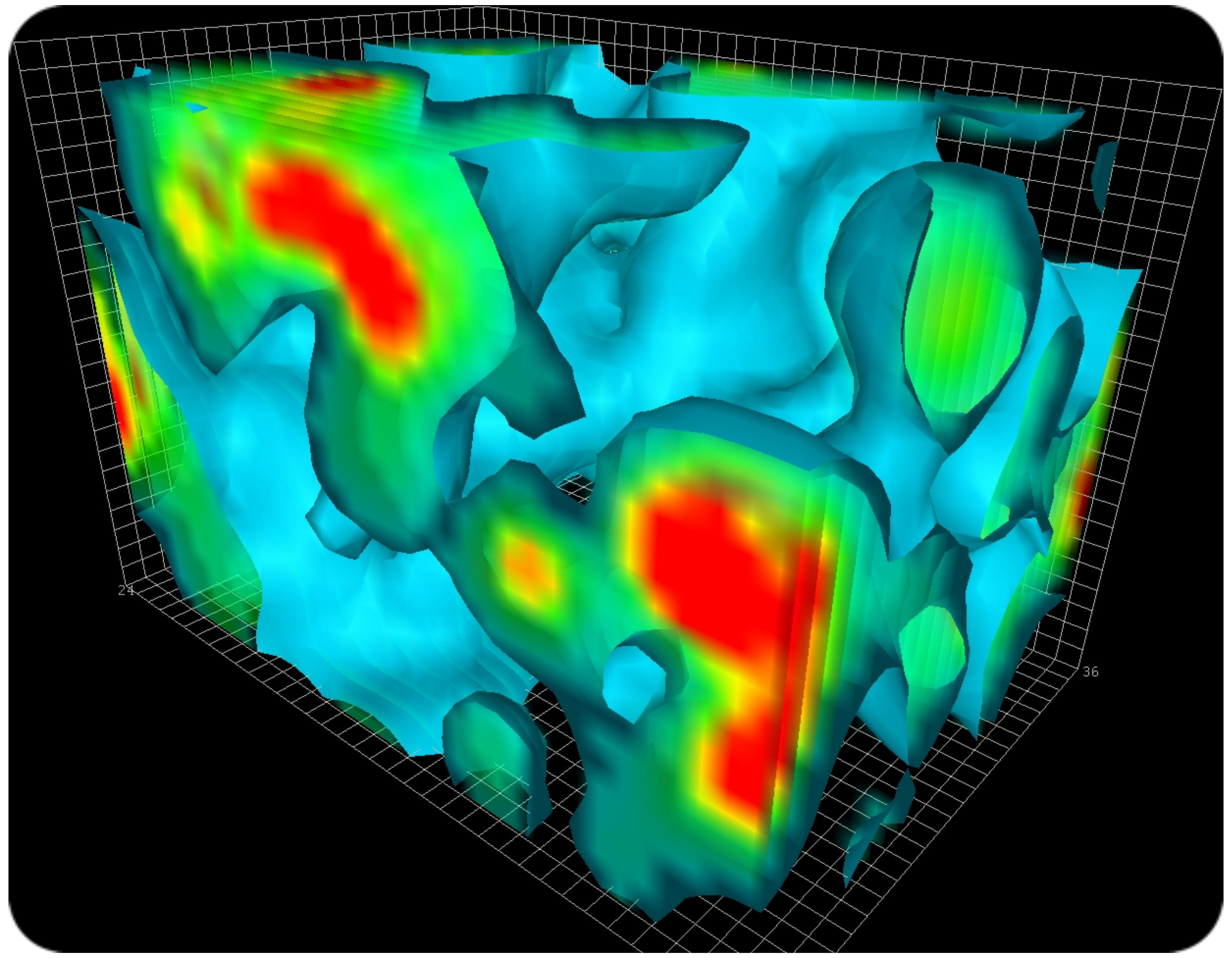
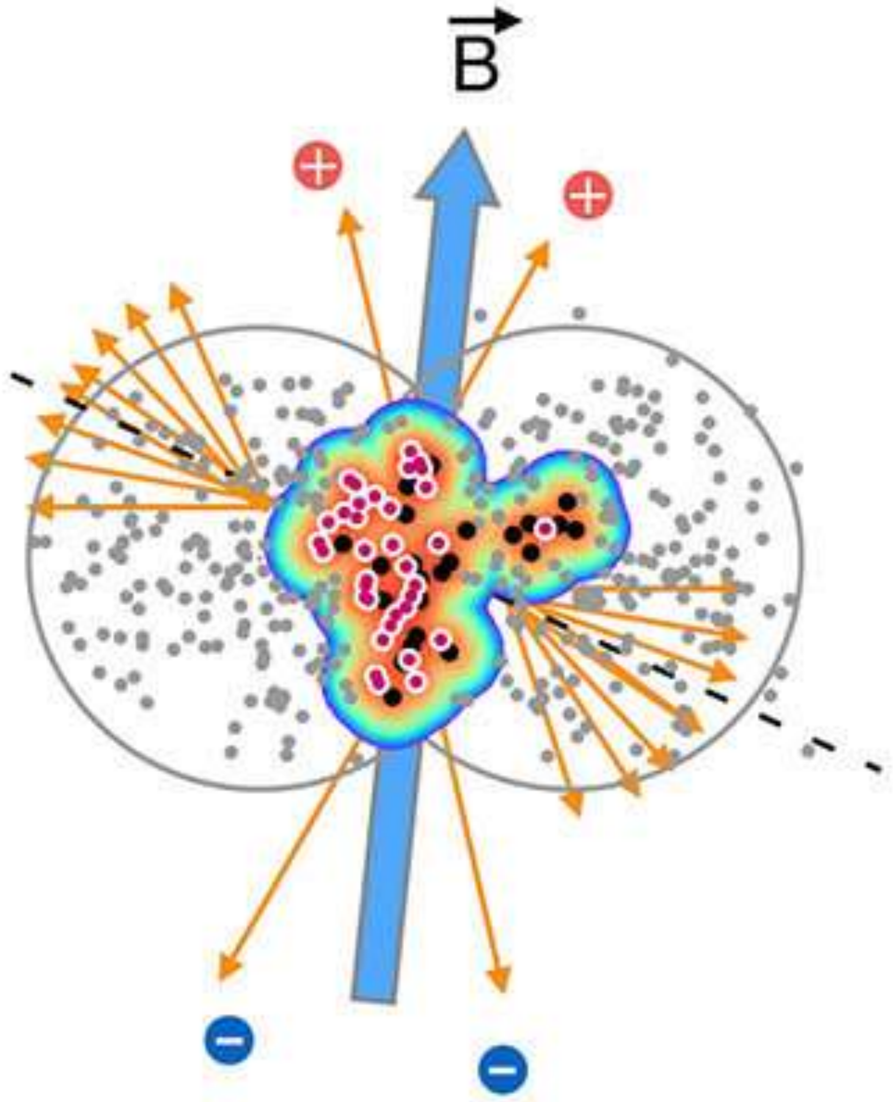
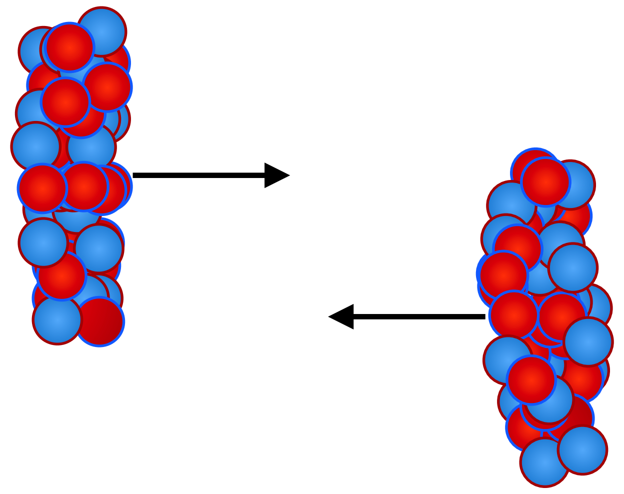
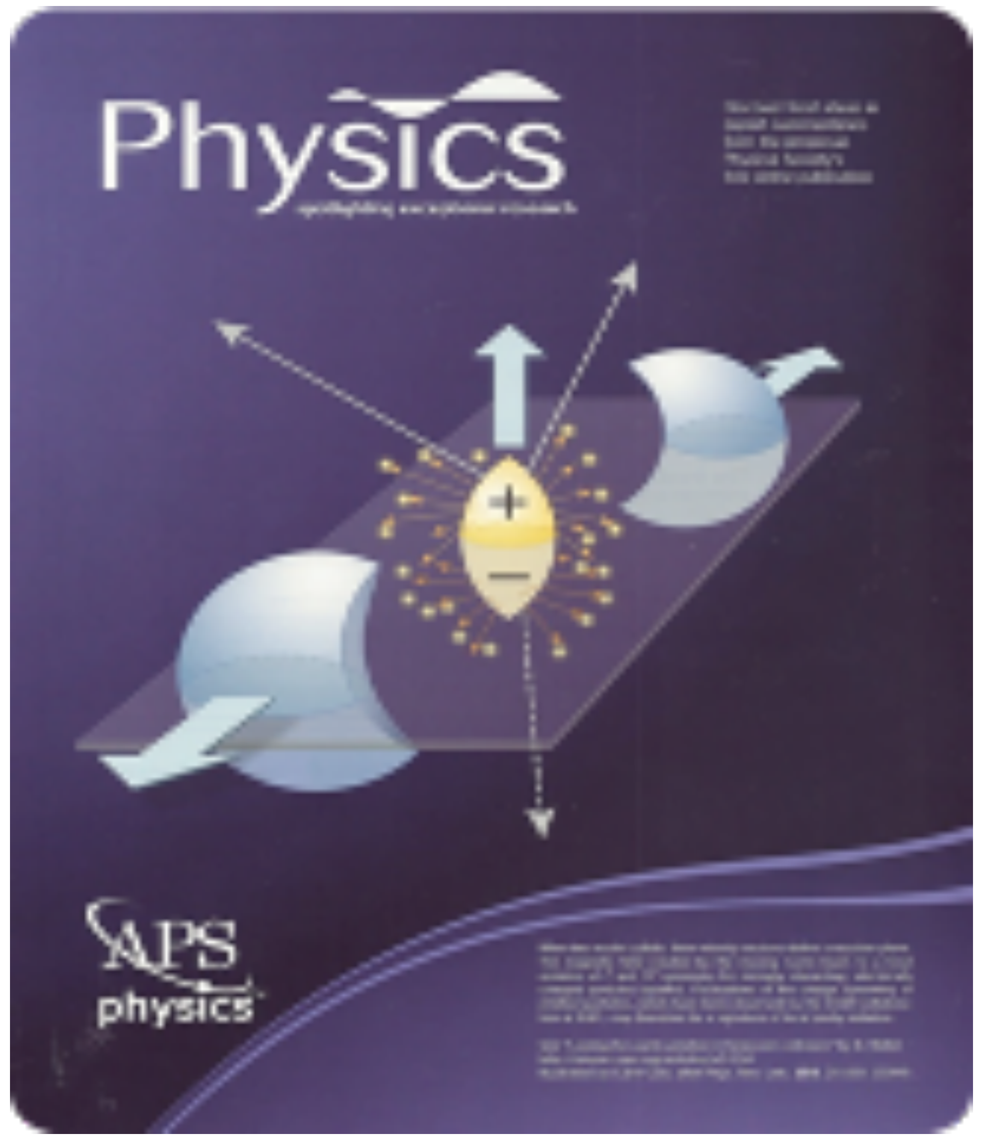
SEARCHES FOR CHIRAL ANOMALIES WITH ALICE





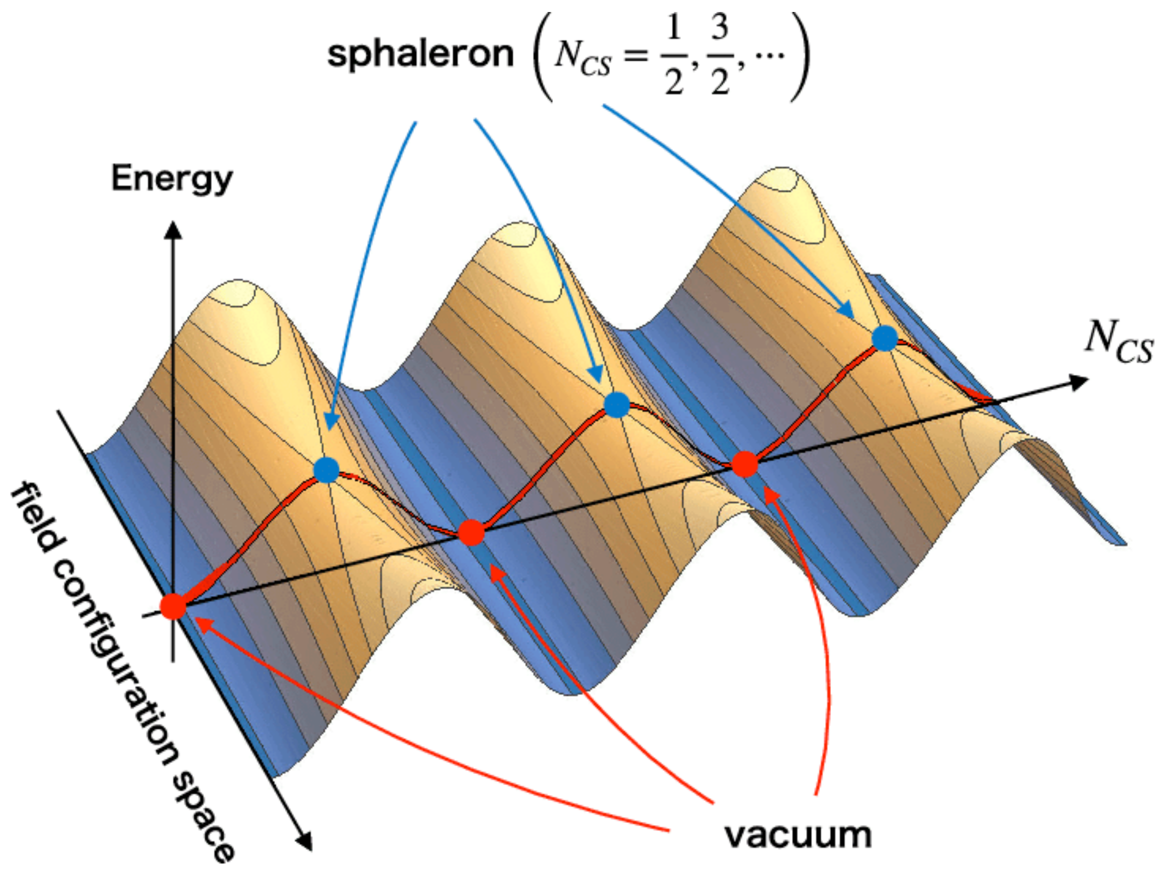




Panos Christakoglou

Nikhef

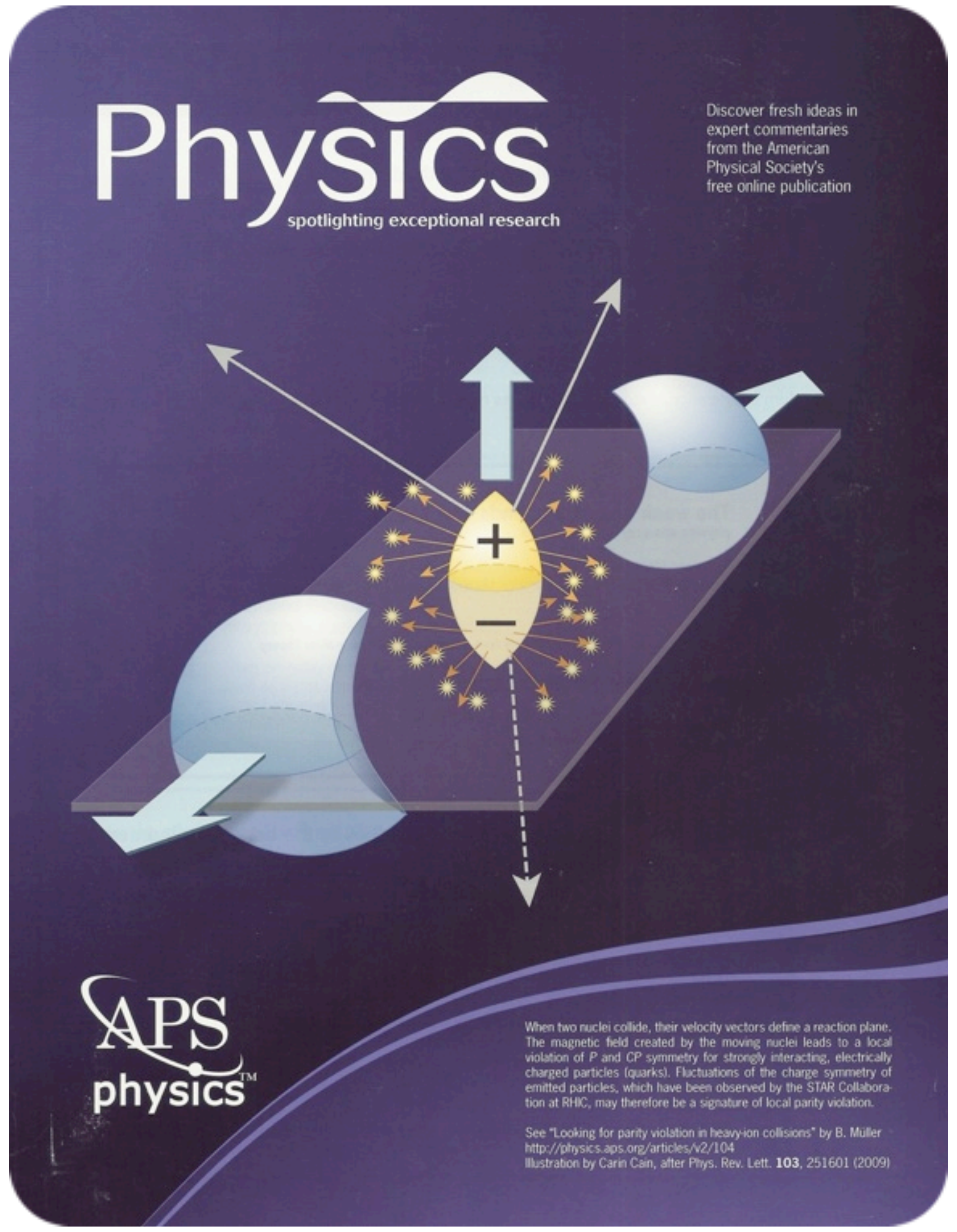
CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



Chirality imbalance

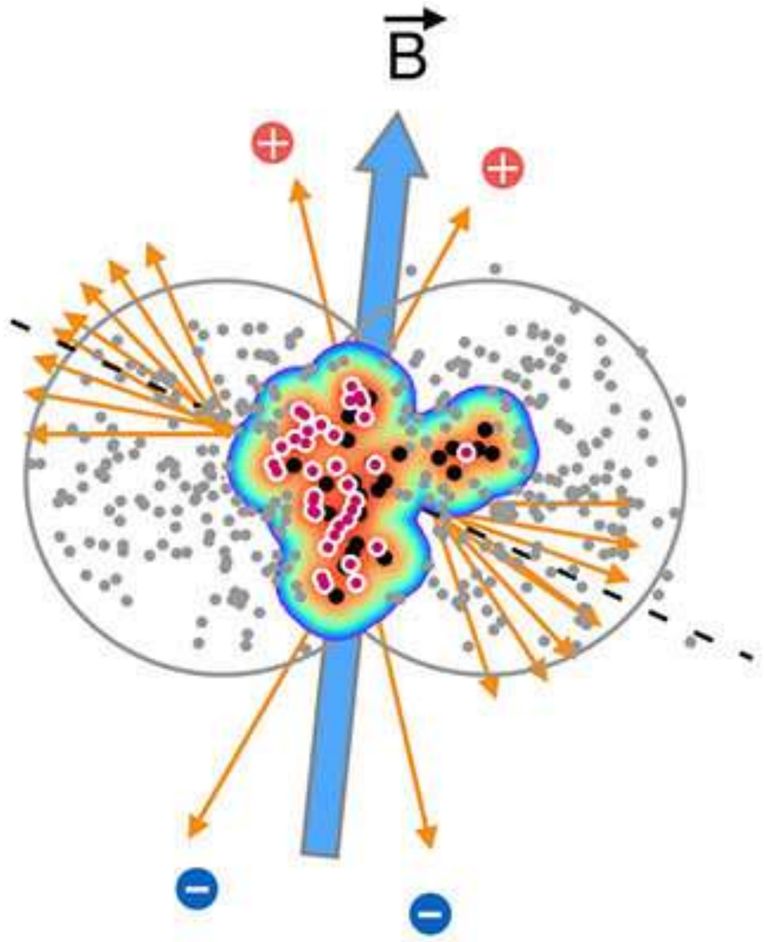
$$\mu_5 = N_L - N_R$$

Chiral Magnetic Effect (CME)



Anomalous transport

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



Magnetic field

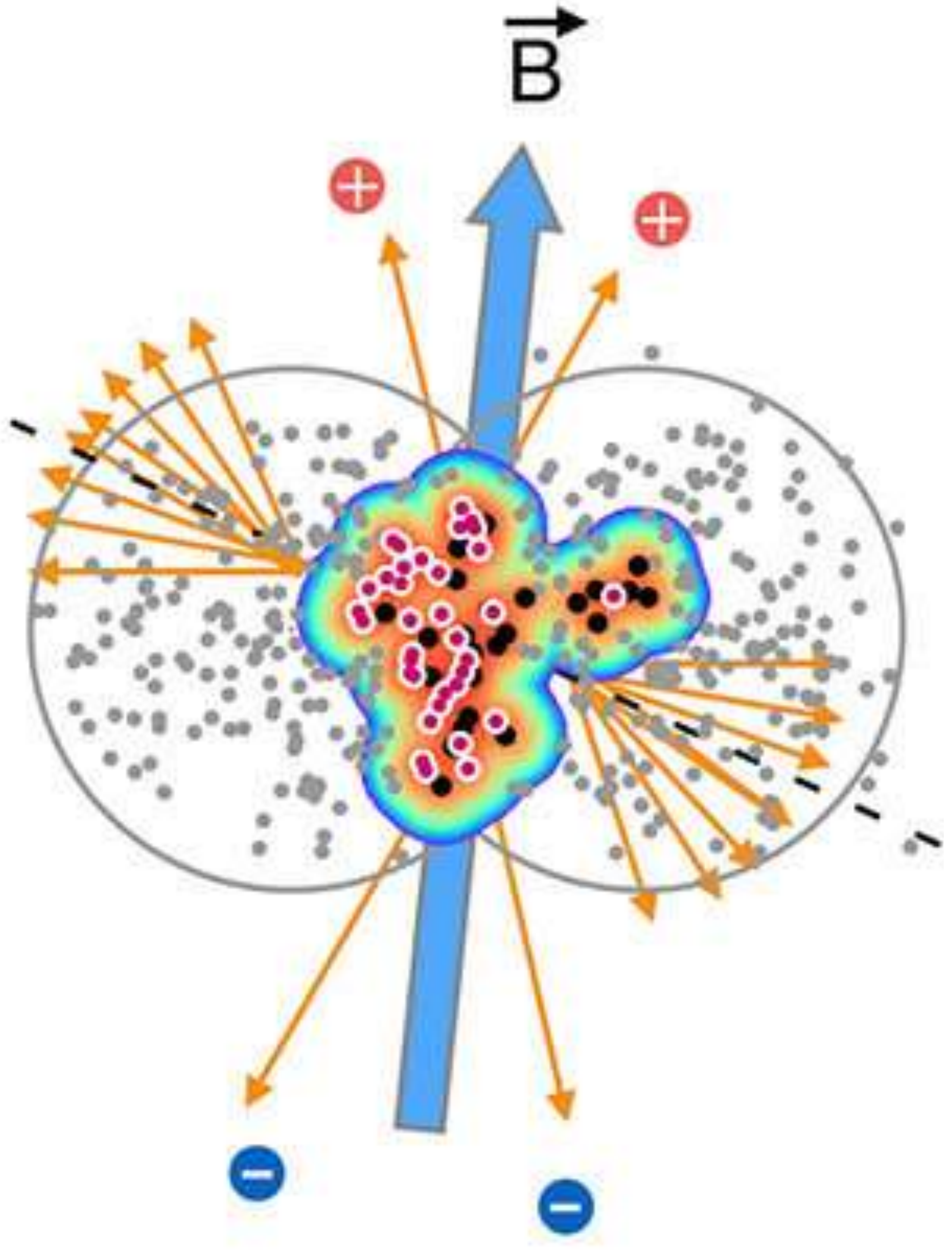
$$B \approx \gamma Z e \frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{\mathrm{NN}}}}{2m_{\mathrm{p}}}$$

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

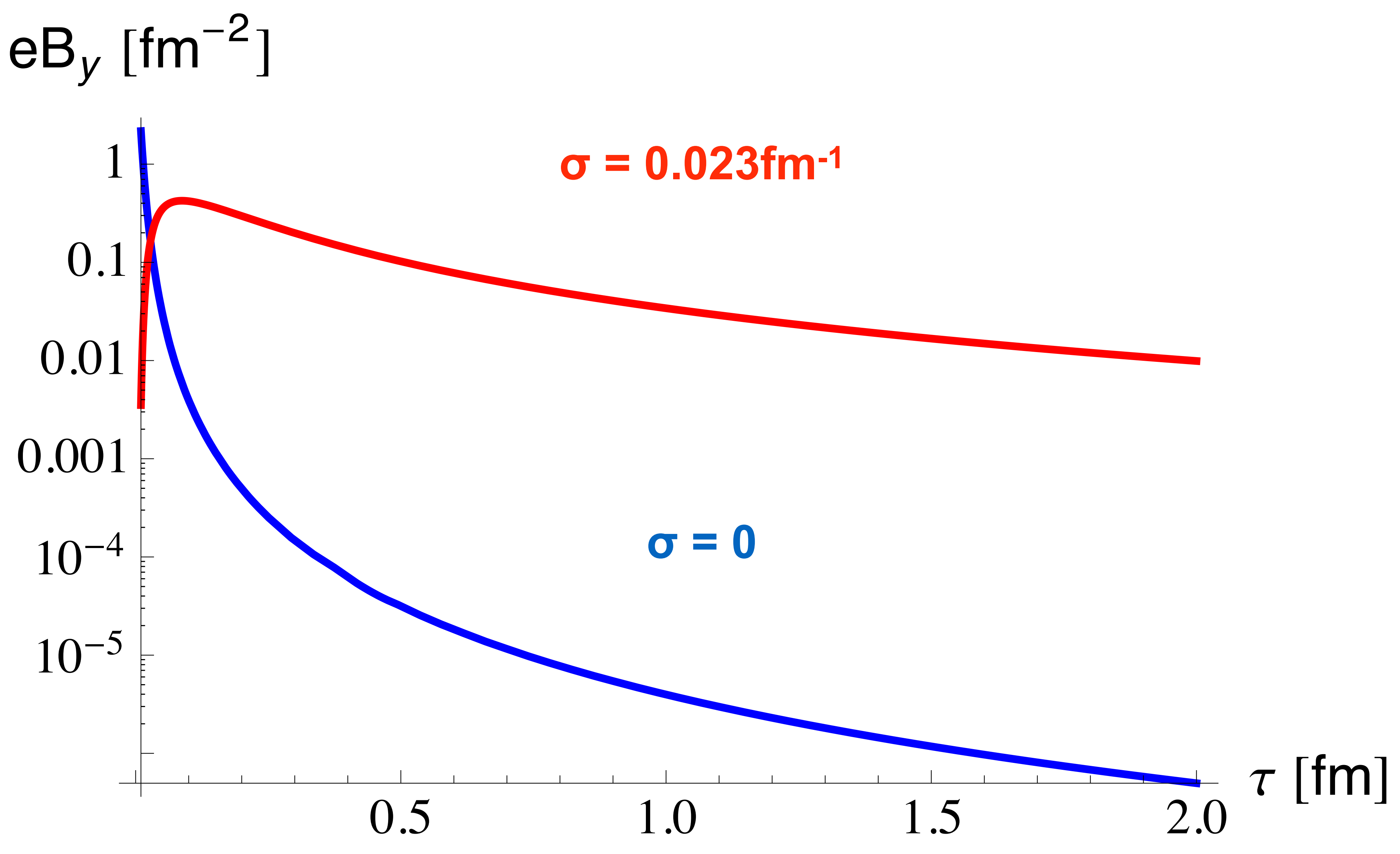
THE STRONGEST MAGNETIC FIELD IN NATURE…

$$\vec{B} = \frac{\mu_0}{4\pi}\int \frac{I d\vec{l}\times\hat{r}}{|\vec{r}|^2} \qquad B \approx \gamma Z e \frac{b}{R^3} \qquad \gamma = \frac{\sqrt{s_{\rm NN}}}{2m}$$

Au-Au collisions @ RHIC	Pb-Pb collisions @ LHC
$\sqrt{s_{NN}}$ = 200 GeV	$\sqrt{s_{NN}}$ = 2.76 GeV
γ = 100	$\gamma = 1.38\times10^3$
Z = 79	Z = 82
b = R_{Au} ~ 7fm	b = R_{Au} ~ 7fm
eB ~ m_π^2	eB ~ $10m_\pi^2$



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



Heavy ion collisions: ~10^{19} G

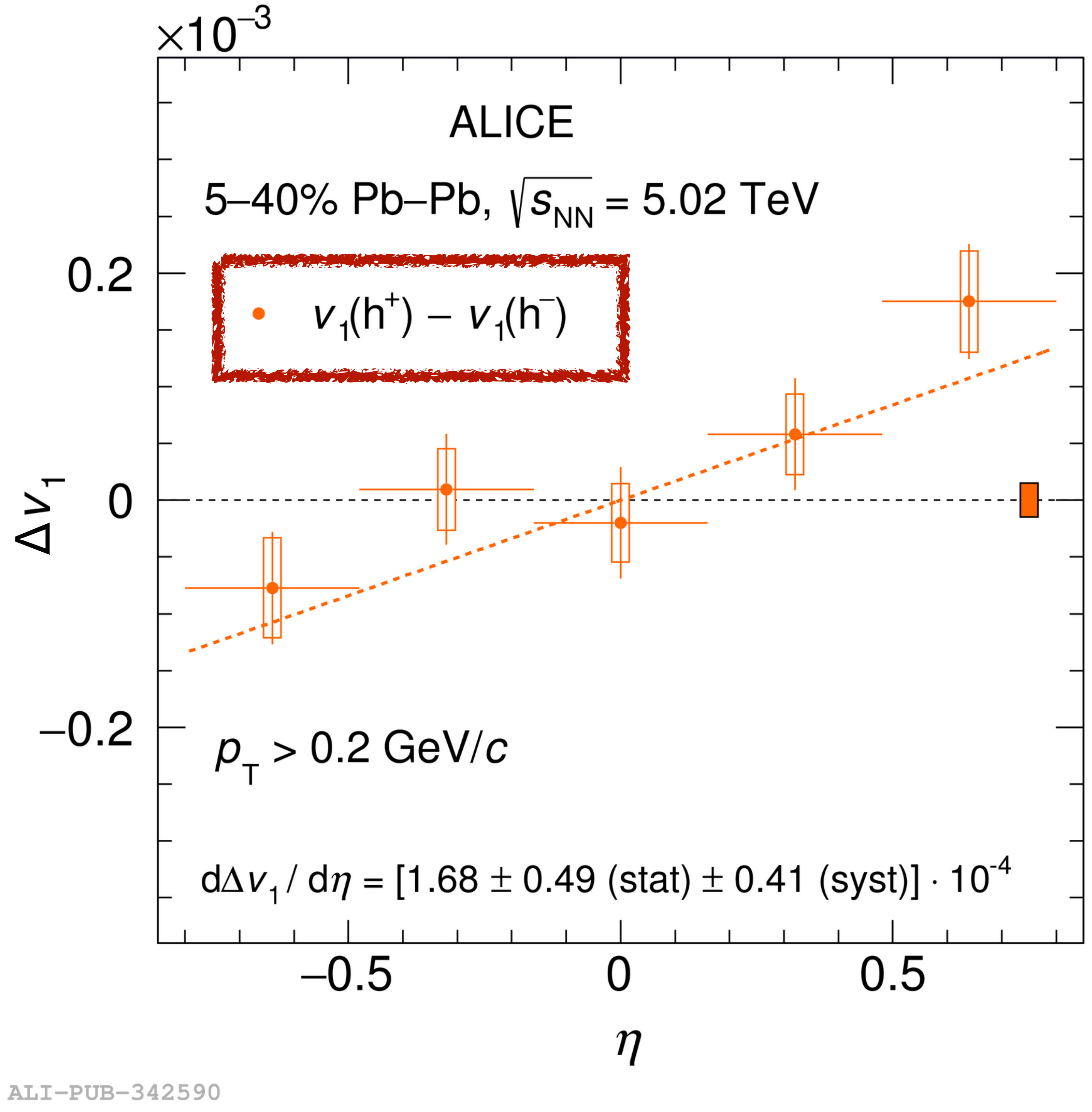
Decay rate depends on electric conductivity → unconstrained experimentally

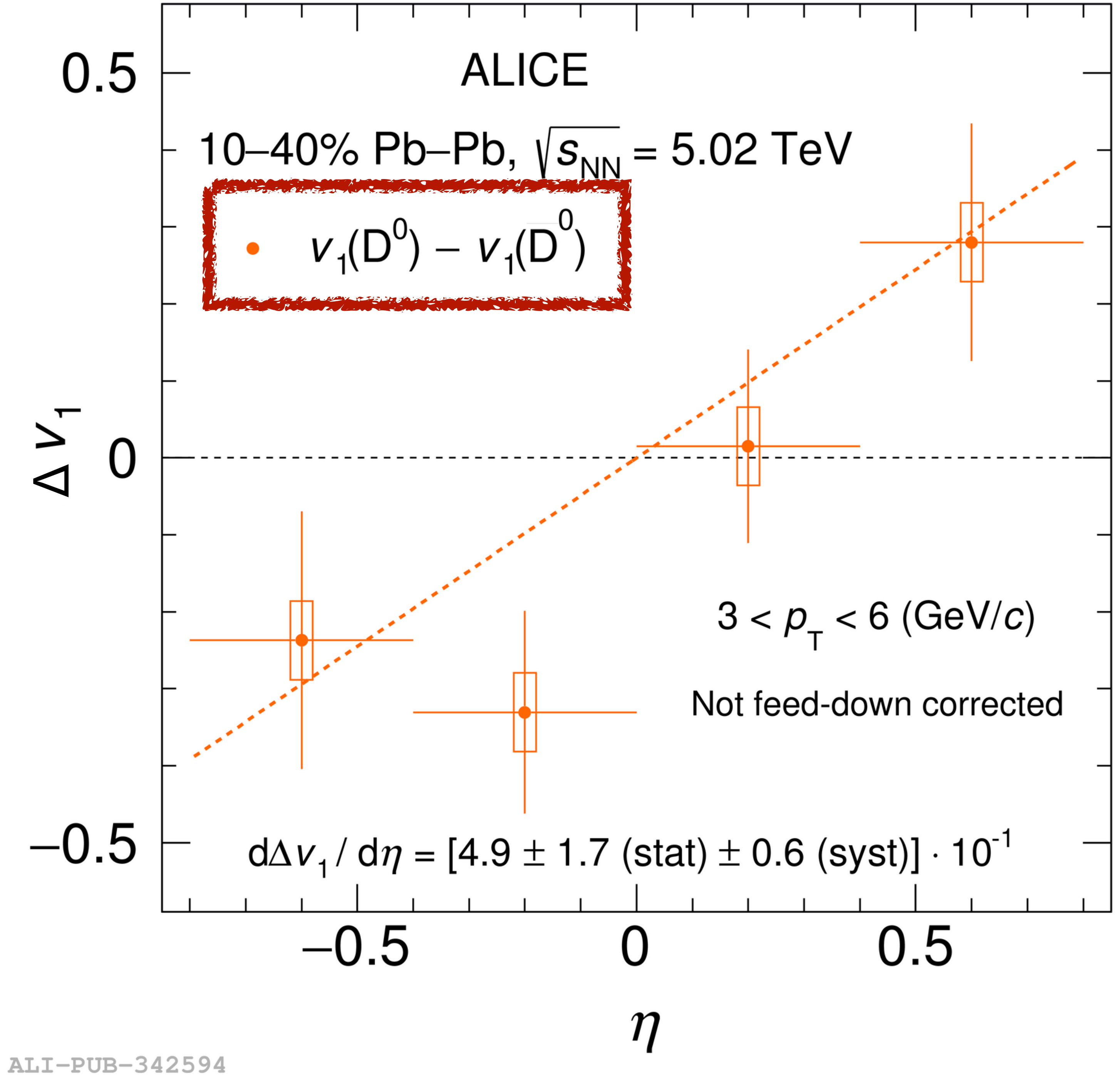
EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

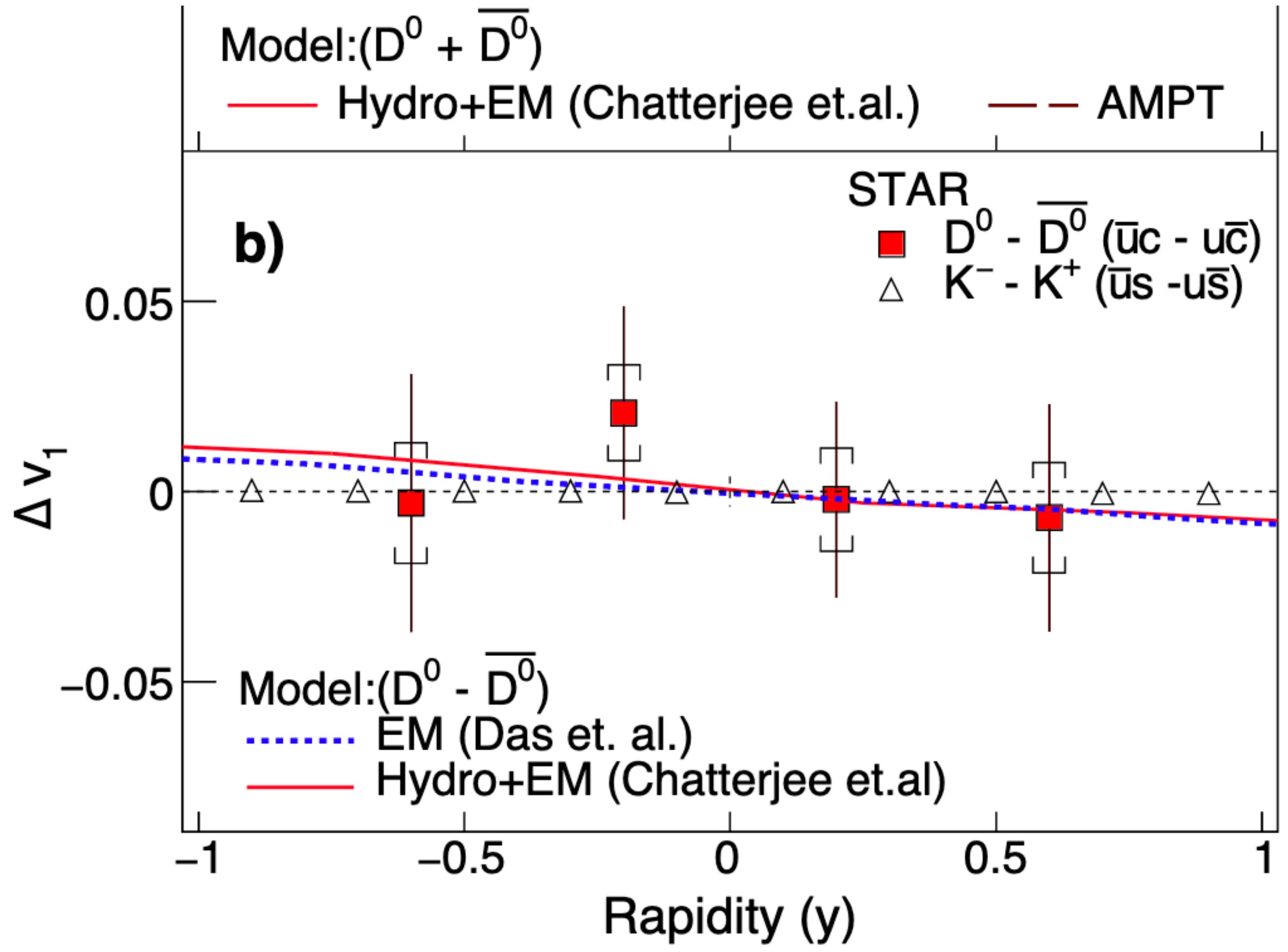
(ALICE Collaboration), Phys. Rev. Lett. 125, 022301 (2020)

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

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







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

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

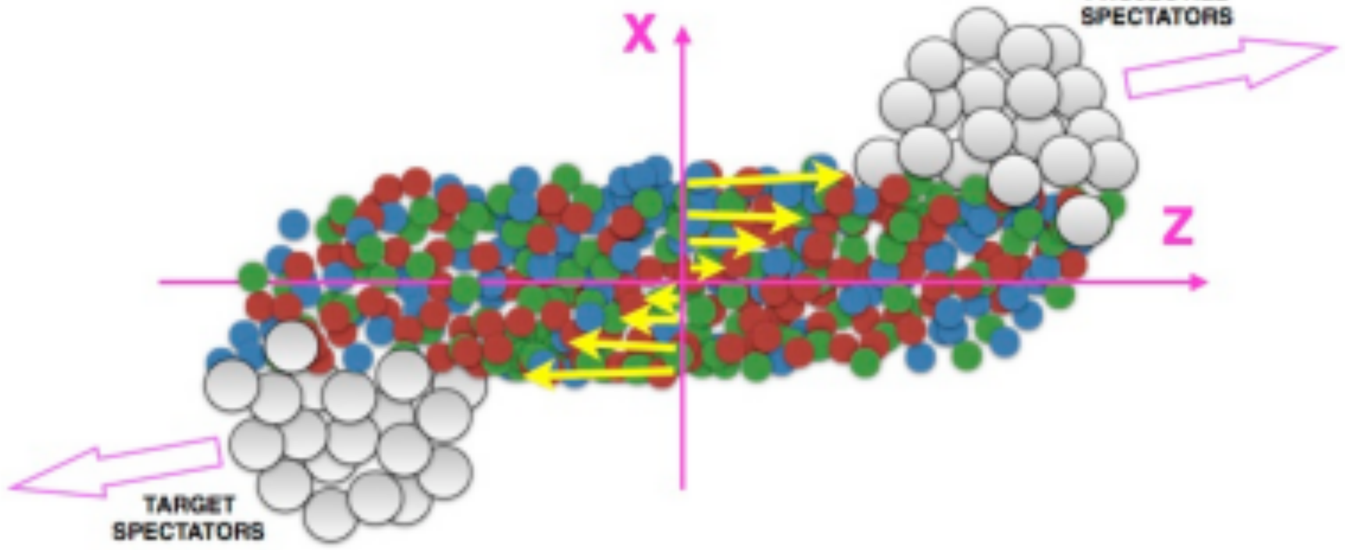
Magnitude smaller than theory expectation and sign reversed

- Larger contribution from the Lorentz force?

