The 13th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics

Search for the anomalous chiral effects and the strong magnetic field at the LHC with ALICE

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恩施，2019年8月

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

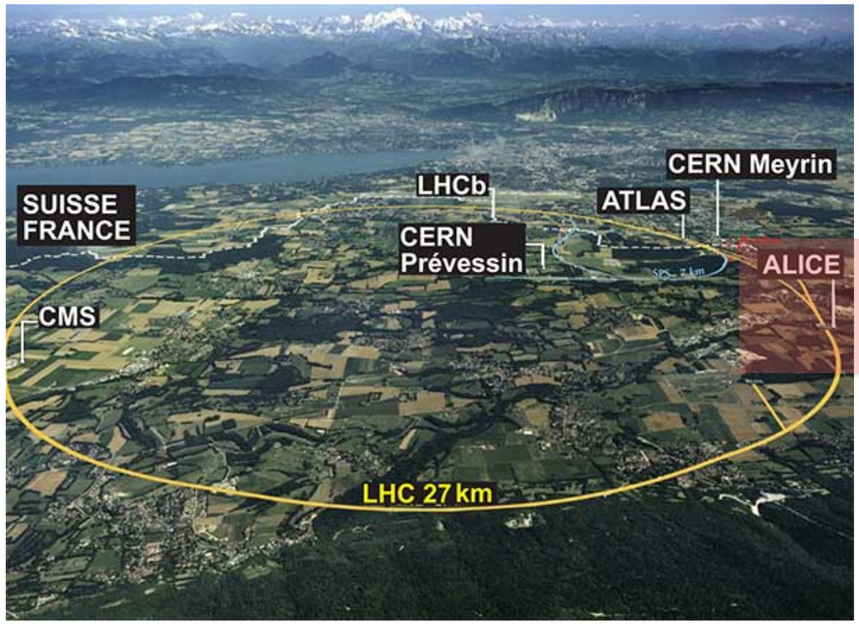
Strong magnetic field & chiral anomaly in heavy-ion collisions

- 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

- 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

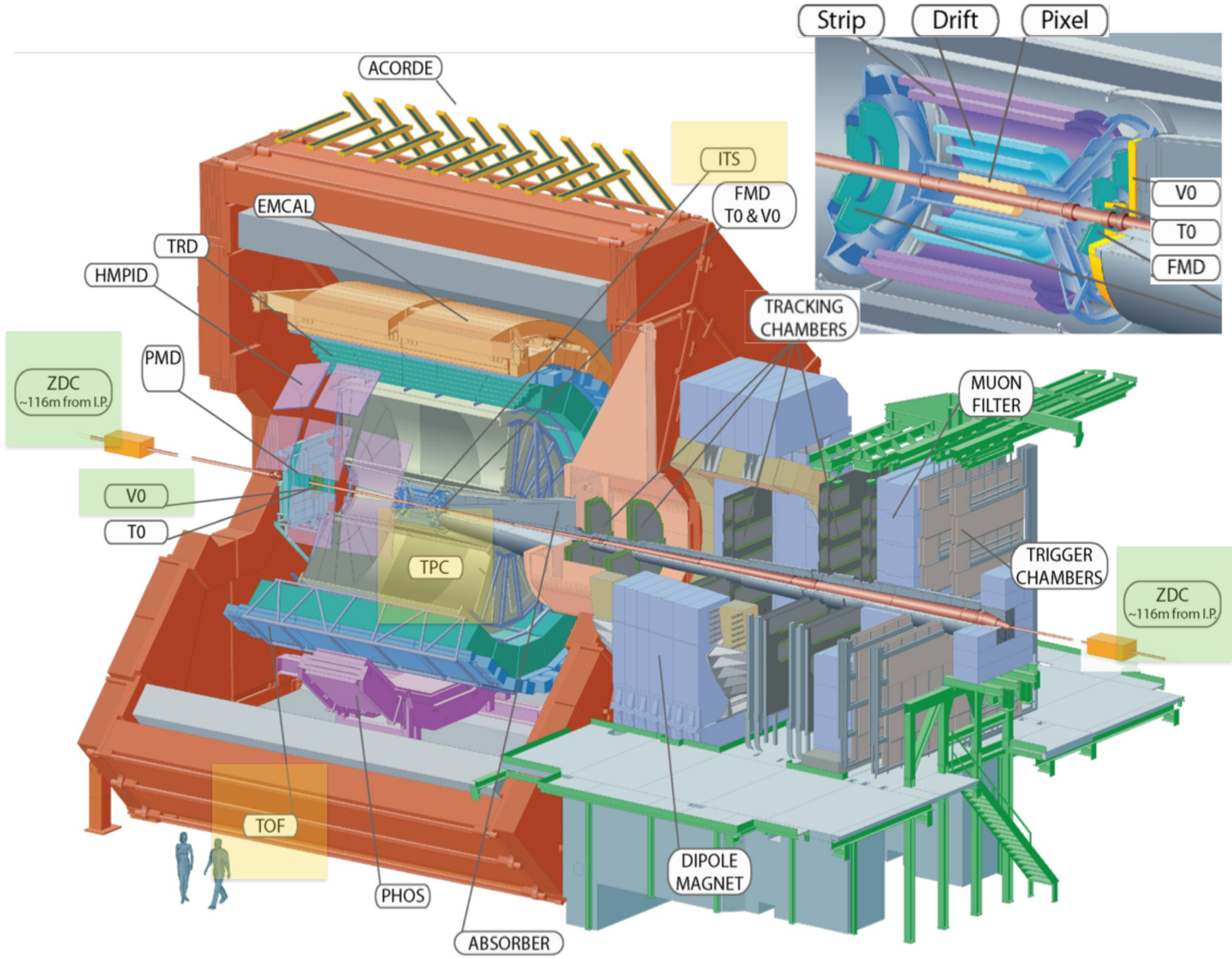
- Particle of interest
  - ✓ Inclusive charged particles
  - ✓ Identified particles: π, K, p, heavy-flavour, etc at various kinematic windows (p_T, η, etc)

