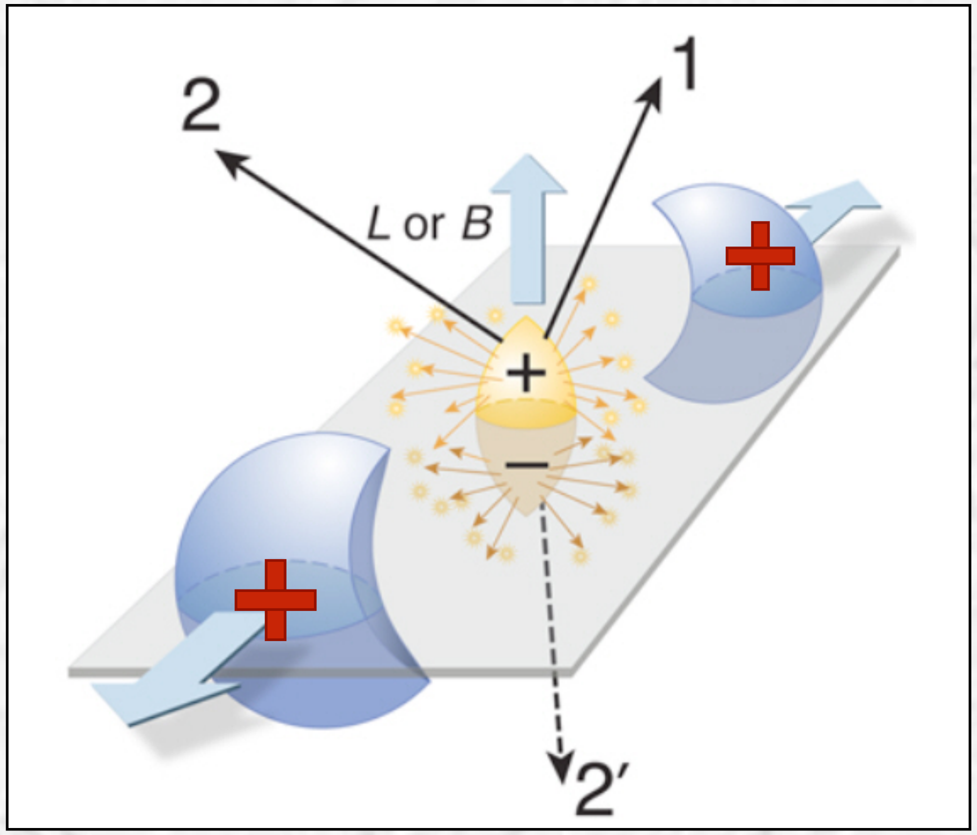
Magnetic field



In a conducting plasma the induction can make the field long lived.

K. Tuchin, Particle production in strong electromagnetic fields in relativistic heavy-ion collisions, Adv. High Energy Phys. **2013**, 490495 (2013).

L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190

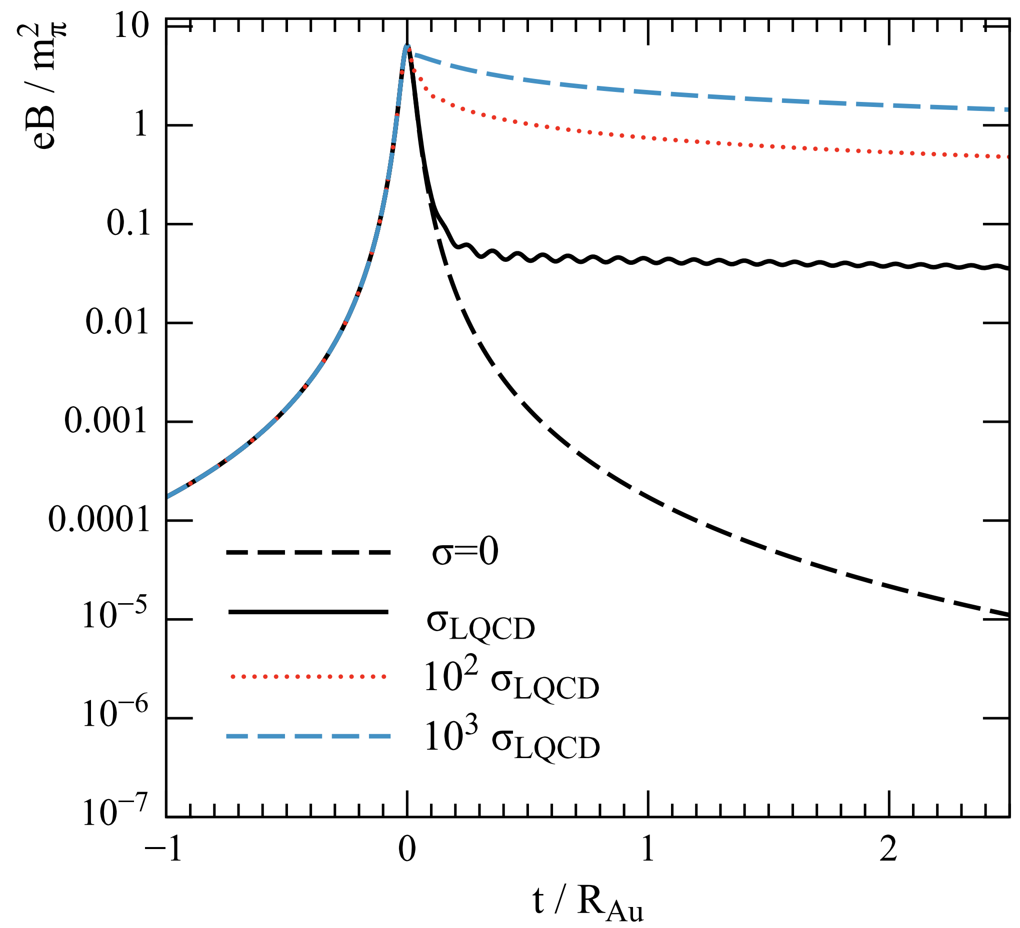
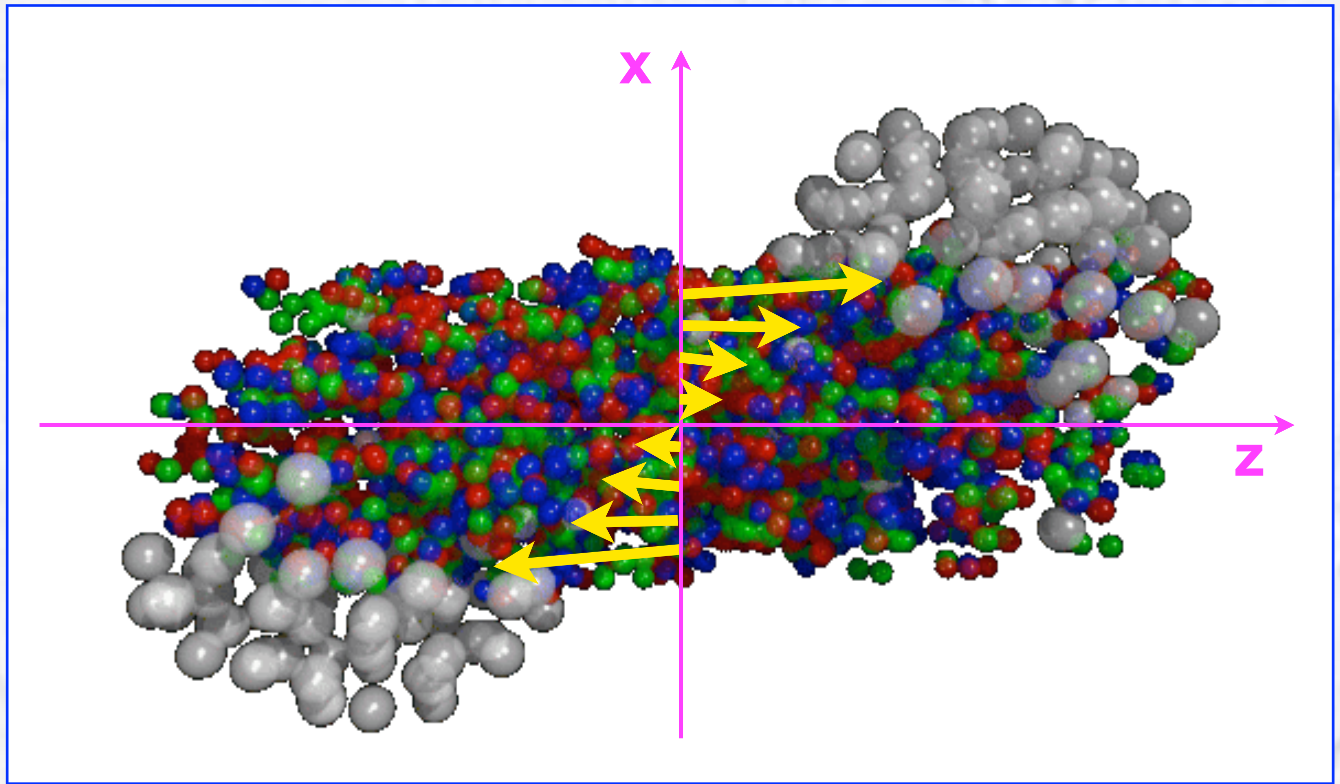


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

Vorticity



$$\boldsymbol{\omega} = \frac{1}{2}\nabla\times\mathbf{v}$$ $$\approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]
PHYSICAL REVIEW C **94**, 044910 (2016)

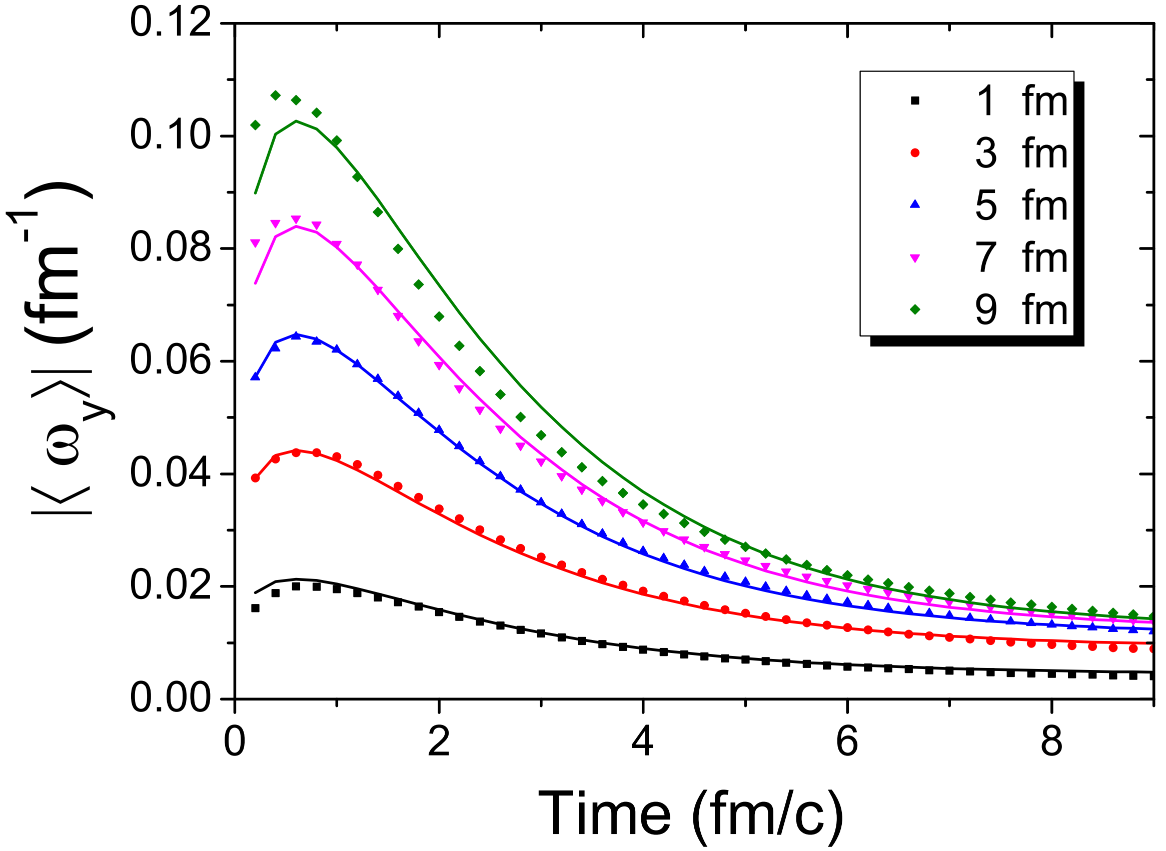
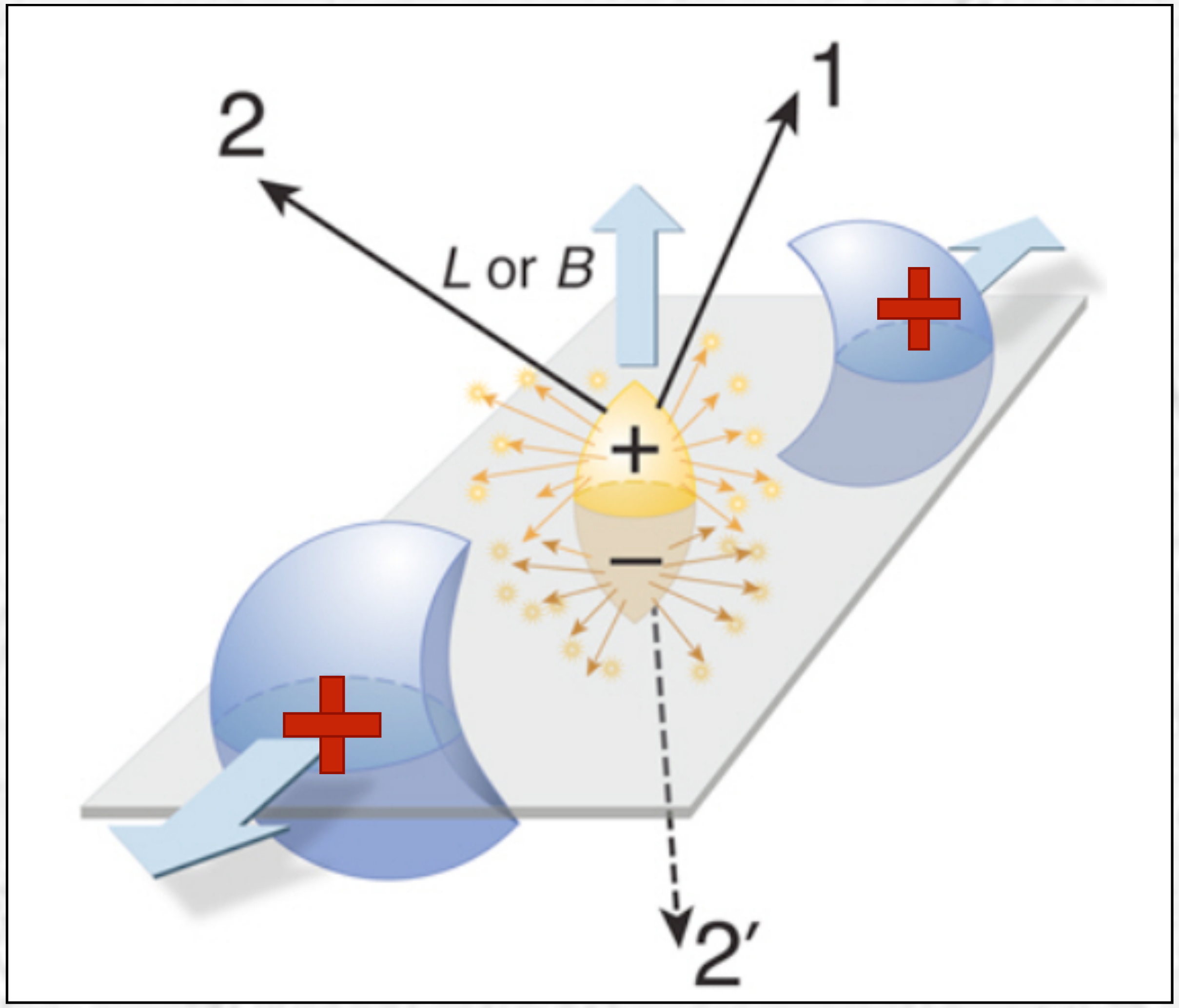


FIG. 11. Averaged vorticity $\langle\omega_y\rangle$ from the AMPT model as a function of time at various impact parameter b for fixed beam energy $\sqrt{s_{NN}} = 200$ GeV. The solid curves are from a fitting formula (see text for details).

+ many earlier papers…

CME, how to measure it?



Due to fluctuations in the direction of separation, on average the effect is zero.

