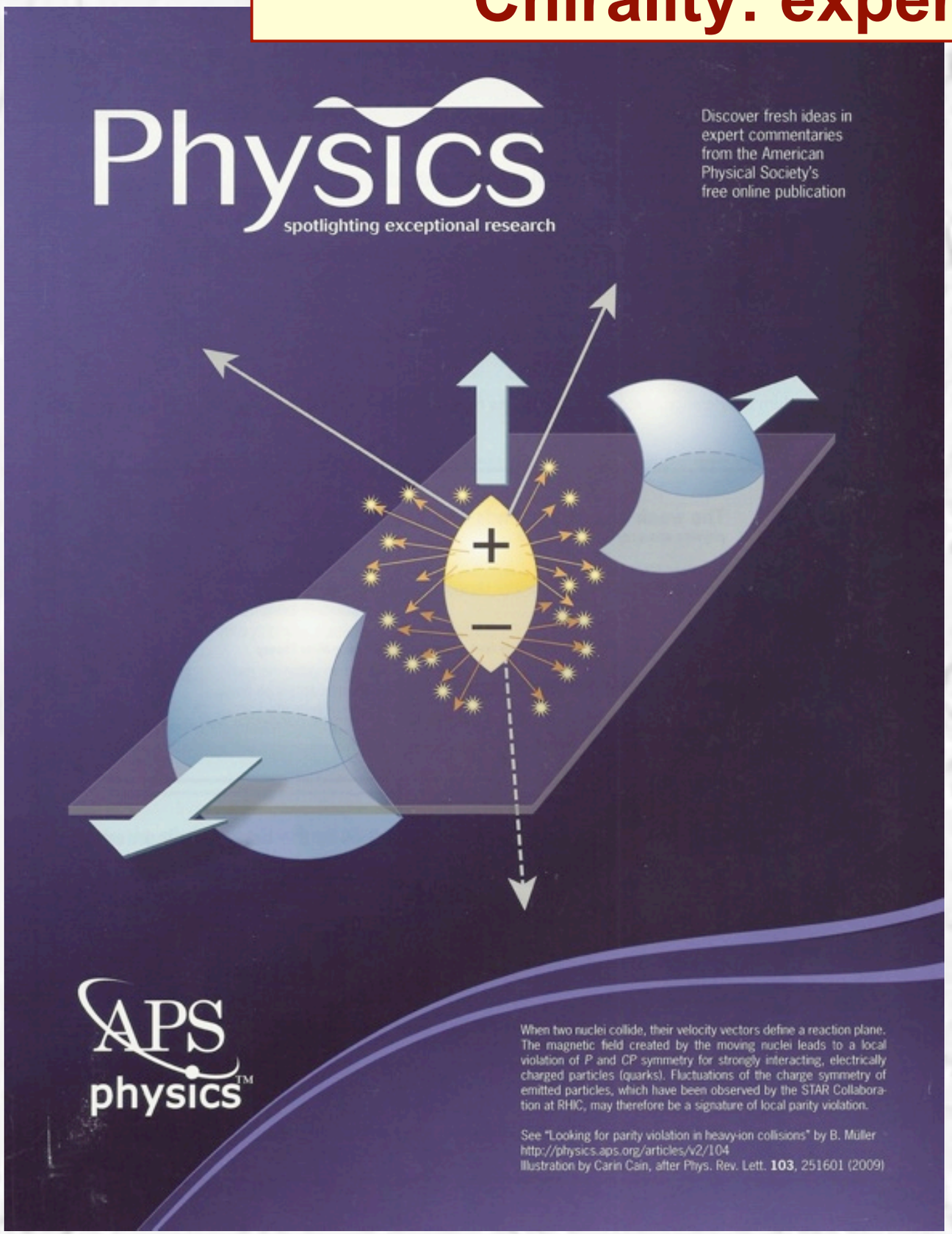
Chirality: experimental overview



Sergei A. Voloshin WAYNE STATE UNIVERSITY

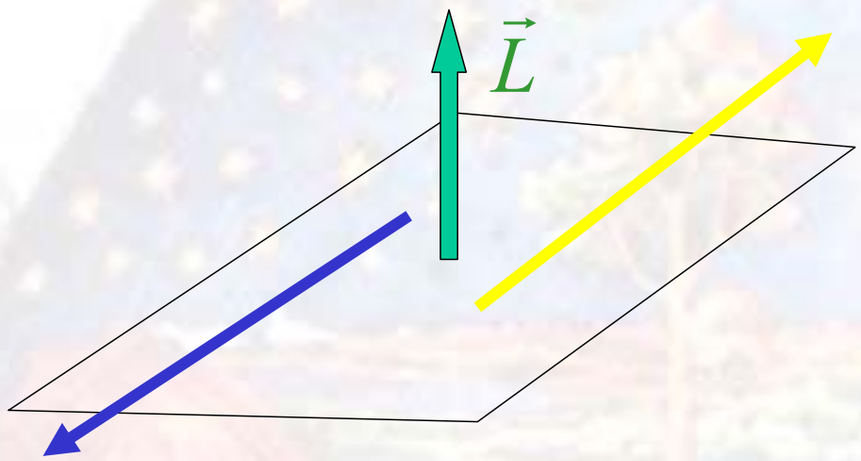
Outline:

- Brief history / introduction
- Some old and new results
- Assumptions, and assumptions, realistic and not realistic
- New approaches
- EM fields estimates
- Current limits and near future

Mostly on CME; CMW, CVE, only in passing

Parity violation study with 3 particle correlations

Sergei Voloshin
Wayne State University



New history, 2004

Looking for the effect of
D. Kharzeev, hep-ph/0406125

Mixed harmonic technique or 3-particle correlations

hep-ph/0406311

$$\frac{dN}{d\varphi} \propto 1 + 2a\sin\varphi$$

a > 0 ➔ preferential emission along the angular momentum
The sign can vary event by event, $a \sim Q/N_\pi$, where Q is the topological charge, |Q|=1,2,...
➔at dN/dy~100, |a|~1%.

projections onto reaction plane

Projections on the direction of angular momentum

$$\left\langle \cos(\varphi_a - \Psi_2)\cos(\varphi_b - \Psi_2) - \sin(\varphi_a - \Psi_2)\sin(\varphi_b - \Psi_2) \right\rangle =$$
$$= \left\langle \cos(\varphi_a + \varphi_b - 2\Psi_2) \right\rangle = (v_{1,a}v_{1,b} - a_a a_b)\left\langle \cos(2\Psi_2 - 2\Psi_{RP}) \right\rangle$$

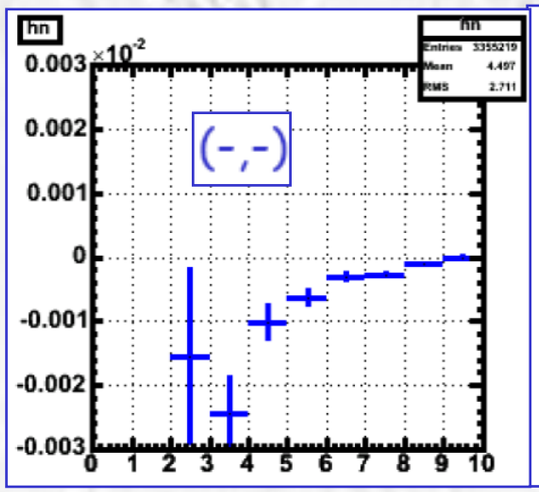
All effects non sensitive to the RP cancel out!

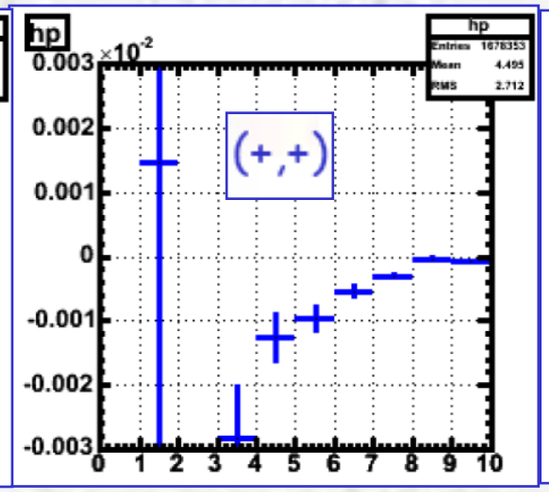
Possible systematics: clusters that flow

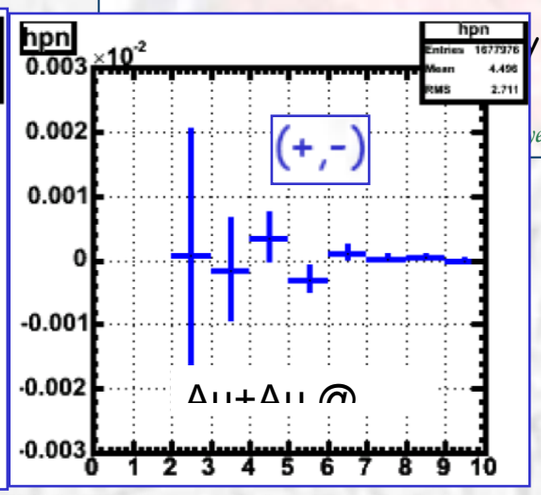
And using only one particle instead of the event flow vector

$$\left\langle \cos(\varphi_a - \varphi_c)\cos(\varphi_b - \varphi_c) - \sin(\varphi_a - \varphi_c)\sin(\varphi_b - \varphi_c) \right\rangle =$$
$$= \left\langle \cos(\varphi_a + \varphi_b - 2\varphi_c) \right\rangle = (v_{1,a}v_{1,b} - a_a a_b)v_{2,c}$$

y region symmetric with respect to the midrapidity v_1=0







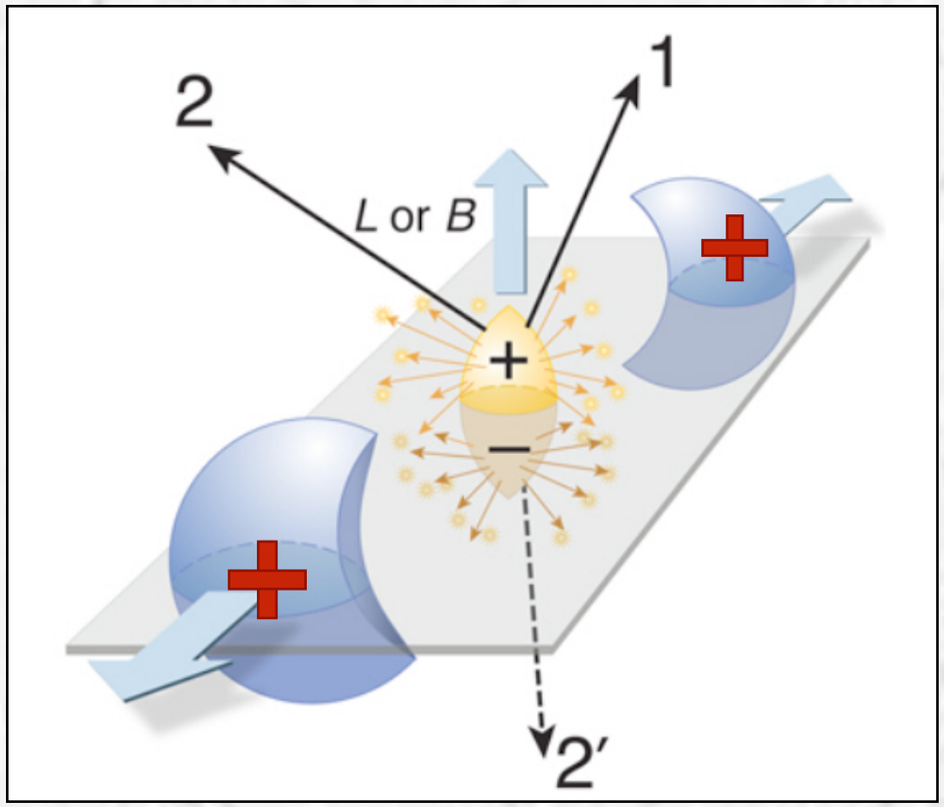
Only (semi-)qualitative predictions from theory: charge separation along the magnetic field

- Still true today (?)

Note cartoon from a discussion of the global polarization

“Gamma” correlator

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

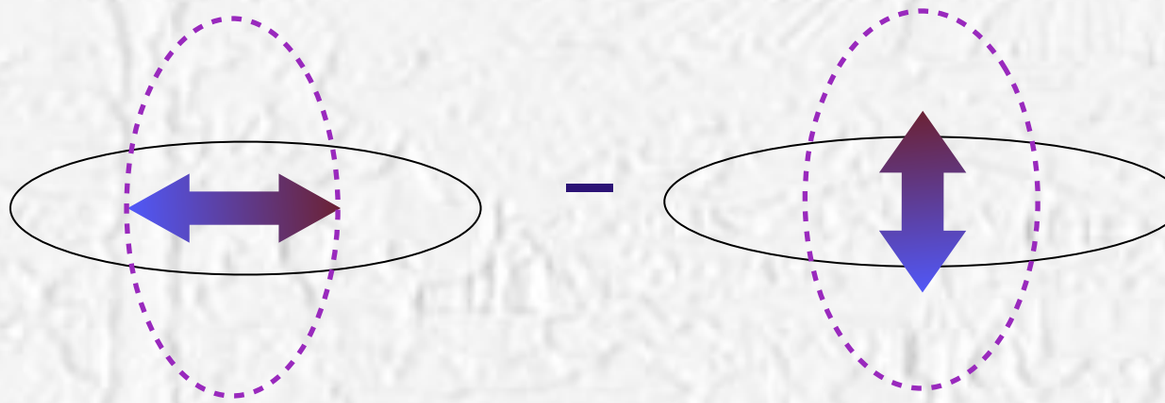


Effective particle distribution

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

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

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 $v_2 < 10^{-1}$.



2008-2010



QM2008 - first public showing of STAR results



Sergei A. Voloshin
Nuclear Physics A 827 (2009) 377c–382c

Suggestion of using isobar beams
$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$
to disentangle CME signal from

QM2009

Experimental study of spontaneous strong parity violation in heavy ion collisions at RHIC

Sergei A. Voloshin WAYNE STATE UNIVERSITY
The STAR Collaboration



Strong parity violation at STAR: Quantifying background effects with Monte-Carlo event generators and detector effects study



Ilya Selyuzhenkov (INDIANA UNIVERSITY) for the STAR Collaboration
Ilya.Selyuzhenkov@gmail.com



Strong parity violation at STAR:
Evaluating experimental measurement technique and estimating background contributions from multi-particle production
Evan Finch (Yale University), *for the STAR Collaboration*



Selected for a Viewpoint in *Physics*

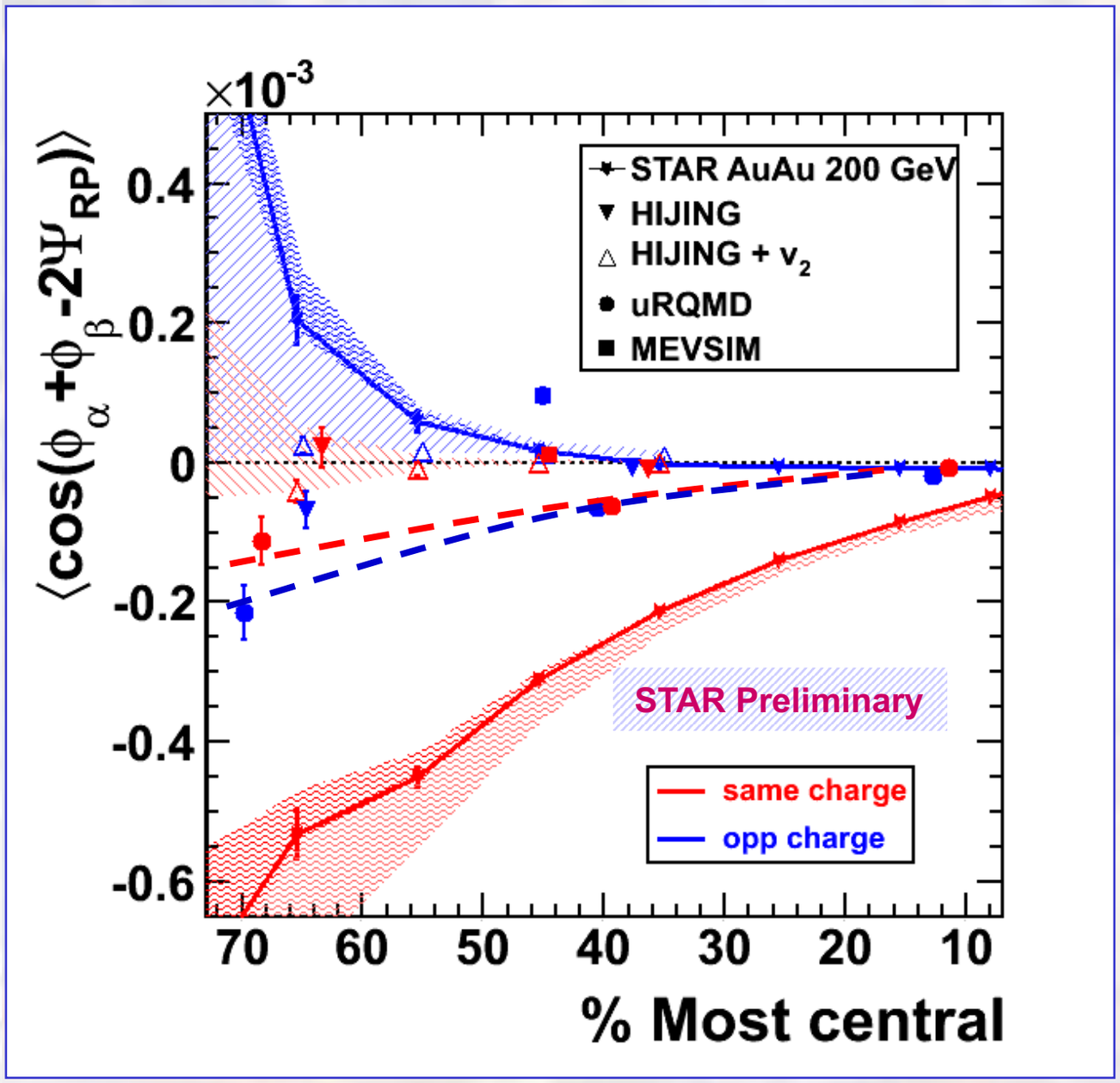
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

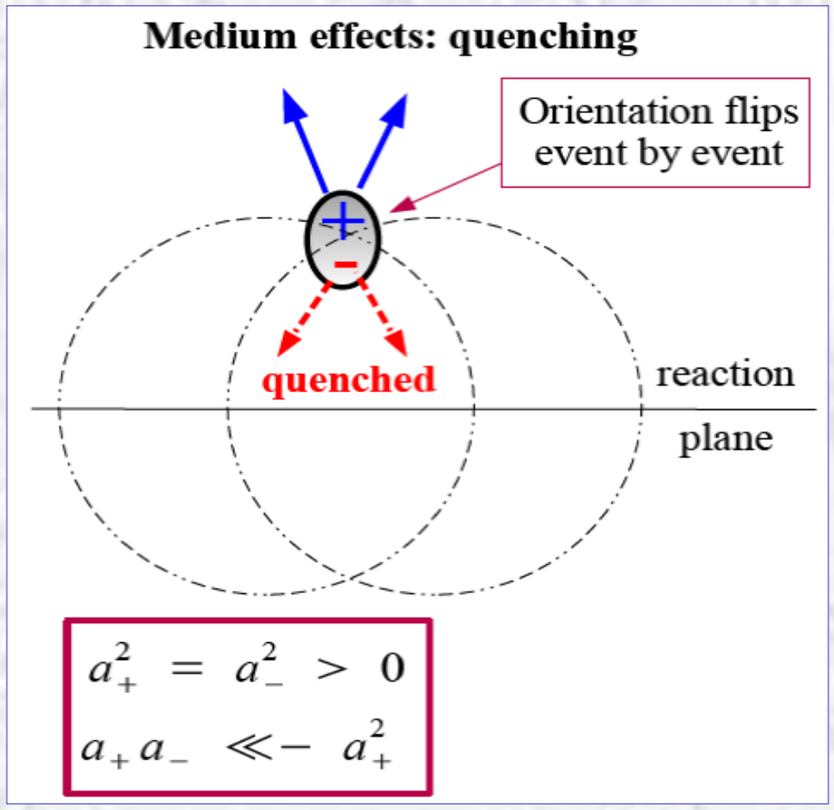
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

PHYSICAL REVIEW C **81**, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

QM2009





- Shifted “baseline” (uRQMD, “quenched correlations”
- Huge “non-flow” contribution in peripheral collisions
- MEVSIM with “max resonances“ “explains” 1/3 of the signal
- No model close to the data

Two types of the backgrounds

I. Physics (RP dependent).

Can not be suppressed

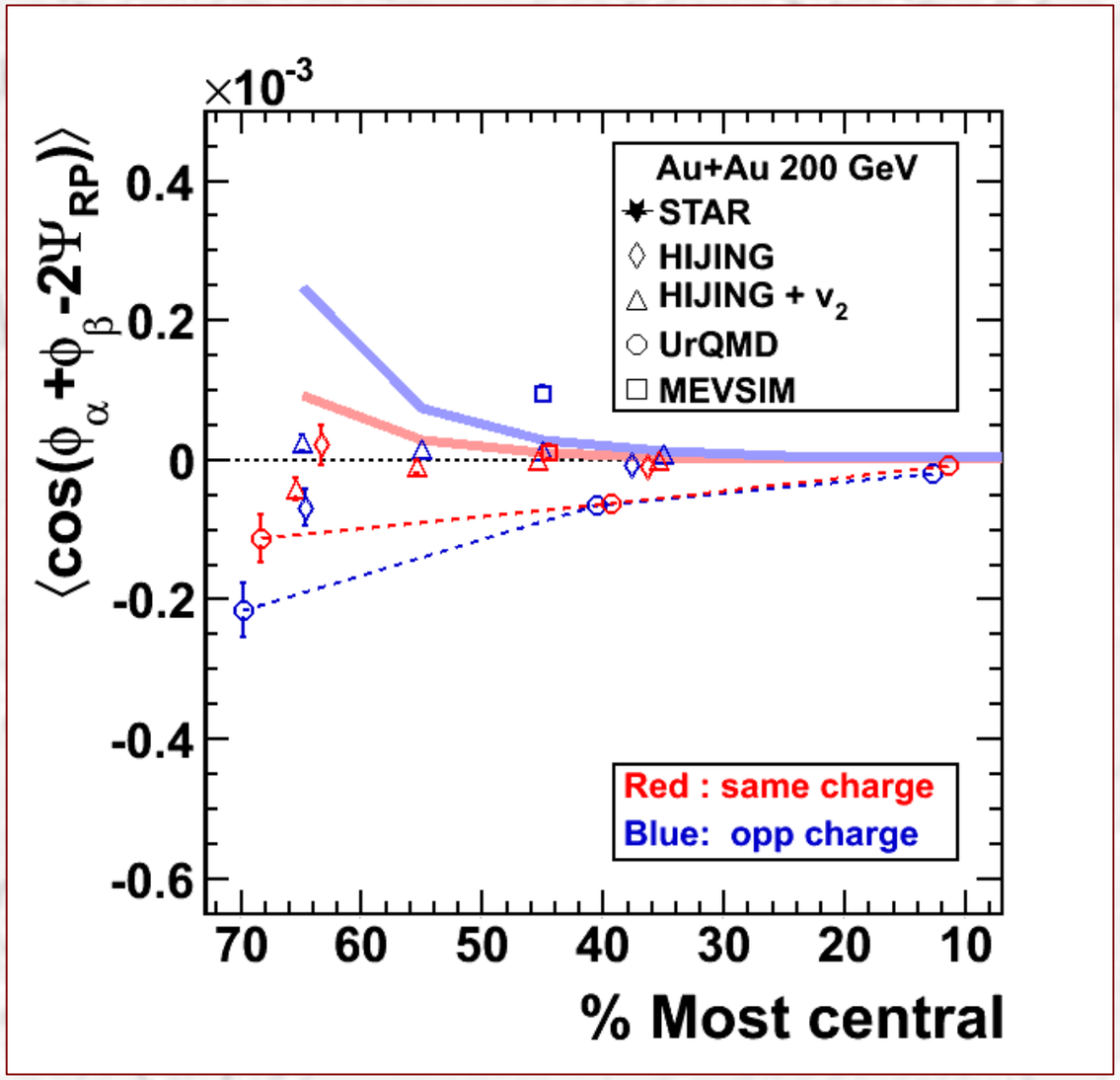
$$\gamma_{\alpha,\beta} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}\rangle$$
$$= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{\rm in}] - [\langle a_{1,\alpha}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

"Flowing clusters", Global polarization, charge dependent directed flow.

II. Measurements (RP independent).

(depends on method, can be reduced)

$$\langle \cos(\phi_a + \phi_b - 2\phi_c)\rangle \overset{?}{\to} \langle \cos(\phi_a + \phi_b - 2\Psi_2)\rangle\, v_{2,c}$$



HIJING+v2 = added "afterburner" to generate flow
MEVSIM: flow as in experiment, number of resonances maximum what is consistent with experiment

Note that in 2004 the idea of global polarization went "on-shell"; in 2007 limits on the global polarization and spin alignments were obtained.

(spin alignment background to gamma - A. Tang)

RP independent background is dominant in peripheral collisions !

First PRL, PRC (2009)

PHYSICAL REVIEW C **81**, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

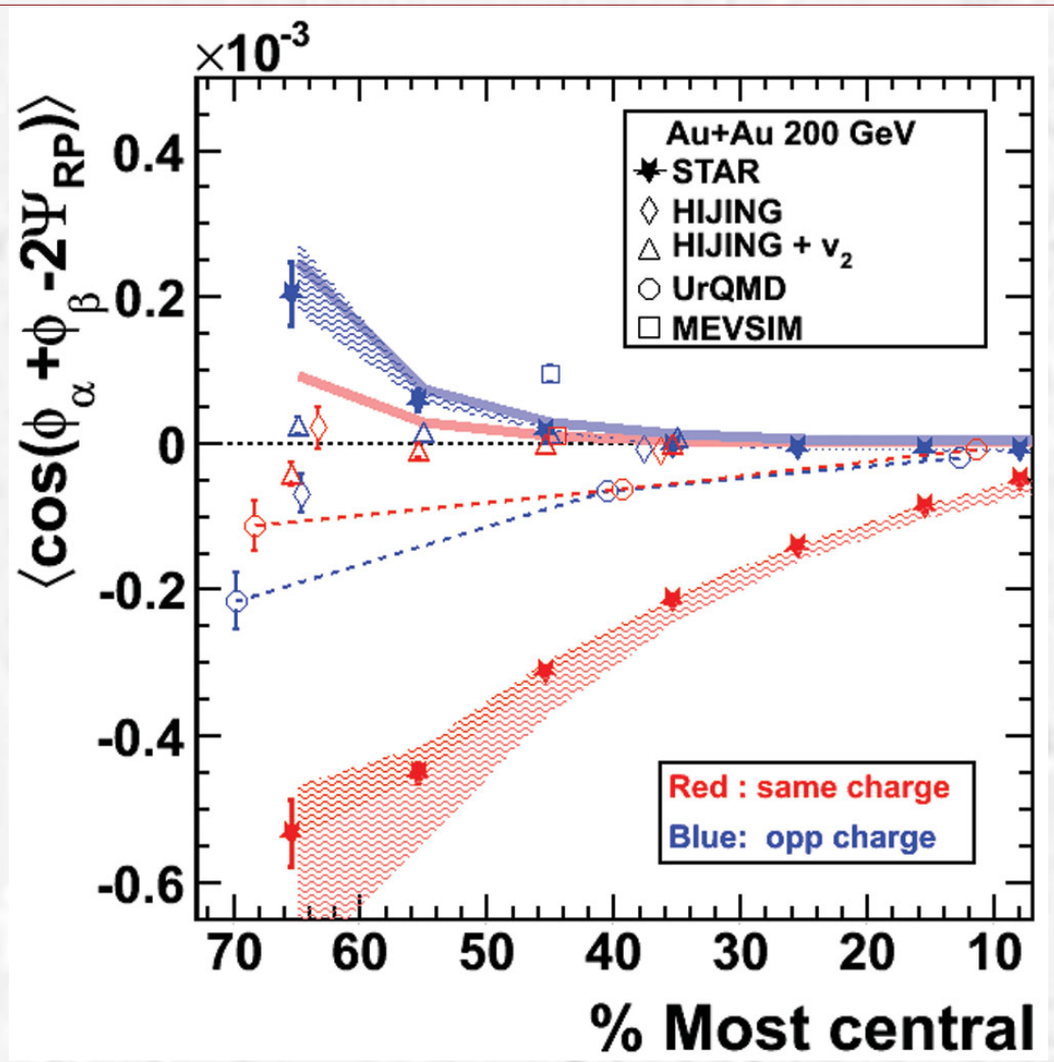


FIG. 4 (color). $\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}})\rangle$ results from 200 GeV Au + Au collisions are compared to calculations with event generators HIJING (with and without an "elliptic flow afterburner"), URQMD (connected by dashed lines), and MEVSIM. Thick lines represent HIJING reaction-plane-independent background.