Effect @RHIC ~10 times smaller

EXPERIMENTAL PROBE: GLOBAL POLARISATION

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



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

Part of L remains I'm the overlap region → rotating QGP

QGP exhibits vortical structure affected by the local velocity field

Spin proportional to magnetic moment

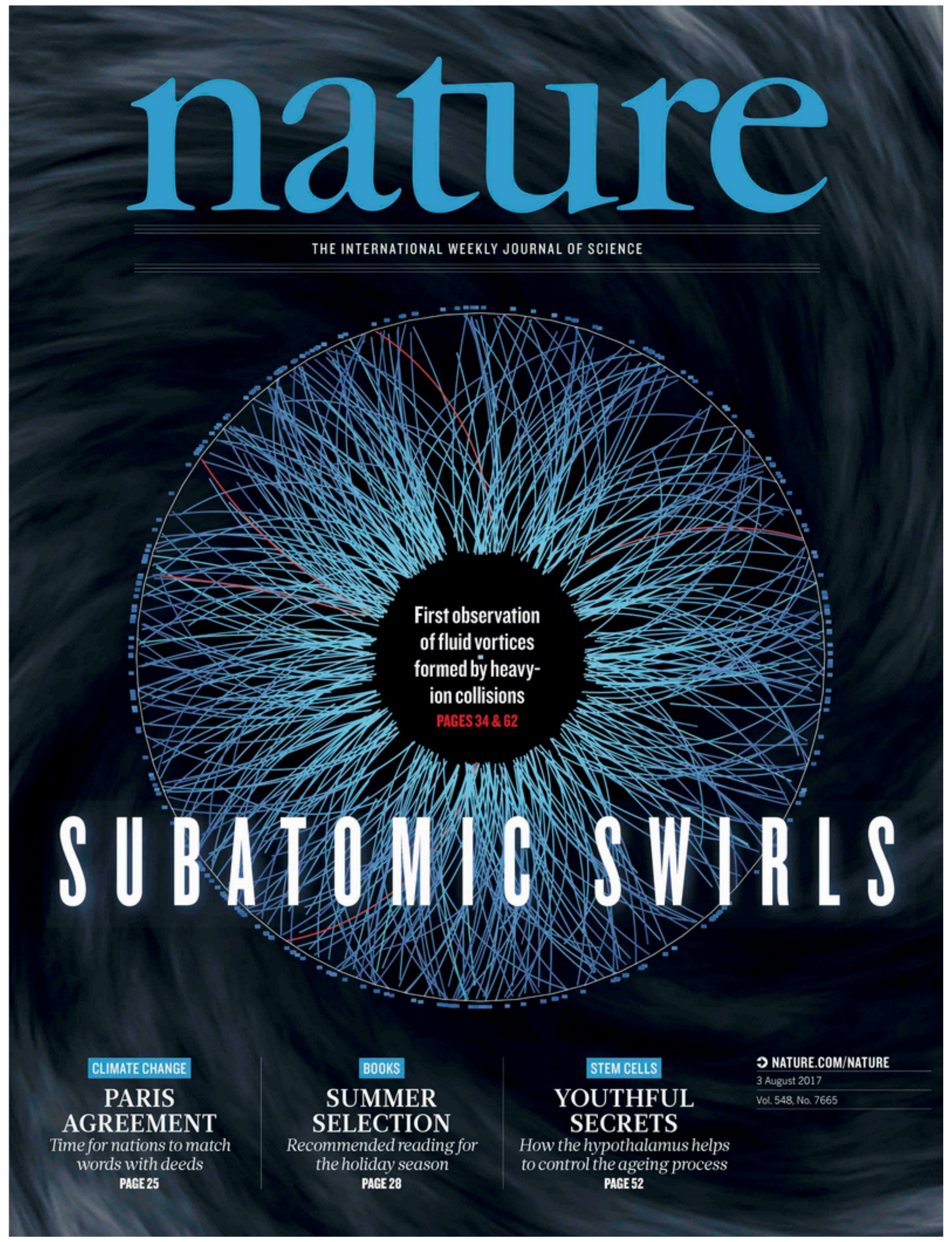
- Particles tend to be polarised along the initial angular momentum of the QGP
- Opposite effect for particles and antiparticles

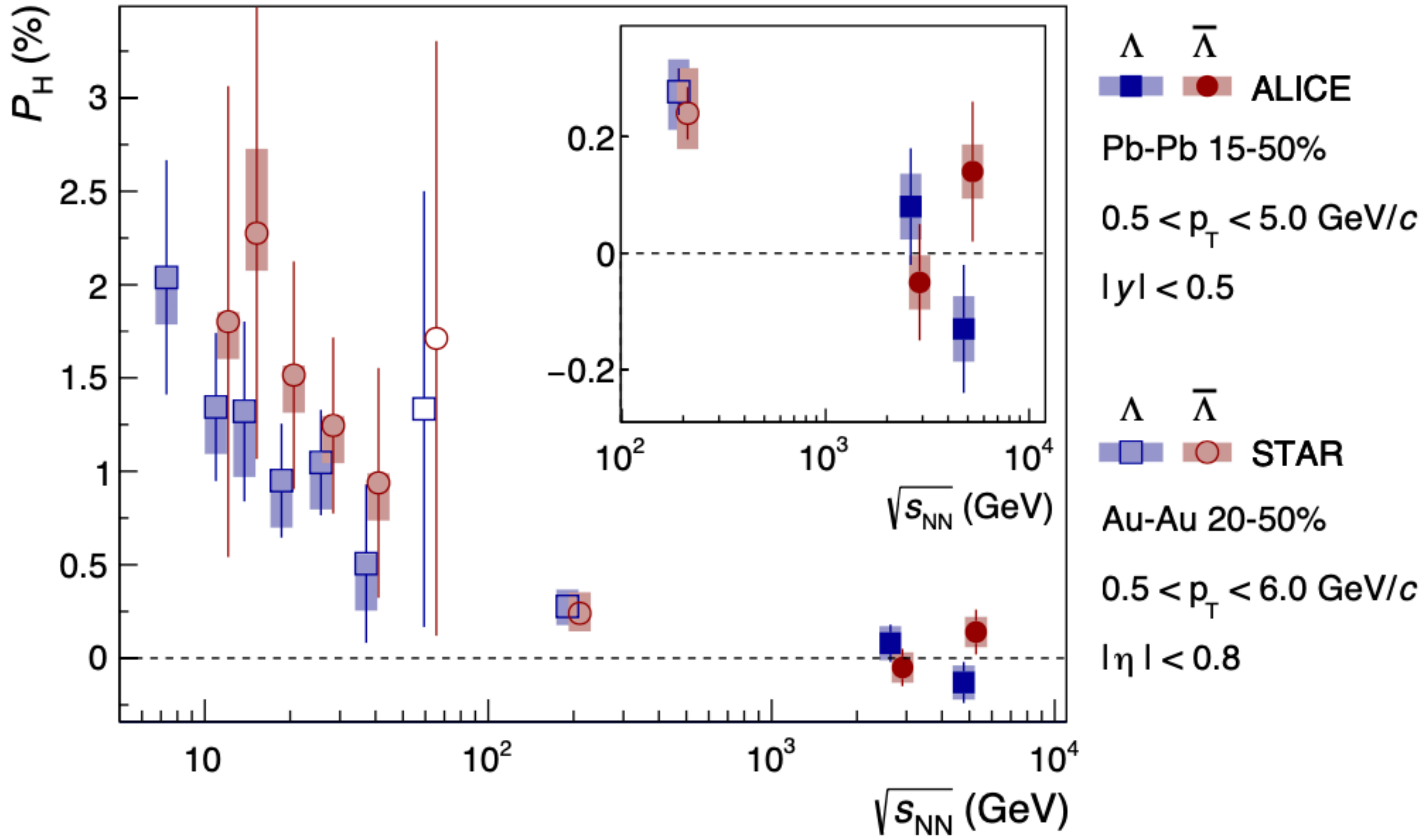
$$P_q^{\mathrm{B}} \approx \mu_q \frac{\mathrm{B}}{\mathrm{T}} = \frac{Q_q}{2m_q}\frac{\mathrm{B}}{\mathrm{T}}$$

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

$$P_{\overline{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{\mathrm{T}} - \mu_\Lambda \frac{\mathrm{B}}{\mathrm{T}}$$

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



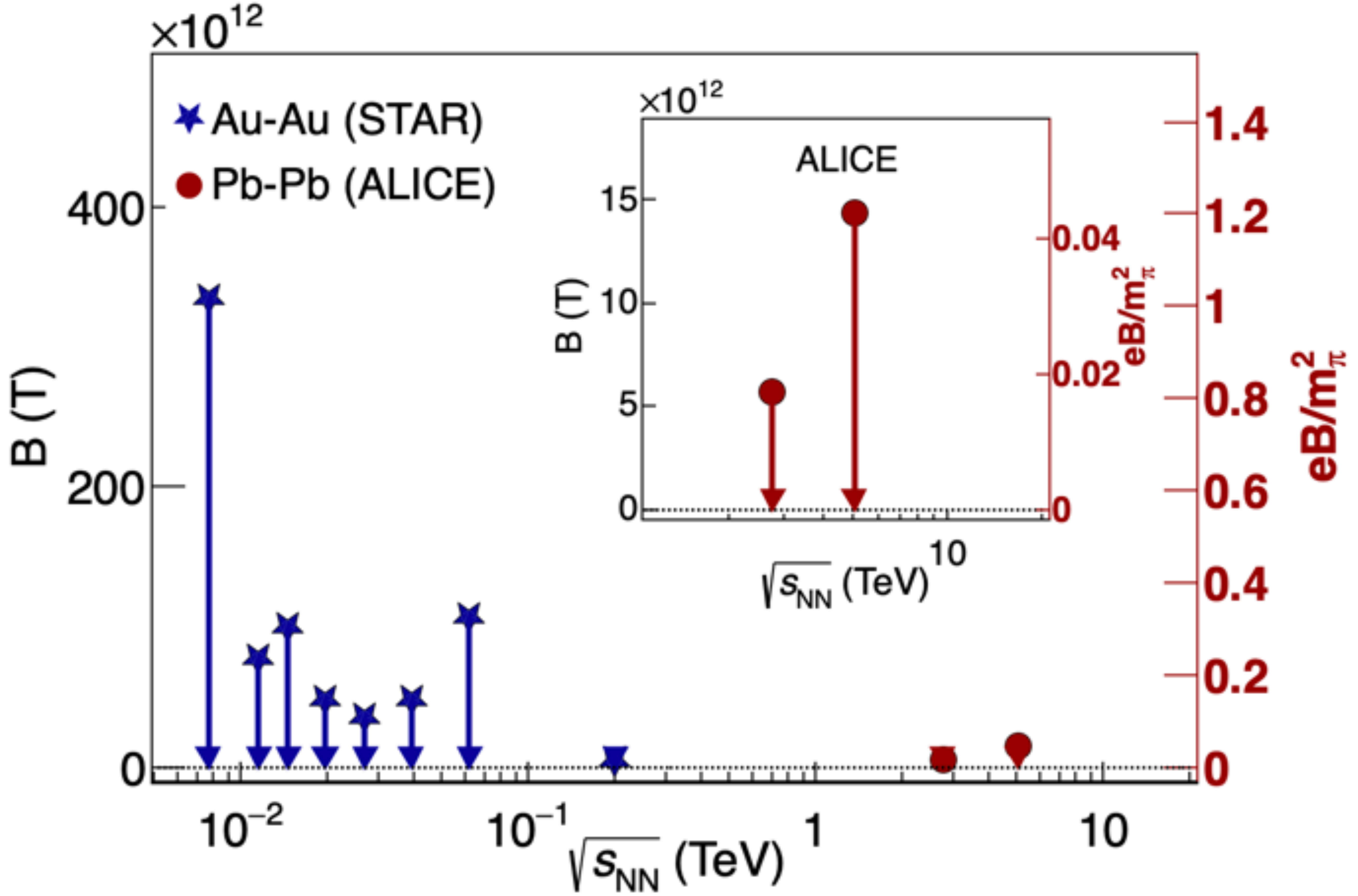


$$P_{\mathrm{H}} = \frac{8}{\pi\alpha_{\mathrm{H}}}\langle\sin(\Psi_{\mathrm{RP}} - \varphi_{\mathrm{p}})\rangle$$

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

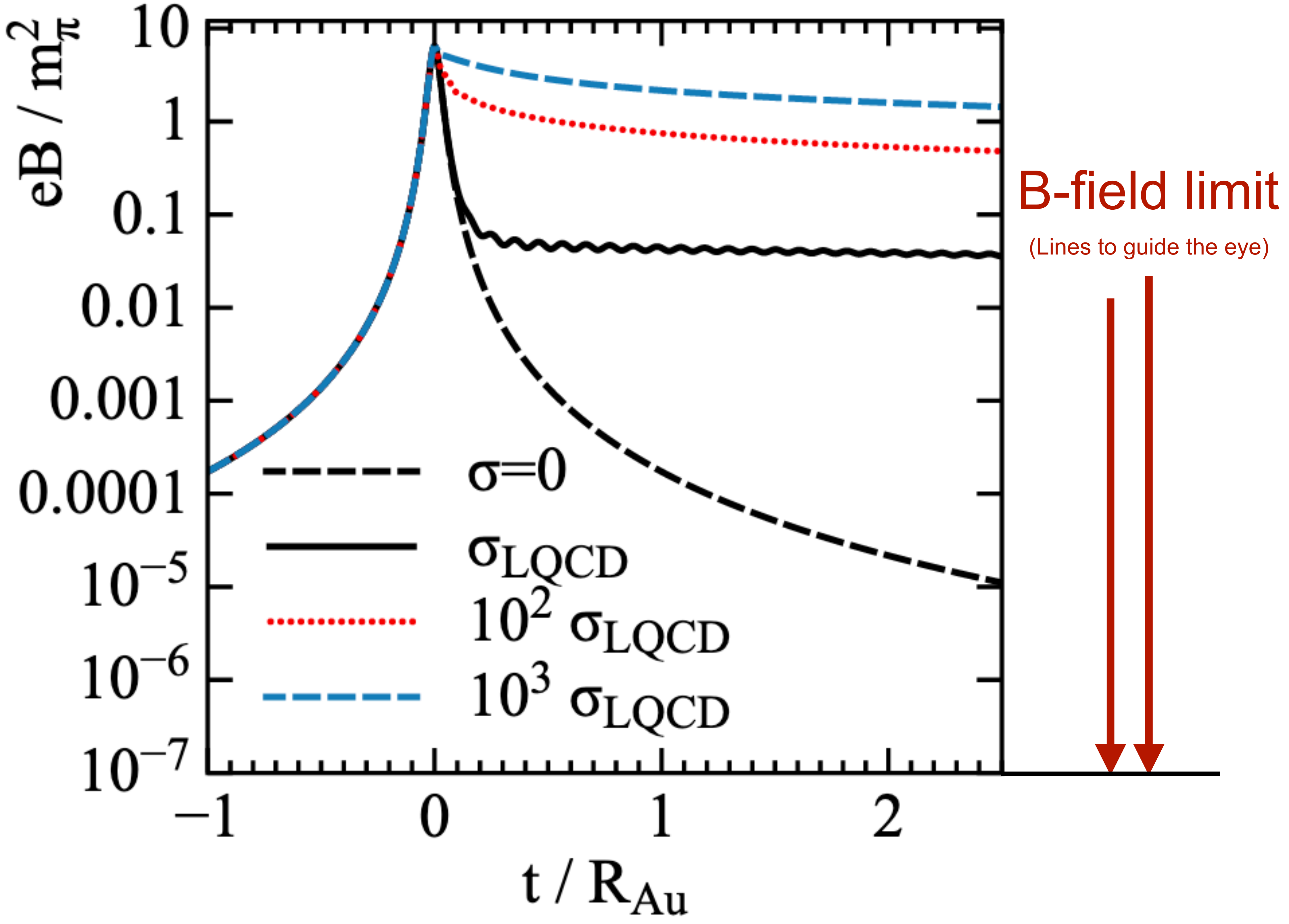
No significant difference between Λ and anti-Λ ➞ (still) not sensitive to effects due to magnetic field

EXPERIMENTAL CONSTRAINS ON B



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

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



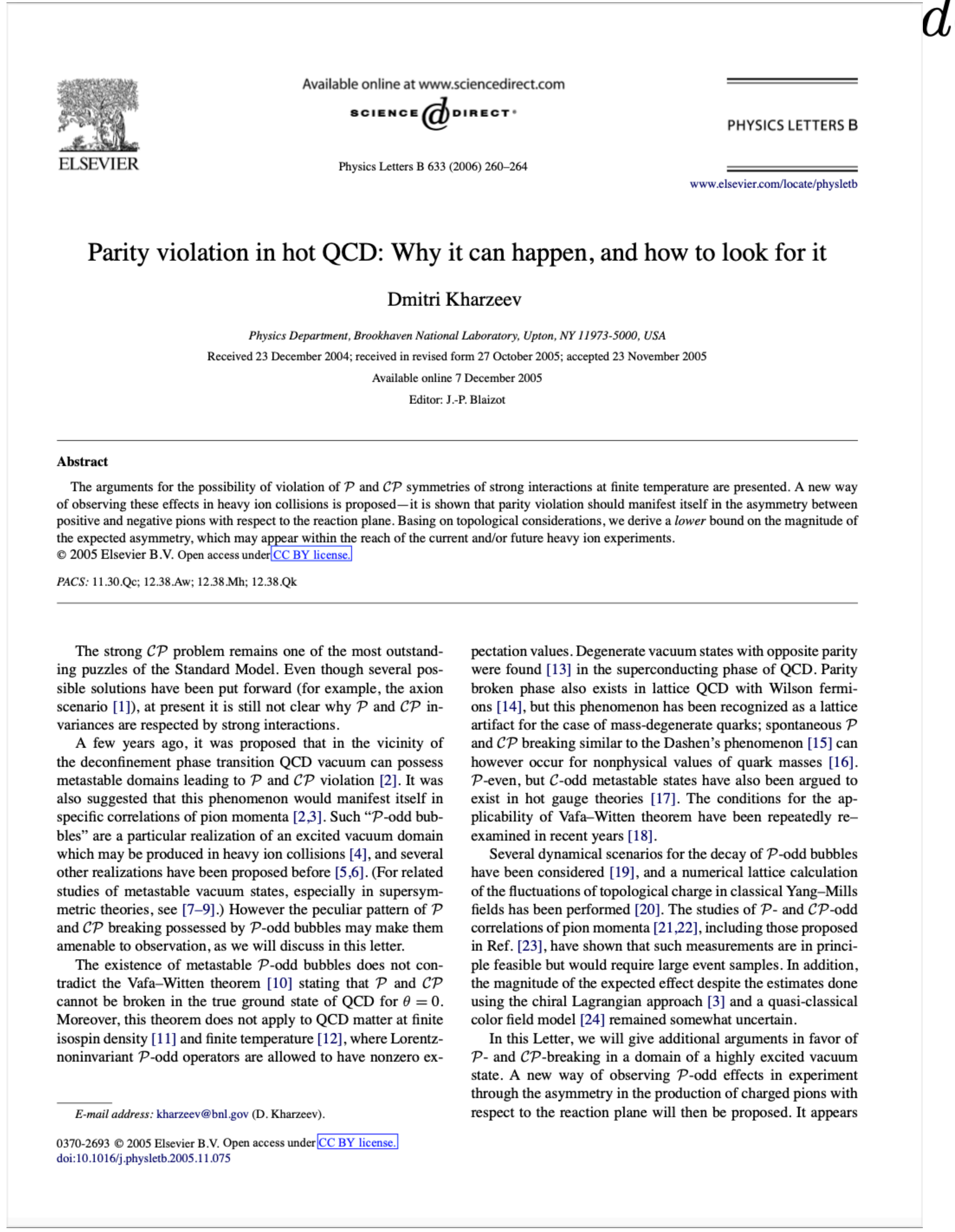
B-field limit

(Lines to guide the eye)

SEARCH FOR NOVEL QCD PHENOMENA…

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

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



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Parity violation in hot QCD: Why it can happen, and how to look for it

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Available online 7 December 2005
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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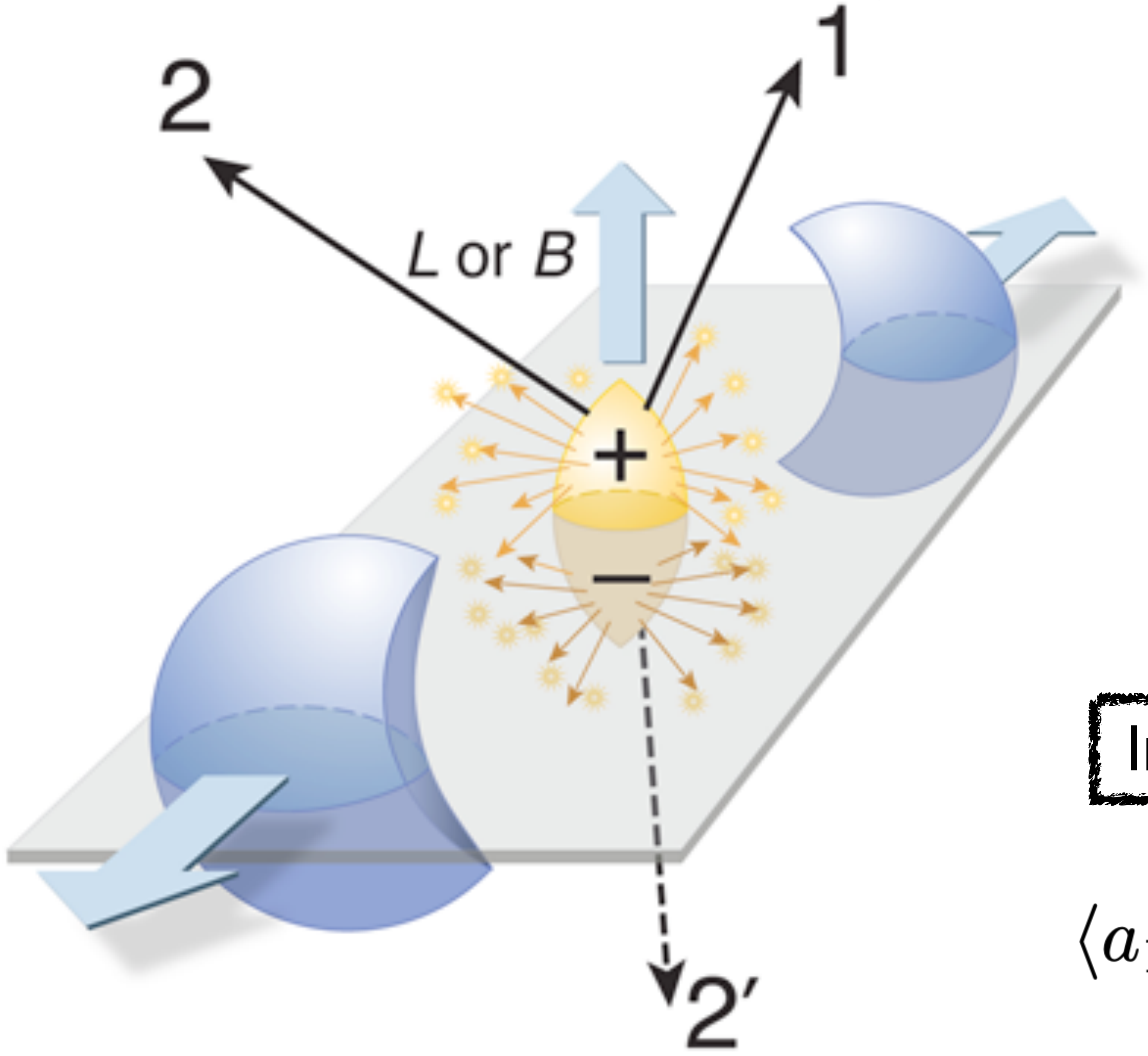
E-mail address: kharzeev@bnl.gov (D. Kharzeev).

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:

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

HOW DO WE TRY TO DETECT IT?

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

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

Parity conserving background effects projected in and out of plane

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

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

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

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

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

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

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

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

γ11

$$\gamma_{m,n} \equiv \langle \cos(m\varphi_a + n\varphi_\beta - (m+n)\Psi_{|m+n|}) \rangle$$

General form

$$\delta_m \equiv \langle \cos(m(\varphi_a - \varphi_\beta)) \rangle$$

δ1

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 ~ 0.1

FIRST LHC RESULTS

Significant charge dependent correlations also at LHC energies

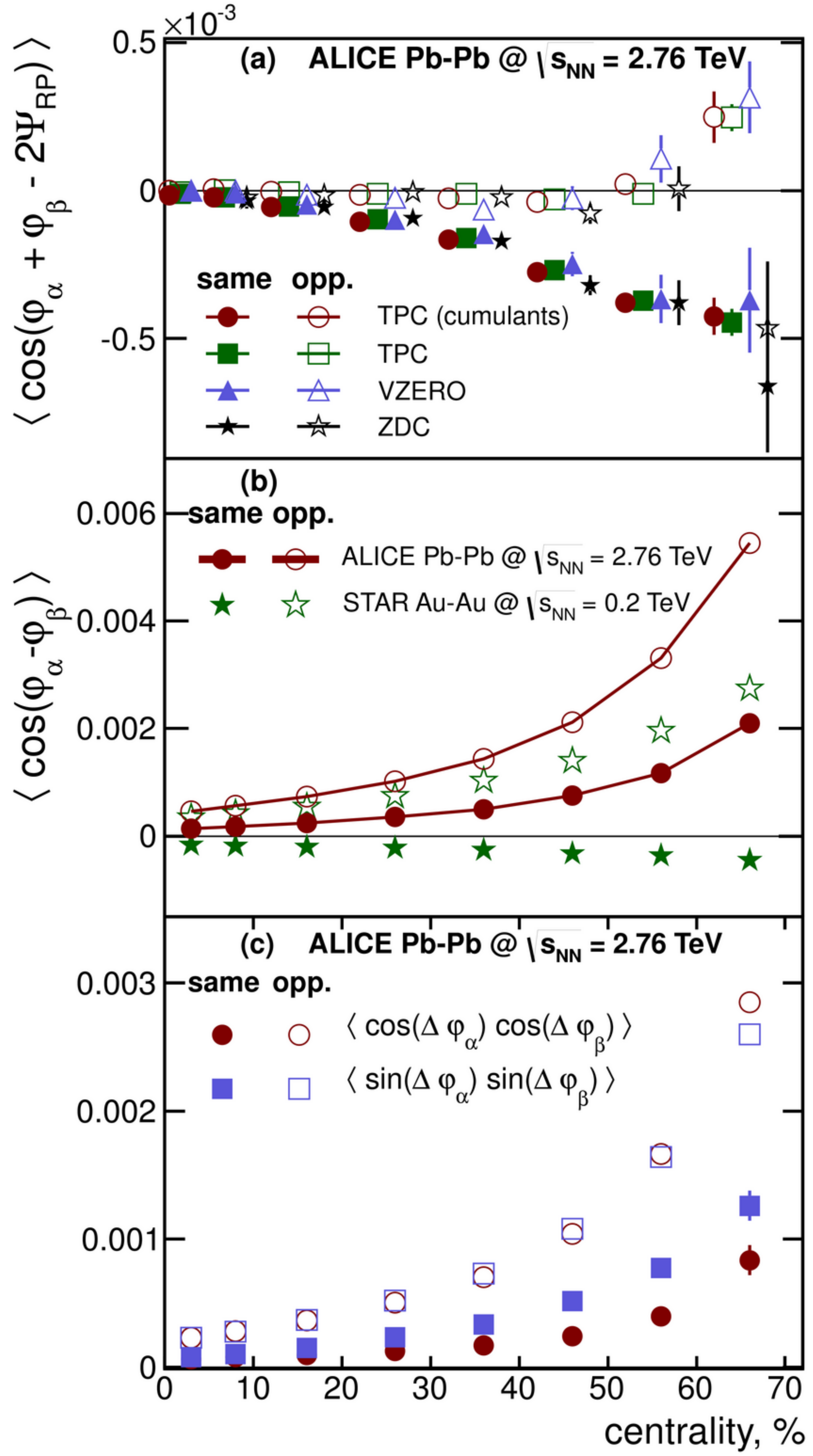
“Dominance” of ⟨sin · sin⟩ terms (proportional to $\langle a_{1,\alpha} \cdot a_{1,\beta} \rangle$) over the ⟨cos · cos⟩ terms for same sign pairs

Consistent with CME expectations

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

γ_{11}

δ_1



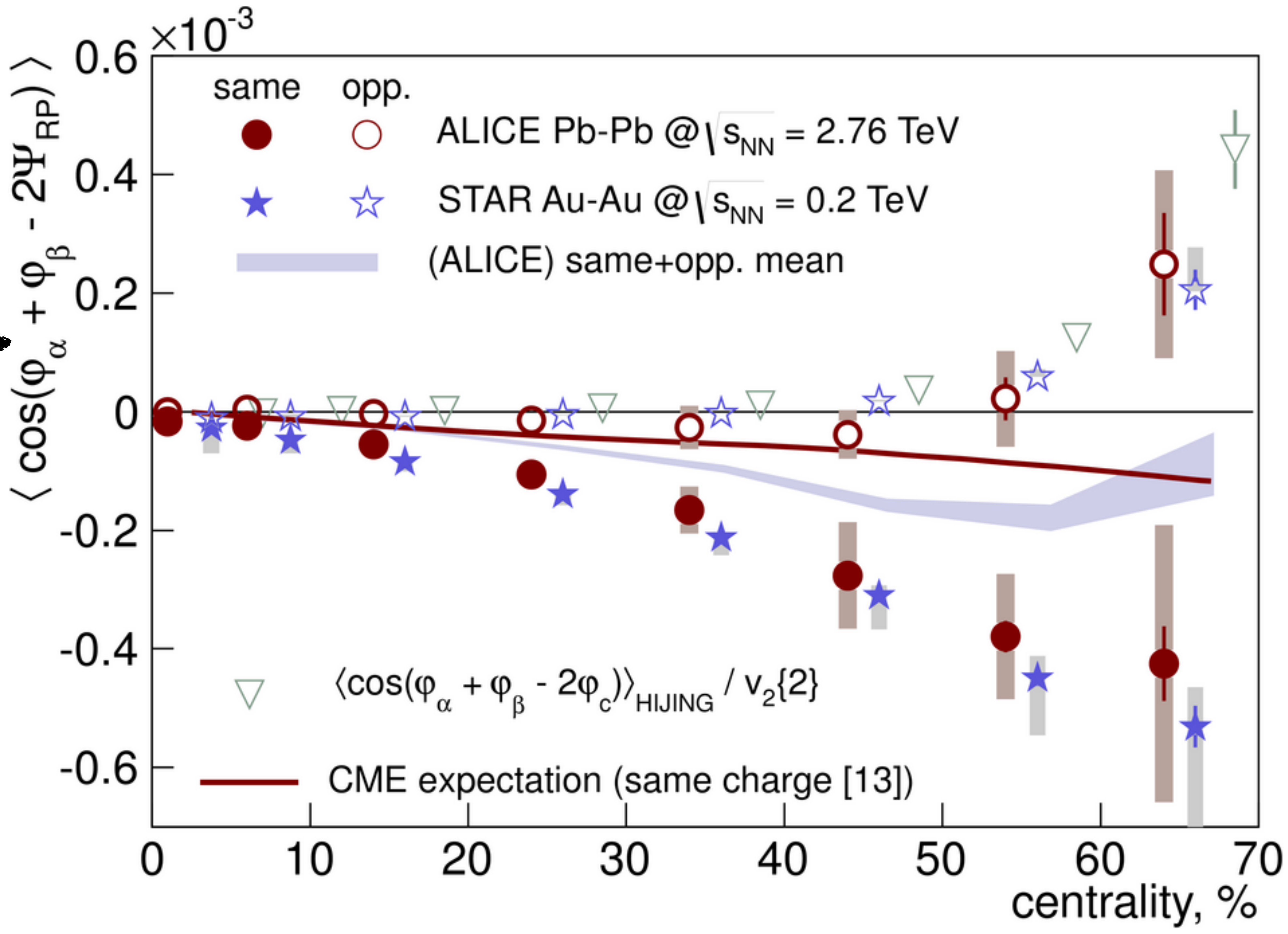
FIRST LHC RESULTS

Strong centrality dependent effects consistent with naive expectations from CME

- But no significant energy dependence between RHIC and LHC

$\gamma_{1,1}$ →

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



Big surprise considering the difference in energy, particle density,…

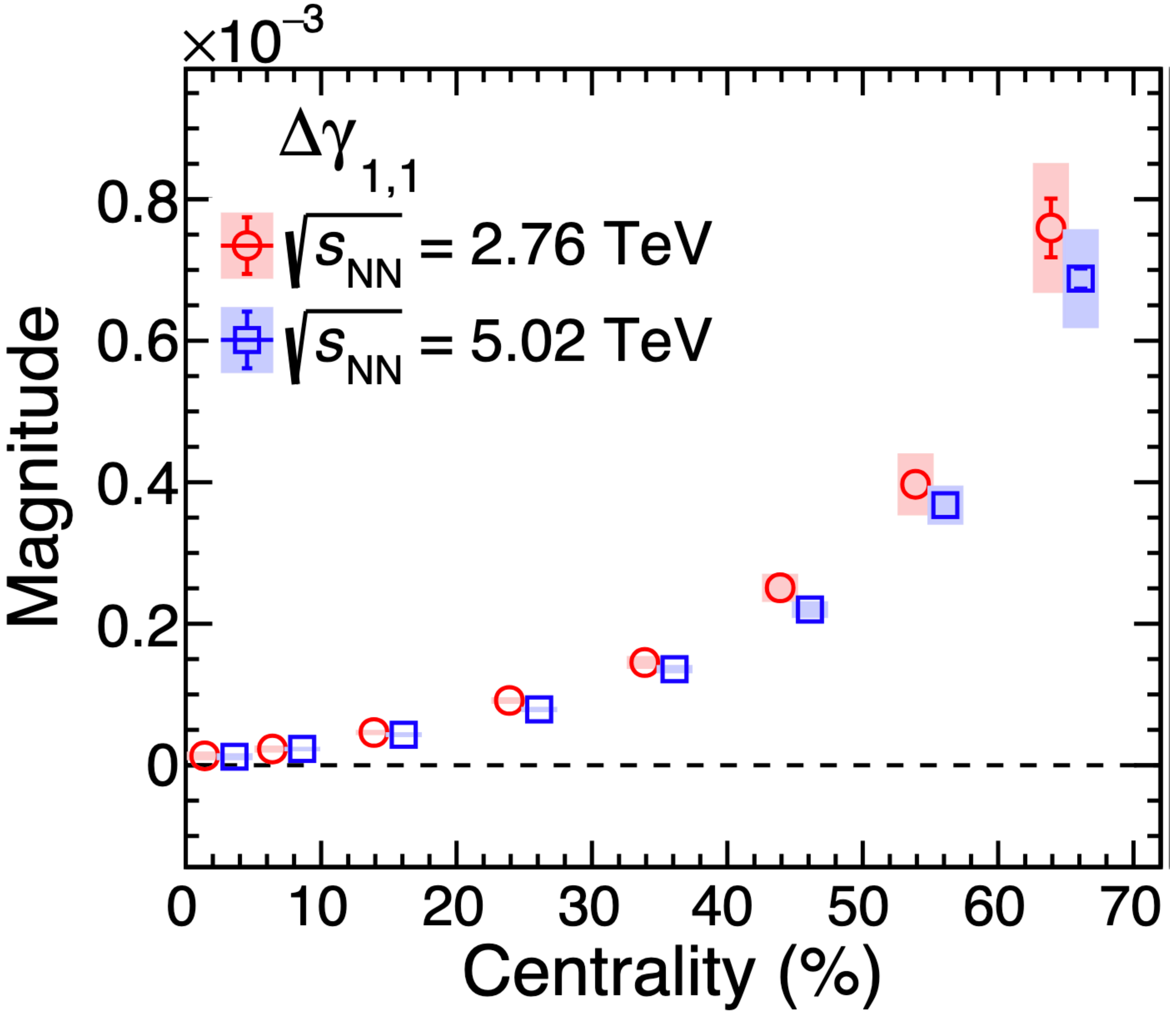
RESULTS @ LHC ENERGIES

CME results consistent (within uncertainties) between the two LHC energies

Background doesn't change much between the two energies

- v_2 changes by ~3%
- Narrowing of the balance function width the same within uncertainties

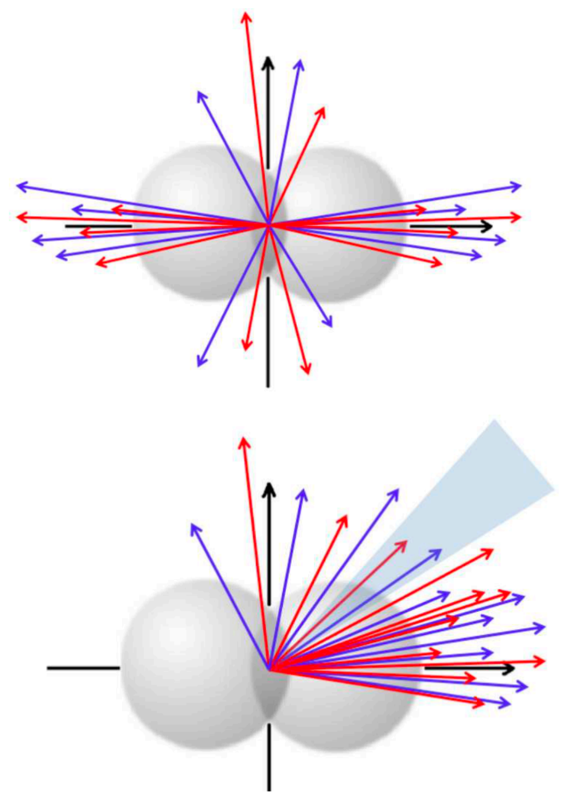
(ALICE Collaboration) JHEP 2020, (2020) 160



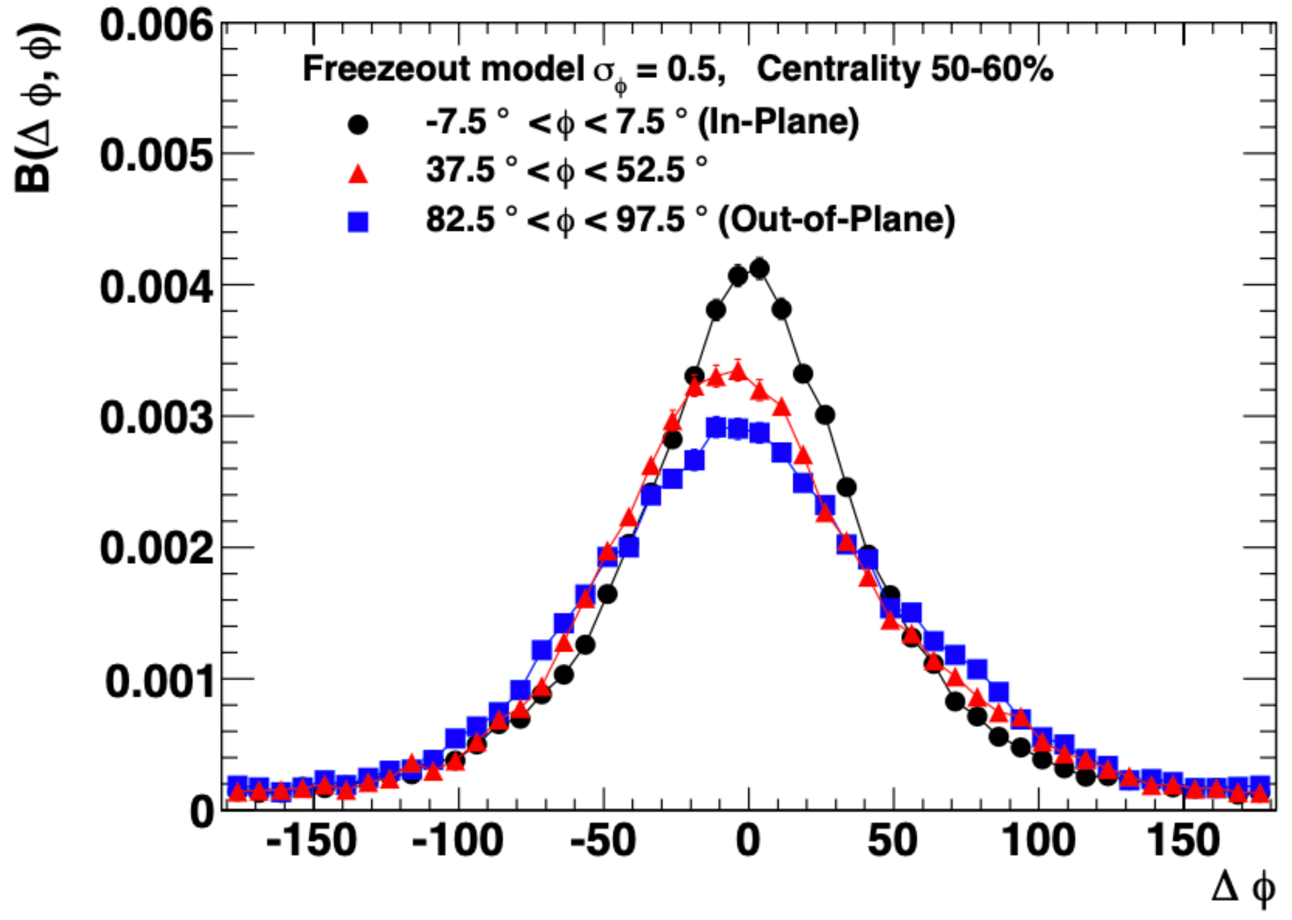
Goal: disentangle the CME signal from the background

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

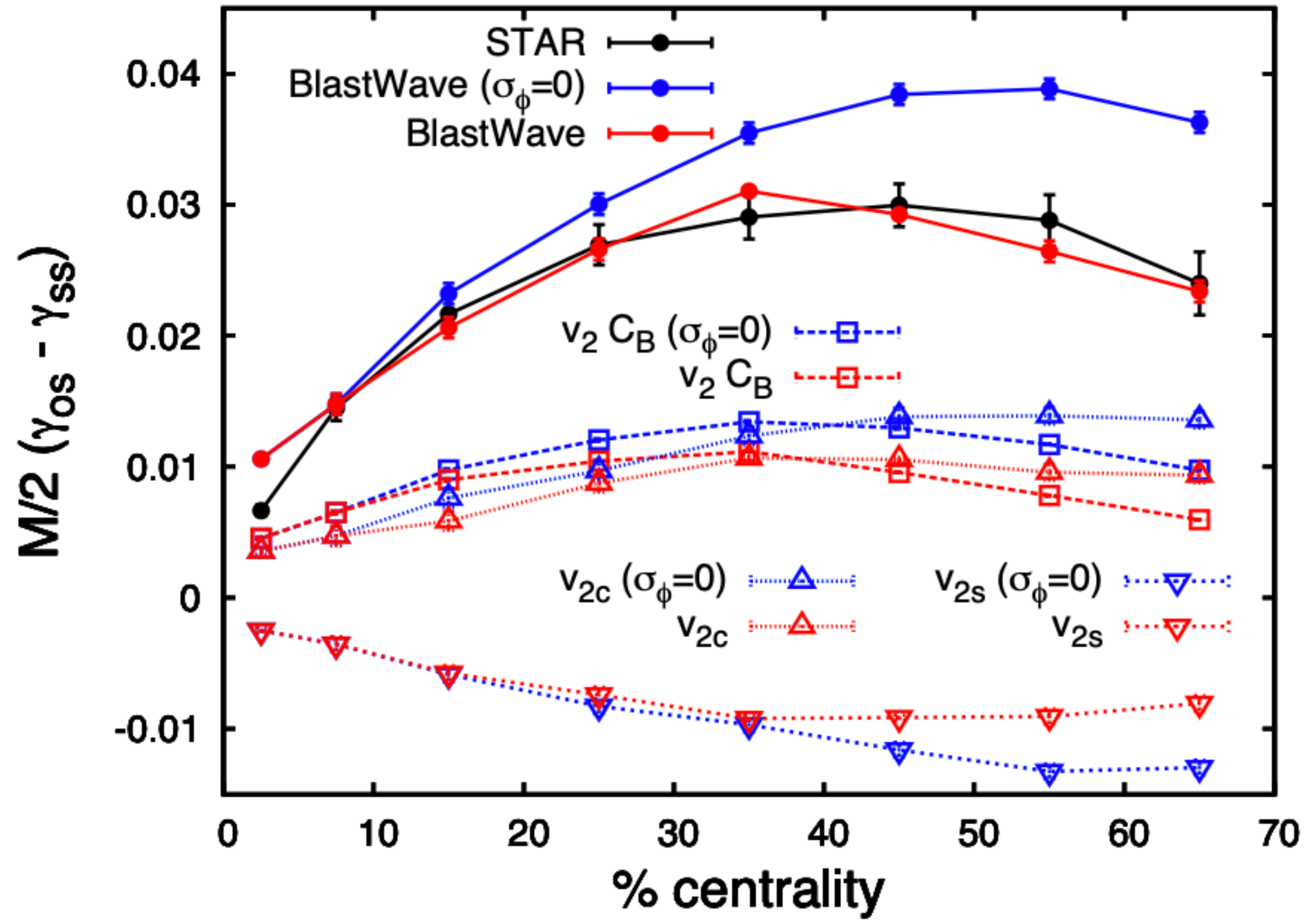
$v_{2,c}$: degree to which in-plane pairs are more tightly correlated than out-of-plane pairs

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

Main background component:

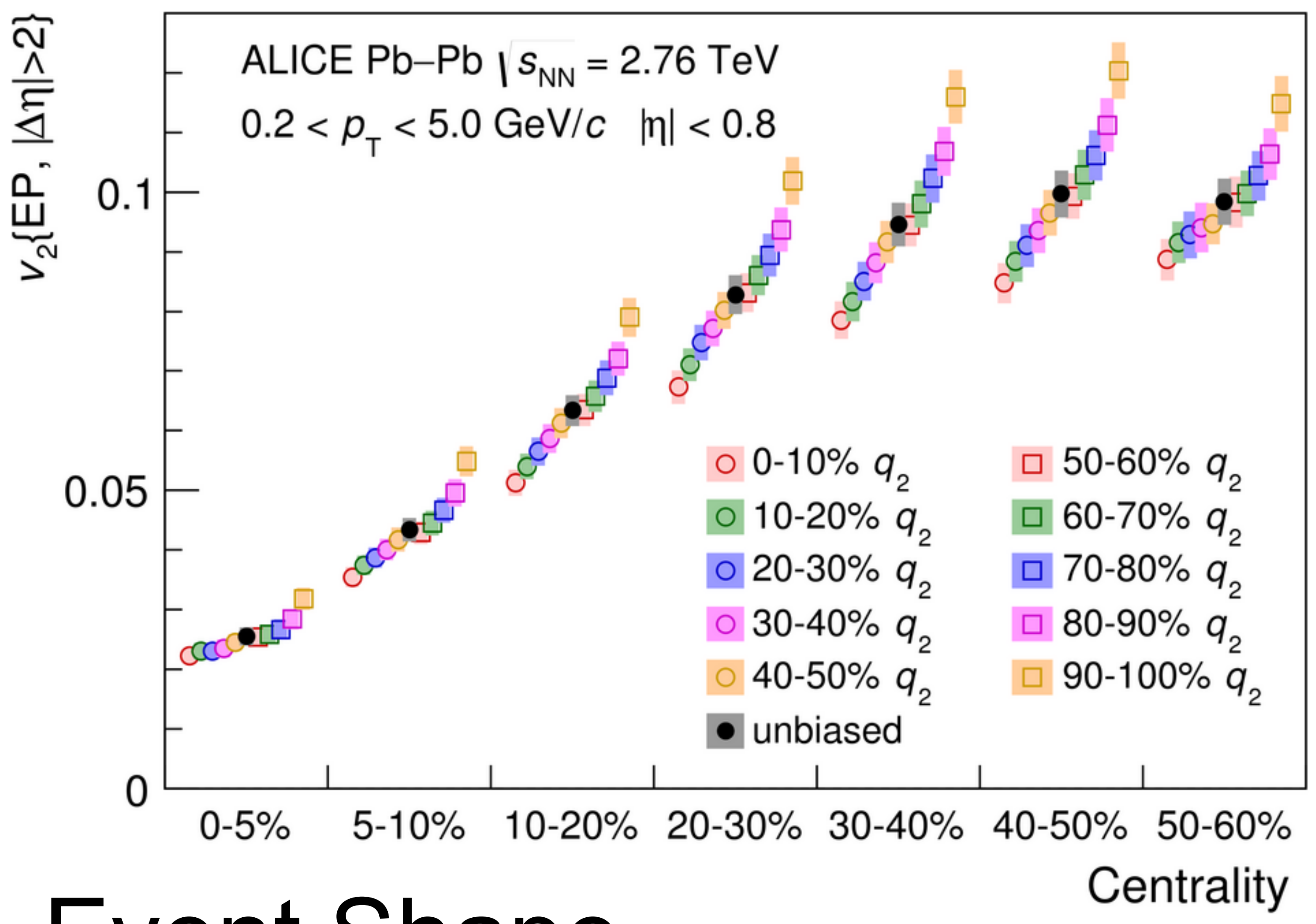
- Local charge conservation (LCC) coupled to anisotropic flow

