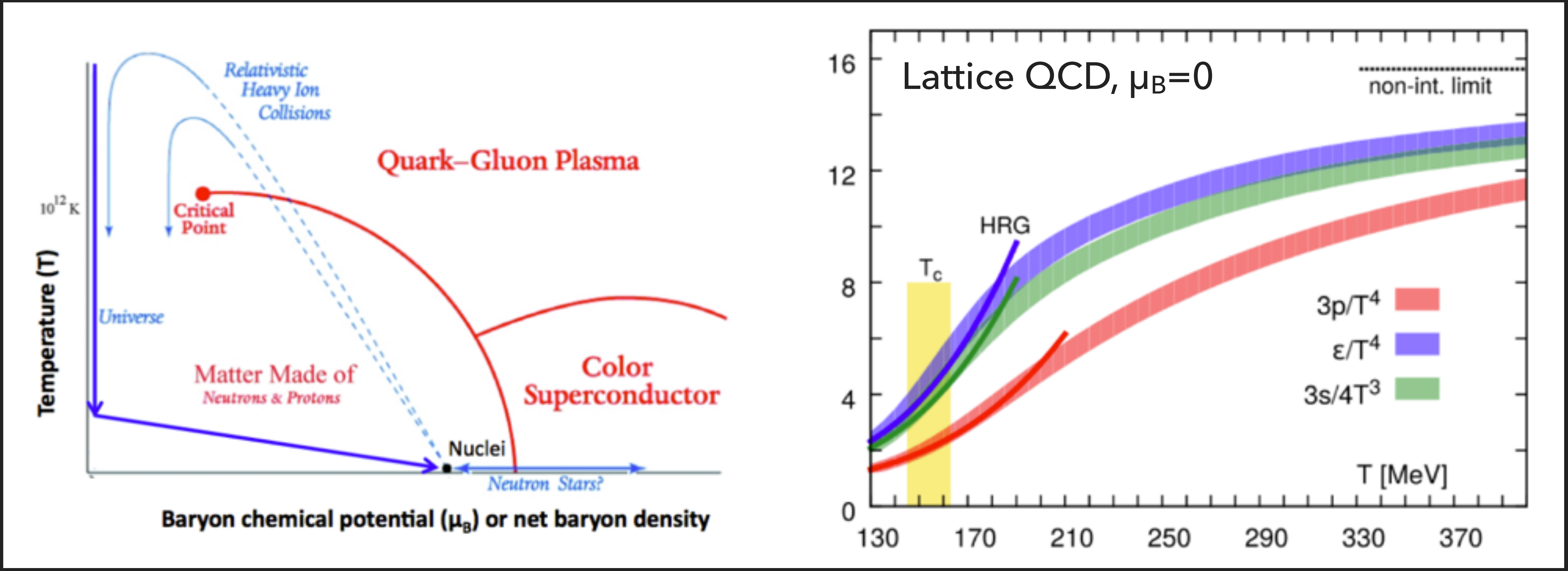
JACOPO MARGUTTI - SPHALERONS WORKSHOP (NIKHEF 12/10/2016)

CHIRALITY AND MAGNETIC FIELDS IN HEAVY-ION PHYSICS

INTRODUCTION

HEAVY-ION PHYSICS

Exploring QCD at high temperatures and/or densities

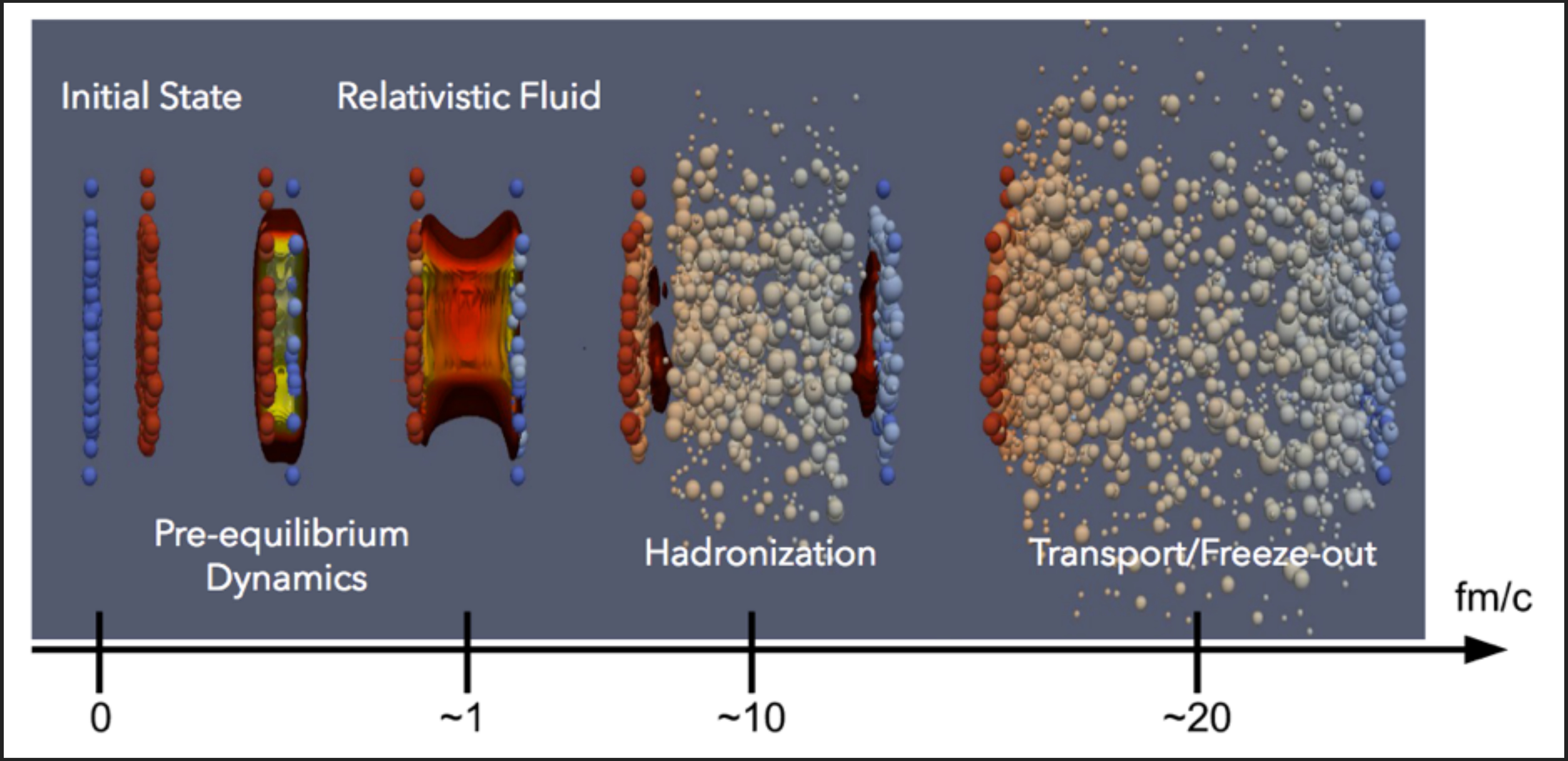


arXiv:1510.04200

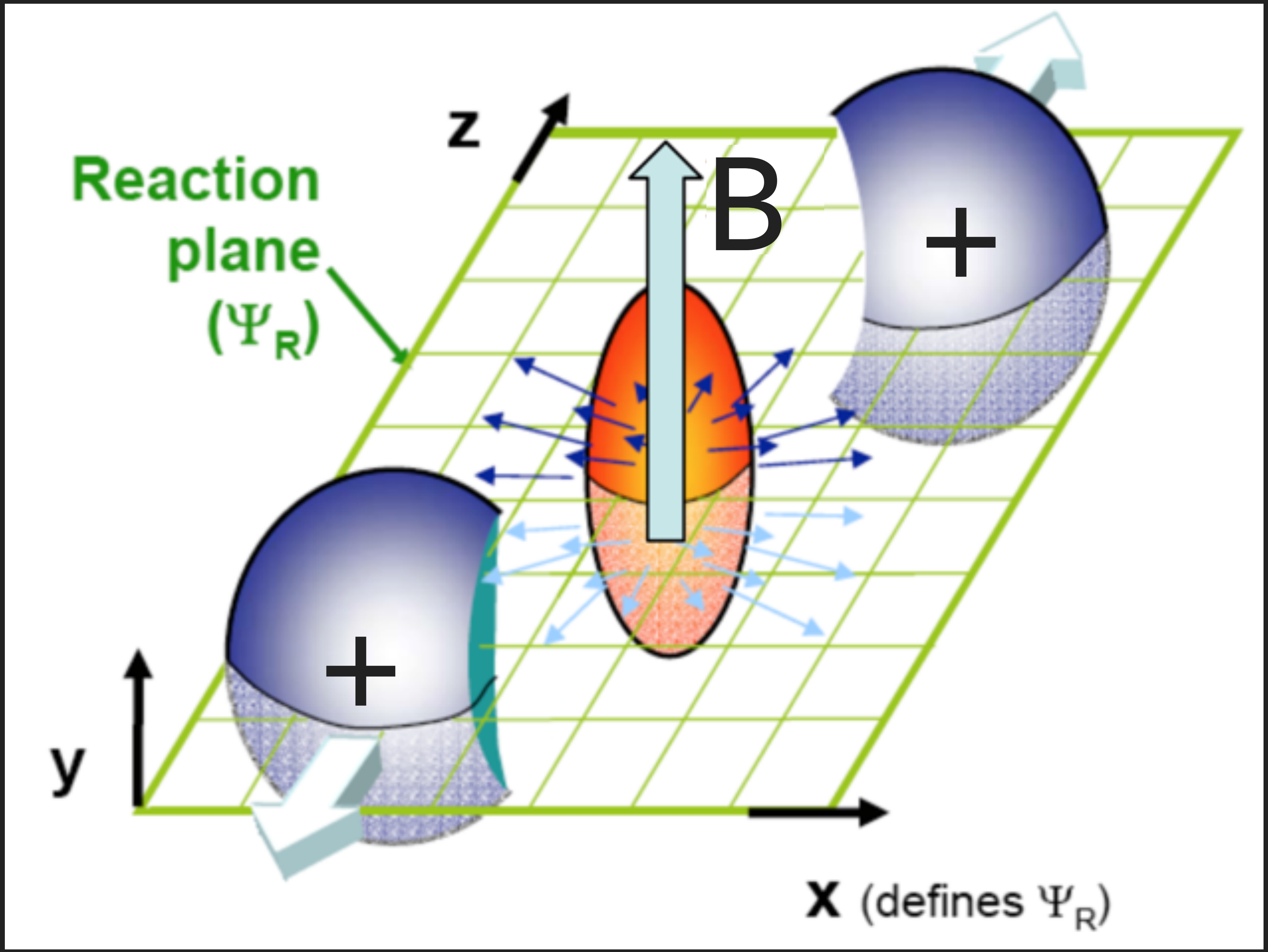
Quark-Gluon Plasma: T>150 MeV, ε>0.2 GeV/fm^3

HEAVY-ION PHYSICS

Different stages in a Heavy-Ion collision:



HEAVY-ION PHYSICS



fast-moving charged spectators (non-interacting protons)

(Biot-Savart law)

strong magnetic field: $\sim 10^{15}$ T

HEAVY-IONS AND SPHALERONS

Sphaleron transition rate favoured at high temperatures!