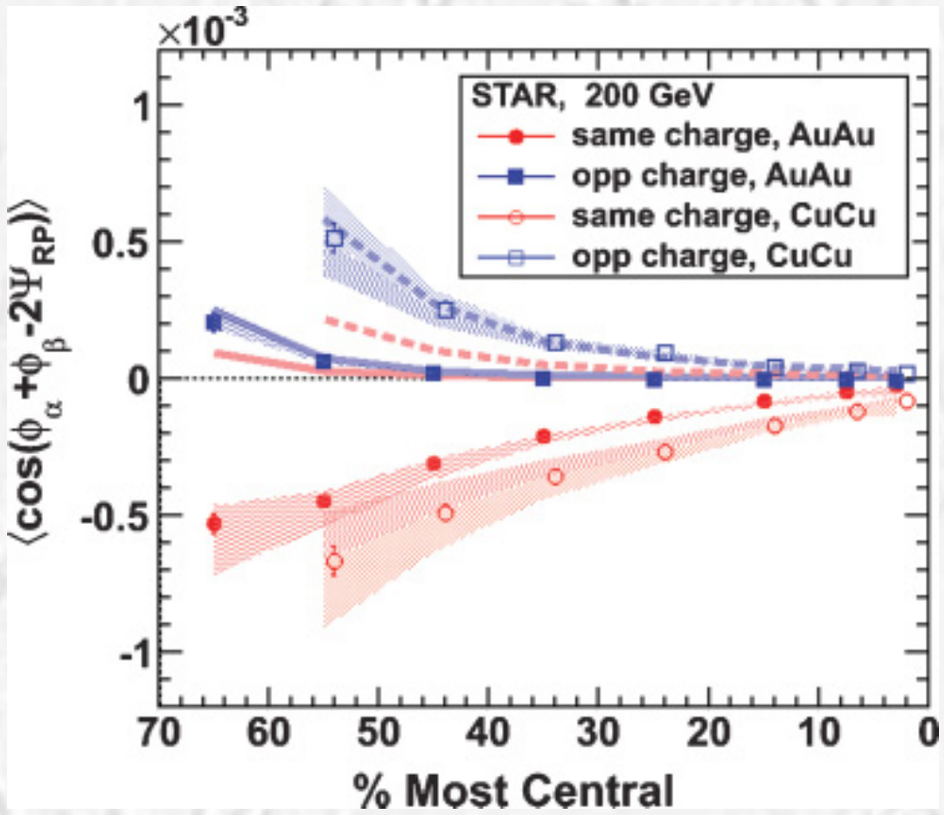
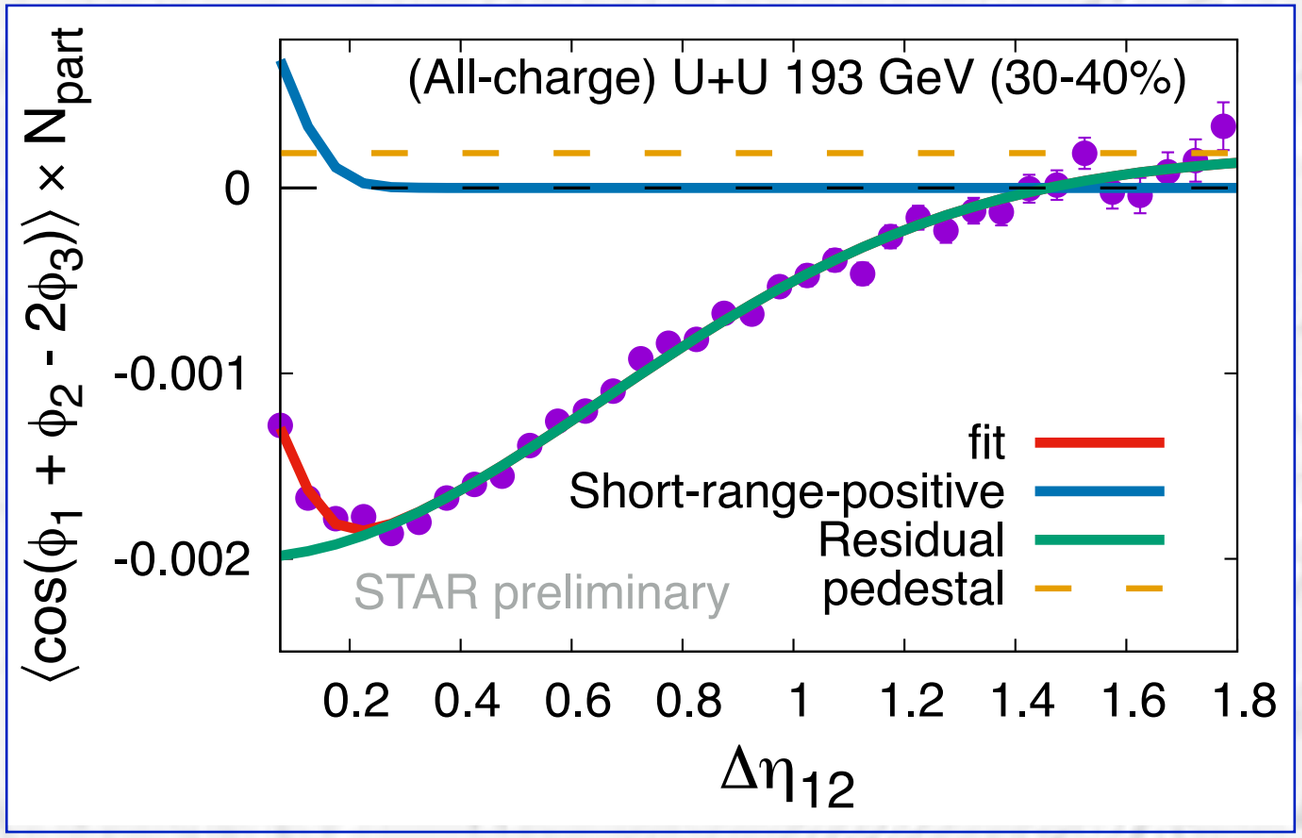
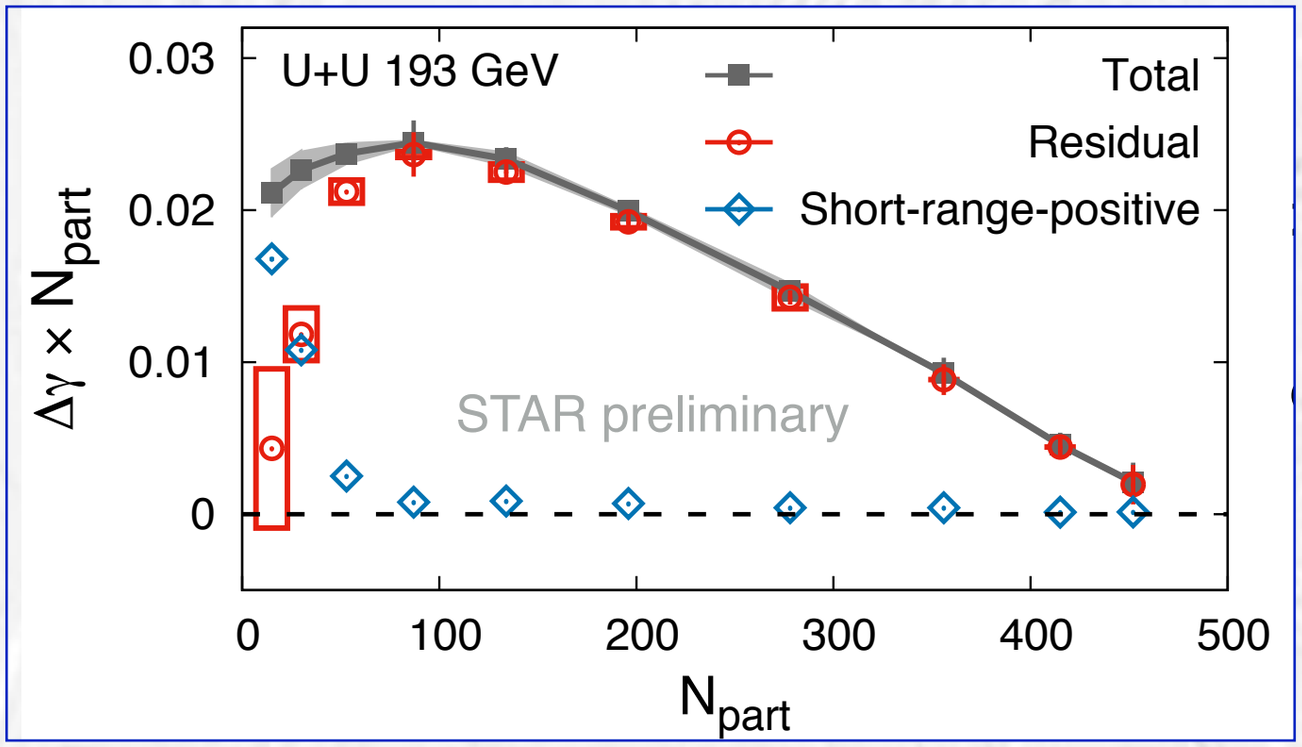


FIG. 7. (Color online) $\langle\cos(\phi_a + \phi_\beta - 2\Psi_{\mathrm{RP}})\rangle$ in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV calculated using Eq. (7). The error bars show the statistical errors. The shaded areas reflect the uncertainty in the elliptic flow values used in calculations, with lower (in magnitude) limit obtained with elliptic flow from two-particle correlations and upper limit from four-particle cumulants. For details, see Sec. IV. Thick solid (Au + Au) and dashed (Cu + Cu) lines represent possible non-reaction-plane-dependent contribution from many-particle clusters as estimated by HIJING (see Sec. VII A).

RP independent background II





XXVIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2017)

Disentangling flow and signals of Chiral Magnetic Effect in U+U, Au+Au and p+Au collisions

Prithwish Tribedy (for the STAR Collaboration)

"short range background"
=
RP independent ?

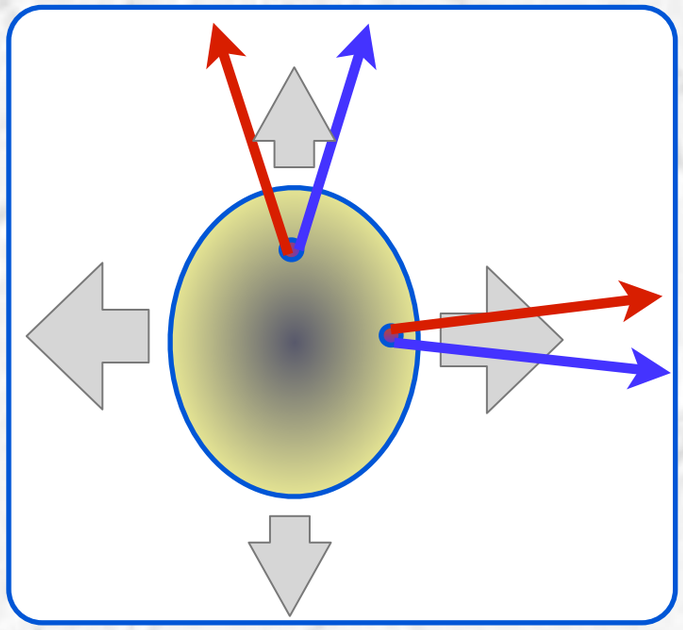
Can be checked,
Might be important for interpretation

RP dependent background

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

"Flowing clusters"

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



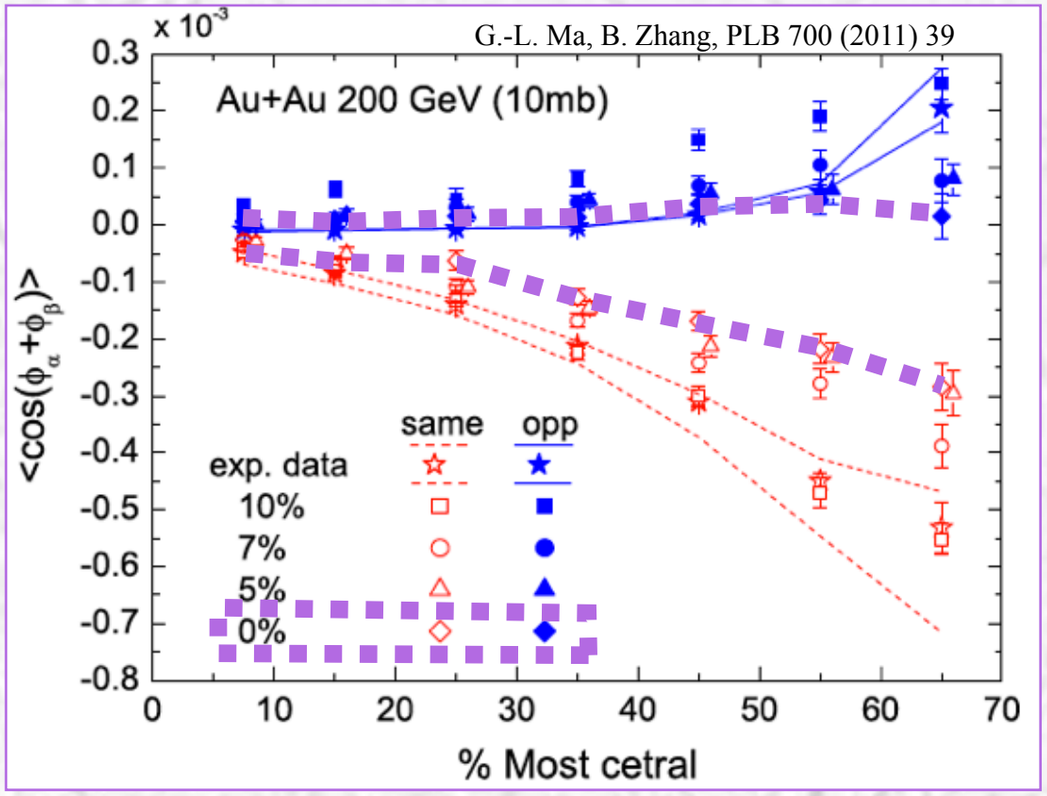
One of the "strong" candidates: Local Charge Conservation at freeze-out + Radial + Elliptic Flow. Blast Wave model:

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 the Blast Wave model

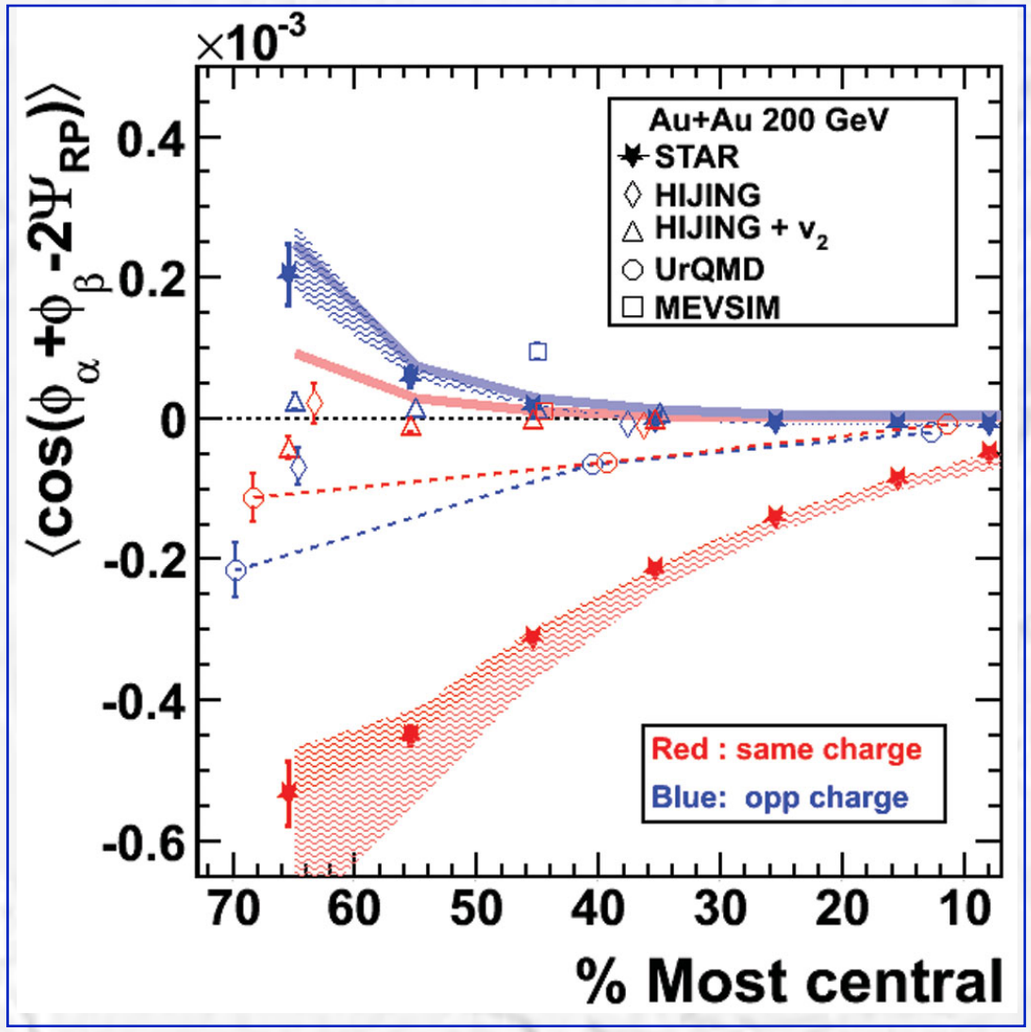


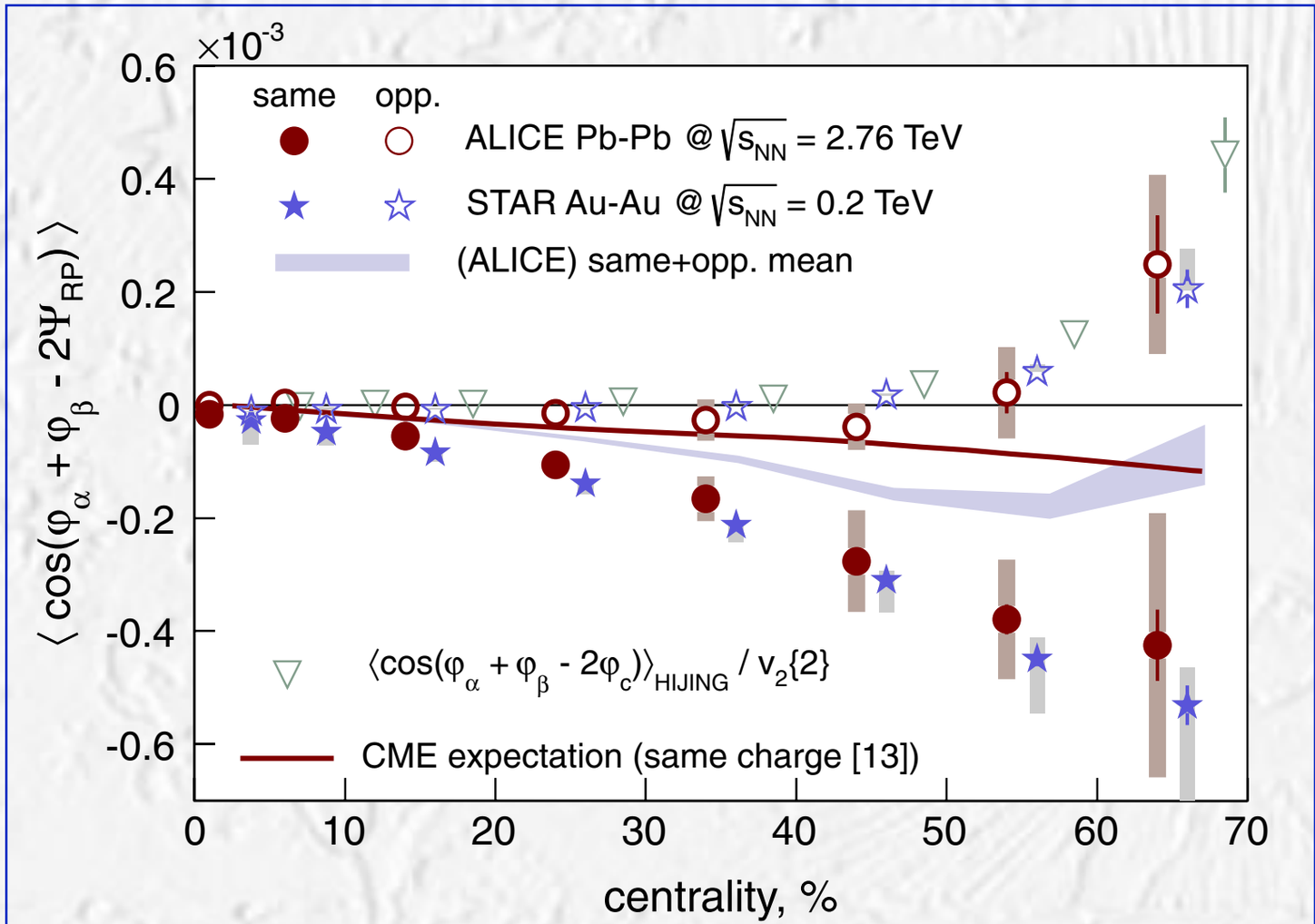
"Best" of transport models: the signal is factor of two small

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

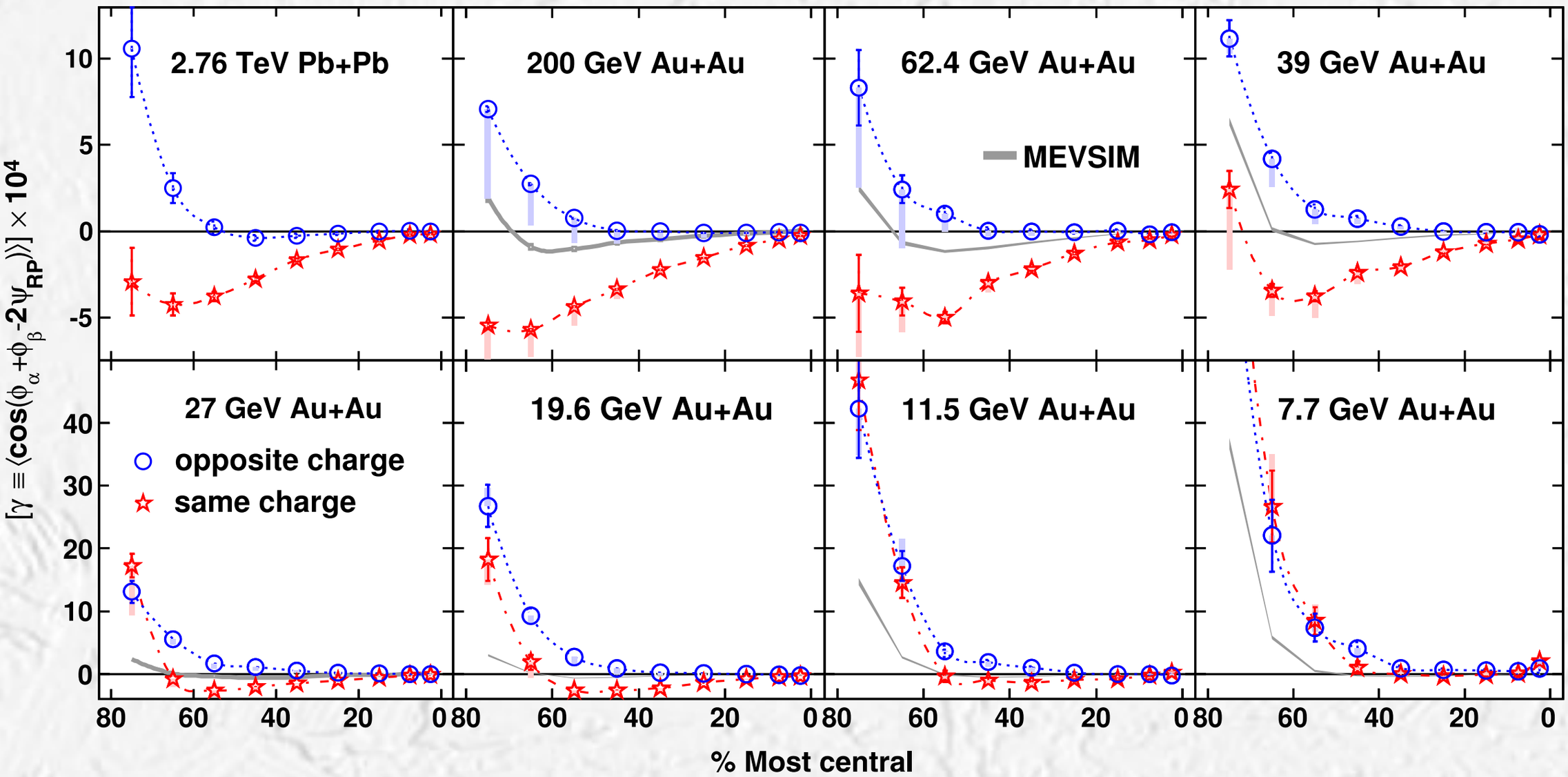
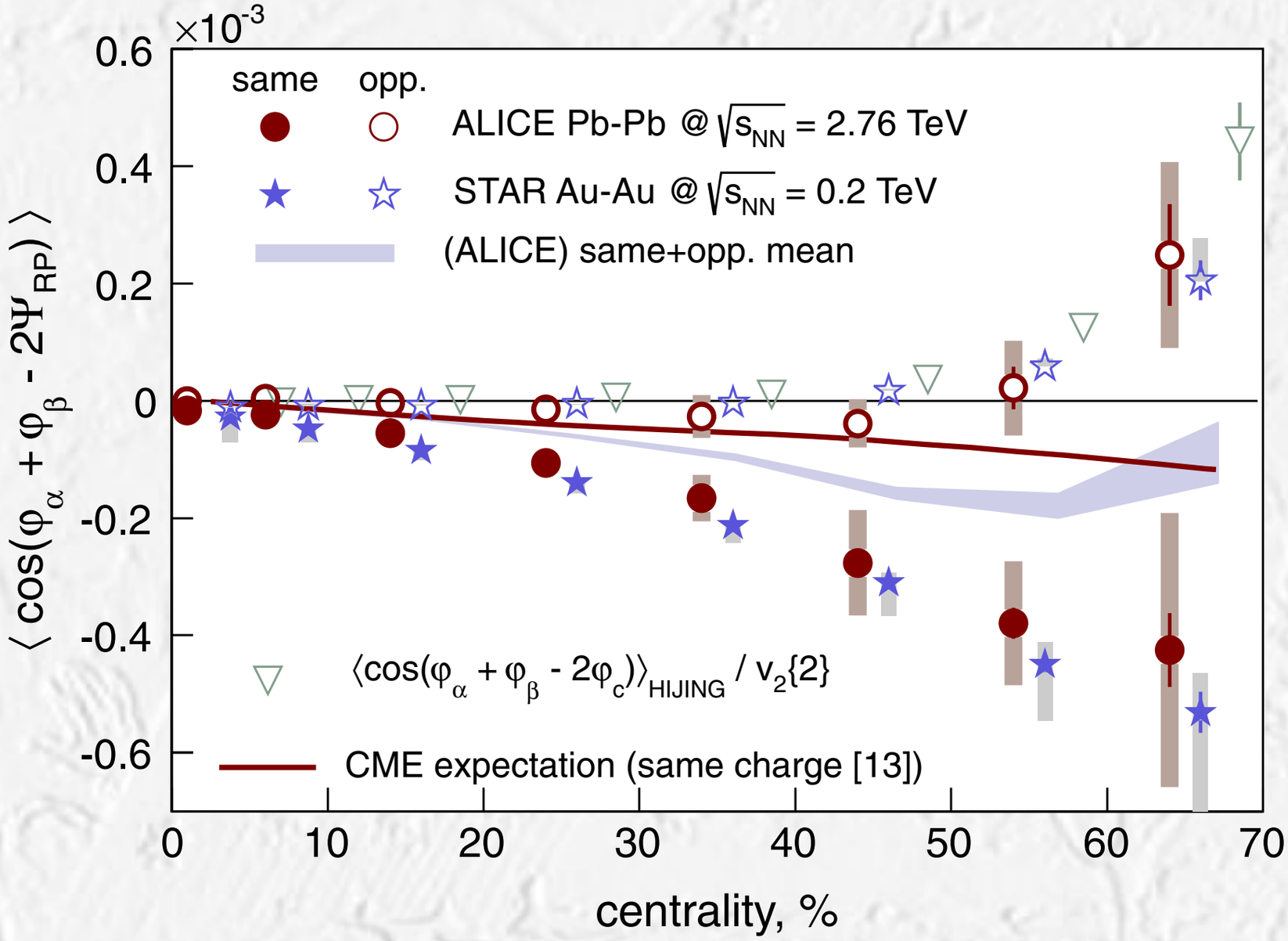


Fig. 13. Three-point correlator as a function of centrality for Au + Au collisions at 7.7–200 GeV [106], and for Pb + Pb collisions at 2.76 TeV [129]. Note that the vertical scales are different for different rows. The systematic errors (gray bars) bear the same meaning as in Fig. 12. Charge independent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

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

LHC vs RHIC

ALICE Collaboration PRL **110,** 012301 (2013)



RHIC and LHC results -- surprisingly close!

- (CME) no effect of change in the magnetic field lifetime (?)
- (Bkg) no effect of almost 3 times higher multiplicity density (?)

Signal vs background

It is likely that the measurements are dominated by the “background” (LCC?).

Goal: identification of the presence or the lack of the CME signal at the level of “ ~5% of the measured gamma correlator value

At hand: Signal depends on the magnetic field/vorticity the background depends on anisotropic flow

- Collision energy dependence, Beam energy scan (signal should disappear at lower energies)
- Isobar collisions (vary magnetic field keeping the same background)
- Event Shape Engineering (increase/decrease background)
- Gamma wrt different Event Planes (Participant, Spectators)
- Higher harmonic correlators (background, no signal)
- Small system collisions (background, no signal)
- Very central collisions (background, no signal)
- U+U (body-body vs tip-tip)
- Correlations with identified particles (e.g. for the next bullet)
- Cross-correlation of different observables, CME X CMW X CVE
- New ideas/observables (invariant mass, Signed BF, R-correlator)

- Studies of the EM fields

Based on the goal stated in the previous page

Observable	(Just a few) names	Problems/questions	My opinion
$\Delta\gamma$ ESE		Dependence of the signal on v2?	
ESE "CMS" U+U			
"q2obs" ESE	F. Wang	"Play" on stat. fluctuations, Not-interpretable?	
small systems	CMS, F. Wang, others	Strong RP independent background, nothing/little to say about CME	
Mixed harmonics	Voloshin, CMS, many others	Requires detailed knowledge about the kinematic of the cluster decays (as e.g. pT)	
invariant mass	F. Wang, J. Zhao	Requires knowledge of the inv. mass spectrum of "sphaleron" decays	
Spectator /participant EP	S. Voloshin F. Wang, J. Zhao	Promising with careful treatment of contributions to v2 and gamma	
$\Delta\gamma,\ \Delta\delta;\ H, F, \kappa$	J. Liao, G. Wang, others	No strict justification => imprecise	
"Balance function"	A. Tang	Needs evaluation	?
ΔS	R. Lacey	"General" questions from previous page	

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, $0<\eta_a<0.8$

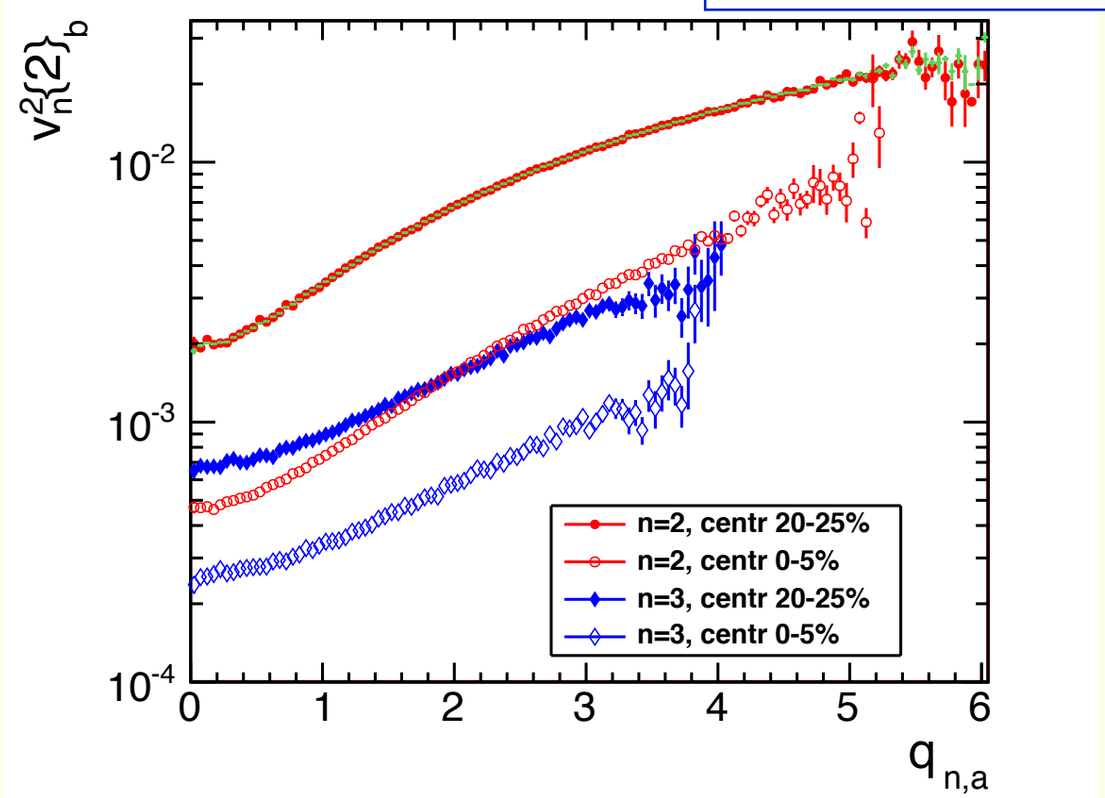


FIG. 1. (color online) Mean elliptic and triangular flow values in a-subevent as function of the corresponding q_n magnitude in b-subevent.