A Large Ion Collider Experiment

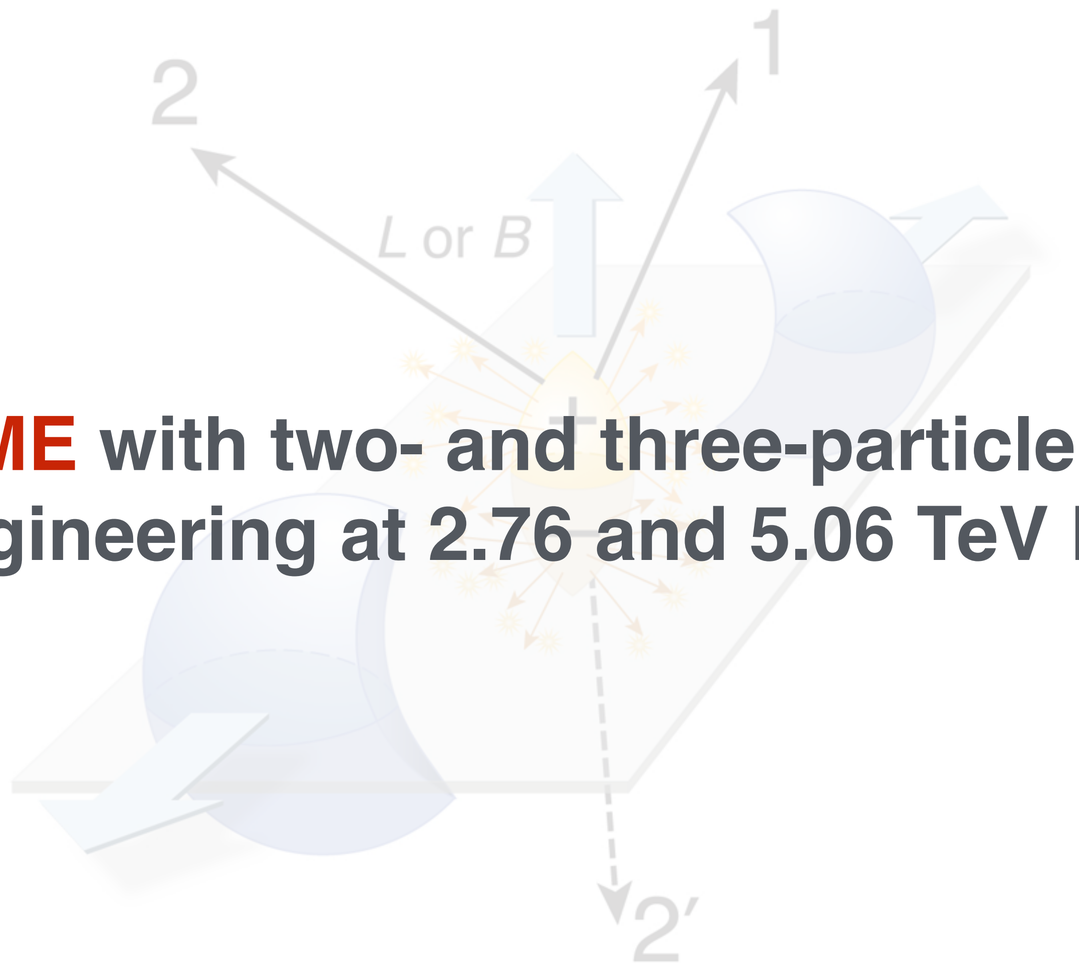


Central:
Inner Tracking System,
Time Projection Chamber,
Time of Flight:
tracking, vertexing, particle identification

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



PART 1



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

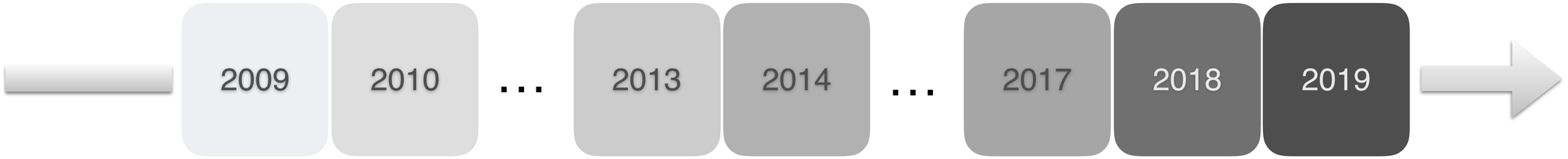
Experimental measurement of CME (timeline of publication)

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

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

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).



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).

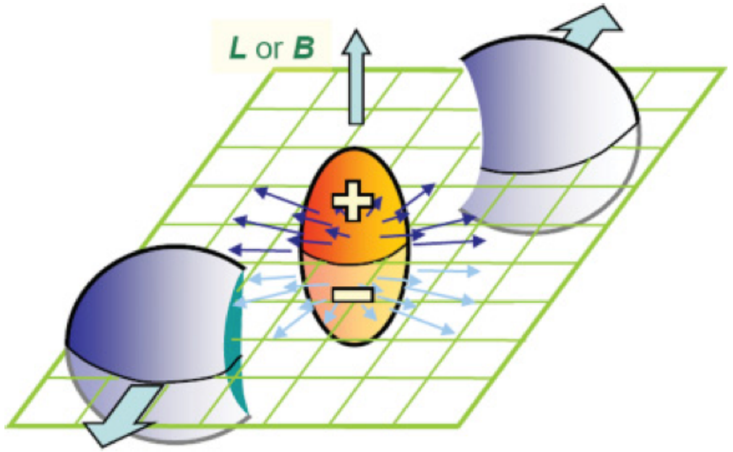
Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider
Phys. Rev. C 97, 044912 (2018).

