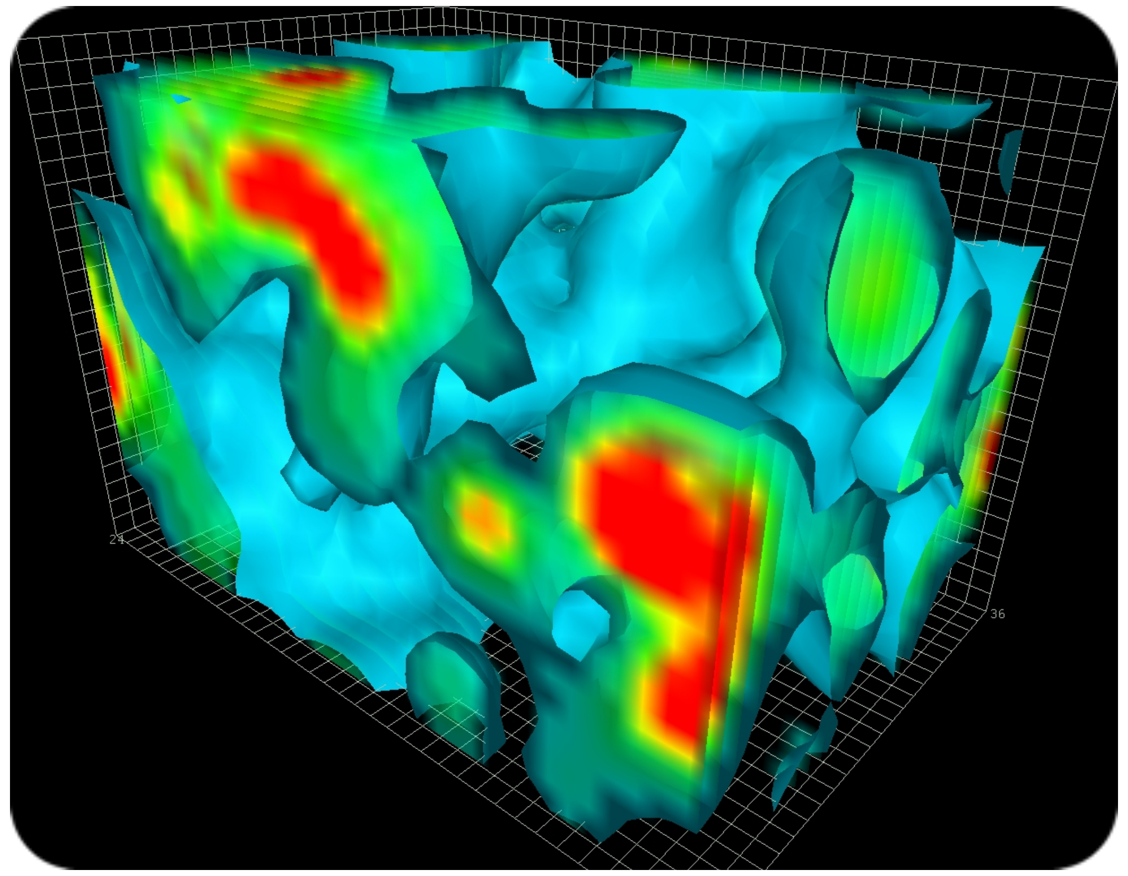
EXPERIMENTAL OVERVIEW ON SEARCHES FOR EARLY STAGE E/M FIELDS AND NOVEL QCD PHENOMENA

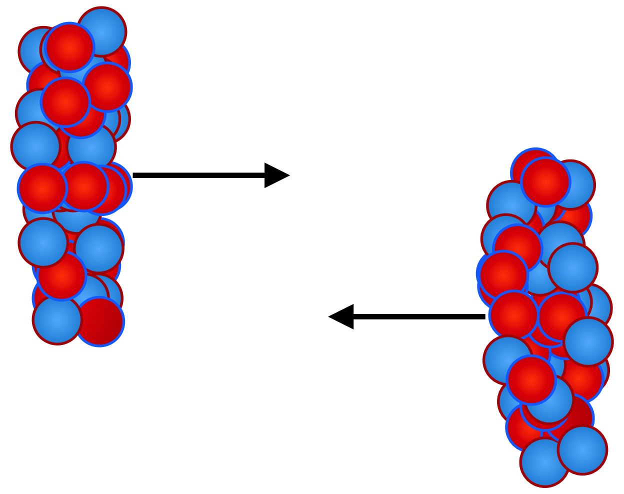
5:40 PM → 6:15 PM **Physics through the arts eye**

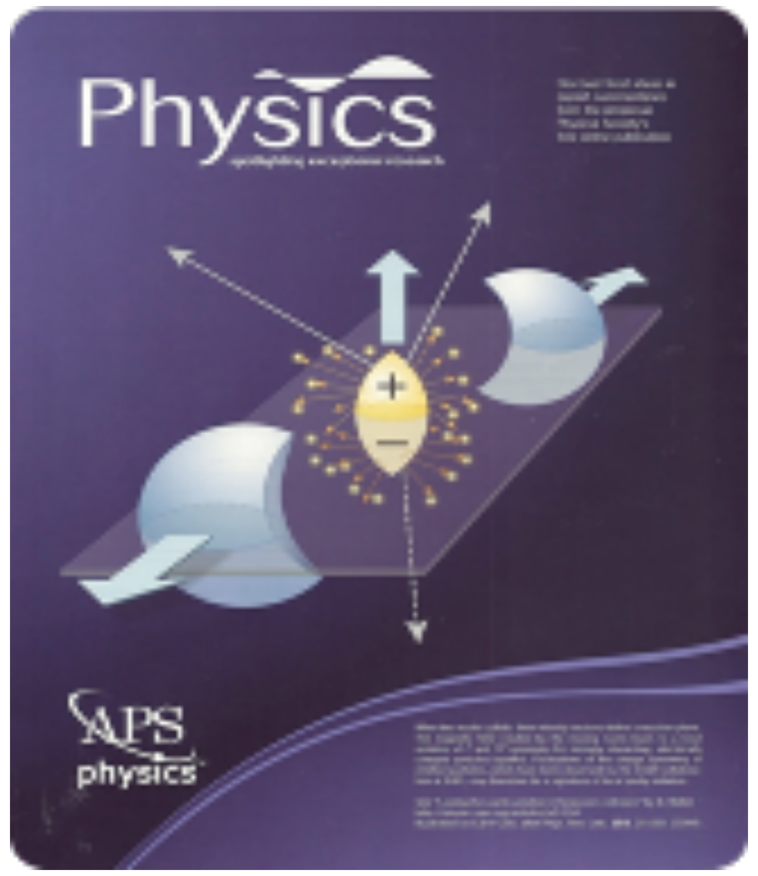
5:40 PM **Experimental overview on searches for early stage E/M fields and novel QCD phenomena** 35m

Speaker: Panos Christakoglou (Nikhef National institute for subatomic physics (NL))



DISCLAIMER
I won't discuss anything related to art…due to lack of any talent





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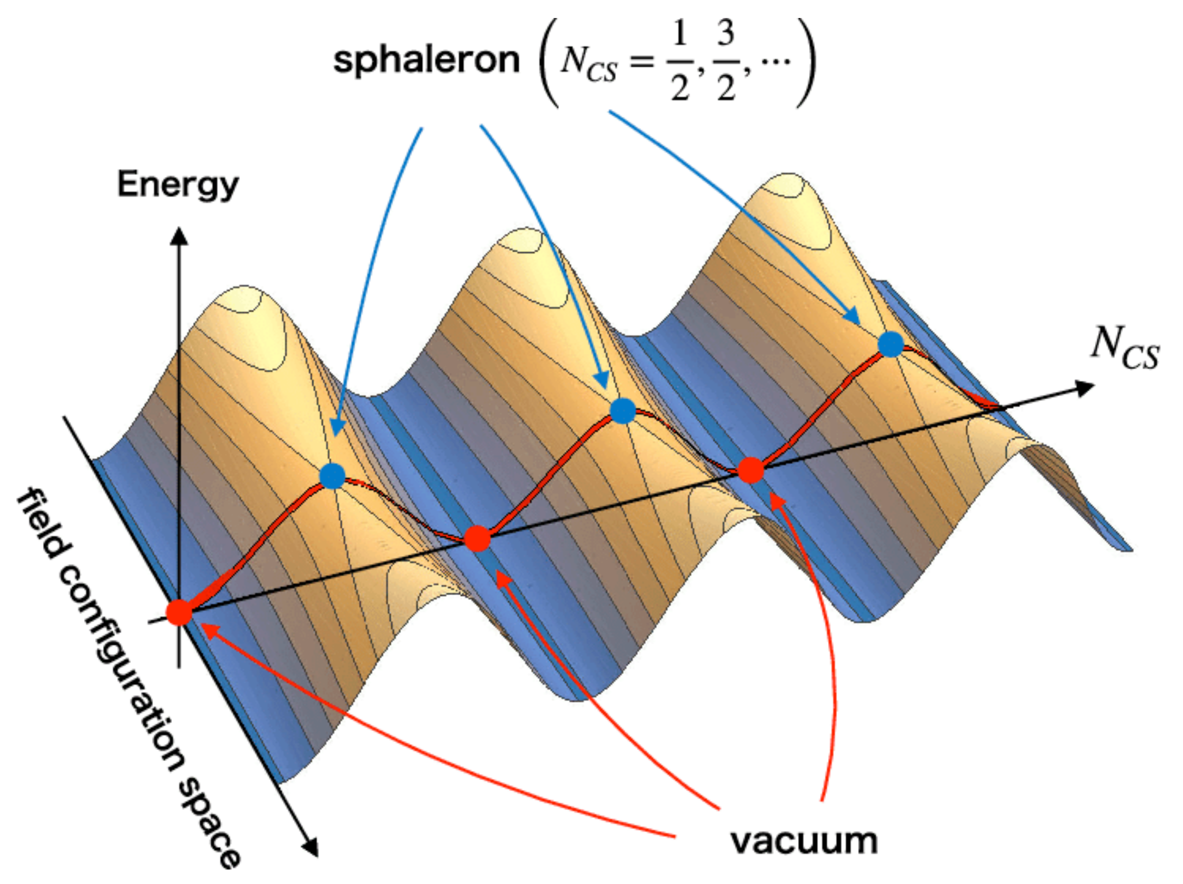
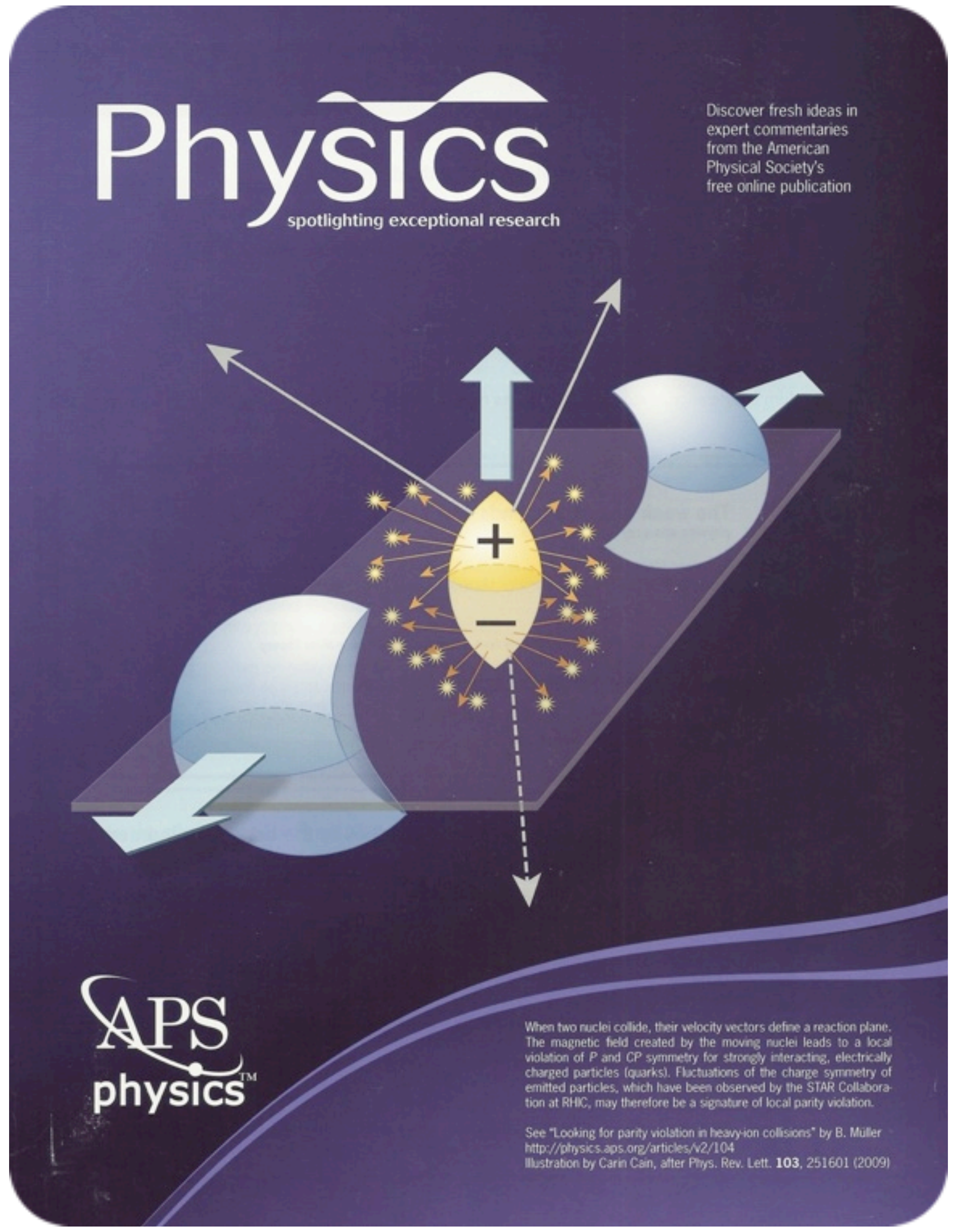
CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



Chirality imbalance

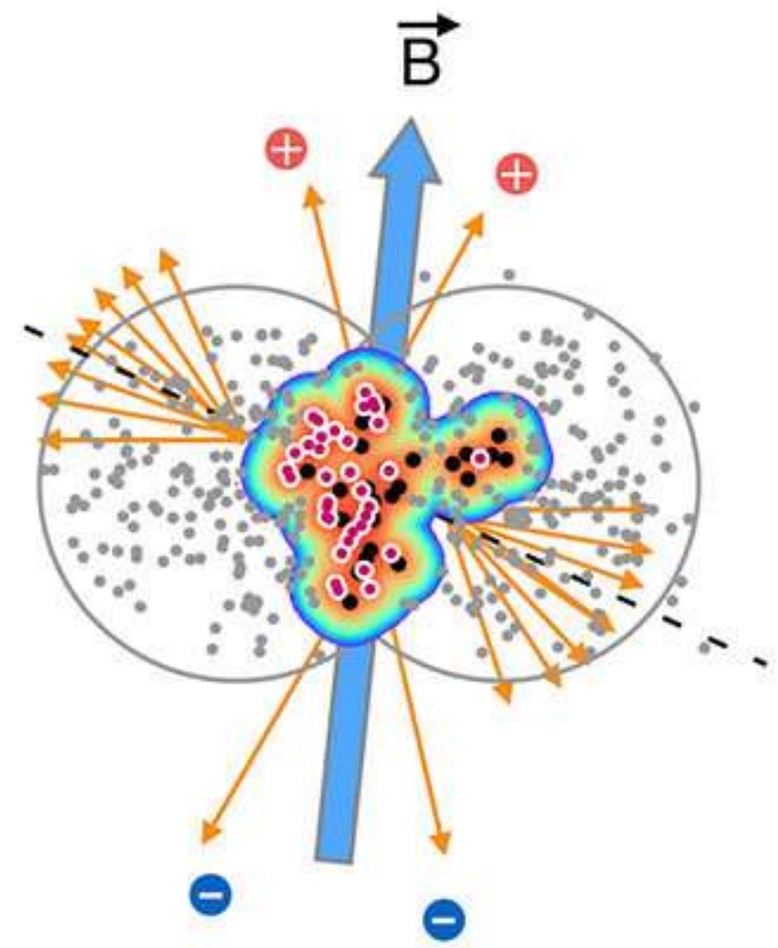
$$\mu_5 = N_L - N_R$$

Chiral Magnetic Effect (CME)



Anomalous transport

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

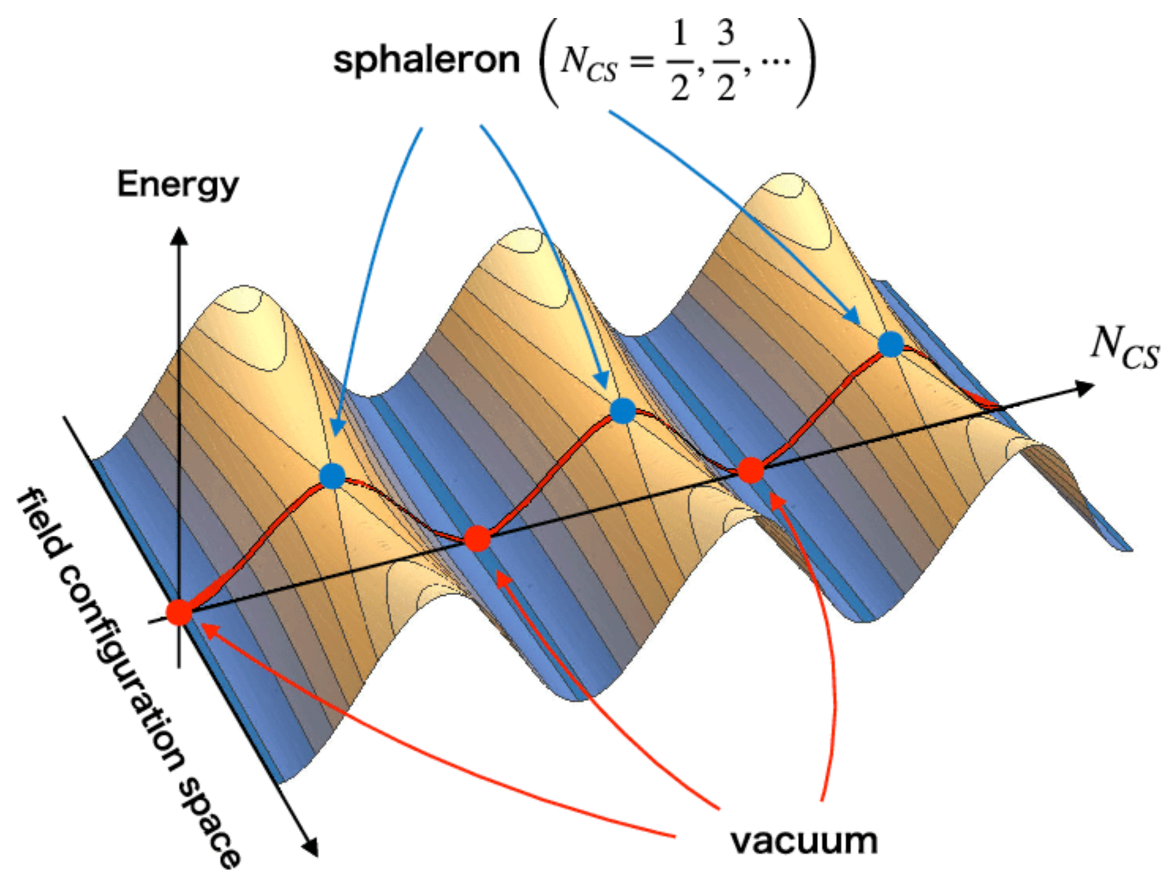


Magnetic field

$$B \approx \gamma Z e \frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{\rm NN}}}{2m_{\rm p}}$$

D. Kharzeev *et al.*, Phys. Rev. Lett. **81**, (1998) 512
D. Kharzeev, Phys. Lett. B **633**, (2006) 260
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



Chirality imbalance

$$\mu_5 = N_L - N_R$$

For any YM field theory (e.g. QCD with SU(3)c gauge symmetry) ➞ the ground state is described as a superposition of different vacua

- Each of this states ∣n⟩ is characterised by a winding number

$$Q_W = \frac{g}{32\pi^2}\int d^4x F^{\alpha}_{\mu\nu}\tilde{F}^{\alpha\mu\nu} \qquad \tilde{F}^{\alpha}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\alpha\rho\sigma}$$

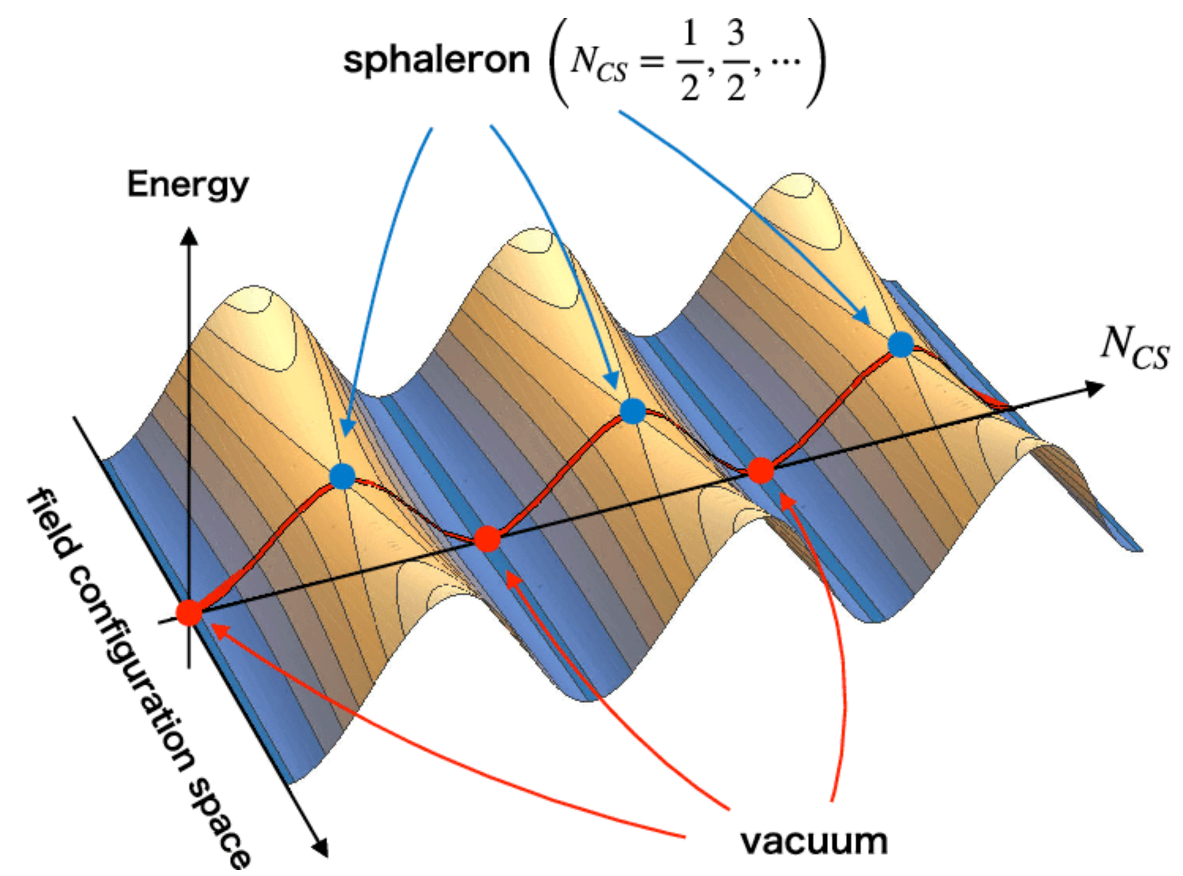
These states are periodic and “separated” by potential barriers

Transitions between these states can be done through

- Tunneling ➞ instantons ➞ P~exp$^{(-E)}$
- “Go-over” process ➞ sphalerons ➞ P~e$^{(-E_0/T)}$

G. t’Hooft, Phys. Rev. Lett. 37, (1976) 8
G. t’Hooft, Phys. Rev. D14, (1976) 3432
R. Jackiw and C. Reb, Phys.Rev.Lett. **37**, (1976) 172
E. Shuryak World Sci. Lect. Notes Phys. 8 (1988)

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



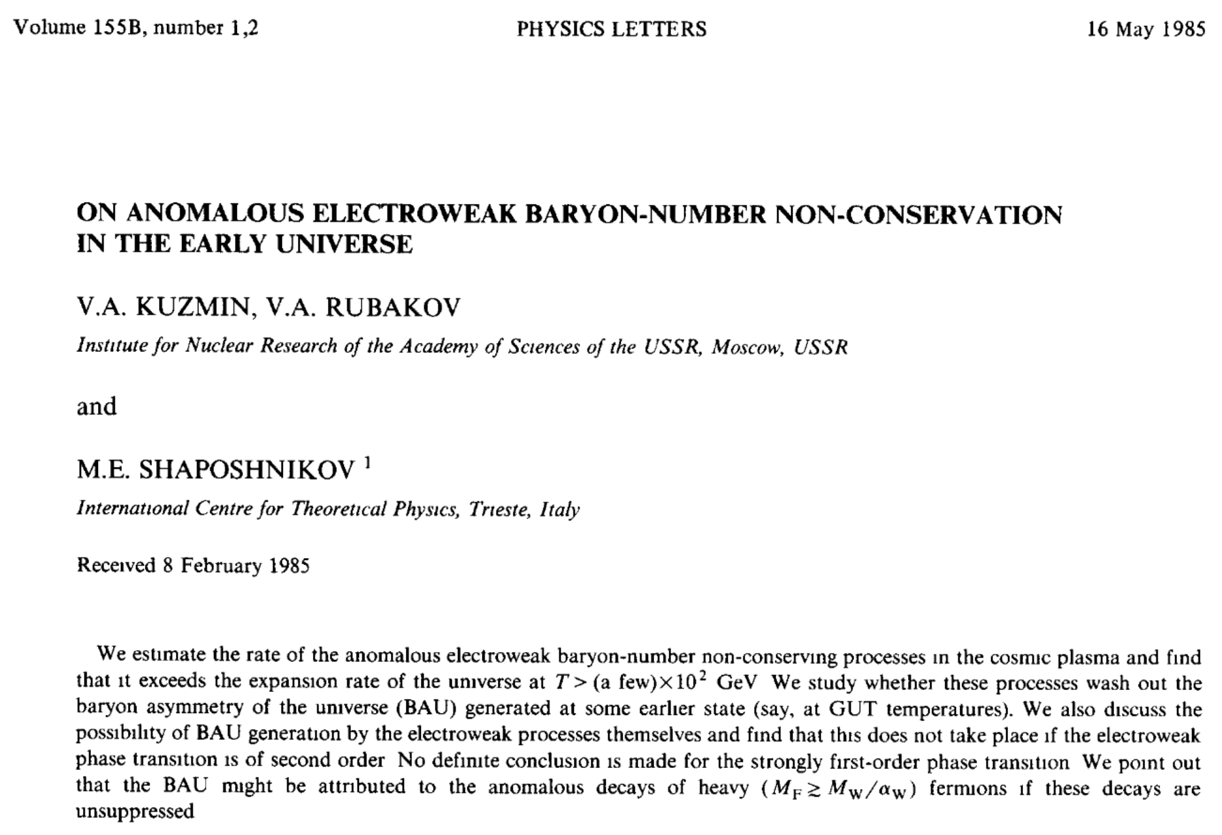
Chirality imbalance

$$\mu_5 = N_L - N_R$$

Physical implication:

- Baryon number violating transitions in E/W theory
  - Transitions happen at large temperatures (~200GeV) → relevant for the early Universe
  - Needed as one of the Sakharov conditions for matter-antimatter asymmetry
- In QCD these transitions lead to chirality not being conserved
  - At a scale of the order of the scale of the theory ($\sim\Lambda_{QCD}$)
  - The axial chemical potential $\mu_5 = N_L - N_R$ is non-zero

Transitions take place at temperatures reached in heavy-ion collisions


Volume 155B, number 1,2 PHYSICS LETTERS 16 May 1985

ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

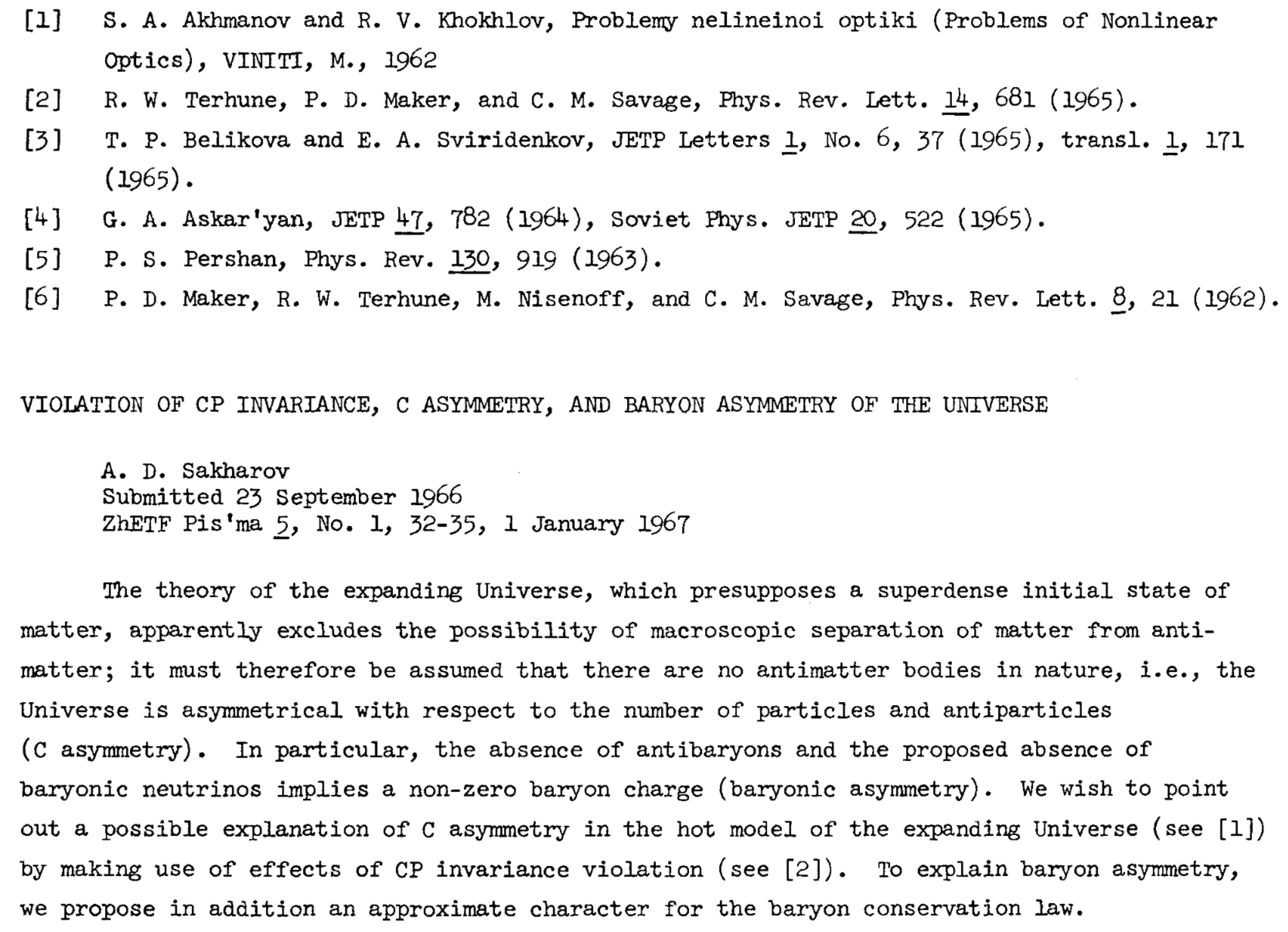
V.A. KUZMIN, V.A. RUBAKOV
Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow, USSR

and

M.E. SHAPOSHNIKOV [1]
International Centre for Theoretical Physics, Trieste, Italy

Received 8 February 1985

We estimate the rate of the anomalous electroweak baryon-number non-conserving processes in the cosmic plasma and find that it exceeds the expansion rate of the universe at $T >$ (a few)$\times 10^2$ GeV We study whether these processes wash out the baryon asymmetry of the universe (BAU) generated at some earlier state (say, at GUT temperatures). We also discuss the possibility of BAU generation by the electroweak processes themselves and find that this does not take place if the electroweak phase transition is of second order No definite conclusion is made for the strongly first-order phase transition We point out that the BAU might be attributed to the anomalous decays of heavy ($M_F \gtrsim M_W/\alpha_W$) fermions if these decays are unsuppressed

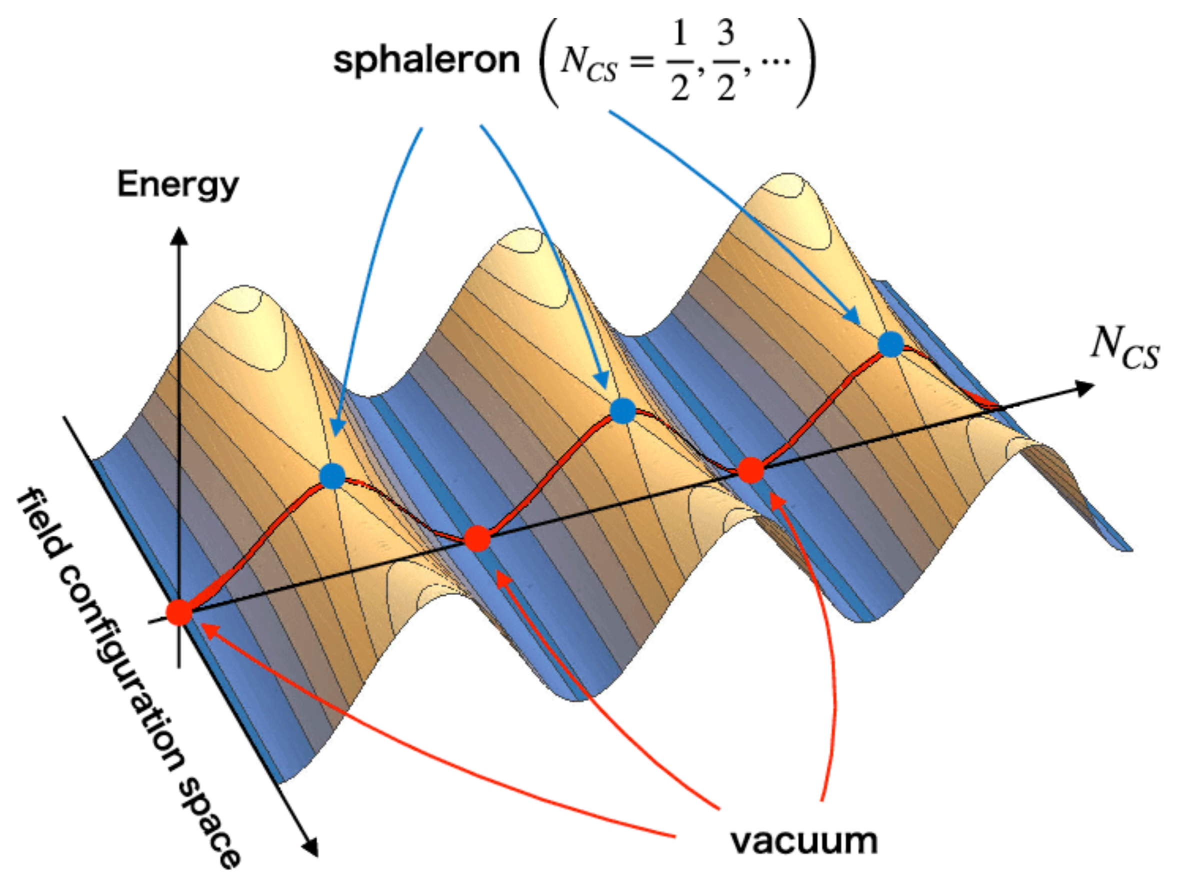

[1] S. A. Akhmanov and R. V. Khokhlov, Problemy nelineinoi optiki (Problems of Nonlinear Optics), VINITI, M., 1962
[2] R. W. Terhune, P. D. Maker, and C. M. Savage, Phys. Rev. Lett. 14, 681 (1965).
[3] T. P. Belikova and E. A. Sviridenkov, JETP Letters 1, No. 6, 37 (1965), transl. 1, 171 (1965).
[4] G. A. Askar'yan, JETP 47, 782 (1964), Soviet Phys. JETP 20, 522 (1965).
[5] P. S. Pershan, Phys. Rev. 130, 919 (1963).
[6] P. D. Maker, R. W. Terhune, M. Nisenoff, and C. M. Savage, Phys. Rev. Lett. 8, 21 (1962).