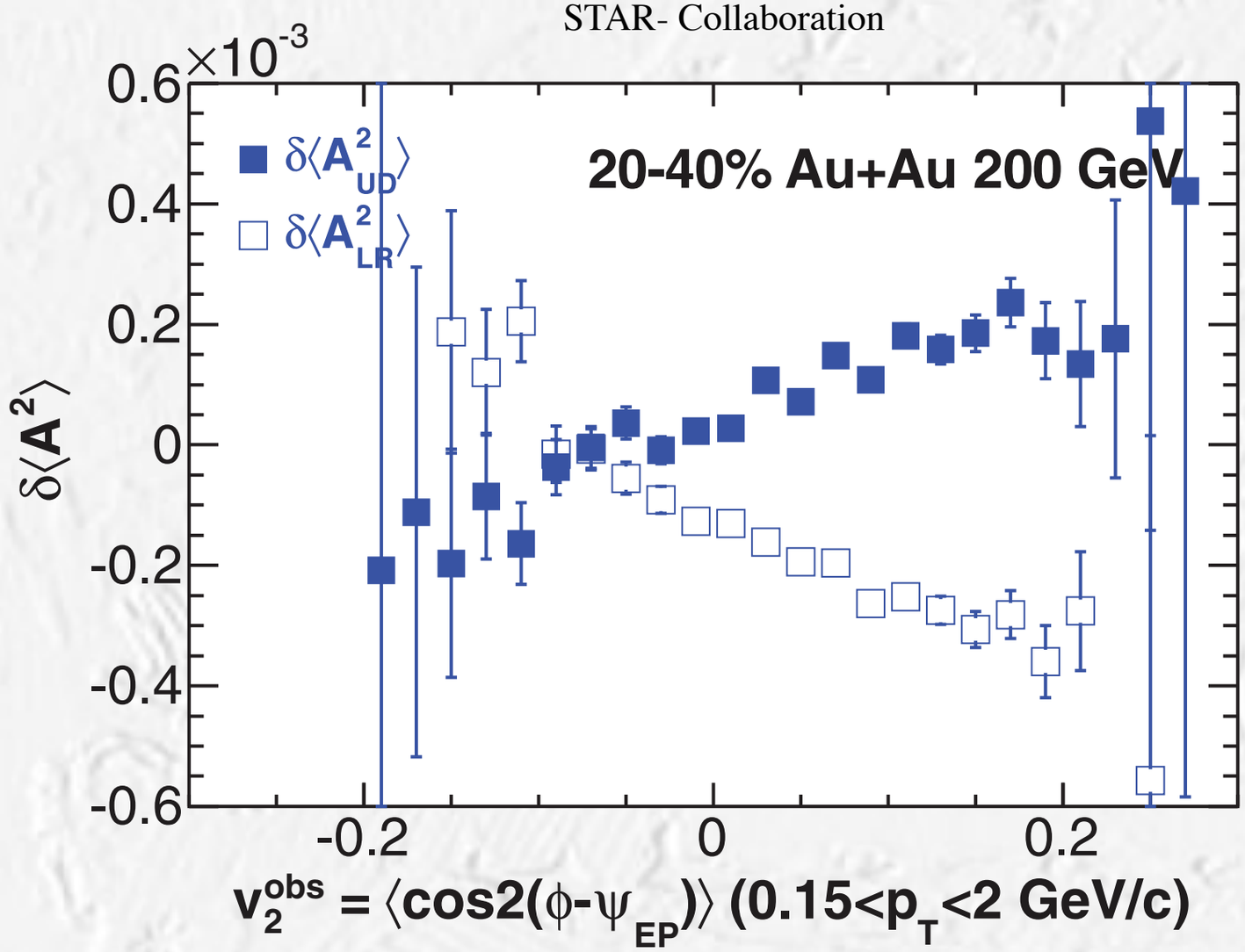
Application to the CME search: BG ~ v_2,
Signal - much weaker dependence (mostly due to decorrelations between **B** and Ψ_2)

Pseudo-ESE

PHYSICAL REVIEW C **89**, 044908 (2014)

Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV

STAR- Collaboration



v2obs (used for "ESE") and the signal are measured with the same particles (in the same pseudorapidity region)

Results are dominated by statistical fluctuations. No possibility to correct for the reaction plane resolution. Uninterpretable.

ESE, almost there

PHYSICAL REVIEW C **97**, 044912 (2018)

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in *p*Pb and PbPb collisions at the CERN Large Hadron Collider

A. M. Sirunyan *et al.**
(CMS Collaboration)

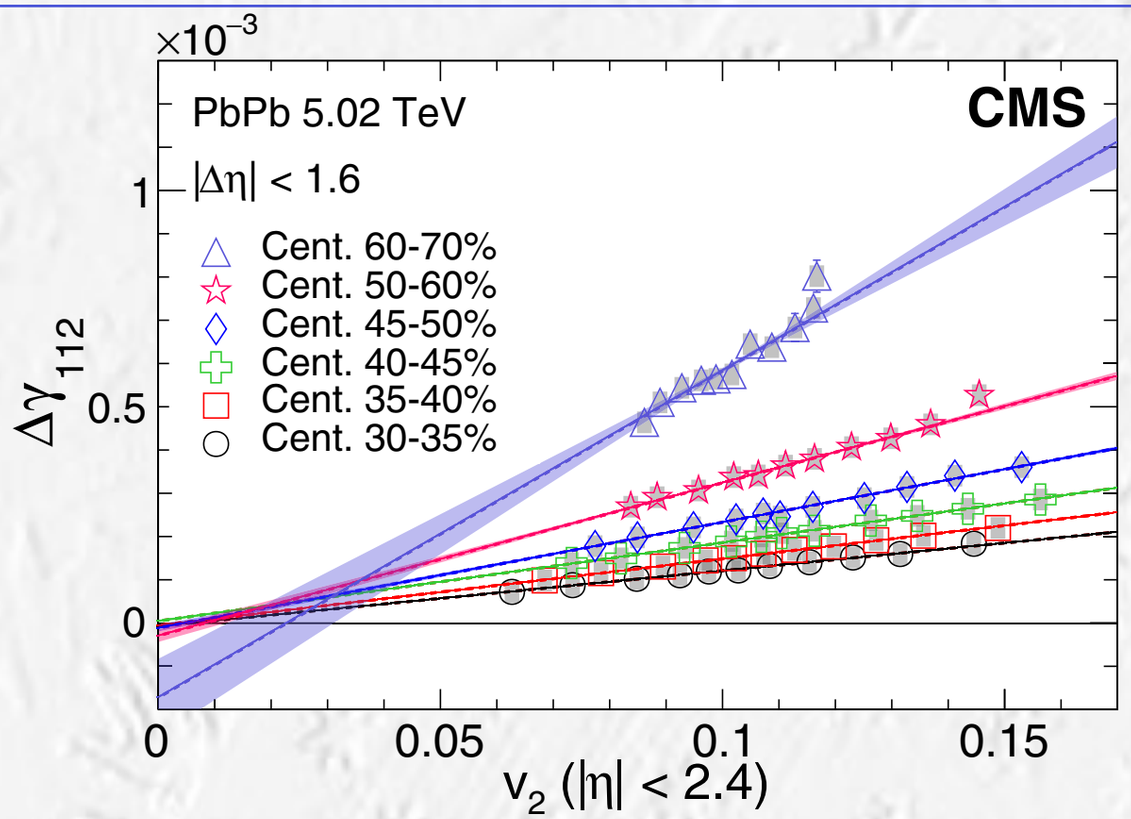


FIG. 12. The difference of the OS and SS three-particle correlators γ_{112} averaged over $|\Delta\eta| < 1.6$ as a function of v_2 evaluated in each q_2 class, for the multiplicity range $185 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV (upper), and for different centrality classes in PbPb collisions at 5.02 TeV (lower). Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively. A one standard deviation uncertainty from the fit is also shown.

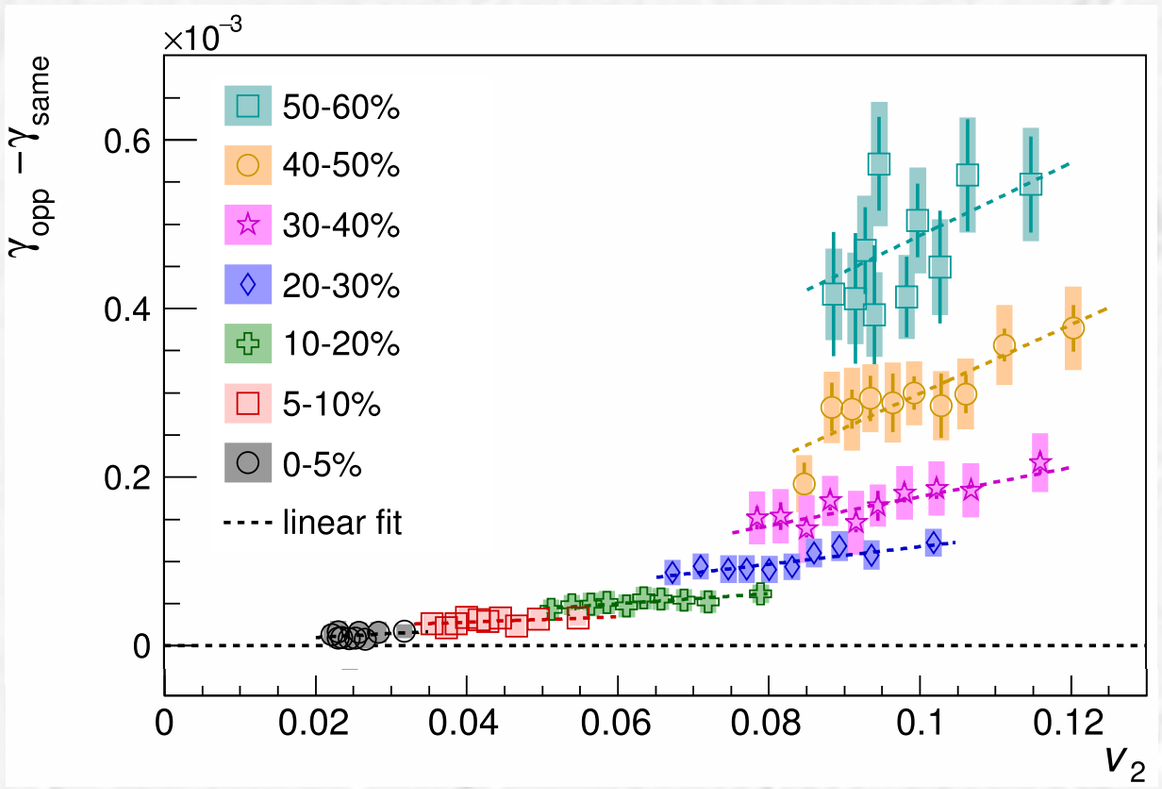
$$\Delta\gamma_{112} = a\, v_2 + b,$$

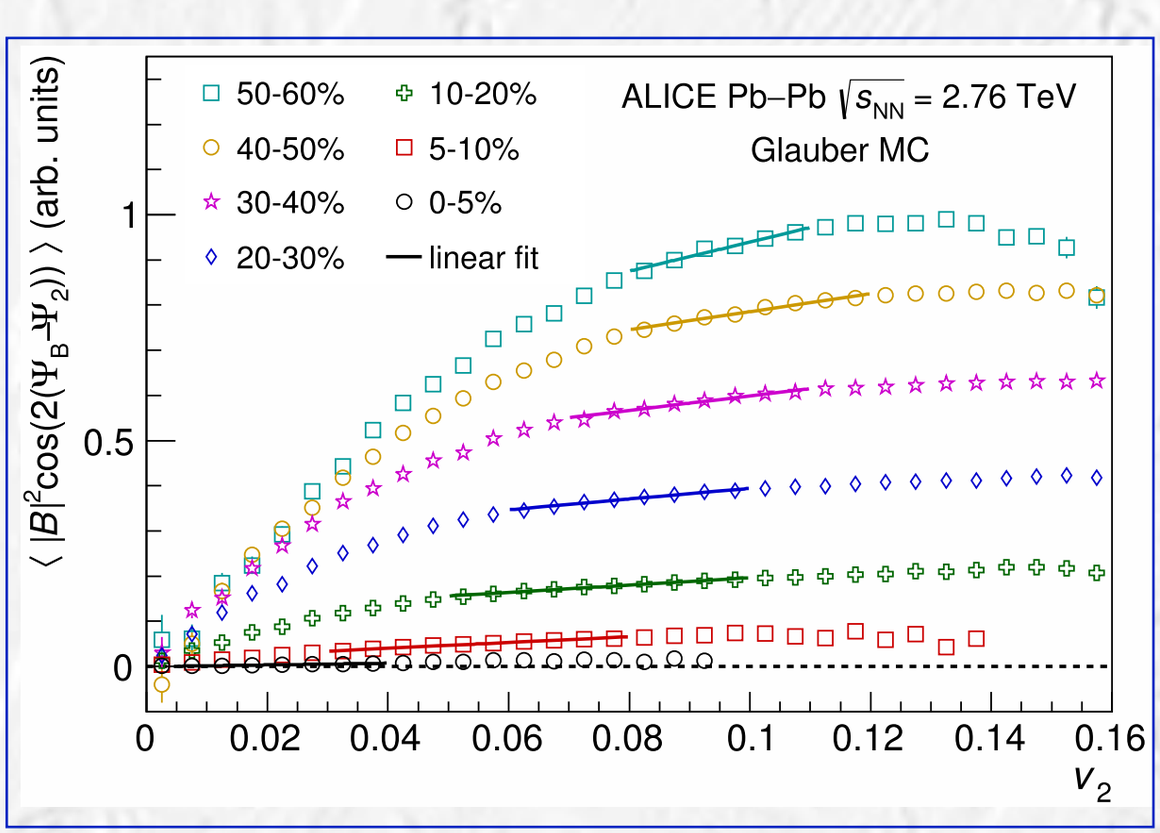
upper limit on the v_2-independent fraction of the three-particle correlator, or the possible CME signal contribution (assumed independent of v_2 within the same narrow multiplicity or centrality range), is estimated to be 13% for pPb data and 7% for PbPb data at a 95% confidence level. The data presented in

Does it make sense to talk about 95% CL, not including uncertainty on the assumptions?

CME signal is not totally v_2 independent, the limit might be somewhat larger than 7%

ALICE: Event shape engineering





Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration / Physics Letters B 777 (2018) 151–162

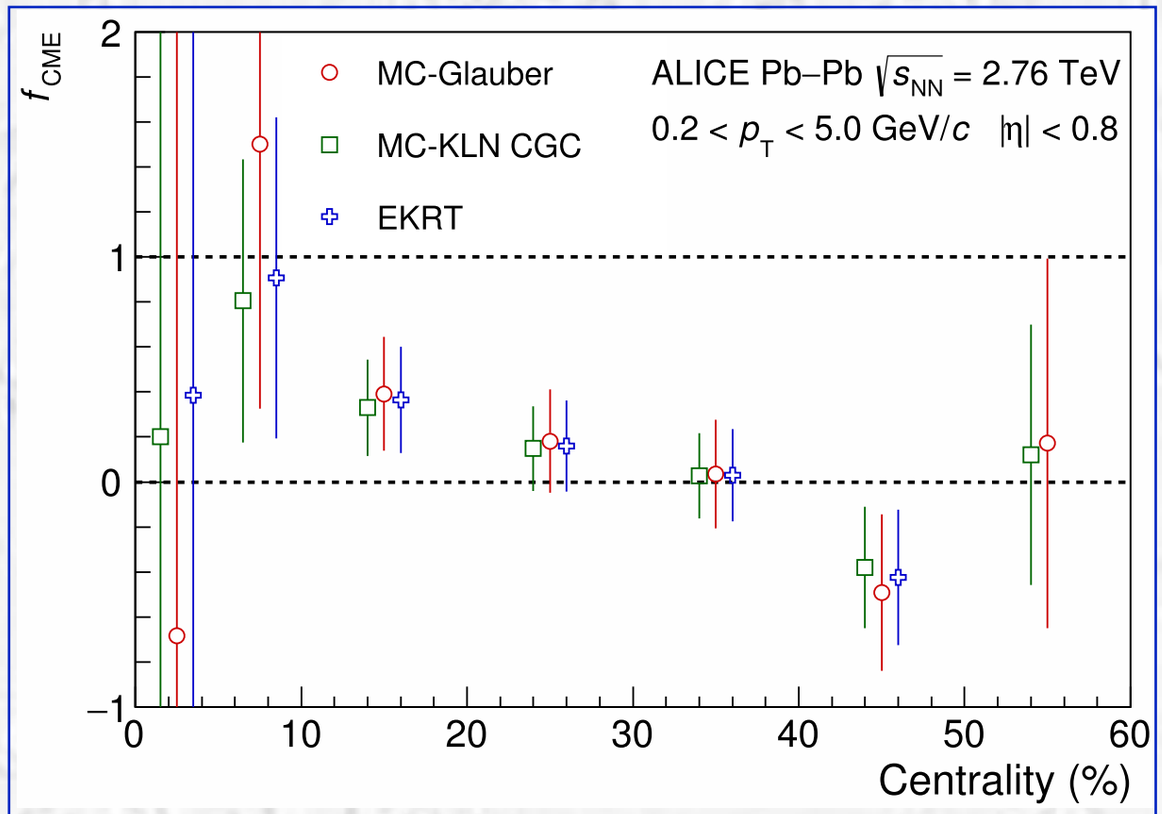


Fig. 6. (Colour online.) Centrality dependence of the CME fraction extracted from the slope parameter of fits to data and MC-Glauber [51], MC-KLN CGC [53,54] and EKRT [55] models, respectively (see text for details). The dashed lines indicate the physical parameter space of the CME fraction. Points are slightly shifted along the horizontal axis for better visibility. Only statistical uncertainties are shown.

Signal dependence on v_2 (due to decorrelation between the EP and magnetic field direction): almost no model dependence

For mid-central collision the CME fraction <~ 20%

Delta-gamma vs invariant mass

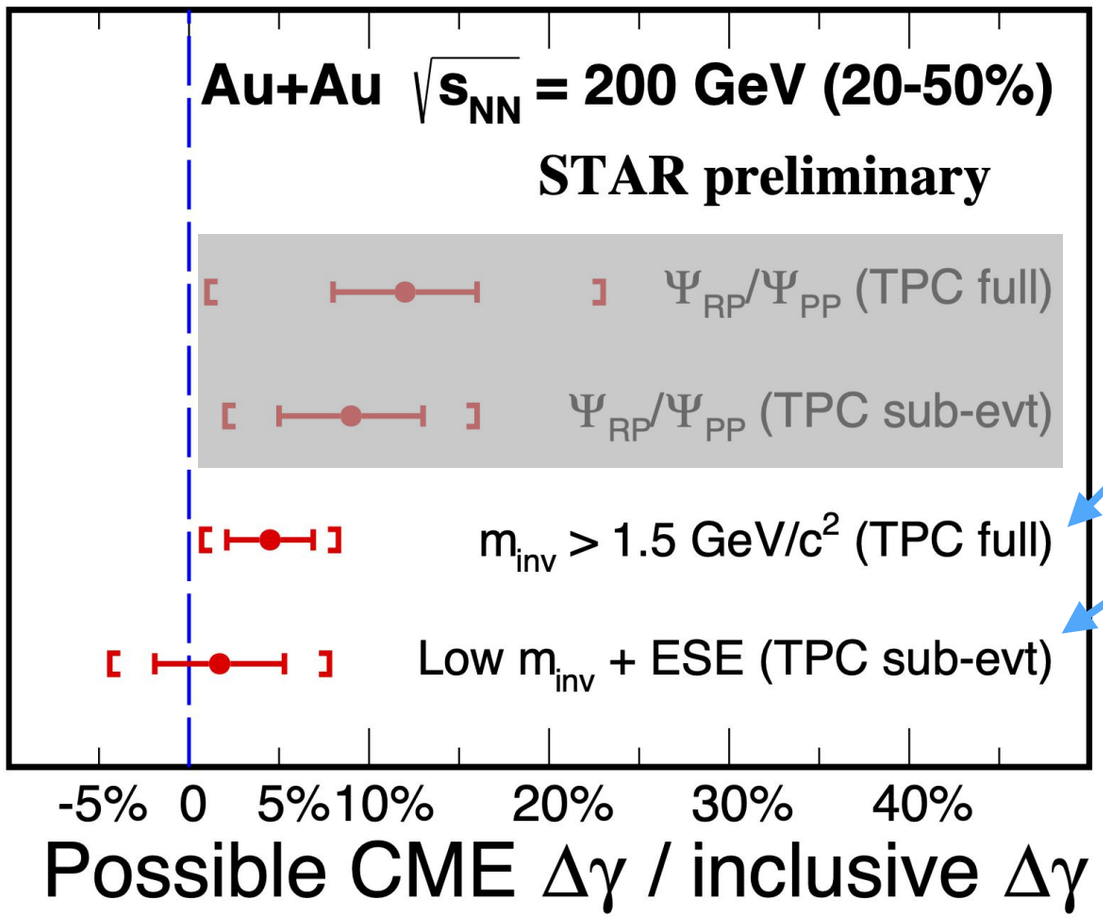
based on:

Isolating the chiral magnetic effect from backgrounds by pair invariant mass

Jie Zhao[1,a], **Hanlin Li**[1,2], **Fuqiang Wang**[1,3,b]

Eur. Phys. J. C (2019) 79:168
https://doi.org/10.1140/epjc/s10052-019-6671-1

J. Zhao (STAR collaboration). NPA 982 (2019) 535



looking in the region where no resonance contribution is measured

assuming no dependence of the “CME part” of Delta-gamma on inv.mass

Both assumptions/approaches are far from being realistic. The obtained limits has little value.

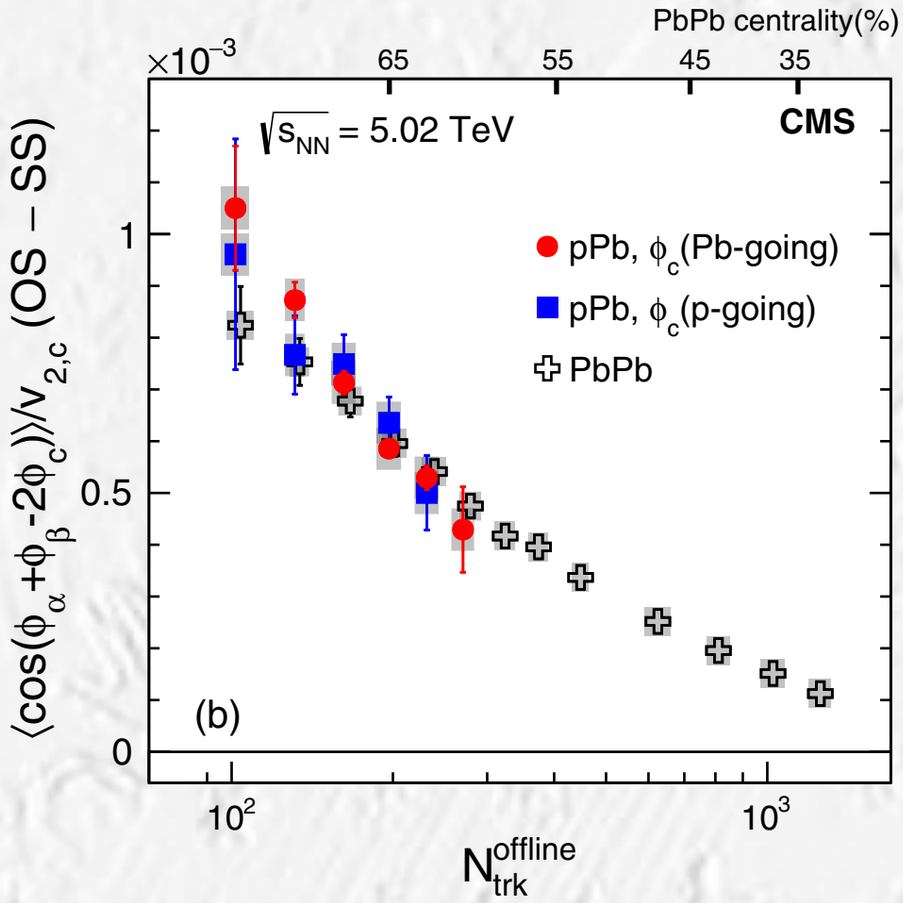
In general it is a valid method, similar to other differential (vs pT, Delta-eta) measurements. Requires theoretical input on dependence of the signal on the invariant mass.

Small systems I

PRL 118, 122301 (2017) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2017

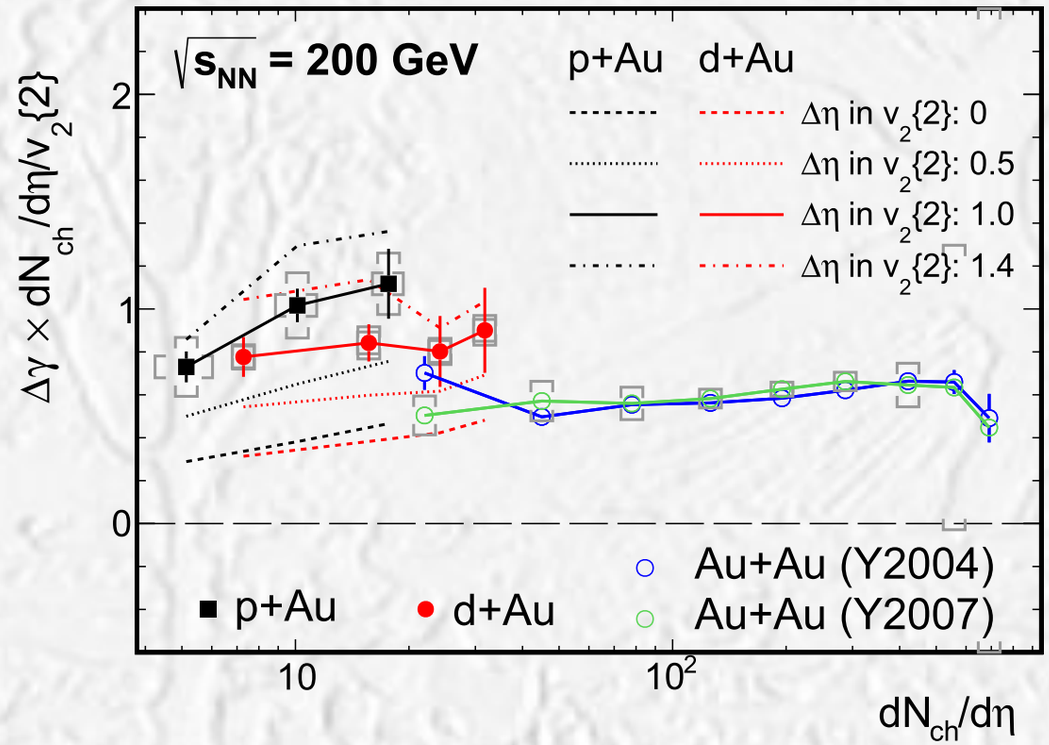
Observation of Charge-Dependent Azimuthal Correlations in *p*-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect

V. Khachatryan *et al.**
(CMS Collaboration)



similarly

These results challenge the CME interpretation for the observed charge-dependent azimuthal correlations in nucleus-nucleus collisions at RHIC and the LHC.



Charge-dependent pair correlations relative to a third particle in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions at RHIC

STAR Collaboration / Physics Letters B 798 (2019) 134975

Fig. 4. The $\Delta\gamma \times dN_{\mathrm{ch}}/d\eta/v_2$ in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions as a function of multiplicity, compared to that in Au + Au collisions [18,19,21]. The data points connected by solid lines are measured using $\Delta\eta$ gap of 1.0 in $v_2\{2\}$. Dashed lines represent the results using $v_{2,c}$ with η gaps of 0, 0.5 and 1.4.

Small systems II

Charge-dependent pair correlations relative to a third particle in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions at RHIC

STAR Collaboration / Physics Letters B 798 (2019) 134975

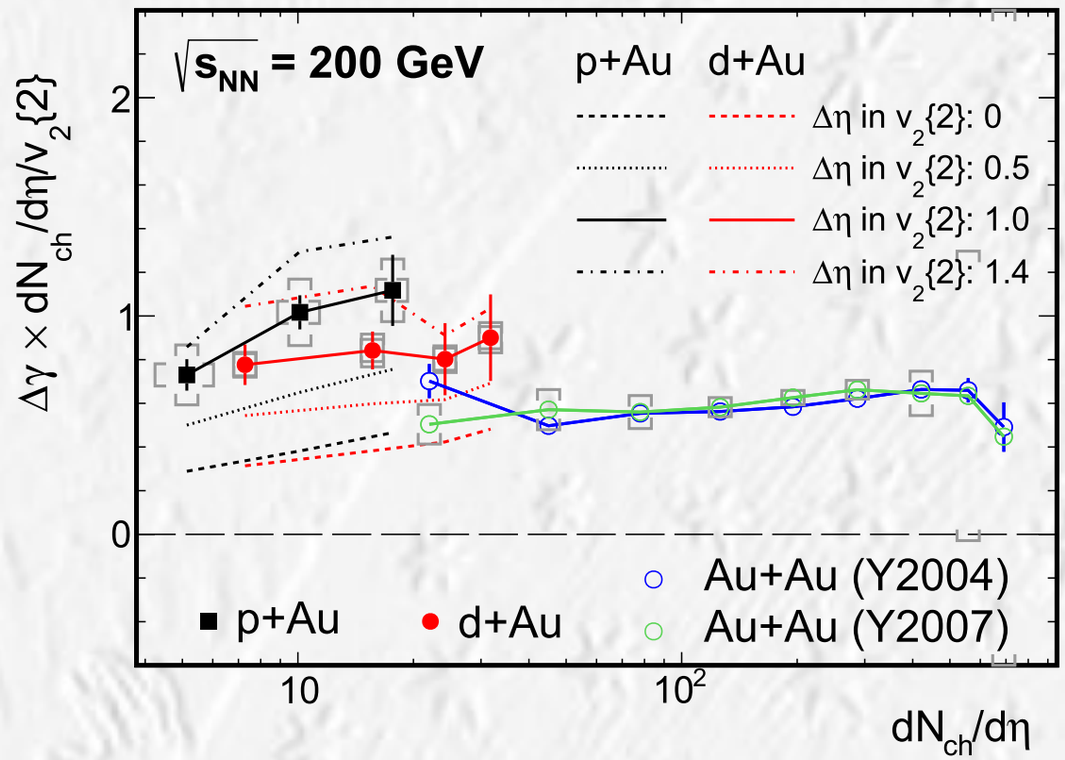
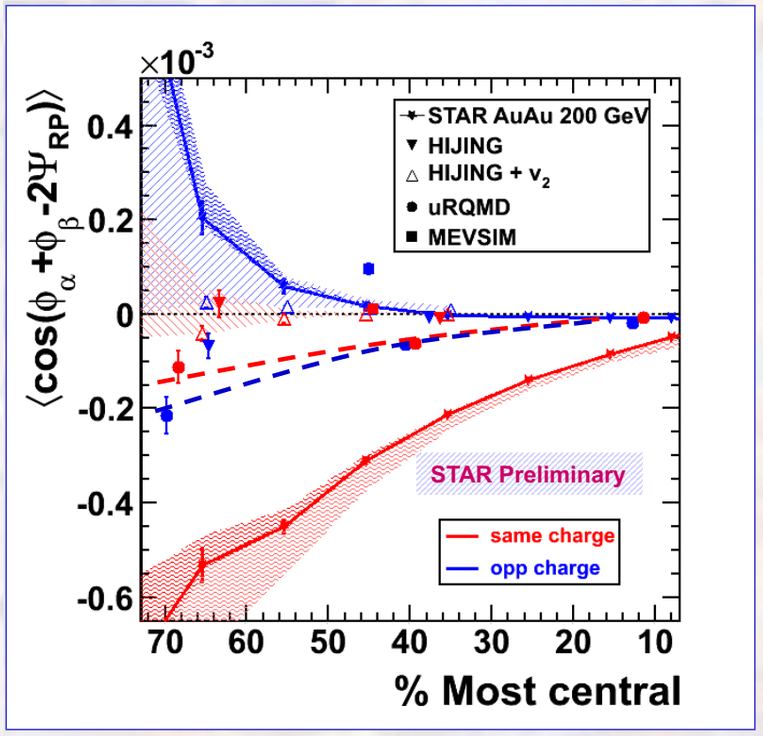


Fig. 4. The $\Delta\gamma \times dN_{\mathrm{ch}}/d\eta/v_2$ in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions as a function of multiplicity, compared to that in Au + Au collisions [18,19,21]. The data points connected by solid lines are measured using $\Delta\eta$ gap of 1.0 in $v_2\{2\}$. Dashed lines represent the results using $v_{2,c}$ with η gaps of 0, 0.5 and 1.4.



What is the "contribution" of the RP independent background to the measurement?

Answer - 100%. HIJING describes very well quantitatively both, "gamma" and "v_2" (simulations done by the authors - not included in the paper!).

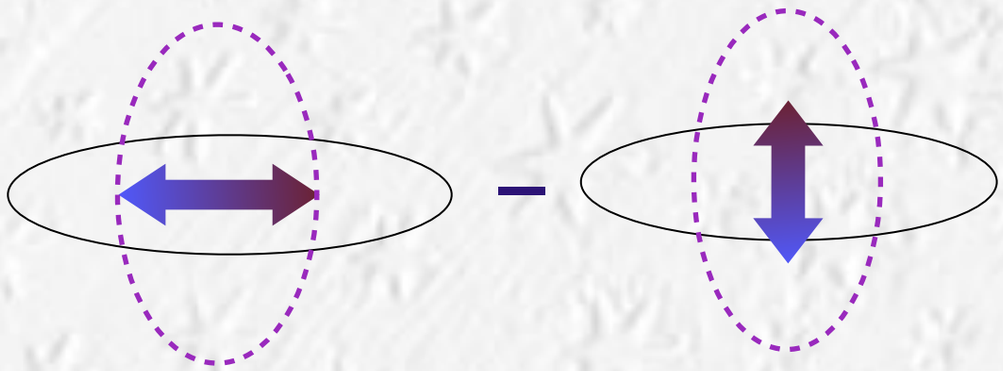
My view - until such a background is kept well under control, no meaningful conclusion can be made. It is misleading not to include HIJING results in the paper.