Can be studied only with correlations

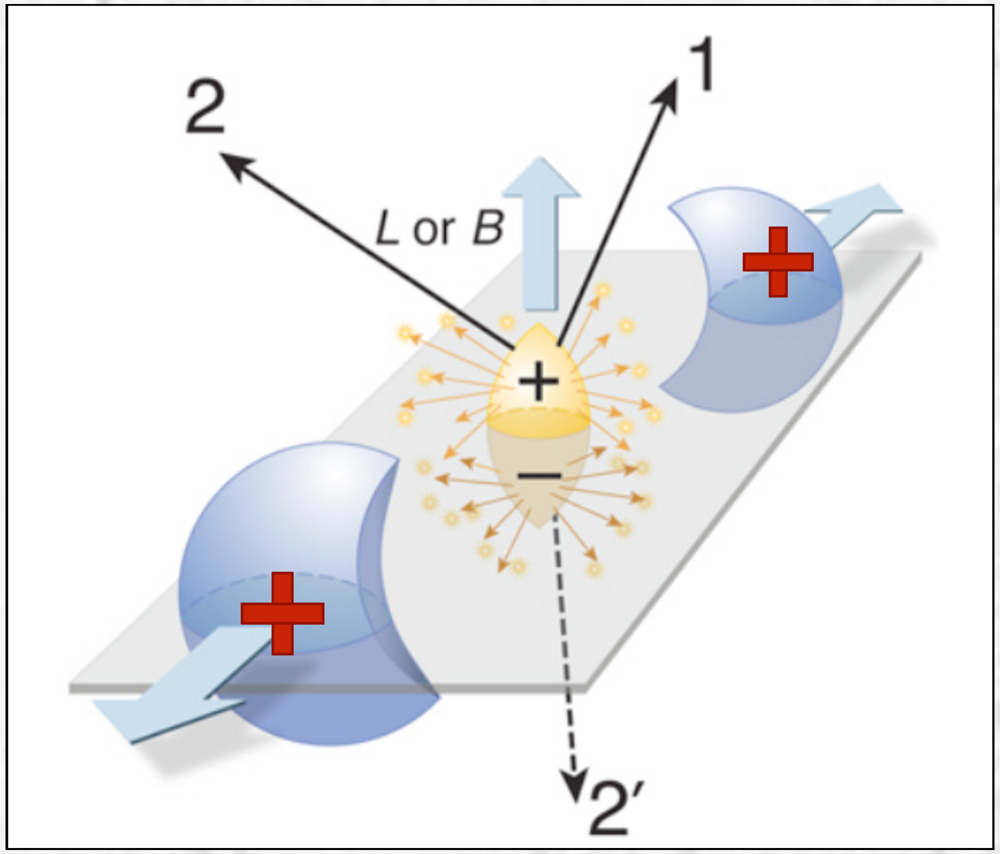
Needs to suppress irrelevant background effects

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + \ldots$$

$$+ 2a_{1,\pm} \sin(\Delta\phi) + \ldots ; \qquad \Delta\phi = \phi - \Psi_{\mathrm{RP}}$$

"Gamma" correlator

S. A. Voloshin, Parity violation in hot QCD: How to detect it, Phys. Rev. C **70**, 057901 (2004).

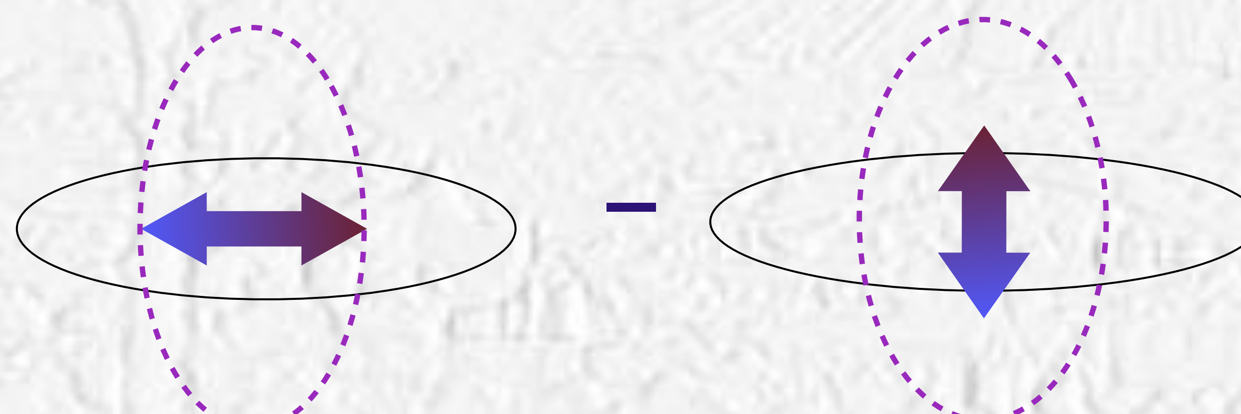


Effective particle distribution

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + \ldots$$
$$+ 2a_{1,\pm} \sin(\Delta\phi) + \ldots ; \qquad \Delta\phi = \phi - \Psi_{\mathrm{RP}}$$

$$\begin{aligned}\gamma_{\alpha,\beta} &\equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle \\ &= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle \\ &= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\mathrm{in}}] - [\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{\mathrm{out}}]\end{aligned}$$

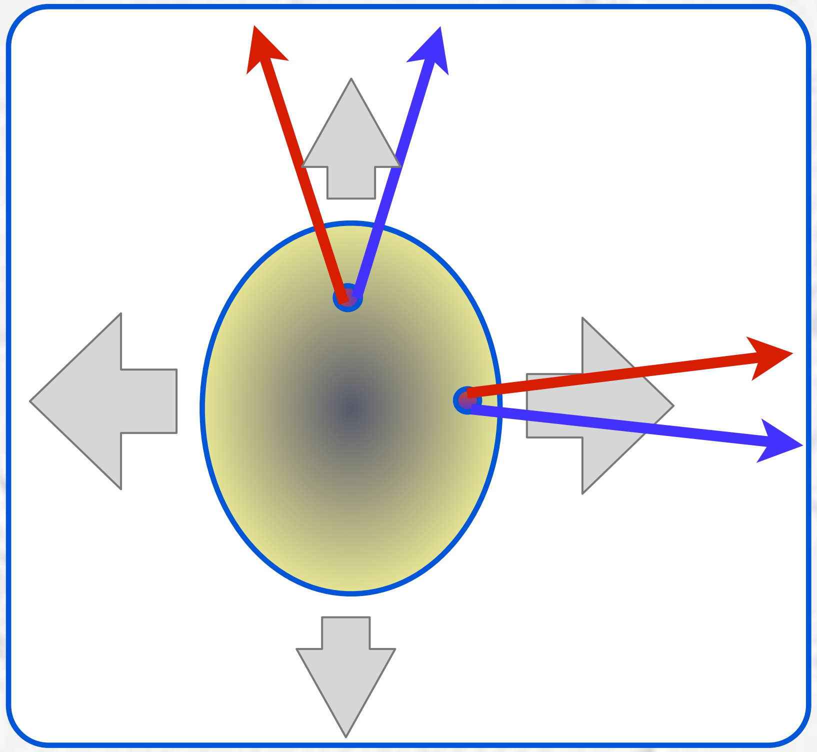
The sign of the correlations is sensitive to the "direction" (in- or out-of-plane), the background is suppressed (B_{in}-B_{out}) at least by a factor of $v_2 < 10^{-1}$.



“Gamma” correlator, background

S. A. Voloshin, Parity violation in hot QCD: How to detect it, Phys. Rev. C **70**, 057901 (2004).

$$\gamma_{\alpha,\beta} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP})\rangle$$
$$= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{\rm in}] - [\langle a_{1,\alpha} a_{1,\beta}\rangle + B_{\rm out}]$$



“Flowing clusters”

$$B_{\rm in} - B_{\rm out} \propto v_{2,\rm clust}\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_{\rm clust})\rangle$$

One of the “strong” candidates: Local Charge Conservation at freeze-out + Radial + Elliptic Flow. Blast Wave model:

Pratt, arXiv:1002.1758v1[nucl-th]

Schlichting and Pratt, PRC83 014913 (2011)

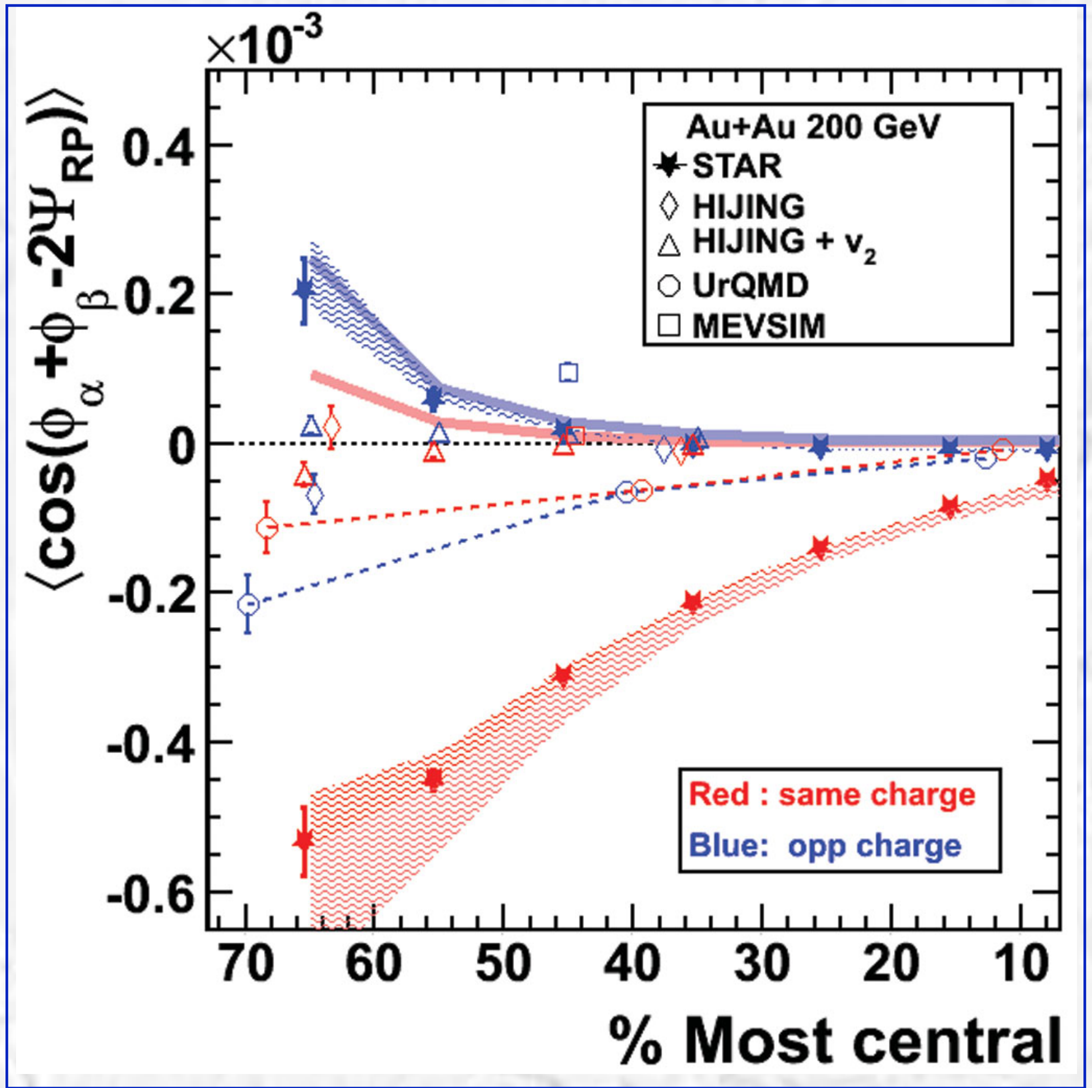
Hori, Gunji, Hamagaki, Schlichting, arXiv:1208.0603

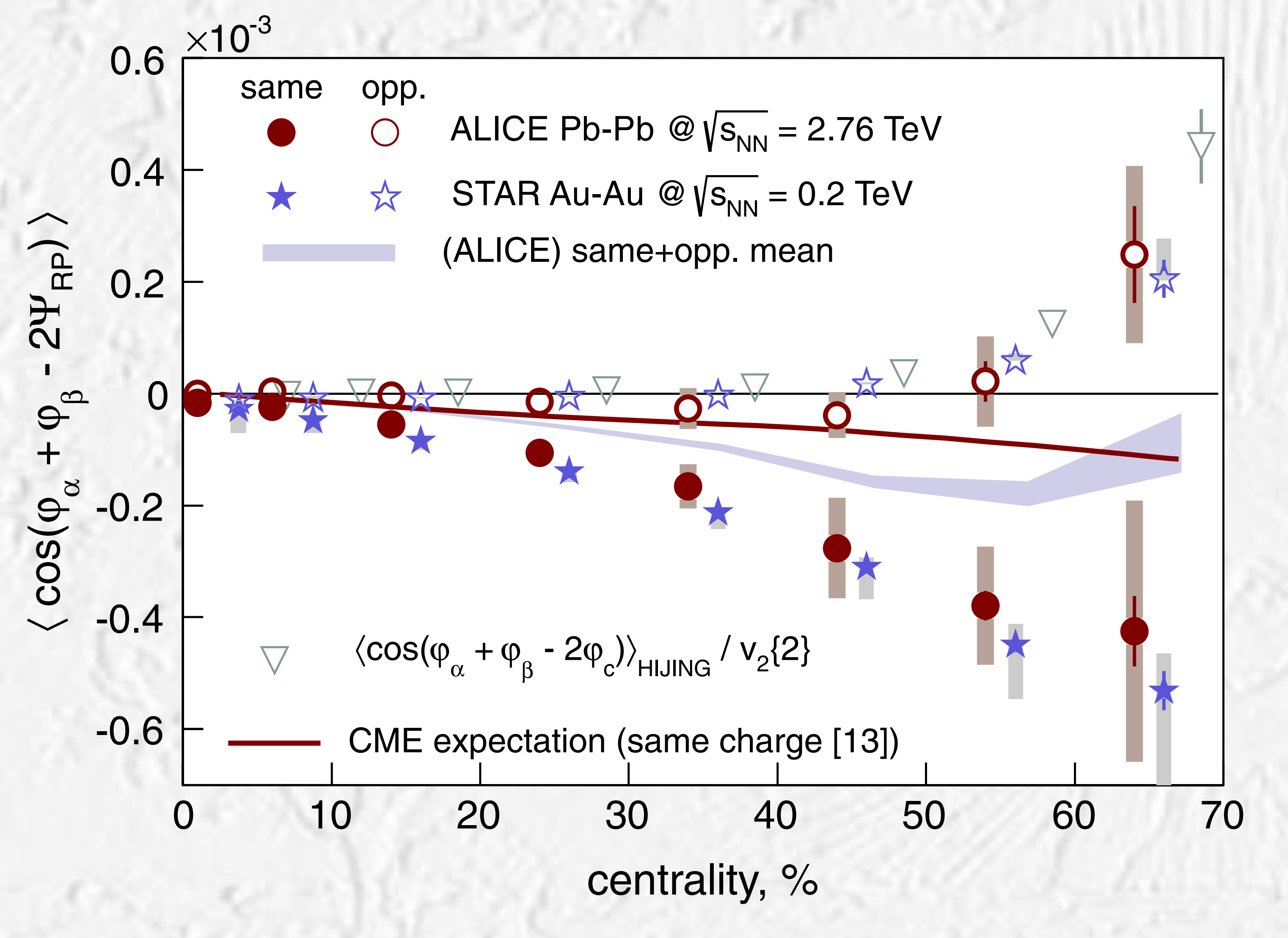
- Correlations only between opposite charges
- To be consistent with data must be combined with (negative) charge independent correlations (e.g. momentum conservation).
- No event generator exhibits such strong correlations as predicted by Blast Wave model

STAR and ALICE results

B. I. Abelev *et al.* (STAR Collaboration), Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation, Phys. Rev. Lett. **103**, 251601 (2009).

J. Adam *et al.* (ALICE Collaboration), Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C **93**, 044903 (2016).





No event generator can describe the data

RHIC and LHC results -- surprisingly close!
- no effect of change in magnetic field lifetime (?)
- no effect of almost factor of 3 higher multiplicity density (?)