L. McLerran et al., Phys. Rev. D 43, 2027

- in YM theory, N colors, weak coupling:

$$\Gamma = const \times (g^2 N)^5 \ln(1/g^2 N)\ T^4,$$

- from AdS/CFT (conformal N=4 SYM), strong coupling:

$$\Gamma = \frac{(g^2 N)^2}{256\ \pi^3}\ T^4,$$

HEAVY-IONS AND SPHALERONS

Sphaleron transitions in QCD → chirality imbalance

$$n_5 = n_{\mathrm{R}} - n_{\mathrm{L}} \neq 0$$

also expressed in terms of chiral chemical potential:

$$n_5 = \frac{\mu_5^3}{3\pi^2} + \frac{\mu_5 T^2}{3}$$

the idea is then to **exploit the large magnetic field** and/or the angular momentum of the system to detect it:

$\langle \vec{S} \cdot \vec{B} \rangle, \quad \langle \vec{S} \cdot \vec{L} \rangle$ → chiral magnetic effect, chiral magnetic wave …

SOME REMARKS

Different pieces of the picture are rather unclear:

- How long does the magnetic field last?
  It depends on the system conductivity! (Faraday's law)

- When do these sphaleron transition take place?
  Vacuum, *Glasma* (pre-equilibrium), QGP?

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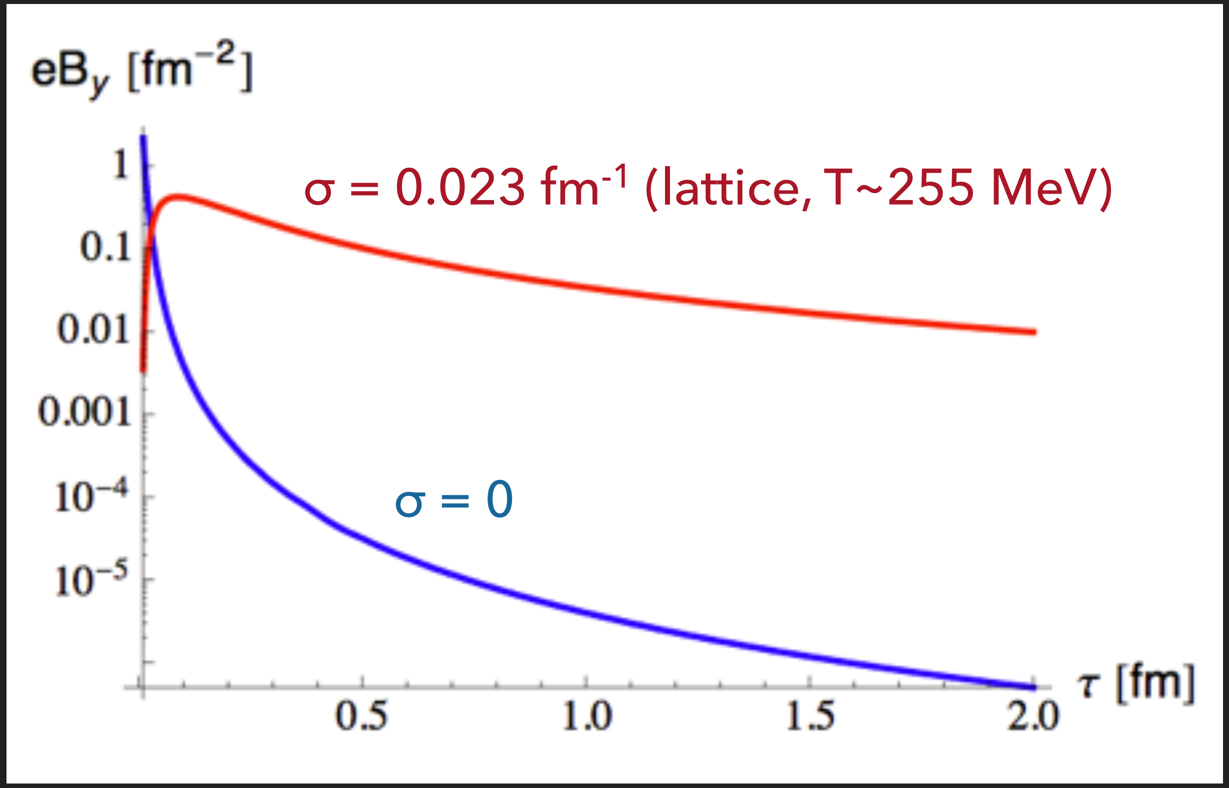

U. Gursoy et al., arXiv:1401.3805

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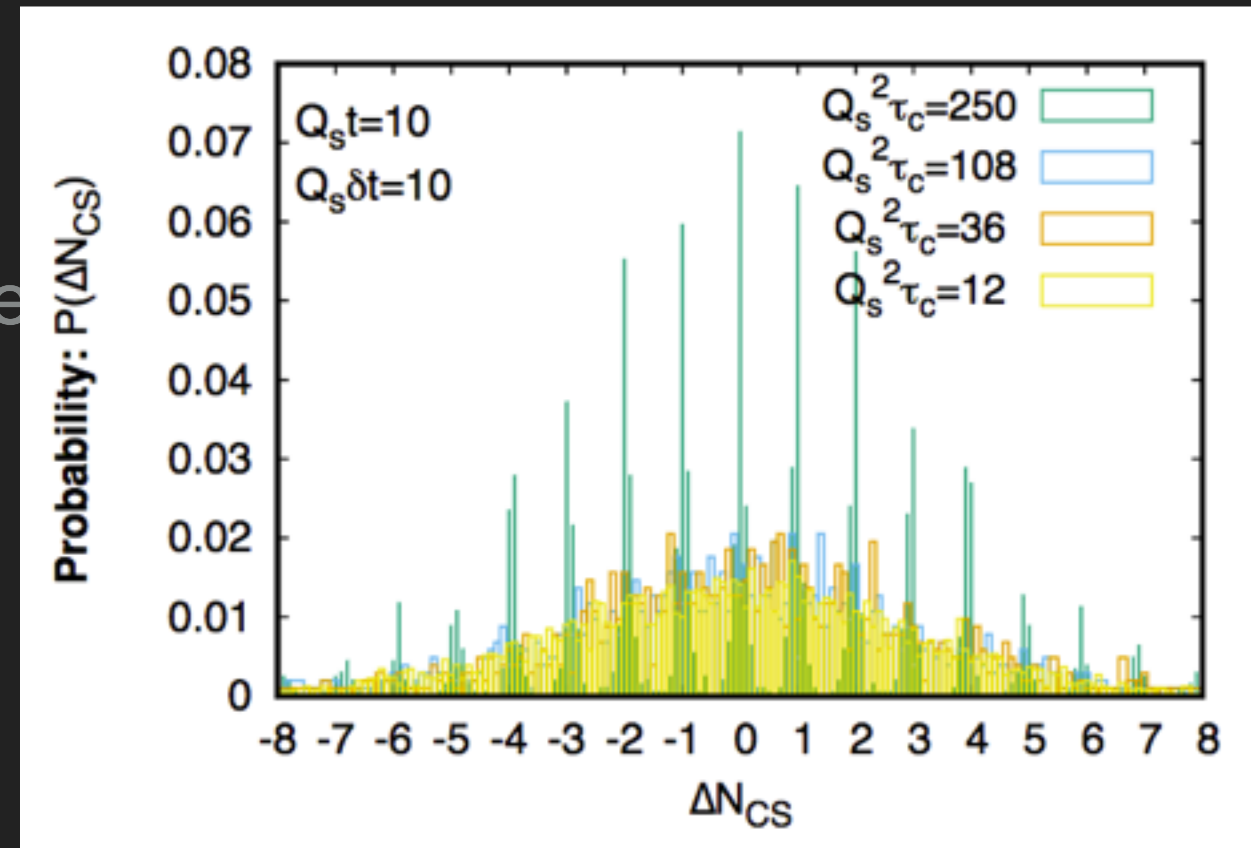

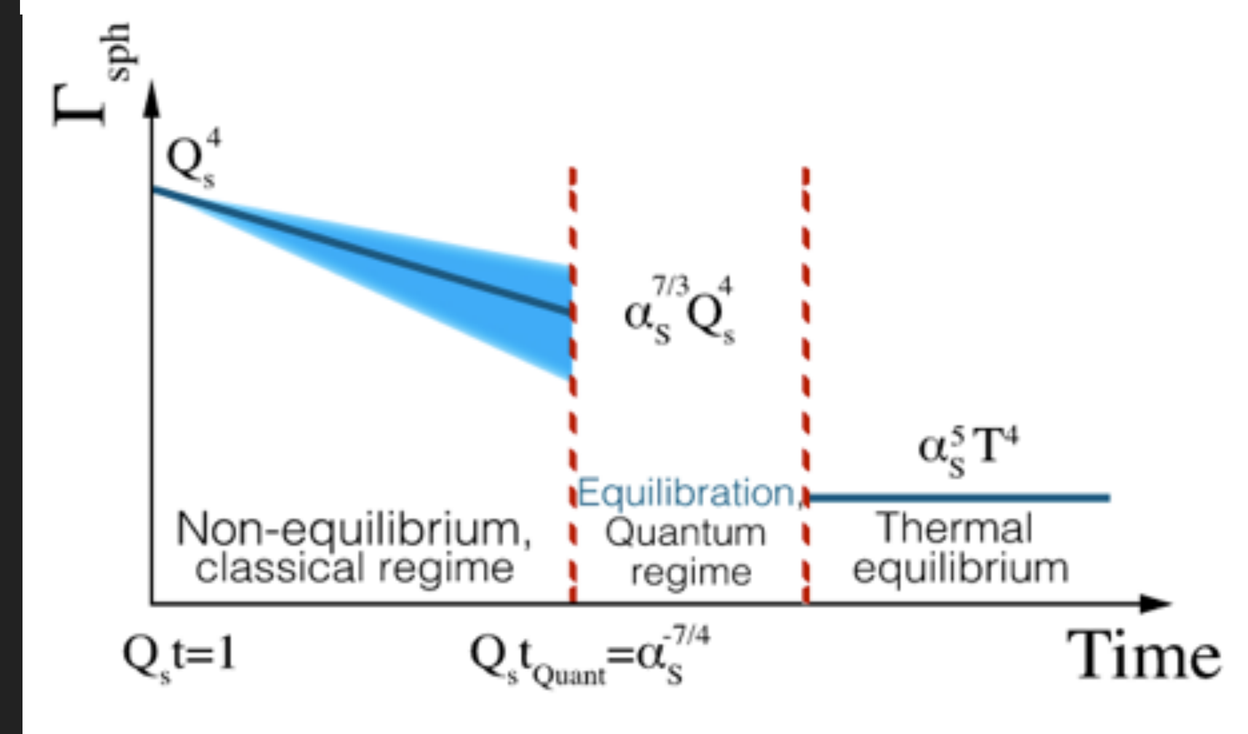

M. Mace et al., arXiv:1601.07342

SOME REMARKS

Different pieces of the picture are rather unclear:

- How long does the magnetic field last?
  It depends on conductivity!

bottom line:
only order-of-magnitude estimates from theory so far

- When do these sphaleron transition take place?
  Vacuum, *Glasma* (pre-equilibrium), QGP?