Double/mixed harmonics

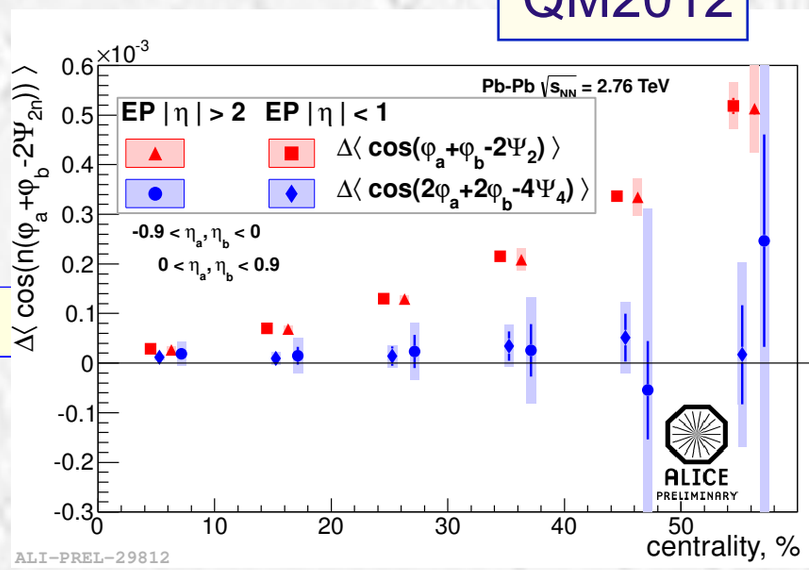
Voloshin, Prog.Part.Nucl.Phys. **67** 541 (2012)

$$\langle\cos(\phi_a+\phi_b-2\Psi_2)\rangle = \langle\cos(\phi_a-\Psi_2)\cos(\phi_b-\Psi_2)\rangle - \langle\sin(\phi_a-\Psi_2)\sin(\phi_b-\Psi_2)\rangle$$

Charge dependent part:
- contribution from CME
- "flowing cluster" background

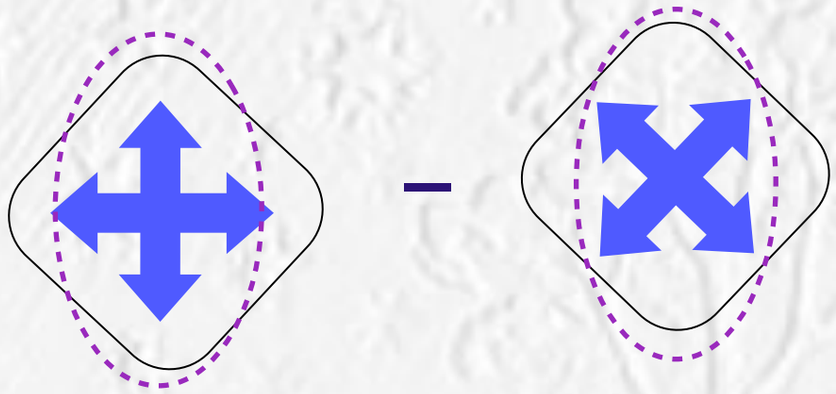


QM2012



$$\langle\cos(2\phi_a+2\phi_b-4\Psi_4)\rangle = \langle\cos(2\phi_a-2\Psi_4)\cos(2\phi_b-2\Psi_4)\rangle - \langle\sin(2\phi_a-2\Psi_4)\sin(2\phi_b-2\Psi_4)\rangle$$

- NO contribution from CME.
- "flowing cluster" background (~ v_4 instead of ~v_2)



$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_2)\rangle = \langle\cos[(\phi_\alpha+\phi_\beta-2\phi_c)+(2\phi_c-2\Psi_2)]\rangle \approx \langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle\, v_{2,c}$$

$$\langle\cos(2\phi_\alpha+2\phi_\beta-4\Psi_2)\rangle = \langle\cos[(2\phi_\alpha+2\phi_\beta-4\phi_c)+(4\phi_c-4\Psi_2)]\rangle \approx \langle\cos(2\phi_\alpha+2\phi_\beta-4\phi_c)\rangle\, v_{4,c}$$

Quite different kinematic factors!

$\langle\cos(2\phi_\alpha+2\phi_\beta-4\phi_c)\rangle$ vs $\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$

Requires detail knowledge of background nature

Not suitable for precise estimates

Mixed harmonics (also $\Delta\gamma$, $\Delta\delta$; H, F, κ)

PHYSICAL REVIEW C **97**, 044912 (2018)

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in *p*Pb and PbPb collisions at the CERN Large Hadron Collider

A. M. Sirunyan *et al.**
(CMS Collaboration)

$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$$

$$\gamma_{112}^{\rm bkg} = \kappa_2 \langle \cos(\phi_\alpha - \phi_\beta)\rangle \langle \cos 2(\phi_\beta - \Psi_{\rm RP})\rangle = \kappa_2\, \delta\, v_2.$$

$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle,$$

$$\gamma_{123}^{\rm bkg} = \kappa_3 \langle \cos(\phi_\alpha - \phi_\beta)\rangle \langle \cos 3(\phi_\beta - \Psi_3)\rangle$$

$$= \kappa_3\, \delta\, v_3,$$

APPENDIX A: GENERAL RELATION OF v_n HARMONICS AND TWO- AND THREE-PARTICLE AZIMUTHAL CORRELATIONS

In Sec. I, Eq. (5) can be derived in a way similar to Eq. (3), with details which can be found in Ref. [24]. Here, a general

$$\gamma_{1,n-1;n} = \frac{1}{2N^2} \int \rho_0(x_\alpha)\rho_0(x_\beta)\delta(x_\alpha, x_\beta) \times [v_n(x_\alpha) + v_n(x_\beta)] dx_\alpha\, dx_\beta,$$

where $N = \int \rho_0(x) dx$.

Therefore, this general form of $\gamma_{1,n-1;n}$ can be applied to any order n and decomposed into the two-particle correlator δ and the nth order harmonic v_n, where $n = 2$ and 3 are studied in detail in Sec. V A.

[24] A. Bzdak, V. Koch, and J. Liao, Charge-dependent correlations in relativistic heavy ion collisions and the chiral magnetic effect, Lect. Notes Phys. **871**, 503 (2013).

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle = \langle \cos[(\phi_\alpha - \phi_\beta) + (2\phi_\beta - 2\Psi_2)]\rangle \neq \langle \cos(\phi_\alpha - \phi_\beta)\rangle \langle \cos(2\phi_\beta - \Psi_2)\rangle$$

$$\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle = \langle \cos[(\phi_\alpha - \phi_\beta) - (2\phi_\beta - 2\Psi_2)]\rangle \neq \langle \cos(\phi_\alpha - \phi_\beta)\rangle \langle \cos(2\phi_\beta - \Psi_2)\rangle$$

Better way to address it:

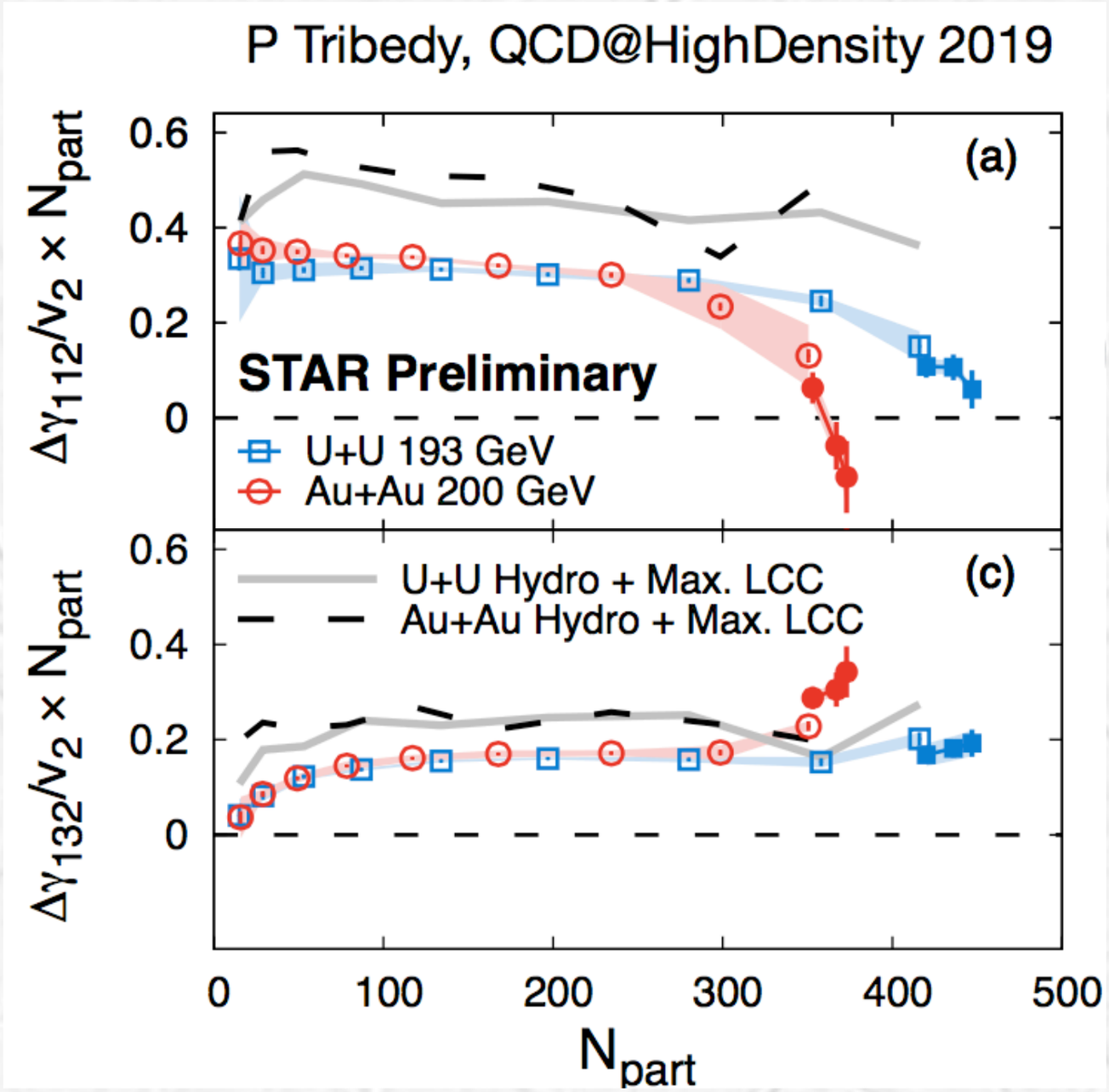
$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle = \langle \cos[(\phi_\alpha + \phi_\beta - 2\phi_c) + (2\phi_c - 2\Psi_2)]\rangle \approx \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle\, v_{2,c}$$

$$\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle = \langle \cos[(\phi_\alpha - 3\phi_\beta + 2\phi_c) - (2\phi_c - 2\Psi_2)]\rangle \approx \langle \cos(\phi_\alpha - 3\phi_\beta + 2\phi_c)\rangle\, v_{2,c}$$

Mixed harmonics, III

$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_2)\rangle=\langle\cos[(\phi_\alpha-\phi_\beta)+(2\phi_\beta-2\Psi_2)]\rangle\neq\langle\cos(\phi_\alpha-\phi_\beta)\rangle\langle\cos(2\phi_\beta-\Psi_2)\rangle$$

$$\langle\cos(\phi_\alpha-3\phi_\beta+2\Psi_2)\rangle=\langle\cos[(\phi_\alpha-\phi_\beta)-(2\phi_\beta-2\Psi_2)]\rangle\neq\langle\cos(\phi_\alpha-\phi_\beta)\rangle\langle\cos(2\phi_\beta-\Psi_2)\rangle$$



Measurements clearly show the difference (unlikely due to CME)

$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$ vs

$\langle\cos(3\phi_\alpha-\phi_\beta-2\phi_c)\rangle$??

Requires detail knowledge of the background nature

Not suitable for precise estimates

Correlations wrt participant and spectator planes

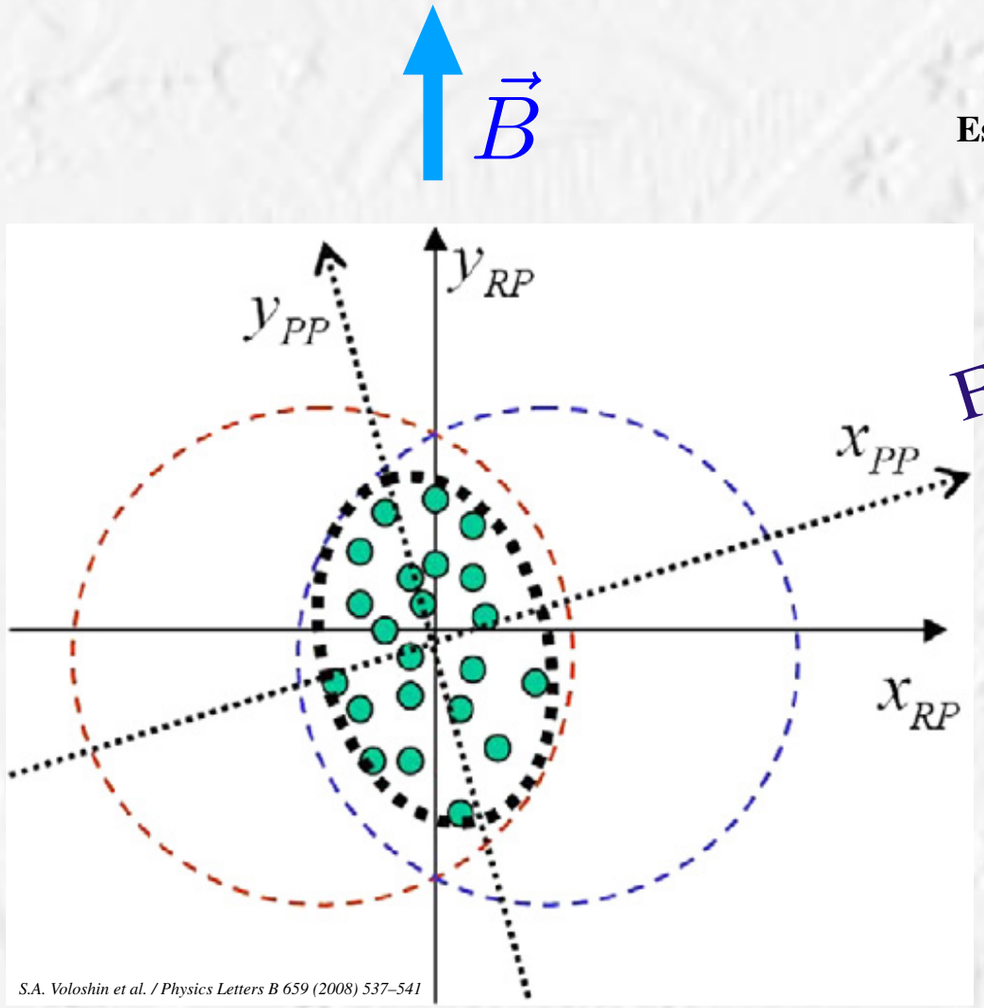


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

Assumption: spectator flow plane defines the magnetic field direction

PHYSICAL REVIEW C **98**, 054911 (2018)

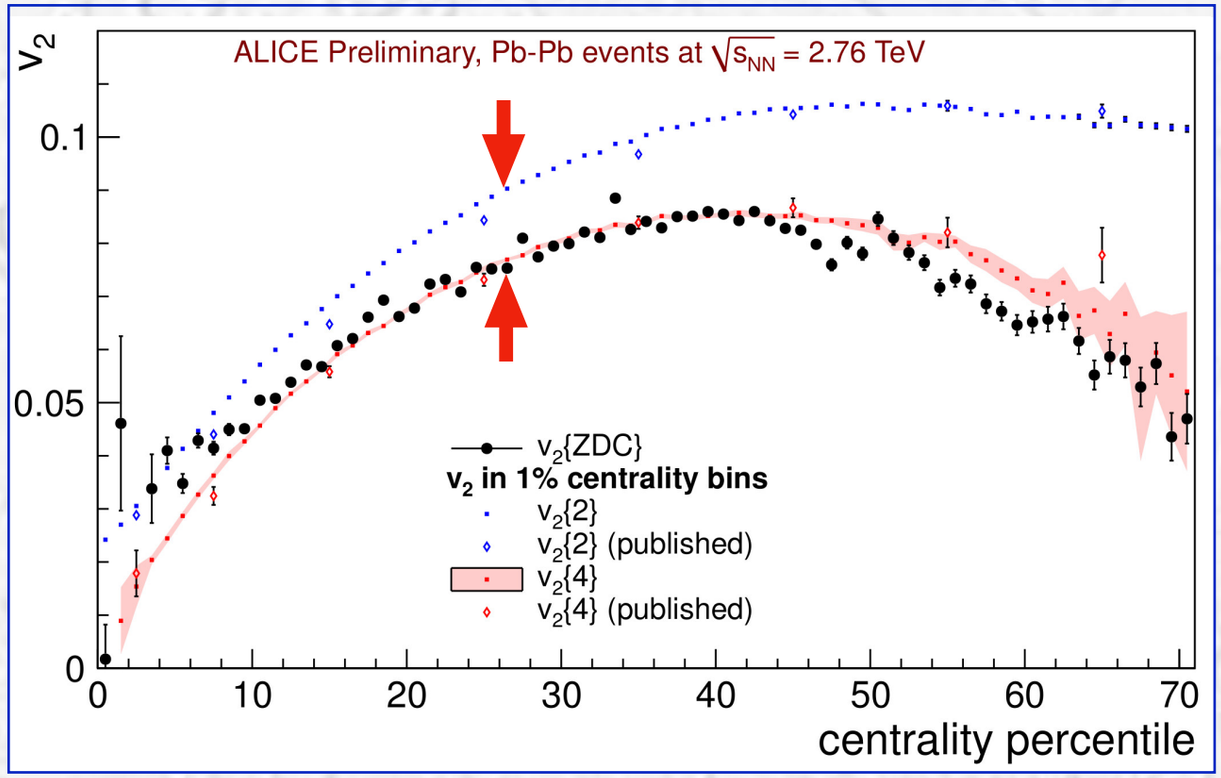
Estimate of the signal from the chiral magnetic effect in heavy-ion collisions from measurements relative to the participant and spectator flow planes

Sergei A. Voloshin
Wayne State University, 666 West Hancock, Detroit, Michigan 48201, USA

Varying the chiral magnetic effect relative to flow in a single nucleus-nucleus collision*

Hao-Jie Xu (徐浩洁)[1], Jie Zhao (赵杰)[2], Xiao-Bao Wang (王小保)[1], Han-Lin Li (李汉林)[3], Zi-Wei Lin (林子威)[4,5], Cai-Wan Shen (沈彩万)[1] and Fu-Qiang Wang (王福强)[1,2]

Published 1 July 2018 • © 2018 Chinese Physical Society and the Institute of High Energy
Chinese Physics C, Volume 42, Number 8



Decorrelation is strong enough to measure the difference in the CME signal

Testing “background scenario”

Sergei A. Voloshin
PHYSICAL REVIEW C **98**, 054911 (2018)

“Background scenario”:

Note that for these calculations **no need** for separate “resolution” calculations (simplify statistical error calculations)

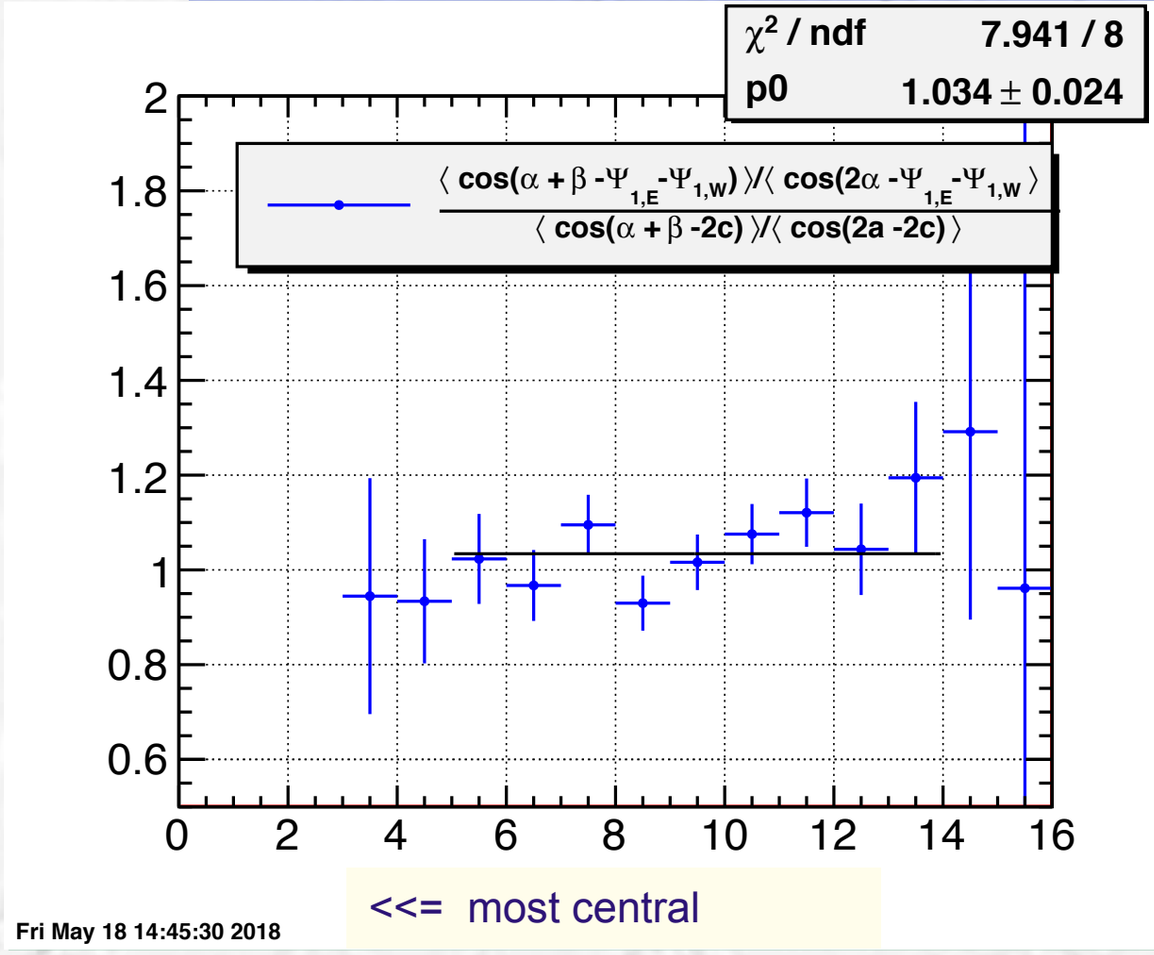
$$\frac{\Delta\langle\cos(\alpha+\beta-2c)\rangle}{\langle\cos(2a-2c)\rangle}\Bigg/\frac{\Delta\langle\cos(\alpha+\beta-\Psi_{1,\mathrm{SPA}}-\Psi_{1,\mathrm{SPB}})\rangle}{\langle\cos(2a-\Psi_{1,\mathrm{SPA}}-\Psi_{1,\mathrm{SPB}})\rangle}=1$$

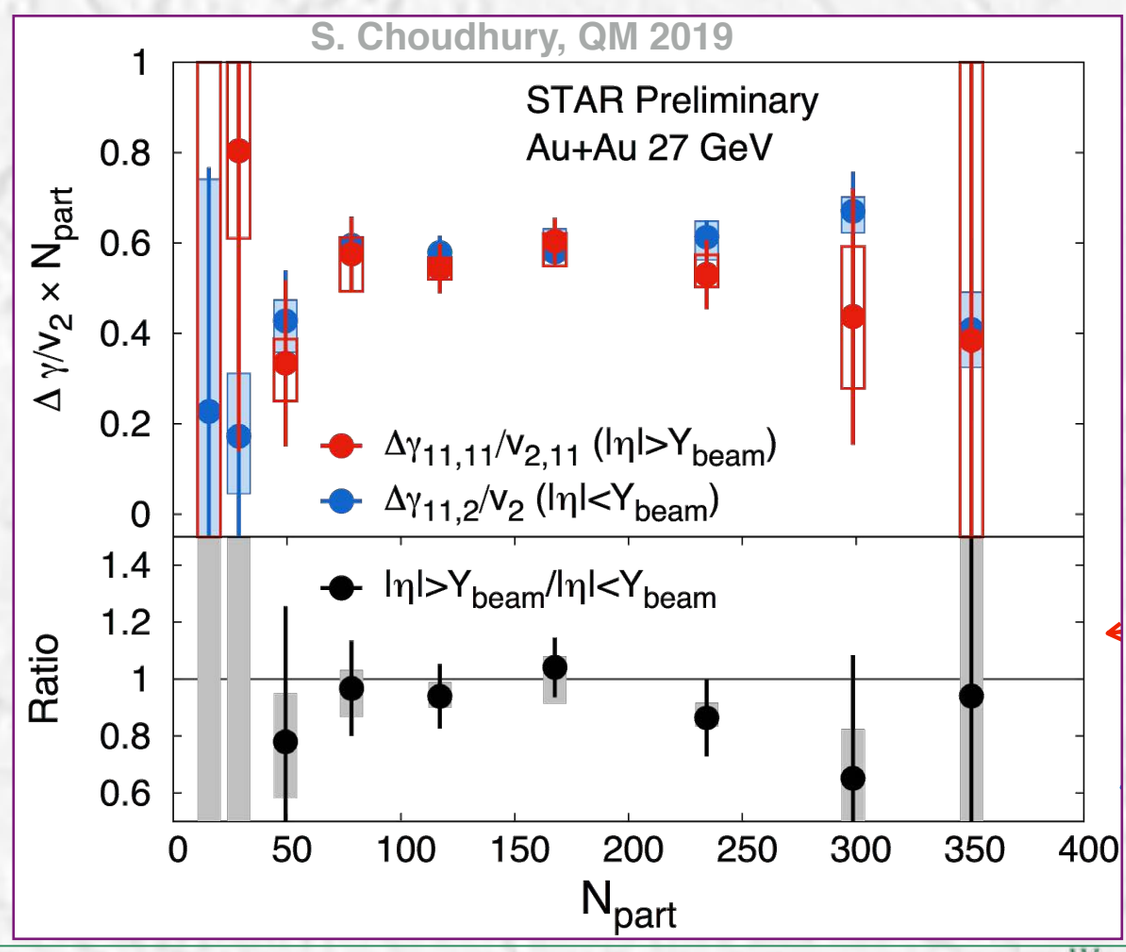
$a=\alpha,\beta$

- if it deviates from unity - it indicates non-zero CME contribution, but to get the real fraction of the signal requires additional assumptions

$$\mathrm{Ratio}=1+\frac{1}{\Delta\gamma_{PP}}\left[\mathrm{CME}_{\mathrm{SP}}\frac{v_2\{2\}}{v_2\{\mathrm{ZDC}\}}-\mathrm{CME}_{\mathrm{PP}}\right]$$

Exact under only one, “main”, assumption”





Getting the CME fraction

$$\text{Ratio} = 1 + \frac{1}{\Delta\gamma_{PP}}\left[\text{CME}_{\text{SP}}\frac{v_2\{2\}}{v_2\{\text{ZDC}\}} - \text{CME}_{\text{PP}}\right]$$

Exact under only one, “main”, assumption”

Requires no “non-flow” contribution, correctly treats flow fluctuations

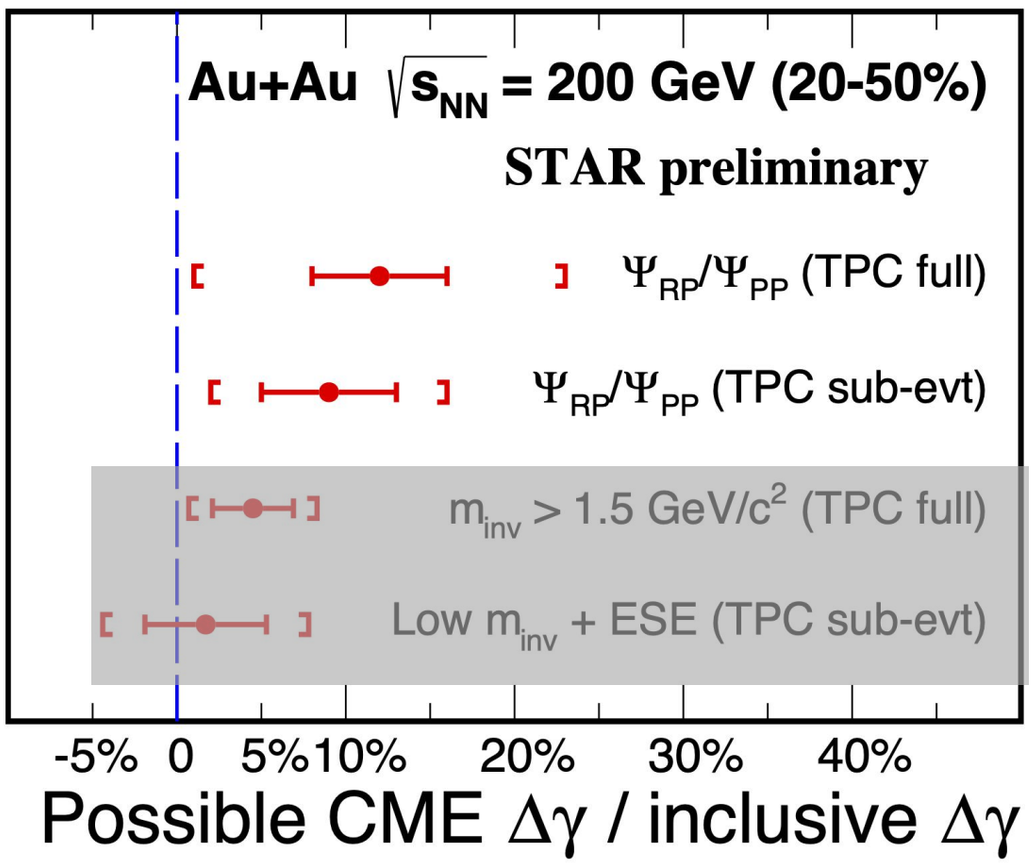
Possible further assumptions:

$$\text{CME}_{\text{SP}} = \text{CME}_{\text{PP}}\frac{v_2\{2\}}{v_2\{\text{ZDC}\}}$$

$$\frac{(\Delta\gamma/v_2)_{\text{SP}}}{(\Delta\gamma/v_2)_{\text{c}}} = 1 + f_{\text{PP}}^{\text{CME}}\left(\frac{\langle v_{2,\text{PP}}^2\rangle}{(v_2\{\Psi_{1,\text{SP}}\})^2} - 1\right)$$

If magnetic field 100% correlated with the SP. “Working” hypothesis.

J. Zhao (STAR collaboration). NPA 982 (2019) 535



Possible non-flow in v_2. Real fraction can be lower

“Precision” of this method likely could be as low as 5%.

Requires careful removal of non-flow and account for flow fluctuations

Isobar collisions

"Double ratio" in analysis of isobar collisions
[instead of two different event planes — different isobar datasets

$$(\Delta\gamma/v_2)_{TPC} = \frac{\Delta\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle}{\langle\cos(2\phi_\alpha-2\phi_c)\rangle}$$

$$\frac{(\Delta\gamma/v_2)_{AA}}{(\Delta\gamma/v_2)_{BB}} = 1+f^{BB}_{CME}[(H_{AA}/H_{BB})^2-1]$$

Subscripts "AA", "BB" == Ru, Zn

Note that the calculation of $(\Delta\gamma/v_2)$ quantities does not require knowledge of the reaction plane resolution [1]. It also "normalizes" the gamma correlator to the elliptic flow value and thus can be used for a direct comparison of the signals in different isobar collisions, even if the values of elliptic flow is slightly different in the two samples.

For isobar "double ratio", non-flow is much less of a problem!