Energy dependence

18 D.E. Kharzeev et al. / Progress in Particle and Nuclear Physics 88 (2016) 1–28

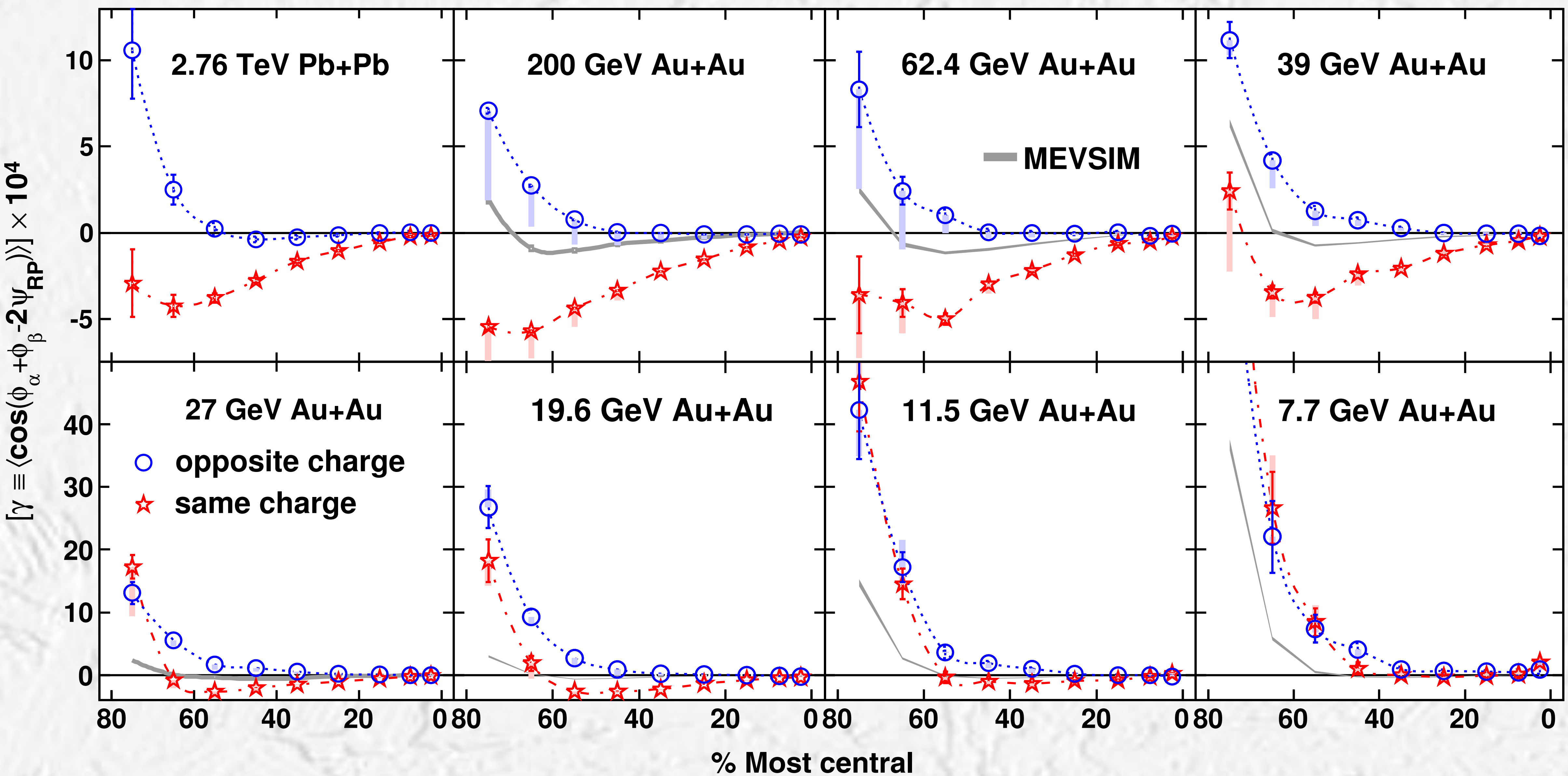


Fig. 13. Three-point correlator as a function of centrality for Au + Au collisions at 7.7–200 GeV [106], and for Pb + Pb collisions at 2.76 TeV [129]. Note that the vertical scales are different for different rows. The systematic errors (gray bars) bear the same meaning as in Fig. 12. Charge independent results from the model calculations of MEVSIM [135] are shown as gray curves.

The difference, $\Delta\gamma$, decreases at lower energy

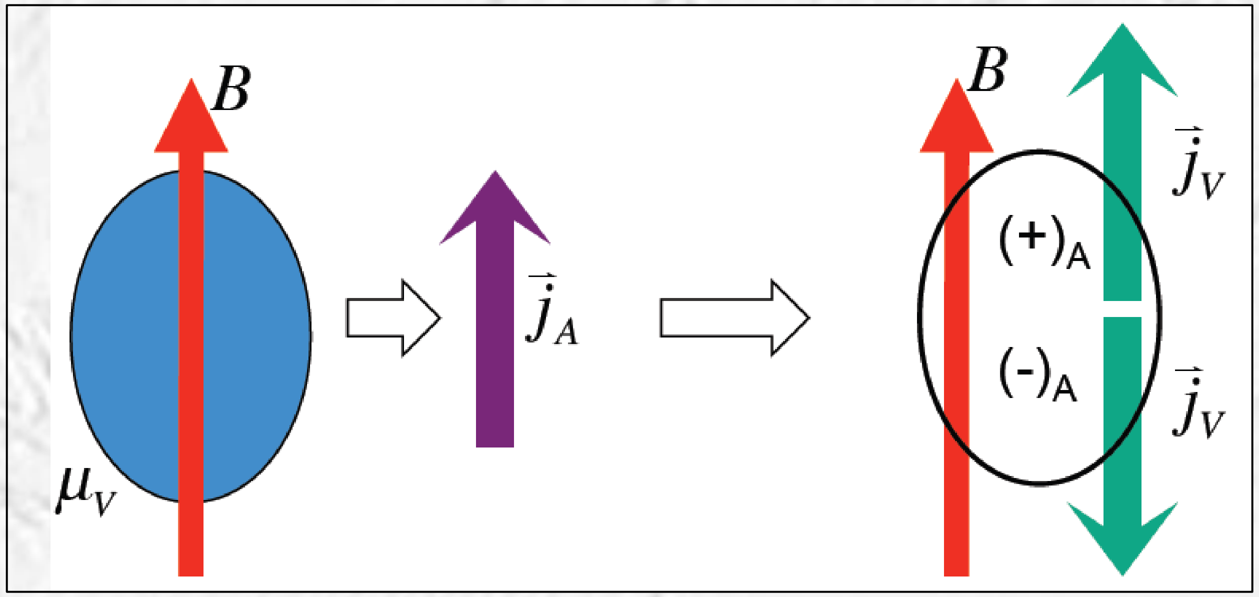
Chiral Magnetic Wave

Yannis Burnier,[1] Dmitri E. Kharzeev,[1,2] Jinfeng Liao,[2] and Ho-Ung Yee[1]

PRL **107,** 052303 (2011)

$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}$$

$$\mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}$$



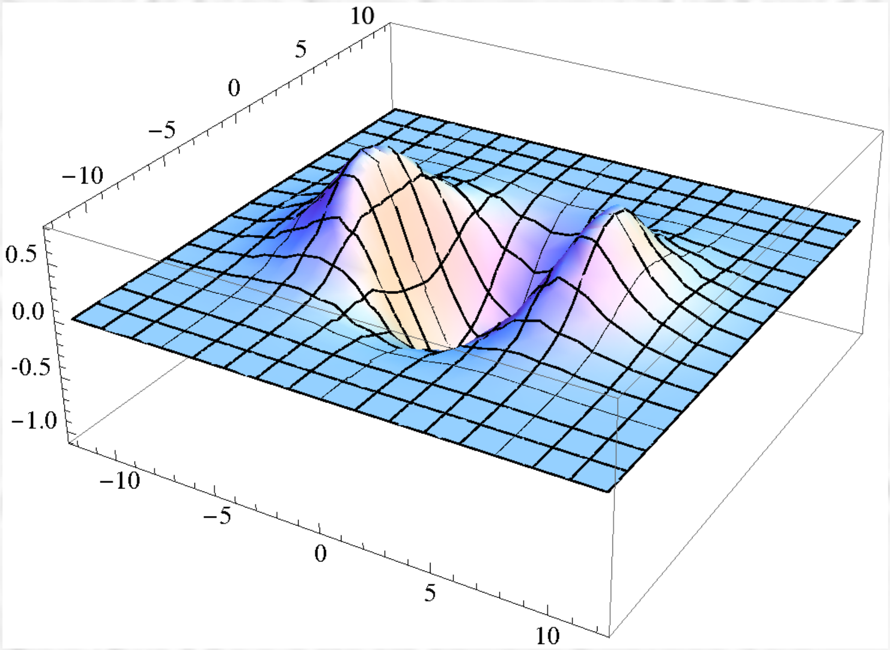


FIG. 2 (color online). Electric charge density in the transverse plane (background subtracted, see text). Same parameters as in Fig. 1.

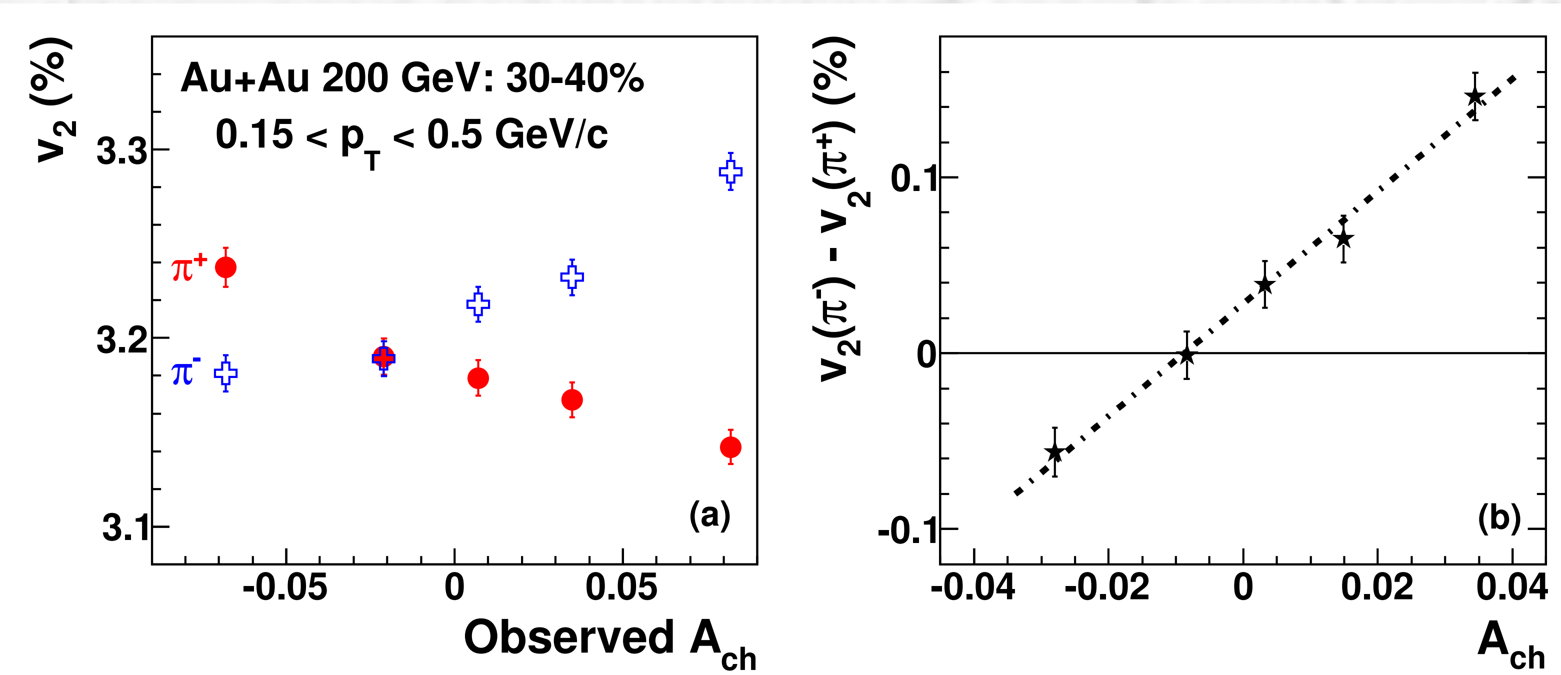
For a given sign of A, the difference in v_2 for positive and negative particles is uniquely predicted

$$v_2^{\pm} = v_2 \mp \frac{rA_{\pm}}{2}$$

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

v2 vs event net charge

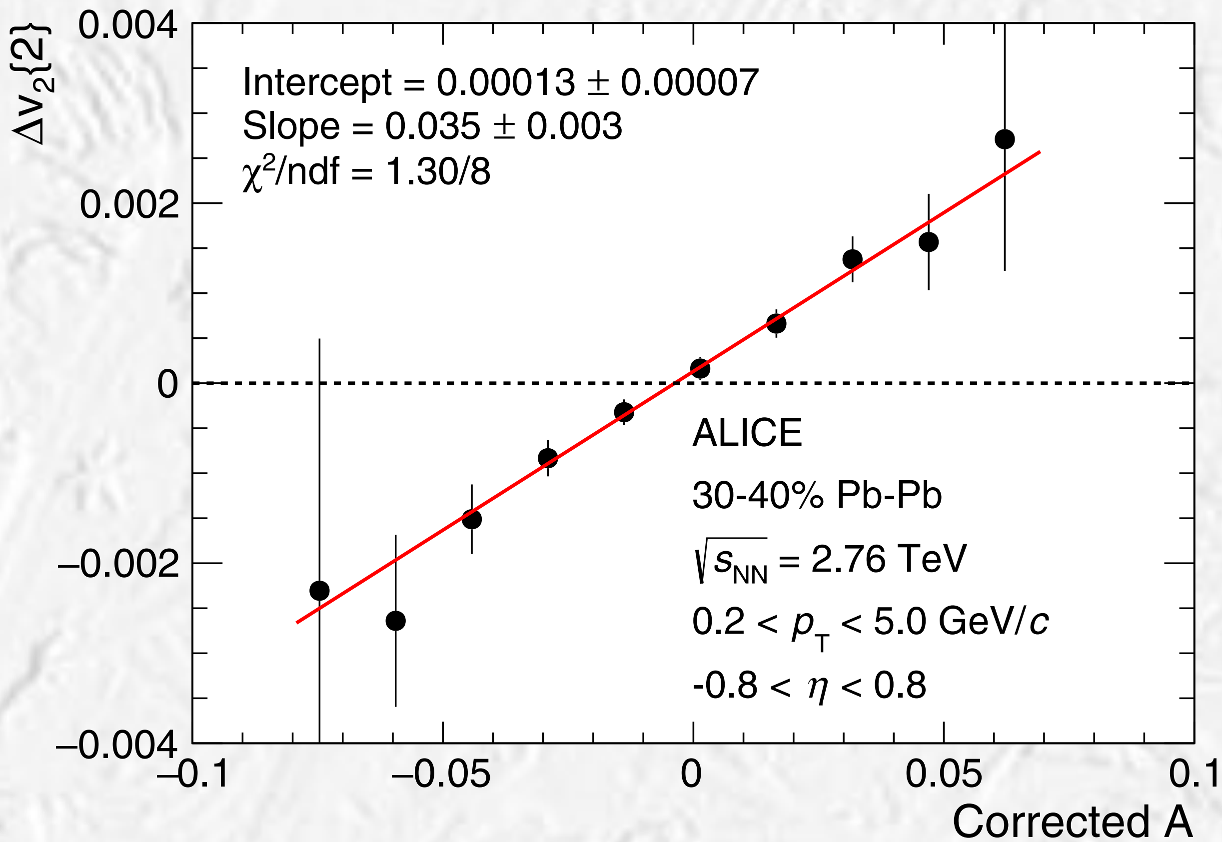
L. Adamczyk *et al.* (STAR Collaboration), Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions, Phys. Rev. Lett. **114**, 252302 (2015).



$$v_2^{\pm} = v_2 \mp \frac{rA_{\pm}}{2}$$

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

- depends on tracking efficiency corrections
- depends on acceptance used for A



Qualitatively follow the expectations

J. Adam *et al.* (ALICE Collaboration), Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C **93**, 044903 (2016).

3 particle correlator

S. A. Voloshin and R. Belmont, Measuring and interpreting charge dependent anisotropic flow, Nucl. Phys. A **931**, 992 (2014).

$$\langle c_3 \rangle = \frac{N_+ - N_-}{N_+ + N_-}$$

$$A_{\rm ch} = (N_+ - N_-)/(N_+ + N_-)$$

Three particle correlator

$$\langle\langle \cos[n(\phi_1 - \Psi_n)]\, c_3 \rangle\rangle \equiv \langle \cos[n(\phi_1 - \Psi_n)]\, c_3 \rangle - \langle \cos[n(\phi_1 - \Psi_n)] \rangle \langle c_3 \rangle_1$$

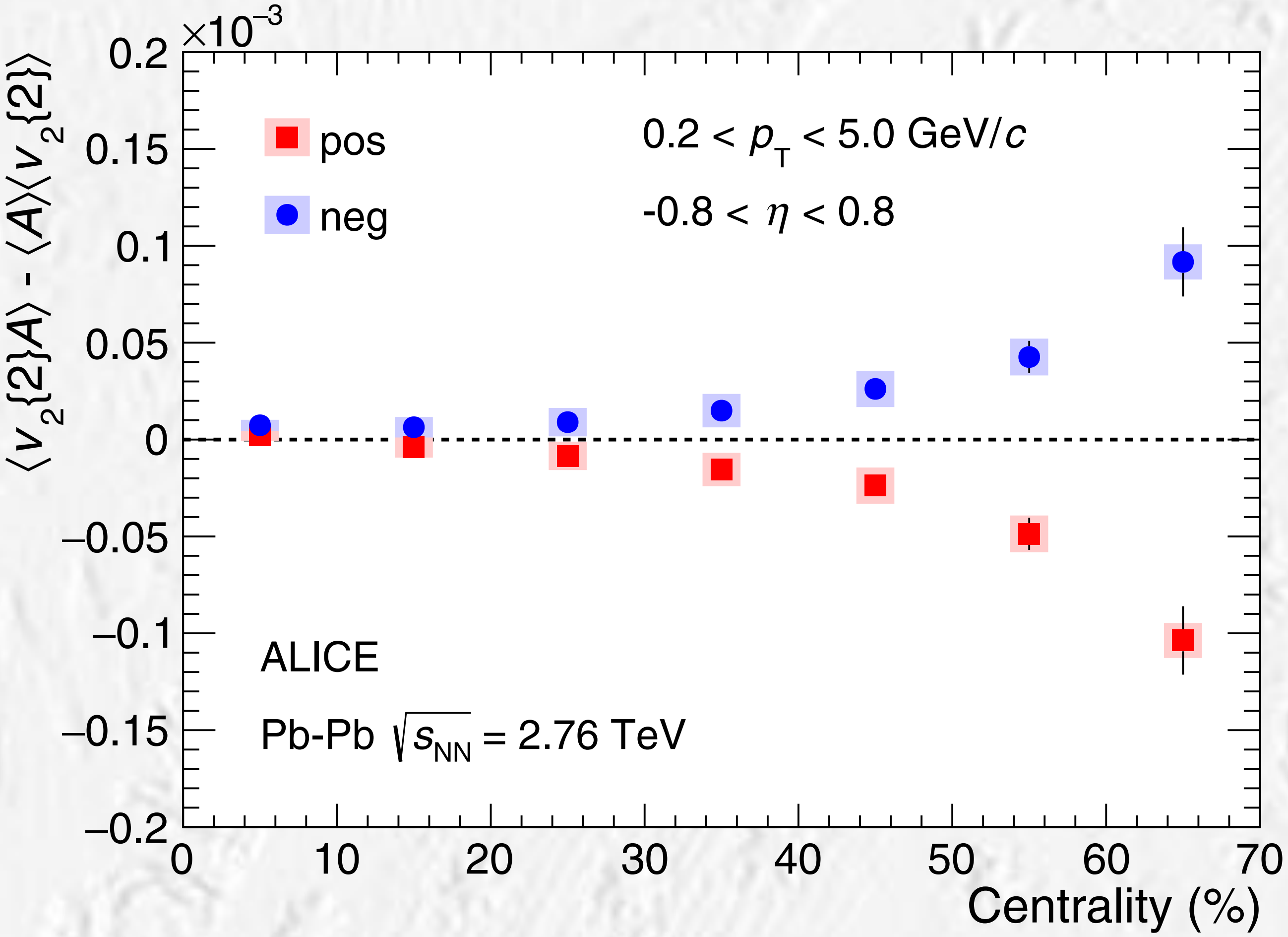
$\langle c_3 \rangle_1$ -- mean charge of particle “3” under condition of particle “1” being observed

