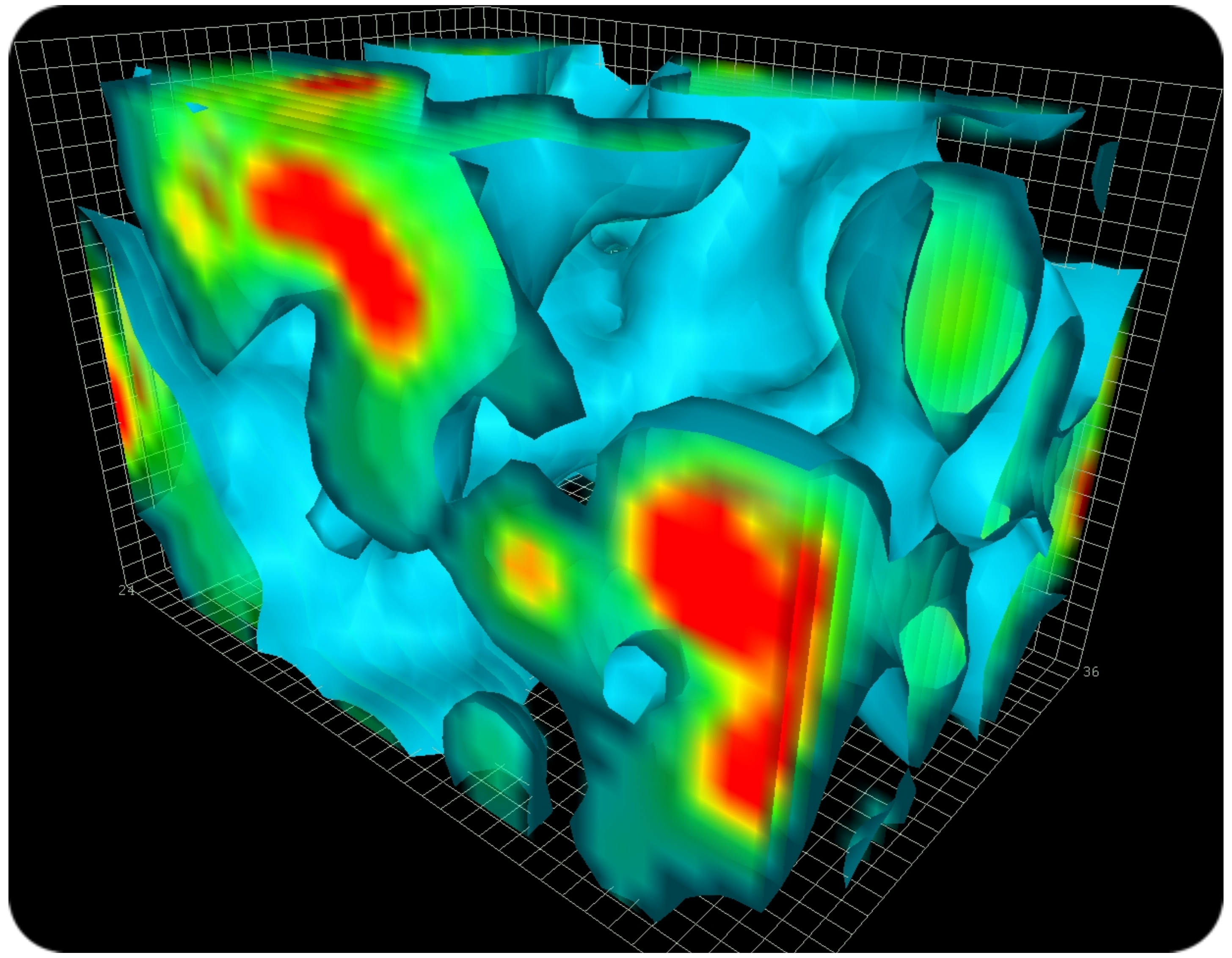
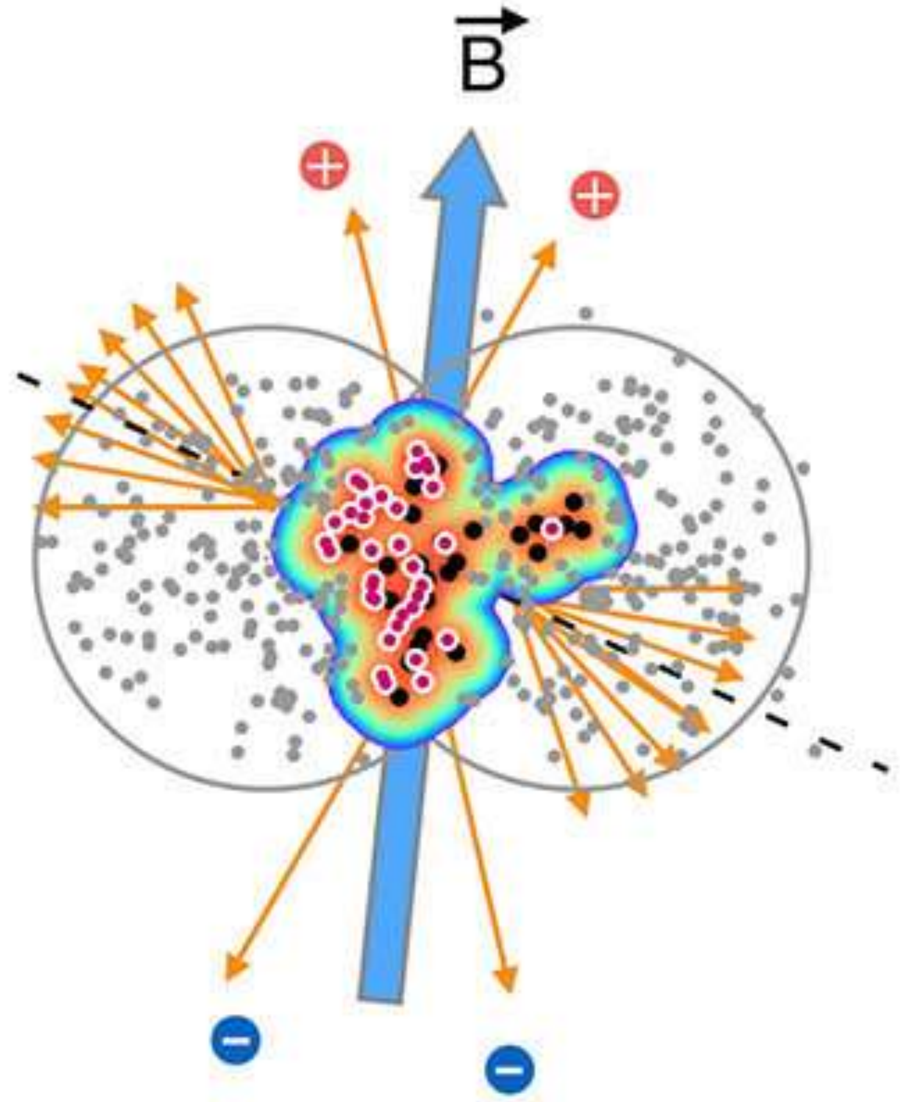
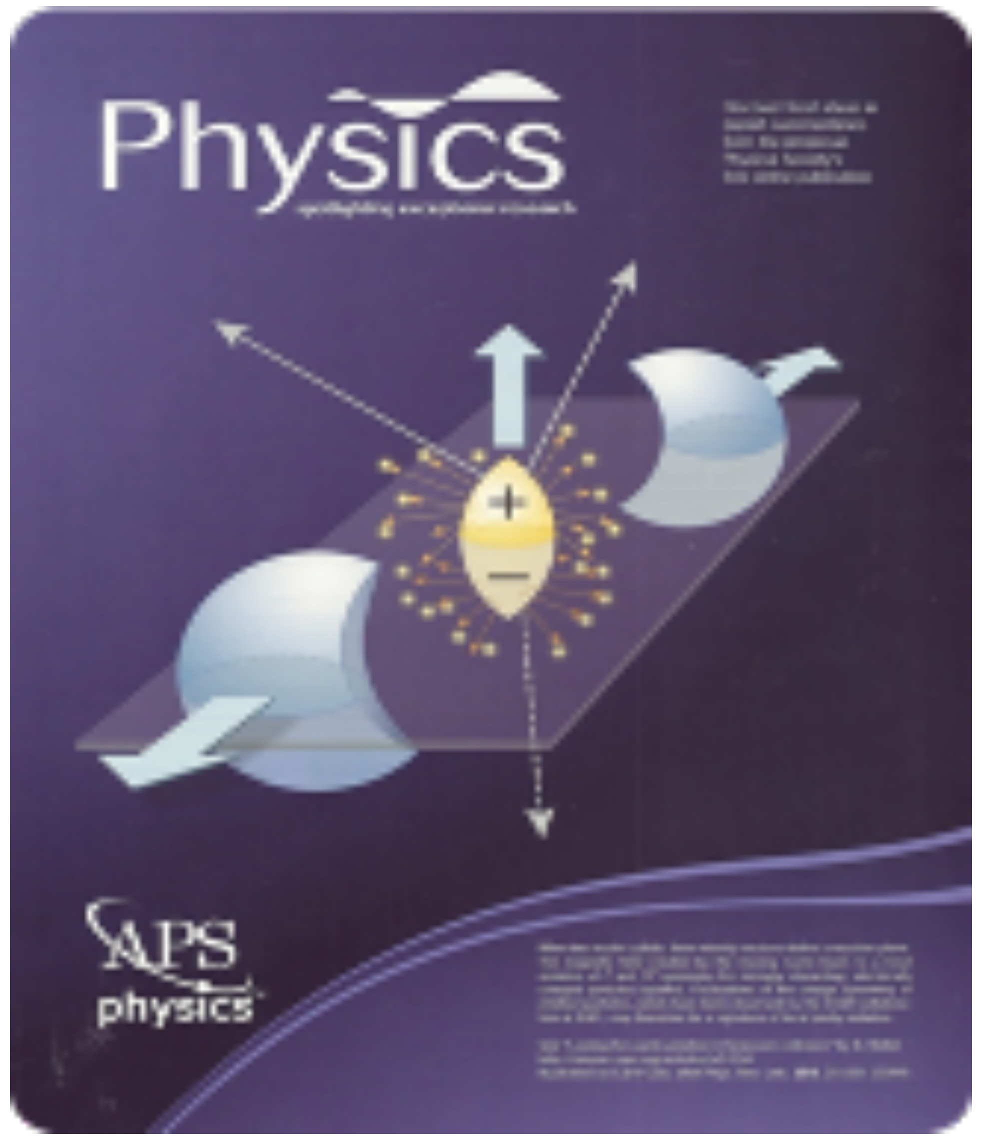
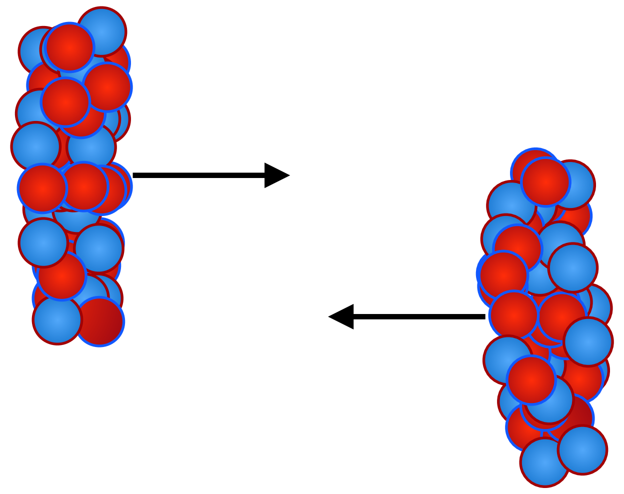
LOOKING FOR CHIRAL ANOMALIES IN HEAVY ION COLLISIONS







Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
Polarisation measurements in ee ep, pp and heavy-ions collisions

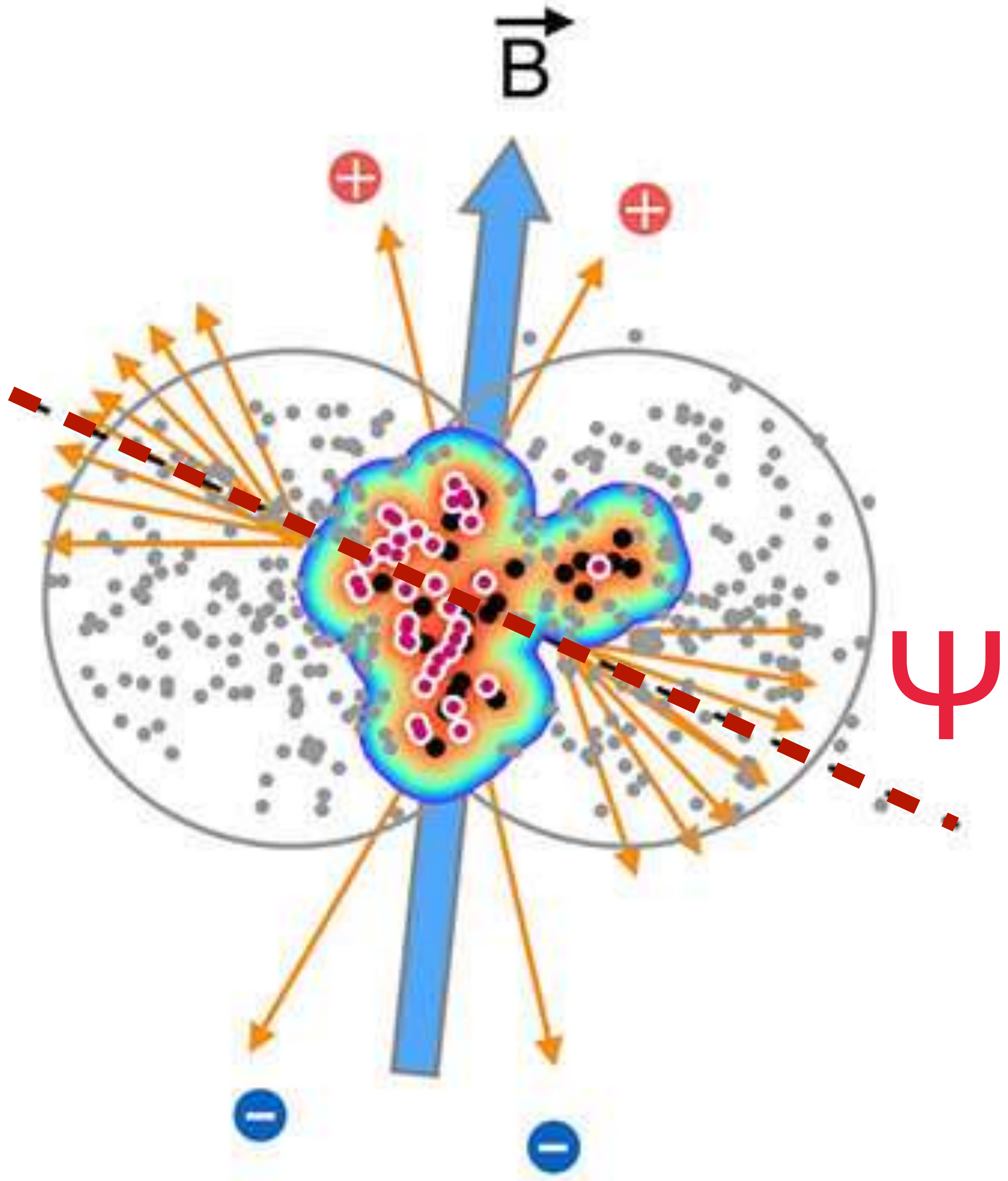


Panos Christakoglou

Nikhef and Utrecht University

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
Polarisation measurements in ee ep, pp and heavy-ions collisions

CHIRAL ANOMALIES IN HEAVY ION COLLISIONS



Ingredients

Strong magnetic field

Chirality imbalance

Chiral quarks

Collective flow

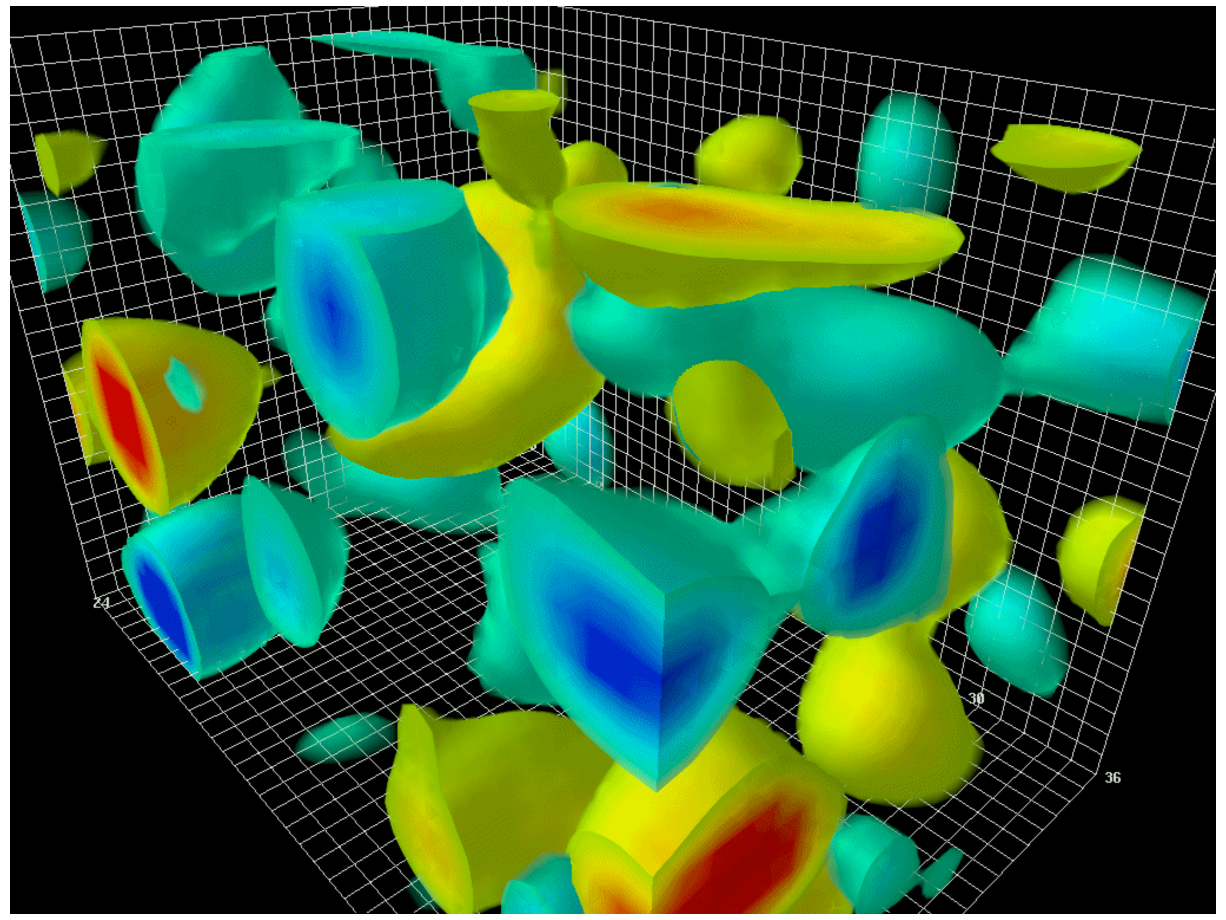
Hadronisation

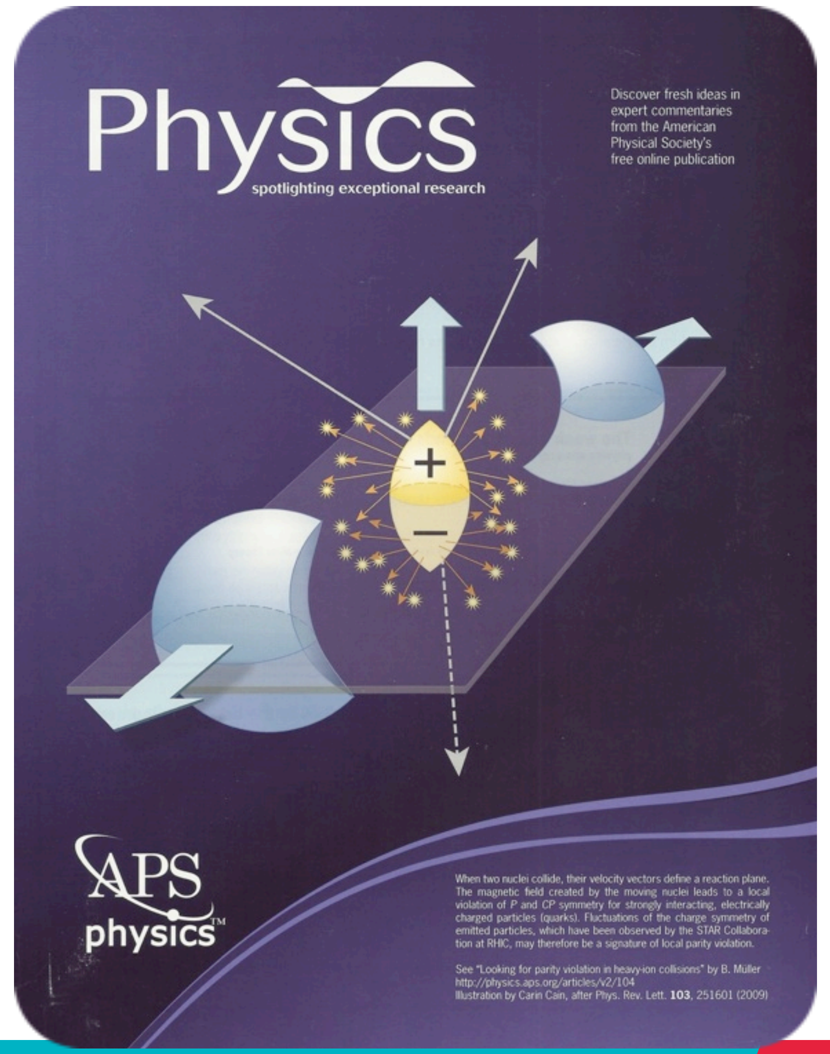
↓

The Chiral Magnetic Effect (CME)