Double ratio is "assumption free", insensitive to small differences in flow, centrality determination, nonflow,

PP/SP planes still can be used for individual isobar datasets to evaluate the CME fraction in each of them

Signed BF

XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

Measurement of the charge separation along the magnetic field with Signed Balance Function in 200 GeV Au + Au collisions at STAR

Yufu Lin for the STAR Collaboration [1]

based on:

Probe Chiral Magnetic Effect with Signed Balance Function

A. H. Tang

- *Chin.Phys.C* 44 (2020) 5, 054101

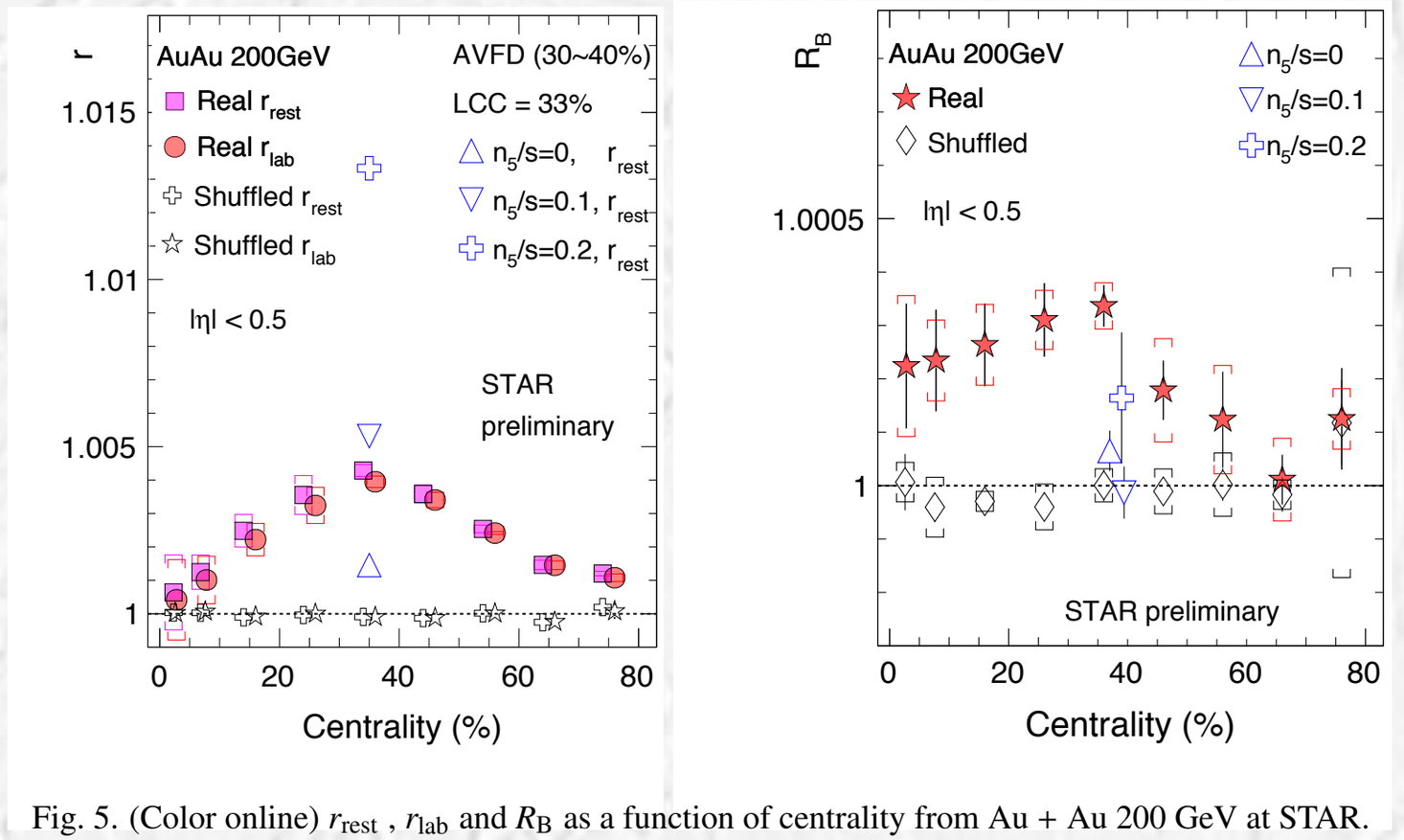


Fig. 5. (Color online) $r_{\rm rest}$, $r_{\rm lab}$ and $R_{\rm B}$ as a function of centrality from Au + Au 200 GeV at STAR.

If both $r_{\rm rest}$ and $R_{\rm B}$ are larger than unity, then it can be regarded as a case in favor of the existence of CME. In Au+Au collisions at 200 GeV, $r_{\rm rest}$, $r_{\rm lab}$ and $R_{\rm B}$ are found to be larger than unity, and larger than AVFD model calculation with no CME implemented. Our results are difficult to be explained by a background-only scenario.

Idea:

Particles get small impulses due to CME. Let us analyze the change in momentum, instead of azimuth. Count the signs of the relative momentum (y component) for each pair, in the lab frame and in the pair rest frame.

Might be slightly more “sensitive” that gamma, but effect is likely small. Needs further investigations. More difficult to calculate

"R" correlator

PHYSICAL REVIEW C **83**, 011901(R) (2011)

New method for the experimental study of topological effects in the quark-gluon plasma

N. N. Ajitanand, Roy A. Lacey, A. Taranenko, and J. M. Alexander

PHYSICAL REVIEW C **97**, 061901(R) (2018)

ns

New correlator to detect and characterize the chiral magnetic effect

Niseem Magdy,[1,*] Shuzhe Shi,[2] Jinfeng Liao,[2] N. Ajitanand,[1,†] and Roy A. Lacey[1,‡]

$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S),$$

$$C_{\Psi_m}(\Delta S) = \frac{N_{\rm real}(\Delta S)}{N_{\rm Shuffled}(\Delta S)}$$

$$\Delta S = \frac{\sum_1^p \sin\left(\frac{m}{2}\Delta\varphi_m\right)}{p} - \frac{\sum_1^n \sin\left(\frac{m}{2}\Delta\varphi_m\right)}{n}$$

The correlation functions $C^{\perp}_{\Psi_m}(\Delta S)$, used to quantify charge separation perpendicular to the $\vec{B}$ field, are constructed with the same procedure outlined for $C_{\Psi_m}(\Delta S)$, but with Ψ_m replaced by $\Psi_m + \pi/m$.

sin() —> cos() in the Eq. above

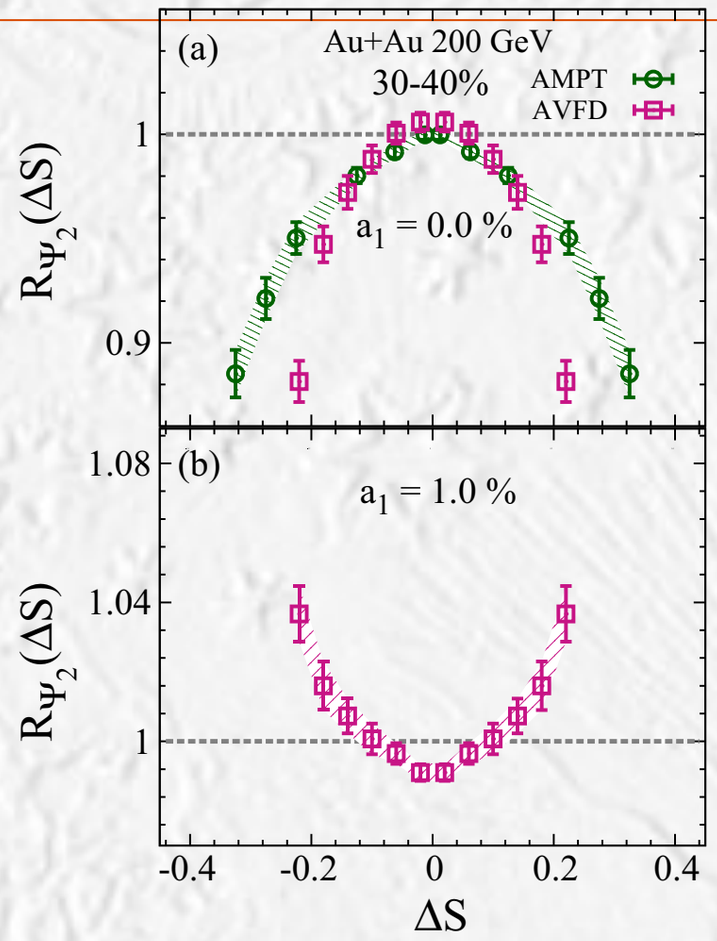


FIG. 1. Comparison of the $R(\Delta S)$ correlators for (a) background-driven charge separation ($a_1 = 0$) in 30–40% Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV) obtained with the AMPT and AVFD models, and (b) the combined effects of background- and CME-driven ($a_1 = 1.0\%$) charge separation in Au+Au collisions obtained with the AVFD model at the same centrality and beam energy.

The shape of the ratio (concave, convex) depends on the widths of the distributions in the denominator and numerator. Those widths are determined by the value of 2-particle correlations (sin-sin or cos-cos). The it is simpler and much more transparent to compare those directly (as done in gamma correlator).

Does not seem to bring anything new

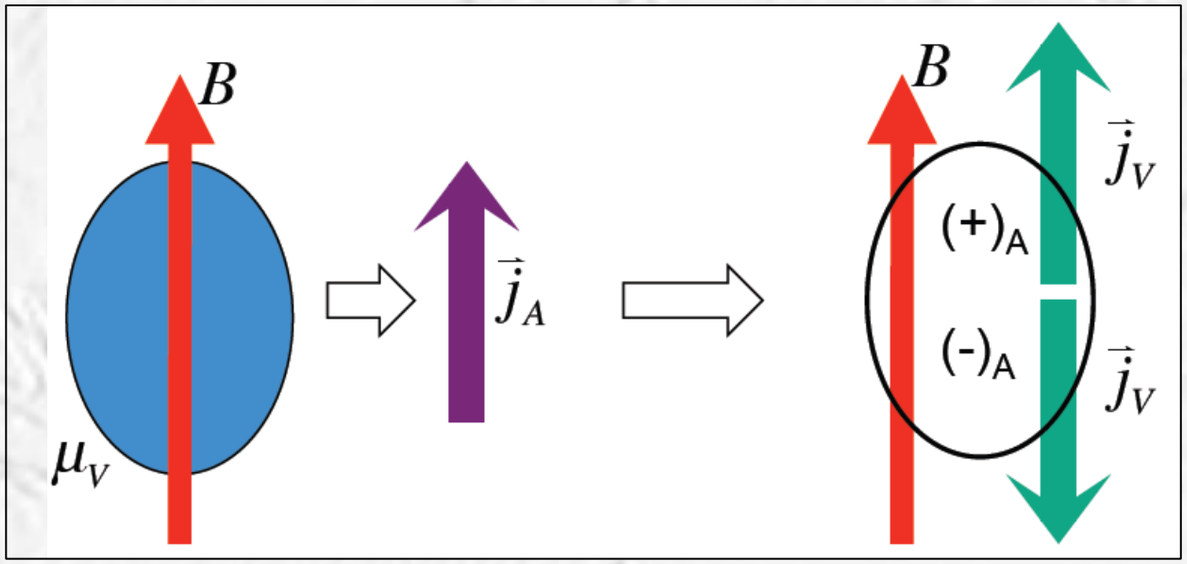
Difficult for quantitative analysis, e,g. what should be the relative contribution of the signal and background for the ratio to be flat?

Chiral Magnetic Wave

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

PRL **107,** 052303 (2011)

$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B} \qquad \mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}$$



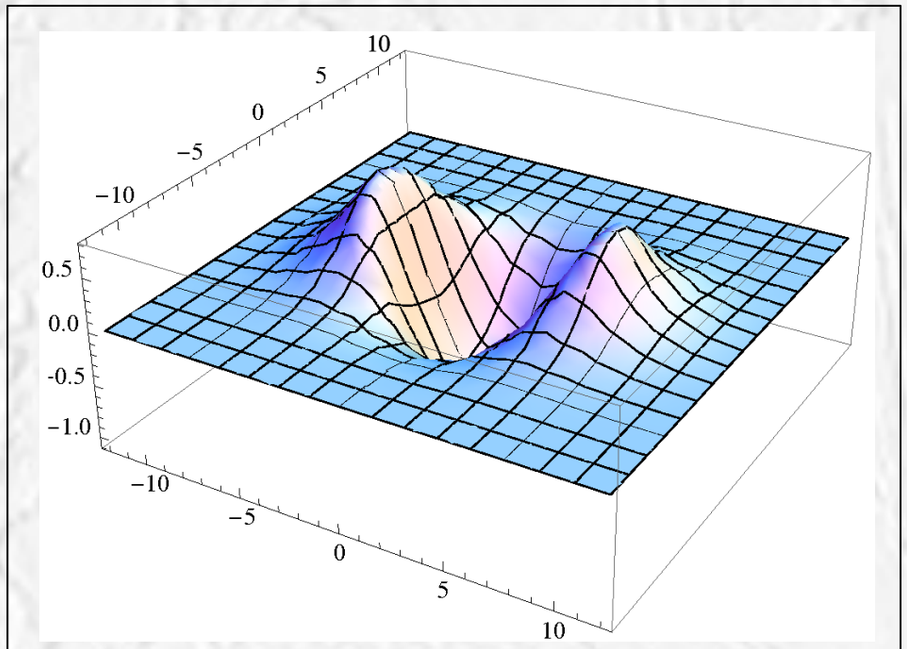


FIG. 2 (color online). Electric charge density in the transverse plane (background subtracted, see text). Same parameters as in Fig. 1.

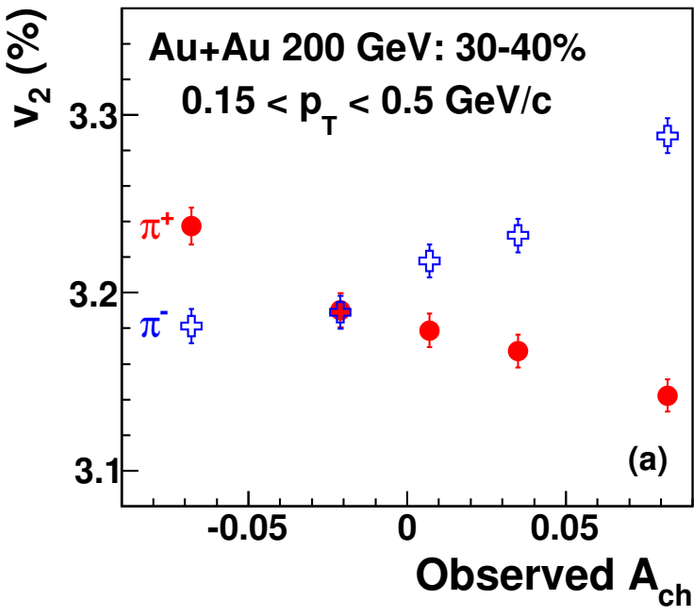
For a given sign of A, the difference in v_2 for positive and negative particles is uniquely predicted

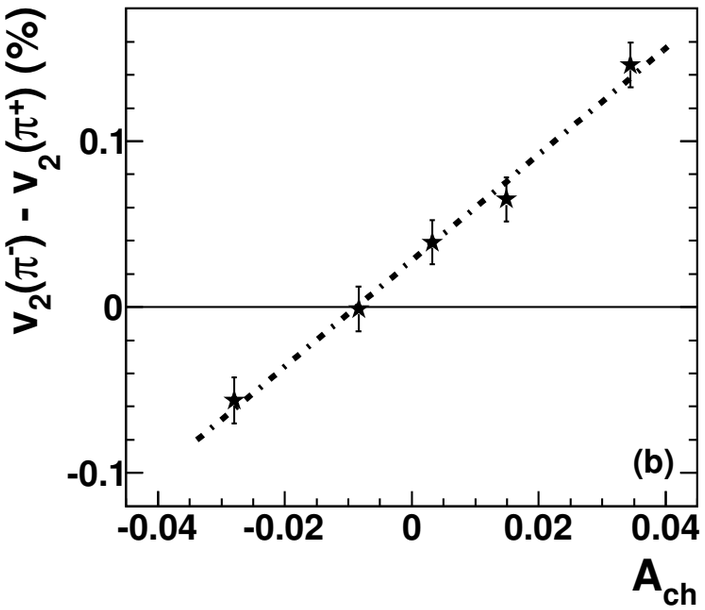
$$v_2^{\pm} = v_2 \mp \frac{rA_{\pm}}{2}$$

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

v_2 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).

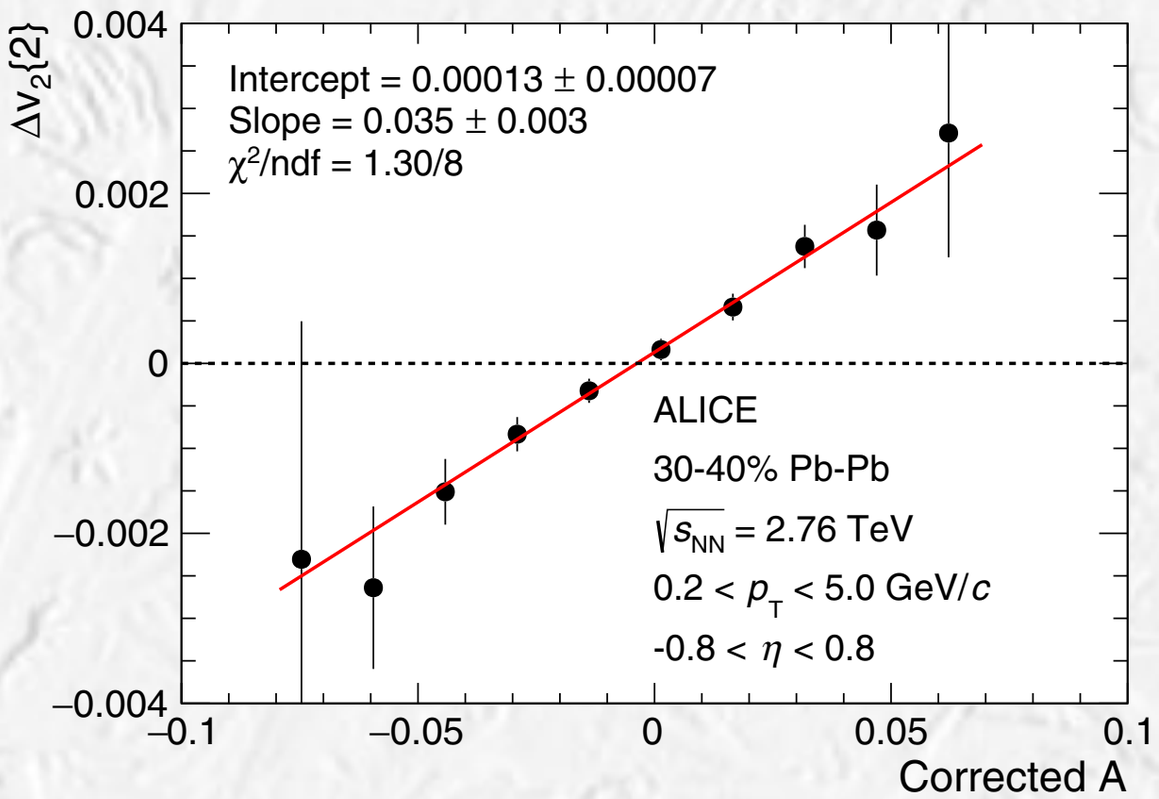




$$v_2^{\mp} = v_2 \mp \frac{rA_{\pm}}{2}$$

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

- 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).

$$\langle c_3 \rangle = \frac{N_+ - N_-}{N_+ + N_-} \qquad A_{\rm ch} = (N_+ - N_-)/(N_+ + N_-)$$

Three particle correlator

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

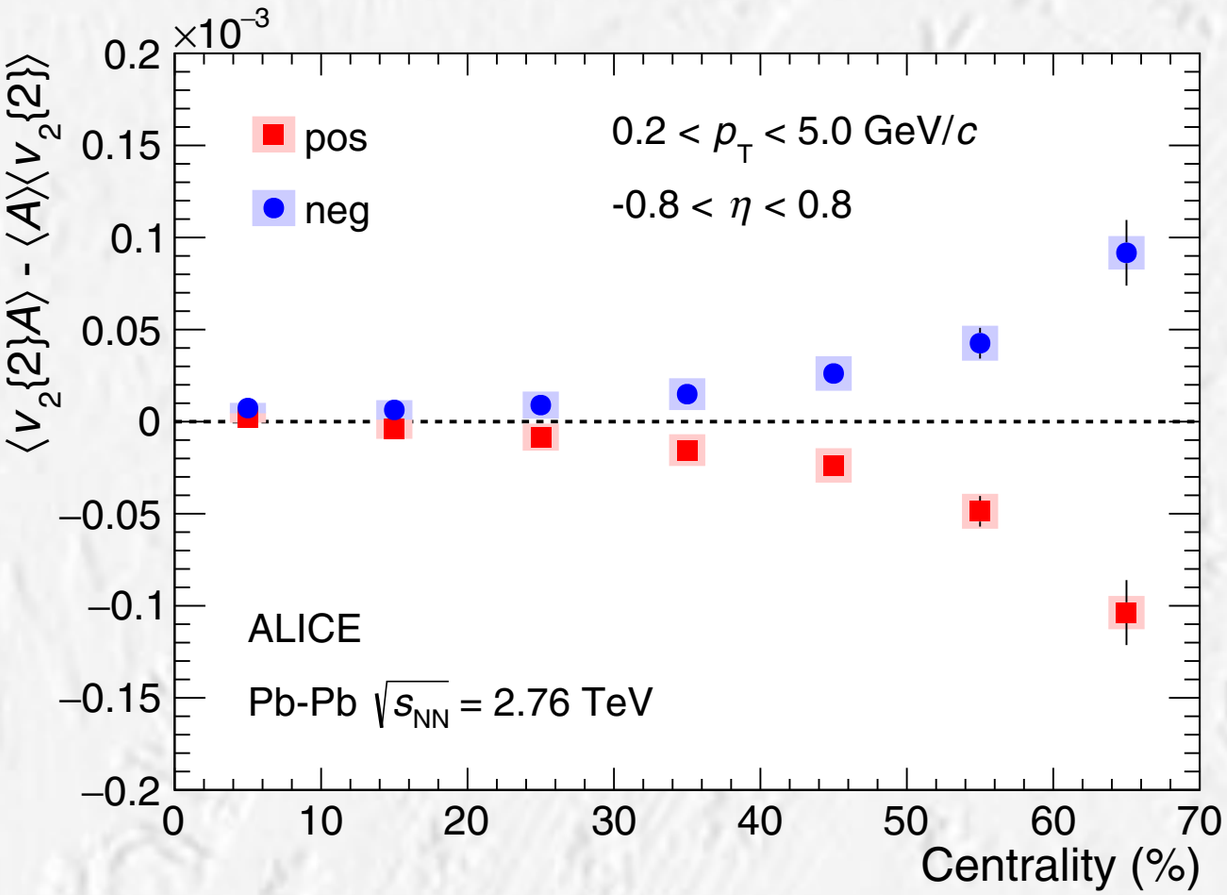
$\langle c_3 \rangle_1$ -- mean charge of particle “3” under condition of particle “1” being observed

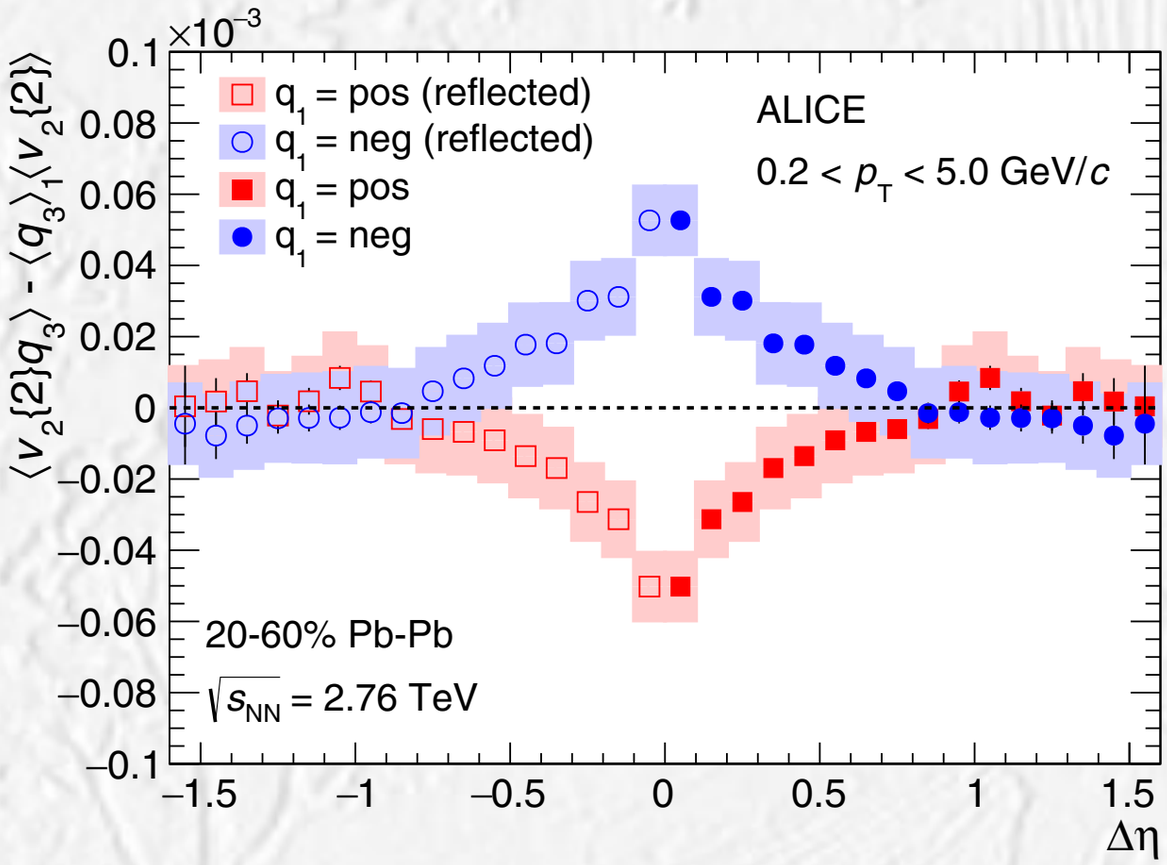
- is tracking efficiency independent
- allows differential studies
- can be used for direct comparison between different experiments

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).

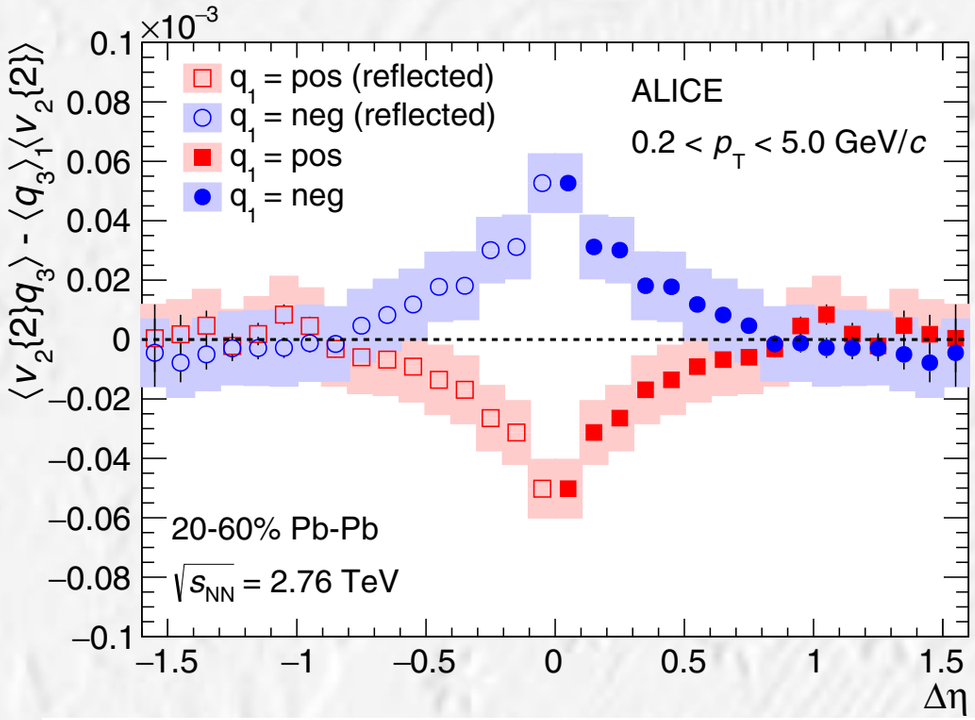


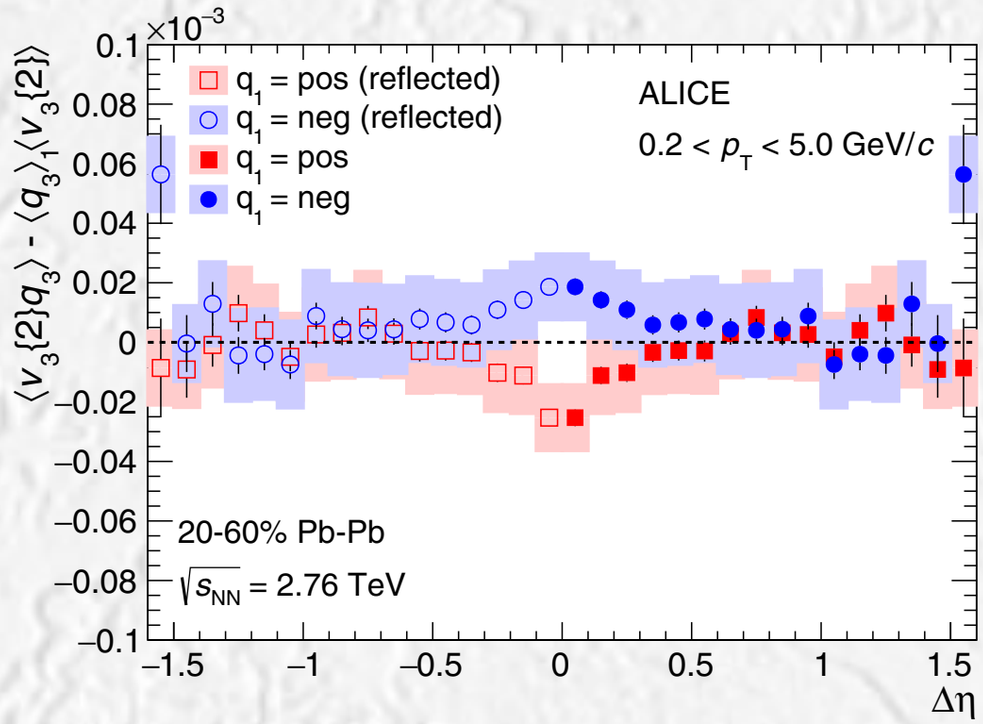


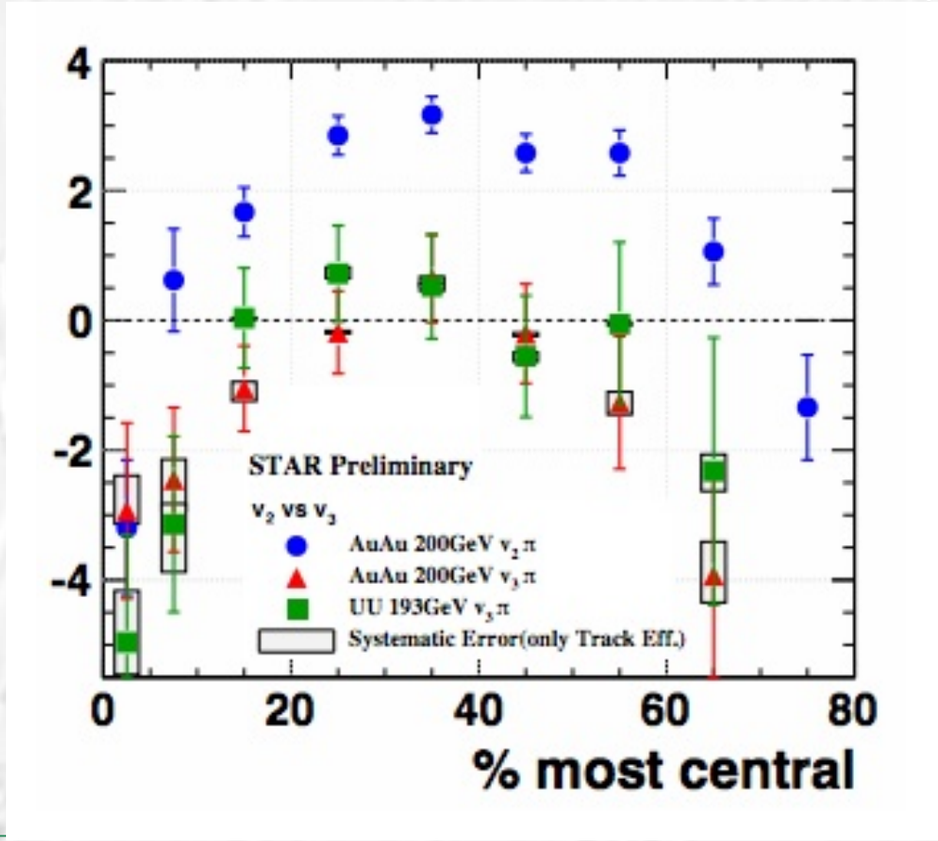
Clear signal, qualitatively consistent with expectations for CMW, pseudorapidity dependence similar to that of gamma correlator

