12th Workshop of France China Particle Physics Laboratory

Strong magnetic field and the experimental search of the anomalous chiral effect at the LHC with ALICE

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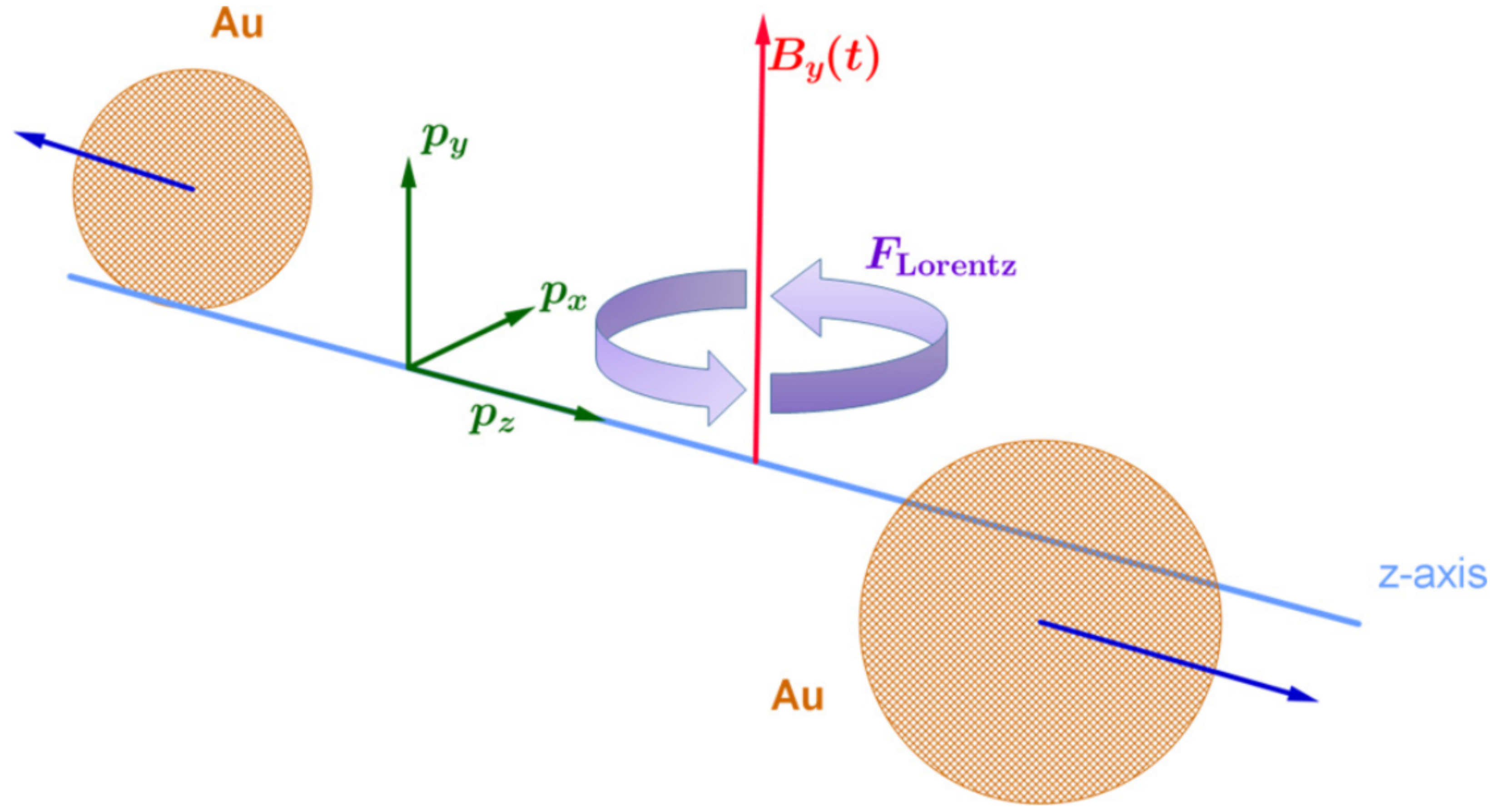
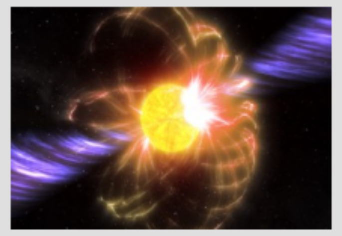
Strong magnetic field & chiral anomaly in heavy-ion collisions



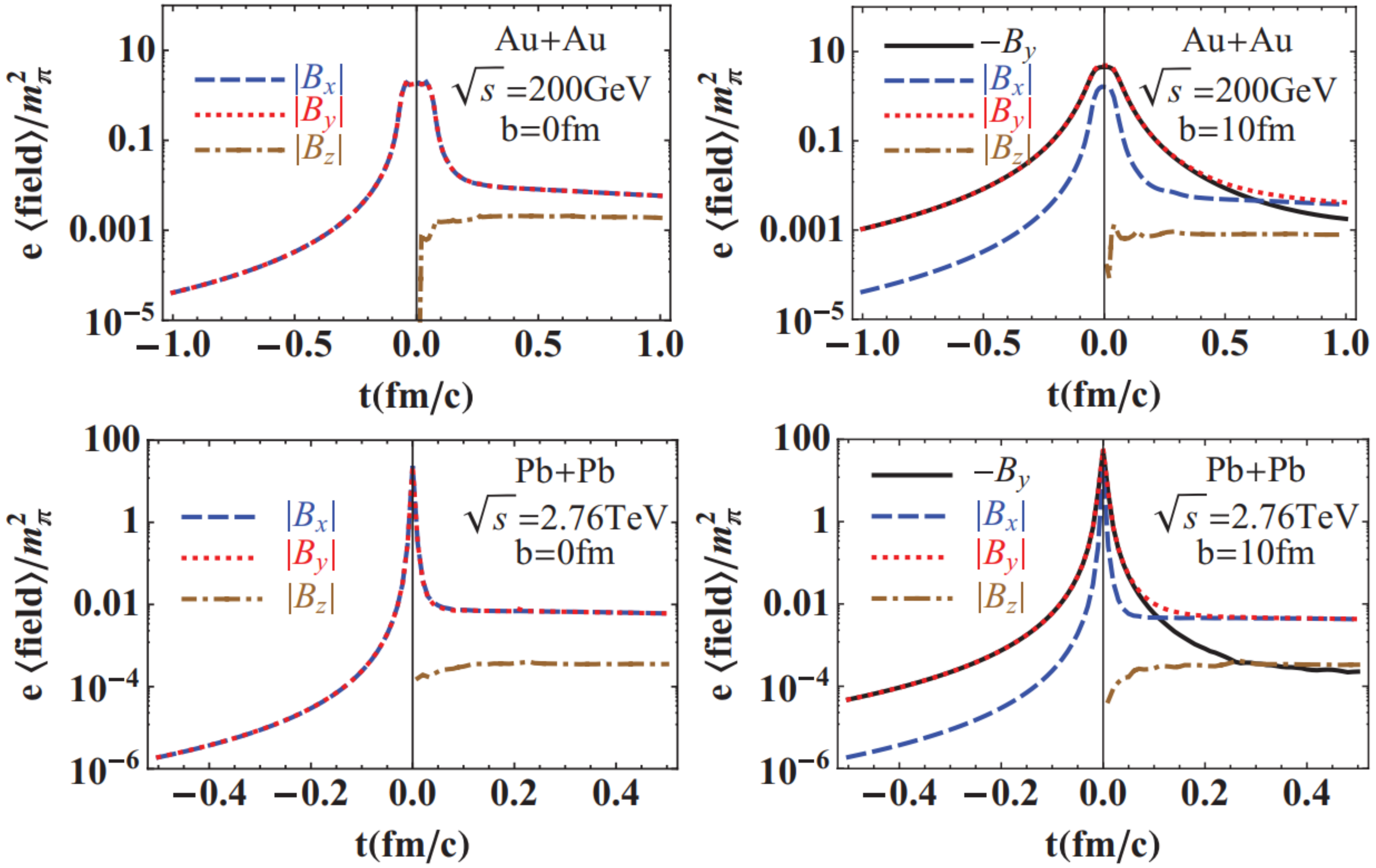
- Thinking — human brain: 10^{-12} Tesla
- Earth's magnetic field: 10^{-5} Tesla
- Refrigerator magnet: 10^{-3} Tesla
- Loudspeaker magnet: 1 Tesla
- Levitating frogs: 10 Tesla
- Strongest field in Lab: 10^{3} Tesla
- Typical neutron star: 10^{6} Tesla
- Magnetar: $10^{7...10}$ Tesla
- Heavy-ion collisions: $10^{15...16}$ Tesla
- Early Universe: even (much) higher

IgNobel 2000 by A.Geim (got Nobel 2010 for graphene)

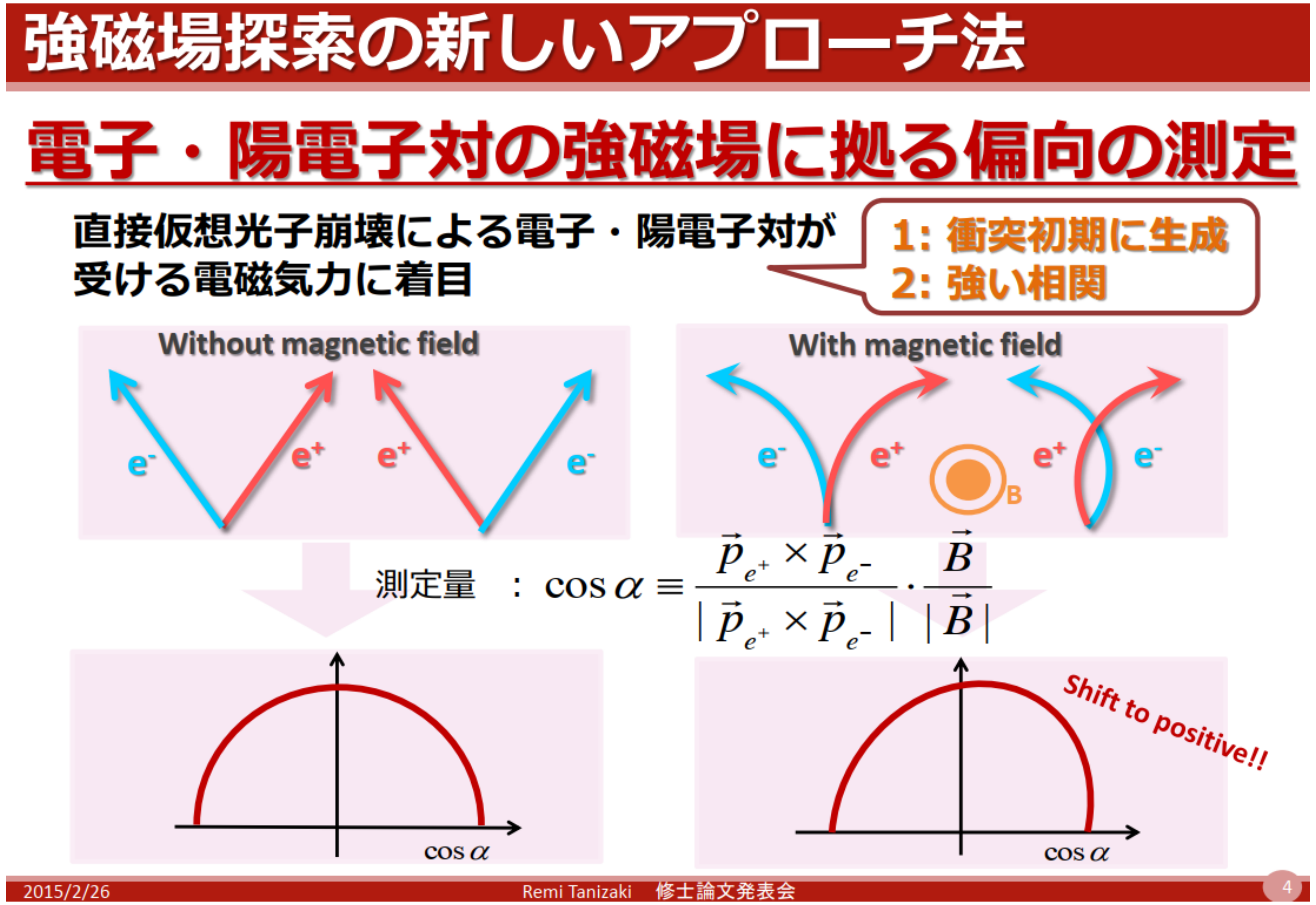
Destructive explosion

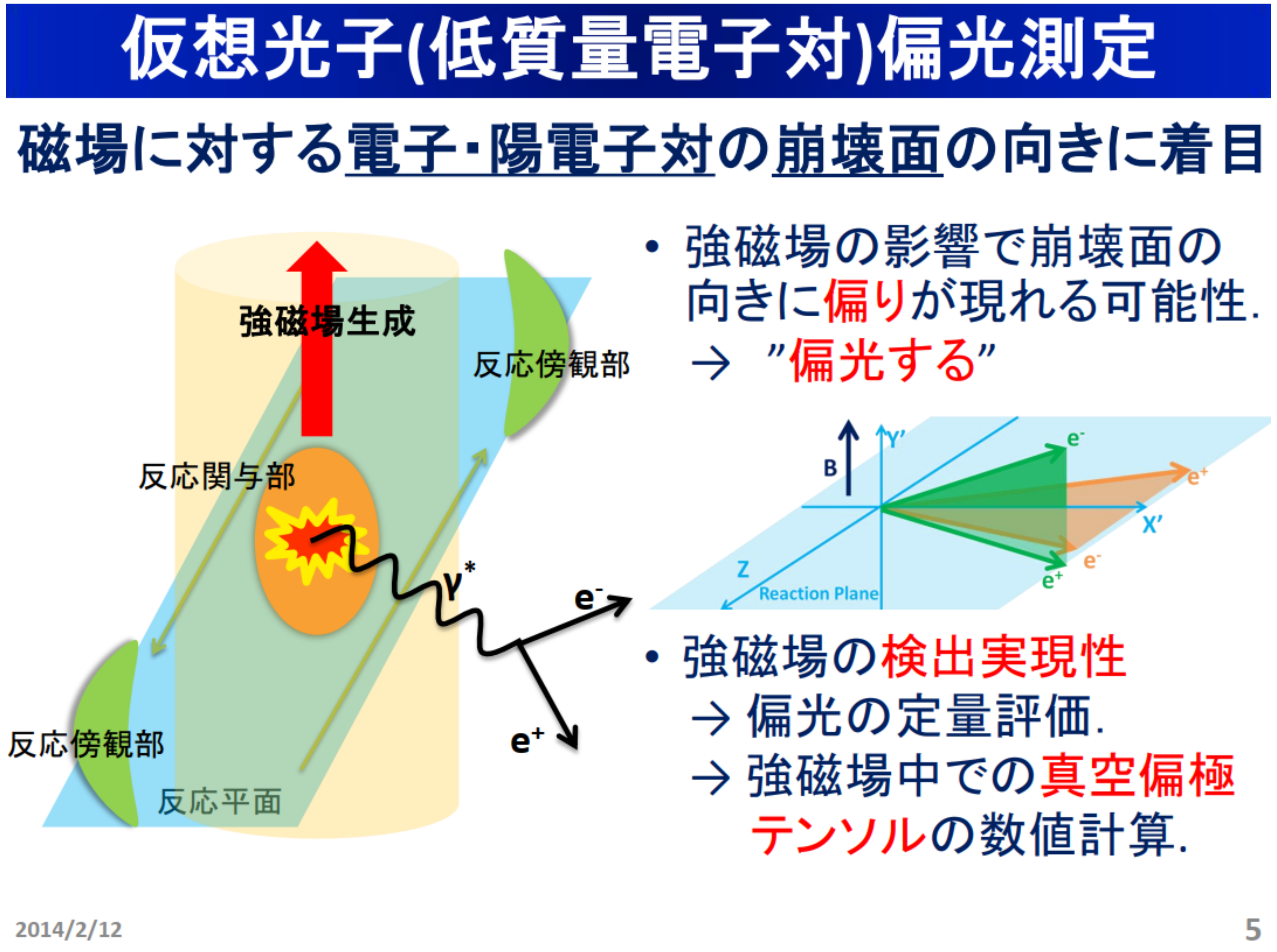


Phys. Rev. Lett. 110, 012301 (2013).