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

Animation @ http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/





THE STRONGEST MAGNETIC FIELD IN NATURE…

Consider two ions with radii R and electric charge Ze colliding at impact parameter b that collide at $\sqrt{s_{NN}}$

The magnetic field at the center-of-mass is given by the Biot-Savart law:

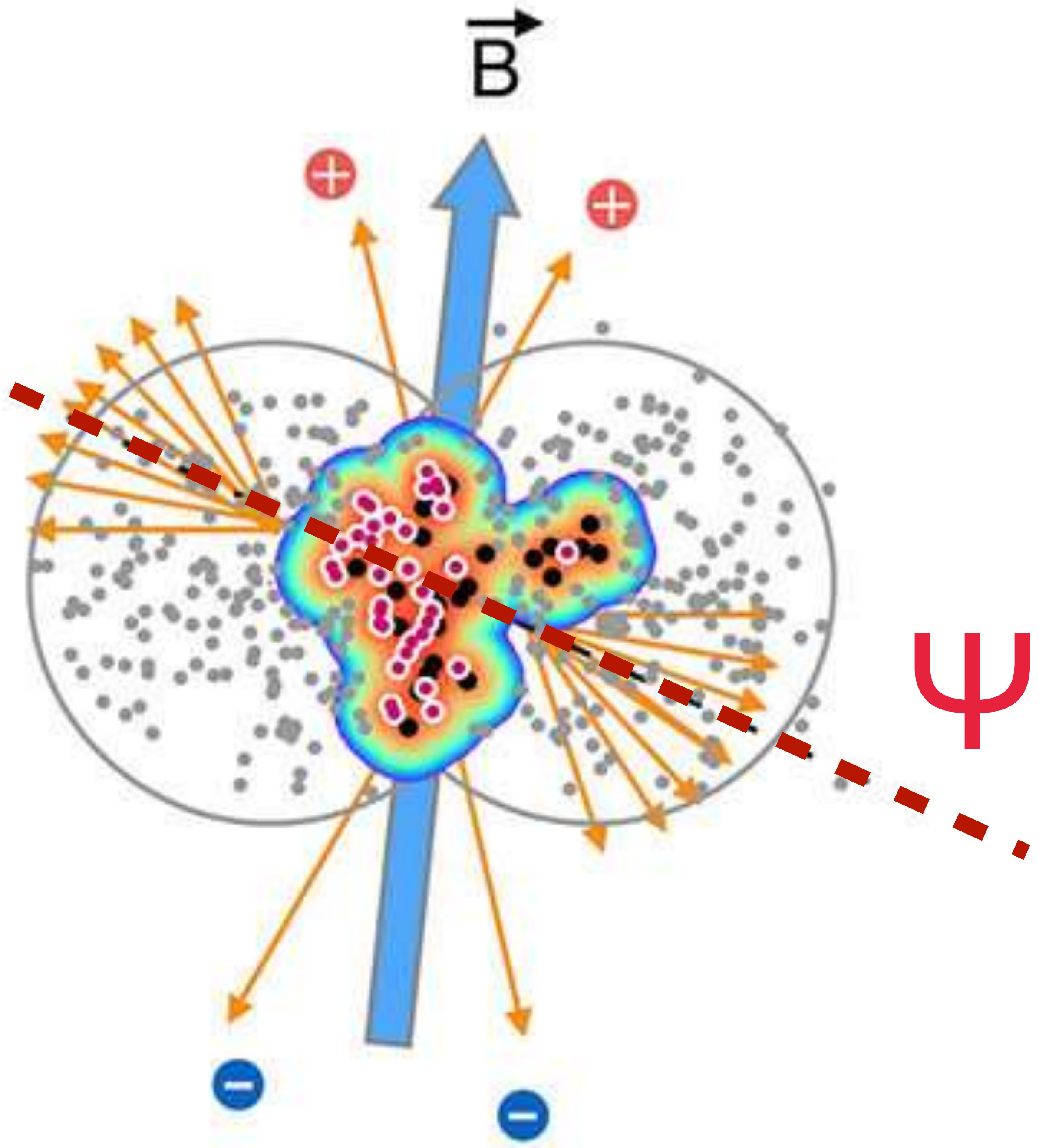
$$\vec{B} = \frac{\mu_0}{4\pi}\int \frac{I d\vec{l} \times \hat{r}}{|\vec{r}|^2}$$

$$B \approx \gamma Z e \frac{b}{R^3}$$

$$\gamma = \frac{\sqrt{s_{NN}}}{2m_p}$$

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 ~ $10m_\pi^2$

Develops perpendicular to the reaction plane



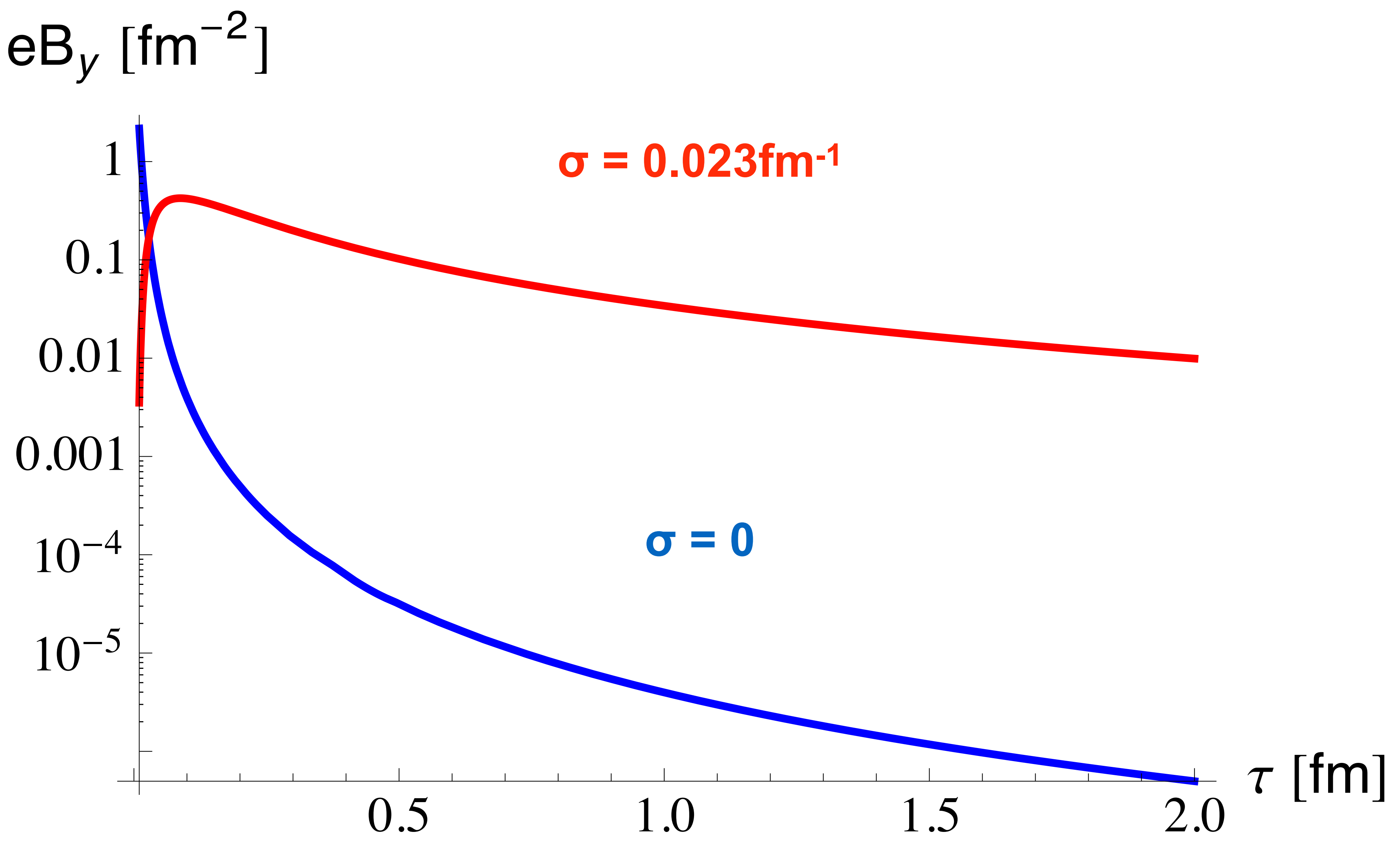
Heavy ion collisions: 10^{18}-10^{19} G

B-FIELD LIFETIME - QGP CONDUCTIVITY

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

The field decays rapidly

- Decay rate depends on the electric conductivity of the medium
- Conductivity depends (in principle) on temperature
  - Poorly constrained so far by experiments

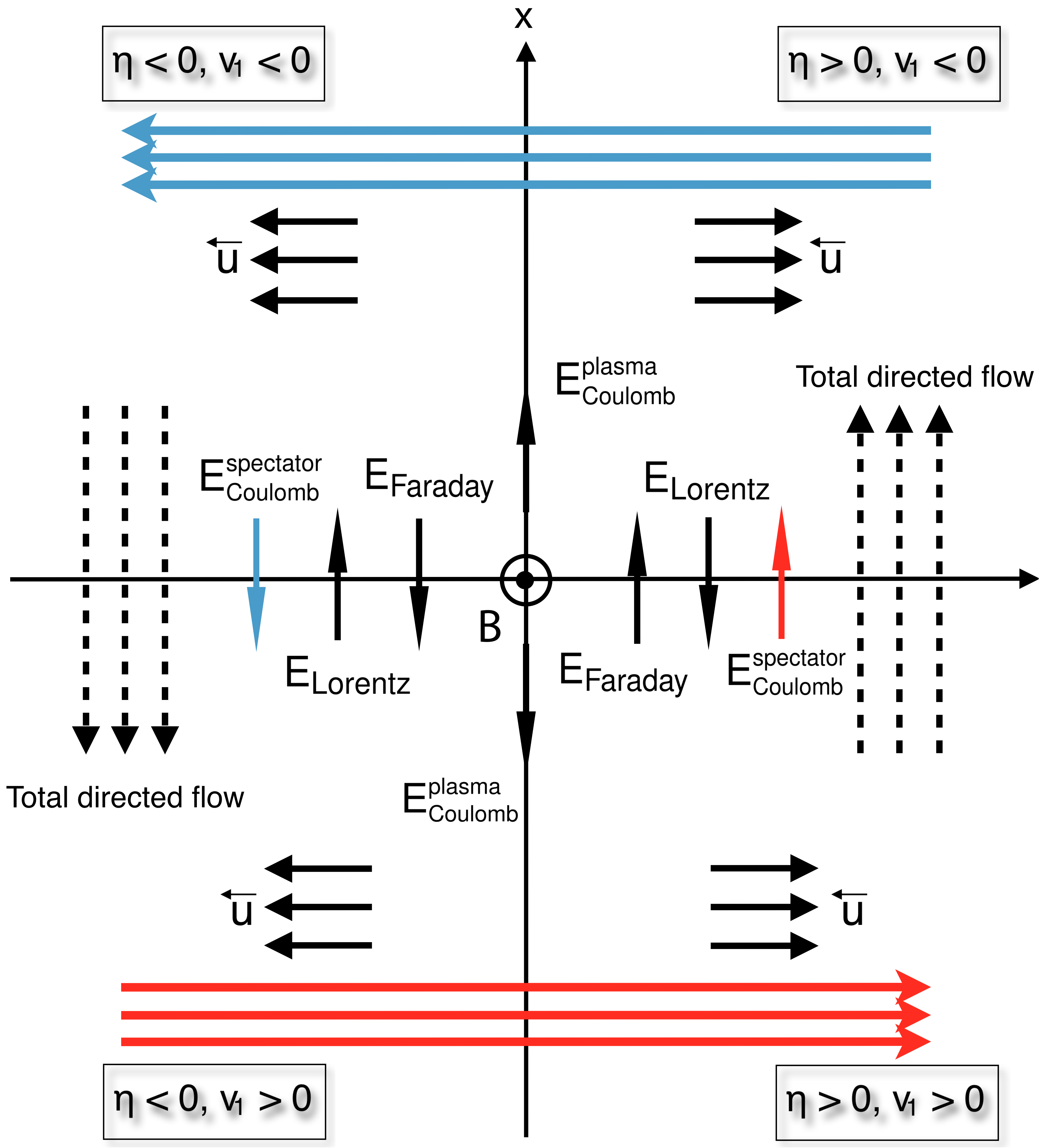


EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

Competing effects:
Faraday + spectator Coulomb vs Lorentz force

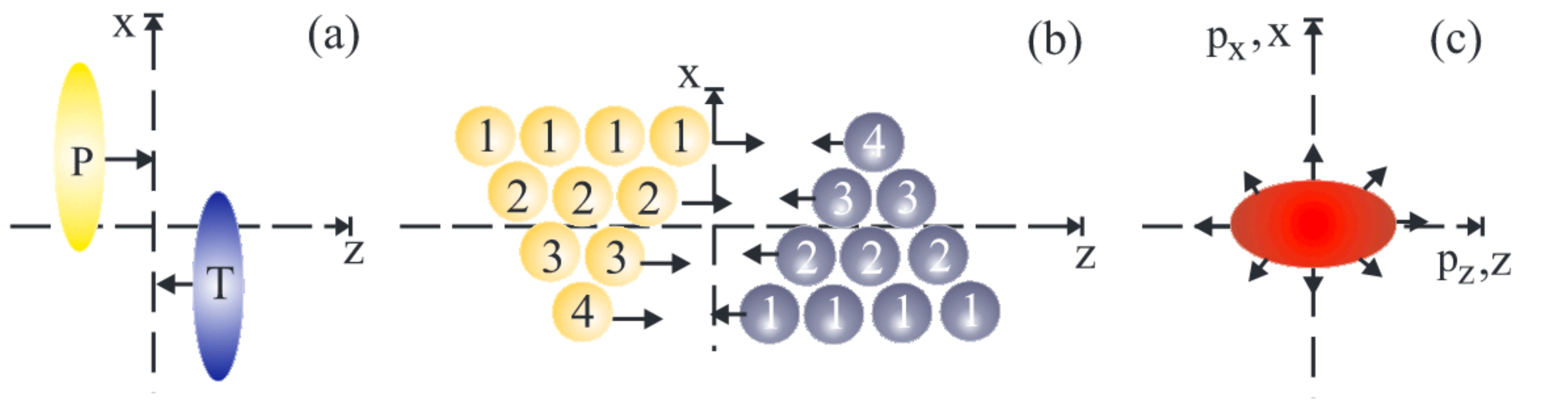
Initial stage E/M fields could affect the motion of particles → experimentally accessible differences in charge dependent odd v_n

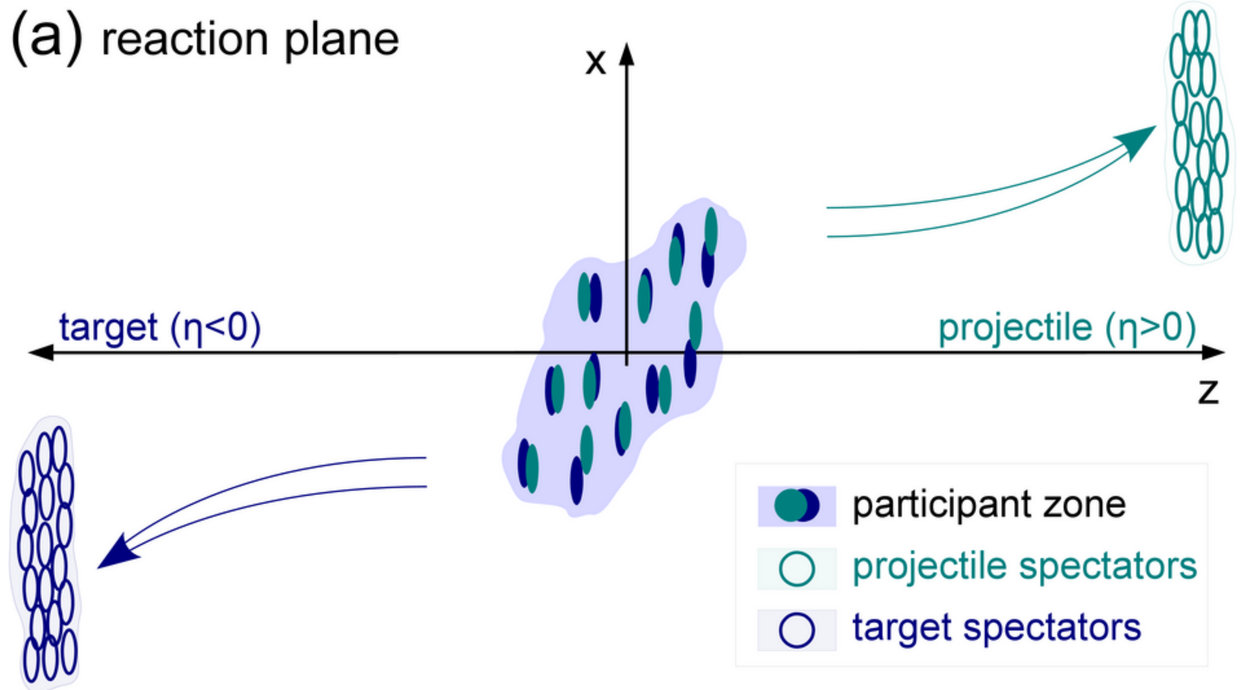
U. Gürsoy *et al.*, Phys. Rev. **C98**, (2018) 055201



