The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

Study of the Chiral Magnetic Effect and the strong magnetic field at the LHC with ALICE

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Strong magnetic field & chiral anomaly in heavy-ion collisions

- In non-central heavy-ion collisions an unprecedented intense magnetic field (~10^{18} G) is generated by the movement of the spectator protons

- In the presence of such magnetic field, several anomalous chiral effects, such as
  Chiral Magnetic Effect,
  Chiral Magnetic Wave, etc, have been theorized to be created in QGP
  ✓ Possible local CP violation in strong interactions
  ✓ The novel topological nature of the QCD vacuum

- ALICE, CMS and STAR experiments have been putting efforts into such studies for more than a decade

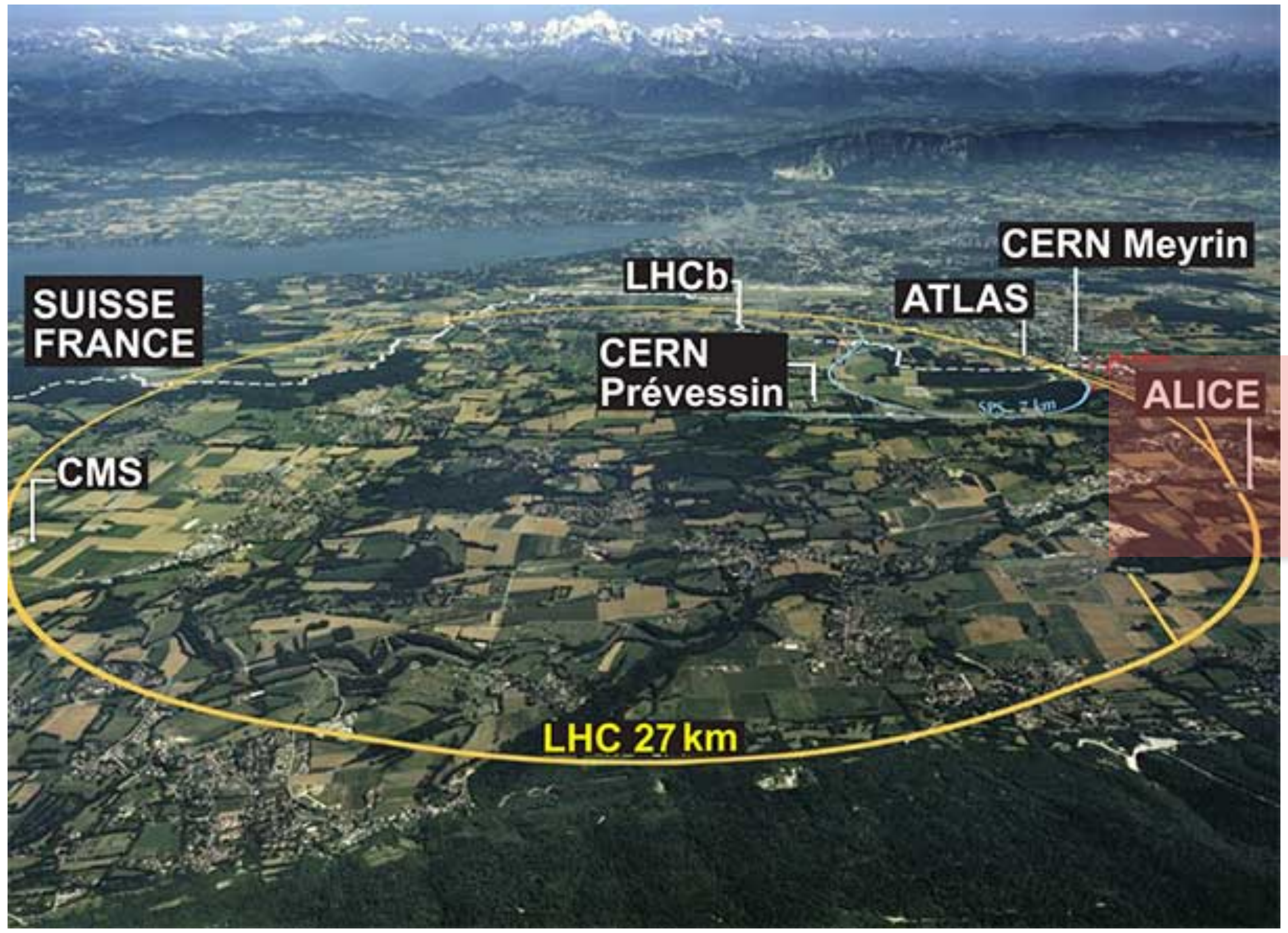
Strong magnetic field & chiral anomaly in heavy-ion collisions

- Observables and methodology
  - ✓ B field: charge dependent directed flow, etc
  - ✓ CME: γ and δ correlator (κ and H), Event Shape Engineering, invariant mass, R(ΔS), etc
  - ✓ CMW: charge asymmetry dependent flow, three particle correlation, etc

- Collisions systems and energies
  - ✓ Pb-Pb, p-Pb, Xe-Xe ➔ ✓ 2.76 TeV, 5.02 TeV, 5.44 TeV at LHC
  - ✓ Au+Au, p(d)+Au, U+U ➔ ✓ BES (7-62 GeV), 200 GeV, 193 GeV at RHIC

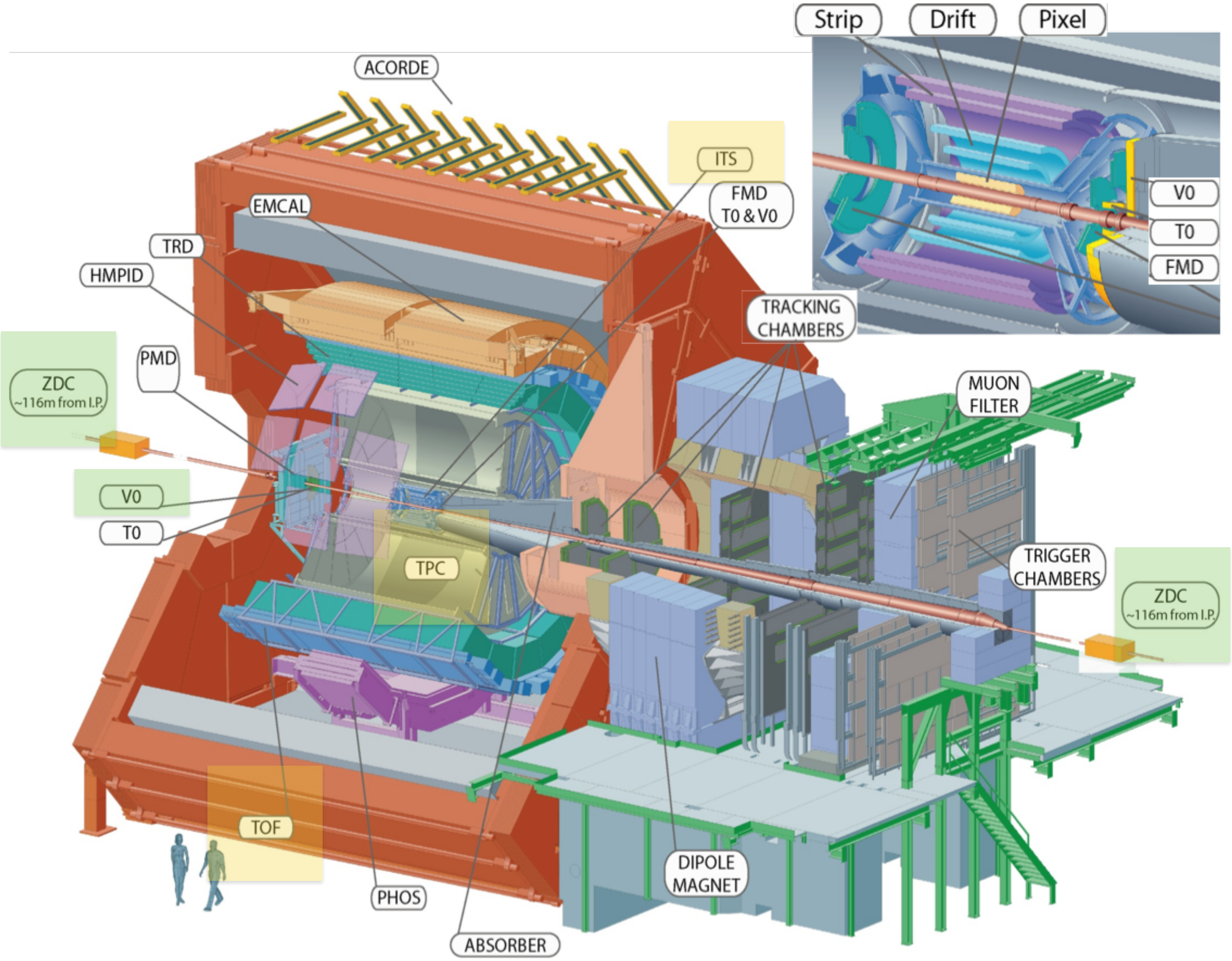
- Particle of interest
  - ✓ Inclusive charged particles
  - ✓ Identified particles: π, K, p, heavy-flavour, etc at various kinematic windows (p_T, η, etc)

A Large Ion Collider Experiment



Central:
Inner Tracking System,
Time Projection Chamber,
Time of Flight:
tracking, vertexing, particle identification

Forward:
Zero Degree Calorimeters: reaction plane
V0: trigger, centrality, EP estimation



PART 1

Search for the **CME** with two- and three-particle correlation and Event Shape Engineering at 2.76 and 5.06 TeV Pb-Pb collisions

Experimental measurement of CME (Timeline of publication)

ALICE

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions
Phys. Rev. C 81, 054908 (2010).

Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
Phys. Rev. Lett. 110, 012301 (2013).

Fluctuations of charge separation perpendicular to the event plane and local parity violation in $\sqrt{s_{NN}}$ = 200 GeV Au + Au collisions at the BNL Relativistic Heavy Ion Collider
Phys. Rev. C 88, 064911 (2013).

Observation of Charge-Dependent Azimuthal Correlations in p-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect
Phys. Rev. Lett. 118, 122301 (2017).

2009 | 2010 | … | 2013 | 2014 | … | 2017 | 2018 | 2019

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation
Phys. Rev. Lett. 103, 251601 (2009).

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au+Au Collisions at RHIC
Phys. Rev. Lett. 113, 052302 (2014).

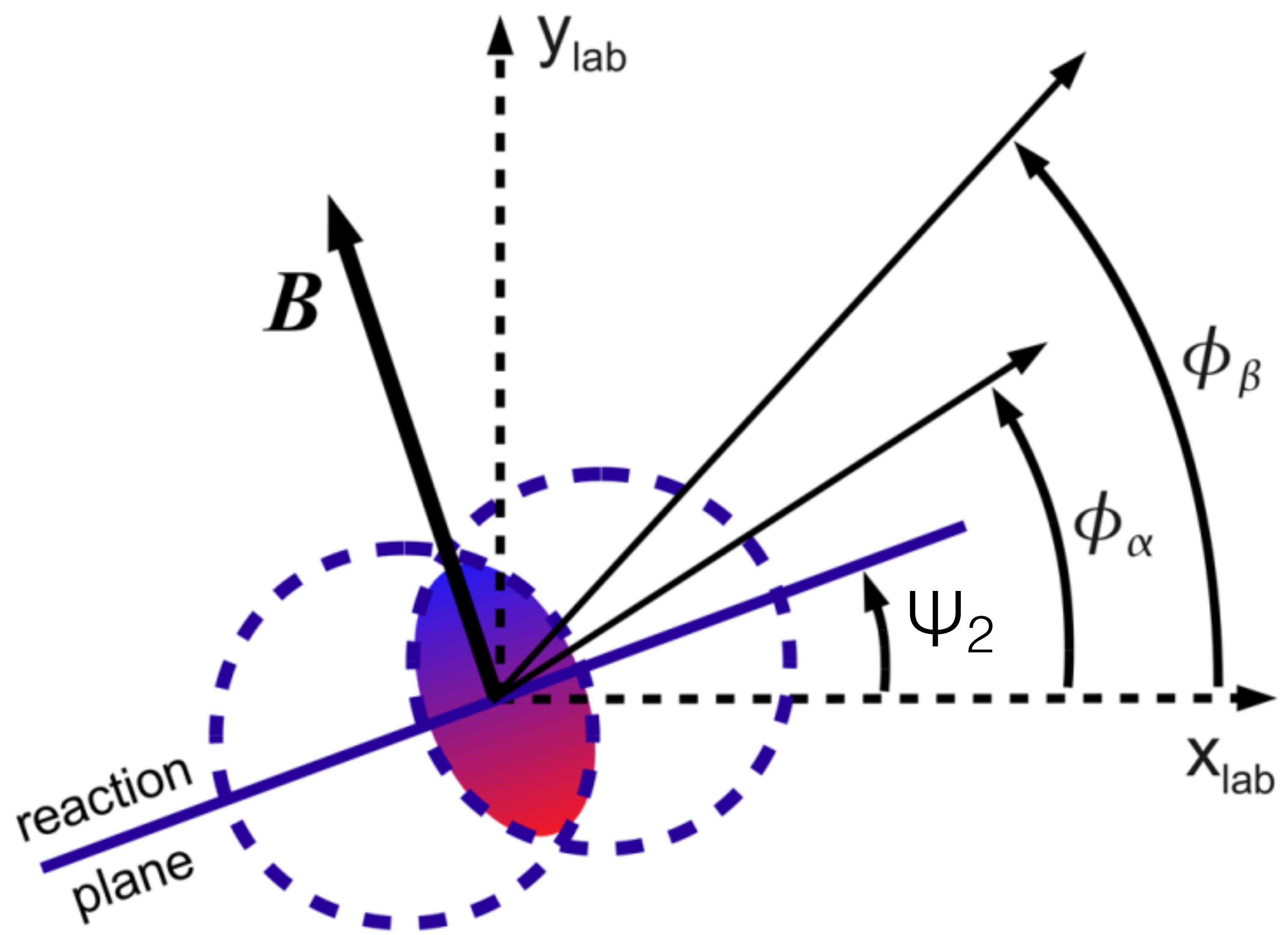
Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 200 GeV
Phys. Rev. C 89, 044908 (2014).

Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
Physics Letters B 777, 151 (2018).

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider
Phys. Rev. C 97, 044912 (2018).

ALICE
CMS
STAR

Measurement of CME with two- and three-particle correlation



$\delta_{11} \equiv \langle\cos(\phi_\alpha - \phi_\beta)\rangle = \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle + \boldsymbol{\langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle}$

$\gamma_{112} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle = \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \boldsymbol{\langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle}$

- ✓ Sensitive to CME
- ✓ Unfortunately also sensitive to the backgrounds

$\gamma_{132} \equiv \langle\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle$

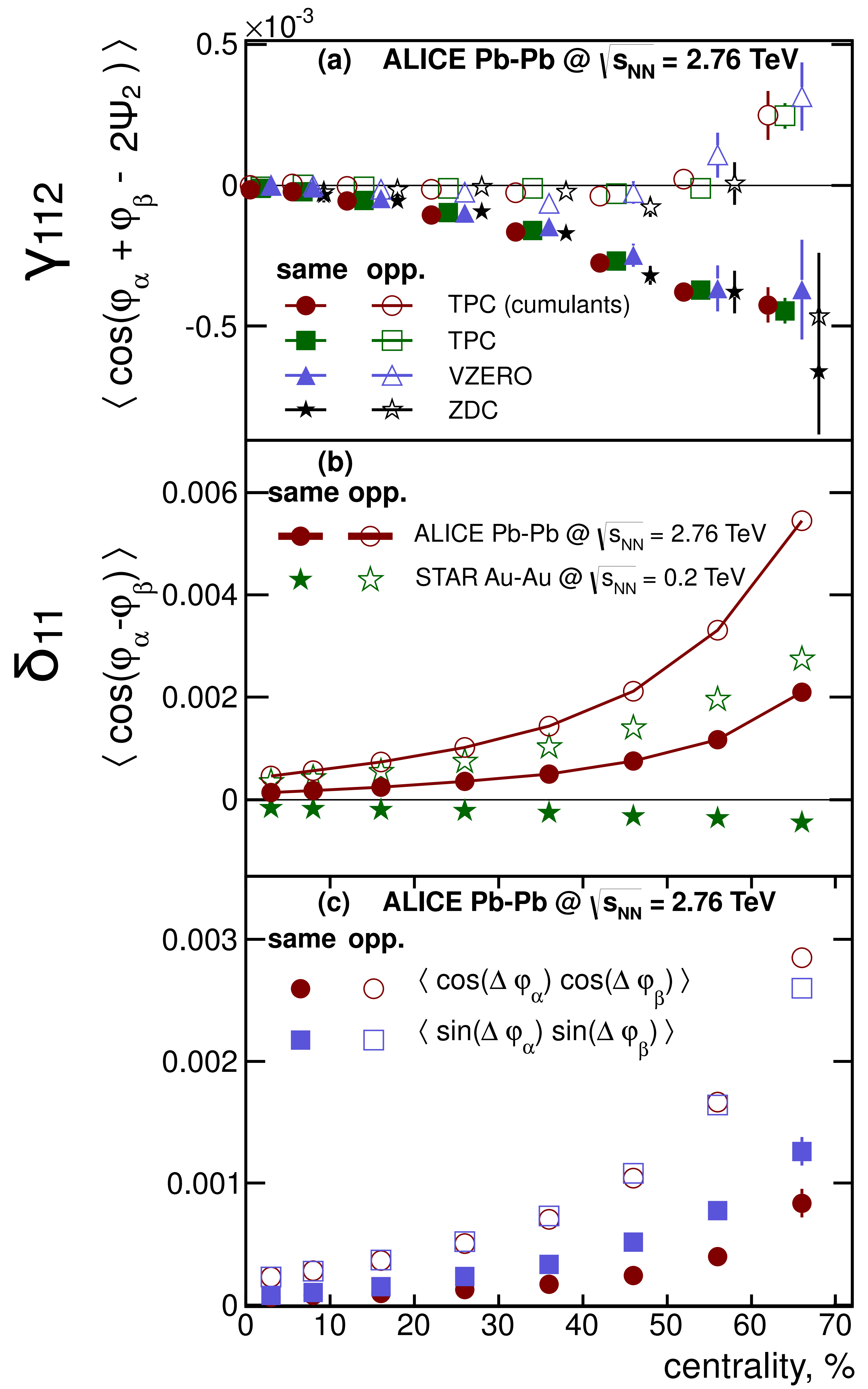
$\gamma_{123} \equiv \langle\cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle$

…

- ✓ Not sensitive to CME
- ✓ Could be used to estimate the background effects in γ_{112}

γ_{112} and δ_{11} at 2.76 TeV Pb-Pb collisions

Phys. Rev. Lett. 110, 012301 (2013).

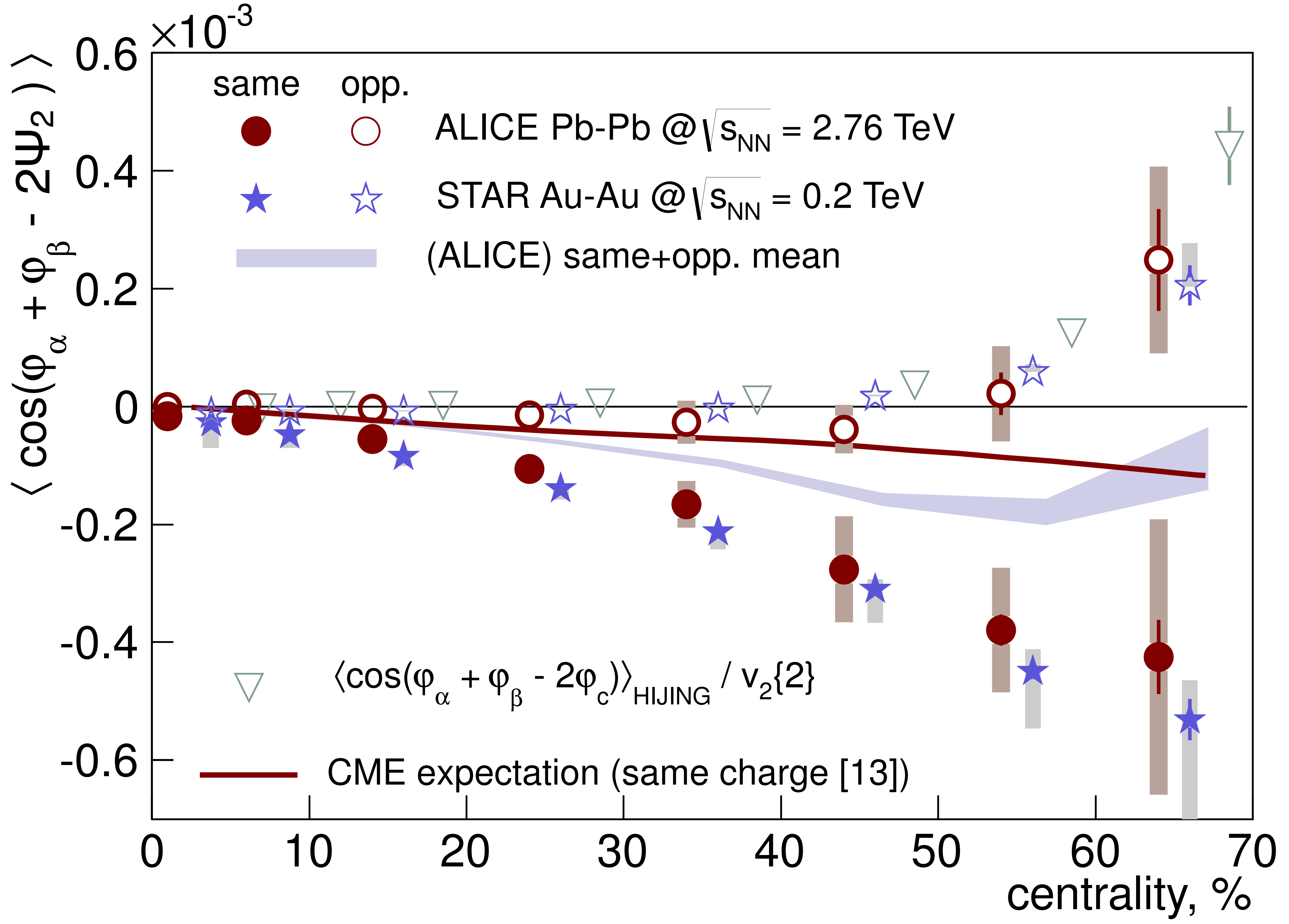


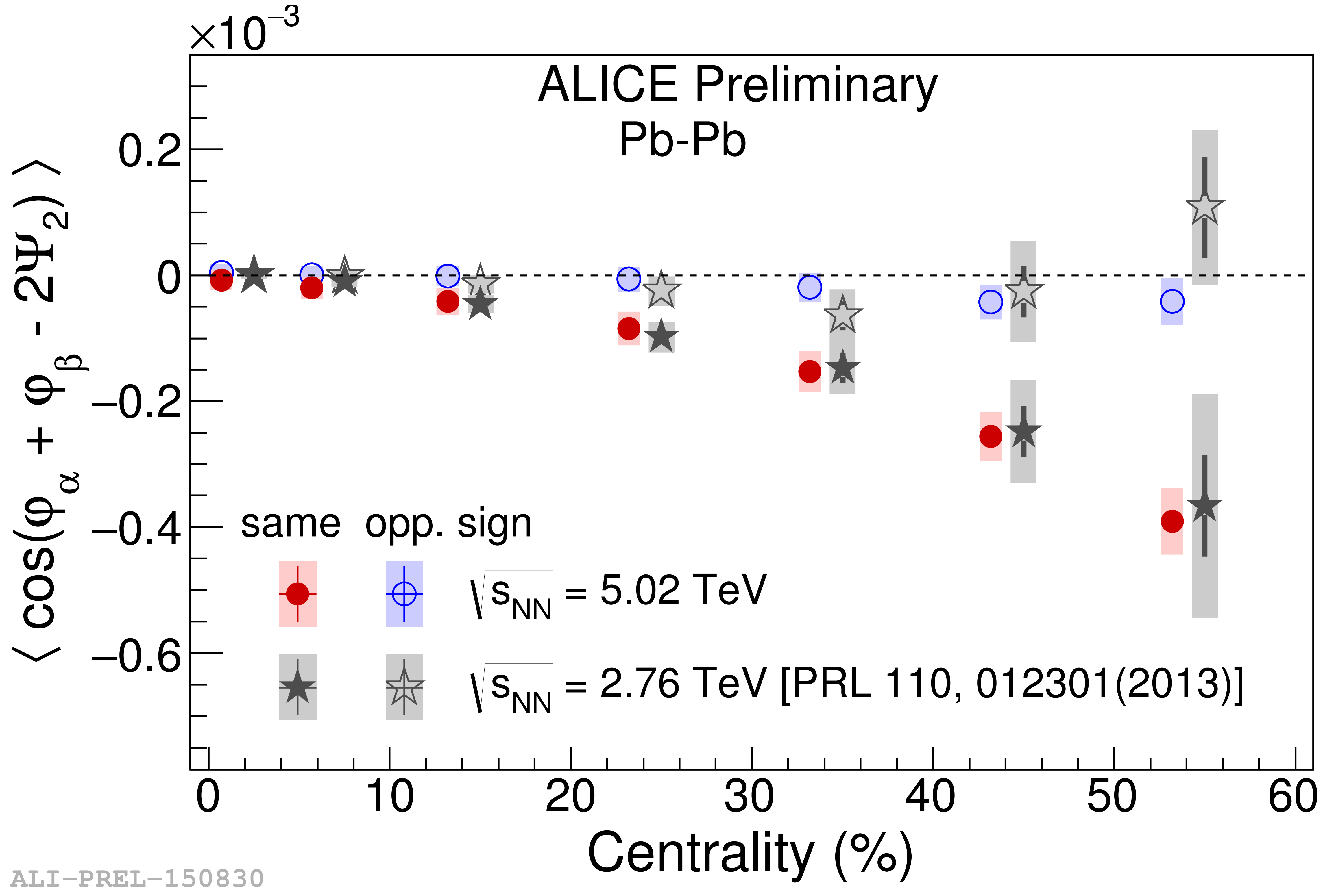
- Good agreement between various γ_{112} obtained with the EP estimated from different detectors
  - ✓ Backgrounds unrelated to the EP are negligible

- δ_{11} for the SS and OS are always positive and exhibit similar centrality dependence
- The magnitude of δ_{11} is smaller for the SS.
- Differ from those reported by the STAR Collaboration

- <$\cos\Delta\phi_\alpha \cos\Delta\phi_\beta$> are larger than <$\sin\Delta\phi_\alpha \sin\Delta\phi_\beta$>
- Consistent behaviour for OS between <cos cos> and <sin sin> terms