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS

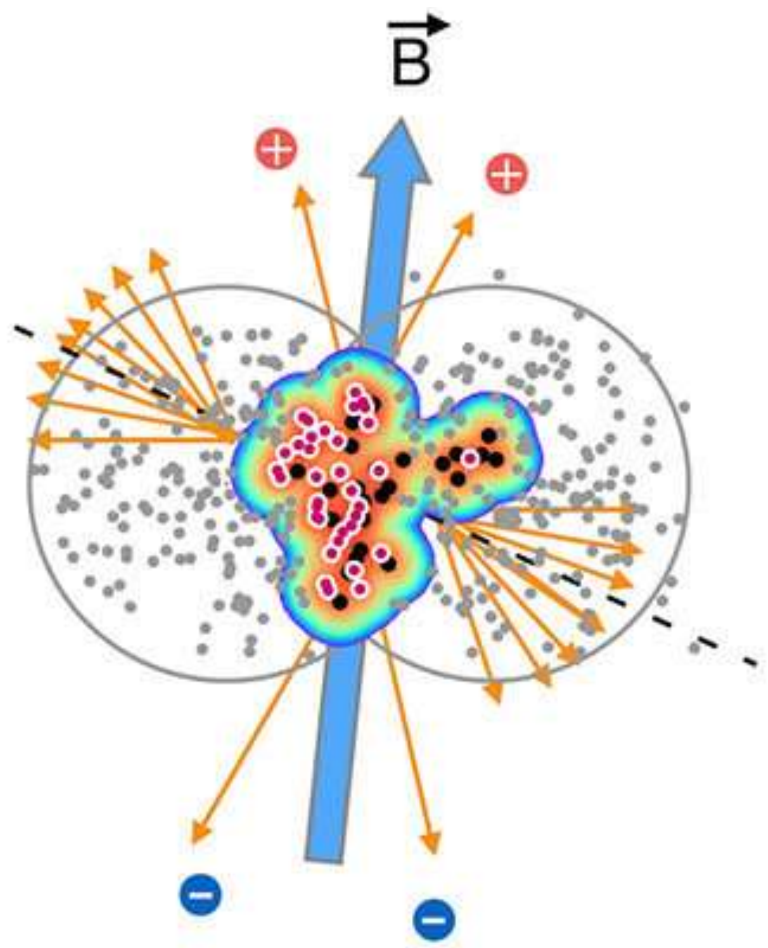


Chirality imbalance

$$\mu_5 = N_L - N_R$$

Anomalous transport

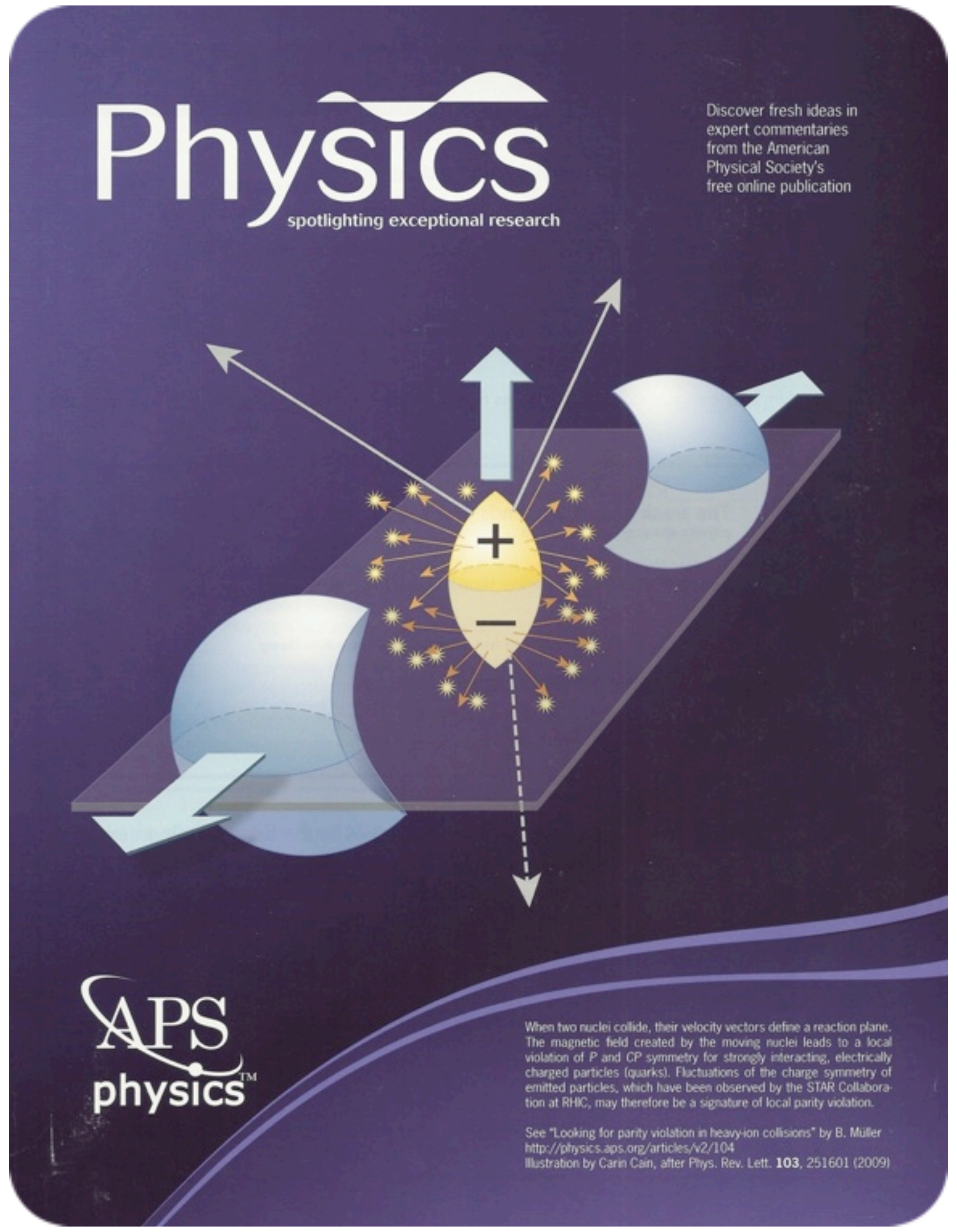
$$J = \frac{e^2}{2\pi^2}\mu_5 B$$



Magnetic field

$$B \approx \gamma Ze\frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{\mathrm{NN}}}}{2m_{\mathrm{p}}}$$

Chiral Magnetic Effect (CME)

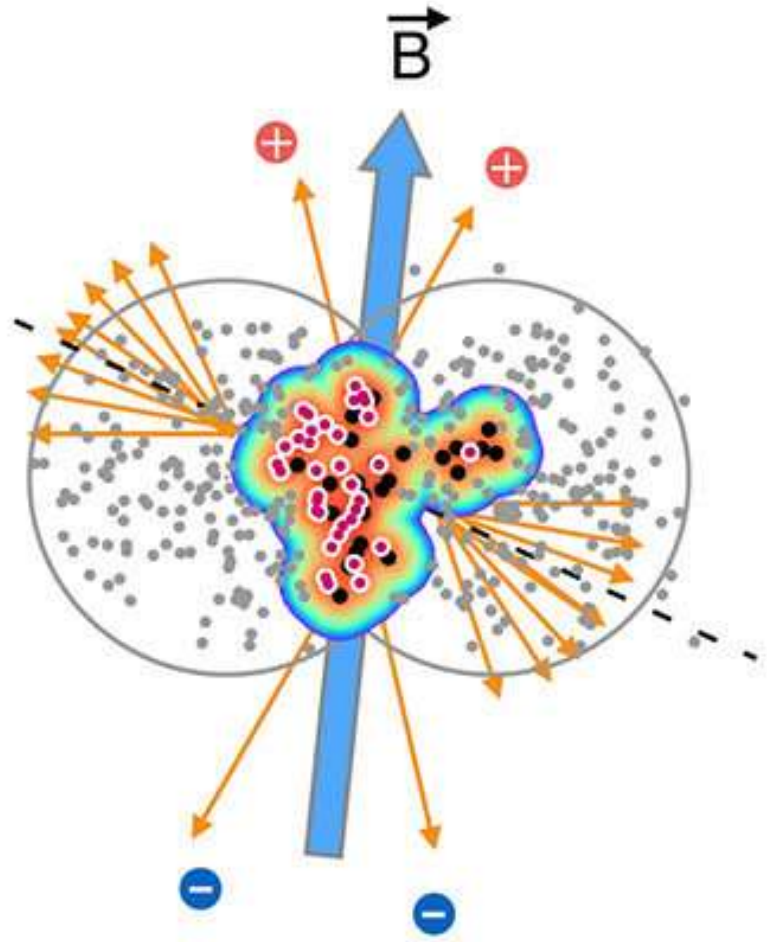


D. Kharzeev *et al.*, Phys. Rev. Lett. **81**, (1998) 512
D. Kharzeev, Phys. Lett. B **633**, (2006) 260
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

THE STRONGEST MAGNETIC FIELD IN NATURE…

Heavy ion collisions: ~10^{19} G

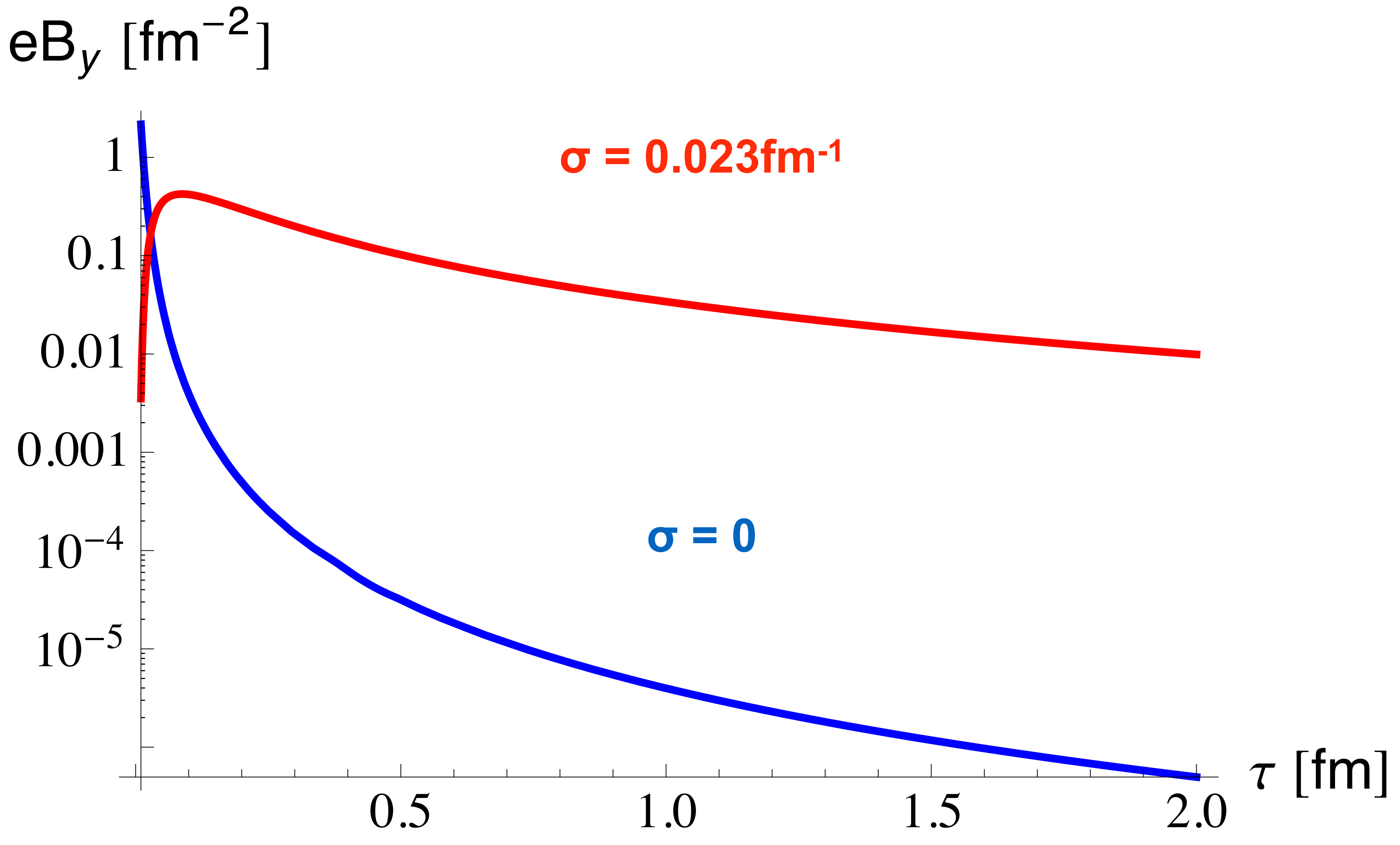
Au-Au collisions @ RHIC	Pb-Pb collisions @ LHC
$\sqrt{s_{NN}}$ = 200 GeV	$\sqrt{s_{NN}}$ = 2.76 GeV
γ = 100	γ = 1.38x10^3
Z = 79	Z = 82
b = R_{Au} ~ 7fm	b = R_{Au} ~ 7fm
eB ~ m_π^2	eB ~ $10m_\pi^2$



Magnetic field

$$B \approx \gamma Z e \frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{NN}}}{2m_p}$$

U. Gürsoy *et al.*, Phys. Rev. **C89**, (2014) 054905

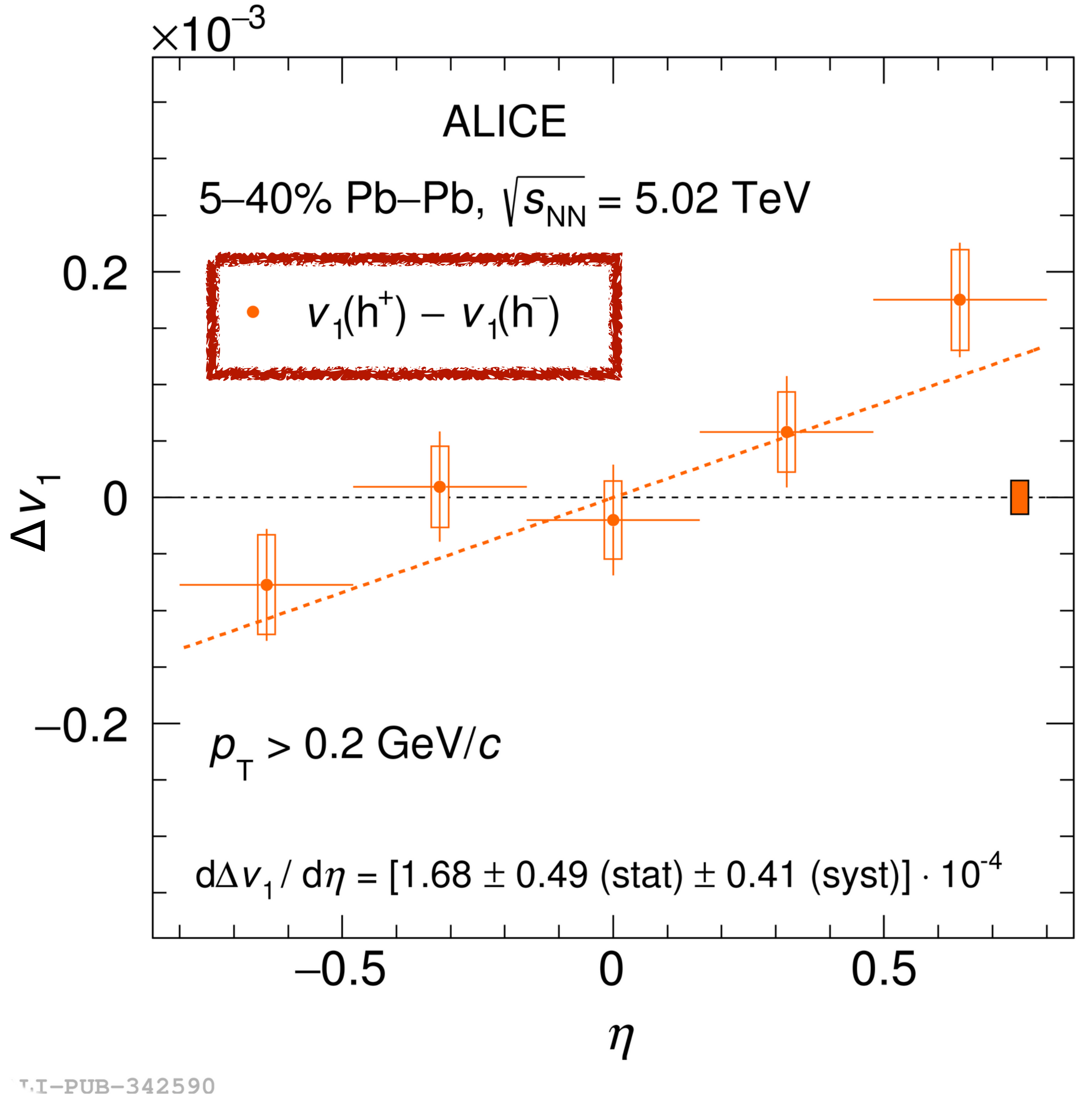


Decay rate depends on electric conductivity → unconstrained experimentally

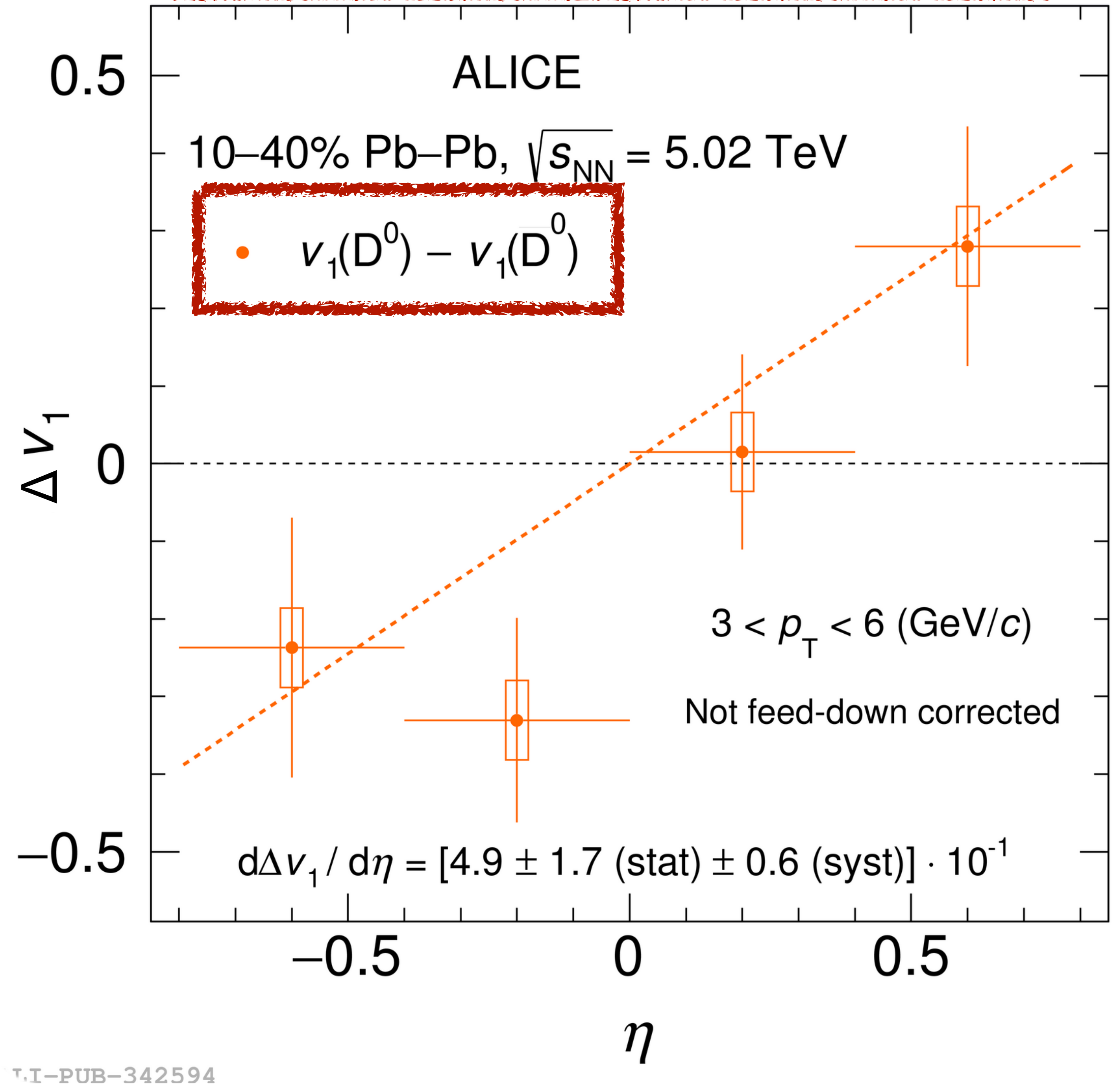
EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

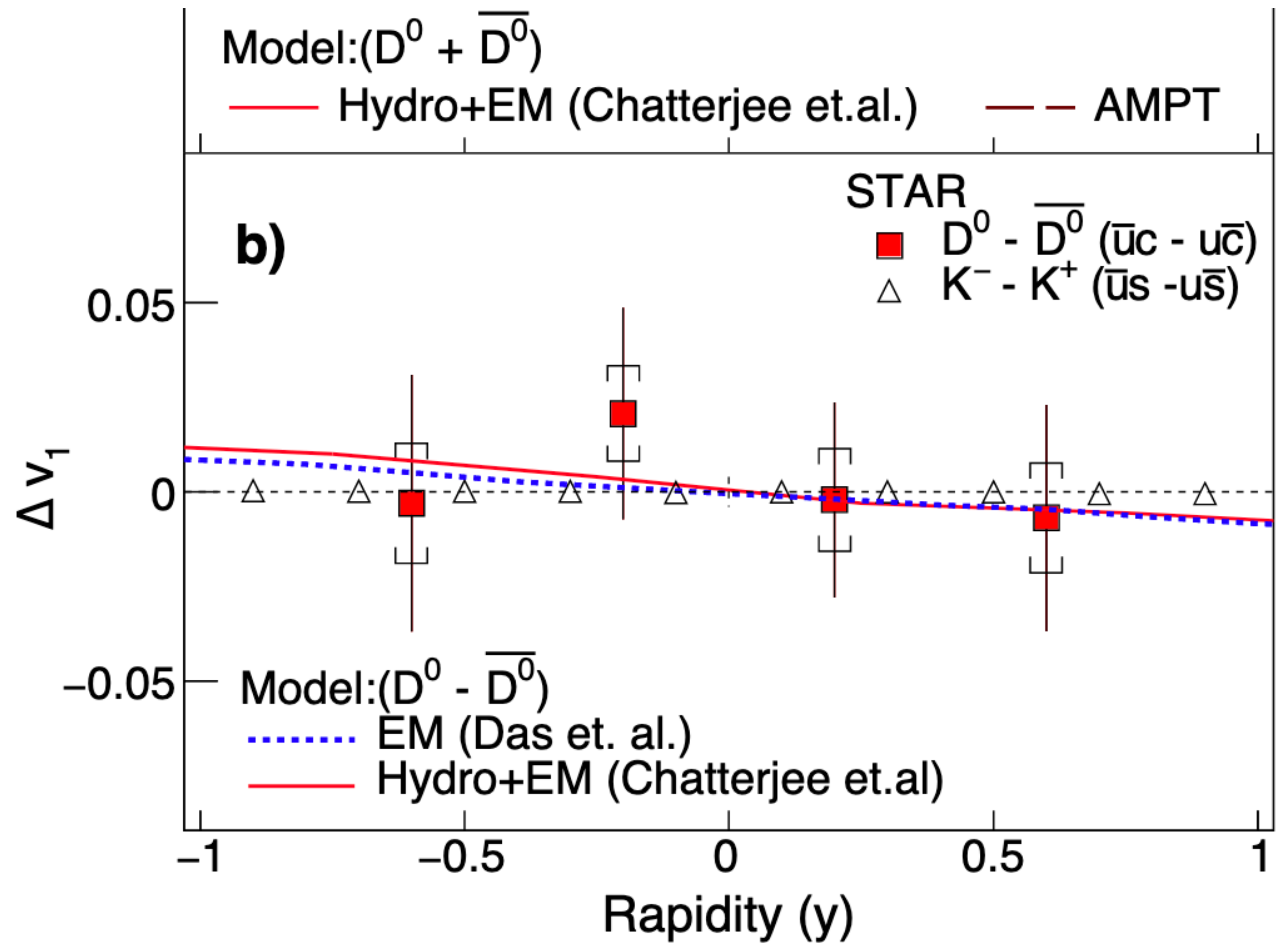
(ALICE Collaboration), Phys. Rev. Lett. 125, 022301 (2020)

(STAR Collaboration), Phys. Rev. Lett. 122, 162301 (2019)



Small formation time → more sensitive probe of the early E/M fields





Effect @RHIC ~10 times smaller

$\Delta v_1 \neq 0$ with a 2.6σ significance

$\Delta v_1 \neq 0$ with a 2.7σ significance

Magnitude smaller than theory expectation and sign reversed

- Larger contribution from the Lorentz force?