ALICE





Have been tested by ALICE-Japan (Hiroshima) group

Strong magnetic field & chiral anomaly in heavy-ion collisions

- Spectrum of (coherent) photons
- Collective motions of direct photons
- Associated emission of jet (low momentum photons)
- Synchrotron radiation from quarks
- Anomalous chiral effect
- Charge dependent directed flow

Strong magnetic field & chiral anomaly in heavy-ion collisions

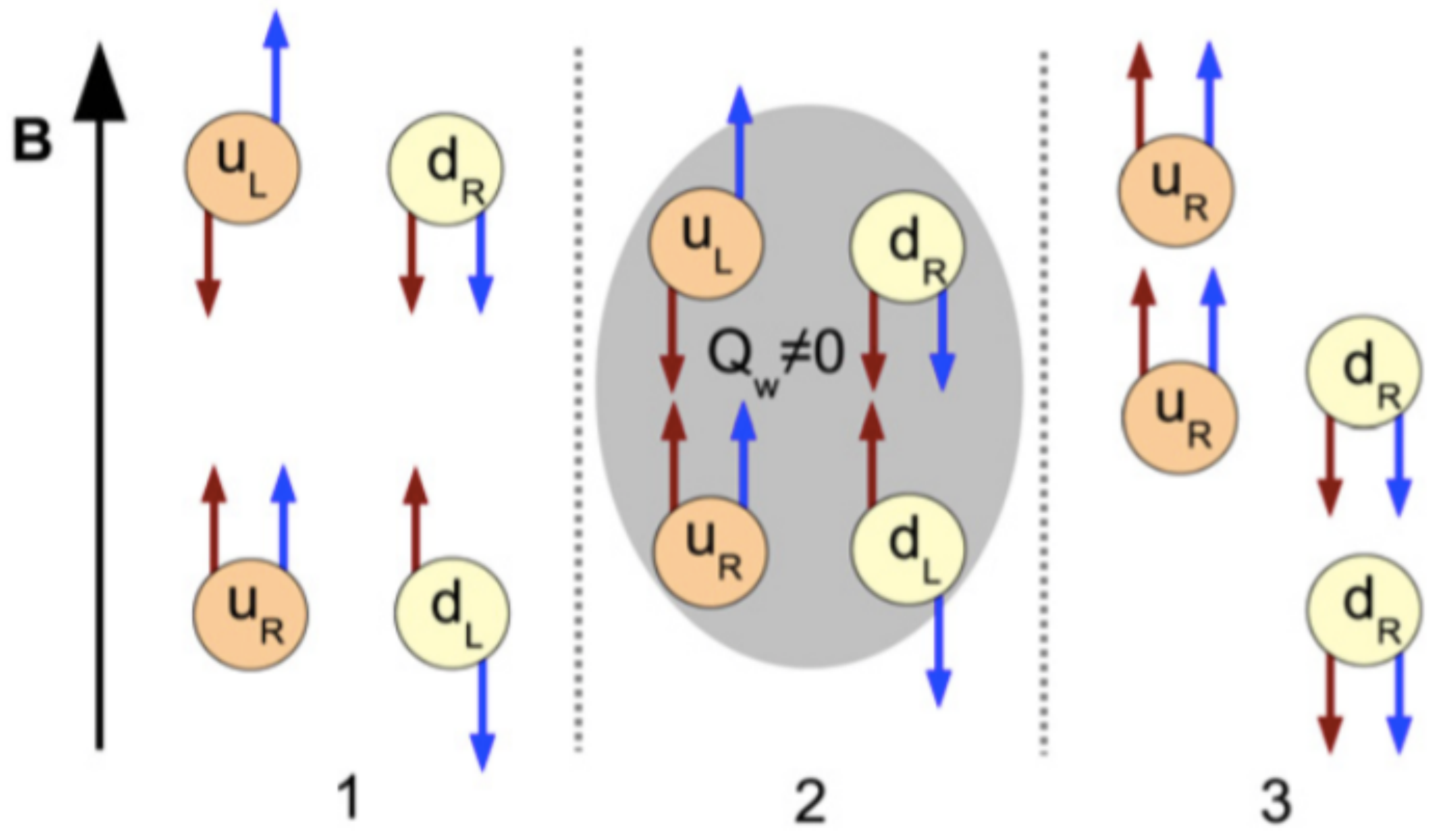
- In non-central heavy-ion collisions an unprecedented intense magnetic field (~10^{18} G) is generated by the movement of the spectator protons

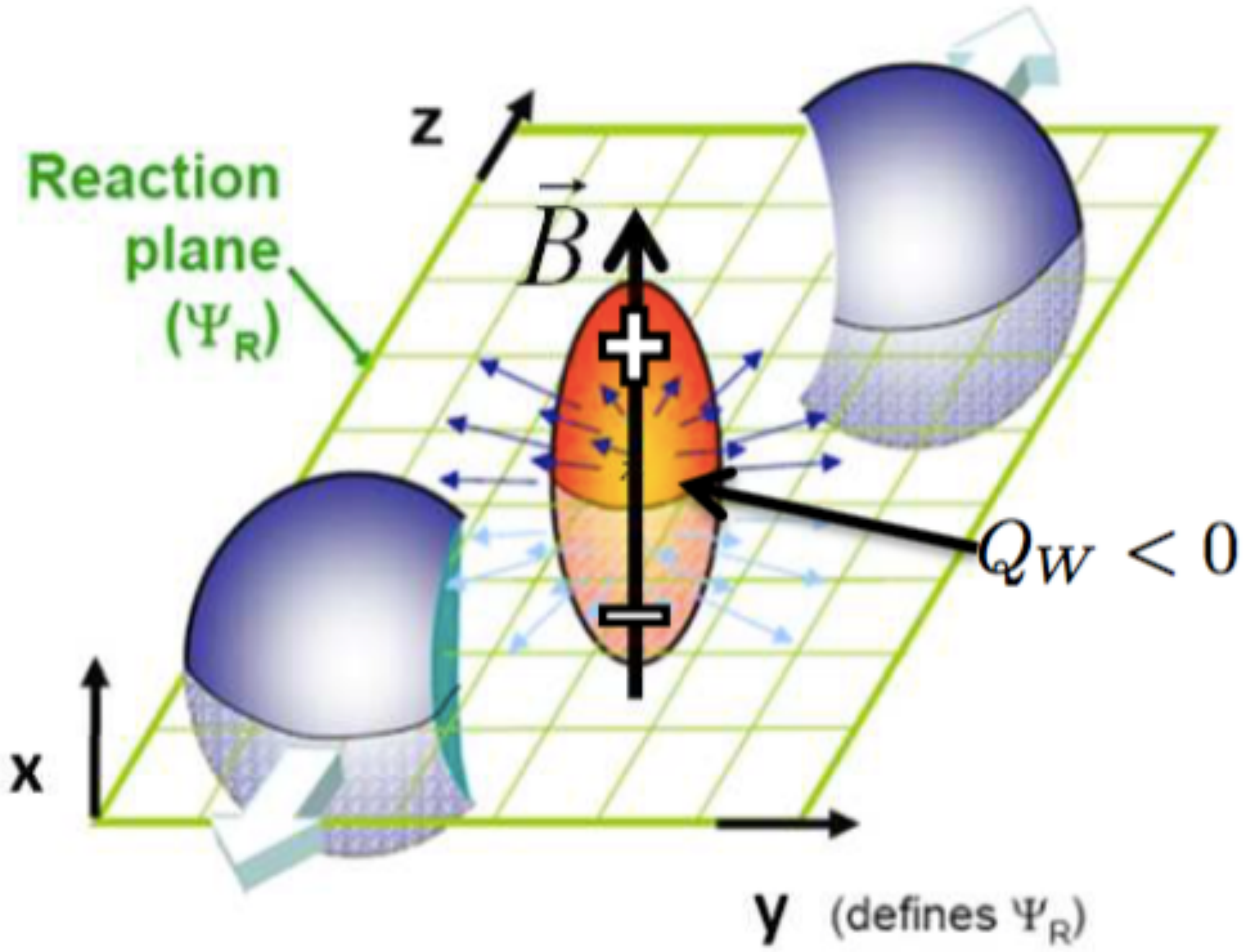
- In the presence of such magnetic field, several anomalous chiral effects, such as
  Chiral Magnetic Effect,
  Chiral Magnetic Wave, etc, have been theorized to be created in QGP
  - ✓ Possible local CP violation in strong interactions
  - ✓ The novel topological nature of the QCD vacuum

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

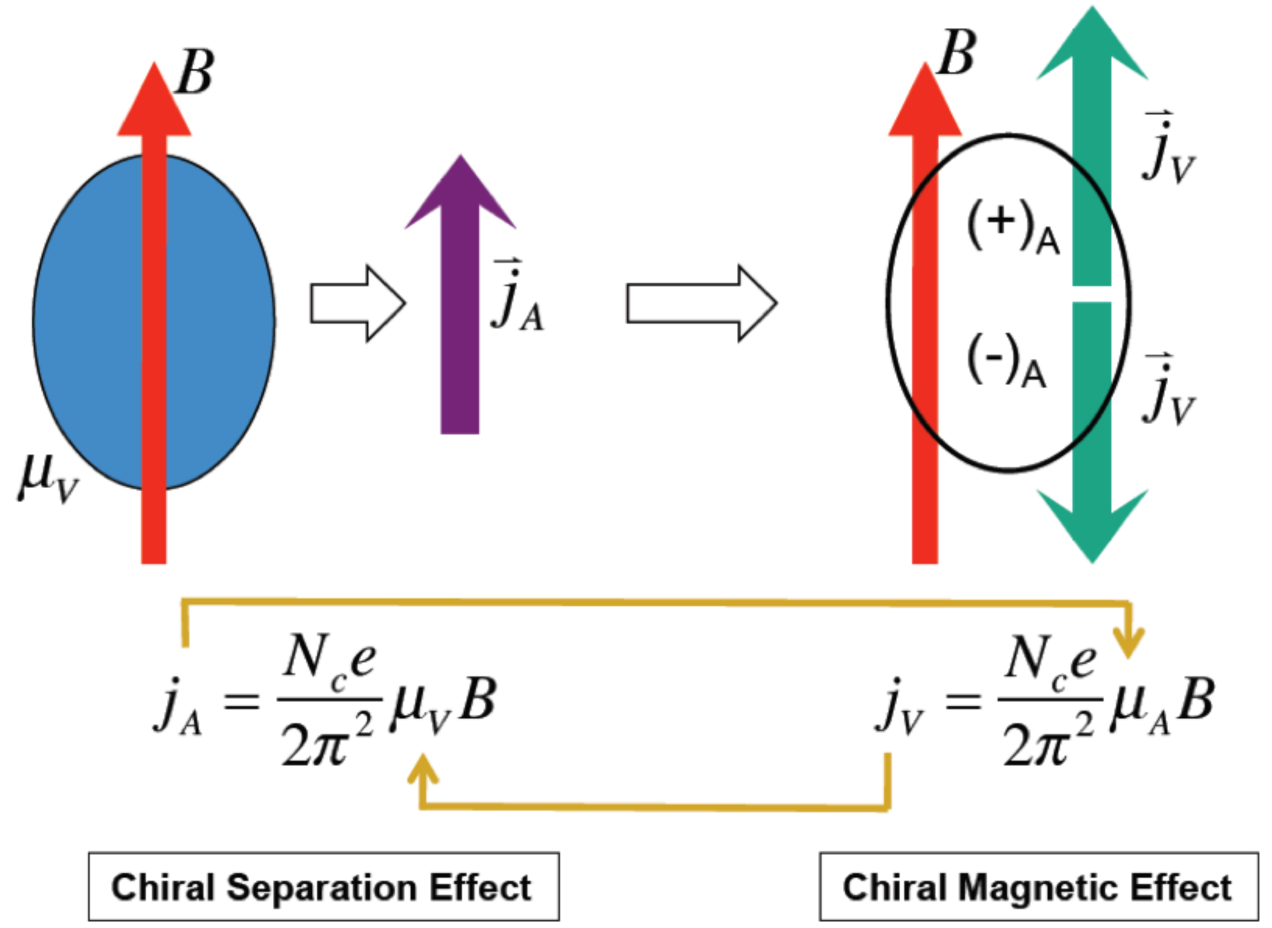
Strong magnetic field & chiral anomaly in heavy-ion collisions