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

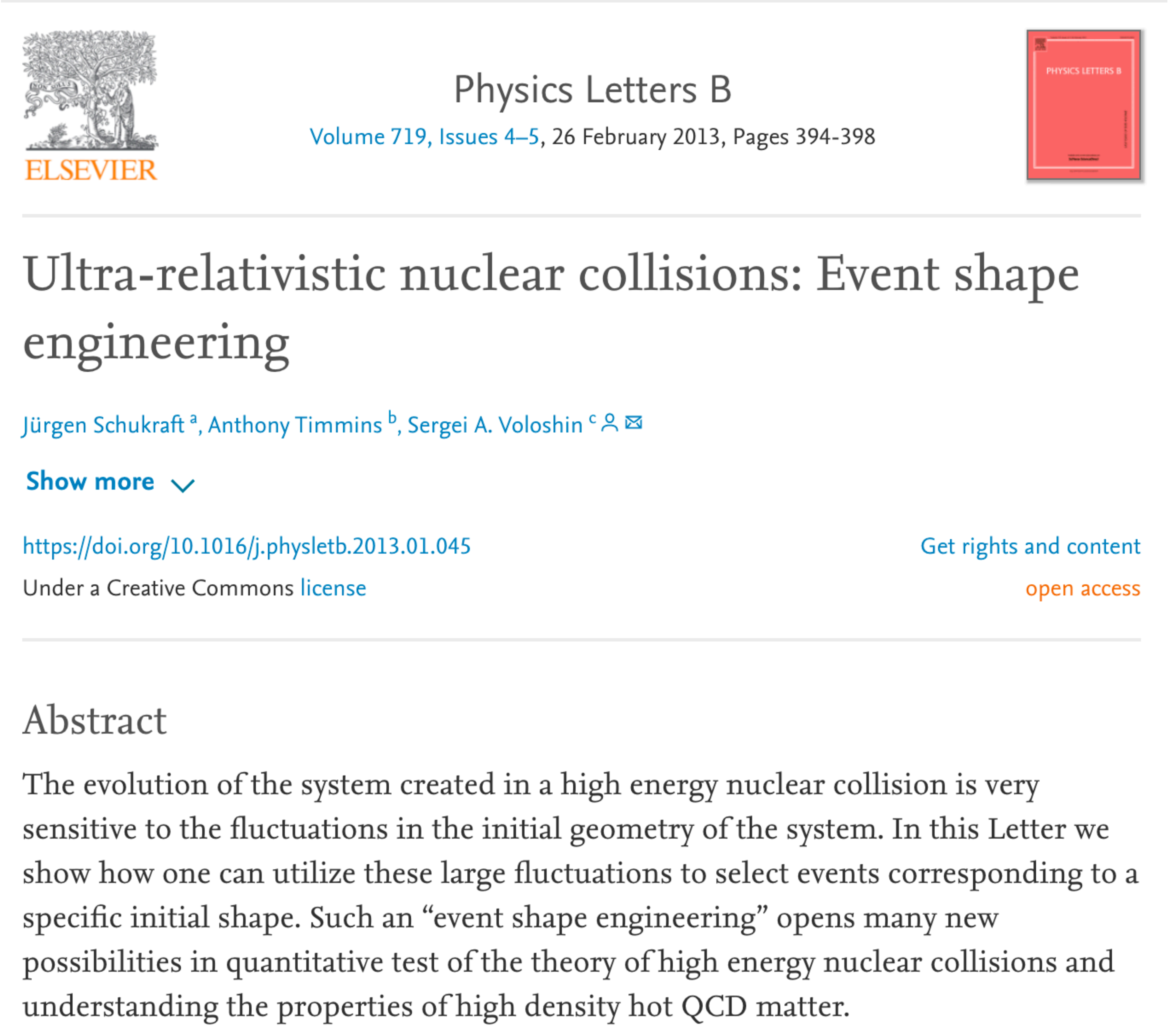


FIRST CME LIMITS @ LHC WITH ESE

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



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



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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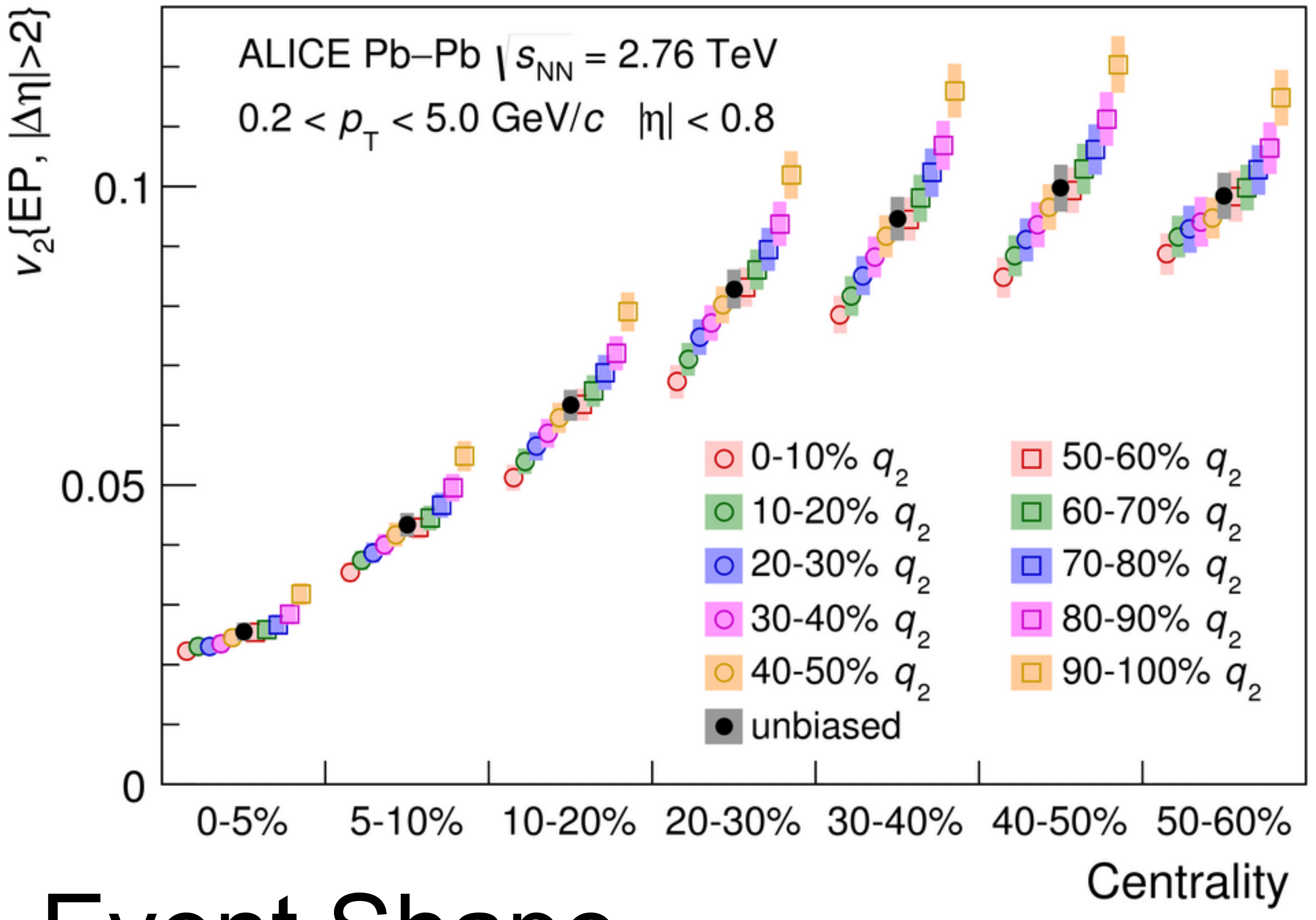
Abstract

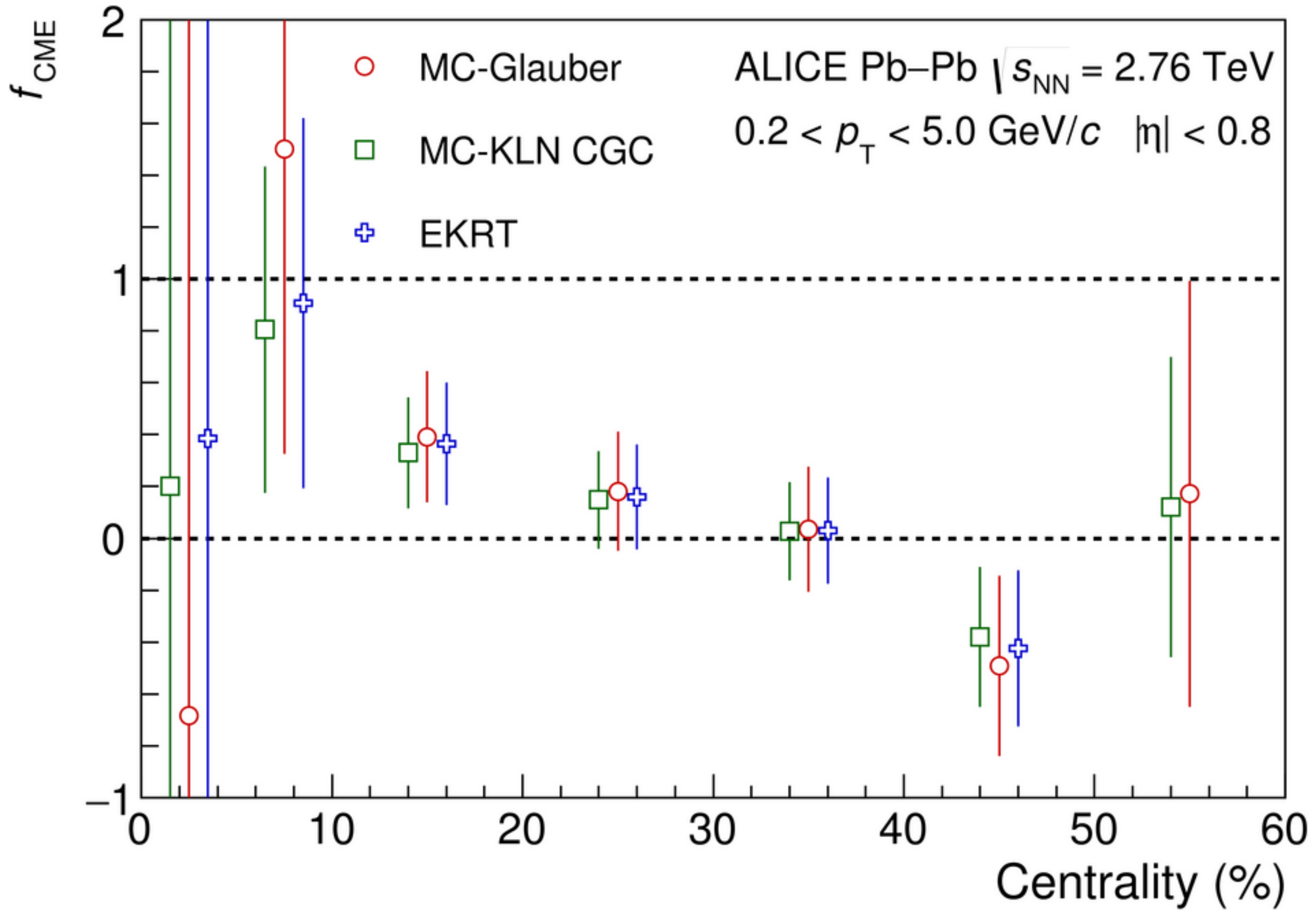
The evolution of the system created in a high energy nuclear collision is very sensitive to the fluctuations in the initial geometry of the system. In this Letter we show how one can utilize these large fluctuations to select events corresponding to a specific initial shape. Such an "event shape engineering" 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.

FIRST CME LIMITS @ LHC WITH ESE

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



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

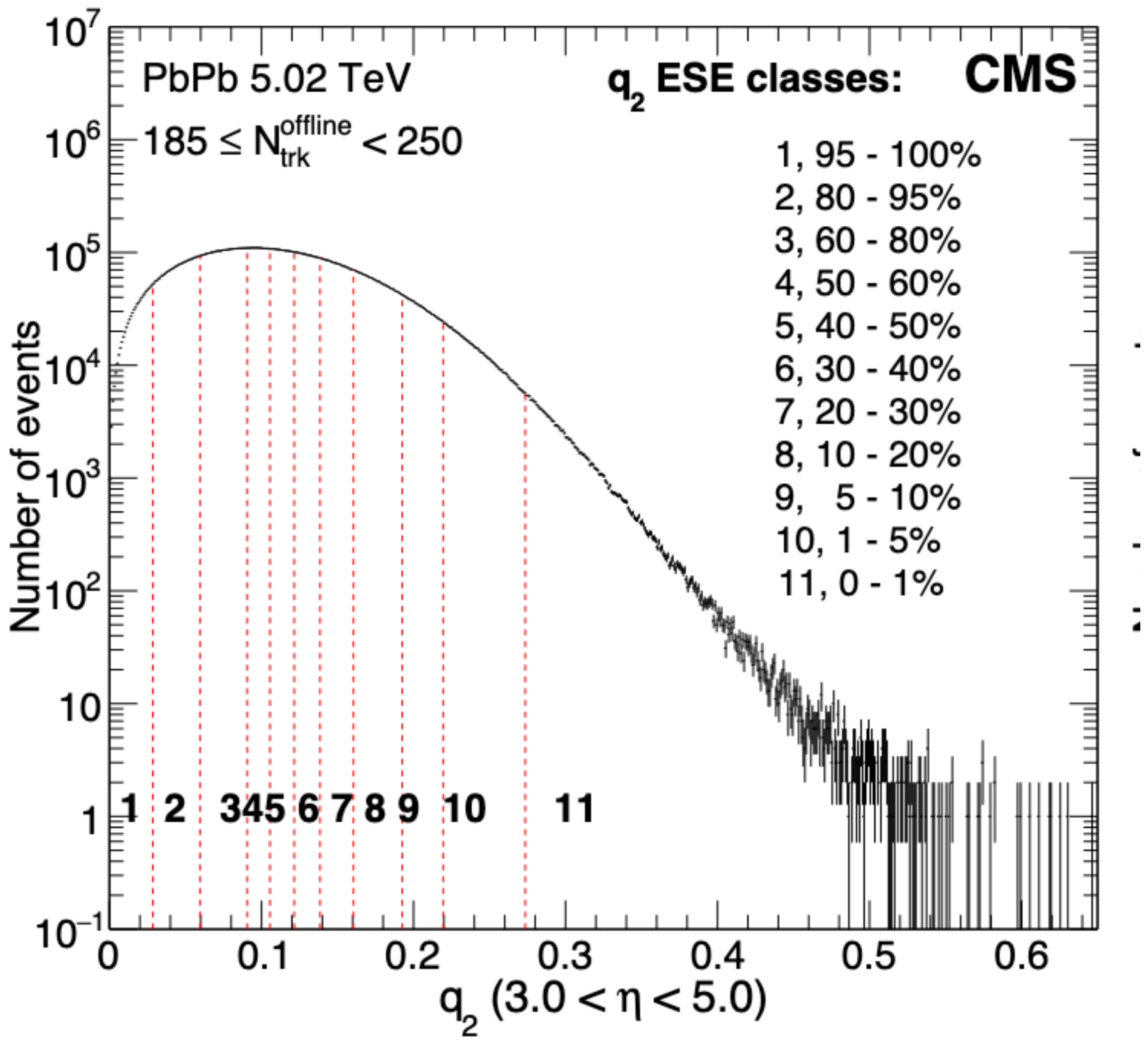


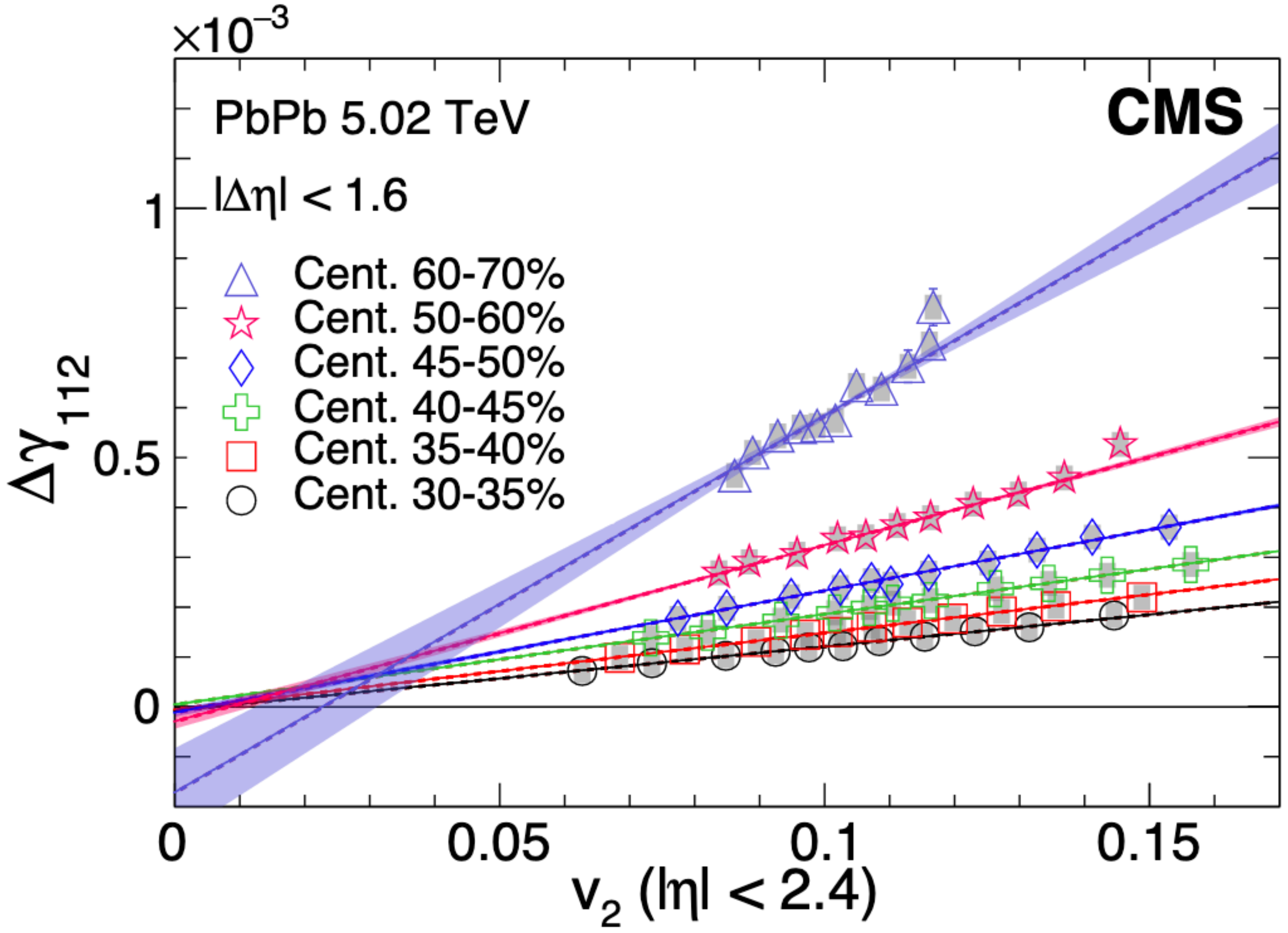
Upper limit on the CME fraction for the 10-50% centrality interval:

- 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

HIGHER HARMONICS

S. Voloshin, arXiv:1111.7241 [nucl-ex]

$$\gamma_{m,n} \equiv \langle \cos(m\varphi_a + n\varphi_\beta \; - (m+n)\Psi_{|m+n|}) \rangle$$

$$\gamma_{1,1} = \langle \cos(\varphi_a + \varphi_\beta - 2\Psi_2) \rangle$$

$$\gamma_{1,-3} = \langle \cos(\varphi_a - 3\varphi_\beta + 2\Psi_2) \rangle$$

CME SENSITIVE

$$\gamma_{1,2} = \langle \cos(\varphi_a + 2\varphi_\beta - 3\Psi_3) \rangle$$

$$\gamma_{2,2} = \langle \cos(2\varphi_a + 2\varphi_\beta - 4\Psi_4) \rangle$$

BACKGROUND SENSITIVE

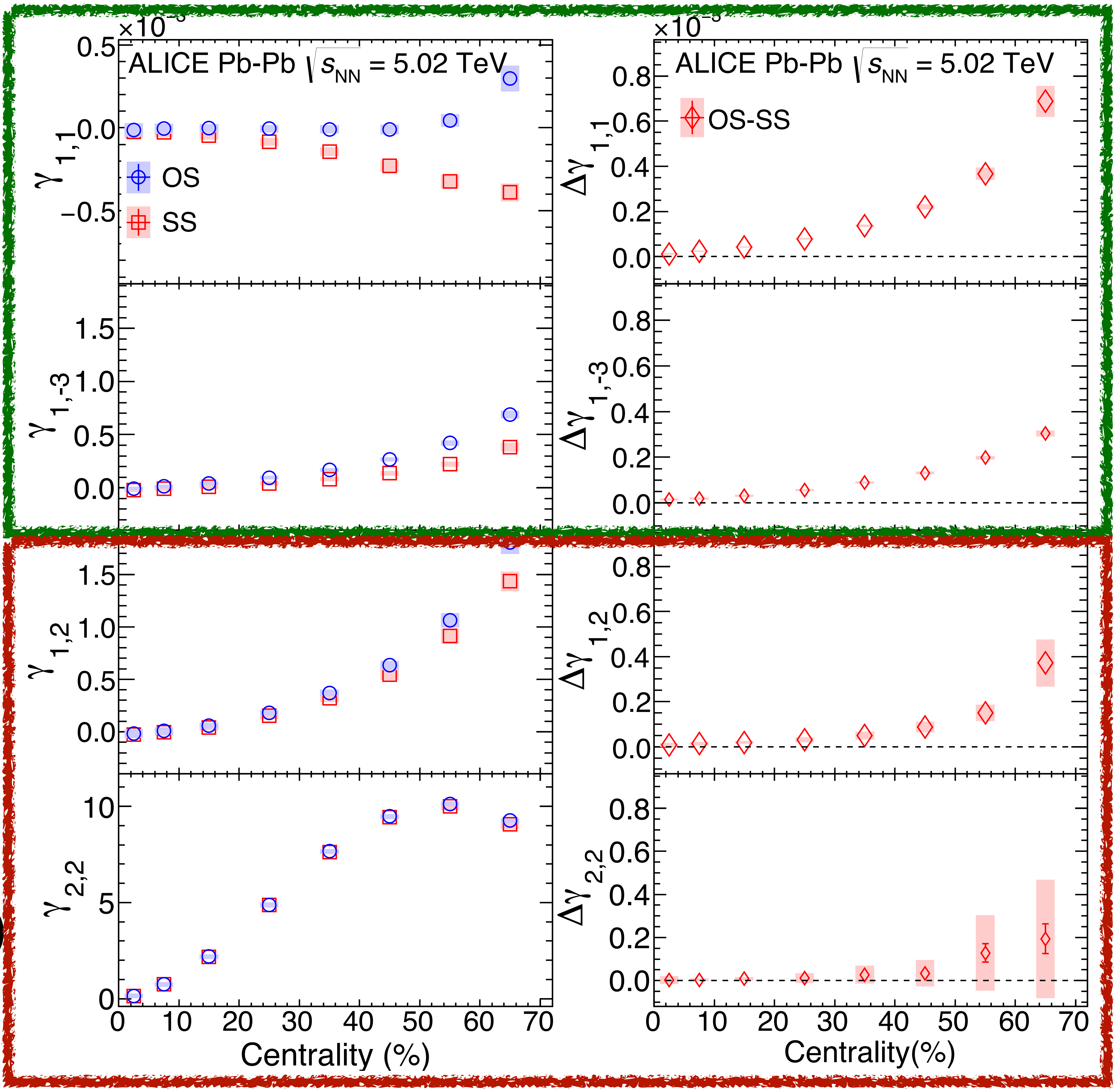
Significant charge dependent signal for the CME sensitive correlators

Correlations relative to Ψ_3 illustrate a significant charge dependence as well

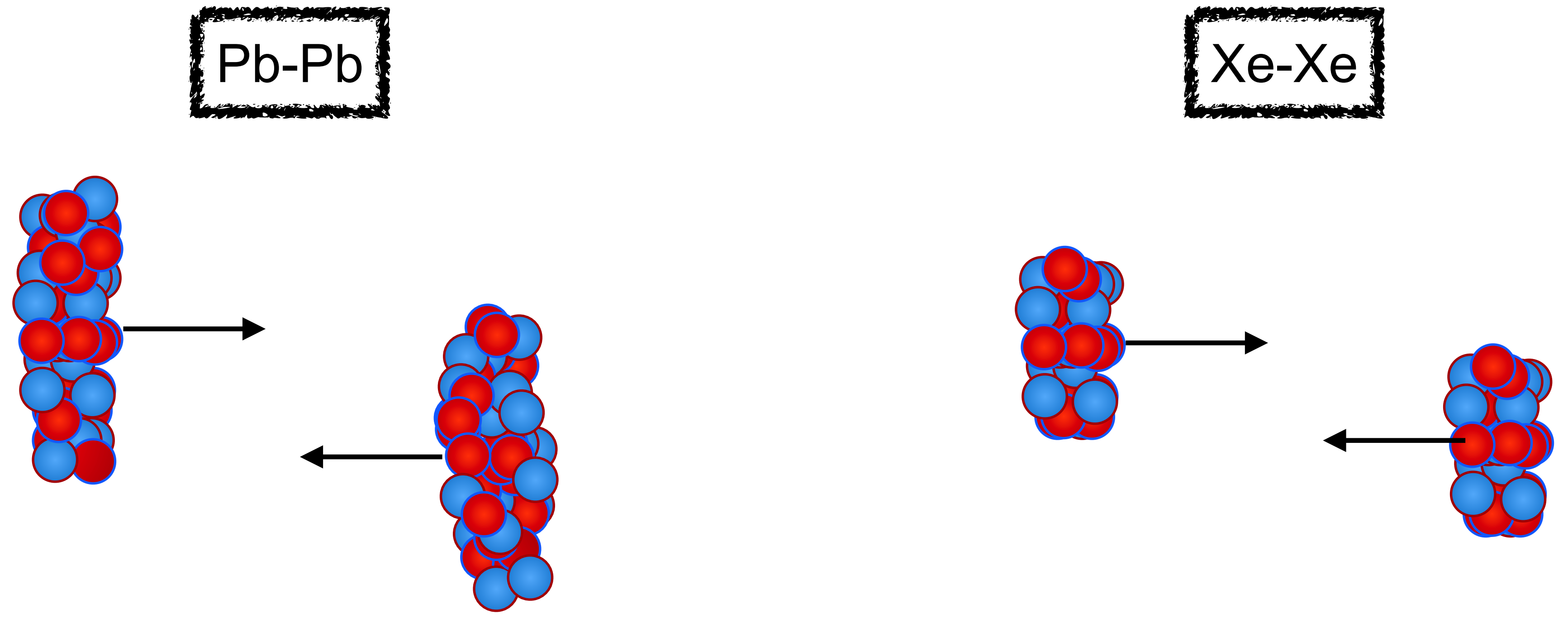
- Dominant contribution from background effects

Correlations relative to Ψ_4 have no significant charge dependence (within the current level of uncertainties)

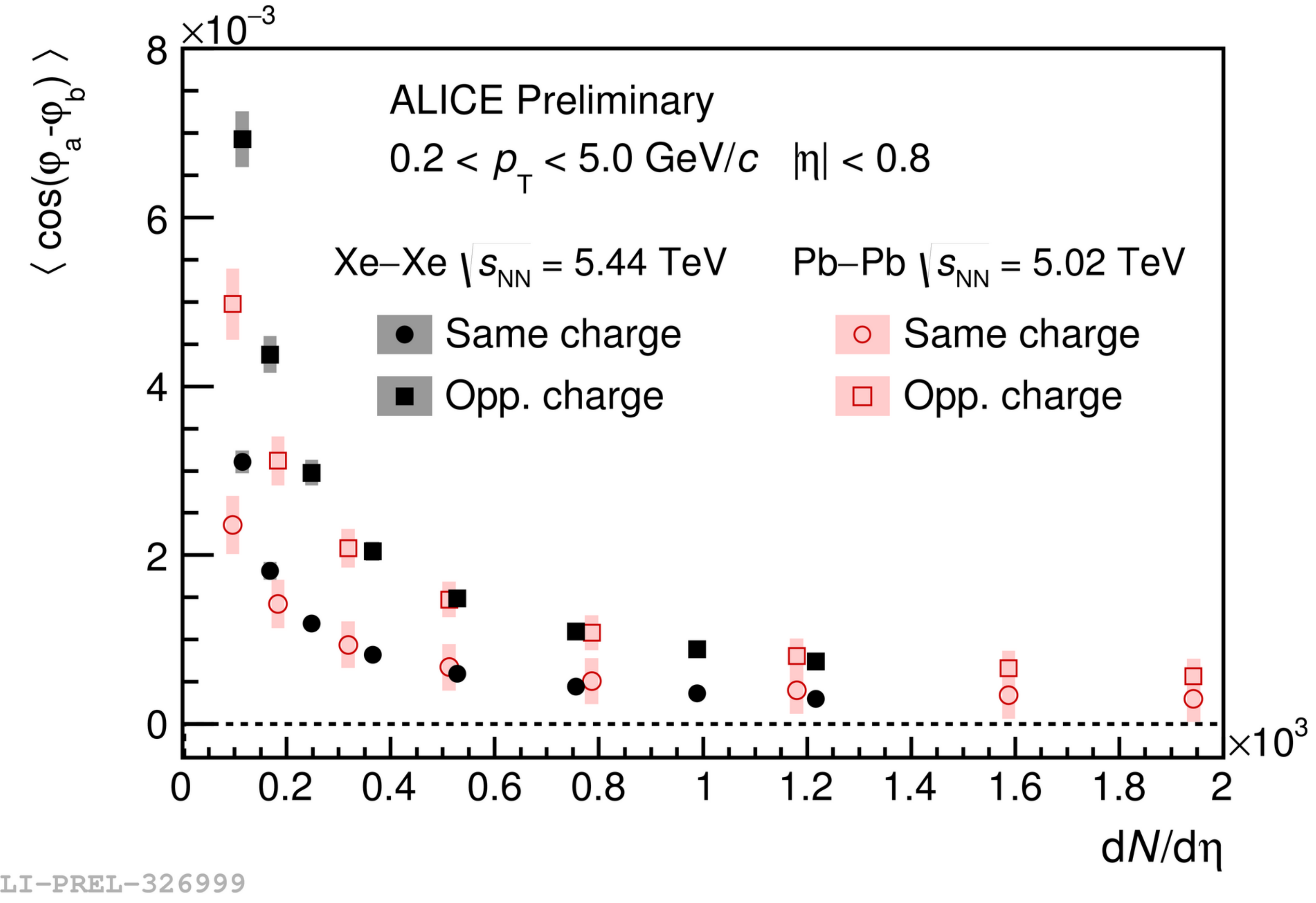
(ALICE Collaboration) JHEP 2020, (2020) 160



RESULTS IN Xe-Xe



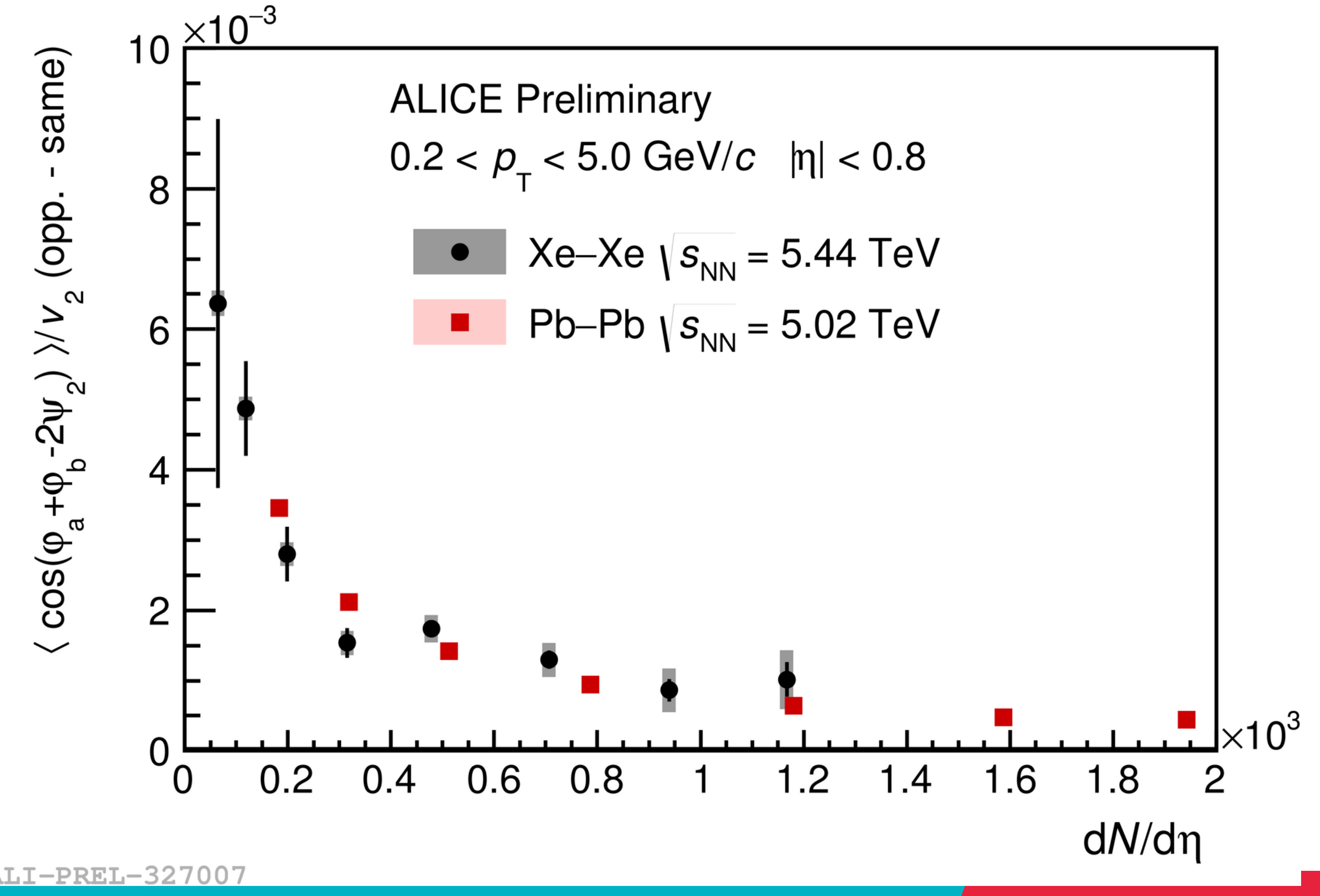
(ALICE Collaboration) QM2019 arXiv:To be submitted



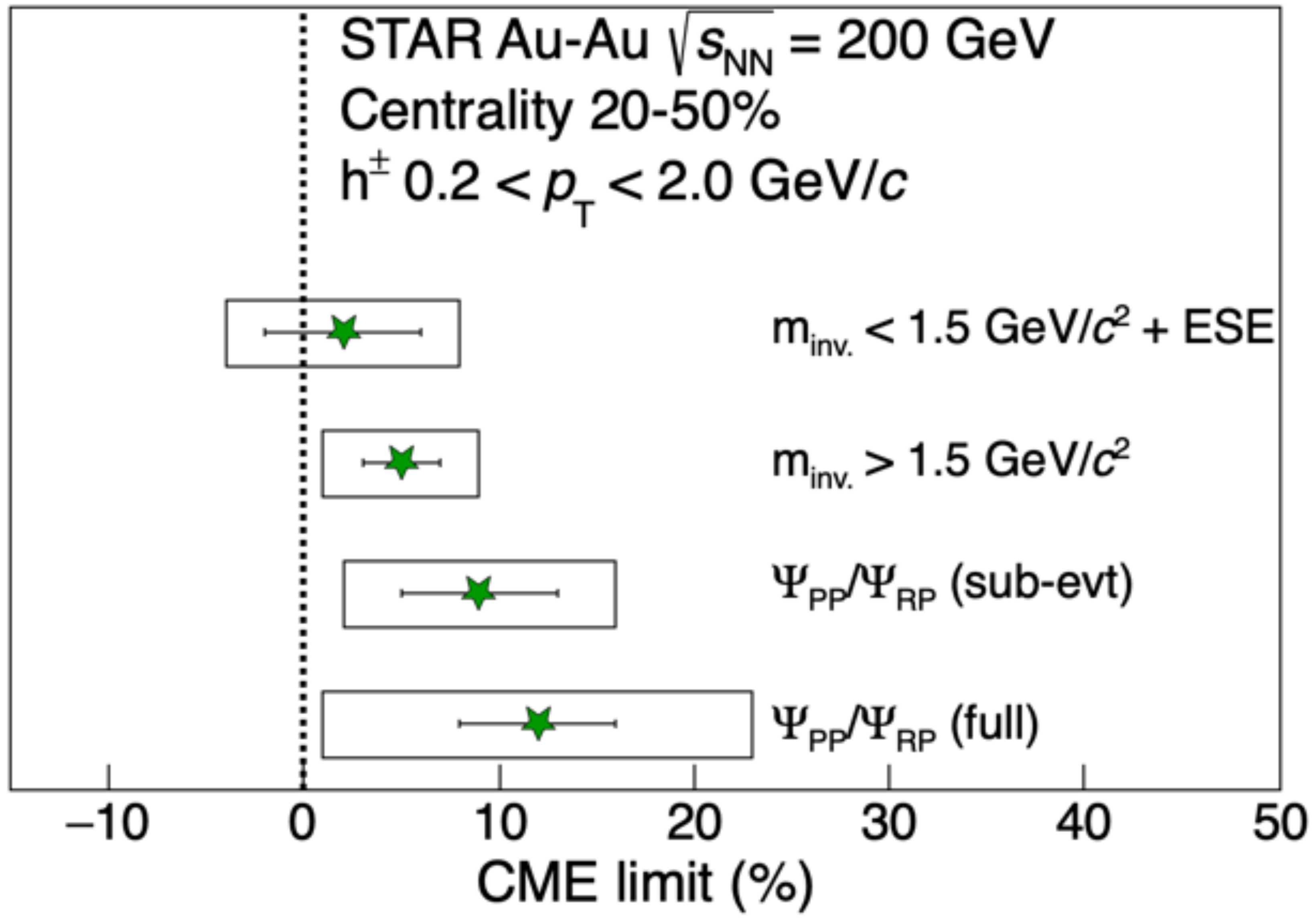
Look at a system where the background effects are similar to the ones in Pb-Pb but the magnetic field is different

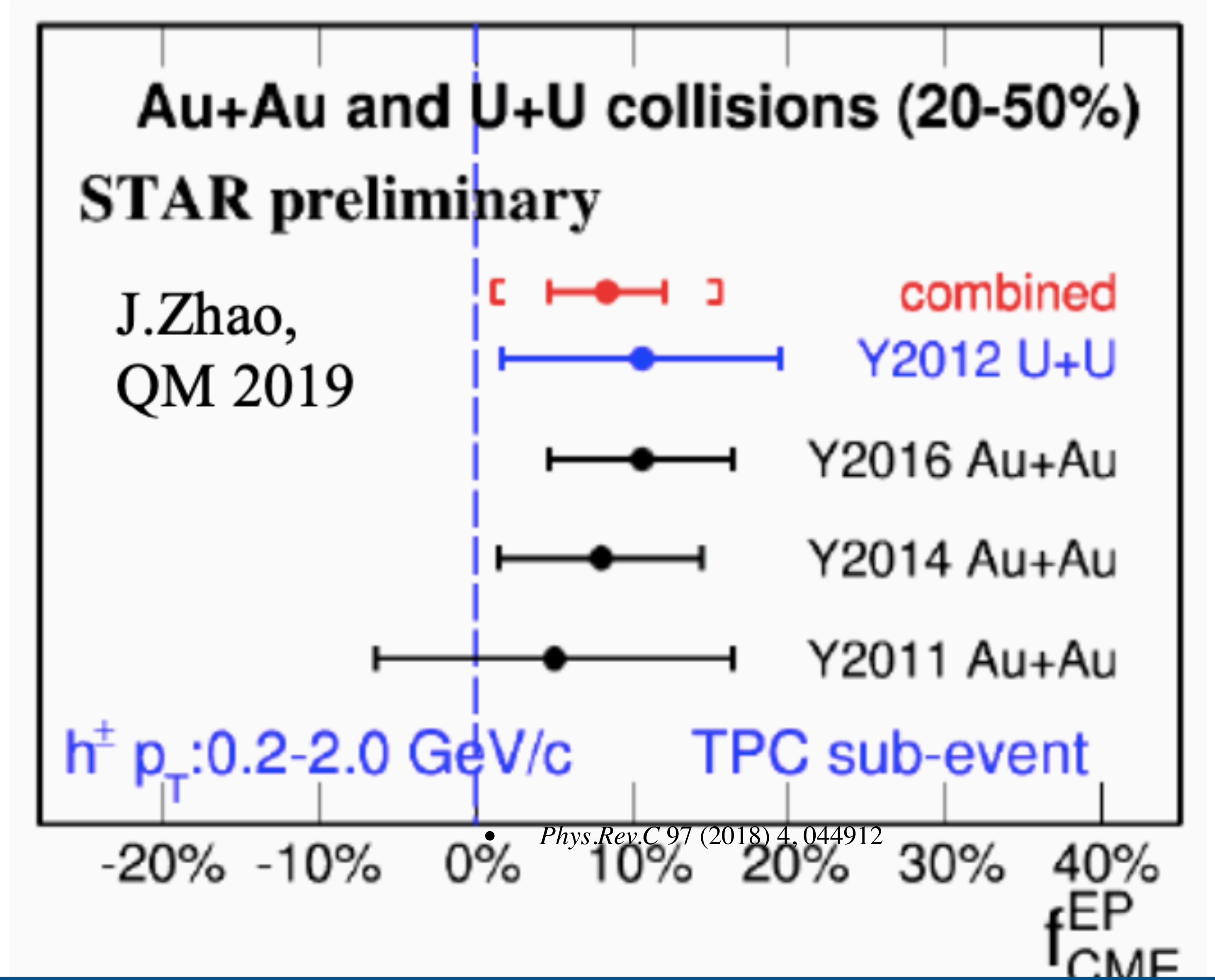
Both results of δ_1 and $\gamma_{1,1}$ in Xe-Xe compatible with the ones in Pb-Pb

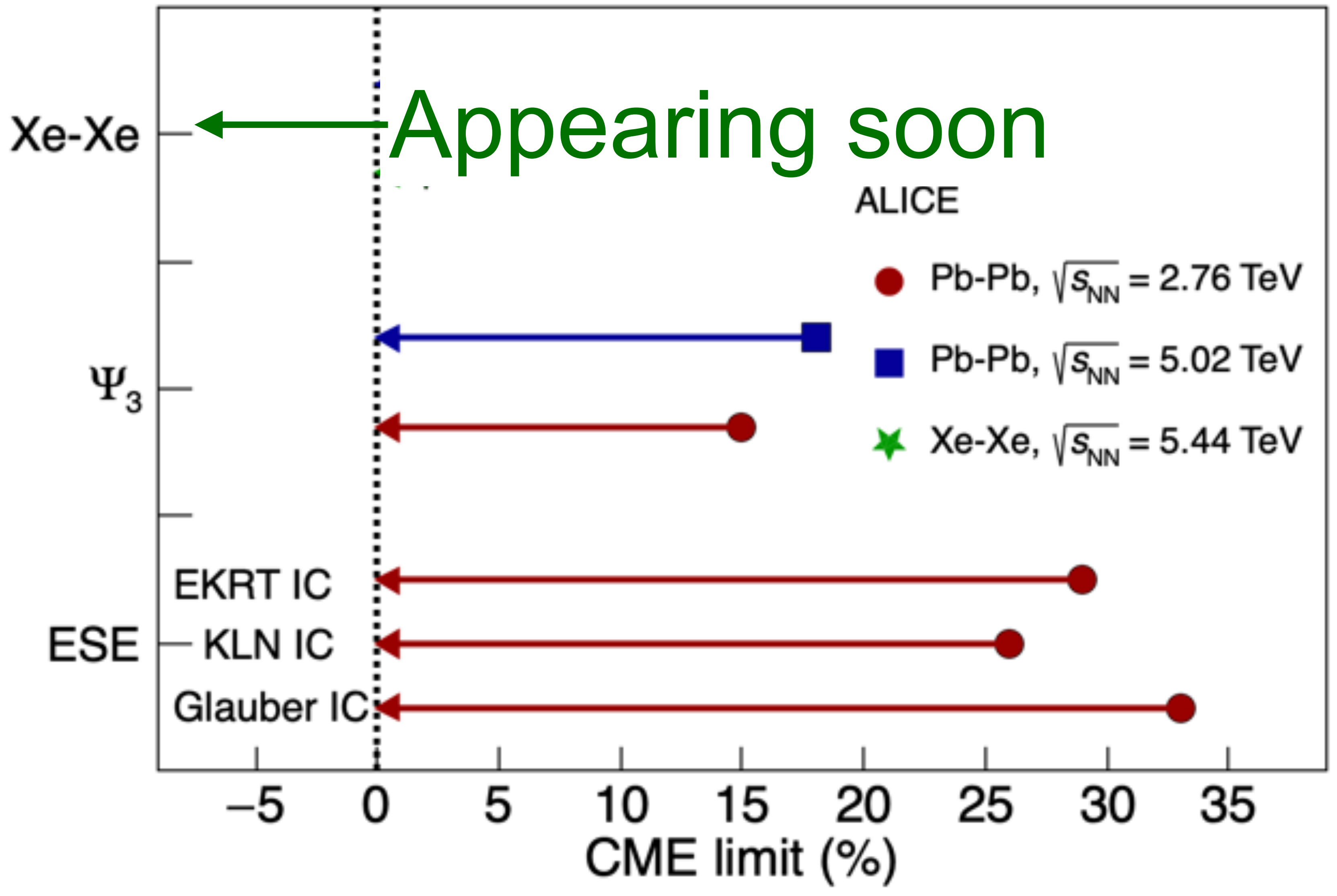
- Dominance of background effects



CME FRACTION UPPER LIMITS







Summary of upper limits @ LHC (95% CL)		
ALICE	ESE in Pb-Pb collisions	26-33%
	Higher harmonics in Pb-Pb collisions	11-15%
CMS	p-Pb collisions	13%**
	ESE in Pb-Pb collisions	7%*

(ALICE Collaboration) Phys. Lett. **B777**, (2018) 151
(CMS Collaboration) Phys.Rev.C 97 (2018) 4, 044912
(ALICE Collaboration) JHEP 2020, (2020) 160