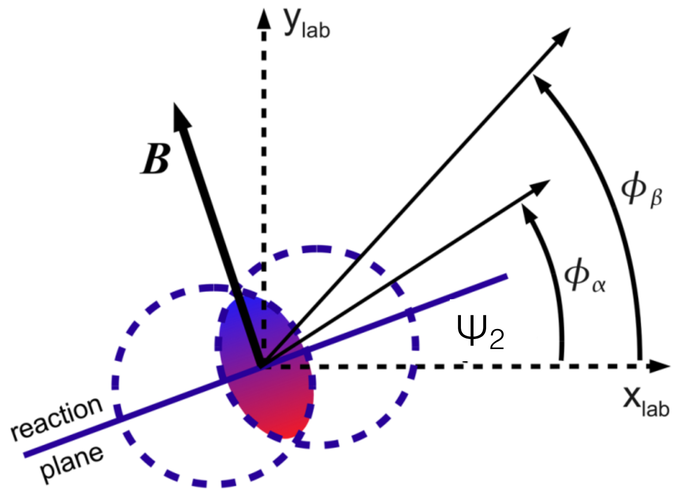
ALICE

CMS

STAR

Measurement of CME with two- and three-particle correlations





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

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

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

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

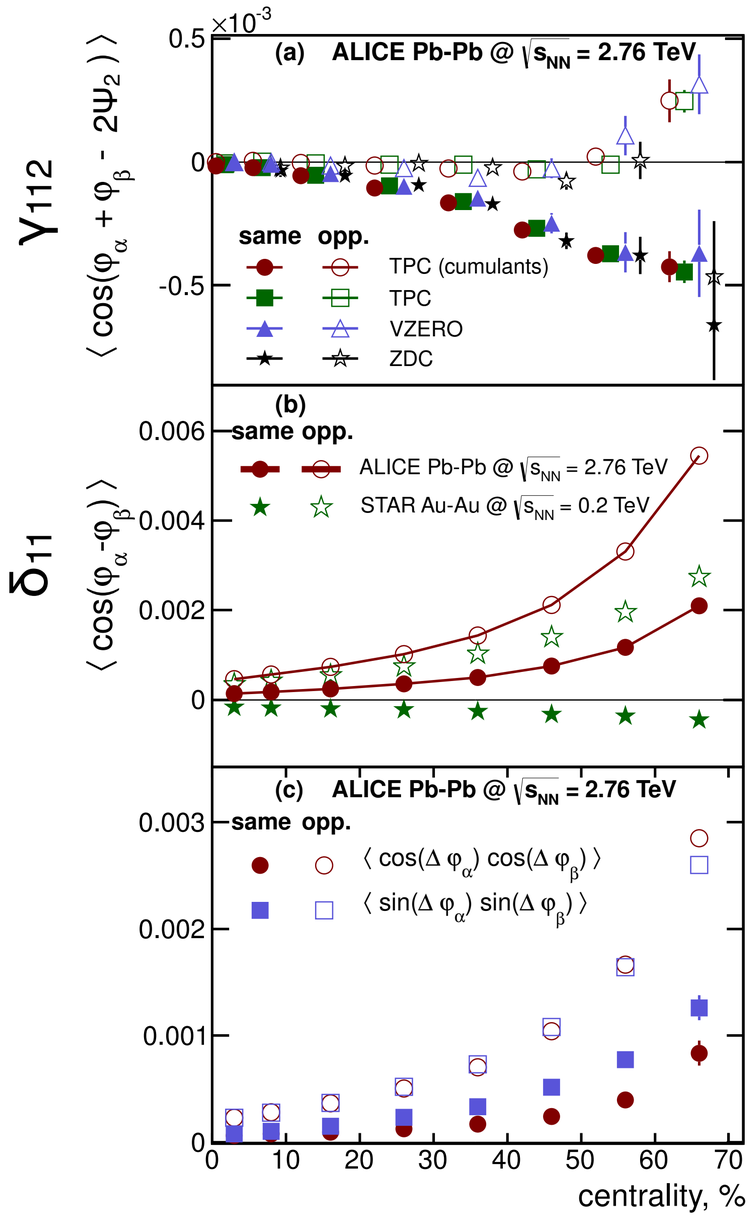
$\gamma_{123} \equiv \langle\cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle$

…

- ✓ 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).