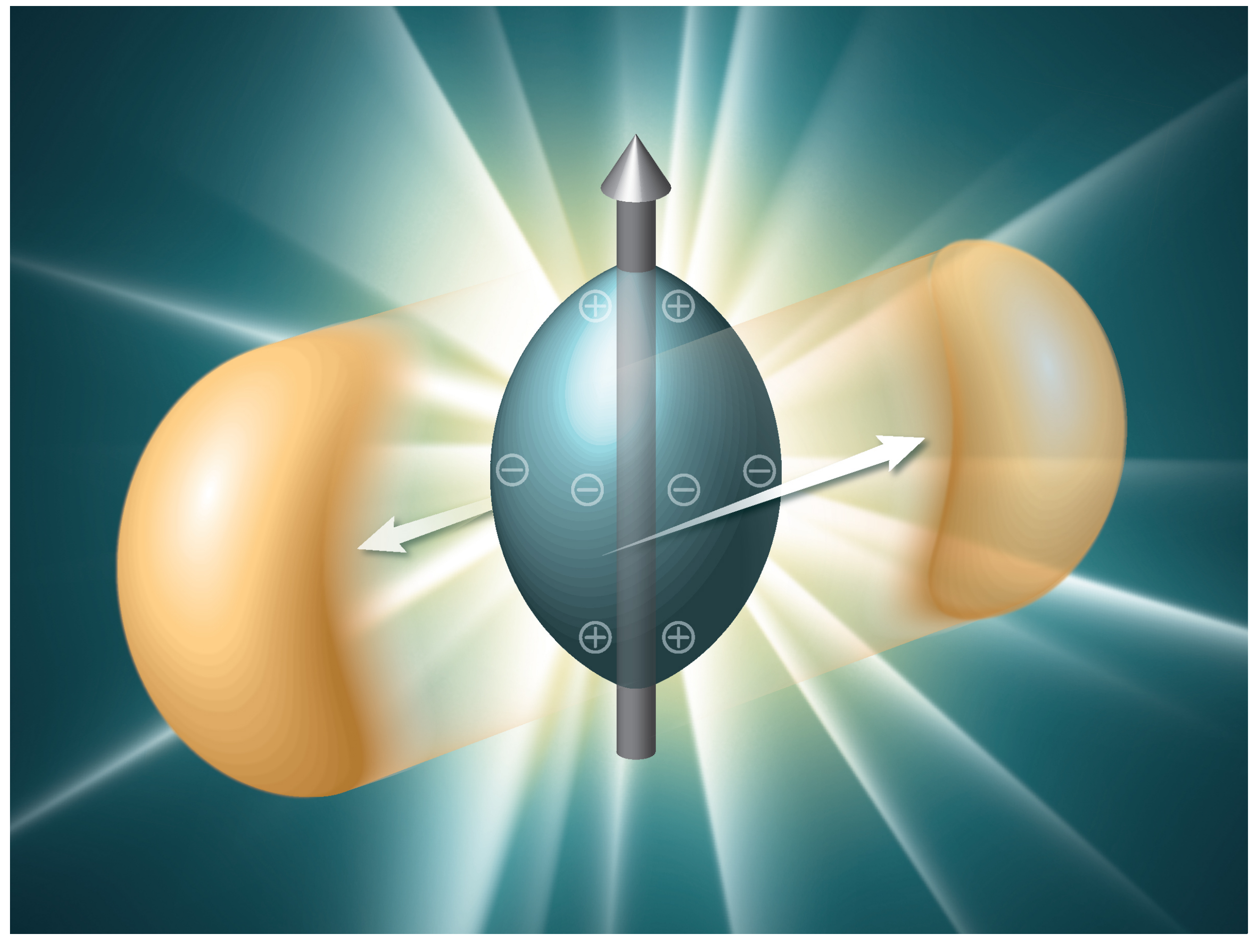
Chiral Magnetic Effect



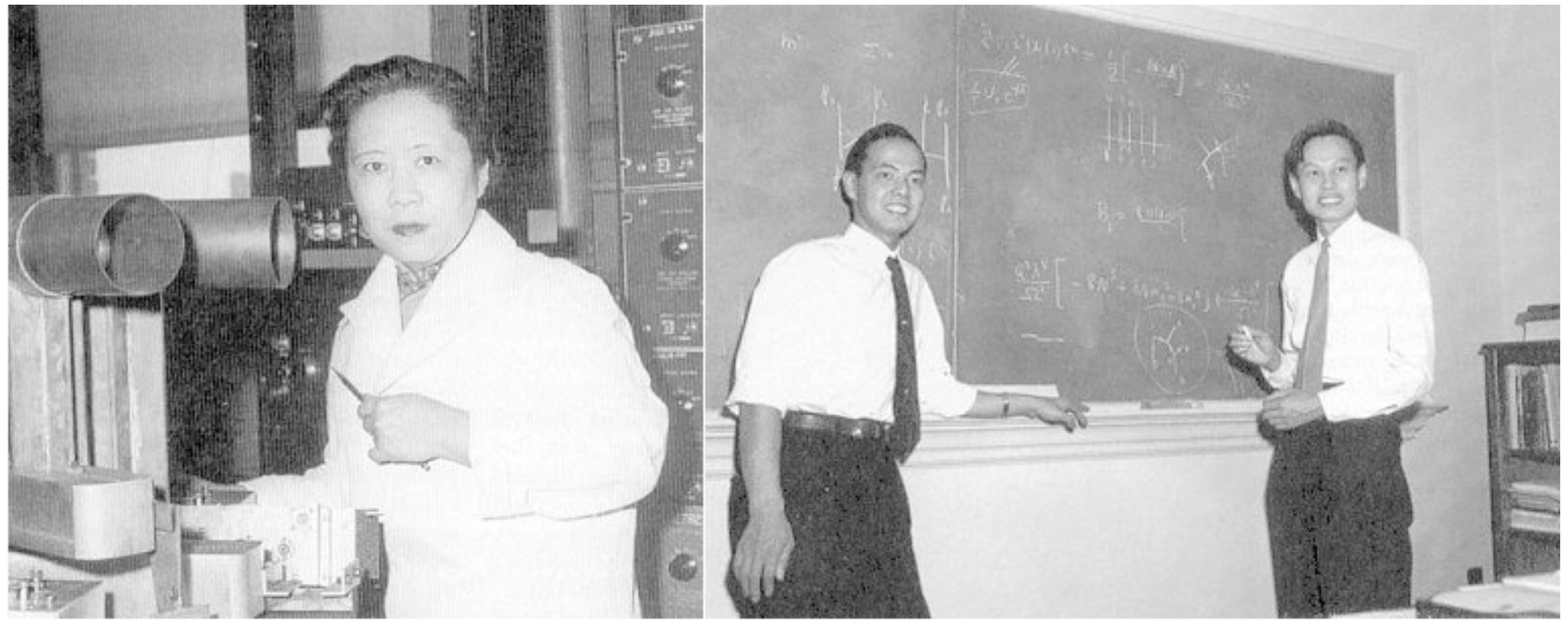


Chiral Magnetic Wave





Strong magnetic field & chiral anomaly in heavy-ion collisions



C. S. Wu T. D. Lee C. N. Yang

Lee and Yang won the Nobel Prize in Physics in 1957 for their work on the P Violation in weak interaction

The discovery of CP violation in 1964 in the decays of neutral kaons resulted in the Nobel Prize in Physics in 1980 for its discoverers James Cronin and Val Fitch

Why is the strong nuclear interaction CP-invariant?
- ✓ QCD allows CP violation in strong interactions
- ✓ No experimentally known violation of the CP-symmetry in strong interactions

In this century, it has been suggested that the QGP created in heavy-ion collisions may form metastable domains where the parity and time-reversal symmetries are locally violated

Strong magnetic field & chiral anomaly in heavy-ion collisions

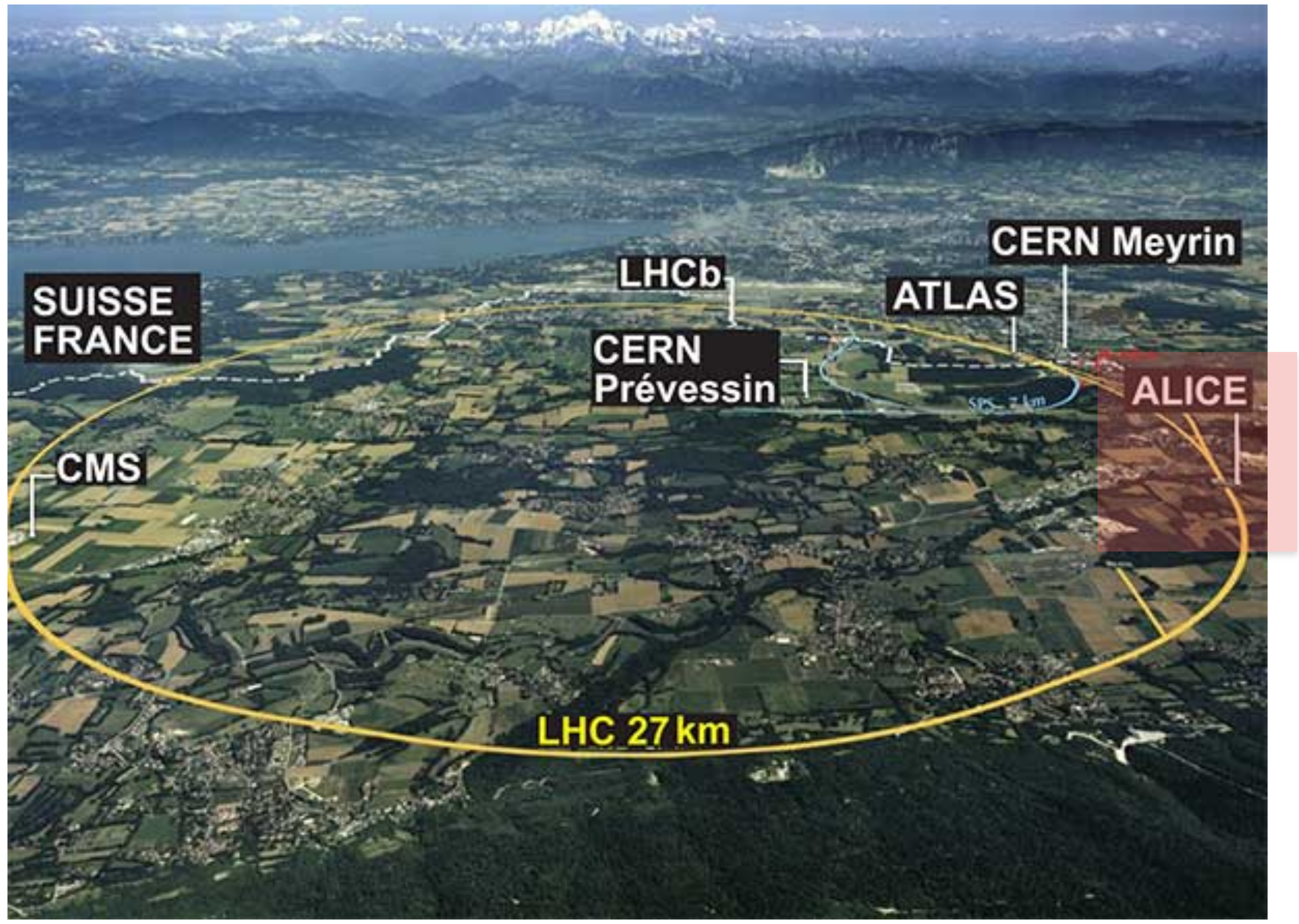
- Studied effects and methodology
  - ✓ B field: charge dependent directed flow, etc
  - ✓ CME: γ and δ correlator (κ and H), Event Shape Engineering, invariant mass, R(ΔS), etc
  - ✓ CMW: charge asymmetry dependent flow, three particle correlation, etc

see following slides for definitions

- Collision 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

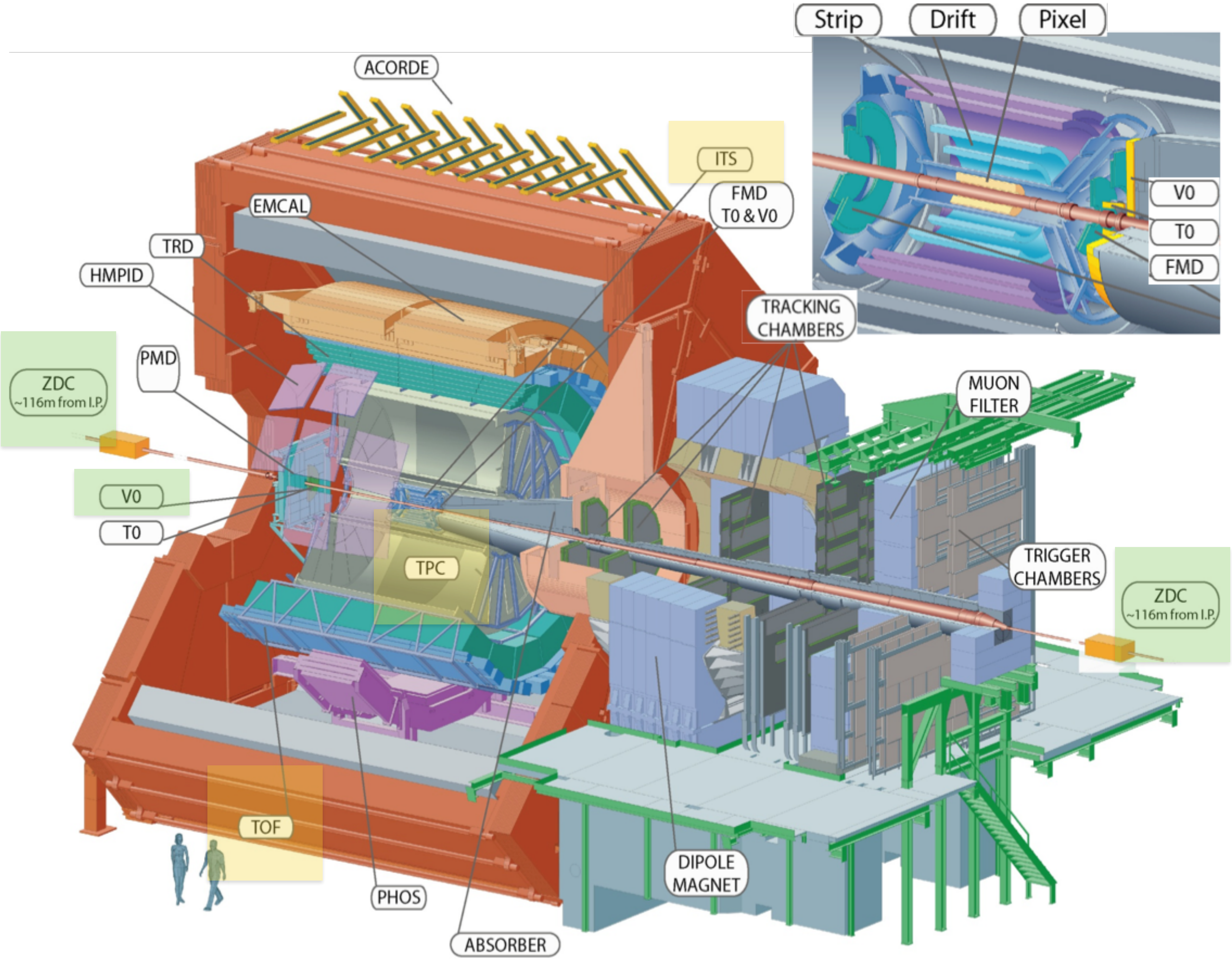
- Particle of interest
  - ✓ Inclusive charged particles
  - ✓ Identified particles: π, K, p, heavy-flavour, etc at various kinematic windows (p_T, η, etc)

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



Search for the CME with two- and three-particle correlations 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).

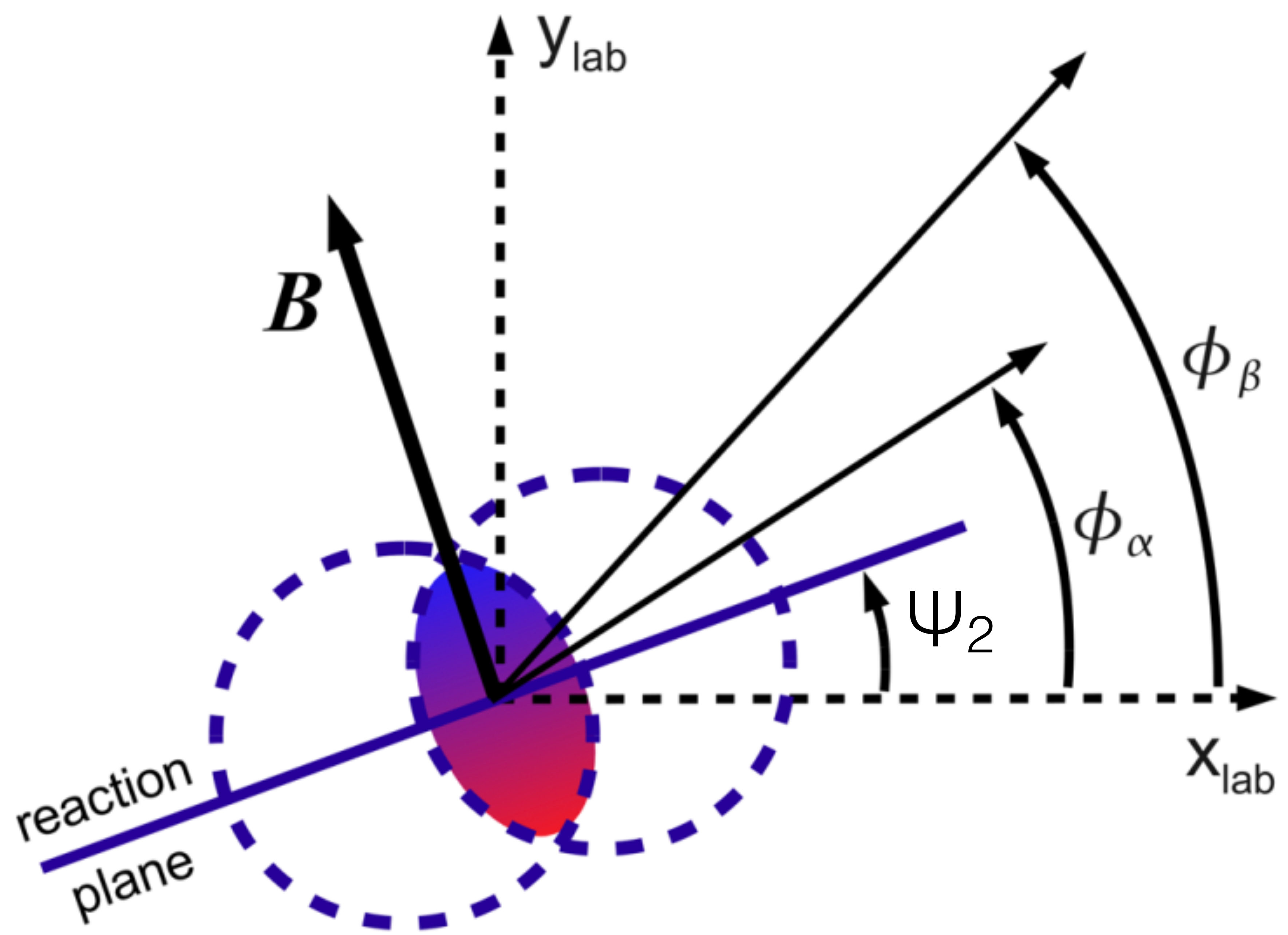
Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 200 GeV
Phys. Rev. C 89, 044908 (2014).