γ_{112} at 2.76 and 5.02 TeV Pb-Pb collisions



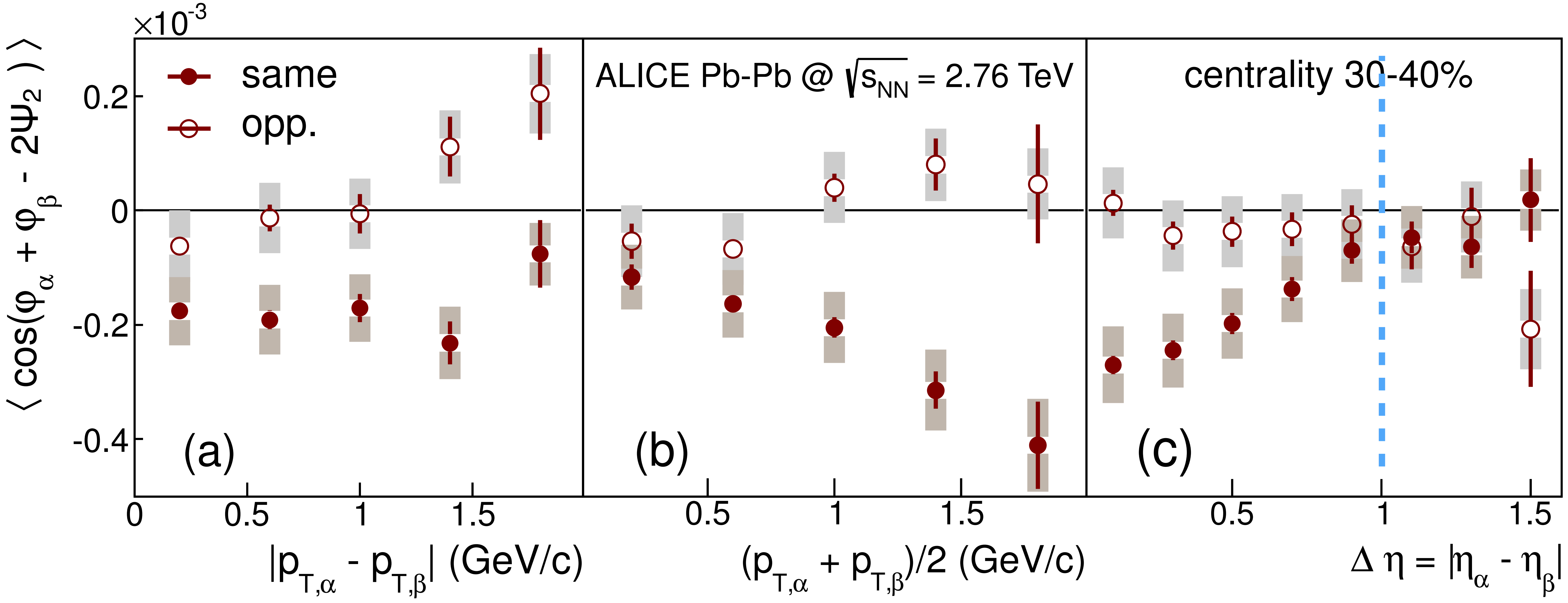


- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

Phys. Rev. Lett. 110, 012301 (2013).

Nucl. Phys. A 982, 543 (2019).

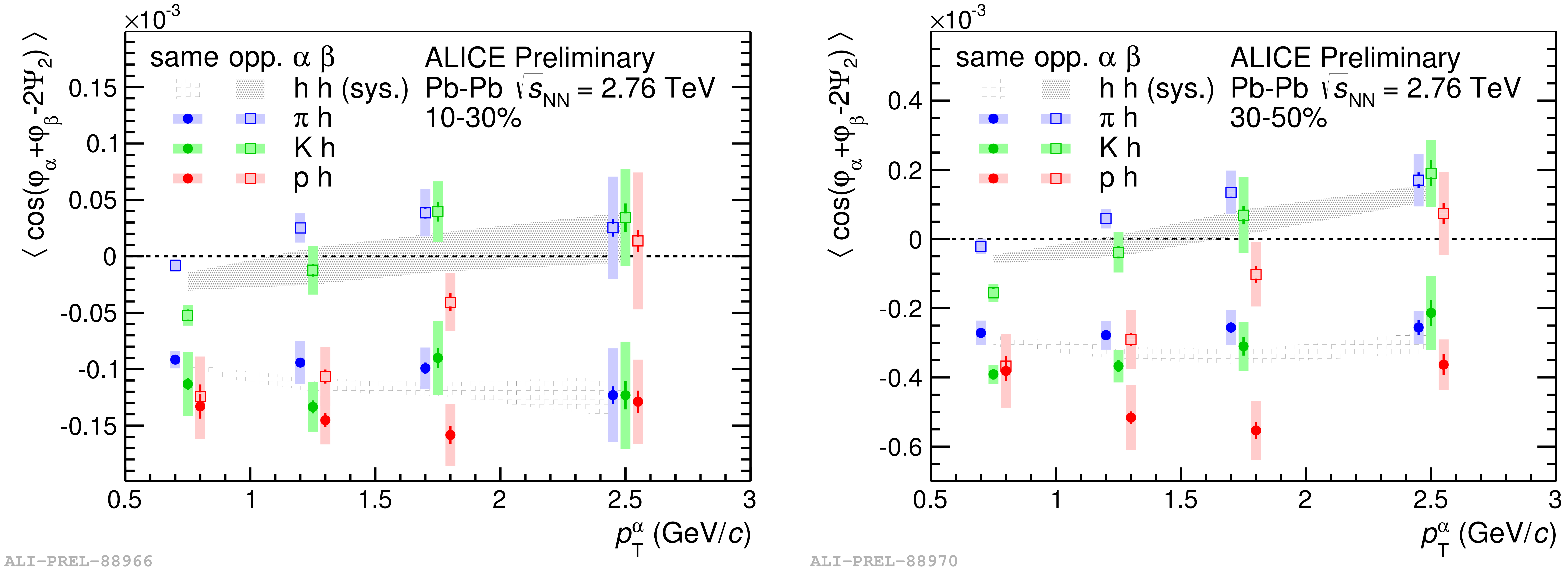
p_T, Δp_T and $\Delta\eta$ dependence of γ_{112} at 2.76 TeV Pb-Pb collisions



- Weak Δp_T dependence for SS
  - ✓ Exclude HBT correlations
- Magnitude increases with increasing average p_T
  - ✓ Not only originating from low-p_T particles
- Close to zero above one unit of $\Delta\eta$

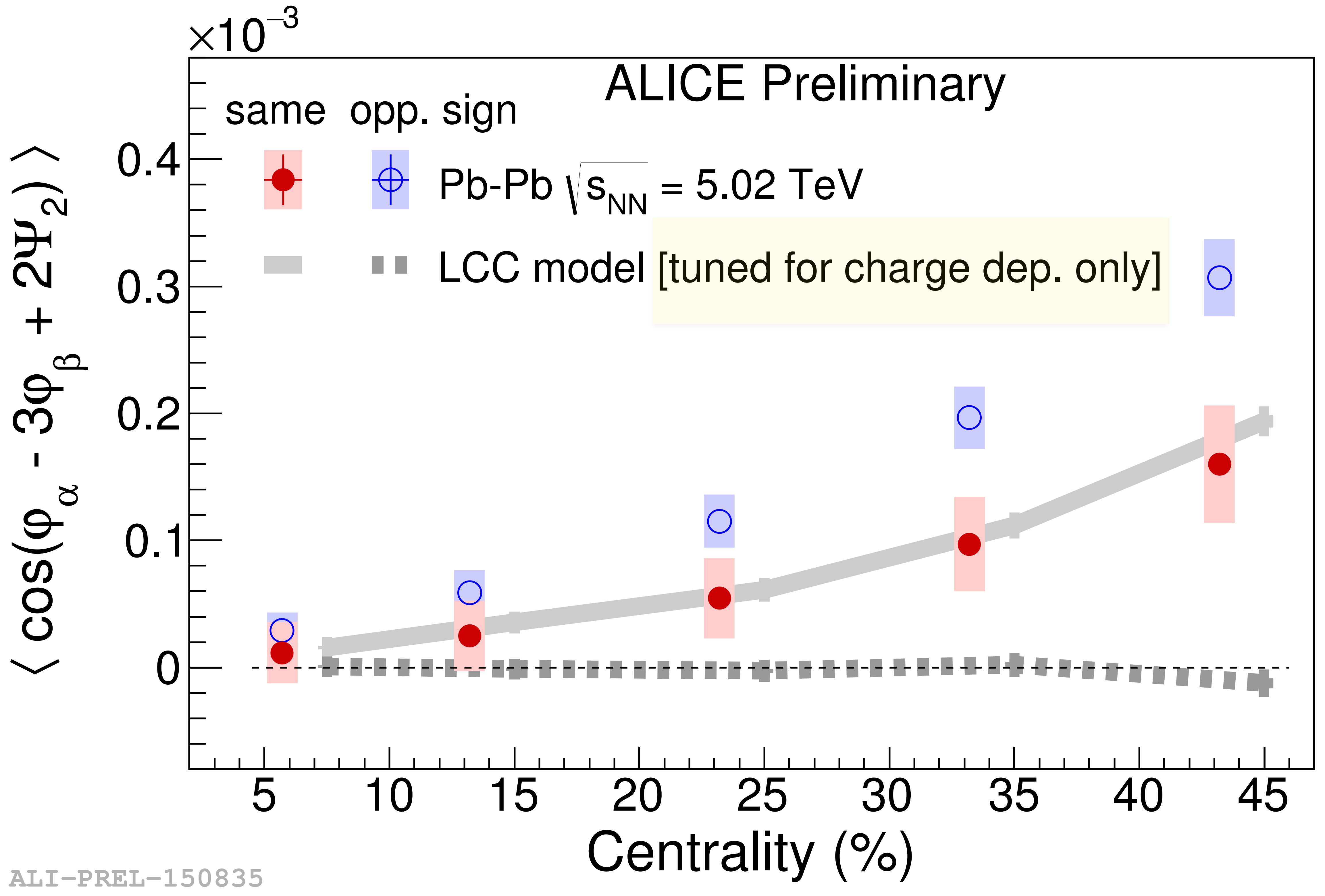
Phys. Rev. Lett. 110, 012301 (2013).

γ_{112} with identified particles at 2.76 TeV Pb-Pb collisions



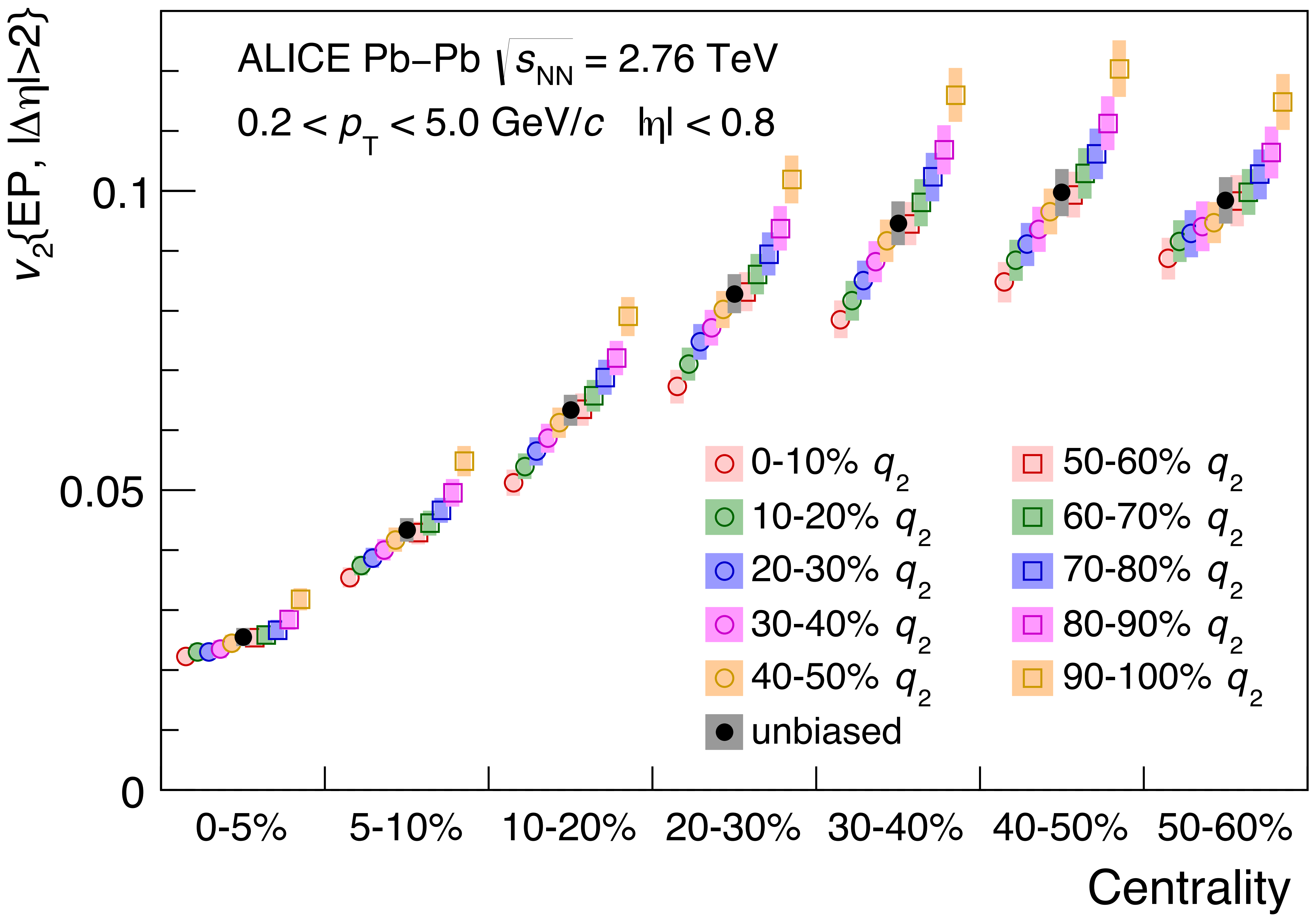
- $\gamma_{112}(\pi)$ and $\gamma_{112}(K)$ are consistent with $\gamma_{112}(h)$
- $\gamma_{112}(p)$ indicates a particle type dependence