Higher harmonics

CMW: v2 vs Ach, 3 pt correlator

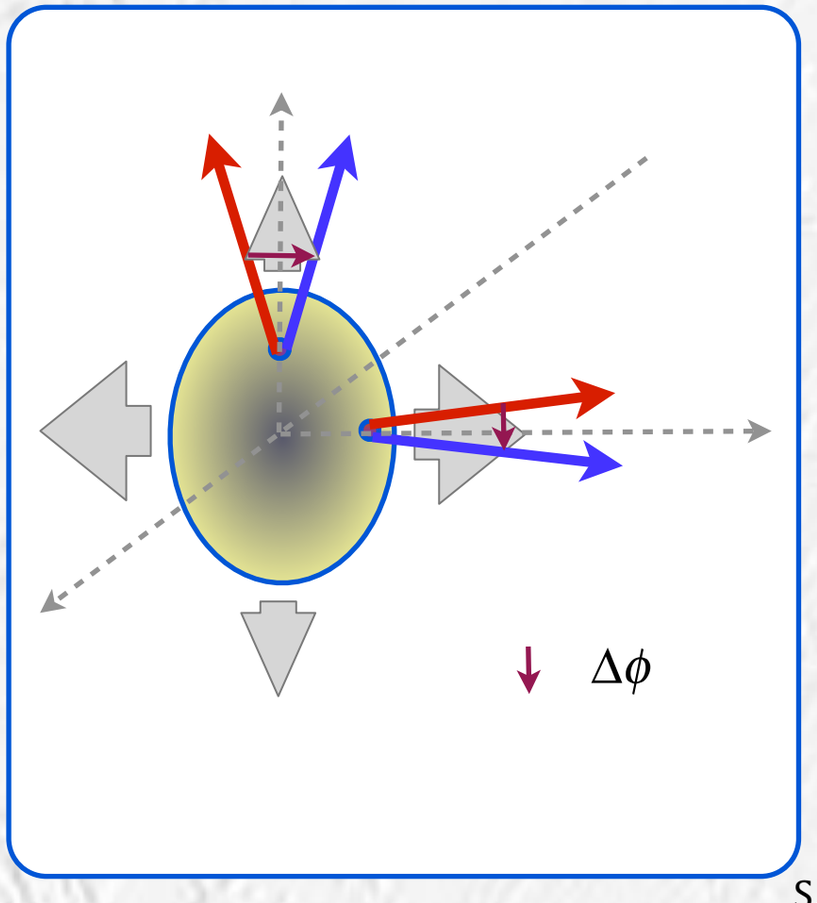


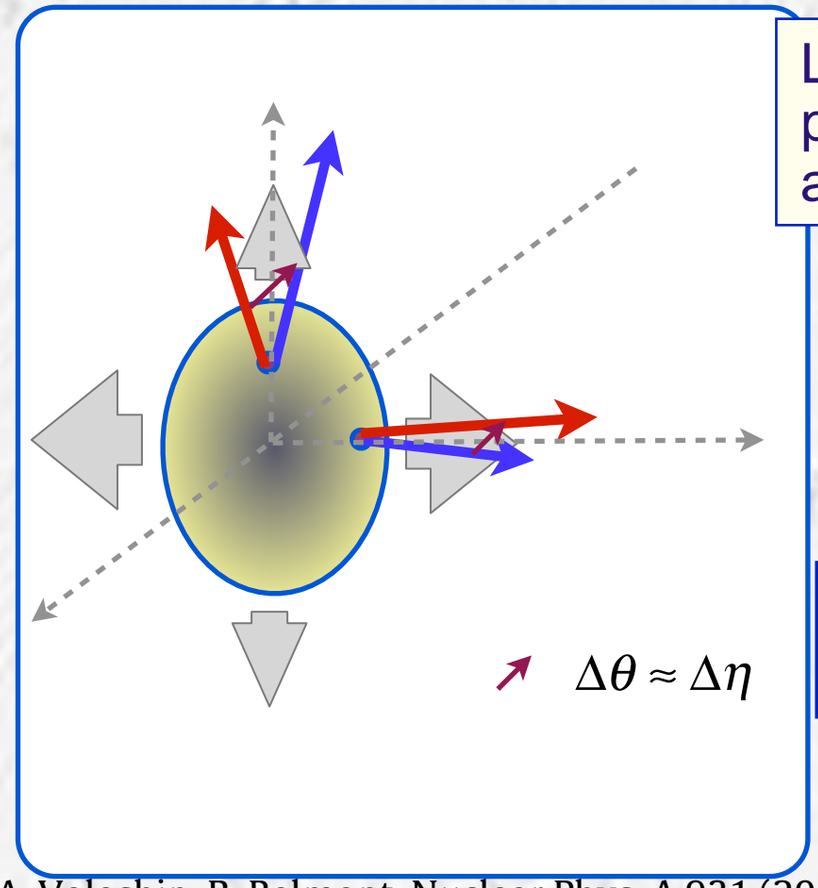




Can be difficult for quantitative interpretation similarly to the CME search

Cross-correlations:

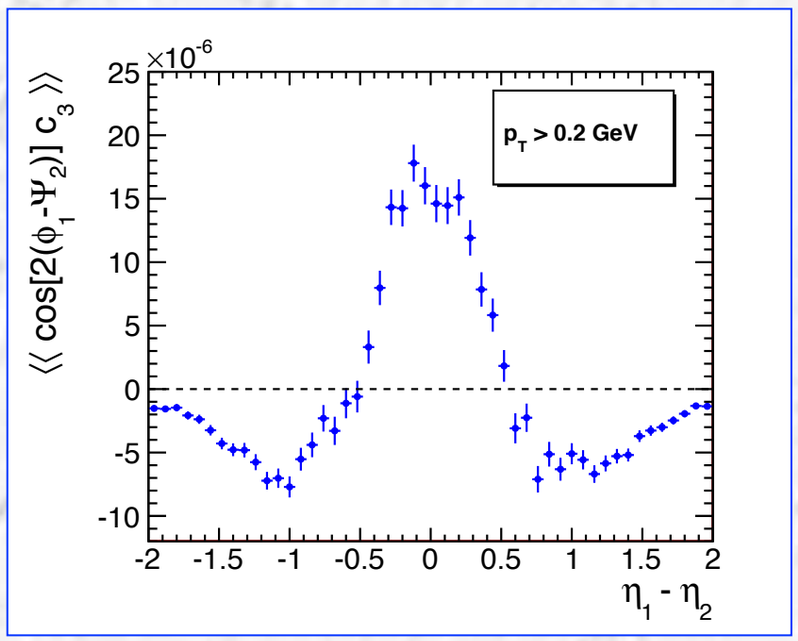


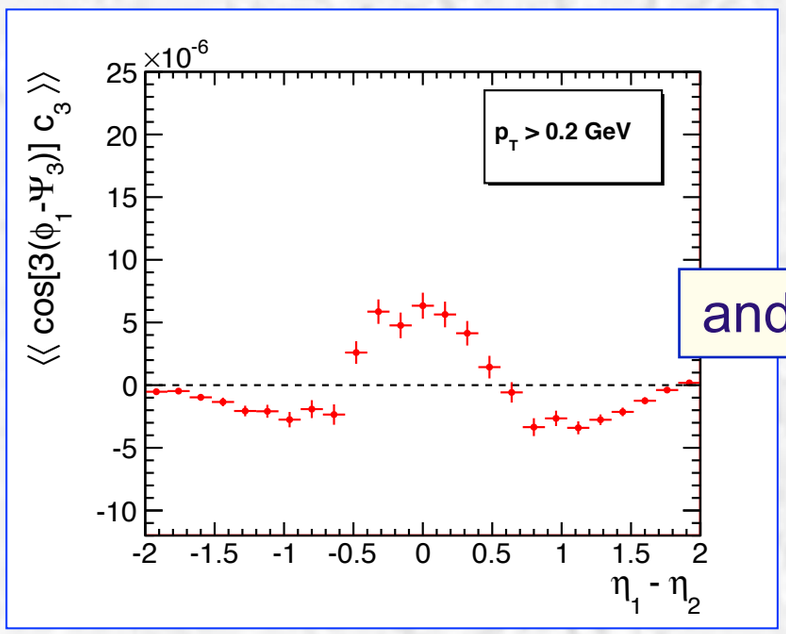


Larger radial flow narrows pair distribution in azimuth as well as in pseudorapidity

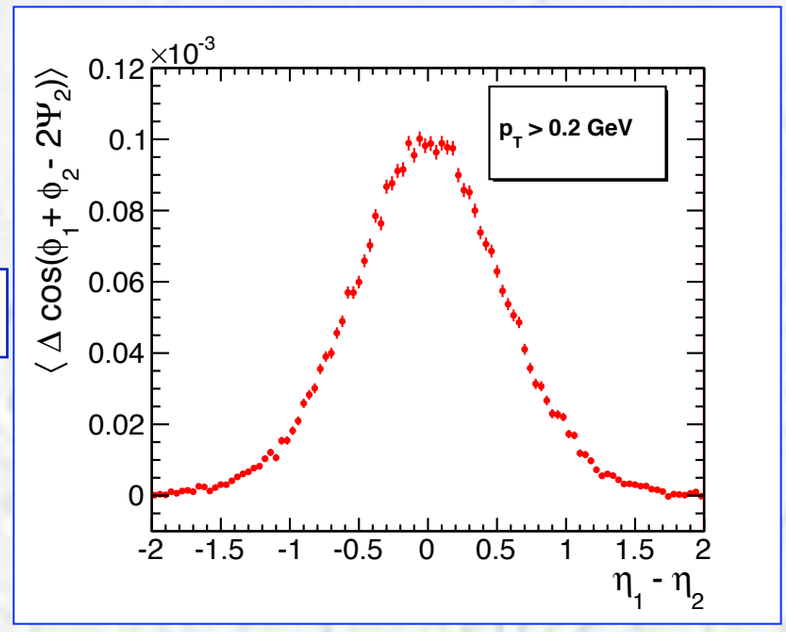
Could serve as a good test for the background nature

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





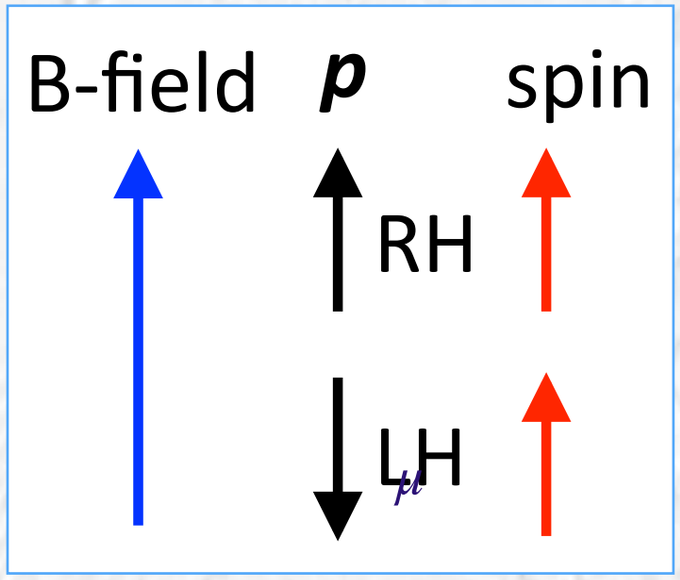
and



CSE and global polarization

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

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



Can be:

net baryon number,
electric charge,
net strangeness

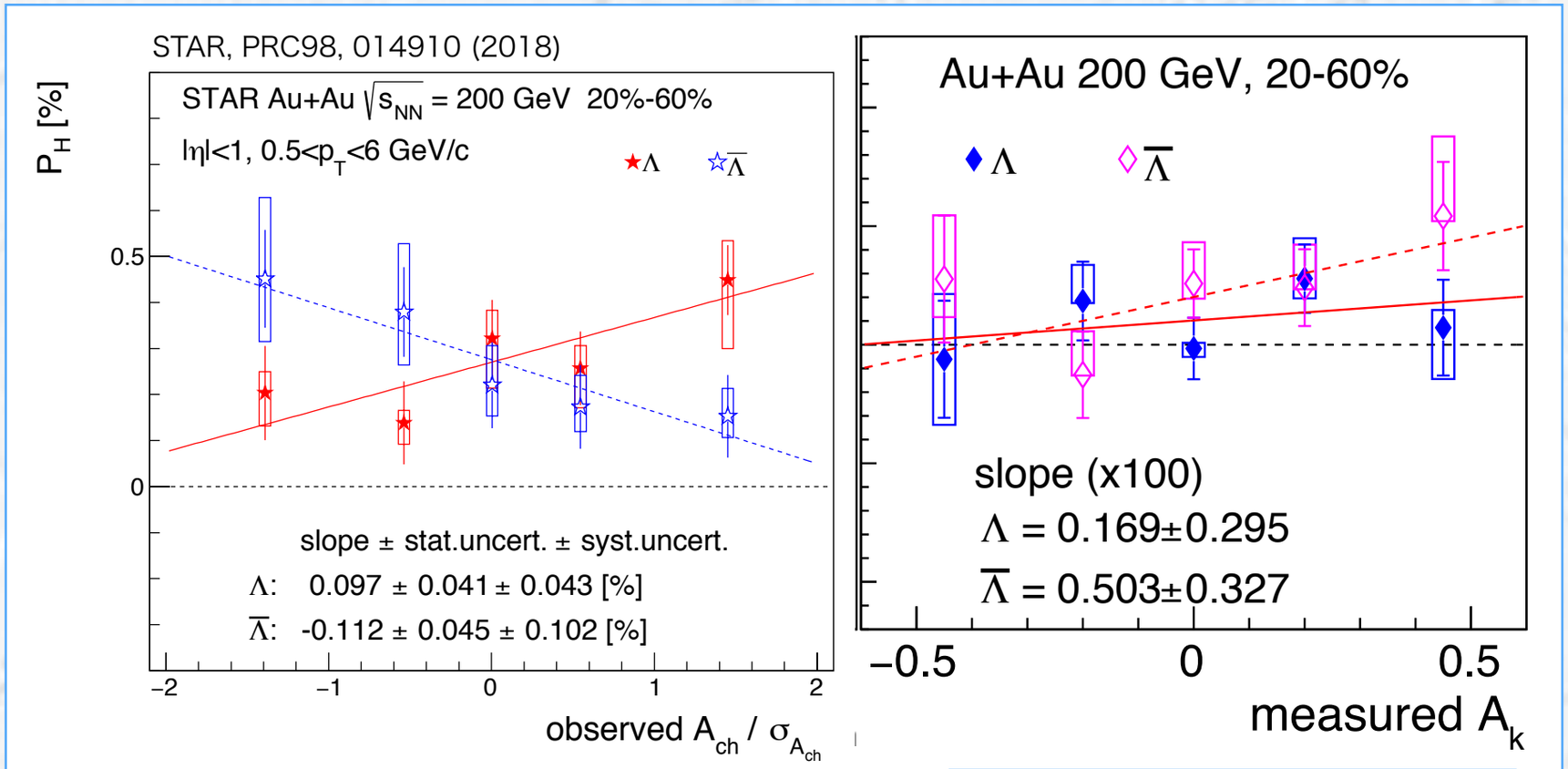
$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_v/T \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}$$

!!: 1/2 of the CMW phenomenon

Difficulties: vs charge - **Λ** is neutral
(but **Ξ** is not!)
vs net kaons - low sensitivity to μ_V

P_Λ vs net charge, net strangeness

$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_v/T \propto \frac{\langle N_{K+} - N_{K-} \rangle}{\langle N_{K+} + N_{K-} \rangle}$$



T. Niida, QCD Chirality Workshop 2017

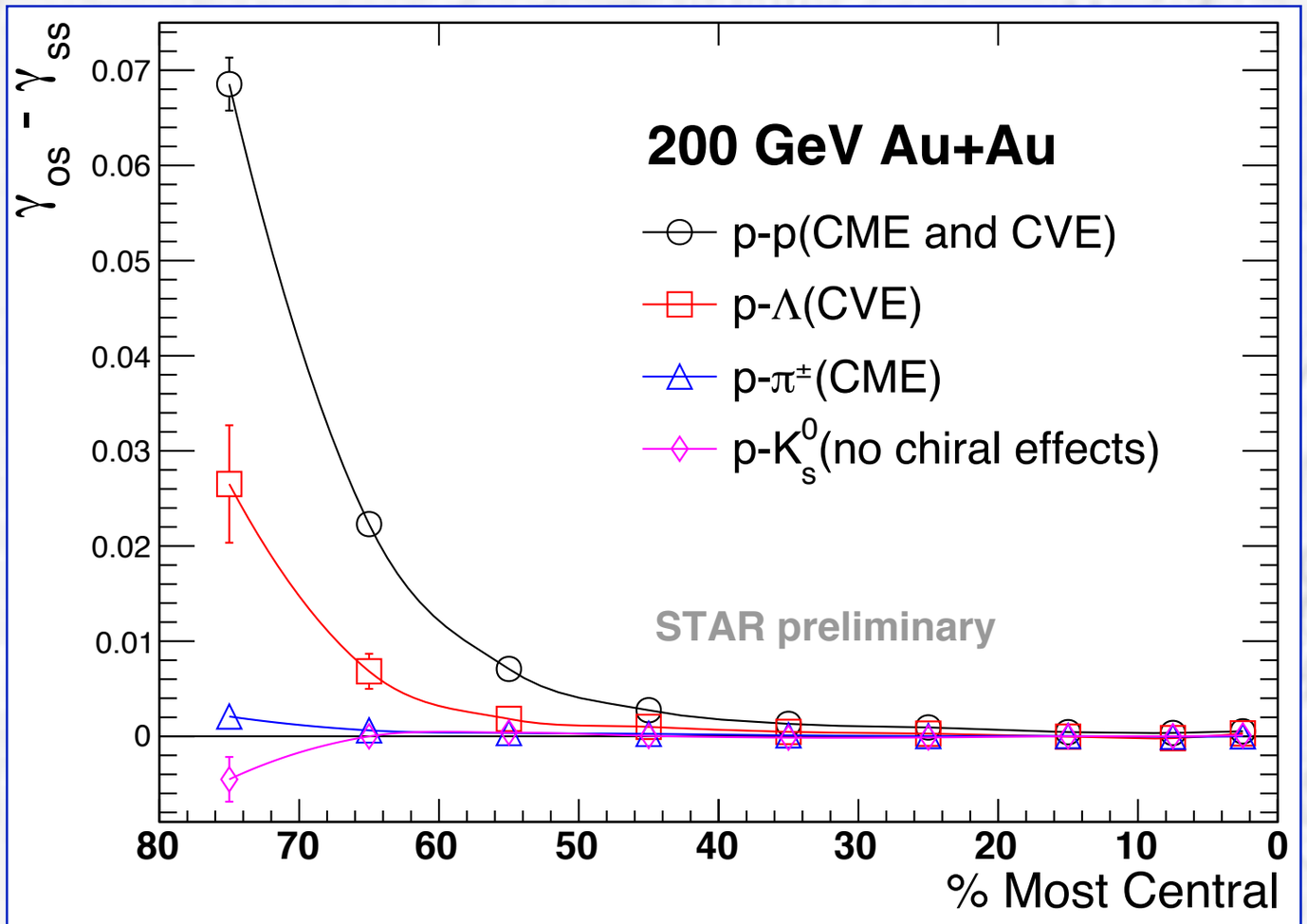
1-2 sigma effect vs event charge asymmetry,

Need more events…

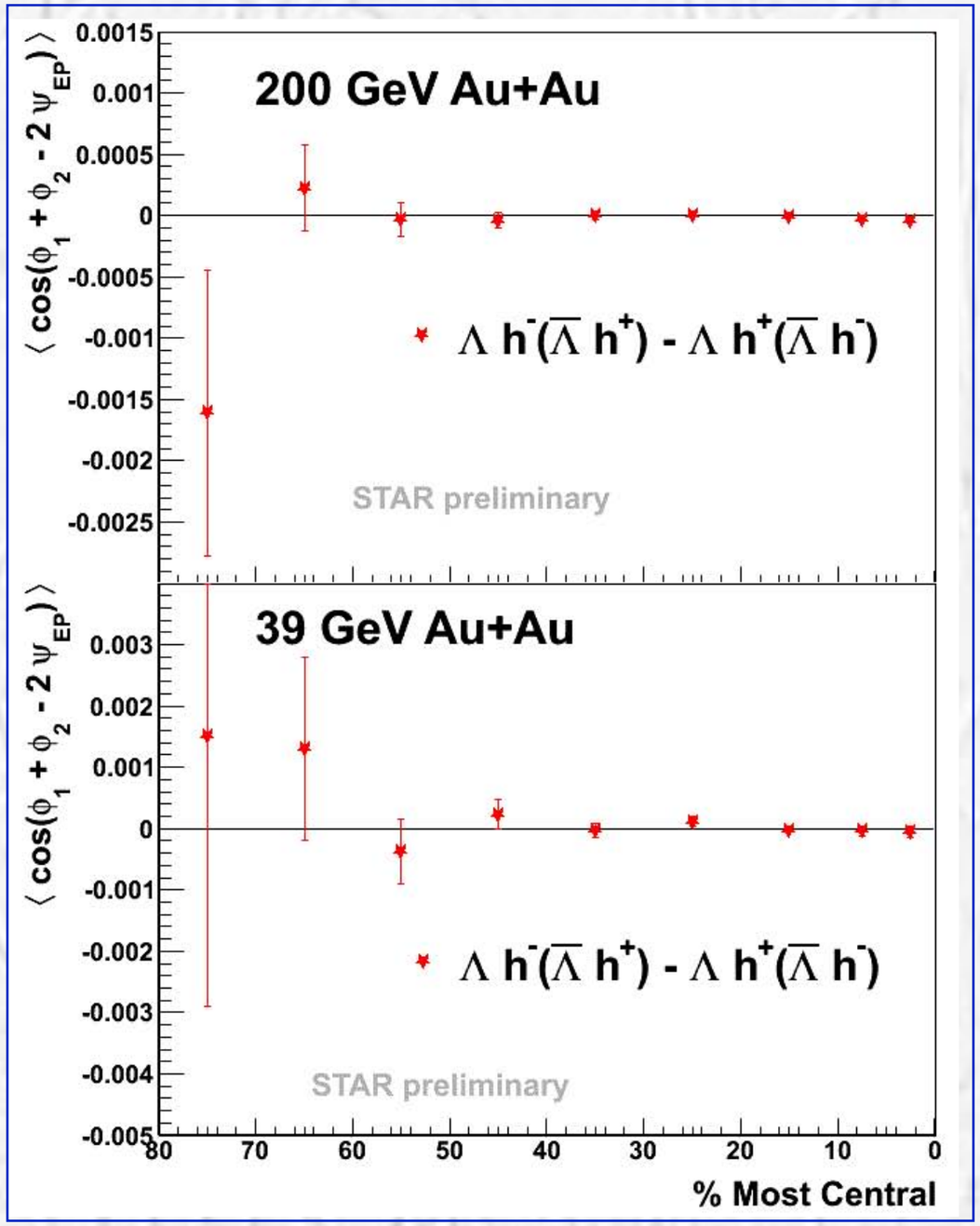
Can it be used to establish CSE?

Cross correlations: CVE x CME comparison

(identified particle correlations)

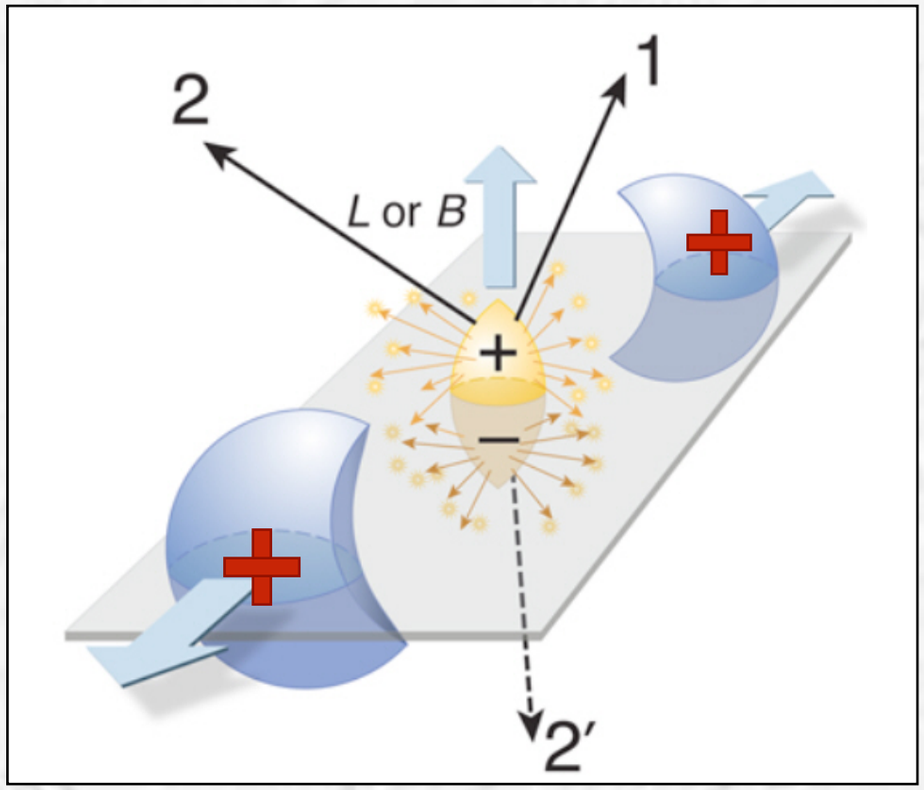


Lambda - CVE
proton - CVE+CME
pion - CME
K^0 - nothing?



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

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

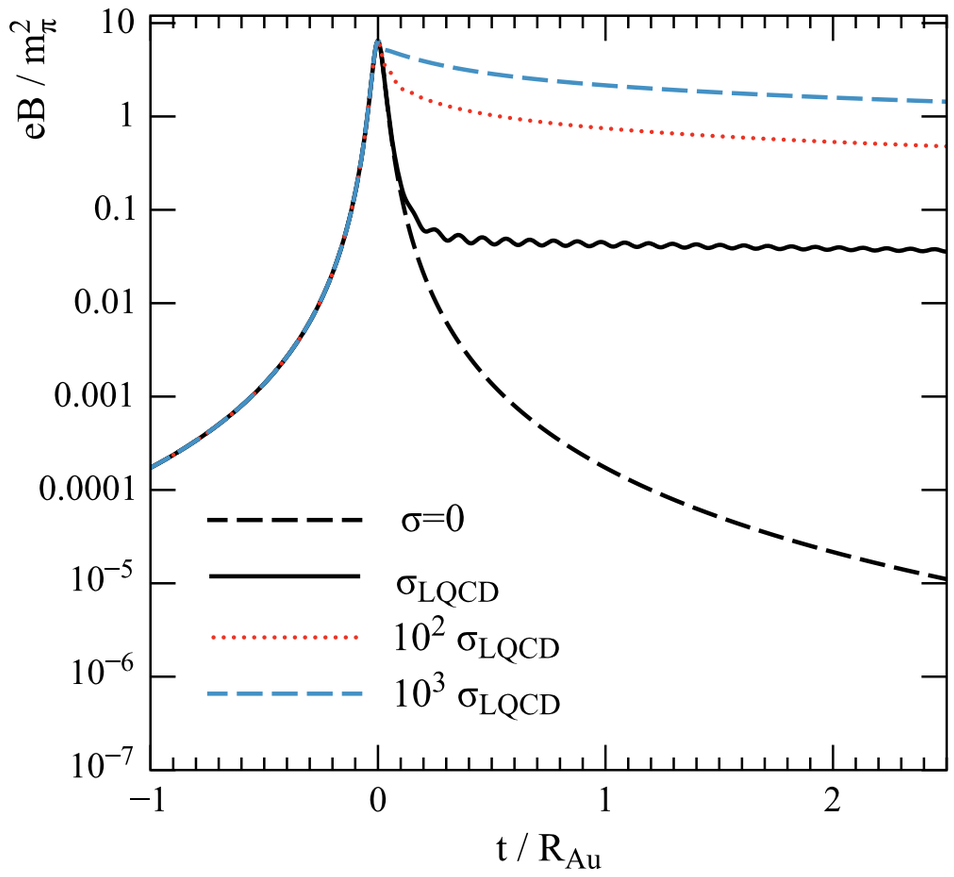
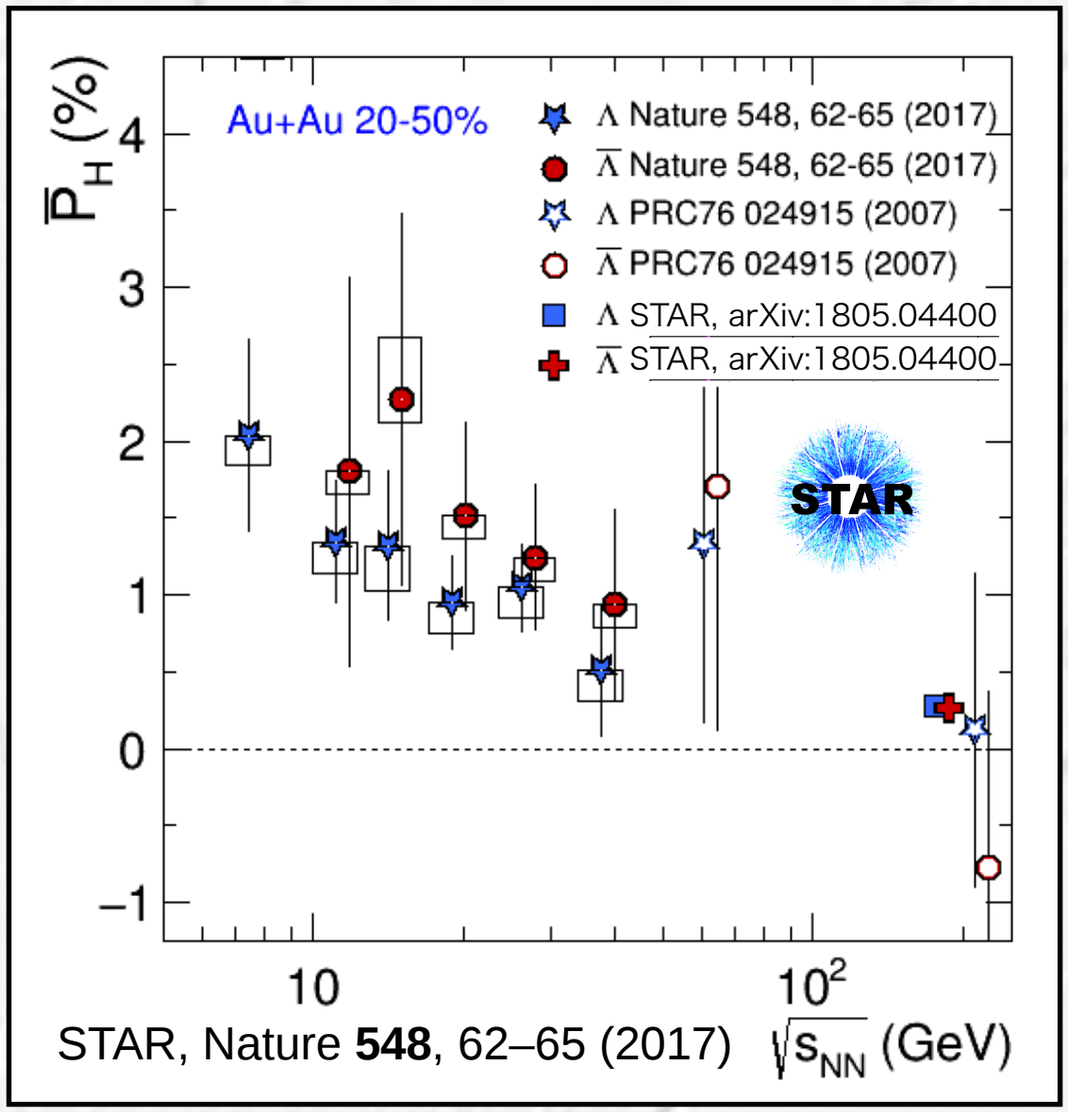


Fig. 1. Magnetic field for static medium with Ohmic conductivity, $\sigma_{\rm Ohm}$.