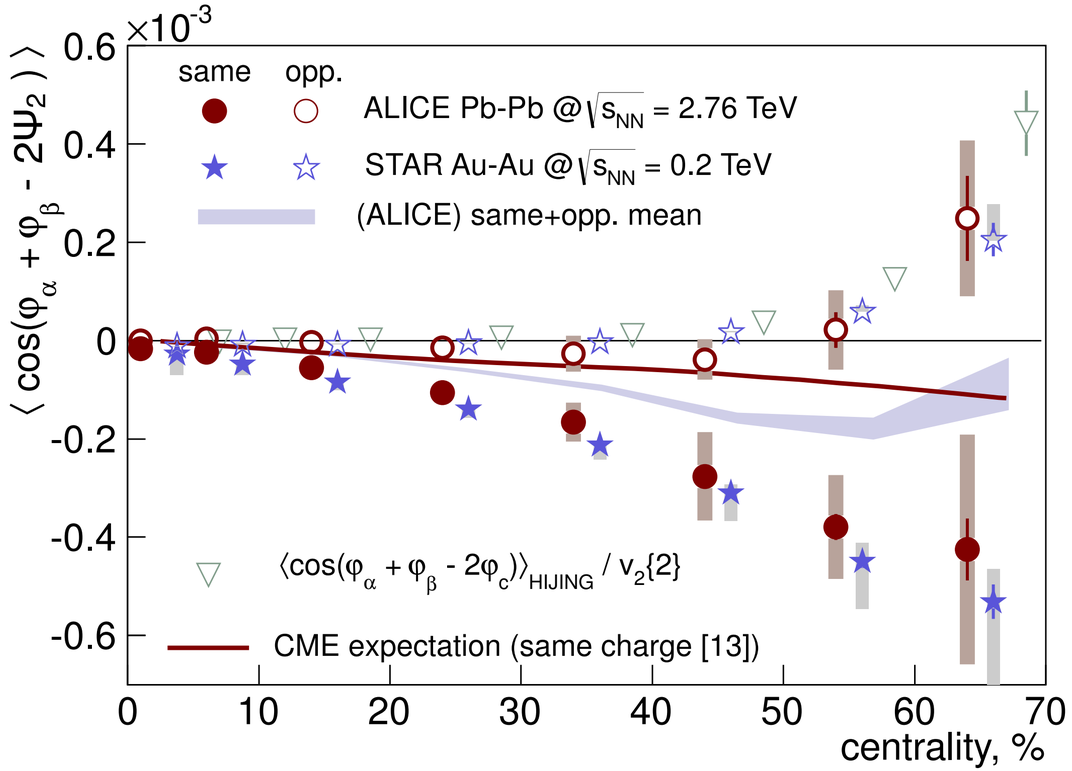


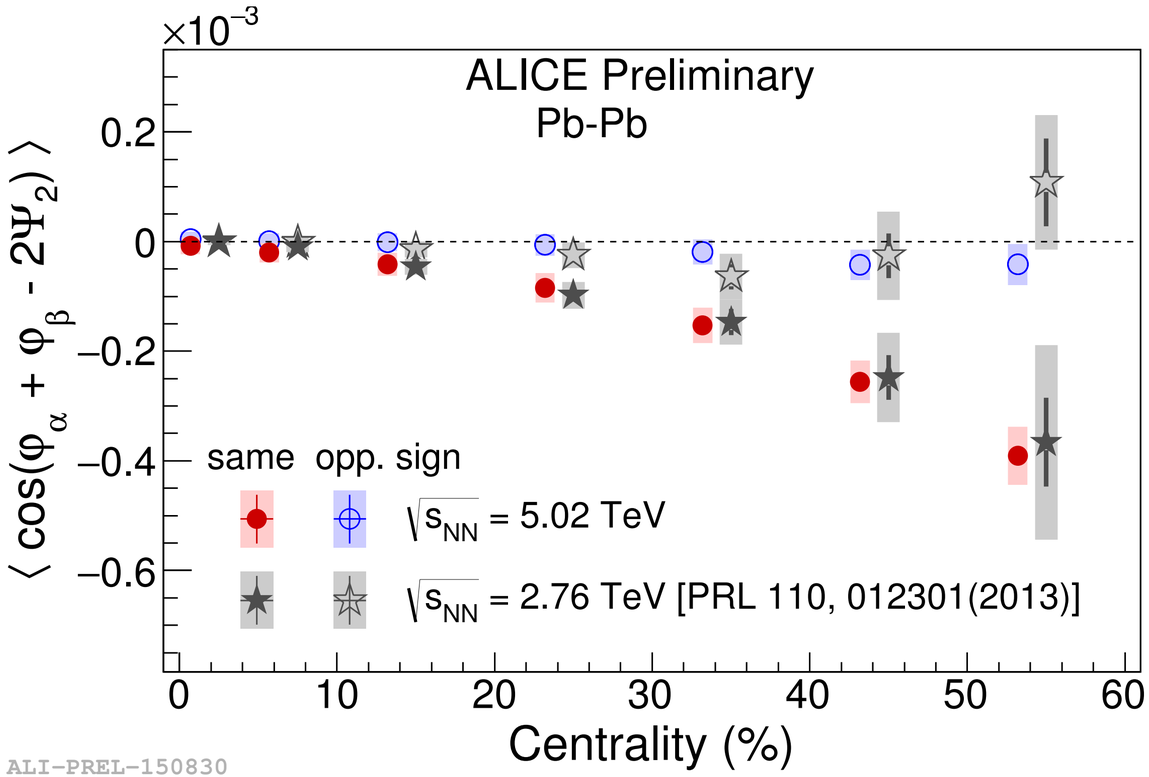
- Good agreement between various γ_{112} obtained with the EP estimated from different detectors
  - ✓ Backgrounds unrelated to the EP are negligible