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 correlations



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

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

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

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

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

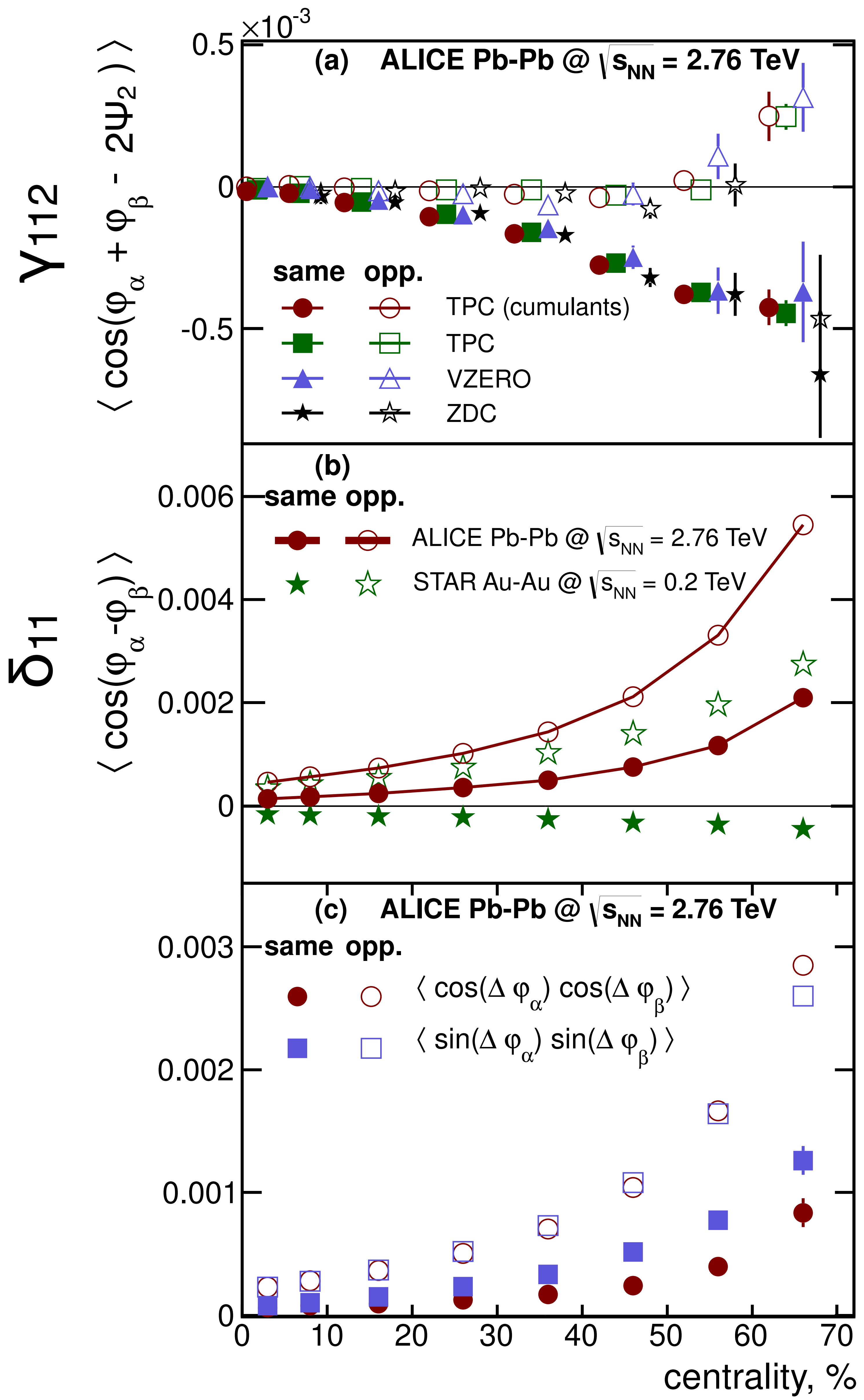
…

- ✓ 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).

ALICE

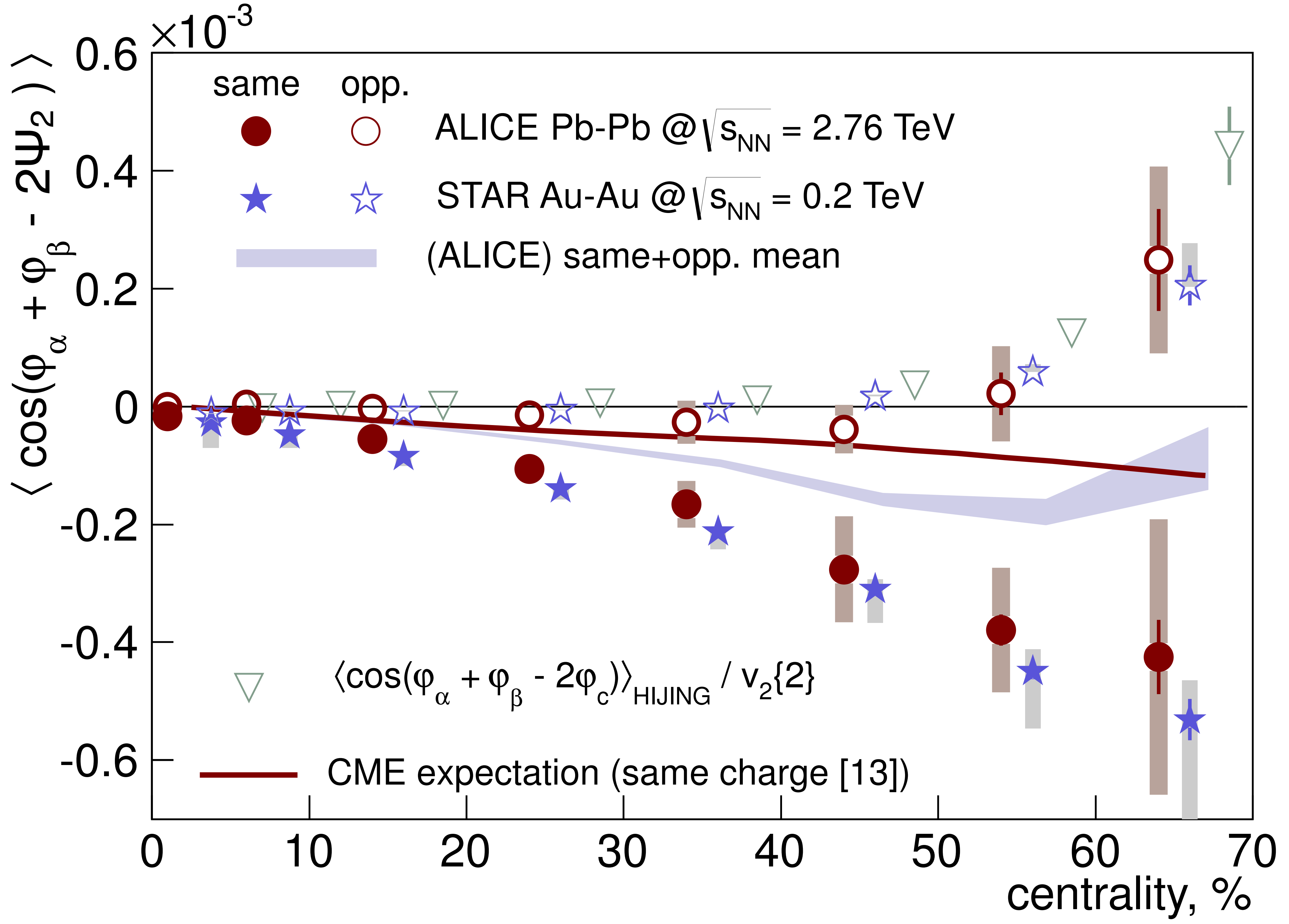


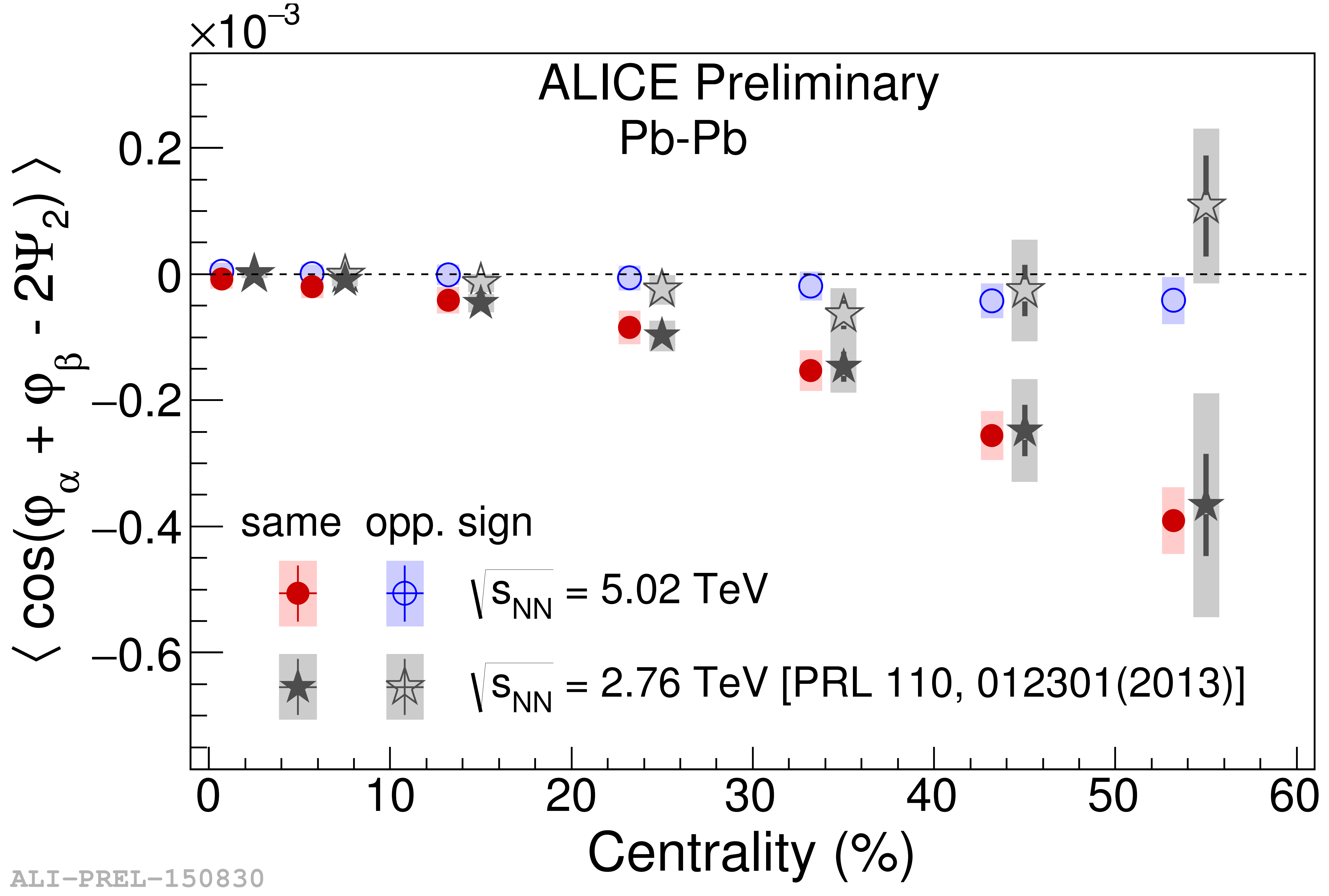
- Good agreement between various γ_{112} obtained with the EP estimated from different detectors
  - ✓ Backgrounds unrelated to the EP are negligible