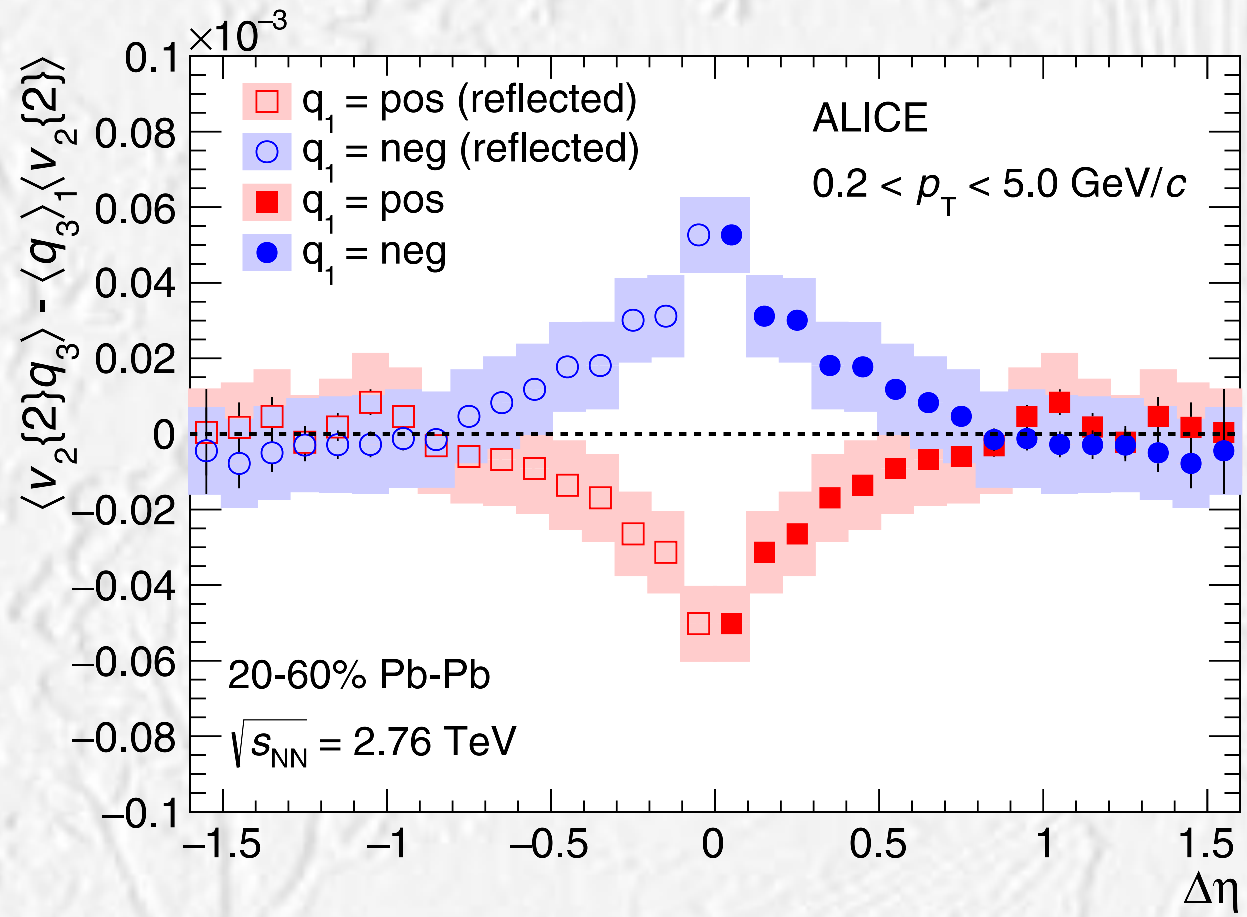
- is tracking efficiency independent
- allows differential studies
- can be used for direct comparison between different experiments

In the integral form the correlator is “equivalent” to the slope of Δv_2 vs A (=slope*sigma^2_A)

3pc, integral and differential

J. Adam *et al.* (ALICE Collaboration), Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C **93**, 044903 (2016).

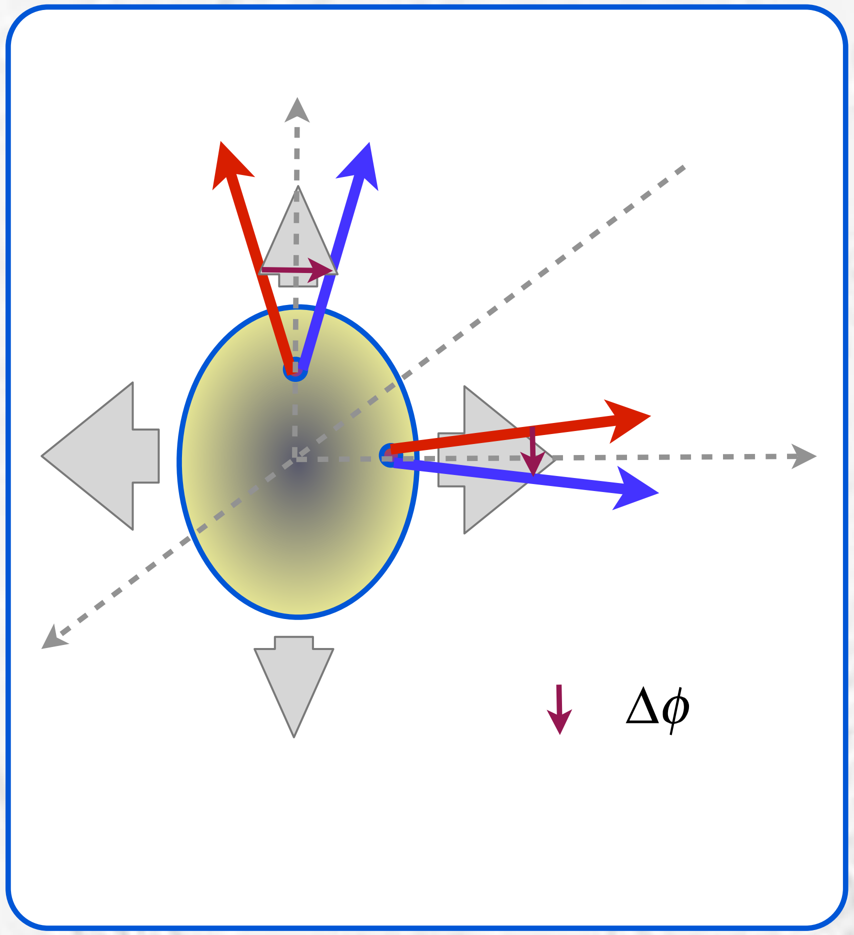


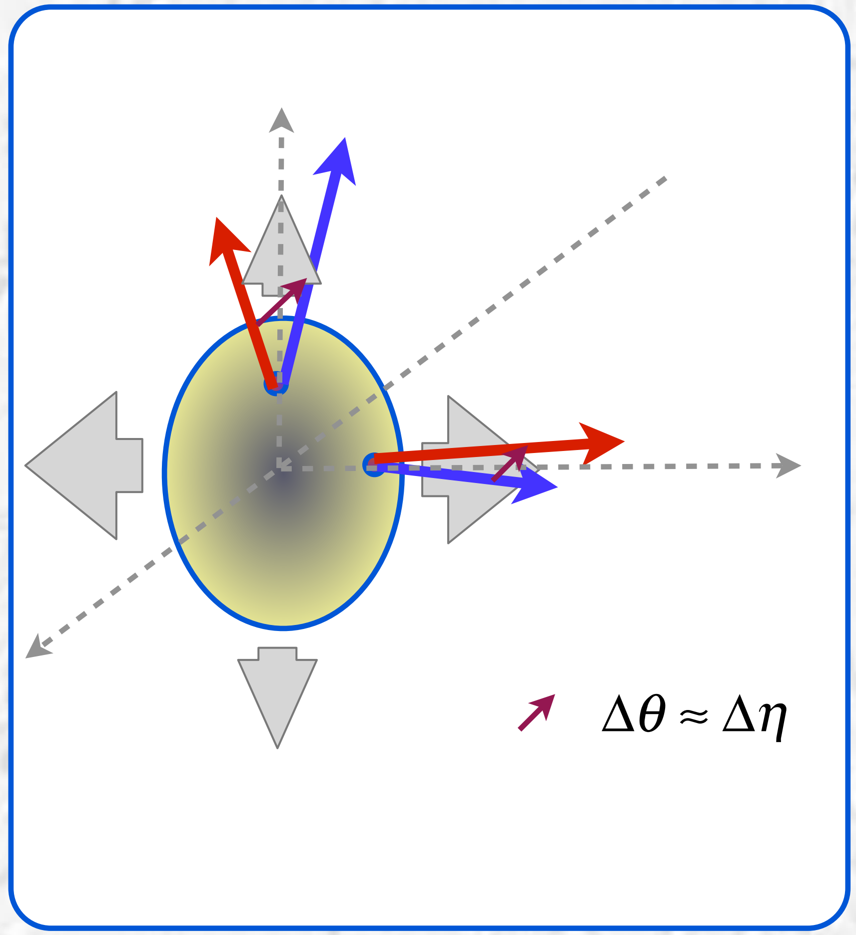


Clear signal, qualitatively consistent with expectations for CMW, pseudorapidity dependence similar to that of gamma correlator

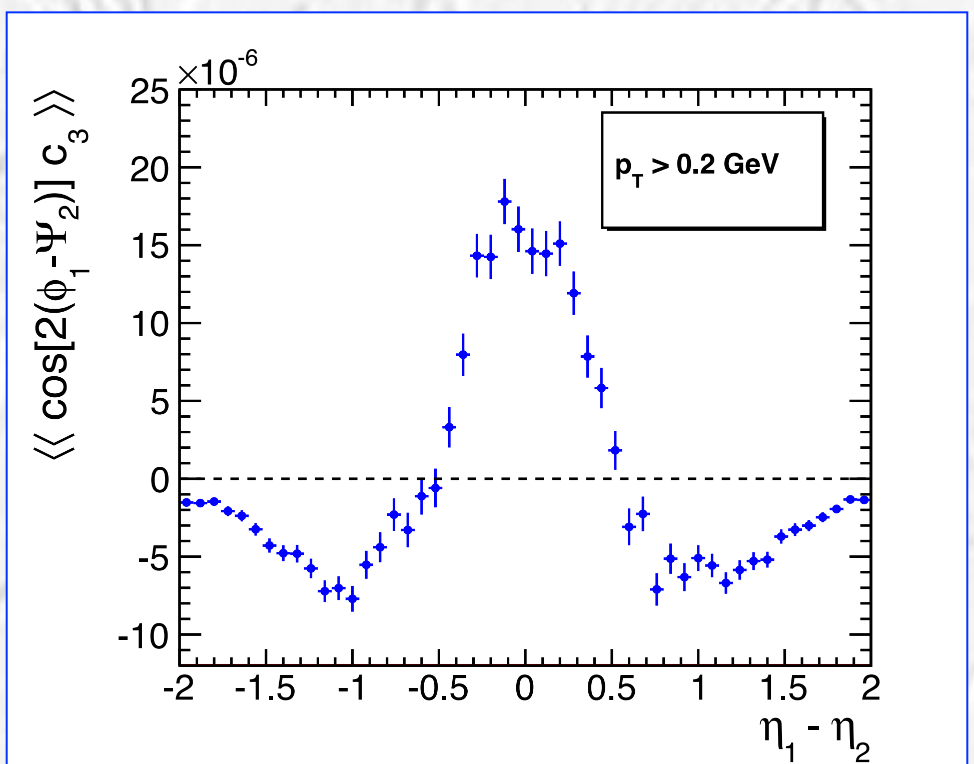
Possible background - LCC+RF

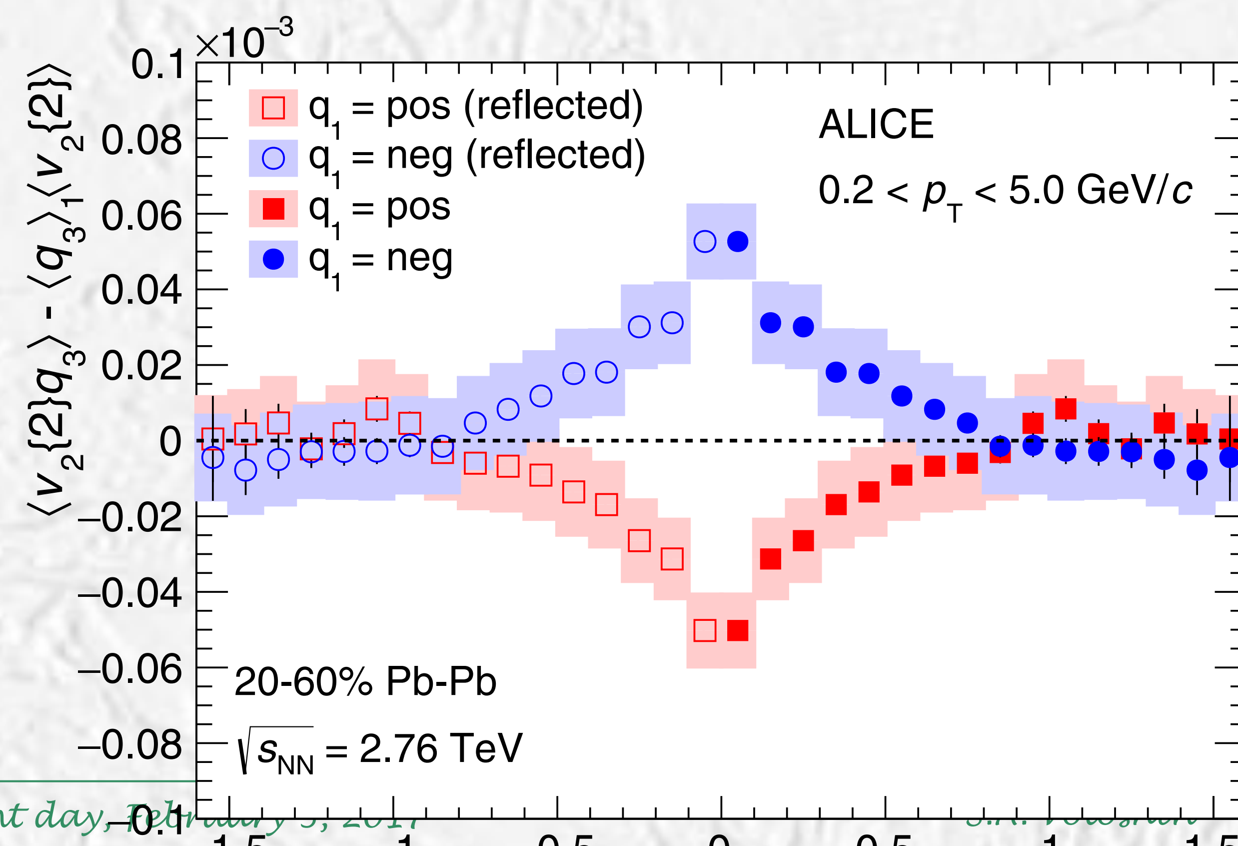
S.A. Voloshin, R. Belmont, Nuclear Phys. A 931 (2014) 992. arXiv:1408.0714





Larger radial flow narrows pair distribution in azimuth as well as in pseudorapidity