- 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

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

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



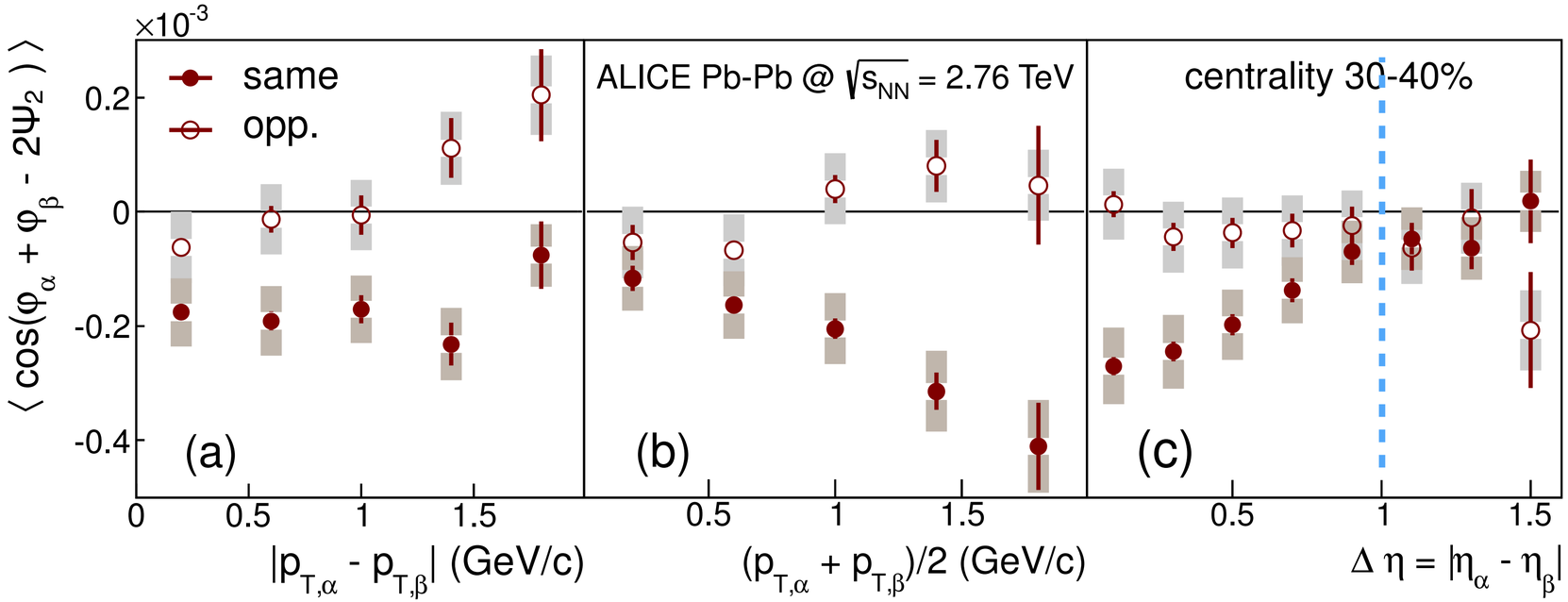


- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

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

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

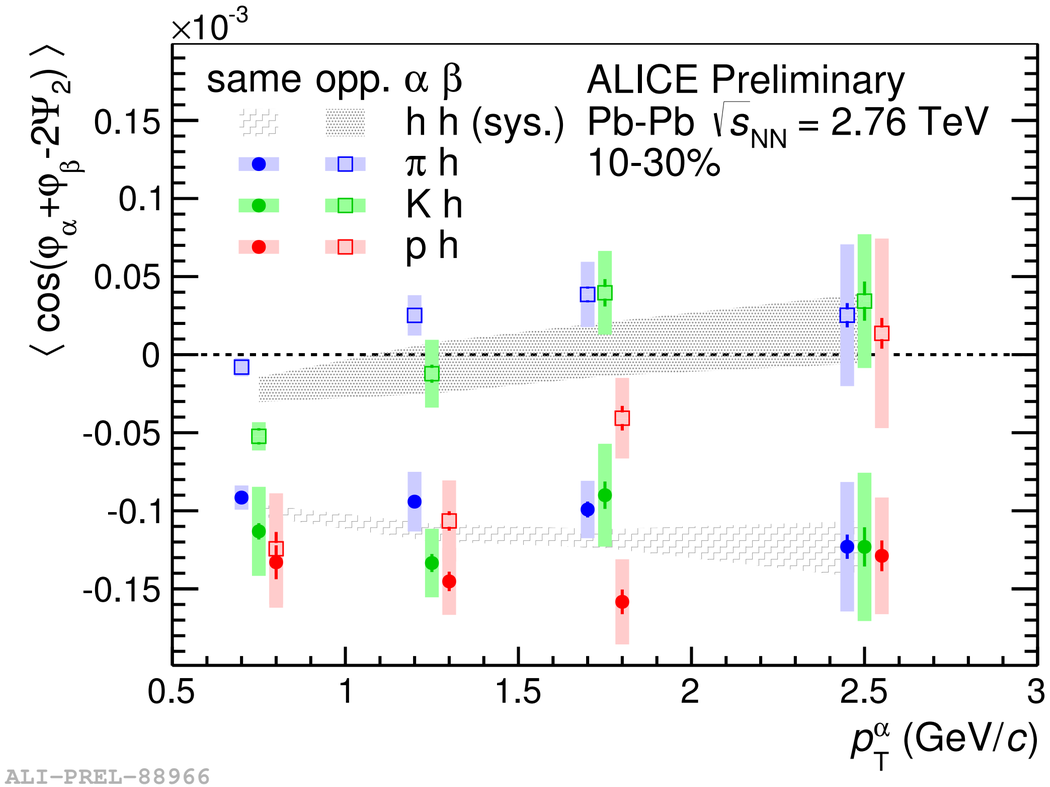
p_T, Δp_T and $\Delta\eta$ dependence of γ_{112} at 2.76 TeV Pb-Pb collisions

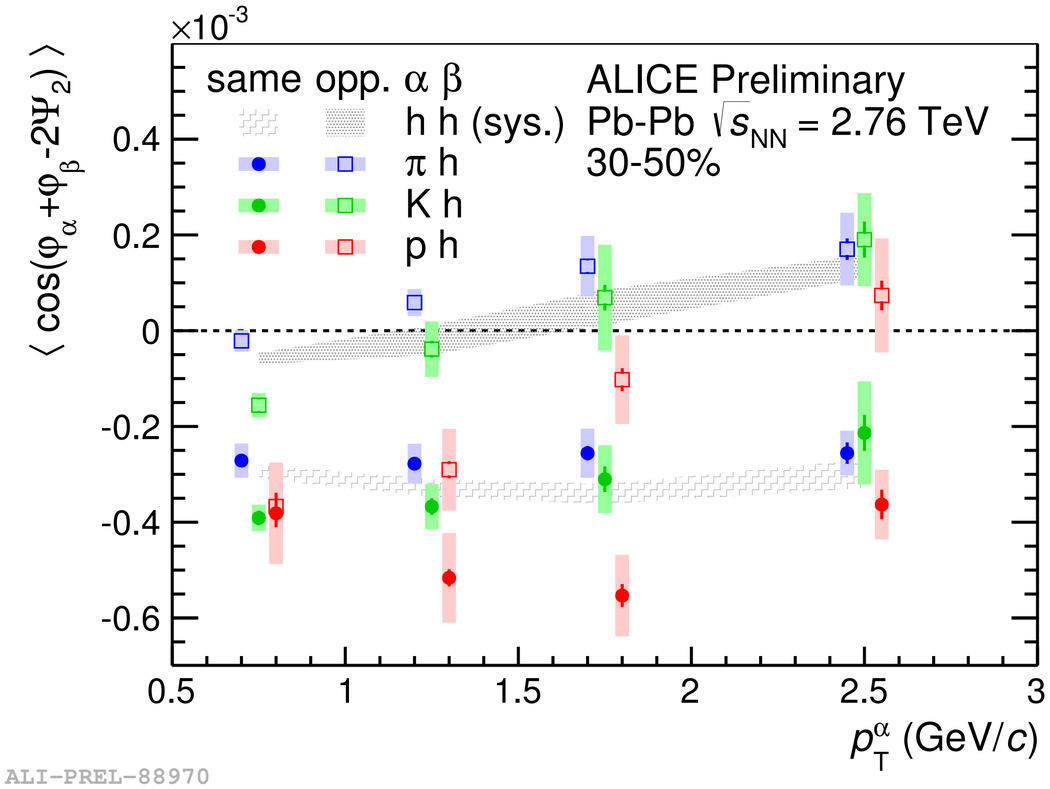


- Weak Δp_T dependence for SS
  - ✓ Exclude HBT correlations
- Magnitude increases with increasing average p_T
  - ✓ Not only originating from low-p_T particles
- Close to zero above one unit of $\Delta\eta$