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

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



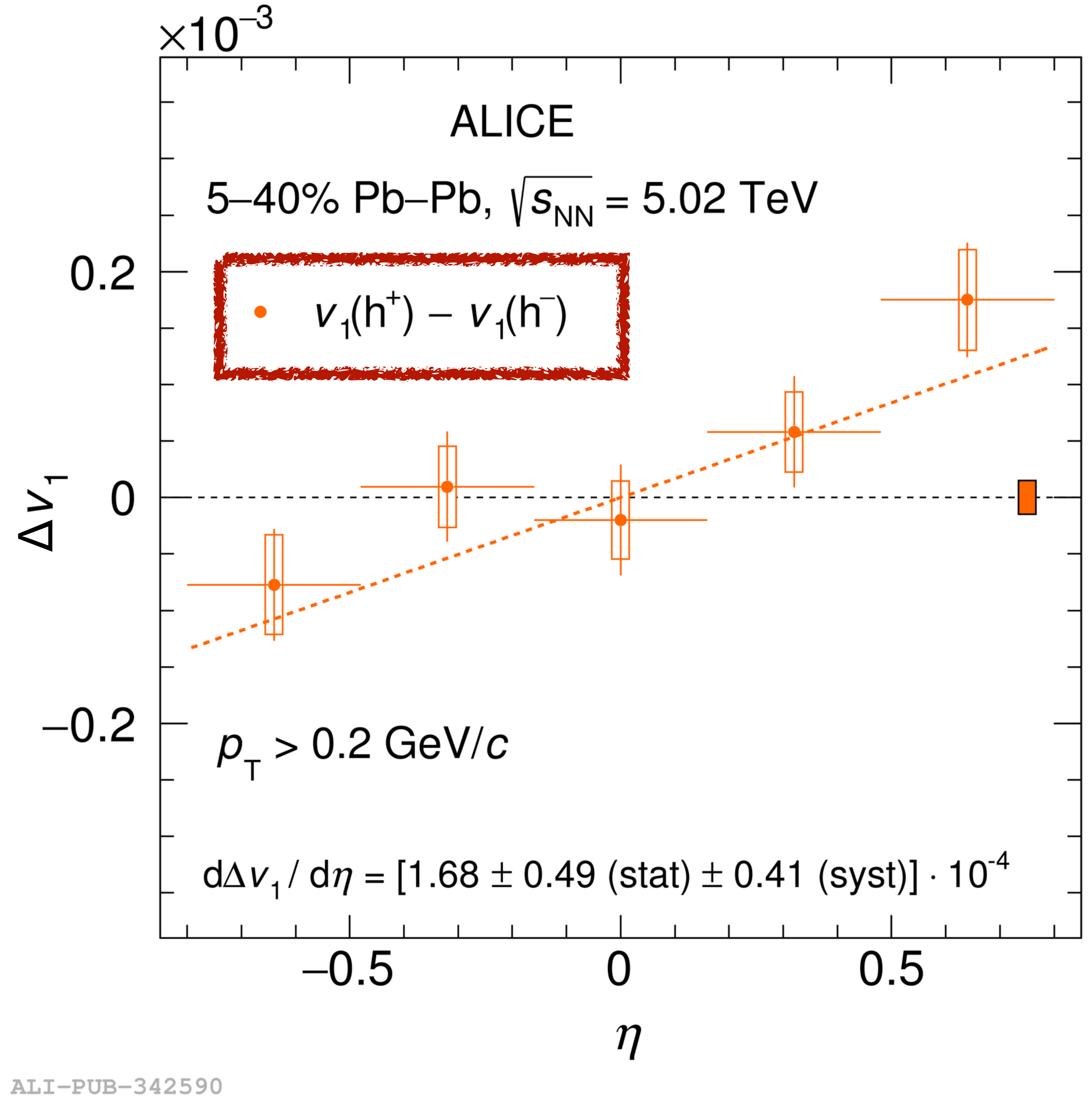


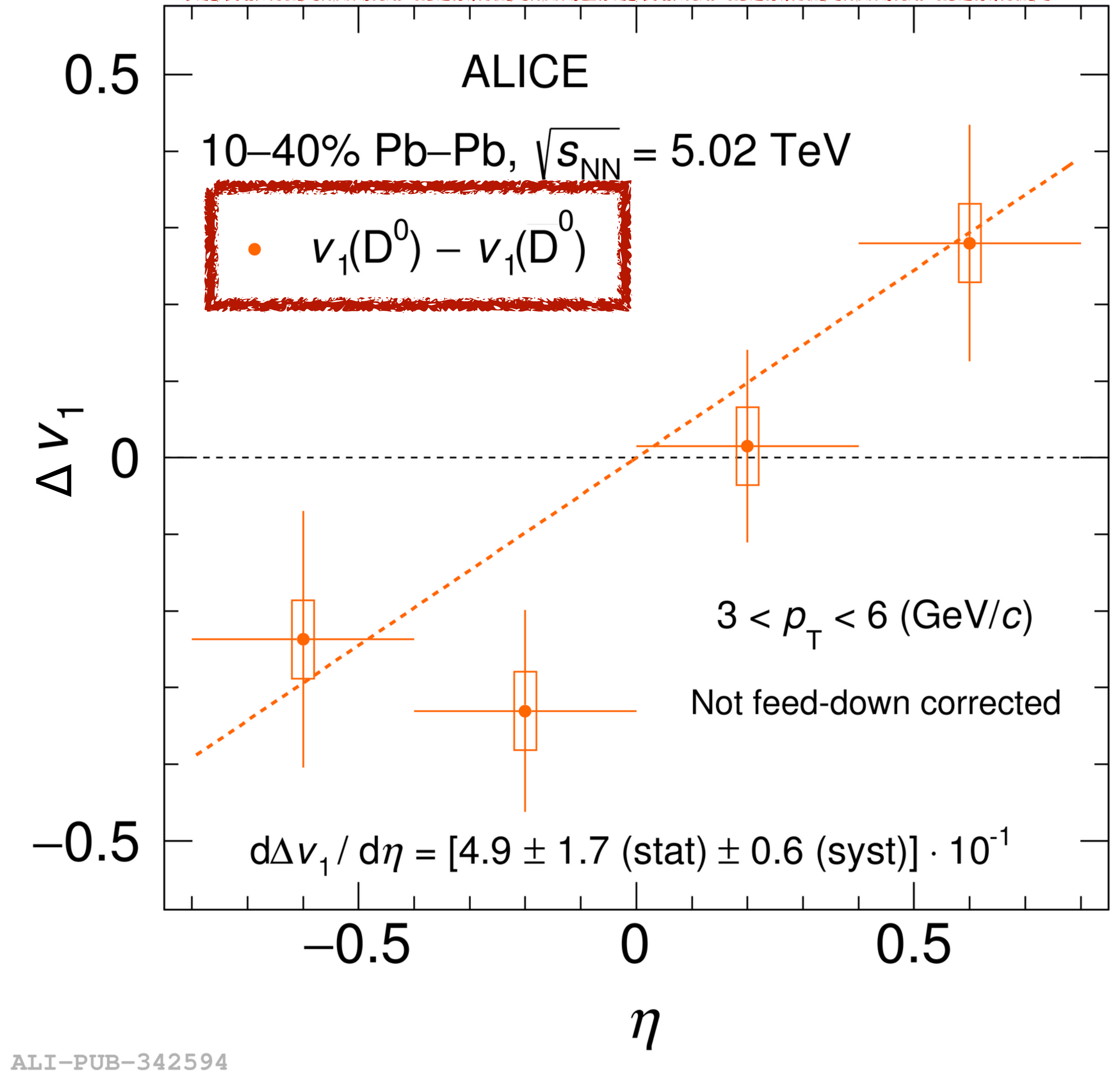
EXPERIMENTAL PROBE: CHARGE DEPENDENT V_N

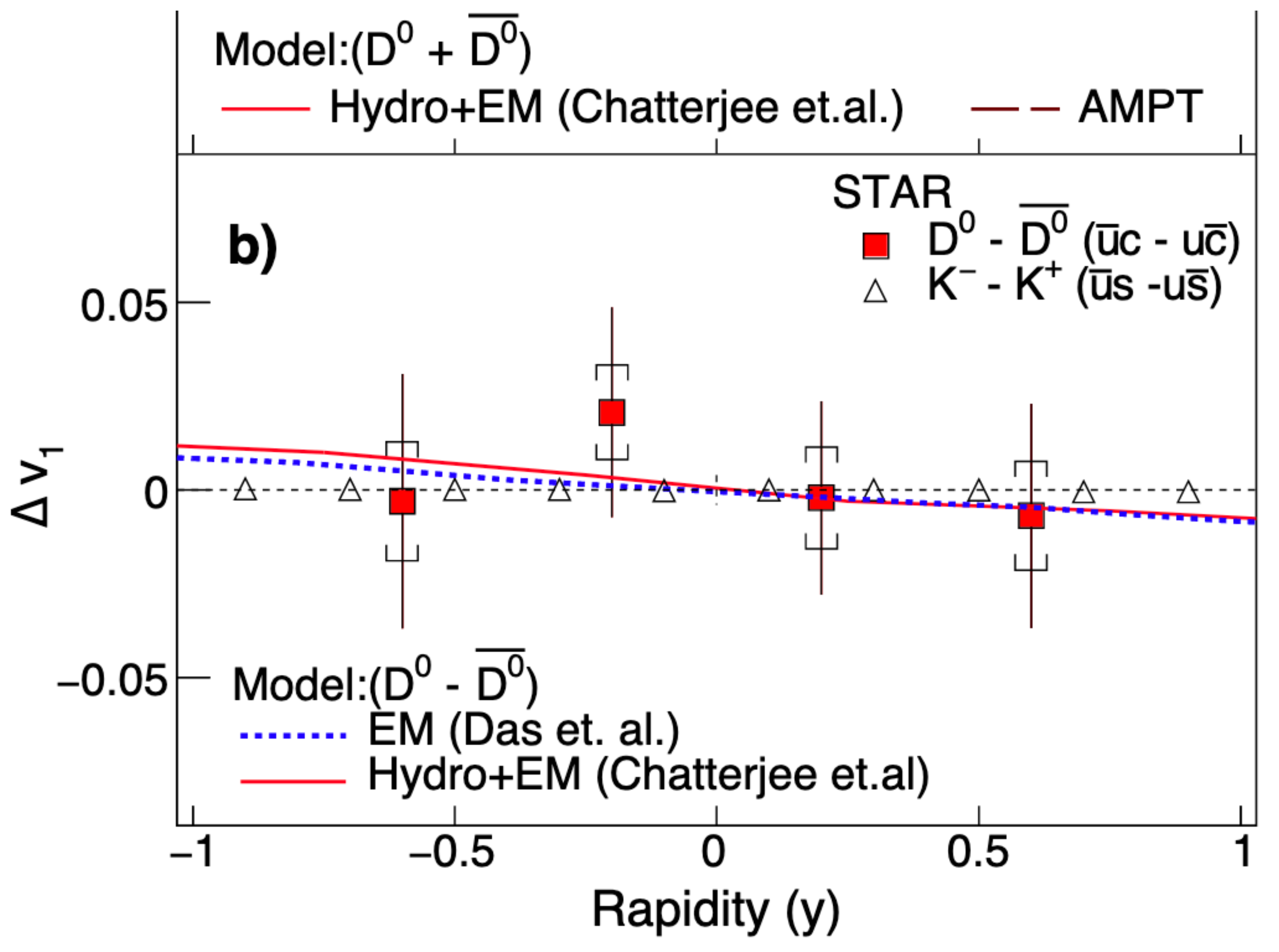
(ALICE Collaboration), Phys. Rev. Lett. 125, 022301 (2020)

(STAR Collaboration), Phys. Rev. Lett. 122, 162301 (2019 16)

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

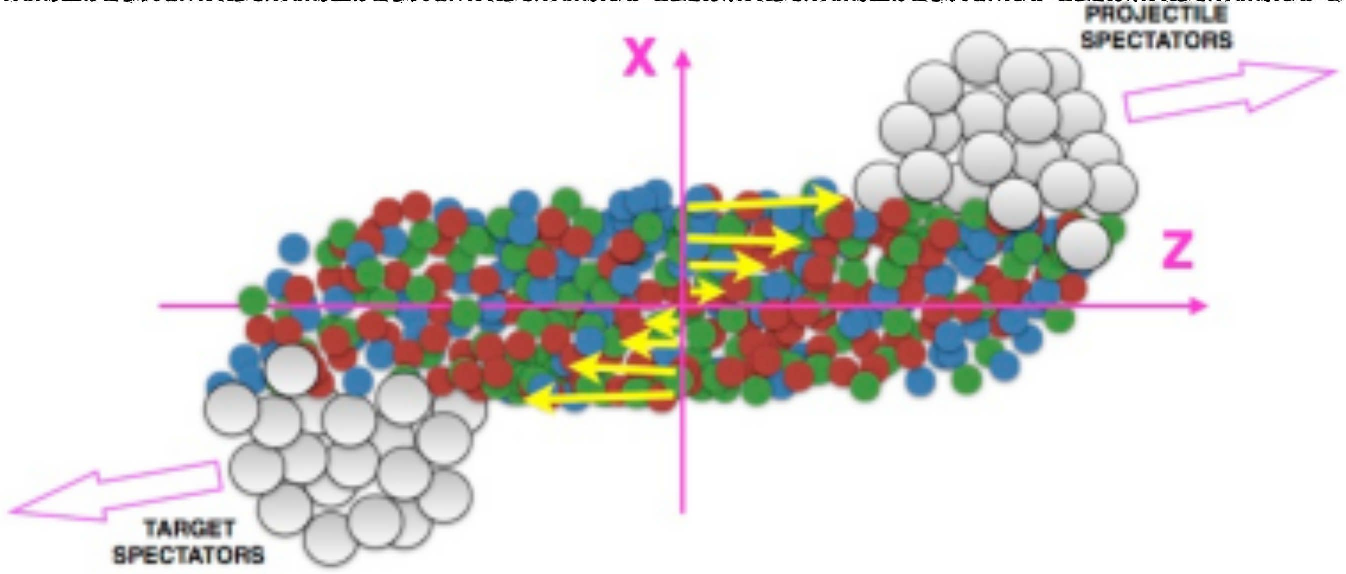
- Larger contribution from the Lorentz force?

Effect @RHIC >10 times smaller

EXPERIMENTAL PROBE: GLOBAL POLARISATION

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

(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 I'm the overlap region → rotating QGP

QGP exhibits vortical structure affected by the local velocity field

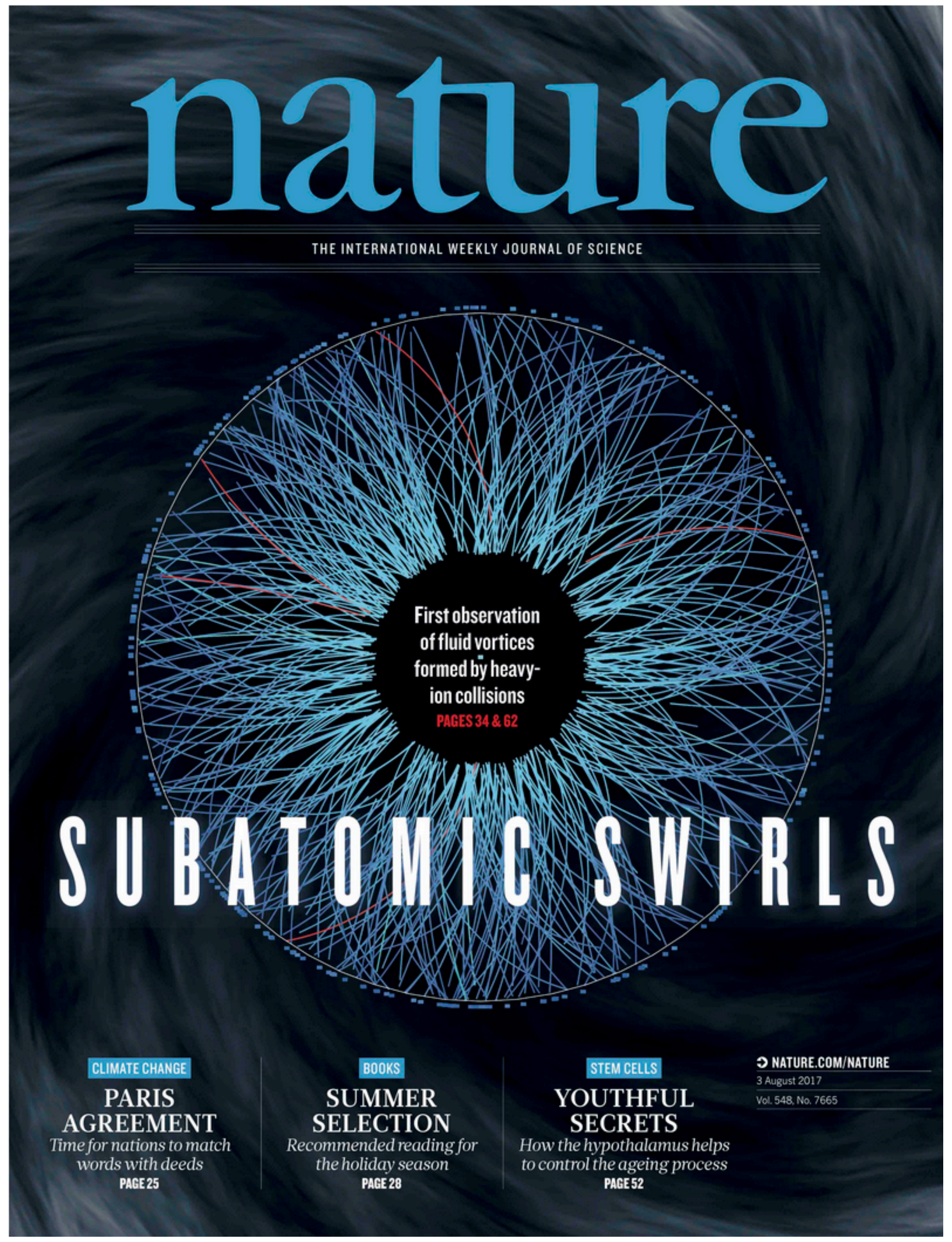
Spin proportional to magnetic moment

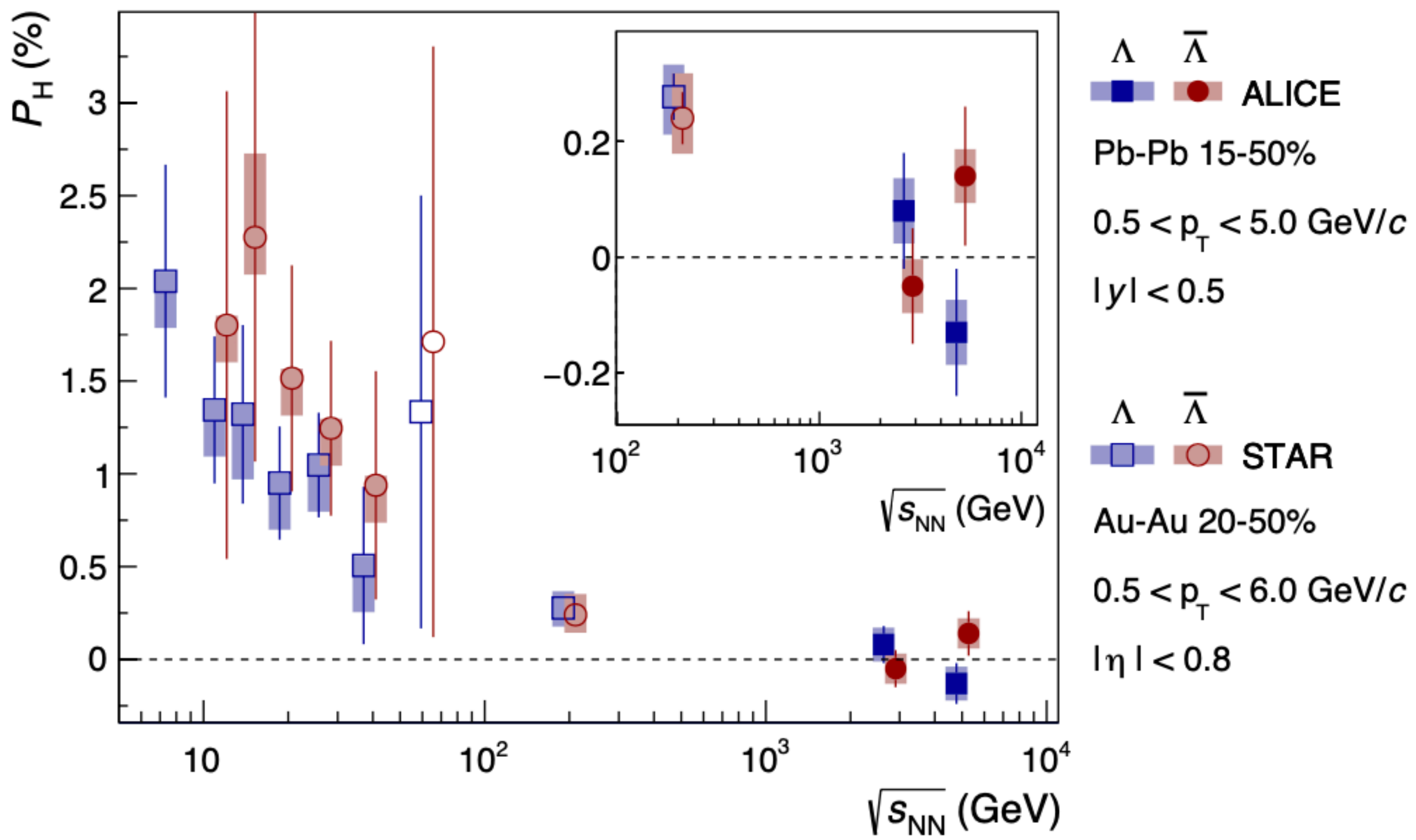
- Particles tend to be polarised along the initial angular momentum of the QGP
- Opposite effect for particles and antiparticles