Hydro: LCC

A. Bzdak, P. Bożek / Physics Letters B 726 (2013) 239–243

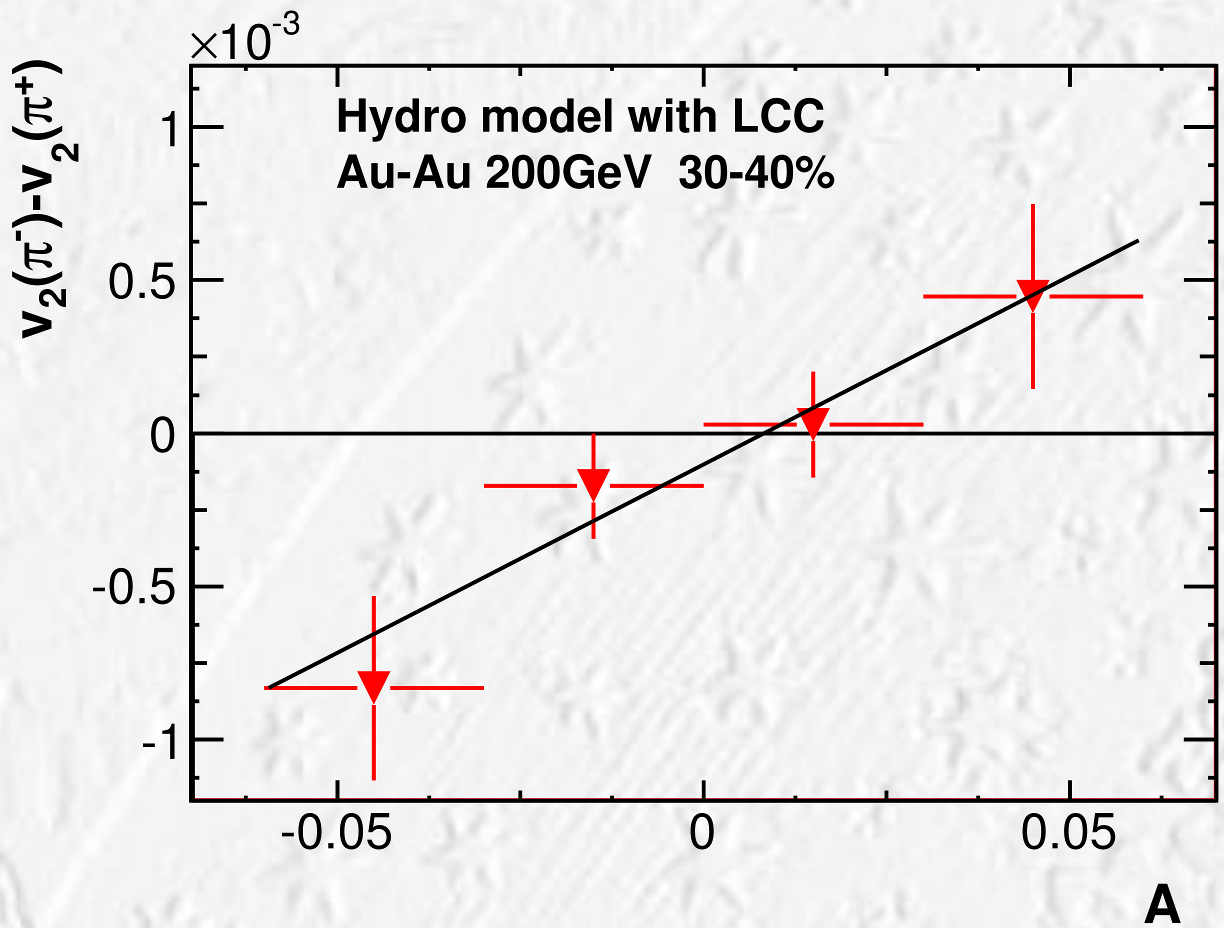


Fig. 4. The charge asymmetry dependence of π^+ and π^- elliptic flow coefficients in the hydrodynamic model followed by statistical emission with local charge conservation. We obtained $r = 0.012 \pm 0.004$ compared with the preliminary STAR data, $r_{exp} \approx 0.03$.

LCC = local charge conservation.

The results indicates that LCC plays a significant role (even though in this particular calculations it might underestimate the 'signal' by a factor of 3)

Signal vs background

It is likely that the current measurements are dominated by the "background" ("LCC"). The present goal — to get a 'reliable' upper/lower limits on the signal(s) and/or background at the level of at least ~0.1- 0.2 of todays "signals"

Signal depends on magnetic field/vorticity
the background depends on anisotropic flow

- Beam energy scan II (signal should disappear at lower energies)
- Vary magnetic field keeping the same flow (isobar collisions)
- Higher harmonic correlators (+ differential)
- Event Shape Engineering (increase/decrease background)
- Correlations with identified particles (e.g. for the next bullet)
- Cross-correlation of different observables, CME X CMW X CVE) (both in experiment and theory)
- U+U (body-body vs tip-tip ??)
- Very central collisions (Signal ~0, BG>0)
- Small system collision (??)

- Studies of EM fields
- Improving the phenomenology

Isobaric collisions (RHIC 2018?)

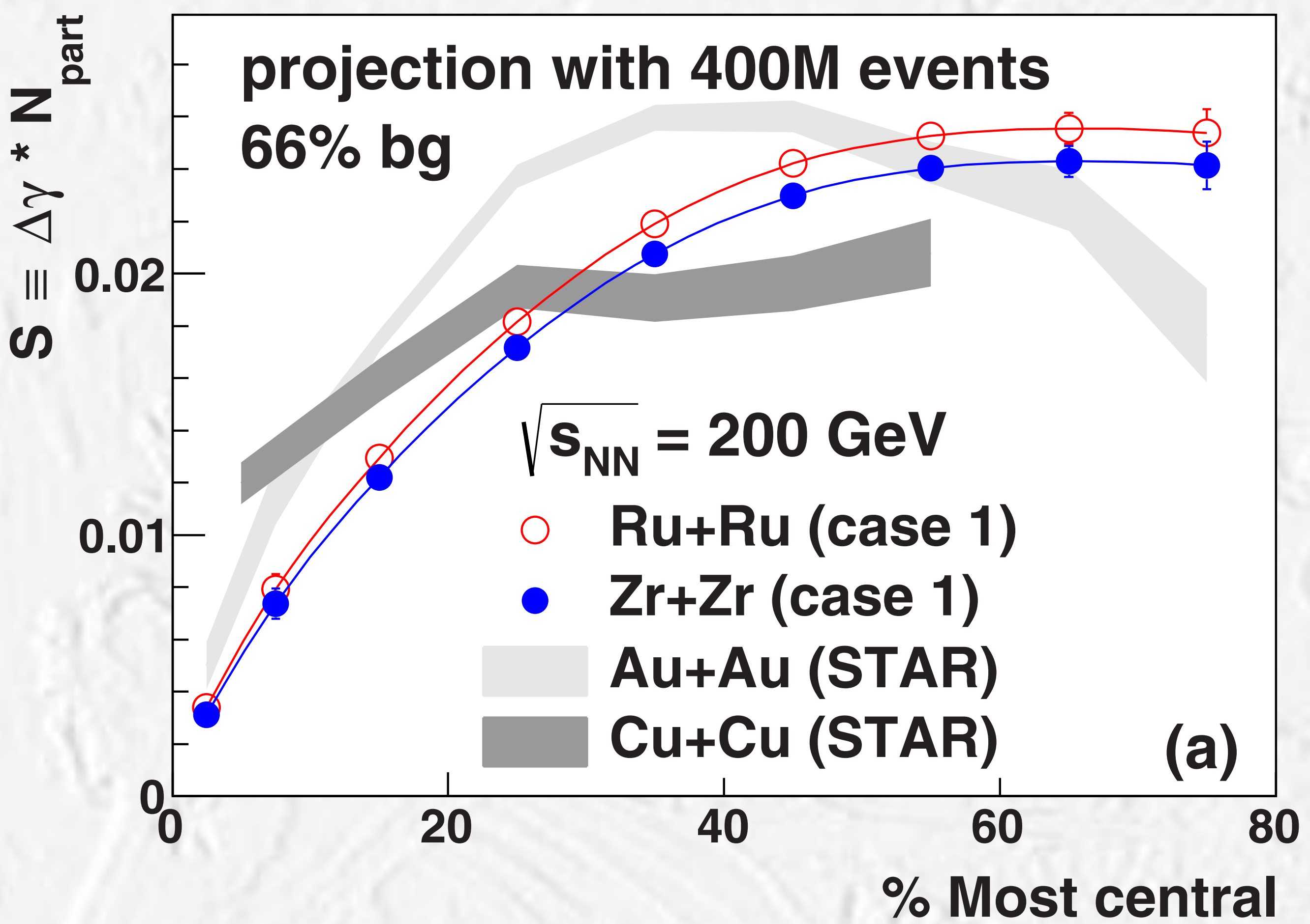
$$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru} \text{ and } ^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$$

S. A. Voloshin, Phys. Rev. Lett. **105**, 172301 (2010).

PHYSICAL REVIEW C **94**, 041901(R) (2016)

Testing the chiral magnetic effect with isobaric collisions

Wei-Tian Deng,[1] Xu-Guang Huang,[2,3] Guo-Liang Ma,[4] and Gang Wang[5]



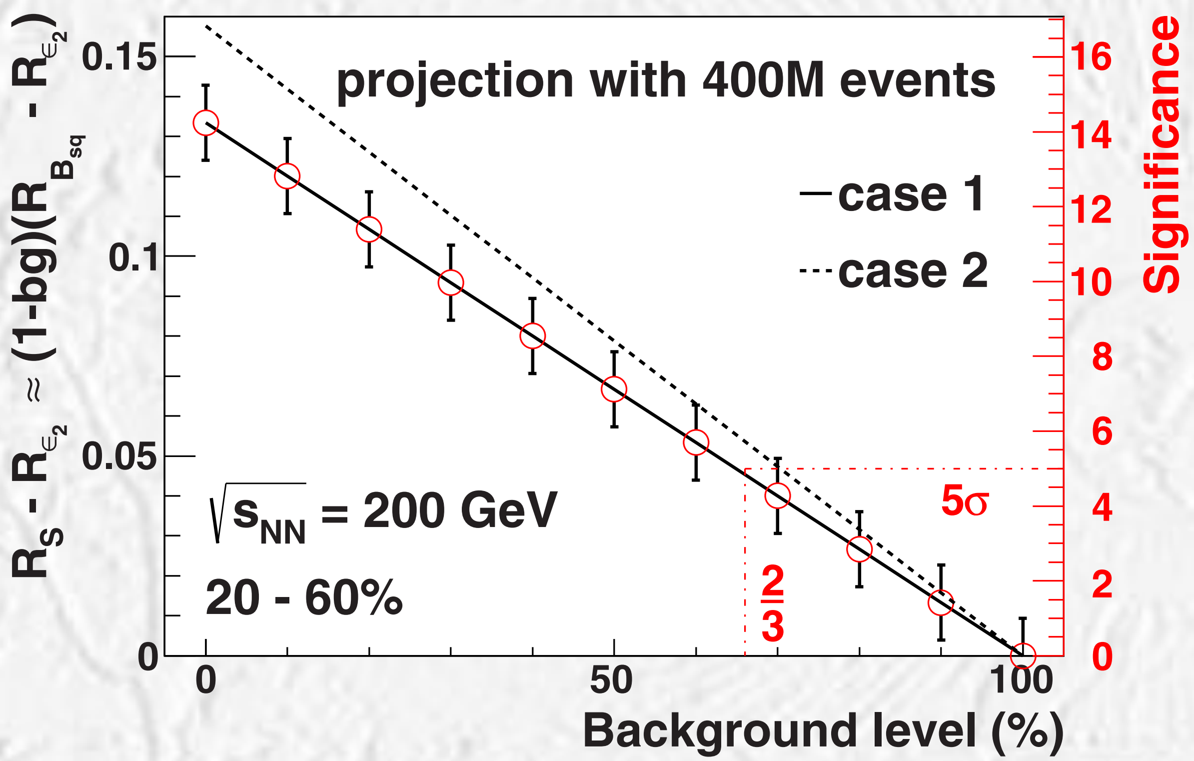
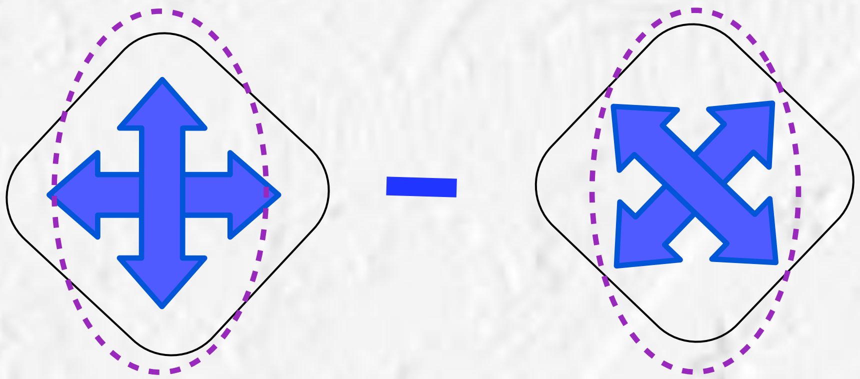


FIG. 4. Magnitude (left axis) and significance (right axis) of the relative difference in the CME signal between Ru + Ru and Zr + Zr at 200 GeV, $R_S - R_{\epsilon_2}$ as a function of the background level.