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

BLAST WAVE MODEL

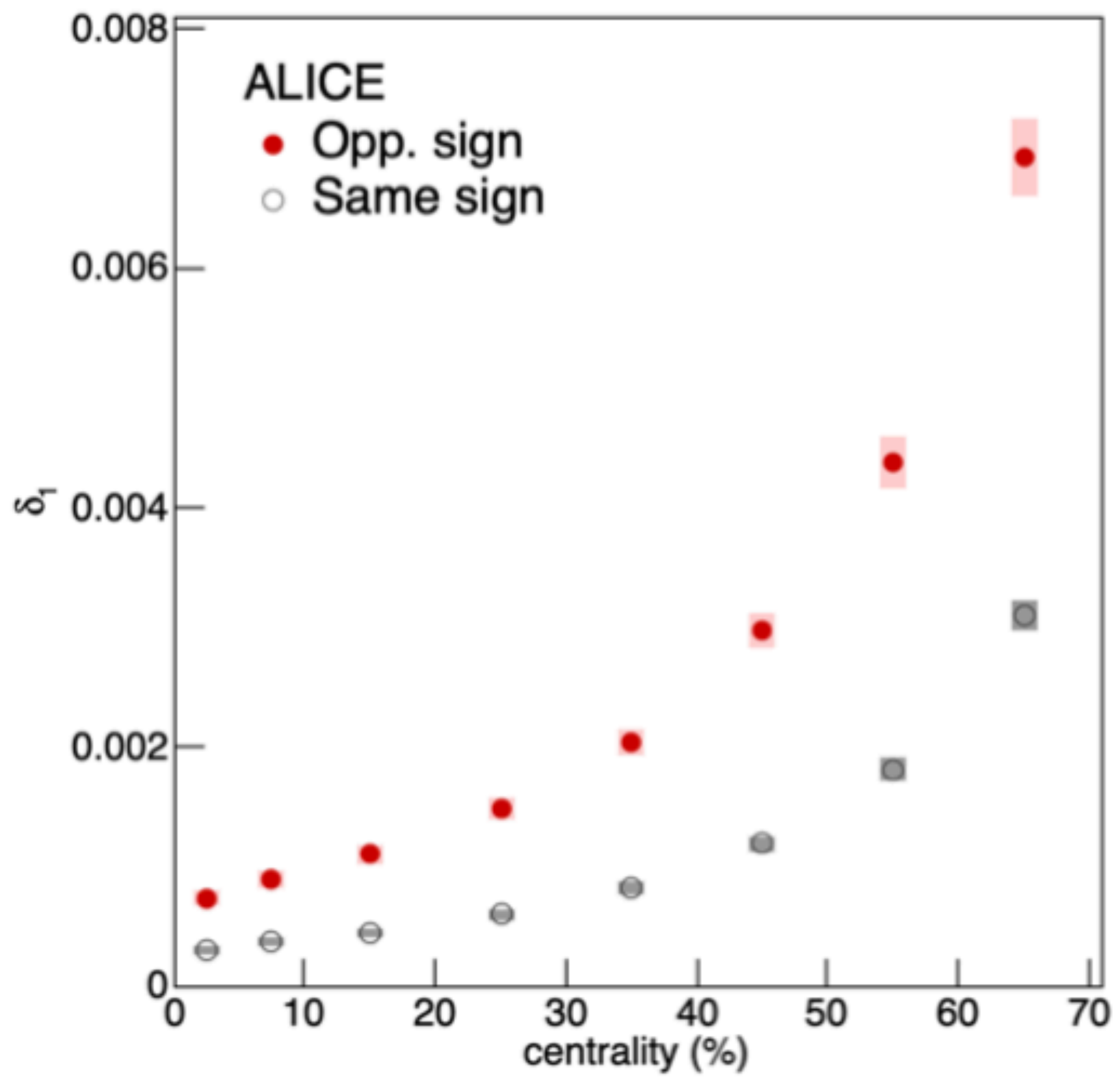
Tune the parameters (T, β,…) of the model as a function of centrality to reproduce

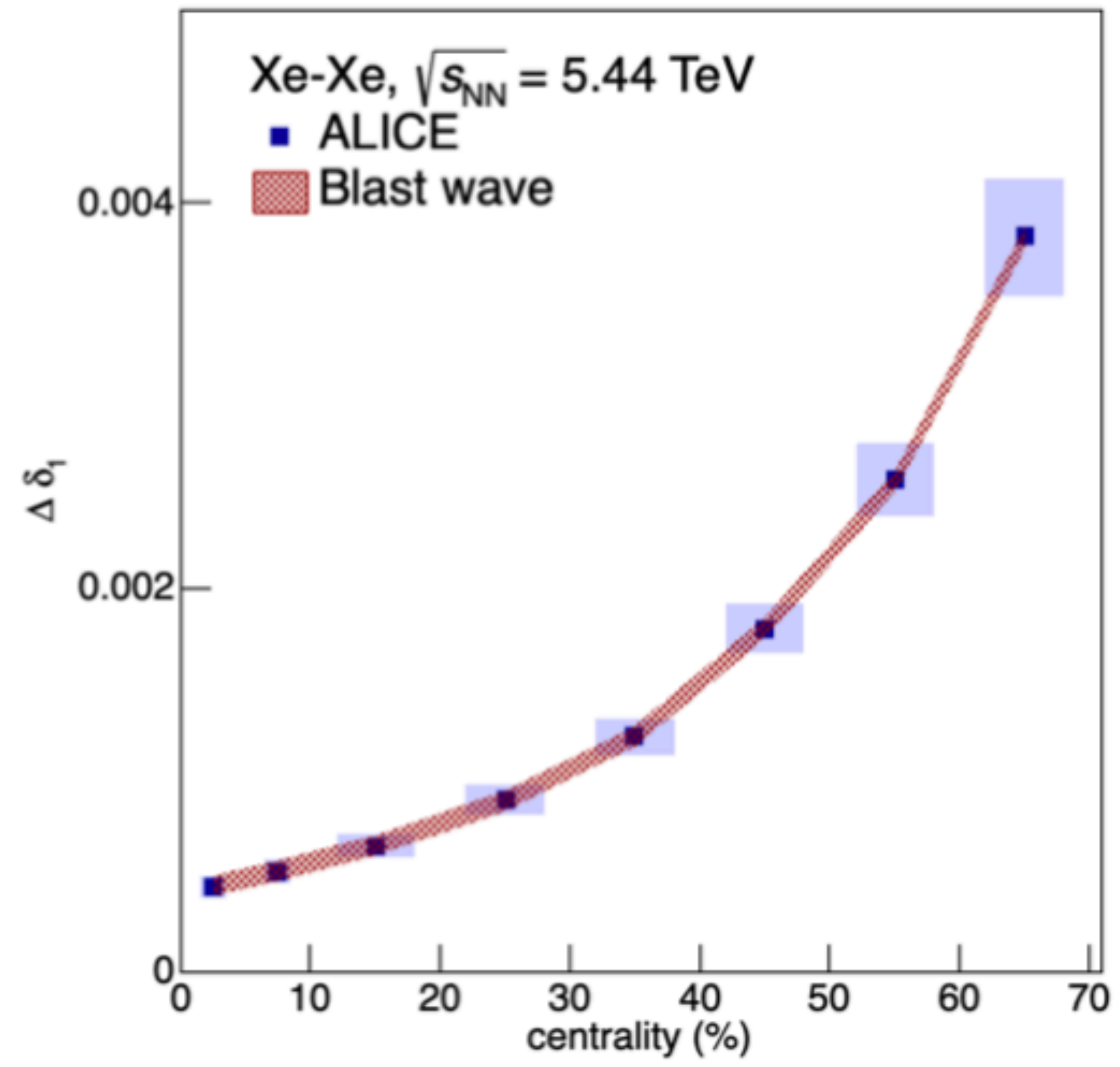
- Spectra of different particle species
- v_2 of different particle species

Tune the amount of “balancing charged” pairs (LCC) to reproduce

- Δδ as a function of centrality

Extract the estimate of the model for Δγ



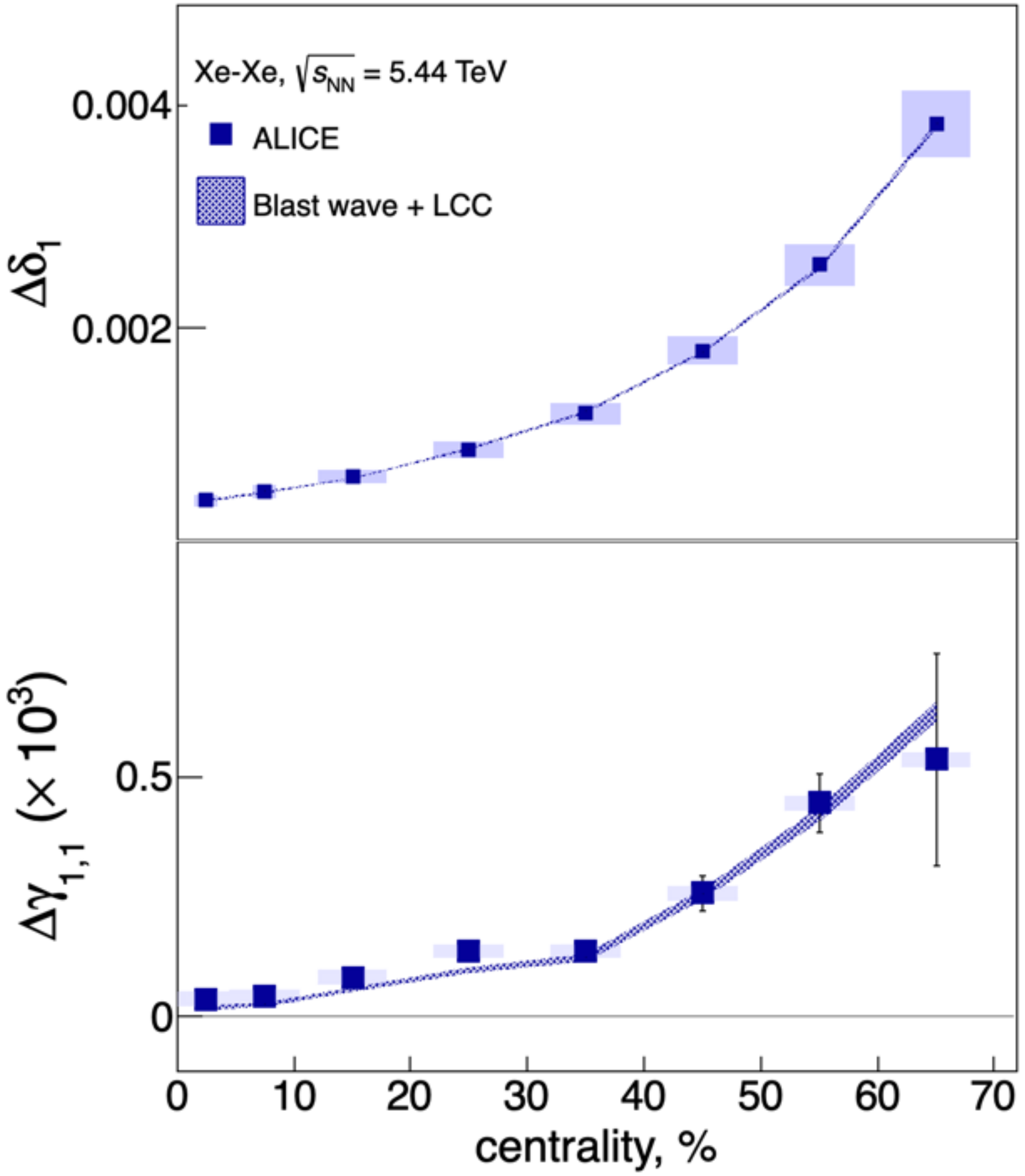


BLAST WAVE MODEL: EXPECTATIONS FOR Δγ

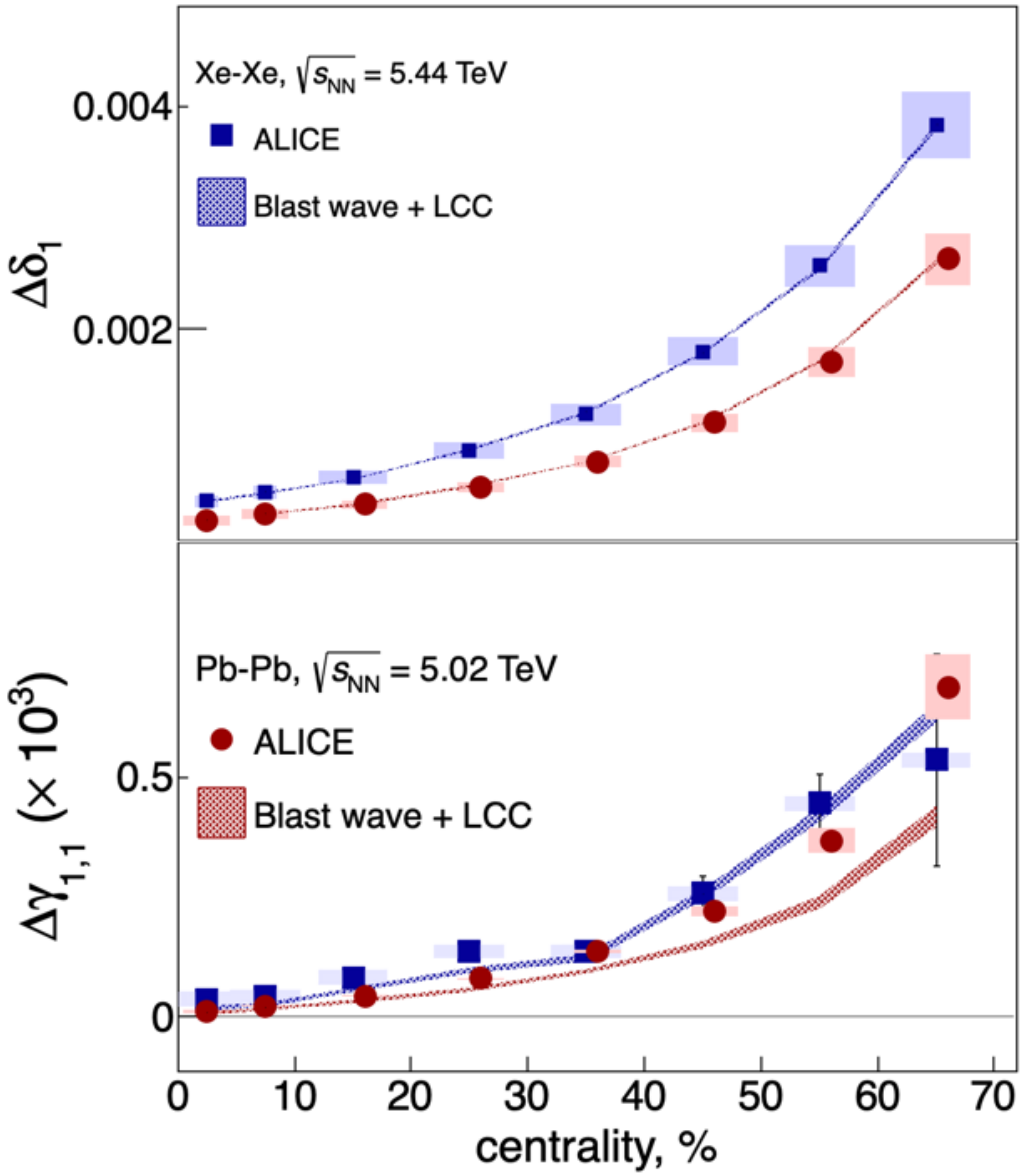
The tuned model is able to describe the experimental measurement of Δγ fairly well

Study should probably not be used to extract any strong conclusions

- However, it is indicative of the dominance of background effects in this system



BLAST WAVE MODEL: EXPECTATIONS FOR Δγ



BW+LCC model

- Describes quantitatively the centrality dependence of $\Delta\gamma_{1,1}$ in Xe-Xe
  - Indicative of dominance of background effects
- Underestimates the centrality dependence of $\Delta\gamma_{1,1}$ in Pb-Pb by ~40%
  - Missing ingredients?
  - Can this be hinting to a CME contribution?

ANOMALOUS VISCOUS FLUID DYNAMICS (AVFD)

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

Anomalous transport → CME signal

VISH2+1 → hydro evolution

Hadronisation + LCC

UrQMD

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

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

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Central China Normal University, Wuhan, 430079, China.

(Dated: May 9, 2018)

Chiral anomaly is a fundamental aspect of quantum theories with chiral fermions. How such microscopic anomaly manifests itself in a macroscopic many-body system with chiral fermions, is a highly nontrivial question that has recently attracted significant interest. As it turns out, unusual transport currents can be induced by chiral anomaly under suitable conditions in such systems, with the notable example of the Chiral Magnetic Effect (CME) where a vector current (e.g. electric current) is generated along an external magnetic field. A lot of efforts have been made to search for CME in heavy ion collisions, by measuring the charge separation effect induced by the CME transport. A crucial challenge in such effort, is the quantitative prediction for the CME signal. In this paper, we develop the Anomalous-Viscous Fluid Dynamics (AVFD) framework, which implements the anomalous fluid dynamics to describe the evolution of fermion currents in QGP, on top of the neutral bulk background described by the VISH2+1 hydrodynamic simulations for heavy ion colli-

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

Quantifying Chiral Magnetic Effect from Anomalous-Viscous Fluid Dynamics

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Central China Normal University, Wuhan, 430079, China.

The Chiral Magnetic Effect (CME) is a macroscopic manifestation of fundamental chiral anomaly in a many-body system of chiral fermions, and emerges as anomalous transport current in the fluid dynamics framework. Experimental observation of CME is of great interest and has been reported in Dirac and Weyl semimetals. Significant efforts have also been made to look for CME in heavy ion collisions. Critically needed for such search, is the theoretical prediction for CME signal. In this paper we report a first quantitative modeling framework, the Anomalous Viscous Fluid Dynamics (AVFD), which computes the evolution of fermion currents on top of realistic bulk evolution in heavy ion collisions and simultaneously accounts for both anomalous and normal viscous transport effects. The AVFD allows a quantitative understanding of the generation and evolution of CME-induced charge separation during hydrodynamic stage as well as its dependence on theoretical ingredients. With reasonable estimates of key parameters, the AVFD simulations provide the first phenomenologically successful explanation of the measured signal in 200AGeV AuAu collisions.

Introduction.— The importance of electricity for modern society cannot be overemphasized. From the physics point of view, lies at the heart of electricity is the conducting transport (of electric charge carriers). In normal materials, conducting transport generates an electric current $\vec{\mathbf{J}}_Q$ along the electric field $\vec{\mathbf{E}}$ (or voltage) applied to the system. This can be described by the usual Ohm's law $\vec{\mathbf{J}}_Q = \sigma_e \vec{\mathbf{E}}$ where the conductivity σ_e arises from competition between "ordered" electric force and "disordered" thermal scatterings, henceforth involving dissipation and typically dependent upon specific dynamics of the system. More recently there have been significant interests, from both high energy and condensed matter physics communities, in a new category of *anomalous chiral transport* in quantum materials containing chiral fermions. A notable example is the Chiral Magnetic Effect (CME) [1–5] — the generation of an electric current $\vec{\mathbf{J}}_Q$ along the *magnetic field* $\vec{\mathbf{B}}$ applied to the system, i.e.

$$\vec{\mathbf{J}}_Q = \sigma_5 \vec{\mathbf{B}} \qquad (1)$$

where $\sigma_5 = C_A \mu_5$ is the chiral magnetic conductivity, expressed in terms of the chiral chemical potential μ_5 that quantifies the imbalance between fermions of opposite (right-handed, RH versus left-handed, LH) chirality.

The σ_5 has two remarkable features that make it markedly different from the normal conductivity σ_e. First, the coefficient C_A takes a *universal value* of $Q_f^2/(4\pi^2)$ (for each species of RH or LH fermions with electric charge Q_f) from non-interacting cases to extremely strongly coupled cases [5–8]. In fact, it is entirely dictated by universal chiral anomaly coefficient, and the CME is really just the macroscopic manifestation of the fundamental quantum anomaly in a many-body setting. Second, the σ_5 is time-reversal even [9] which implies the non-dissipative nature of the underlying transport process that leads to the CME current in (1).

Given the magnificent physics of Chiral Magnetic Effect, it is of utmost interest to search for its manifestation in real-world materials. Two types of systems for experimental detection of CME have been enthusiastically investigated. One is the so-called Dirac and Weyl semimetals where electronic states emerge as effective chiral fermions and exhibit chiral anomaly [10, 11]. Discoveries of CME were reported in those systems [12–15]. The other is the quark-gluon plasma (QGP), which is the deconfined form of nuclear matter at very high temperatures $T \sim$ trillion degrees, consisting of approximately massless light quarks. Such a new form of hot matter once filled the whole universe and is now (re)created in laboratory at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Search for potential CME signals has been ongoing at RHIC and the LHC [16–21], with encouraging evidences for CME-induced charge separation signal. The interpretation of these data however suffers from backgrounds arising from the complicated environment in a heavy ion collision (see e.g. [22–25]). Currently the most pressing challenge for the search of CME in heavy ion collisions is to clearly separate background contributions from the desired signal. A mandatory and critically needed step, is to develop state-of-the-art modeling tools to compute CME signal in a realistic heavy ion collision environment. In this Letter we present such a tool, the Anomalous Viscous Fluid Dynamics (AVFD) framework, which simulates the evolution of chiral fermion currents in the QGP on top of the VISHNU bulk hydrodynamic evolution for heavy ion collisions. We demonstrate the features of this framework

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[*] Electronic address: liaoji@indiana.edu

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

AVFD: DEPENDENCE ON LCC

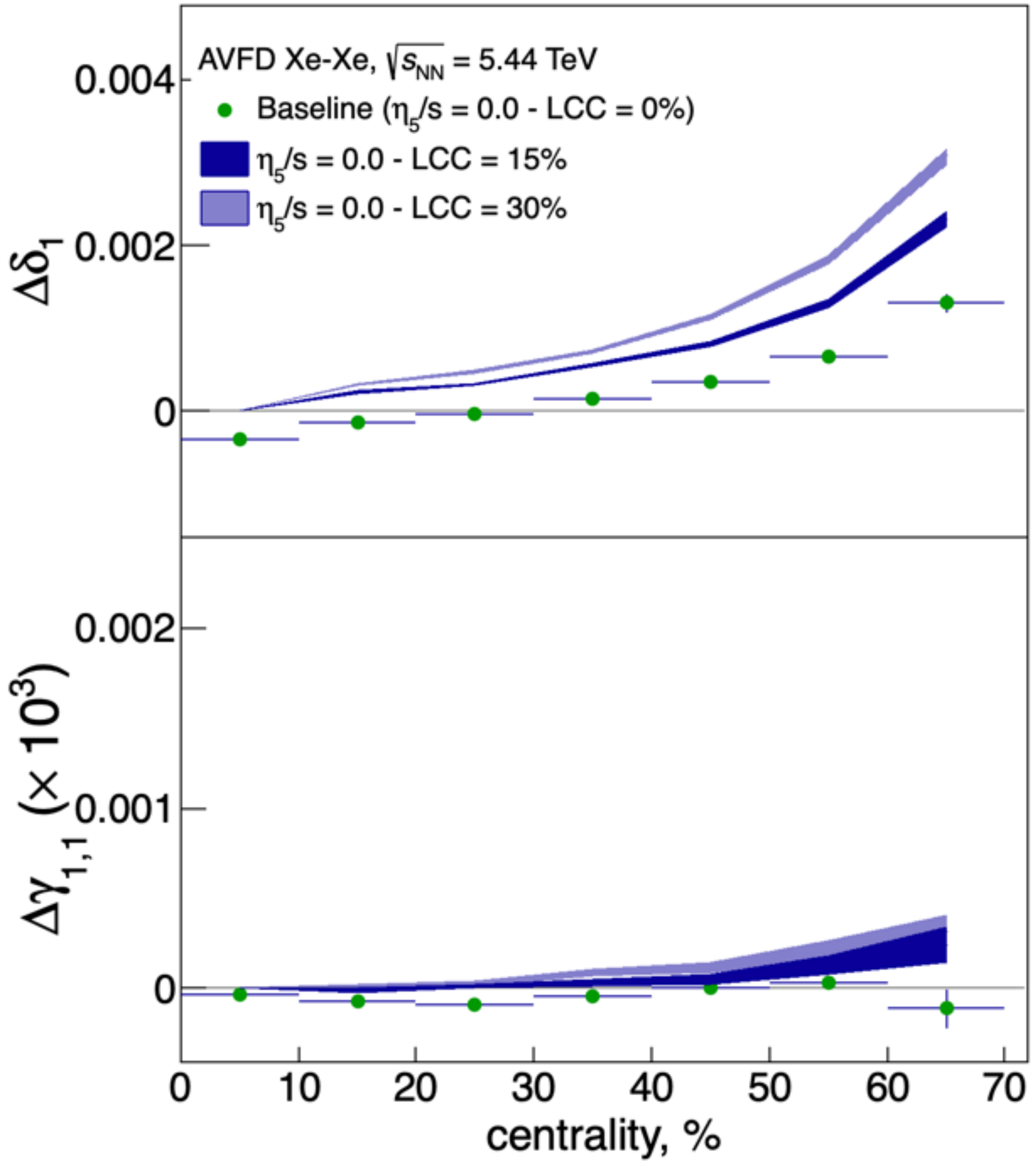
S. Voloshin, Phys. Rev. **C70**, (2004) 057901

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

Parity conserving background effects projected in and out of plane

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

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



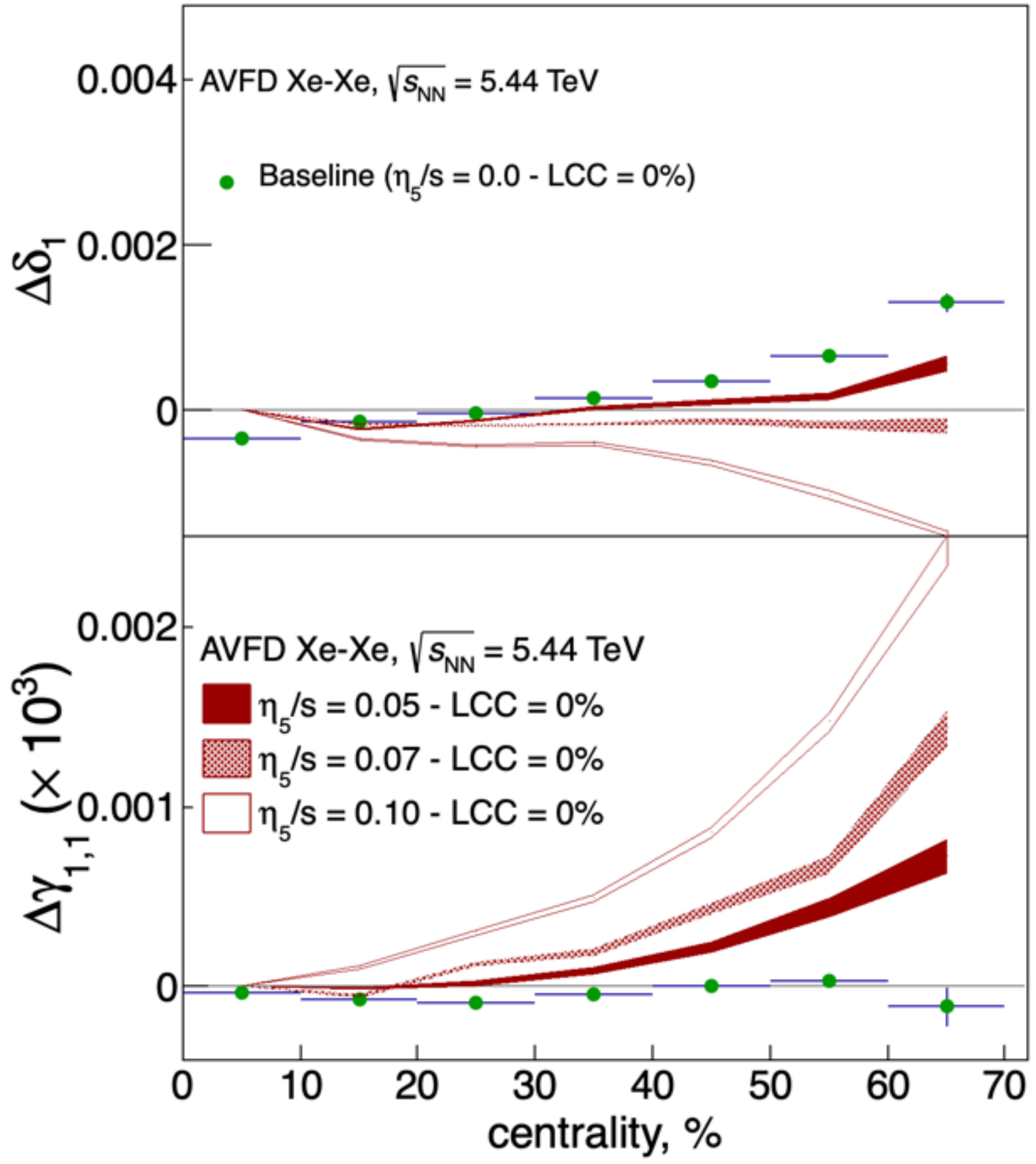
AVFD: DEPENDENCE ON AXIAL CURRENT

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

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

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

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



AVFD: SUMMARY

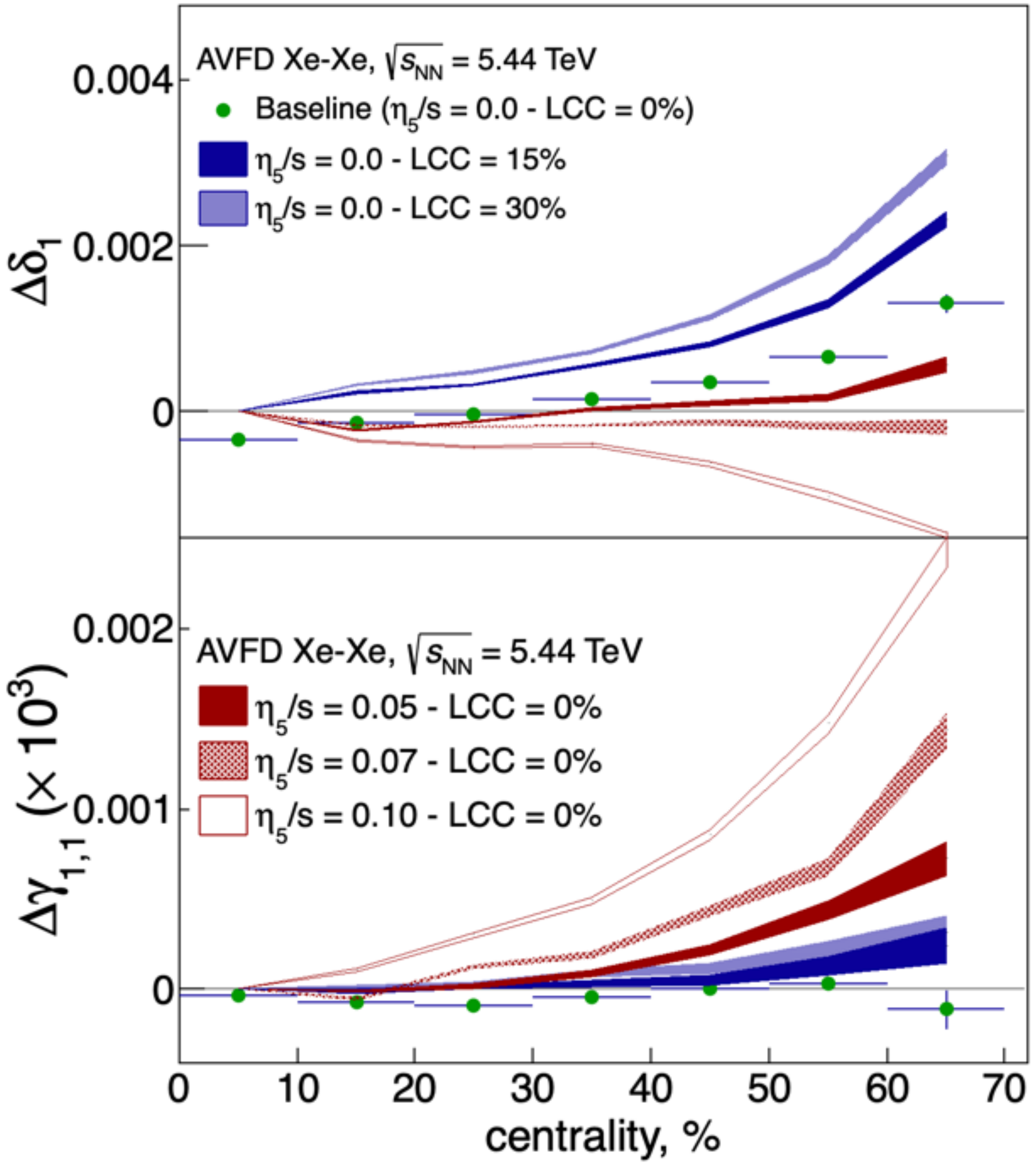
S. Voloshin, Phys. Rev. **C70**, (2004) 057901

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

Parity conserving background effects projected in and out of plane

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

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



AVFD: PARAMETRISING THE DEPENDENCES

Eur. Phys. J. C (2021) 81:717
https://doi.org/10.1140/epjc/s10052-021-09498-7

The European
Physical Journal C

Regular Article - Experimental Physics

Systematic study of the chiral magnetic effect with the AVFD model at LHC energies

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Nikhef, Amsterdam, The Netherlands

Received: 7 June 2021 / Accepted: 26 July 2021 / Published online: 10 August 2021

Abstract We present a systematic study of the correlators used experimentally to probe the Chiral Magnetic Effect (CME) using the Anomalous Viscous Fluid Dynamics (AVFD) model in Pb–Pb and Xe–Xe collisions at LHC energies. We find a parametrization that describes the dependence of these correlators on the value of the axial current density (n_5/s), which dictates the CME signal, and on the parameter that governs the background in these measurements i.e., the percentage of local charge conservation (LCC) within an event. This allows to deduce the values of n_5/s and the LCC percentage that provide a quantitative description of the centrality dependence of the experimental measurements. We find that the results in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV are consistent with a background only scenario. On the other hand, the model needs a significant non-zero value of n_5/s to match the measurements in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

1 Introduction

Collisions between heavy ions accelerated at ultra-relativistic energies provide the necessary conditions to form a deconfined state of matter, the Quark Gluon Plasma [1]. In this phase, the fundamental constituents of quantum chromodynamics (QCD), the quarks and gluons, are not anymore confined inside their usual hadronic bags. The transition to a QGP from normal hadronic matter is expected to take place at a temperature of about 155 MeV, and an energy density of about 0.5 GeV/fm^3, according to lattice QCD calculations [2–4]. These conditions can be reached in collisions between Pb ions at the Large Hadron Collider (LHC) [5–7].

Heavy ion collisions also provide the possibility to study novel QCD phenomena that are otherwise not accessible experimentally. One characteristic example is related to local parity (P) as well as charge conjugation and parity (CP) symmetry violation in strong interactions. The possibility to observe parity violation in the strong interaction using relativistic heavy-ion collisions has been discussed in [8–10] and was further reviewed in [11–19]. In QCD, this symmetry violation originates from the interaction between the chiral fermions of the theory and topologically non-trivial gluonic fields that induce net-chirality. In the presence of a strong magnetic field, such as the one created in peripheral heavy ion collisions with a magnitude of around 10^{15} T [20–22], these interactions lead to an asymmetry between left and right-handed quarks. The generated net-chirality, in turns, leads to an excess of positively and negatively charged particles moving in opposite directions relative to the system's symmetry plane. This introduces an electromagnetic current and the creation of an electric dipole moment of QCD matter. The experimental search for these effects has intensified recently, following the realisation that the subsequent creation of charged hadrons results in an experimentally accessible magnitude of charge separation along the direction of this magnetic field, and perpendicular to the symmetry plane. This phenomenon is called the Chiral Magnetic Effect (CME) [23] and its existence was recently reported in semi-metals like zirconium pentatelluride ($ZrTe_5$) [24].

Early enough it was realised that a way to probe these effects is to rely on measuring two-particle azimuthal correlations relative to the reaction plane (Ψ_{RP}) [25], the plane defined by the impact parameter and the beam axis. Since then, intensive experimental efforts have been made to identify unambiguously signals of the CME. The first measurements using this approach were reported by the STAR Collaboration in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 0.2$ TeV [26,27] and were consistent with initial expectations for a charge separation relative to the reaction plane due to the CME. Soon after, the first results from the LHC in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV were reported and showed a quantita-

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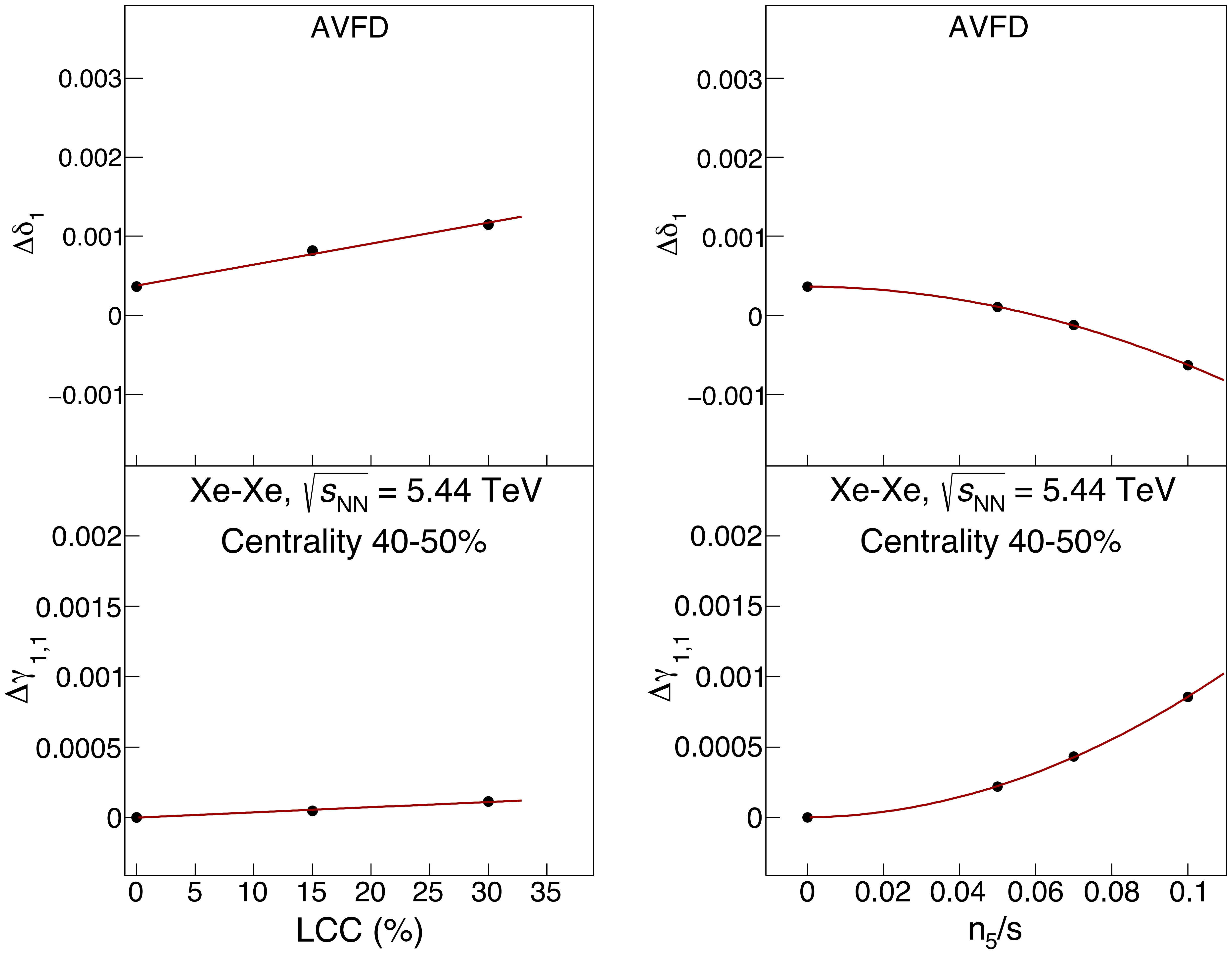
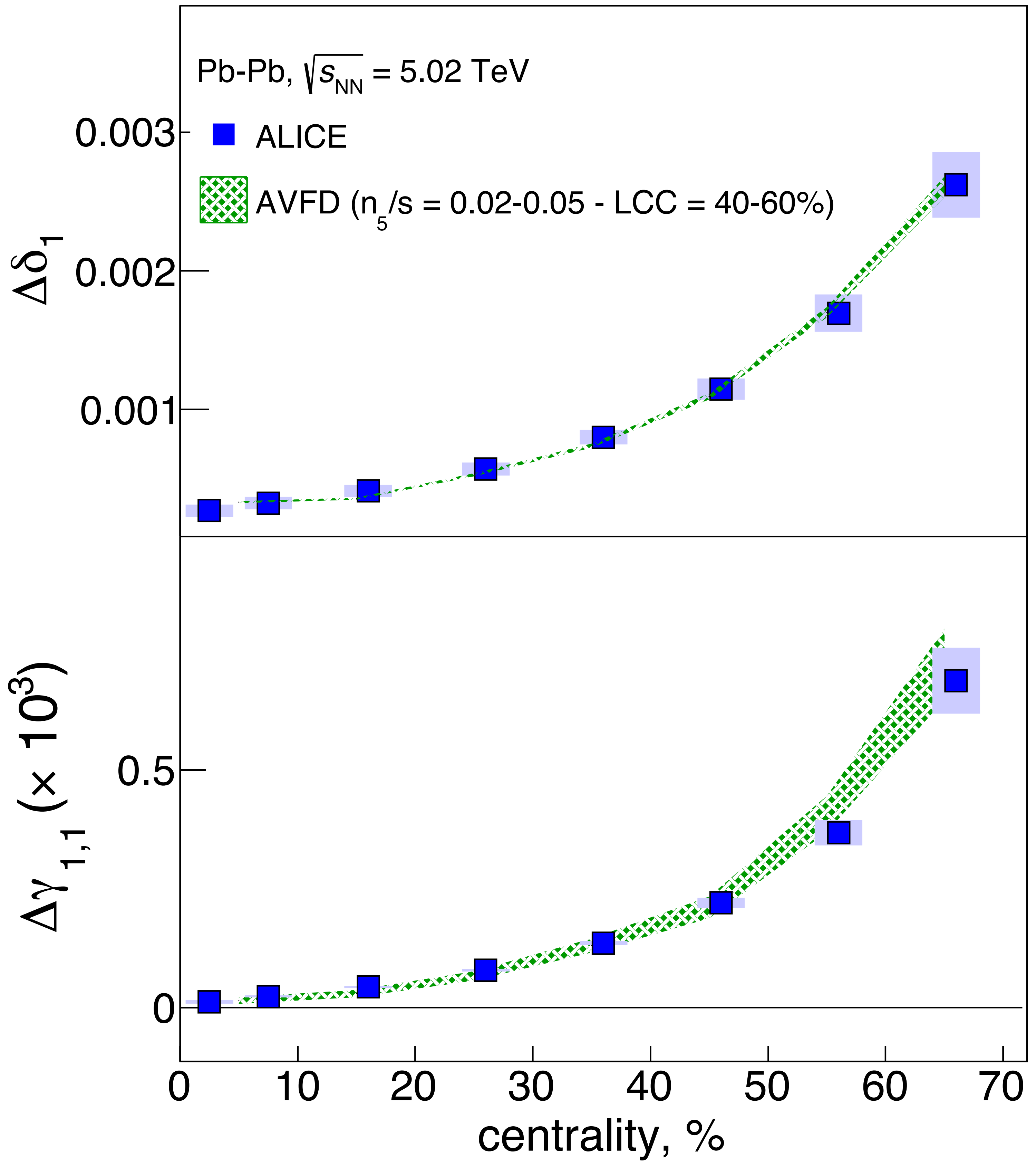


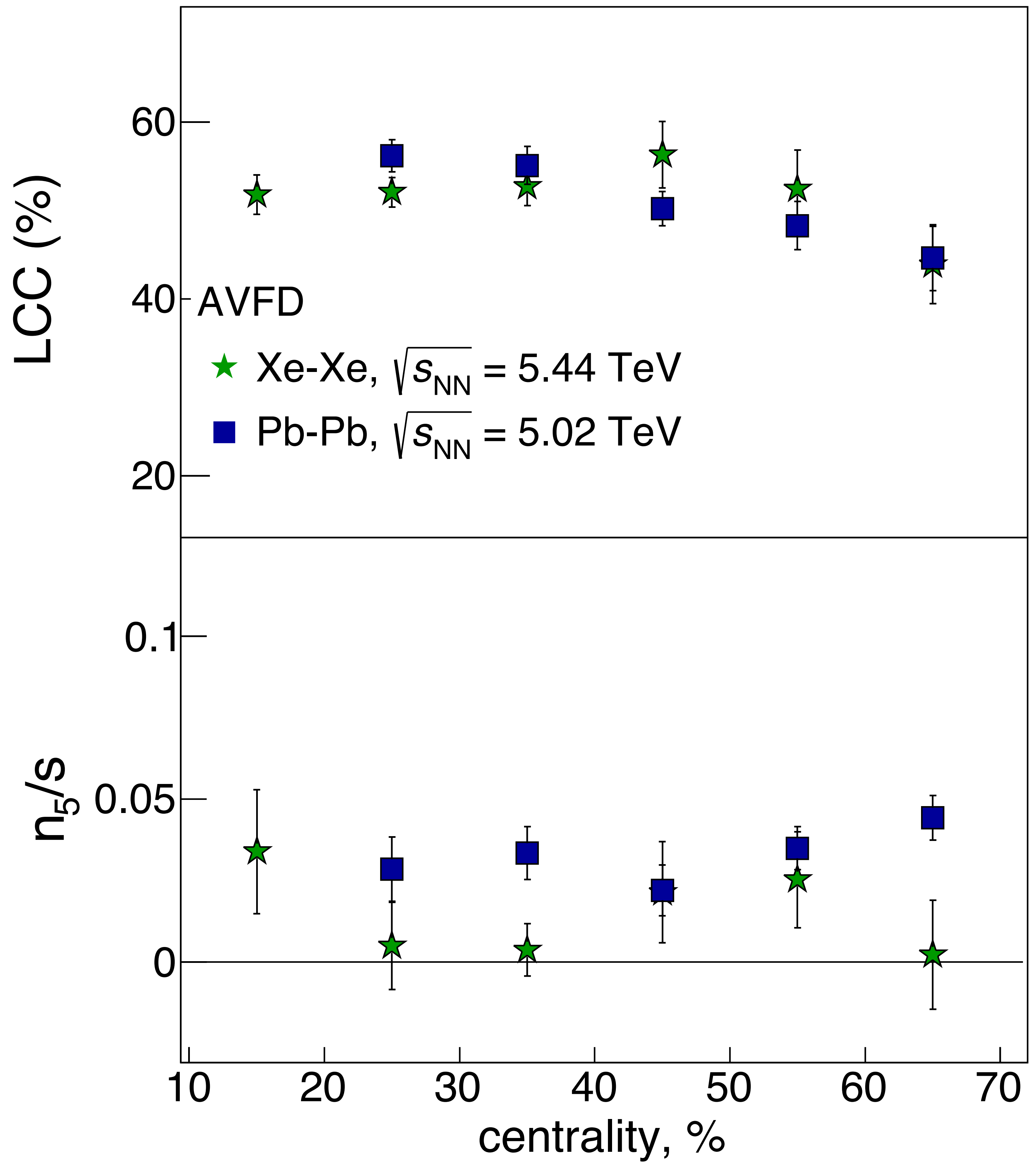
AVFD: MODEL TUNING

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



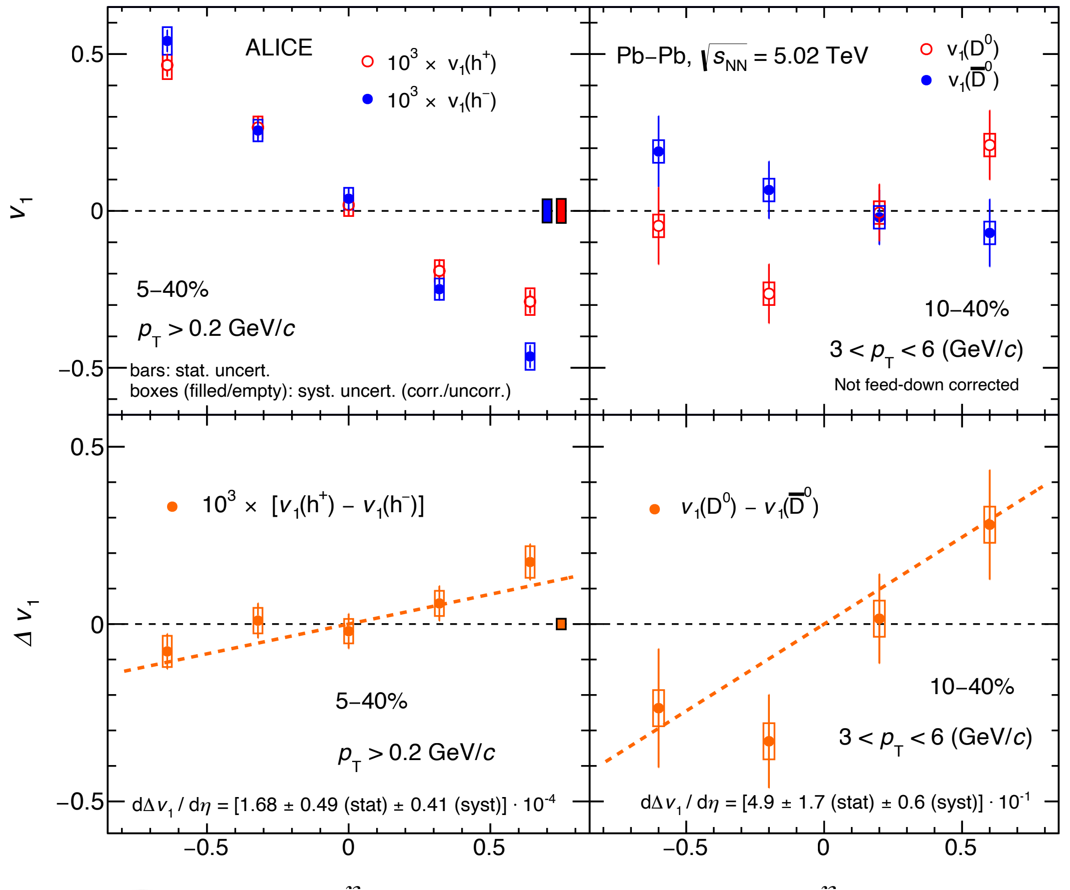
$(\eta_5/s)_{Xe\text{-}Xe}$ consistent with 0