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

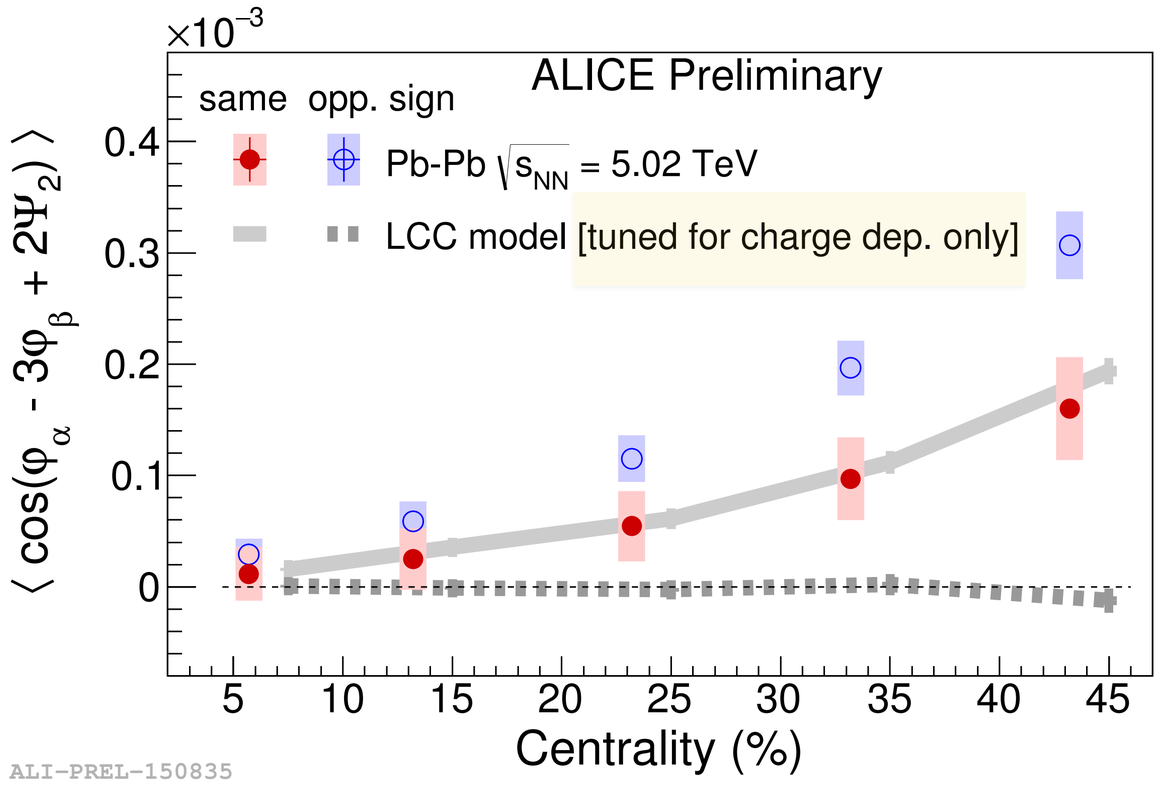
γ_{112} with identified particles at 2.76 TeV Pb-Pb collisions





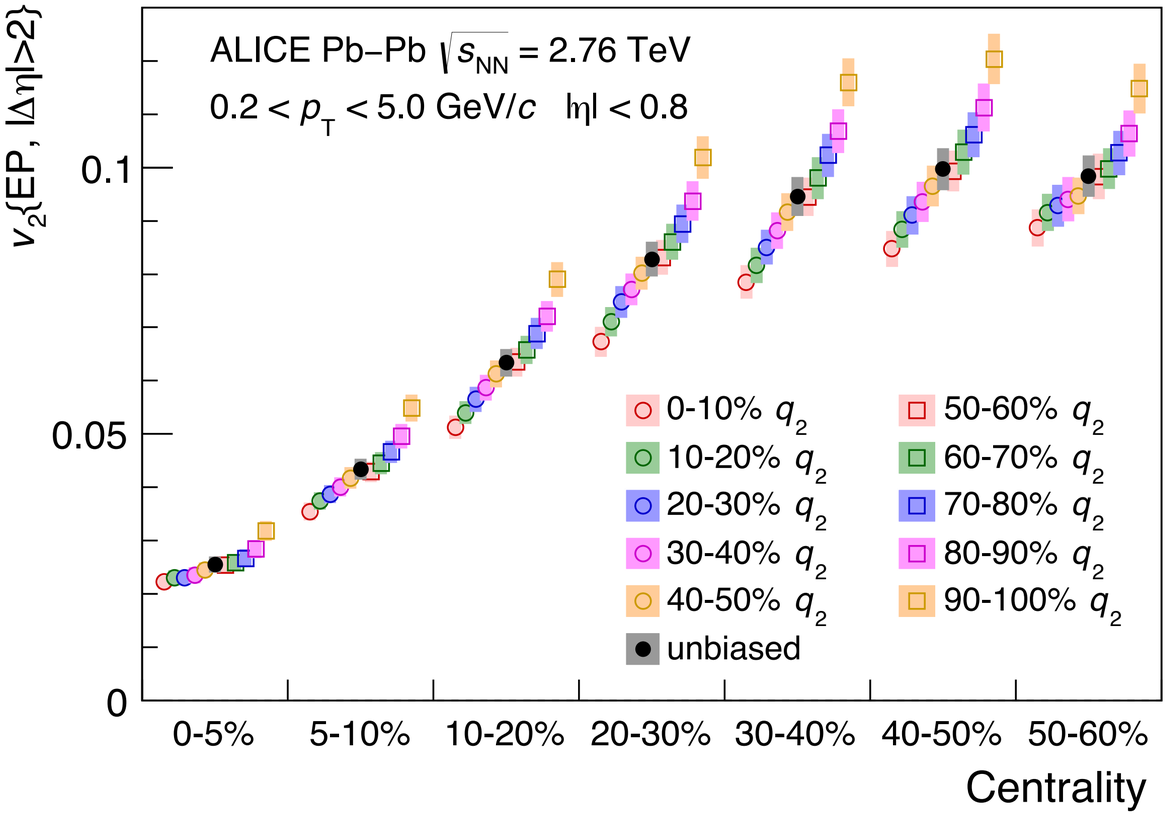
- $\gamma_{112}(\pi)$ and $\gamma_{112}(K)$ are consistent with $\gamma_{112}(h)$
- Difference between $\gamma_{112}(p)$ and $\gamma_{112}(\pi)$