γ_{132} at 5.02 TeV Pb-Pb collisions



- Expected to have different contributions compared to γ_{112}
- BW+LCC model could reproduce the SS, but under predicts the OS

Event Shape Engineering

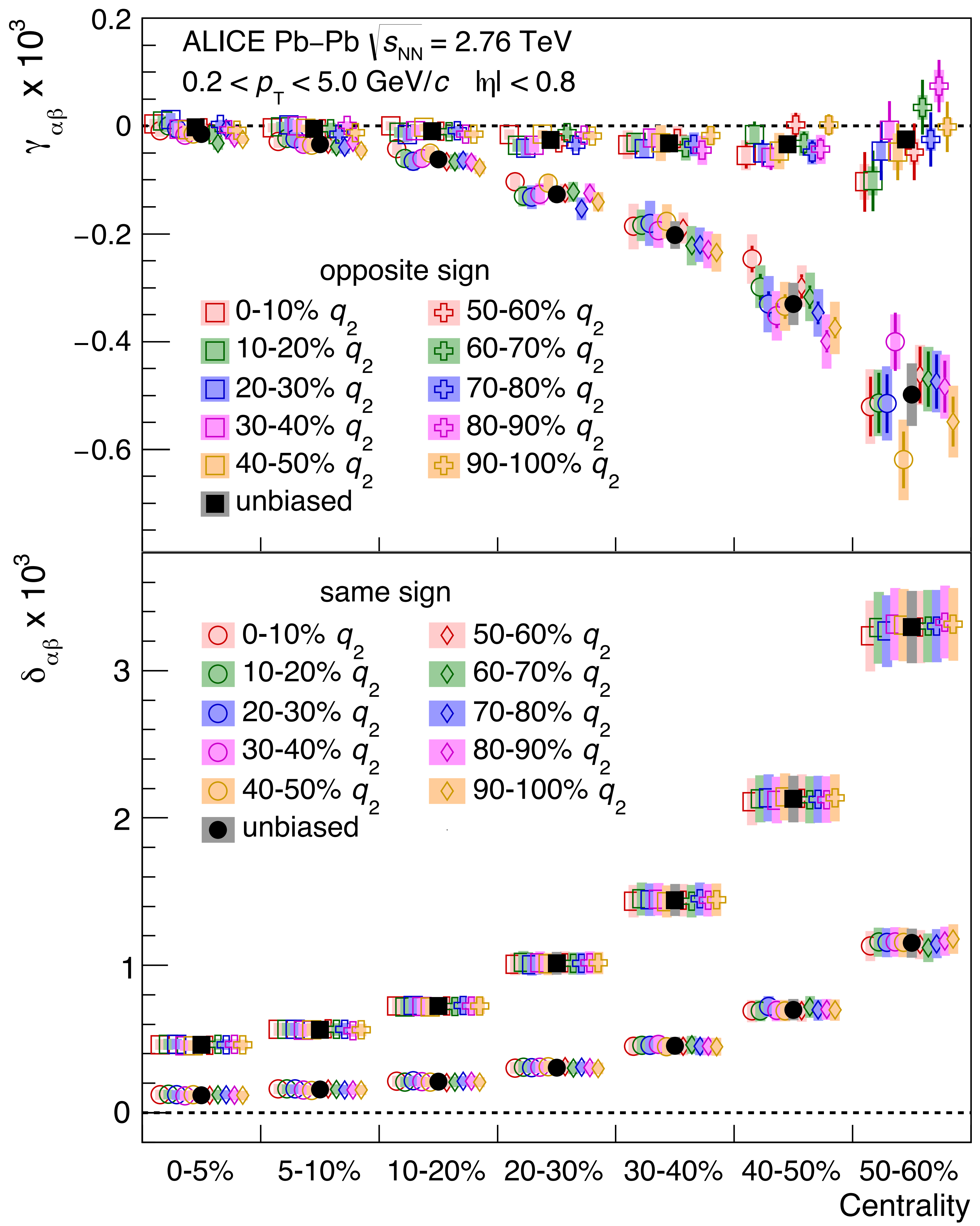


Physics Letters B 777, 151 (2018).

- Events with the desired initial spatial anisotropy (or v_2) can be experimentally selected by q_2
  - ✓ Help to disentangle eccentricity and v_2 related backgrounds from the potential CME signal

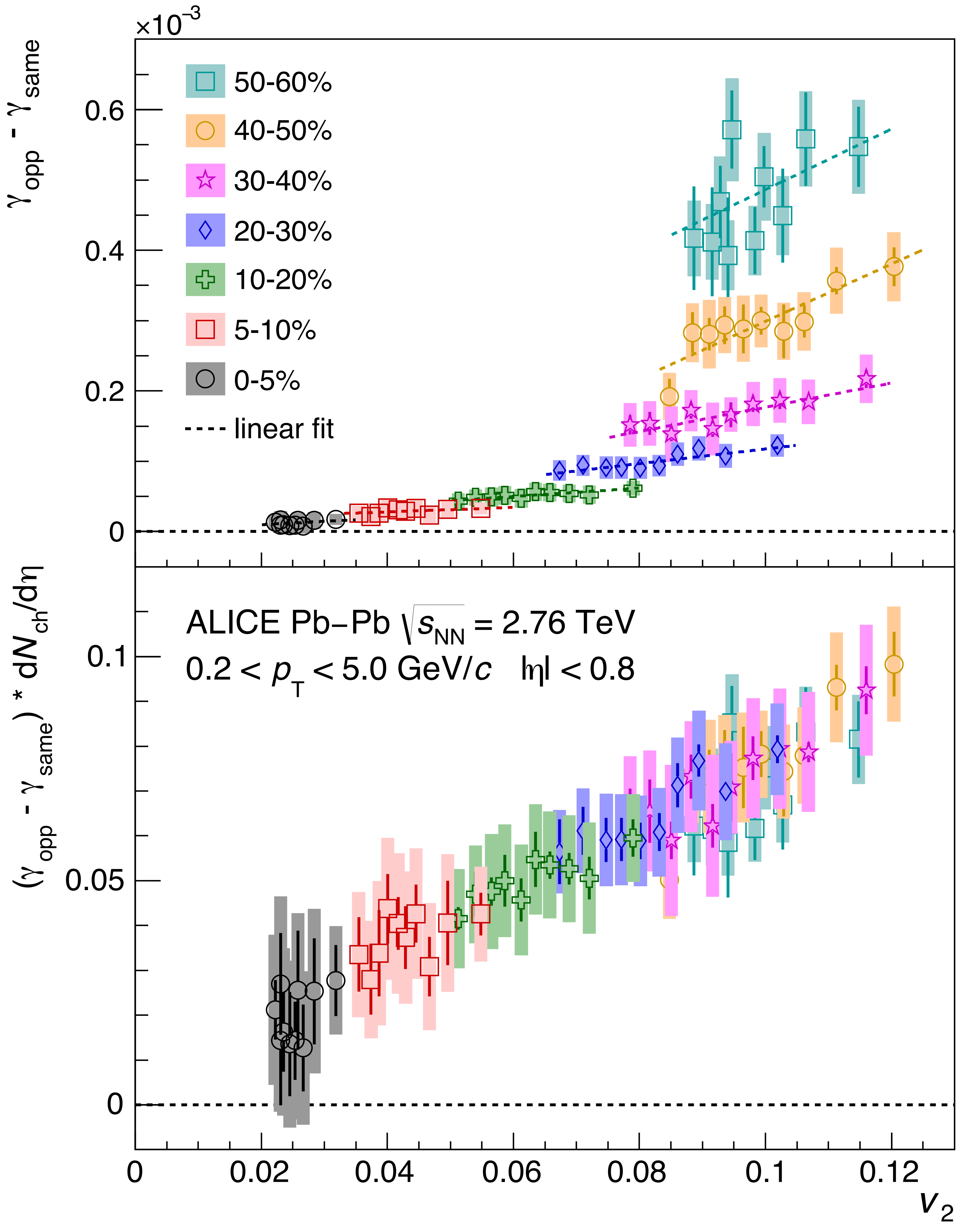
γ_{112} and δ_{11} after event shape selection

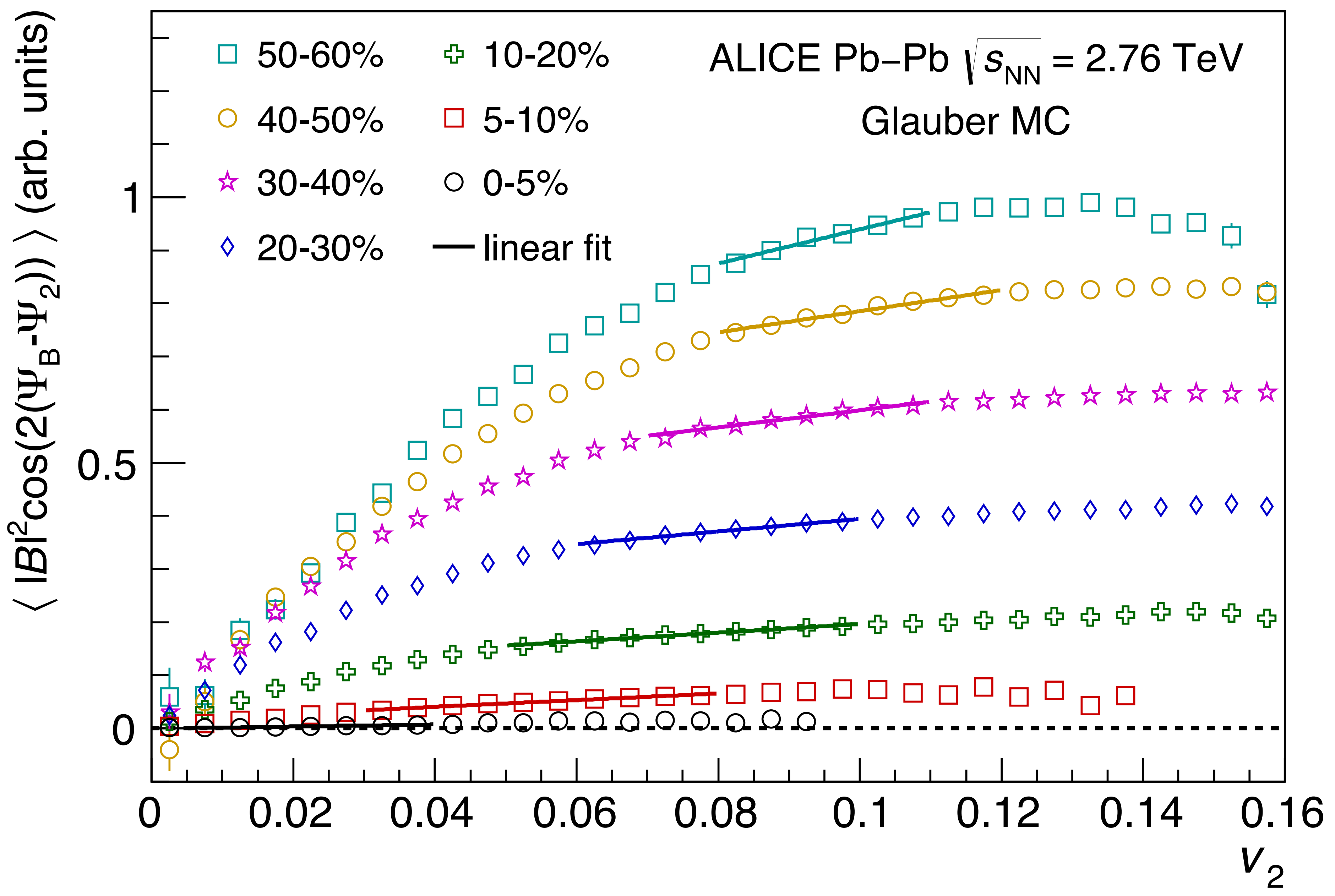
Physics Letters B 777, 151 (2018).



