JACOPO MARGUTTI (NIKHEF & UU) FOR THE ALICE COLLABORATION
CERN-LHC SEMINAR (07-NOV-2017)

THE SEARCH FOR QCD SPHALERONS AND THE CHIRAL MAGNETIC EFFECT

IN HEAVY-ION COLLISIONS WITH ALICE

OUTLINE

- Introduction — *what are we talking about?*
- Chiral Magnetic Effect (CME) — *how do we measure it?*
- CME with Event-Shape Engineering — *constraining signal/background*
- Charge-dependent directed flow — *constraining the magnetic field*
- Outlook — *what's next?*

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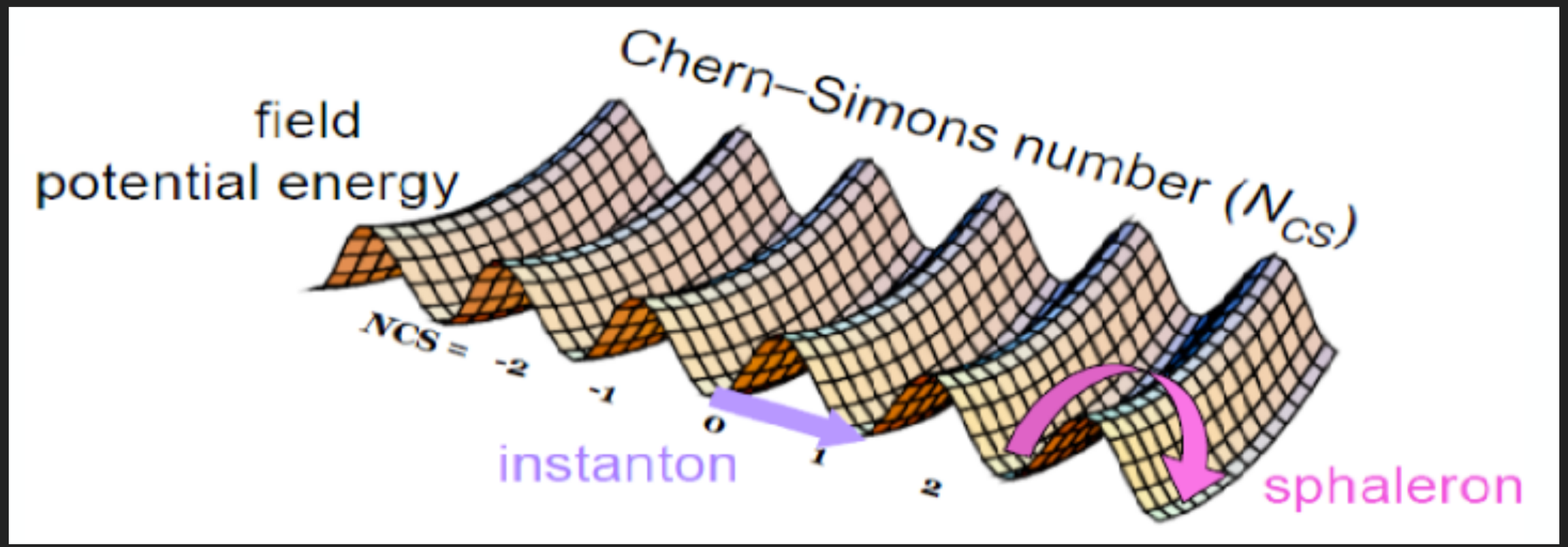
SPHALERONS AND INSTANTONS



- non-Abelian YM theory –> several vacua with different topology (N_{cs})
- transitions are allowed: <u>sphalerons</u> and instantons
  - strictly non-perturbative phenomenon
  - predicted by SM, not yet observed
  - associated to quantum anomalies
    –> non-conservation of quantum numbers

G. 't Hooft, PRL 37, 8 (1976)
A.A Belavin *et al.*, Phys. Lett. 59B:85 (1975)
V. A. Kuzmin *et al.*, Phys. Lett. 155B:36 (1985)
L. McLerran *et al.*, PRD 42, 171 (1990)
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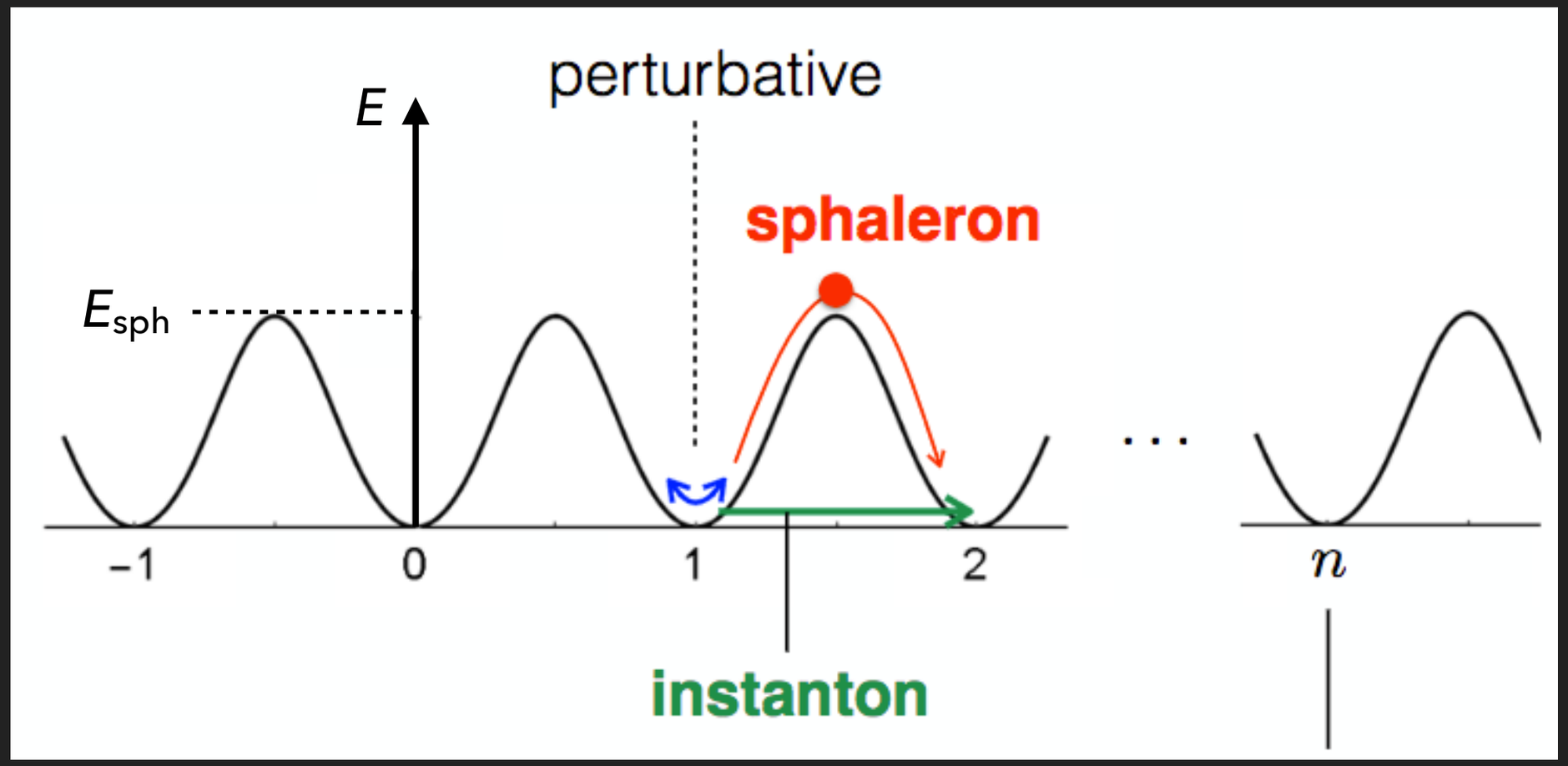

for a given energy barrier $E_{sph} \sim 1/\alpha$

- $E < E_{sph}$: instantons (tunneling) $\sigma \propto \exp(-2\pi E_{\rm sph})$
- $E > E_{sph}$: sphalerons (thermal) $\sigma \propto \exp(-E_{\rm sph}/kT)$

QCD VS EW

theory	SU(3) QCD	SU(2) EW
non-conserved quantum number	Chirality	B+L
E_{sph}	Λ_{QCD} - ?	~10 TeV

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hard to estimate, <u>potentially accessible</u>

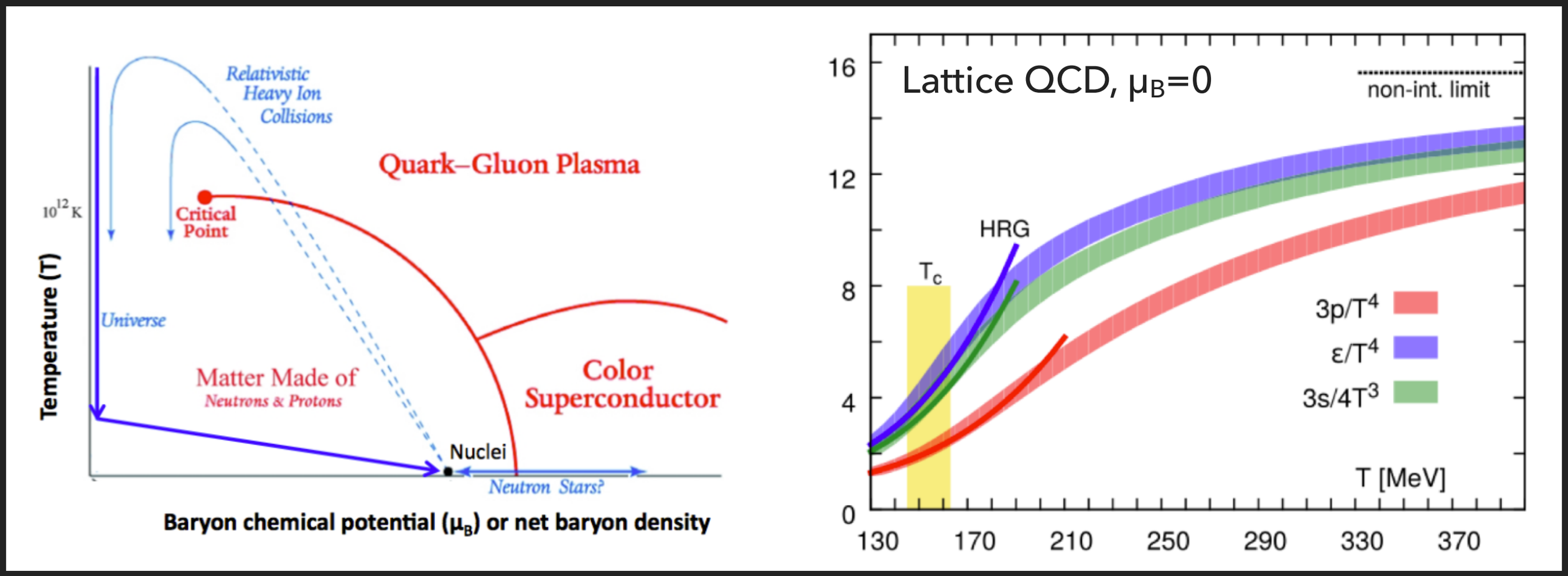
estimates exist, hard to access

↓

heavy-ion collisions: QCD system with $kT > \Lambda_{QCD}$

HEAVY-ION PHYSICS

Heavy-Ion Physics: exploring QCD at high temperatures and/or densities

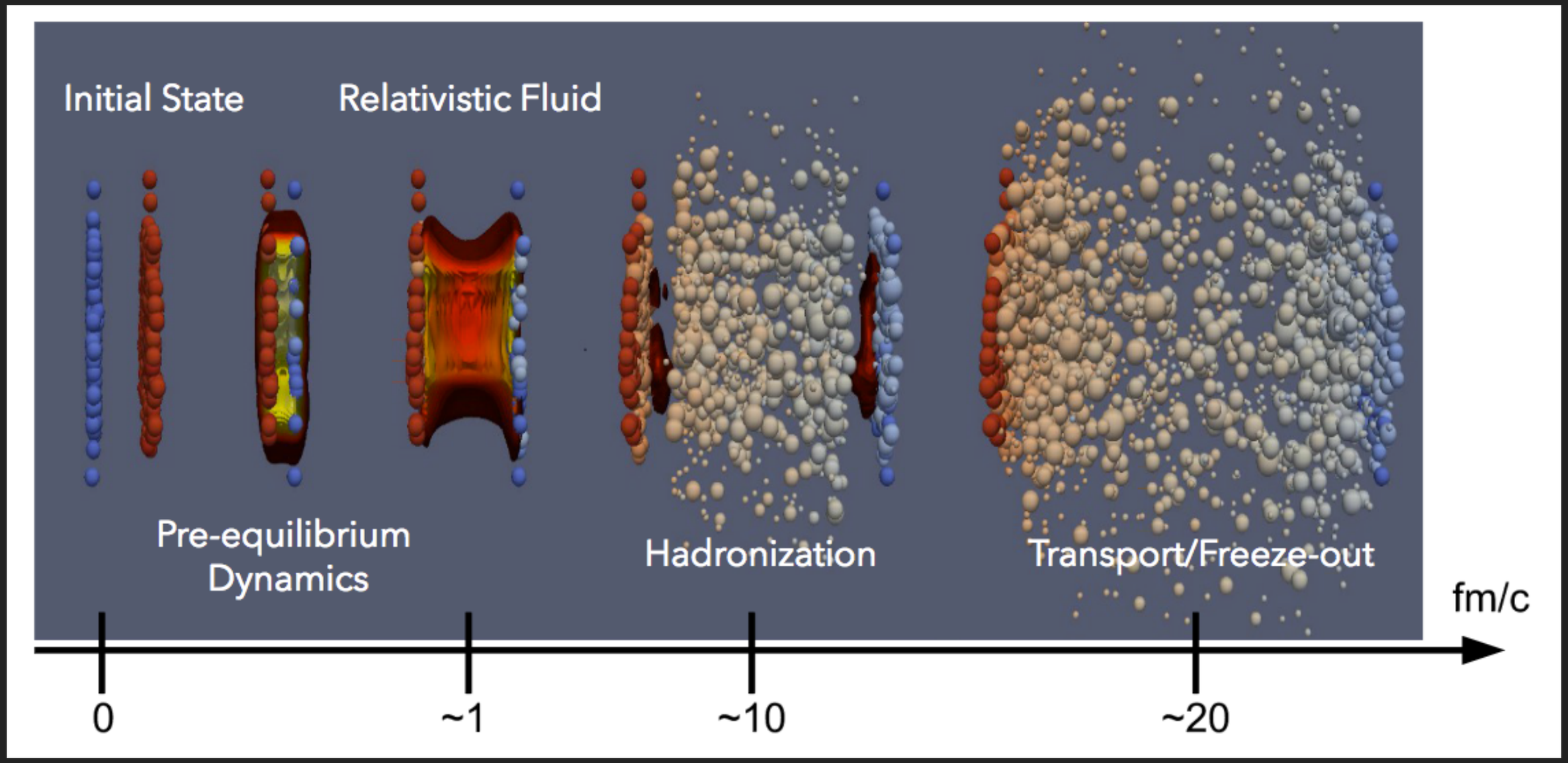


arXiv:1510.04200

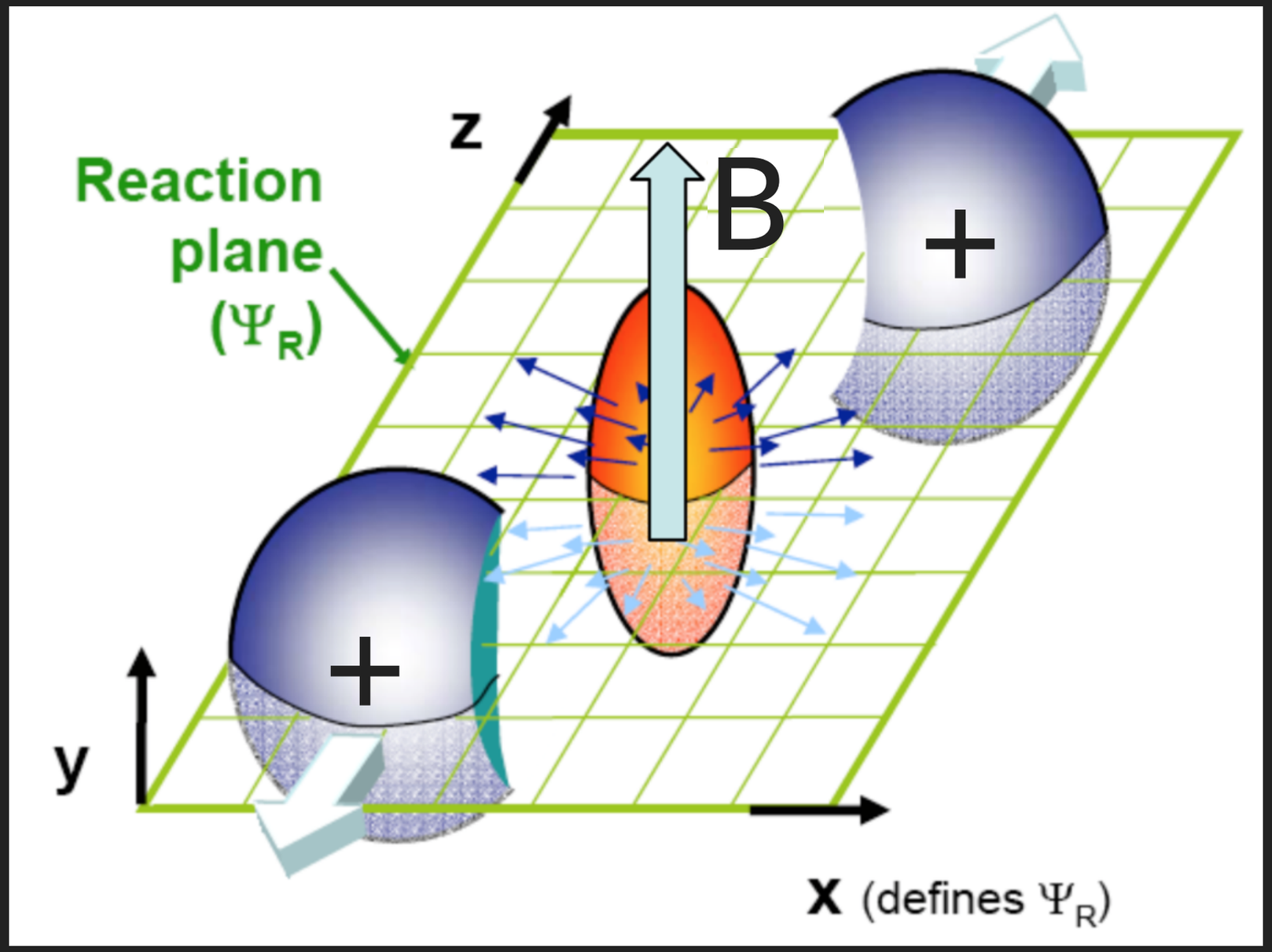
Quark-Gluon Plasma: T>150 MeV, ε>0.2 GeV/fm^3

HEAVY-ION COLLISIONS

Different stages in a Heavy-Ion collision



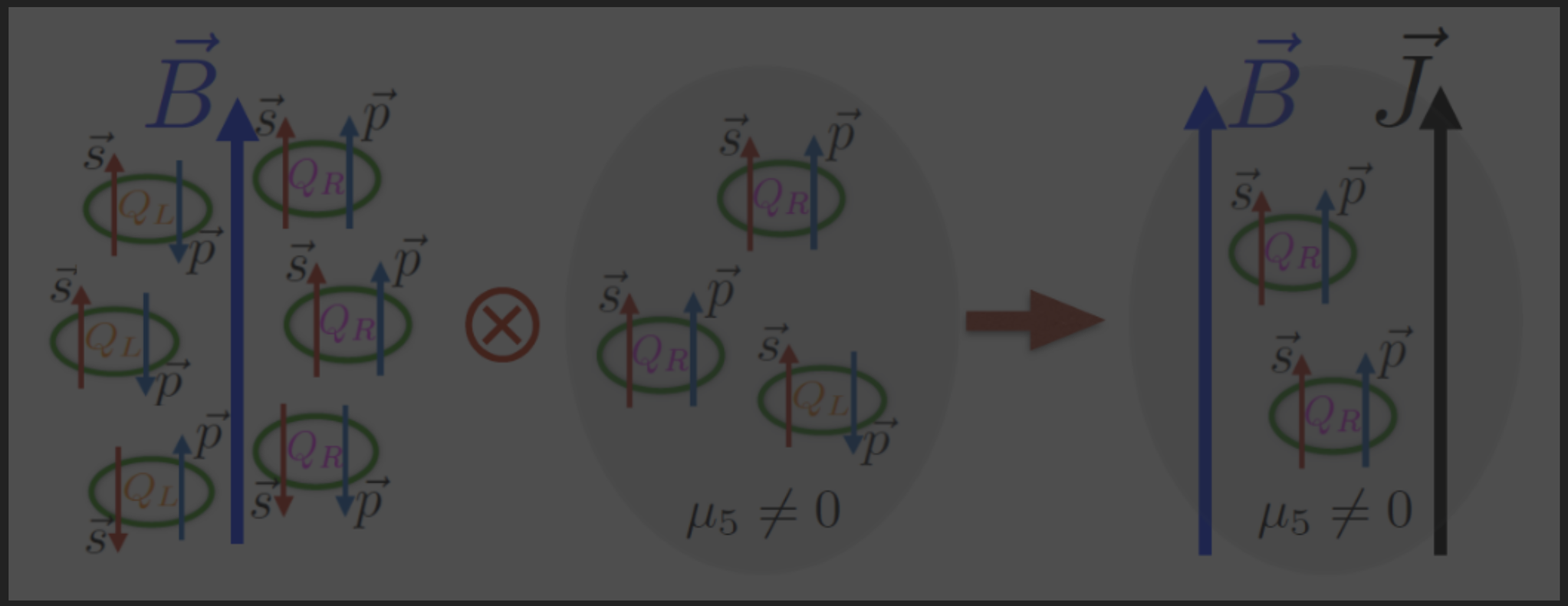
MAGNETIC FIELD



fast-moving non-colliding protons → strong (~10^{15} T) magnetic field

CHIRAL MAGNETIC EFFECT

QCD sphalerons → chiral imbalance: $\mu_5 = n_{\mathrm{L}} - n_{\mathrm{R}} \neq 0$



strong magnetic field + chiral imbalance → charge separation along B

D. Kharzeev, PLB 633, 260 (2006)
D. Kharzeev et al, NPA 797, 67 (2007)
D. Kharzeev et al, NPA 803, 227 (2008)
K. Fukushima et al, PRD 78, 074033 (2008)

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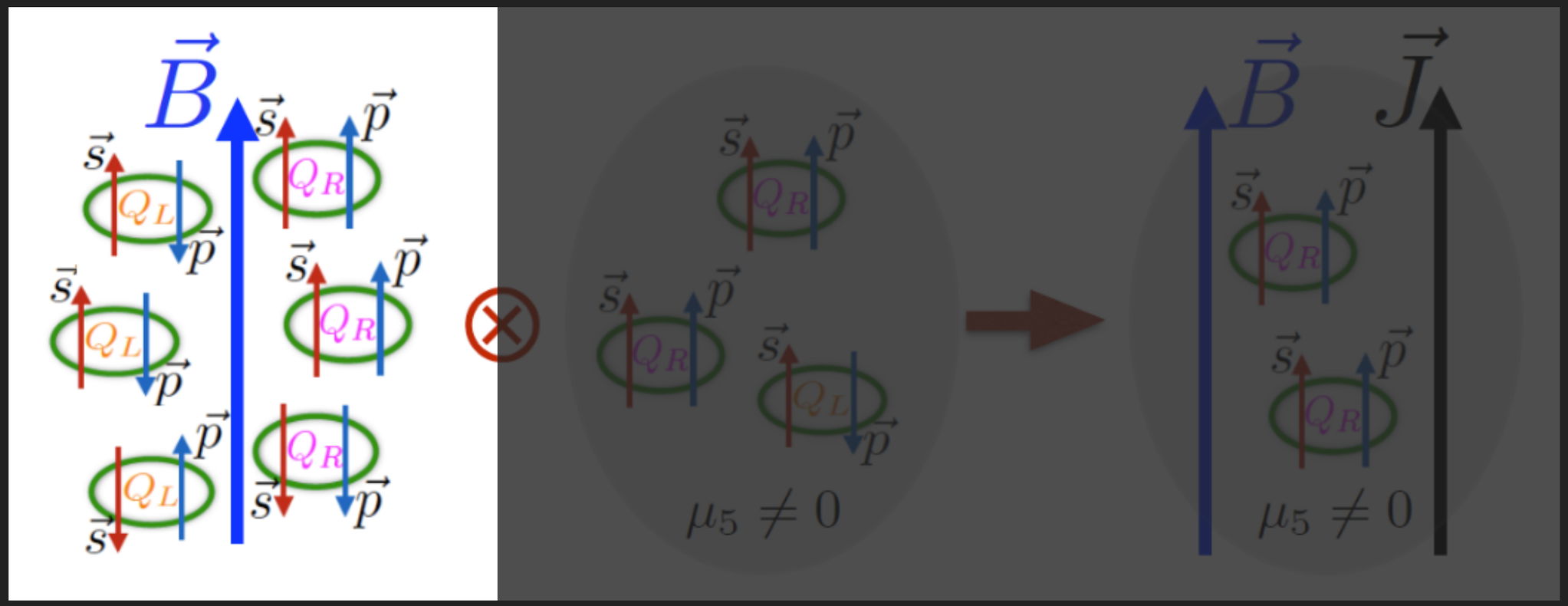

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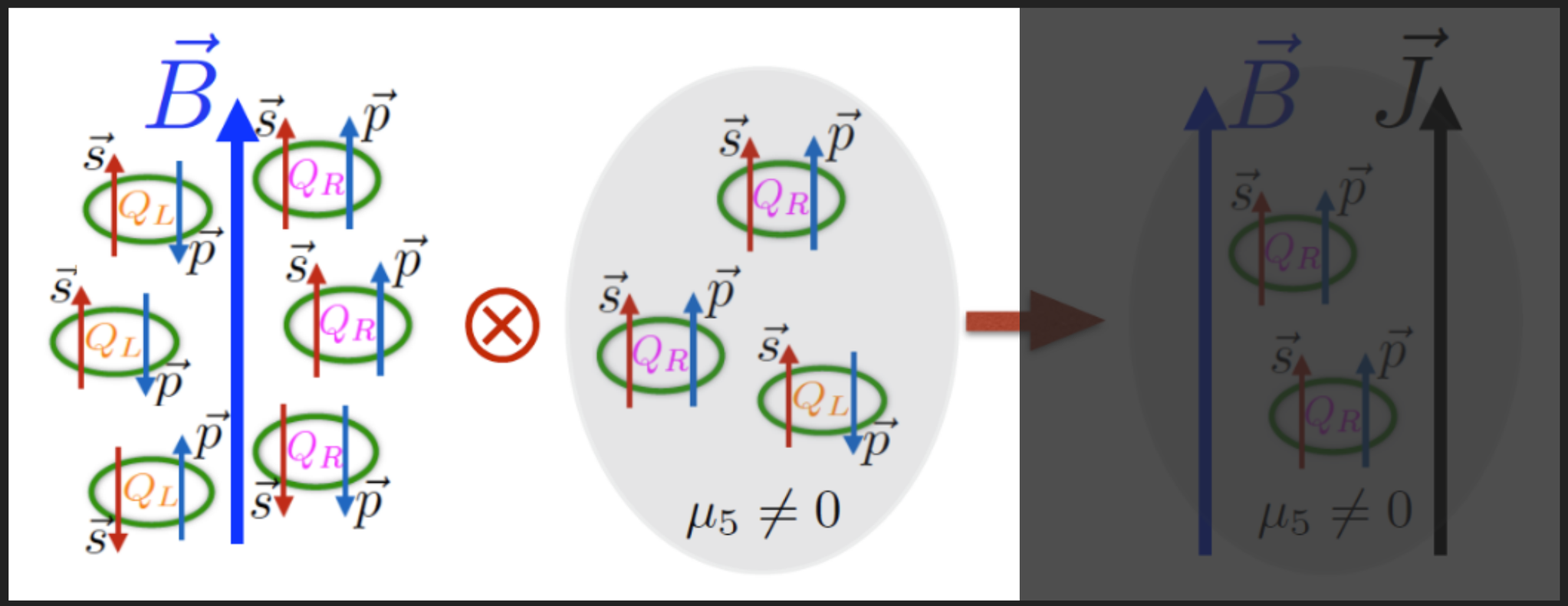