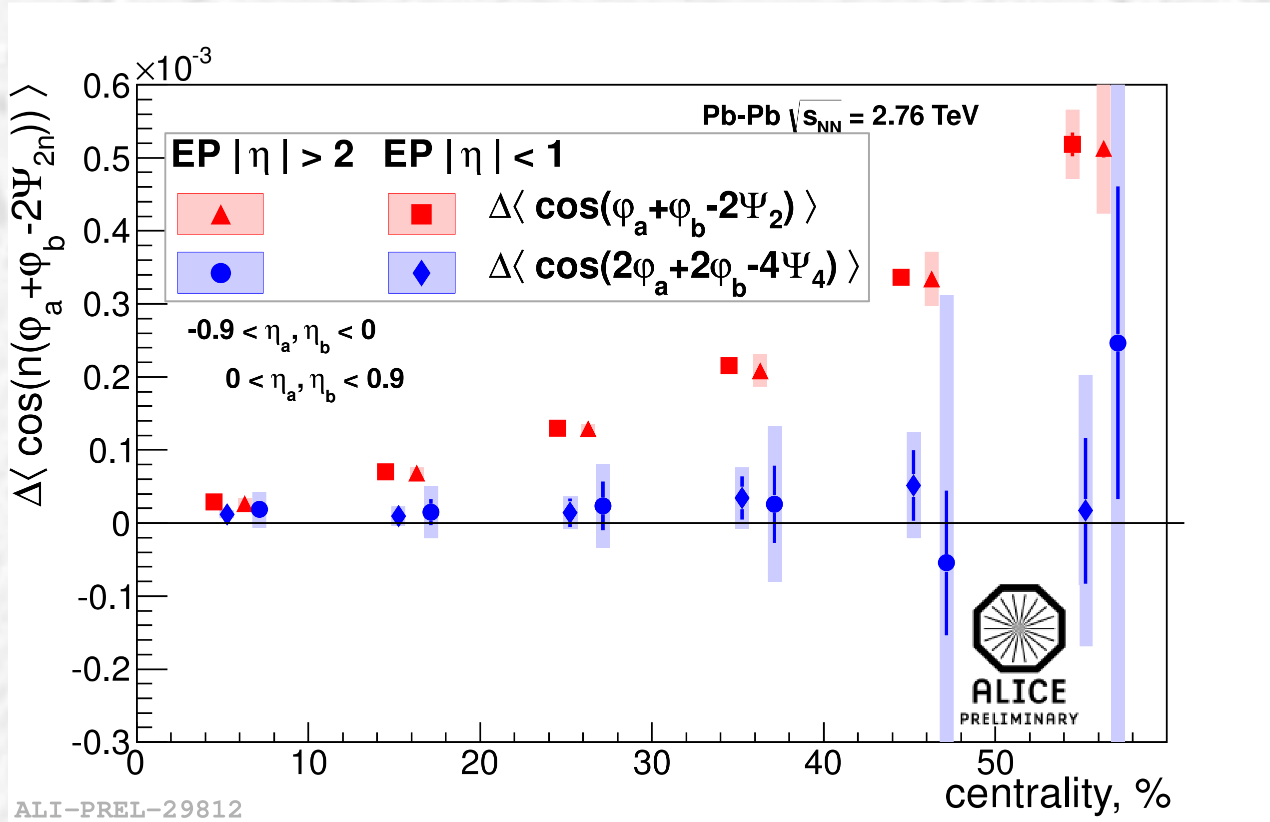
"Higher harmonics" correlators

CME: "Double harmonic" gamma

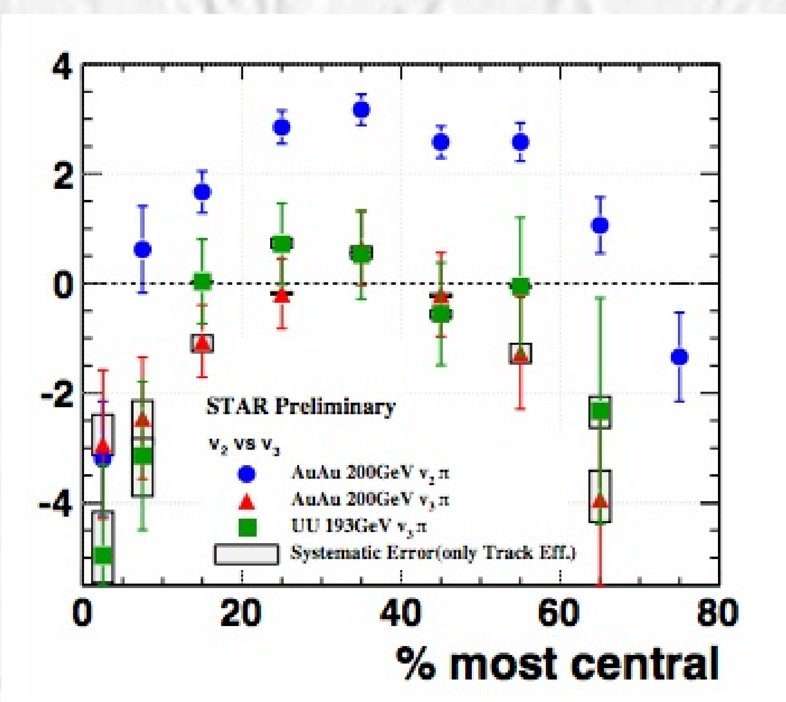


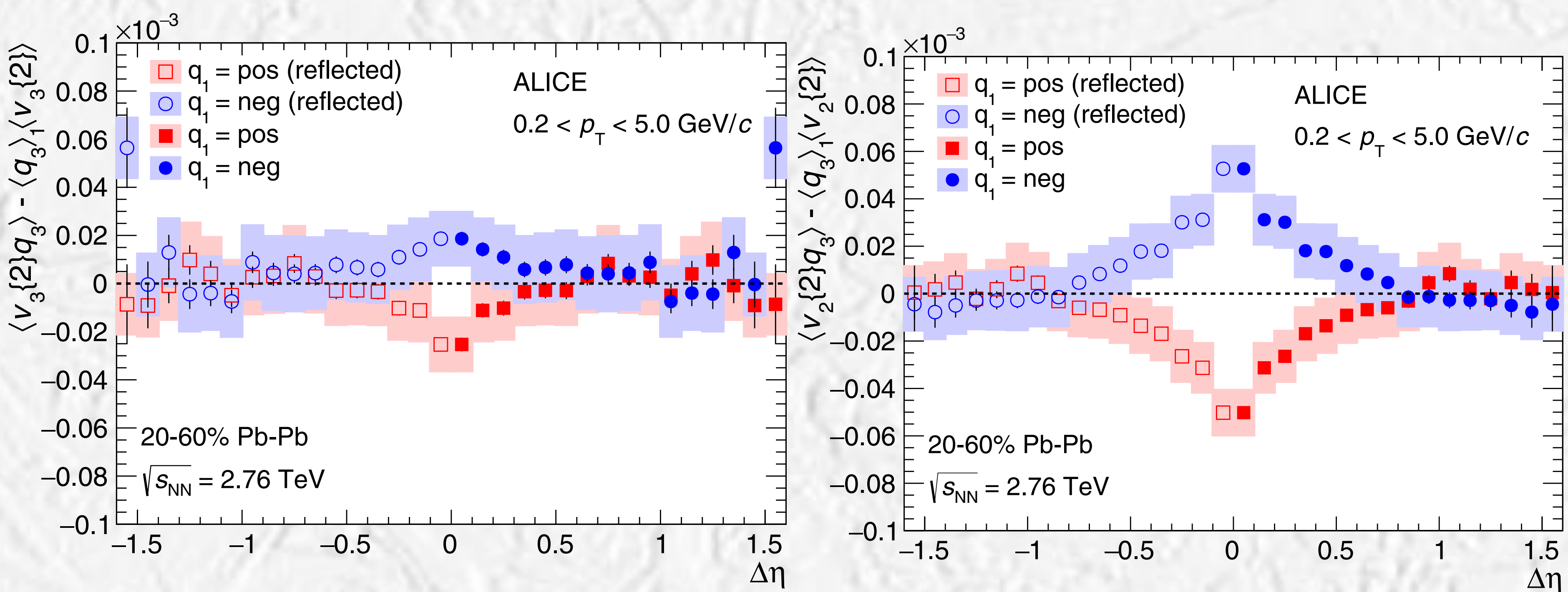
$$\Delta\langle\ldots\rangle = \langle\ldots\rangle_{\text{opposite}} - \langle\ldots\rangle_{\text{same}}$$

Needs more/better data



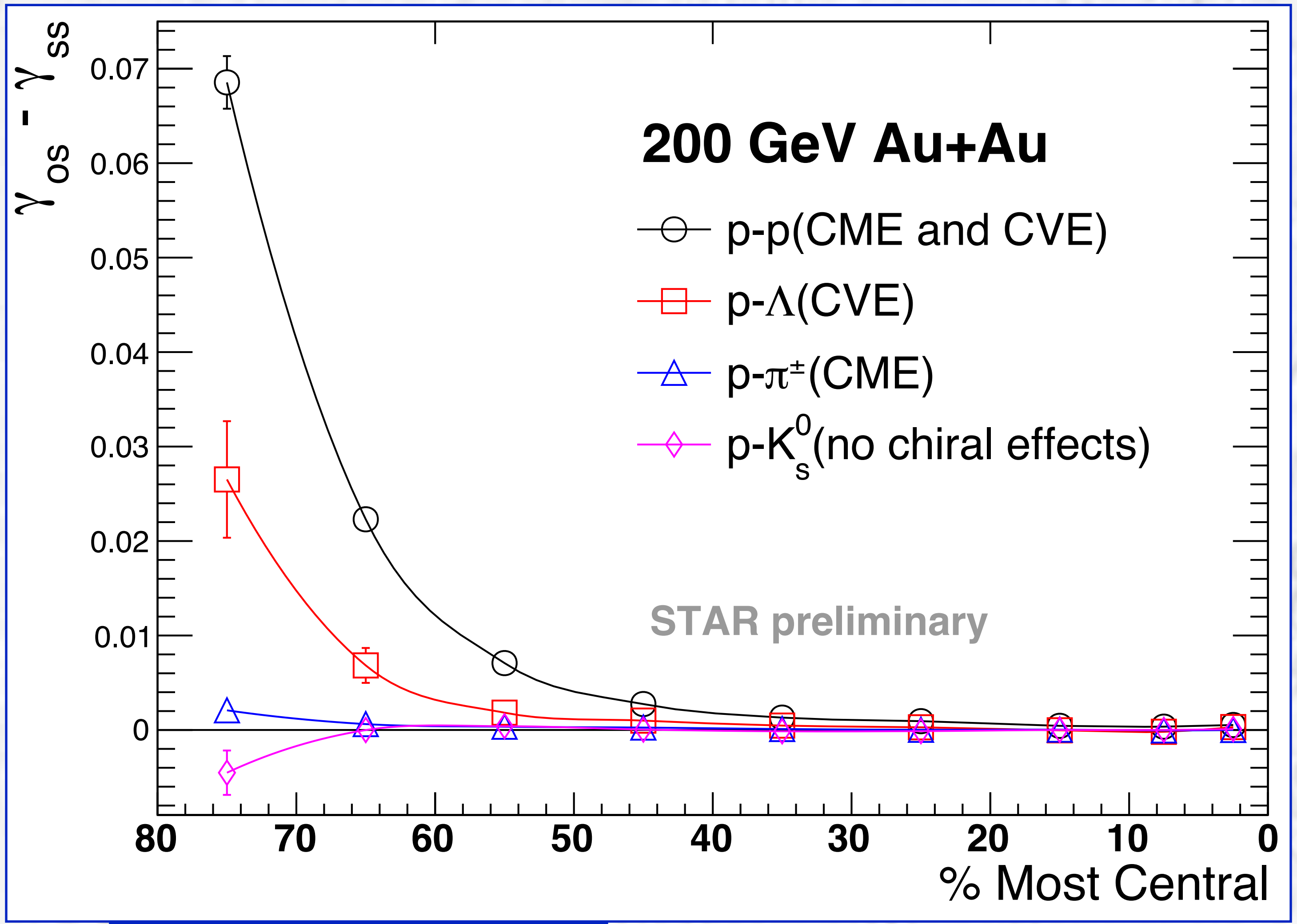
CMW: v2 vs Ach, 3 pt correlator

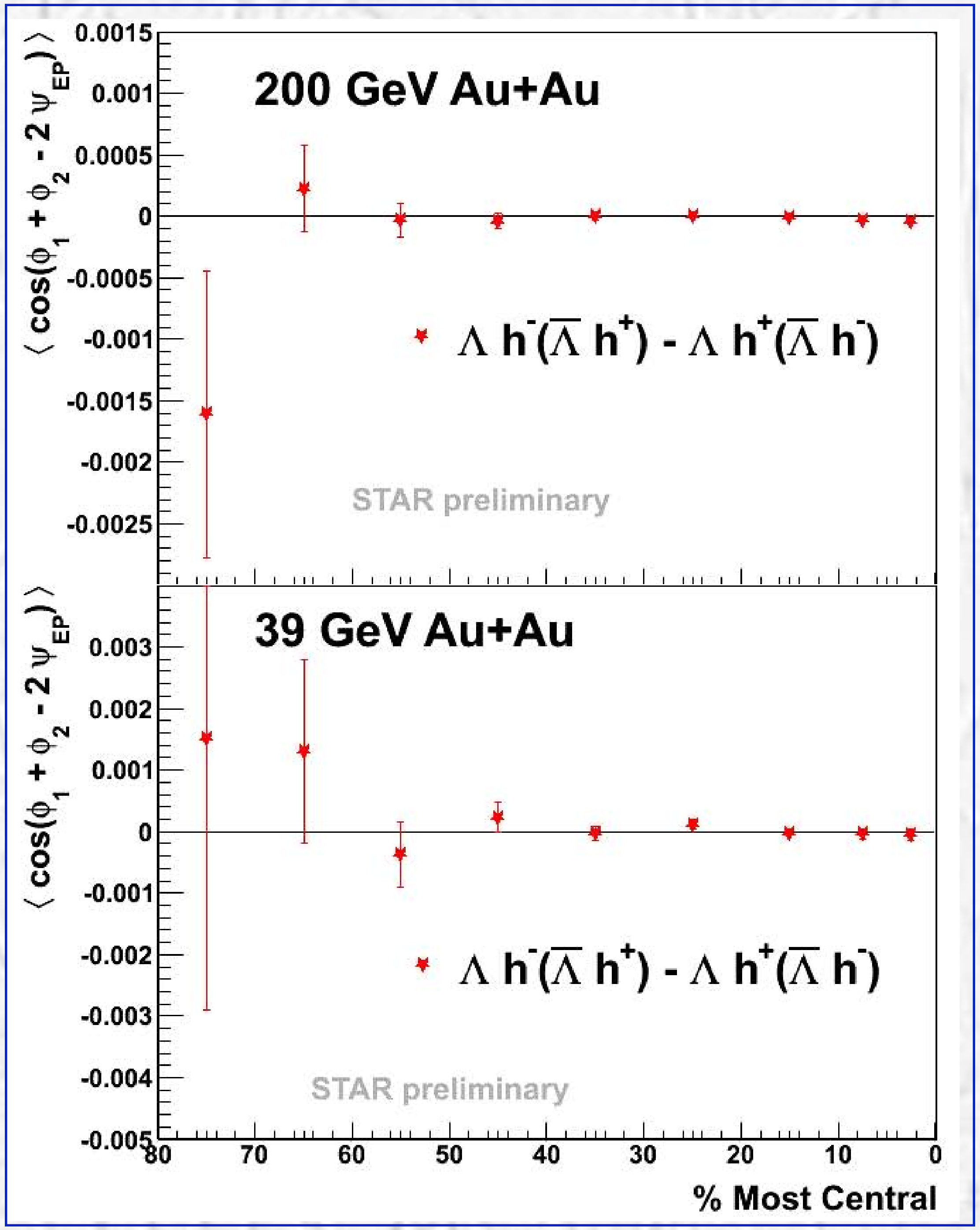




Cross correlations: CVE x CME comparison

(identified particle correlations)

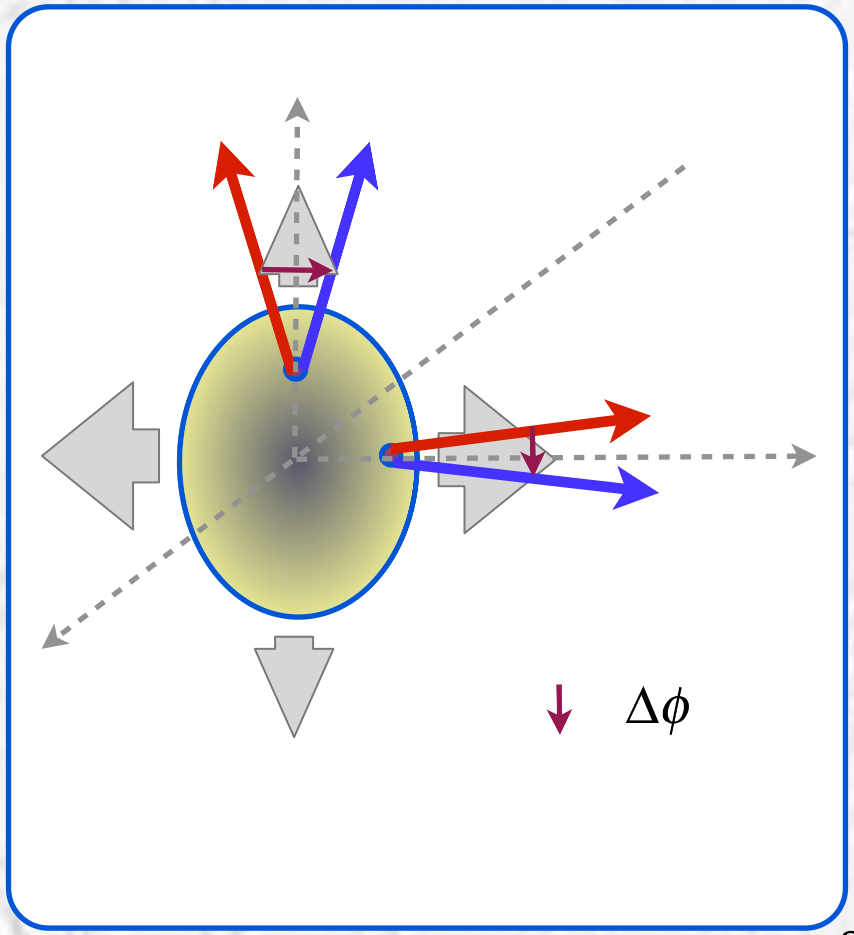


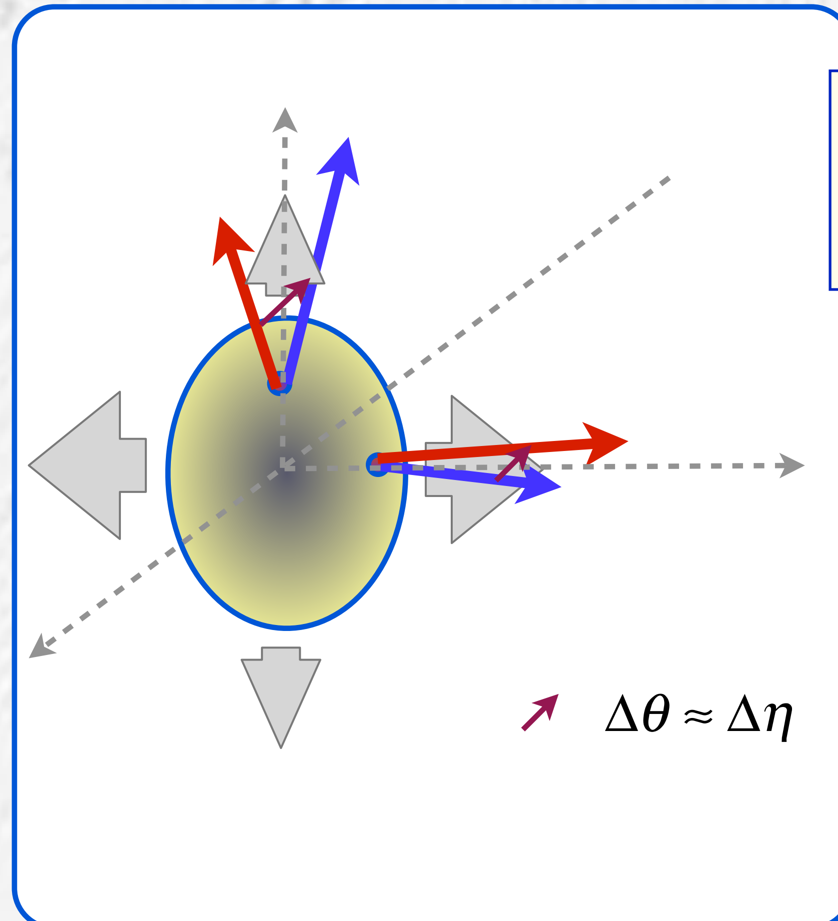


Lambda - CVE
proton - CVE+CME
pion - CME
K^0 - nothing?