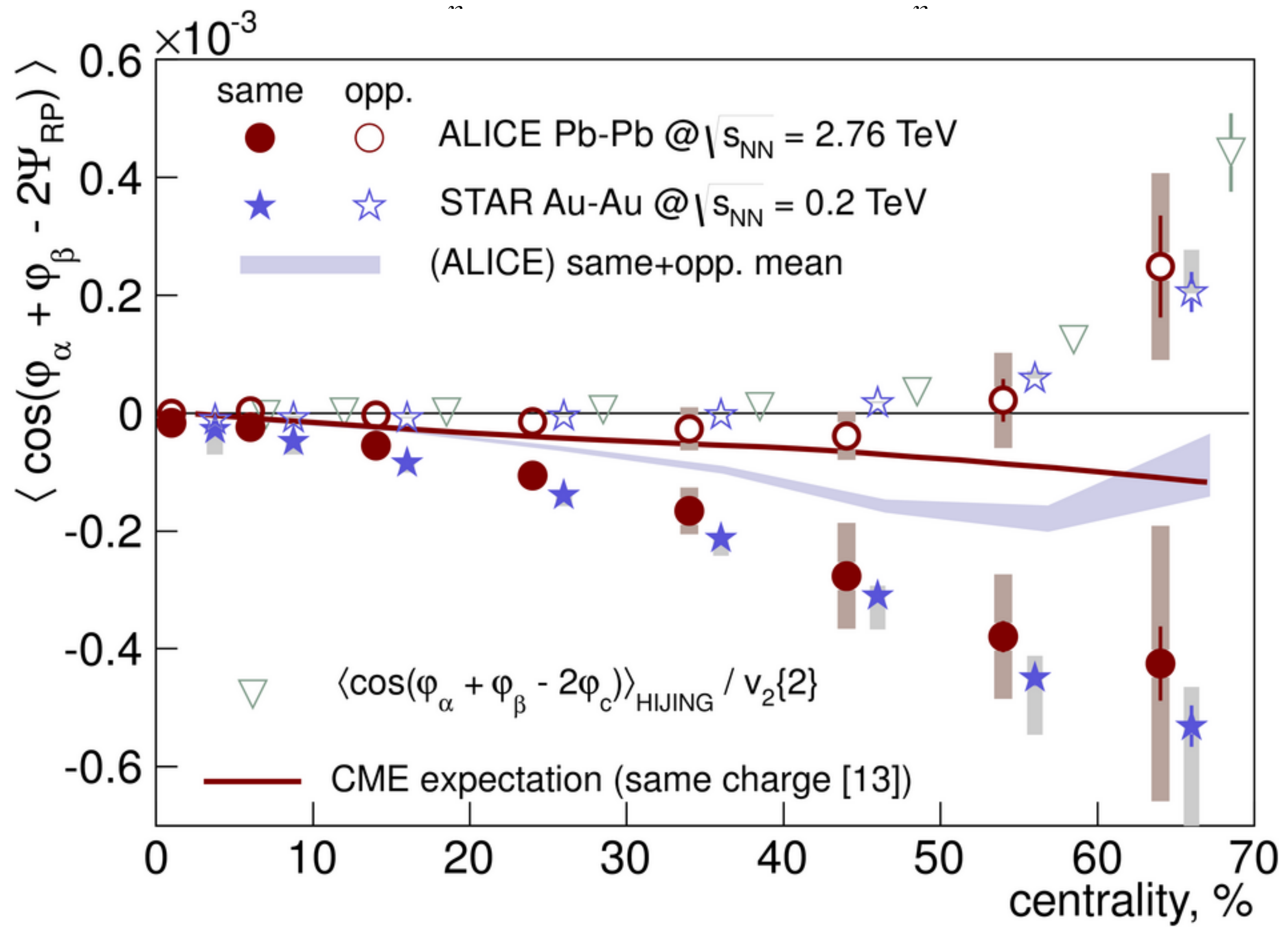
$(\eta_5/s)_{Pb\text{-}Pb}$ = 0.034 +- 0.003

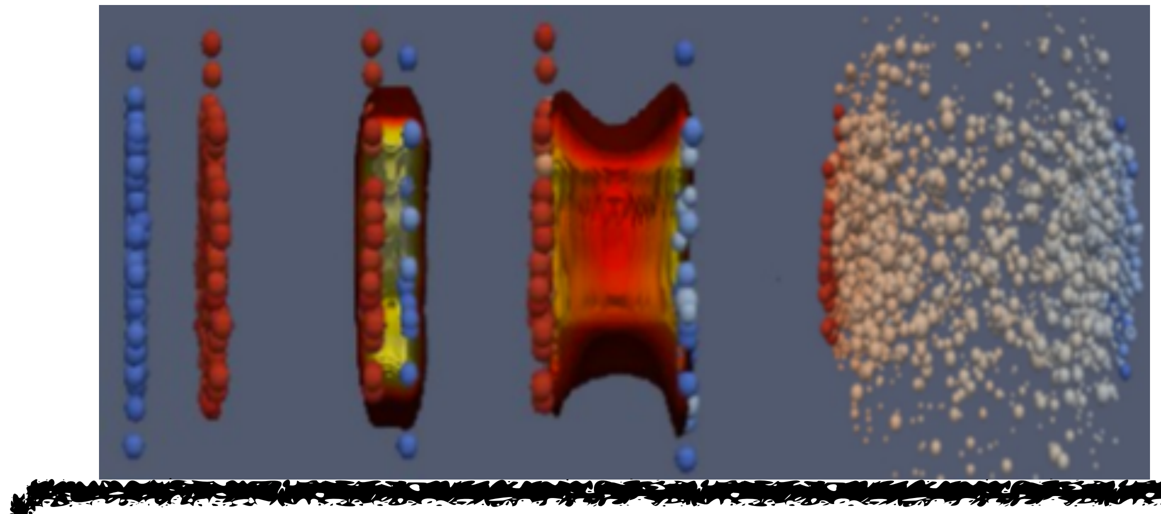


AN ATTEMPT FOR A SUMMARY…

First hint of effects of the initial E/M fields on the motion of final state particles

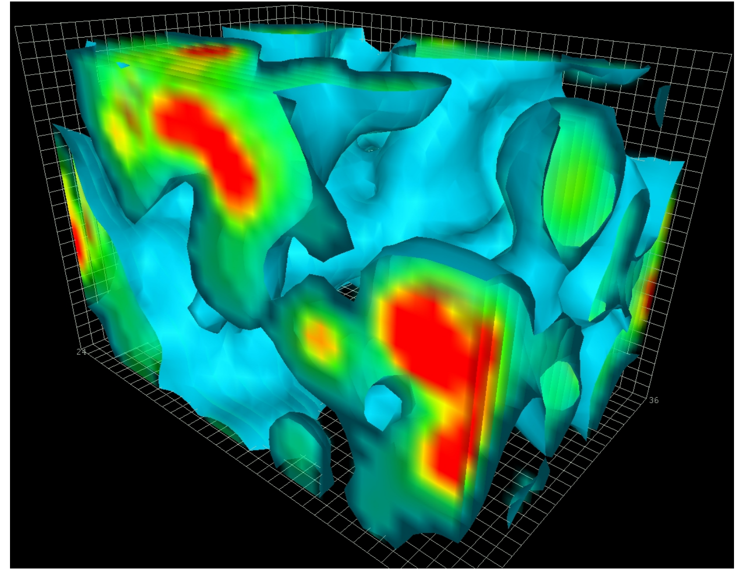




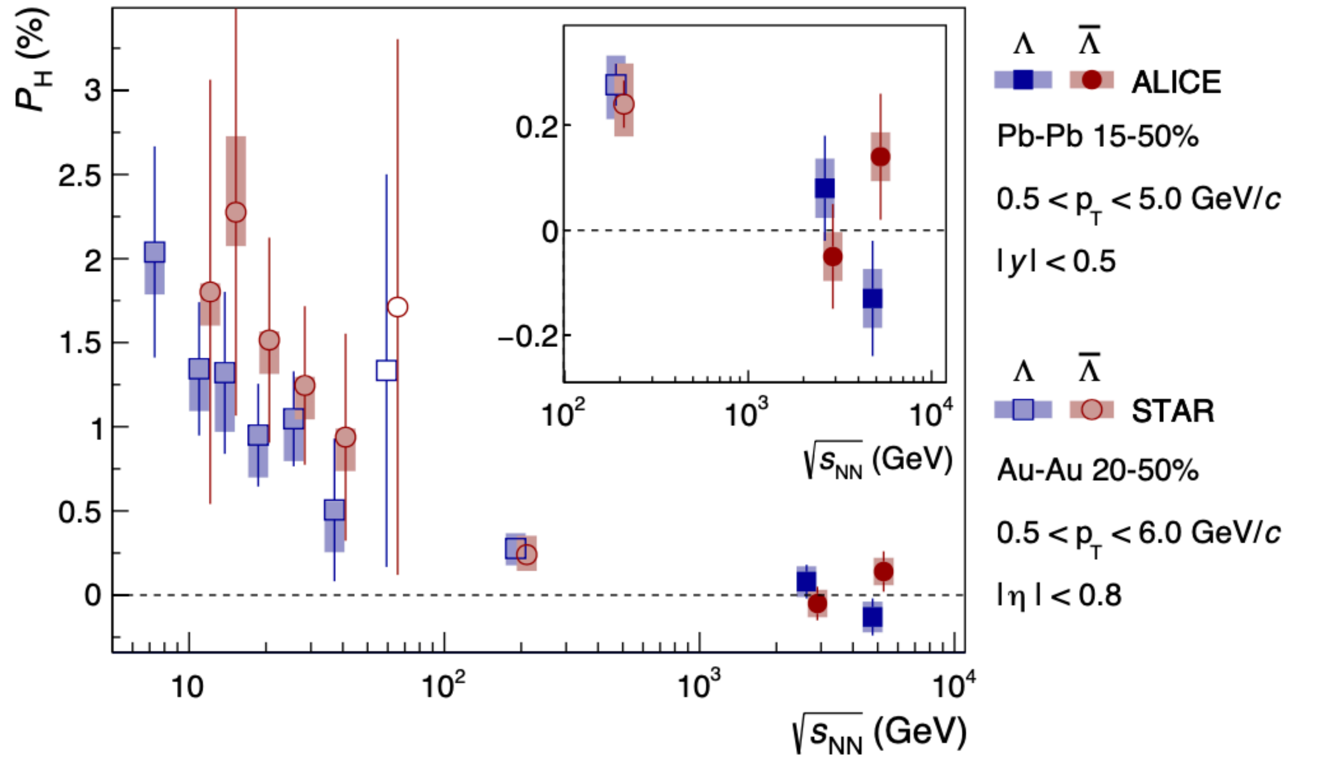


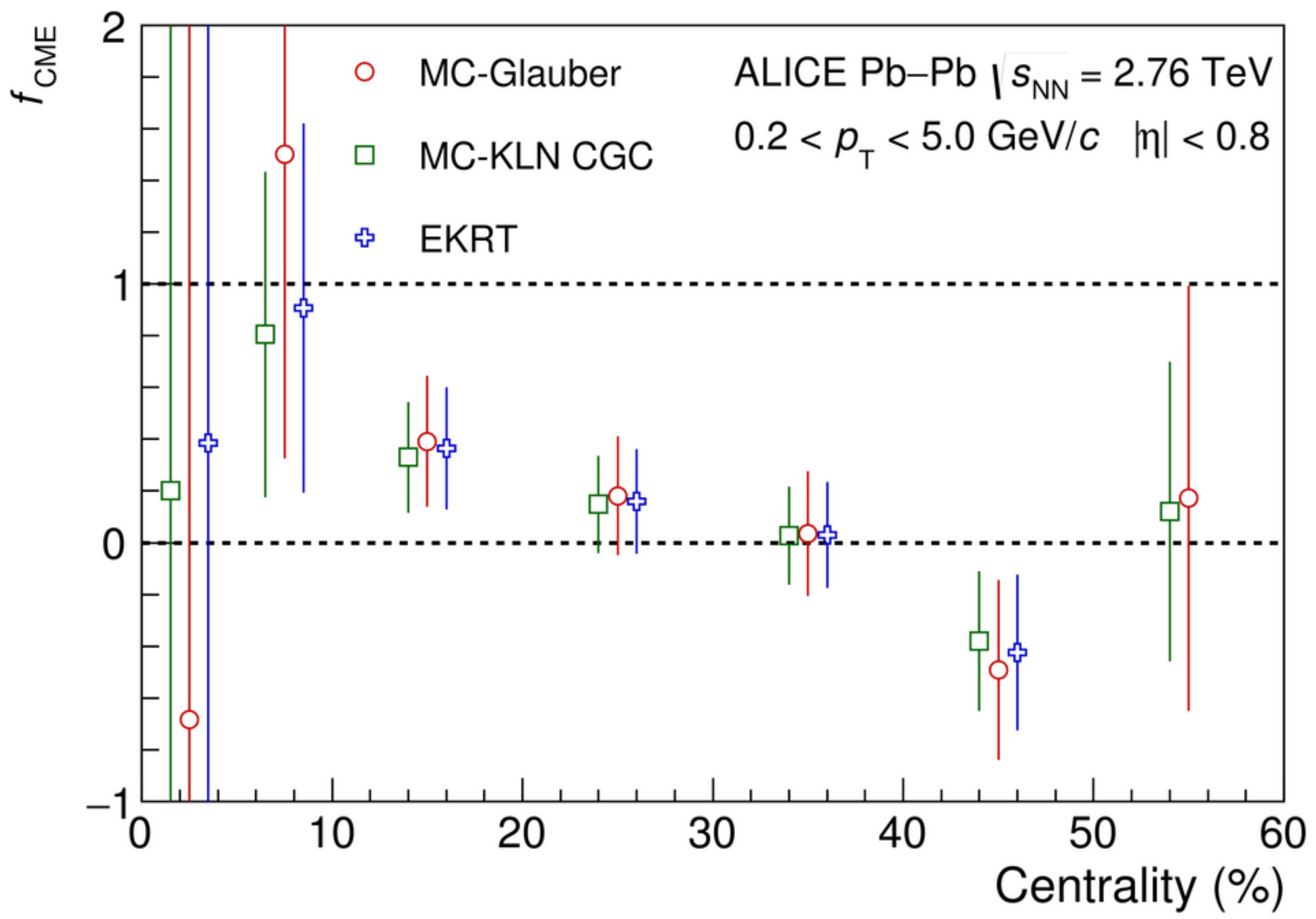
CME signal (if any) very elusive ➞ background effects are dominant

goal: either discover the CME or set a limit at the %-level



$P_H(\Lambda) \approx P_H(\text{anti-}\Lambda) \approx 0$ ➞ not sensitive to effects due to magnetic field



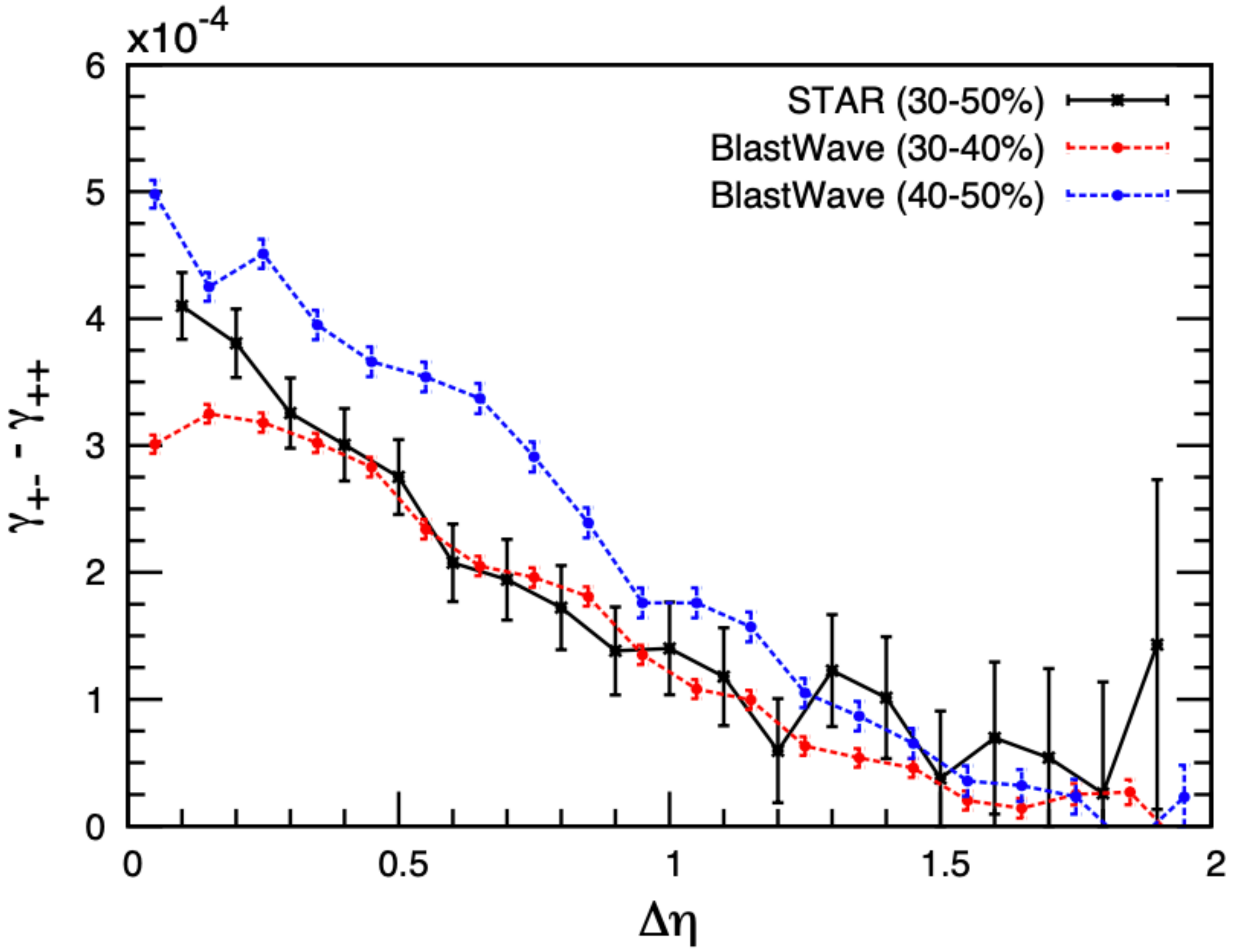


FUTURE PROSPECTS: DIFFERENTIAL RESULTS

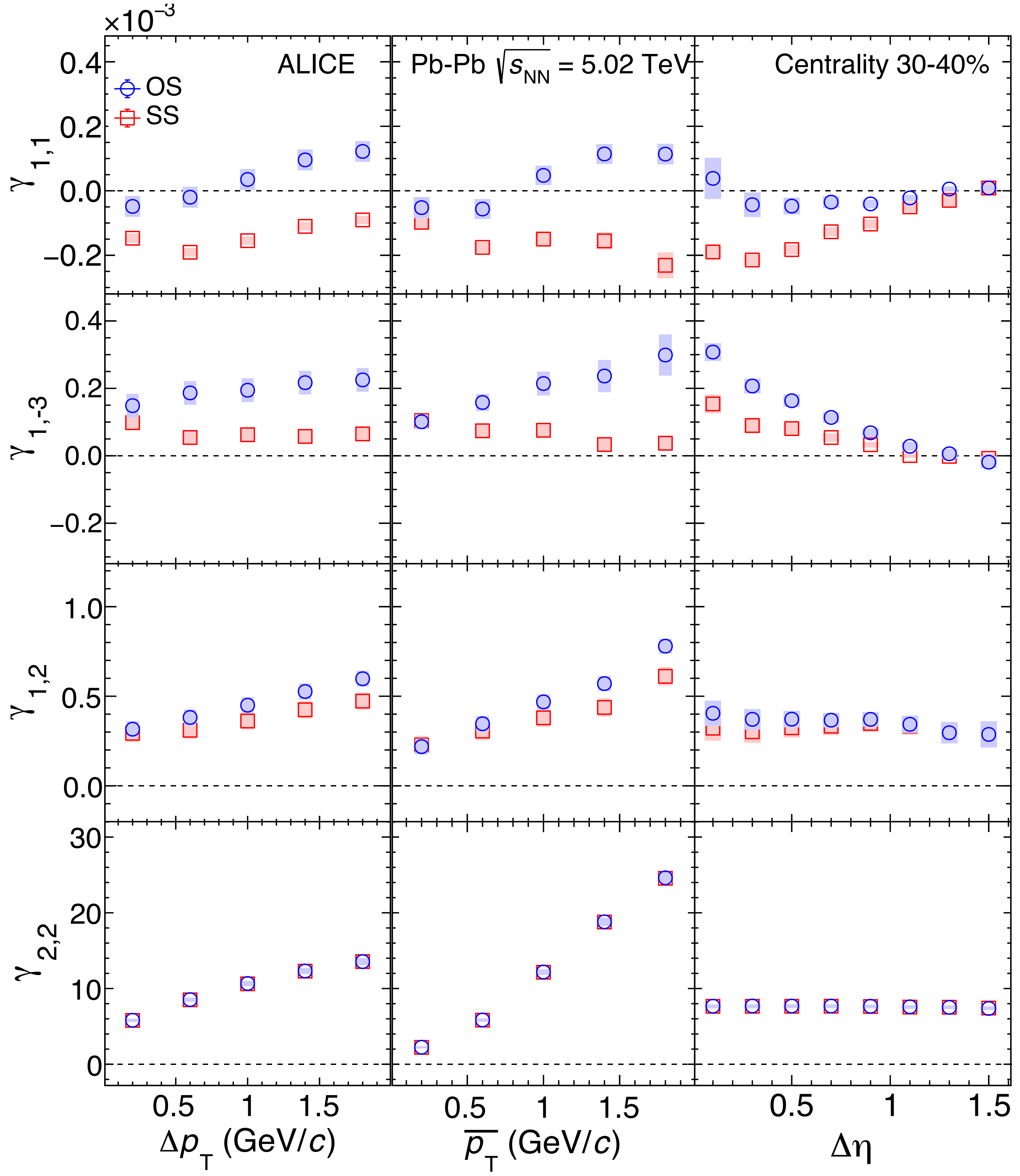
Are all systematics of the measurements described by the background?

- Differential results might give a hint as to where background effects fail to describe the data (if anywhere at all)

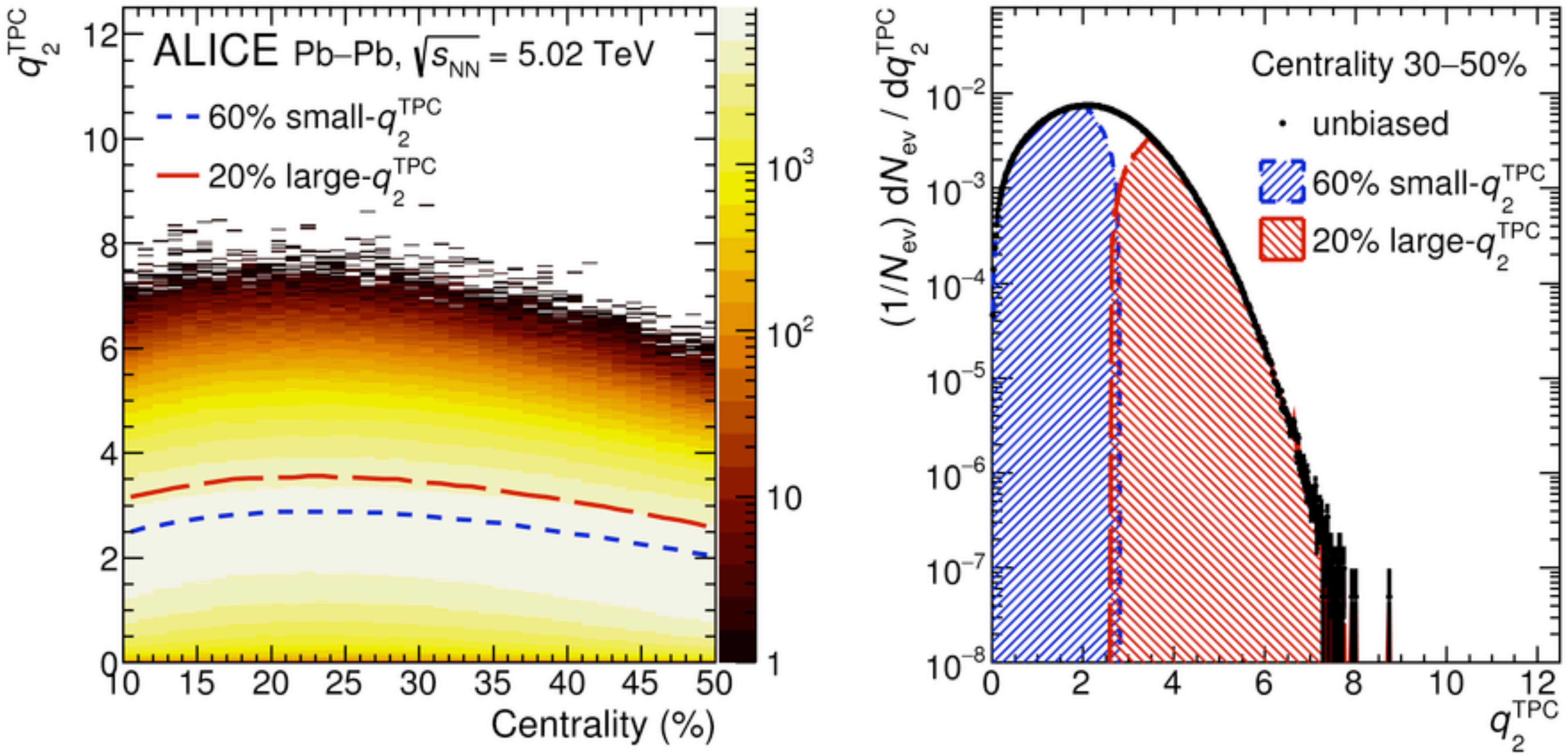
S. Schlichting and S. Pratt Phys.Rev. C83 (2011) 014913

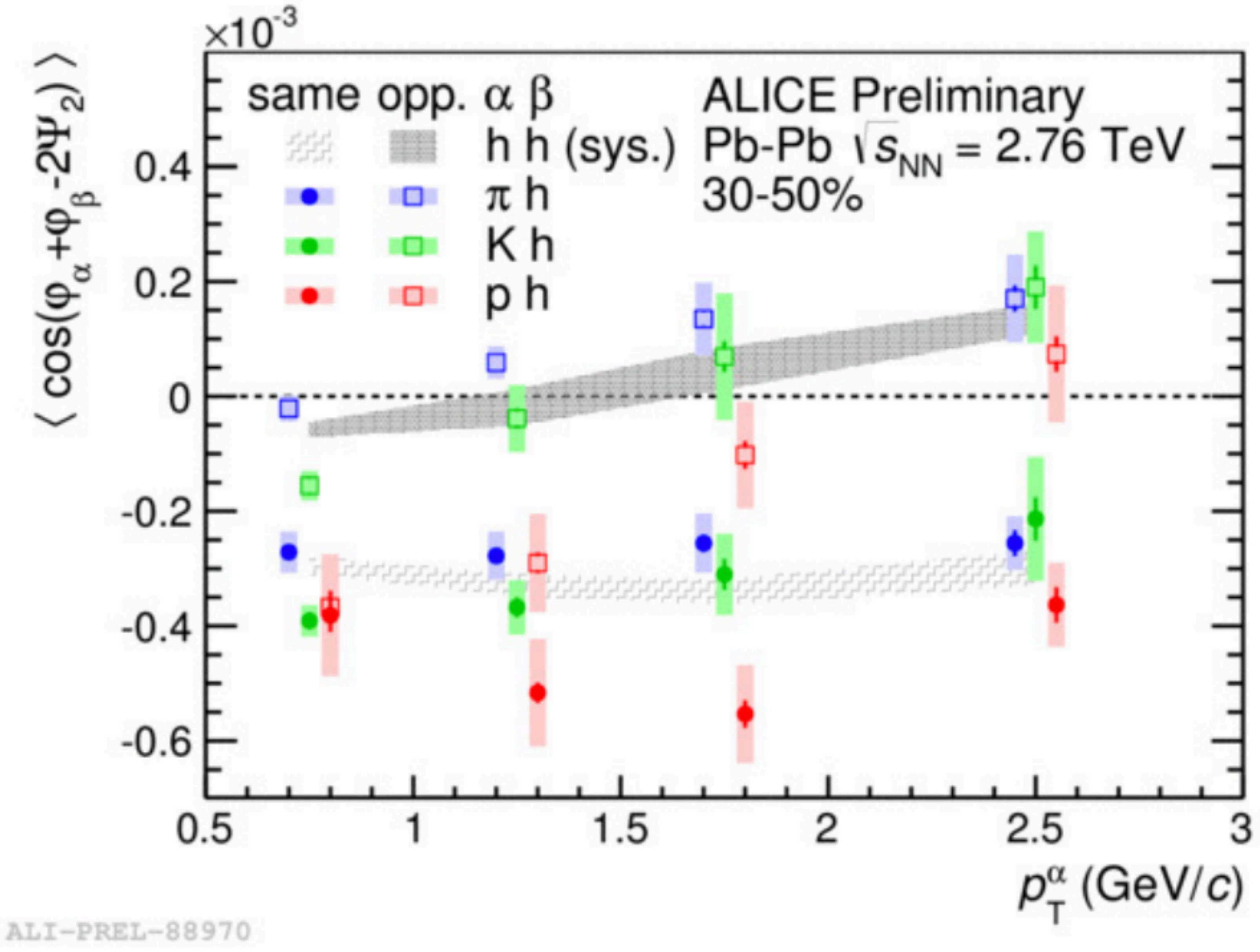


(ALICE Collaboration) JHEP 2020, (2020) 160



FUTURE PROSPECTS: SPECIES DEPENDENCE

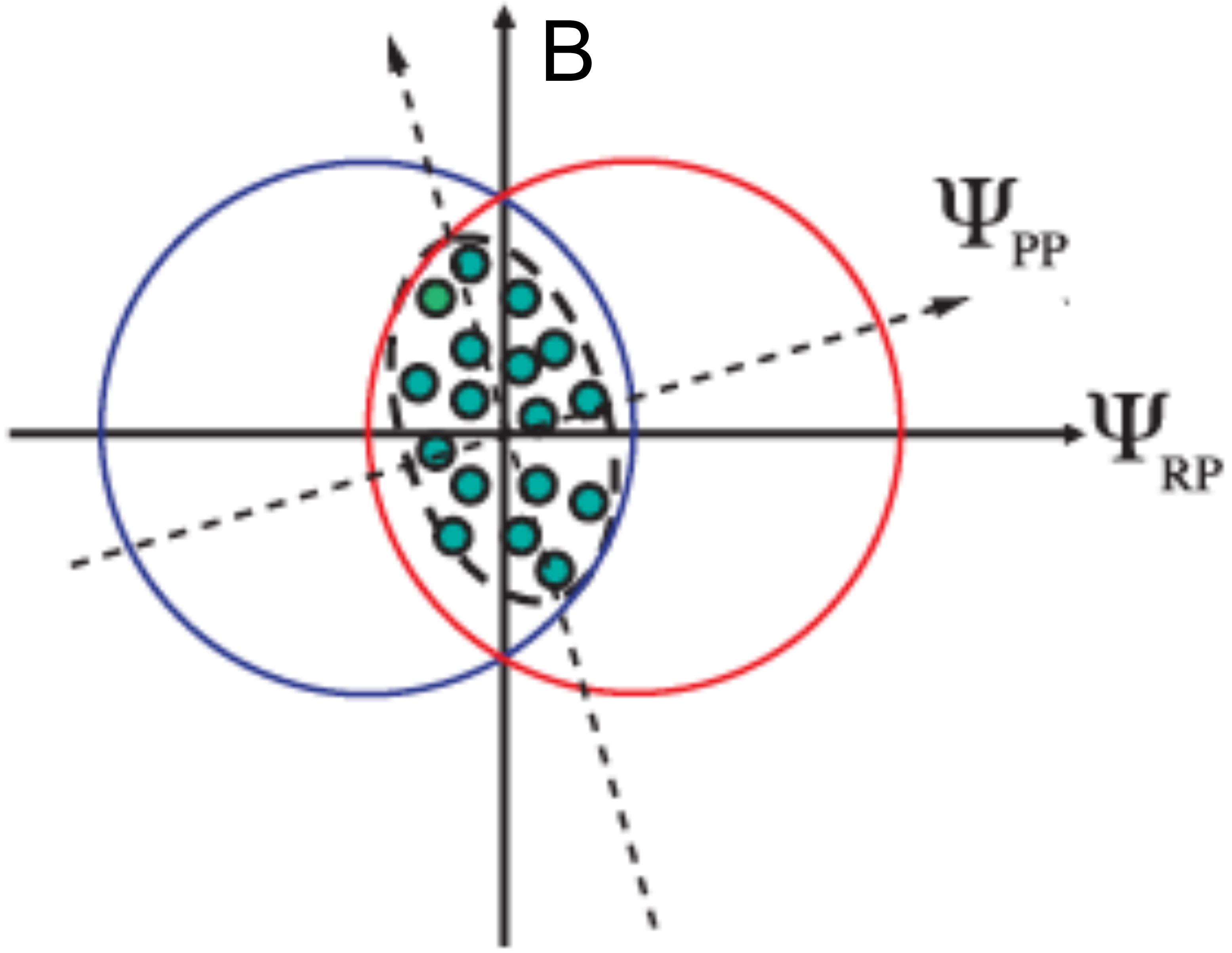




Investigate the background contribution to different particle species in combination with ESE

FUTURE PROSPECTS: Ψ_{SP} VS Ψ_{PP}

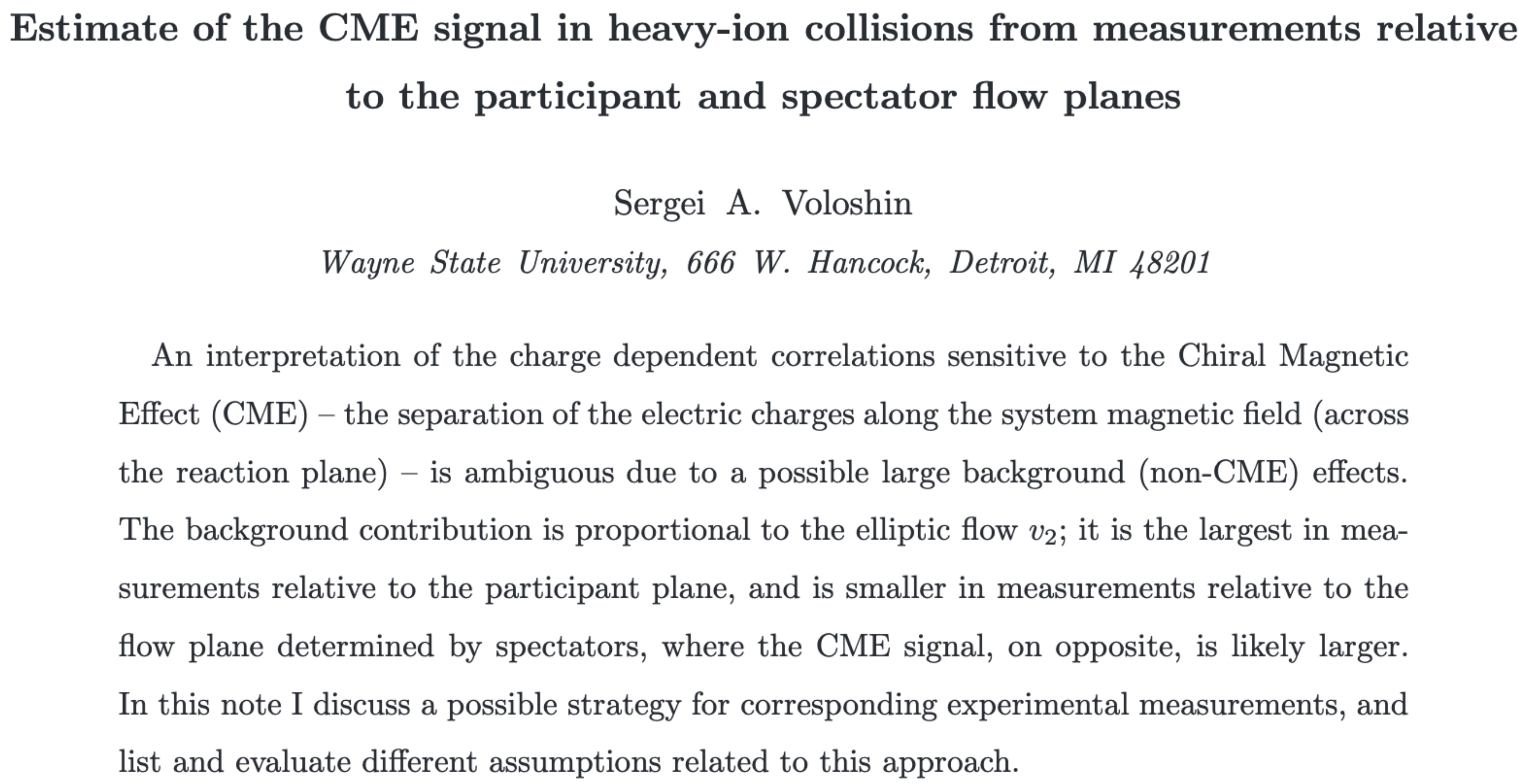
S. Voloshin, Phys. Rev. C 98, (2018) 054911



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

Background contribution larger when studied relative to Ψ_{PP} → larger v_2

CME contribution larger when studied relative to Ψ_{SP} → correlated with B



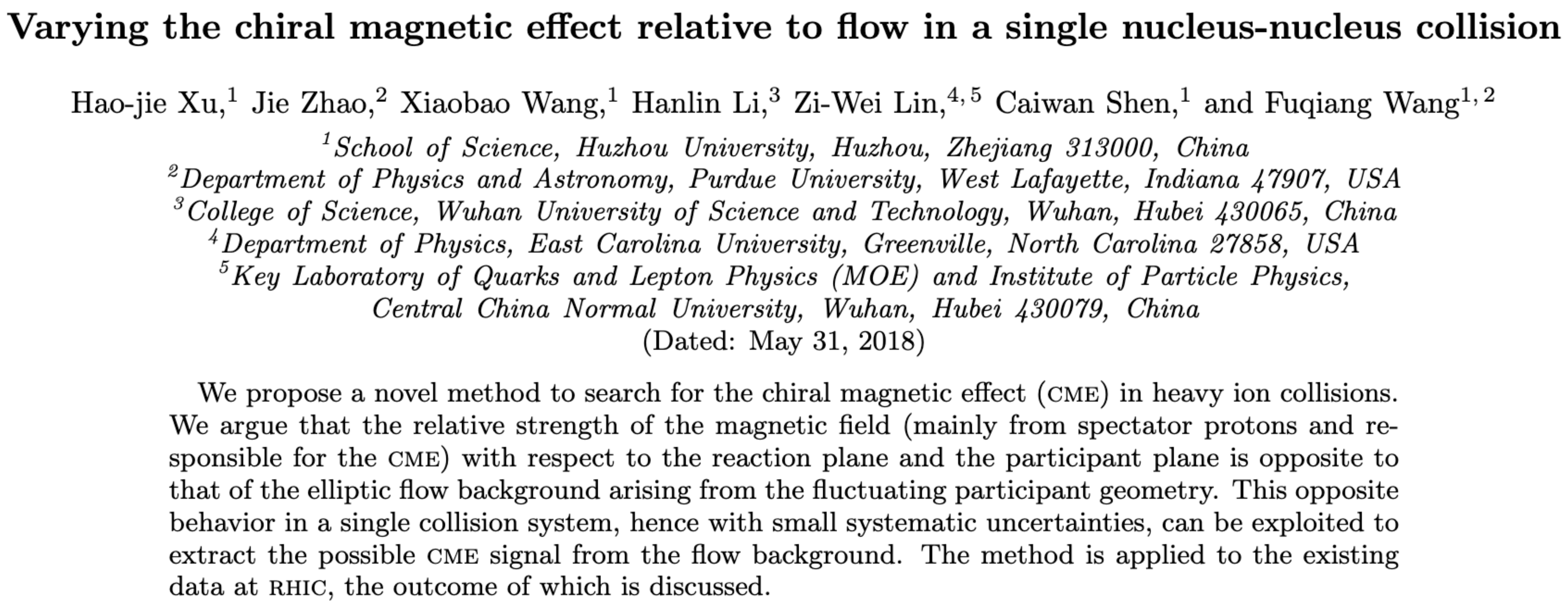
Estimate of the CME signal in heavy-ion collisions from measurements relative to the participant and spectator flow planes

Sergei A. Voloshin

Wayne State University, 666 W. Hancock, Detroit, MI 48201

An interpretation of the charge dependent correlations sensitive to the Chiral Magnetic Effect (CME) – the separation of the electric charges along the system magnetic field (across the reaction plane) – is ambiguous due to a possible large background (non-CME) effects. The background contribution is proportional to the elliptic flow v_2; it is the largest in measurements relative to the participant plane, and is smaller in measurements relative to the flow plane determined by spectators, where the CME signal, on opposite, is likely larger. In this note I discuss a possible strategy for corresponding experimental measurements, and list and evaluate different assumptions related to this approach.

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



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

Hao-jie Xu,[1] Jie Zhao,[2] Xiaobao Wang,[1] Hanlin Li,[3] Zi-Wei Lin,[4,5] Caiwan Shen,[1] and Fuqiang Wang[1,2]
[1]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[2]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
[3]*College of Science, Wuhan University of Science and Technology, Wuhan, Hubei 430065, China*
[4]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*
[5]*Key Laboratory of Quarks and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, Hubei 430079, China*
(Dated: May 31, 2018)

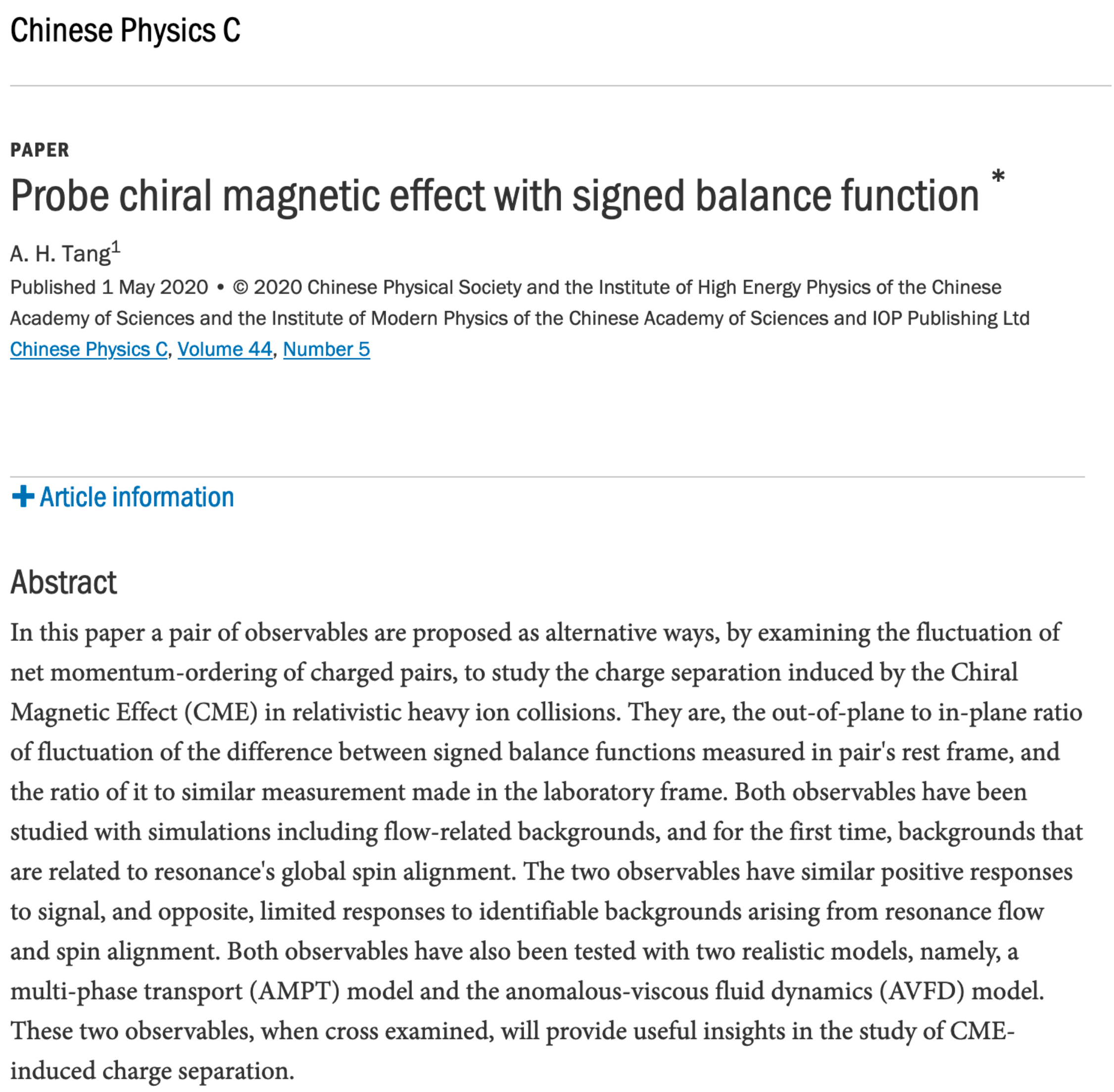
We propose a novel method to search for the chiral magnetic effect (CME) in heavy ion collisions. We argue that the relative strength of the magnetic field (mainly from spectator protons and responsible for the CME) with respect to the reaction plane and the participant plane is opposite to that of the elliptic flow background arising from the fluctuating participant geometry. This opposite behavior in a single collision system, hence with small systematic uncertainties, can be exploited to extract the possible CME signal from the flow background. The method is applied to the existing data at RHIC, the outcome of which is discussed.