- The magnitude of γ_{112} and δ_{11} for SS and OS depends weakly on the event-shape selection in a given centrality

$\Delta\gamma_{112}$ after event shape selection



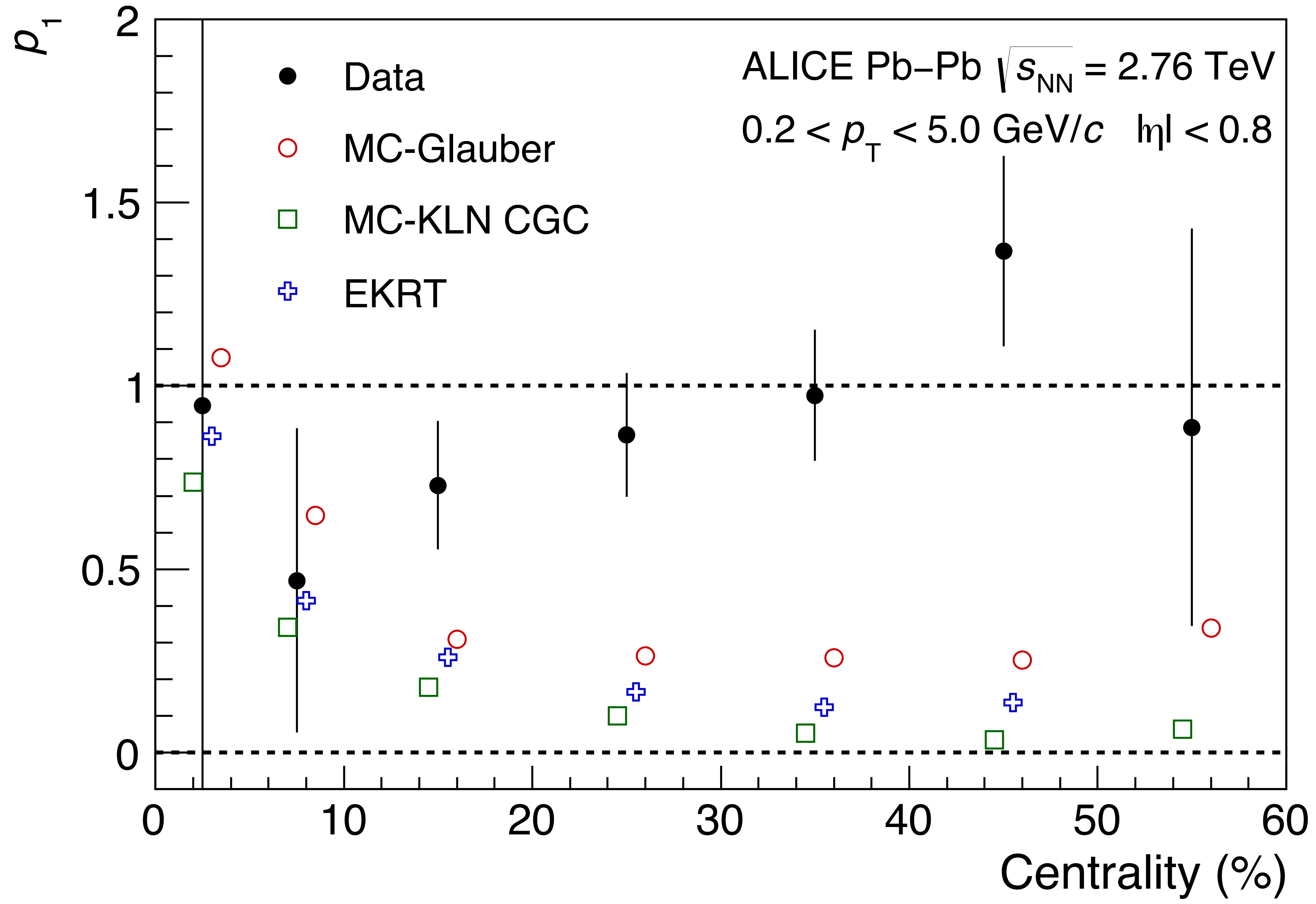


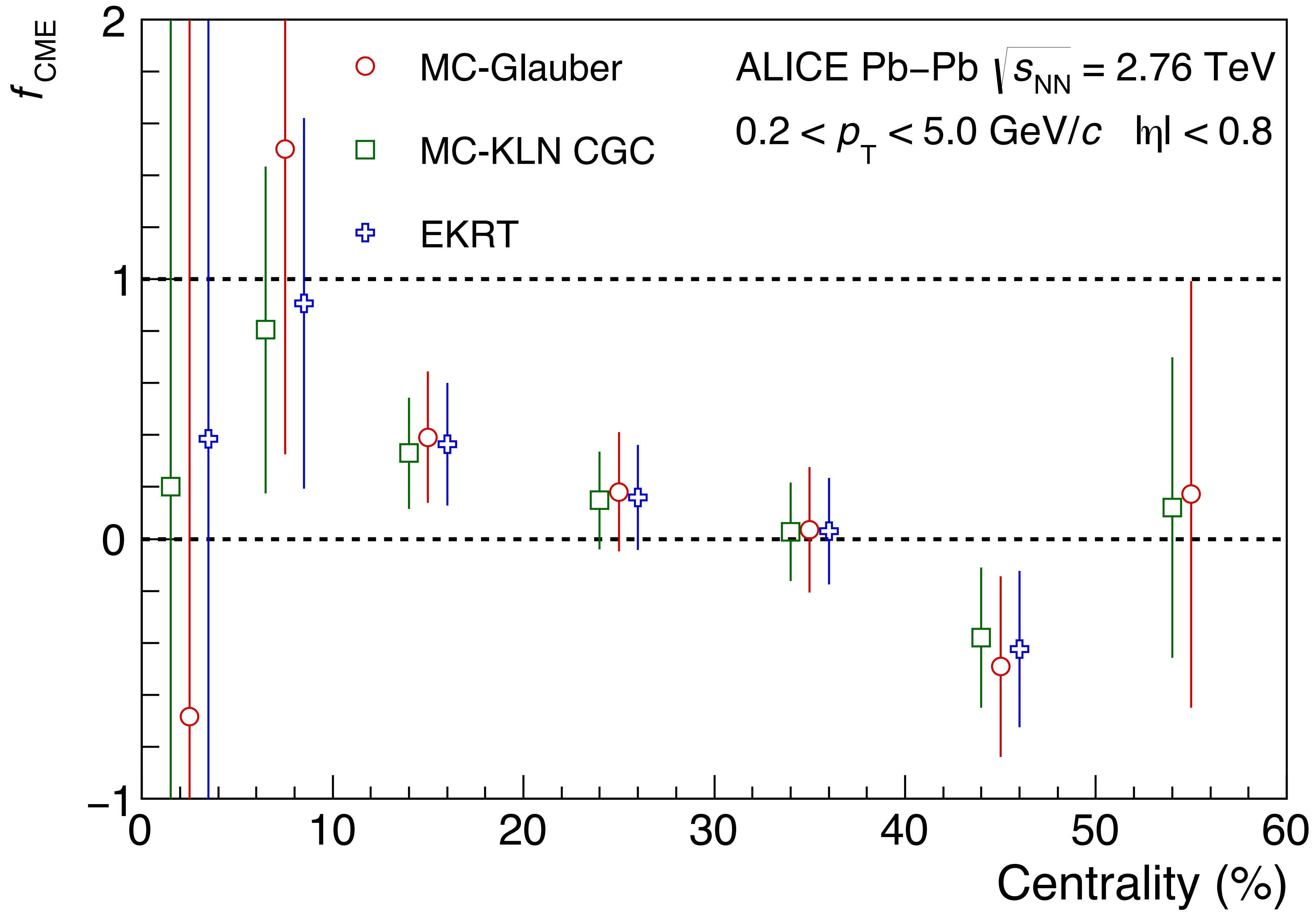
- $\Delta\gamma_{112}$ is positive for all centralities
- The magnitude decreases for more central collisions and with decreasing v_2 (in a given centrality bin)
- After scaling by $dN_{ch}/d\eta$, $\Delta\gamma_{112}$ is approximately proportional to v_2

- The expected CME dependence on v_2 could be evaluated by the MC including a *B* field

Physics Letters B 777, 151 (2018).

Disentangle CME component from v_2 driven background





$F_1(v_2) = p_0(1 + p_1(v_2 - \langle v_2\rangle)/\langle v_2\rangle)$ to fit both data and model

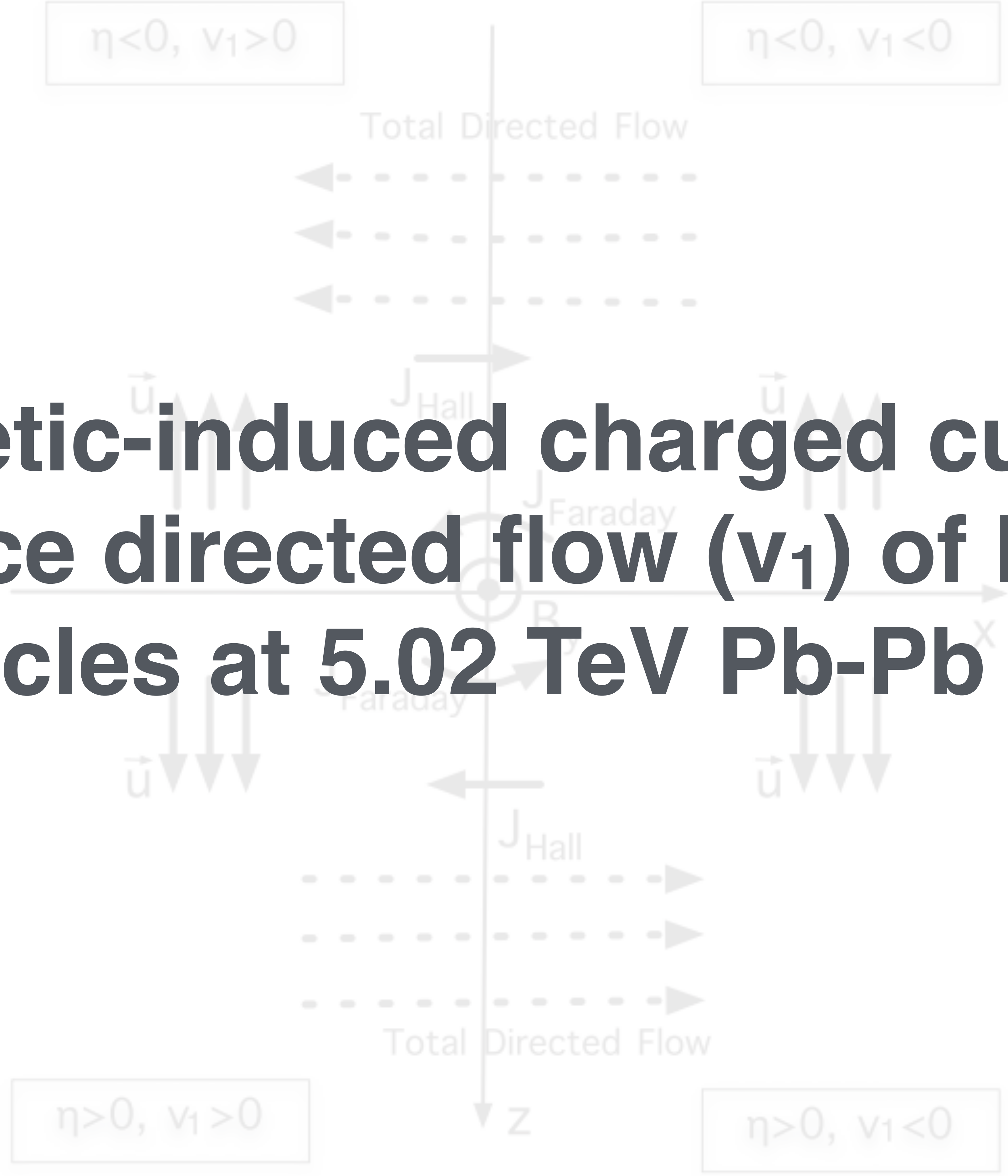
$f_{CME} \times p_{1,MC} + (1 - f_{CME}) \times 1 = p_{1,data}$ ➔ $f_{CME} = \Delta\gamma^{CME} / (\Delta\gamma^{CME} + \Delta\gamma^{Bkg})$

At semi-central collisions (10–50%) f_{CME} ~26% - 33% at 95% C.L.

Physics Letters B 777, 151 (2018).