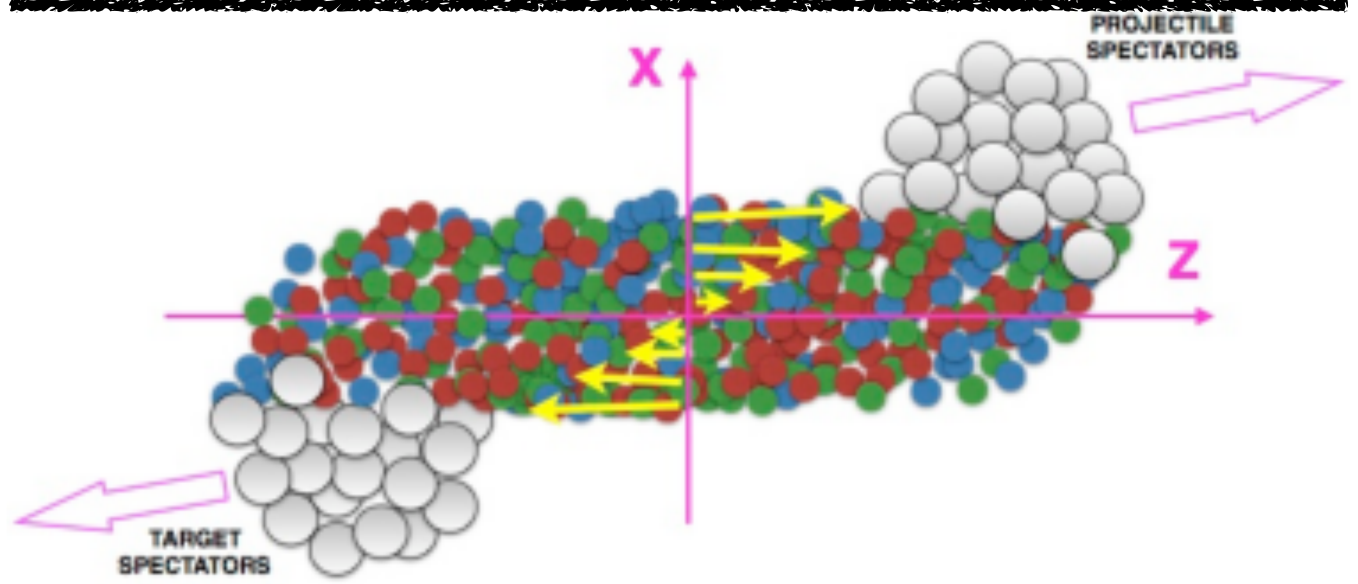
Significant progress expected with the upcoming Run3 data @ LHC

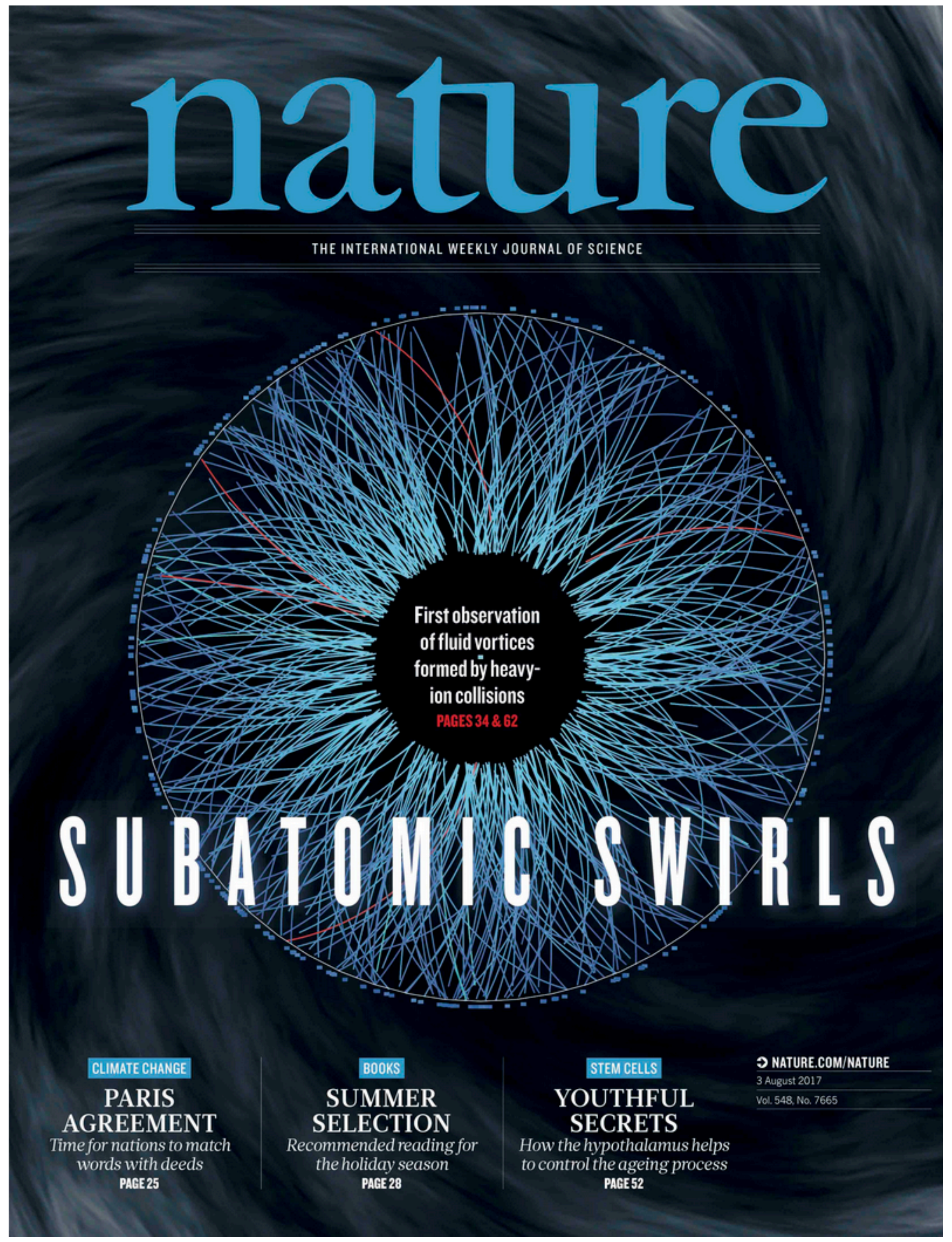
Nikhef

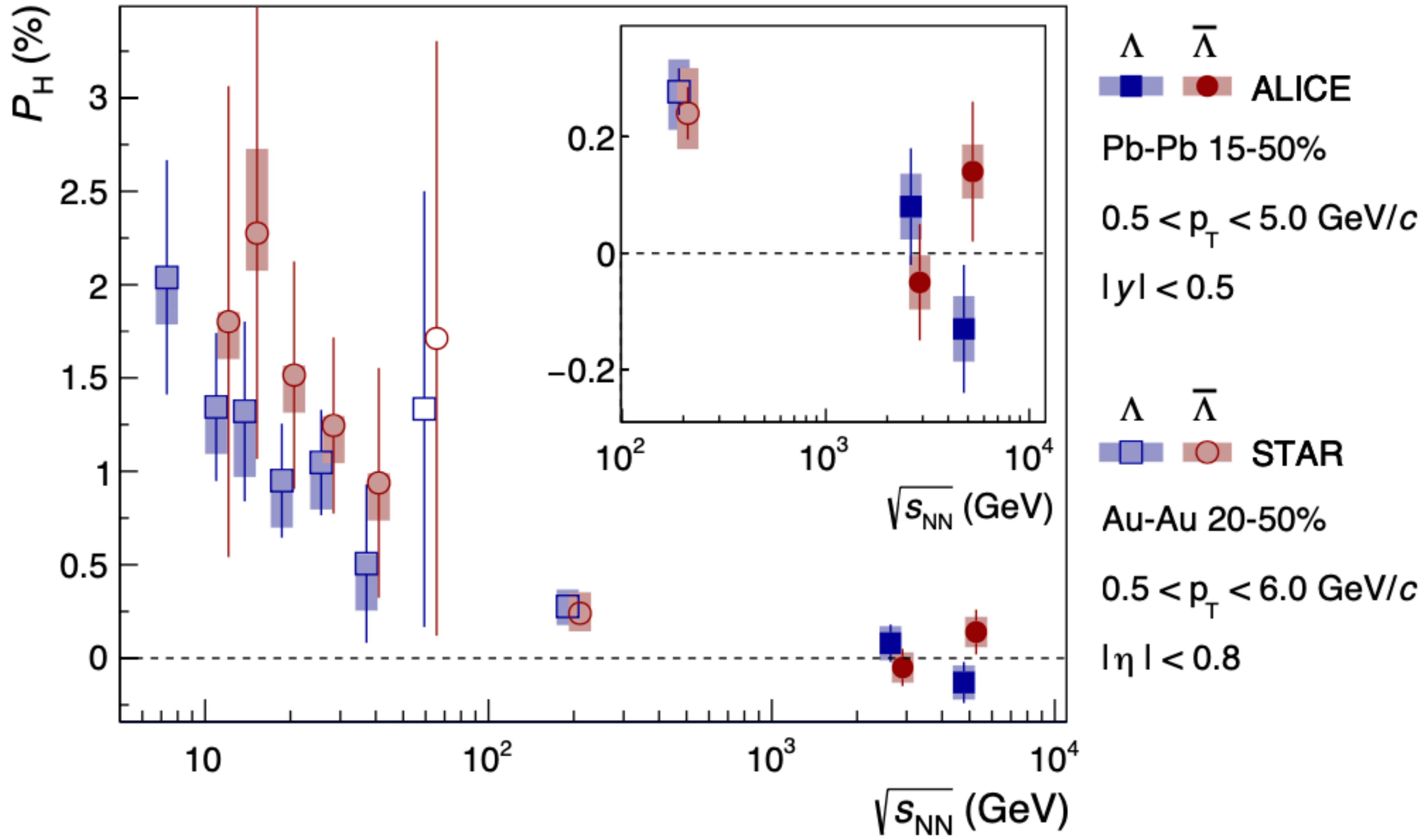
EXPERIMENTAL PROBE: GLOBAL POLARISATION

F. Becattini *et al.*, Phys. Rev. C77, (2008) 024906

(STAR Collaboration) Nature 548, 62 (2017)
(ALICE Collaboration), Phys. Rev. C101 (2020) 044611







Large values of magnetic field and angular momentum at the initial stage of a HI collision

Part of L remains in the overlap region → rotating QGP

QGP exhibits vortical structure affected by the local velocity field

Spin proportional to magnetic moment

- Particles tend to be polarised along the initial angular momentum of the QGP
- Opposite effect for particles and antiparticles

$$P_{\rm H} = \frac{8}{\pi\alpha_{\rm H}}\langle\sin(\Psi_{\rm RP} - \varphi_{\rm p})\rangle$$

$$P_q^{\rm B} \approx \mu_q \frac{\rm B}{\rm T} = \frac{Q_q}{2m_q}\frac{\rm B}{\rm T}$$

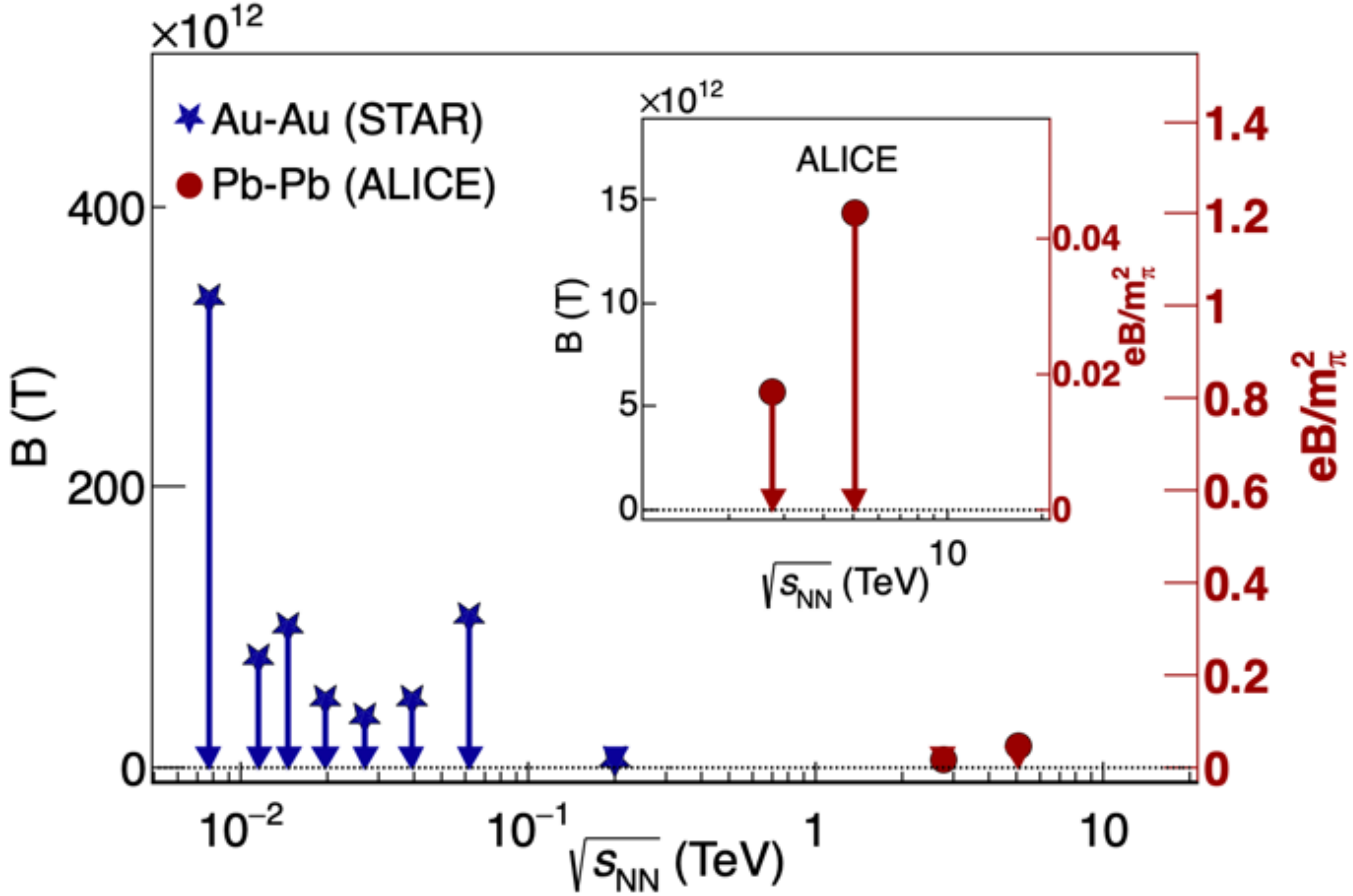
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{\rm T} + \mu_\Lambda \frac{\rm B}{\rm T}$$

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

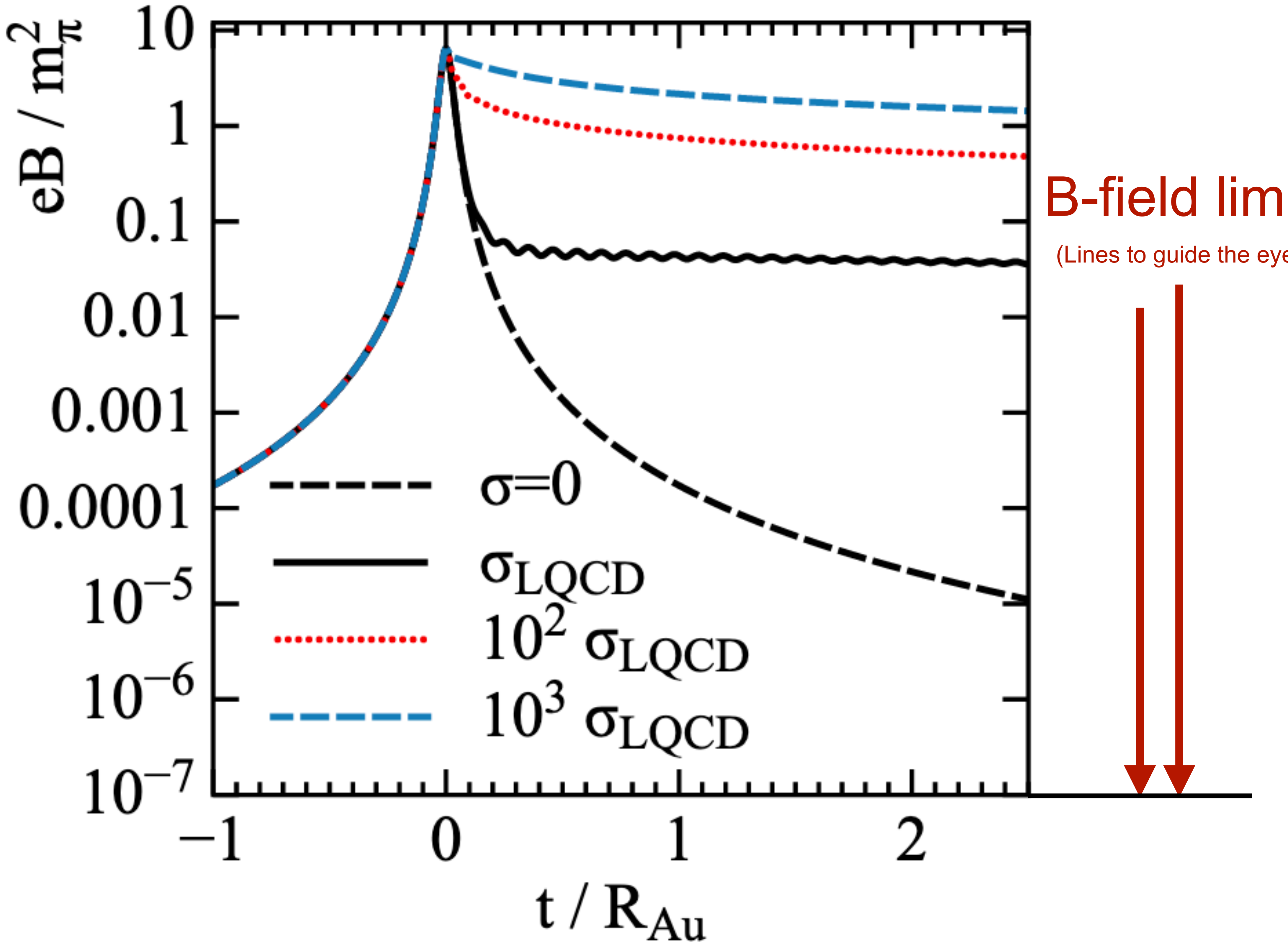
Significant reduction of $P_{\rm H}$ at the LHC energies relative to RHIC

No significant difference between Λ and anti-Λ ➞ (still) not sensitive to effects due to magnetic field

EXPERIMENTAL CONSTRAINS ON B



L. McLerran, V. Skokov, Nucl. Phys. *A* 929 (2014) 184

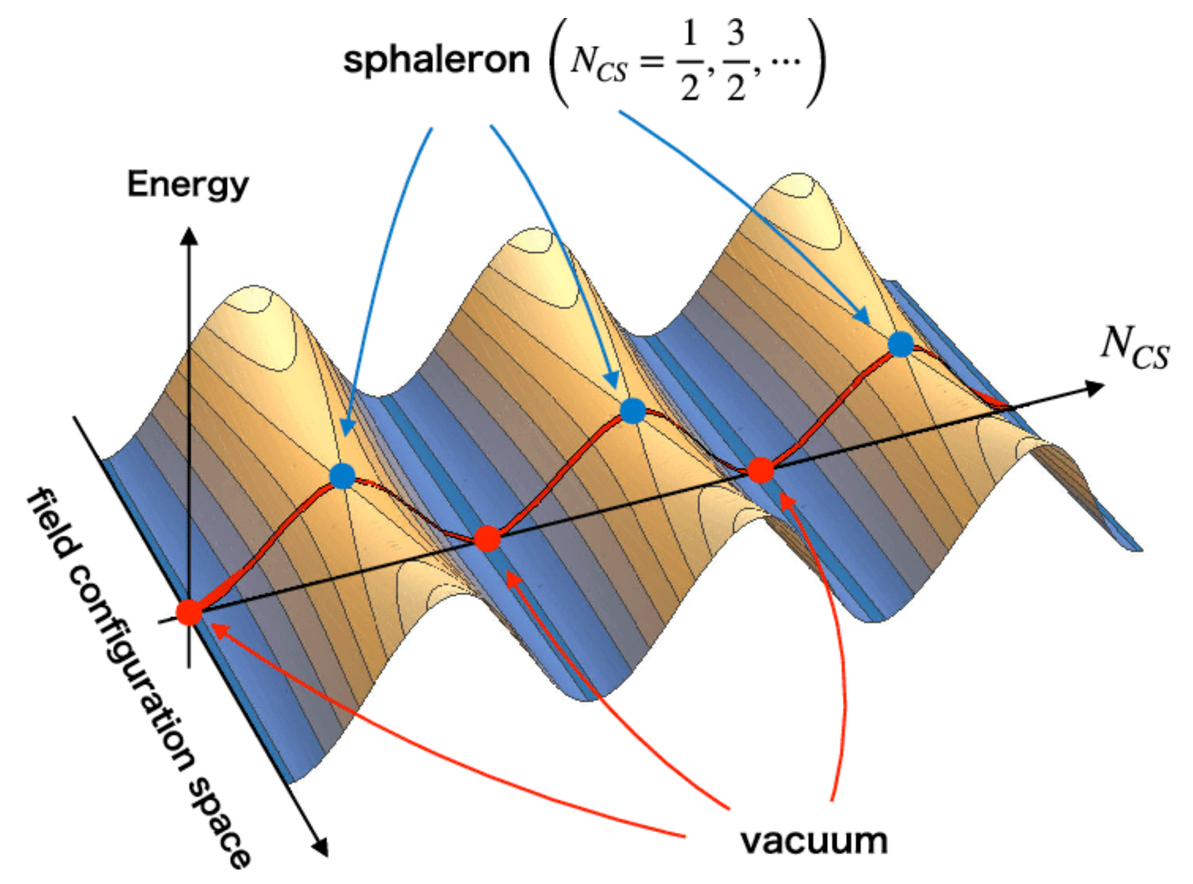


B-field limit

(Lines to guide the eye)

Current measurements provide tight constrains on the value of B at freeze out

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



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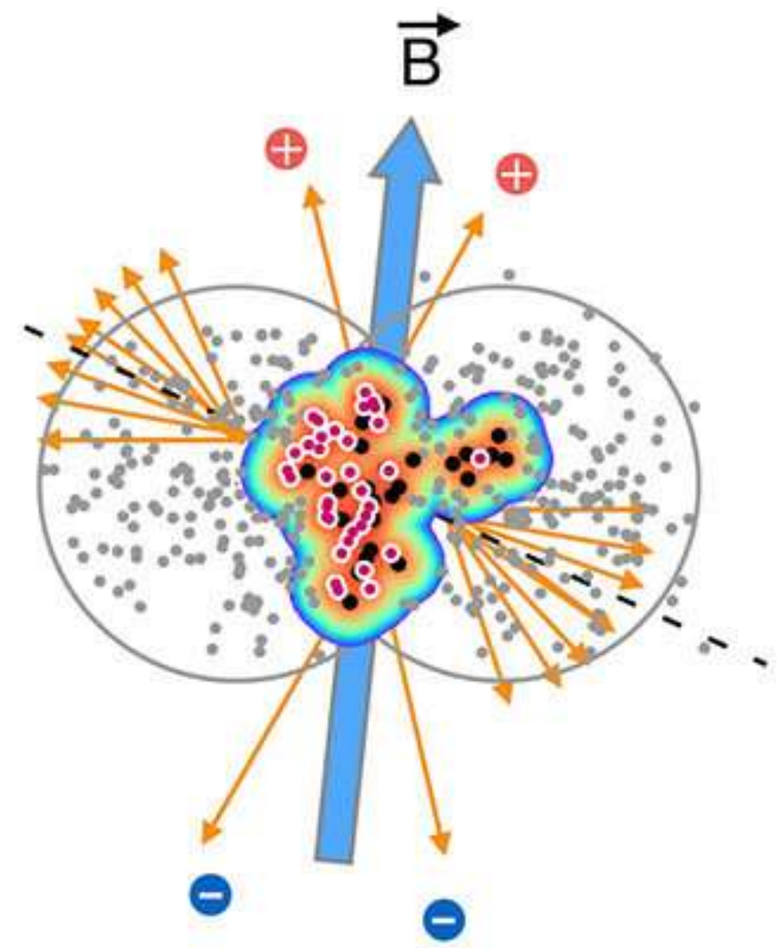

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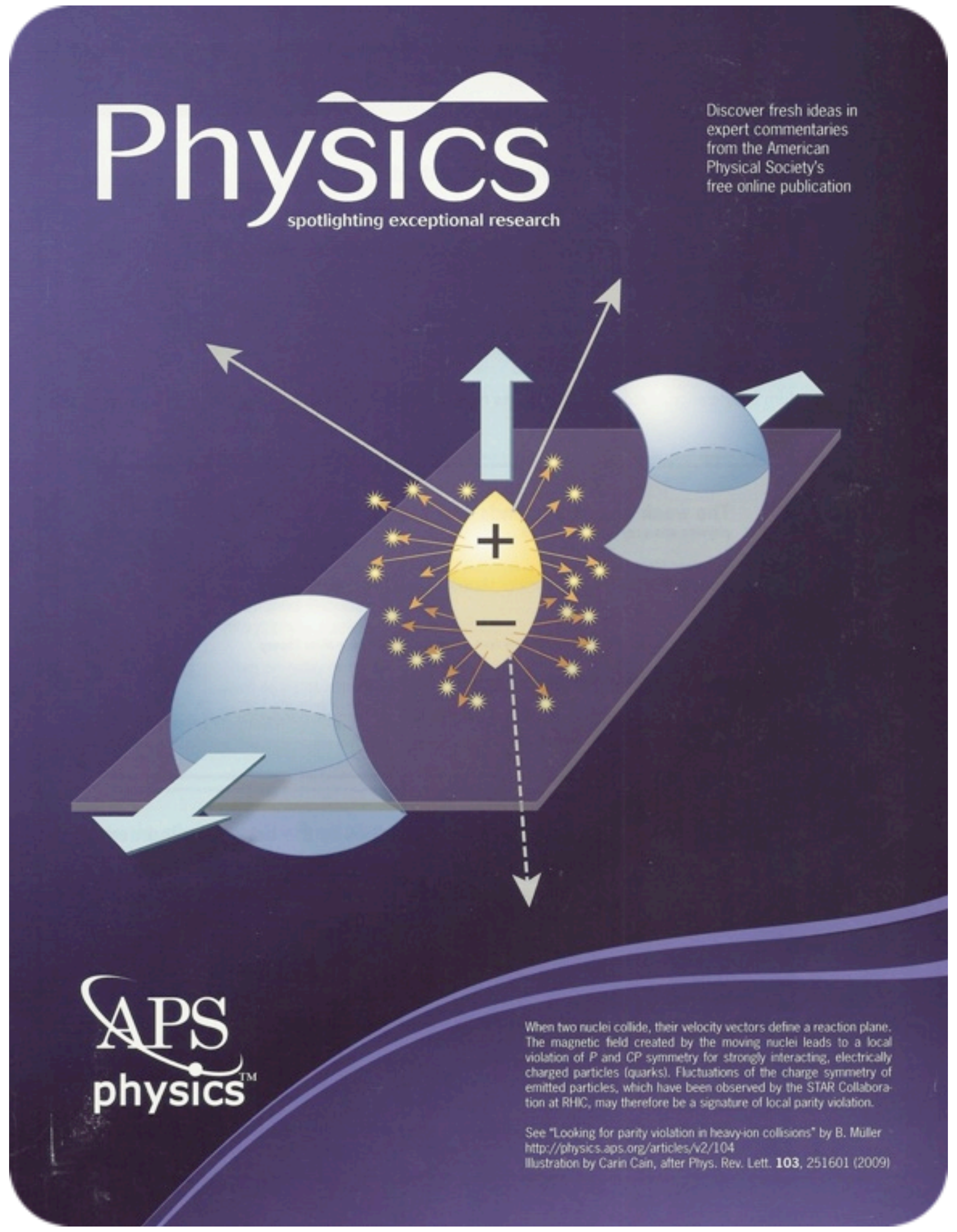

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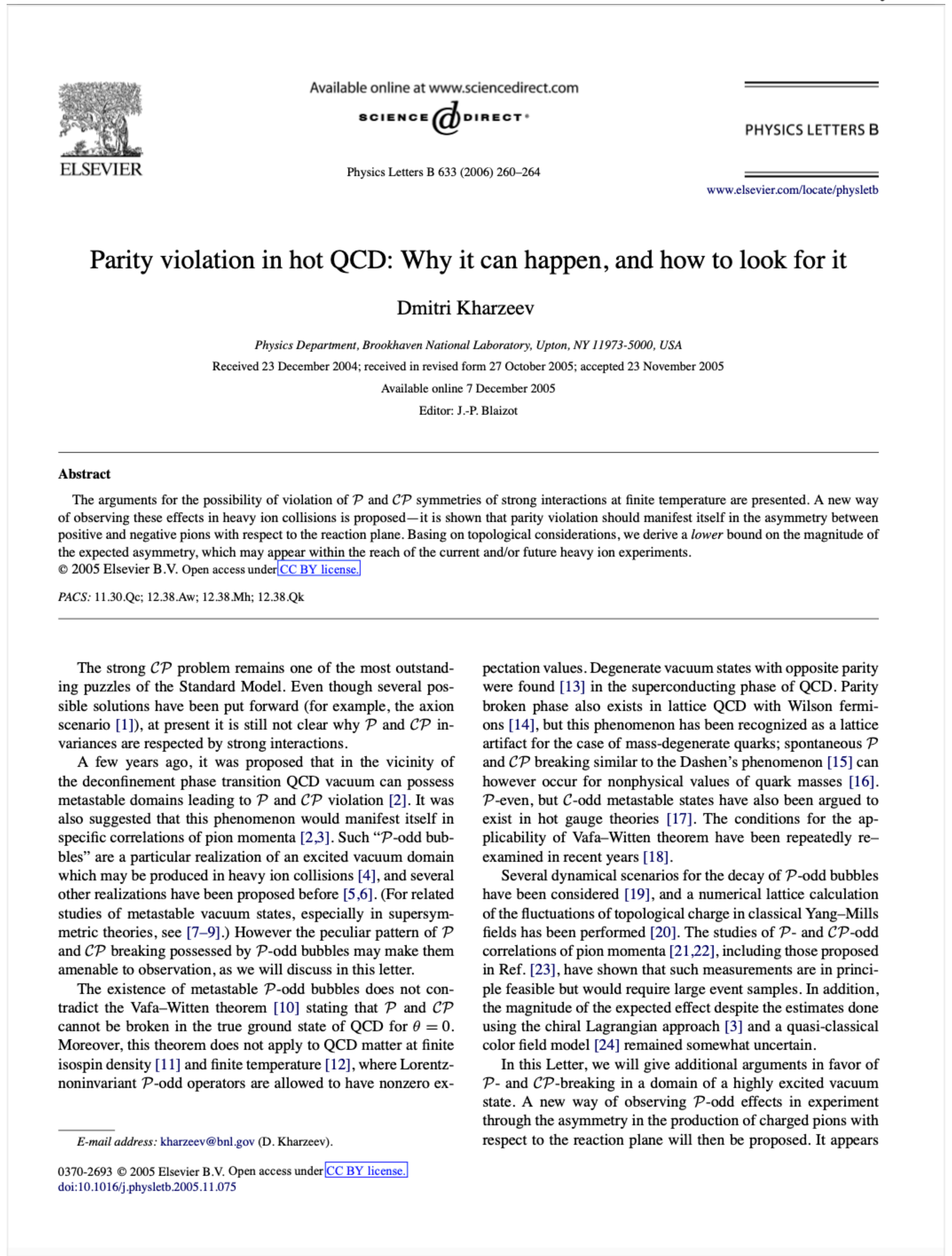
D. Kharzeev, Phys. Lett. B **633**, (2006) 260
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS

$$\frac{dN_{\pm}}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi_{\mathrm{RP}}) + 2v_2\cos[2(\varphi - \Psi_{\mathrm{RP}})] + \ldots$$

$$+2\alpha_{1,\pm}\sin(\varphi - \Psi_{\mathrm{RP}}) + \ldots$$

Chiral Magnetic Effect (CME)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Parity violation in hot QCD: Why it can happen, and how to look for it

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Editor: J.-P. Blaizot

Abstract

The arguments for the possibility of violation of $\mathcal{P}$ and $\mathcal{CP}$ symmetries of strong interactions at finite temperature are presented. A new way of observing these effects in heavy ion collisions is proposed—it is shown that parity violation should manifest itself in the asymmetry between positive and negative pions with respect to the reaction plane. Basing on topological considerations, we derive a *lower* bound on the magnitude of the expected asymmetry, which may appear within the reach of the current and/or future heavy ion experiments.

PACS: 11.30.Qc; 12.38.Aw; 12.38.Mh; 12.38.Qk

The strong $\mathcal{CP}$ problem remains one of the most outstanding puzzles of the Standard Model. Even though several possible solutions have been put forward (for example, the axion scenario [1]), at present it is still not clear why $\mathcal{P}$ and $\mathcal{CP}$ invariances are respected by strong interactions.

A few years ago, it was proposed that in the vicinity of the deconfinement phase transition QCD vacuum can possess metastable domains leading to $\mathcal{P}$ and $\mathcal{CP}$ violation [2]. It was also suggested that this phenomenon would manifest itself in specific correlations of pion momenta [2,3]. Such "$\mathcal{P}$-odd bubbles" are a particular realization of an excited vacuum domain which may be produced in heavy ion collisions [4], and several other realizations have been proposed before [5,6]. (For related studies of metastable vacuum states, especially in supersymmetric theories, see [7–9].) However the peculiar pattern of $\mathcal{P}$ and $\mathcal{CP}$ breaking possessed by $\mathcal{P}$-odd bubbles may make them amenable to observation, as we will discuss in this letter.

The existence of metastable $\mathcal{P}$-odd bubbles does not contradict the Vafa–Witten theorem [10] stating that $\mathcal{P}$ and $\mathcal{CP}$ cannot be broken in the true ground state of QCD for $\theta = 0$. Moreover, this theorem does not apply to QCD matter at finite isospin density [11] and finite temperature [12], where Lorentz-noninvariant $\mathcal{P}$-odd operators are allowed to have nonzero expectation values. Degenerate vacuum states with opposite parity were found [13] in the superconducting phase of QCD. Parity broken phase also exists in lattice QCD with Wilson fermions [14], but this phenomenon has been recognized as a lattice artifact for the case of mass-degenerate quarks; spontaneous $\mathcal{P}$ and $\mathcal{CP}$ breaking similar to the Dashen's phenomenon [15] can however occur for nonphysical values of quark masses [16]. $\mathcal{P}$-even, but $\mathcal{C}$-odd metastable states have also been argued to exist in hot gauge theories [17]. The conditions for the applicability of Vafa–Witten theorem have been repeatedly re–examined in recent years [18].