CHIRAL MAGNETIC EFFECT

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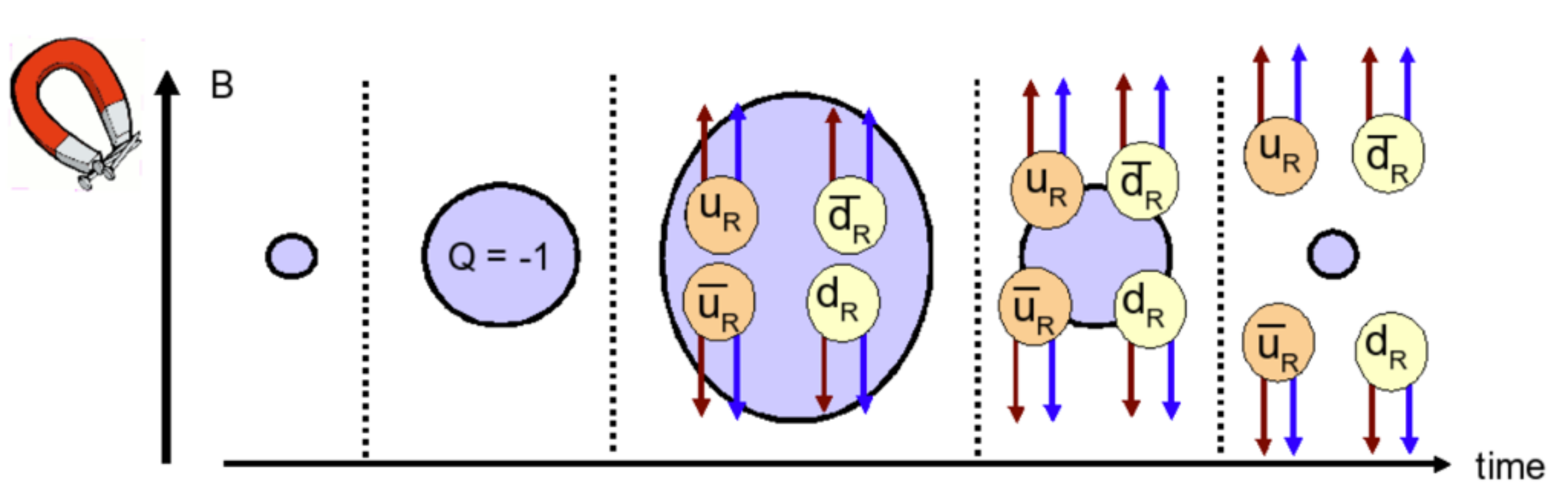
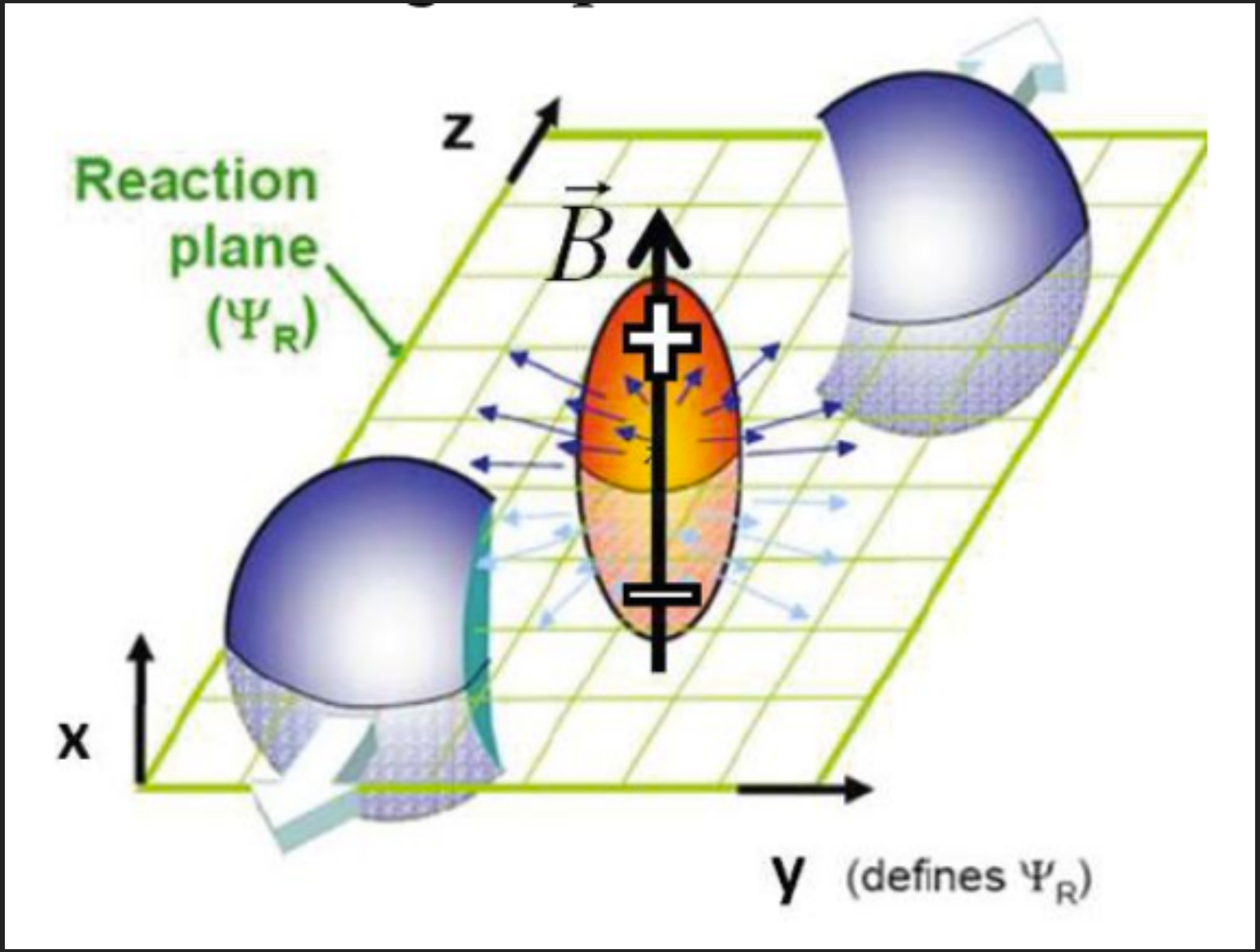
sphaleron transitions in QCD ➜ chirality imbalance

chirality imbalance + strong magnetic field ➜ charge separation



CHIRAL MAGNETIC EFFECT



the experimental observable: charge separation across the reaction plane

OBSERVABLES

CME: charge-dependent out-of-plane directed flow

$$\frac{dN_\pm}{d\phi} \propto 1 + 2\, a_\pm \sin(\phi_\pm - \Psi_{\mathrm{RP}})$$

whose sign changes event by event.

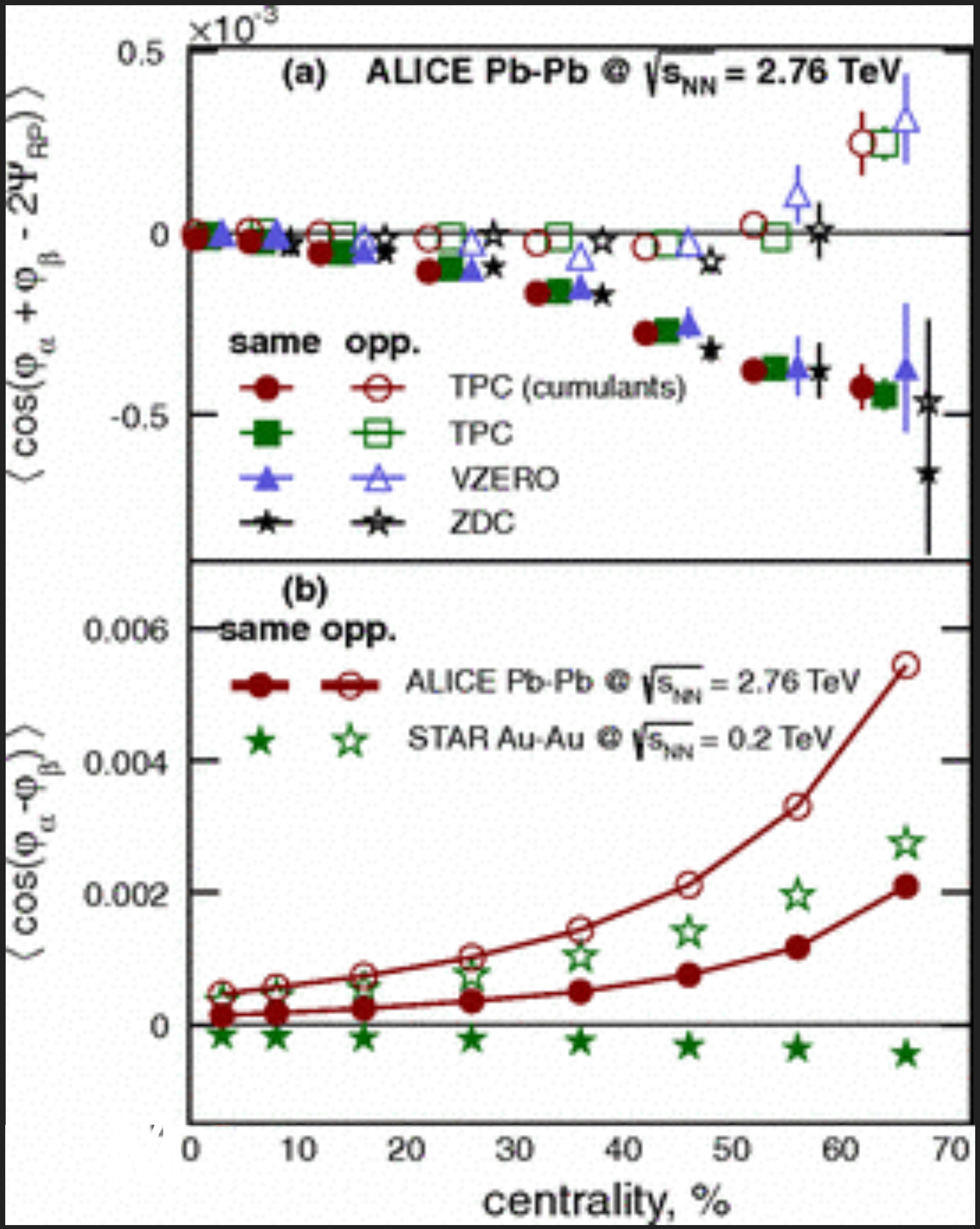
It was proposed to measure it with the parity-even charge-dependent 2- and 3-particle correlators:

$$\delta_{a,b} = \langle \cos(\phi_a - \phi_b) \rangle \sim \langle v_{1a} v_{1b} + a_a a_b \rangle \qquad a, b = \pm$$

$$\gamma_{a,b} = \langle \cos(\phi_a + \phi_b - 2\Psi_{\mathrm{RP}}) \rangle \sim \langle v_{1a} v_{1b} - a_a a_b \rangle$$