PART 2

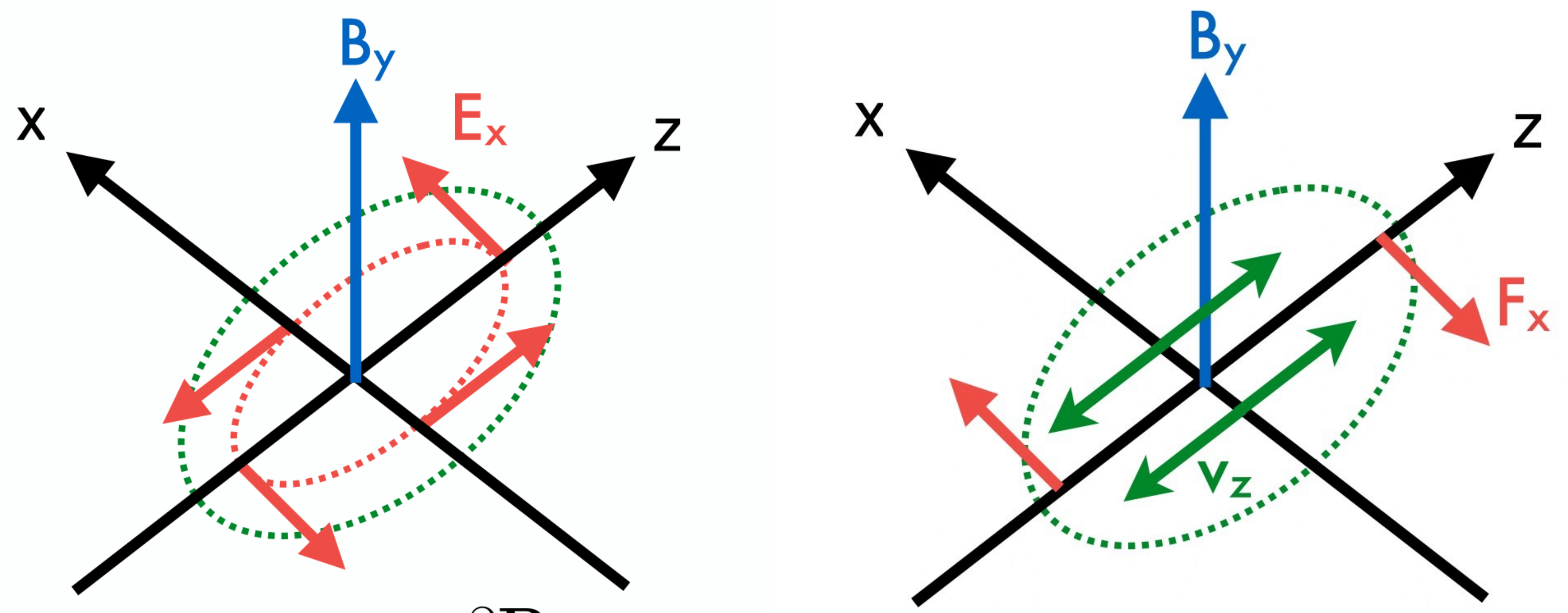
Search for magnetic-induced charged currents with the charge dependence directed flow (v_1) of light and heavy-flavour particles at 5.02 TeV Pb-Pb collisions



Magnetic-induced charged currents

- In non-central heavy-ion collisions an unprecedented intense magnetic field (~10^{18} G) is generated by the movement of the spectator protons (Biot-Savart law)

- Charged currents owing to the combination of
  - ✓ Electric field induced by decreasing B (Faraday effect)
  - ✓ Lorentz force on moving charges (Hall effect)



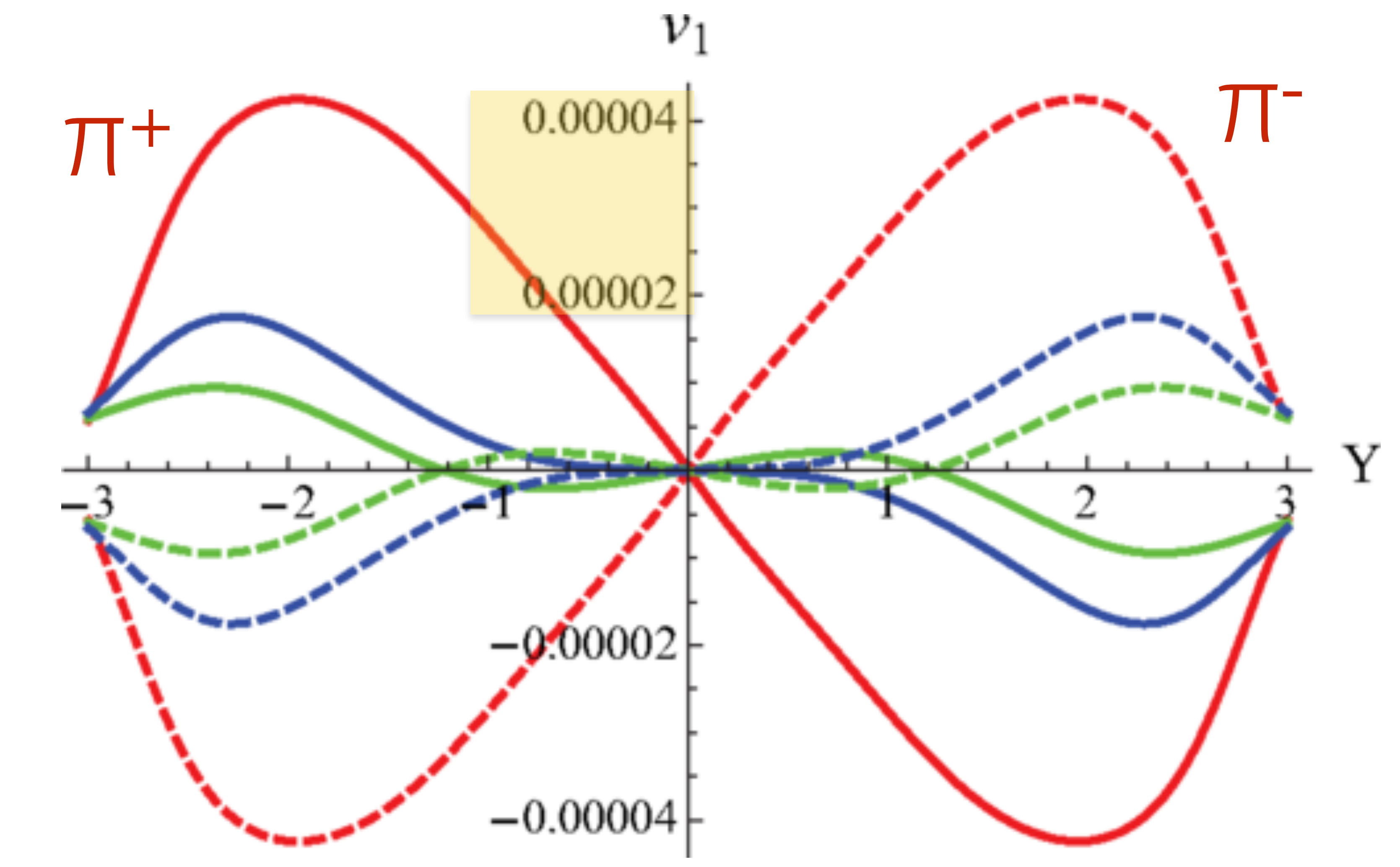
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

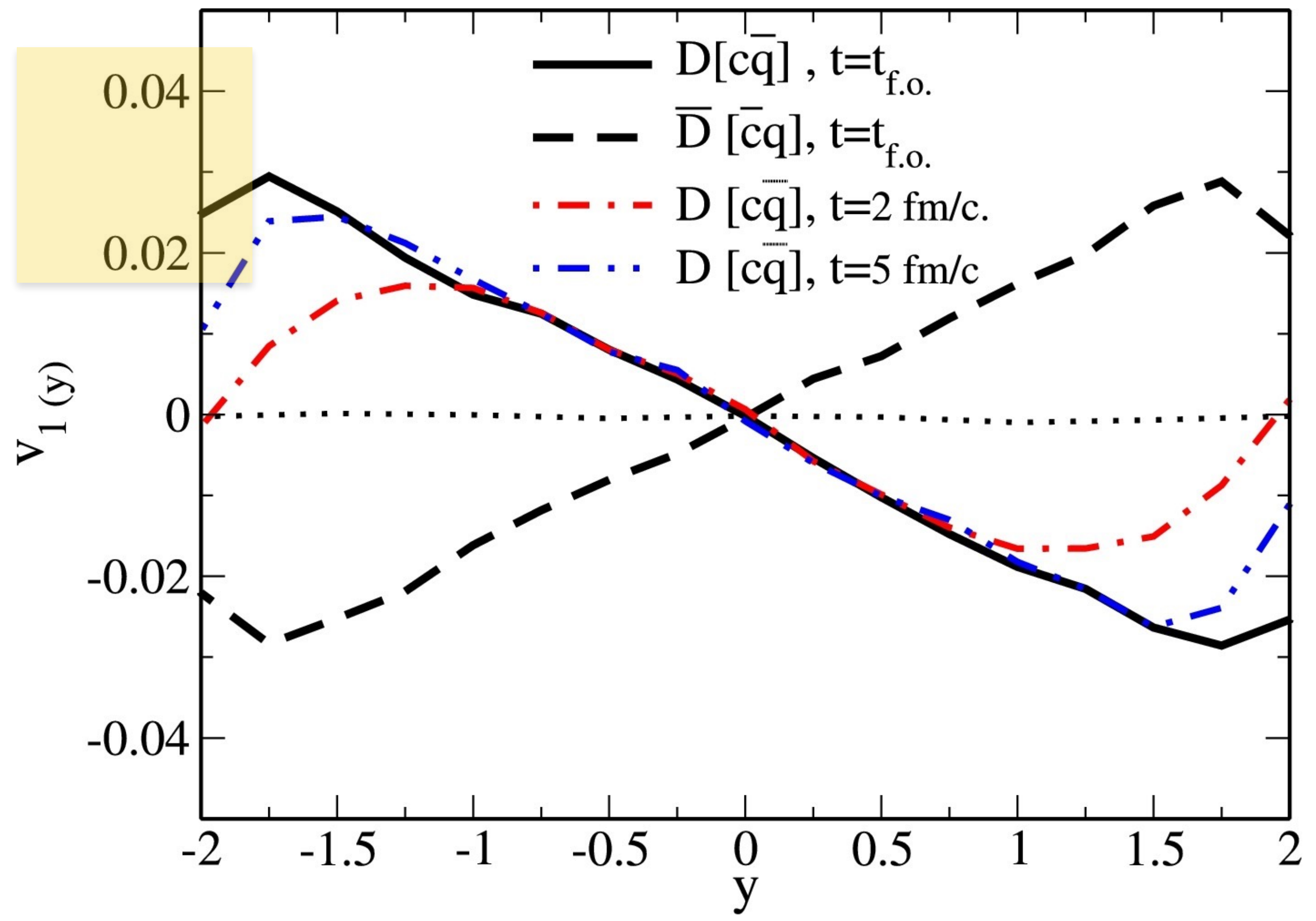
$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

- The varying magnetic field will influence the moving charges and could be tested by the charge-dependent v_1 of light and heavy-flavour particles

Phys. Rev. C 89, 054905 (2014).

Charge dependence v_1

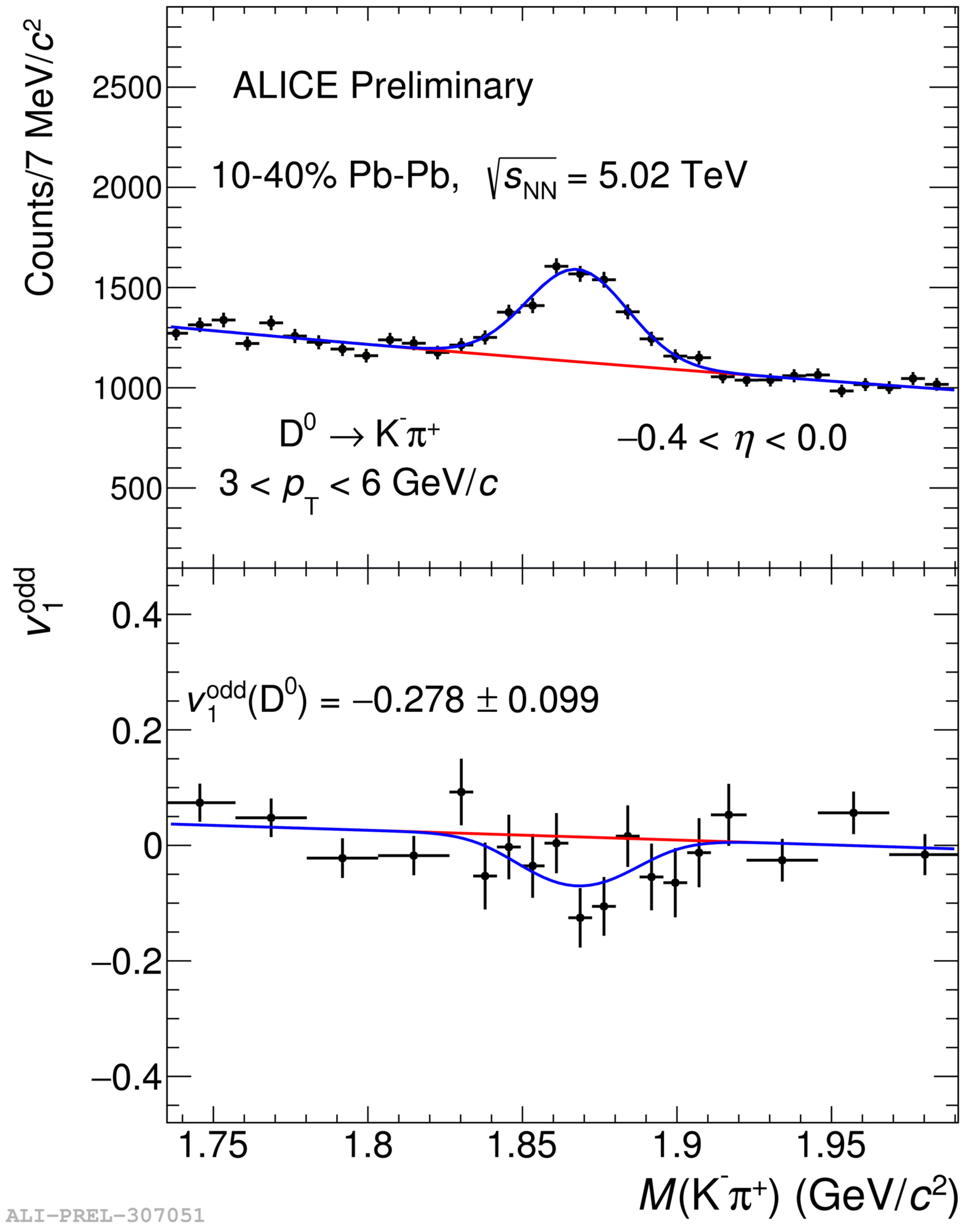




Phys. Rev. C 89, 054905 (2014).
Phys. Lett. B 768, 260 (2017).