Several dynamical scenarios for the decay of $\mathcal{P}$-odd bubbles have been considered [19], and a numerical lattice calculation of the fluctuations of topological charge in classical Yang–Mills fields has been performed [20]. The studies of $\mathcal{P}$- and $\mathcal{CP}$-odd correlations of pion momenta [21,22], including those proposed in Ref. [23], have shown that such measurements are in principle feasible but would require large event samples. In addition, the magnitude of the expected effect despite the estimates done using the chiral Lagrangian approach [3] and a quasi-classical color field model [24] remained somewhat uncertain.

In this Letter, we will give additional arguments in favor of $\mathcal{P}$- and $\mathcal{CP}$-breaking in a domain of a highly excited vacuum state. A new way of observing $\mathcal{P}$-odd effects in experiment through the asymmetry in the production of charged pions with respect to the reaction plane will then be proposed. It appears

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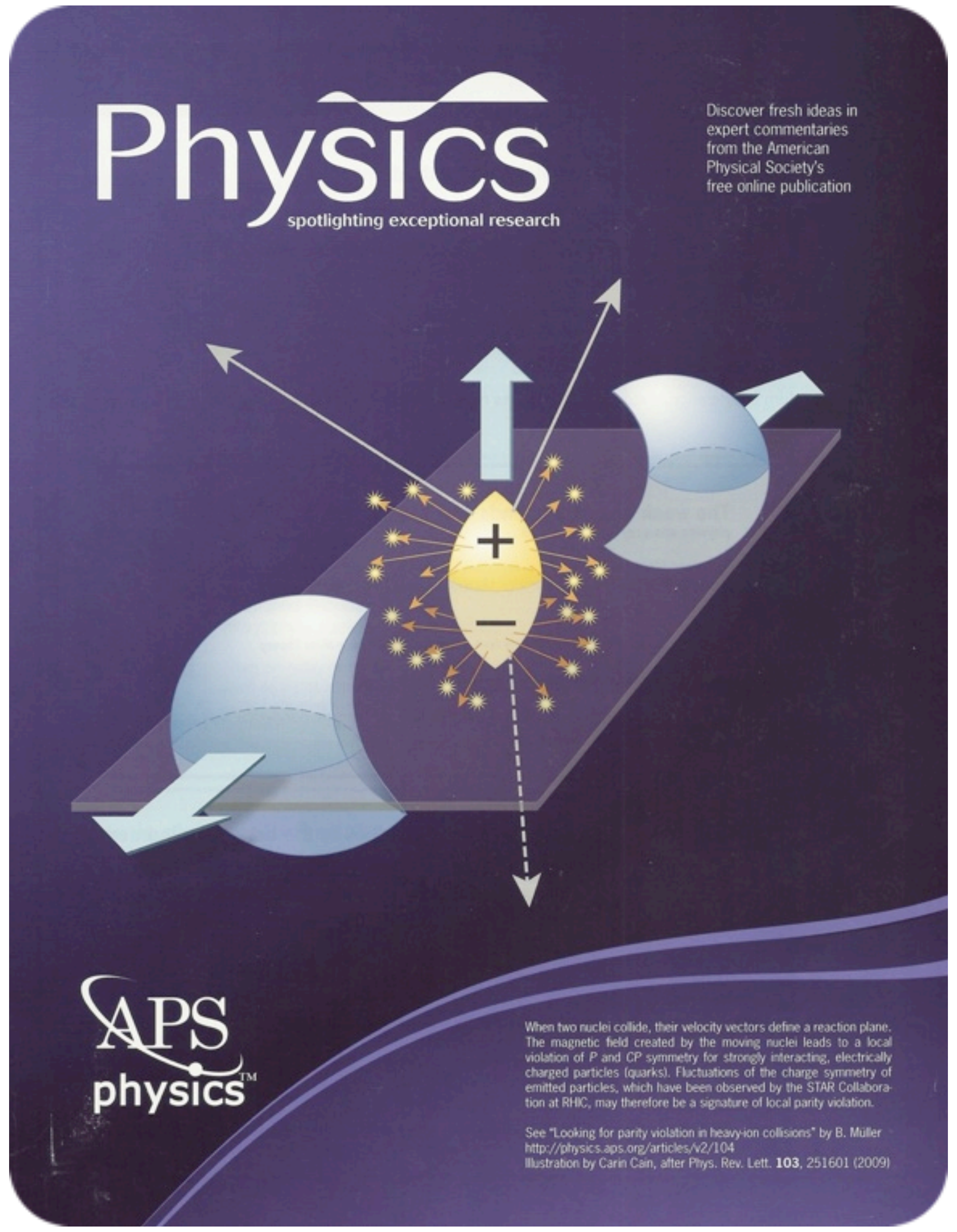
doi:10.1016/j.physletb.2005.11.075

Average over many events:

$$\langle a_{1,+}\rangle = \langle a_{1,-}\rangle = \langle \sin(\varphi - \Psi_{\mathrm{RP}})\rangle = 0$$

Instead measure correlations over many events:

$$\langle a_{1,\alpha}a_{1,\beta}\rangle = \langle \sin(\varphi_\alpha - \Psi_{\mathrm{RP}})\sin(\varphi_\beta - \Psi_{\mathrm{RP}})\rangle$$



D. Kharzeev *et al.*, Phys. Rev. Lett. **81**, (1998) 512
D. Kharzeev, Phys. Lett. B **633**, (2006) 260
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

HOW DO WE TRY TO DETECT IT?

S. Voloshin, Phys. Rev. **C70**, (2004) 057901

$$\gamma_{a,\beta} \equiv \langle \cos(\varphi_a + \varphi_\beta - 2\Psi_{\mathrm{RP}}) \rangle =$$
$$\langle \cos[(\varphi_a - \Psi_{\mathrm{RP}}) + (\varphi_\beta - \Psi_{\mathrm{RP}})] \rangle =$$
$$\langle \cos(\Delta\varphi_a + \Delta\varphi_\beta) \rangle =$$
$$\langle \cos(\Delta\varphi_a)\cos(\Delta\varphi_\beta) \rangle - \langle \sin(\Delta\varphi_a)\sin(\Delta\varphi_\beta) \rangle =$$
$$\langle v_{1,a} v_{1,\beta} \rangle + \mathrm{B_{in}} - \langle \alpha_{1,a}\alpha_{1,\beta} \rangle - \mathrm{B_{out}}$$

$$\delta_{a,\beta} \equiv \langle \cos(\varphi_a - \varphi_\beta) \rangle =$$
$$\langle \cos[(\varphi_a - \Psi_{\mathrm{RP}}) - (\varphi_\beta - \Psi_{\mathrm{RP}})] \rangle =$$
$$\langle \cos(\Delta\varphi_a - \Delta\varphi_\beta) \rangle =$$
$$\langle \cos(\Delta\varphi_a)\cos(\Delta\varphi_\beta) \rangle + \langle \sin(\Delta\varphi_a)\sin(\Delta\varphi_\beta) \rangle =$$
$$\langle v_{1,a} v_{1,\beta} \rangle + \mathrm{B_{in}} + \langle \alpha_{1,a}\alpha_{1,\beta} \rangle + \mathrm{B_{out}}$$

Parity violation in hot QCD: how to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201
(Dated: November 2, 2018)

In a recent paper (arXive:hep-ph/0406125) entitled *Parity violation in hot QCD: why it can happen, and how to look for it*, D. Kharzeev argues for the possibility of $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in $\pi^\pm$ production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

PACS numbers: 11.30.Qc, 12.38.Qk, 25.75.Ld, 25.75.Nq

The possibility of strong $\mathcal{P}$- and $\mathcal{CP}$-violation in heavy ion collisions has been proposed first in [1]. Different experimental observables sensitive to the presence of $\mathcal{P}$- and/or $\mathcal{CP}$-odd domains in the deconfined QCD vacuum have been already discussed in the original papers and later in [2, 3]. Remarkably, all the observables which have been discussed are related in smaller or larger extent to the anisotropic flow study efforts. In general, $\mathcal{P}$- and $\mathcal{CP}$-symmetry violation effects proposed in [1] manifest itself via a non-statistical difference of the reaction planes reconstructed using different groups of particles, either of different charge, or in different kinematic regions. In symmetric nuclear collision (only those are discussed in this note) there should be only one plane of symmetry, and therefore any observation of the opposite would mean $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects. Interestingly, many of the 'symmetry sensitive' quantities are routinely calculated in flow analyses for 'quality assurance' purposes (checking analysis consistency). No deviation from expectations based on symmetry with respect to the reaction plane has been observed so far.

However, refs. [1, 2, 3] do not discuss one important case, namely the possibility of preferential emission of particle/antiparticle, e.g. $\pi^\pm$, into opposite sides of the reaction plane. This happens to be exactly the observable signal of the $\mathcal{P}$- and $\mathcal{CP}$-breaking mechanism discussed by Kharzeev in his recent preprint [4]. Kharzeev argues that due to the parity violating interactions, the asymmetry in pion production along the direction of the system angular momentum (perpendicular to the reaction plane) could be as high as of the order of one percent in midcentral Au+Au collisions at RHIC. The orientation of the asymmetry (parallel or anti-parallel to the direction of the angular momentum) can change from event to event, and therefore the effect can be detected only by correlation study.

In this short note we propose to use for that purpose a technique that is well known in anisotropic flow analysis and usually referred to as mixed harmonics technique [5] or three particle correlations [6]. The essence of this technique is just in the isolation of correlations related to a given direction. Suppose that positive pions are emitted preferentially in positive y direction (along the angular momentum). The azimuthal distribution in this case can be written as $dN/d\phi \propto (1 + 2a\sin(\phi))$, where ϕ is the particle emission azimuthal angle relative to the reaction plane (Ψ_{RP}), and the parameter a can be directly related to the asymmetry in pion production discussed in [4]: $A_{\pi^+} = \pi a/4 \approx Q/N_{\pi^+}$. In the latter expression Q is the topological charge ($Q \geq 1$) and N_{π^+} is the pion multiplicity in about one unit of rapidity [4]. For midcentral Au+Au collisions at RHIC $N_{\pi^+} \sim 100$ and these estimates yield a low limit on a of the order of one percent. Let us consider azimuthal correlation between particles a and b by evaluating the quantity

$$\begin{aligned} &\langle \cos(\phi_a - \Psi_2)\cos(\phi_b - \Psi_2) \\ &\qquad - \sin(\phi_a - \Psi_2)\sin(\phi_b - \Psi_2) \rangle \\ &= \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle = (v_{1,a}v_{1,b} - a_a a_b)\,\langle \cos(2\Psi_2) \rangle \end{aligned} \quad (1)$$

where the average is taken over events, Ψ_2 is the second harmonic event plane, $\langle \cos(\Psi_2 - \Psi_{RP}) \rangle$ is the so called event plane resolution (how well on average one reconstructs the reaction plane from elliptic flow; for details see [5]). The final expression reflects the correlations along the two axes, one in the reaction plane (directed flow, characterized by $\langle \cos(\phi - \Psi_{RP}) \rangle \equiv v_1$) and perpendicular to the reaction plane – the manifestation of symmetry breaking discussed in [4]. All other correlations, being not sensitive to the orientation of the reaction plane, cancel out (for the systematic uncertainty in this statement see [6, 7] and discussion below). The proportionality to the reaction plane resolution reflects a decrease in correlations due to finite ability to resolve the true reaction plane orientation. If only one particle is used to determine the event plane the equation reduces to

$$\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle = (v_{1,a}v_{1,b} - a_a a_b)\, v_{2,c}, \quad (2)$$

where the typical values of the parameter $v_{2,c}$, elliptic flow of particle of type c, is of the order of 0.04–0.05 for midcentral collisions. Equations (1) and (2) are usually employed for directed flow study [5, 6, 7]. The main advantage of these observables is their sensitivity to correlations in particle production along a given direction. As already discussed above, these observables represent the difference in correlations along the x and y axes, therefore any correlations that do not depend on the orientation with respect to the reaction plane cancel out. If

HOW DO WE TRY TO DETECT IT?

S. Voloshin, Phys. Rev. **C70**, (2004) 057901

$$\gamma_{a,\beta} \equiv \langle \cos(\varphi_a + \varphi_\beta - 2\Psi_{\mathrm{RP}}) \rangle =$$
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Parity conserving background effects projected in and out of plane

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Parity violation in hot QCD: how to detect it

Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201
(Dated: November 2, 2018)

In a recent paper (arXive:hep-ph/0406125) entitled *Parity violation in hot QCD: why it can happen, and how to look for it*, D. Kharzeev argues for the possibility of $\mathcal{P}$- and/or $\mathcal{CP}$- violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in $\pi^\pm$ production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

PACS numbers: 11.30.Qc, 12.38.Qk, 25.75.Ld, 25.75.Nq

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Theory expectations (signal)

$$a_1 \propto \frac{Q}{N_{\mathrm{ch.}}} \simeq 10^{-2}$$

$$\langle a_{1,\alpha} a_{1,\beta} \rangle \simeq 10^{-4}$$

$$\langle a_{1,+} a_{1,+} \rangle \simeq \langle a_{1,-} a_{1,-} \rangle \simeq -\langle a_{1,+} a_{1,-} \rangle$$

$$\langle a_{1,\alpha} a_{1,\beta} \rangle (\mathrm{centrality}) \simeq \frac{f(\mathrm{B})}{N_{\mathrm{ch}}}$$

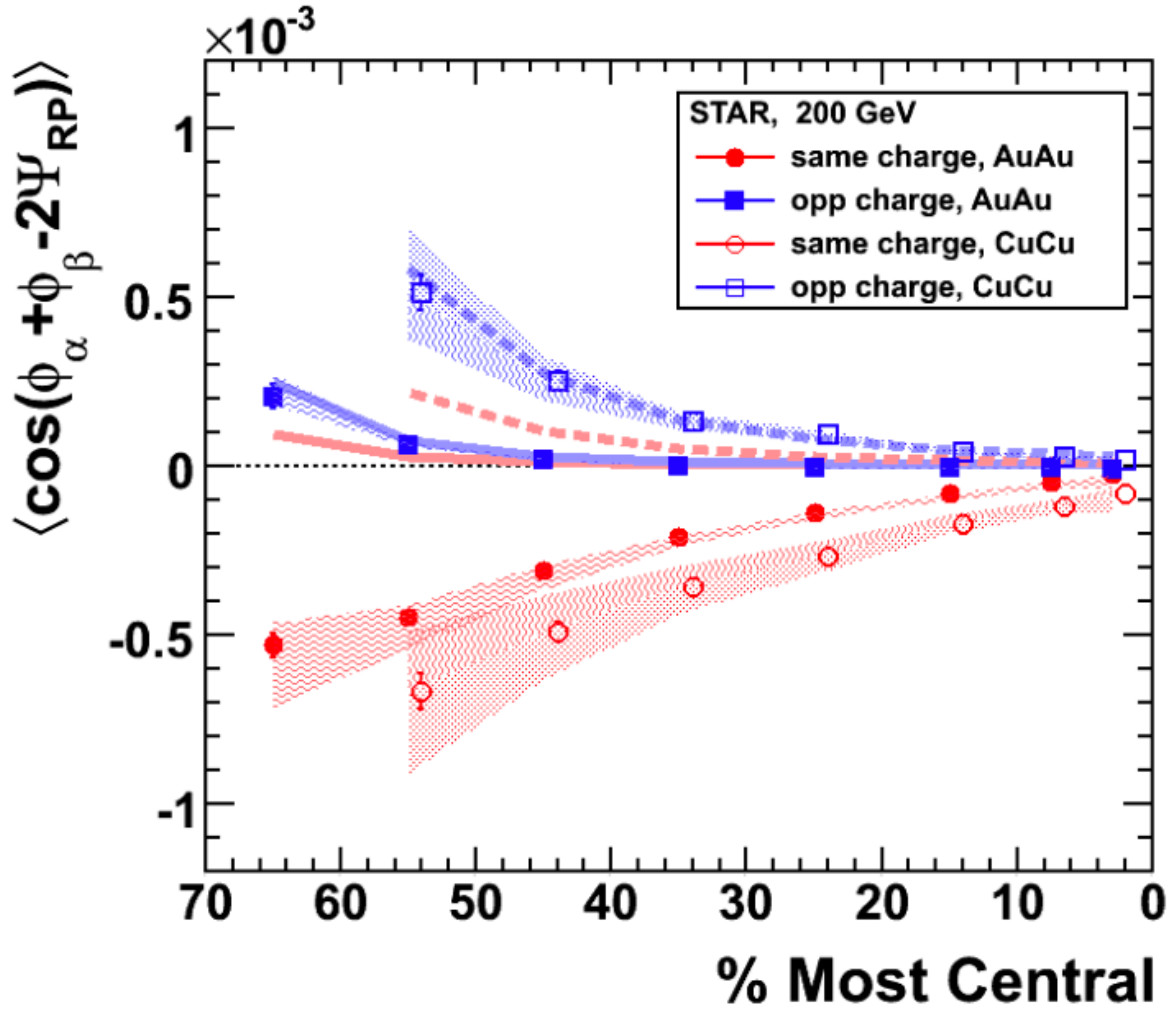
Theory expectations (bkg)

$$\mathrm{B_{in}} - \mathrm{B_{out}} \propto v_{2,\mathrm{cluster}} \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\mathrm{cluster}}) \rangle$$

Background suppressed by a factor of $v_2 \sim 0.1$

FIRST EXPERIMENTAL RESULTS @ RHIC

(STAR Collaboration), Phys. Rev. Lett. **103**, 251601 (2009)



Significant charge dependent correlations measured for the first time at RHIC

Qualitatively consistent with initial expectations for a small CME signal

System size dependence consistent with the dilution (N_{ch}) picture

FIRST LHC RESULTS

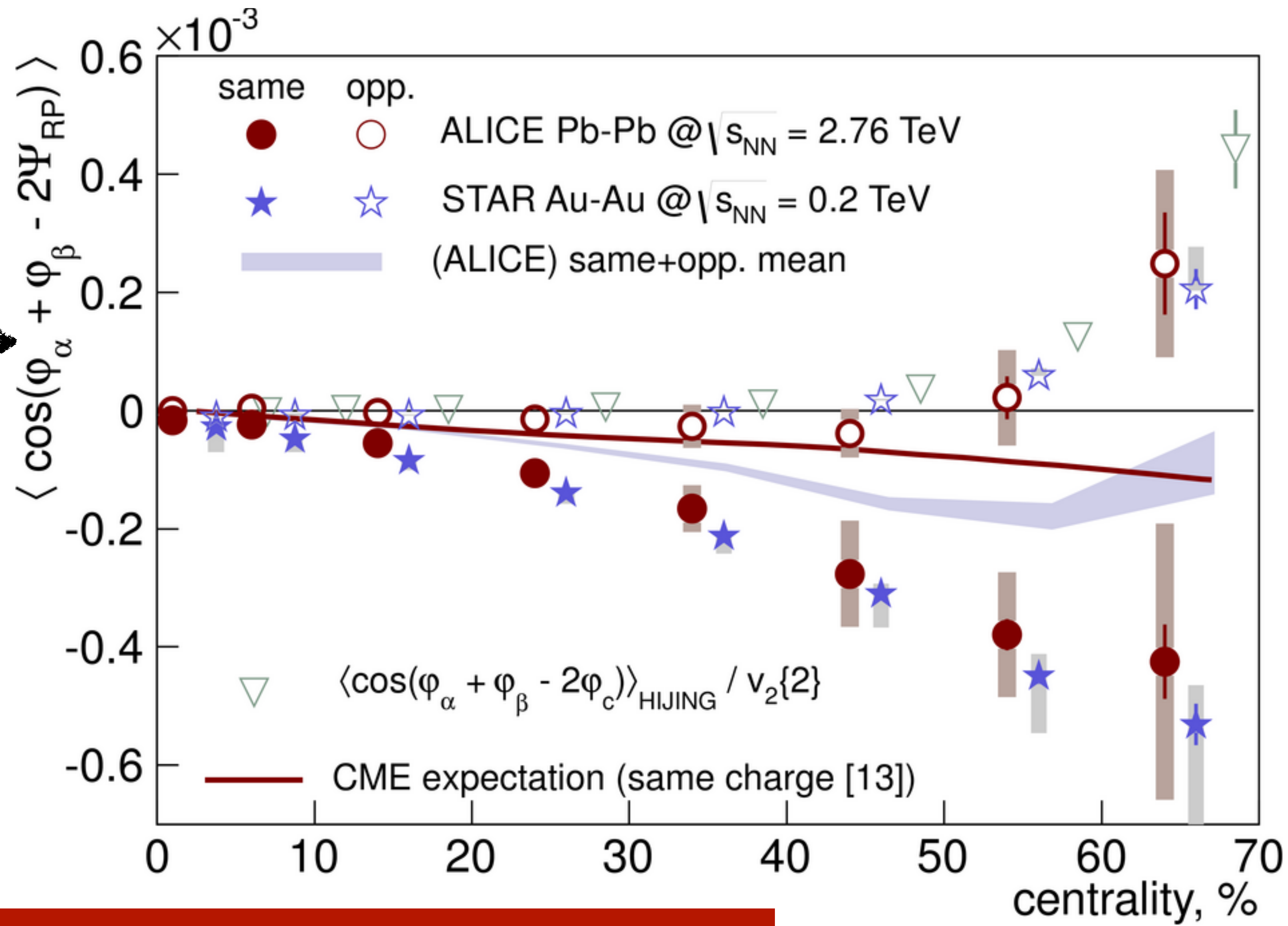
Goal: disentangle the CME signal from the background

(ALICE Collaboration), Phys. Rev. Lett. **110** (2013) 012301

Strong centrality dependent effects consistent with naive expectations from CME

- But no significant energy dependence between RHIC and LHC

$\gamma_{1,1}$

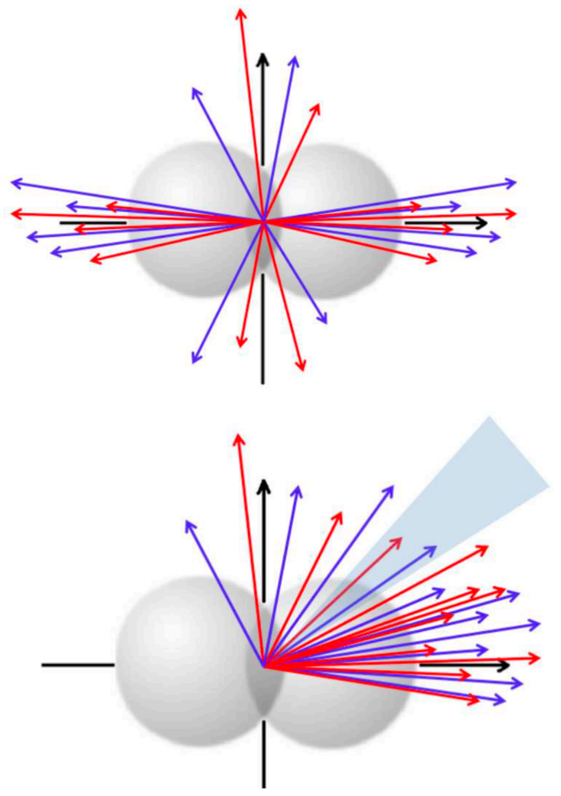


The agreement was a big surprise considering the difference in energy, particle density,…

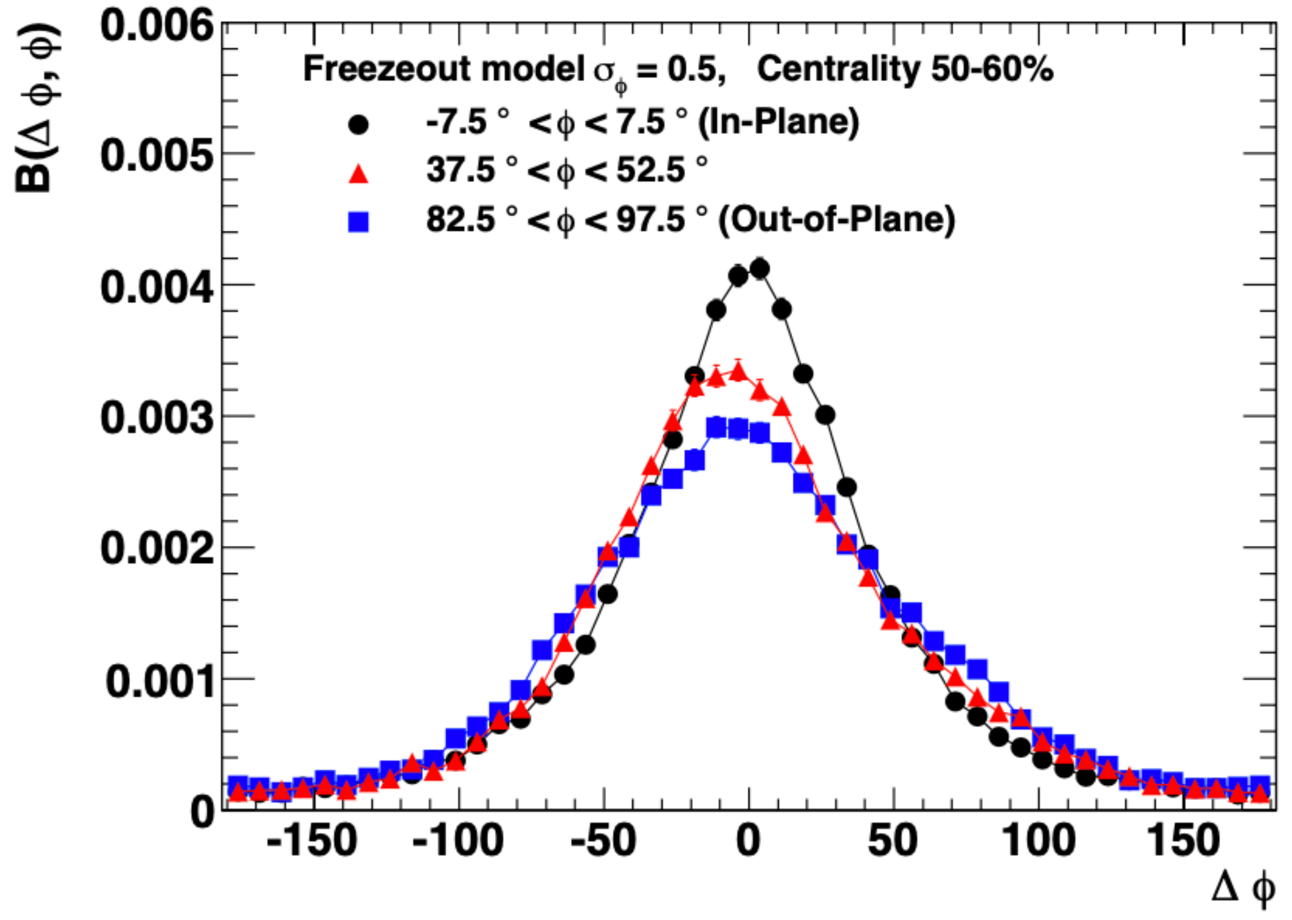
Panos.Christakoglou@nikhef.nl

IDENTIFYING BACKGROUND EFFECTS

S. Voloshin, Phys. Rev. **C70**, (2004) 057901



"Flowing clusters"



S. Schlichting and S. Pratt Phys.Rev. C83 (2011) 014913

v_2 C_B: more balancing pairs in-plane than out-of-plane

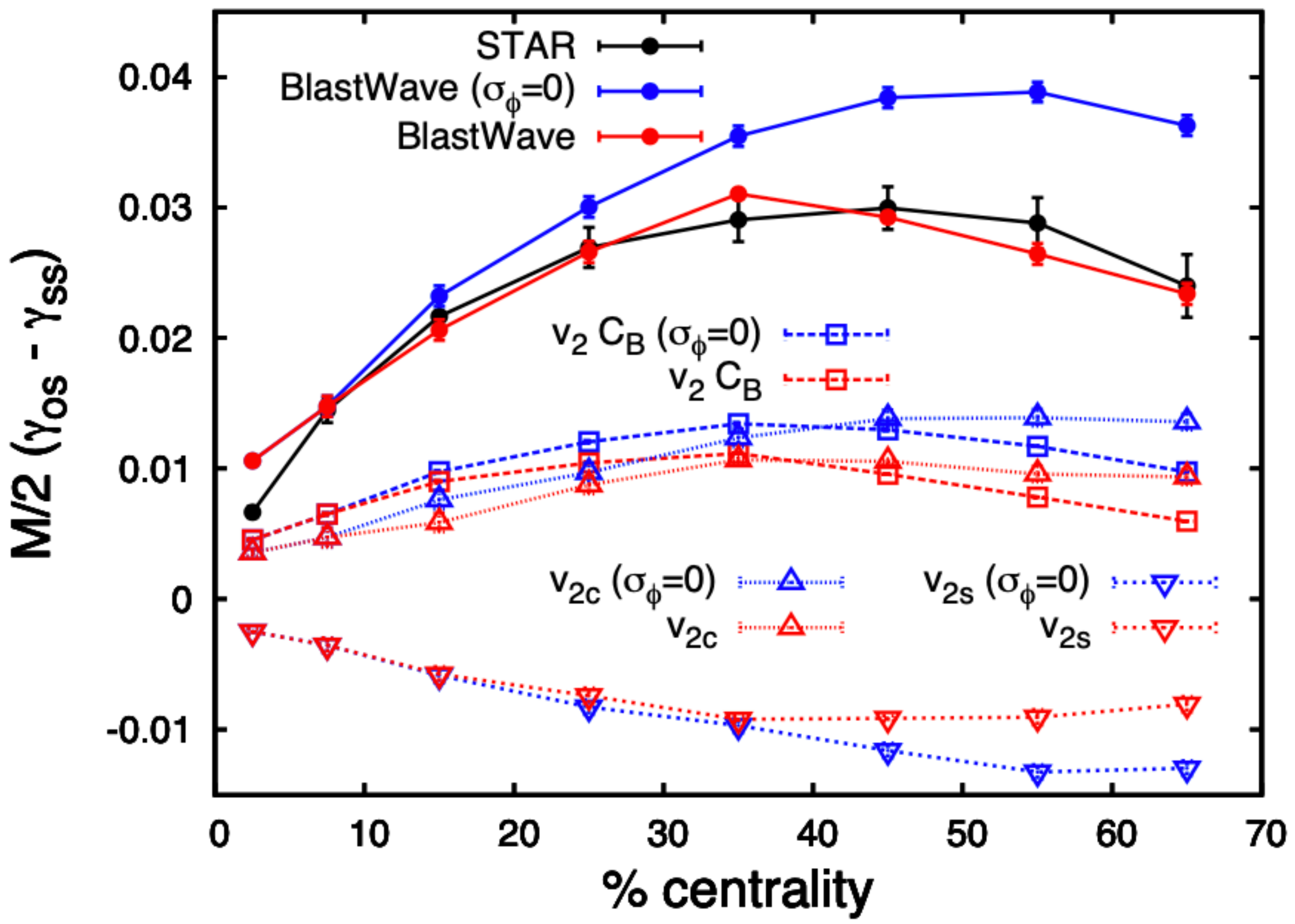
$v_{2,c}$: degree to which in-plane pairs are more tightly correlated than out-of-plane pairs

$v_{2,s}$: balancing charge is more likely to be found toward the event plane.