- 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



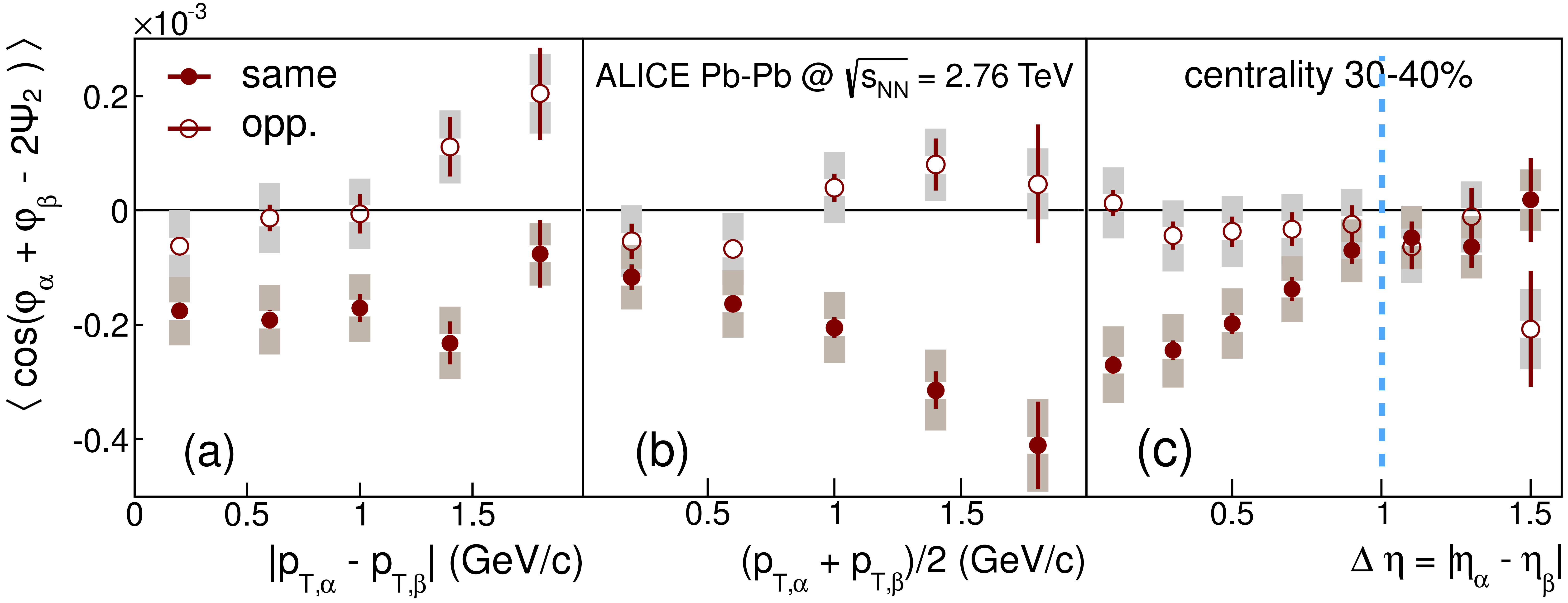


- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

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

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

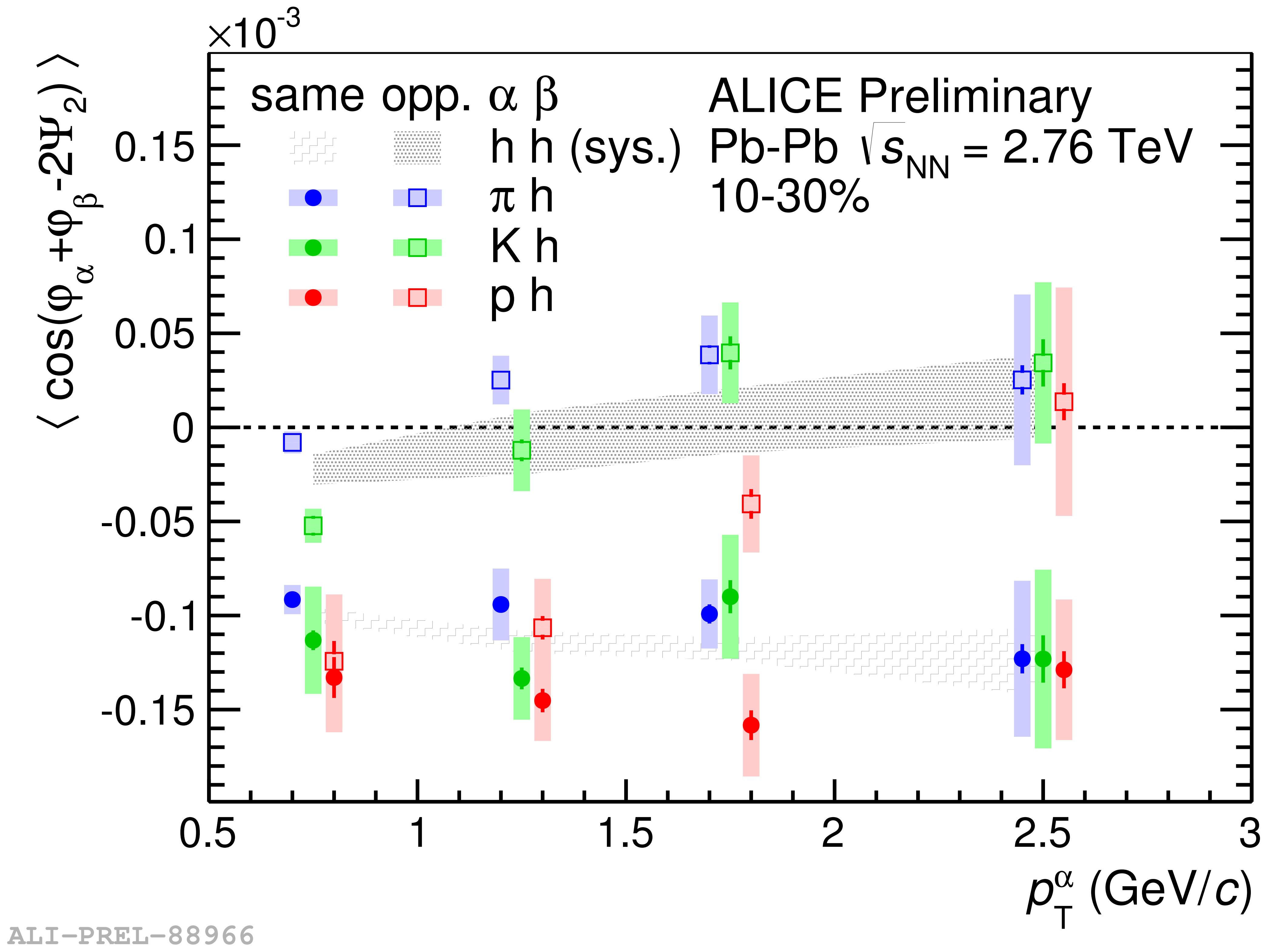
p_T, Δp_T and $\Delta\eta$ dependence of γ_{112} at 2.76 TeV Pb-Pb collisions

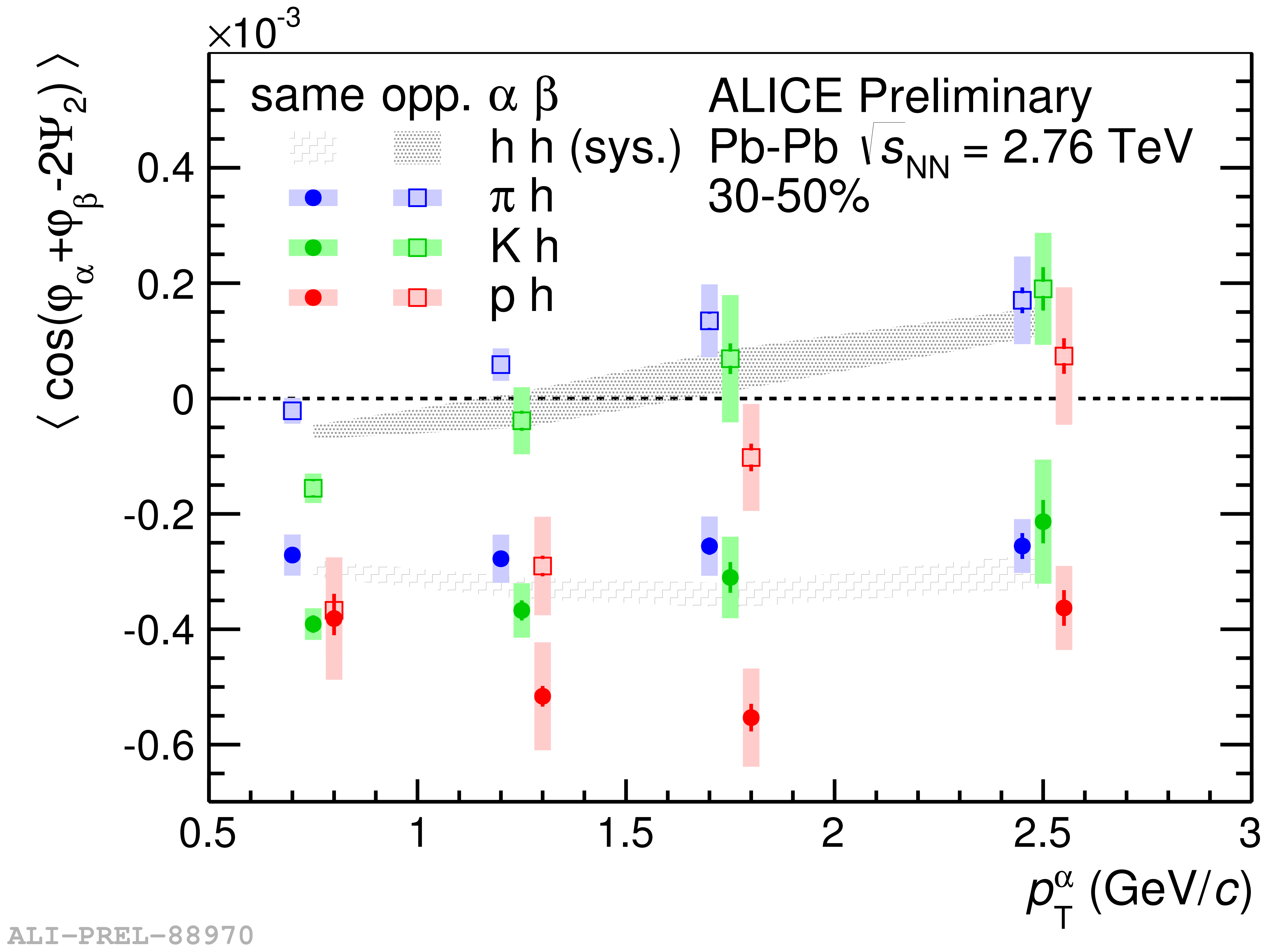


- Weak Δp_T dependence for SS
  - ✓ Exclude HBT correlations
- Magnitude increases with increasing average p_T
  - ✓ Not only originating from low-p_T particles
- Close to zero above one unit of $\Delta\eta$

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

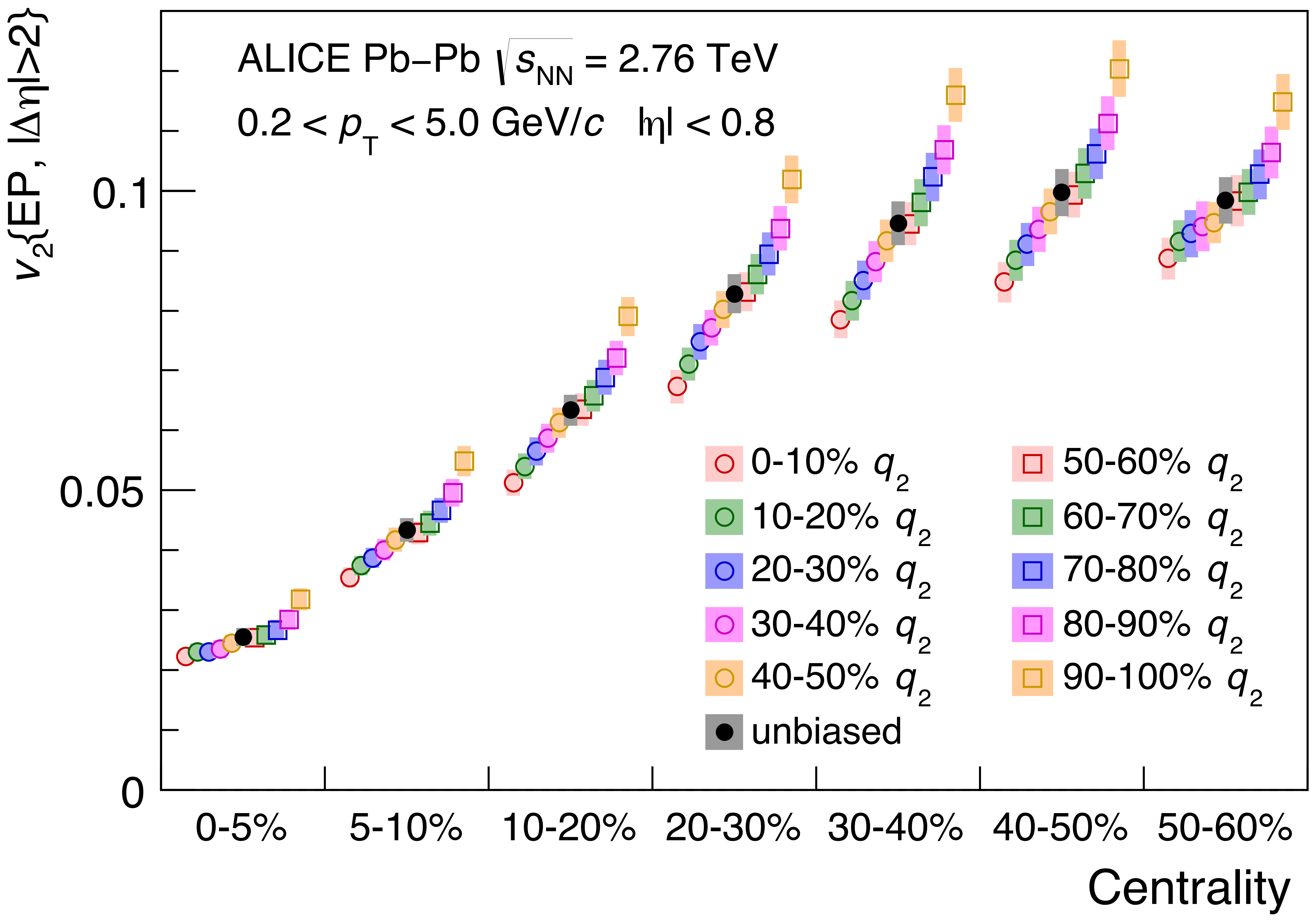
γ_{112} with identified particles at 2.76 TeV Pb-Pb collisions





- $\gamma_{112}(\pi)$ and $\gamma_{112}(K)$ are consistent with $\gamma_{112}(h)$
- Difference between $\gamma_{112}(p)$ and $\gamma_{112}(\pi)$

Event Shape Engineering

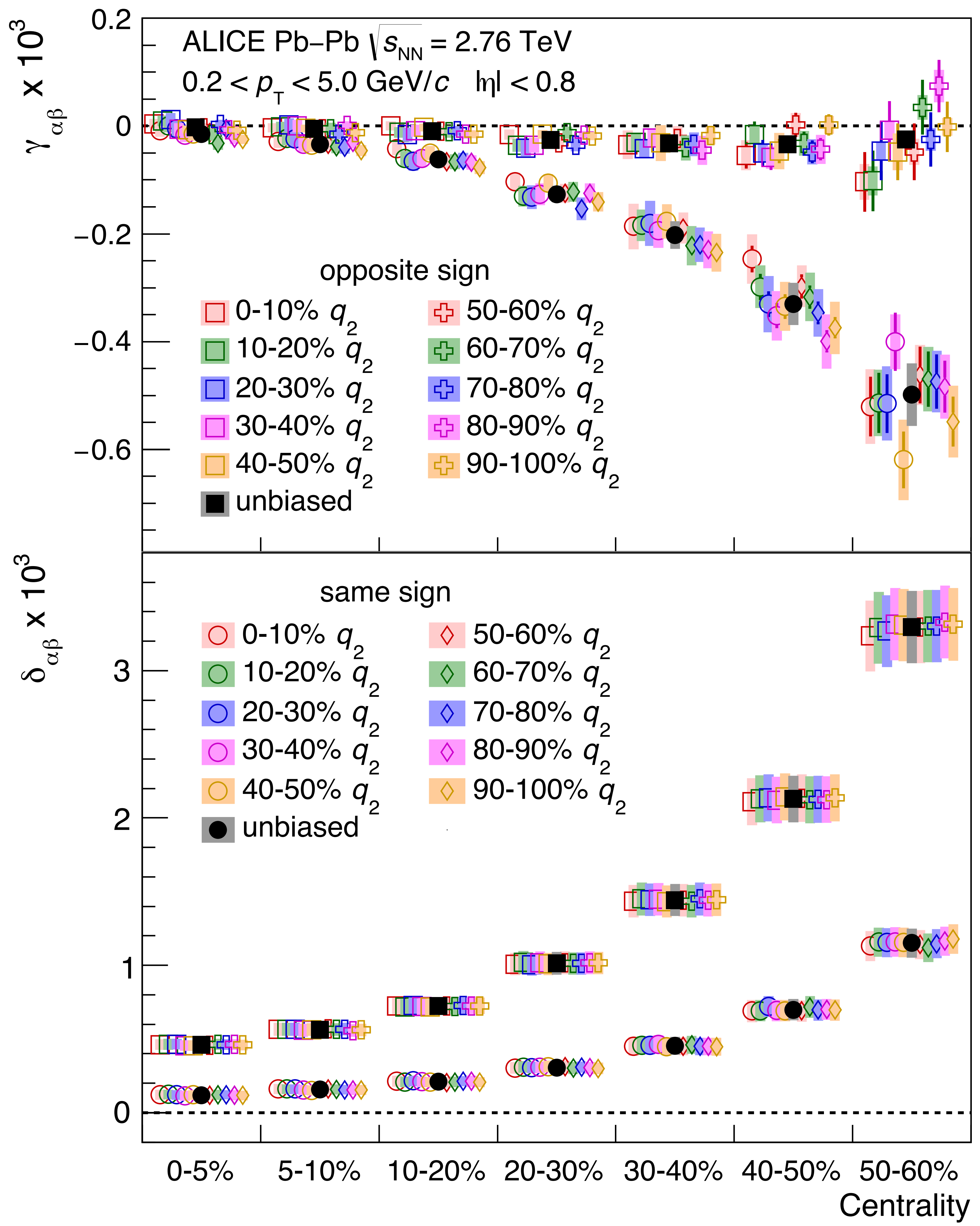


Physics Letters B 777, 151 (2018).