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

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

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





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

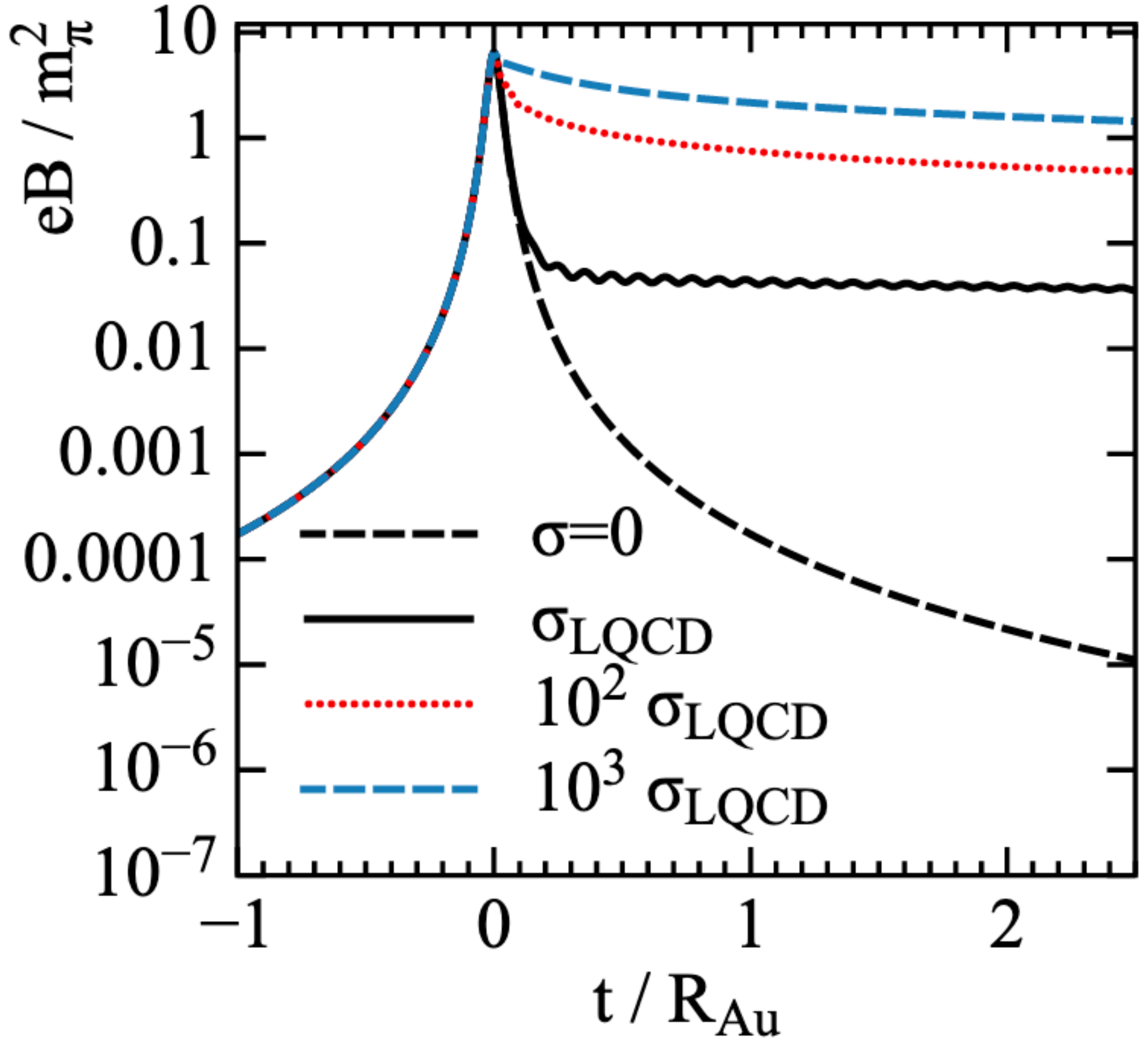
Significant reduction of P_H at the LHC energies relative to RHIC

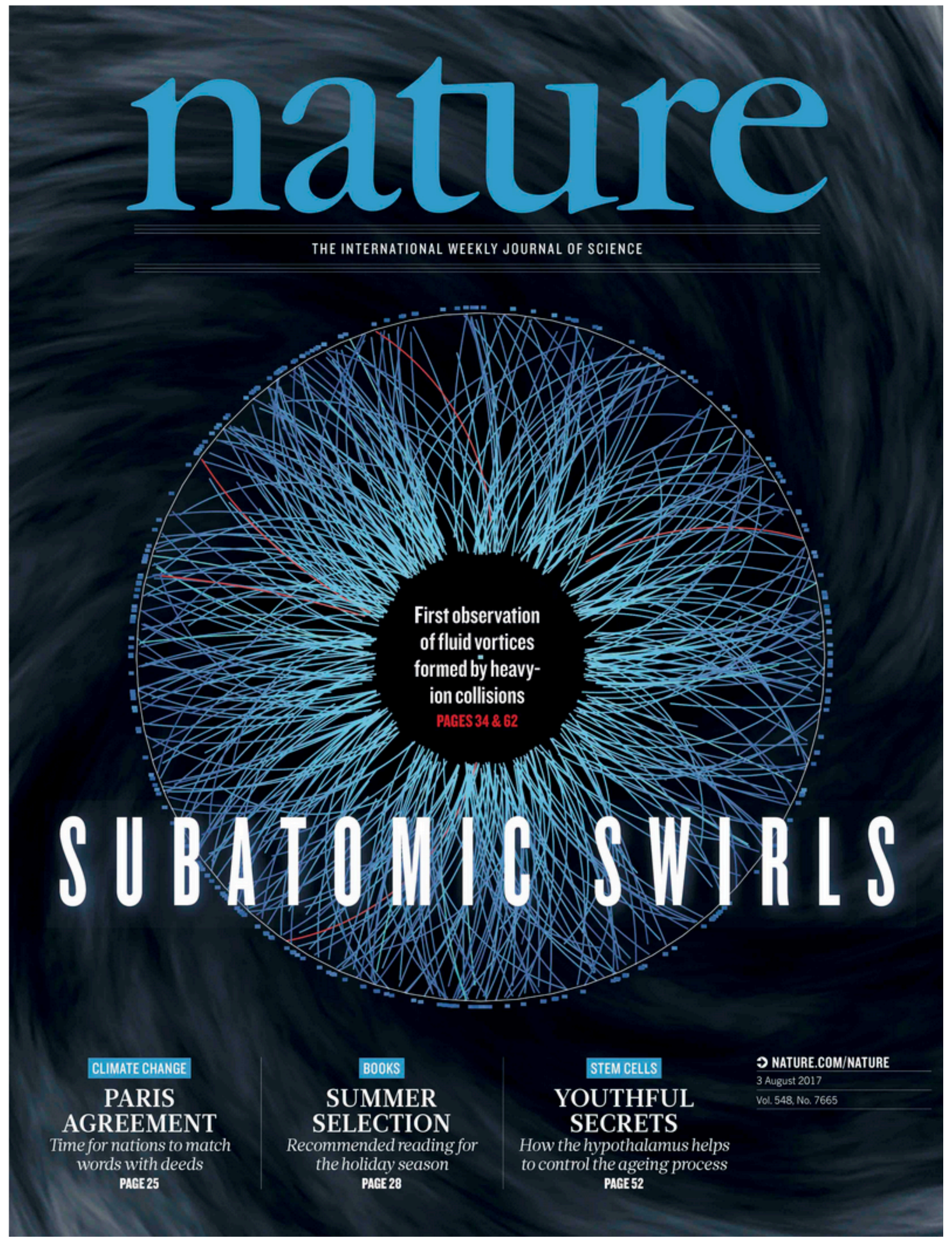
No significant difference between Λ and anti-Λ ➞ (still) not sensitive to effects due to magnetic field

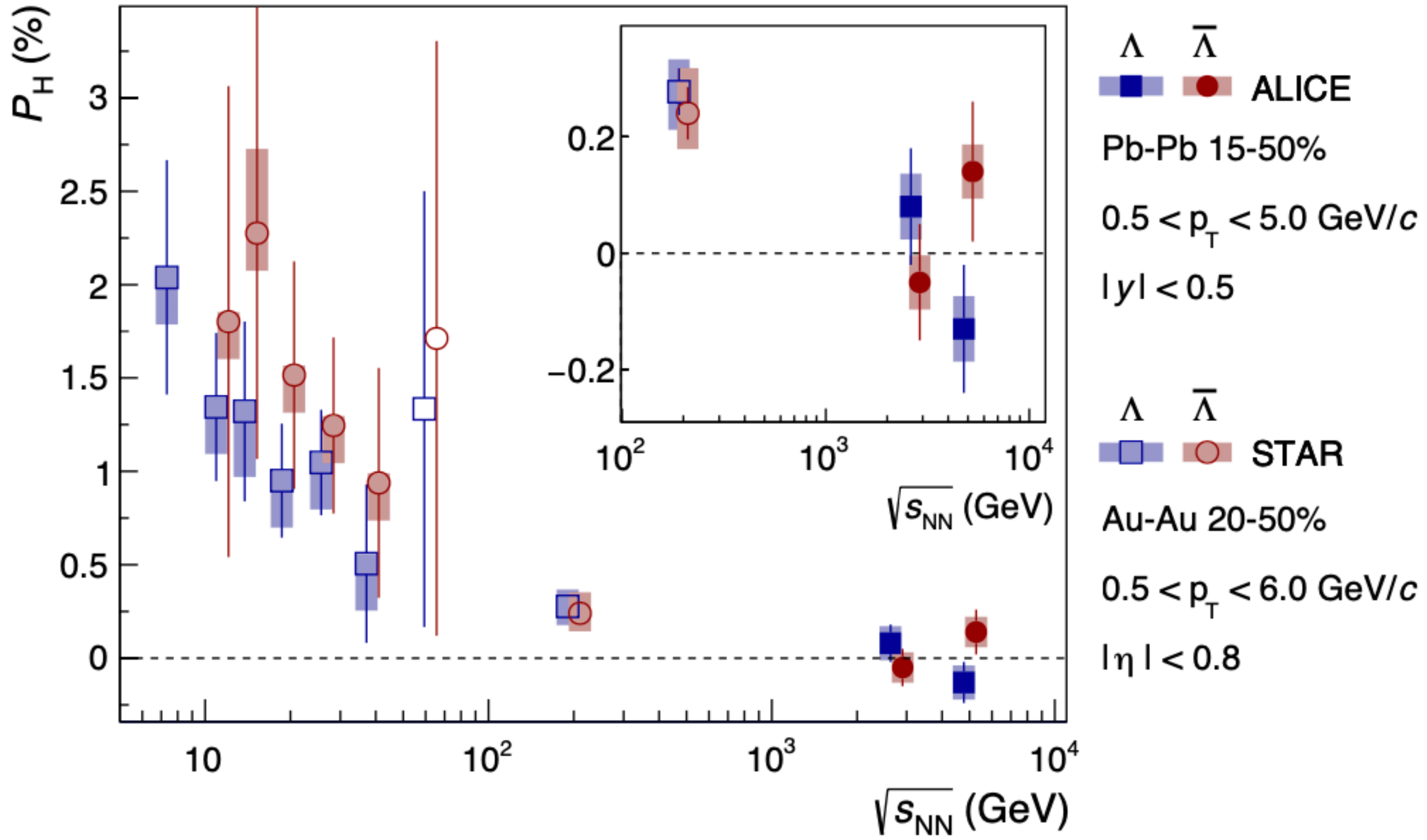
EXPERIMENTAL PROBE: GLOBAL POLARISATION

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

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







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

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

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

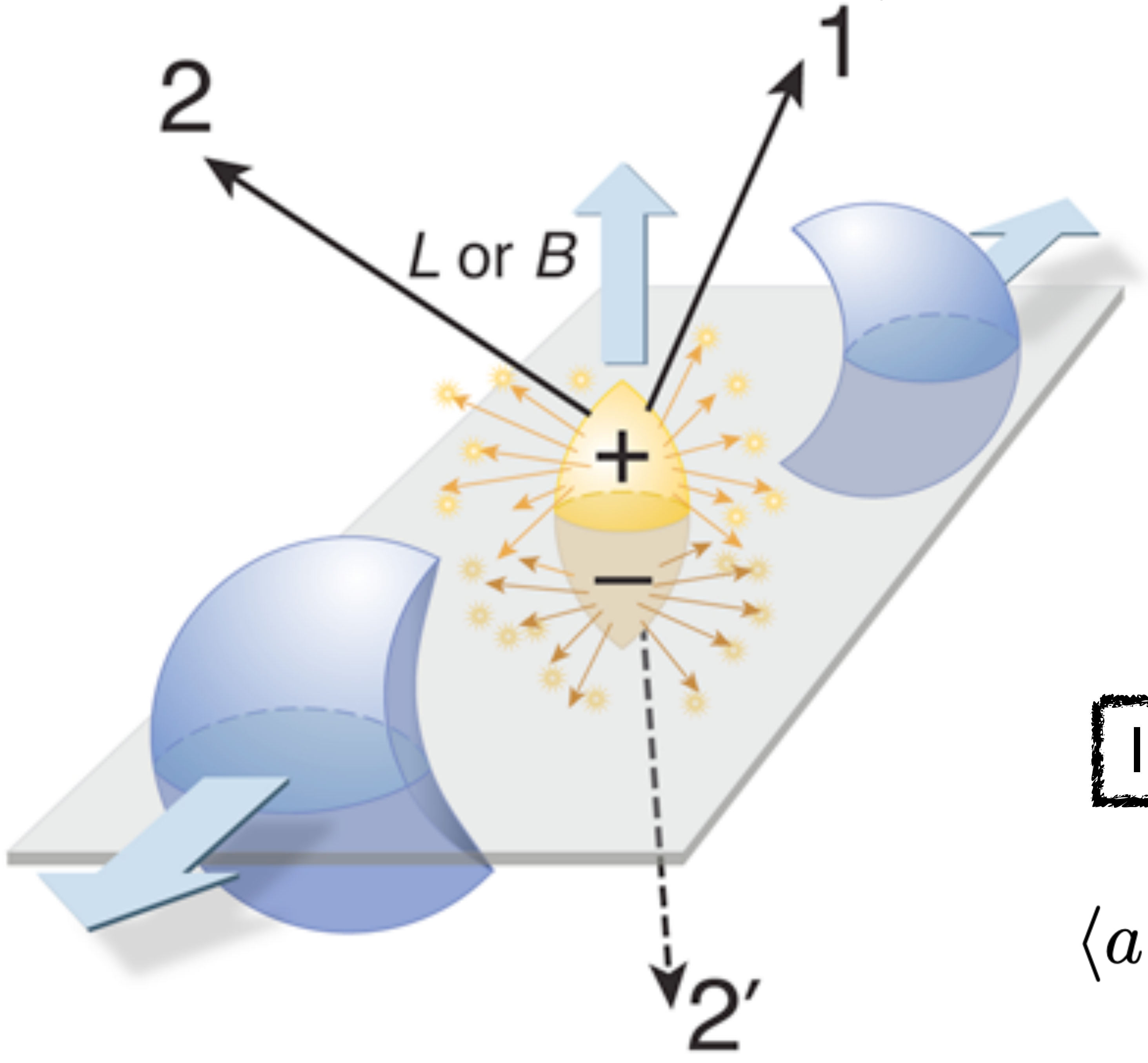
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{\mathrm{T}} - \mu_\Lambda \frac{\mathrm{B}}{\mathrm{T}}$$

Current measurements provide tight constrains on the value of B at freeze out, even if they are compatible with 0

SEARCH FOR NOVEL QCD PHENOMENA…

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

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



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

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

Parity conserving background effects projected in and out of plane

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

γ_{11}

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

General form

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

δ_1

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 RESULTS AT RHIC

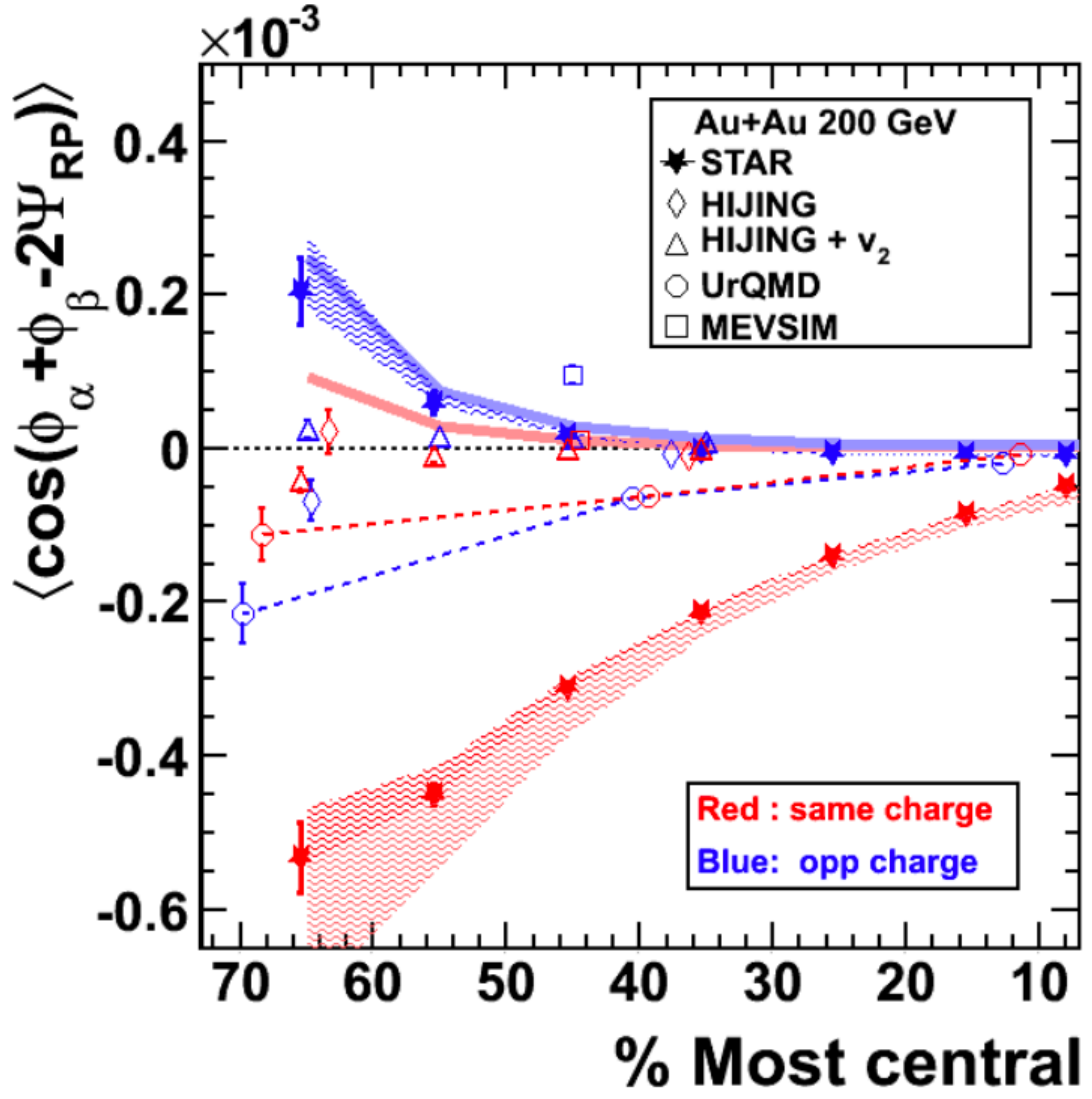
Significant charge dependent correlations that develop for more peripheral Au-Au collisions

γ_{11}

Consistent with CME expectations

Models that include “conventional physics” (e.g. flow, fragmentation) were unable to describe the measurements