Main background component:

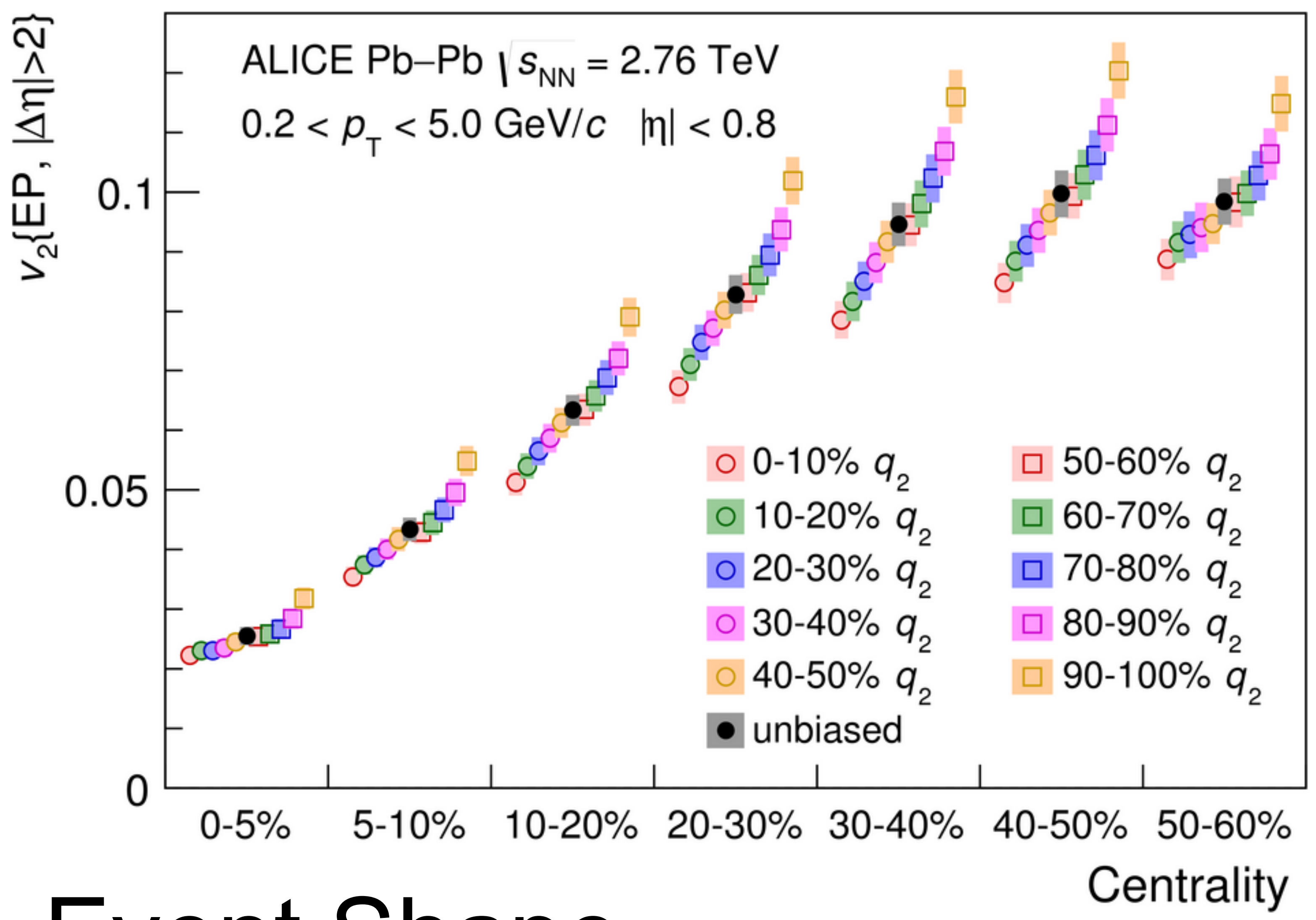
- Local charge conservation (LCC) coupled to anisotropic flow

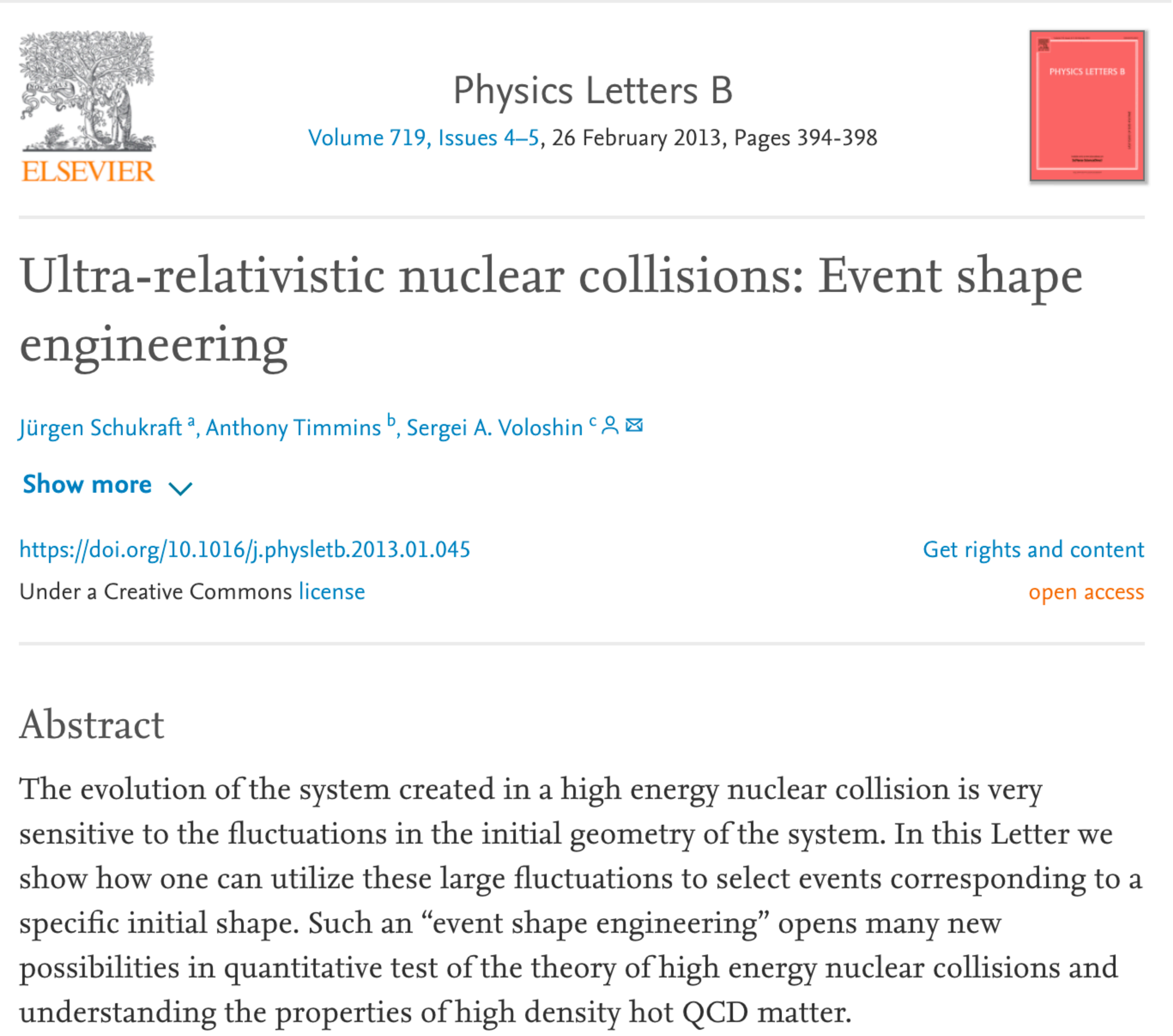
A simple BW model + LCC can provide a qualitative description of some of the systematics of the measurement of $\Delta\gamma_{11}$



FIRST CME LIMITS @ LHC WITH ESE

(ALICE Collaboration) Phys. Lett. **B777**, (2018) 151





Physics Letters B

Volume 719, Issues 4–5, 26 February 2013, Pages 394-398

Ultra-relativistic nuclear collisions: Event shape engineering

Jürgen Schukraft [a], Anthony Timmins [b], Sergei A. Voloshin [c]

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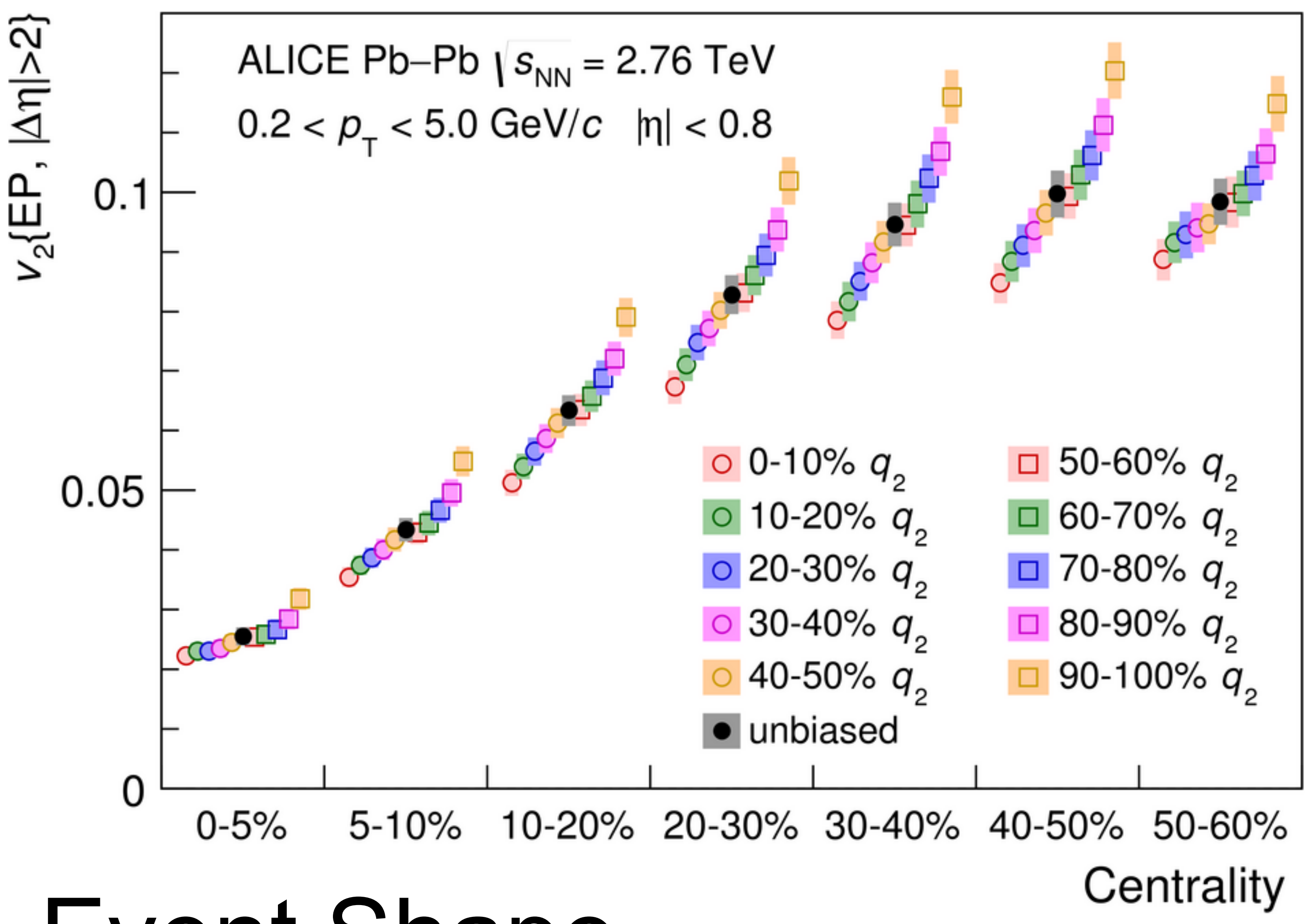
Abstract

The evolution of the system created in a high energy nuclear collision is very sensitive to the fluctuations in the initial geometry of the system. In this Letter we show how one can utilize these large fluctuations to select events corresponding to a specific initial shape. Such an "event shape engineering" opens many new possibilities in quantitative test of the theory of high energy nuclear collisions and understanding the properties of high density hot QCD matter.

Event Shape Engineering(ESE) allows you to select events by "dialling in" the amount of v_2 they have within the same centrality

FIRST CME LIMITS @ LHC WITH ESE

(ALICE Collaboration) Phys. Lett. **B777**, (2018) 151



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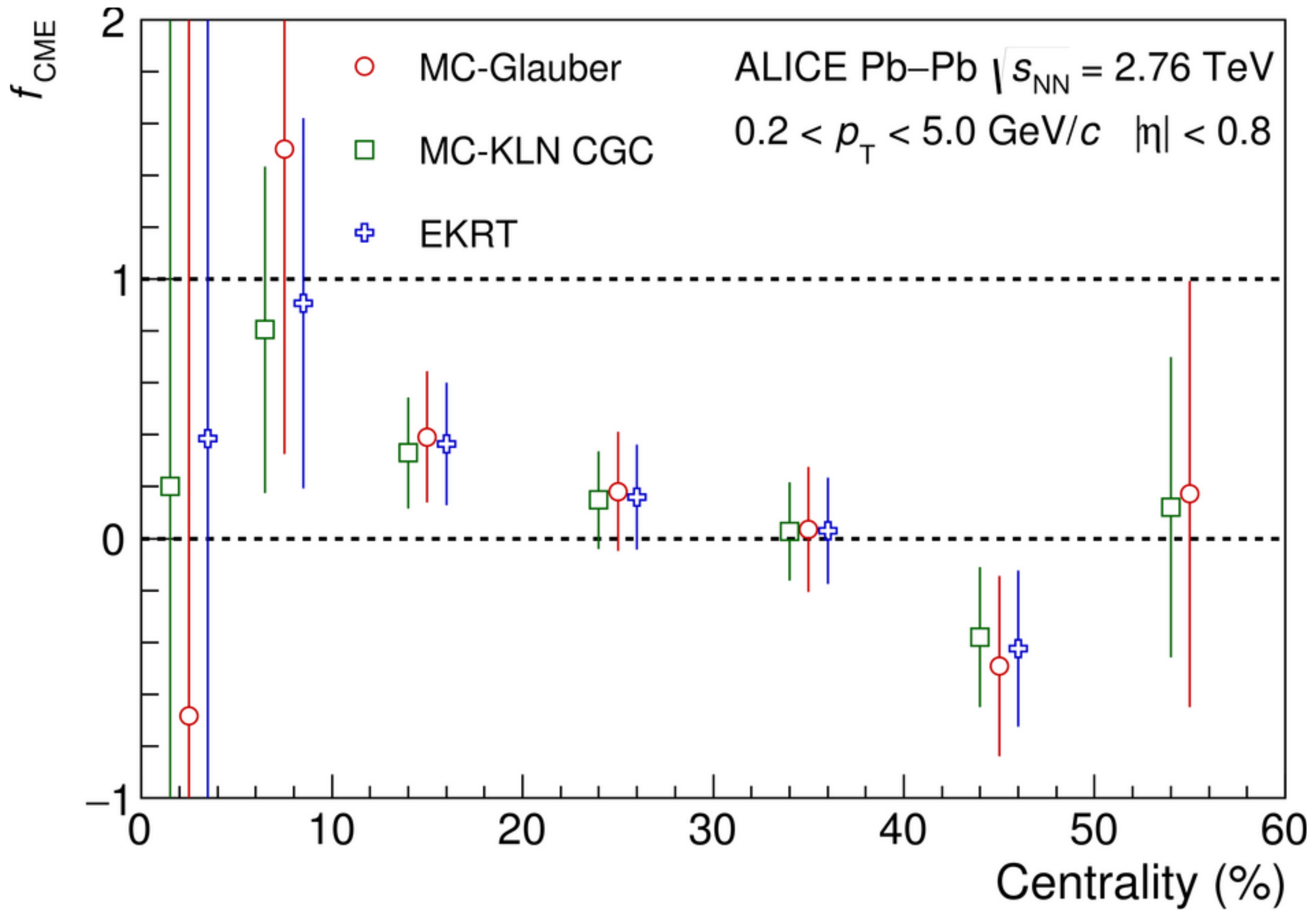
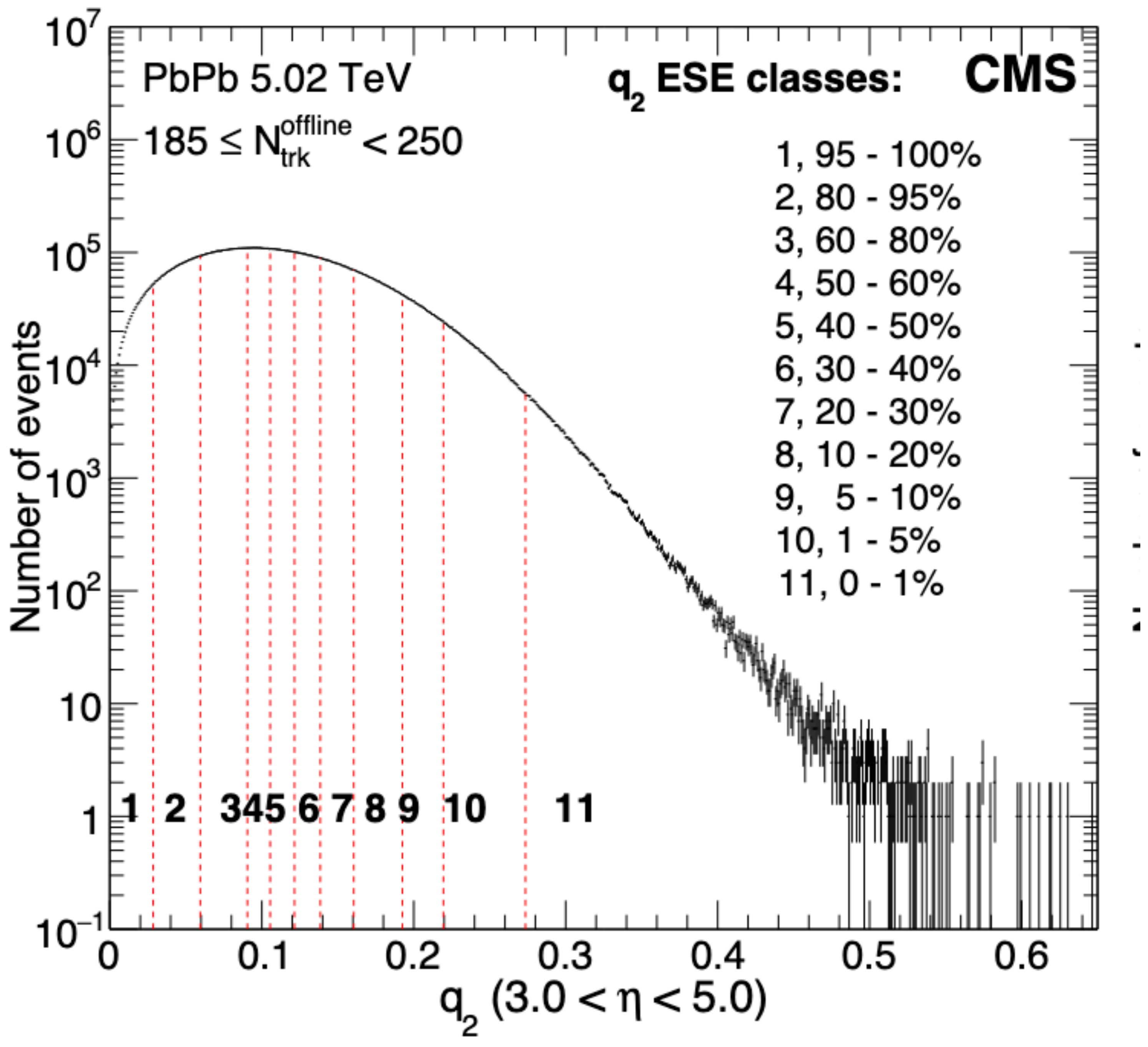


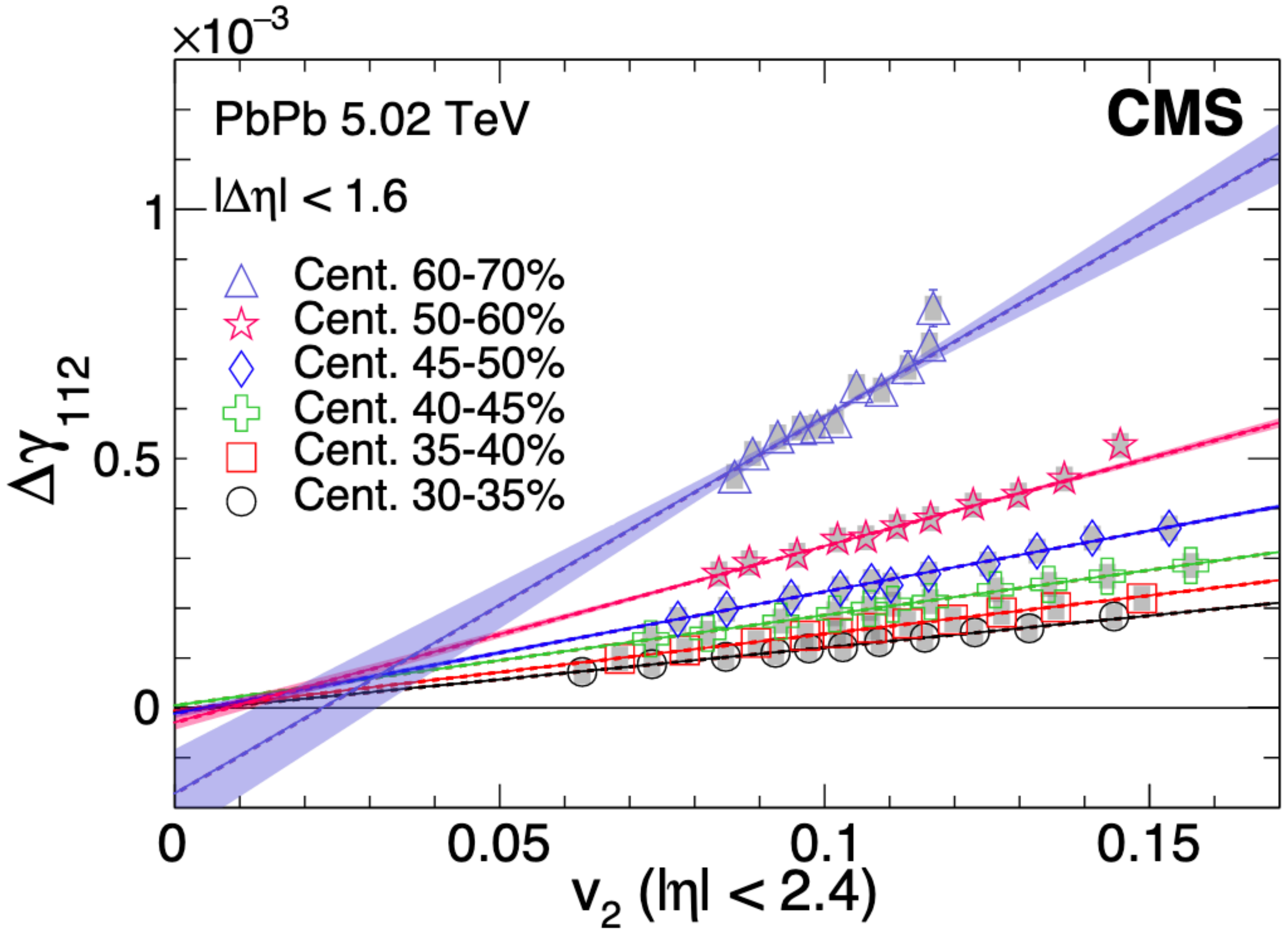
Upper limit on the CME fraction for the 10-50% centrality interval:

- 26-33% at 95% C.L. depending on models of initial state

CME LIMITS WITH ESE (CMS)

(CMS Collaboration) Phys.Rev.C 97 (2018) 4, 044912





Upper limit on the CME fraction for Pb-Pb collisions ~7% @ 95% CL

- Based on the assumption of a CME signal independent of v_2 in a narrow multiplicity or centrality range

ISOBAR STUDIES @ RHIC

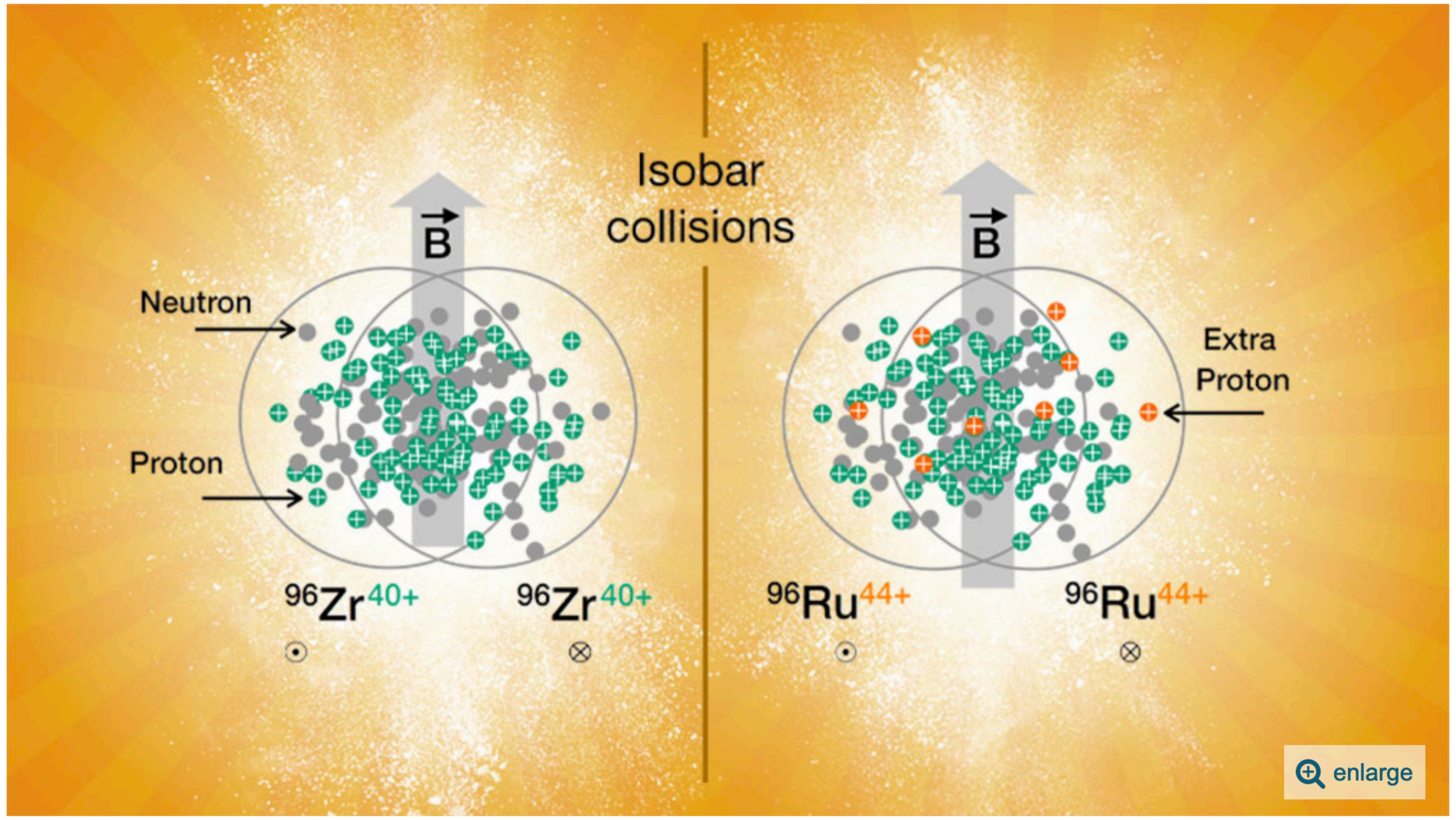
S. Voloshin Phys. Rev. Lett. 105, 172301

(STAR Collaboration) Nucl.Sci.Tech. 32 (2021) 5, 48

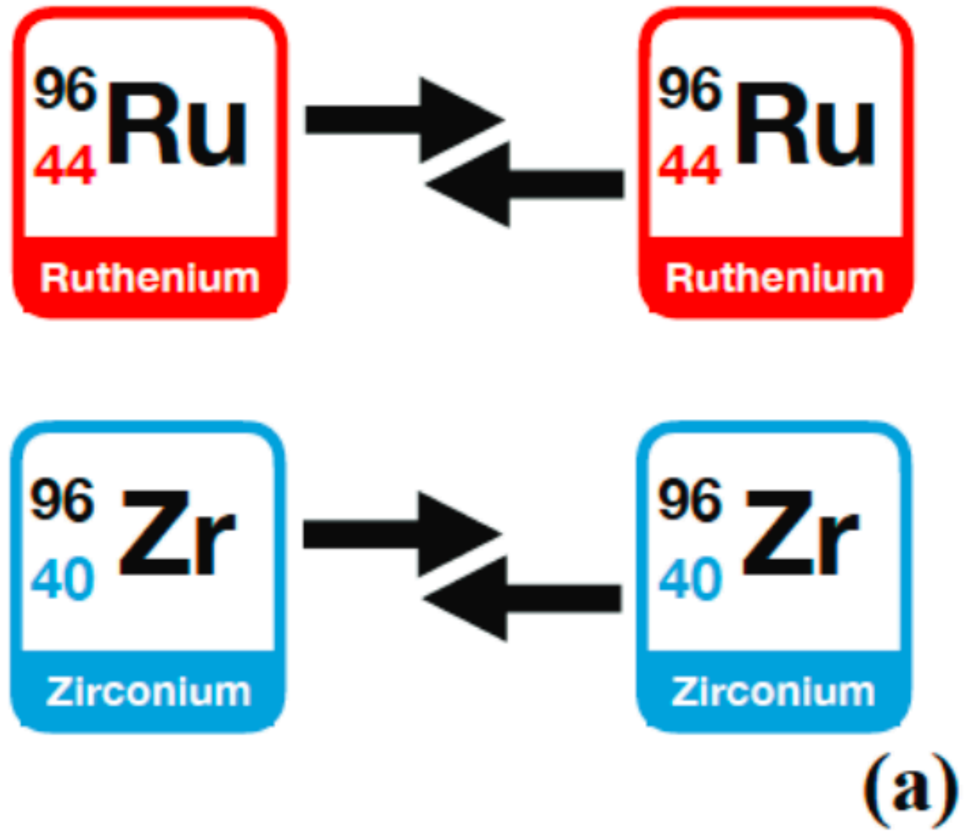
Results from Search for 'Chiral Magnetic Effect' at RHIC

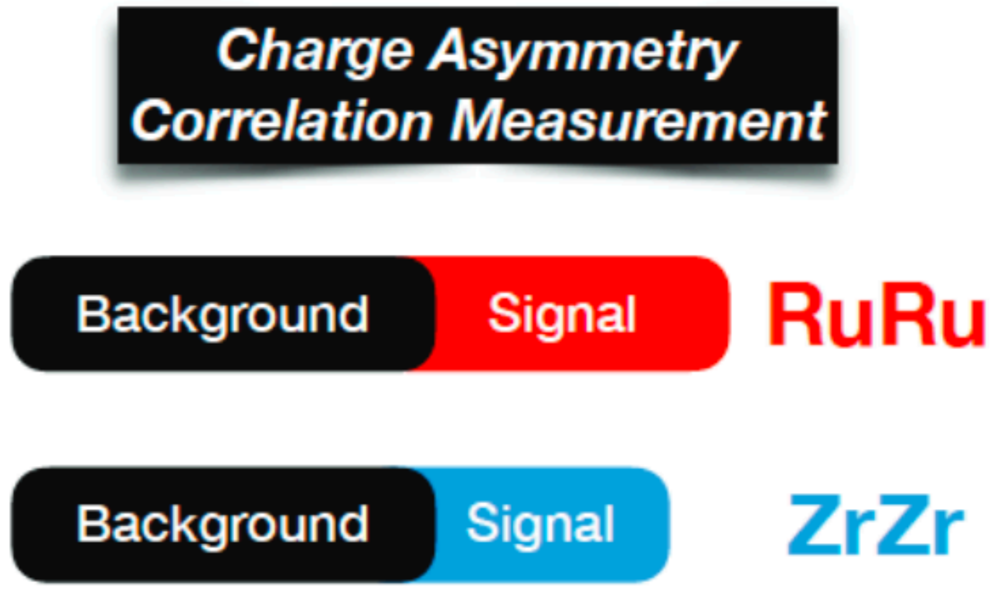
Collisions of 'isobars' test effect of magnetic field, searching for signs of a broken symmetry

August 31, 2021



Physicists compared collisions of two different sets of isobars, which are ions that have the same overall mass but different numbers of protons —zirconium (^{96}Zr), with 40 protons, and ruthenium (^{96}Ru) with 44 protons. The higher proton number (and thus electric charge) in ruthenium should generate a stronger magnetic field during collisions than zirconium (indicated by size of gray arrows). Scientists expected the stronger magnetic field of ruthenium collisions to result in greater separation of charged particles emerging from those collisions than seen in zirconium collisions.