- 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

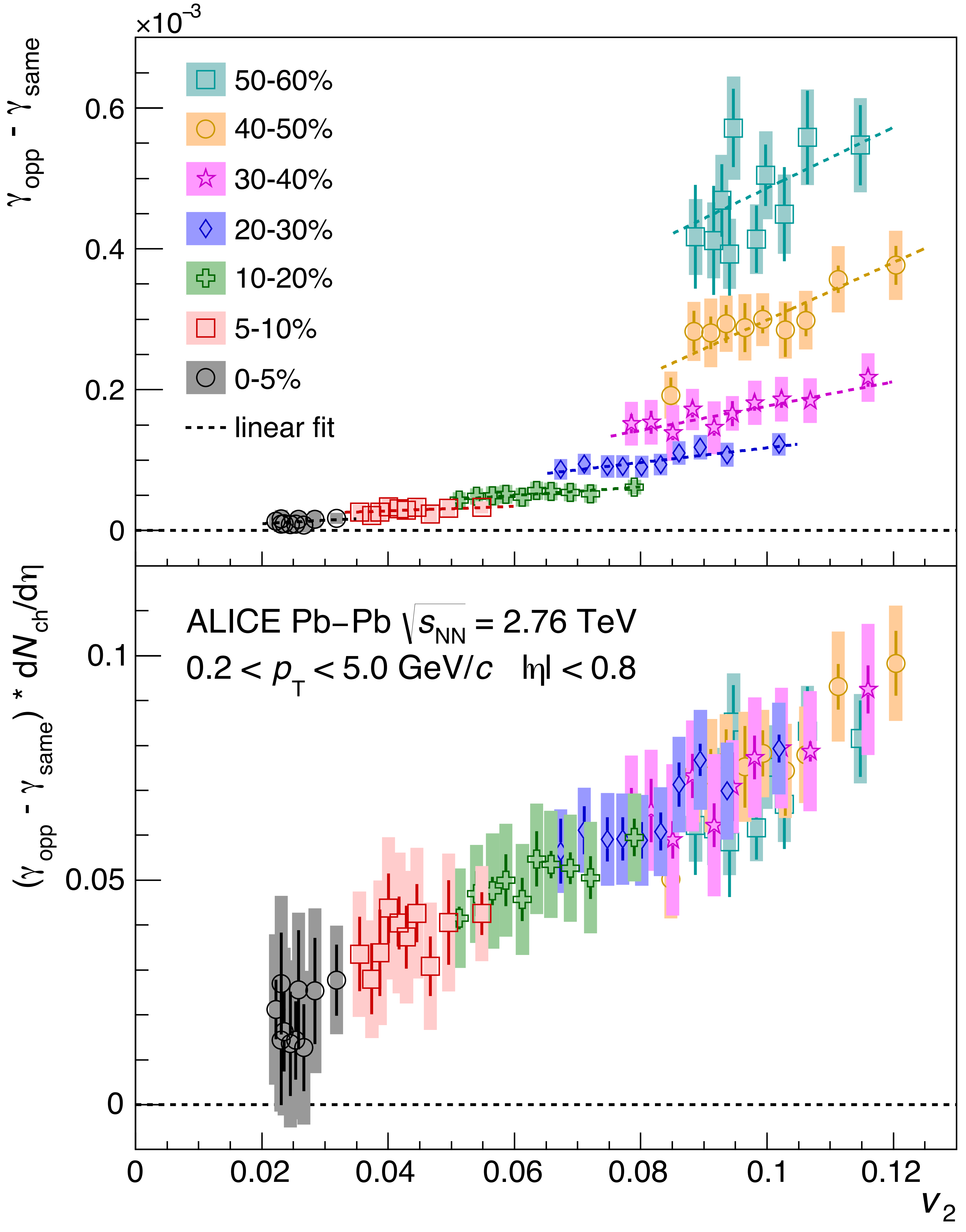
γ_{112} and δ_{11} after event shape selection

Physics Letters B 777, 151 (2018).

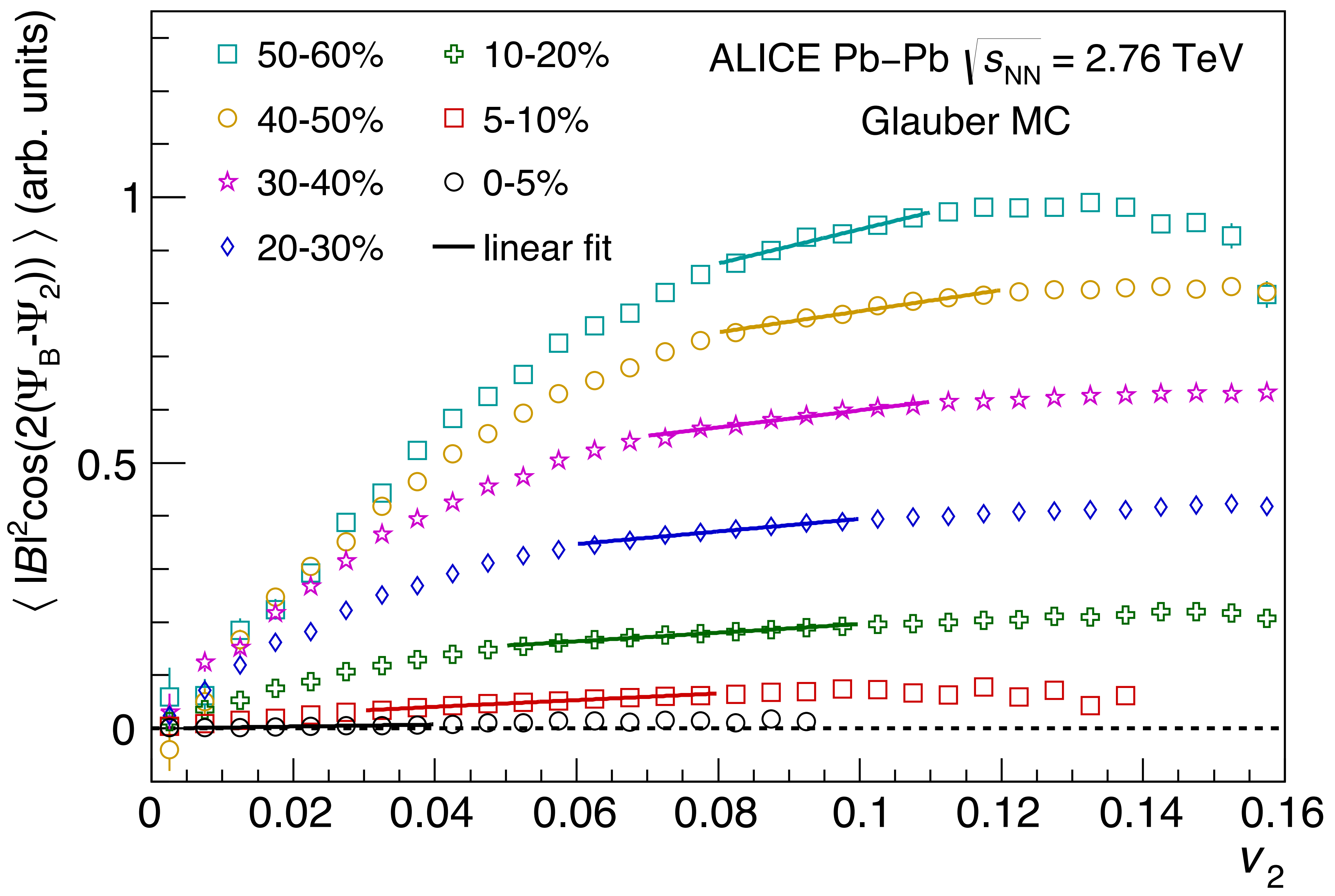


- The magnitude of γ_{112} and δ_{11} for SS and OS depends weakly on the event-shape selection in a given centrality

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



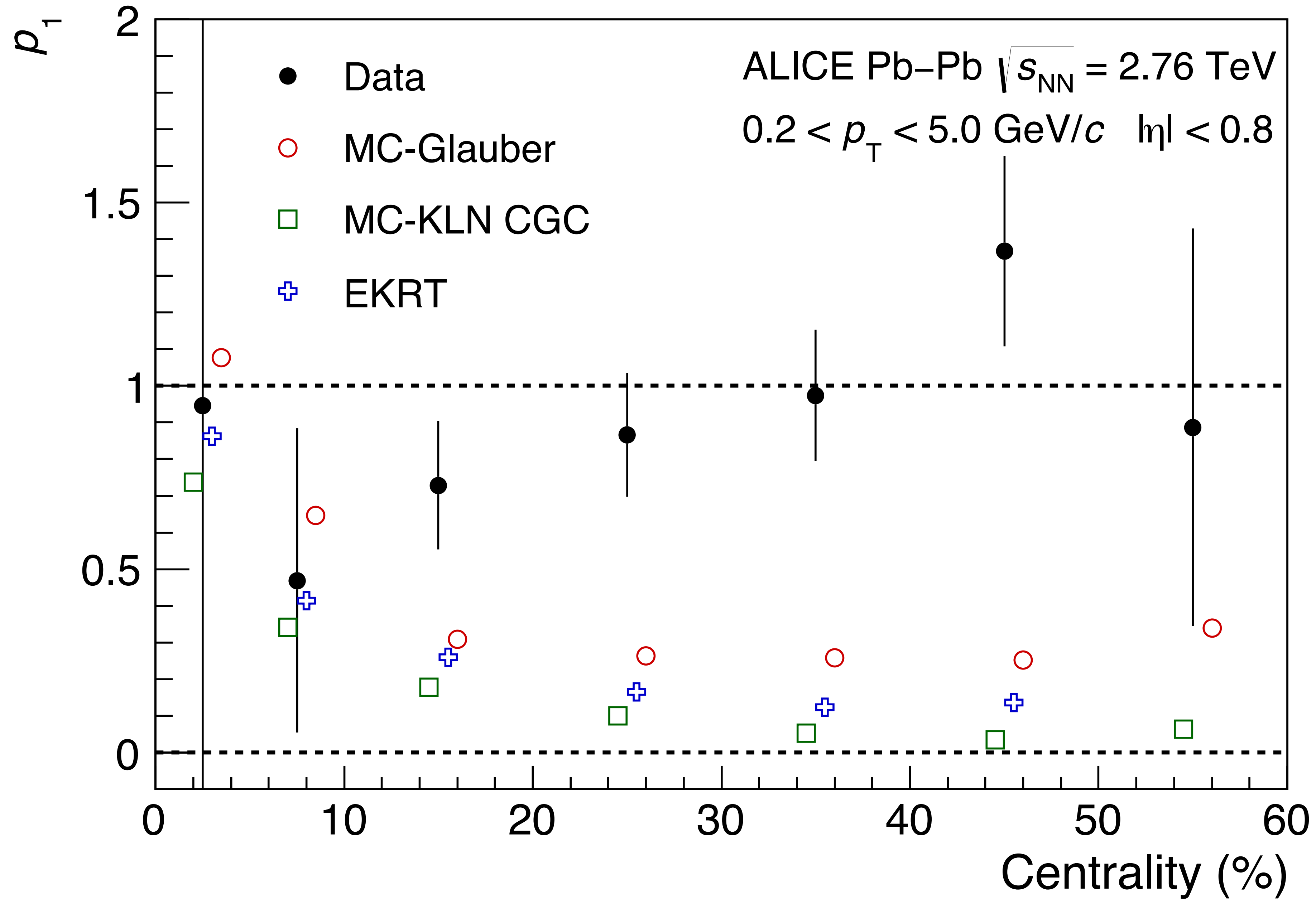
Physics Letters B 777, 151 (2018).

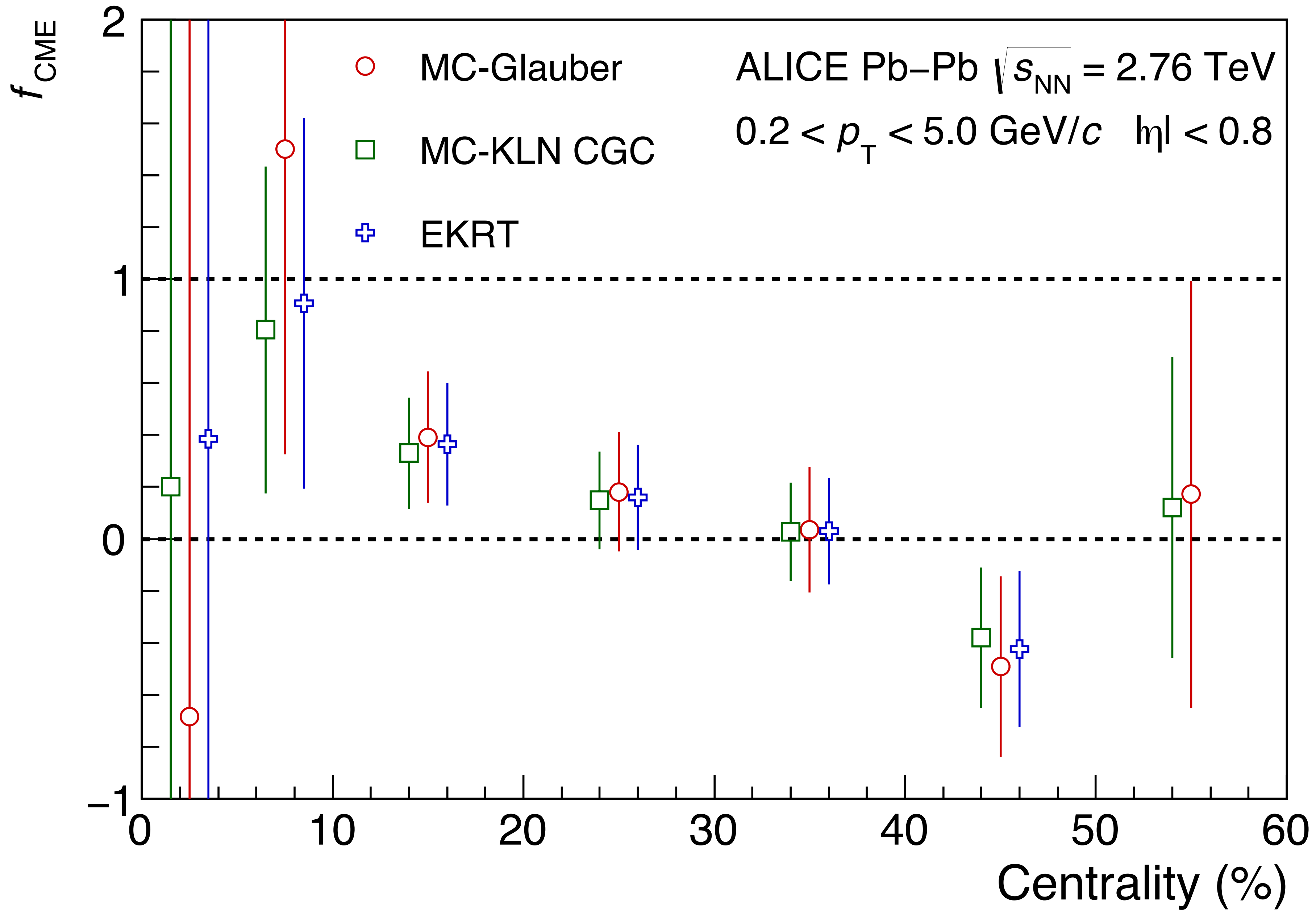


- $\Delta\gamma_{112}$ is positive for all centralities
- The magnitude decreases for more central collisions and with decreasing v_2 (in a given centrality bin)
- After scaling by $dN_{ch}/d\eta$, $\Delta\gamma_{112}$ is approximately proportional to v_2

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

Disentangle CME component from v_2 driven background





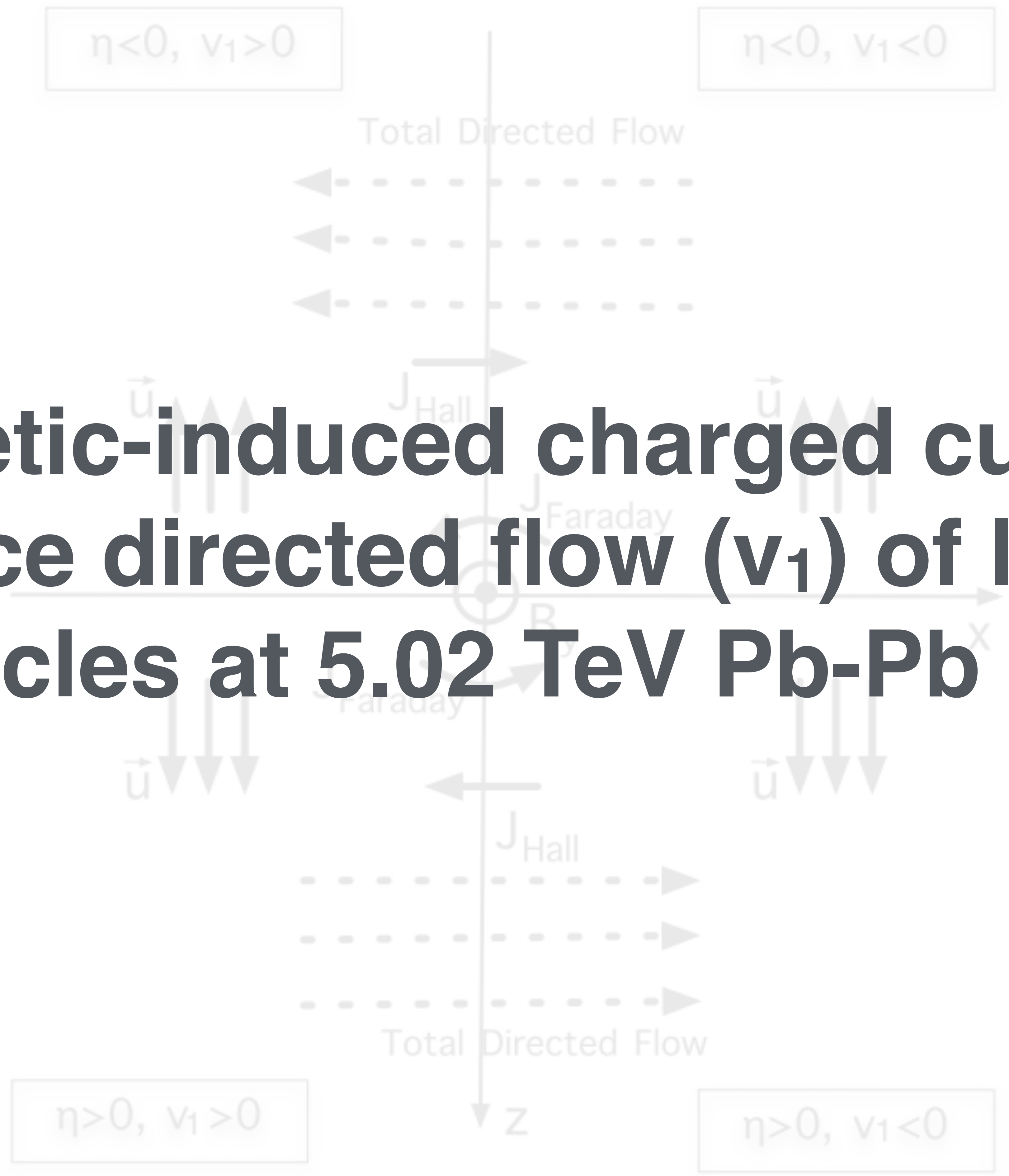
$F_1(v_2) = p_0(1 + p_1(v_2 - \langle v_2\rangle)/\langle v_2\rangle)$ to fit both data and model