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



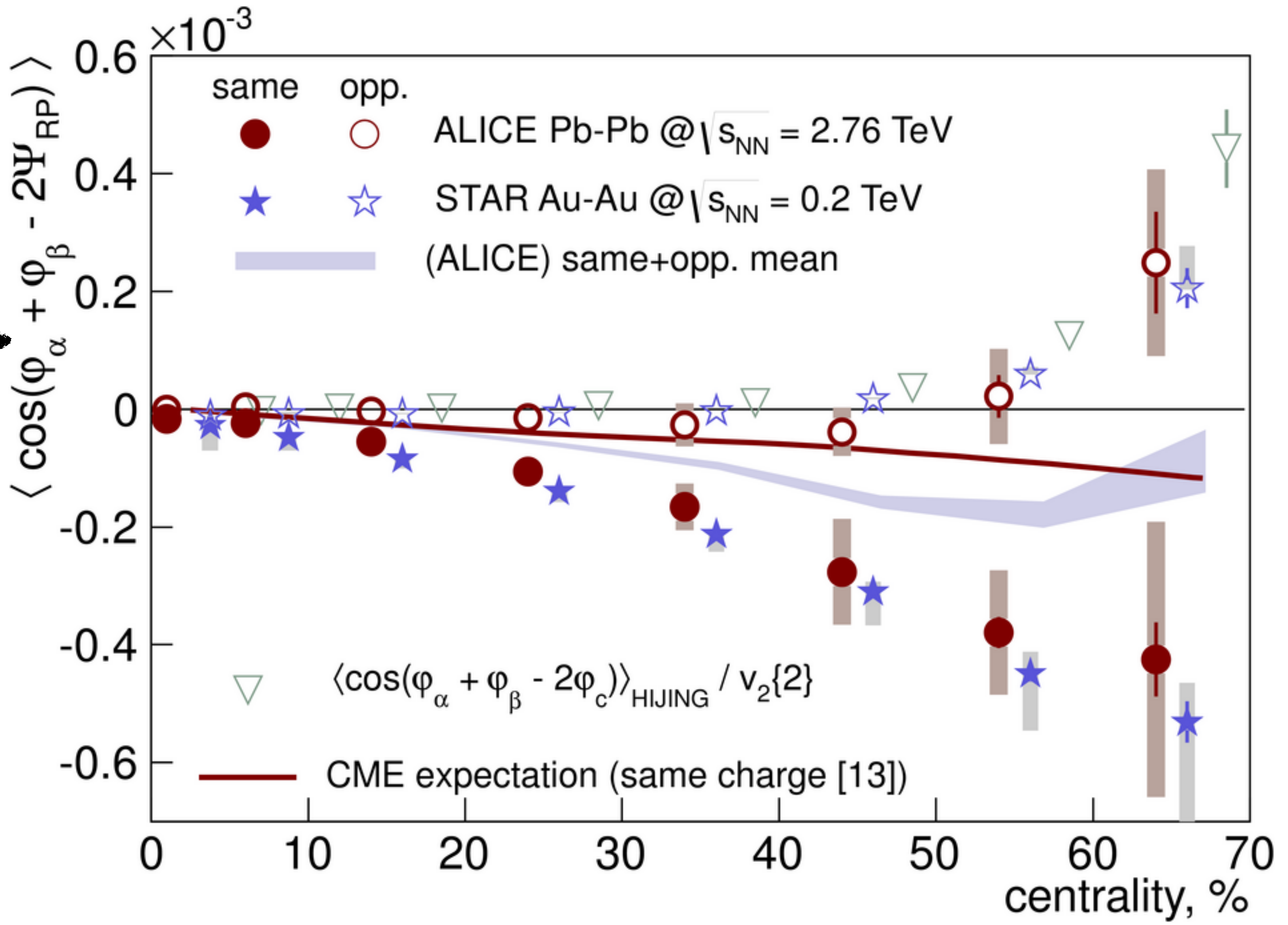
FIRST LHC RESULTS

(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

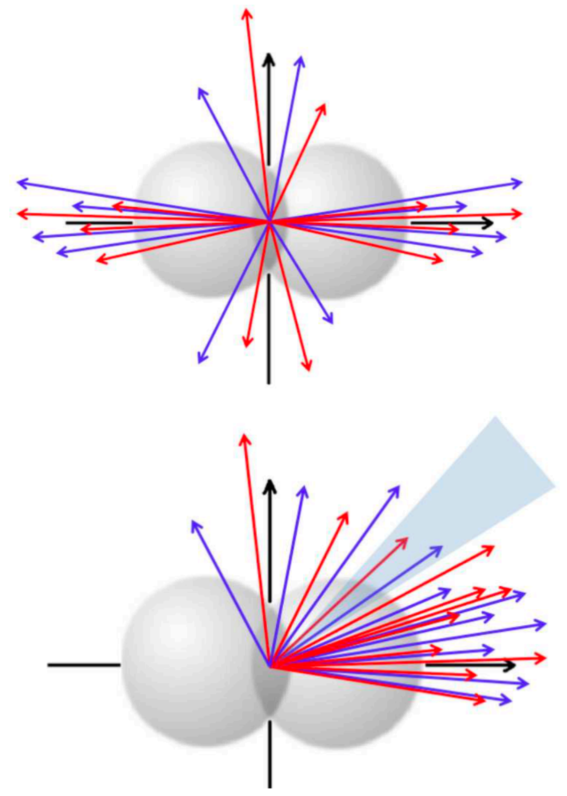
$\gamma_{1,1}$ →



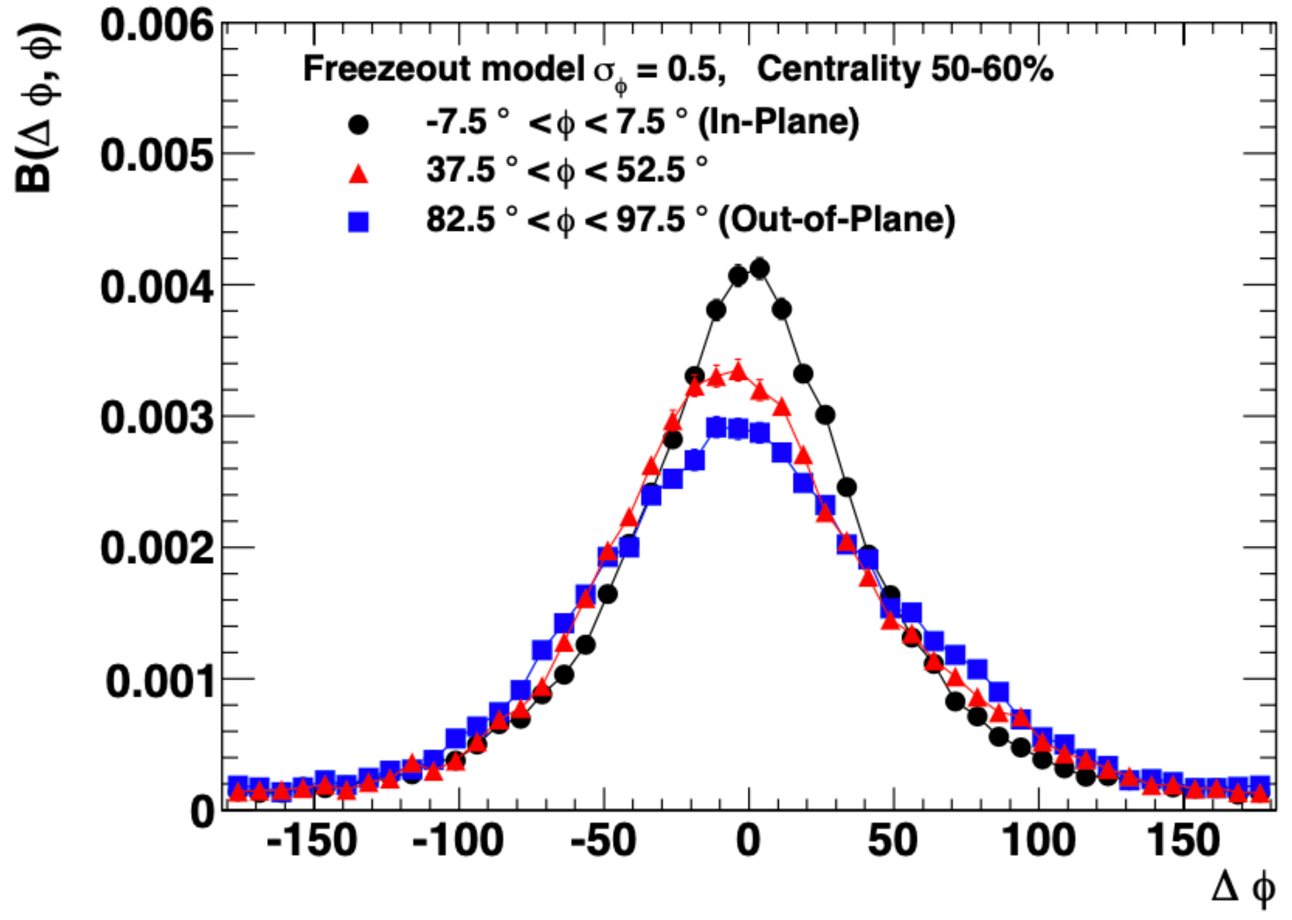
Big surprise considering the difference in energy, particle density,…

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

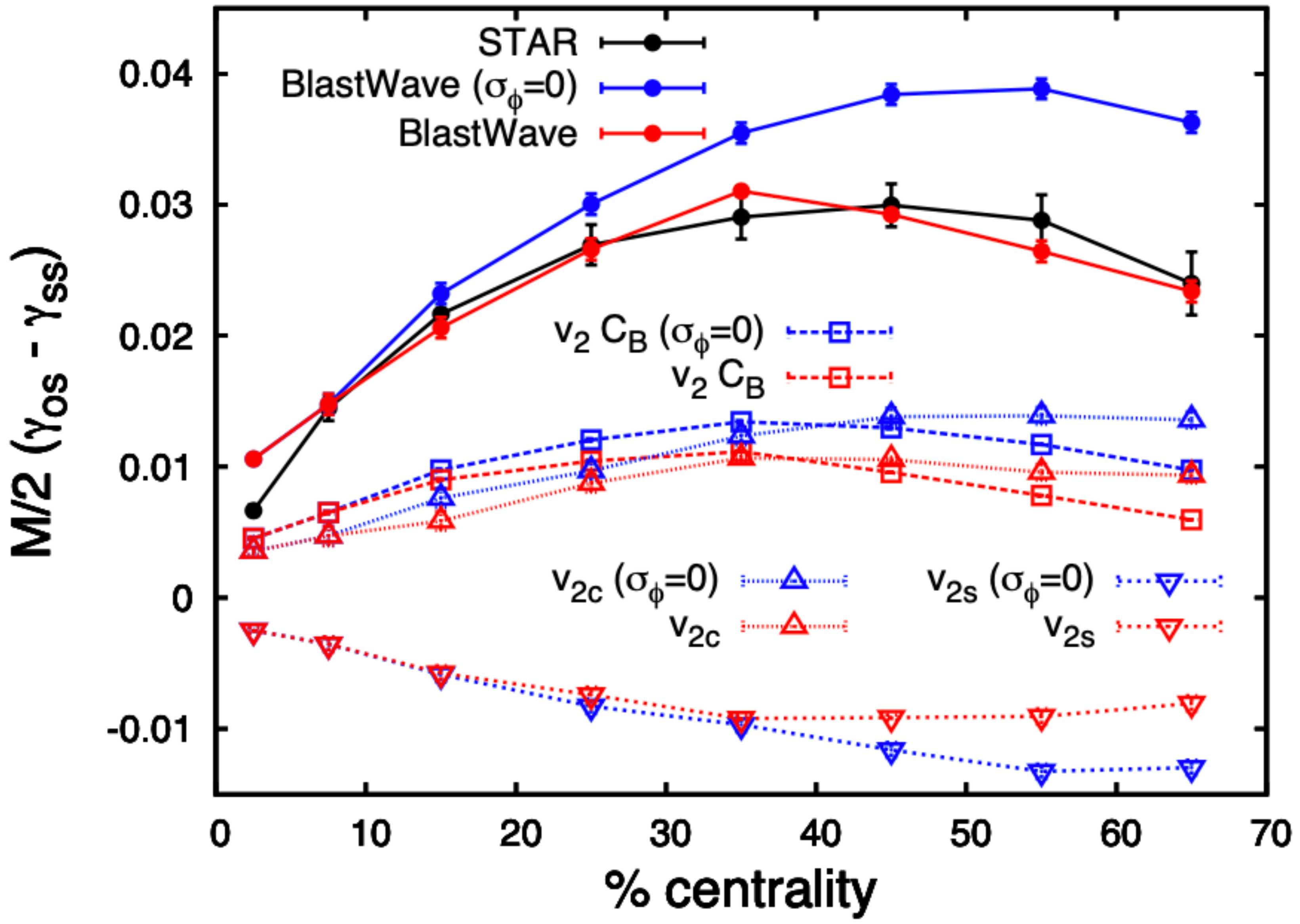
$v_{2,c}$: degree to which in-plane pairs are more tightly correlated than out-of-plane pairs

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

Main background component:

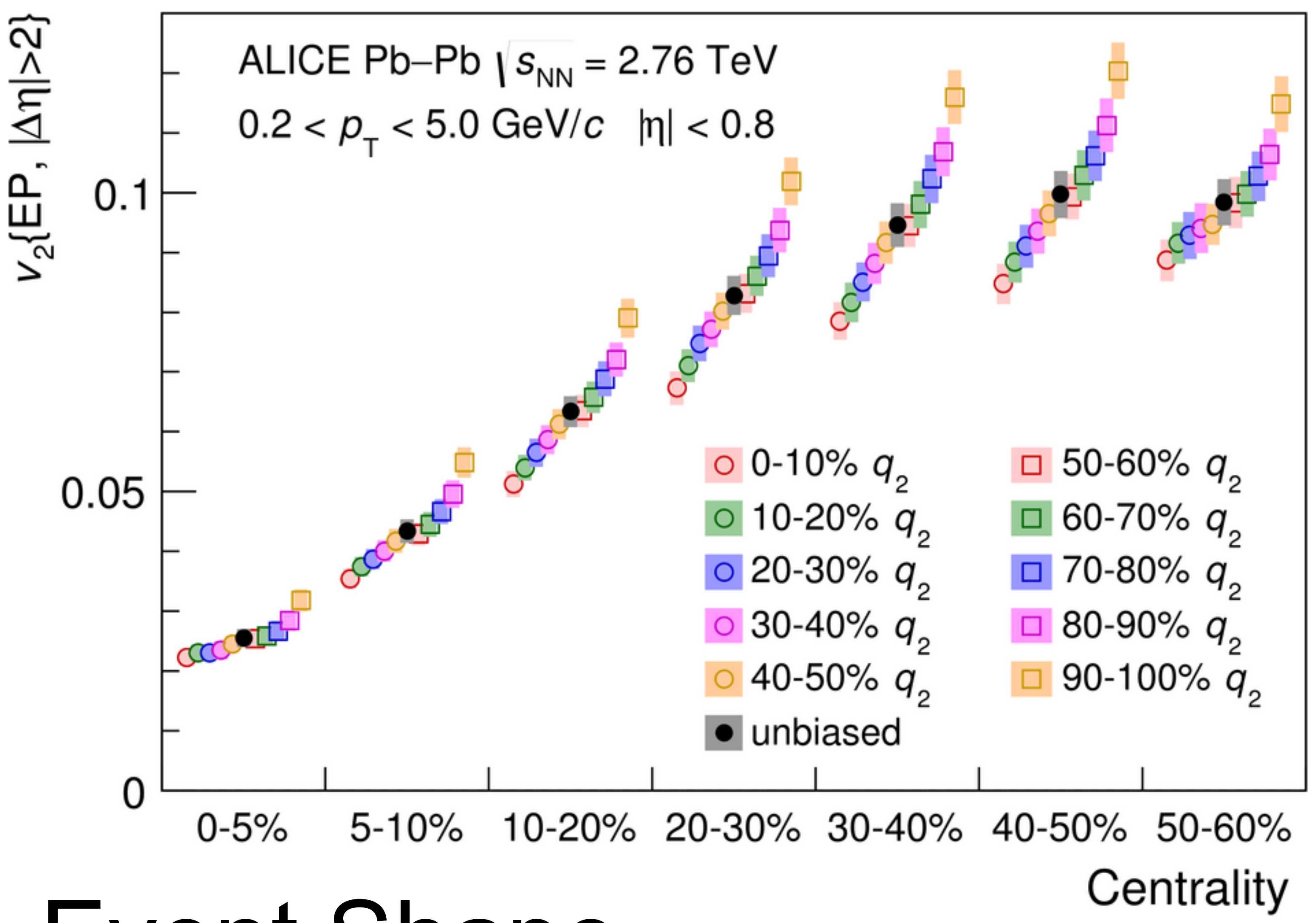
- Local charge conservation (LCC) coupled to anisotropic flow

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

ELSEVIER
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

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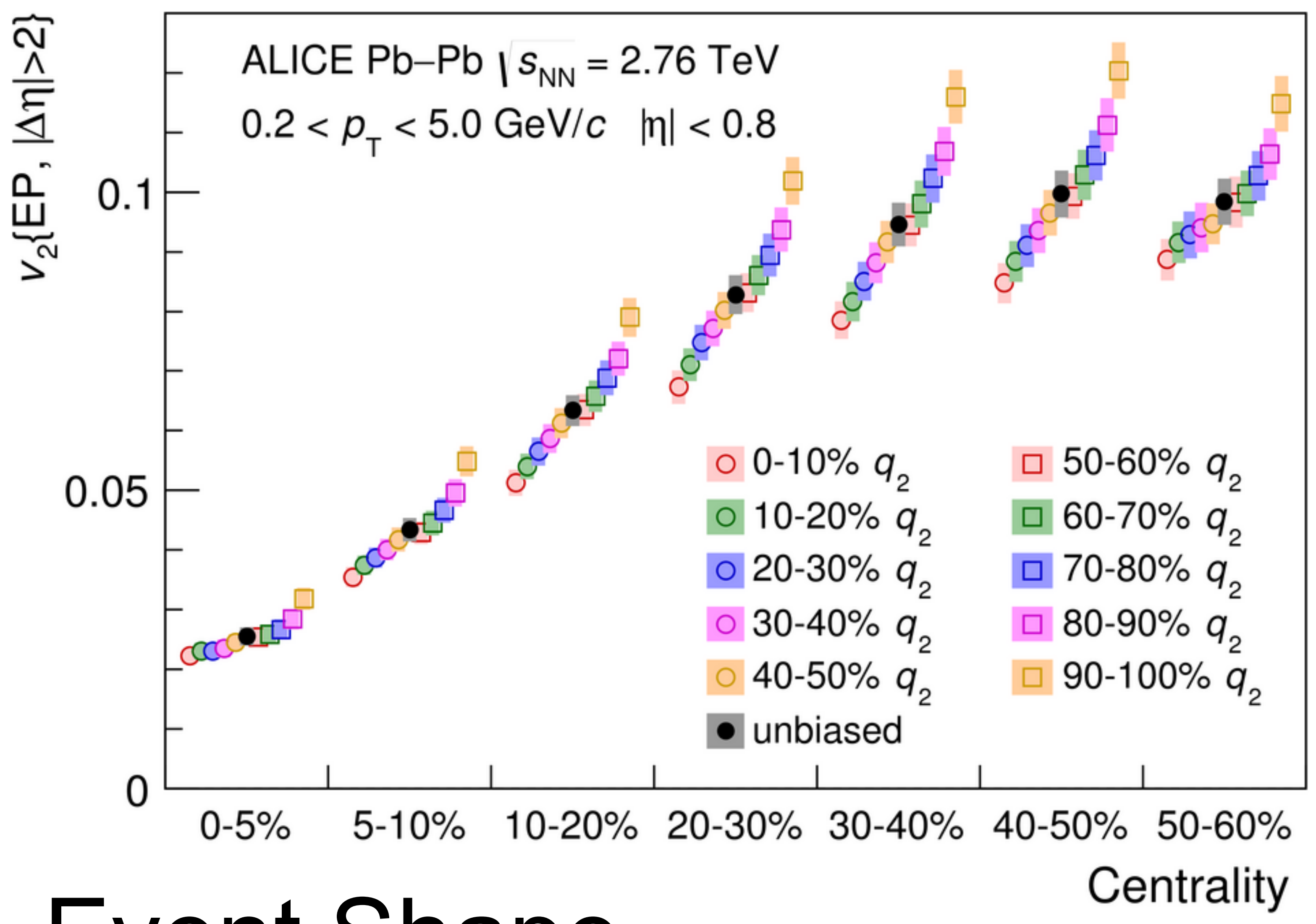
Abstract