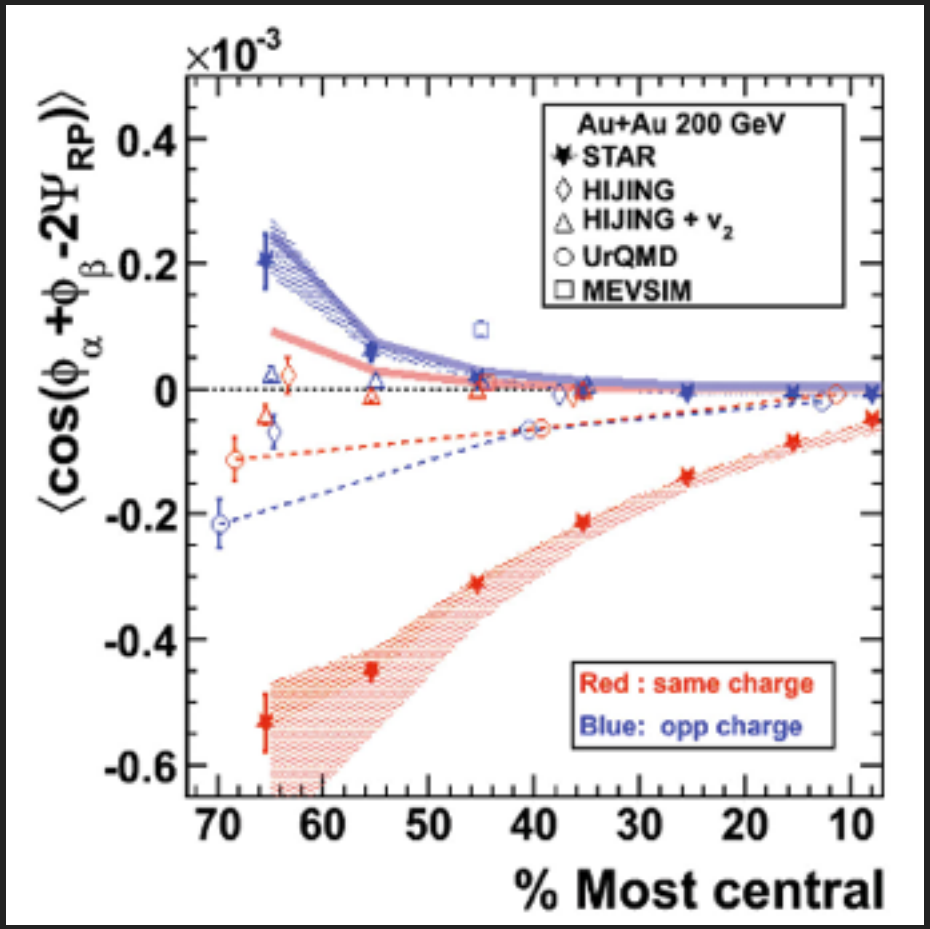
S. Voloshin, arXiv:hep-ph/0406311

CME CORRELATORS



ALICE, arXiv:1207.0900

2- and 3-particle correlators already measured: non-zero signal, but <u>background</u> largely present!



STAR, arXiv:0909.1739

BACKGROUND

Different sources of background in these correlators:

- Transverse Momentum Conservation (TMC)
- Flow Fluctuations
- Local Charge Conservation (LCC)

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charge-independent: negligible in like- vs unlike-sign difference:

$$\Delta\cos(\phi_a - \phi_b) \equiv \frac{1}{2}(\delta_{+,-} + \delta_{-,+} - \delta_{+,+} - \delta_{-,-}) \sim \langle a_a a_b \rangle$$

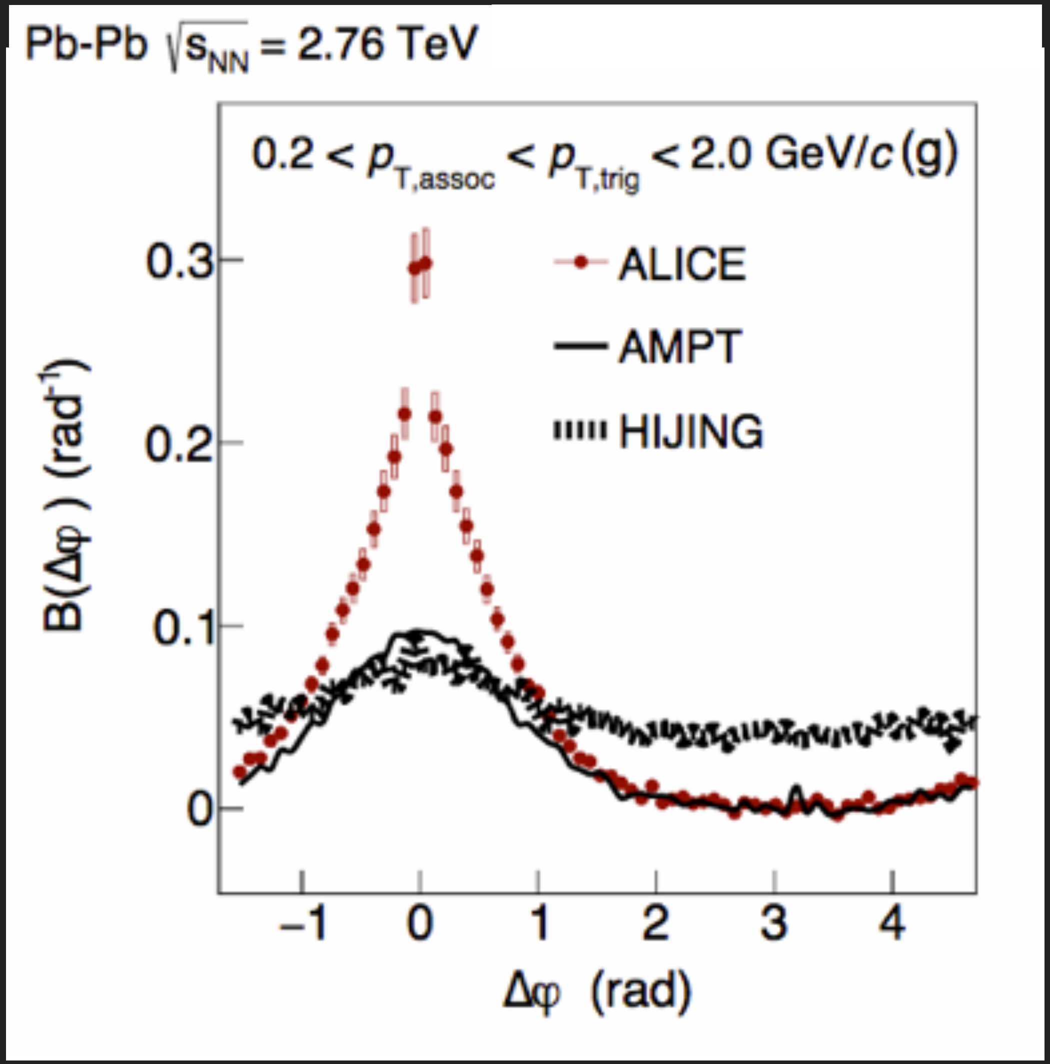
BACKGROUND

Different sources of background in these correlators:

- Transverse Momentum Conservation
- Flow Fluctuations
- Local Charge Conservation (LCC)

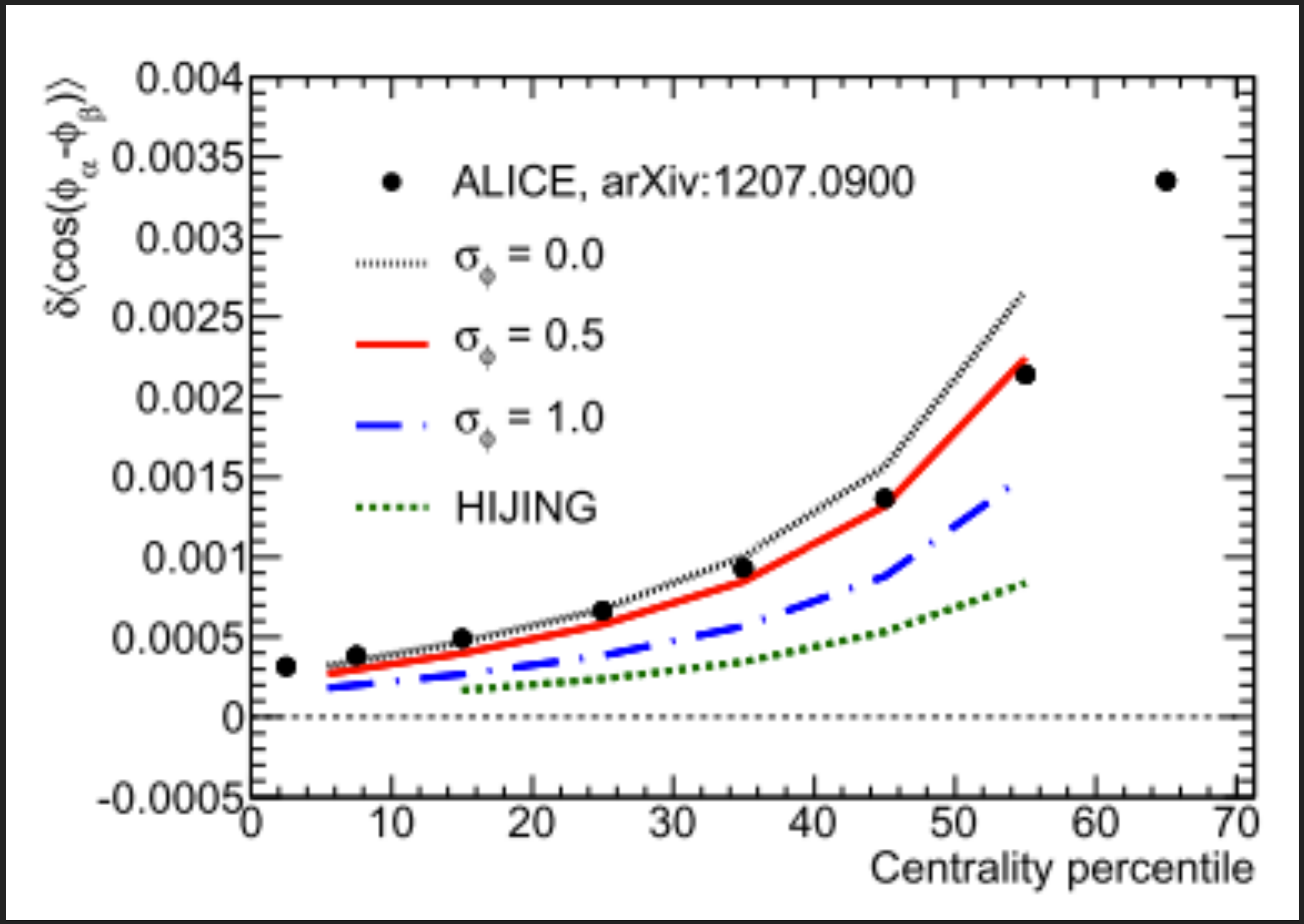
To be understood!
Not correctly reproduced
by standard MCs
(AMPT, HIJING…)