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

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

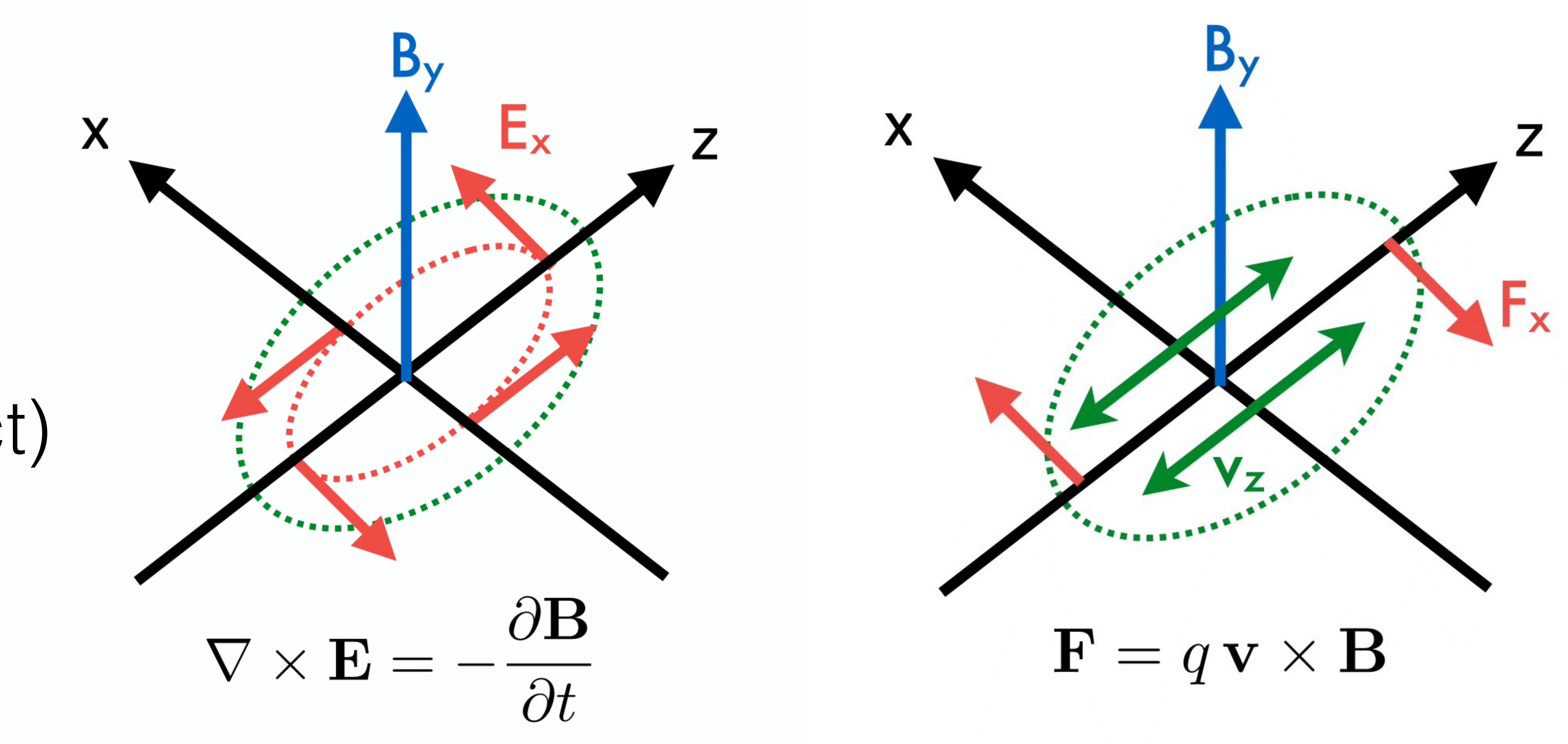
Physics Letters B 777, 151 (2018).

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)

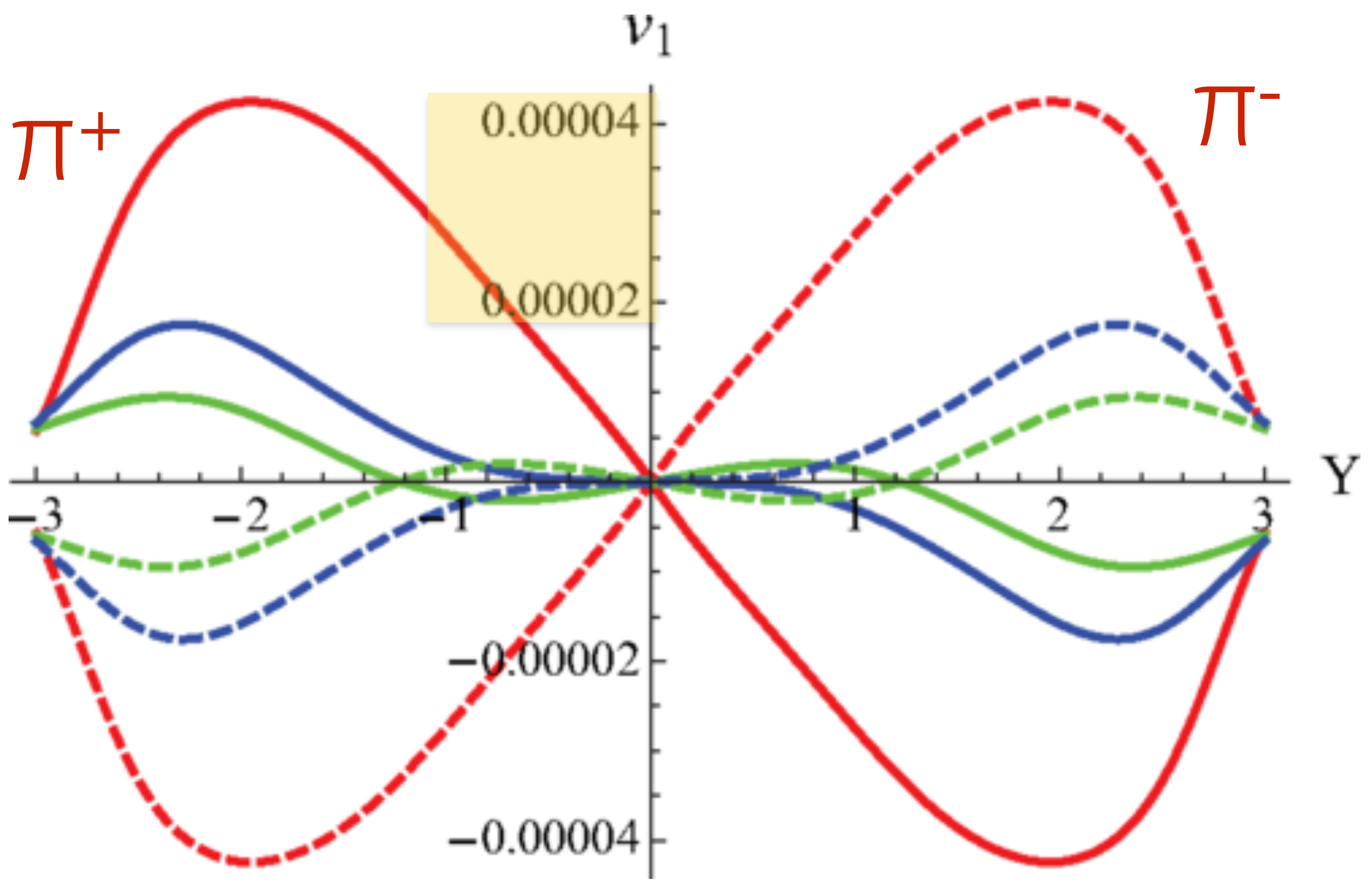


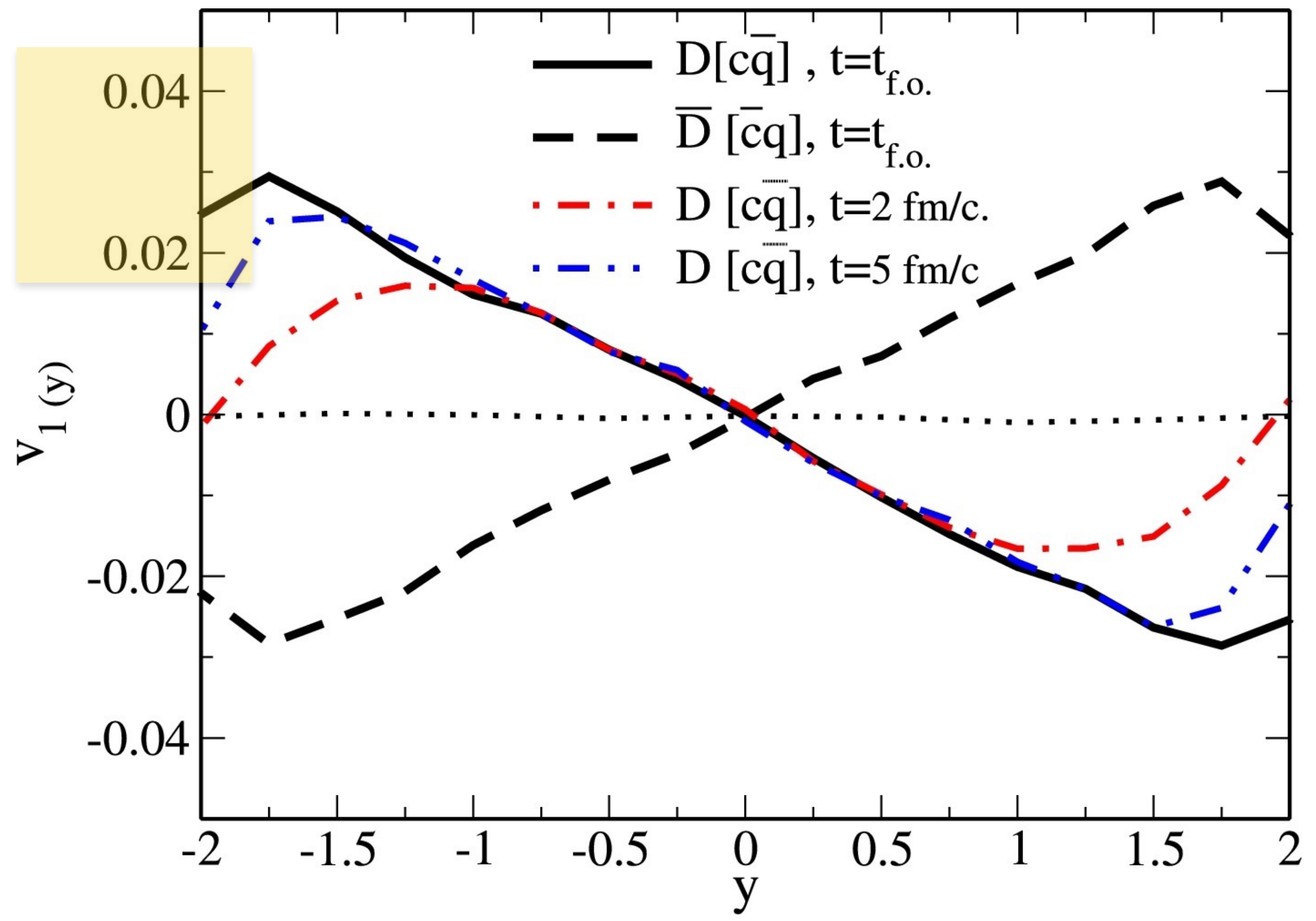
- Charged currents owing to the combination of
  - ✓ Electric field induced by decreasing B (Faraday effect)
  - ✓ Lorentz force on moving charges (Hall effect)

- 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

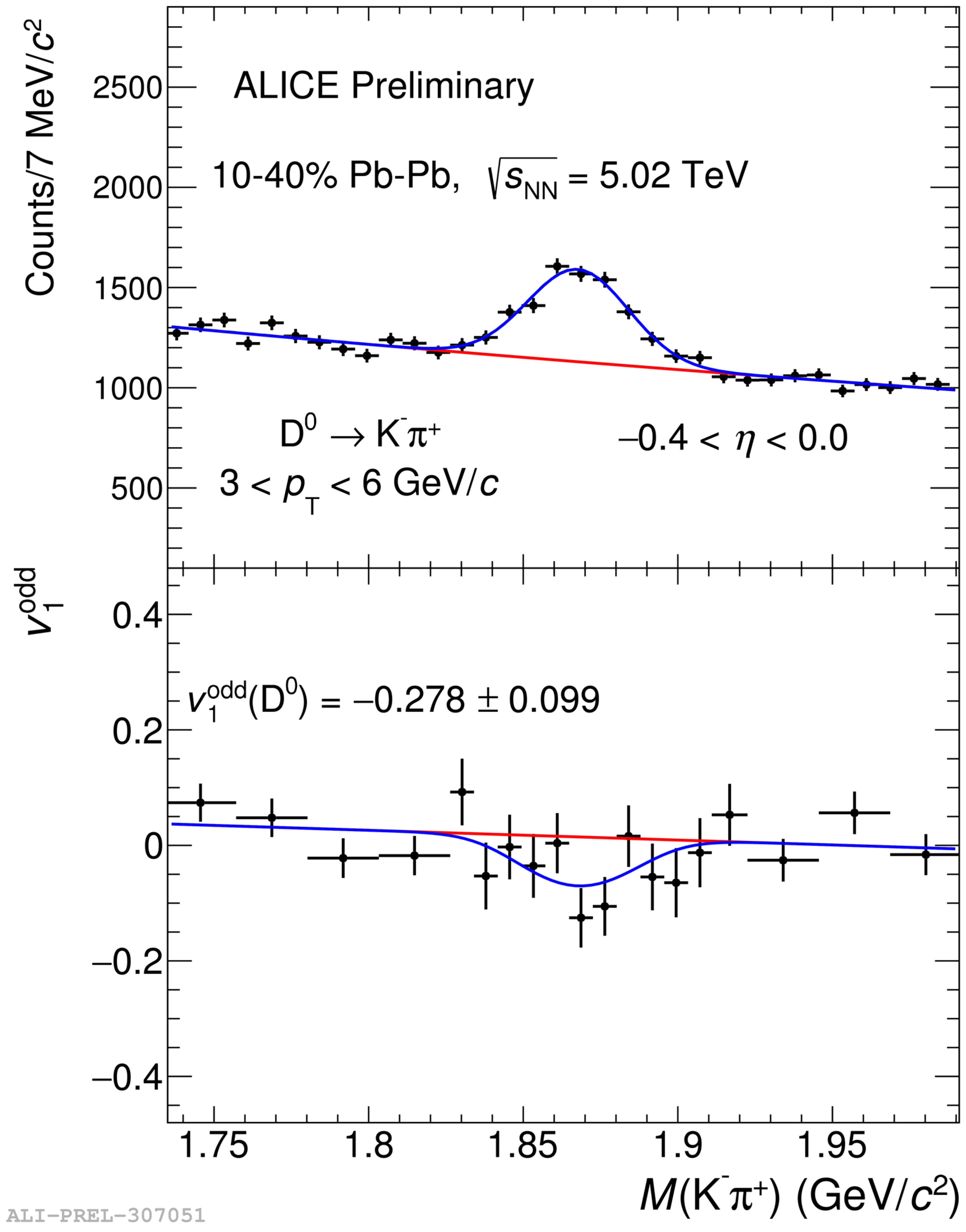




Phys. Rev. C 89, 054905 (2014).
Phys. Lett. B 768, 260 (2017).