FUTURE PROSPECTS: SIGNED BALANCE FUNCTIONS

Usual direction followed → look at the charge-dependent production of particles in azimuth relative to the symmetry plane

Challenge → measurements dominated by background → local charge conservation + anisotropic flow

Possible new direction: look at charge-dependent momentum asymmetries relative to the symmetry plane



Chinese Physics C

PAPER

Probe chiral magnetic effect with signed balance function *

A. H. Tang[1]

Published 1 May 2020 • © 2020 Chinese Physical Society and the Institute of High Energy Physics of the Chinese Academy of Sciences and the Institute of Modern Physics of the Chinese Academy of Sciences and IOP Publishing Ltd

Chinese Physics C, Volume 44, Number 5

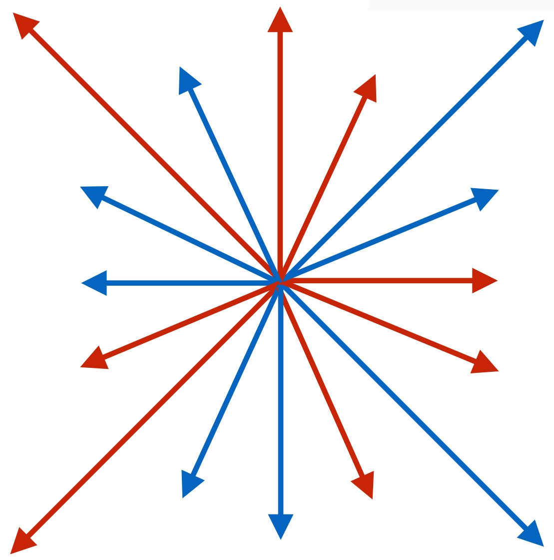
+ Article information

Abstract

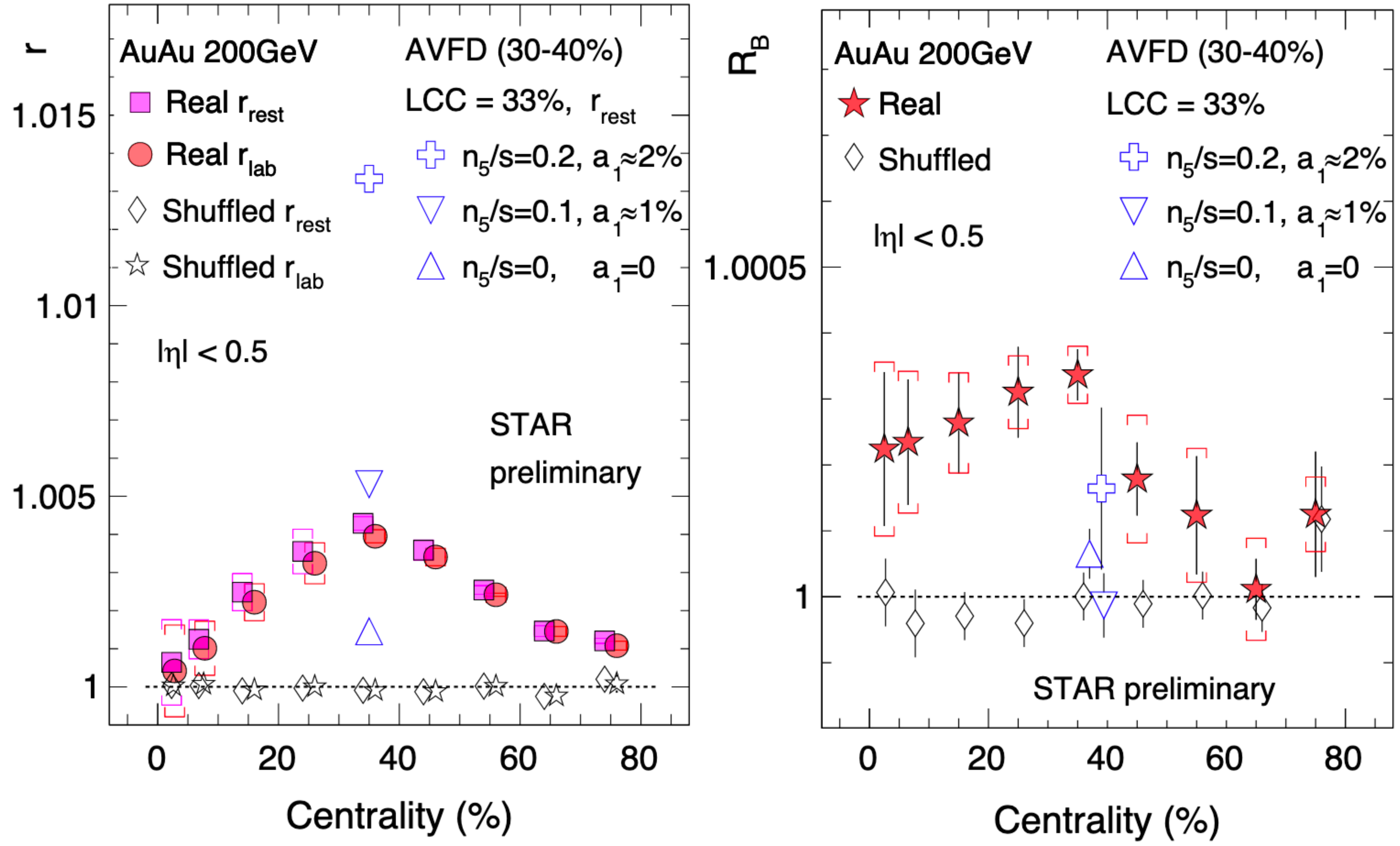
In this paper a pair of observables are proposed as alternative ways, by examining the fluctuation of net momentum-ordering of charged pairs, to study the charge separation induced by the Chiral Magnetic Effect (CME) in relativistic heavy ion collisions. They are, the out-of-plane to in-plane ratio of fluctuation of the difference between signed balance functions measured in pair's rest frame, and the ratio of it to similar measurement made in the laboratory frame. Both observables have been studied with simulations including flow-related backgrounds, and for the first time, backgrounds that are related to resonance's global spin alignment. The two observables have similar positive responses to signal, and opposite, limited responses to identifiable backgrounds arising from resonance flow and spin alignment. Both observables have also been tested with two realistic models, namely, a multi-phase transport (AMPT) model and the anomalous-viscous fluid dynamics (AVFD) model. These two observables, when cross examined, will provide useful insights in the study of CME-induced charge separation.

Look at momentum differences relative to the symmetry plane:

ΔP_y → CME contribution vs ΔP_x → no CME contribution



(STAR Collaboration) QM2019

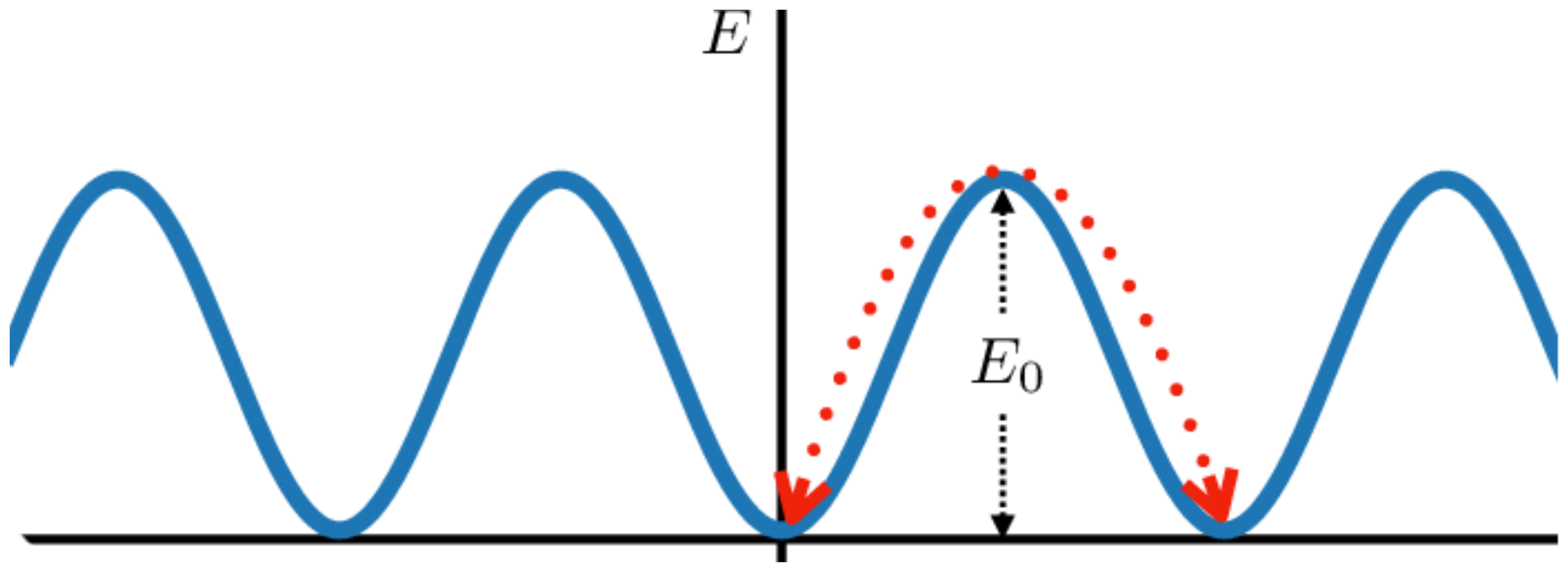


Thank you for
your attention!

BACKUP

THE QCD VACUUM AND CHIRAL ANOMALIES

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)



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 $|n\rangle$ 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

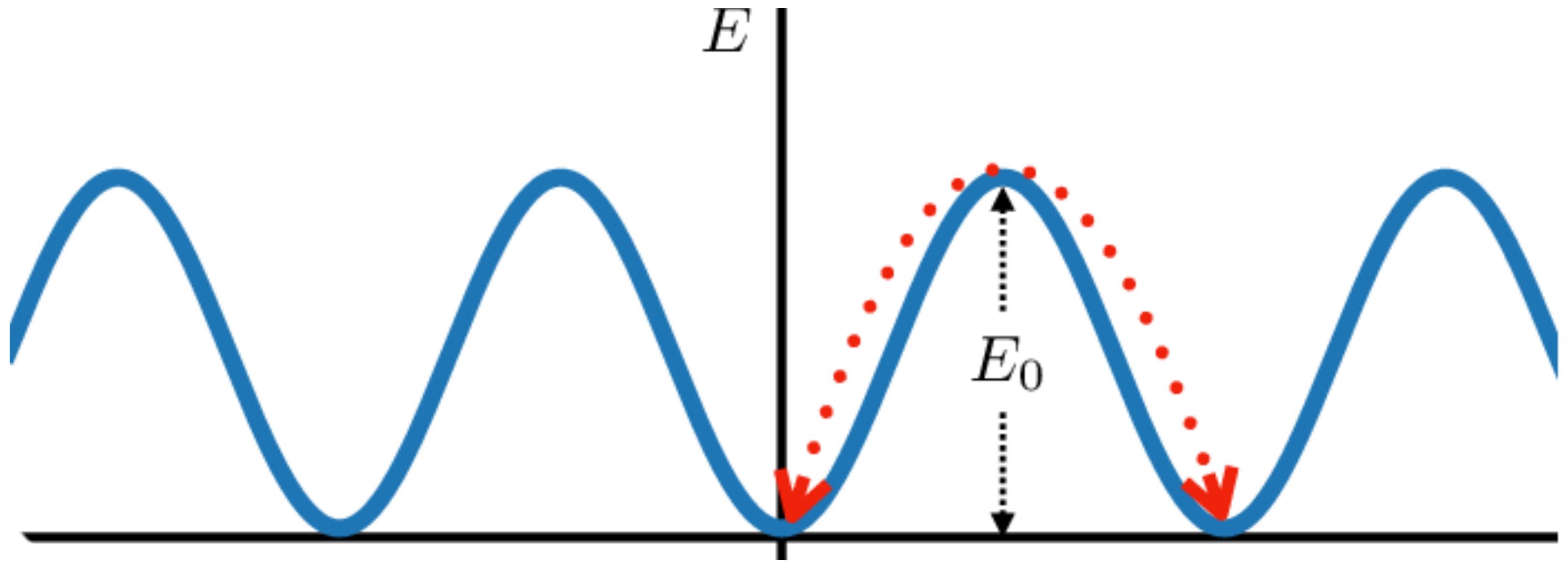
Transitions between these states can be done through

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

Physical implication (for QCD):

- Chirality is not conserved at a scale of the order of the scale of the theory (~Λ_{QCD})
  - The axial chemical potential $\mu_5 = N_L - N_R$ is non-zero

THE QCD VACUUM AND CHIRAL ANOMALIES



A direct consequence is that P and CP invariance in QCD is no longer natural

- Add a CP violating term to the QCD Lagrangian density

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\alpha\mu\nu} + \sum_f \overline{\Psi}_f[i\gamma_\mu(\partial^\mu - ig_s A^{\alpha\mu}\lambda^\alpha) - m_f]\Psi_f - \frac{\theta}{32\pi^2}g_s^2 F^{\alpha}_{\mu\nu}\tilde{F}^{\alpha\mu\nu}$$

If θ≠0, CP invariance is lost in QCD

However, global parity violation has never been detected experimentally in QCD (see neutron EDM measurement) → $\langle\theta(\mathbf{x},t)\rangle = 0$

M. A. Shifman, A. Vainshtein, and V. I. Zakharov, Nucl. Phys. B166(1980) 493

- Strong CP problem → many proposed solutions e.g. axion particle (candidate for DM)

Theory allows for local parity violation

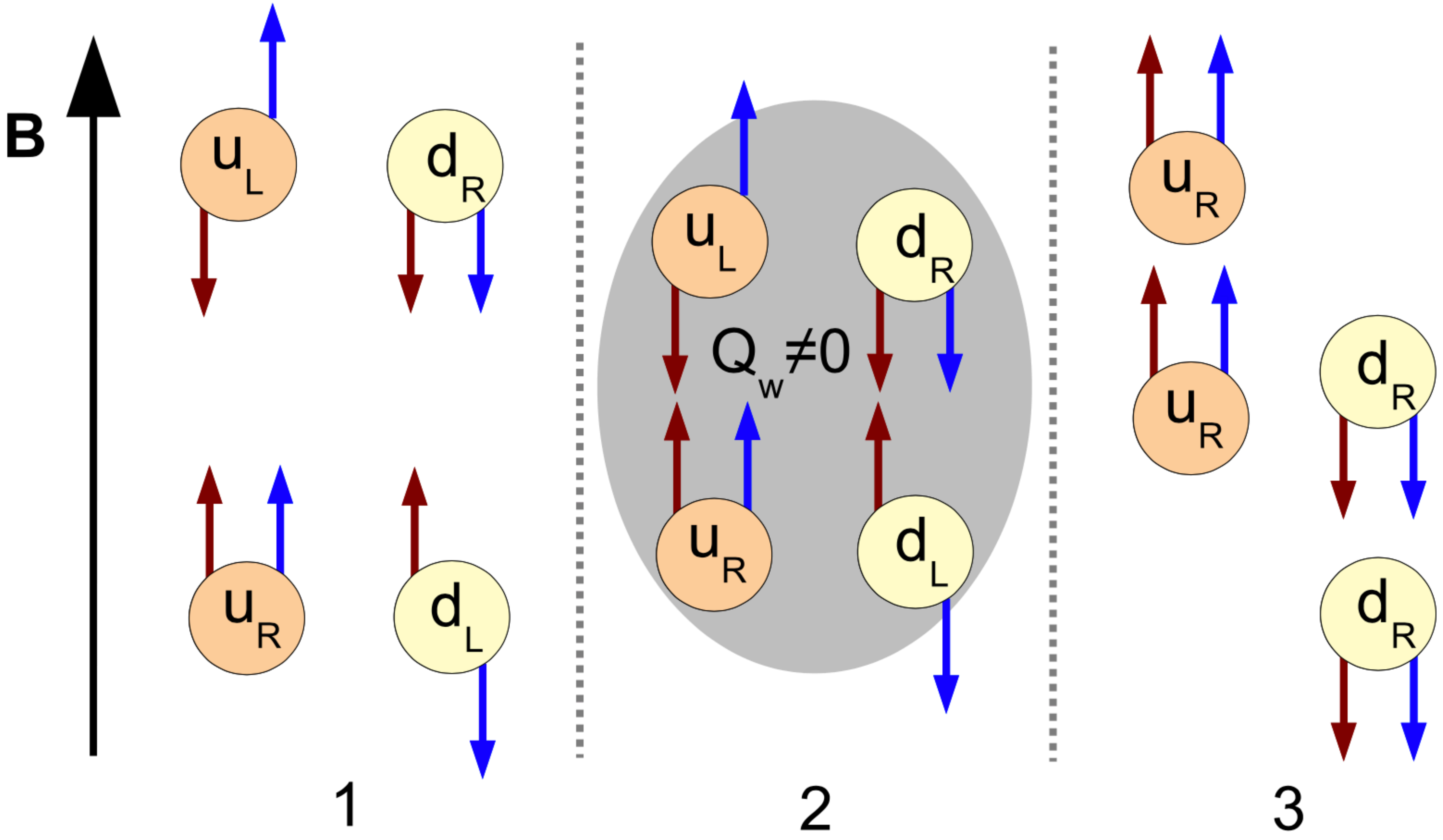
D. Kharzeev, arXiv:1312.333348 [hep-ph]

- e.g. probed by observables that fluctuate from event to event → effect reflected in dynamical fluctuations > statistical fluctuations

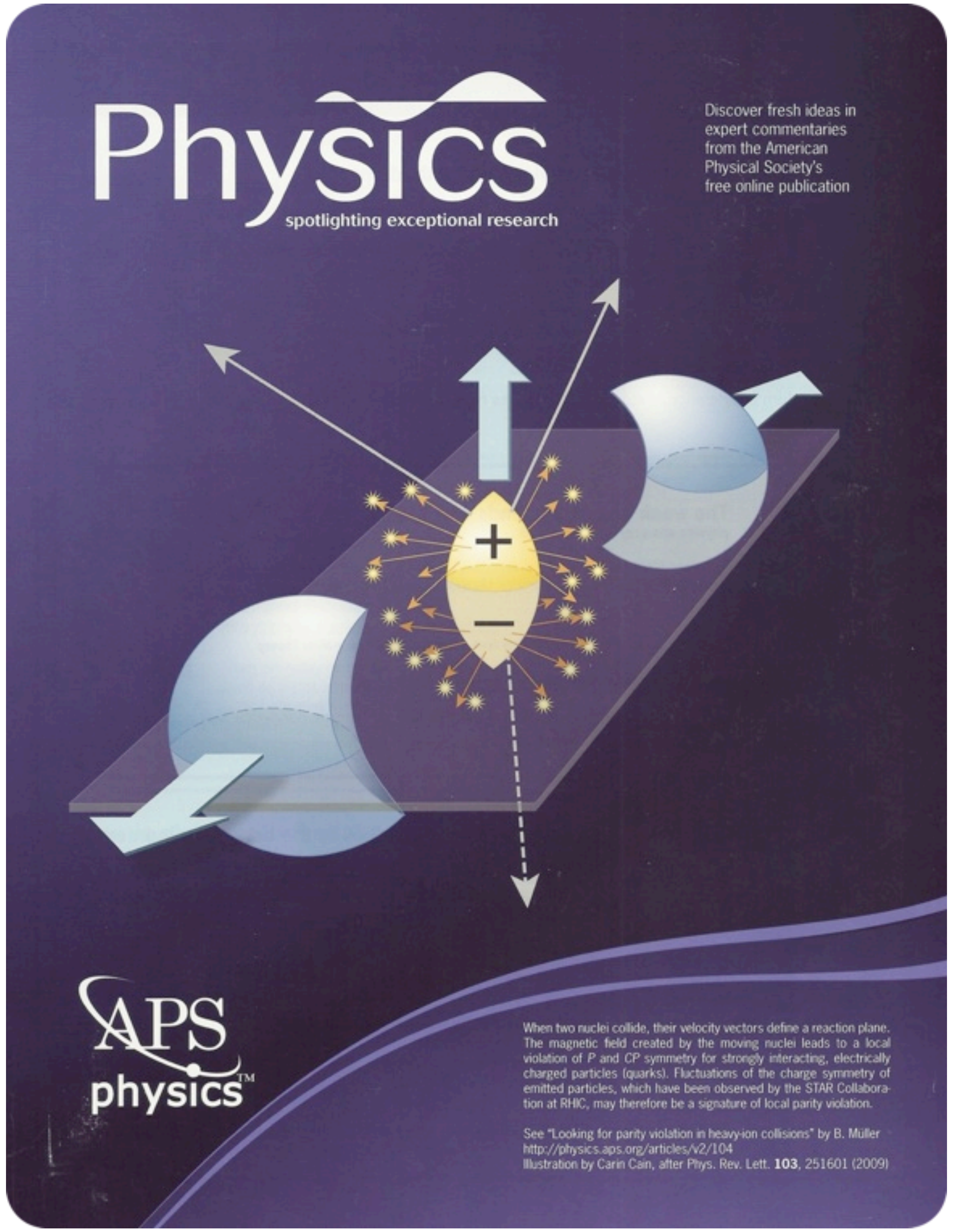
Theory is vetted: local P and CP odd effects can be experimentally observed in heavy ion collisions

THE CHIRAL MAGNETIC EFFECT (CME)

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



Not only CME but also CSE, CMW,…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APS
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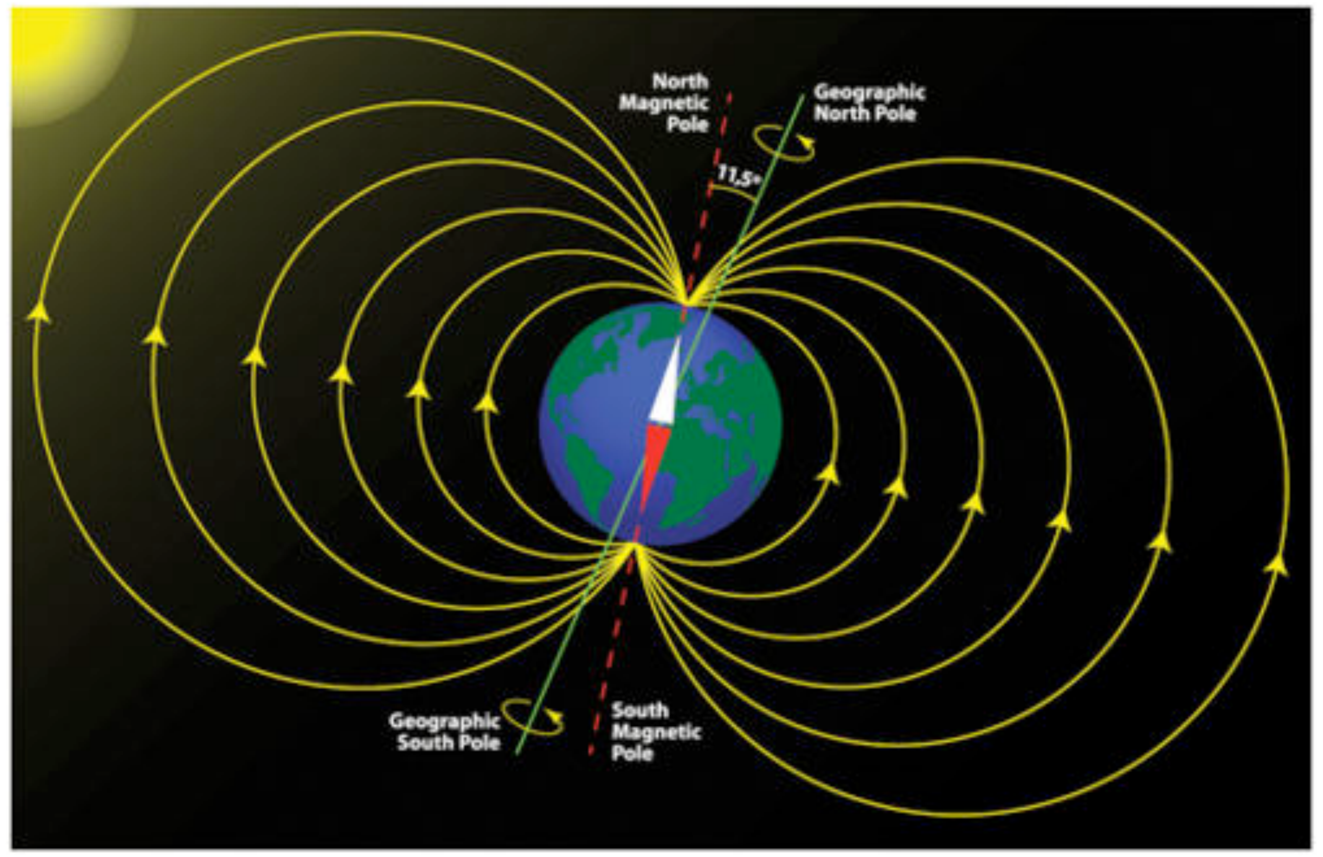
When two nuclei collide, their velocity vectors define a reaction plane. The magnetic field created by the moving nuclei leads to a local violation of *P* and *CP* symmetry for strongly interacting, electrically charged particles (quarks). Fluctuations of the charge symmetry of emitted particles, which have been observed by the STAR Collaboration at RHIC, may therefore be a signature of local parity violation.

See "Looking for parity violation in heavy-ion collisions" by B. Müller
http://physics.aps.org/articles/v2/104
Illustration by Carin Cain, after Phys. Rev. Lett. **103**, 251601 (2009)

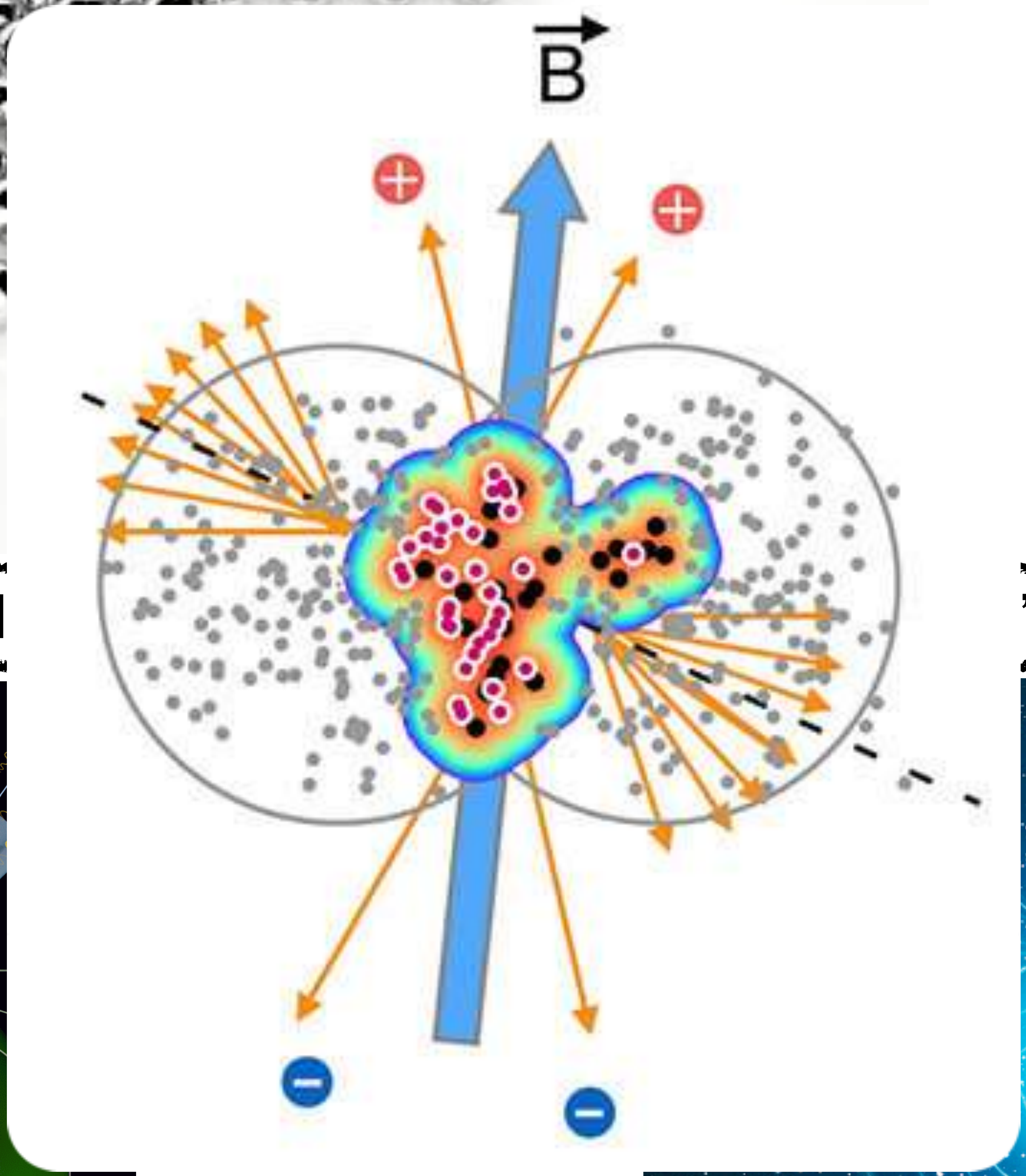
THE STRONGEST MAGNETIC FIELD IN NATURE…

Earth's magnetic field: ~0.5 G

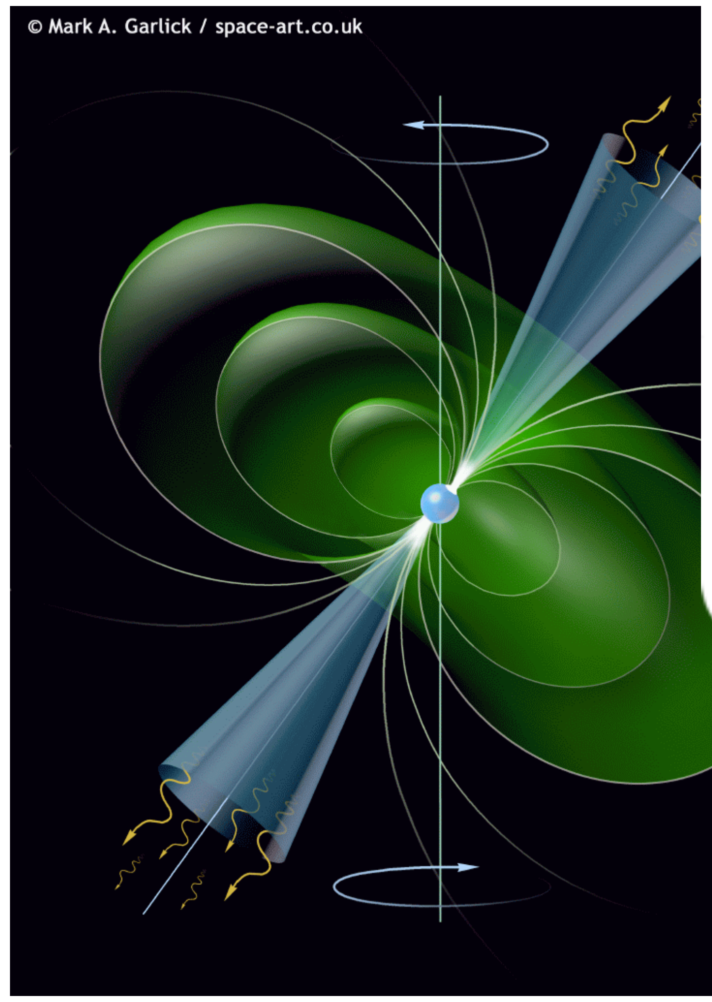


Common magnet: ~50 G

The strongest man-made field: ~10^6 G



Pulsar's magnetic field


© Mark A. Garlick / space-art.co.uk

's field: 10^{12} -10^{15} G

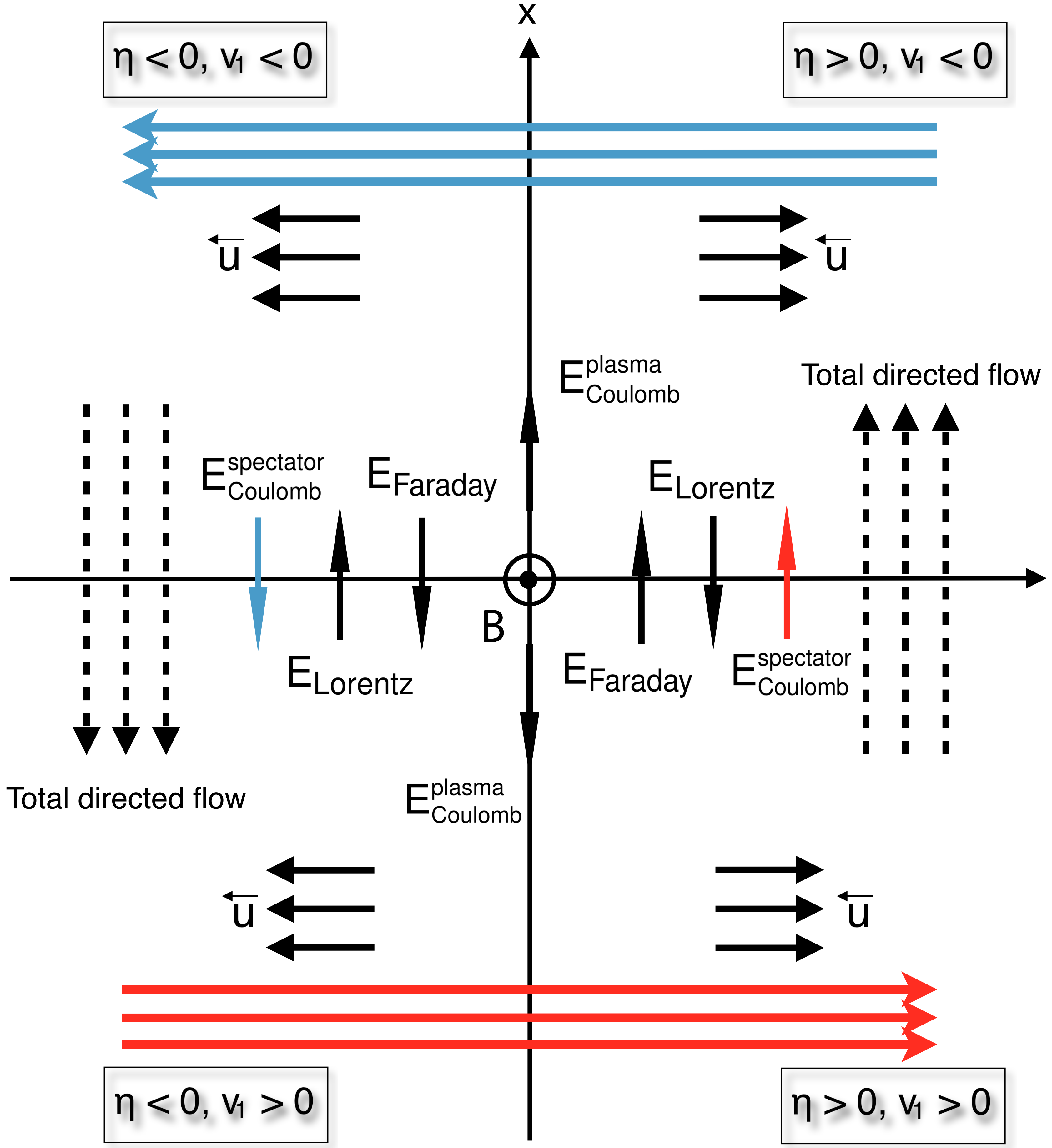
EXPERIMENTAL PROBE: CHARGE DEPENDENT V$_N$

Competing effects:

Faraday + spectator Coulomb vs Lorentz force

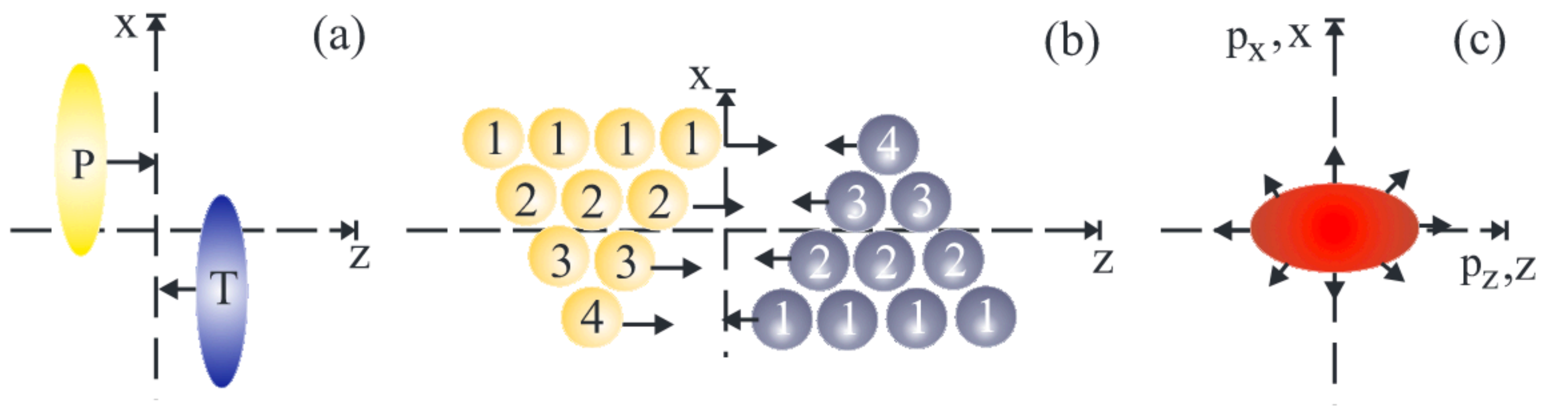
Initial stage E/M fields could affect the motion of particles → experimentally accessible differences in charge dependent odd v_n

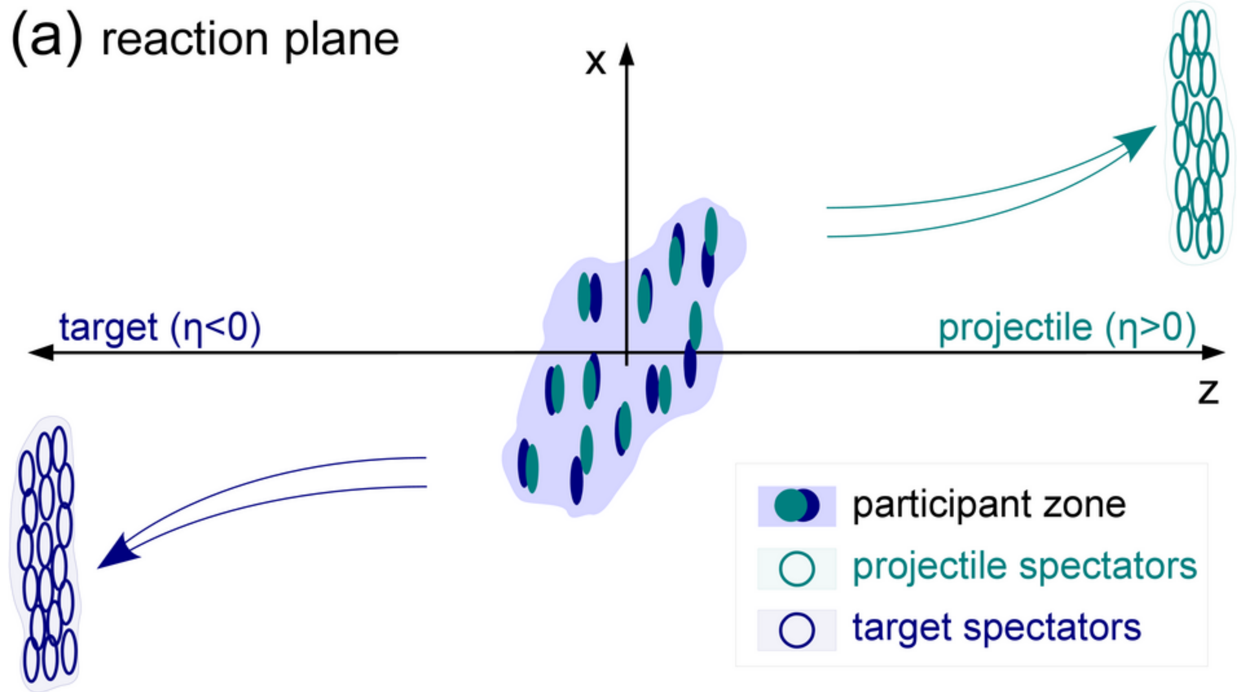
U. Gürsoy *et al.*, Phys. Rev. **C98**, (2018) 055201