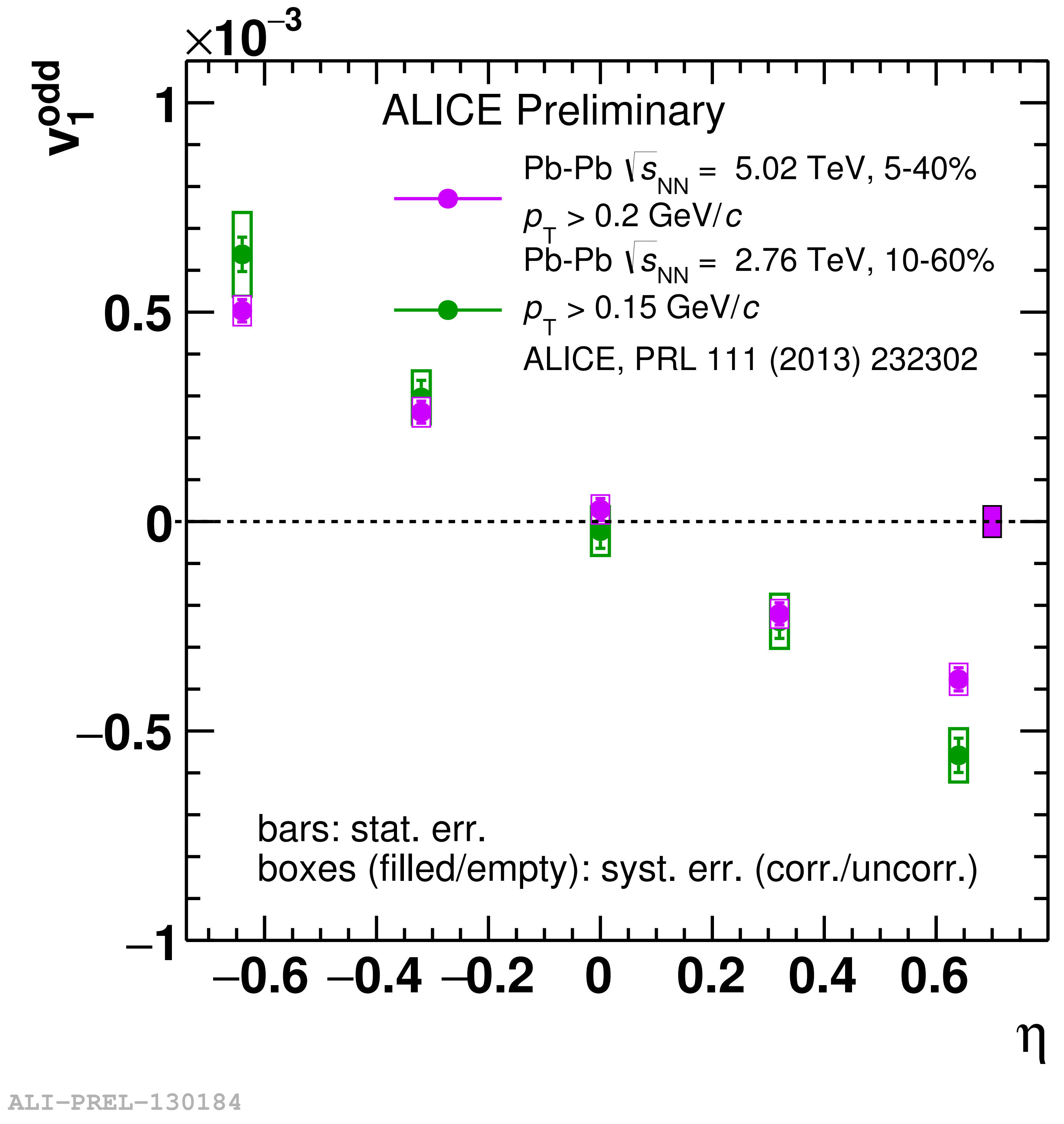
- Charge-dependent v_1 of light and heavy-flavour particles
  - ✓ Formation time ~ 0.1 fm/c, comparable to the time scale when B is maximum
  - ✓ The kinetic relaxation time of charm is similar to the QGP lifetime
  - ✓ Possible larger v_1 of charm quarks compared to light quarks (~10^3)
- Rapidity-odd v_1 with respect to the spectator plane measured by the scalar product method

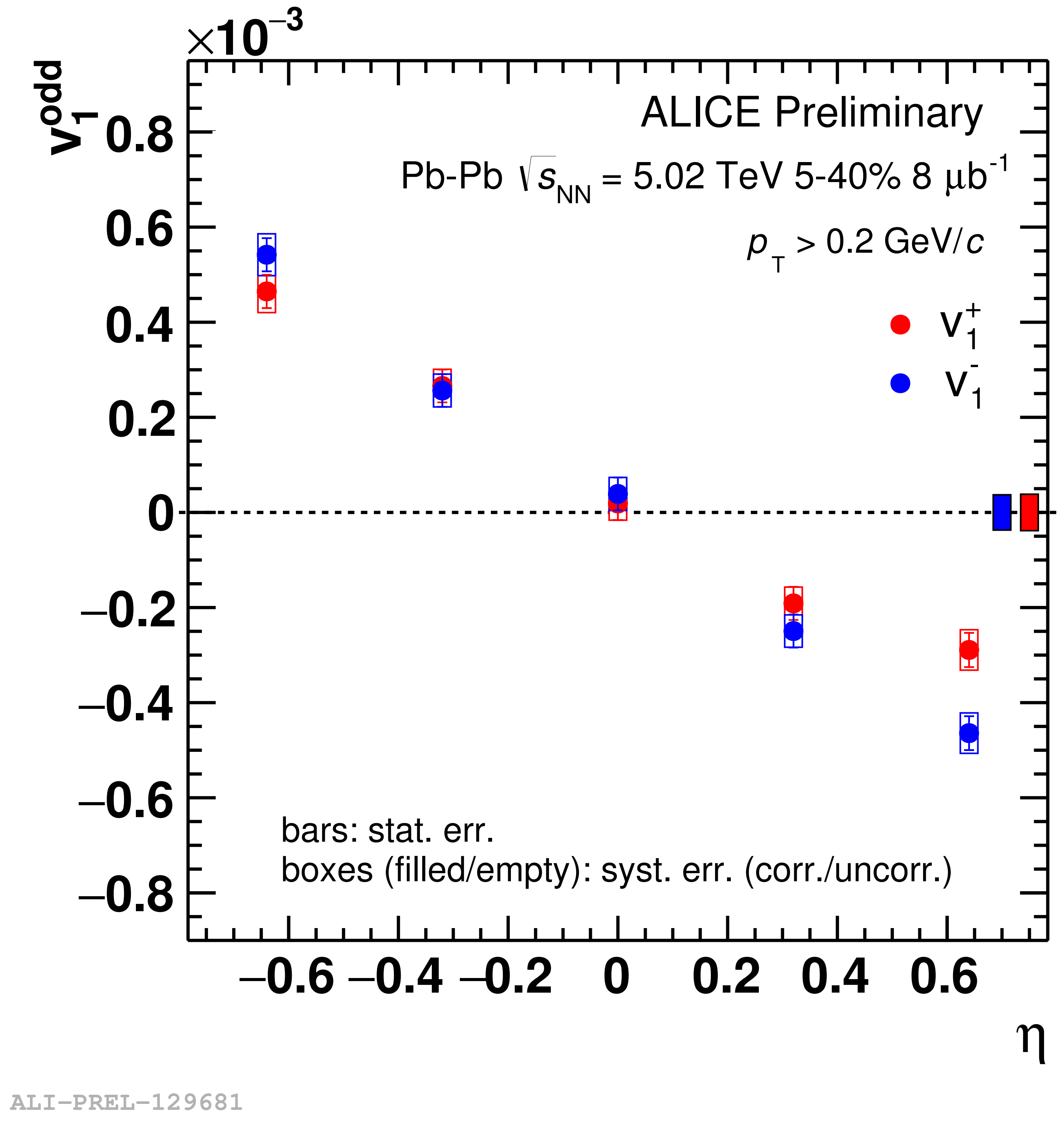
D^0 v_1 extraction

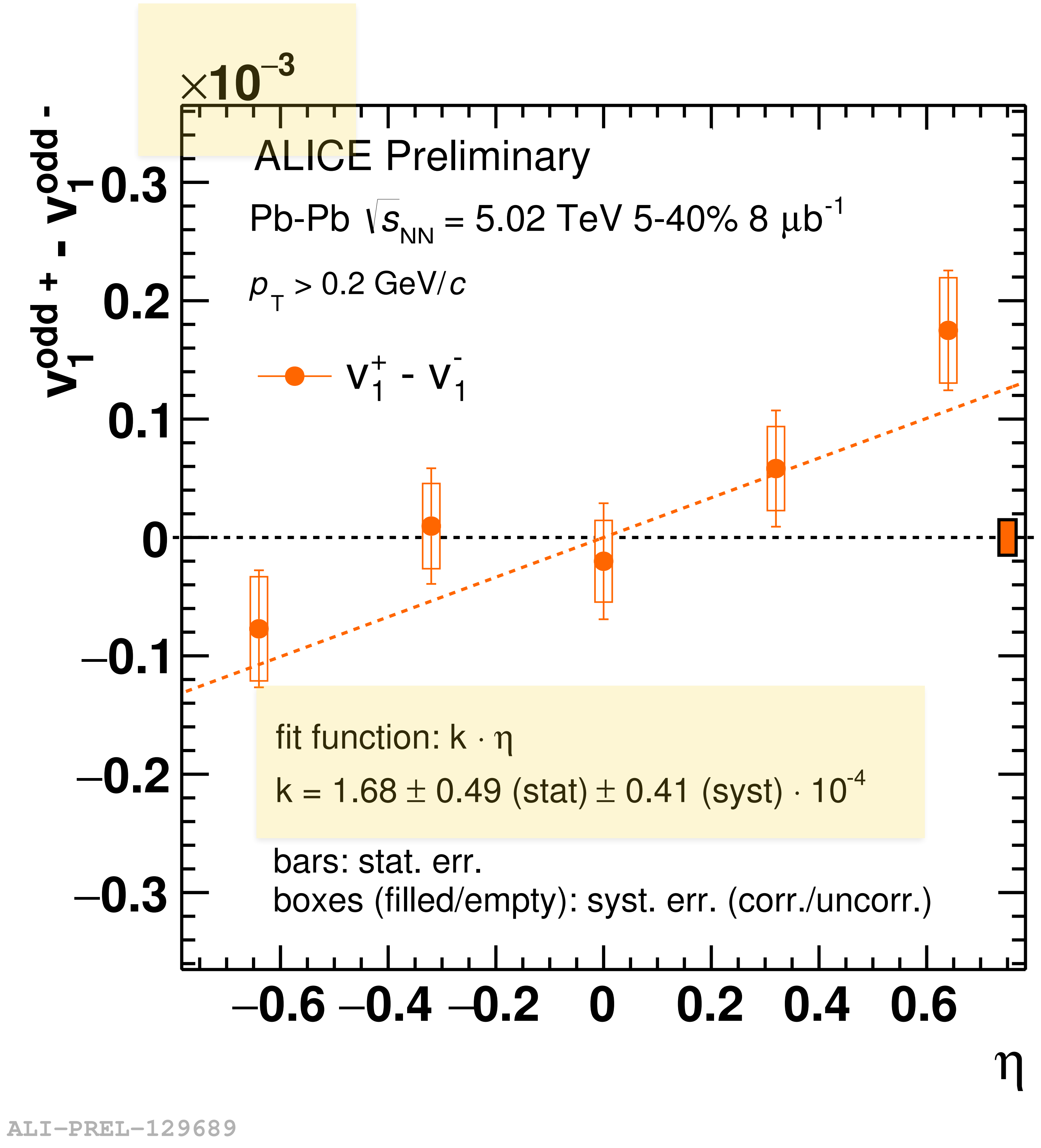


- D^0 mesons and their antiparticles are reconstructed in the central rapidity region from their charged hadronic decay channels $D^0 \rightarrow K^-\pi^+$
- $v_1^{odd}(D^0)$ extracted from a simultaneous fit to the invariant mass and to the $v_1^{odd}(M)$ distributions