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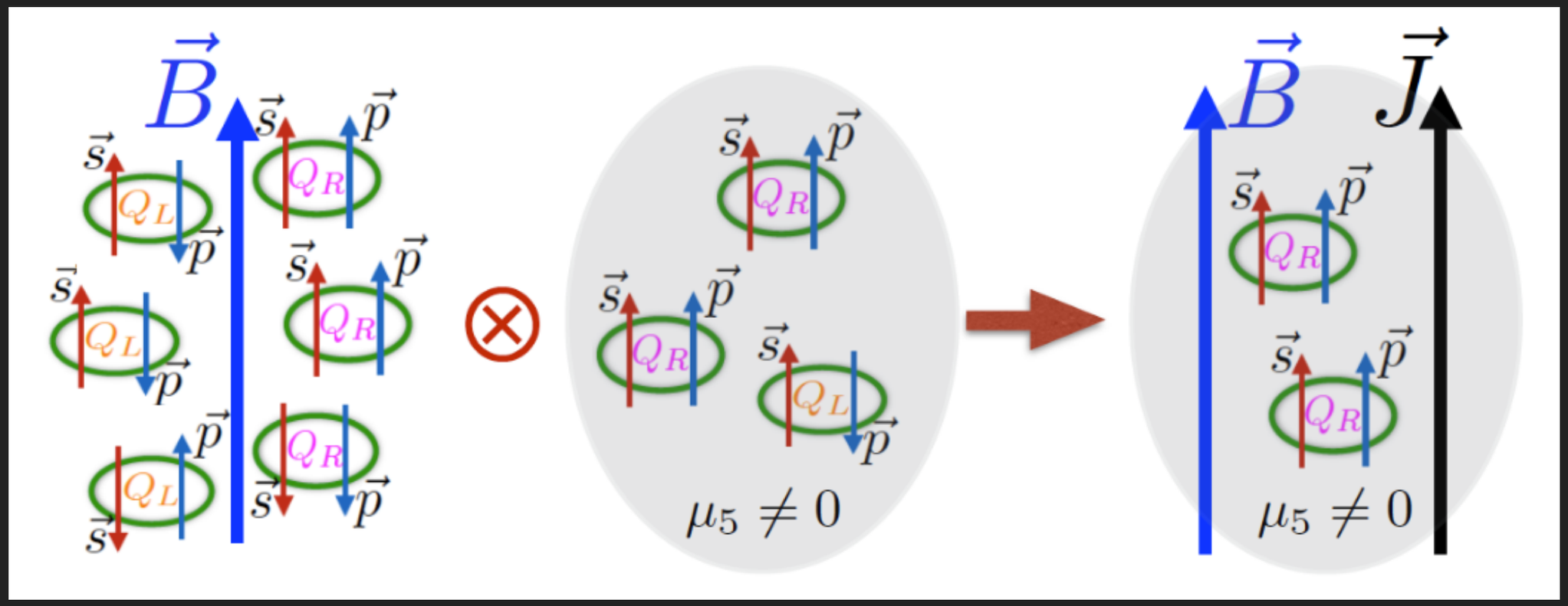

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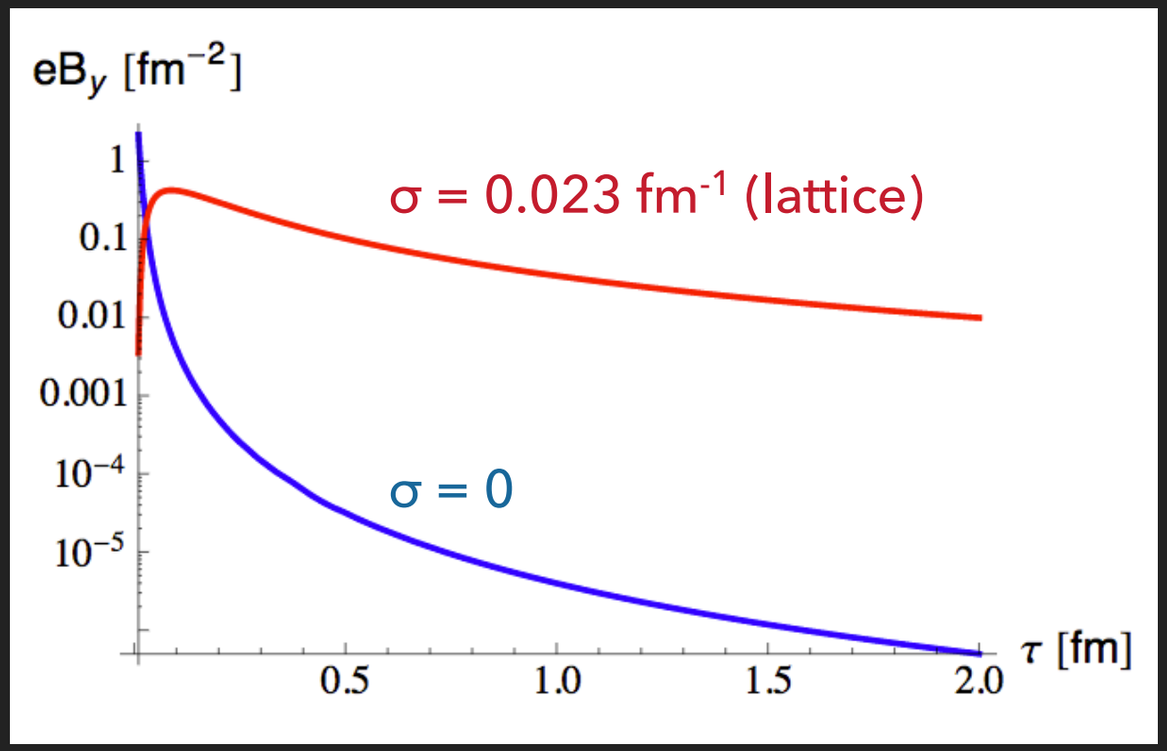
UNKNOWNS

- Evolution of the magnetic field
  How long does it last?
  What is the conductivity of the system?
- Competing sources of chiral imbalance
  Local axial currents (e.g. due to CSE)?
- Pre-equilibrium dynamics
  Sphalerons in vacuum, Glasma or QGP?
- Collective dynamics and hadronization
  Electric charge conservation (local in phase-space)?
  Effects of the anisotropic expansion of the medium?



U. Gursoy *et al.*, PRC 89, 054905 (2014)

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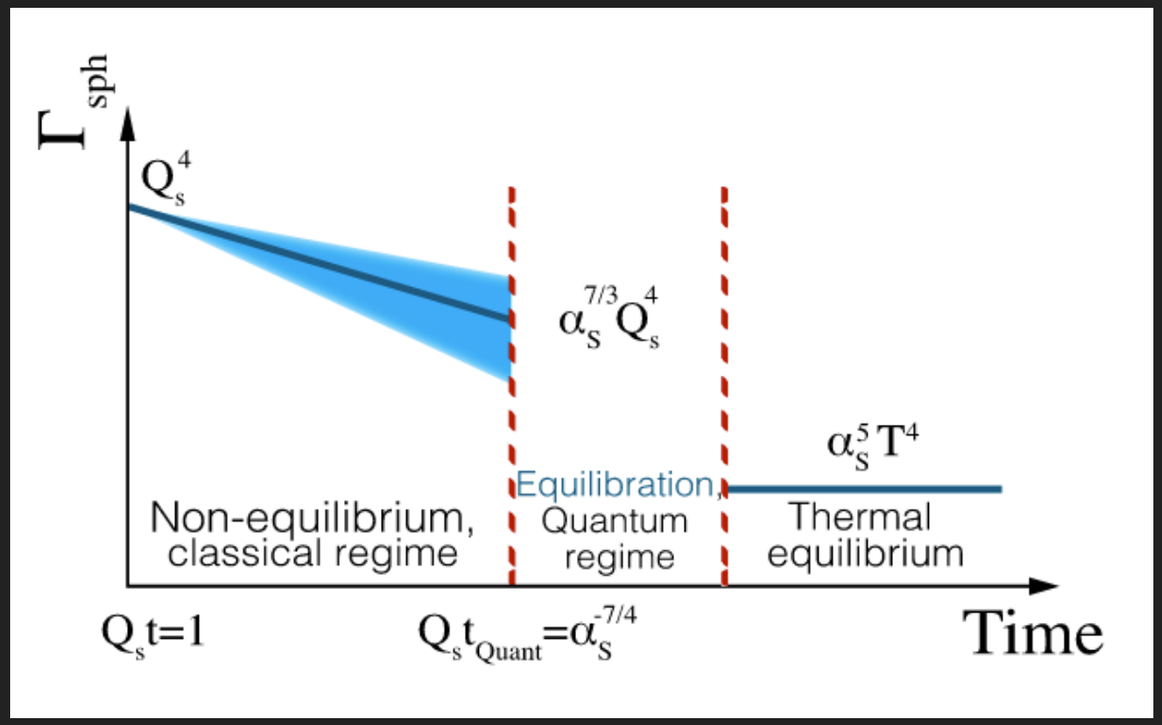

M. Mace *et al.*, PRD 93, 074036 (2016)

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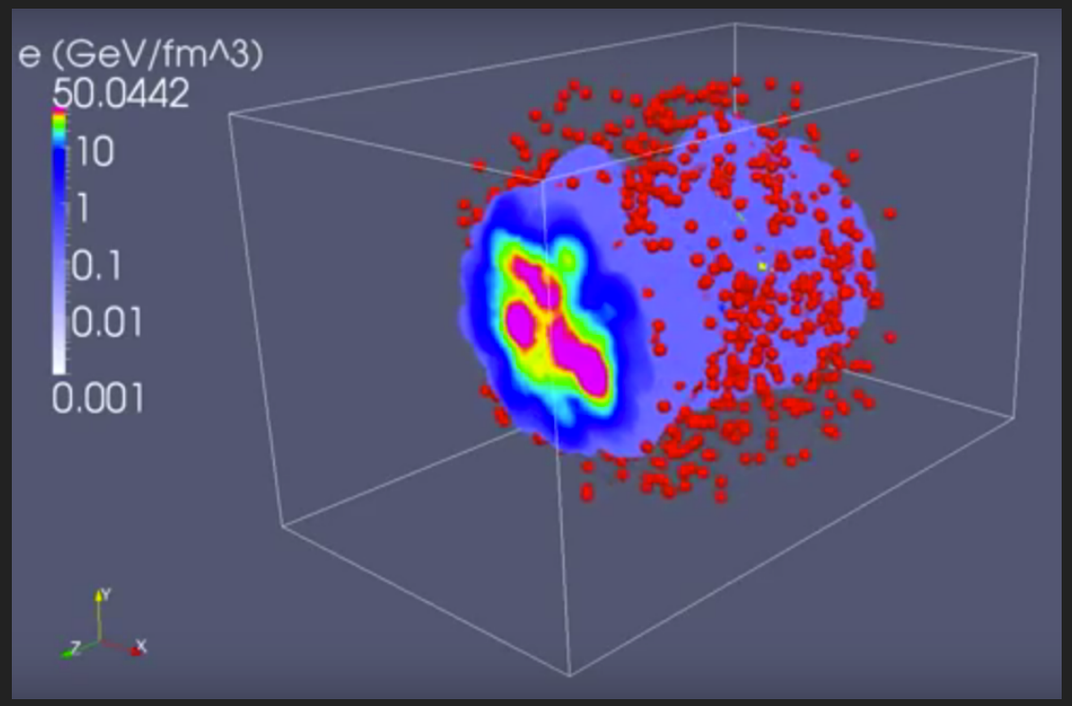
QGP, hadrons



C. Shen, iEBE-VISHNU

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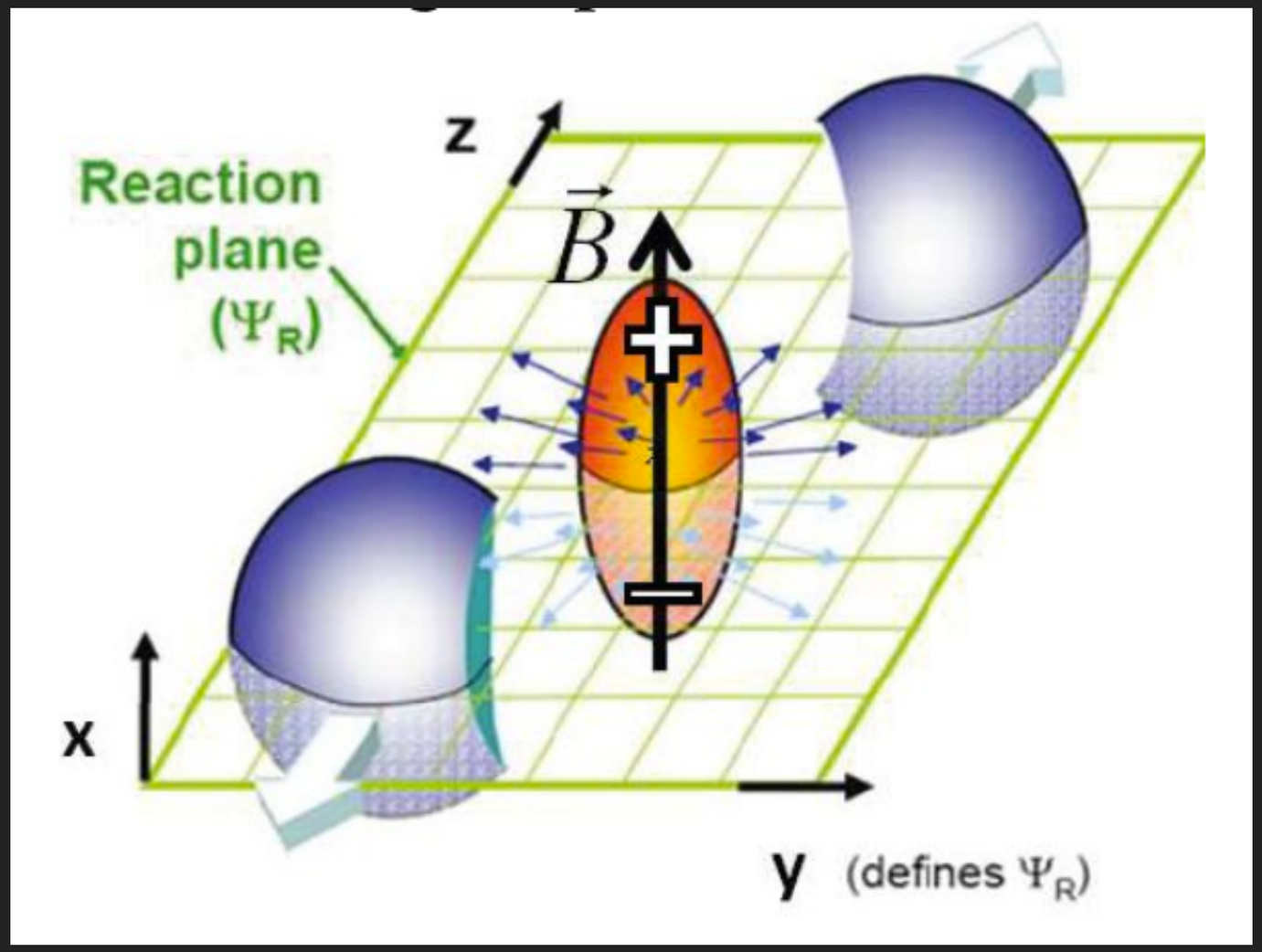

the experimental observable: charge separation across the reaction plane

OBSERVABLES

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

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

It can be measured with charge-dependent 2- and 3-particle correlators:

$$\delta_{+,-} = \langle \cos(\phi_+ - \phi_-) \rangle \qquad \sim \langle a_+ a_- \rangle$$

$$\gamma_{+,-} = \langle \cos(\phi_+ + \phi_- - \Psi_{\mathrm{RP}}) \rangle \sim -\langle a_+ a_- \rangle$$

S. Voloshin, PRC 70 (2004) 057901

the sign of $a_\pm$ changes event-by-event, but is always opposite for opposite charges

- $\gamma_{a,b} < 0$ for same charges (±,±) and $\gamma_{a,b} > 0$ for opposite charges (±,∓)
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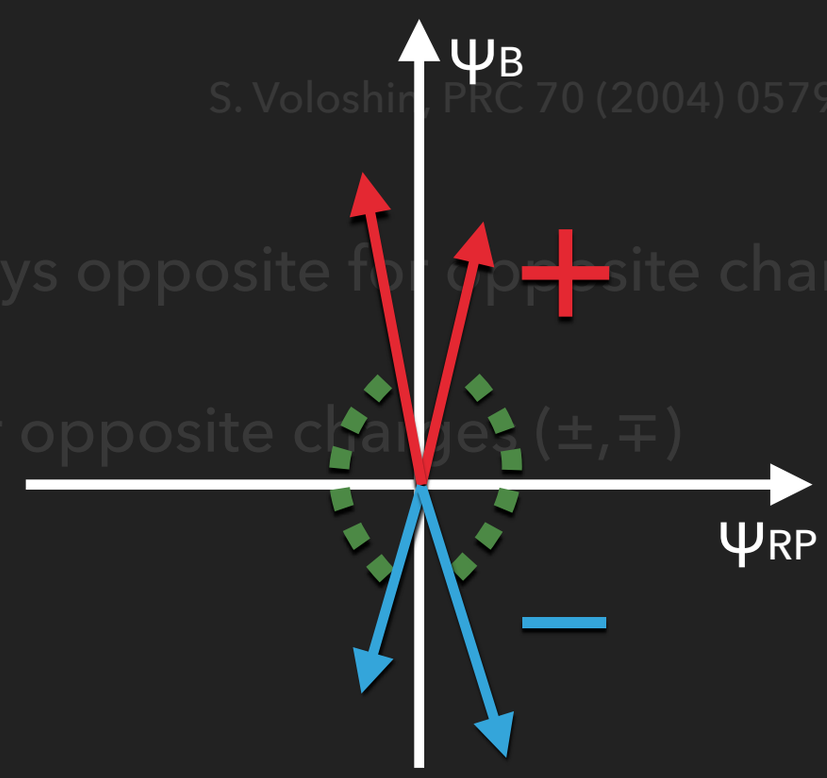

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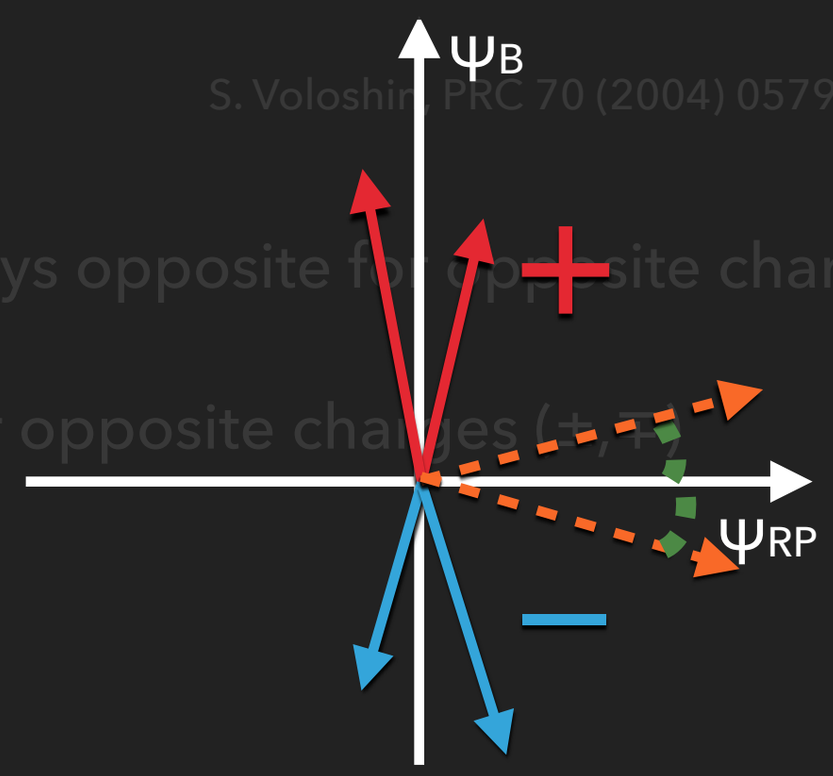

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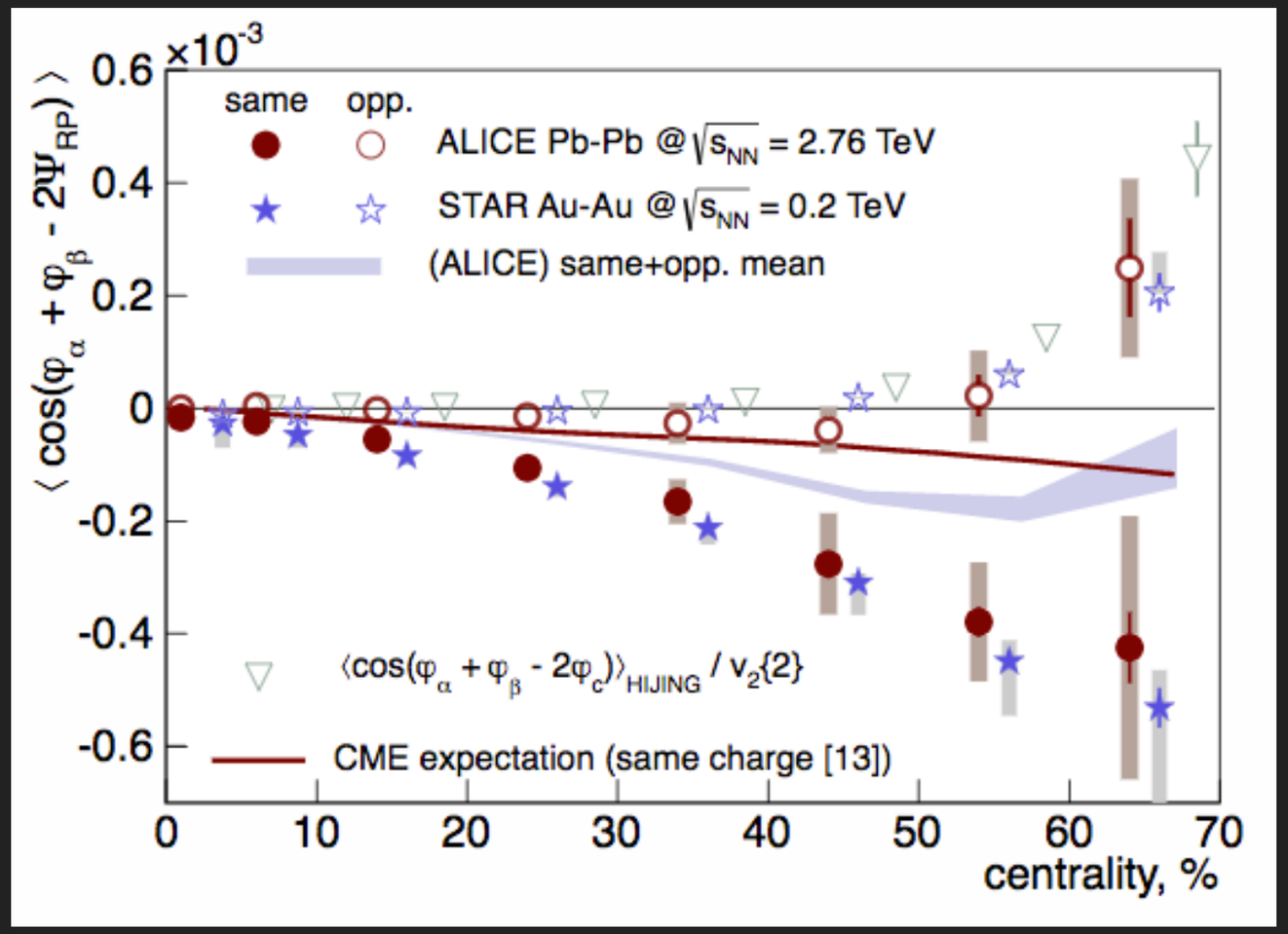
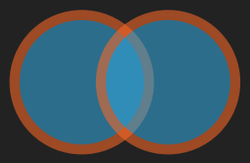
CME CORRELATORS

- significant difference in $\gamma_{a,b}$ same vs opp.
- sign of the difference correct, but the average is not 0

  → background largely present!



ALICE, PRL 110 (2013) 012301



BACKGROUND

Main sources:

- transverse momentum conservation (TMC)
- flow fluctuations
- local charge conservation (LCC)

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charge-independent: cancel in opp.- vs same-charge difference:

$$\Delta\delta_{a,b} \equiv \frac{1}{2}(\delta_{\pm,\mp} - \delta_{\pm,\pm})$$

$$\Delta\gamma_{a,b} \equiv \frac{1}{2}(\gamma_{\pm,\mp} - \gamma_{\pm,\pm})$$

BACKGROUND

Main sources:

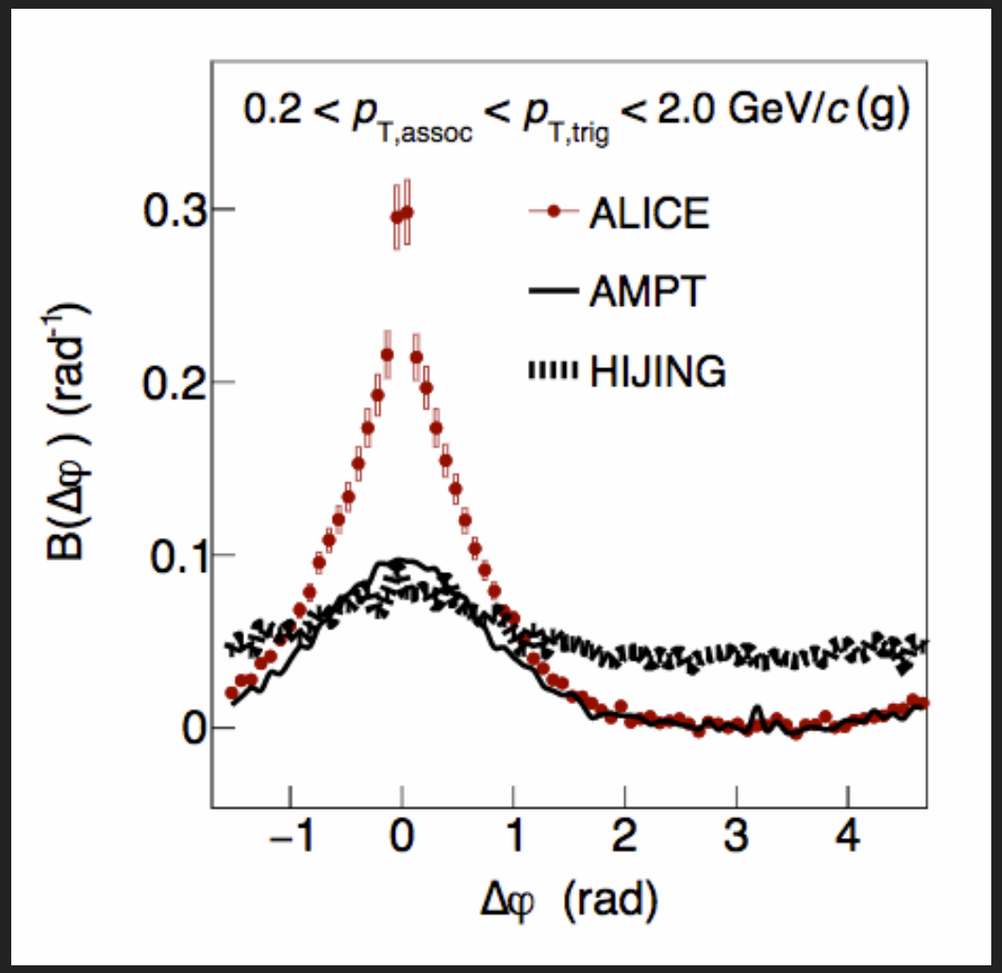
- transverse momentum conservation (TMC)
- flow fluctuations
- local charge conservation (LCC)

To be understood!
Not correctly reproduced by existing MC
(Pythia, AMPT, HIJING…)

e.g. Balance Functions:

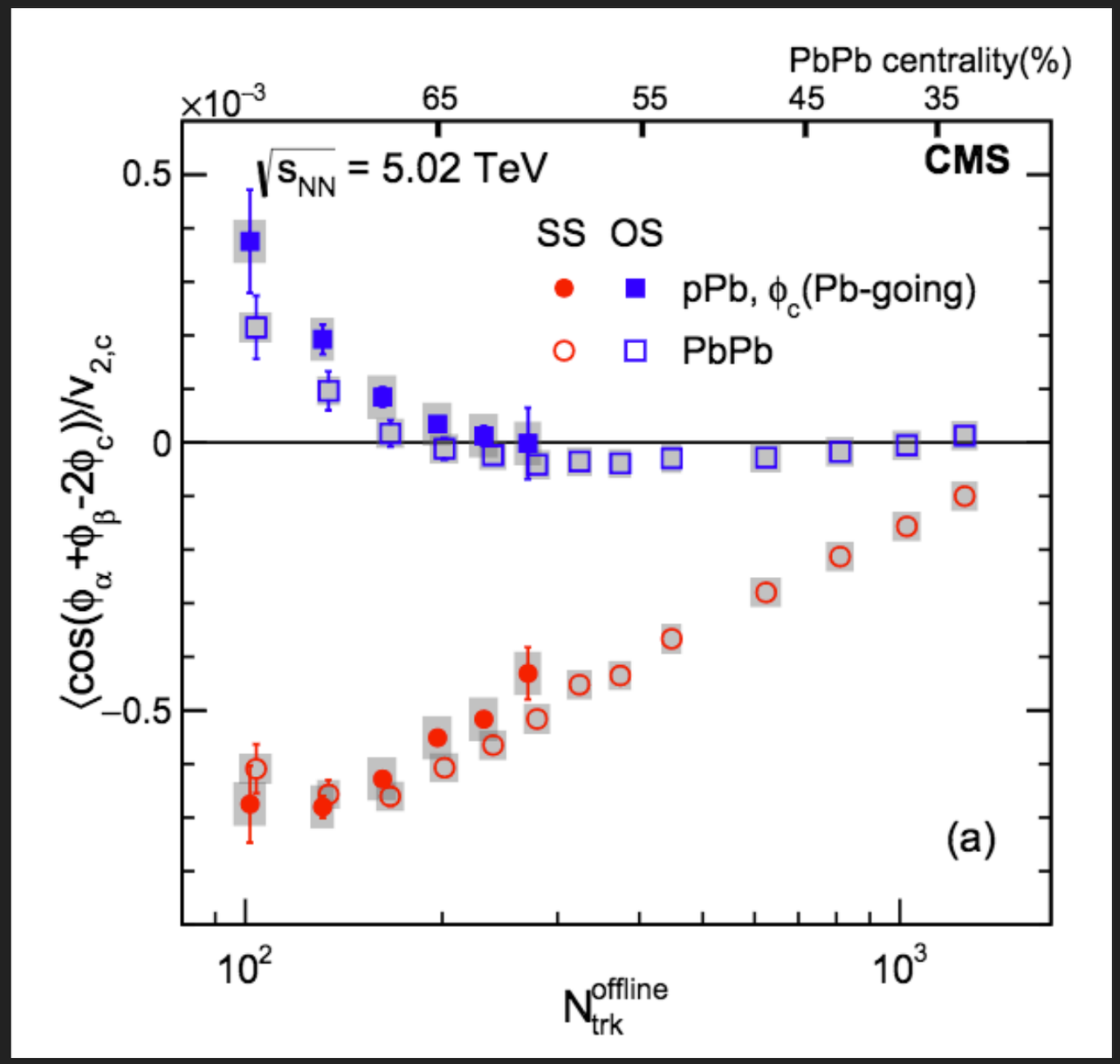
$$c_{(+,-)} = \frac{1}{N_{\mathrm{trig},+}} \frac{\mathrm{d}^2 N_{\mathrm{assoc},-}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$$

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



ALICE, EPJ C 76 (2016) 86

SYSTEM DEPENDENCE



CMS compared Pb-Pb and p-Pb:

- expected in p-Pb collisions: small magnetic field, uncorrelated with ψ_{RP}
- at comparable system size (~charged track multiplicity), results are consistent: no CME?