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

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



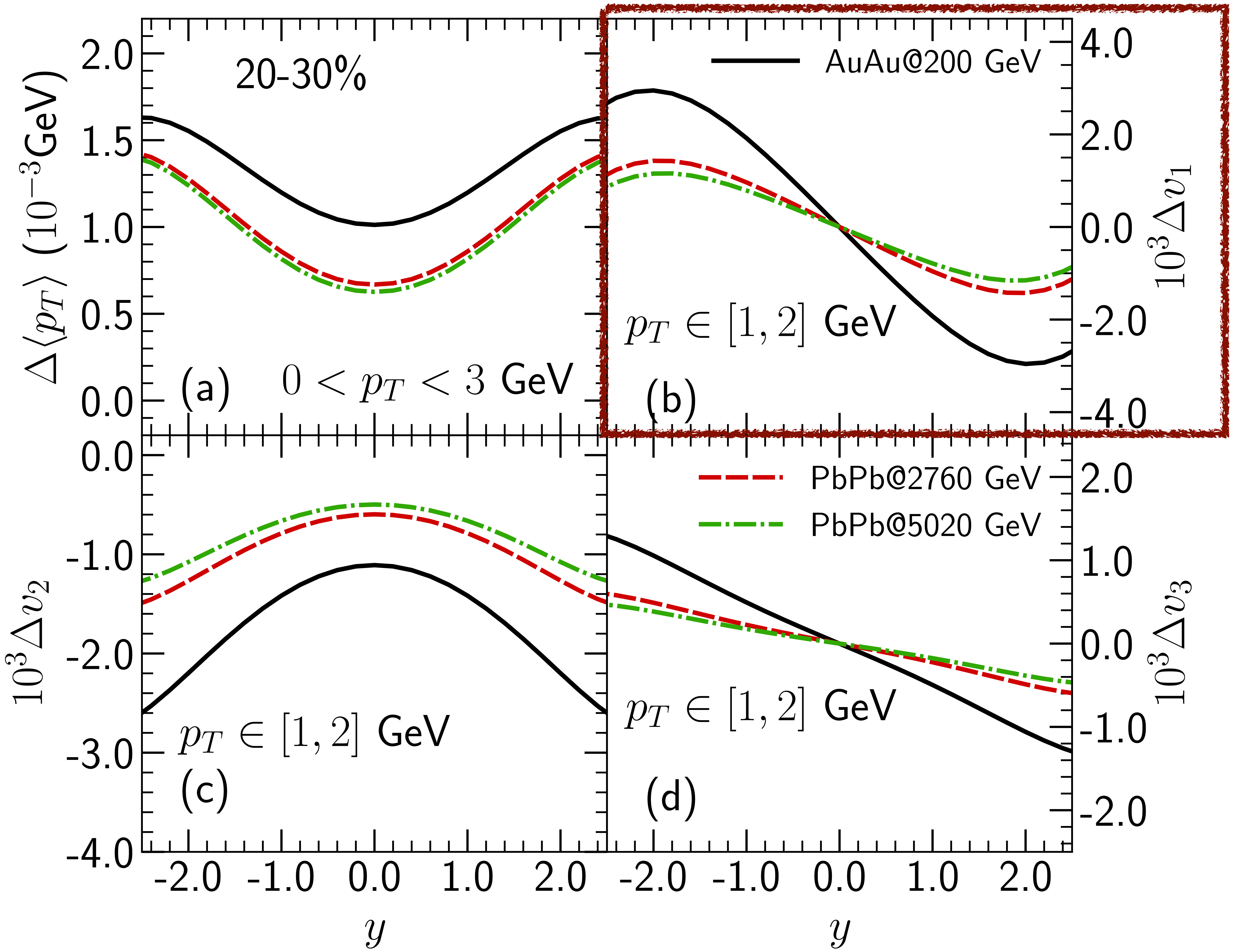


EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

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

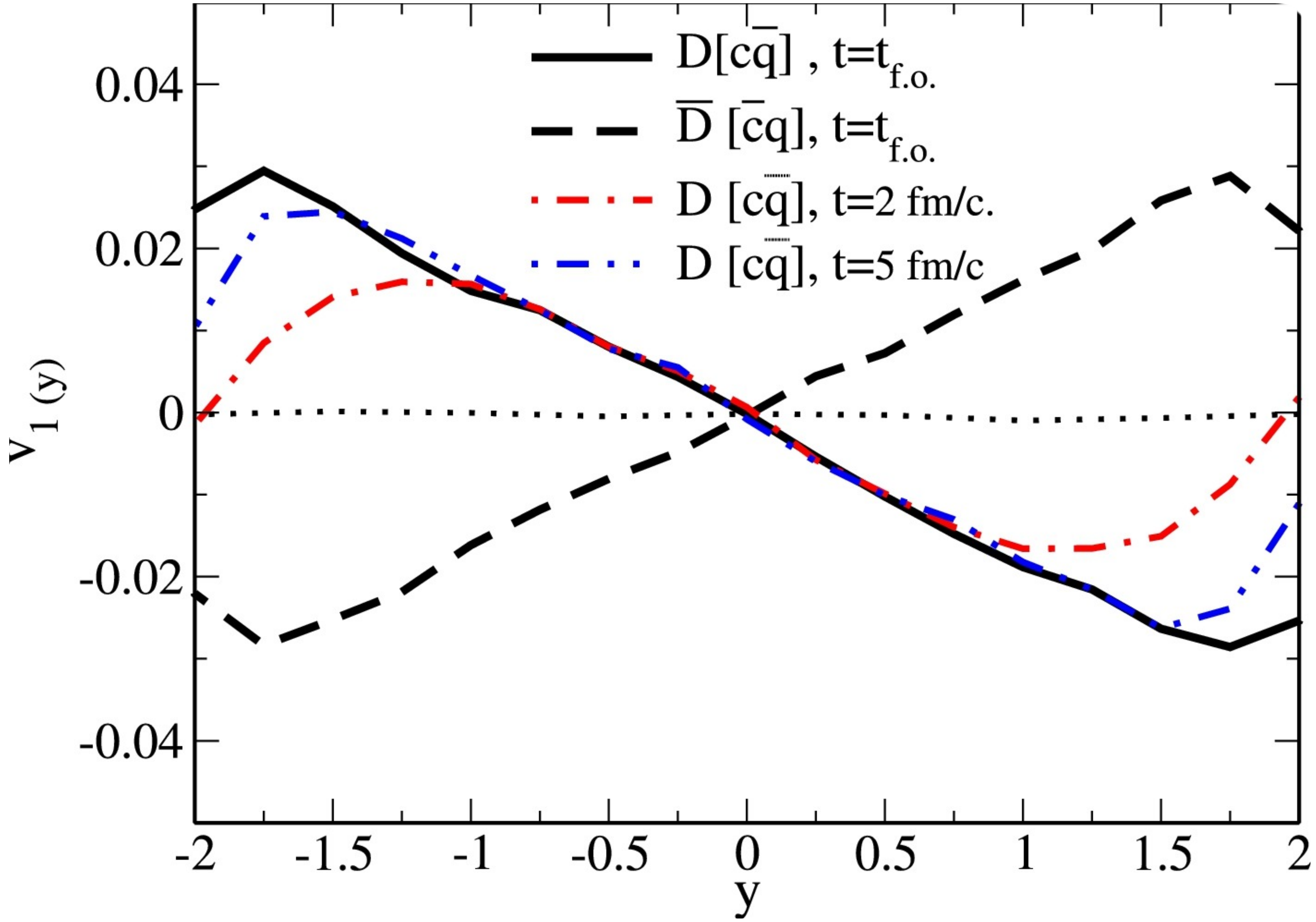


EXPERIMENTAL PROBE: CHARGE DEPENDENT V$_N$

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



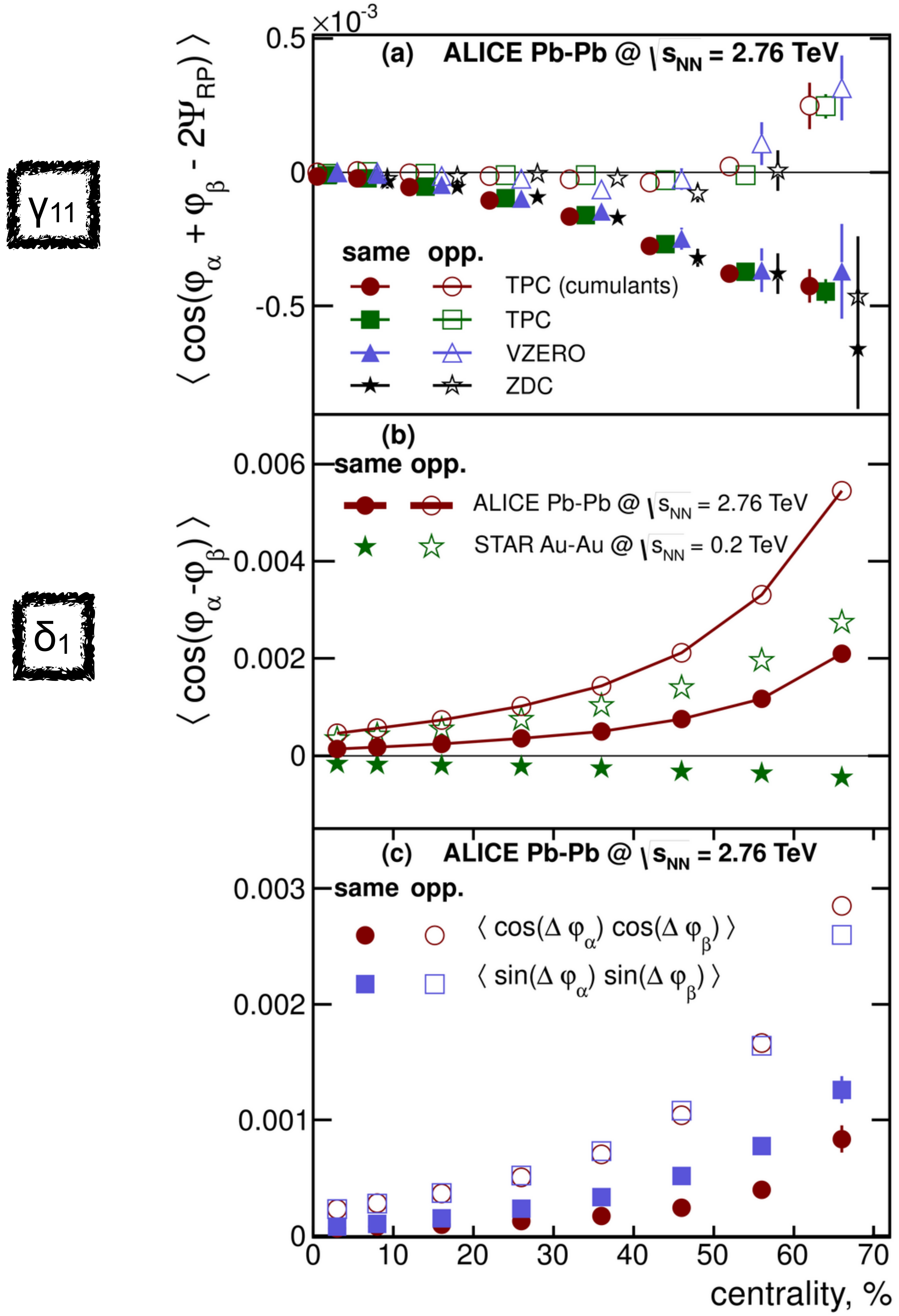
FIRST RESULTS AT THE LHC

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

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



CME SENSITIVE CORRELATOR: RESULTS @ LHC ENERGIES

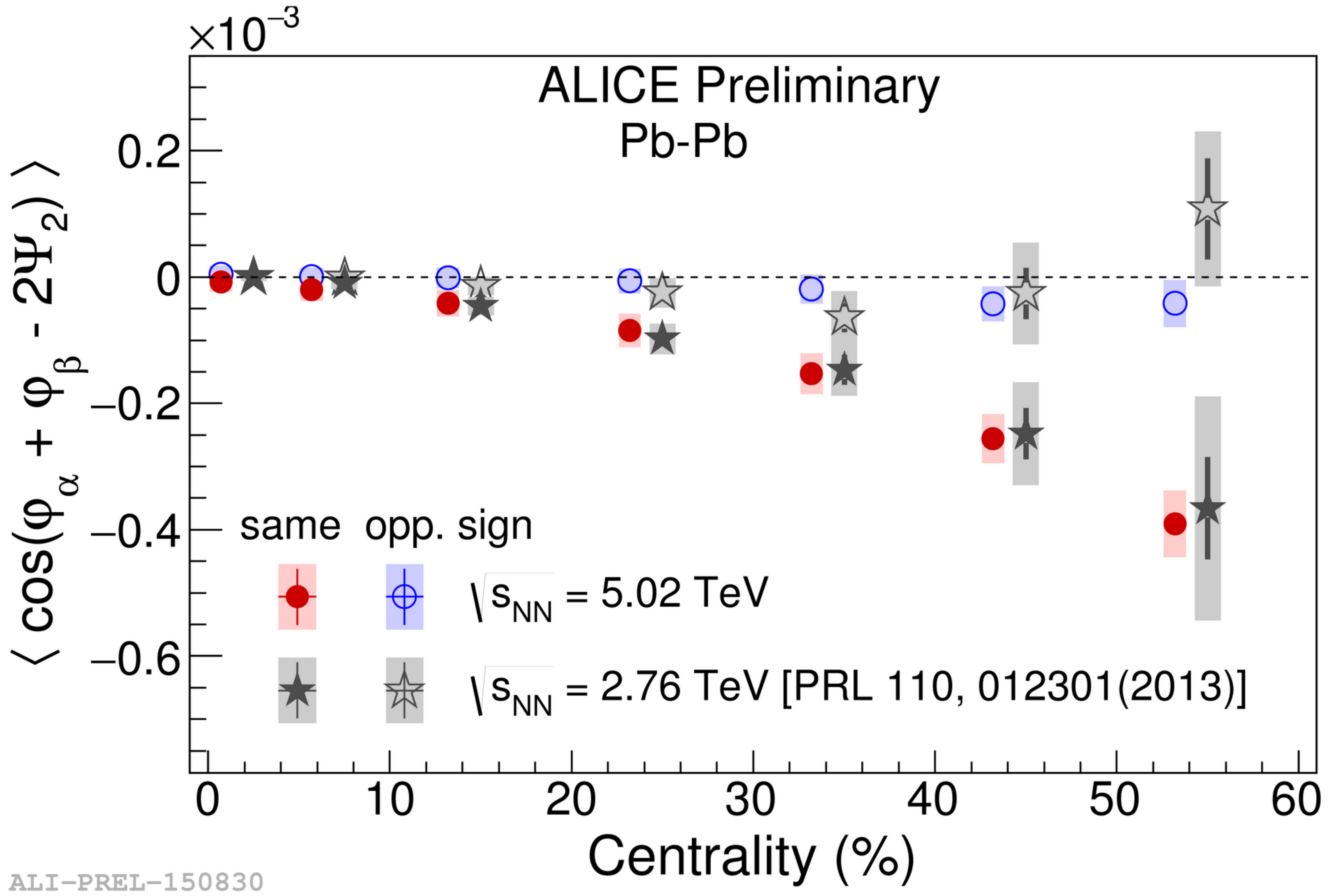
CME results consistent (within uncertainties) between the two LHC energies

Background doesn't change much between the two energies

- v_2 changes by ~3%
- Narrowing of the balance function width the same within uncertainties

$\gamma_{1,1}$ →

(ALICE Collaboration) JHEP 2020, (2020) 160



Goal: disentangle the CME signal from the background

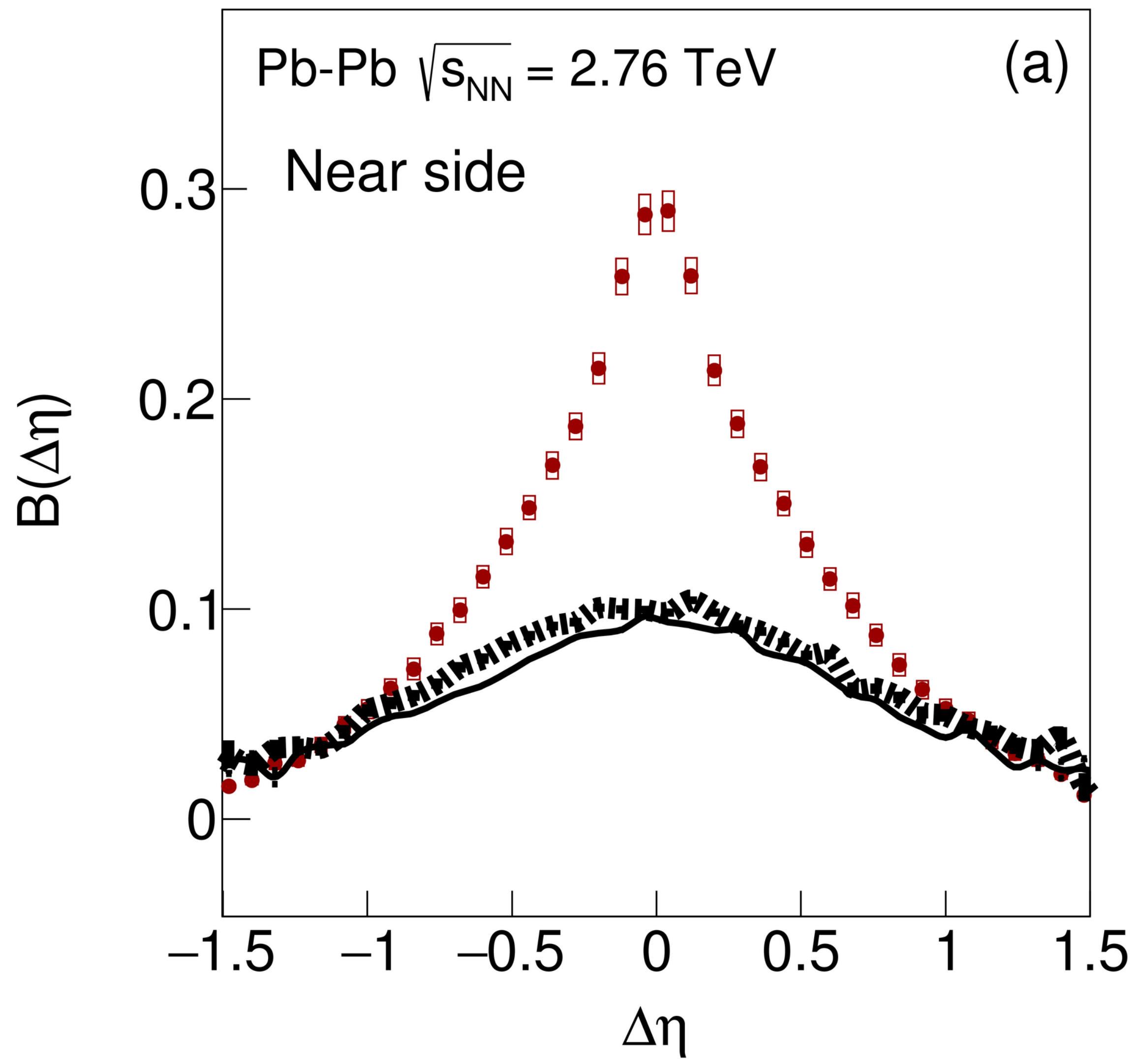
CHARGE DEPENDENT CORRELATIONS @ LHC

$$B(\Delta\eta,\Delta\varphi)=\frac{1}{2}[C_{(+,-)}+C_{(-,+)}-C_{(+,+)}-C_{(-,-)}]$$

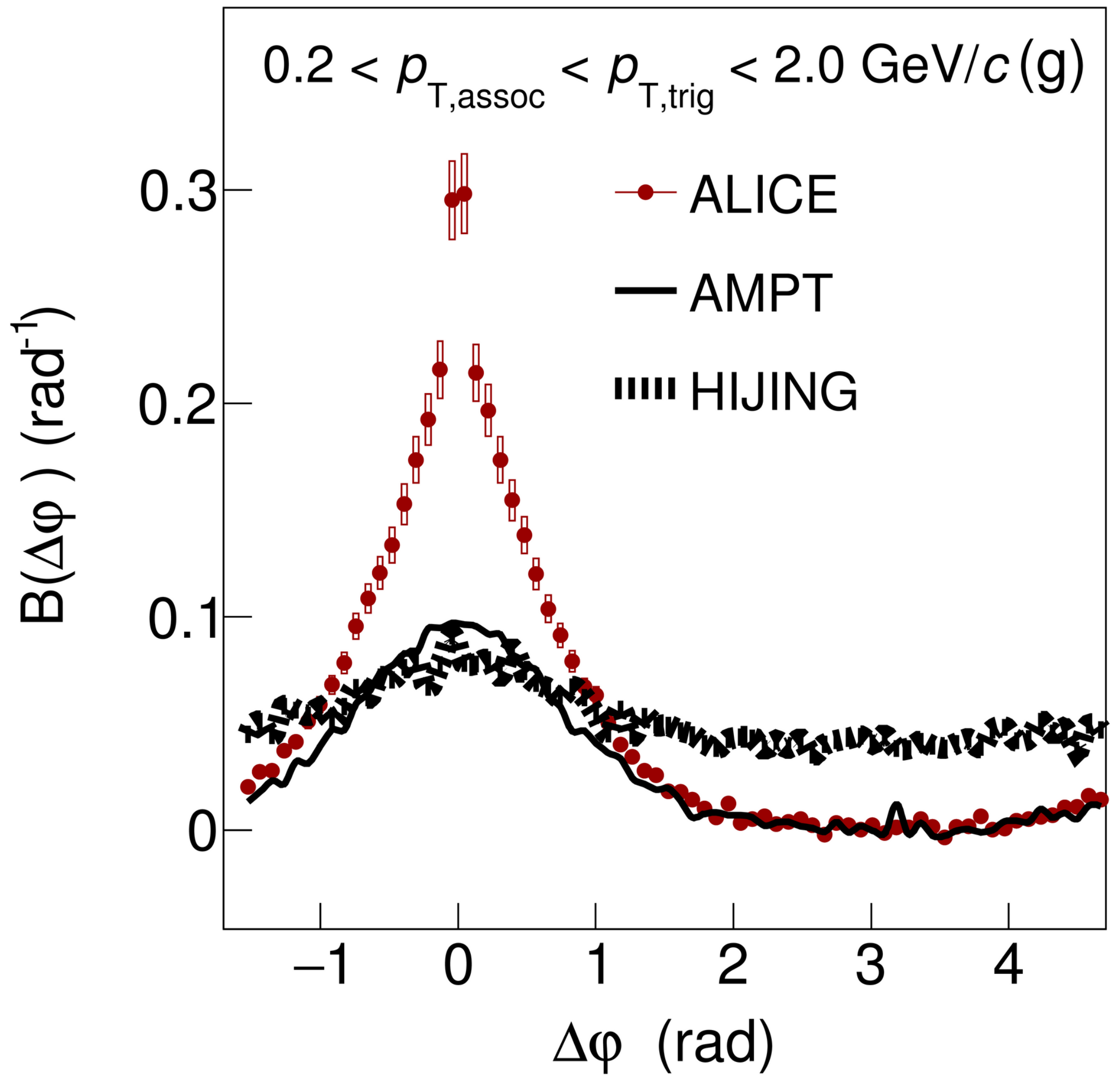
S. Bass et al., Phys. Rev. Lett. 85, (2000) 2689

(ALICE Collaboration) Phys. Lett. **B723**, (2013) 267

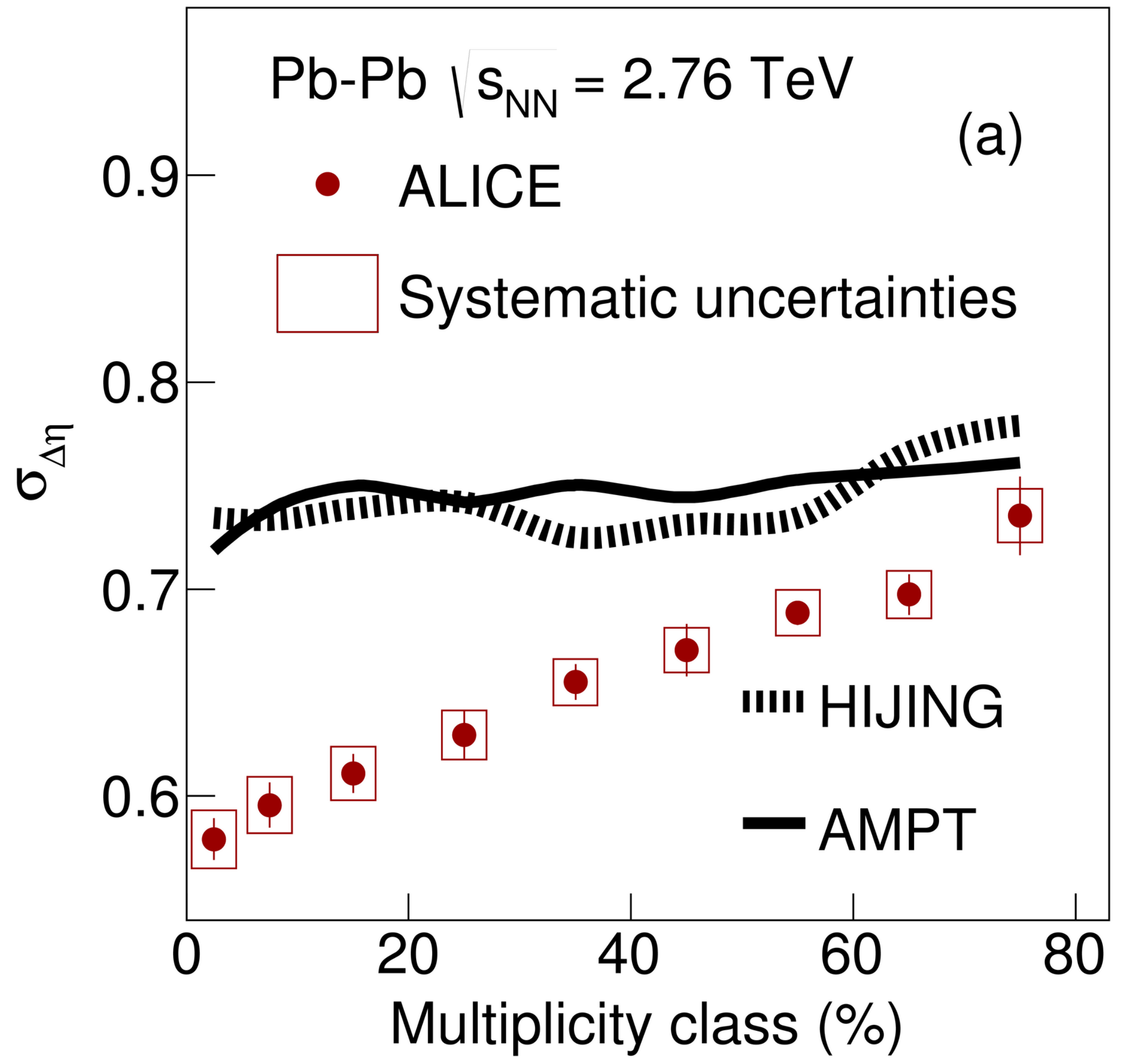
(ALICE Collaboration) EPJ **C76**, (2016) 86



ALI-PUB-103538



ALI-PUB-103546



ALI-PUB-99702

Significant charge dependent effects that develop as a function of centrality

These effects can not be reproduced by any of the models

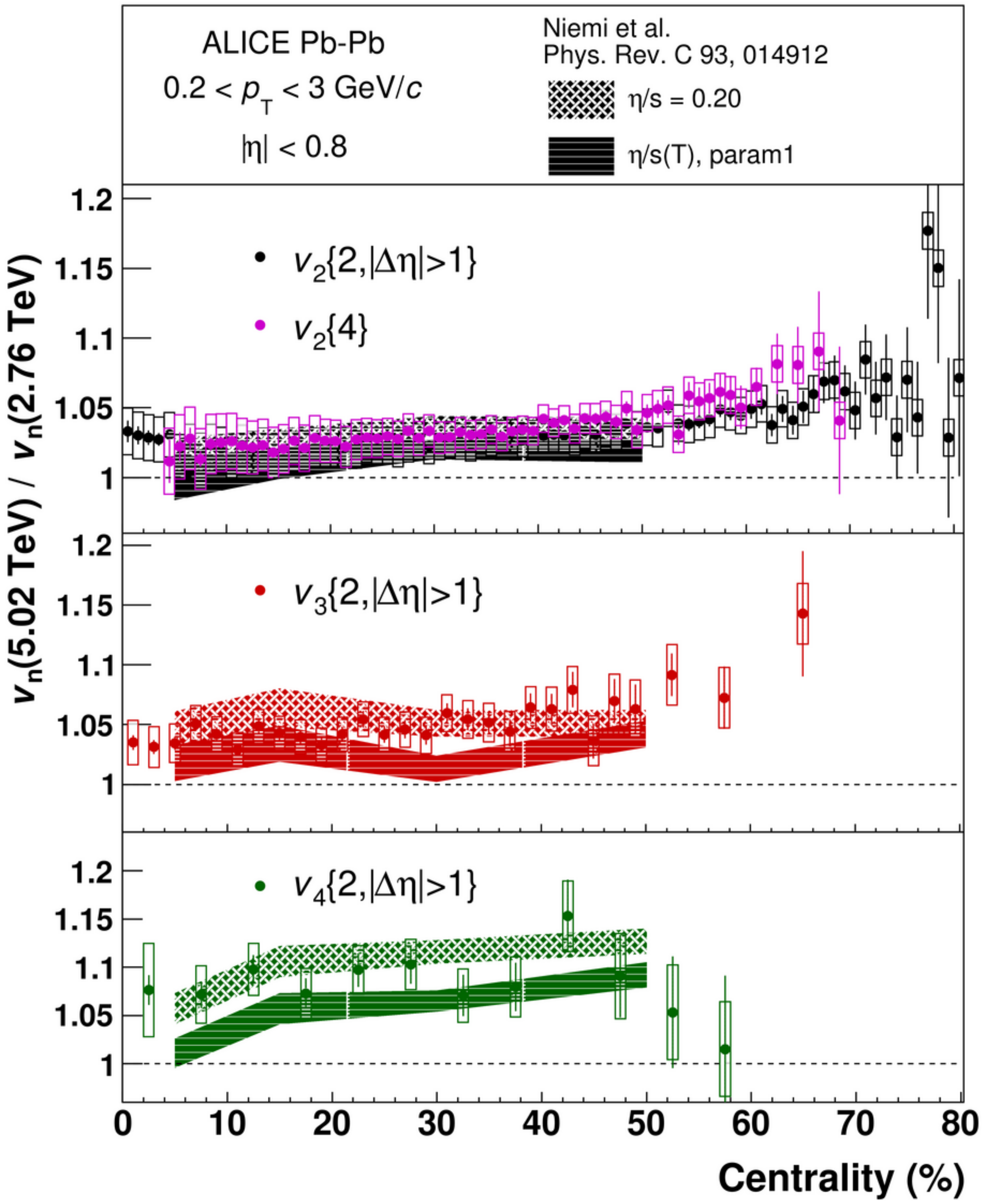
- AMPT does a better job in Δφ

BACKGROUND COMPONENTS VS ENERGY

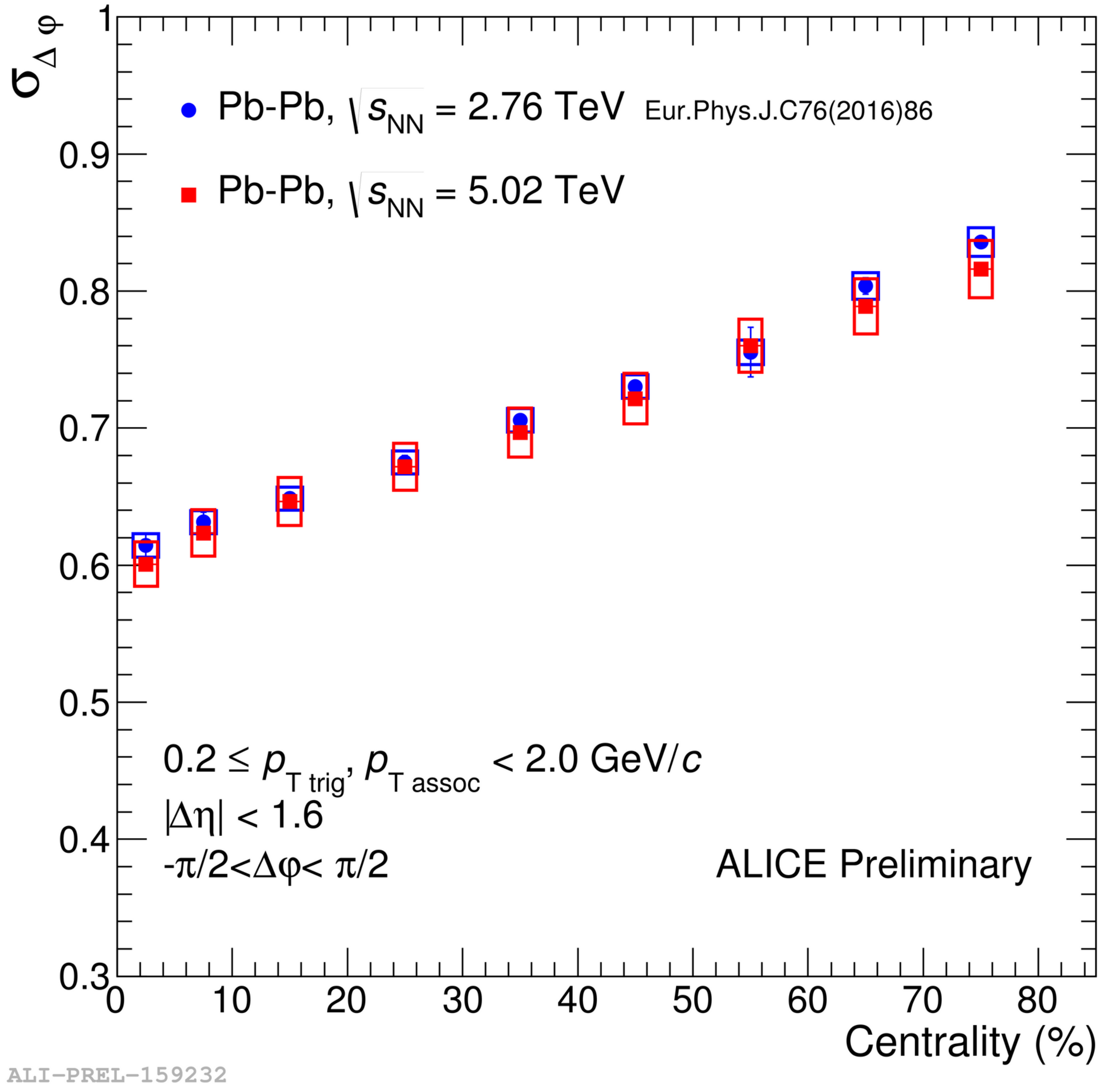
Background doesn't change much between the two energies

- v_2 changes by ~3%
- Narrowing of the balance function width the same within uncertainties

(ALICE Collaboration) JHEP07, (2018) 103

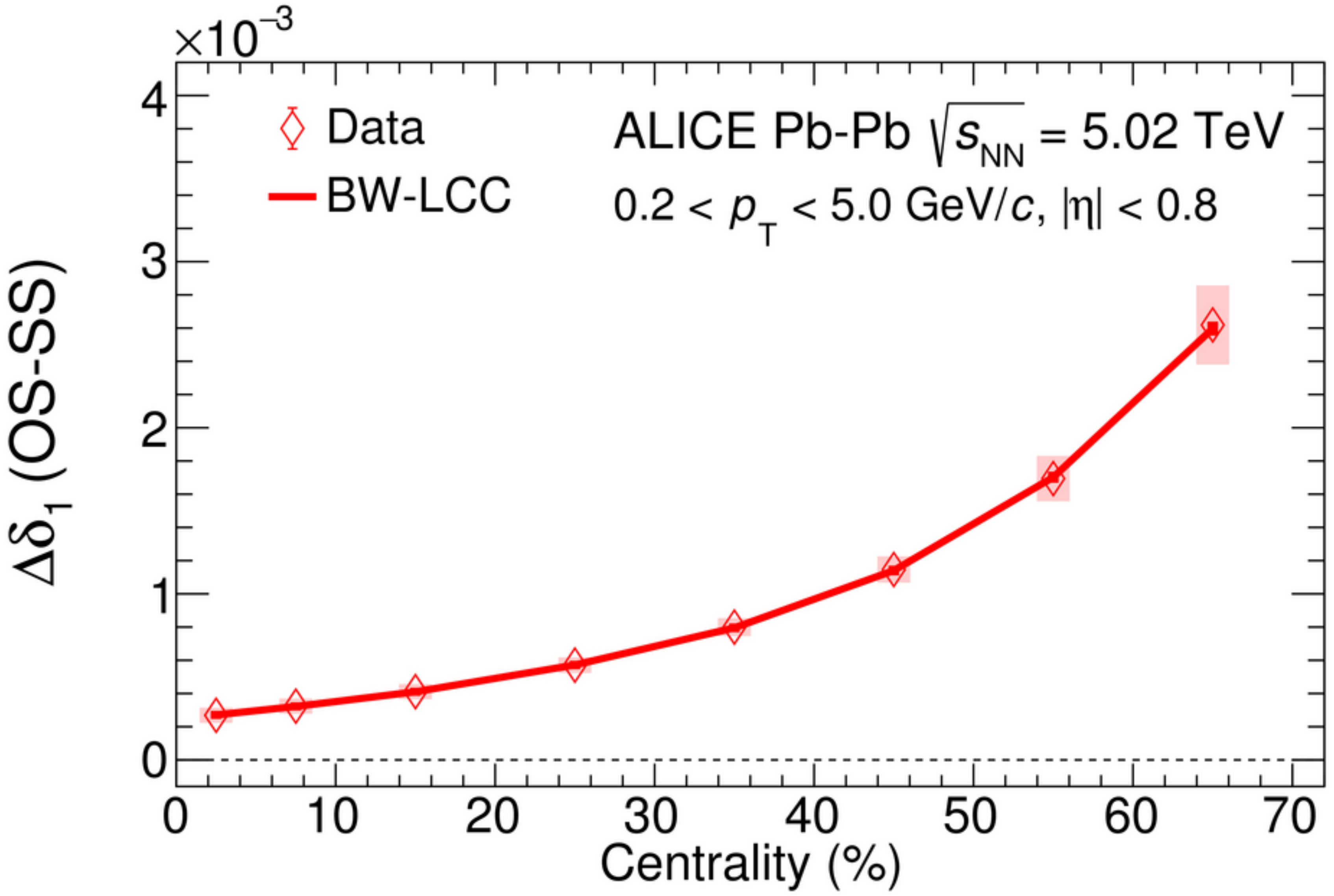


J. Pan arXiv: 1807.10377



COMPARISON WITH BLAST WAVE + LCC

(ALICE Collaboration) JHEP 2020, (2020) 160

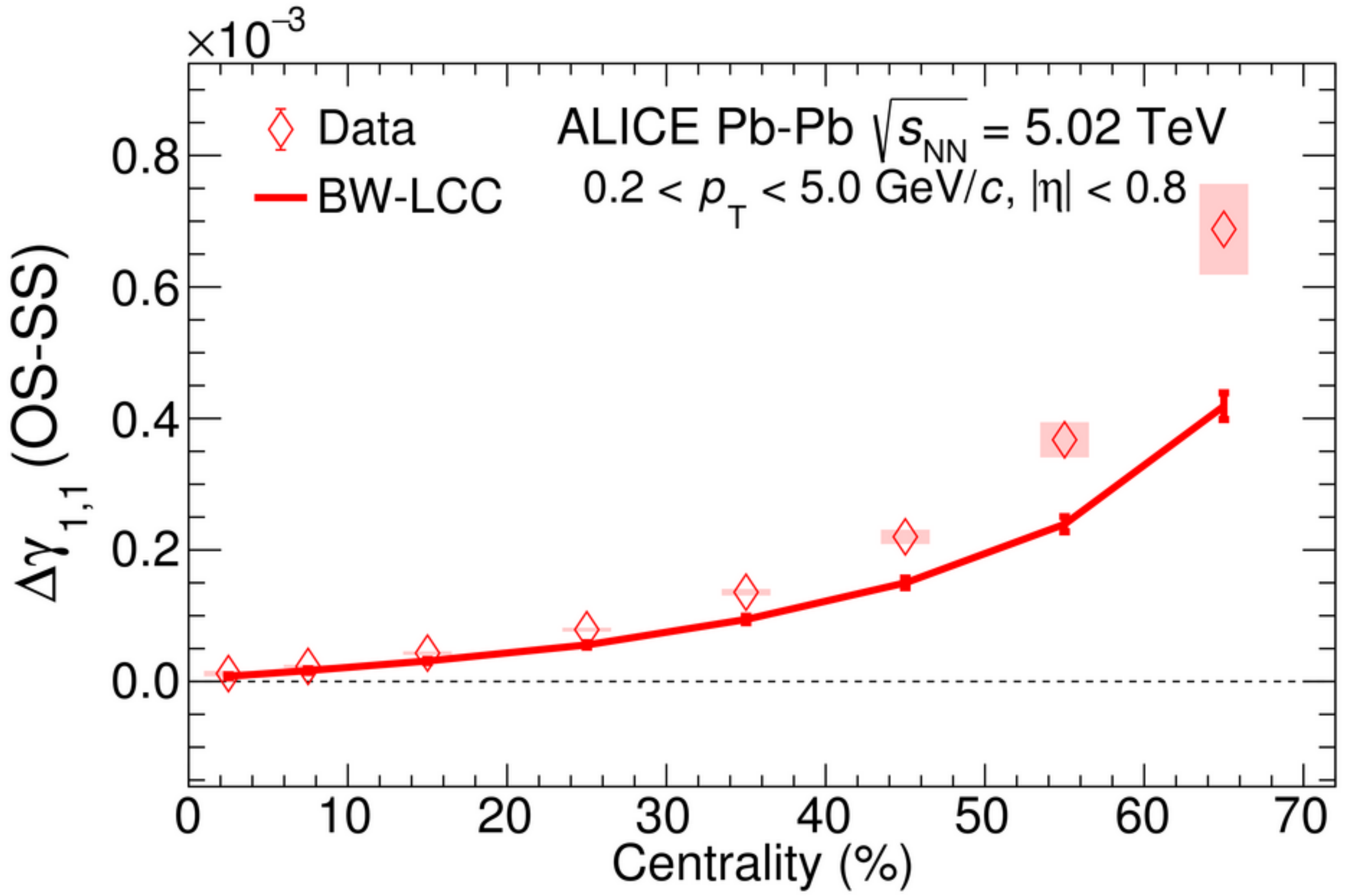


The model describes qualitatively the centrality dependence of $\Delta\gamma_{1,1}$

- Due to missing ingredients (besides CME)?

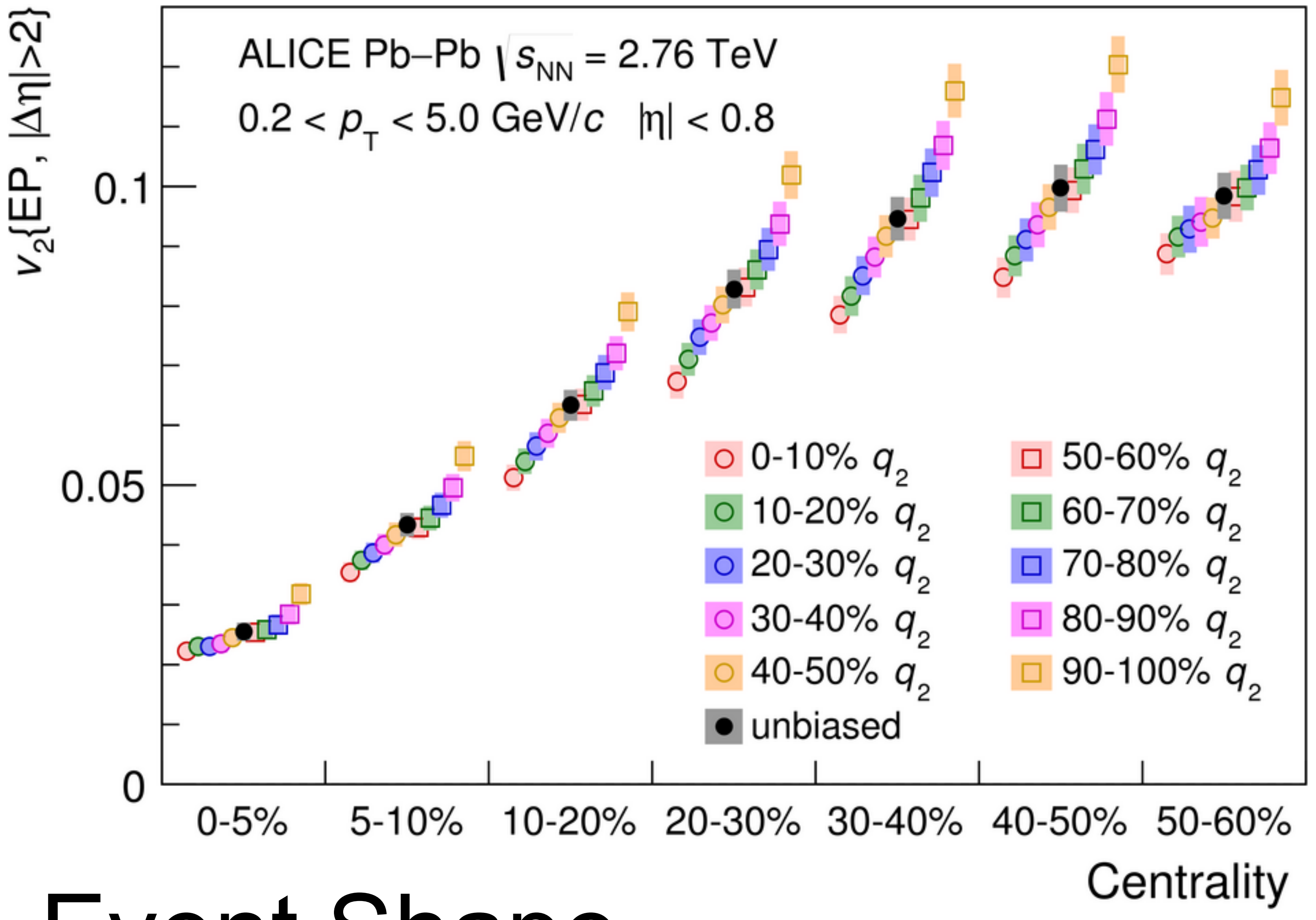
BW model + LCC tuned to describe $\Delta\gamma_{1,1}$

- Spectra and v_2 of identified particles
- The charge dependent δ_1 measurements (balance functions)

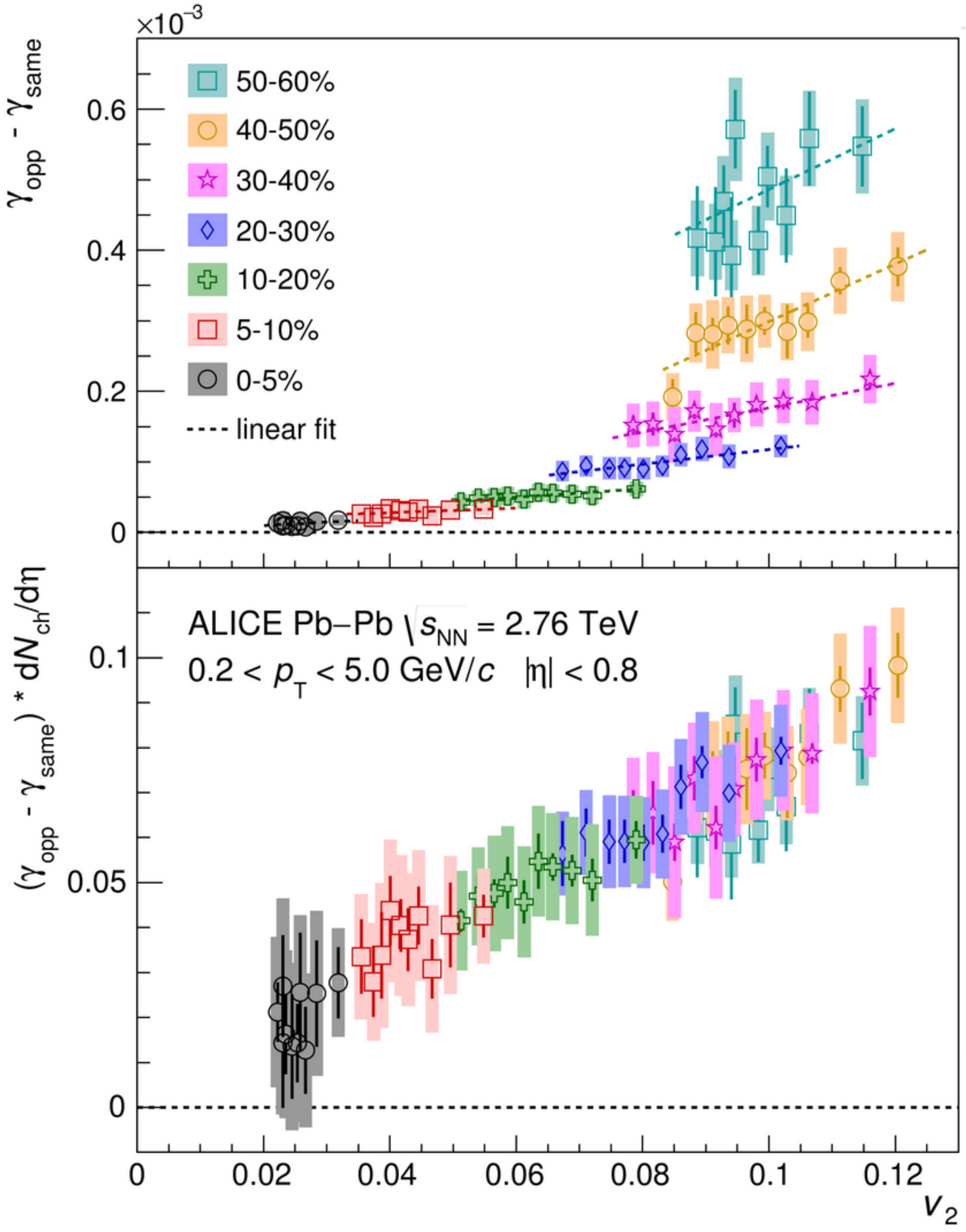


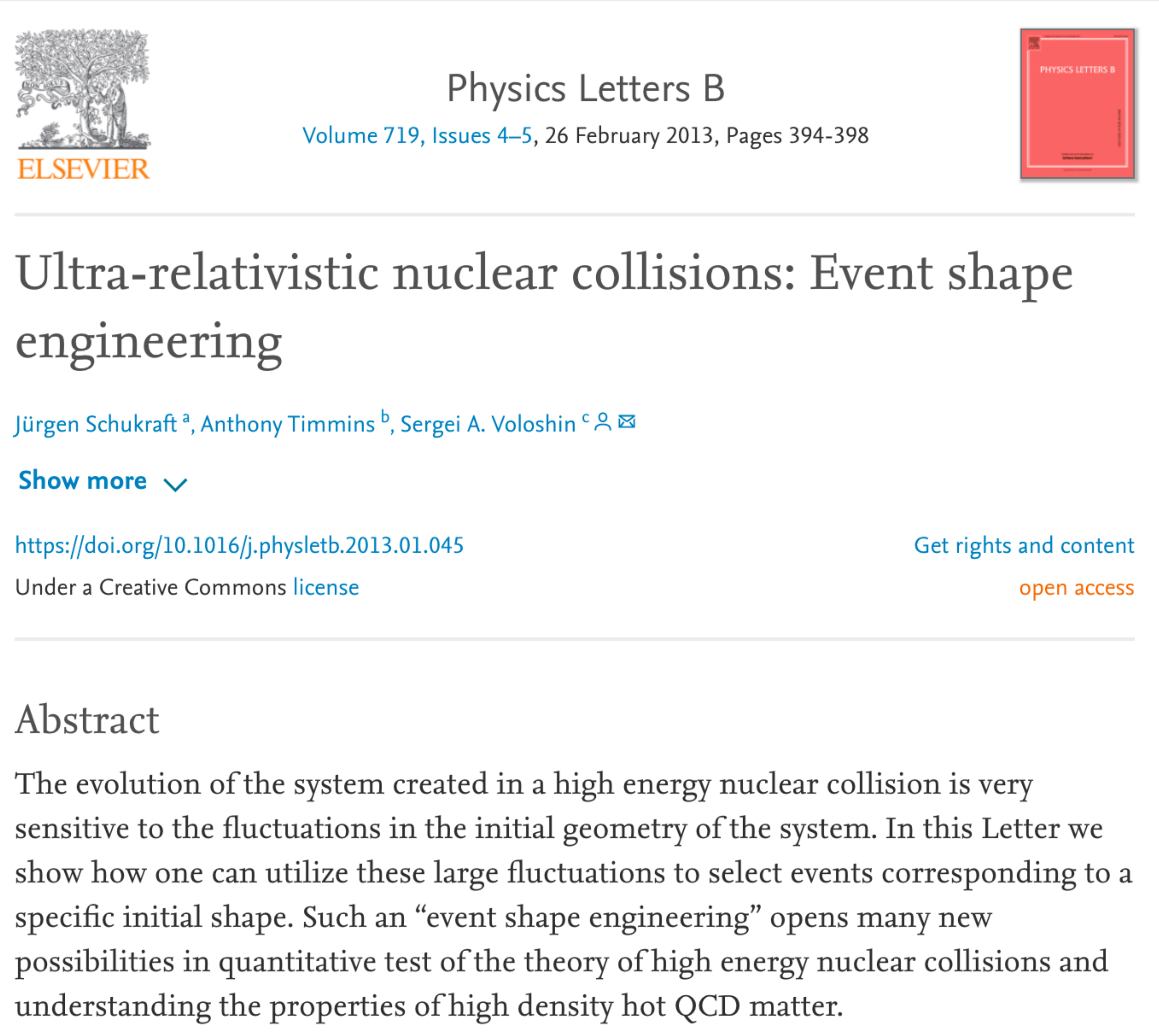
FIRST CME LIMITS @ LHC WITH ESE

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



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




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]