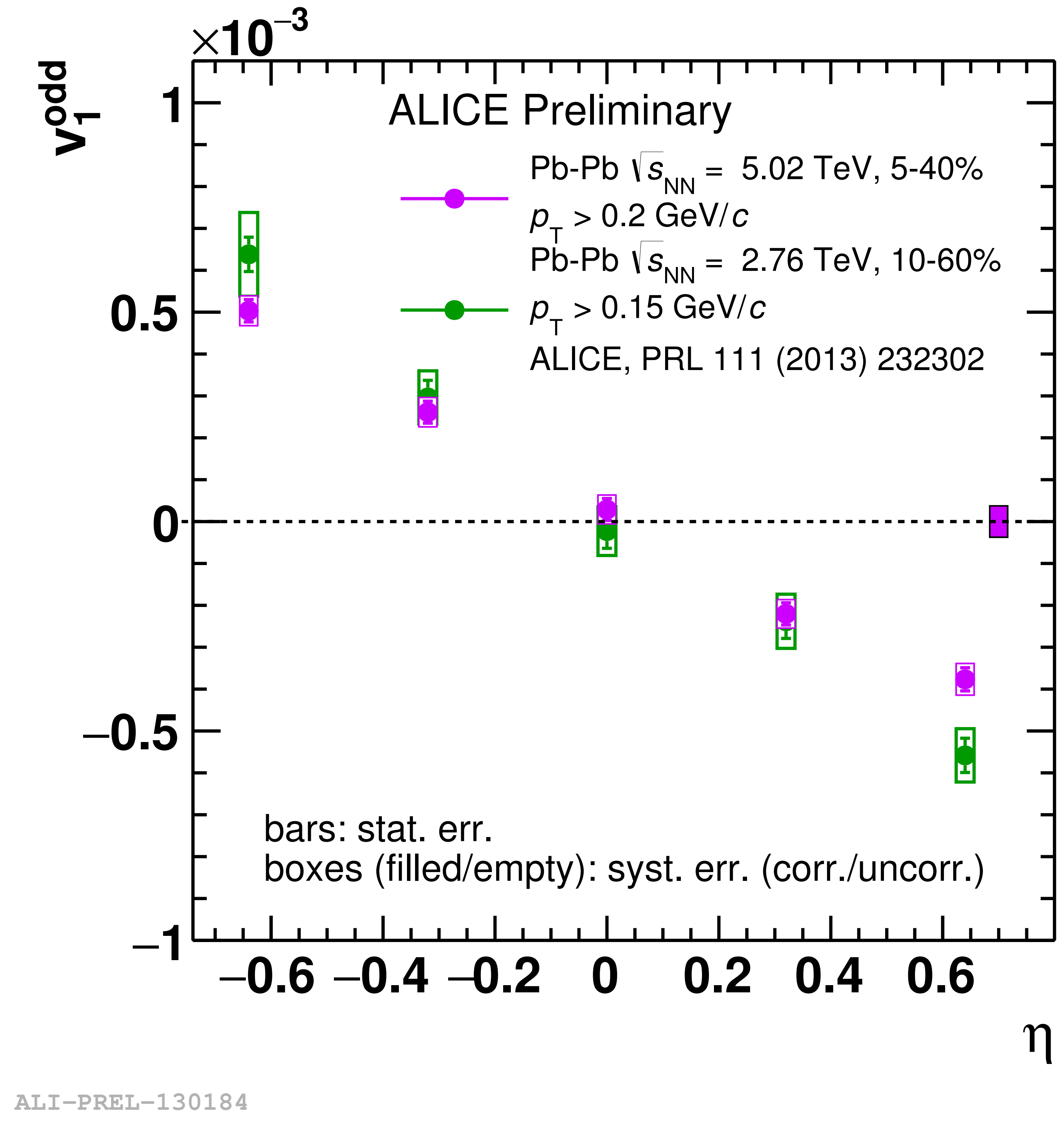
- Charge-dependent v_1 of light and heavy-flavour particles
  - ✓ Formation time ~ 0.1 fm/c, comparable to the time scale when B is maximum
  - ✓ The kinetic relaxation time of charm is similar to the QGP lifetime
  - ✓ Possible larger v_1 of charm quarks compared to light quarks (~10^3)
- Rapidity-odd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

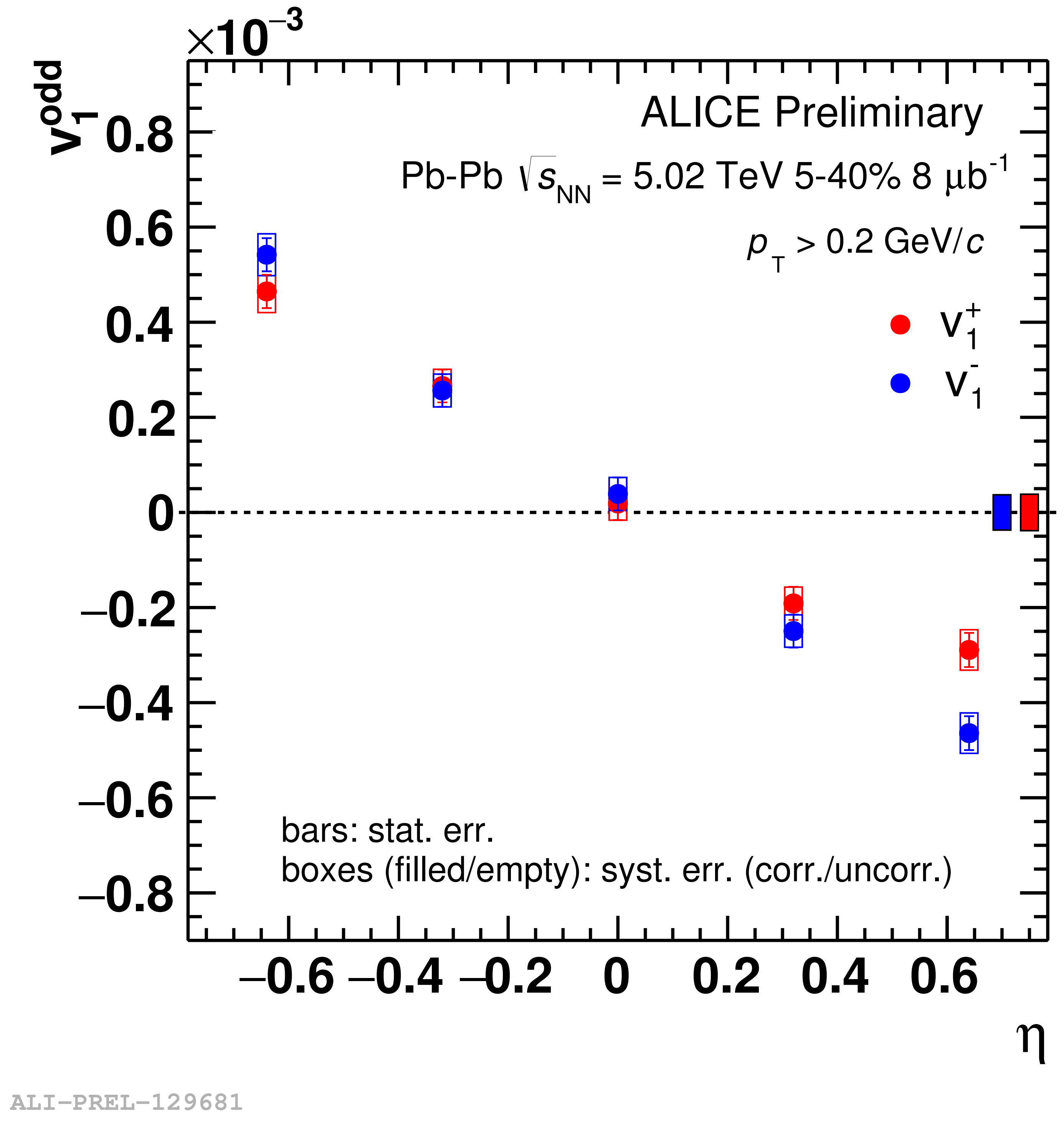
D^0 v_1 extraction

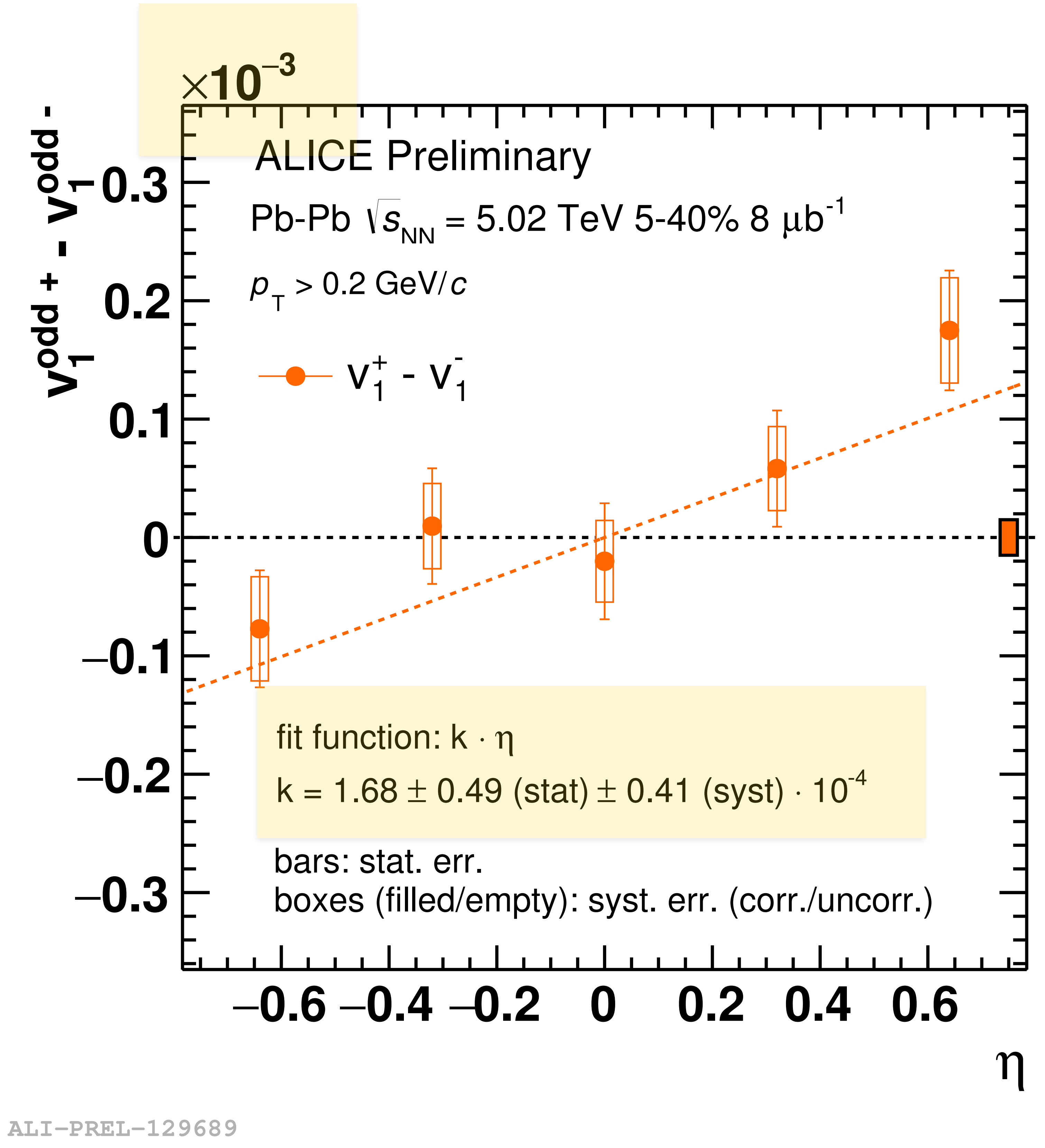


- D^0 mesons and their antiparticles are reconstructed in the central rapidity region from their charged hadronic decay channels $D^0 \rightarrow K^-\pi^+$
- $v_1^{odd}(D^0)$ extracted from a simultaneous fit to the invariant mass and to the $v_1^{odd}(M)$ distributions

Charge dependence v_1 of charged hadrons at 5.02 TeV



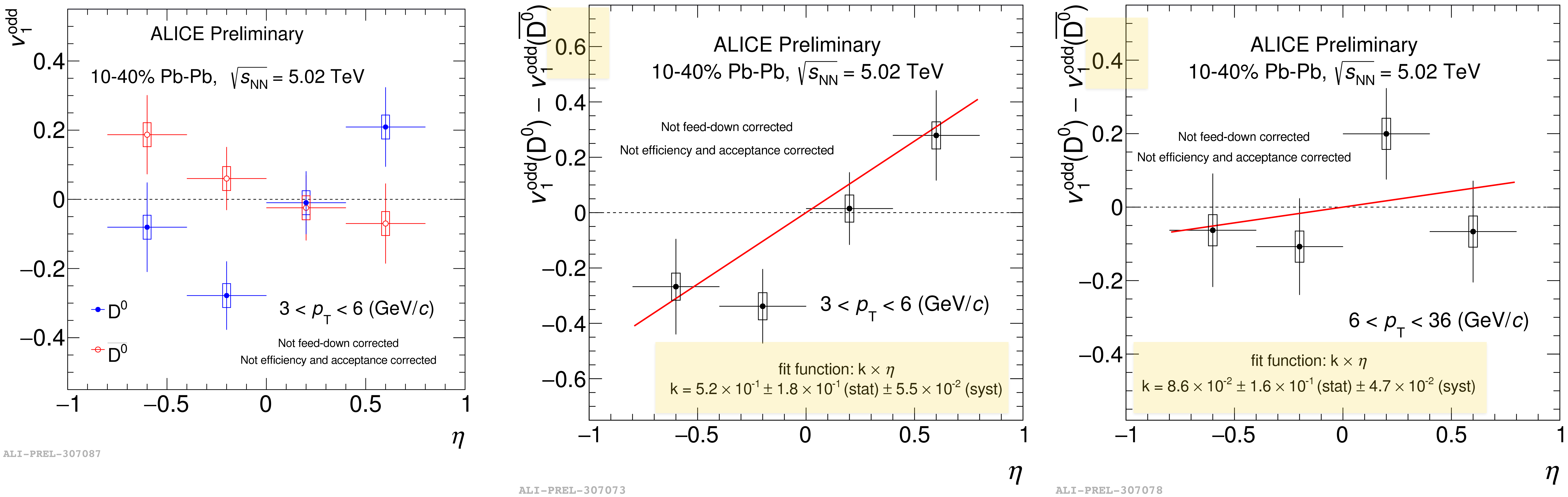




- $dv_1^{odd}/d\eta$ slightly decreases at 5.02 TeV

- 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

- After the LS2, 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

- Considering the fact that a few French groups, such as Clermont-Ferrand and Nantes, are richly experienced on the dilepton/photon studies as well as in PWG-DQ/GA, it would be beneficial for both sides to collaboratively launch such researches under the FCPPL

Thank you for your attention!