charge-dependent correlation functions



ALICE, arXiv:1509.07255

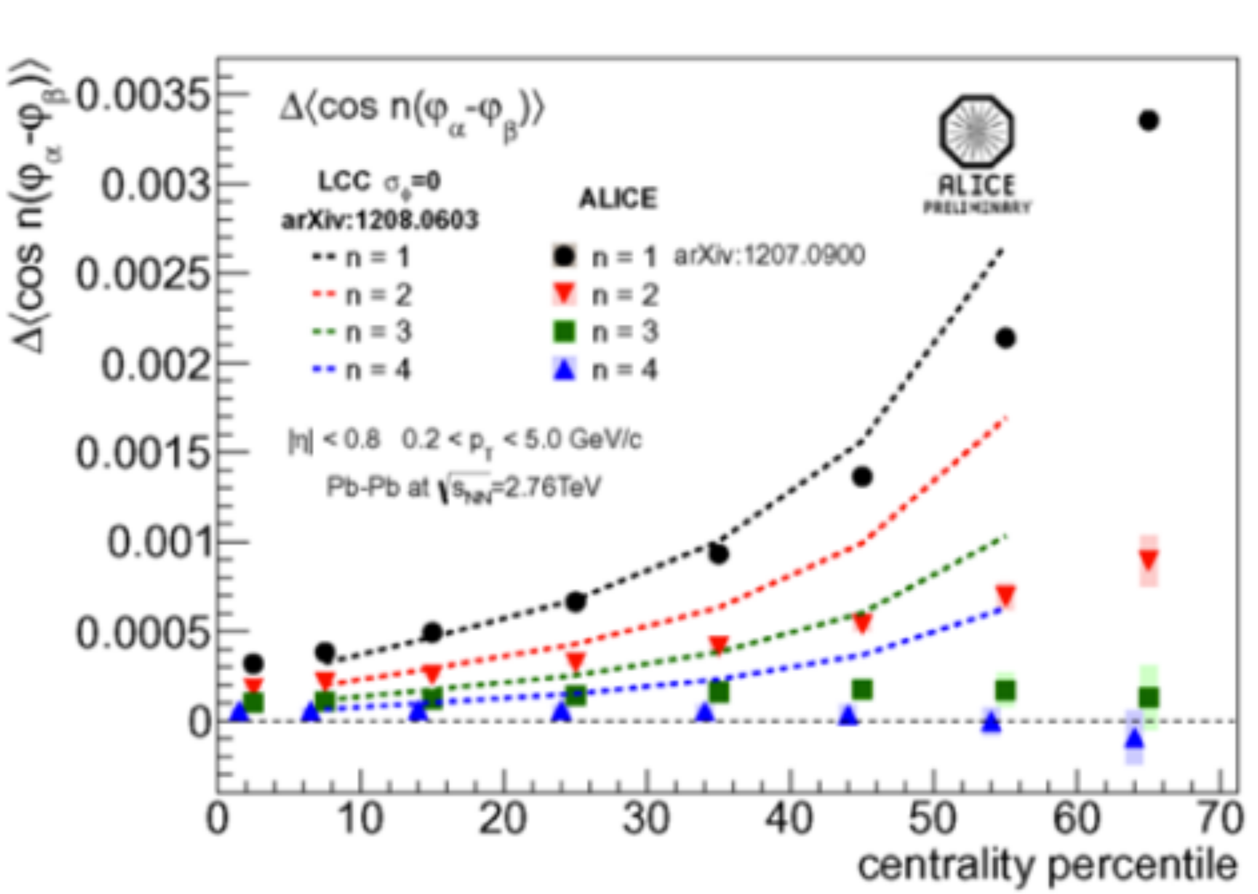
BACKGROUND VS DATA

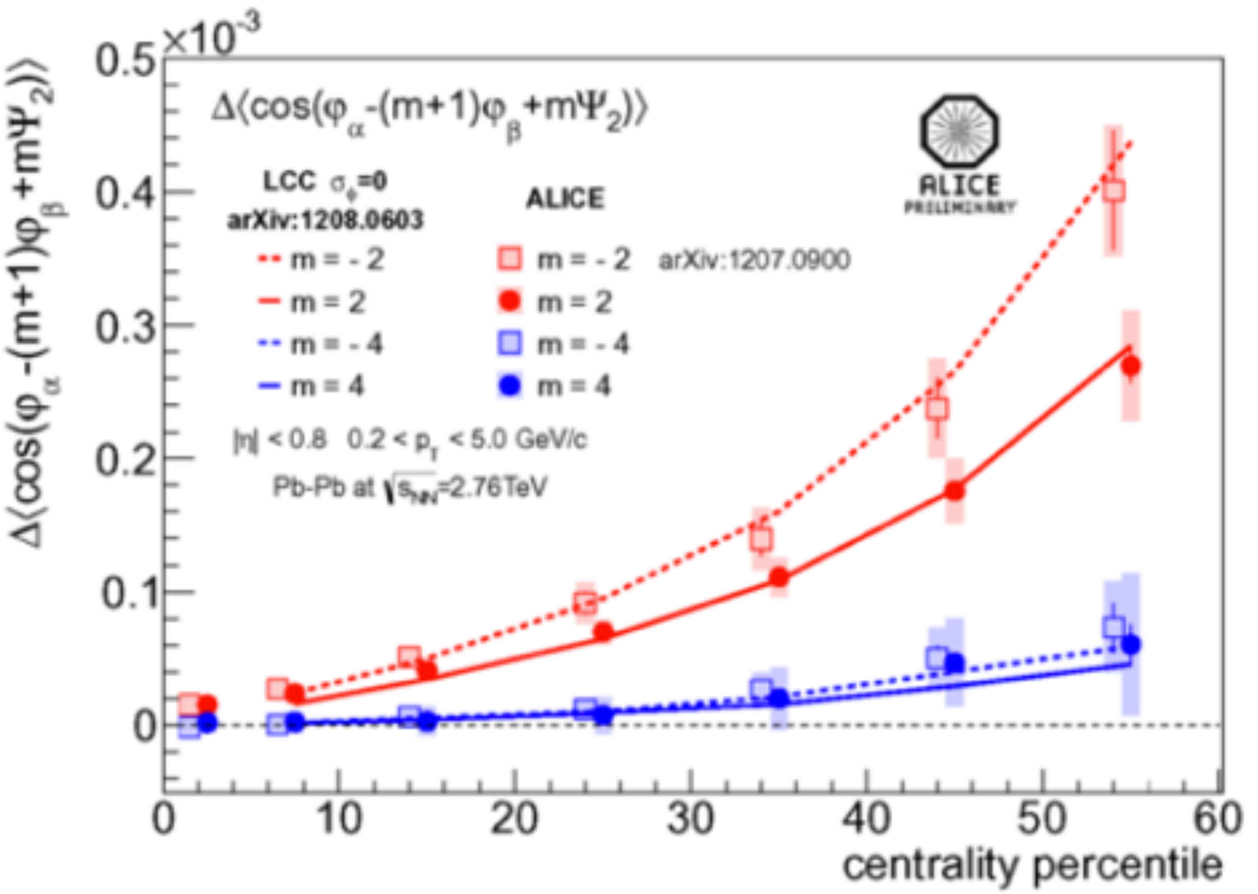


Y. Hori et al., arXiv:1208.0603

Blast-Wave models incorporating LCC are able to explain the entire difference between like- and unlike-sign correlators –> consistent with NO CME signal…

BACKGROUND VS DATA



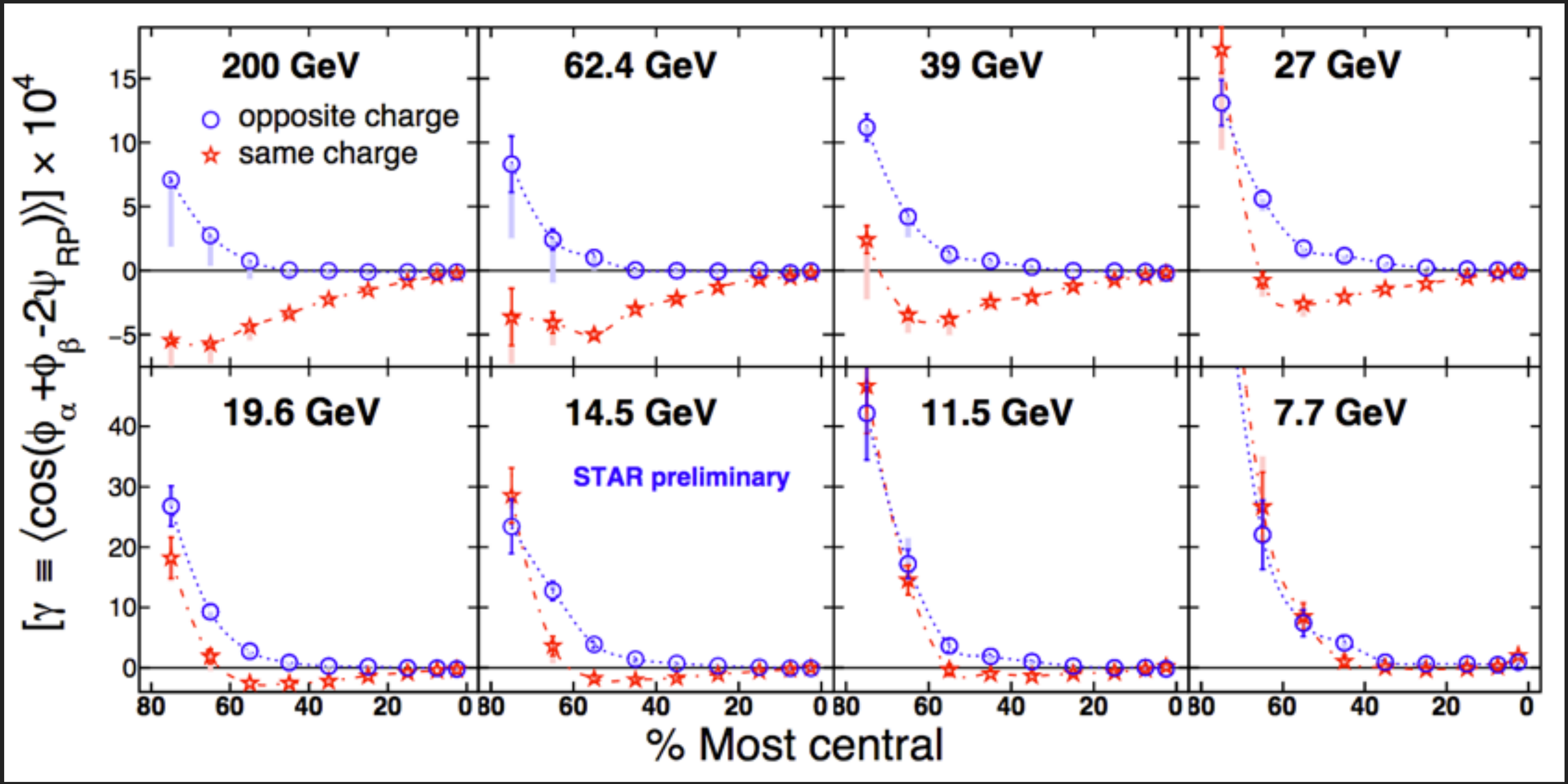


Y. Hori, QM12

… but fail to reproduce all correlators simultaneously!