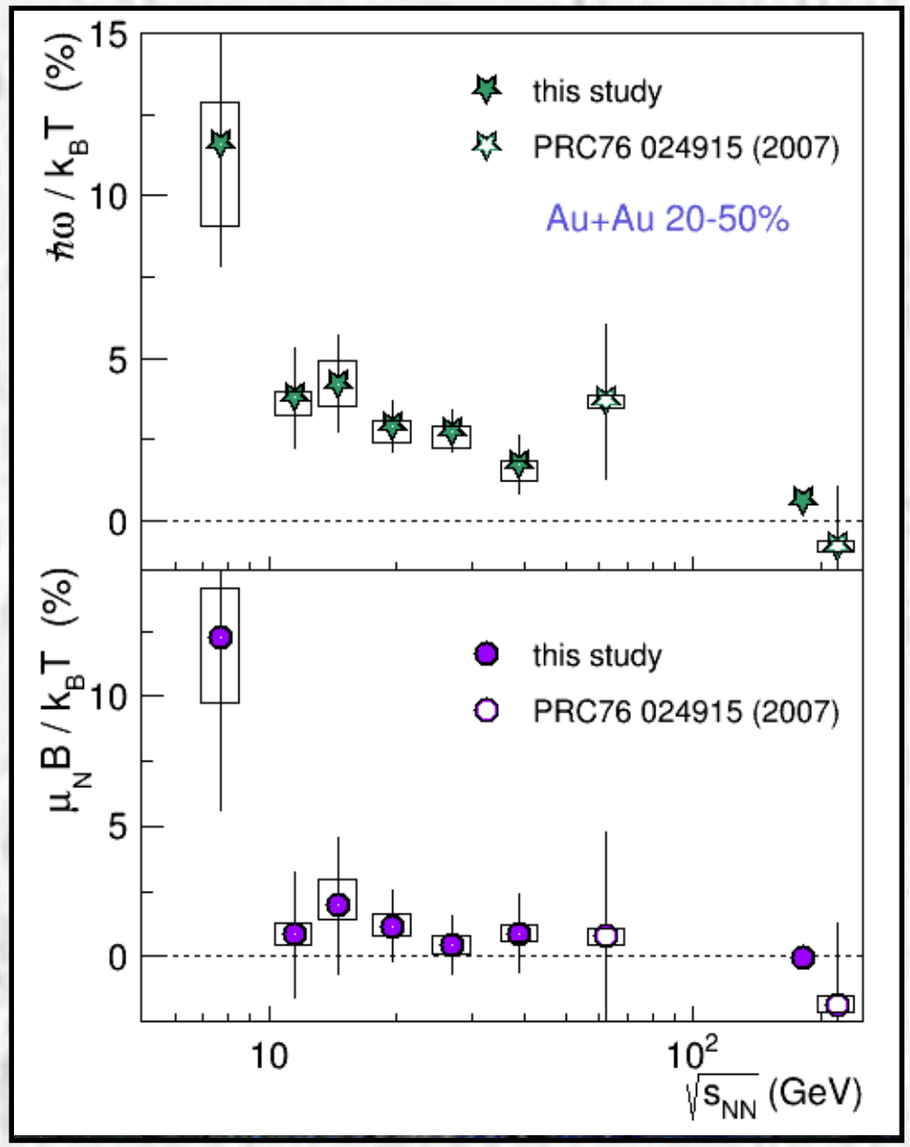
Global/local polarization and the magnetic field

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$
$$P_{\bar\Lambda} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$



STAR, Nature **548**, 62–65 (2017)

Polarization of anti-Lambdas is higher than that of Lambdas - indication of the magnetic field effect?



➜ Omega/T of the order of a few percent

➜ Magnetic fields $eB \sim 10^{-2} m_\pi^2$

EM field lifetime. Quark density evolution

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

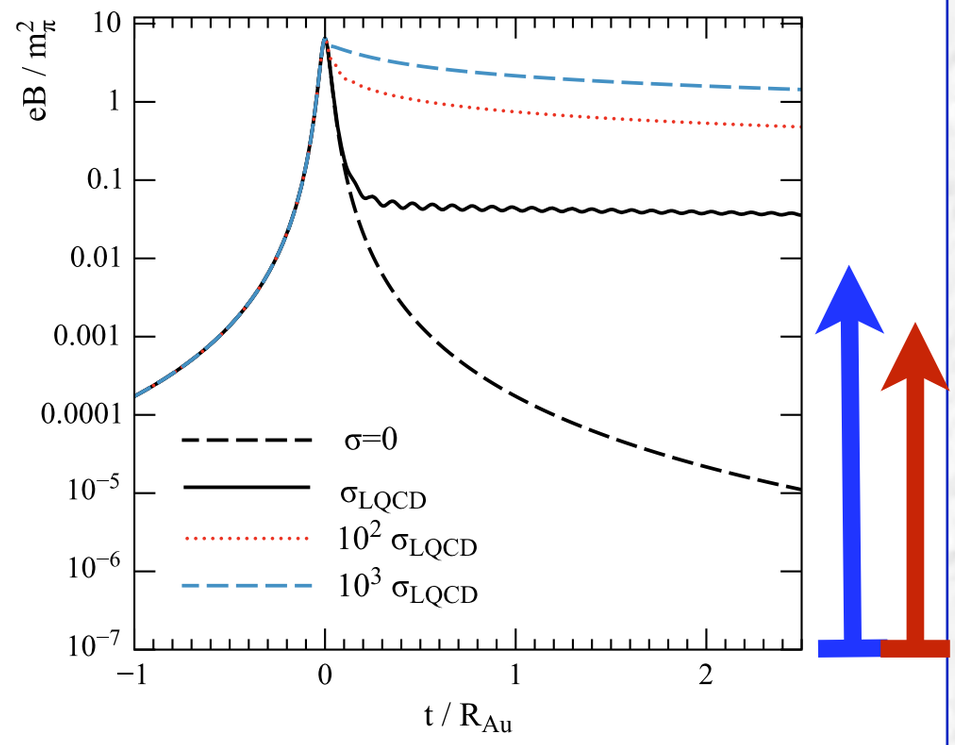


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

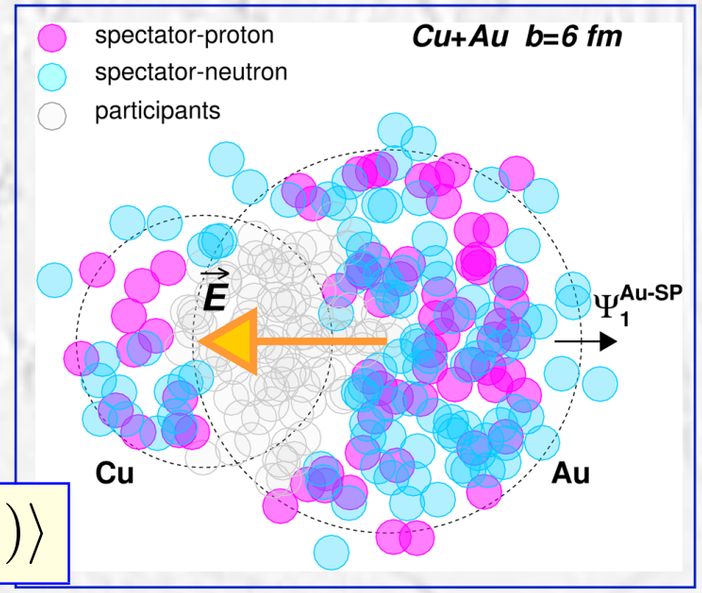
Upper limits from the global polarization measurements:

Blue: for BES
Red: 200 GeV

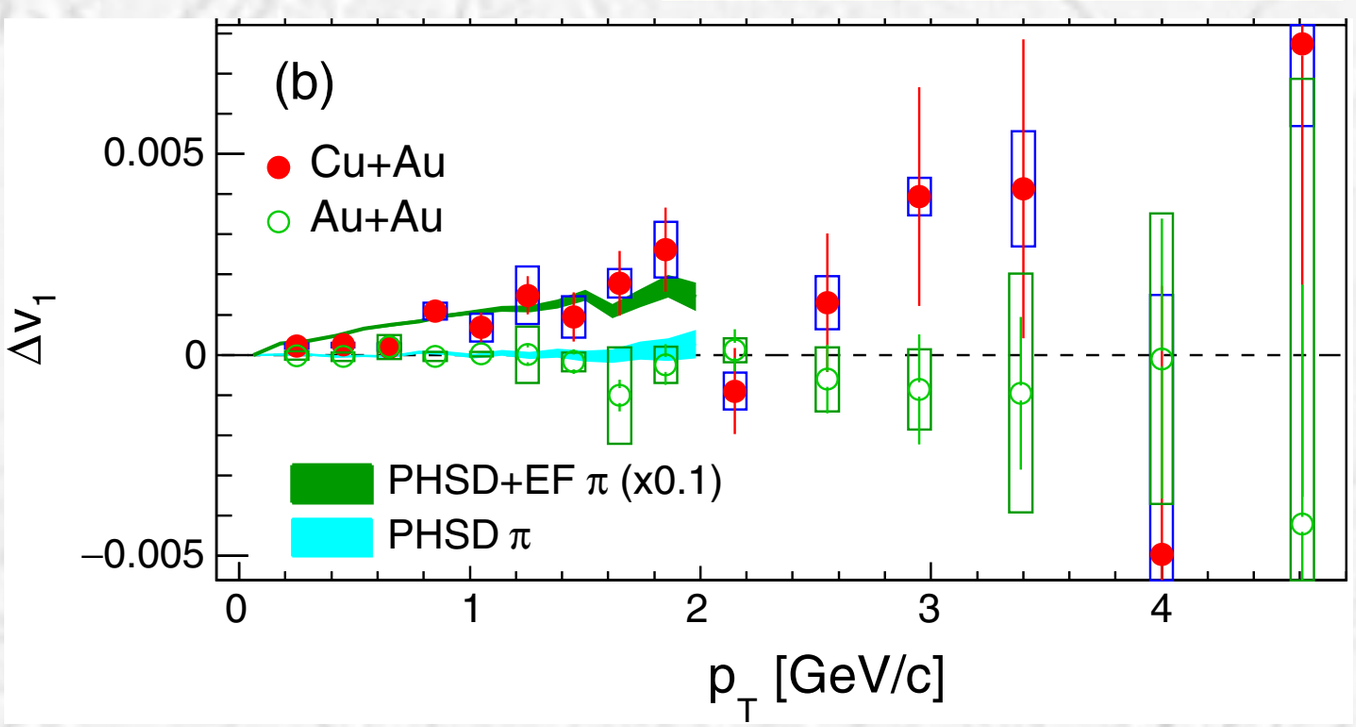
PRL **118,** 012301 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

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

(STAR Collaboration)



$$v_1(y, p_T) = \langle \cos(\phi - \Psi_{\mathrm{RP}}) \rangle$$



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

Final remarks

Current limit on the “CME fraction” is about < 15%
With isobars, ESE, SP/PP we will know it at the level ~ 5%

Getting anything better than that seems to be difficult

“New” directions:

PID? $2N_f|Q|$ quark interaction?
many-particle correlation?

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



Glasma: do we have long range correlations in rapidity? Multiparticle?

(To avoid incoherent statements from experimentalists)
Real help from theorists would be an active involvement in the discussion of the measurements and evaluation of the results

Is it our world - “fake news”, distrust to printed matter?

Thank you for your attention!

EXTRA SLIDES

Prehistory (1998 - …)

Preprehistory also exists..

$\mathcal{P}$-odd domains in heavy ion collisions

Efremov, Kharzeev, PLB366:311(1996) ← (DIS)
Kharzeev, Pisarsky, Tytgat, PRL81:512(1998)
Kharzeev, Pisarsky, PRD61:111901(2000)
Voloshin, PRC62:044901(2000)
Kharzeev, Krasnitz, Venugopalan, PLB545:298(2002)
Finch, Chikanian, Longacre, Sandweiss, Thomas, PRC65:014908(2002)

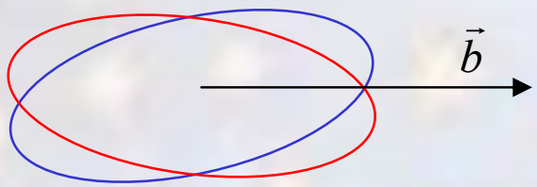
D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, Phys. Rev. Lett. **81**, 512 (1998).

$$J=\sum_{\pi^+,\pi^-}\frac{(\vec{p}_{\pi^+}\times\vec{p}_{\pi^-})_z}{p_{\pi^+}p_{\pi^-}}.$$

Sergei A. Voloshin

PHYSICAL REVIEW C, VOLUME 62, 044901

➔

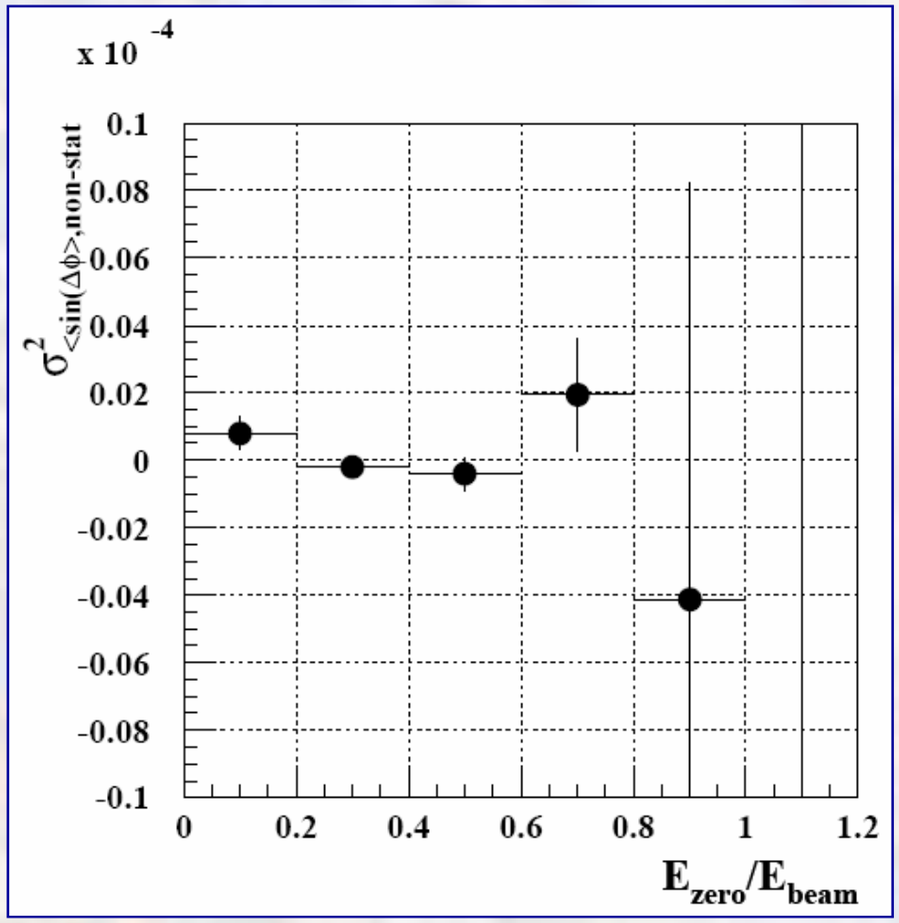


Difference in the orientation of the event plane determined with positive or negative particles!

$$\sigma_{\sin(\Delta\phi),nonstat}\approx\alpha(1-3)\times10^{-3}.$$

where α is the fraction of particles originating from the $\mathcal{P}$-odd domain

S. Voloshin and the NA49 Collaboration, ''Search for parity violation in minimum bias Pb-Pb collisions at SPS,'' LBNL 1998 annual report, http://ie.lbl.gov/nsd1999/rnc/RNC.htm, report R10.



NA49 – QM'99

CME "components"

Chirality imbalance
+
Magnetic field

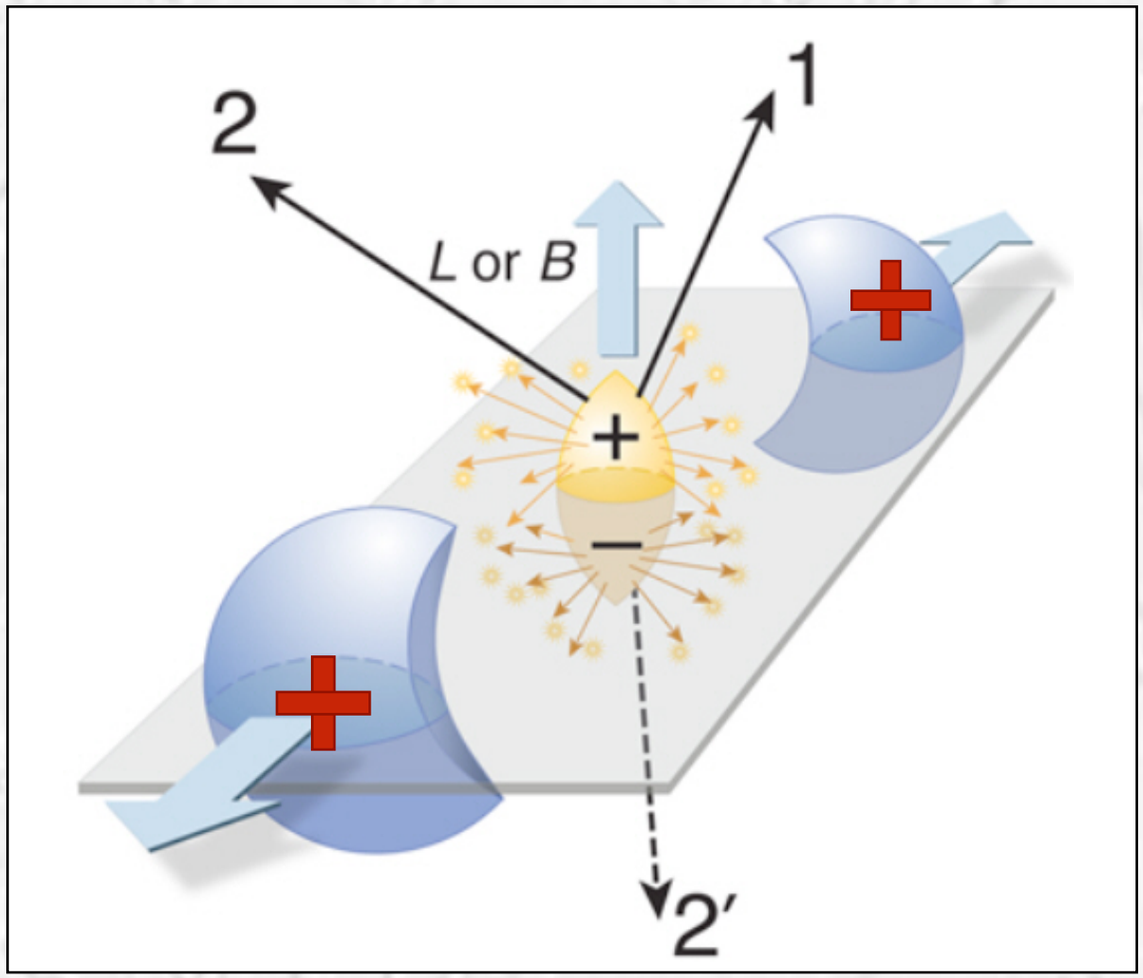
$$\mu_5 \sim \vec{E}\vec{B}\ t$$

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



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

2009

Building a program?

Dedicated experimental and theoretical program focused on the strong parity violation, and more generally on non-perturbative QCD: structure of the vacuum, hadronization, etc.

Theory: Theoretical guidance and detailed calculations are needed
- Dependence on collision energy, centrality, system size, PID, etc.
- Understanding physics background !

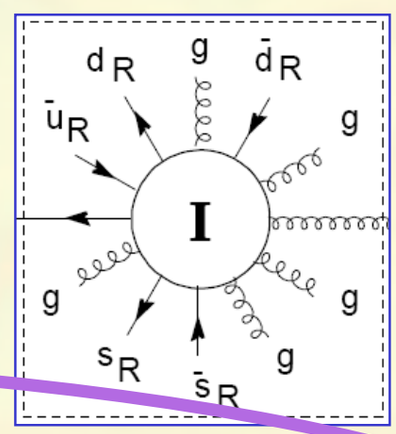
Experiment:
- Beam energy scan / Critical point search

Look for critical behavior, as $\mathcal{TIP}$ predicted to depend strongly on deconfinement and chiral symmetry restoration

- High statistics PID studies / properties of the clusters

e.g. sphaleron "bubble" decays isotropically (?), into q-qbar pairs of different flavors. We can check this!

Do these contribute to clusters seen at ISR, RHIC?



- Isobaric beams

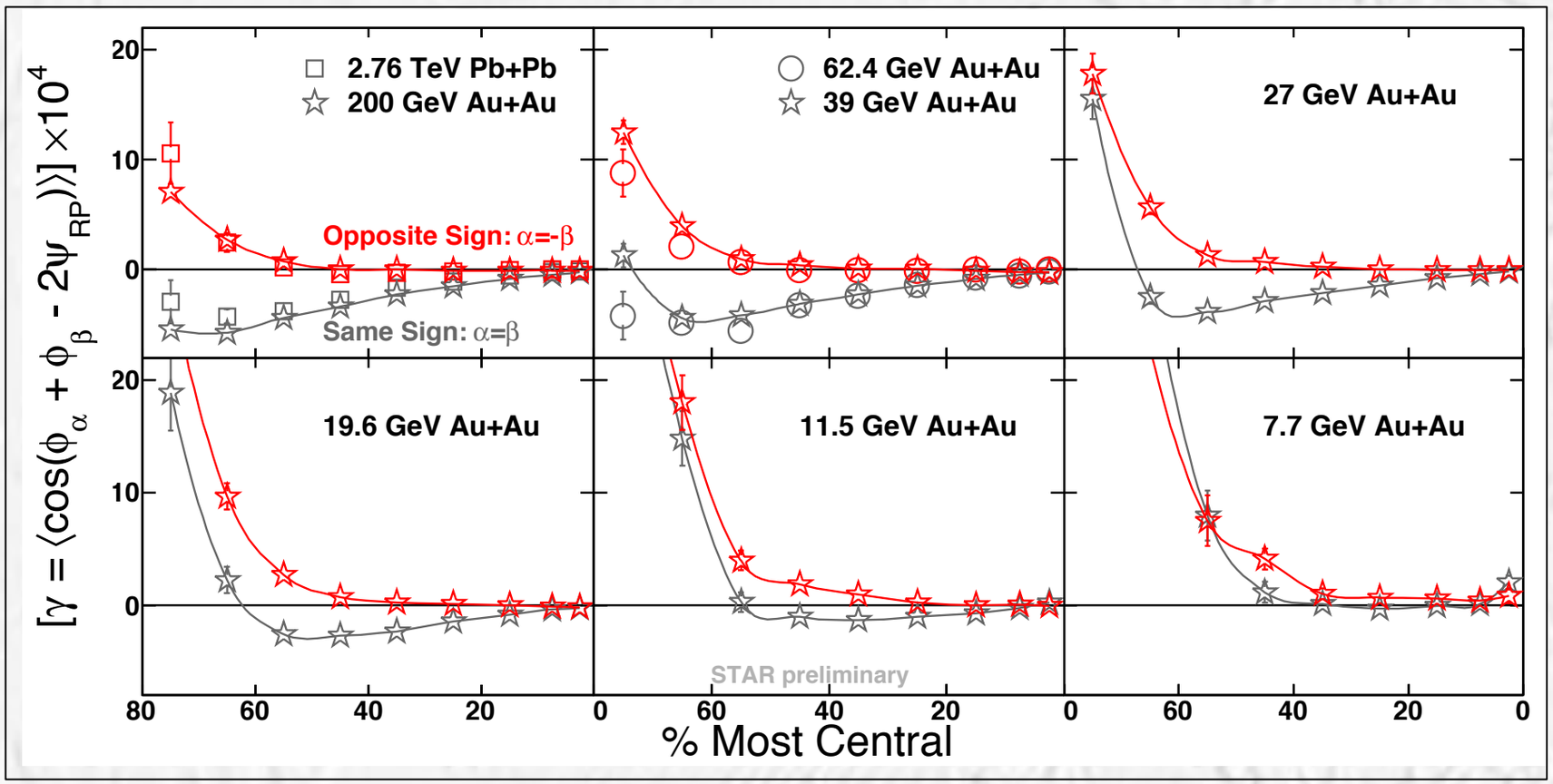
Colliding isobaric nuclei (the same mass number and different charge) and by that controlling the magnetic field

e.g. GSI: FOPI Collab.

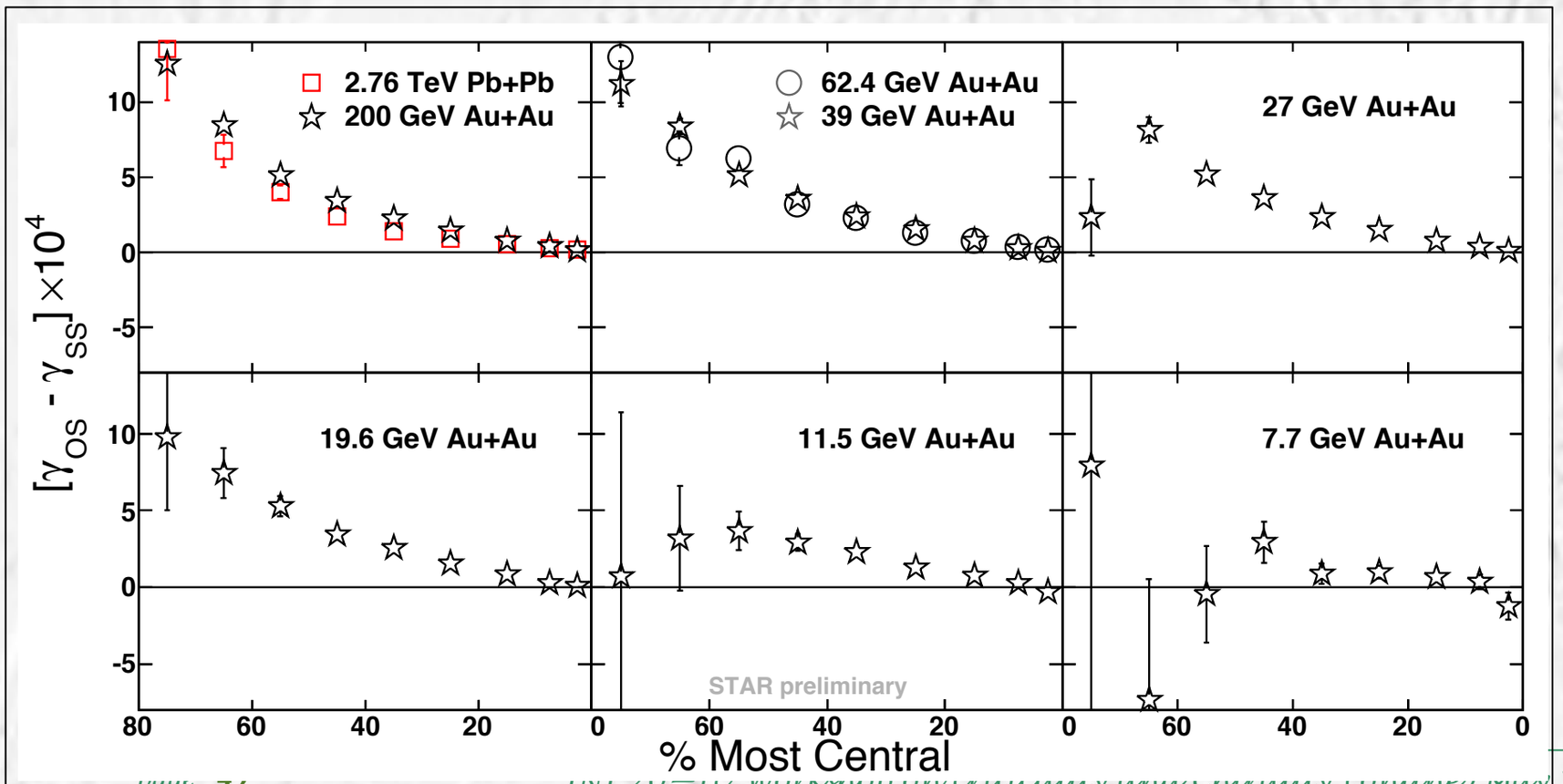
$^{96}_{44}\mathrm{Ru} + ^{96}_{40}\mathrm{Zr}$

Note that such studies will be also very valuable for understanding the initial conditions, origin of the directed flow, etc.