CMS, PRL 118, 122301 (2017)

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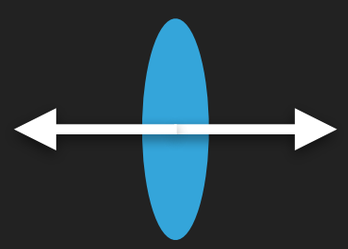
EVENT SHAPE ENGINEERING

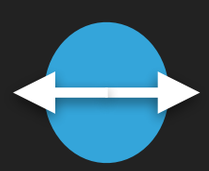
Event Shape Engineering (ESE)
(J. Schukraft *et al.*, arXiv:1208.4563) :

classify events according to the strength of elliptic flow (v_2)

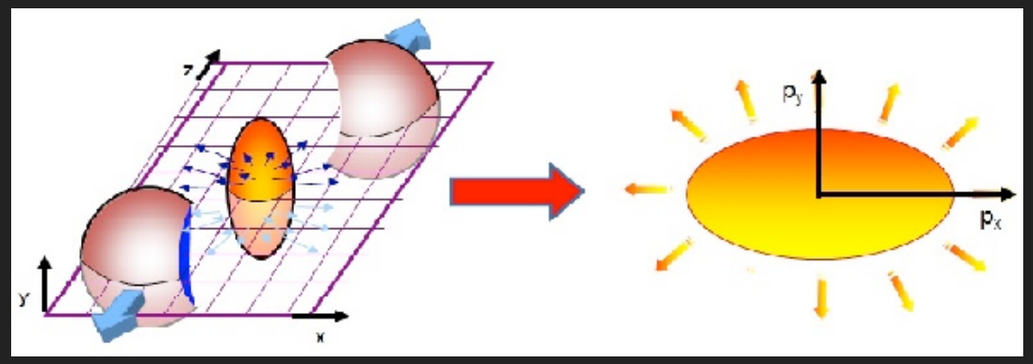
$$Q_2 = \sum_{j=1}^{M} e^{2i\varphi_j} \rightarrow q_2 = |Q_2|/\sqrt{M}$$

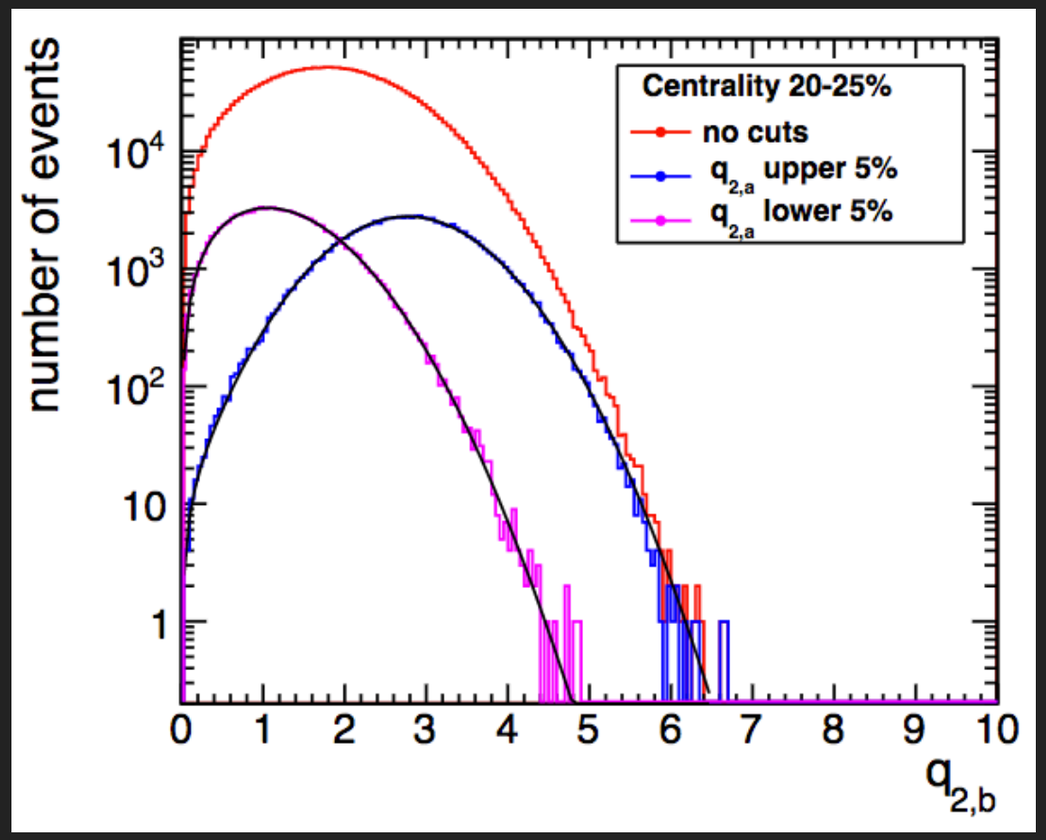


large q_2
90-100%
$v_2 > \langle v_2 \rangle$



small q_2
0-10%
$v_2 < \langle v_2 \rangle$





J. Schukraft *et al.*, arXiv:1208.4563

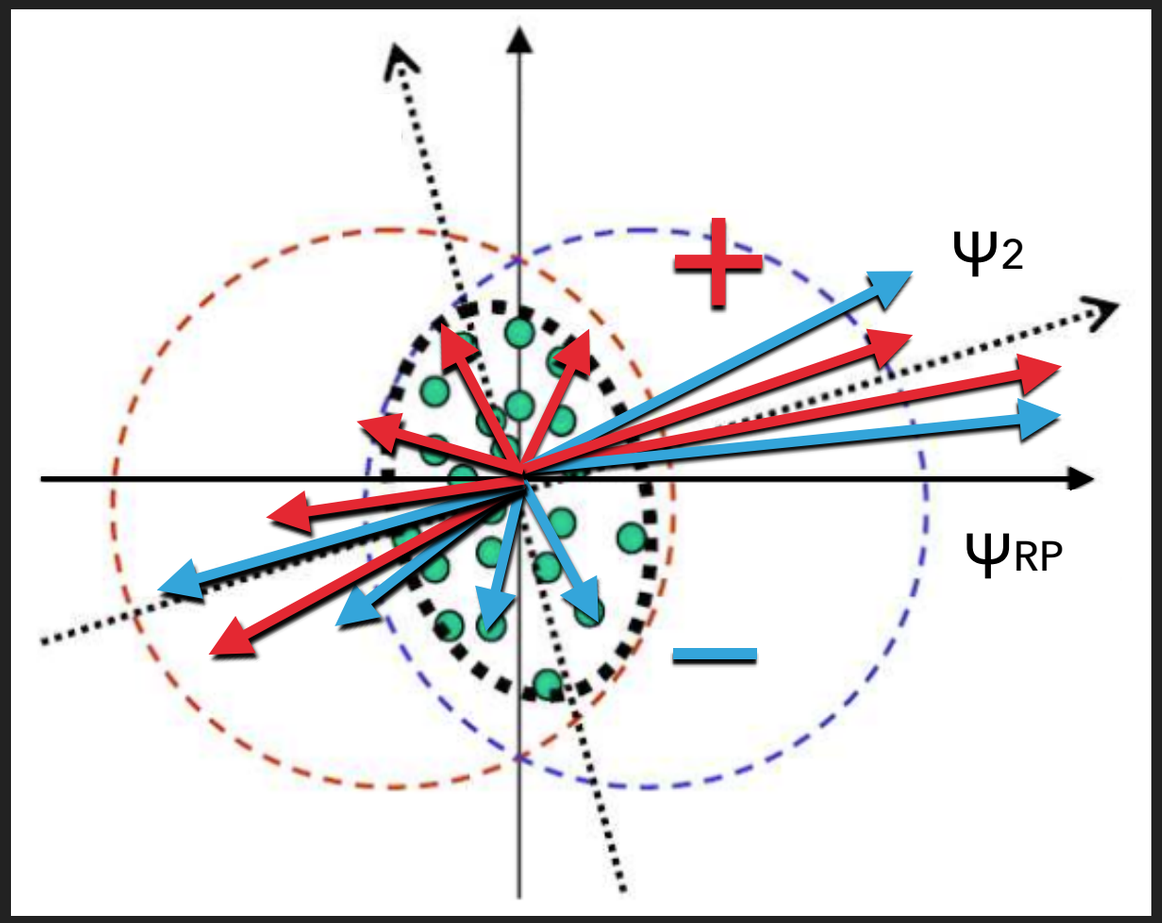
CME CORRELATORS

- Reaction plane angle (ψ_{RP}) not accessible experimentally
- Main axis along which v_2 develops (ψ_2) is used instead

$$Q_2 = \sum_{j=1}^{M} e^{2i\varphi_j}$$

$$\Psi_2 = \frac{1}{2}\,\mathrm{atan2}(\mathrm{Im}\,Q_2, \mathrm{Re}\,Q_2)$$

$$\gamma_{a,b} = \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle$$



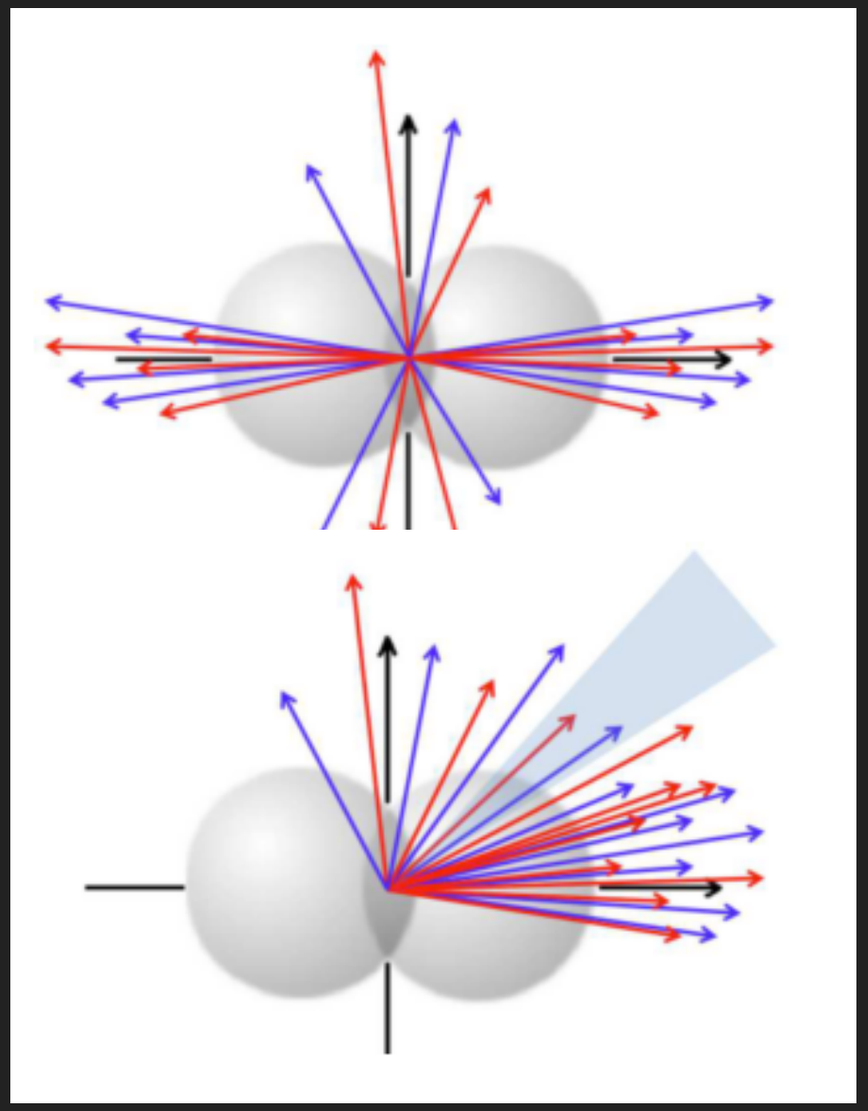
adapted from S. Voloshin *et al.*, PLB 659 537-541 (2008)

BACKGROUND: FLOW MODULATION

why studying CME correlators with ESE?

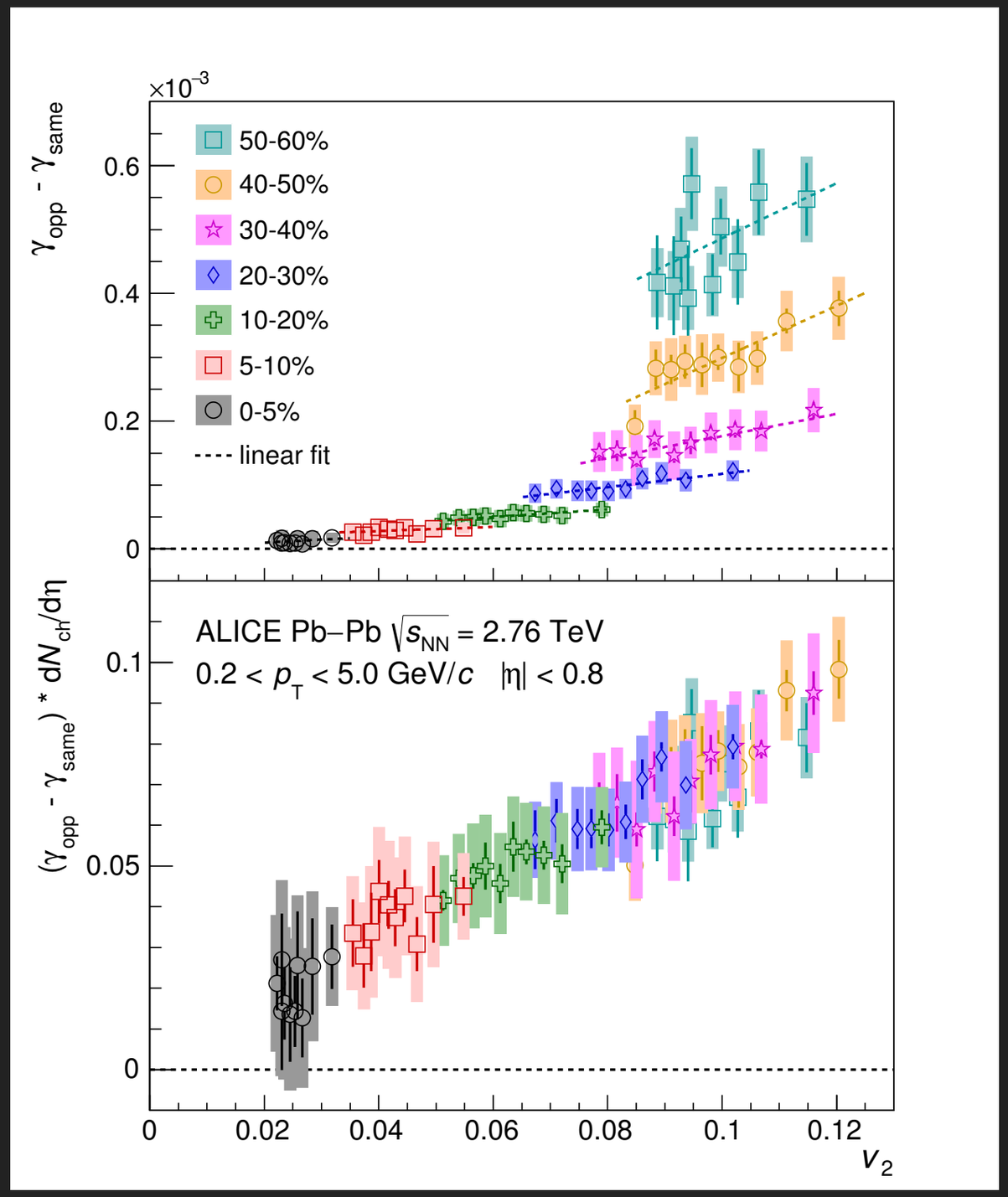
LCC background is modulated by v_2:

- charge-independent:
  stronger v_2 –> stronger boost –>
  stronger correlation in phase-space
- charge-dependent:
  balancing charge more likely in-plane (ψ_2)



Simple expectation: background in $\Delta\gamma_{a,b}$ scales linearly with v_2

CME CORRELATORS WITH ESE



ALICE, arXiv:1709.04723

Pb-Pb $\sqrt{s_{NN}}$= 2.76 TeV
CME correlators (δ, γ) vs v_2

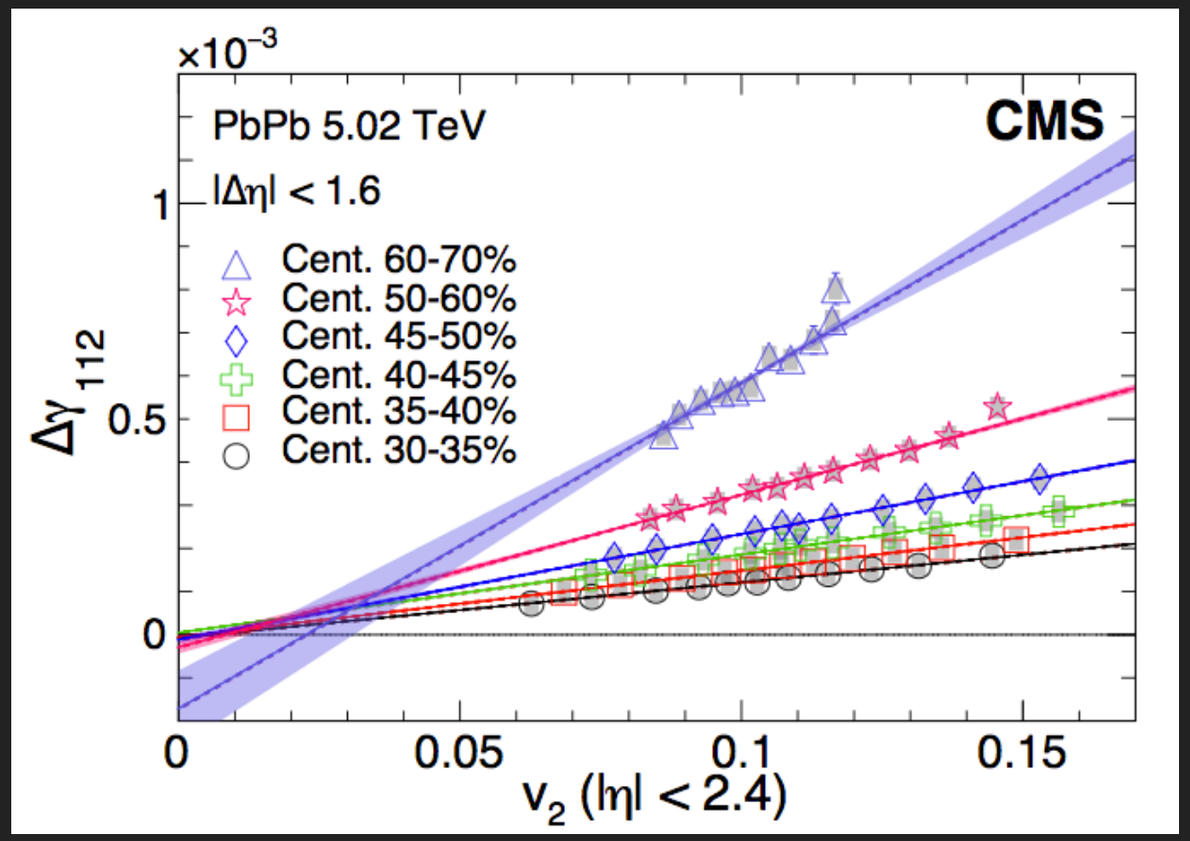
Observations:

- $\Delta\gamma_{ab}$ depends linearly on v_2
- $\Delta\gamma_{ab}$ scaled by multiplicity (dN/dη) falls on a common line

→ higher mult. dilutes LCC?

Qualitatively consistent with background-only hypothesis!

UPPER LIMIT (1)

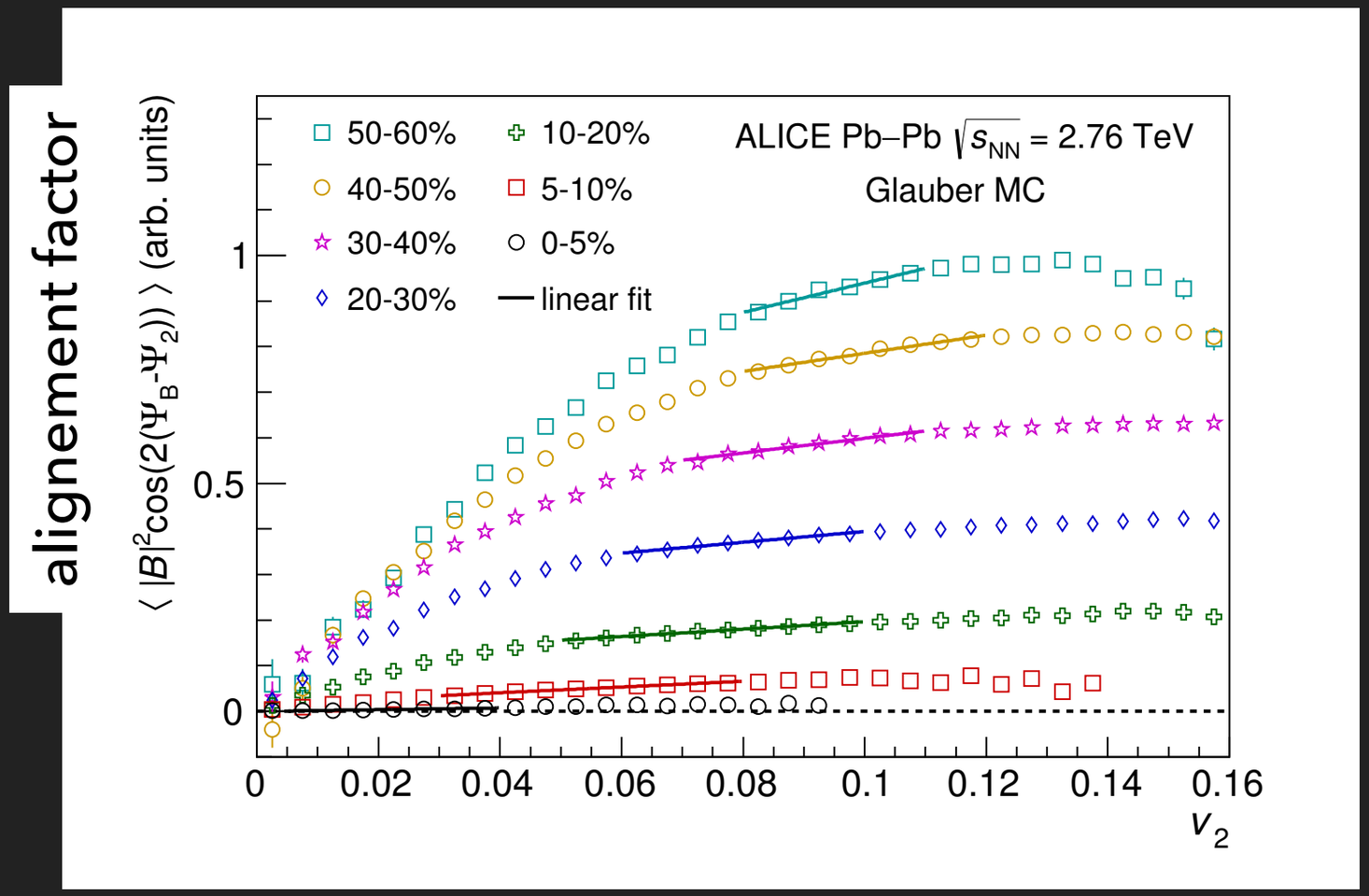


CMS, arXiv:1708.01602

- CMS reported similar observations in Pb-Pb $\sqrt{s_{NN}}$= 5.02 TeV
- Assumption: CME is v_2-independent, background is not
- Upper limit extracted from intercept p_0 in the fit $\frac{\Delta\gamma_{a,b}}{\Delta\delta_{a,b}} = p_1 v_2 - p_0$