ENERGY DEPENDENCE

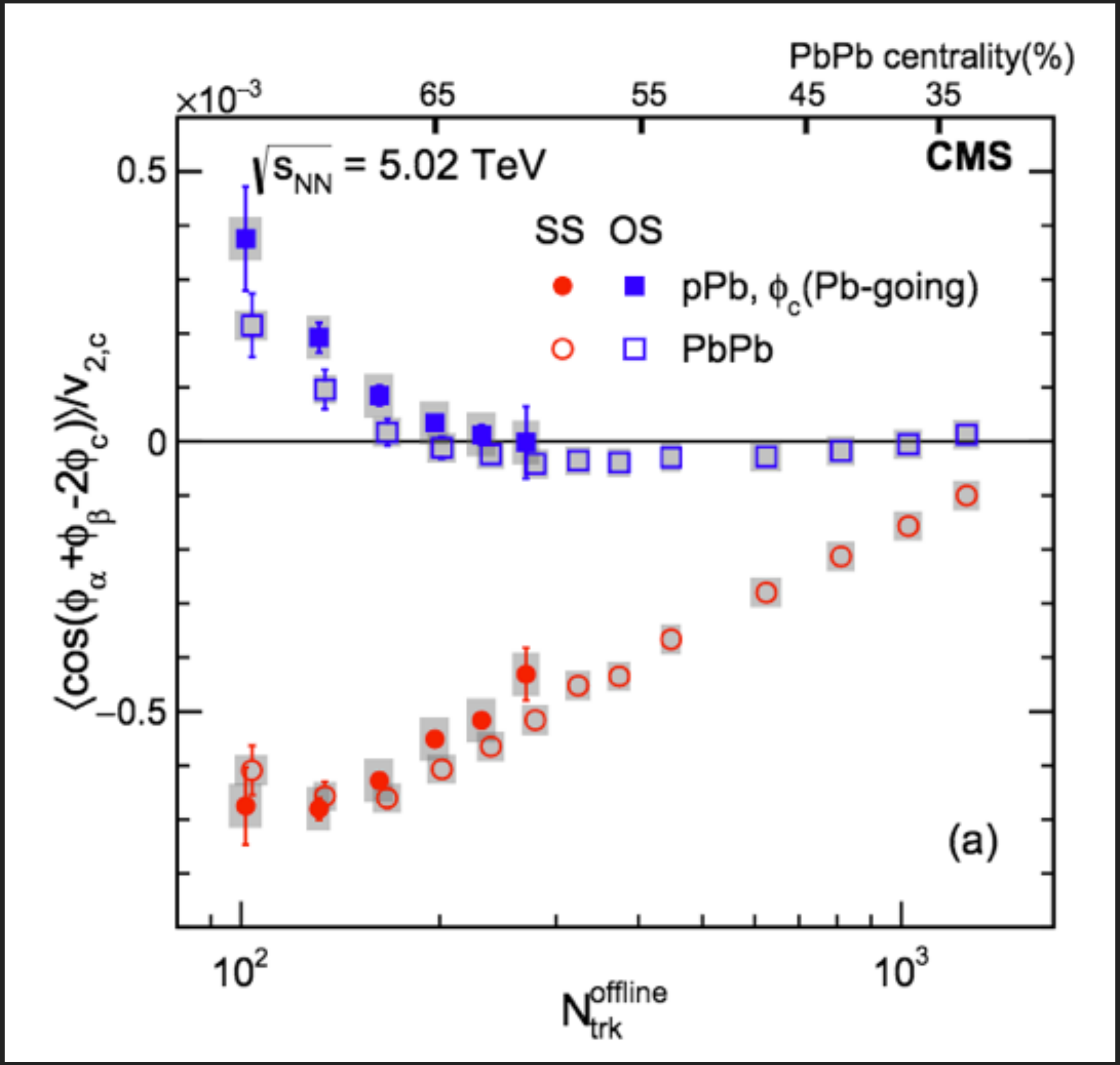
STAR, arXiv:1404.1433



RHIC Beam Energy Scan (Au+Au from 200 to 7.7 GeV):

- consistent with signal expectations;
- not clear how the background changes with energy…

SYSTEM DEPENDENCE

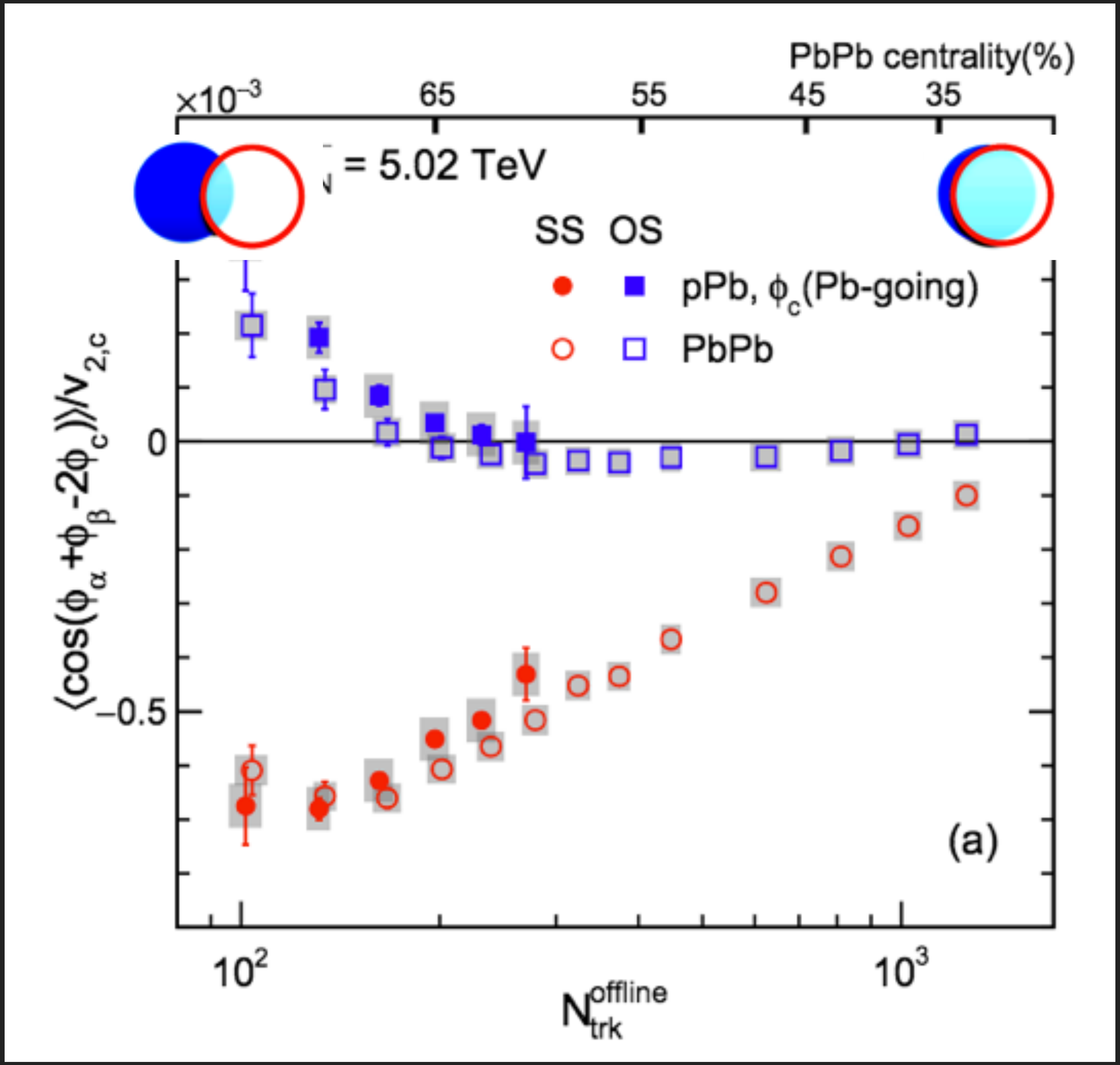


CMS compared Pb-Pb and p-Pb:

- no/small magnetic field expected in p-Pb collisions
- at comparable system size (~charged track multiplicity), results are similar: no CME?

CMS, arXiv:1610.00263

SYSTEM DEPENDENCE



CMS compared Pb-Pb and p-Pb:

- no/small magnetic field expected in p-Pb collisions
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very peripheral Pb-Pb collisions: smaller, short-lived system, no conductivity, no magnetic field?