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

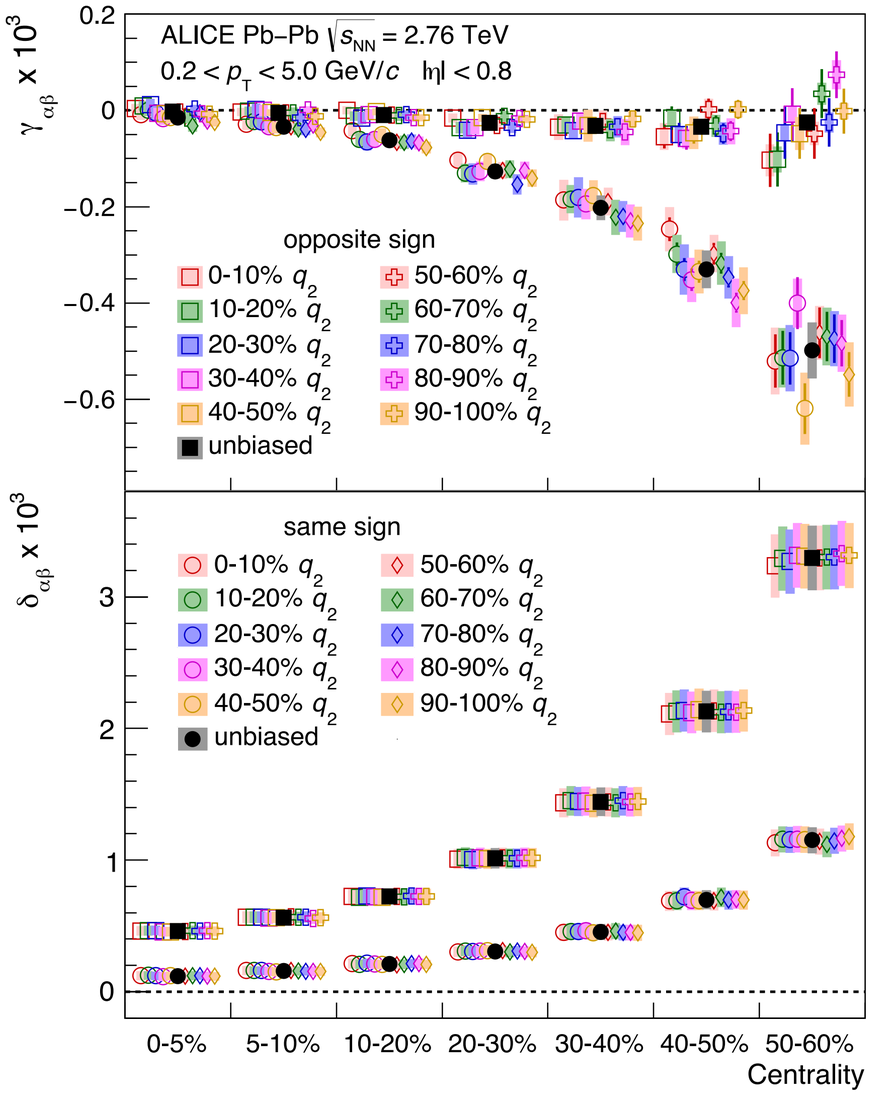


- Events with the desired initial spatial anisotropy (or v_2) can be experimentally selected by q_2
  - ✓ Help to disentangle eccentricity and v_2 related backgrounds from the potential CME signal

Physics Letters B 777, 151 (2018).

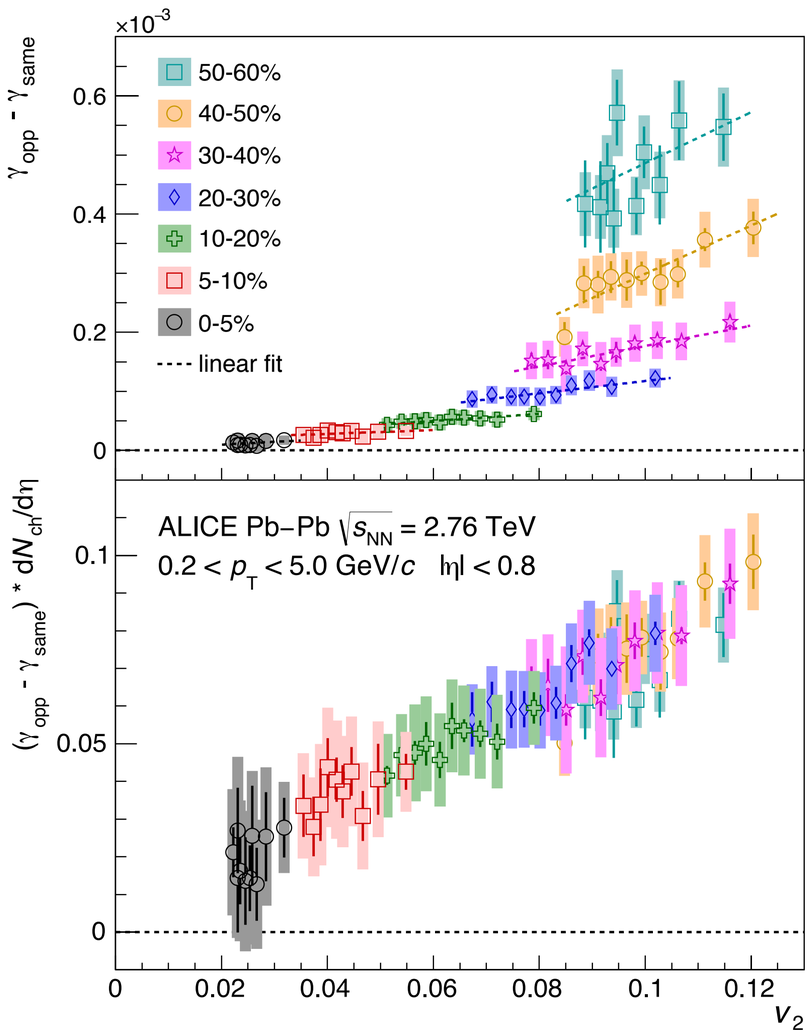
γ_{112} and δ_{11} after event shape selection