→ CME signal 3.8% of $\Delta\gamma_{ab}$ at 95% C.L. in centrality 30-70%

ALIGNING B AND V_2



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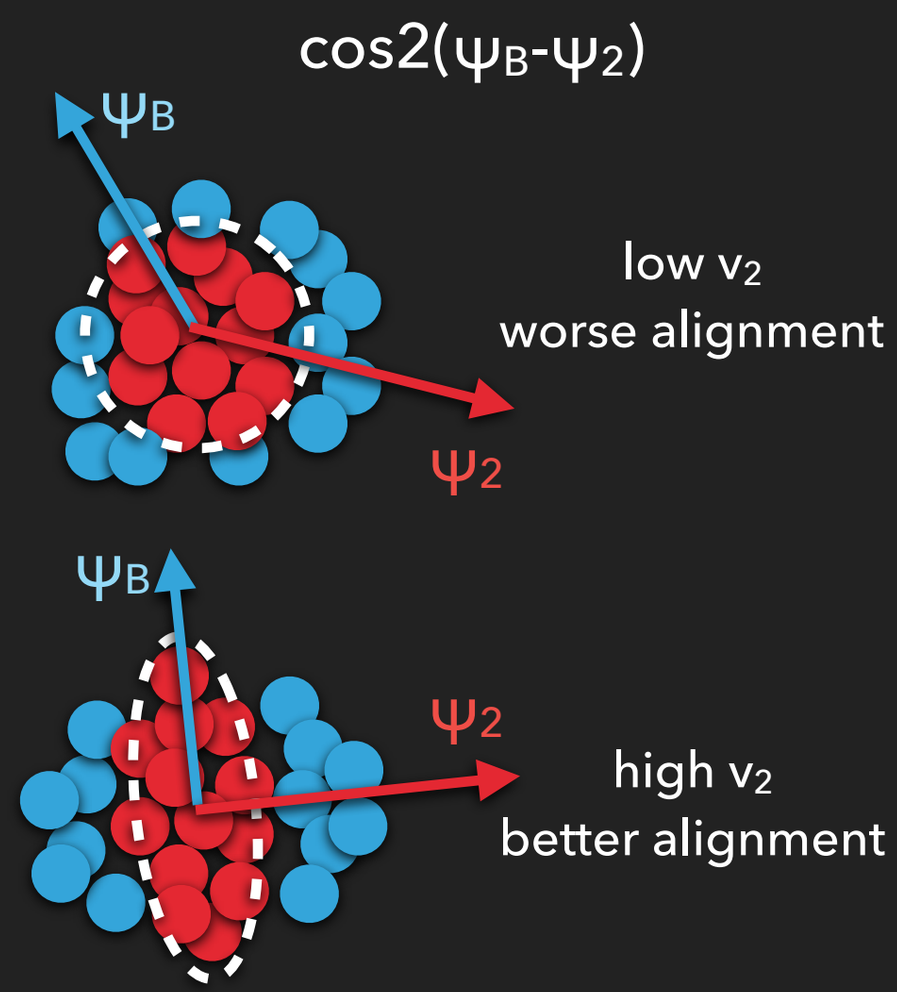
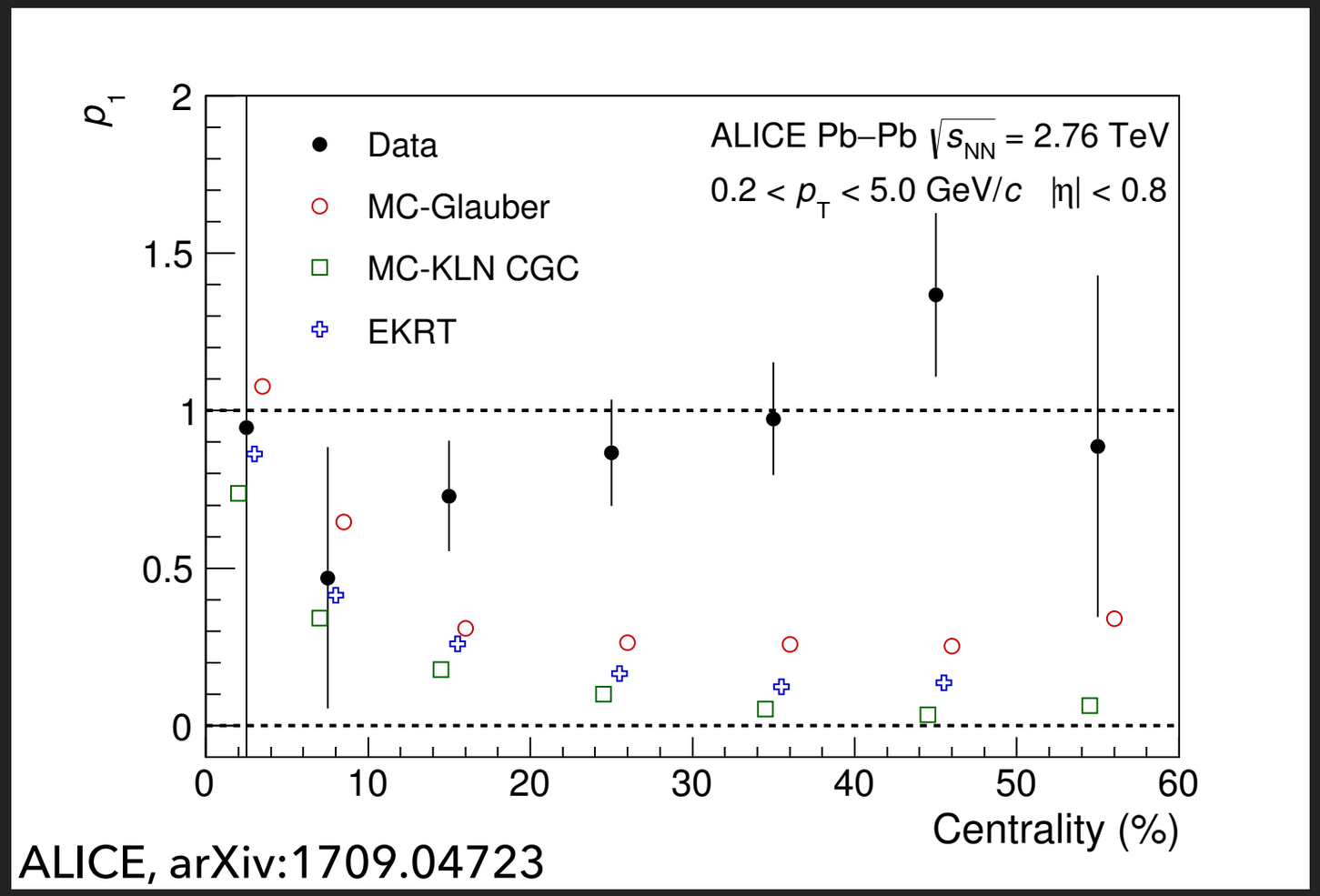


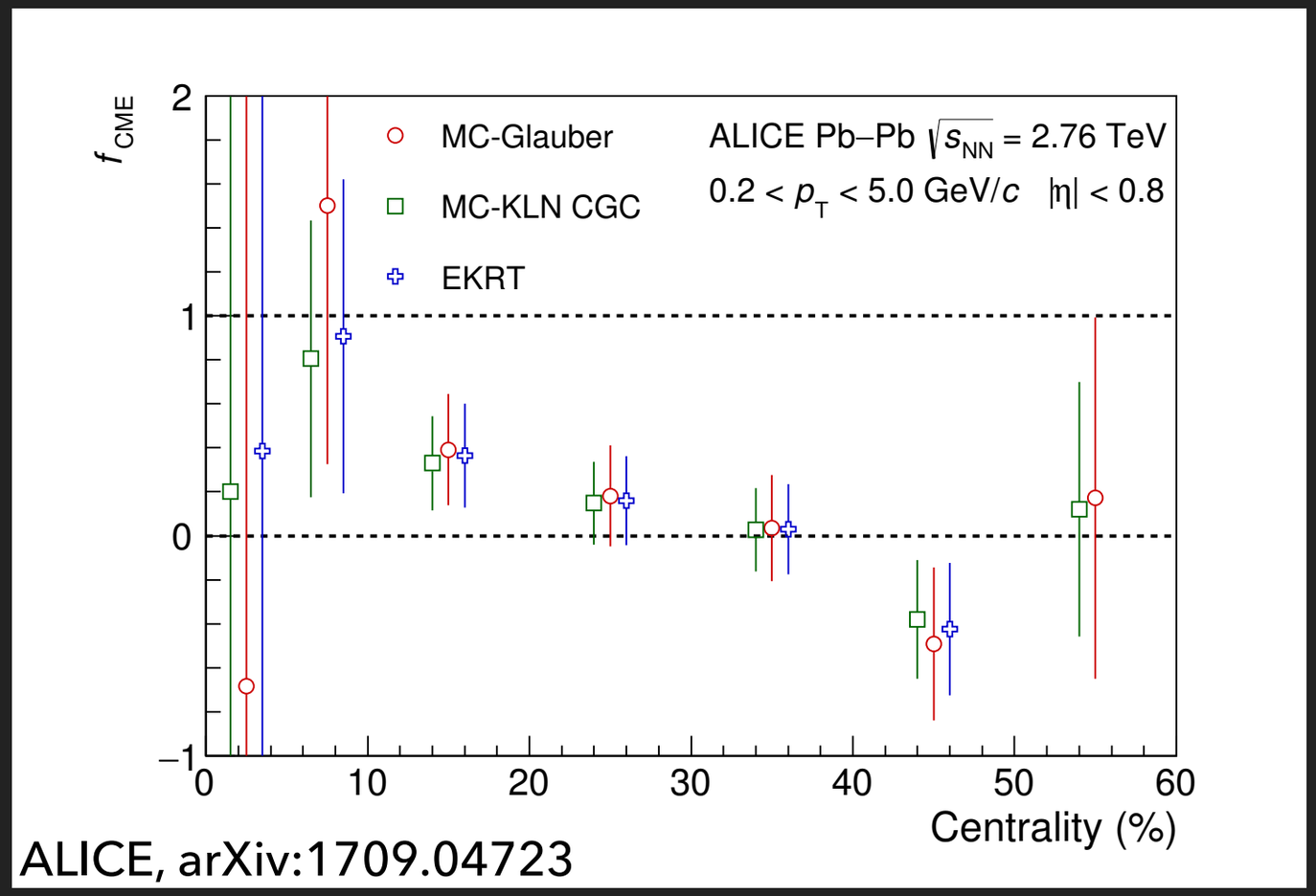
alignment between B and ψ_2 depends linearly on v_2 around $\langle v_2 \rangle$ → signal in $\Delta\gamma_{ab} \propto |B|^2\cos2(\psi_B-\psi_2) \propto v_2$

DATA VS MC



- Possible to extract a slope p_1 from a fit $F(v_2) = p_0\,(1 + p_1\,(v_2 - \langle v_2 \rangle)/v_2)$
- Both for measured $\Delta\gamma_{ab}$ (p_1^{data}) and simulated $|B|^2\cos2(\psi_B-\psi_2)$ (p_1^{MC})
- Some differences observed between different initial-state models

UPPER LIMIT (2)



ALICE, arXiv:1709.04723

assumptions on signal and background scaling with v_2:

signal slope as $|B|^2\cos2(\psi_B-\psi_2)$

background slope is unity

CME signal fraction S/(S+B) computed as $f_{\mathrm{CME}} \times p_1^{\mathrm{MC}} + (1 - f_{\mathrm{CME}}) \times 1 = p_1^{\mathrm{data}}$

→ CME signal 26-33% of $\Delta\gamma_{ab}$ at 95% C.L. in centrality 10-50%

CONCLUSIONS

- First measurements on CME correlators with Event-Shape-Engineering in Pb-Pb collisions at the LHC by ALICE and CMS
- Results are compatible with background-only hypothesis
- Upper limits (3.8% CMS, 26-33% ALICE) strongly depend on assumptions on signal and background: more studies are needed!

OUTLINE

- Introduction — *what are we talking about?*
- Chiral Magnetic Effect (CME) — *how do we measure it?*
- CME with Event-Shape Engineering — *constraining signal/background*
- Charge-dependent directed flow — *constraining the magnetic field*
- Outlook — *what's next?*

MAGNETIC-INDUCED CHARGED CURRENTS

The proposal (U. Gursoy *et al.*, PRC 89, 054905 (2014)):

- measure a simpler observable (not related to chiral imbalance), use it to calibrate the strength and lifetime of the magnetic field

charge-dependent directed flow

Where does it come from?

- electric field induced by decreasing B (Faraday effect)
- Lorentz force on moving charges (Hall effect)

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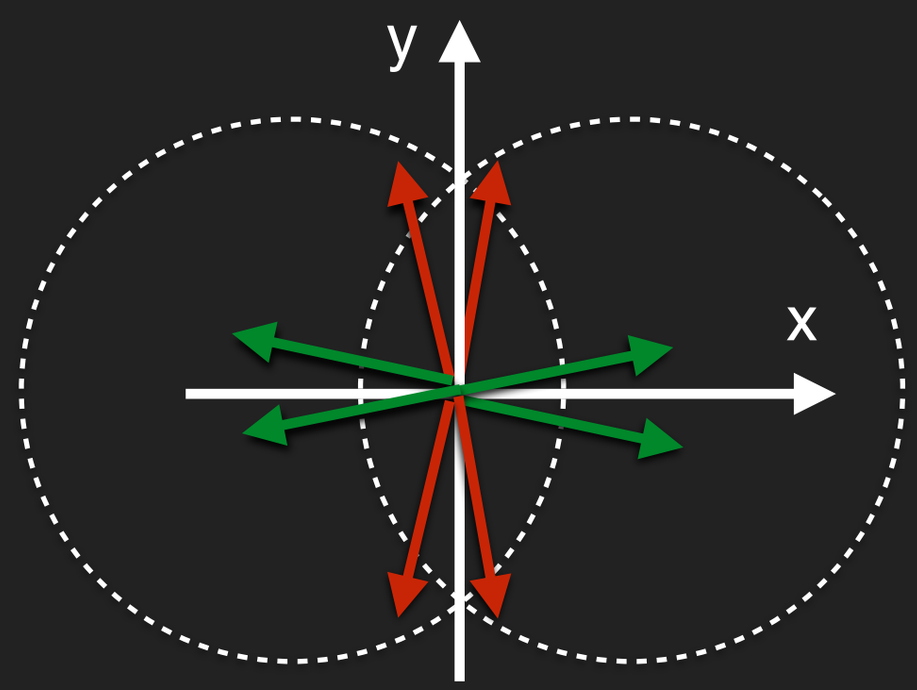
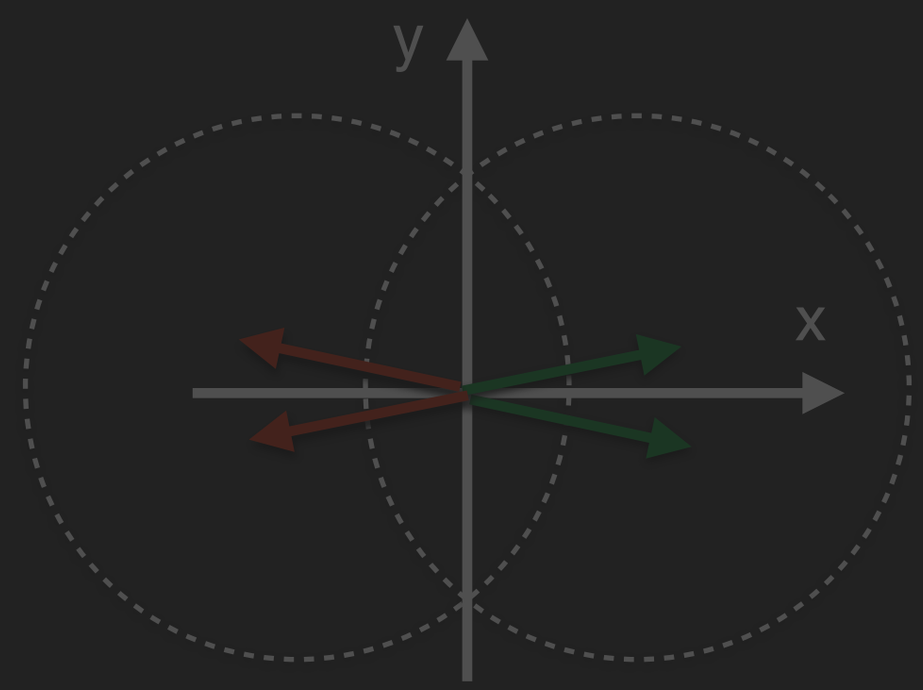
ELLIPTIC VS DIRECTED FLOW

elliptic flow: in-plane vs out-of-plane



directed flow: same or opposite
direction w.r.t. the impact parameter



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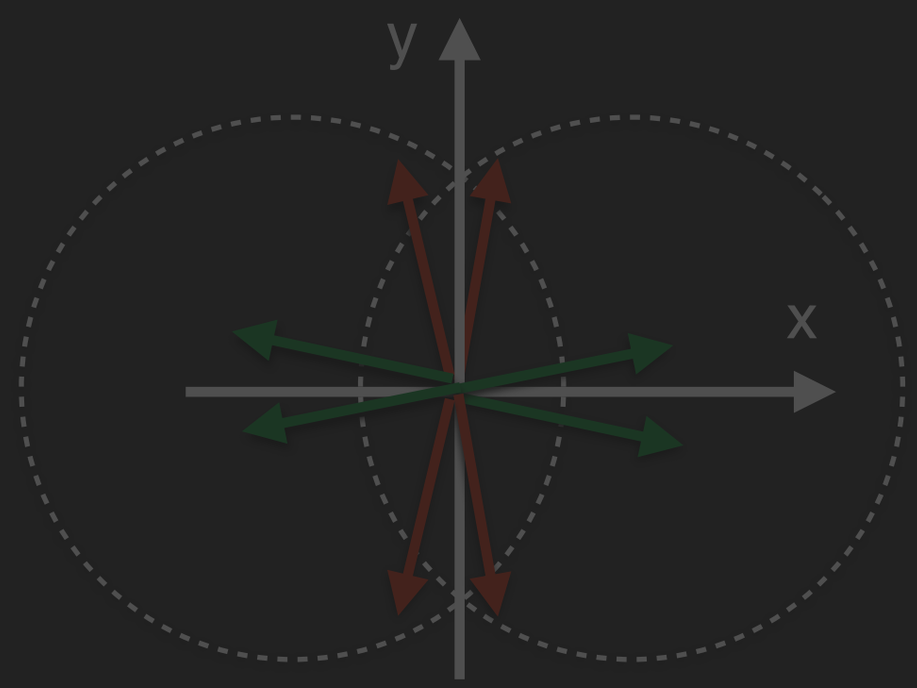

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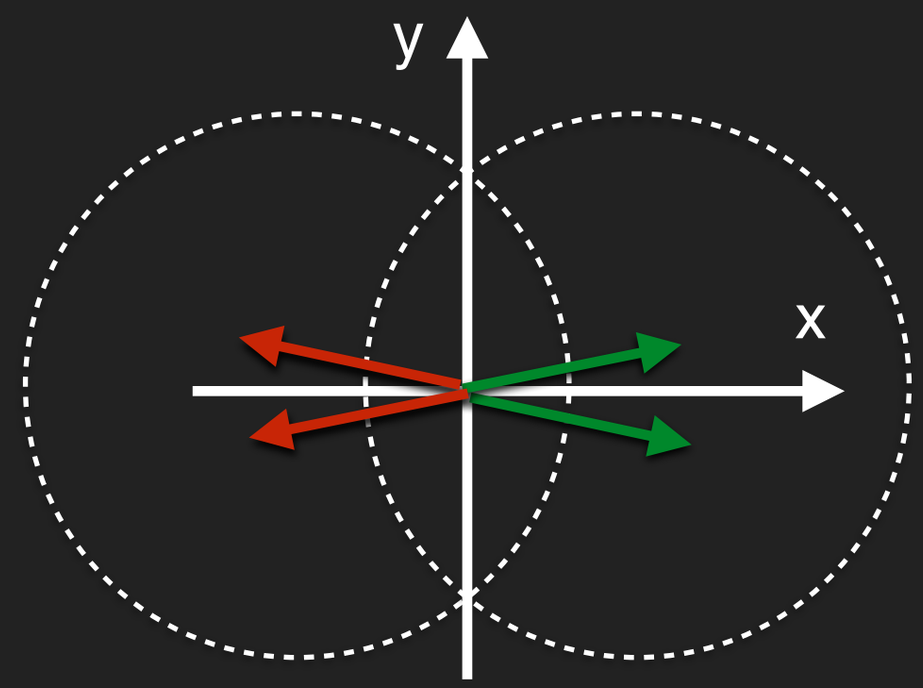

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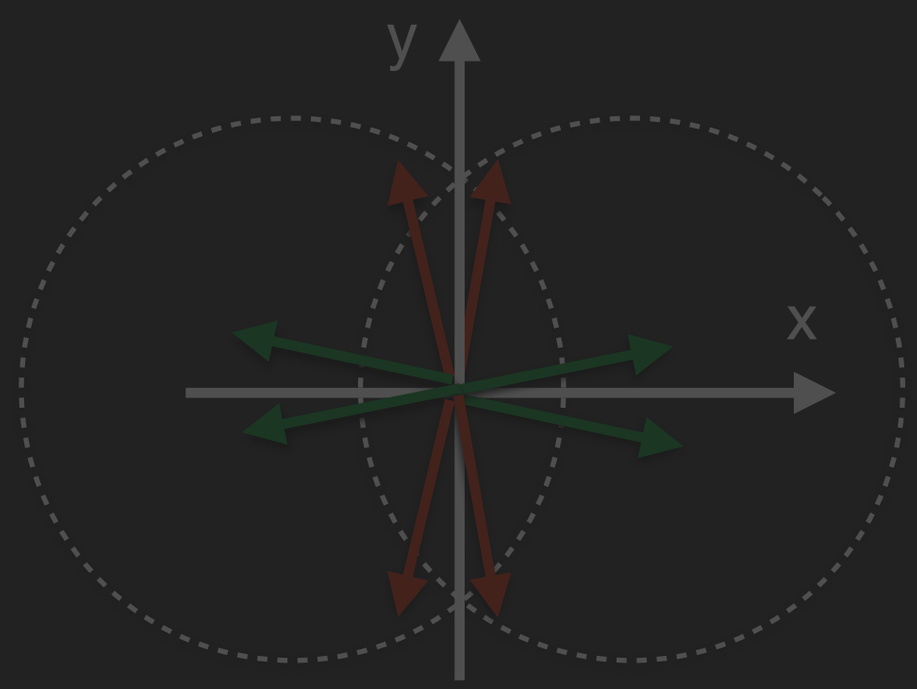
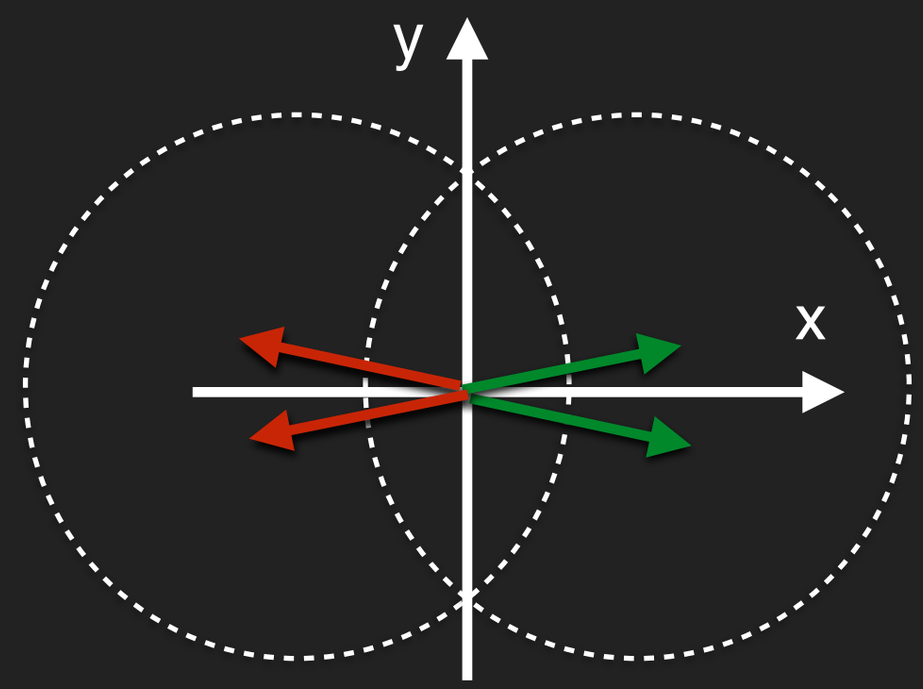


directed flow: same or opposite direction w.r.t. the impact parameter



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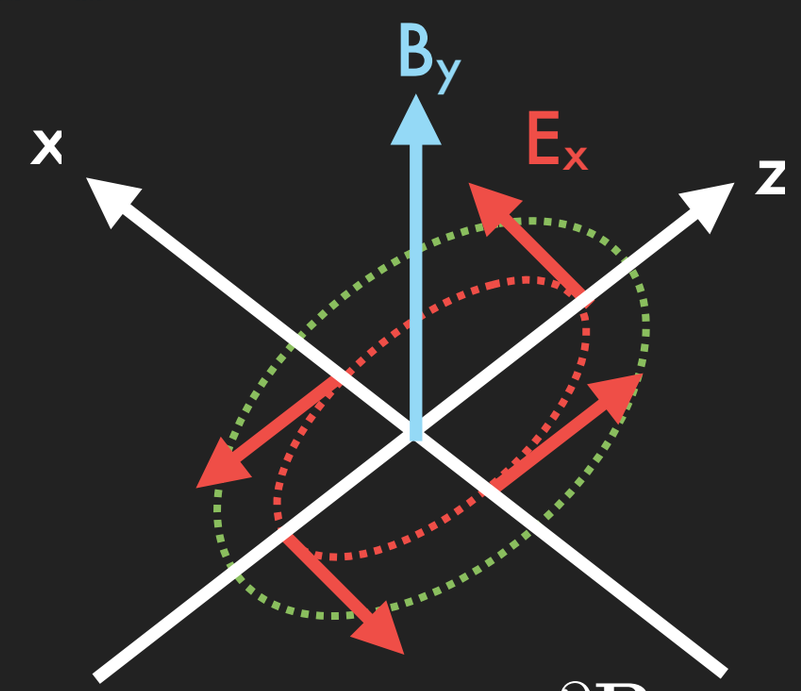

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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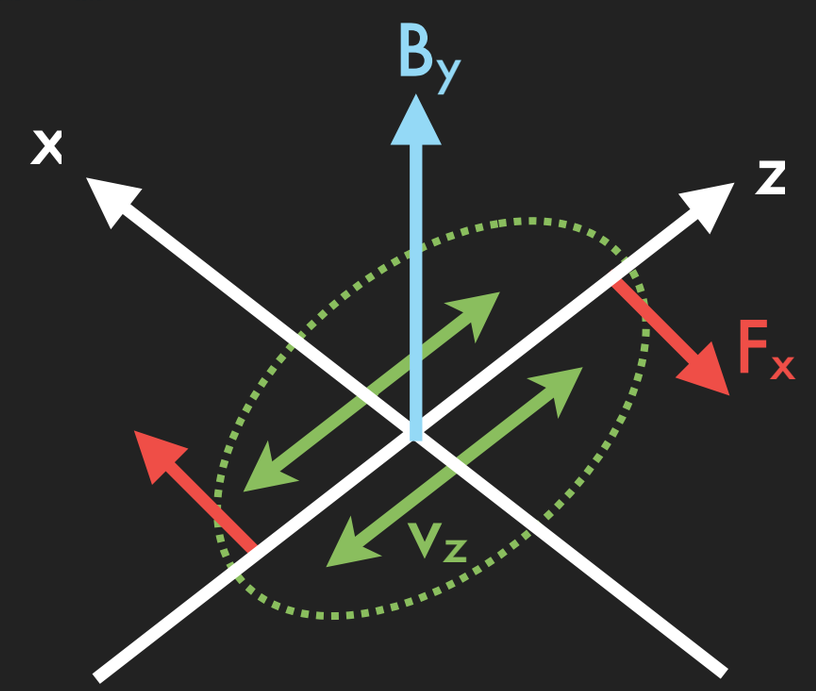

$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

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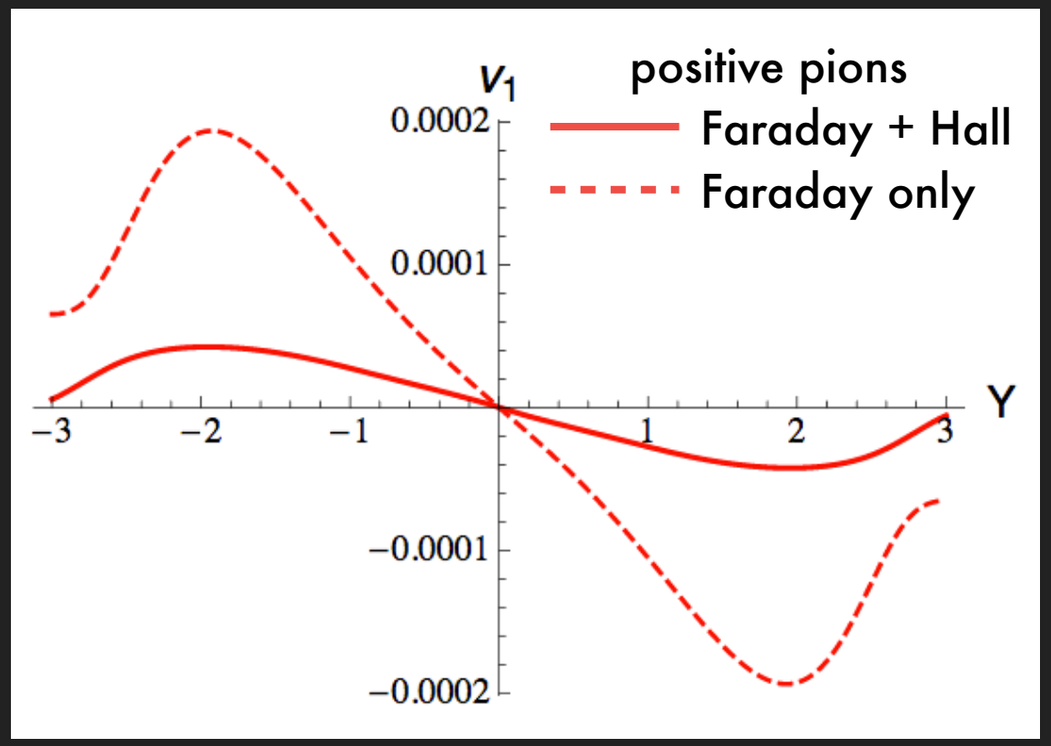
competing effects!