Zero Lambda-pion correlations might be in contradiction to "CVE" and "CME" effect explanation

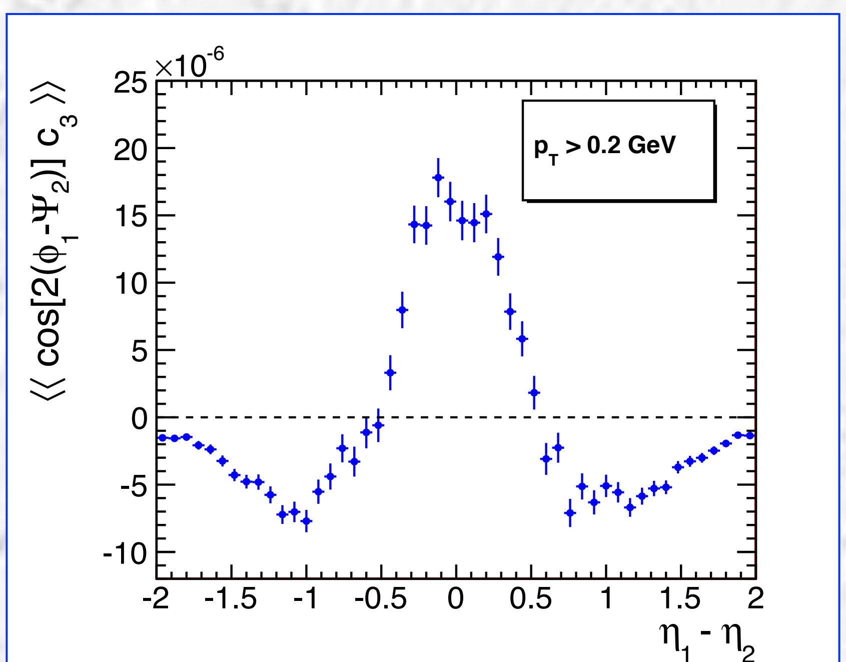
Cross-correlations: LCC in azimuth and (pseudo)rapidity

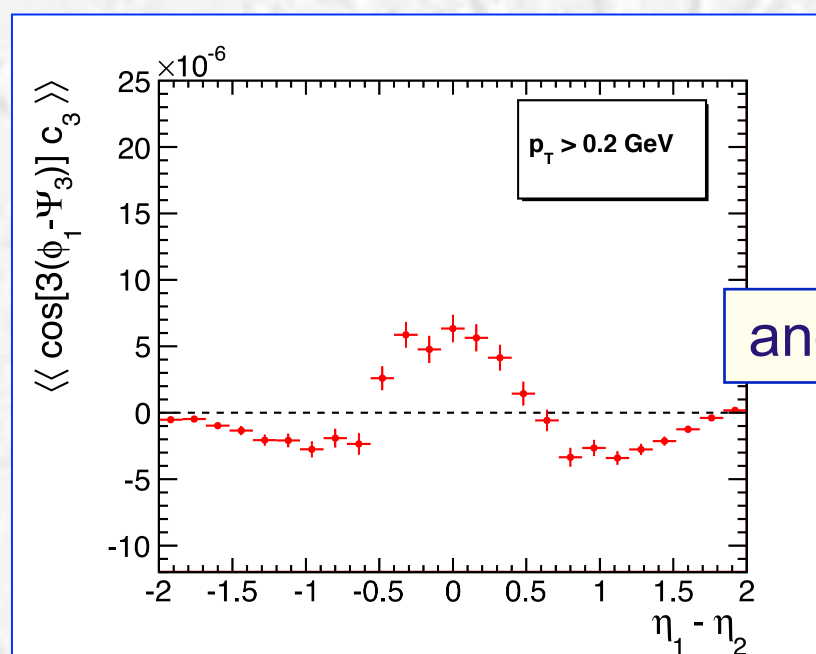




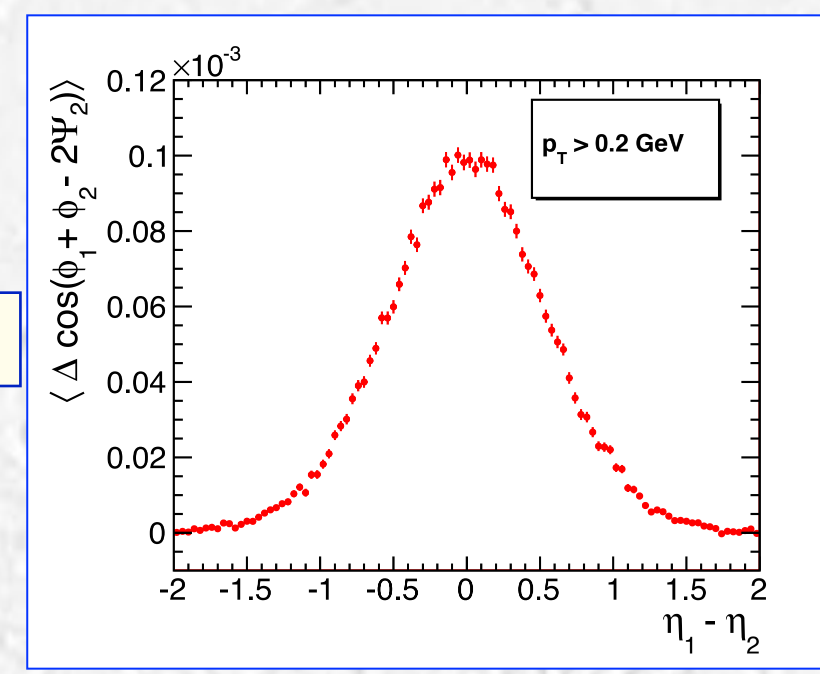
Larger radial flow narrows pair distribution in azimuth as well as in pseudorapidity

S.A. Voloshin, R. Belmont, Nuclear Phys. A 931 (2014) 992. arXiv:1408.0714





and



Event Shape Engineering

Jürgen Schukraft[a], Anthony Timmins[b], Sergei A. Voloshin[c,*]
Physics Letters B 719 (2013) 394–398

1. Select events based on q_n-*vector* in one momentum region ("subevent")
2. Perform an analysis of these events in another region (subevent).

$$X_n = \sum_{i=1}^{M} \cos(n\phi_i); \quad Y_n = \sum_{i=1}^{M} \sin(n\phi_i)$$

$$Q_n = \{X_n, iY_n\}; \quad q_n = |Q_n|/\sqrt{M}$$

ESE with cutting on q_2:
variation of flow values up to factor of ~2

MC Glauber, with parameters tuned to LHC multiplicity and flow, $0<\eta_a<0.8$

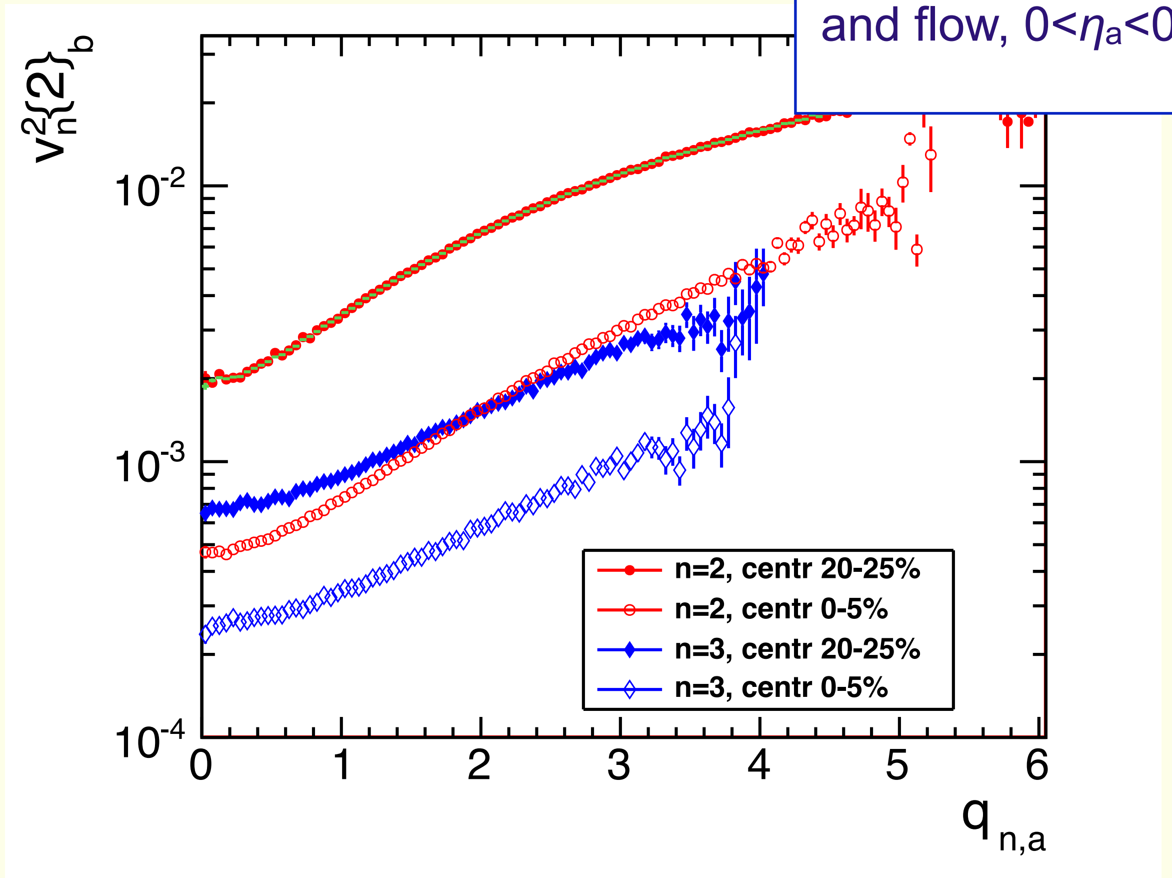


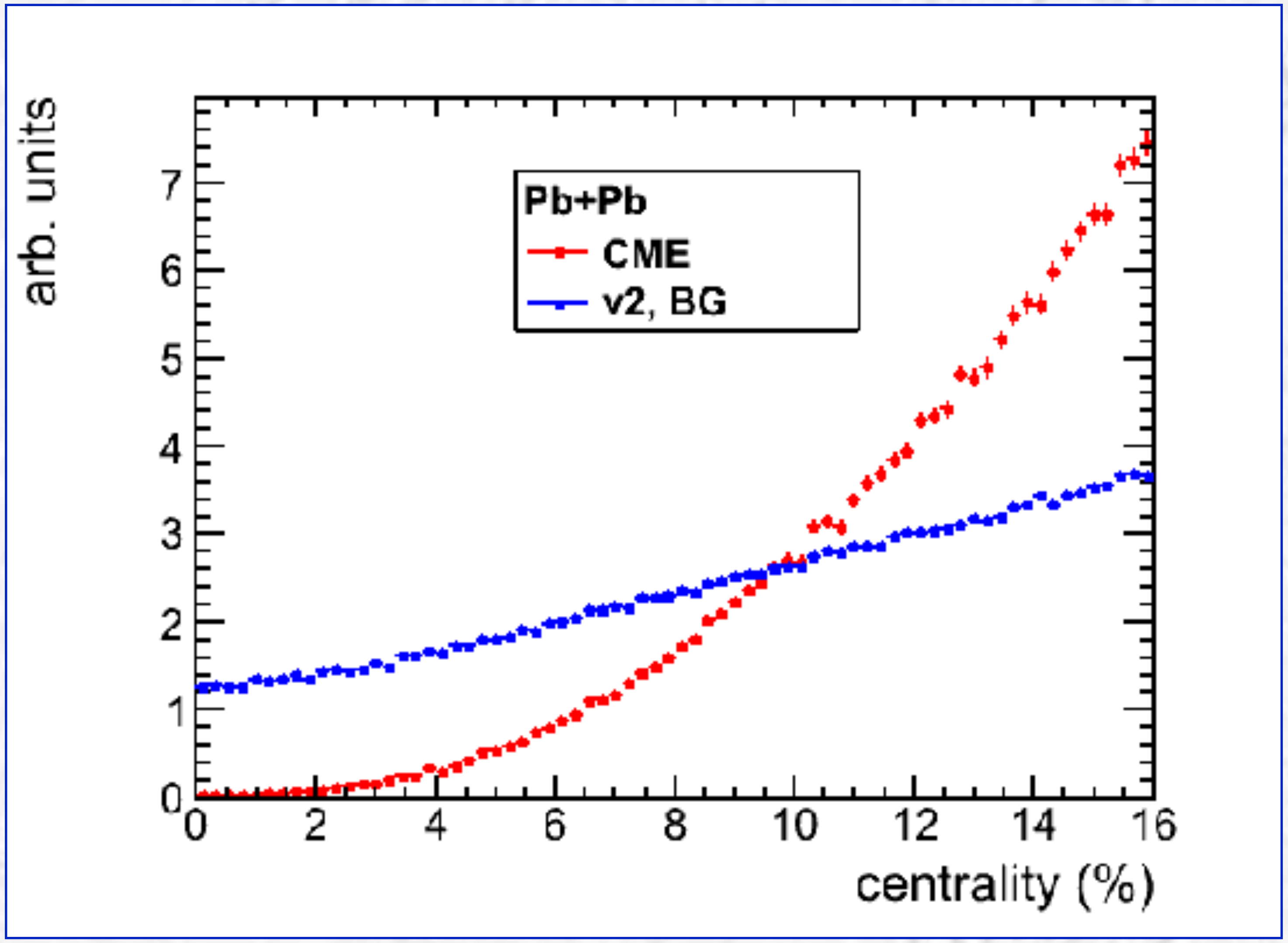
FIG. 1. (color online) Mean elliptic and triangular flow values in a-subevent as function of the corresponding q_n magnitude in b-subevent.

BG ~ v_2,
Signal - much weaker dependence (mostly due to decorrelations between **B** and Ψ_2

"gamma" correlator in central collisions

$$\gamma_B \propto \langle B^2 \cos(2\Psi_B - 2\Psi_2)\rangle$$

S. Chatterjee and P. Tribedy, Phys. Rev. **C92**, 011902 (2015), 1412.5103.



In central collisions, the CME effect should be suppressed due to decorrelation between direction of magnetic field and elliptic flow plane, while BG should remain finite

EM field lifetime. Quark density evolution

E-conductivity, quark production time, etc...

L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190

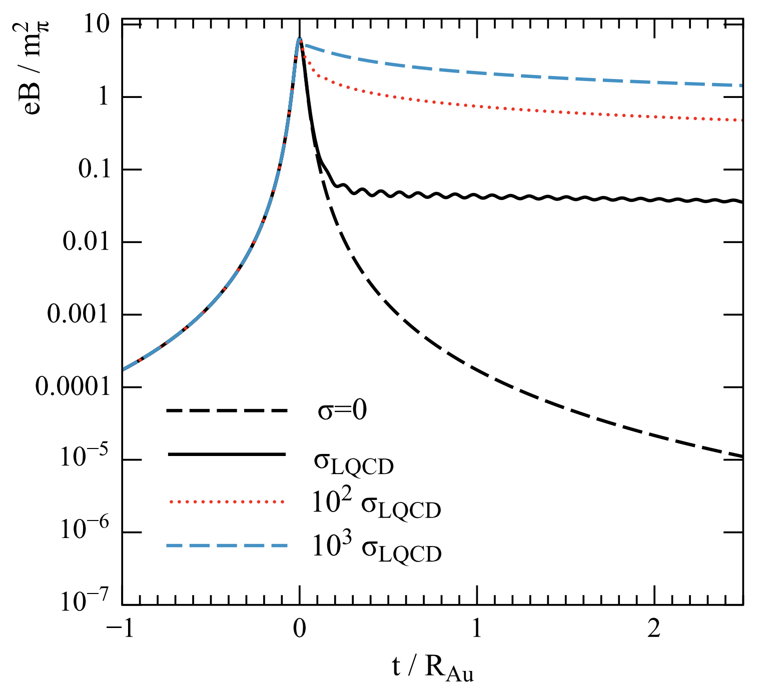


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

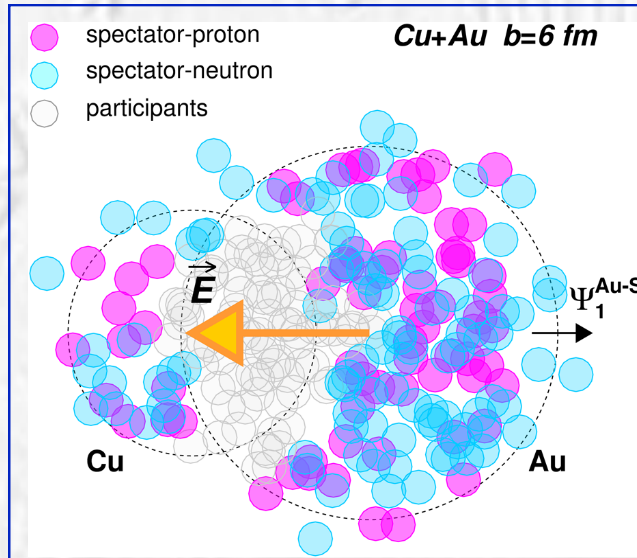
In a conducting plasma the induction can make the field long lived.