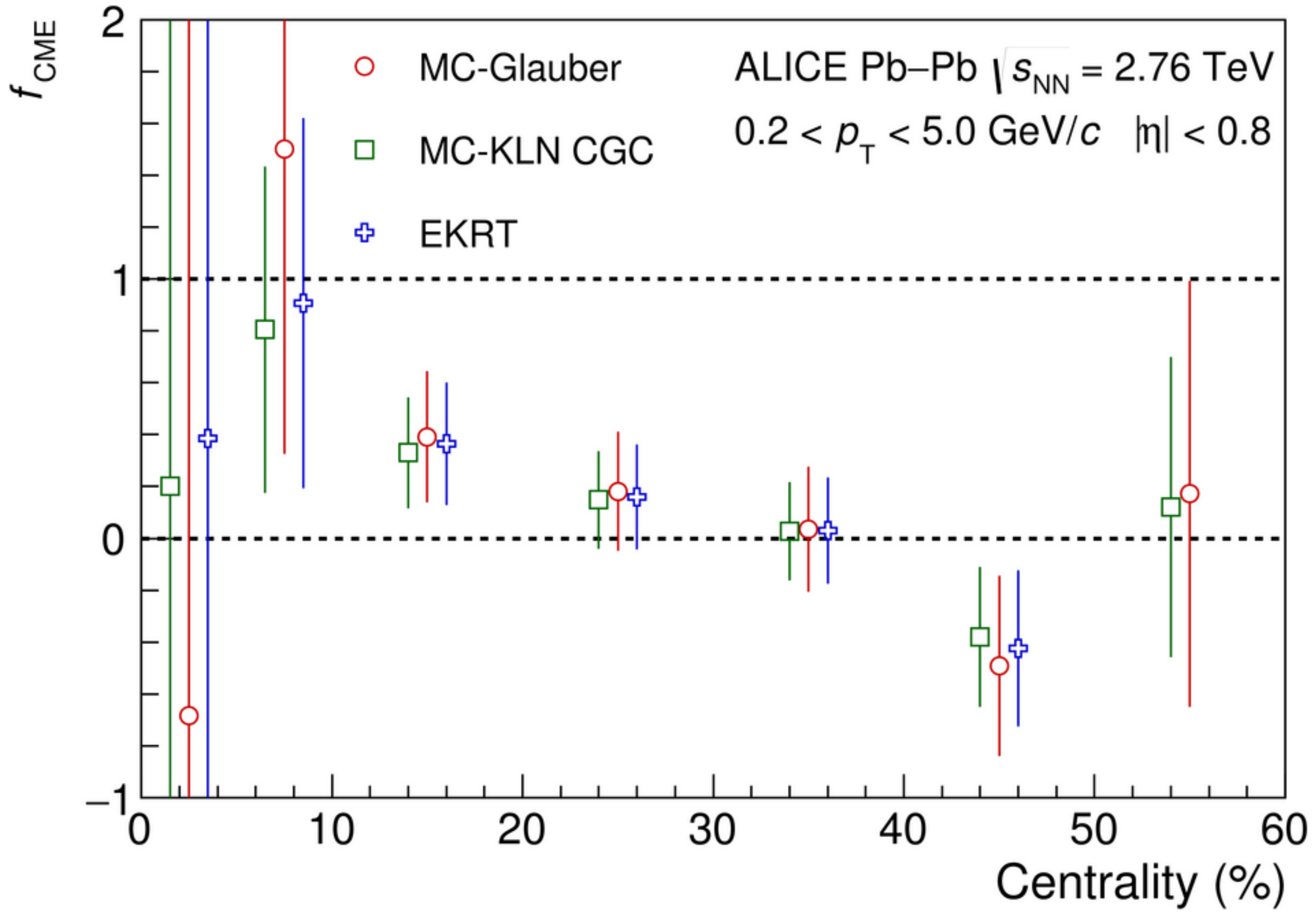
The evolution of the system created in a high energy nuclear collision is very sensitive to the fluctuations in the initial geometry of the system. In this Letter we show how one can utilize these large fluctuations to select events corresponding to a specific initial shape. Such an "event shape engineering"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



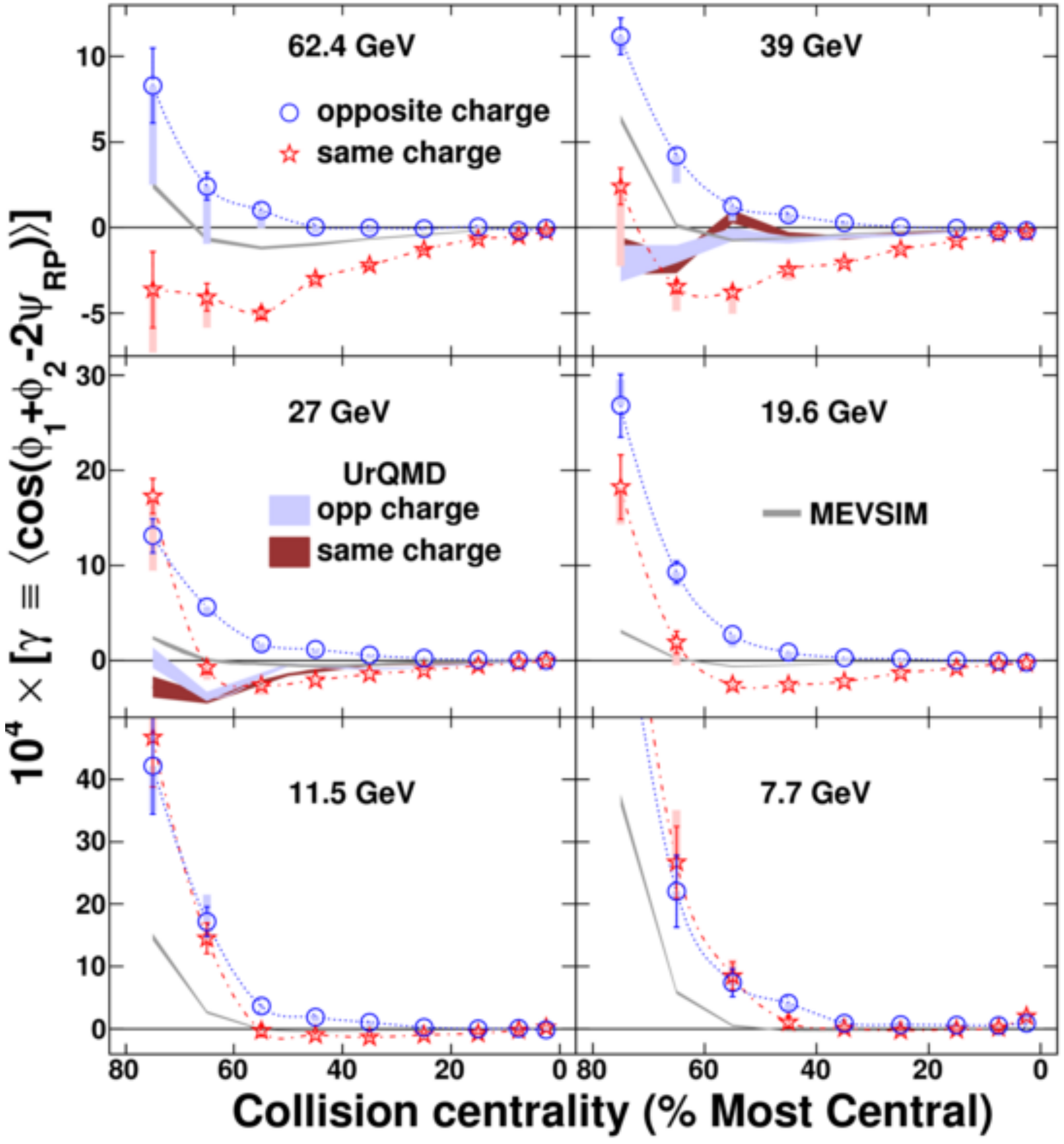
Upper limit on the CME fraction for the 10-50% centrality interval:

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

AT THE SAME TIME…ENERGY SCAN

$\Delta\gamma_{1,1}$ reduces with decreasing energy

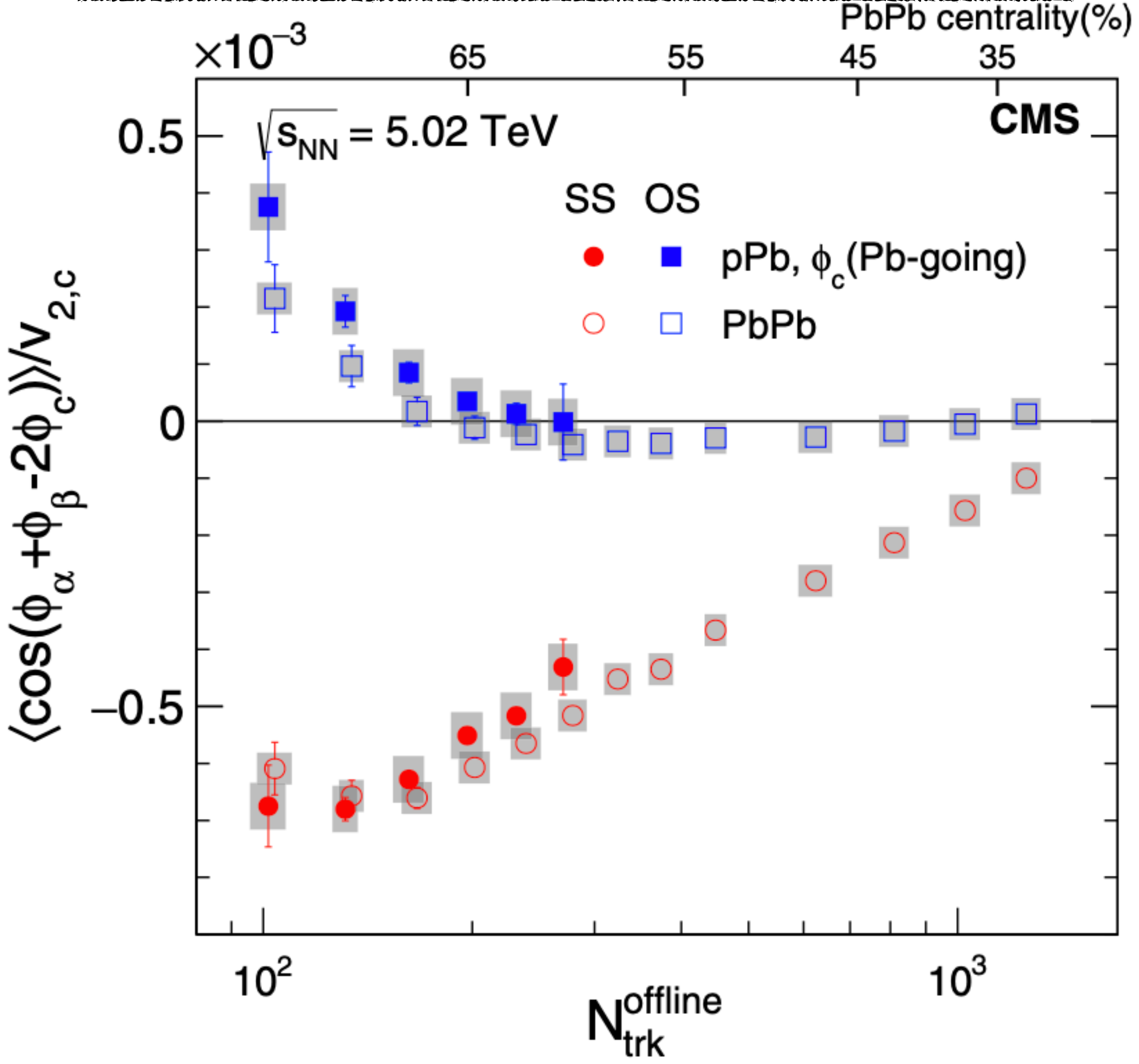
Compatible with 0 at low RHIC energies



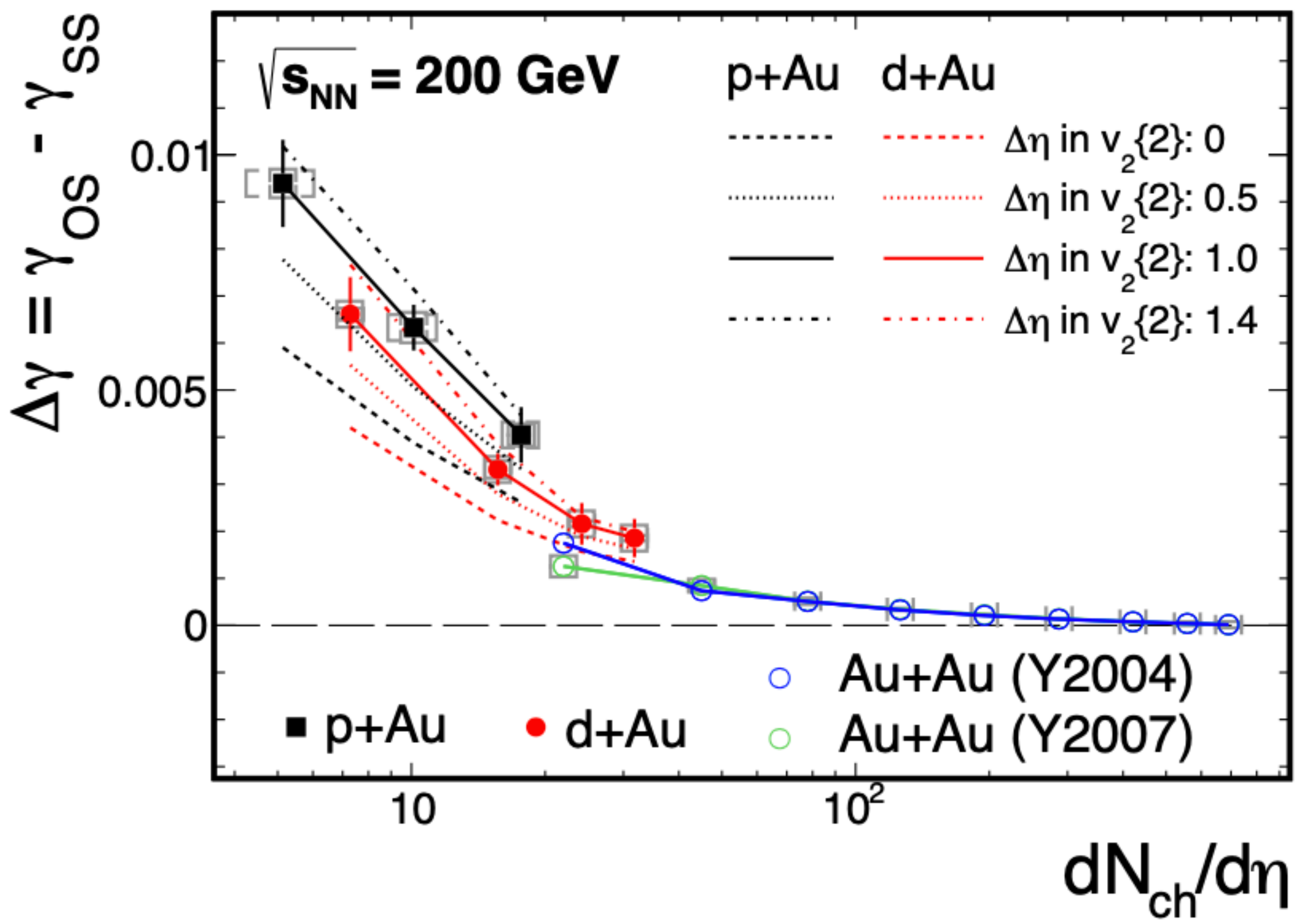
(STAR Collaboration) PRL **113** (2014) 52302

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)