CHIRAL MAGNETIC WAVE

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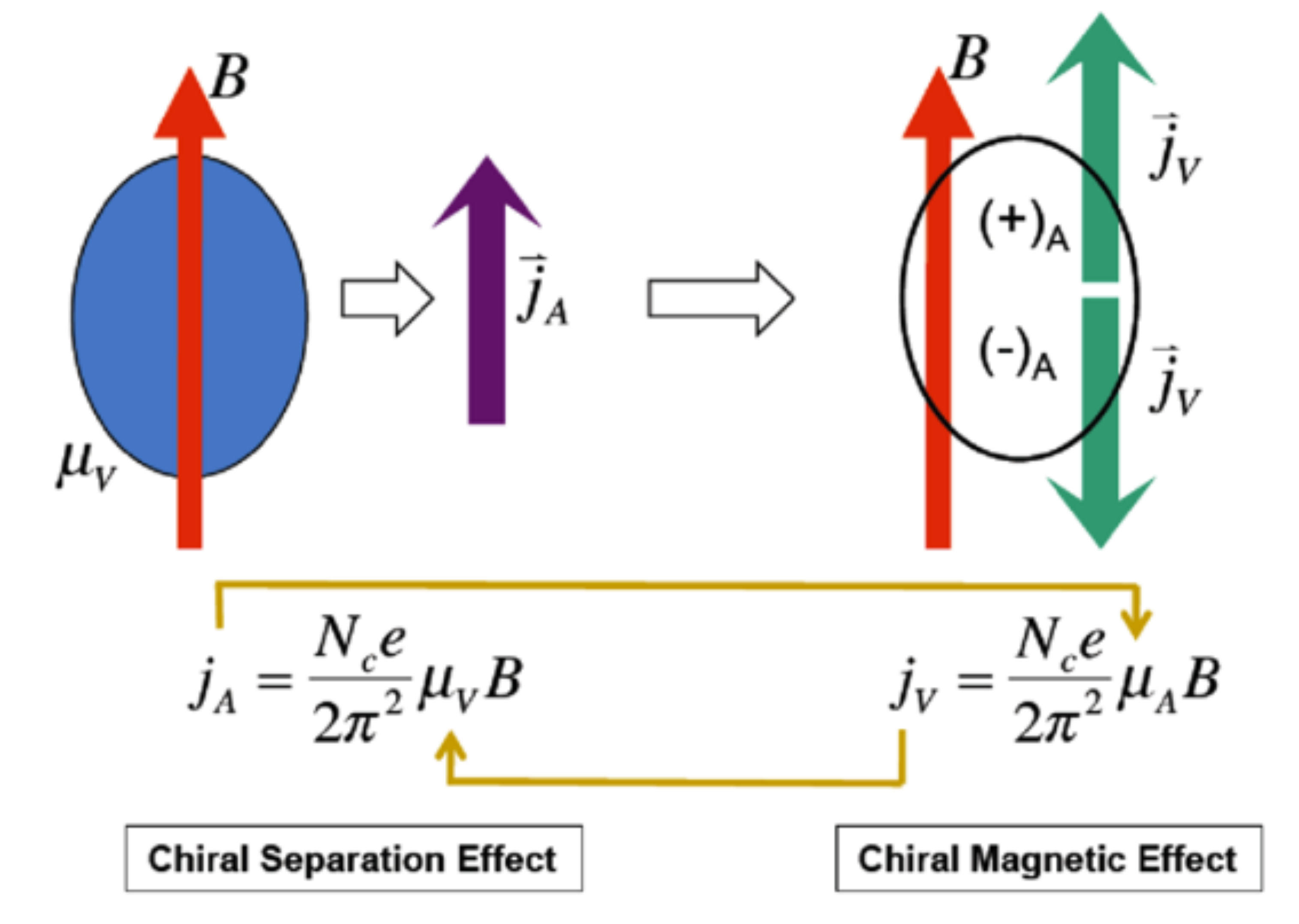
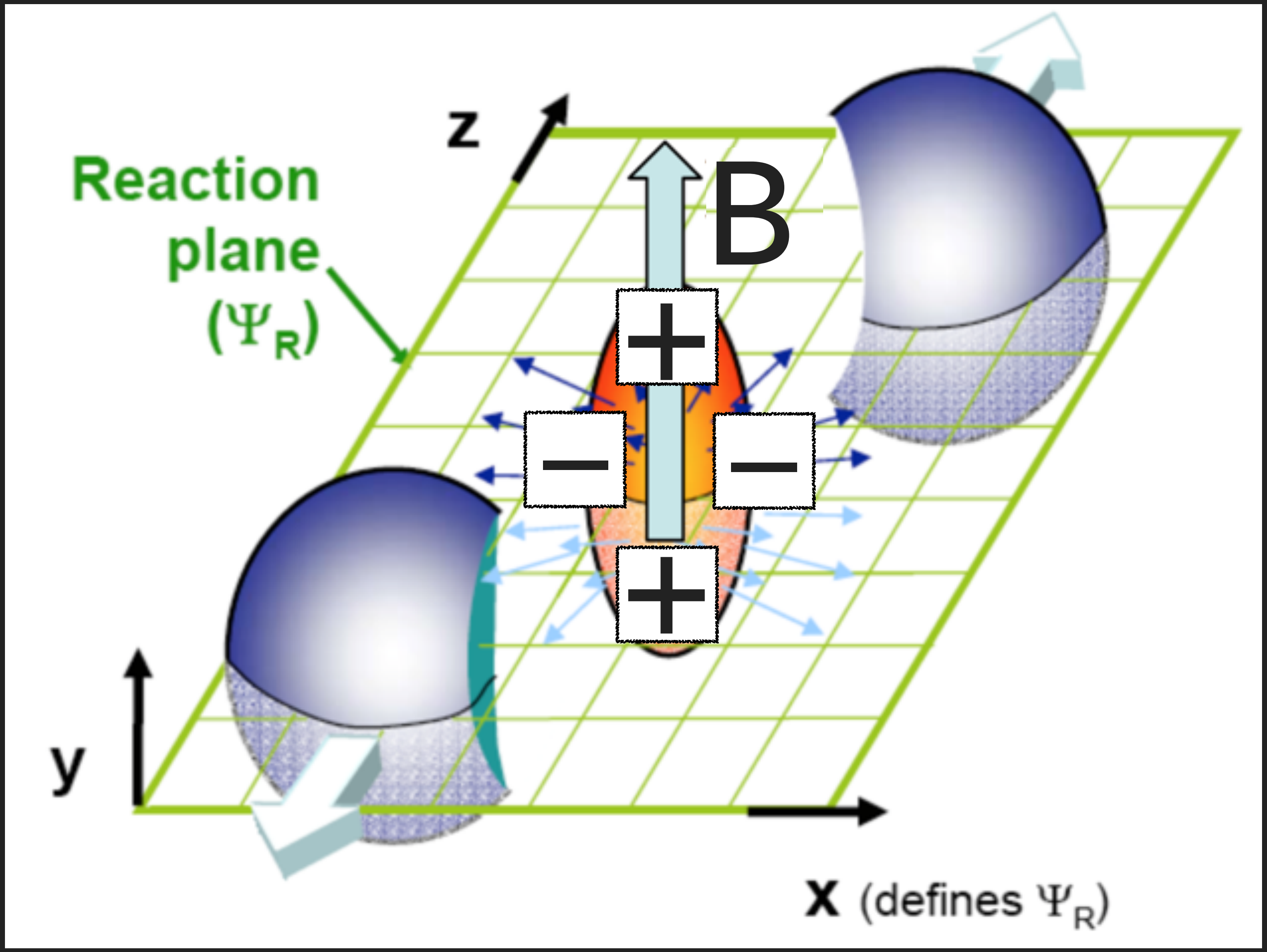


Electric charge separation (CME) is coupled to chiral charge separation (CSE);

the two, combined, give rise to what is called Chiral Magnetic Wave (CMW)

CHIRAL MAGNETIC WAVE



the experimental observable: charge-dependent elliptic flow

OBSERVABLES

CMW: charge-dependent elliptic flow

$$\frac{\mathrm{d}N_\pm}{\mathrm{d}\phi} = N_\pm \left[1 + 2v_2 \cos(2\phi)\right]$$

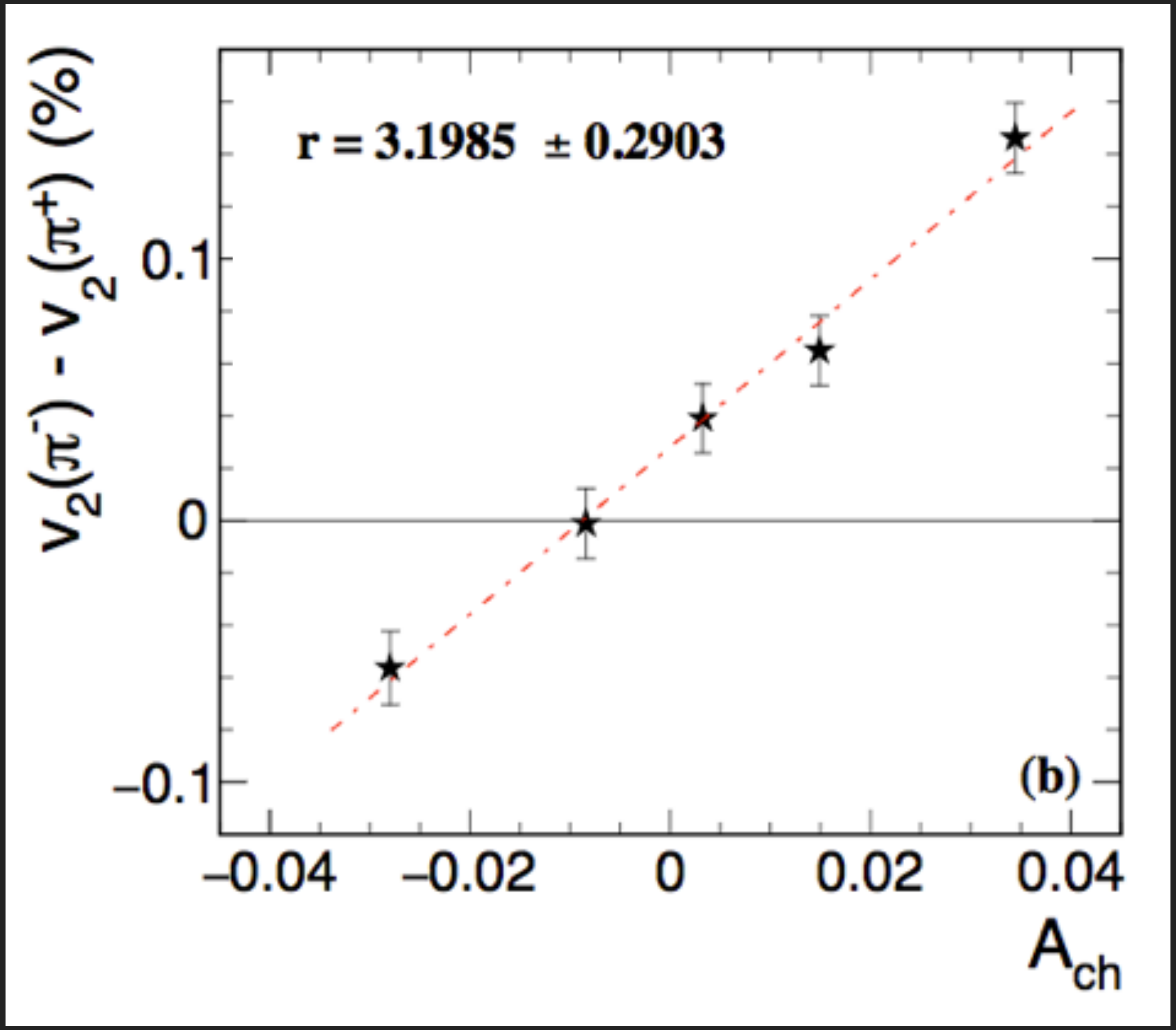
$$\approx \bar{N_\pm} \left[1 + 2v_2 \cos(2\phi) \mp A_{ch} r \cos(2\phi)\right]$$