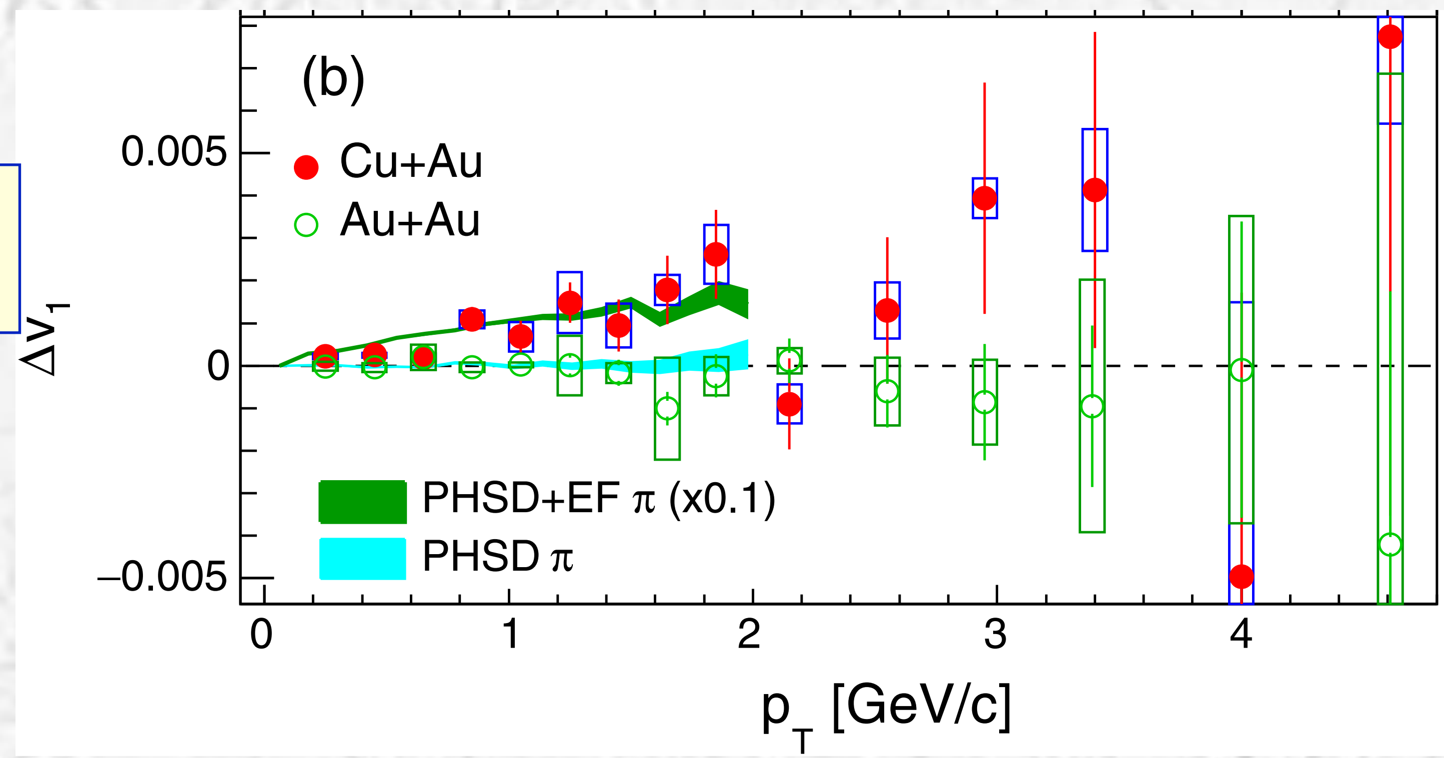
K. Tuchin, Particle production in strong electromagnetic fields in relativistic heavy-ion collisions, Adv. High Energy Phys. **2013**, 490495 (2013).

PRL **118,** 012301 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Charge-Dependent Directed Flow in Cu + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

(STAR Collaboration)



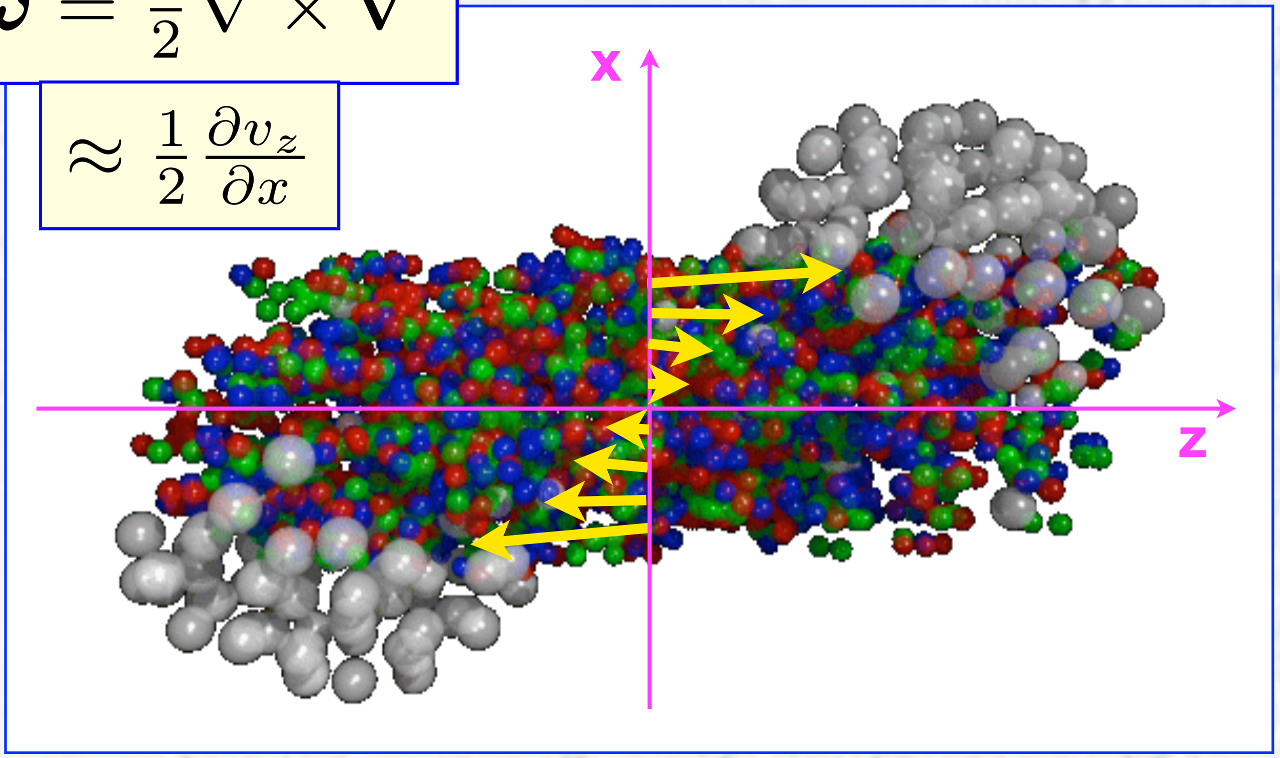


At the time of the strong EM fields (~0.25 fm) only about 10% of all charges are produced

Vorticity

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \mathbf{v}$$

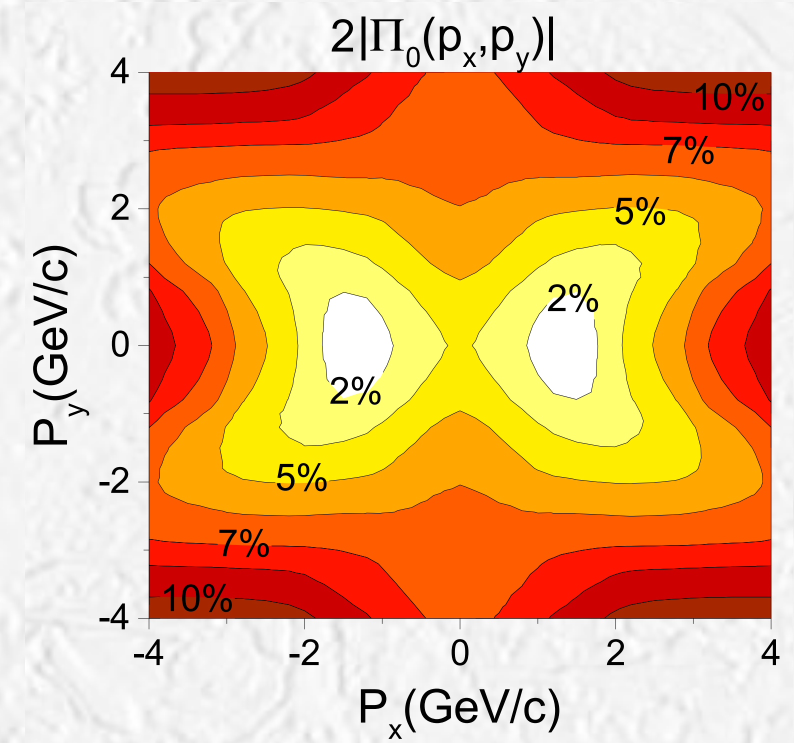
$$\approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$



Global polarization

Erratum: Λ Polarization in Peripheral Heavy Ion Collisions
F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C 88, 034905 (2013)

F. Becattini, L.P. Csernai, D.J. Wang, and Y.L. Xie



Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]
PHYSICAL REVIEW C **94**, 044910 (2016)

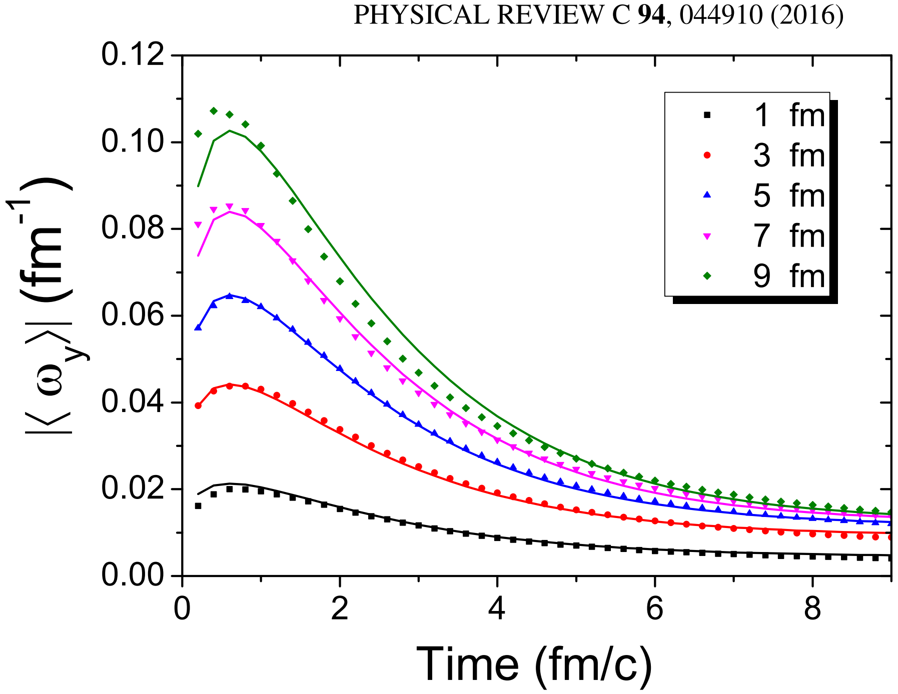


FIG. 11. Averaged vorticity $\langle\omega_y\rangle$ from the AMPT model as a function of time at various impact parameter b for fixed beam energy $\sqrt{s_{NN}} = 200$ GeV. The solid curves are from a fitting formula (see text for details).

Directed flow

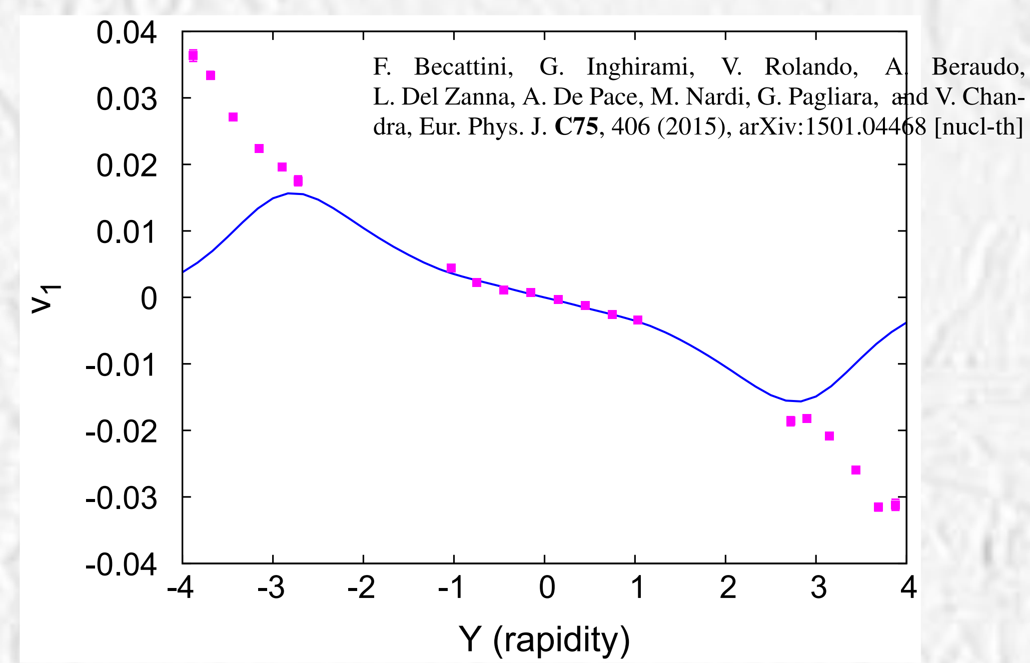


Fig. 8 Directed flow of pions at $\eta/s = 0.1$ and $\eta_m = 2.0$ compared with STAR data [22]

Summary

Very important and interesting physics.

The first measurements qualitatively agree with expectations, but likely are dominated by the "background" ("LCC")

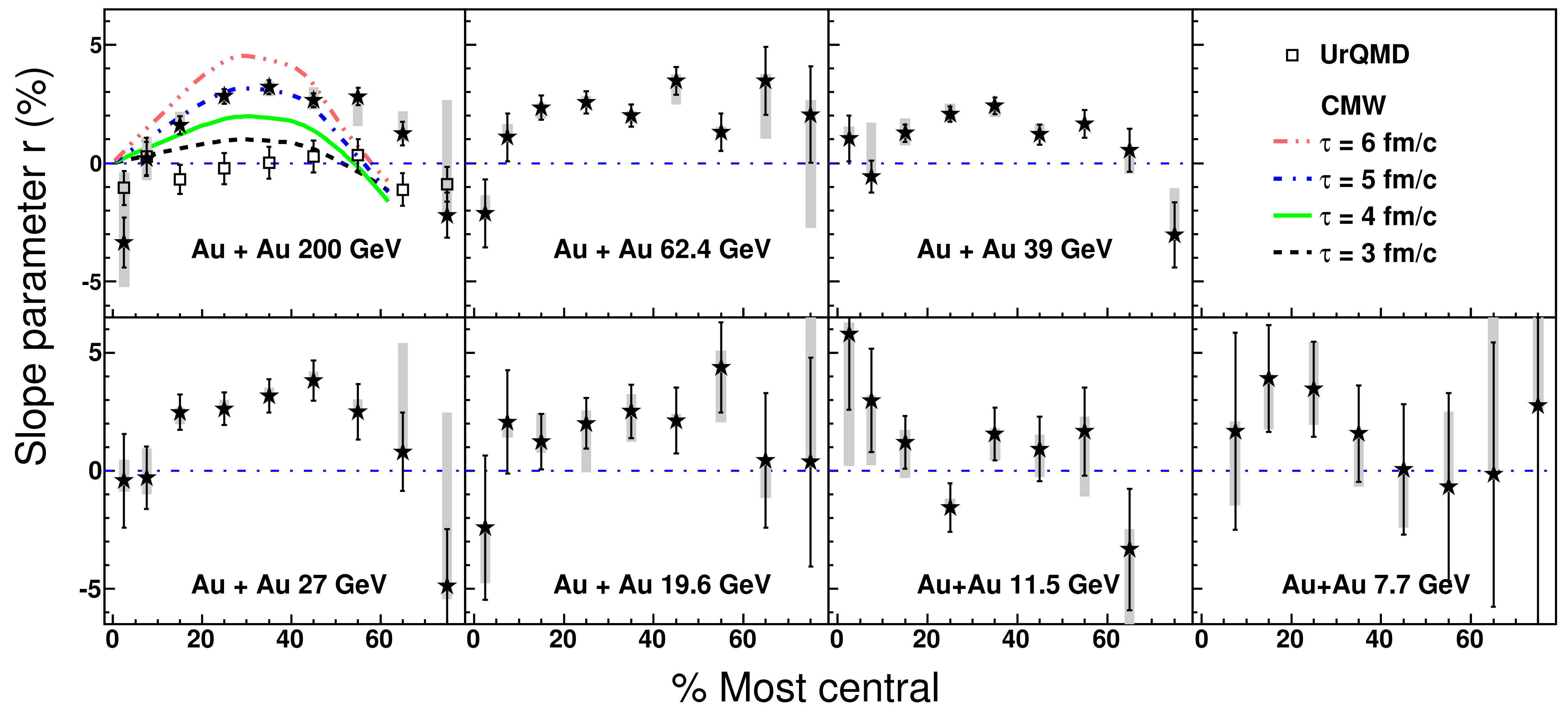
Current goal: get a 'reliable' upper/lower limits on C'XY' signal(s) and/or background contributions at the level of ~0.1-0.2 of todays "signals"

Hopefully QM2017 will bring more results/insights

EXTRA SLIDES

Centrality/energy dependence

L. Adamczyk *et al.* (STAR Collaboration), Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions, Phys. Rev. Lett. **114**, 252302 (2015).



Energy dependence is not that obvious