Show more

https://doi.org/10.1016/j.physletb.2013.01.045 Get rights and content

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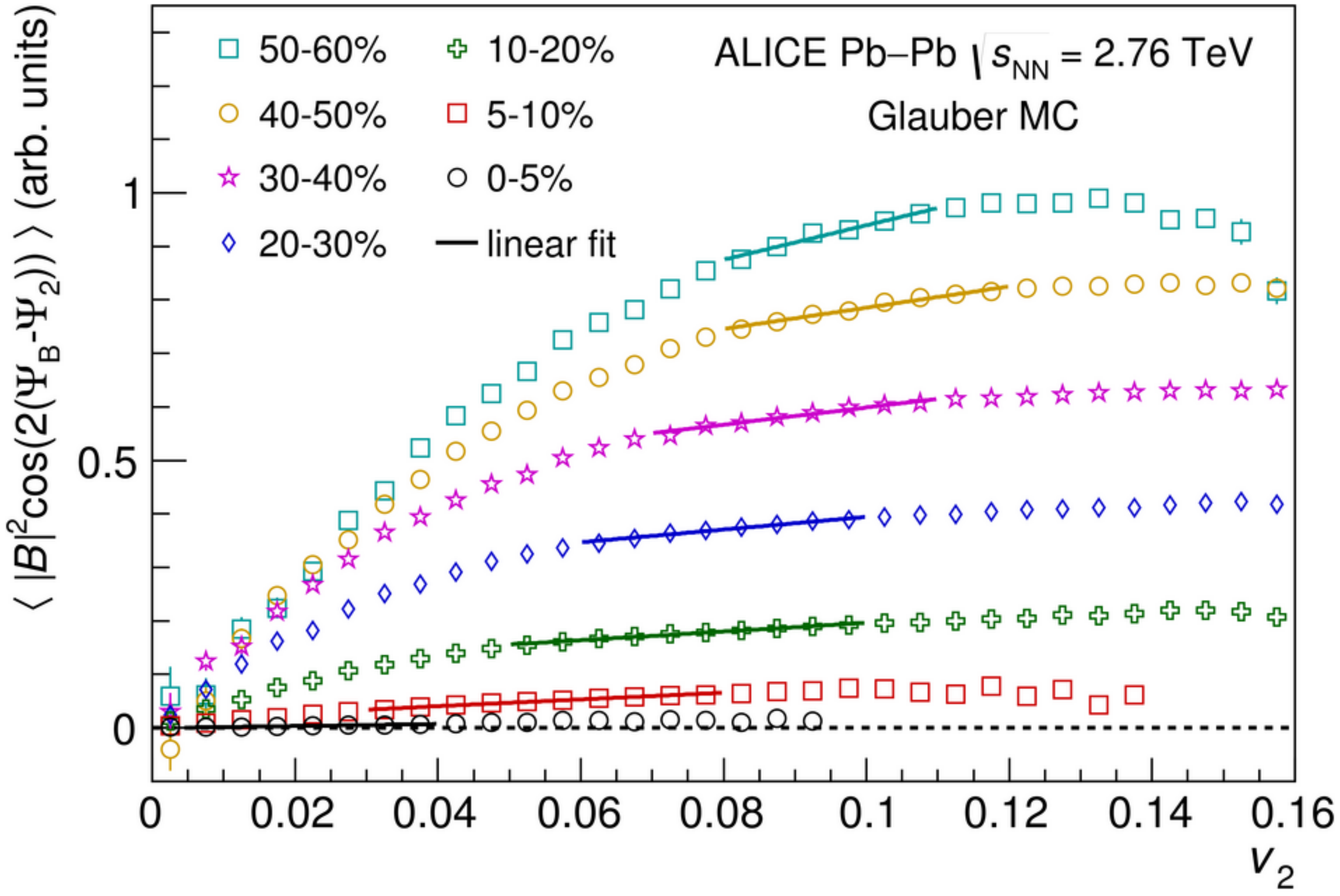
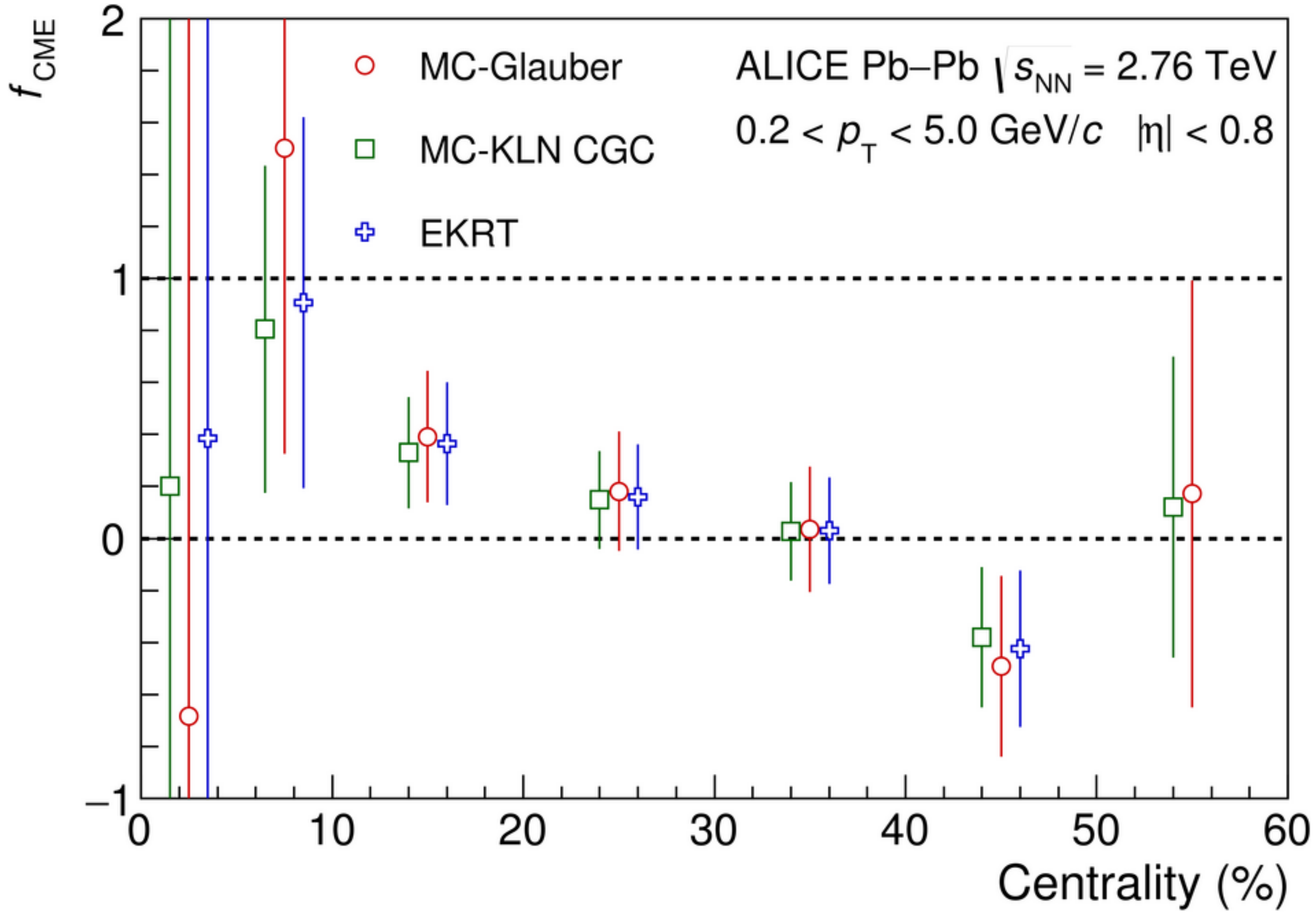
Abstract

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.

FIRST CME LIMITS @ LHC WITH ESE

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





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

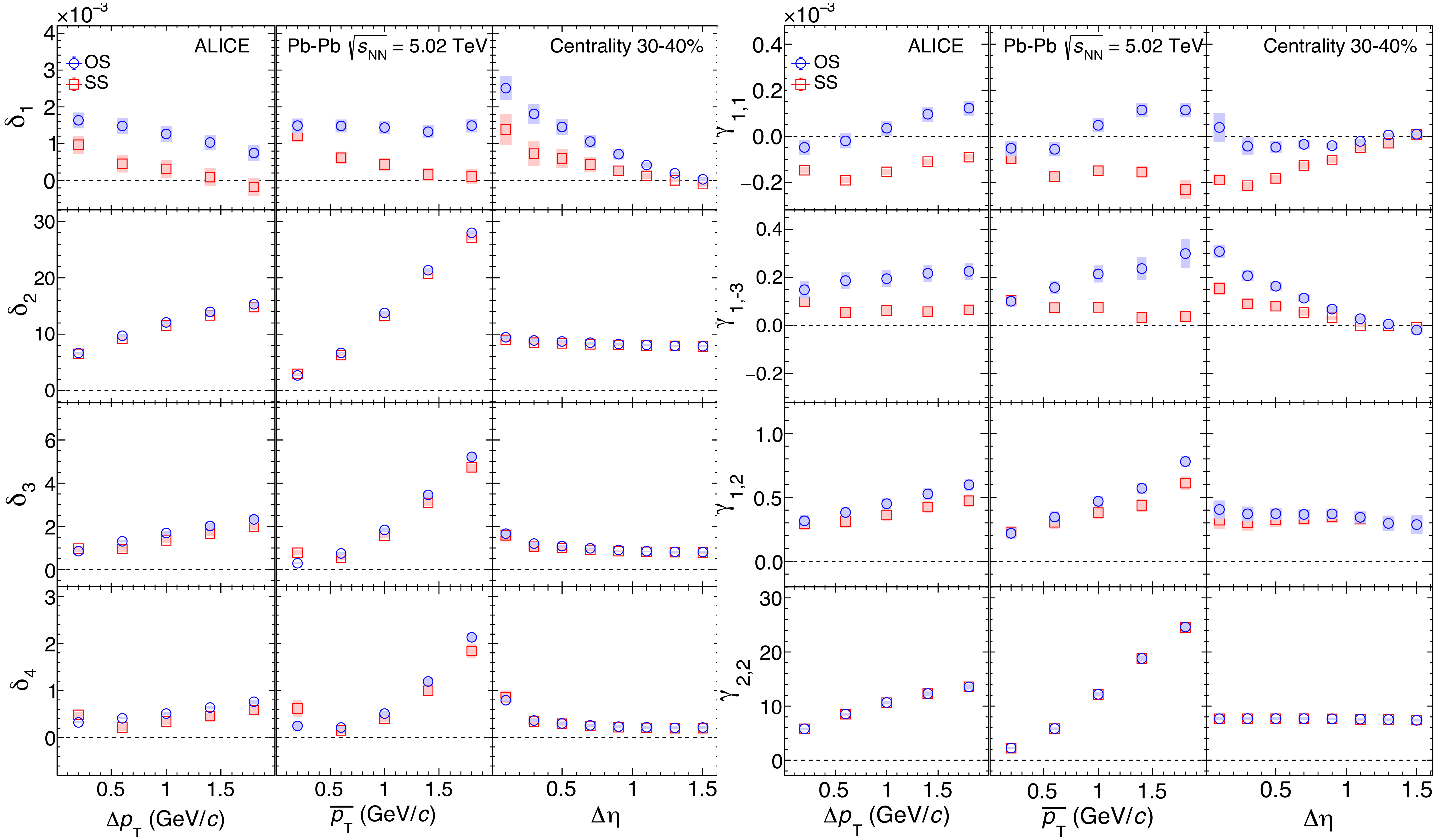
- 26-33% at 95% C.L. depending on models of initial state

DIFFERENTIAL RESULTS

(ALICE Collaboration) JHEP 2020, (2020) 160

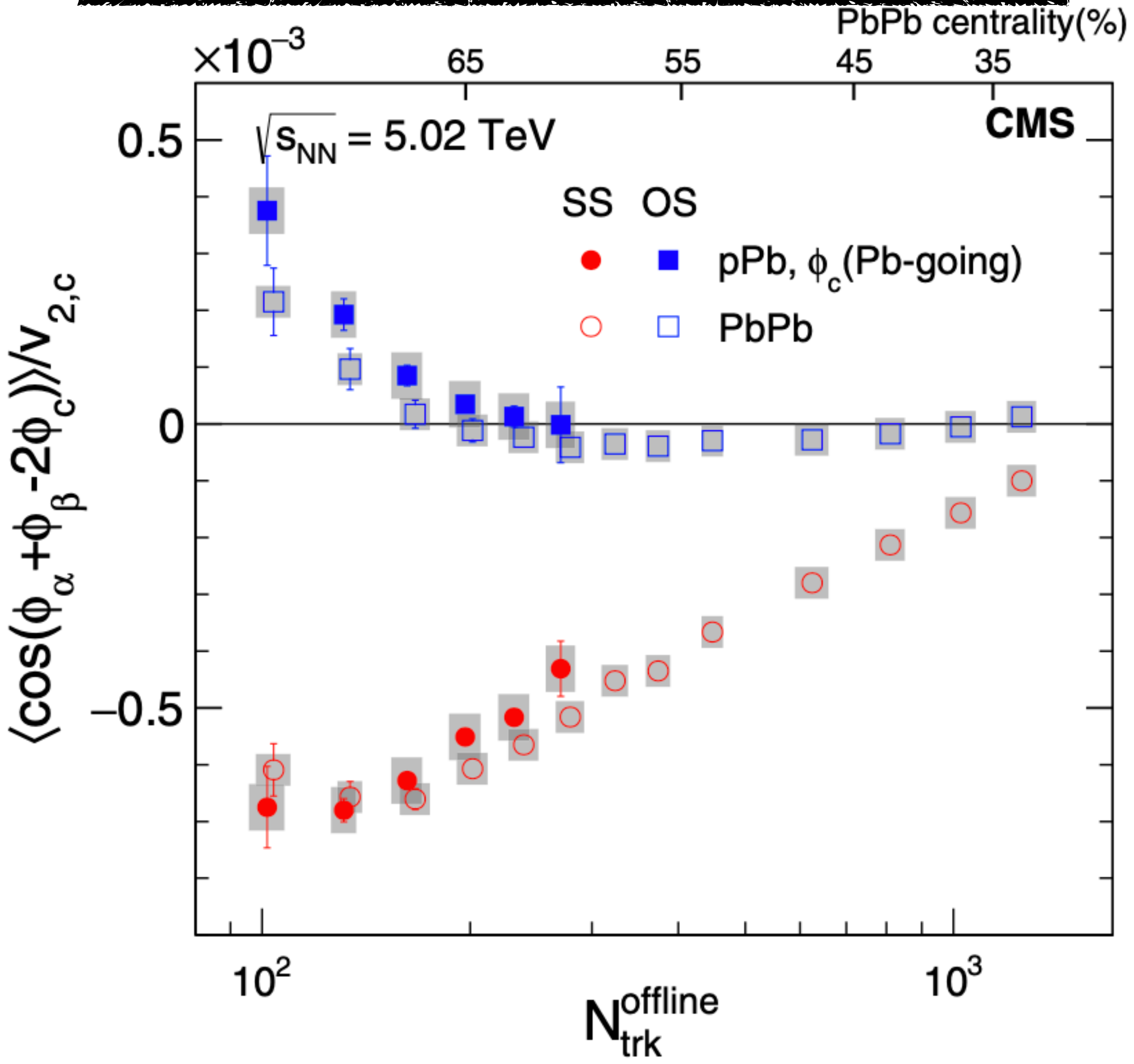
Are all systematics of the measurements described by the background?

- Differential results might give a hint as to where background effects fail to describe the data (if anywhere at all)

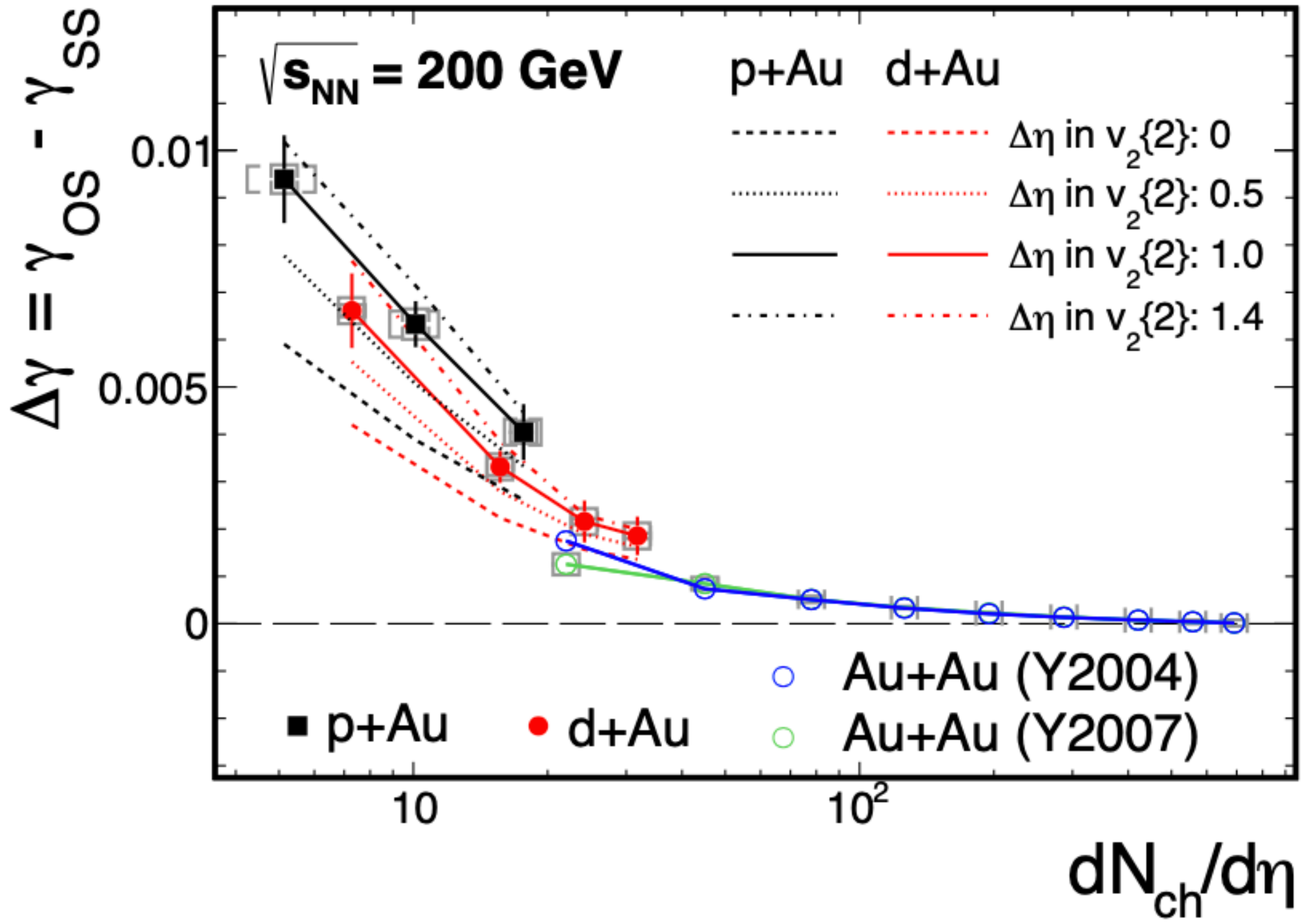


AT THE SAME TIME…SMALL SYSTEMS

(CMS Collaboration) PRL **118**, (2017) 122301



(STAR Collaboration) PRL **118**, (2017) 122301



Significant charge dependent correlations in small systems

- Note: the results should not be used to rule out the CME
- They can be used (at best) as an indication that background effects can be dominant ➞ (measurements hampered by dominant parity independent effects)

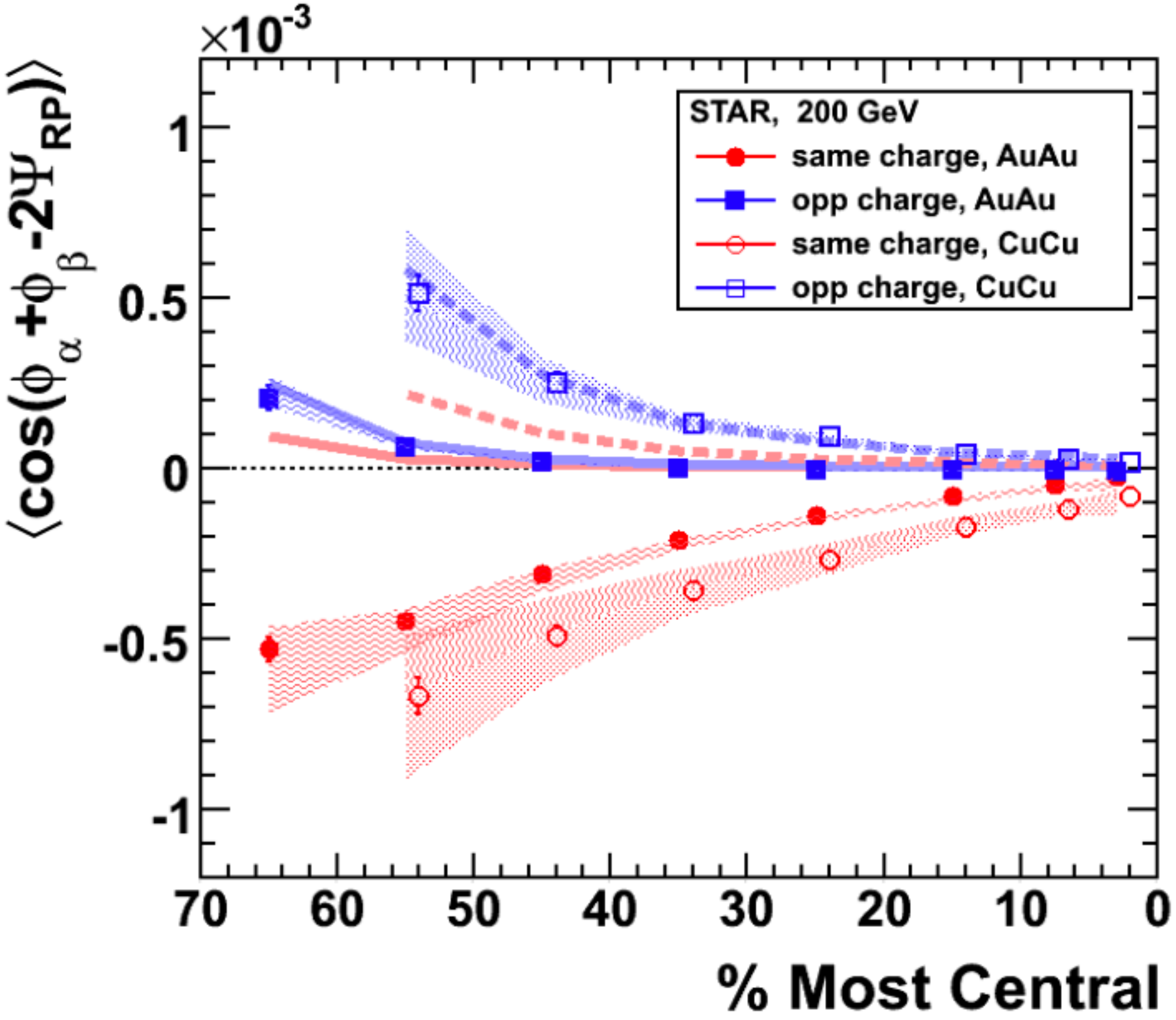
AT THE SAME TIME…SMALL SYSTEMS

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

Lines: Expectations from HIJING on 3-particle correlations

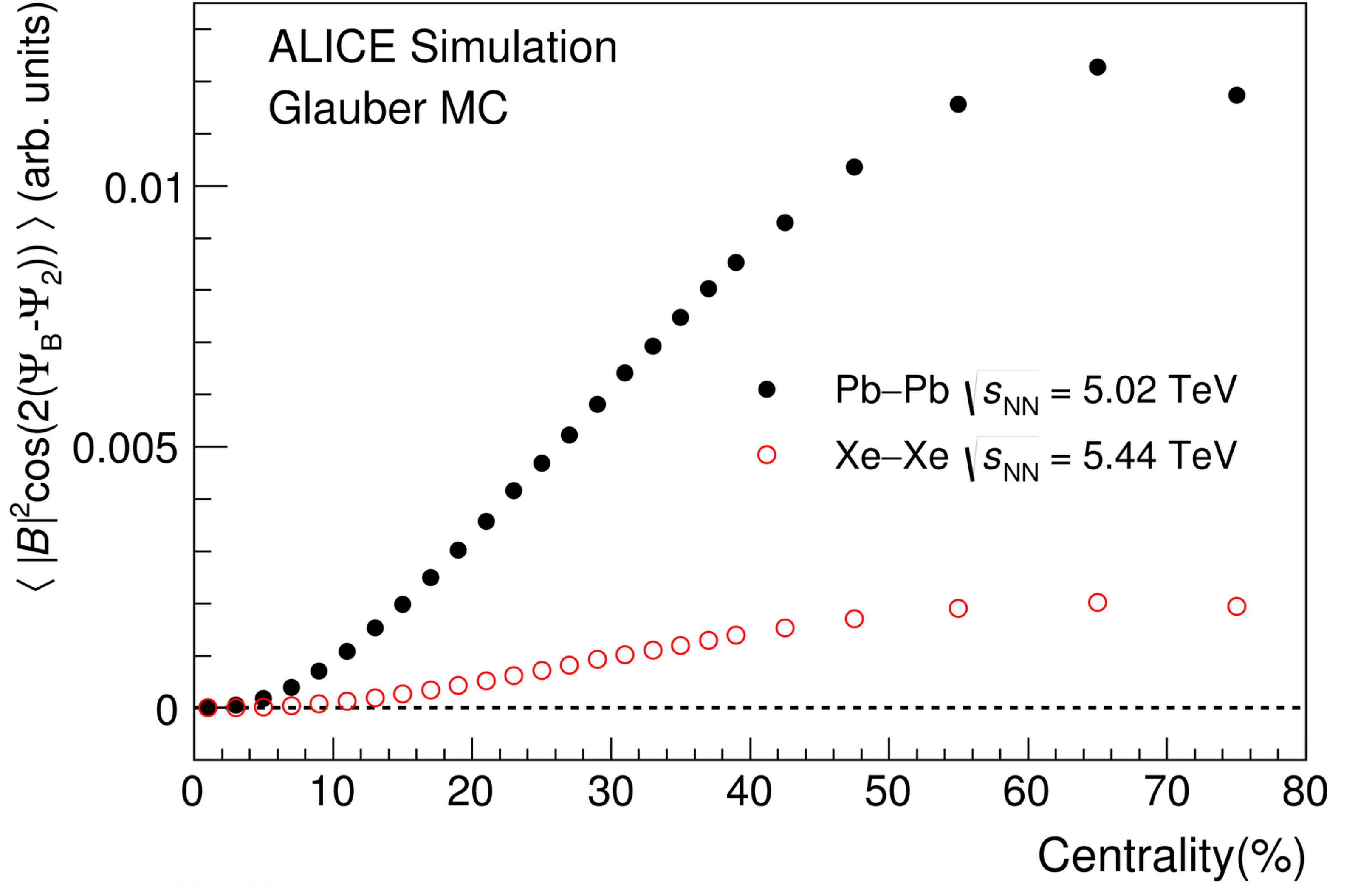
Solid: Au-Au

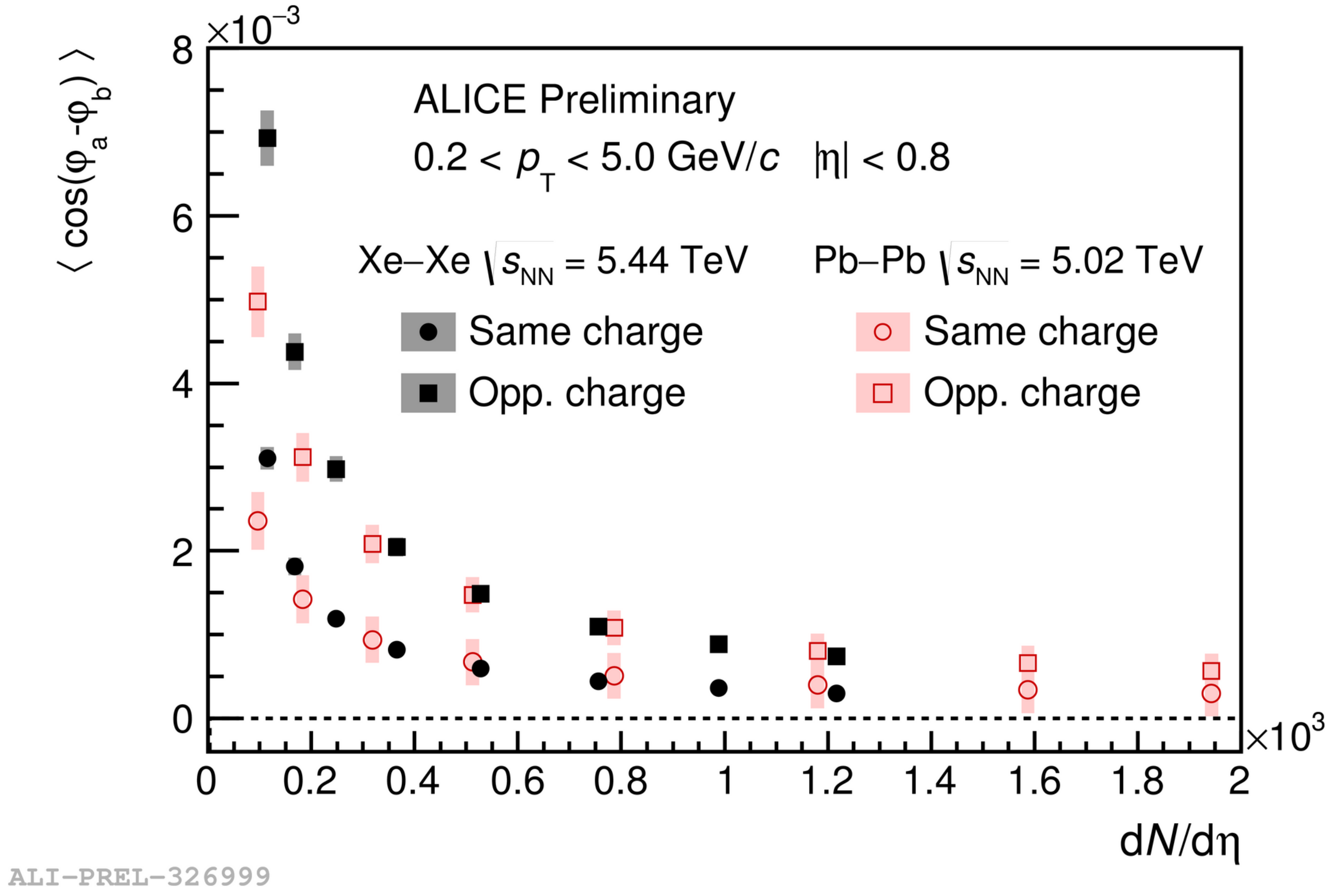
Dashed: Cu-Cu

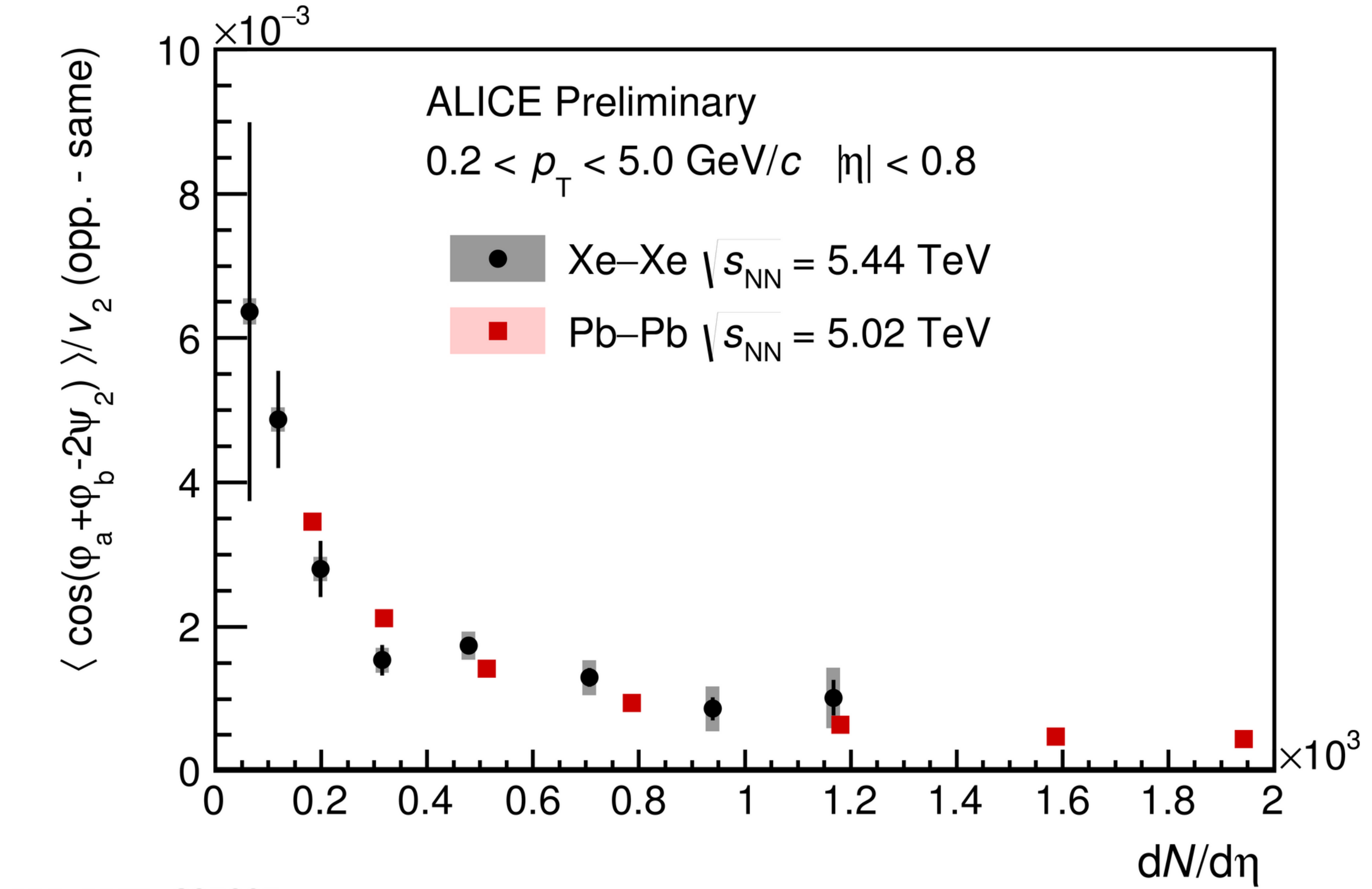


FUTURE PROSPECTS: RESULTS IN XE-XE VS PB-PB

(ALICE Collaboration) QM2019 arXiv:To be submitted







Look at a system where the background effects are similar as the ones in Pb-Pb but the magnetic field is different

Both results of δ_1 and $\gamma_{1,1}$ in Xe-Xe compatible with the ones in Pb-Pb

- Dominance of background effects

FUTURE PROSPECTS: NEW CORRELATOR

Possible new direction: look at charge-dependent correlation function in- and out-of-plane

A New Correlator to Detect and Characterize the Chiral Magnetic Effect

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(Dated: June 27, 2018)

A charge-sensitive in-event correlator is proposed and tested for its efficacy to detect and characterize charge separation associated with the Chiral Magnetic Effect (CME) in heavy ion collisions. Tests, performed with the aid of two reaction models, indicate discernible responses for background- and CME-driven charge separation, relative to the second- (Ψ_2) and third-order (Ψ_3) event planes, which could serve to identify the CME. The tests also indicate a degree of sensitivity which would enable robust characterization of the CME via Anomalous Viscous Fluid Dynamics (AVFD) model comparisons.

PACS numbers: 25.75.-q, 25.75.Gz, 25.75.Ld

High-energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) can result in the creation of a plasma composed of strongly coupled chiral quarks and gluons or the Quark-Gluon Plasma (QGP). Topological transitions such as sphalerons [1, 2], which occur frequently in the QGP [3, 4], can induce a net axial charge asymmetry of the chiral quarks which fluctuate from event to event. In the presence of the strong electromagnetic $\vec{B}$-fields created in the same collisions, this chiral anomaly is predicted to convert into an electric current which produces a final-state charge separation known as the Chiral Magnetic Effect (CME) [5–10]. For recent reviews, see e.g. [11–13].

The electric current $\vec{J}_Q$, created along the $\vec{B}$-field, stems from anomalous chiral transport of the chiral fermions in the QGP:

$$\vec{J}_Q = \sigma_5 \vec{B}, \quad \sigma_5 = \mu_5 \frac{Q^2}{4\pi^2}, \tag{1}$$

where σ_5 is the chiral magnetic conductivity, μ_5 is the chiral chemical potential that quantifies the axial charge asymmetry or imbalance between right-handed and left-handed quarks in the plasma, and Q is the quark electric charge [8, 14–16]. Thus, experimental observation of its associated charge separation, could provide crucial insights on anomalous transport and the interplay of chiral symmetry restoration, axial anomaly, and gluonic topology in the QGP.

The $\vec{B}$-field, which is strongly time-dependent [17–19], is generated perpendicular to the reaction plane (Ψ_{RP}) defined by the impact parameter and the beam axis. Consequently, CME-driven charge separation can be identified and characterized via the first P-odd sine term (a_1) in a Fourier decomposition of the charged-particle azimuthal distribution [20]:

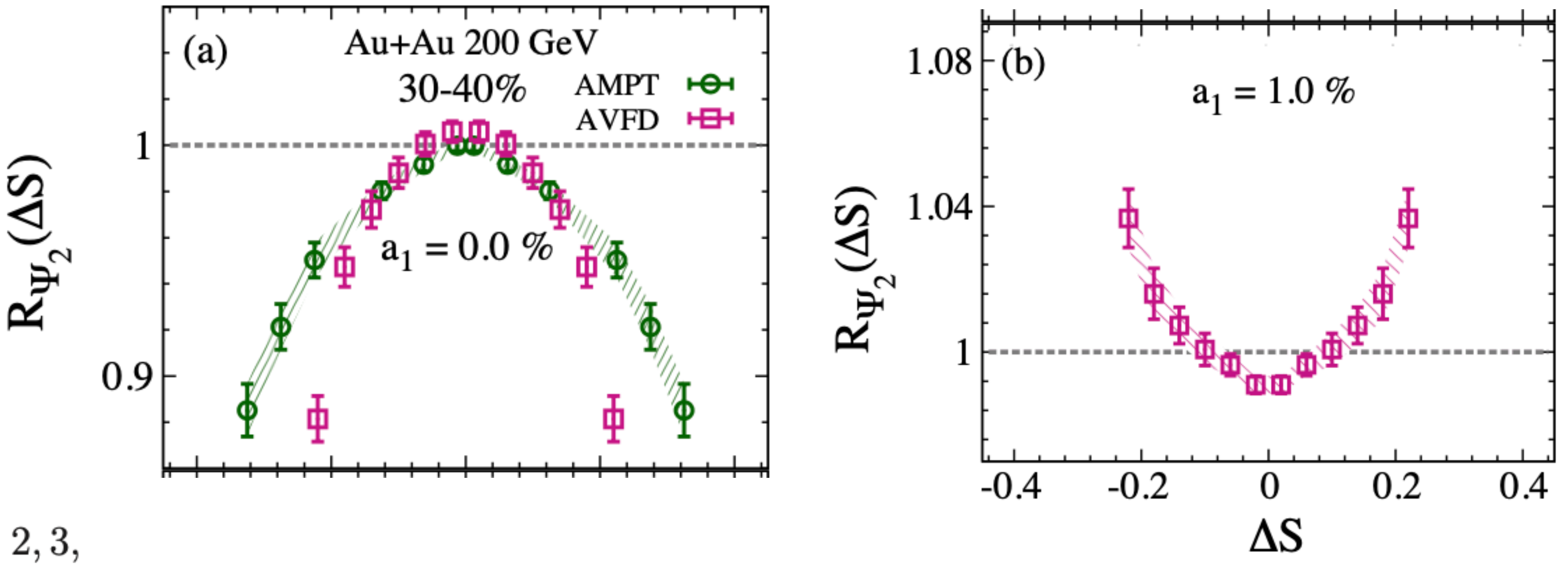
$$\frac{\mathrm{dN^{ch}}}{\mathrm{d}\phi} \propto [1 + 2\sum_{\mathrm{n}} \mathrm{v_n} \cos(\mathrm{n}\Delta\phi) + \mathrm{a_n} \sin(\mathrm{n}\Delta\phi) + ...] \tag{2}$$

where $\Delta\phi = \phi - \Psi_{\mathrm{RP}}$ gives the particle azimuthal angle with respect to the reaction plane angle, and $\mathrm{v_n}$ and $\mathrm{a_n}$ denote the coefficients of P-even and P-odd Fourier terms, respectively. The second-order event plane, Ψ_2, determined by the maximal particle density in the elliptic azimuthal anisotropy and the beam axis, is usually employed as a proxy for Ψ_{RP} in experimental measurements. Here, it is noteworthy that the third-order event plane, Ψ_3, can not be used to detect CME-driven charge separation, since there is little, if any, correlation between Ψ_{RP} and Ψ_3. The event-by-event fluctuations contribute to an event-wise de-correlation between the magnetic field direction imposed by Ψ_{RP}, and the orientation of Ψ_2 imposed by the bulk collision geometry [21]. The dispersion of Ψ_2 about Ψ_{RP} reduces the magnitude of a_1, which depends on both the initial axial charge and the time evolution of the magnetic field (c.f. Eq. 1). The latter are both not well constrained theoretically.

The charge-dependent correlator, $\gamma_{\alpha\beta}$, has been widely used at RHIC [22–28] and the LHC [29, 30] in ongoing attempts to identify and quantify CME-driven charge separation:

$$\gamma_{\alpha\beta} = \left\langle \cos\left(\phi_\alpha^{(\pm)} + \phi_\beta^{(\pm)} - 2\Psi_2\right)\right\rangle, \tag{3}$$

where ϕ_α, ϕ_β denote the azimuthal emission angles for like-sign ($+\,+$ or $-\,-$) and unlike-sign ($+\,-$) particle pairs. A charge-dependent azimuthal correlation, qualitatively consistent with the expectation for CME-driven charge separation, has been observed in these measurements. However, they remain inconclusive because of several identified sources of background correlations that can account for most, if not all, of the measurements [31–35]. A recent cause for pause, is the observation that the charge-dependent azimuthal correlations for p+Pb and Pb+Pb collisions, have nearly identical values for similar multiplicity selections [30]. This poses a significant challenge for the use of the $\gamma_{\alpha\beta}$ correlator in such measurements, because CME-induced charge separation is predicted to be negligible in p+Pb collisions. That is,



$$R_{\Psi_m}(\Delta S) = C_{\Psi_m}(\Delta S)/C^{\perp}_{\Psi_m}(\Delta S),\ m = 2, 3,$$

$$C_{\Psi_m}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{Shuffled}}(\Delta S)},\ m = 2, 3,$$

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

(STAR Collaboration) QM2019