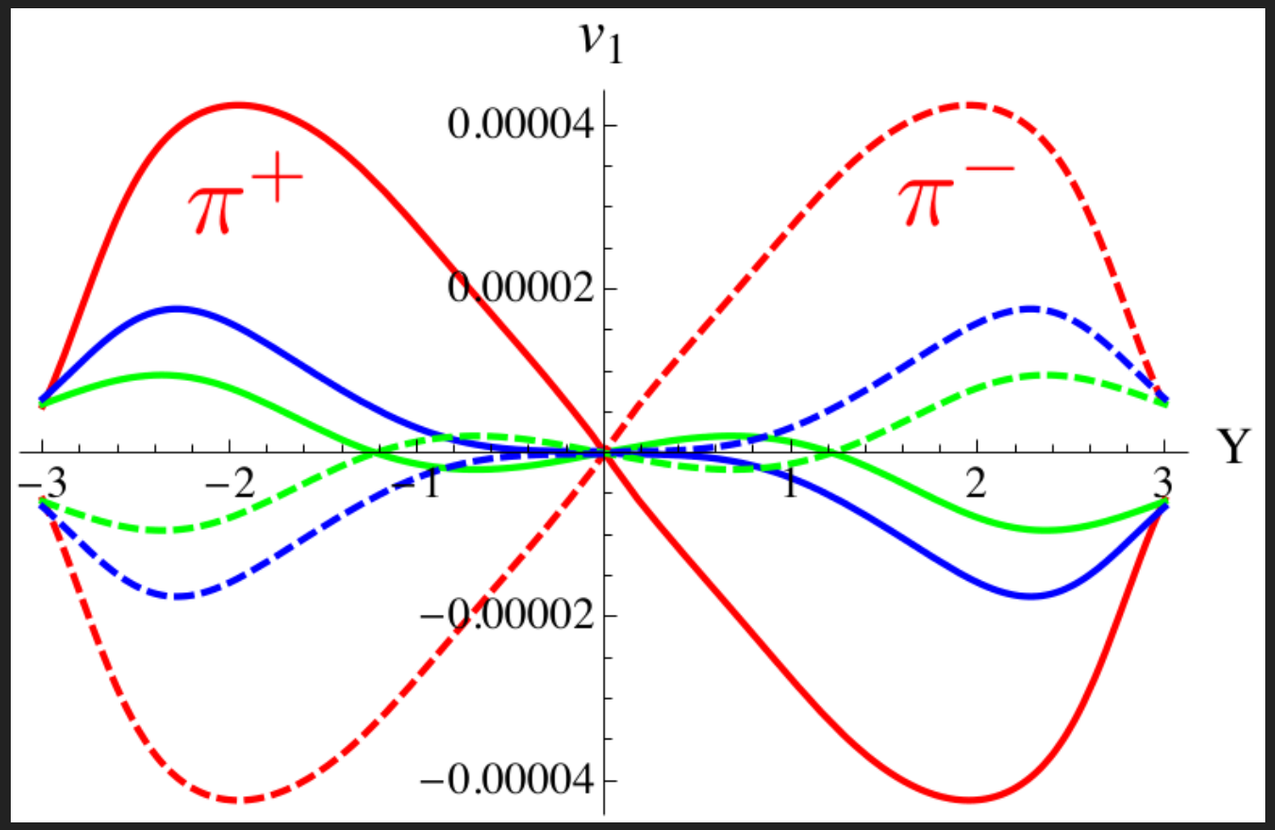


adapted from U. Gursoy *et al.*, PRC 89, 054905 (2014)

CHARGE-DEPENDENT DIRECTED FLOW

- the signal: $\Delta v_1^{odd} = v_1^{odd}(+) - v_1^{odd}(-)$
- predictions for Pb-Pb @ 2.76 TeV: 10^{-5} or less

U. Gursoy *et al.*, PRC 89, 054905 (2014)

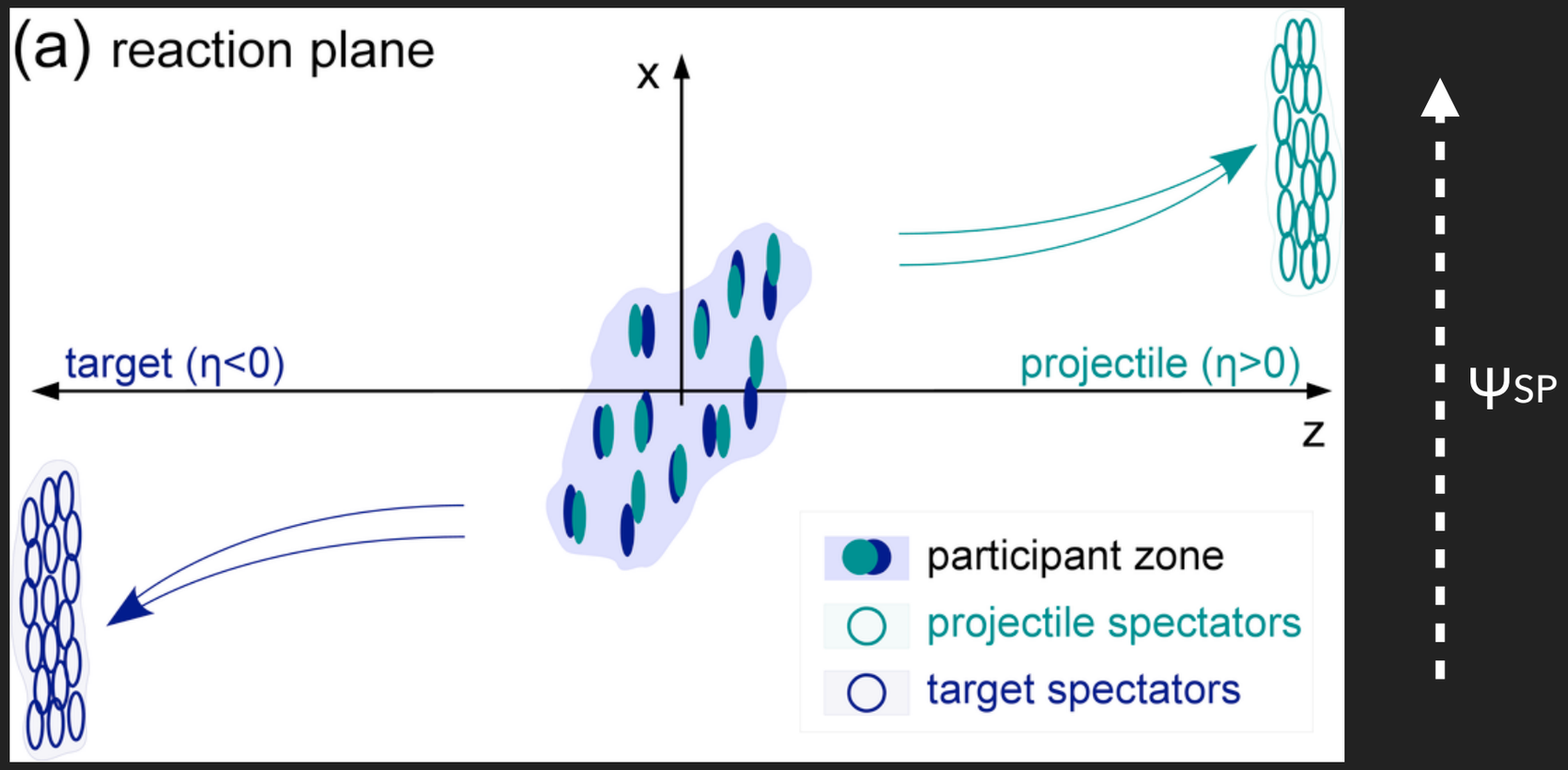


Pb-Pb 2.76 TeV
p_T = 0.25 GeV/c
p_T = 0.5 GeV/c
p_T = 1.0 GeV/c

DIRECTED FLOW W.R.T. SPECTATORS

How do we measure directed flow?

- as a proxy for reaction plane, we use the direction of the <u>spectator neutrons</u> ⟶ "spectator plane"



- N.B. the convention is to choose $v_1>0$ for spectators at $\eta>0$

SPECTATOR PLANE RECONSTRUCTION

Zero-Degree Calorimeters (ZDC), energy of spectator neutrons

- located at beam rapidity: $|\eta| > 8.8$
- hadronic "spaghetti" calorimeters: tungsten + quartz fibres
- fibres divided into 4 segments going to 4 PMTs (+ 1 common)

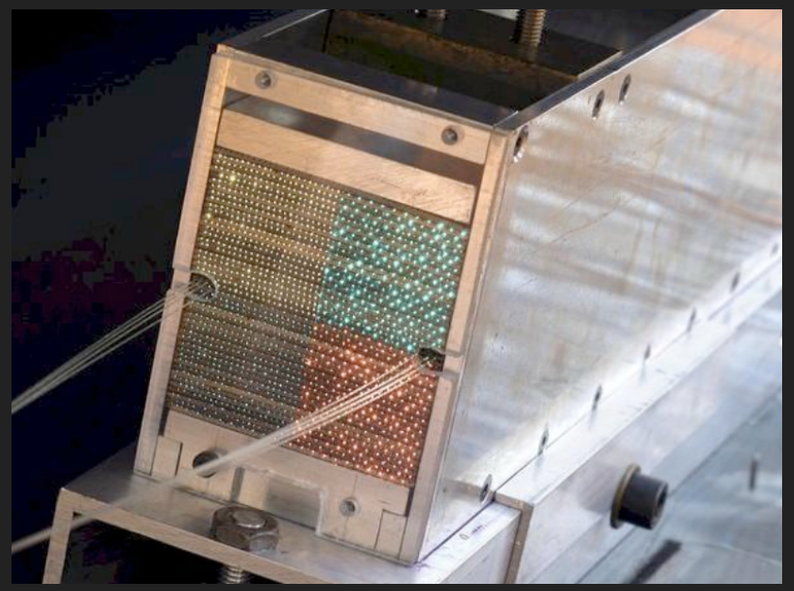
Spectator plane fro

$$\vec{Q}_{\mathrm{A,C}} = \frac{\sum_{i=1}^{4} \vec{x}}{\sum_{i=1}^{4}}$$

$$\Psi_{\mathrm{A,C}} = \mathrm{atan2}(Q$$

x_i coordinates of t

α = 0.395, ZDC-A



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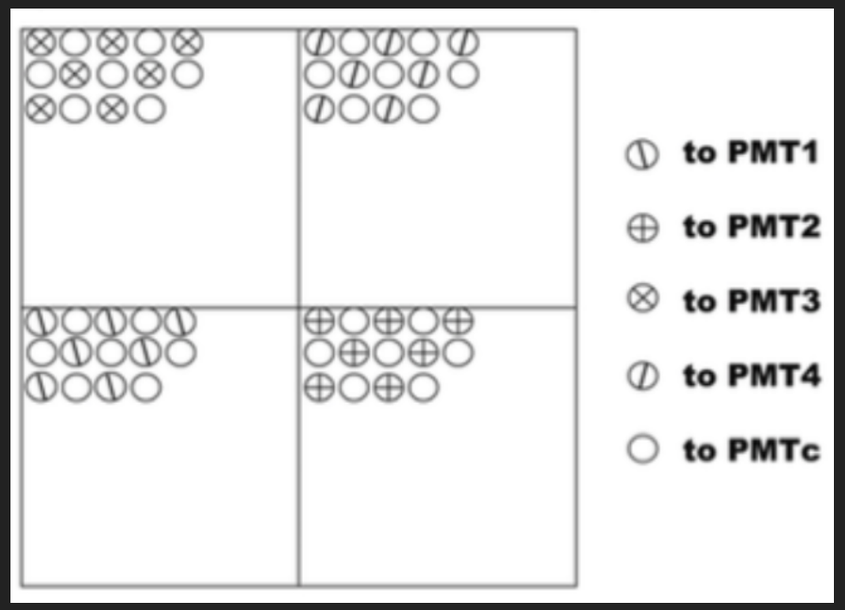
- fibres divided into 4 segments going to 4 PMTs (+ 1 common)

Spectator plane from the signal (E_i) into the 4 ZDC segments:

$$\vec{Q}_{\mathrm{A,C}} = \frac{\sum_{i=1}^{4} \vec{x}_i \, E_i^{\alpha}}{\sum_{i=1}^{4} E_i^{\alpha}}$$

$$\Psi_{\mathrm{A,C}} = \mathrm{atan2}(Q_{\mathrm{A,C}y}, Q_{\mathrm{A,C}x})$$

x_i coordinates of tower centre positions (cm),
α = 0.395, ZDC-A: η>8.8, ZDC-C: η<-8.8



MEASURING DIRECTED FLOW

Directed flow measured with the scalar product method:

$$v_1\{\Psi_{\mathrm{A,C}}\} = \frac{\langle \vec{u} \cdot \vec{Q}_{\mathrm{A,C}} \rangle}{\sqrt{|\langle \vec{Q}_{\mathrm{A}} \cdot \vec{Q}_{\mathrm{C}} \rangle|}} \qquad \vec{u} = \left(\frac{\sum_{i=1}^{N_{\mathrm{trk}}} w_i \cos\varphi}{\sum_{i=1}^{N_{\mathrm{trk}}} w_i}, \frac{\sum_{i=1}^{N_{\mathrm{trk}}} w_i \sin\varphi}{\sum_{i=1}^{N_{\mathrm{trk}}} w_i} \right)$$

track weights $w_i(\varphi, \eta, p_{\mathrm{T}})$ for non-uniform acceptance and reconstruction efficiency

then separate rapidity-odd component:

$$v_1^{\mathrm{odd}} = \frac{1}{2}(v_1\{\Psi_{\mathrm{A}}\} - v_1\{\Psi_{\mathrm{C}}\})$$

separately for pos. and neg. charged tracks: $v_1^{\mathrm{odd}}(\pm)$

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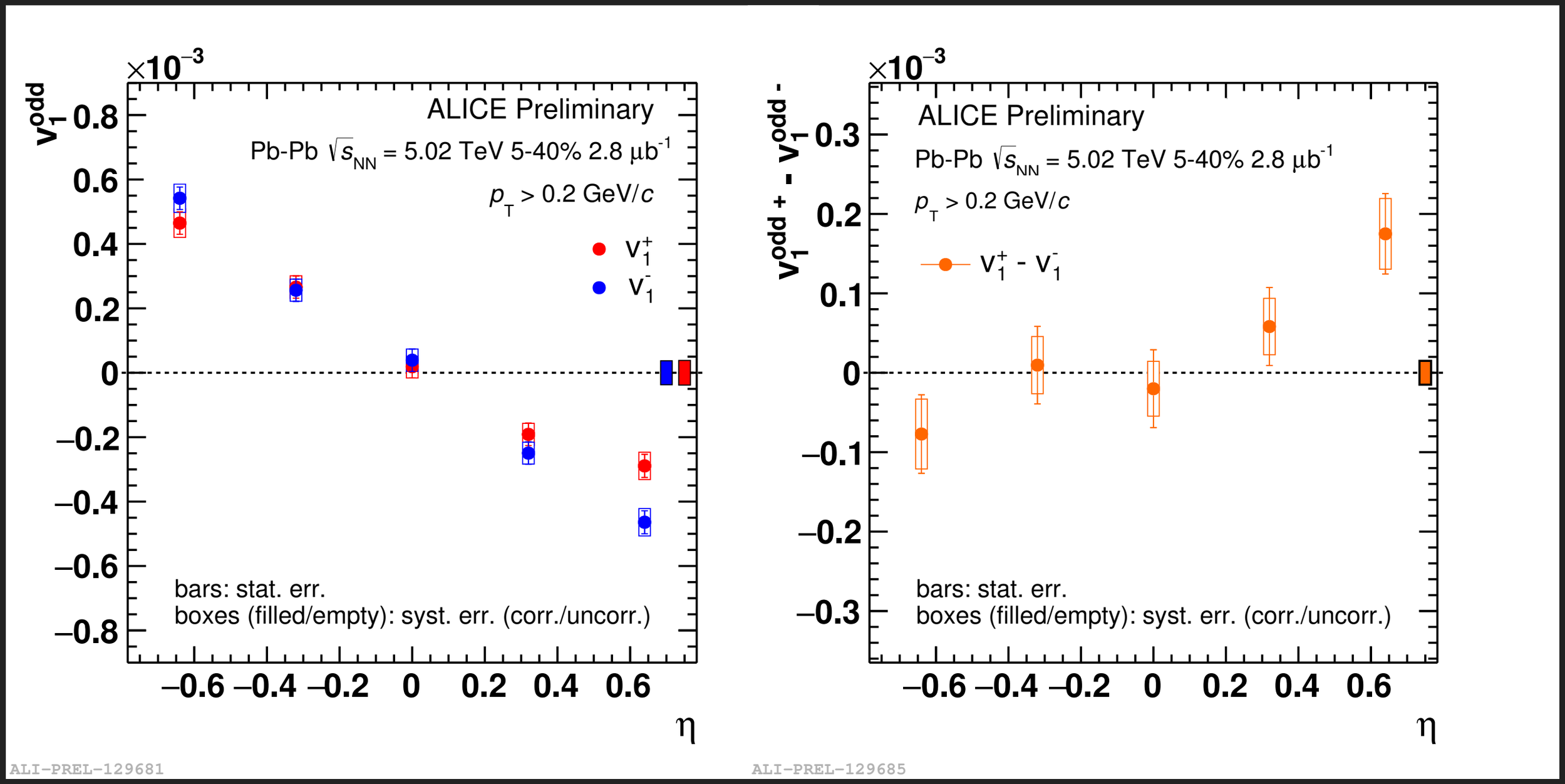
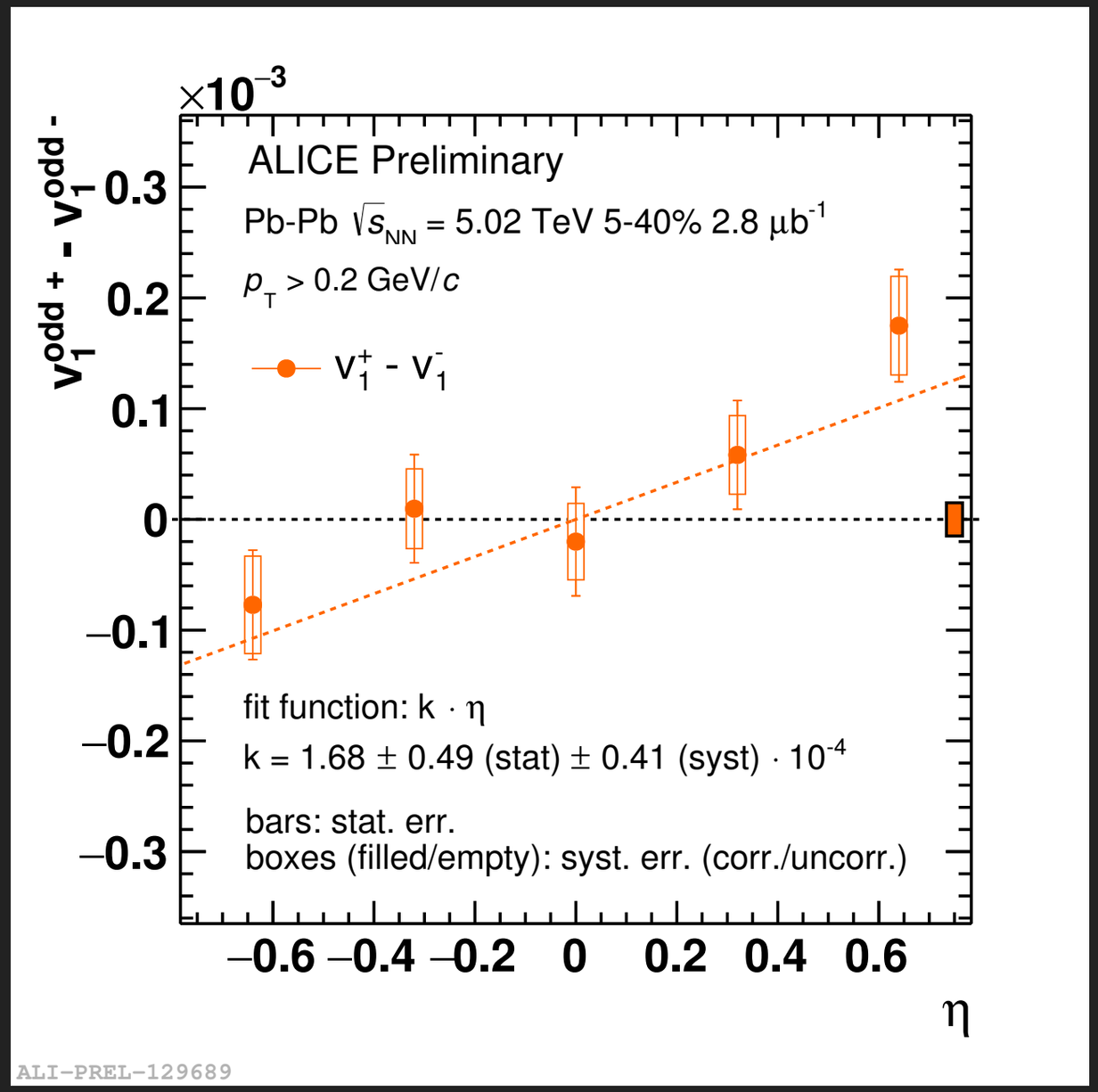


hint of a charge difference: $\Delta v_1^{odd} = v_1^{odd}(+) - v_1^{odd}(-) \neq 0$

RESULTS



fit with a function: v1 = k · η

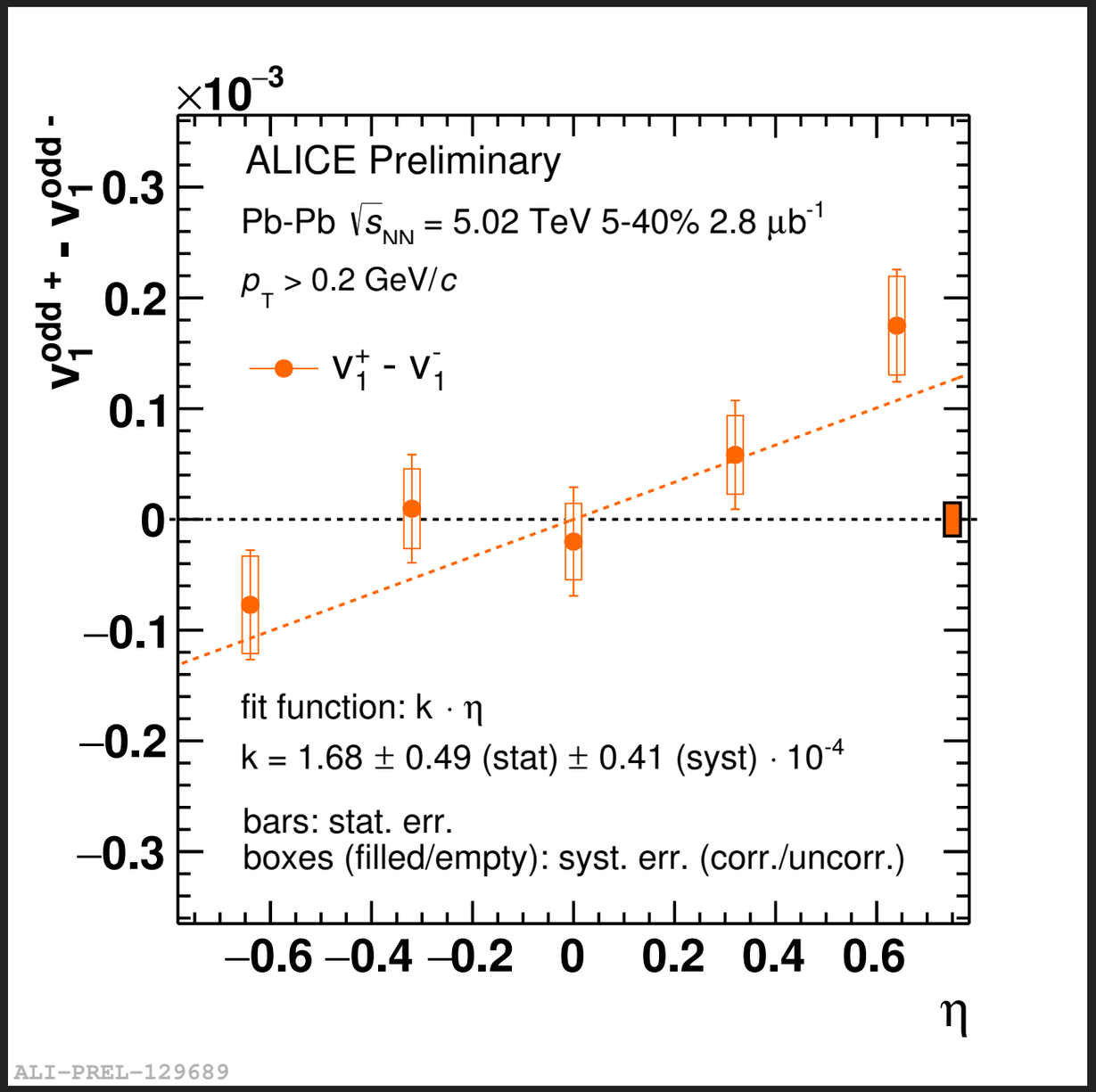
k = 1.68 ± 0.49 (stat) ± 0.41 (syst) ·10^{-4}

2.6σ significance of a non-zero slope in Δv_1^{odd}

Compared to predictions at 2.76 TeV and similar <p_T>:

- 1-2 orders of magnitude bigger:
  long-lived magnetic field?
  early thermalisation?
- opposite sign:
  dominance of Hall effect?

RESULTS



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- opposite sign: *dominance of Hall effect?*

CONCLUSIONS

- Rapidity-odd directed flow (v_1^{odd}) with respect to the spectator plane measured for the first time in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- Hint of a charge-dependent difference Δv_1^{odd} of $\mathcal{O}(10^{-4})$
  - can be caused by early-time magnetic field
  - results at 5.02 TeV compared to predictions for 2.76 TeV:
    1-2 orders of magnitude bigger, opposite sign —> challenge predictions
- More statistics needed to confirm or disprove it

OUTLINE

- Introduction — *what are we talking about?*
- Chiral Magnetic Effect (CME) — *how do we measure it?*
- CME with Event-Shape Engineering — *constraining signal/background*
- Charge-dependent directed flow — *constraining the magnetic field*
- Outlook — *what's next?*

OUTLOOK: WHAT'S NEXT?

- Understand the background: tune and/or improve existing MC generators to match data on charge-dependent angular correlations
  - balance functions
  - higher harmonic correlators (background-only)

    $\langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle$
- Understand the signal
  - dynamics of chiral charges in the medium: magneto-hydrodynamics
  - constrain the magnetic field: charge-dep. v_1, global lambda polarisation
- Try different experimental approaches
  - isobaric collisions at RHIC: dedicated run in 2018
  - searches for new phenomena: Chiral Magnetic Wave, ecc.