$$v_2^- - v_2^+ = 2\left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} \qquad r = 2\left(\frac{q_e}{\bar{\rho}_e}\right)$$

first idea: look at the difference v_2^+ - v_2^- as a function of A_{ch}

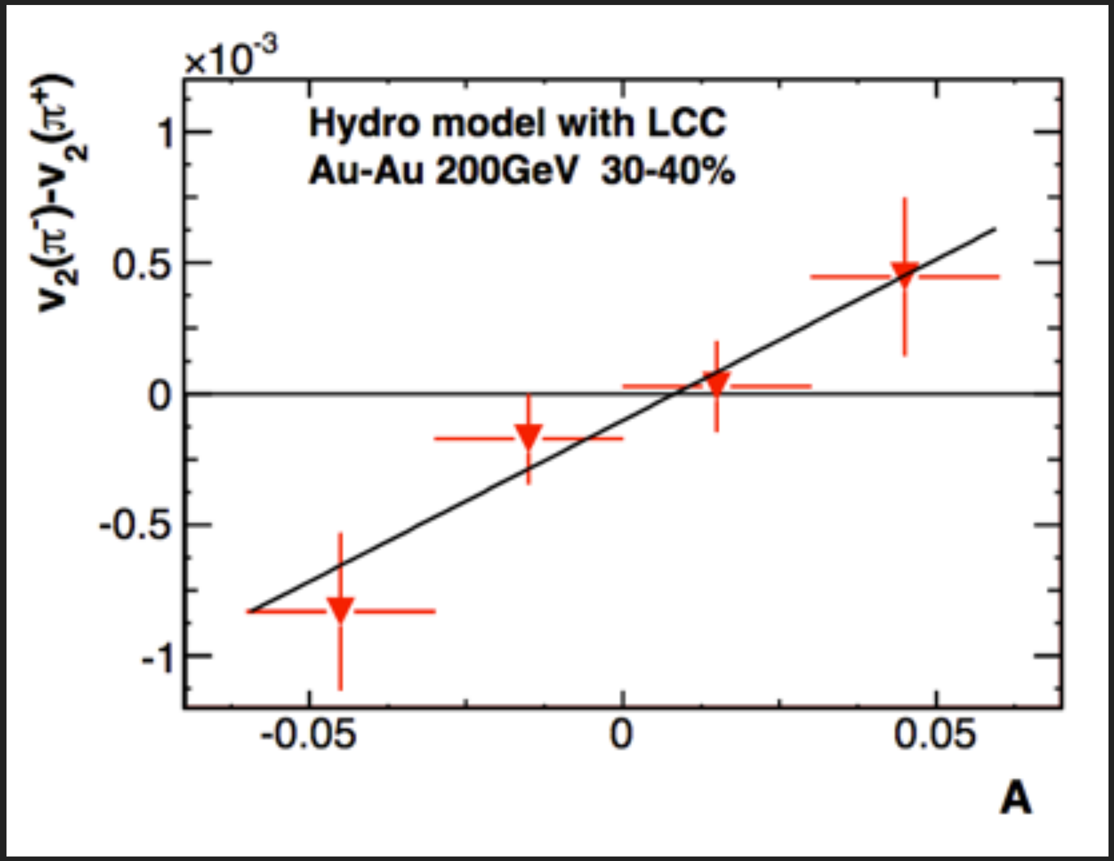
CMW MEASUREMENTS



Same conclusion: non-zero signal, but background largely present!

STAR, arXiv:1504.02175

ALICE, arXiv:1512.05739

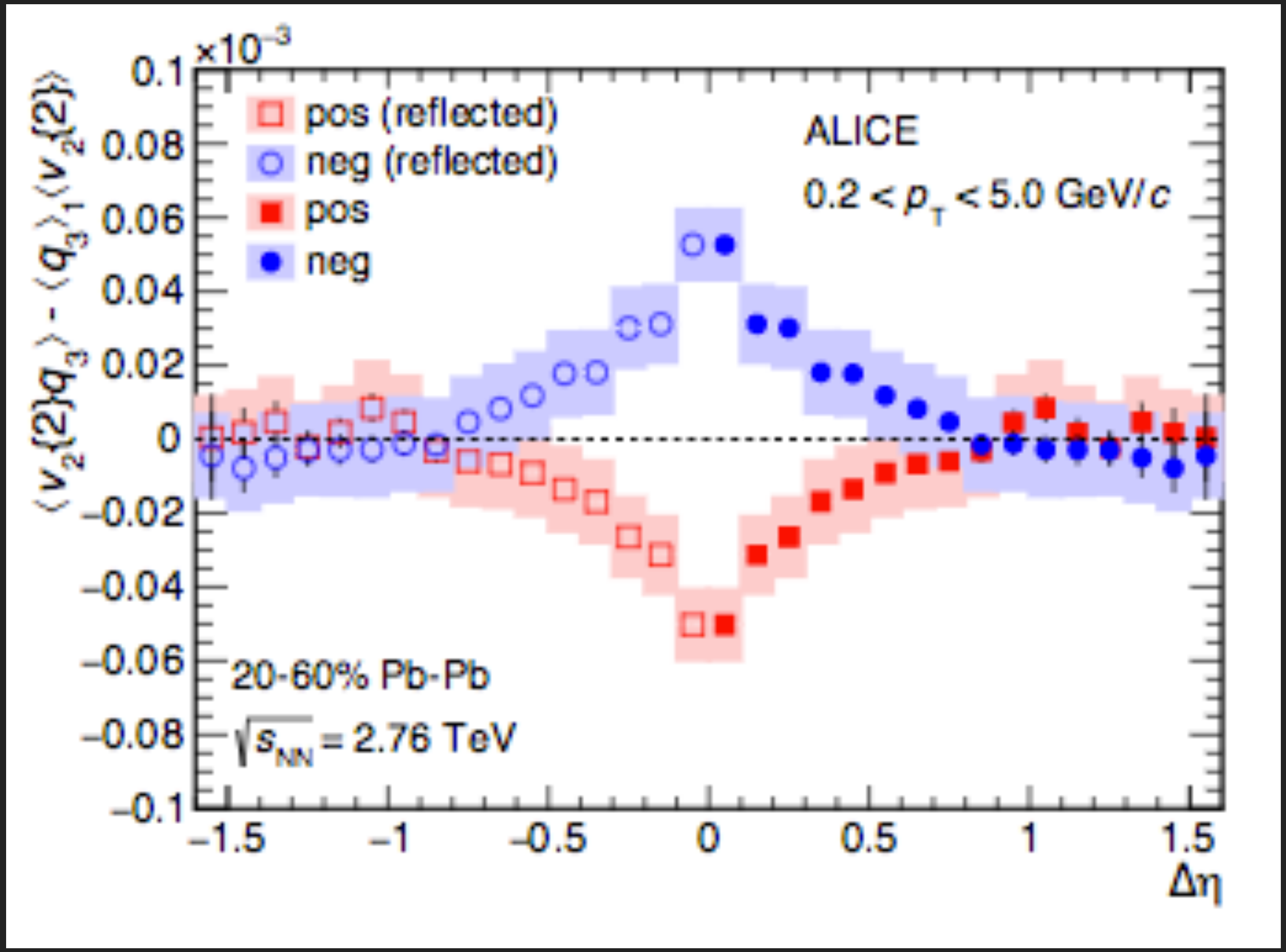


CMW MEASUREMENTS

Measured with the 3-particle correlator:

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

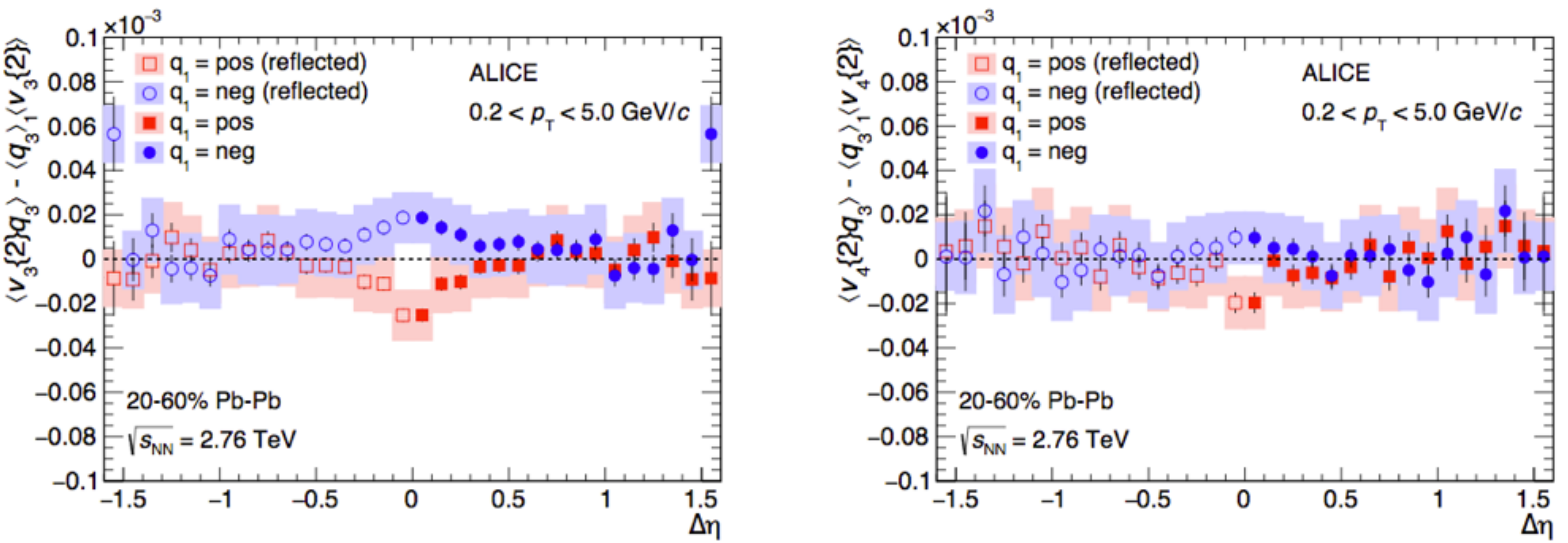
S. Voloshin, R. Belmont
arXiv:1408.0714



ALICE, arXiv:1512.05739

allows more differential studies –> more discriminating power

CMW MEASUREMENTS



"signal" still present in higher harmonics –> background contribution

CONCLUSIONS

- Different phenomena connected to chiral imbalance have been predicted to arise in Heavy-Ion collisions: CME, CSE, CMW…
- On the theoretical side, many issues remain to be clarified, before having realistic predictions of these effects.
- On the experimental one, different observables have been proposed and measured, but all showed to suffer from background contributions which are not fully understood. No upper limits set so far.