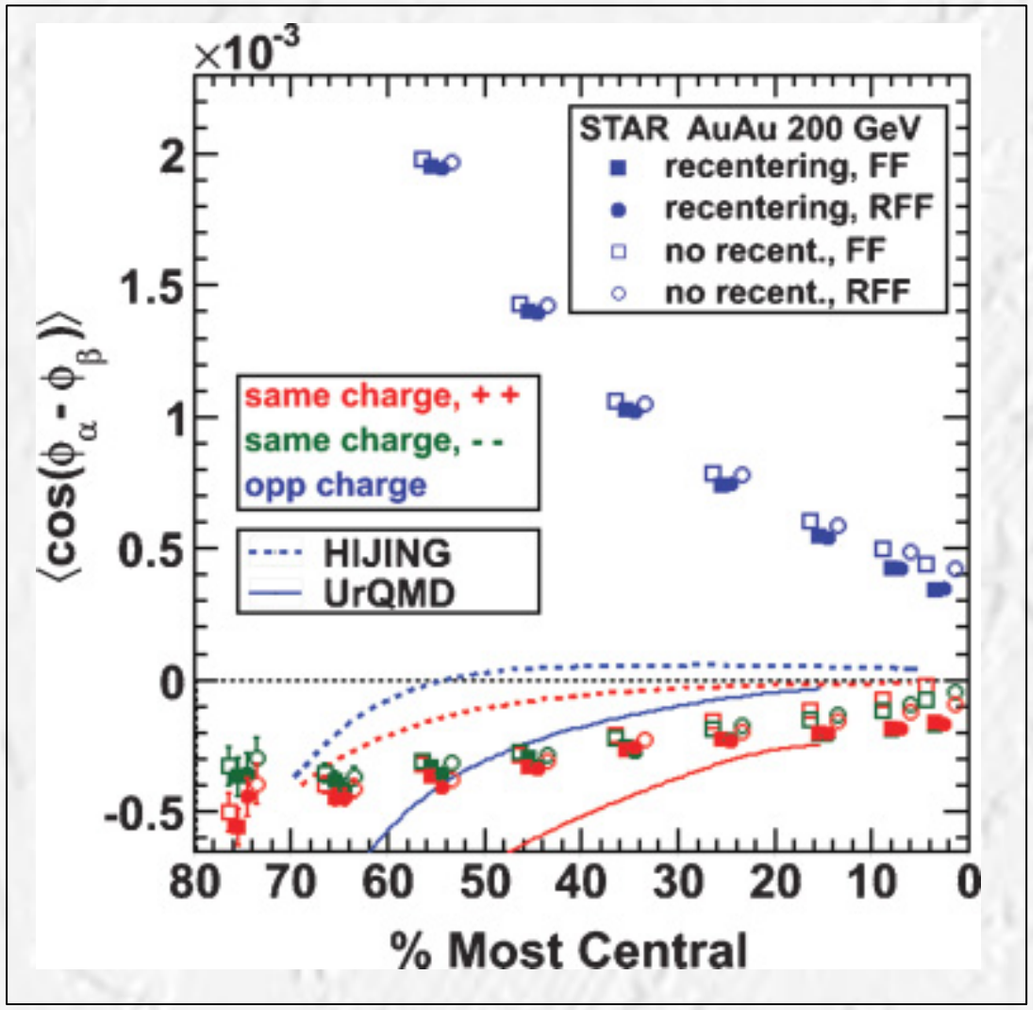
RHIC BES results



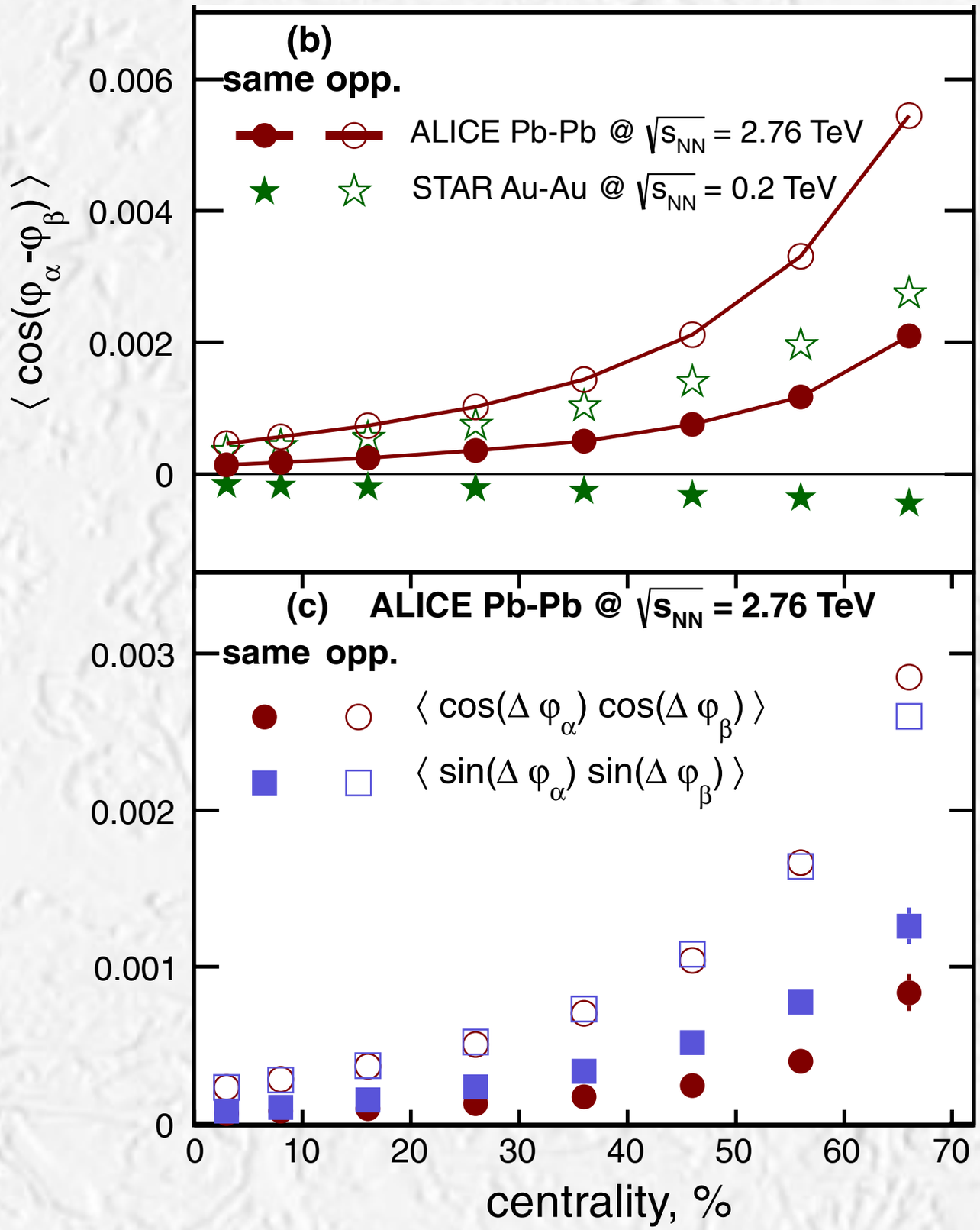
- Again, the signal is surprisingly "stable" over the wide range of energies
- Disappears at 7 GeV?



LHC vs RHIC, II

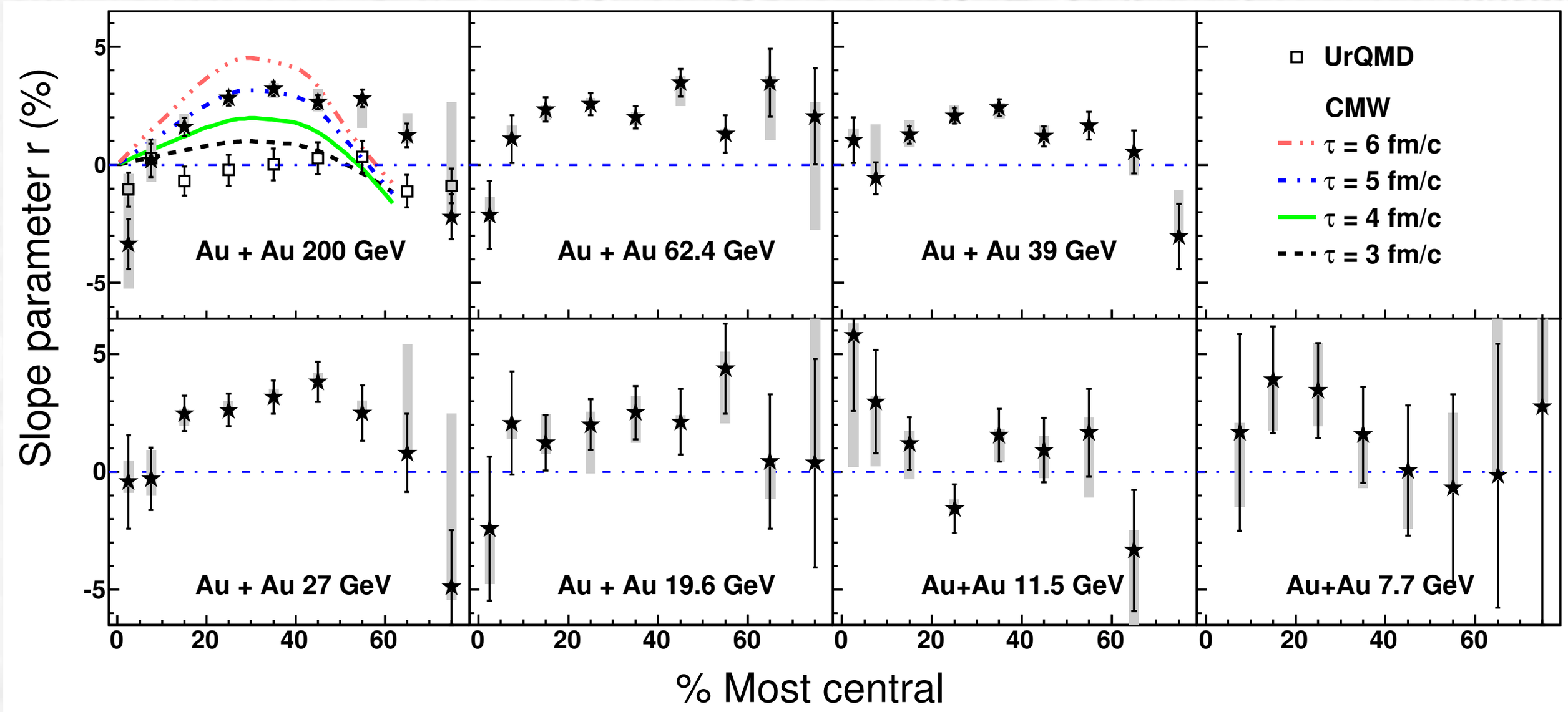


- HIJING and RQMD are way different from data
- 2-particle correlations are quite different at RHIC and LHC



Centrality/energy dependence

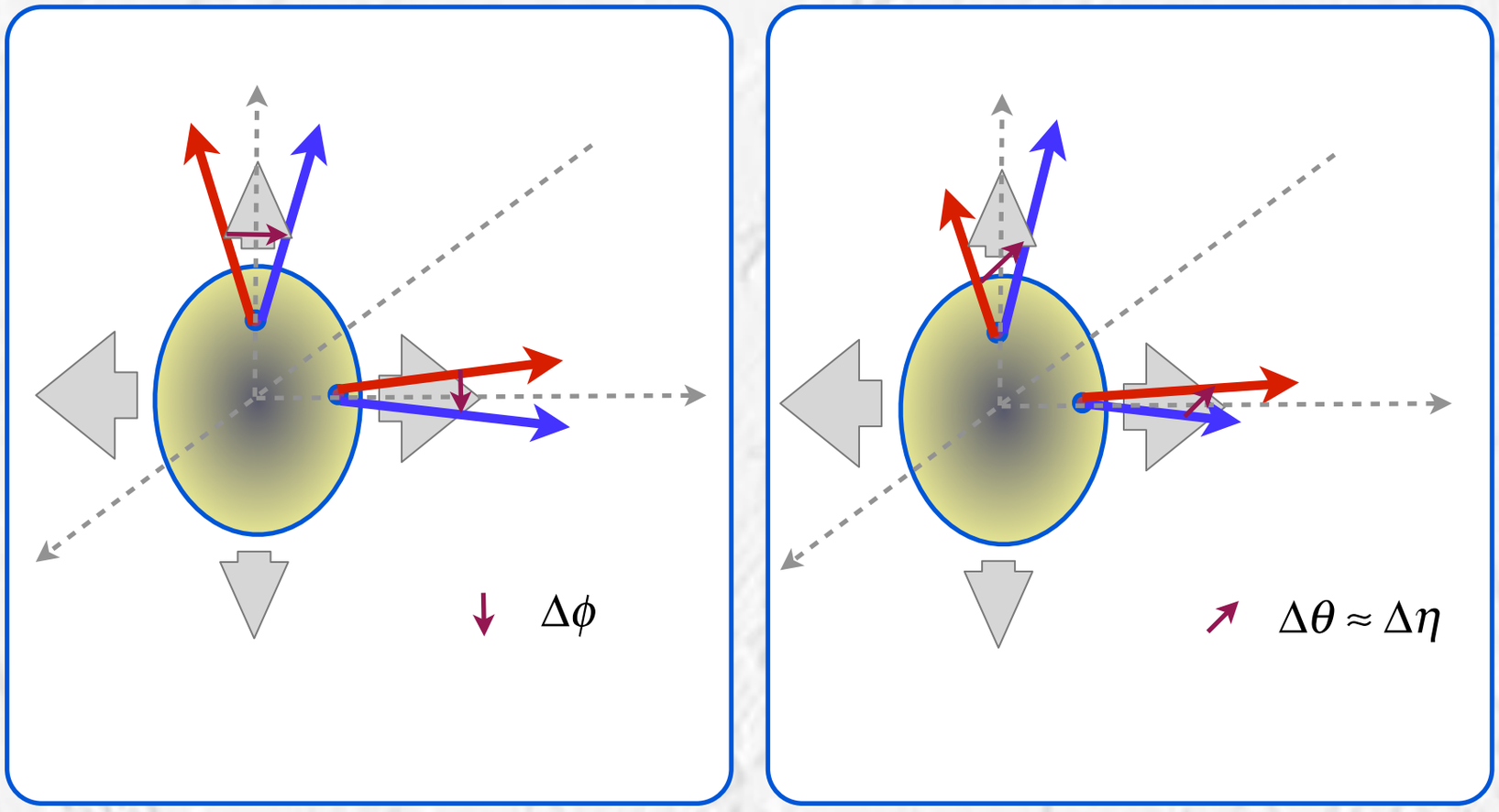
L. Adamczyk *et al.* (STAR Collaboration), Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions, Phys. Rev. Lett. **114**, 252302 (2015).



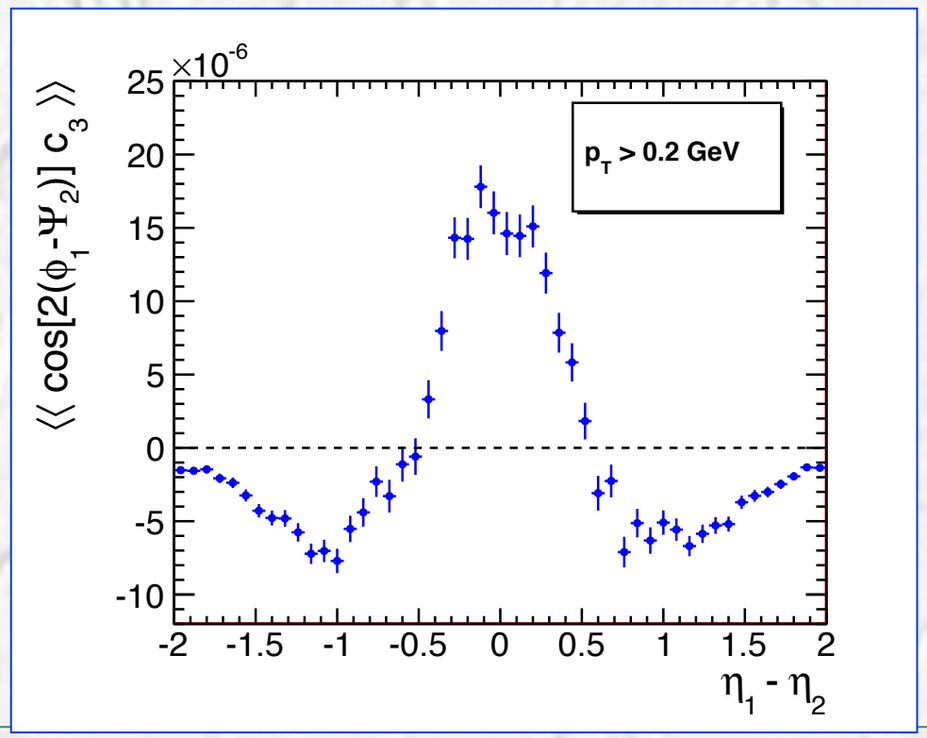
Energy dependence is not that obvious

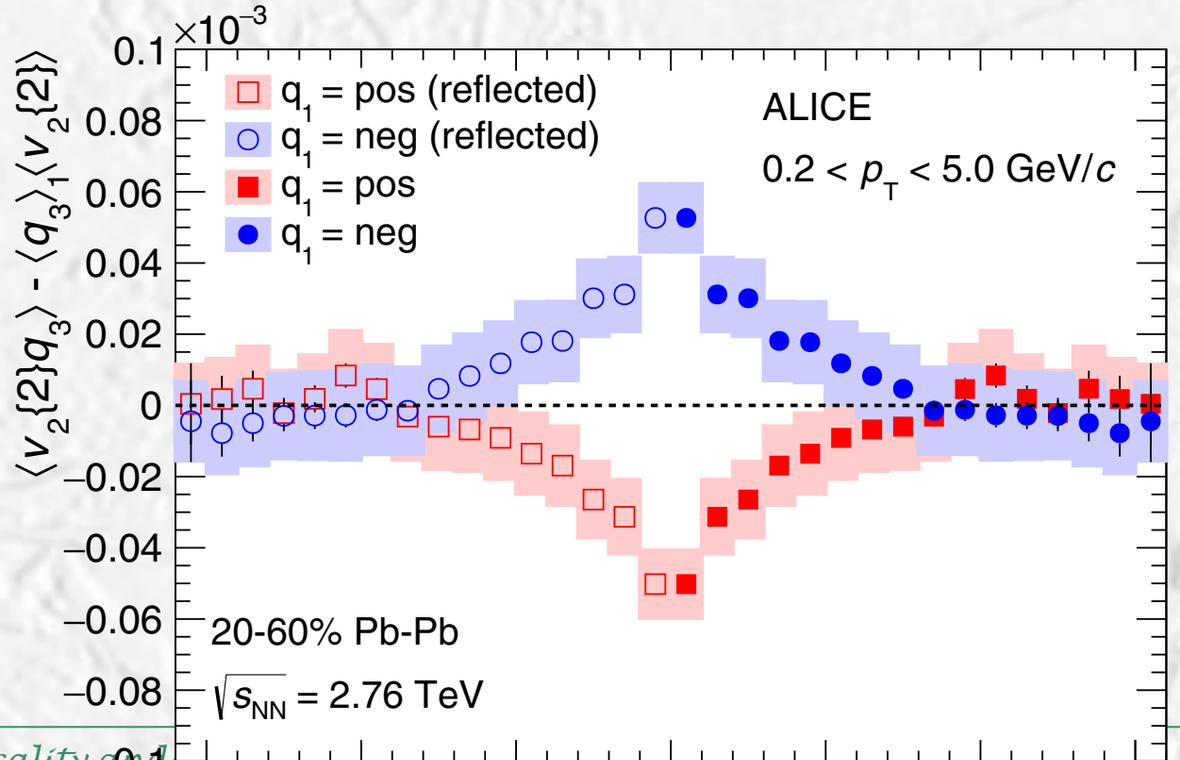
Possible background - LCC+RF

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





CMW and LCC : Hydro

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

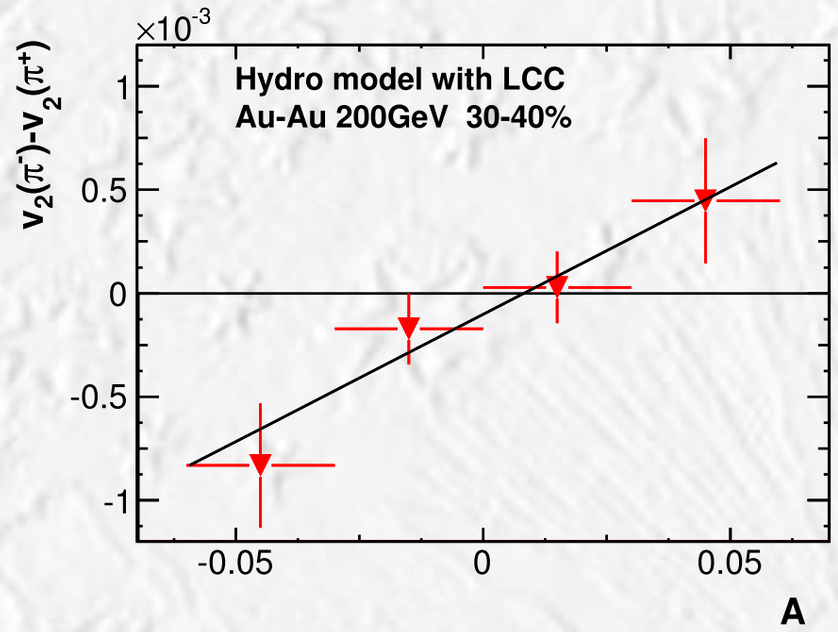


Fig. 4. The charge asymmetry dependence of π^+ and π^- elliptic flow coefficients in the hydrodynamic model followed by statistical emission with local charge conservation. We obtained $r = 0.012 \pm 0.004$ compared with the preliminary STAR data, $r_{\rm exp} \approx 0.03$.

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)

CME vs background. U+U

S. Voloshin, PRL 105 (2010) 172301

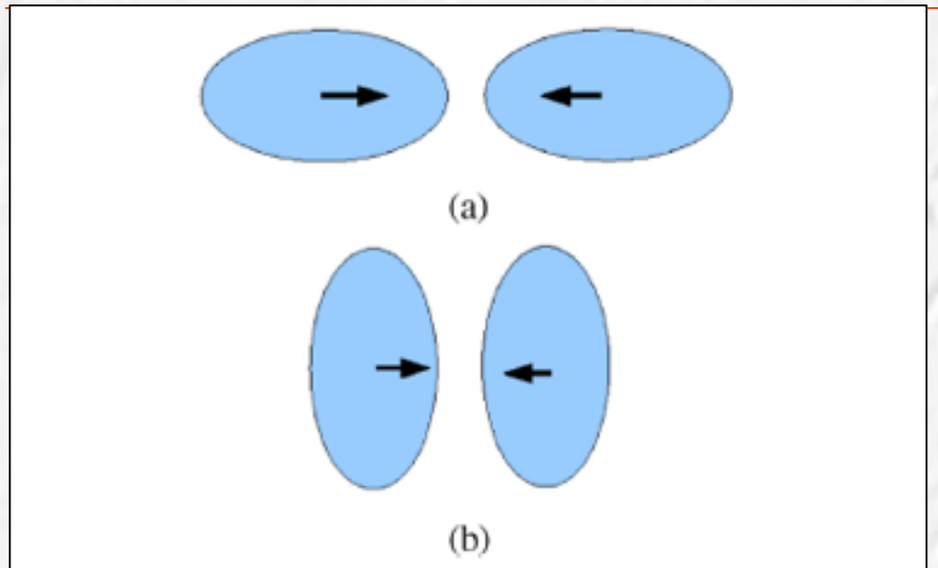


FIG. 1 (color online). Schematic view of central $U + U$ collisions: (a) tip-tip and (b) body-body.

In both cases the magnetic field is small, but elliptic flow is large in body-body.
A way to disentangle two effects!

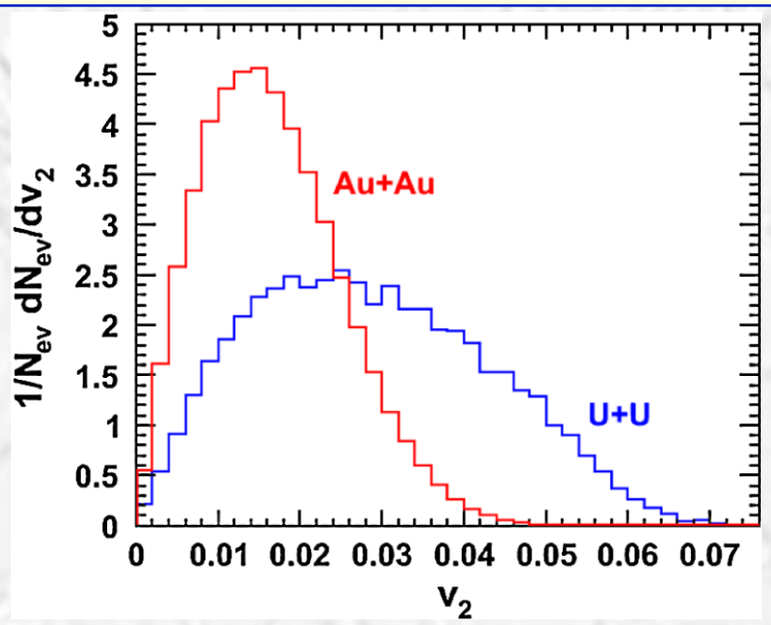


FIG. 2 (color online). Event distributions in v_2 for Au + Au and $U + U$ collisions in event samples with the number of spectators $N_{sp} < 20$.

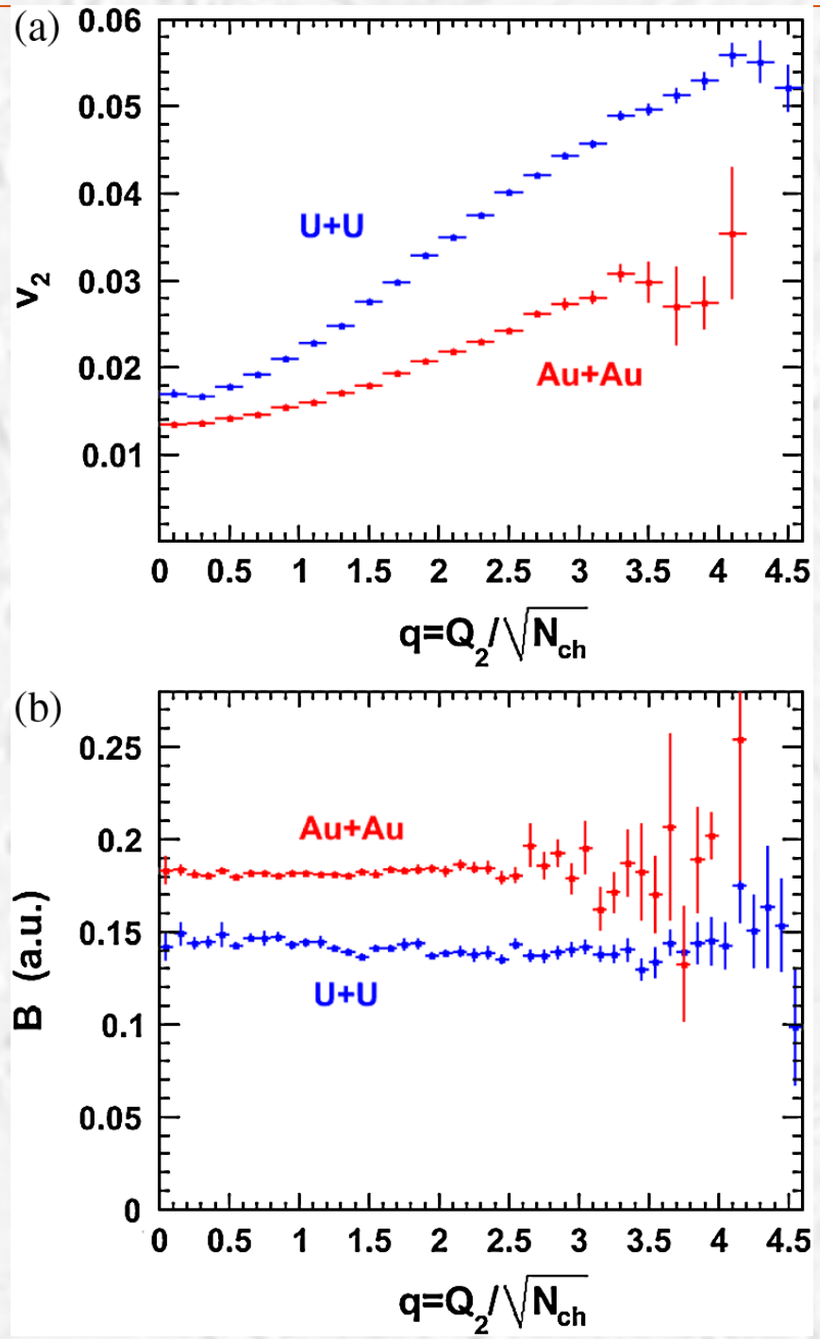


FIG. 3 (color online). Elliptic flow and the magnetic field (in arbitrary units) as a function of q, the magnitude of the flow vector, in events with the number of spectators $N_{sp} < 20$.

Note that one can use a similar trick with Au+Au, but there, one would "play" on fluctuations, not nuclear shape

Isobaric collisions (RHIC 2018)

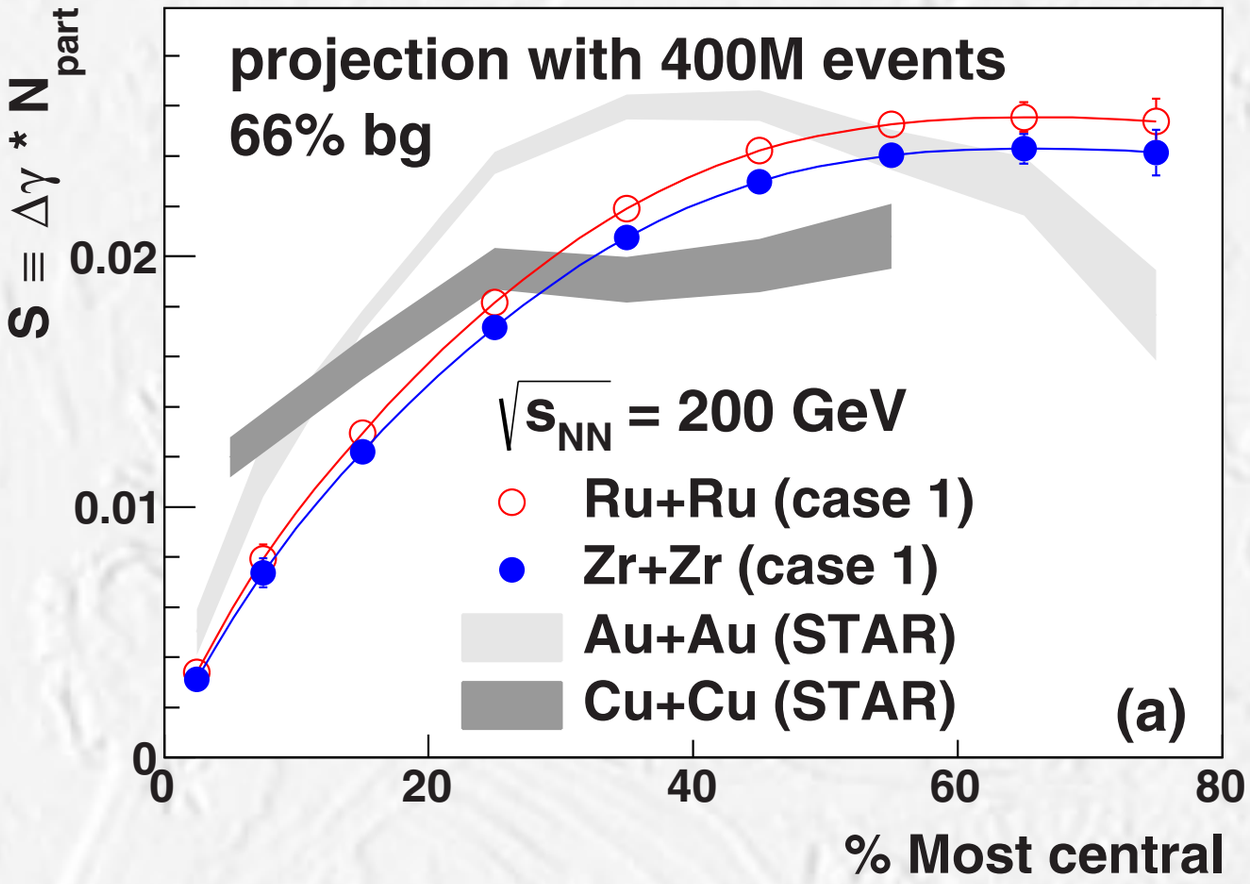
S. A. Voloshin, Phys. Rev. Lett. **105**, 172301 (2010).

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

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]



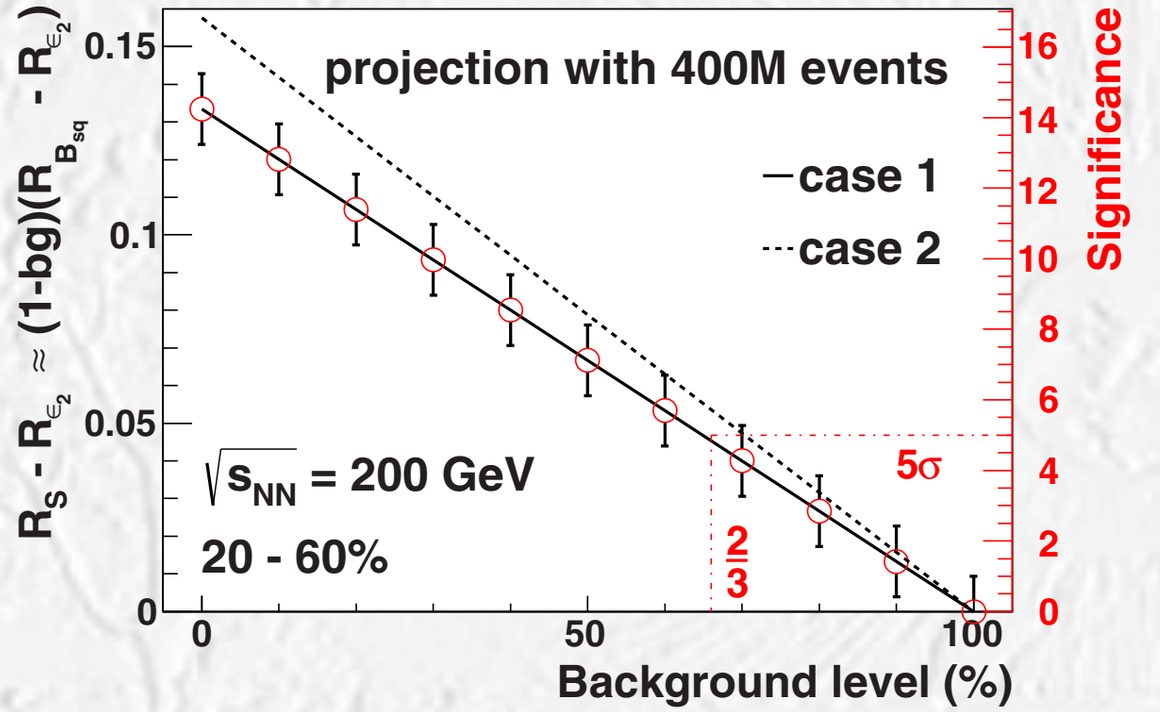


FIG. 4. Magnitude (left axis) and significance (right axis) of the relative difference in the CME signal between Ru + Ru and Zr + Zr at 200 GeV, $R_S - R_{\epsilon_2}$ as a function of the background level.