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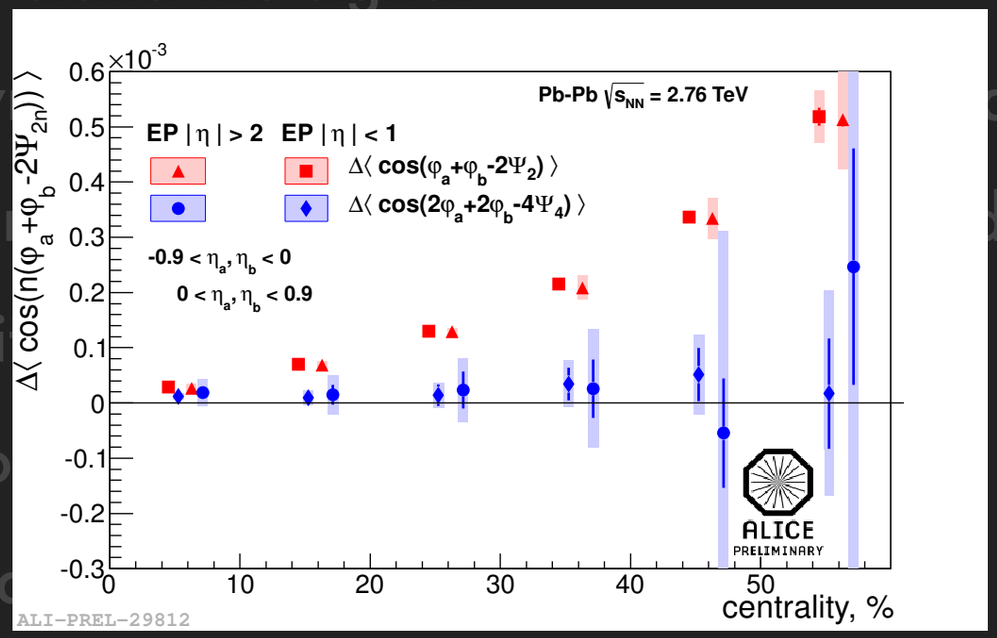
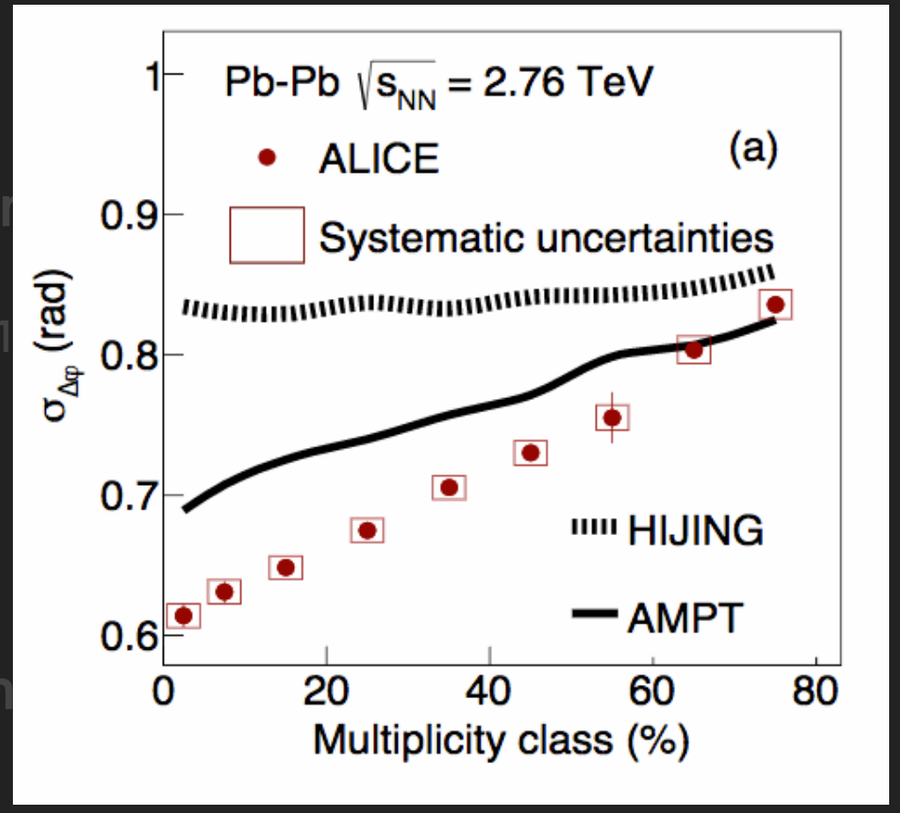
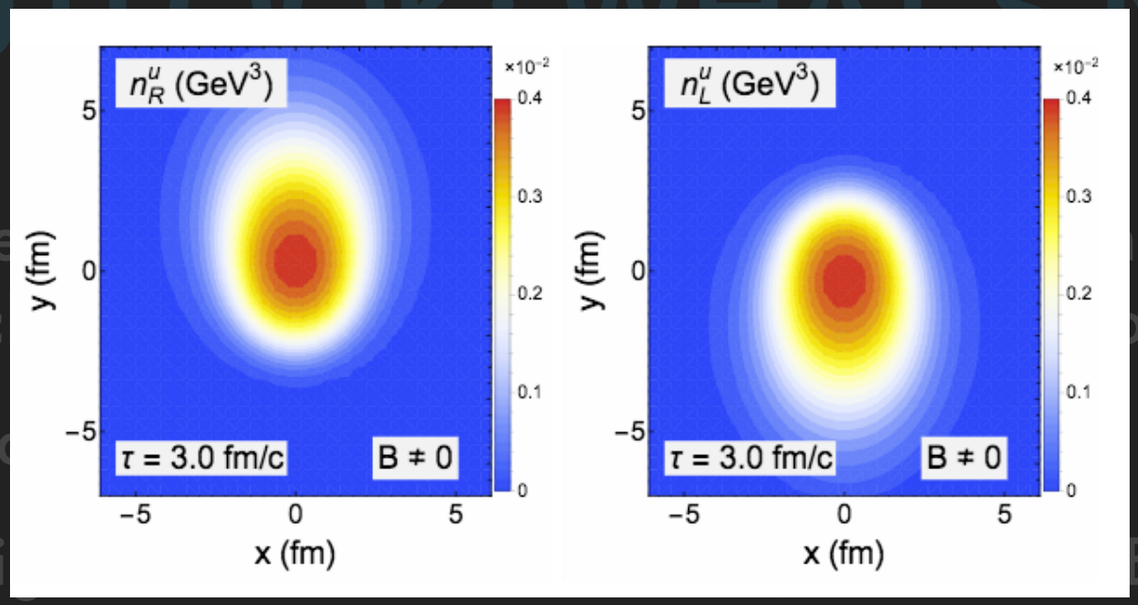


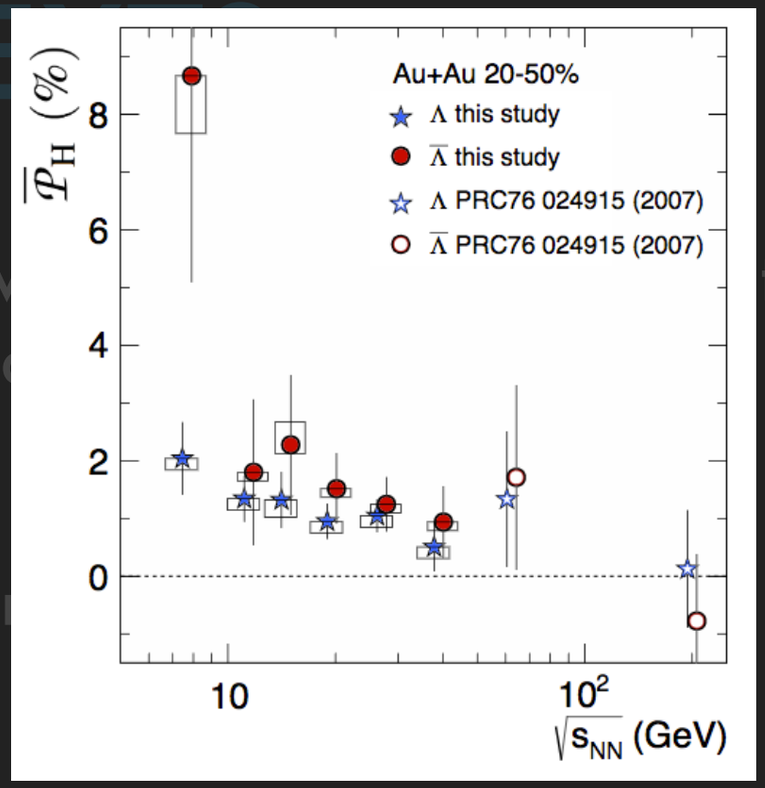
J. Mlynarz, QM'12



ALICE, EPJ C 76 (2016) 86



Y. Jiang *et al.*, arXiv:1611.04586



STAR, Nature 548, 62 (2017)

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  - chirality in the medium: anomalous-magneto-hydrodynamics
  - constrain the magnetic field: charge-dep. v_1, global lambda polarisation
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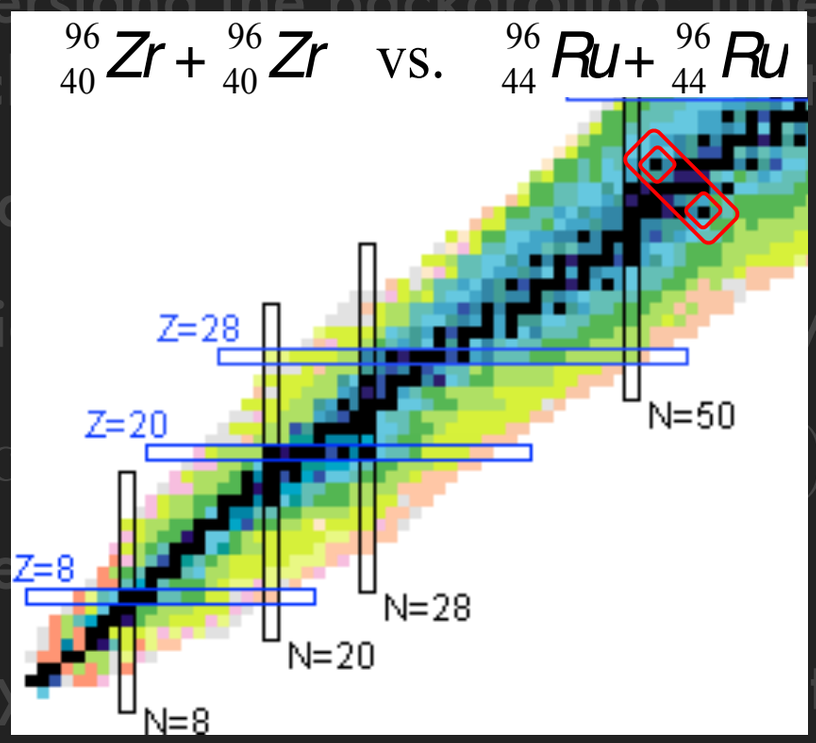
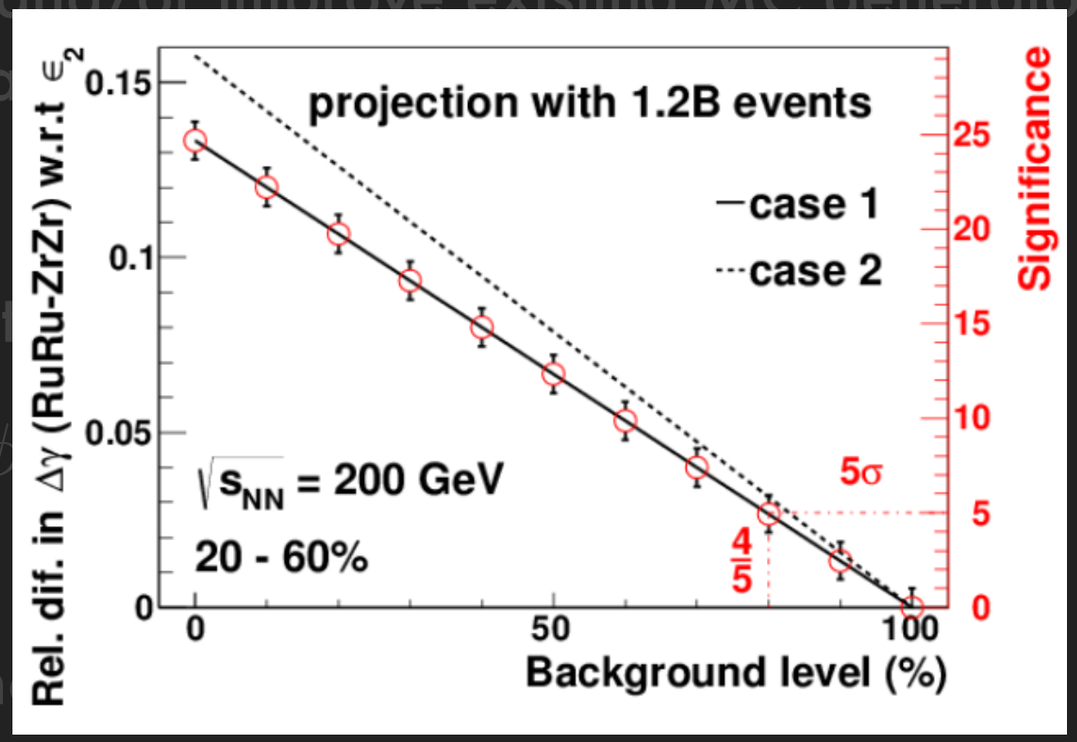


V. Skokov *et al.*, arXiv:1608.00982



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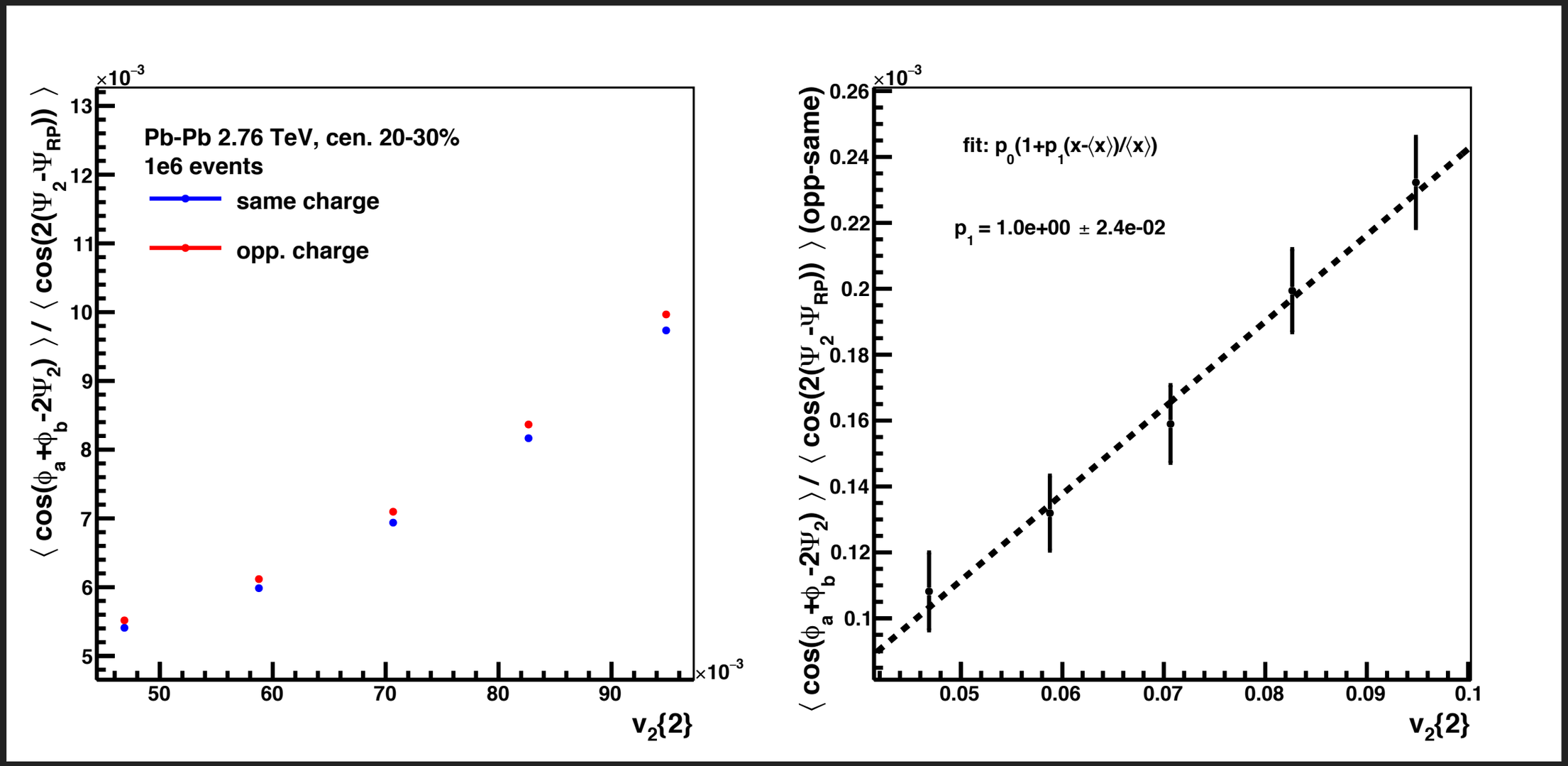
thank you!

BACKUP

BACKGROUND: FLOW MODULATION



Blast-Wave models incorporating LCC show that in a background-only scenario $\Delta\gamma_{a,b}$ scales linearly with v_2

DIRECTED FLOW

directed flow (v_1) usually decomposed into a rapidity-odd and rapidity-even component:

- v_1^{odd}: compressibility —> initial tilt / rotation of the system
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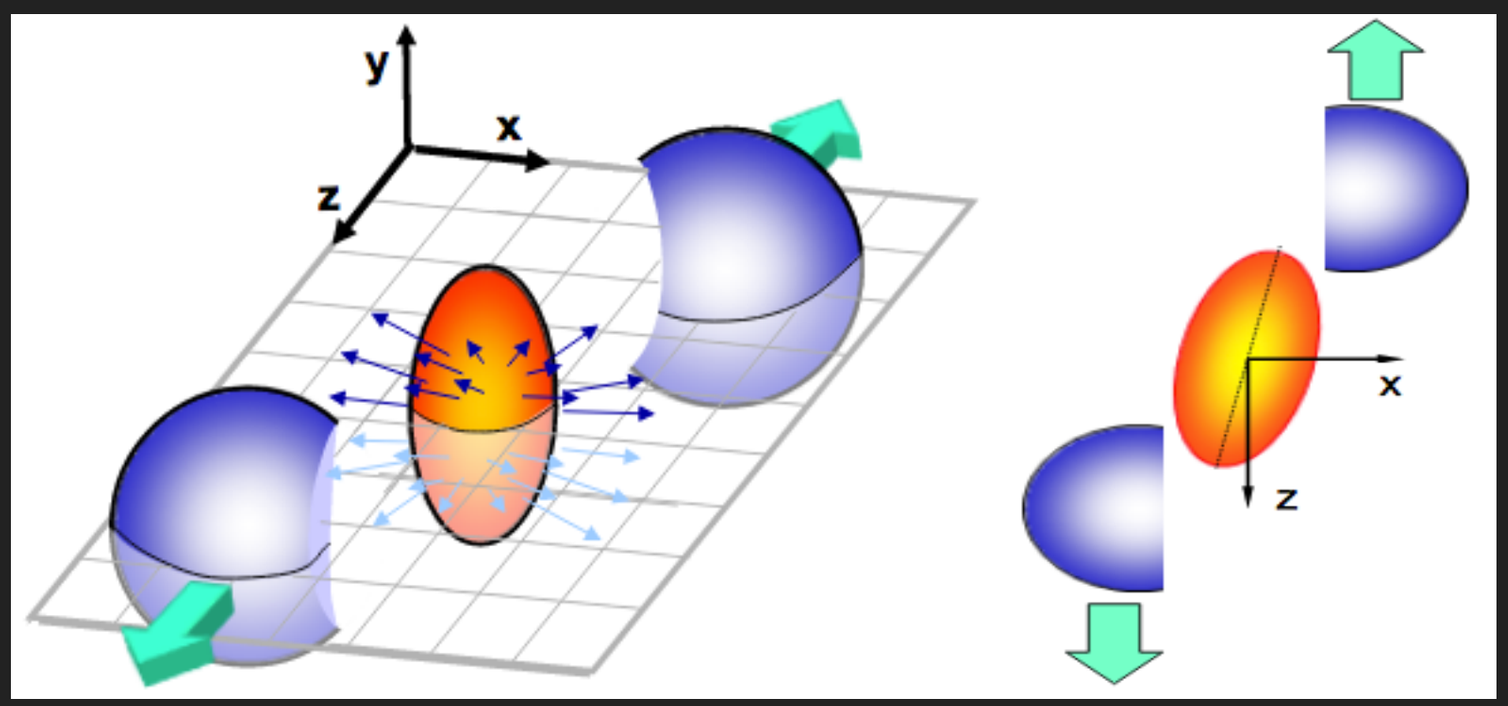

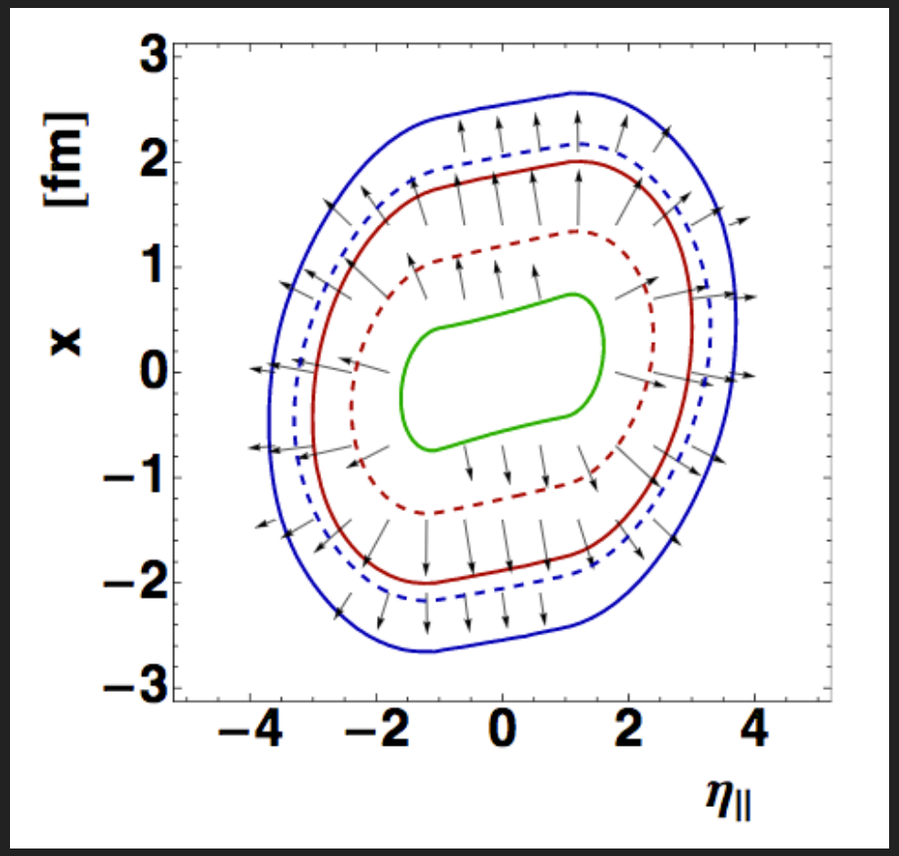

P. Bosek *et al.*, PRC 81 054902 (2010)

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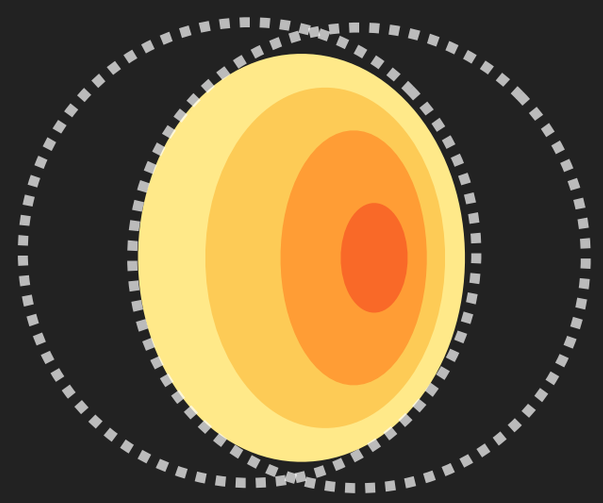
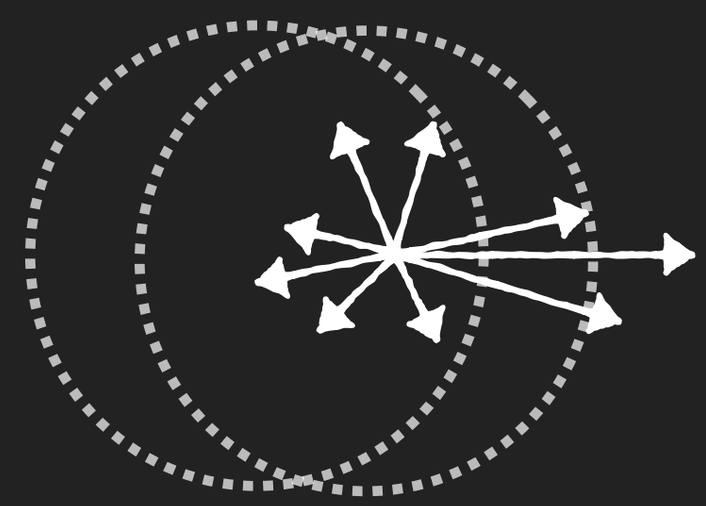
pressure



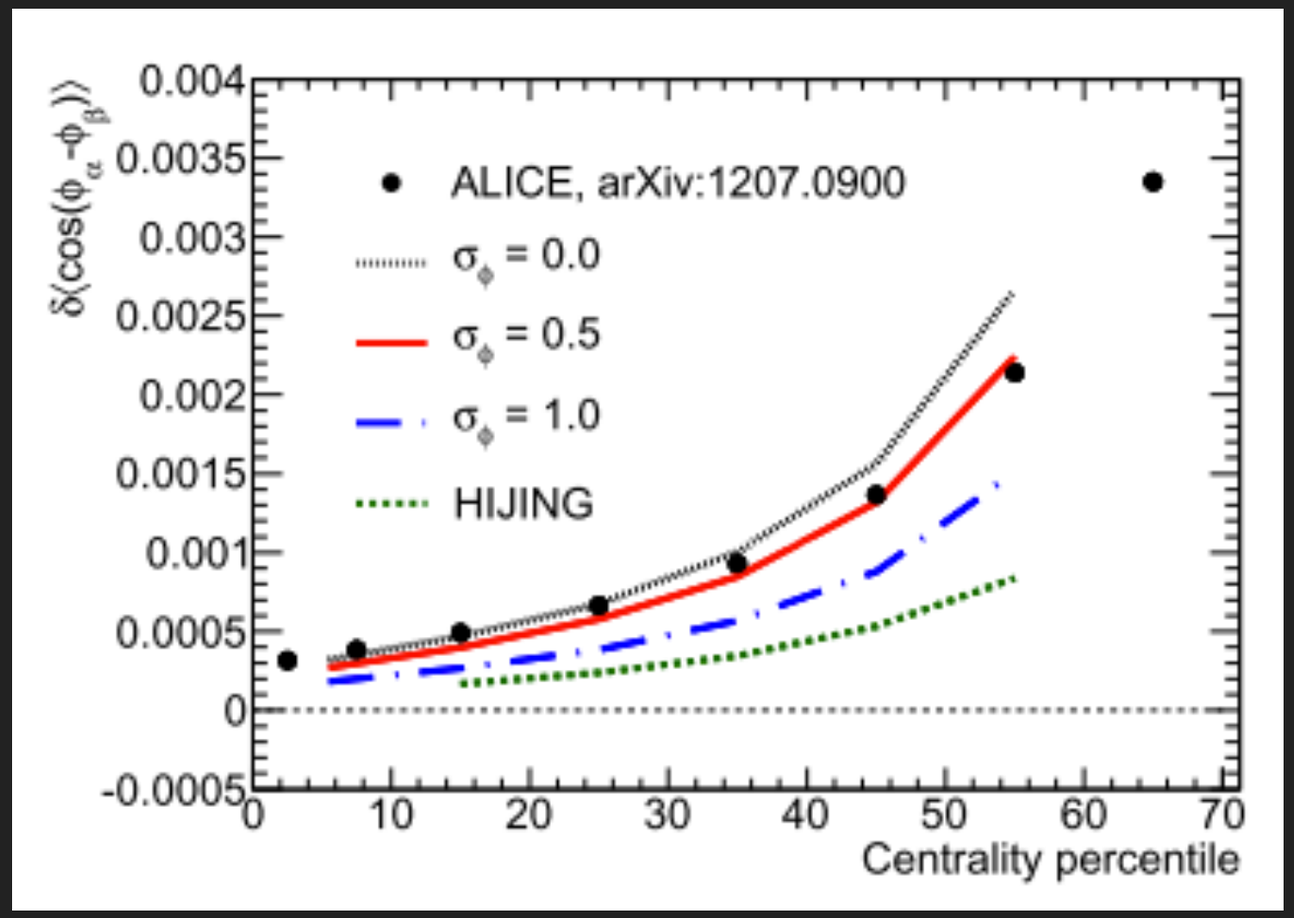
$$\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} P$$

hydro

momenta



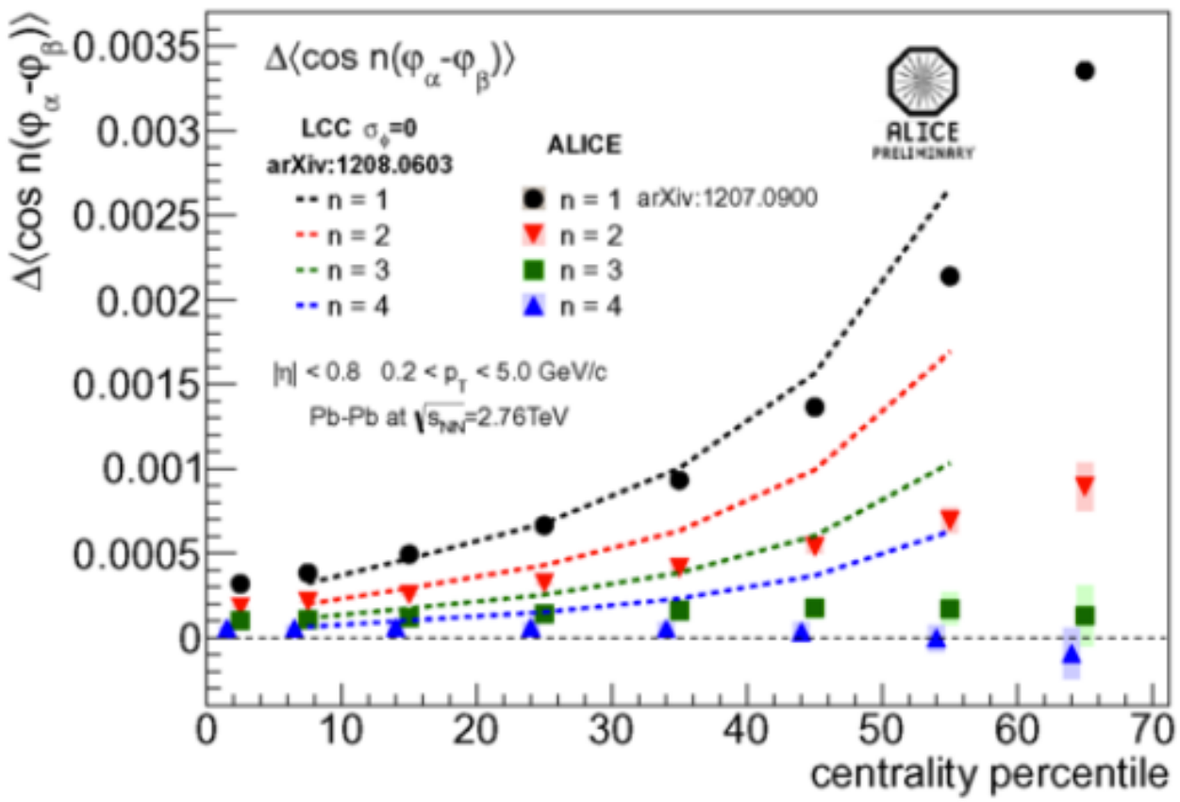
BACKGROUND VS DATA

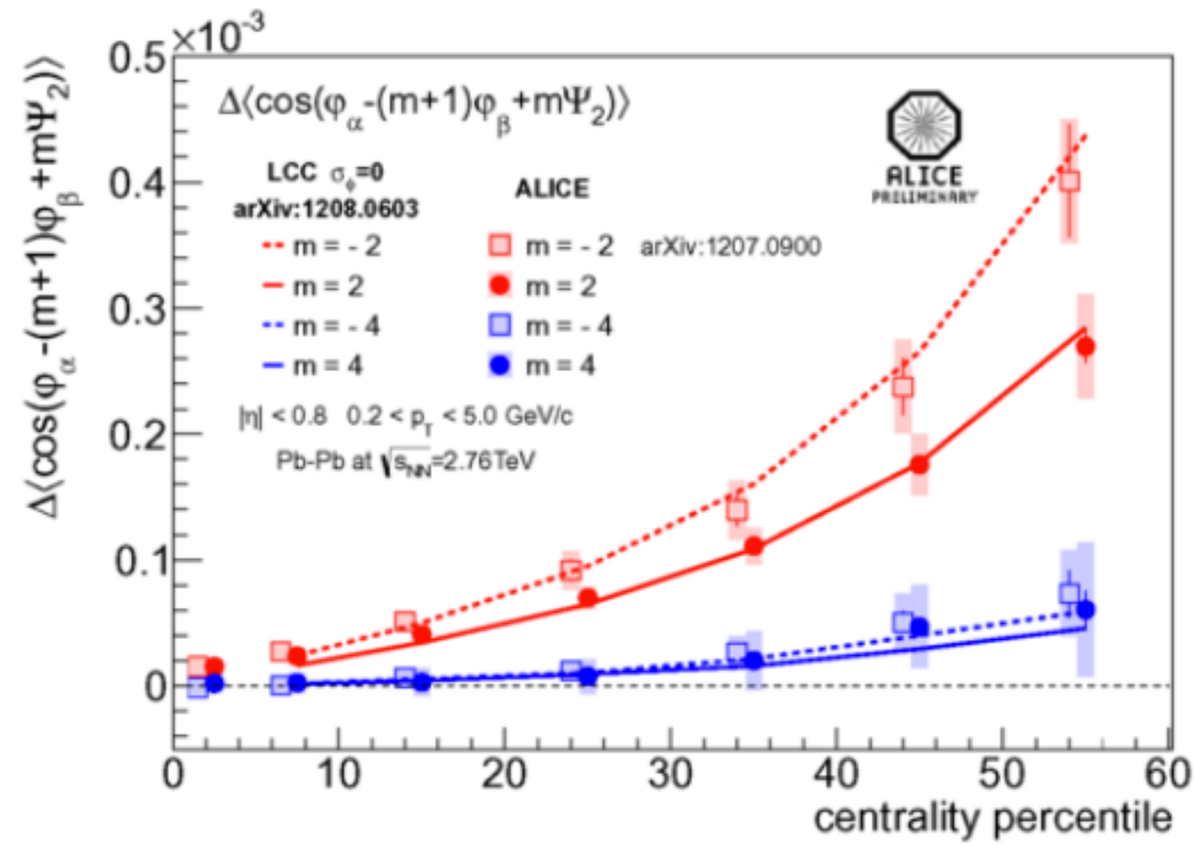


Y. Hori *et al.*, arXiv:1208.0603

Blast-Wave models incorporating LCC are able to explain the <u>entire</u> difference in $\Delta\delta_{ab}$ –> consistent with NO CME signal …