Charge dependence v_1 of charged hadrons at 5.02 TeV



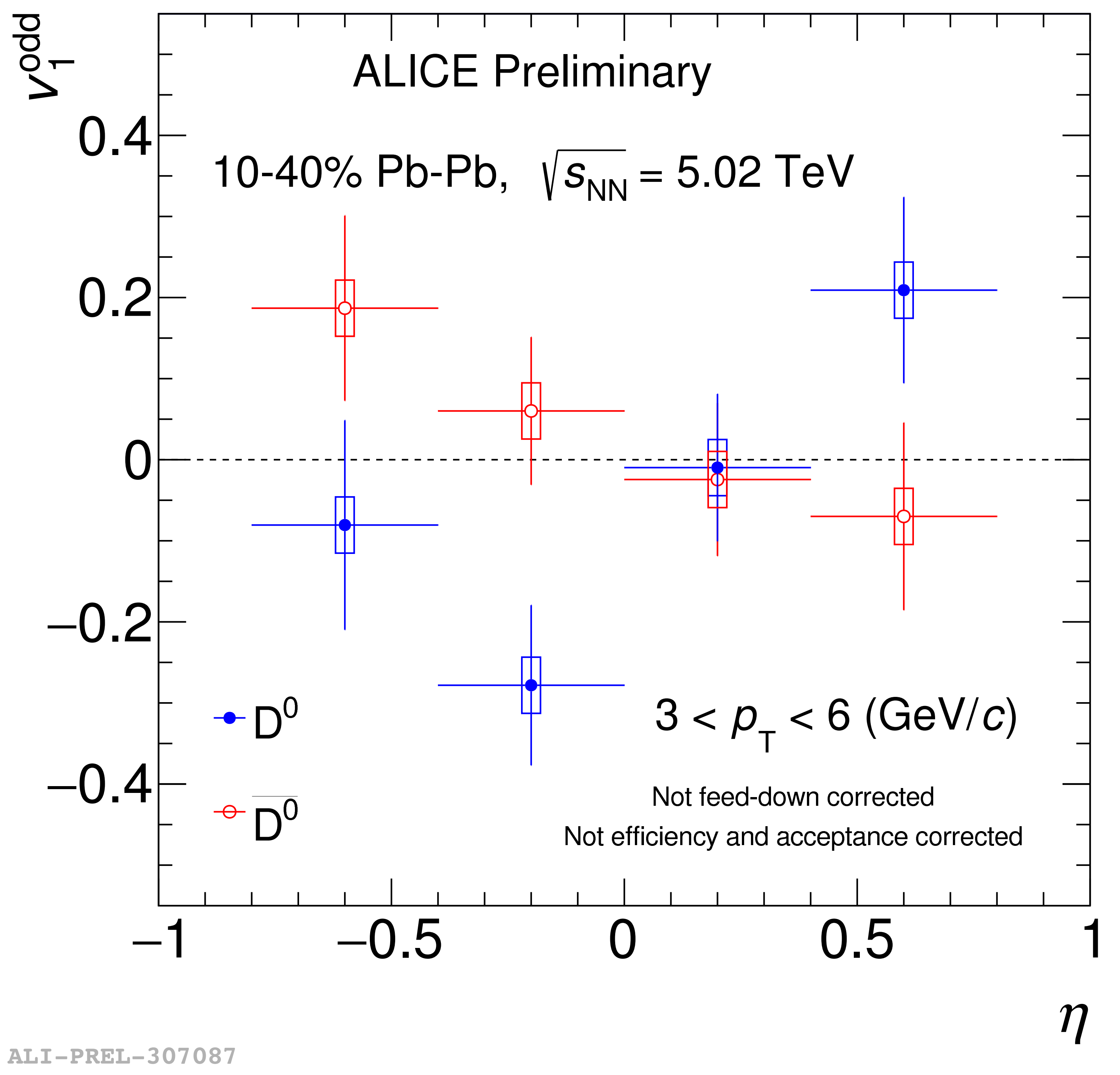


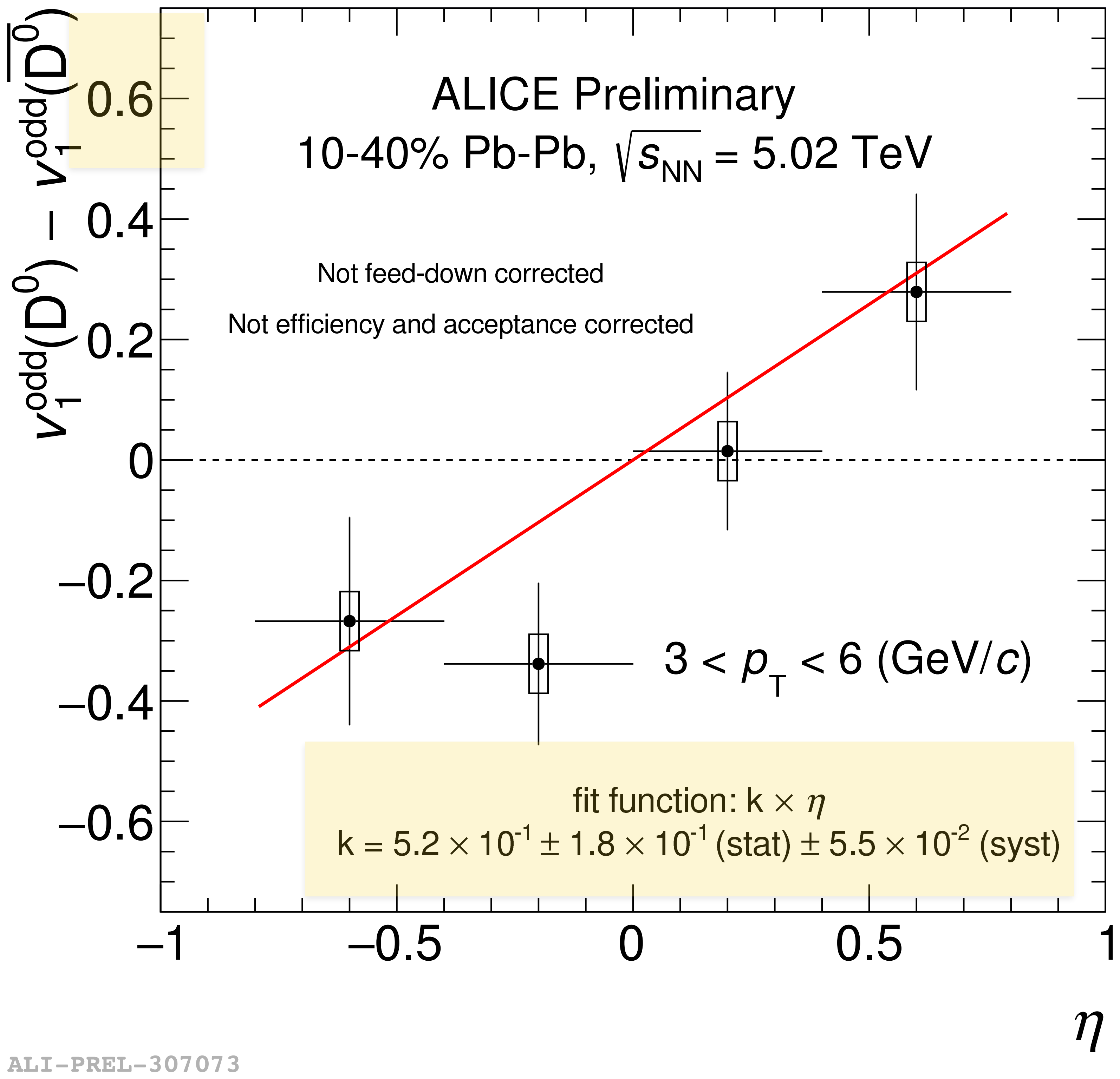


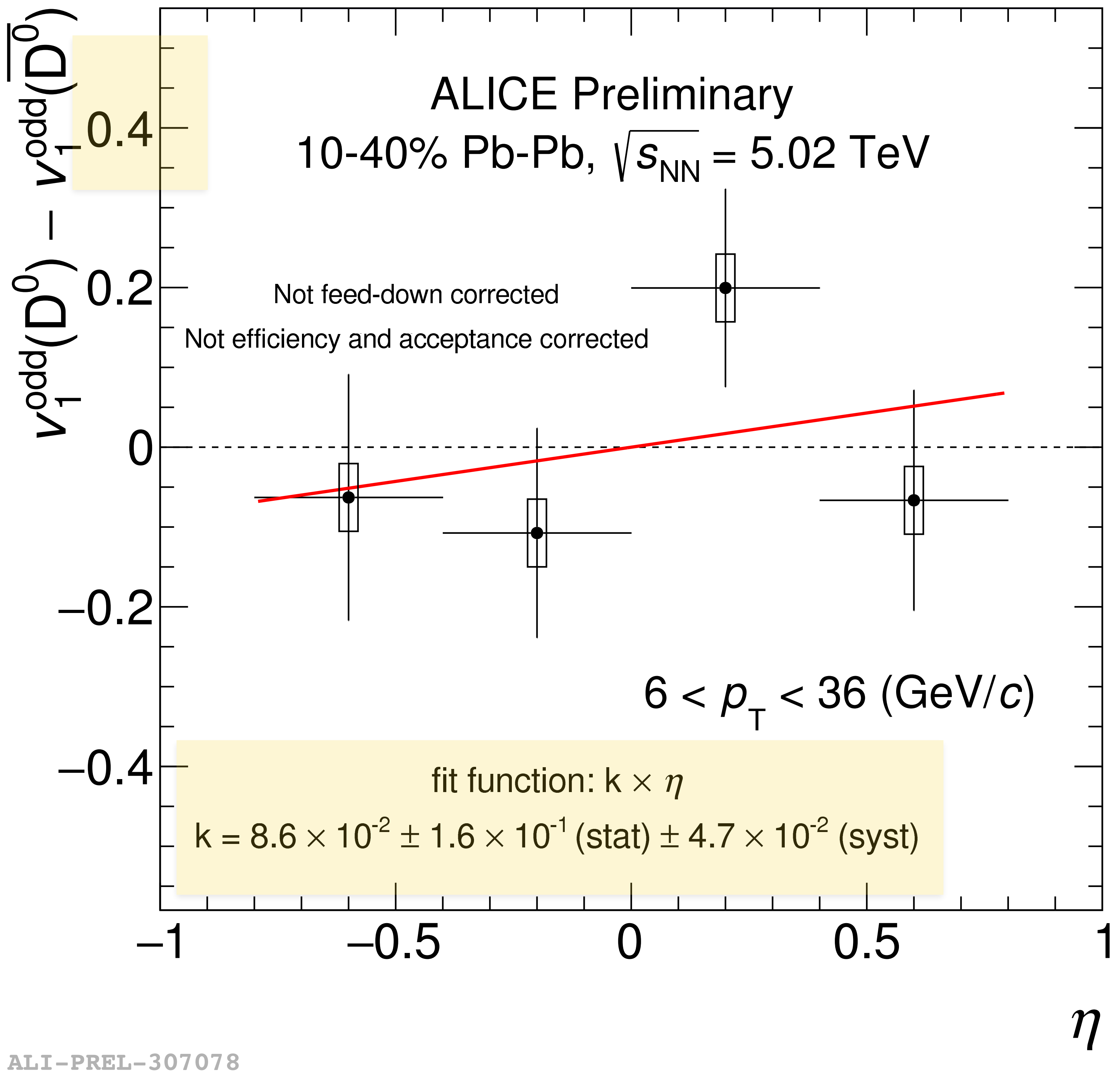
- $dv_1^{odd}/d\eta$ slightly decreases at 5.02 TeV

- Hint of a charge-dependent difference
- Non-zero slope (2.6σ) in v_1^{odd}
- Larger than the theoretical prediction
- Opposite sign in the theory prediction Phys. Rev. C 89, 054905 (2014).

Charge dependence v_1 of D^0 mesons





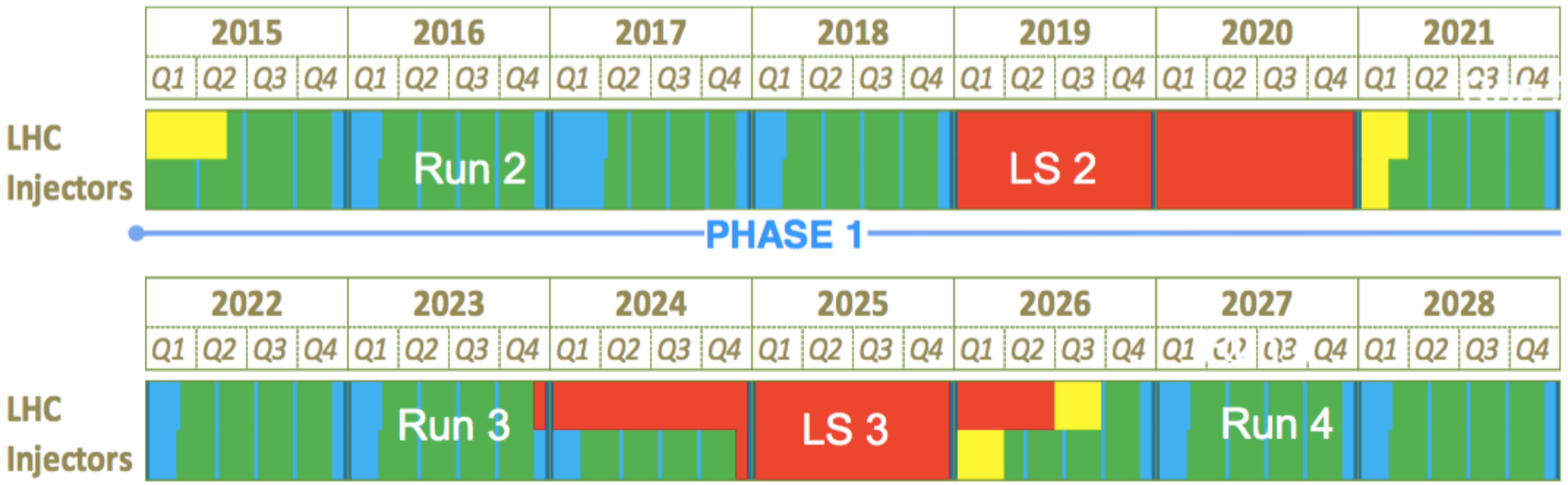


- Despite the large uncertainties, hint of a positive slope of $\Delta v_1^{odd}(D^0)$ (2.7σ)
- Larger slope for D^0 than that for charged-particles
- Larger than the theoretical prediction Phys. Lett. B 768, 260 (2017).

Summary

- The ALICE measurements of the CME with two- and three-particle correlation and ESE technique, as well as the charge dependence v_1 of light and heavy-flavour particles have been reviewed

- With the help of **the upgraded detector** and **the increased statistics** (~10) in the future Run 3/4, the measurements will be improved with high significance



Thank you for your attention!