Expectations

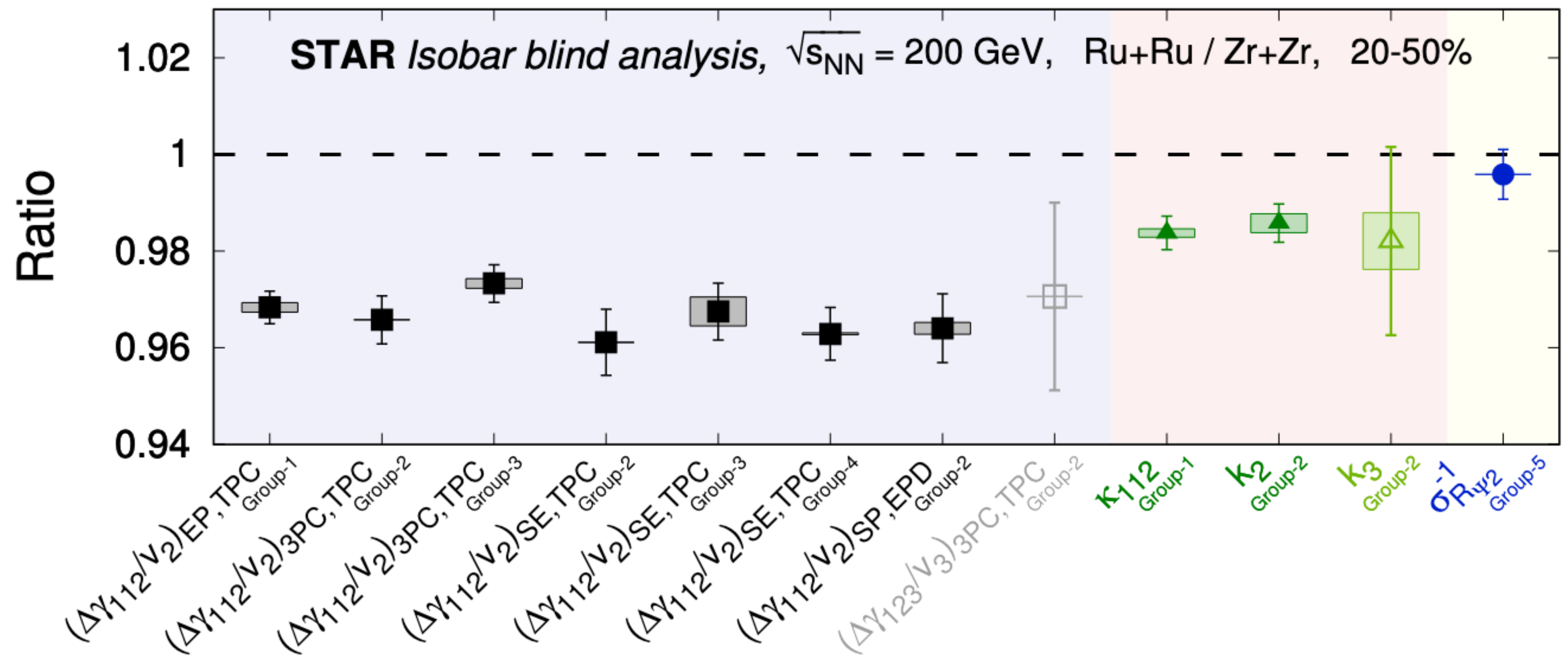
- Signal scales with B
  - CME signal larger in Ru
- Background scales with multiplicity and v_2
  - Background similar in both systems

$$\frac{\left(\frac{\Delta\gamma}{v_2}\right)_{\mathrm{RuRu}}}{\left(\frac{\Delta\gamma}{v_2}\right)_{\mathrm{ZrZr}}} > 1$$

Nikhef

ISOBAR STUDIES @ RHIC

(STAR Collaboration) *Phys.Rev.C* 105 (2022) 1, 014901



None of the analyses fulfil the predefined criteria

$$\frac{\left(\frac{\Delta\gamma}{v_2}\right)_{\mathrm{RuRu}}}{\left(\frac{\Delta\gamma}{v_2}\right)_{\mathrm{ZrZr}}} > 1$$

ISOBAR STUDIES @ RHIC

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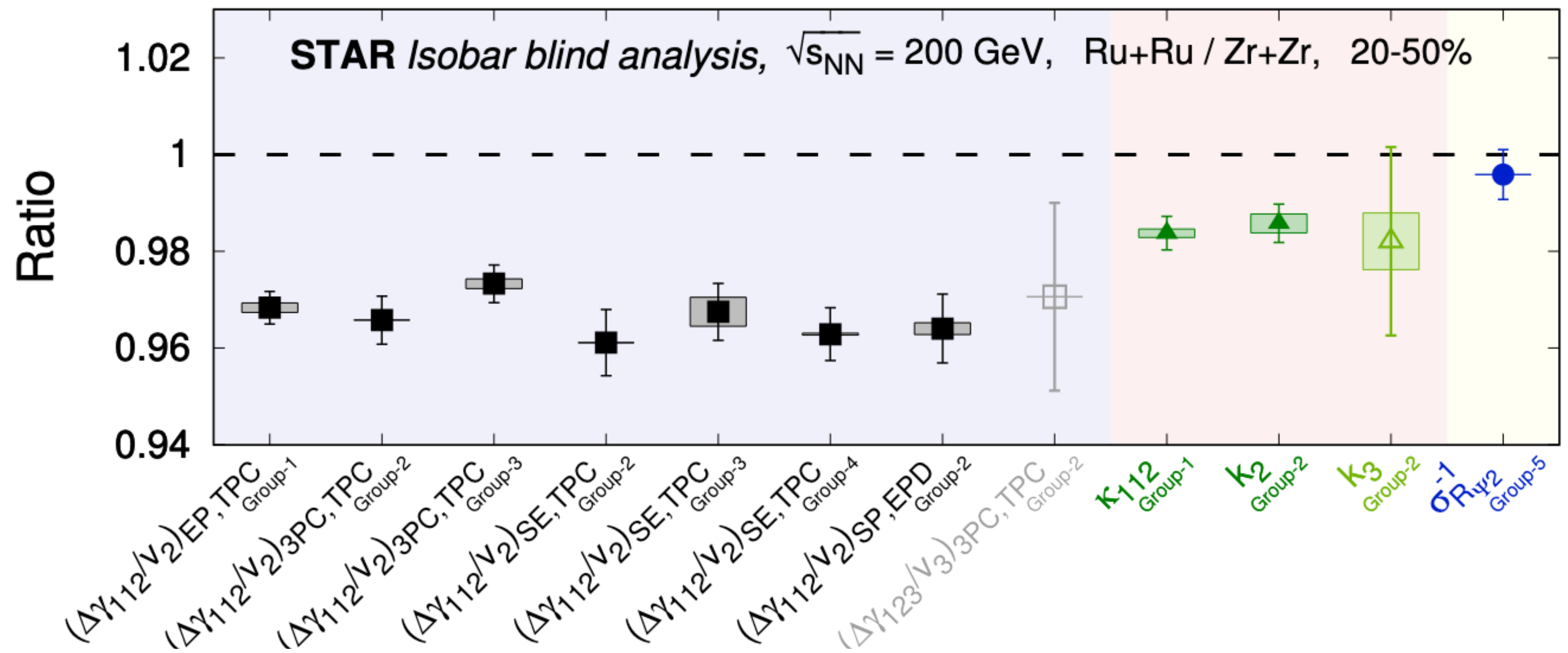

The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of $\mathcal{P}$ and $\mathcal{CP}$ symmetries of the strong interaction amidst a strong electro-magnetic field generated in relativistic heavy-ion collisions. Experimental manifestation of the CME involves a separation of positively and negatively charged hadrons along the direction of the magnetic field. Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions. In order to better control the influence of signal and backgrounds, the STAR Collaboration performed a blind analysis of a large data sample of approximately 3.8 billion isobar collisions of $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr at $\sqrt{s_{NN}} = 200$ GeV. Prior to the blind analysis, the CME signatures are predefined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former. A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

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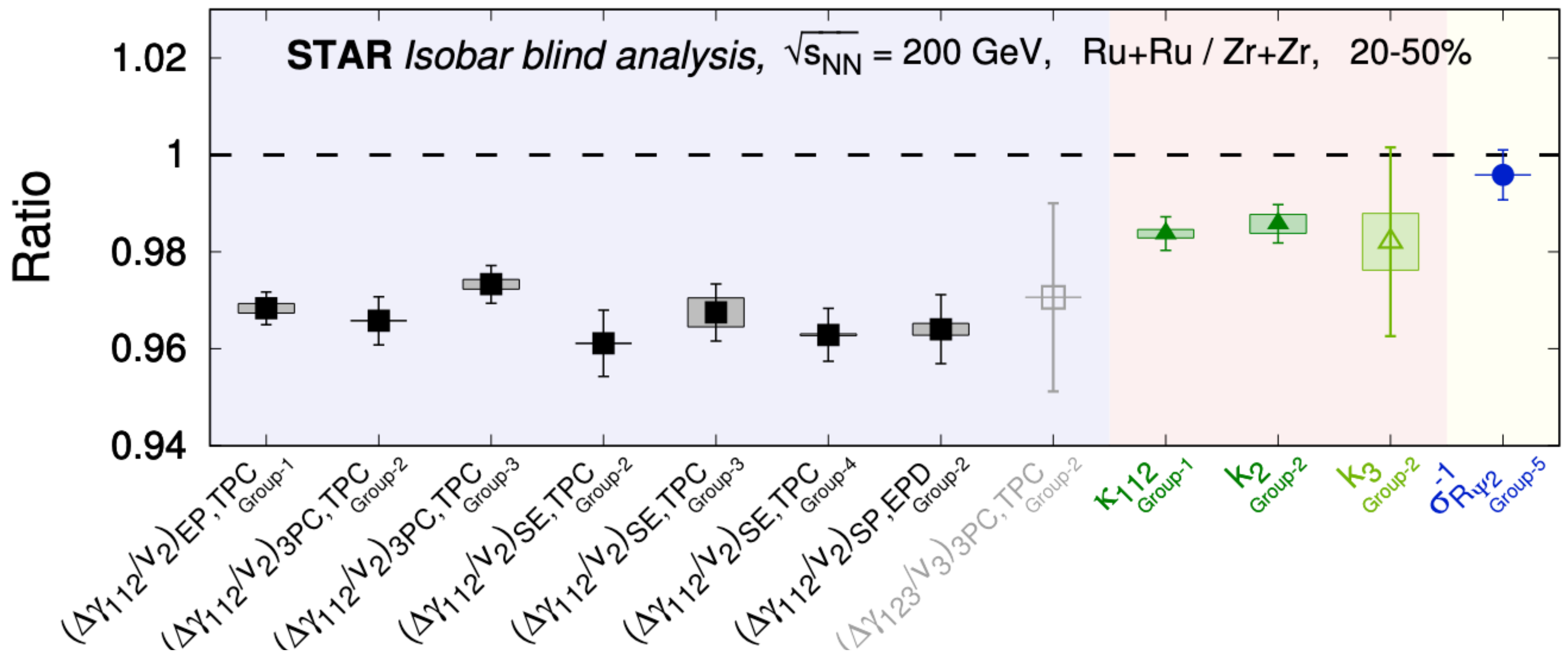

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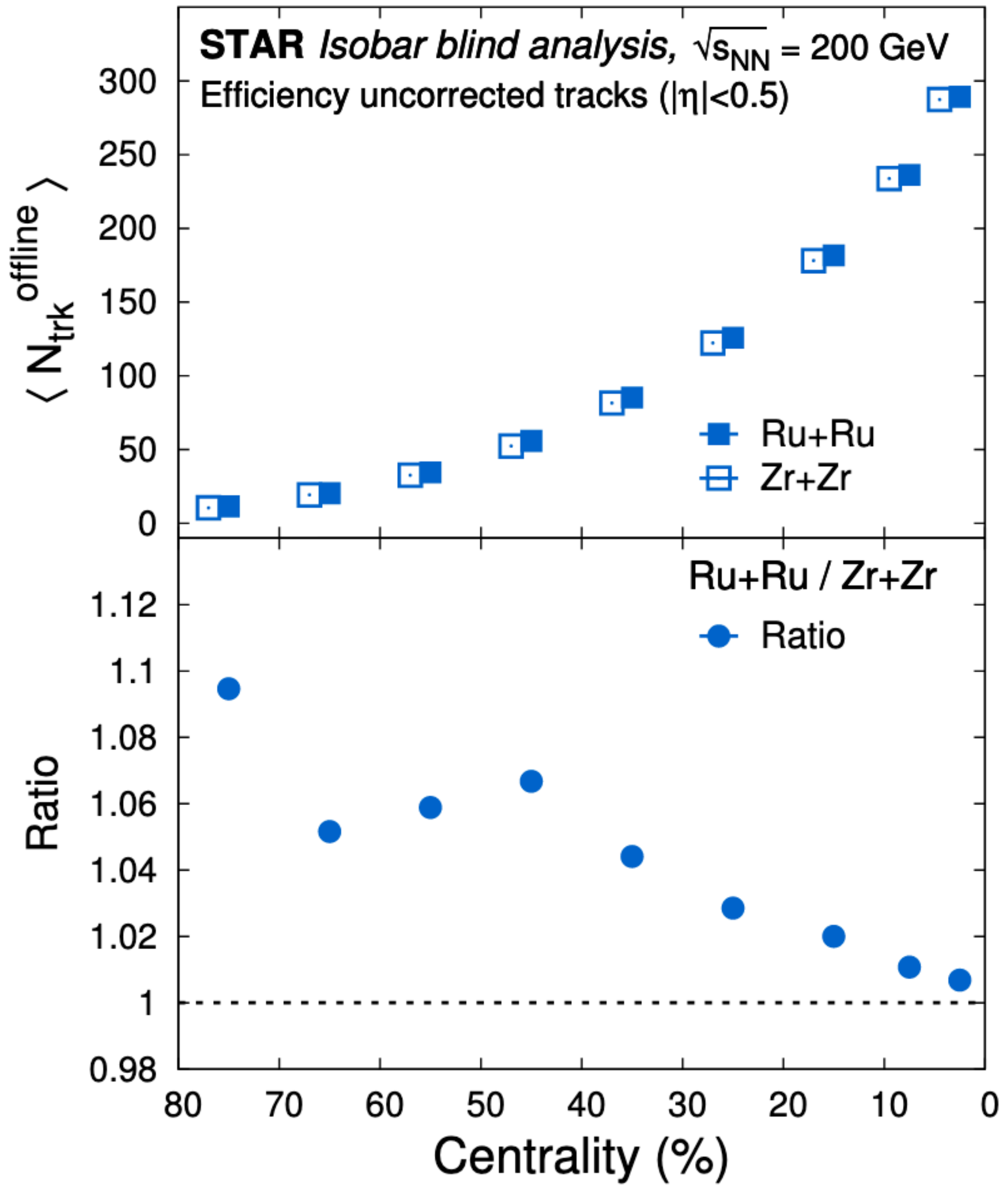
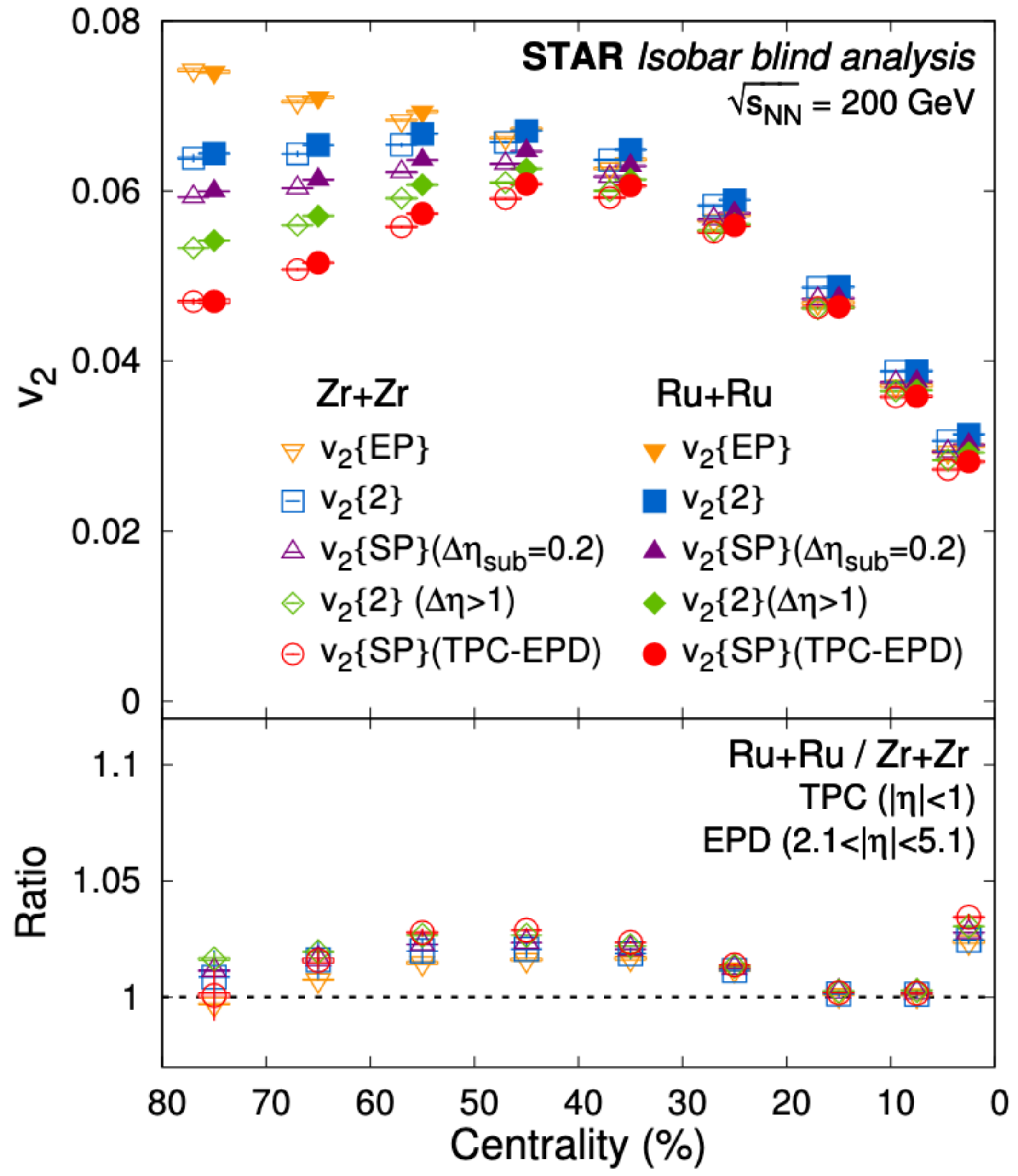
Background components





Details are important!

- Nuclear structure should be well understood and studied
  - Neutron skin/charge radius
  - Overall size differences → energy density → multiplicity

Important before extracting final conclusions → Ongoing

ISOBAR STUDIES @ RHIC

(STAR Collaboration) *Phys.Rev.C* 105 (2022) 1, 014901

More appropriate sentence:

None of the predefined criteria are relevant since they are invalidated by data

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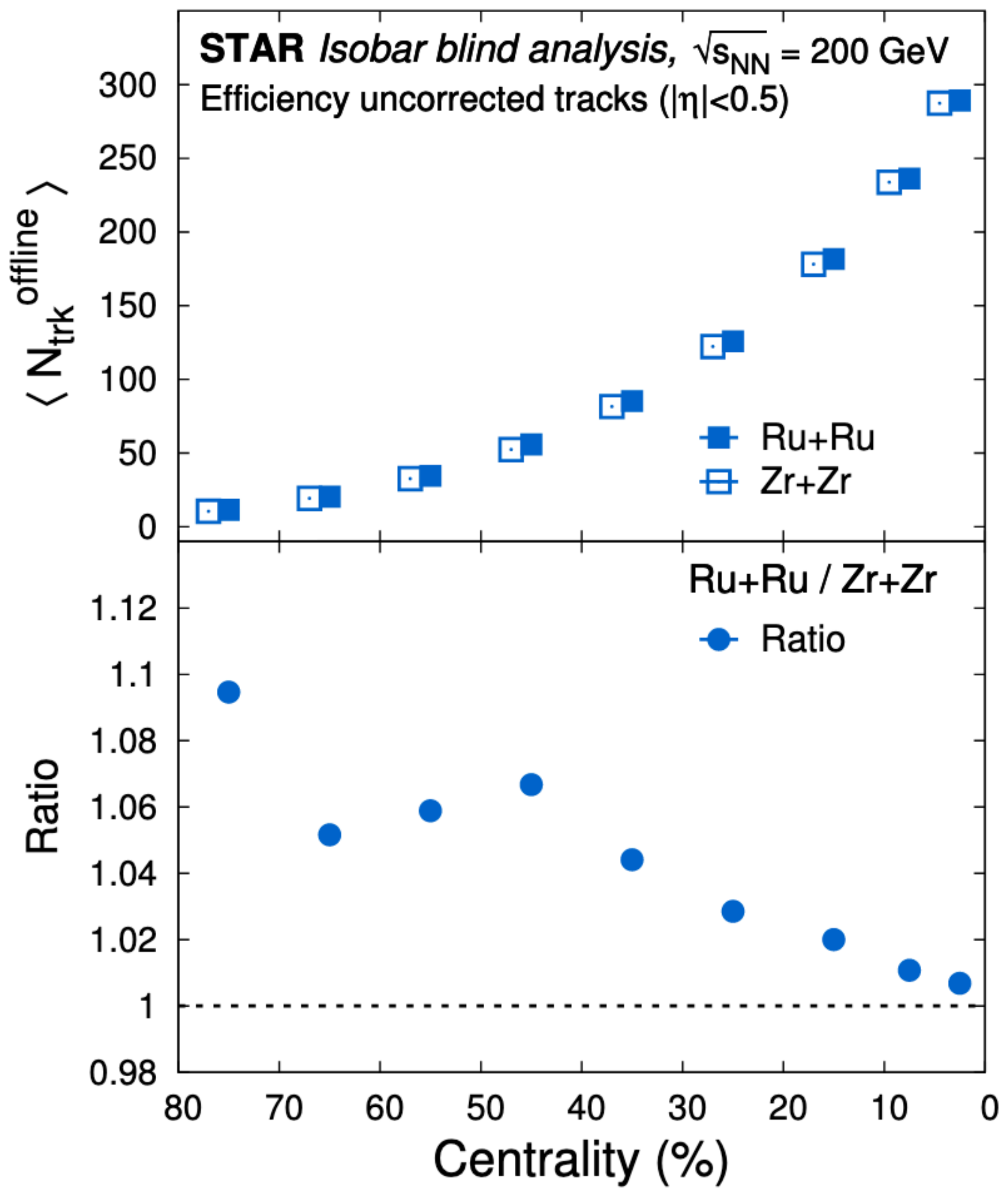

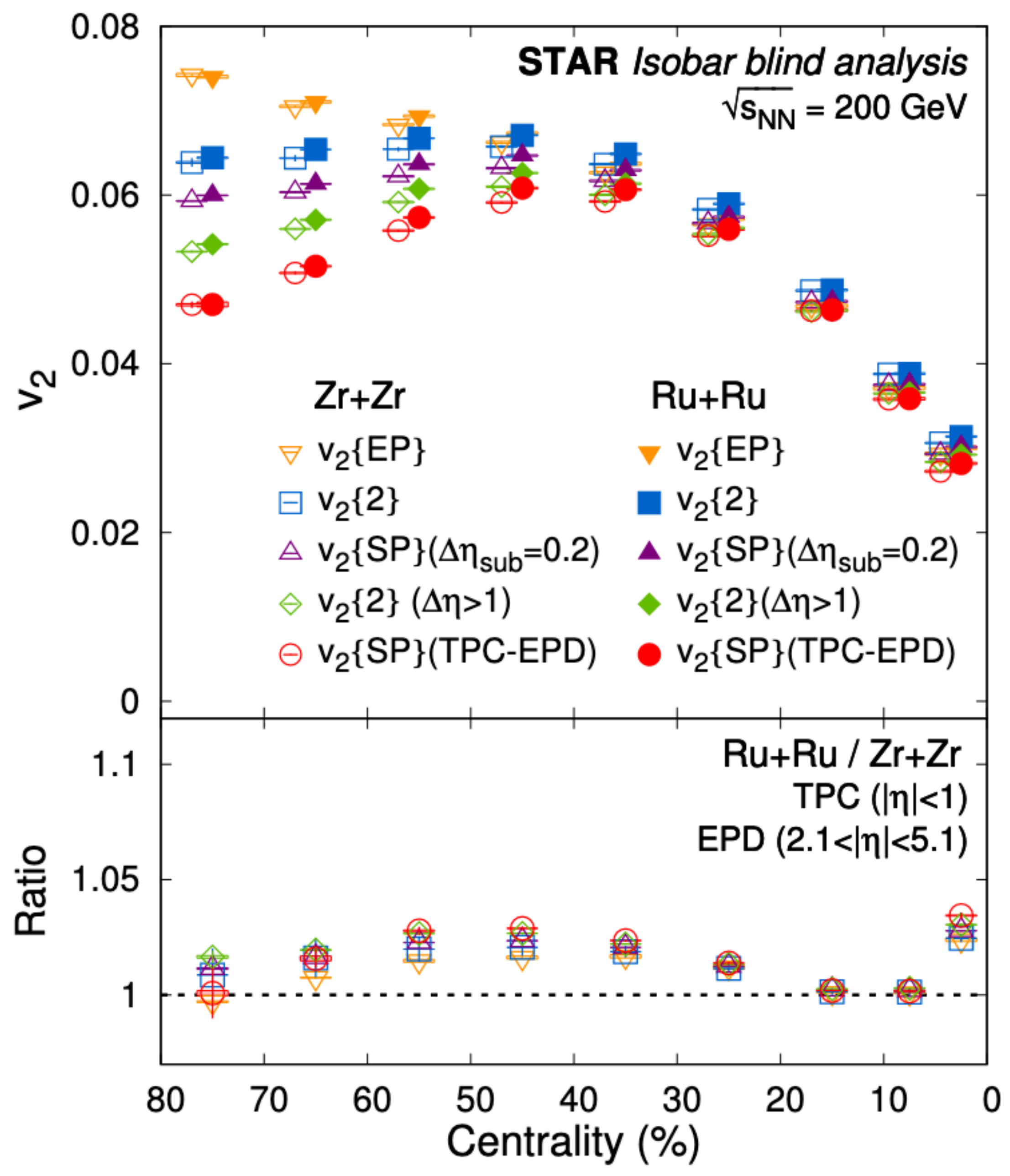

Details are important!

- Nuclear structure should be well understood and studied
  - Neutron skin/charge radius
  - Overall size differences → energy density → multiplicity

The result does not mean that the CME is excluded but rather that the initial criteria were not accurate!

POST BLIND ANALYSIS: ISOBAR STUDIES @ RHIC

D. Kharzeev, J. Liao, S. Shi, Phys. Rev C 106, L051903 (2022)

Implications of the isobar run results for chiral magnetic effect in heavy ion collisions

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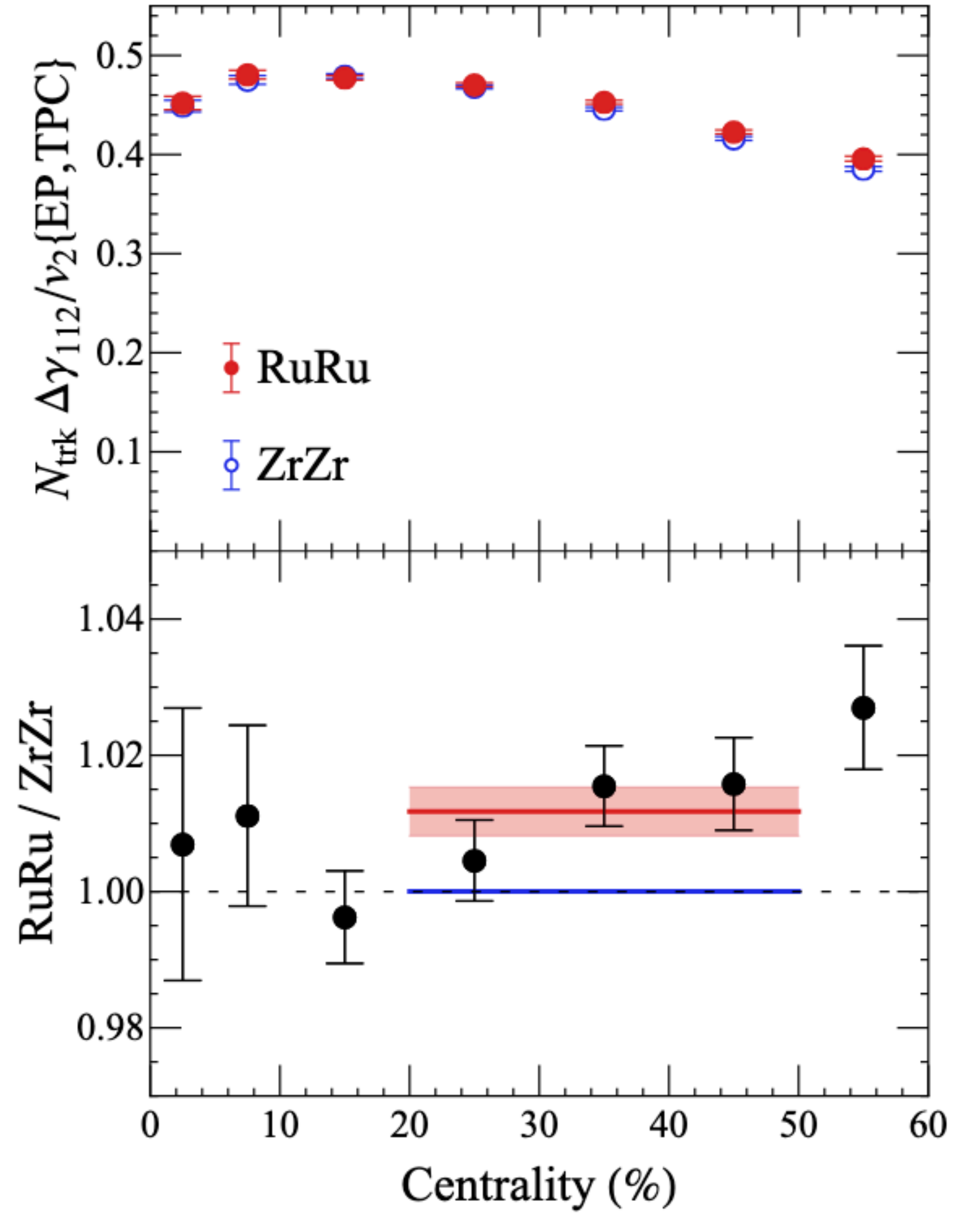
[2] *Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[3] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
(Dated: November 29, 2022)

Chiral magnetic effect (CME) is a macroscopic transport phenomenon induced by quantum anomaly in the presence of chiral imbalance and an external magnetic field. Relativistic heavy ion collisions provide the unique opportunity to look for CME in a non-Abelian plasma, where the chiral imbalance is created by topological transitions similar to those occurring in the Early Universe. The isobar run at Relativistic Heavy Ion Collider was proposed as a way to separate the possible CME signal driven by magnetic field from the background. The first blind analysis results from this important experiment have been recently released by the STAR Collaboration. Under the pre-defined assumption of identical background in RuRu and ZrZr, the results are inconsistent with the presence of CME, as well as with all existing theoretical models (whether including CME or not). However the observed difference of backgrounds must be taken into account before any physical conclusion is drawn. In this paper, we show that once the observed difference in hadron multiplicity and collective flow are quantitatively taken into account, the STAR results could be consistent with a finite CME signal contribution of about $(6.8 \pm 2.6)\%$.