BACKGROUND VS DATA



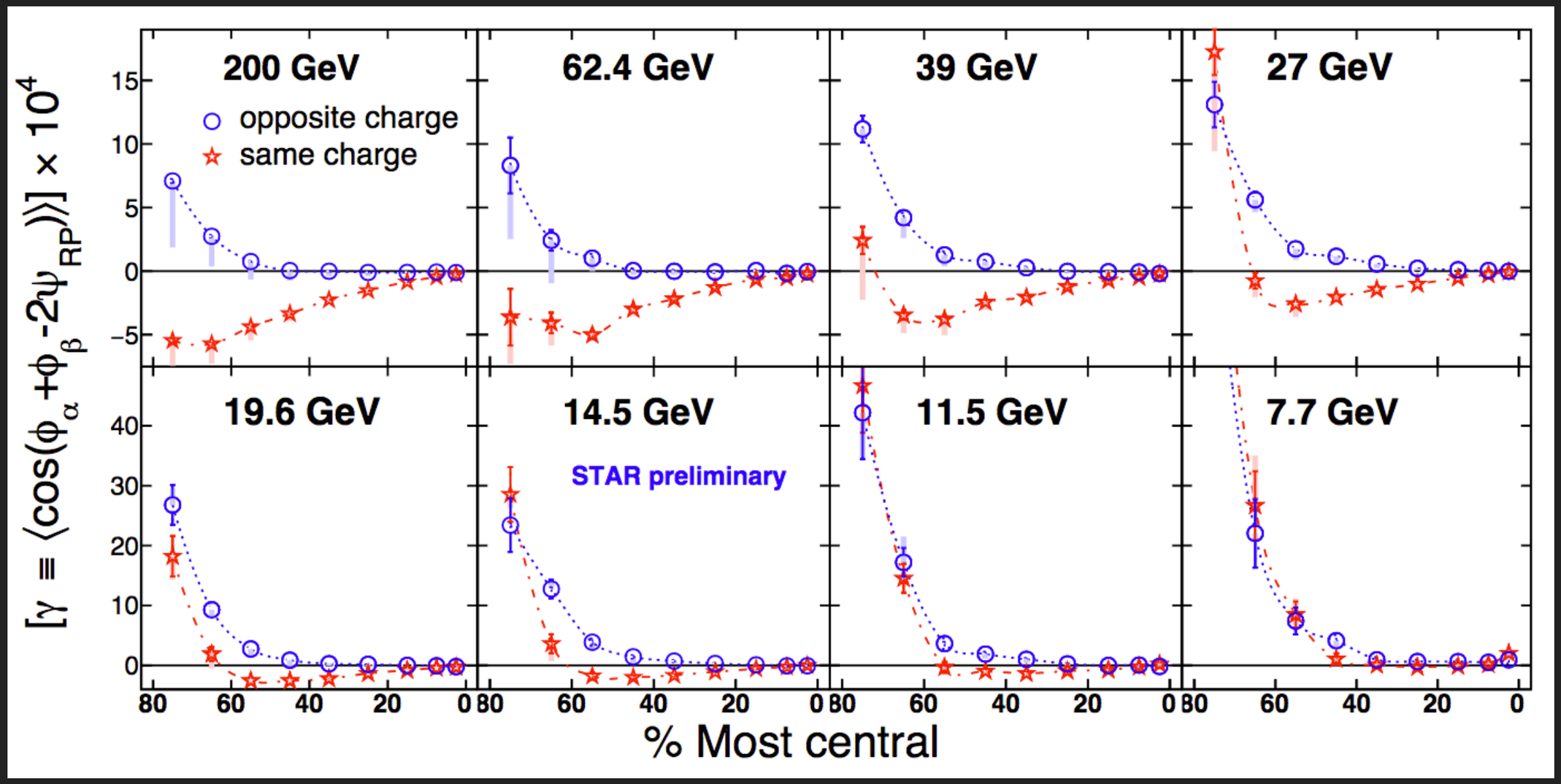


ALICE, NPA 904-905 (2013) 475c-478c

… but fail to reproduce all correlators simultaneously!
background remains largely unconstrained

ENERGY DEPENDENCE

STAR, PRL 113, 052302 (2014)



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

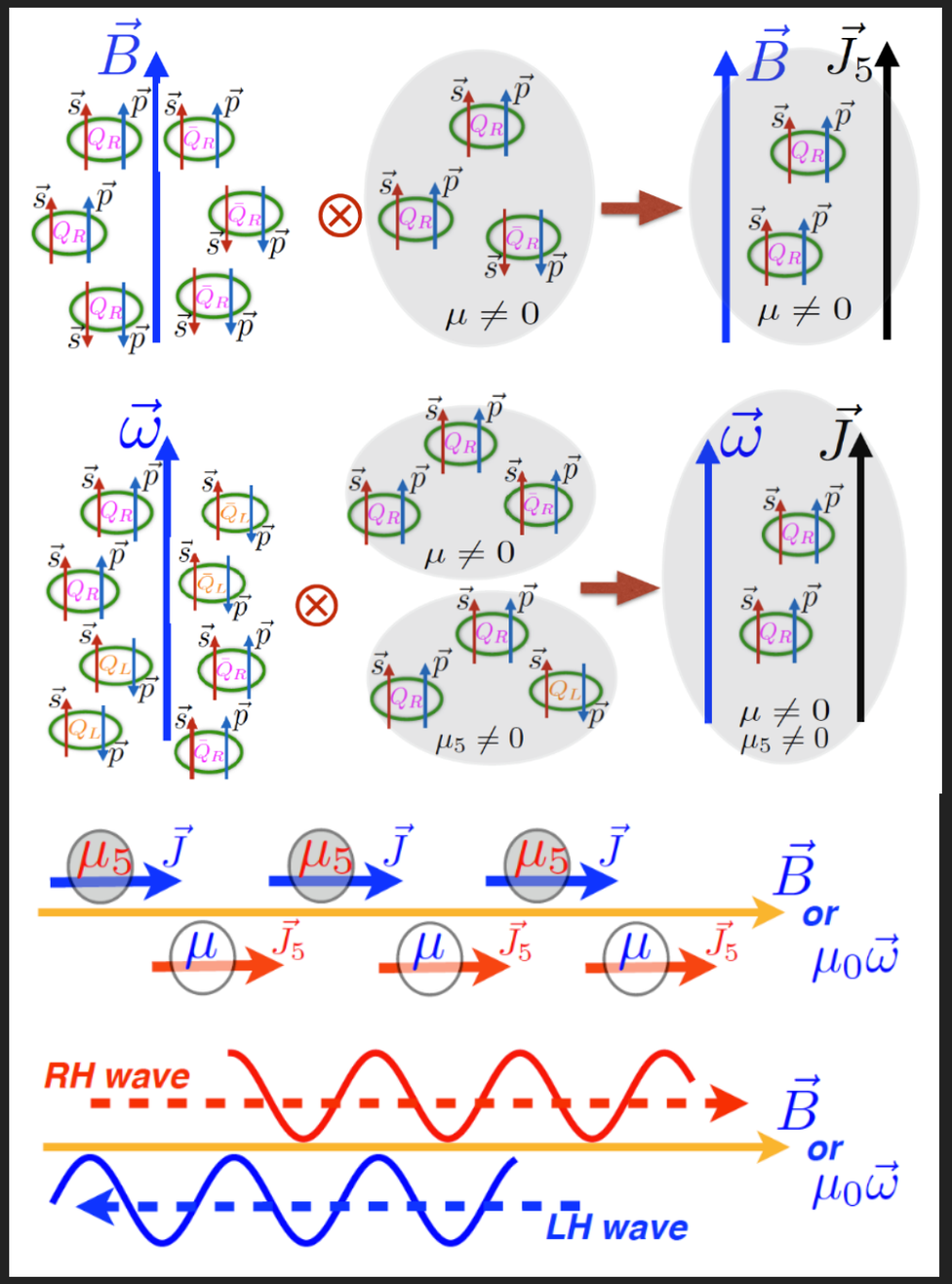
- $\Delta\gamma_{ab}$ decreases with energy: qualitative consistent with signal expectations
- not clear how the background depends on collision energy

ANOMALOUS CHIRAL EFFECTS

Several other phenomena predicted from the interplay of chiral imbalance + magnetic fields and/or angular momentum of the system

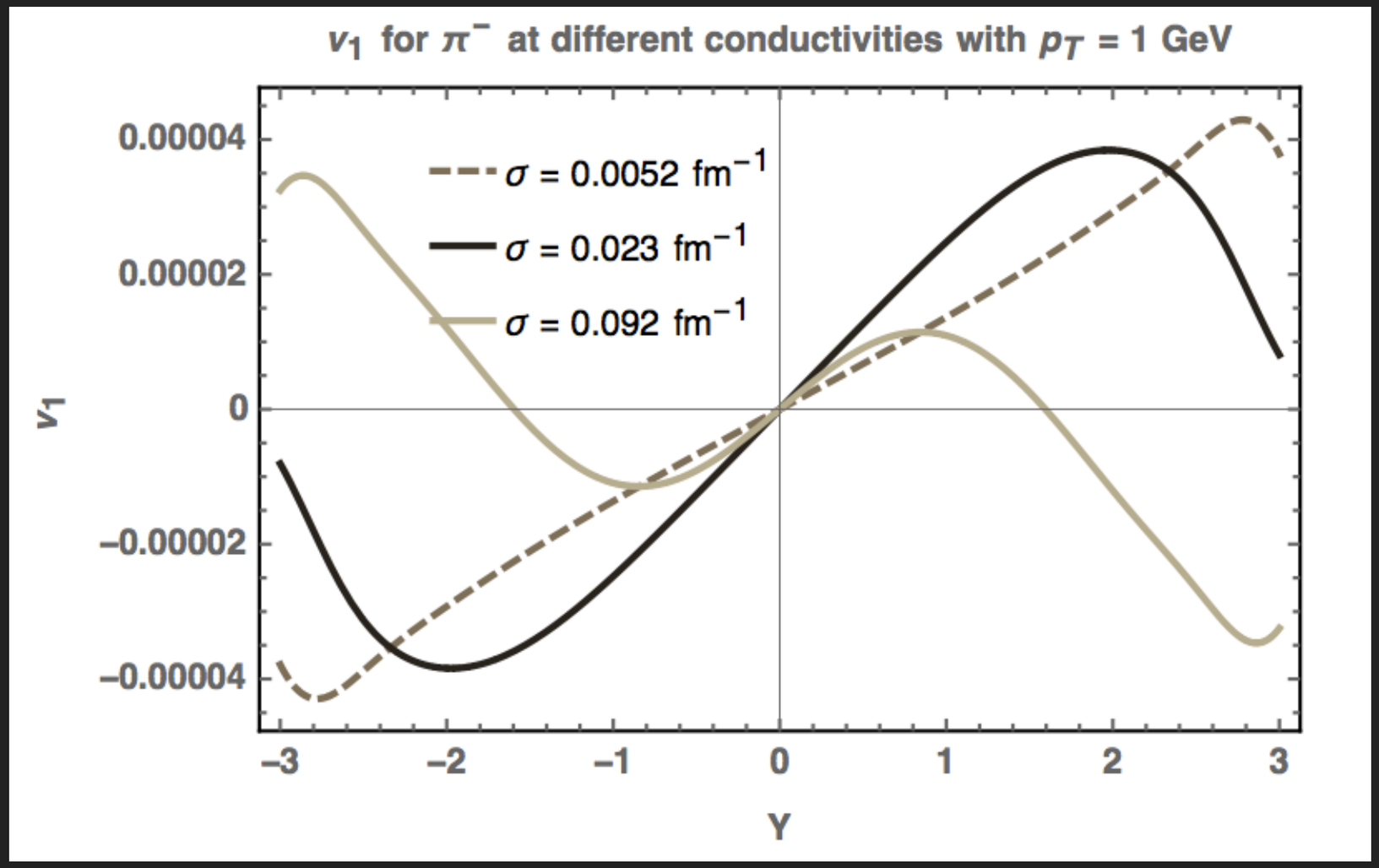
- Chiral Separation Effect (CSE)
- Chiral Electric Separation Effect (CESE)
- Chiral Vortical Effect (CVE)
- Chiral Magnetic Wave (CMW)
- Chiral Vortical Wave (CVW)

D. E. Kharzeev, Prog. Part. Nucl. Phys. 75, 133 (2014)
J. Liao, Pramana 84 , no. 5, 901 (2015)
D. E. Kharzeev, Ann. Rev. Nucl. Part. Sci. 65, 0000 (2015)
A. Bzdak *et al.*, Lect. Notes Phys. 871 503 (2013
V. A. Miransky *et al.*, Phys. Rept. 576, 1 (2015)
X. G. Huang, arXiv:1509.04073



D.E. Kharzeev *et al.*, arXiv:1511.04050

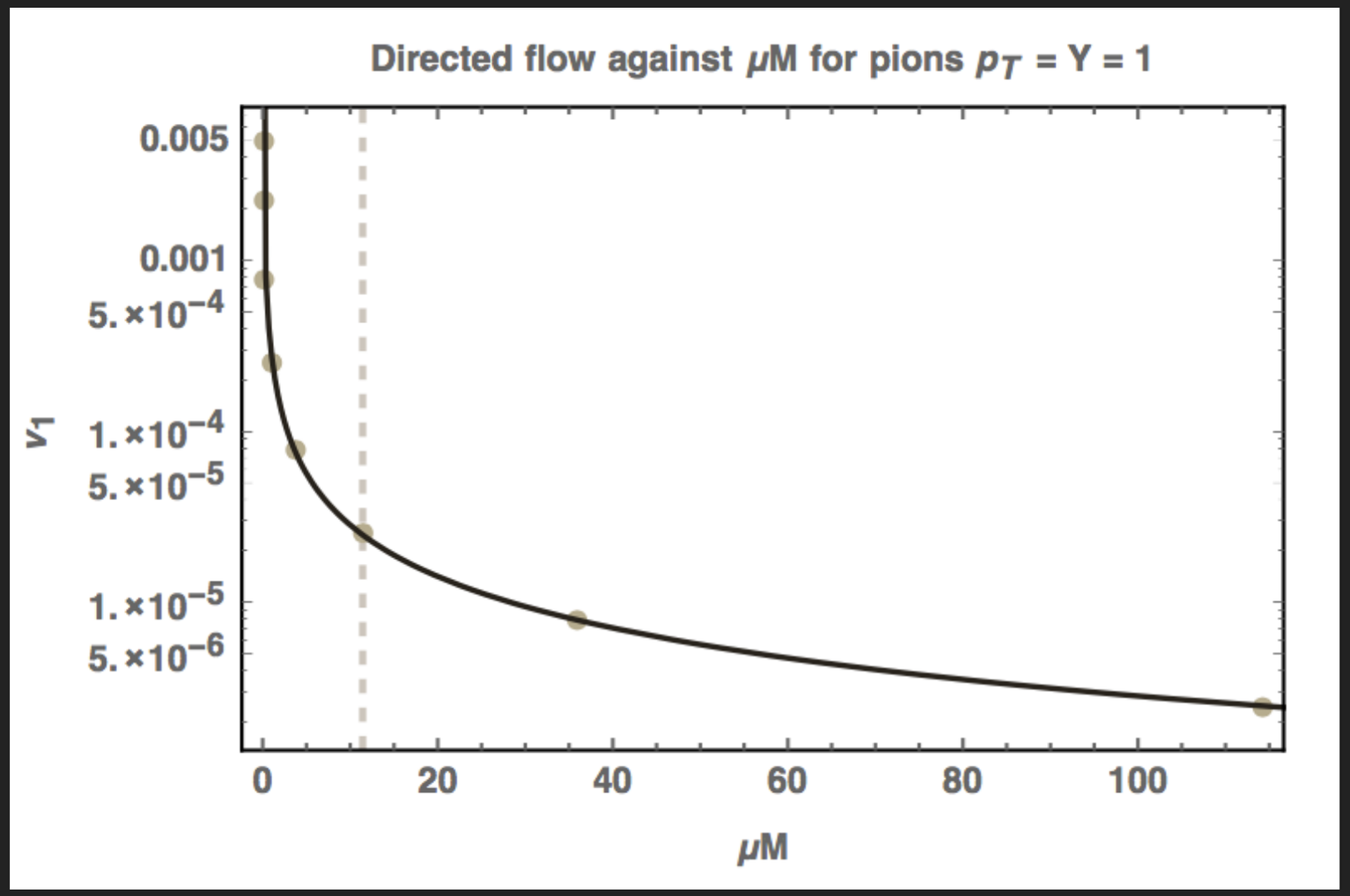
theory uncertainties: QGP conductivity



- QGP conductivity σ = 0.023 fm^{-1} taken from lattice calculations
- small effect on dv_1/dY at mid-rapidity (|Y|<1)

from E. Marcus, "Magnetohydrodynamics at Heavy Ion Collisions", Bachelor thesis (Utrecht University)

theory uncertainties: drag coeff.



- drag coefficient μm taken from heavy quarks in N = 4 SYM
- v_1 extremely sensitive around <μm>

from E. Marcus, "Magnetohydrodynamics at Heavy Ion Collisions", Bachelor thesis (Utrecht University)

predictions at LHC: protons

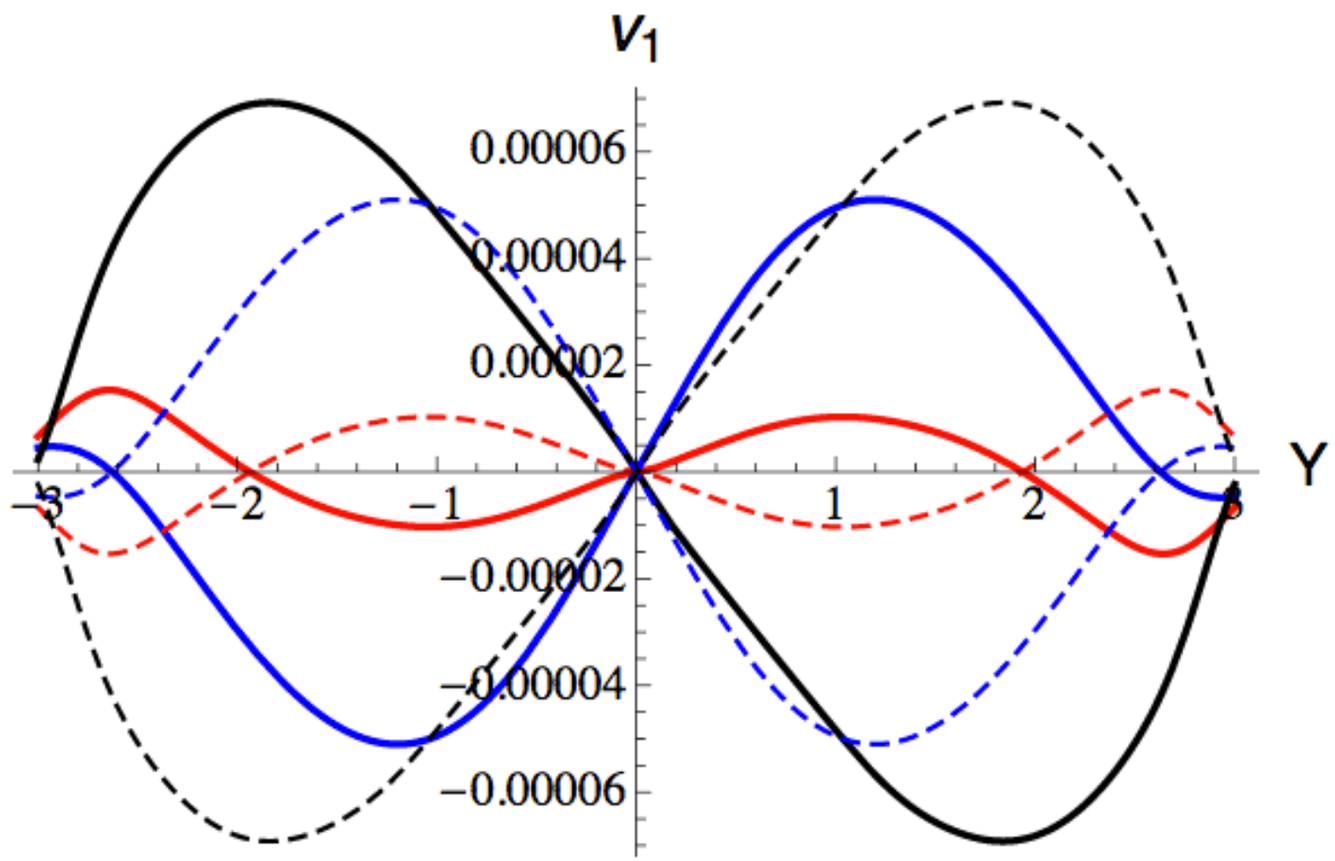


FIG. 6: v_1 for protons (solid curves) and antiprotons (dashed curves) in our calculation with the same parameters as in Fig. 4, namely parameters chosen with 20-30% centrality heavy ion collisions at the LHC in mind. We plot v_1 as a function of momentum space rapidity Y at $p_T = 0.5$ (blue), 1 (red) and 2 GeV (black).

arXiv:1401.3805

predictions at RHIC

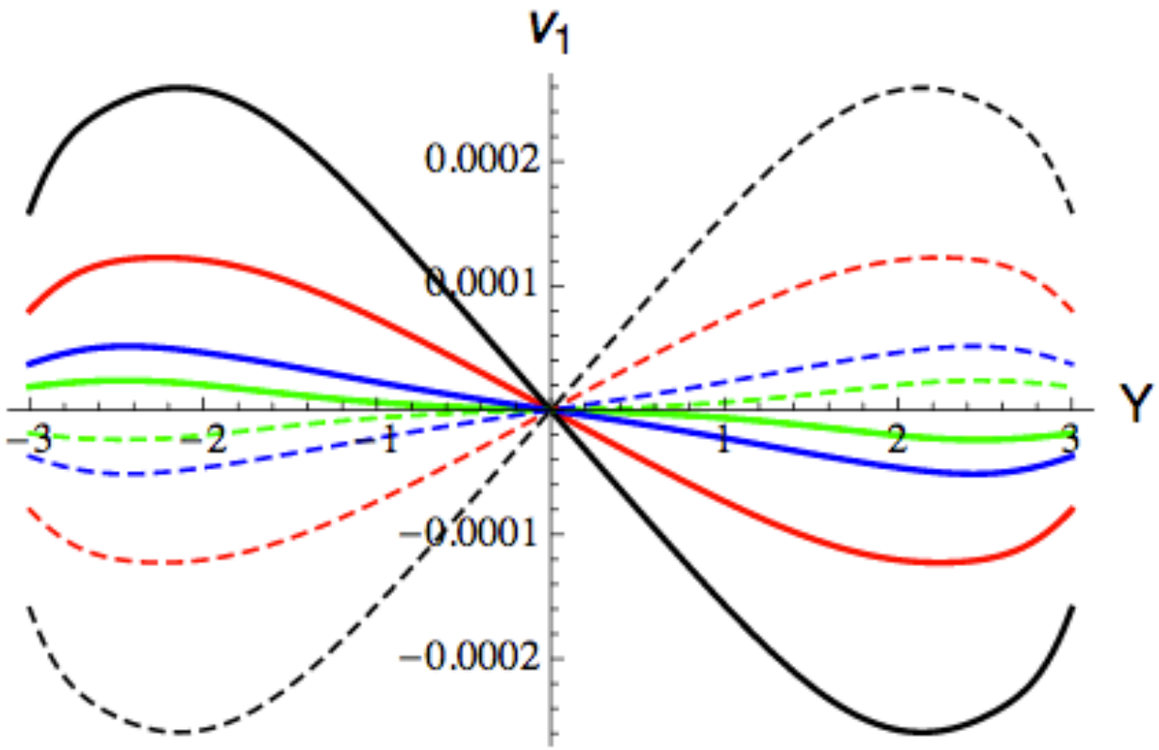


FIG. 7: v_1 for positively (solid curves) and negatively (dashed curves) charged pions with parameters chosen as for a 20-30% centrality heavy ion collision at RHIC. We plot v_1 as a function of momentum space rapidity Y at $p_T = 0.25$ (green), 0.5 (blue) 1 (red) and 2 GeV (black). Antiprotons are not displayed in this figure for visual clarity.