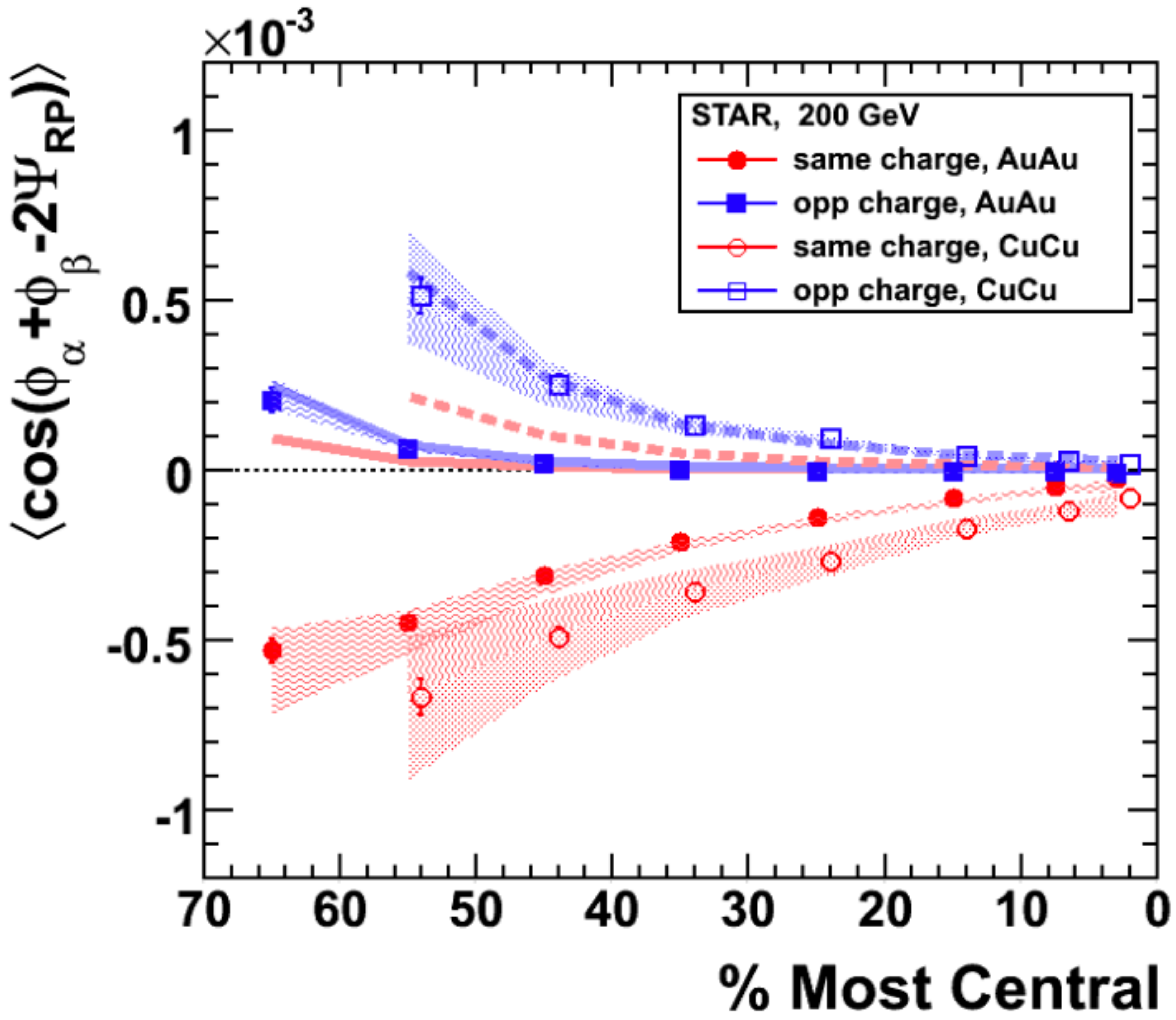
AT THE SAME TIME…SMALL SYSTEMS

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

Lines: Expectations from HIJING on 3-particle correlations

Solid: Au-Au

Dashed: Cu-Cu



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

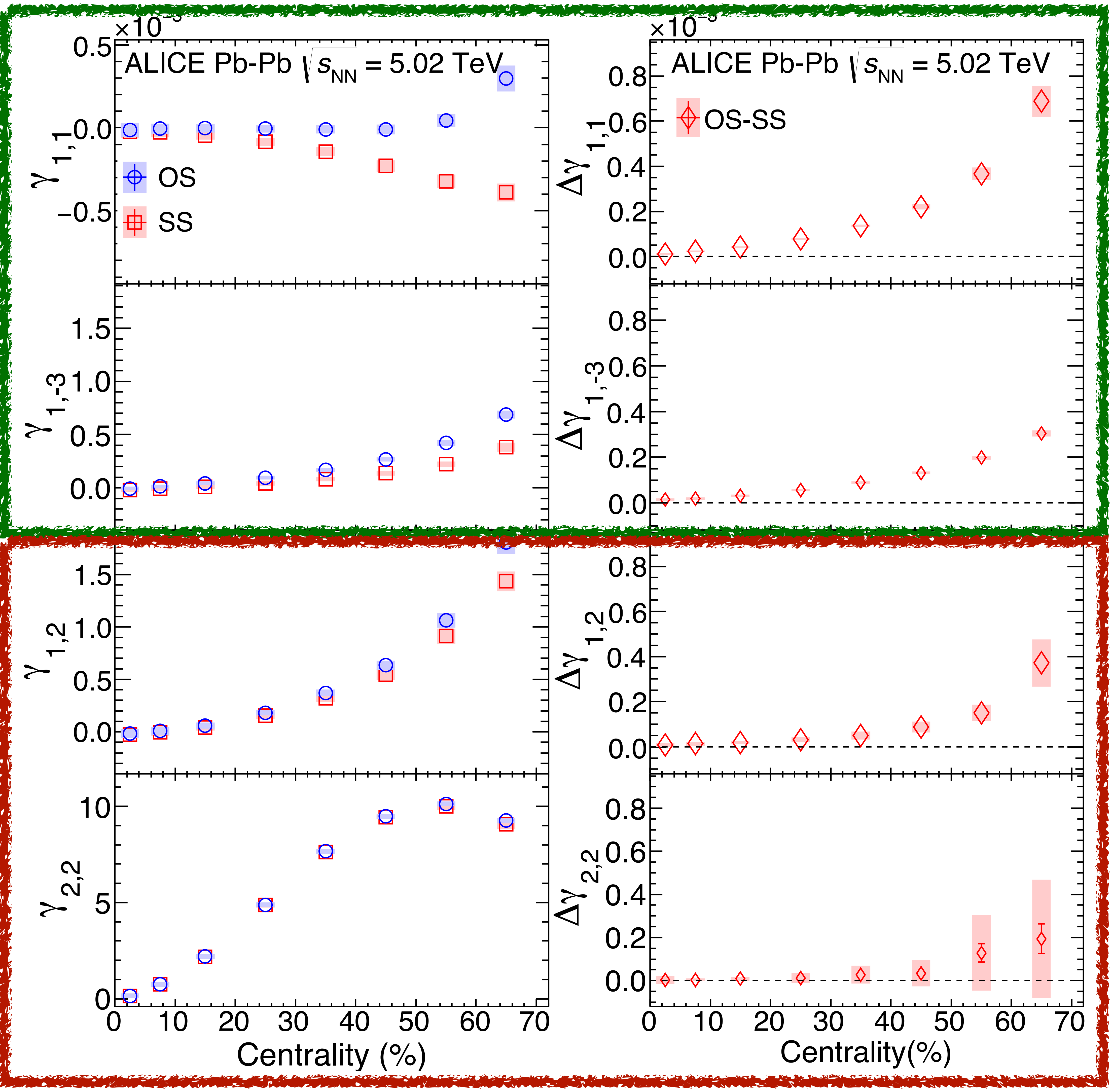
Significant charge dependent signal for the CME sensitive correlators

Correlations relative to Ψ_3 illustrate a significant charge dependence as well

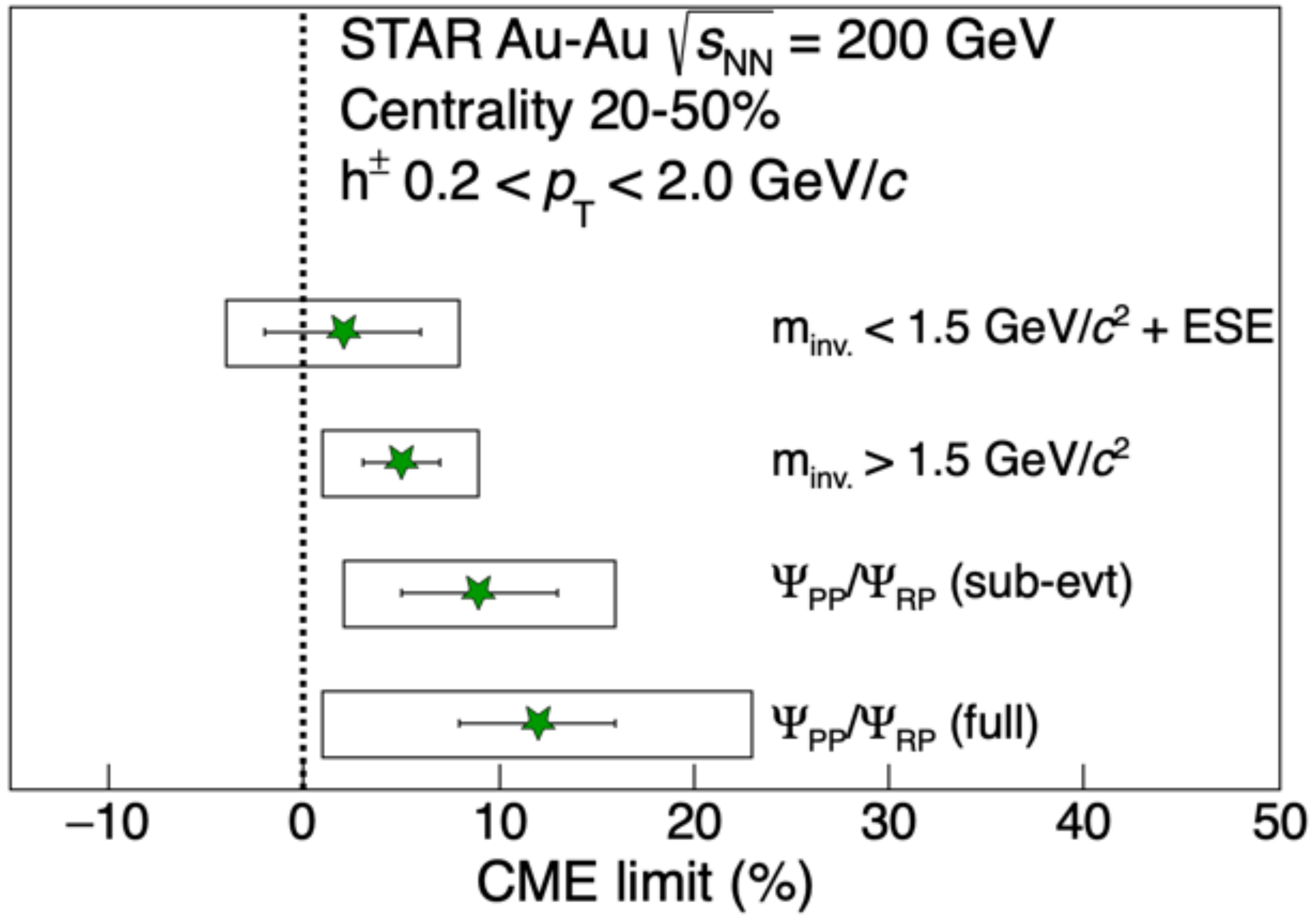
- Dominant contribution from background effects

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

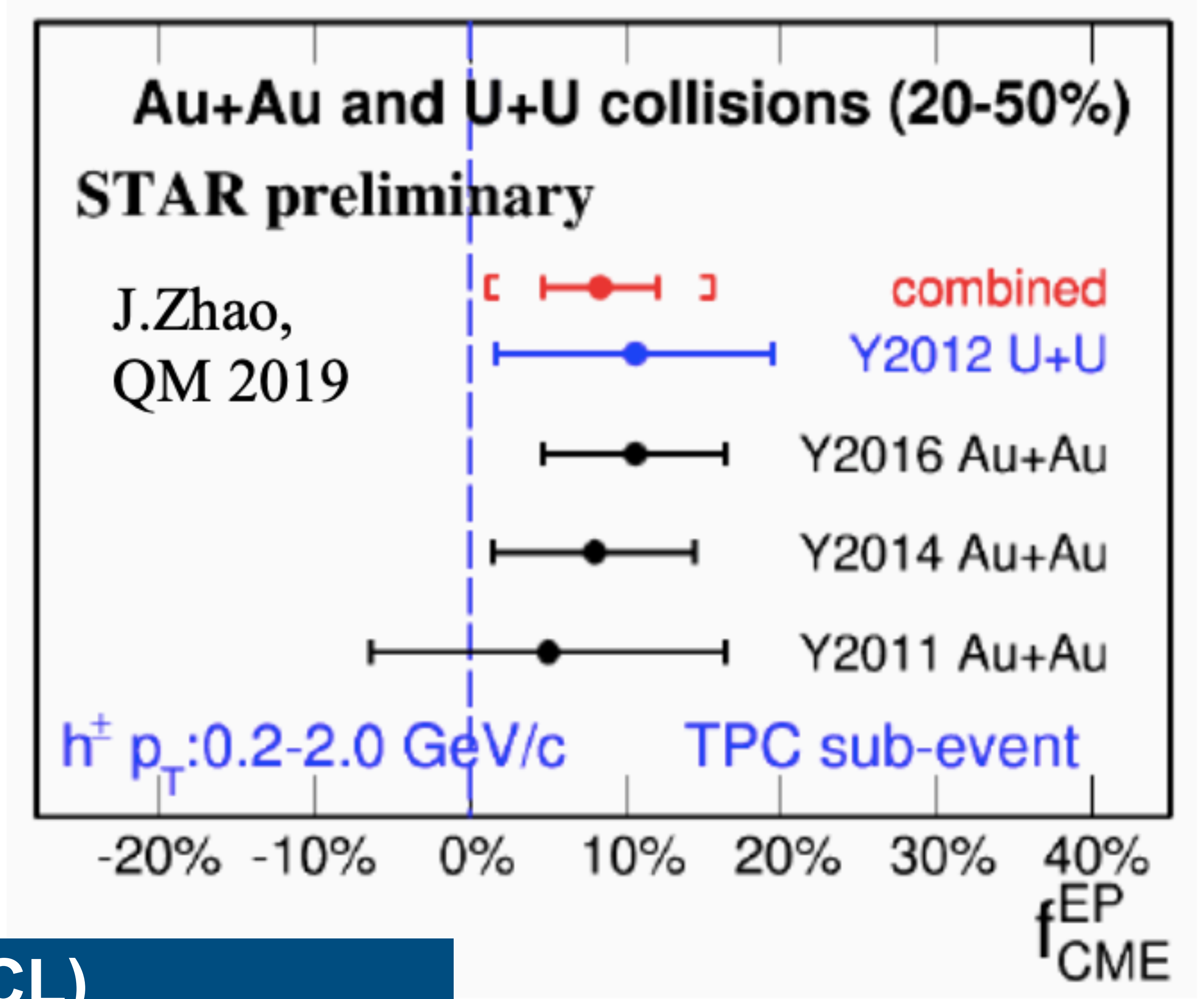
(ALICE Collaboration) JHEP 2020, (2020) 160



CME FRACTION UPPER LIMITS



- *Phys.Rev.C* 97 (2018) 4, 044912



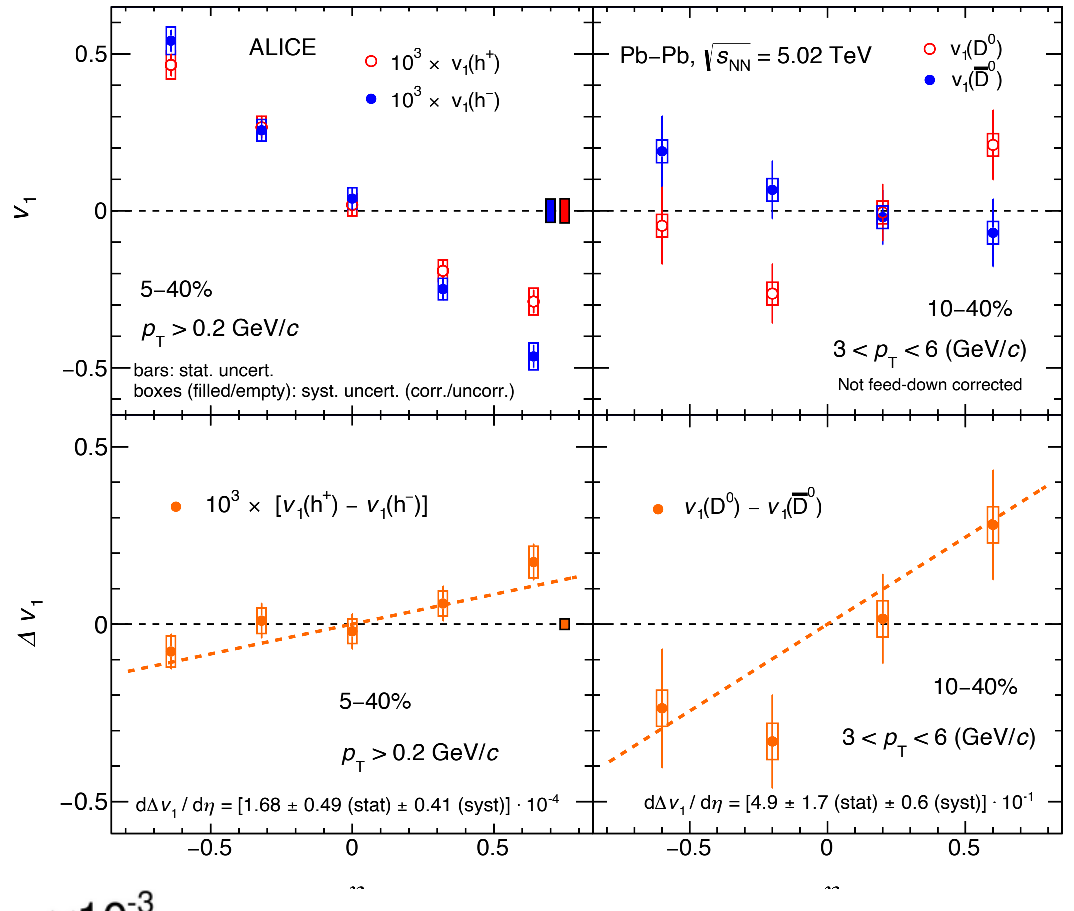
Summary of upper limits @ LHC (95% CL)		
ALICE	ESE in Pb-Pb collisions	26-33%
	Higher harmonics in Pb-Pb collisions	11-15%
CMS	p-Pb collisions	13%**
	ESE in Pb-Pb collisions	7%*

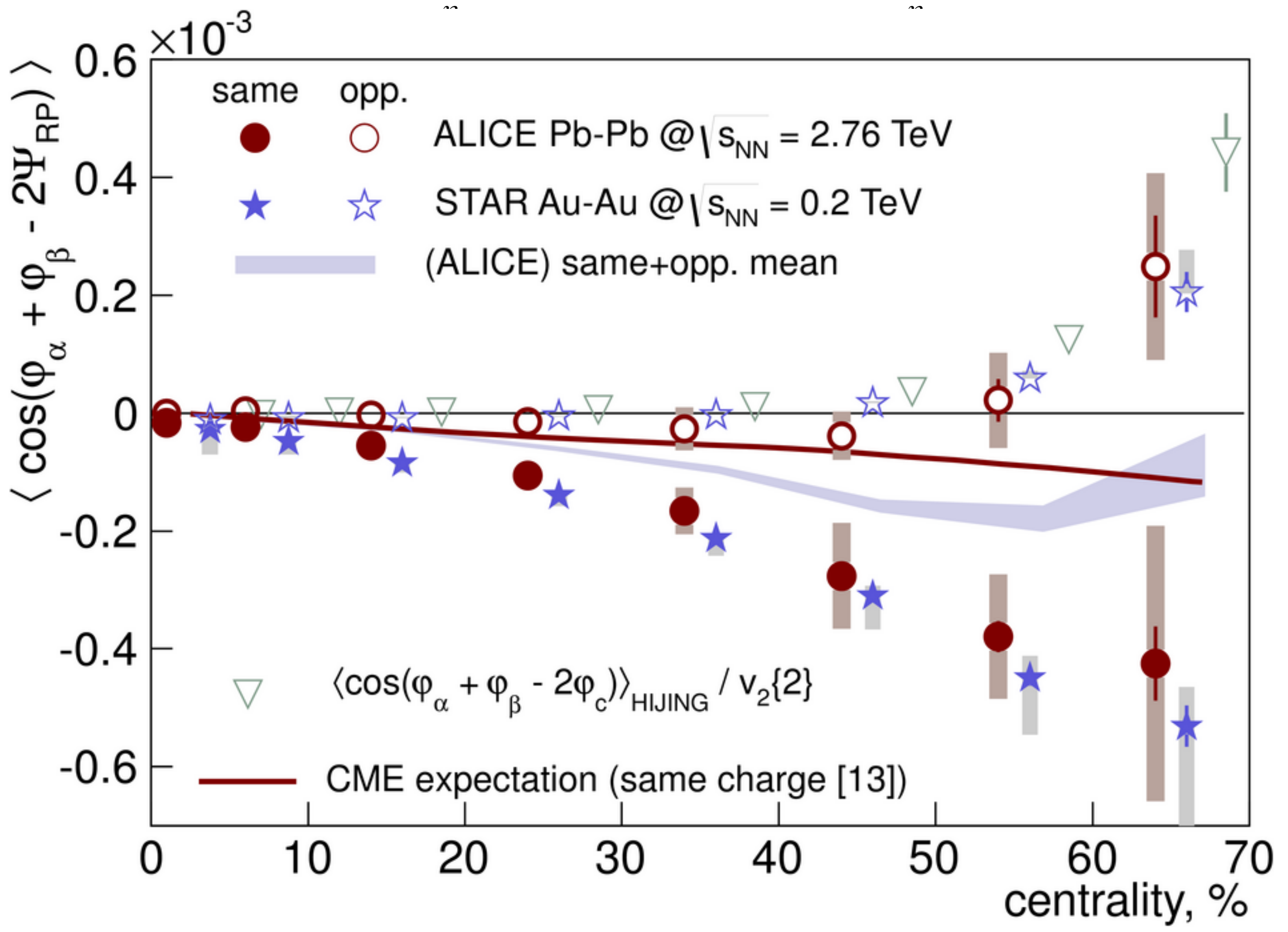
(ALICE Collaboration) Phys. Lett. **B777**, (2018) 151
(CMS Collaboration) Phys.Rev.C 97 (2018) 4, 044912
(ALICE Collaboration) JHEP 2020, (2020) 160

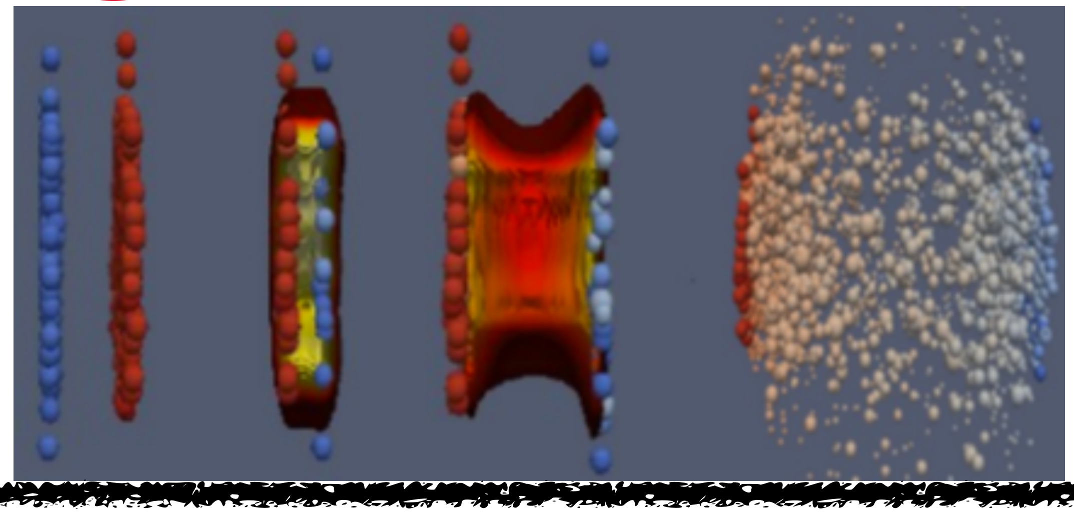
Current analyses provide stringent upper limits for the CME fraction at both RHIC and LHC energies → CME signal, if any, at the level of few %