$$f_s \simeq (6.8 \pm 2.6)\%$$

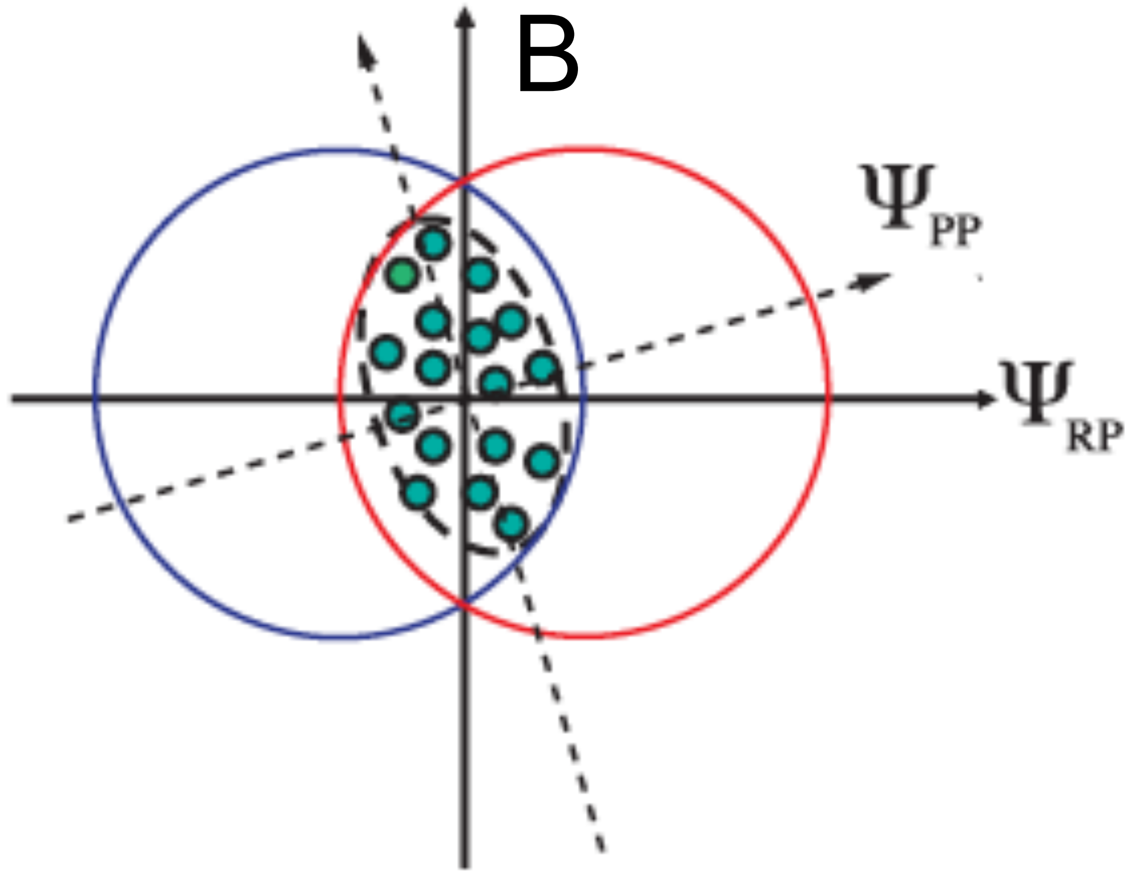
Analysis suggests non-zero CME fraction, with the right centrality dependence

Needs to be (re)done by the experimentalists

HINT FOR CME? Ψ_{SP} VS Ψ_{PP}

S. Voloshin, Phys. Rev. C 98, (2018) 054911

H. Xu *et al.*, Chin.Phys.C 42 (2018) 8, 084103

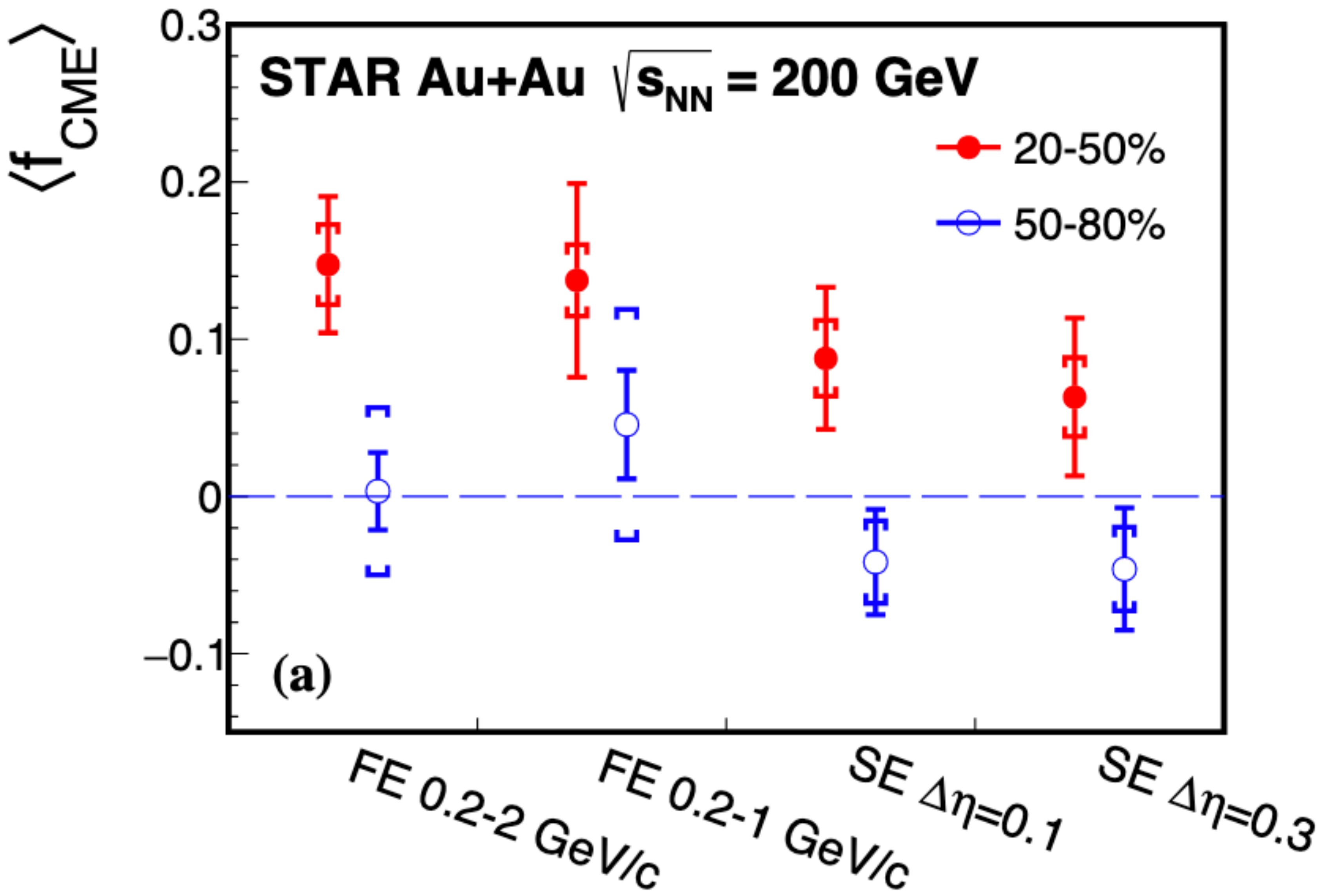


Study correlations relative to the participant (Ψ_{PP}) and spectator (Ψ_{SP}) planes

Background contribution larger when studied relative to $\Psi_{PP} \rightarrow$ larger v_2

CME contribution larger when studied relative to $\Psi_{SP} \rightarrow$ correlated with B

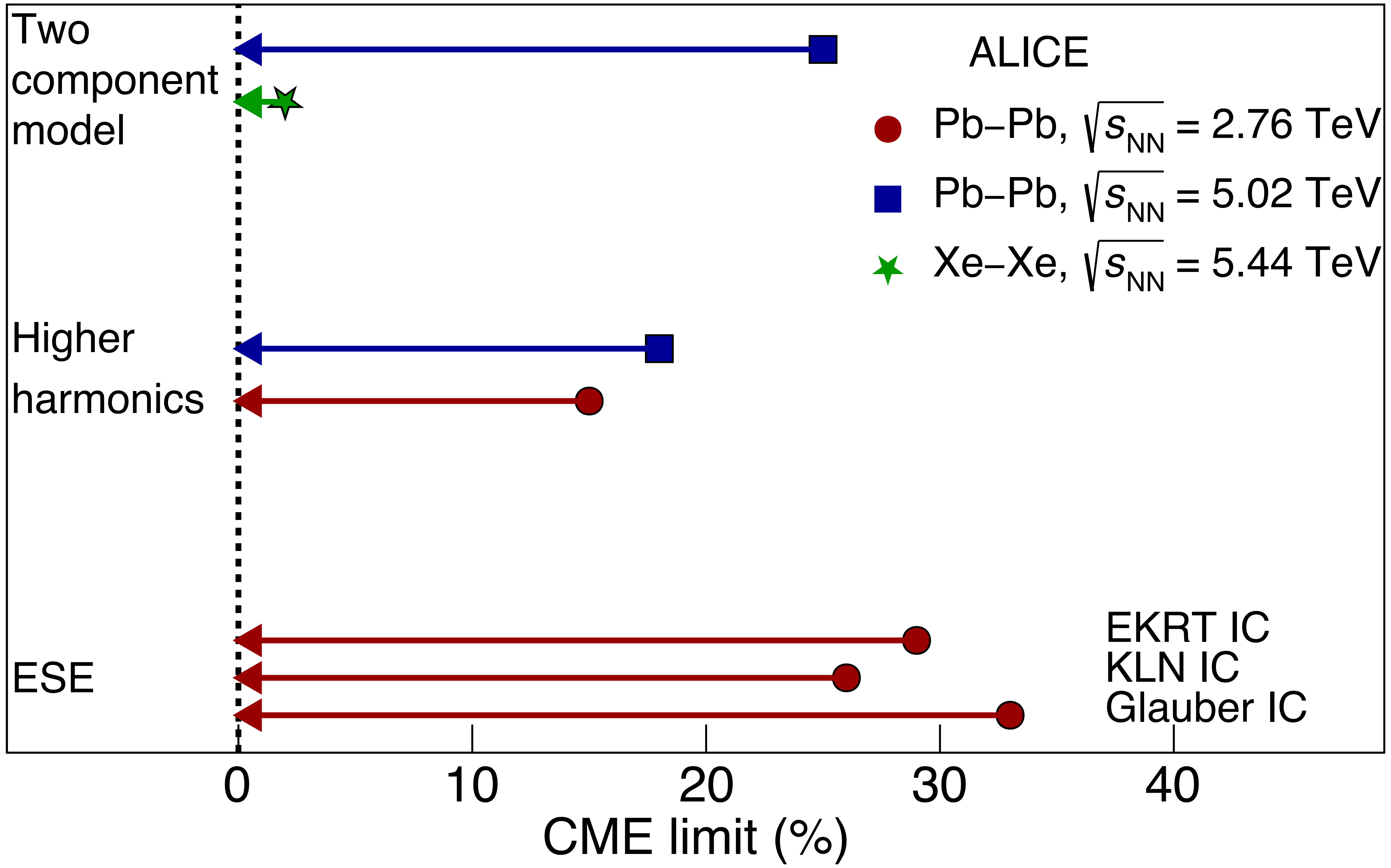
(STAR Collaboration) Phys. Rev. Lett. 128, 092301



Indications of finite signal in mid-central 20-50% collisions → 1-3σ significance

CME FRACTION UPPER LIMITS @ LHC

(ALICE Collaboration), arXiv:2211.04384



Summary of upper limits @ LHC (95% CL)		
ALICE	ESE in Pb-Pb collisions	26-33%
	Higher harmonics in Pb-Pb collisions	11-15%
	2-component model	2%(Xe) - 25%(Pb)
CMS	p-Pb collisions	13% ⚠
	ESE in Pb-Pb collisions	7% ⚠

Current analyses provide stringent upper limits for the CME fraction at both RHIC and LHC energies → CME signal at the level of few % max

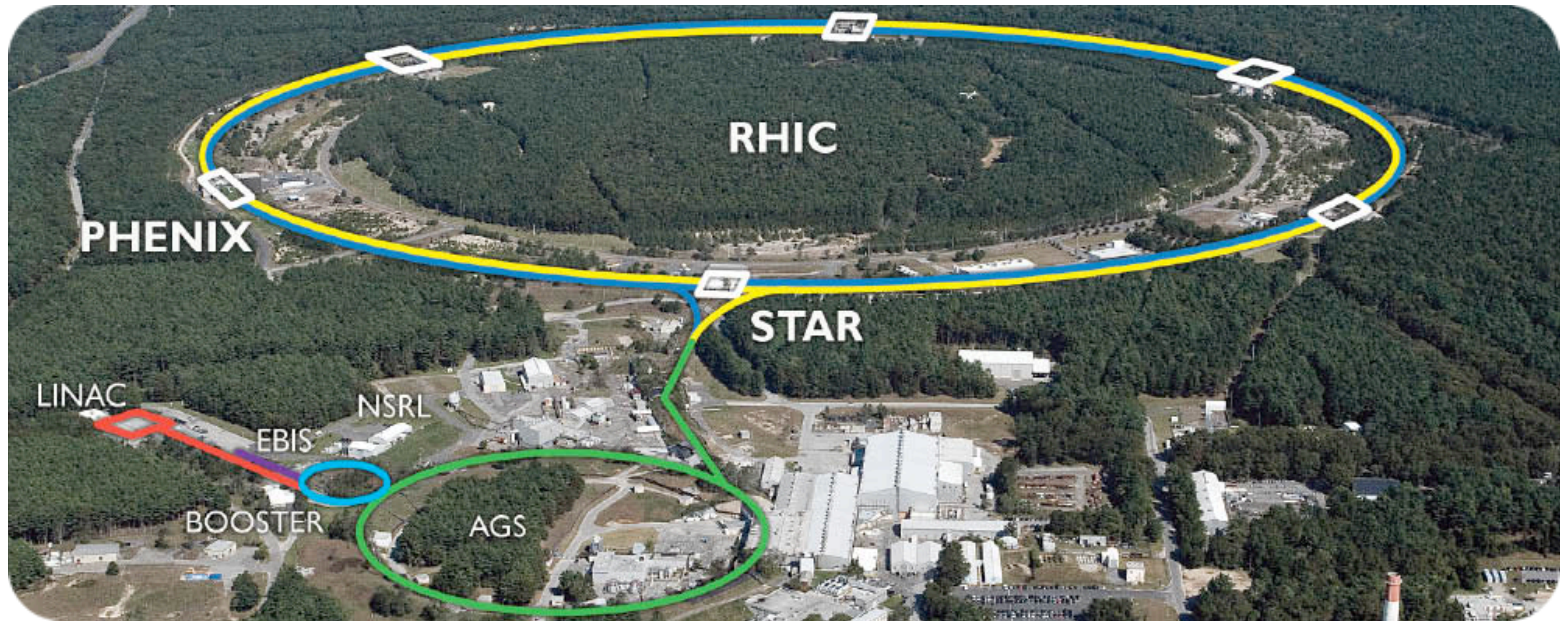
RUN1-RUN2: DATA SAMPLES COLLECTED & RESULTS

	2010	2011	2013	2015	2016	2017	2018
γ_{11}	ALICE-1		CMS-1	ALICE-4 CMS-1	CMS-2	ALICE-5	
ESE	ALICE-3				CMS-2		Ongoing
Higher harmonics	ALICE-4			ALICE-4	CMS-2		
Ψ_{PP} vs Ψ_{SP}				Ongoing			Ongoing
PID	Preliminary						
CMW	ALICE-2		CMS-3	CMS-3			
CMW/ESE							Ongoing
CMW/Higher harmonics			CMS-3	CMS-3			Ongoing

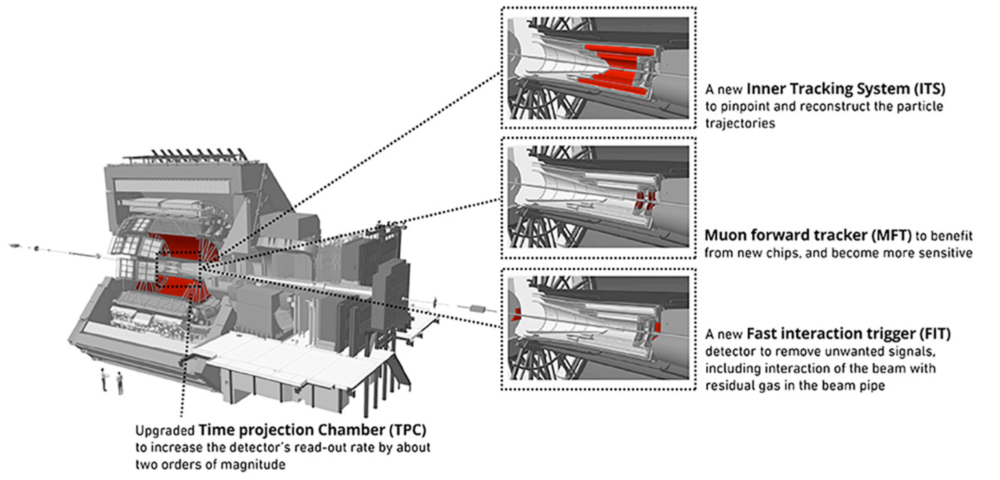
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011	2.76	~75 μb^{-1}
	2015, 2018	5.02	~0.8 nb^{-1} ~2 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013, 2016	5.02	~18 nb^{-1} ~50 μb^{-1}
	2016	8.16	~25 nb^{-1} ~186 nb^{-1}

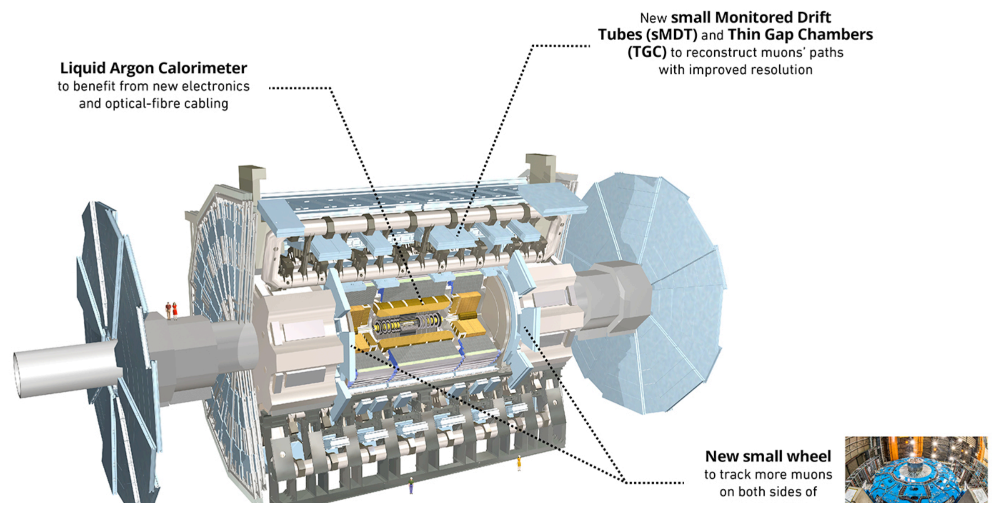
Anticipated results for CME can drive the limit to lower than 10%

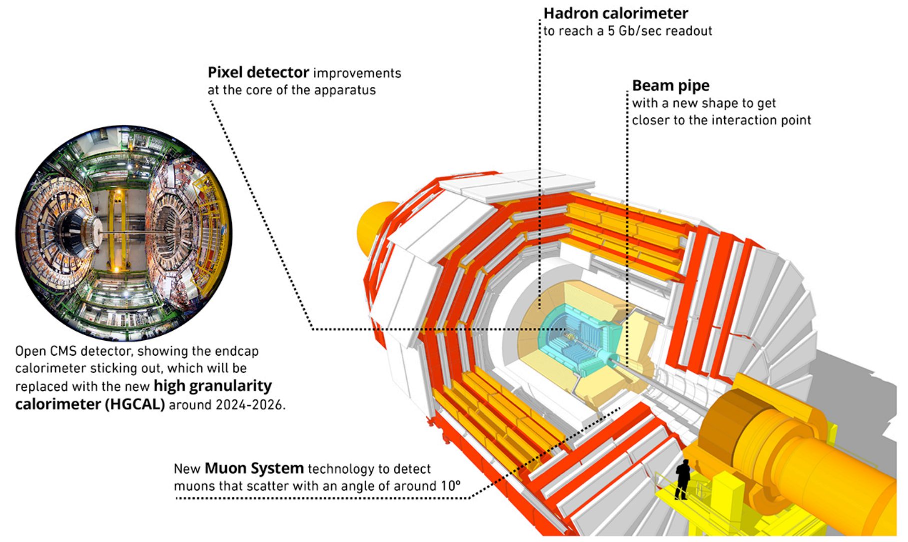
FUTURE PROSPECTS

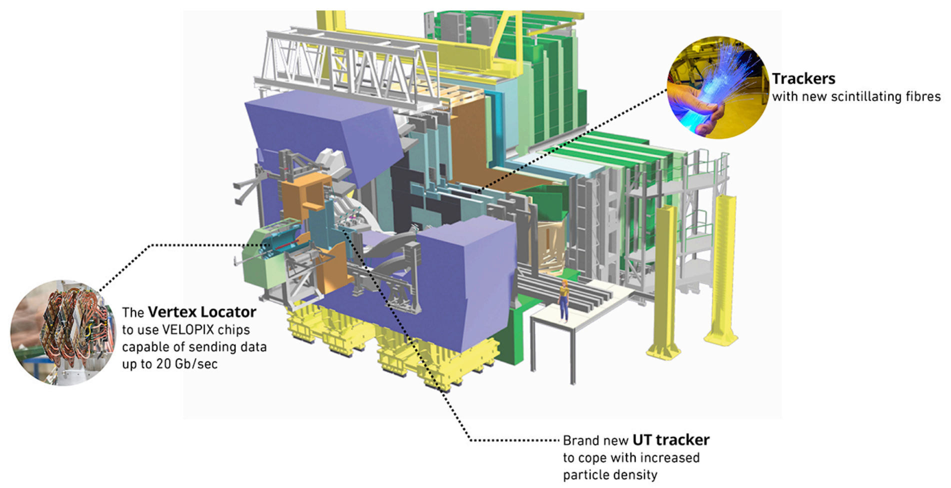


2023-2025:10x AuAu MB data than the existing sample



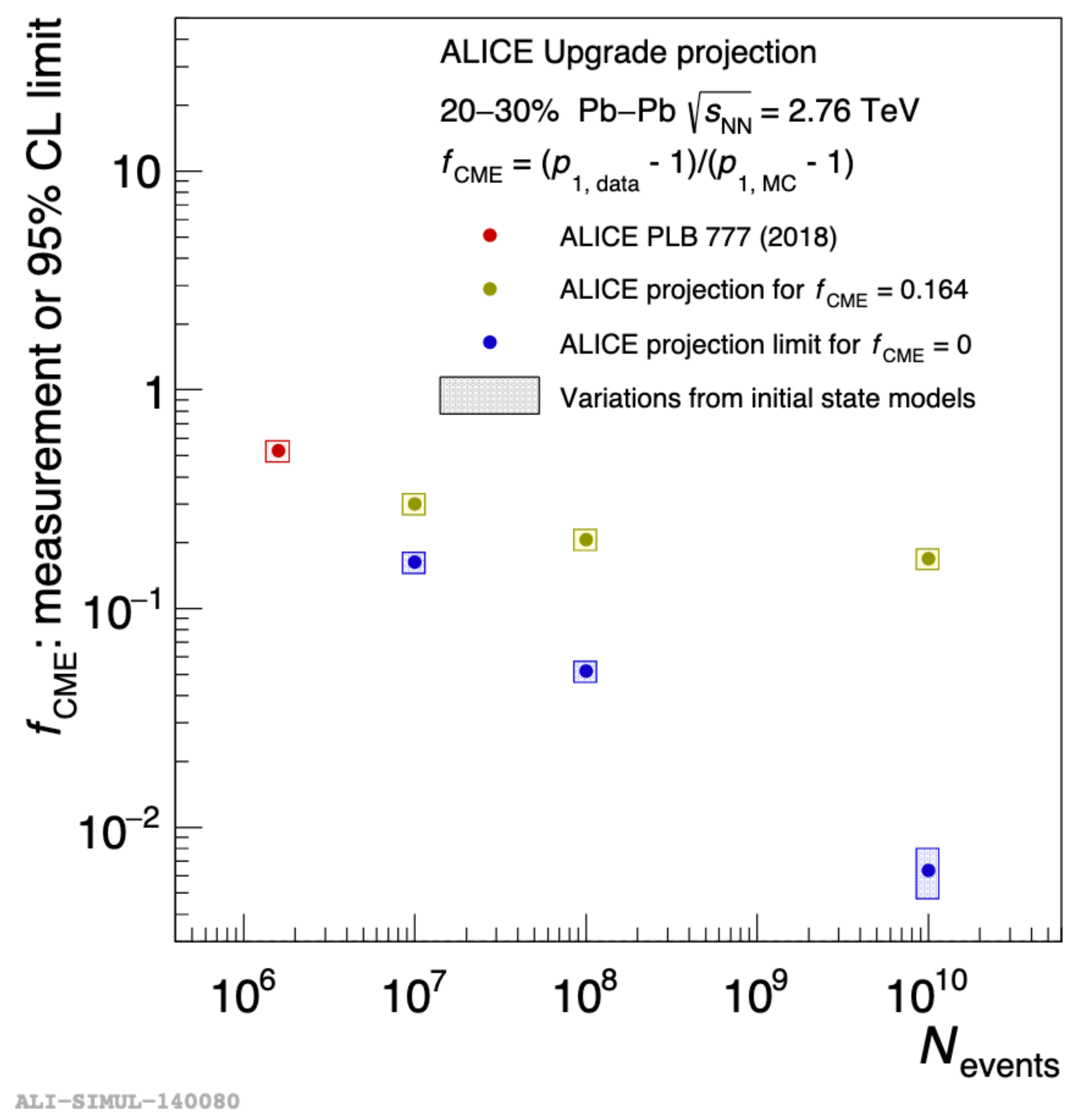






+Isobaric collisions @ LHC?

arXiv:1812.06772



System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011	2.76	~75 μb^{-1}
	2015, 2018	5.02	~0.8 nb^{-1} ~2 nb^{-1}
	2023-2030	**5.5**	**~12 nb^{-1}**
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013, 2016	5.02	~18 nb^{-1} ~50 μb^{-1}
	2016	8.16	~25 nb^{-1} ~186 nb^{-1}

The signal is there…we just have to find it

Thank you for your attention!

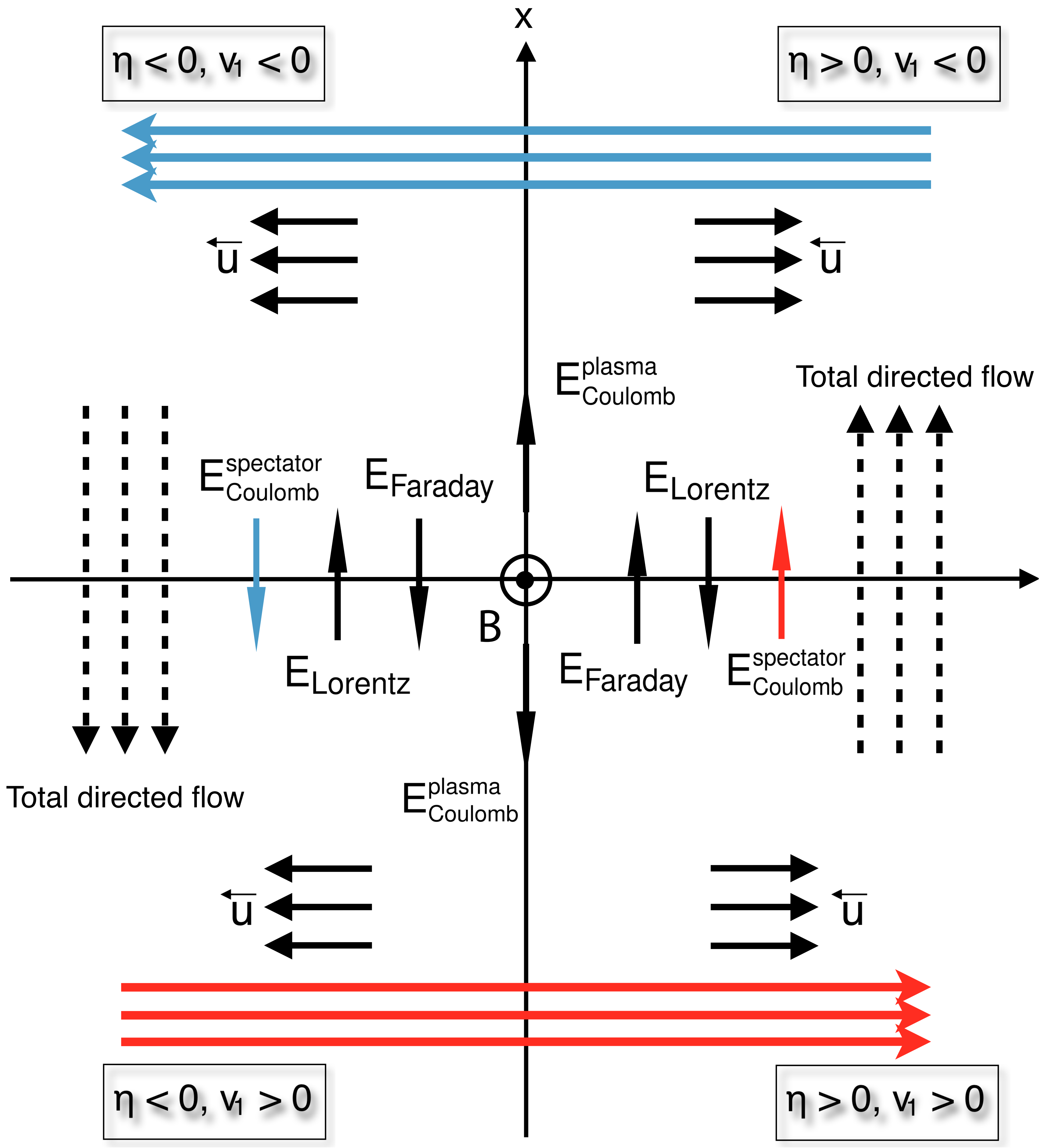
BACKUP

EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

Competing effects:
Faraday + spectator Coulomb vs Lorentz force

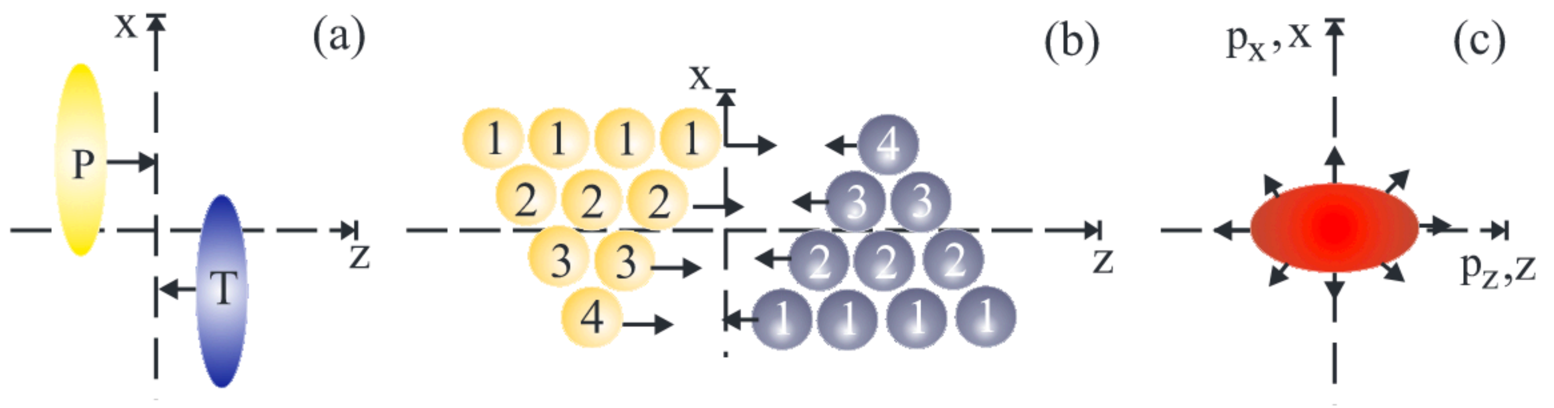
Initial stage E/M fields could affect the motion of particles → experimentally accessible differences in charge dependent odd v_n