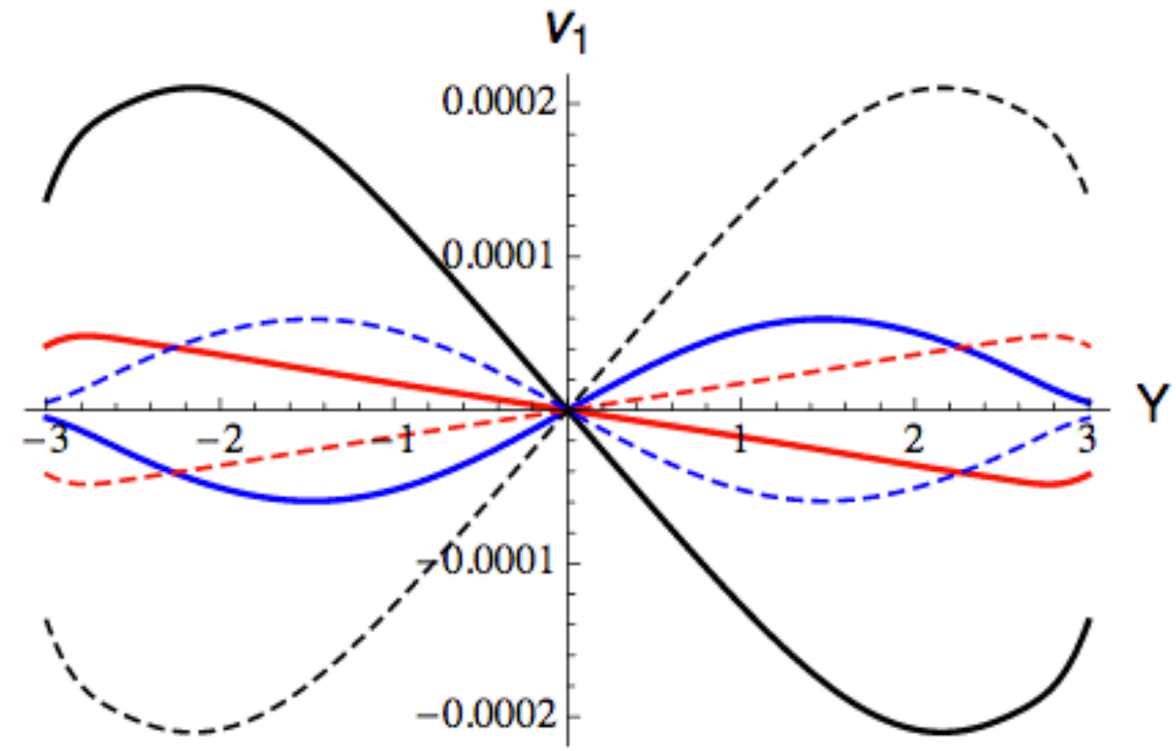
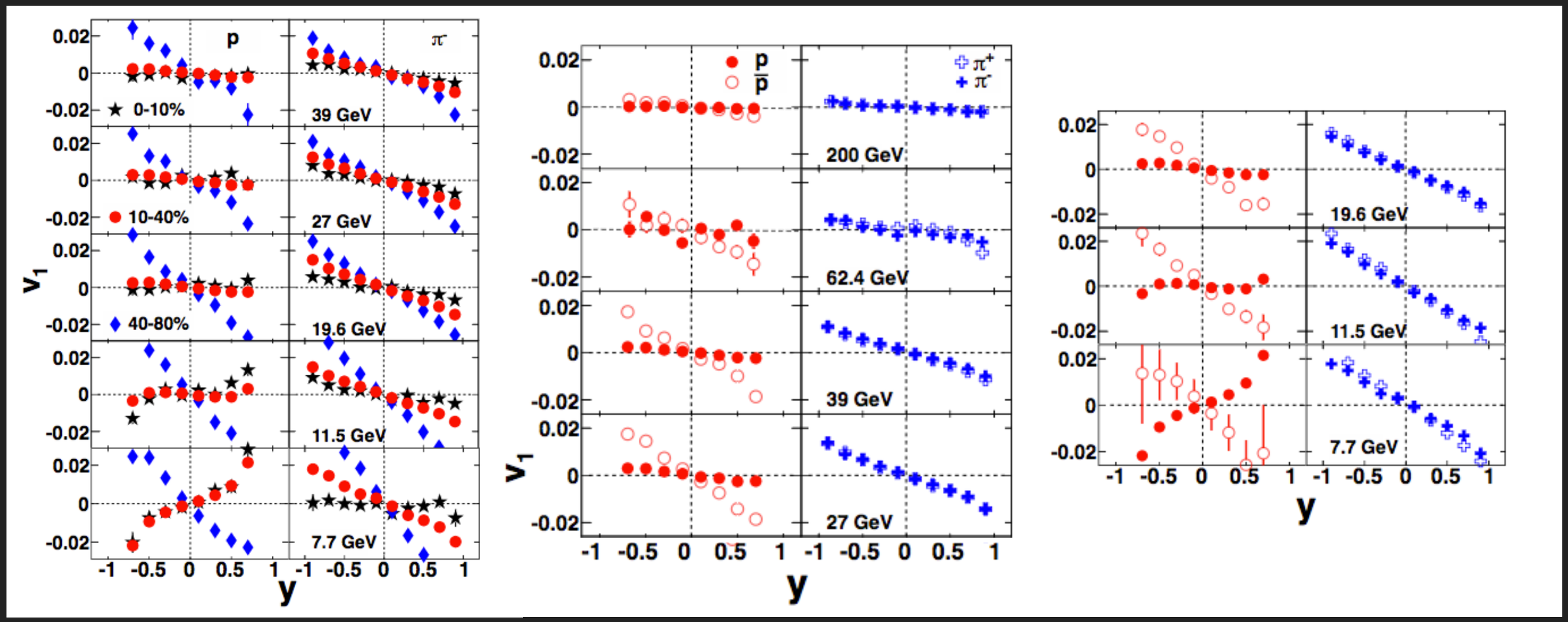


FIG. 8: v_1 for protons with parameters chosen as in Fig. 7, so as to yield estimates for RHIC. We plot v_1 as a function of Y at $p_T = 0.5$ (blue), 1 (red) and 2 GeV (black). Anti-protons are not displayed in this figure for visual clarity.

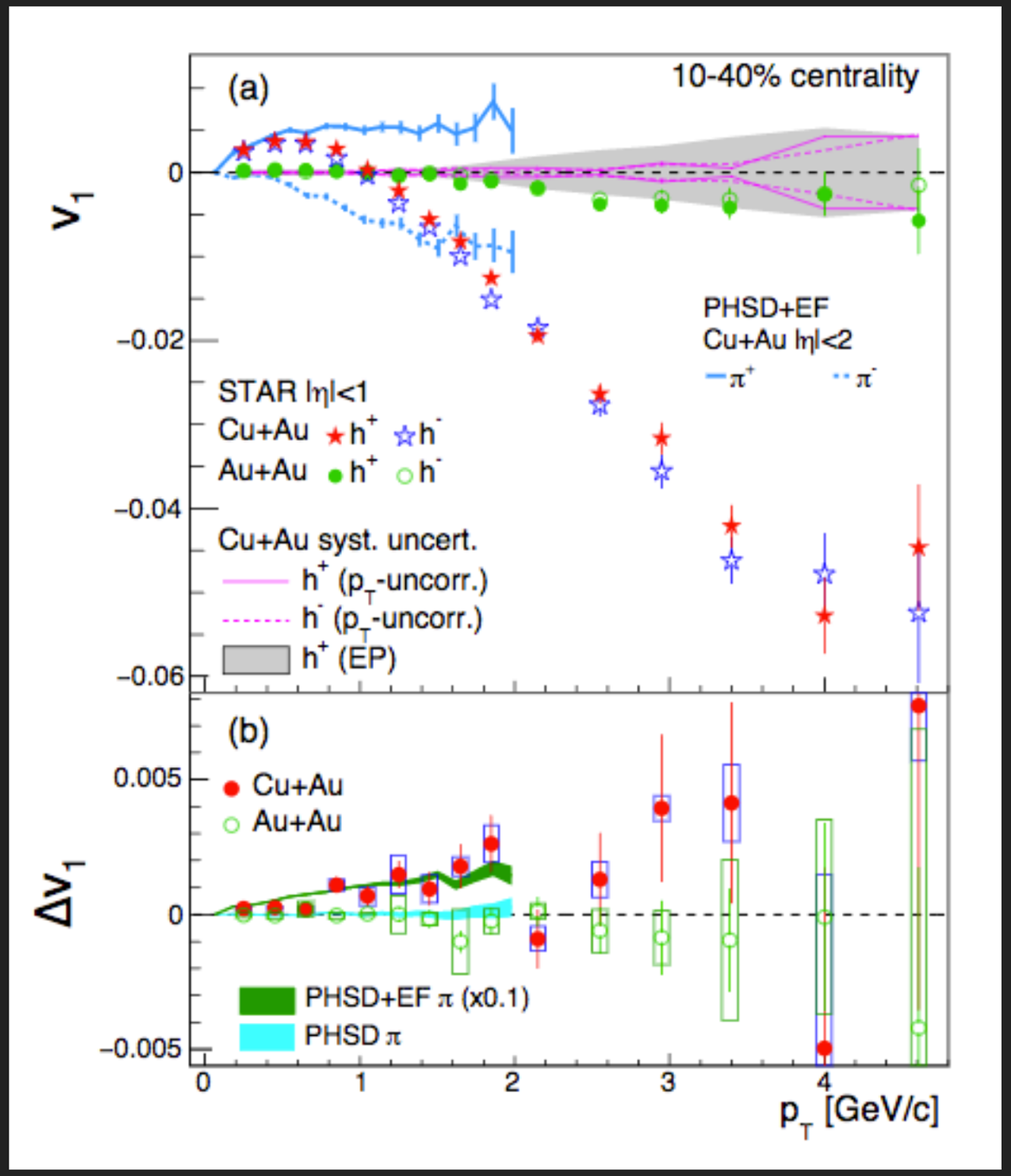
arXiv:1401.3805

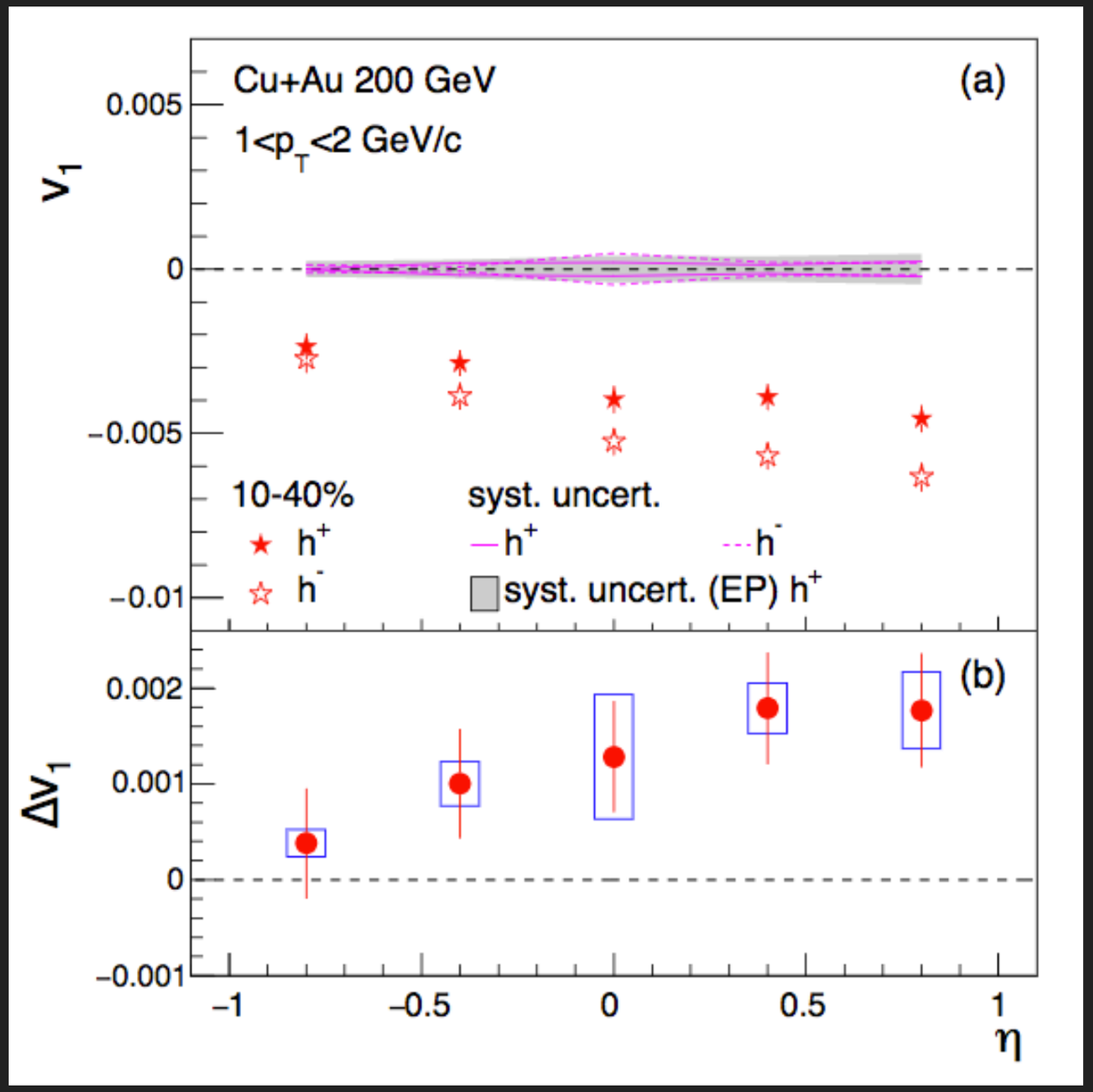
v_1^{odd} from BES I (STAR)



STAR, PRL 112 (2014) 162301

Δv_1^{odd} in Cu-Au @ 200 GeV (STAR)



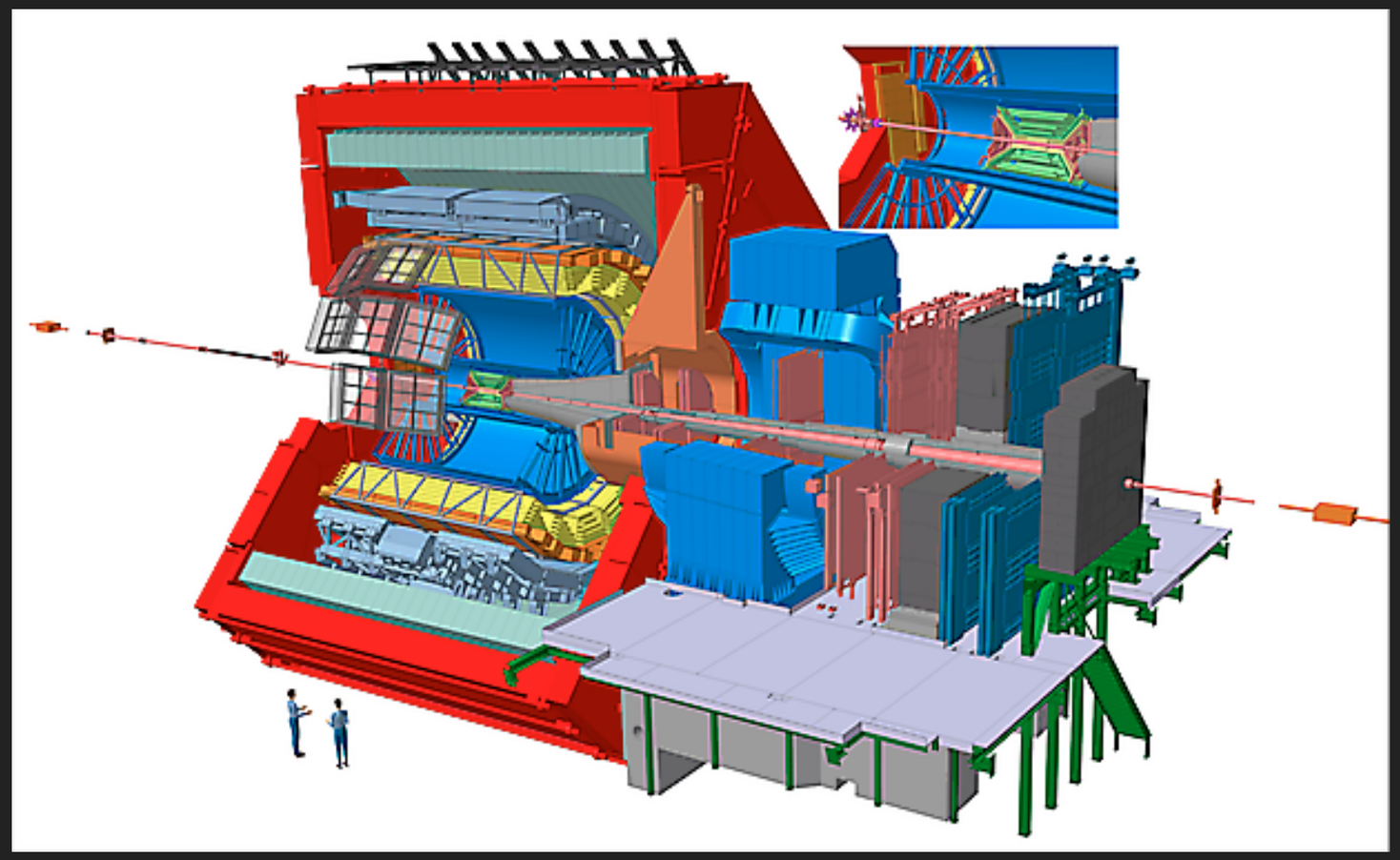


STAR, PRL 118 (2017) 012301

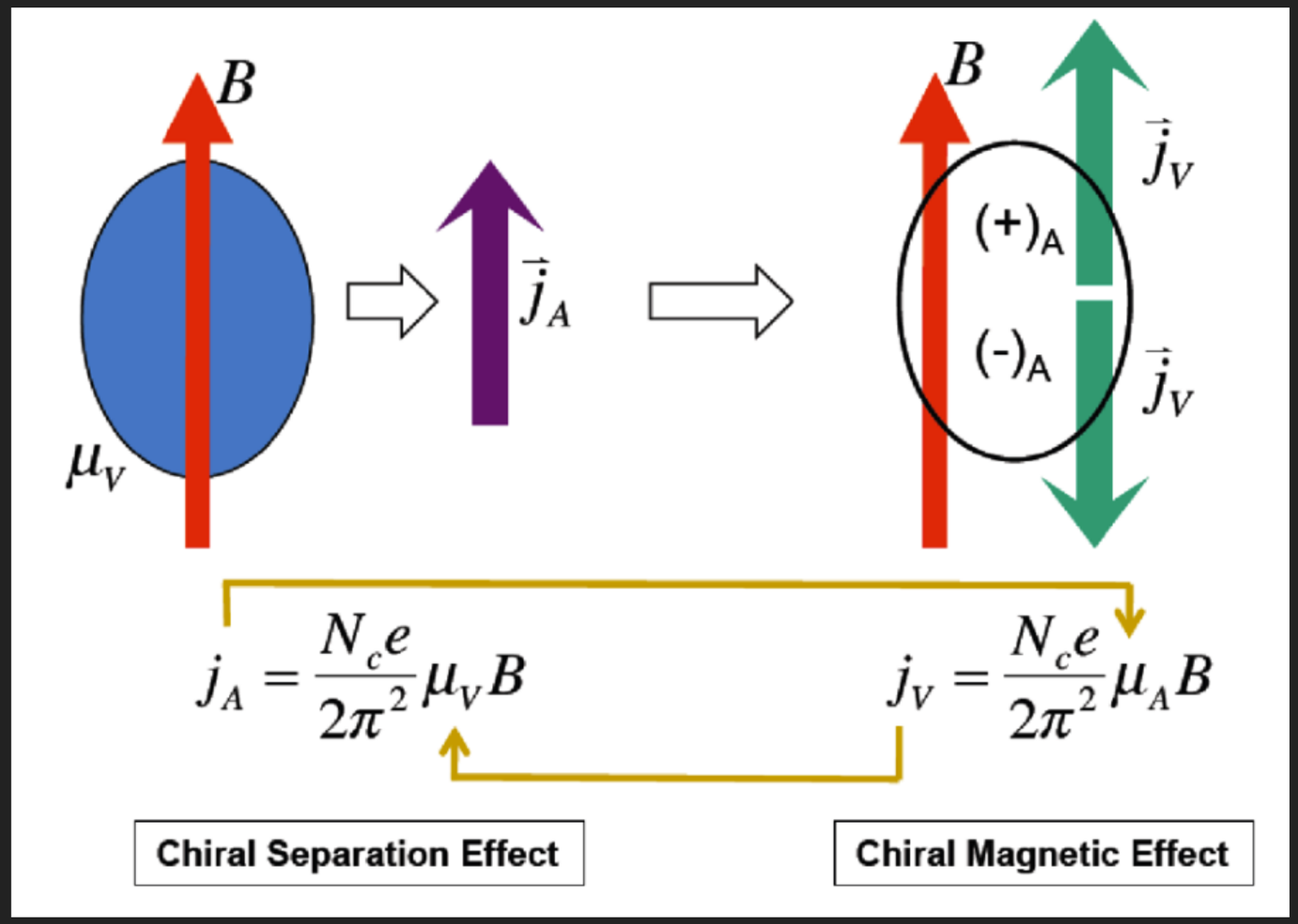
detectors and data samples

- Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, $55 \cdot 10^6$ minimum bias events
- Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, $14 \cdot 10^6$ minimum bias events
- track selection: $|\eta| < 0.8$, $p_T > 0.2$ GeV/c

- Time-Projection Chamber
  tracking, vertexing
- Inner Tracking System
  tracking vertexing
- V0
  trigger, centrality
- Zero Degree Calorimeters
  spectator plane

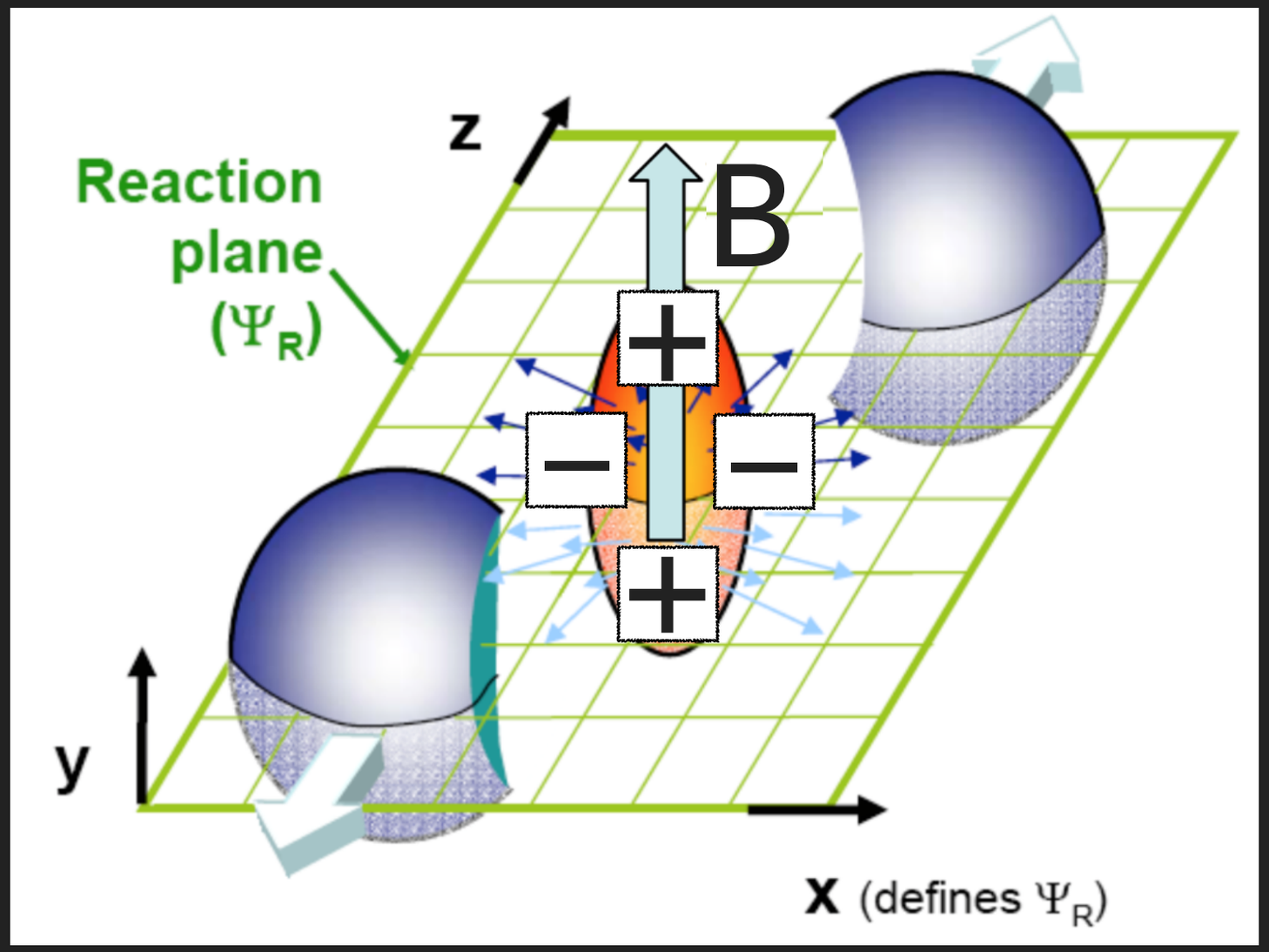


CHIRAL MAGNETIC WAVE



Electric charge separation (CME) is coupled to chiral charge separation (CSE); the two, combined, give rise to what is called Chiral Magnetic Wave (CMW)

CHIRAL MAGNETIC WAVE



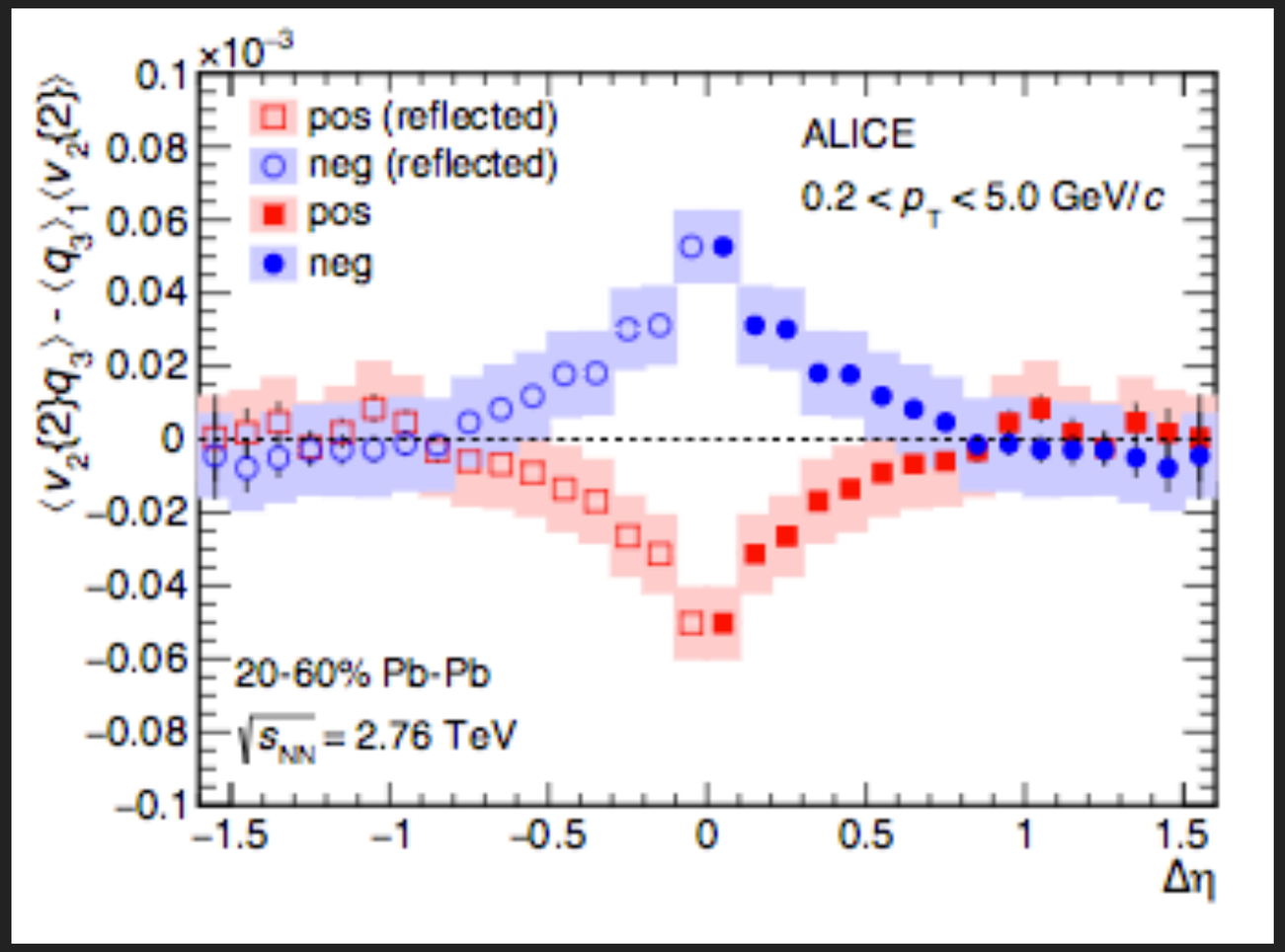
the experimental observable: charge-dependent elliptic flow

CMW MEASUREMENTS

Measured with the 3-particle correlator:

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

S. Voloshin, R. Belmont
arXiv:1408.0714



ALICE, arXiv:1512.05739

allows more differential studies –> more discriminating power