AN ATTEMPT FOR A SUMMARY…

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

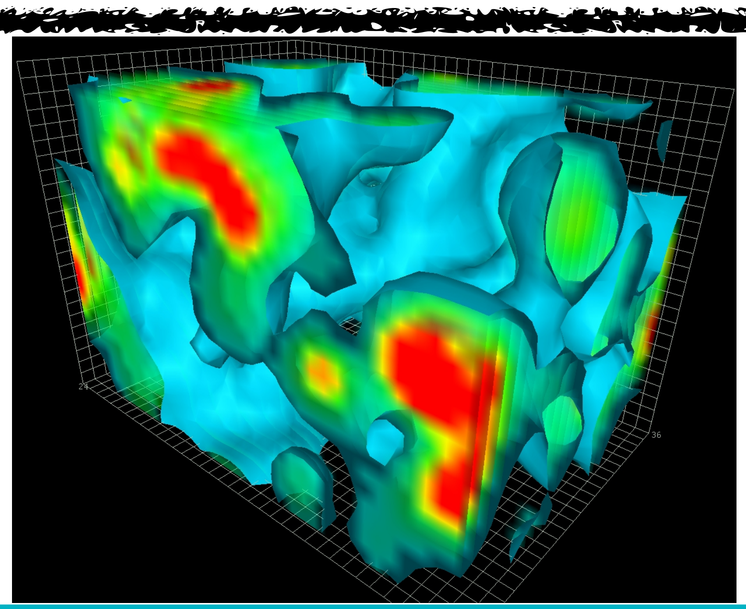




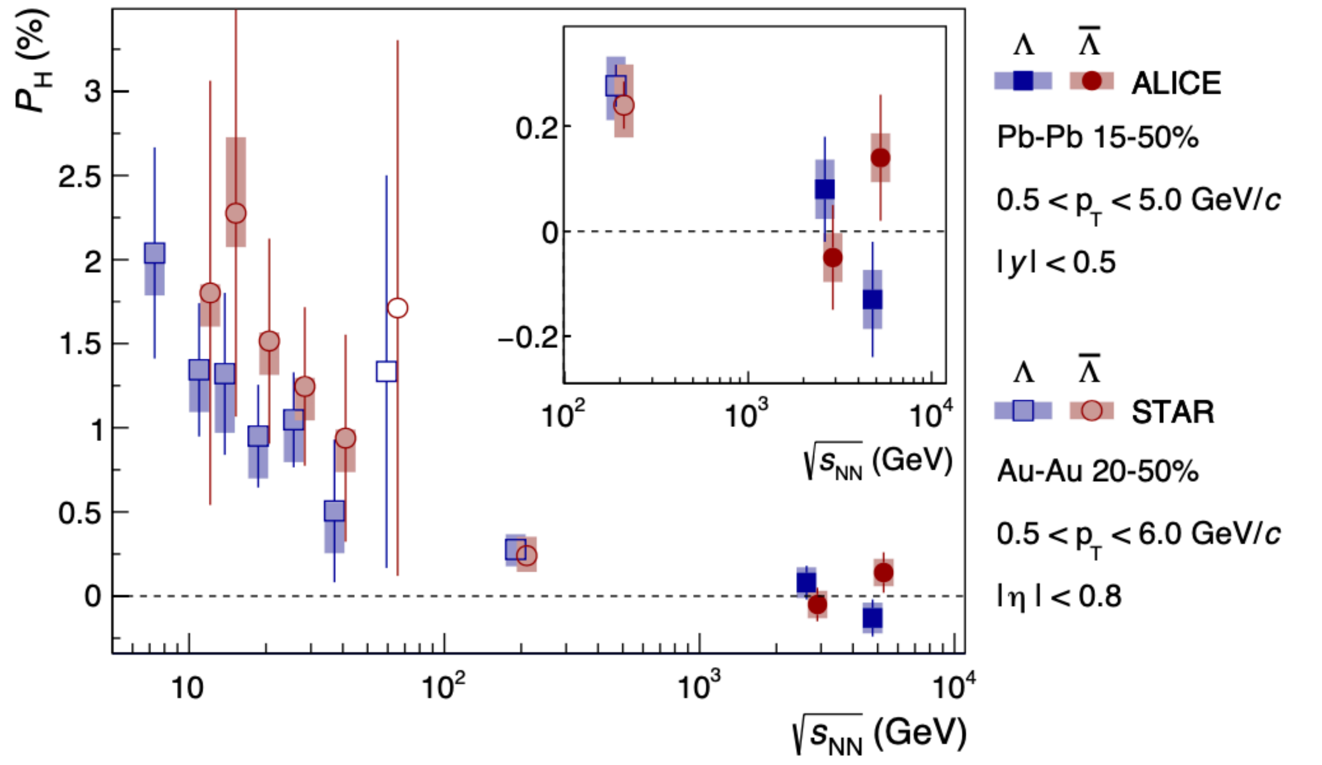


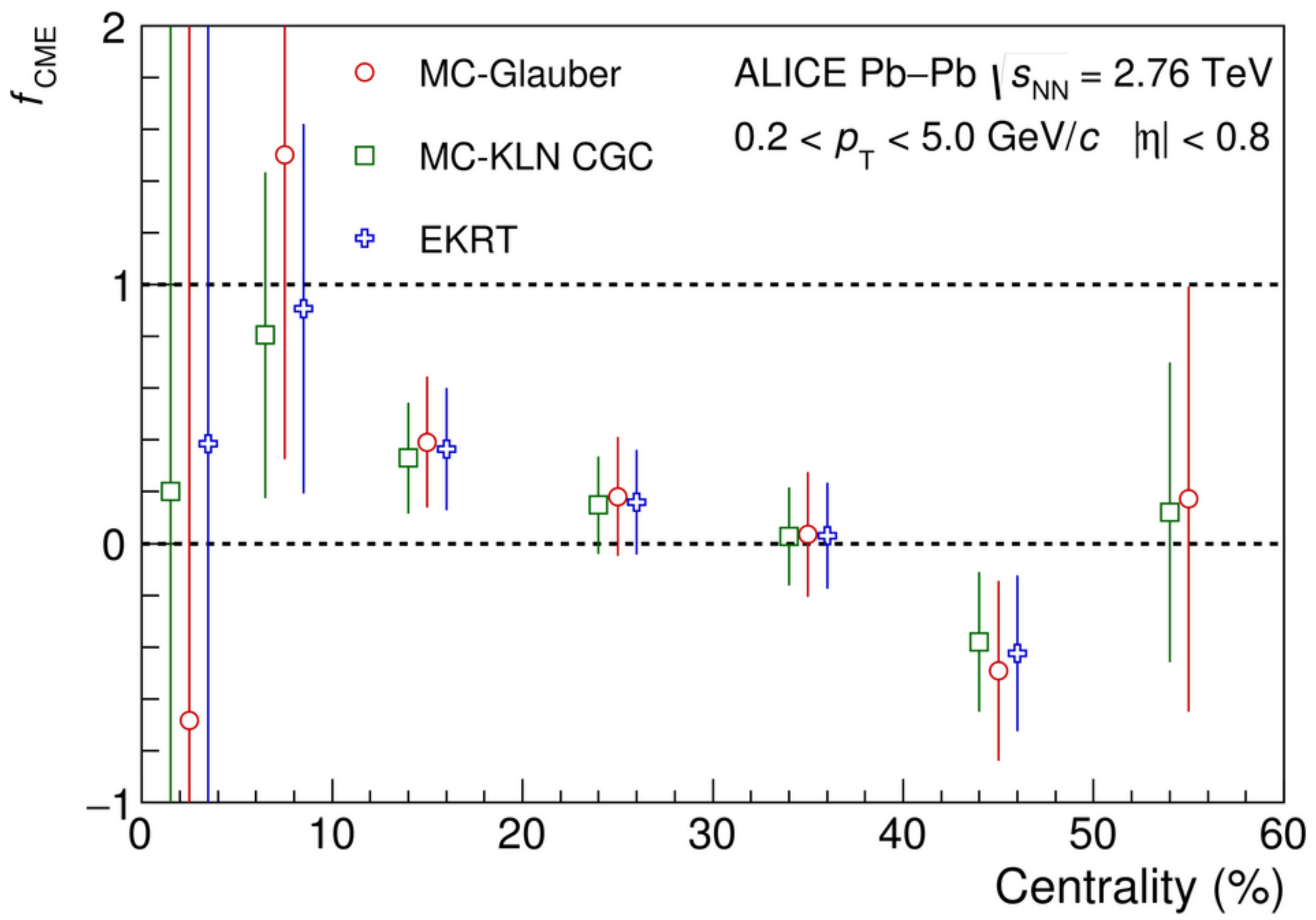
CME signal (if any) very elusive ➞ background effects are dominant

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

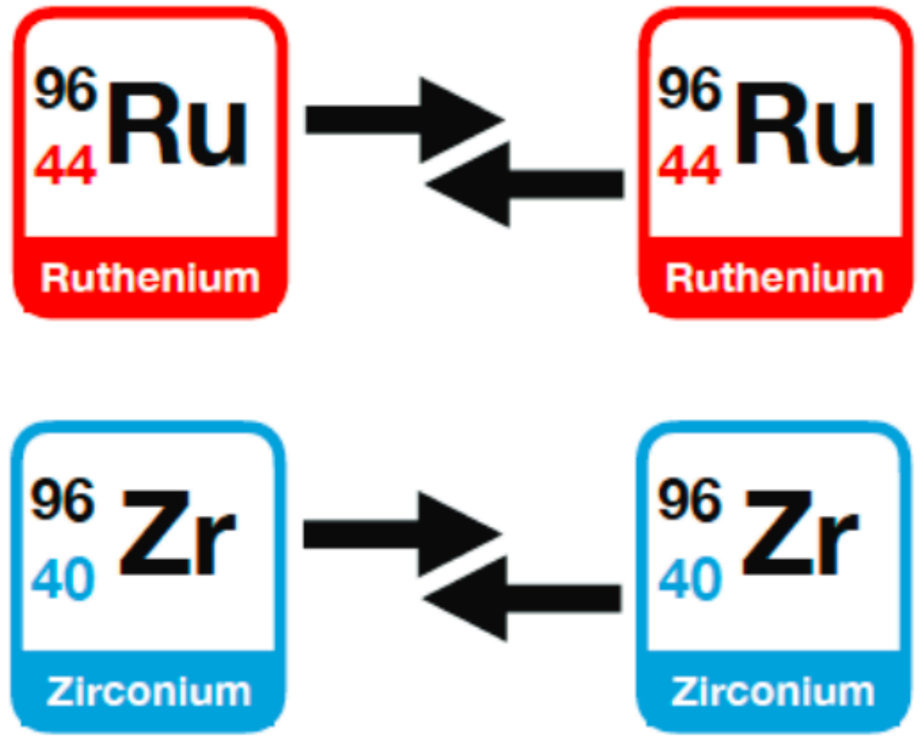


$P_H(\Lambda) \approx P_H(\text{anti-}\Lambda) \approx 0$ ➞ not sensitive to effects due to magnetic field

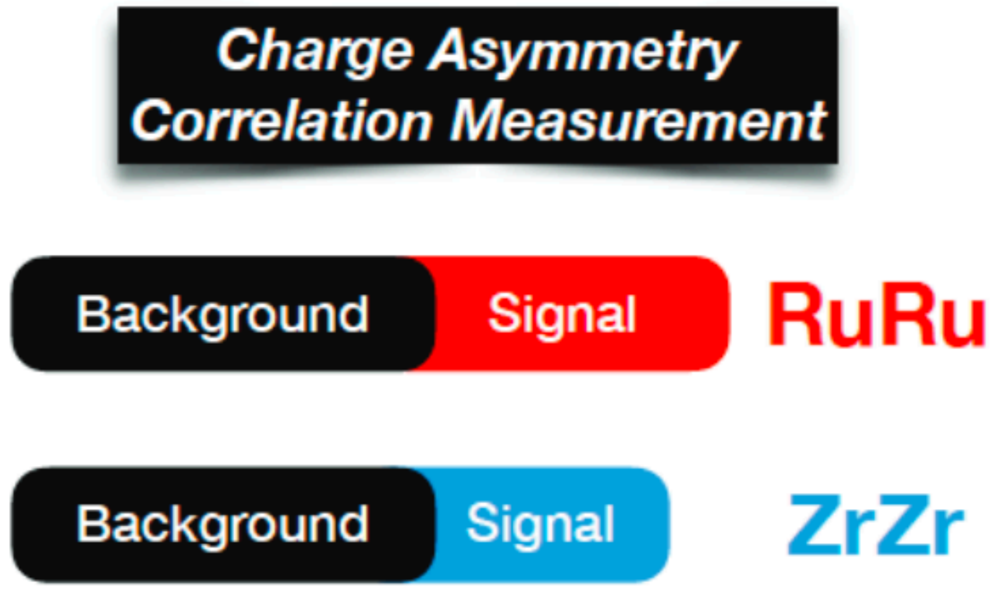




FUTURE PROSPECTS: ISOBAR ANALYSIS

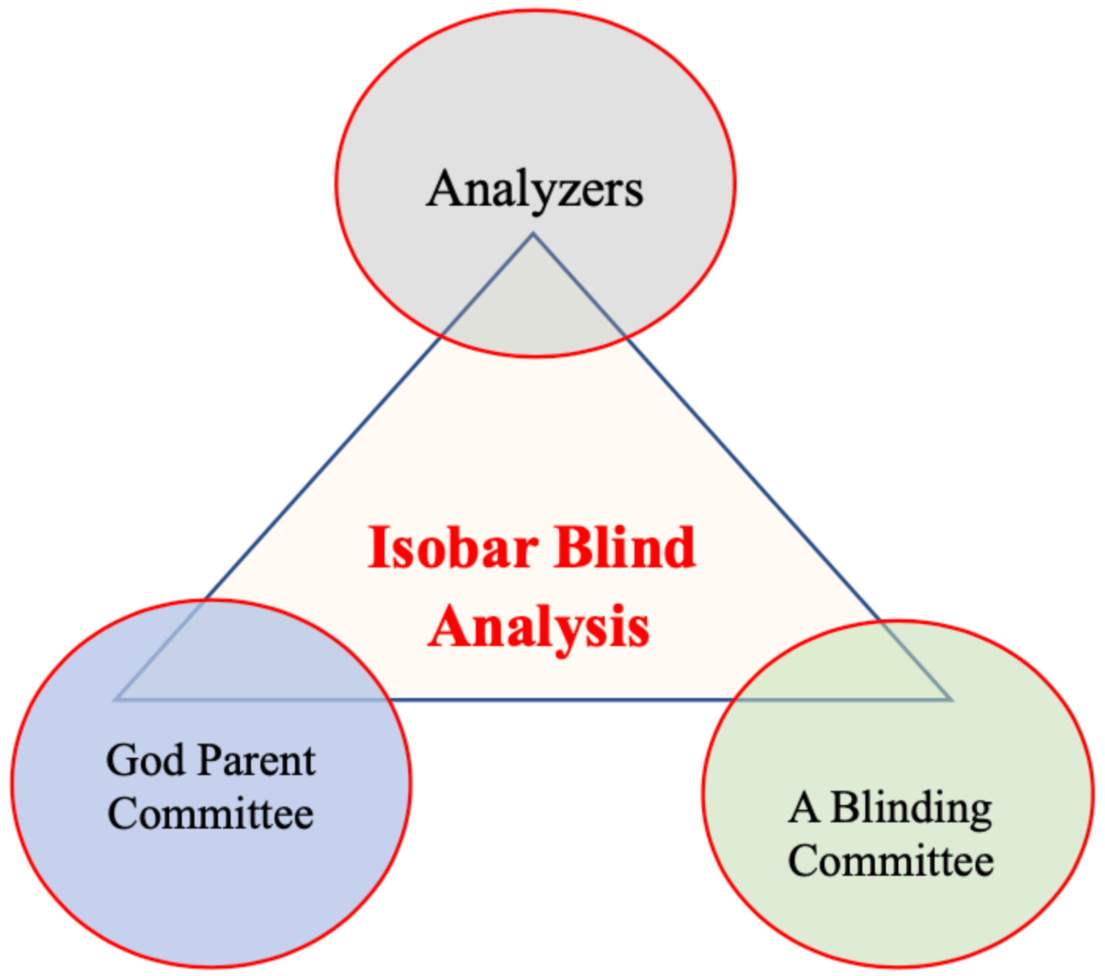


(a)



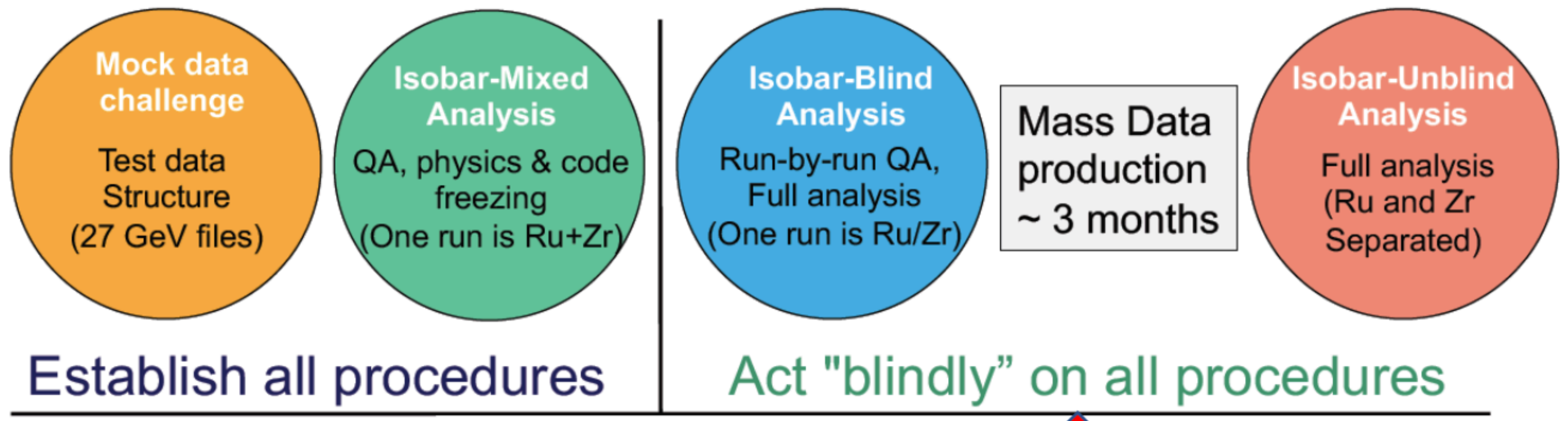
❖ Isobar Analysis:

A large, collective effort



P. Tribedy WWND 2020

A. Tang PAC meeting, Sept 2020



STAR, arXiv:1911.00596 (2019)

We are here

5-Isobar Blind Analyses

- $\Delta\gamma, \Delta\delta$ and κ
- $\Delta\gamma, \Delta\delta$ and $\Delta\gamma(\Delta\eta)$
- $\Delta\gamma$ in PP/SP and $\Delta\gamma(M_{inv})$
- $\Delta\gamma$ in PP/SP
- $R(\Delta S)$ Correlator.

1-Isobar Unblinded Analysis

- The signed balance function

Case for CME:

- $\Delta\gamma$ and its derivatives
  $\Delta\gamma/v_2$(Ru/Zr) > 1
  $\Delta\gamma_{112}/v_2$(Ru/Zr) $> \Delta\gamma_{123}/v_3$(Ru/Zr)
  κ(Ru/Zr) > 1
  $\Delta\gamma^{Ru} - a'r'\Delta\gamma^{Zr} > 0$
- $R(\Delta S)$ (Ru/Zr) show concave shape
- $f_{CME}^{Ru} > f_{CME}^{Zr} > 0$

Slide "stolen" from talk of Niseem Magdy Abdelrahman @ RHIC & AGS Annual User's meeting

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC and Wayne State

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Thank you for
your attention!

BACKUP