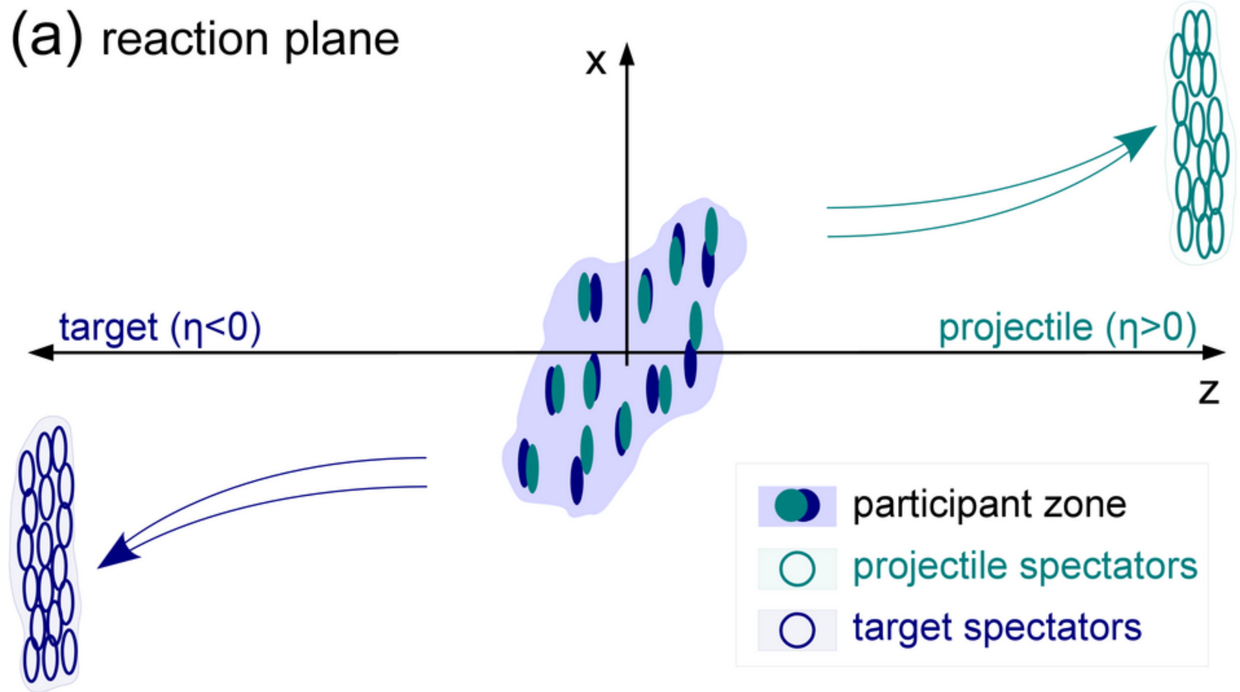
U. Gürsoy *et al.*, Phys. Rev. **C98**, (2018) 055201



S. Voloshin and Y. Zhang, Z. Phys. **C70**, 665 (1996)

$$\frac{dN}{d\varphi} \propto 1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos[2(\varphi - \Psi_{RP})] + \ldots$$





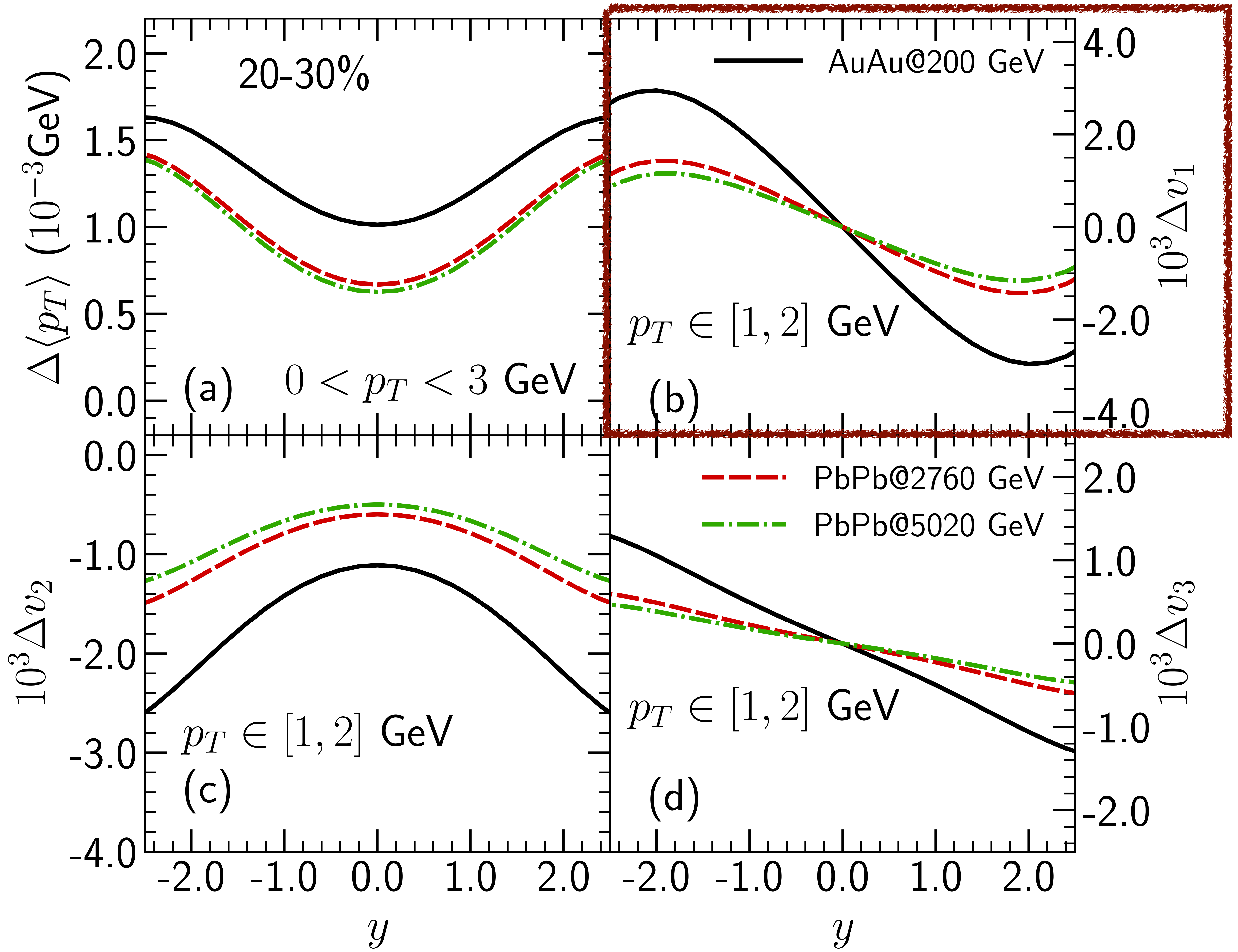
Nikhef

EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

U. Gürsoy *et al.*, Phys. Rev. **C98**, (2018) 055201

Competing effects:
Faraday + spectator
Coulomb vs Lorentz
force

Initial stage E/M fields could affect the motion of particles → experimentally accessible differences in charge dependent odd v_n

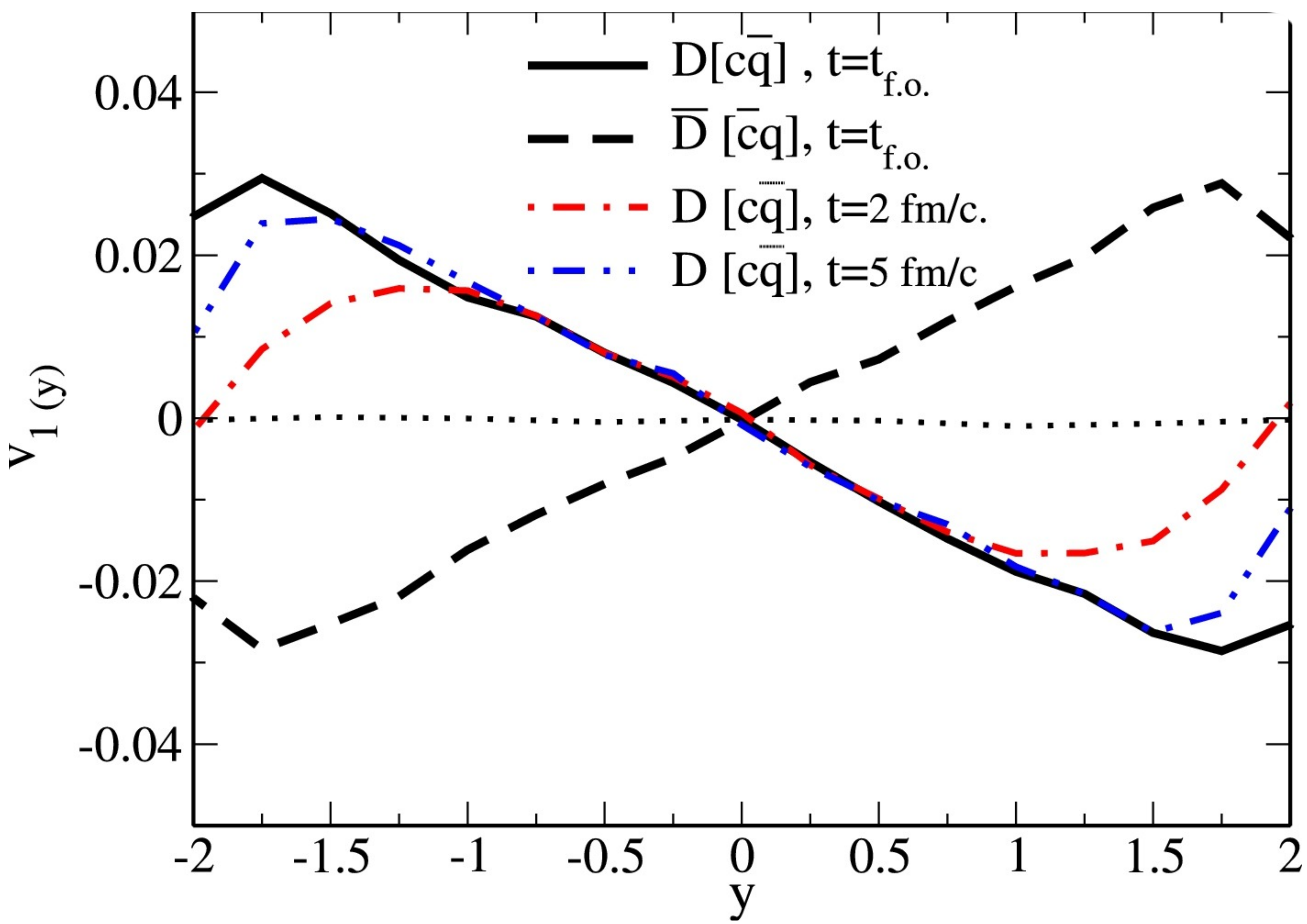


EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

S. Das *et al.*, Phys. Let **B768**, (2017) 260

Charm quark (small formation time) suitable probe of the early stage E/M fields

Expectation of large values of directed flow



FIRST LHC RESULTS

(ALICE Collaboration), Phys. Rev. Lett. **110** (2013) 012301

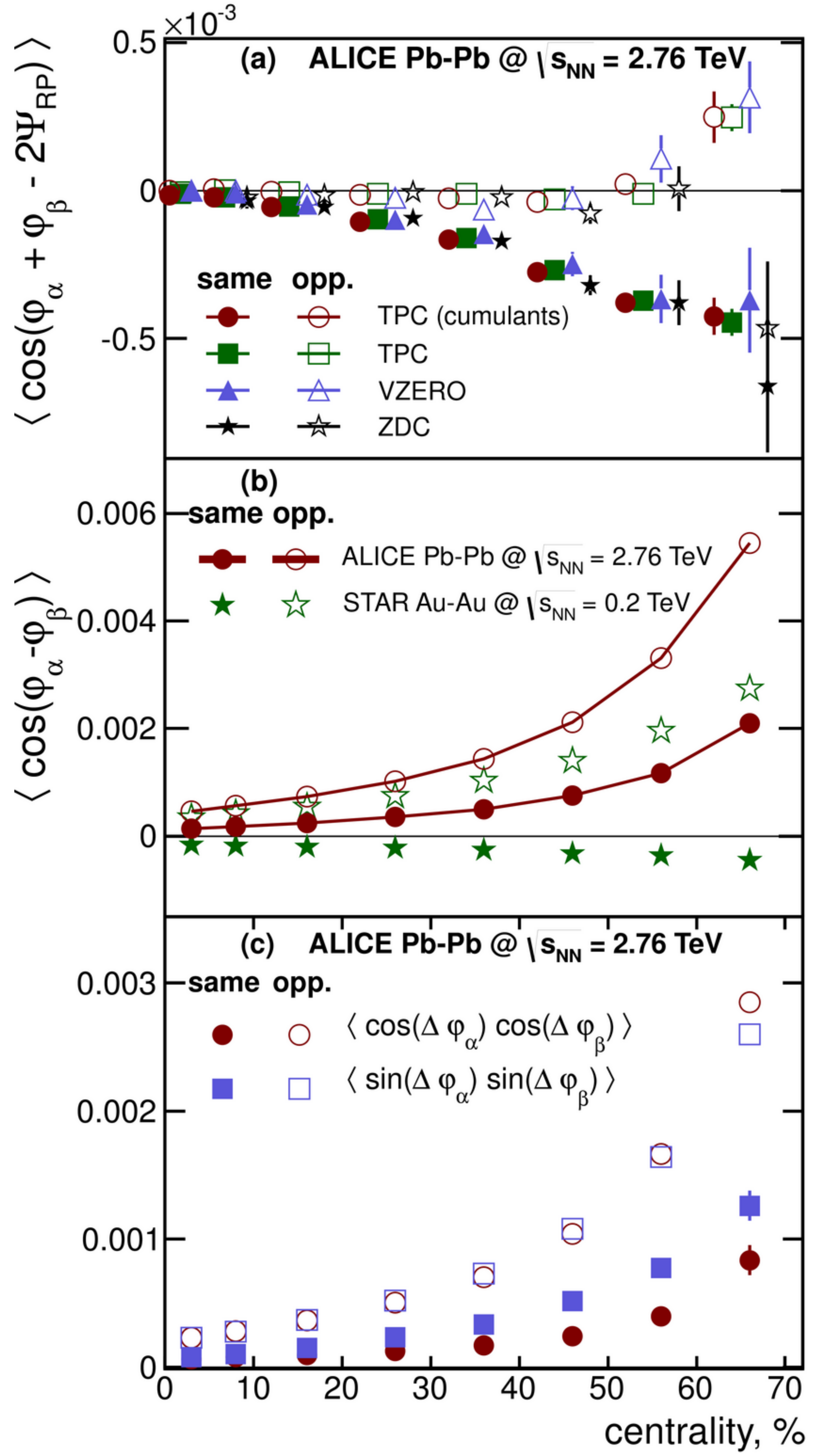
Significant charge dependent correlations also at LHC energies

"Dominance" of ⟨sin · sin⟩ terms (proportional to $\langle a_{1,\alpha} \cdot a_{1,\beta} \rangle$) over the ⟨cos · cos⟩ terms for same sign pairs

Consistent with CME expectations

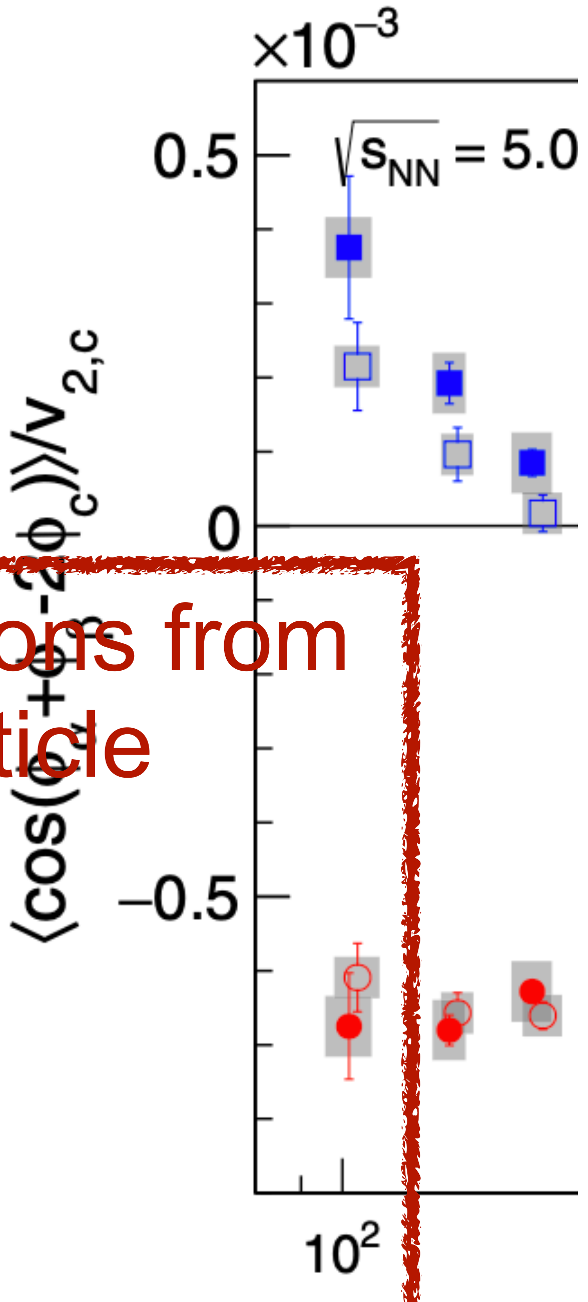
γ_{11}

δ_1



AT THE SAME TIME…SMALL SYSTEMS

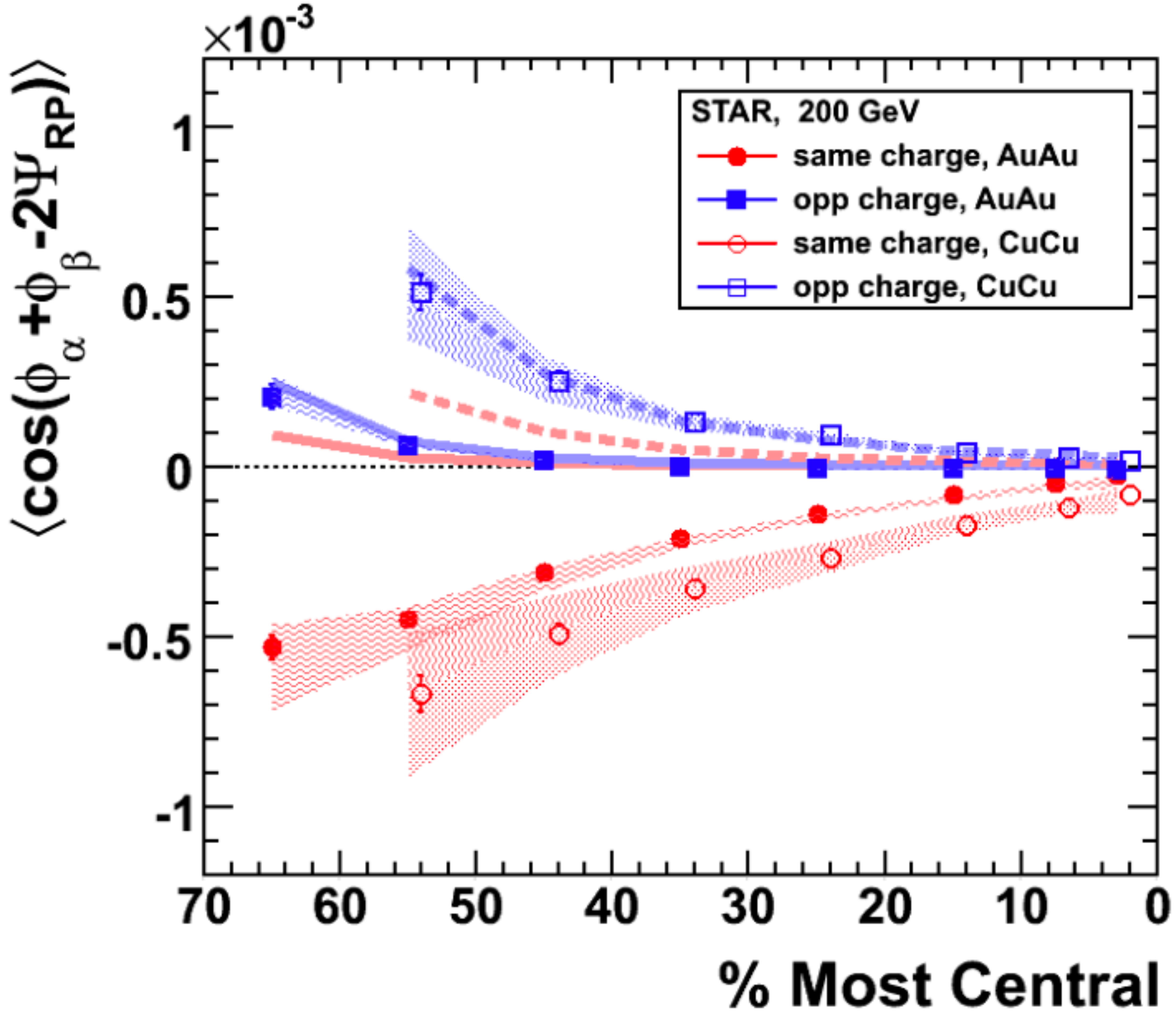
(CMS Collaboration) PRL **118**, (2017) 122301 (STAR Collaboration), Phys. Rev. Lett. **103**, 251601 (2009) (STAR Collaboration) PRL **118**, (2017) 122301

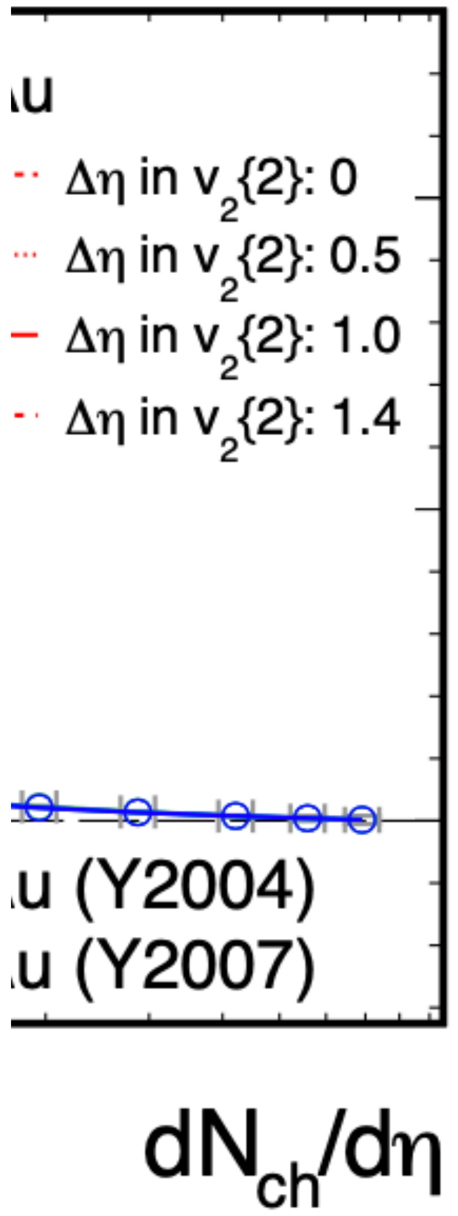


Lines: Expectations from HIJING on 3-particle correlations

Solid: Au-Au

Dashed: Cu-Cu





Significant charge …

- Note: the resul…
- They can be u… …effects can be dominant → (n… …dependent effects)

ANOMALOUS VISCOUS FLUID DYNAMICS (AVFD)

Anomalous Chiral Transport in Heavy Ion Collisions from Anomalous-Viscous Fluid Dynamics

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(Dated: May 9, 2018)

arXiv:1711.02496v2 [nucl-th] 8 May 2018

Quantifying Chiral Magnetic Effect from Anomalous-Viscous Fluid Dynamics

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[3] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
[4] Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China.

arXiv:1611.04586v3 [nucl-th] 30 Nov 2017

S. Shi *et al.*, Annals Phys. 394 (2018) 50
Y. Jiang *et al.*, Chin.Phys.C 42 (2018) 1, 011001

EbyE IC + E/M fields (field lifetime as input)

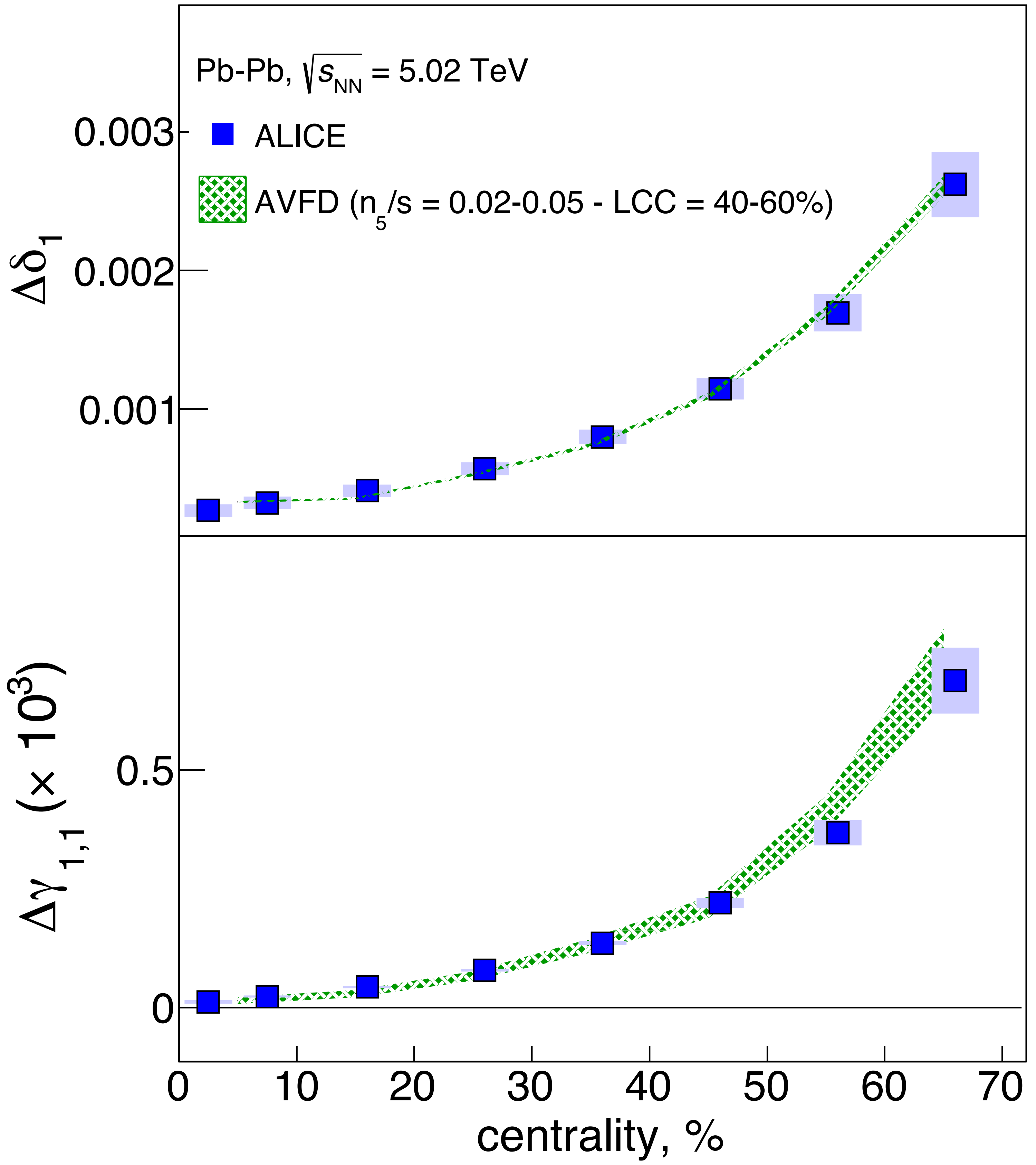
Anomalous transport → CME signal (n_5/s)

VISH2+1 → hydro evolution

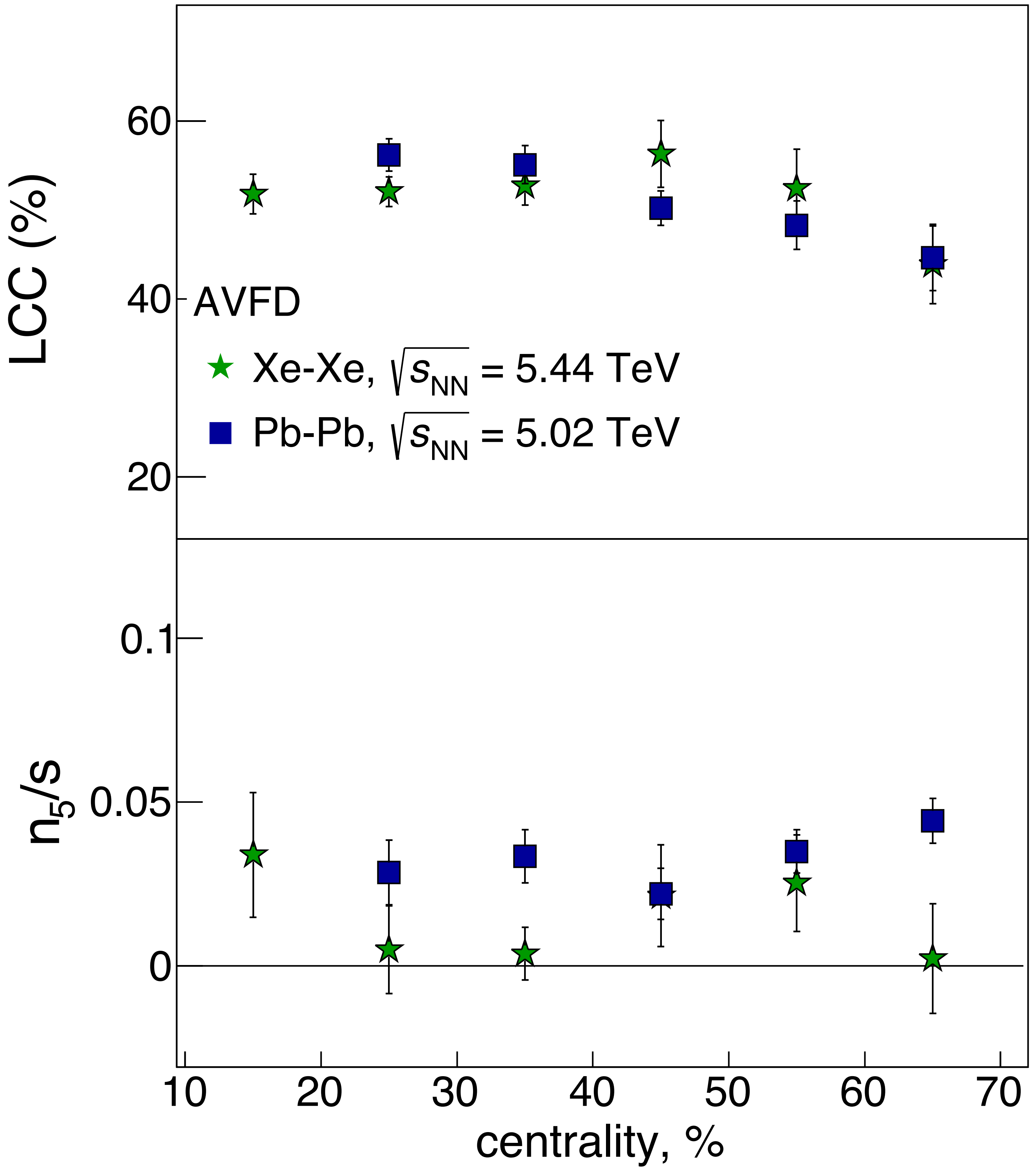
Hadronisation + LCC

UrQMD

Model tuned to describe at the same time both Δδ and Δγ



$(\eta_5/s)_{Xe-Xe}$ consistent with 0
$(\eta_5/s)_{Pb-Pb}$ = 0.034 ± 0.003



P.C. S. Qiu, J. Staa, Eur. Phys. J. C 81 (2021) 717