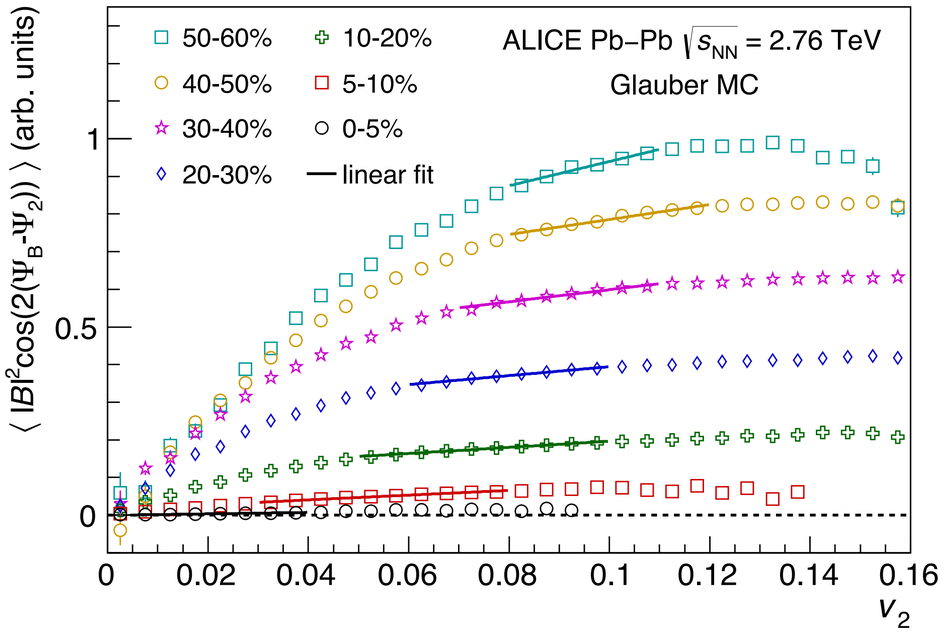
Physics Letters B 777, 151 (2018).



- 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



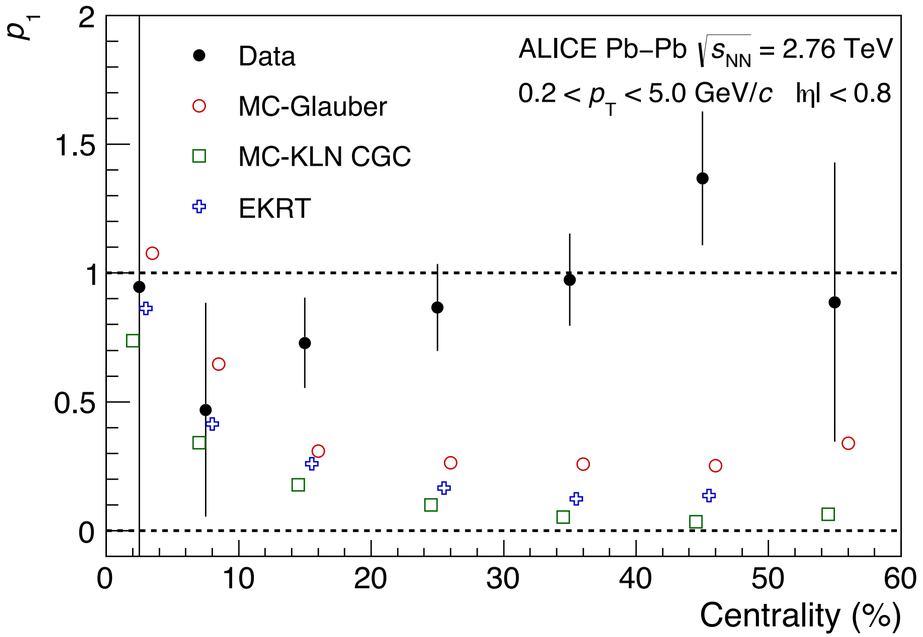


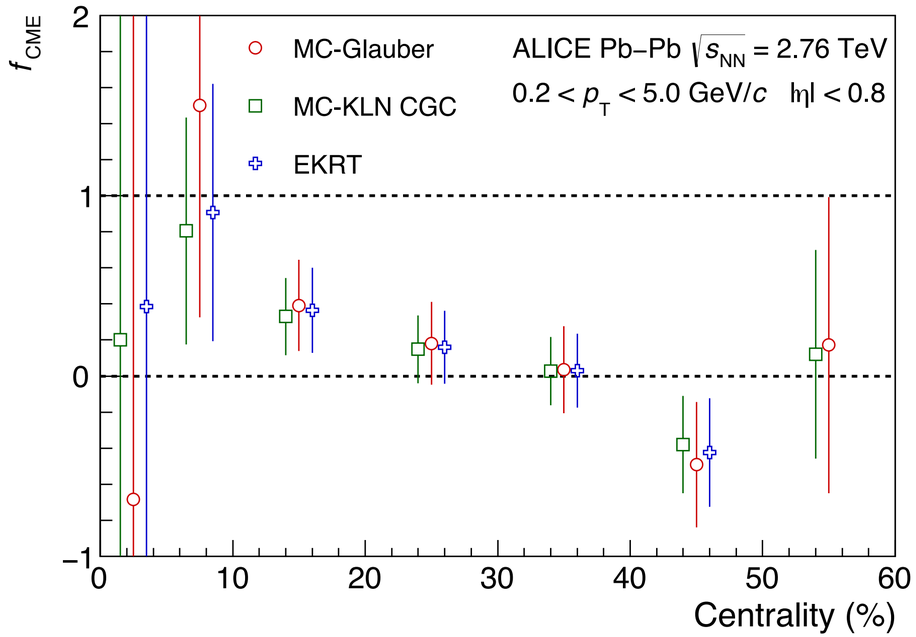
- $\Delta\gamma_{112}$ is positive for all centralities
- The magnitude decreases for more central collisions and with decreasing v_2 (in a given centrality bin)
- After scaling by dN_{ch}/dη, $\Delta\gamma_{112}$ is approximately proportional to v_2

- 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





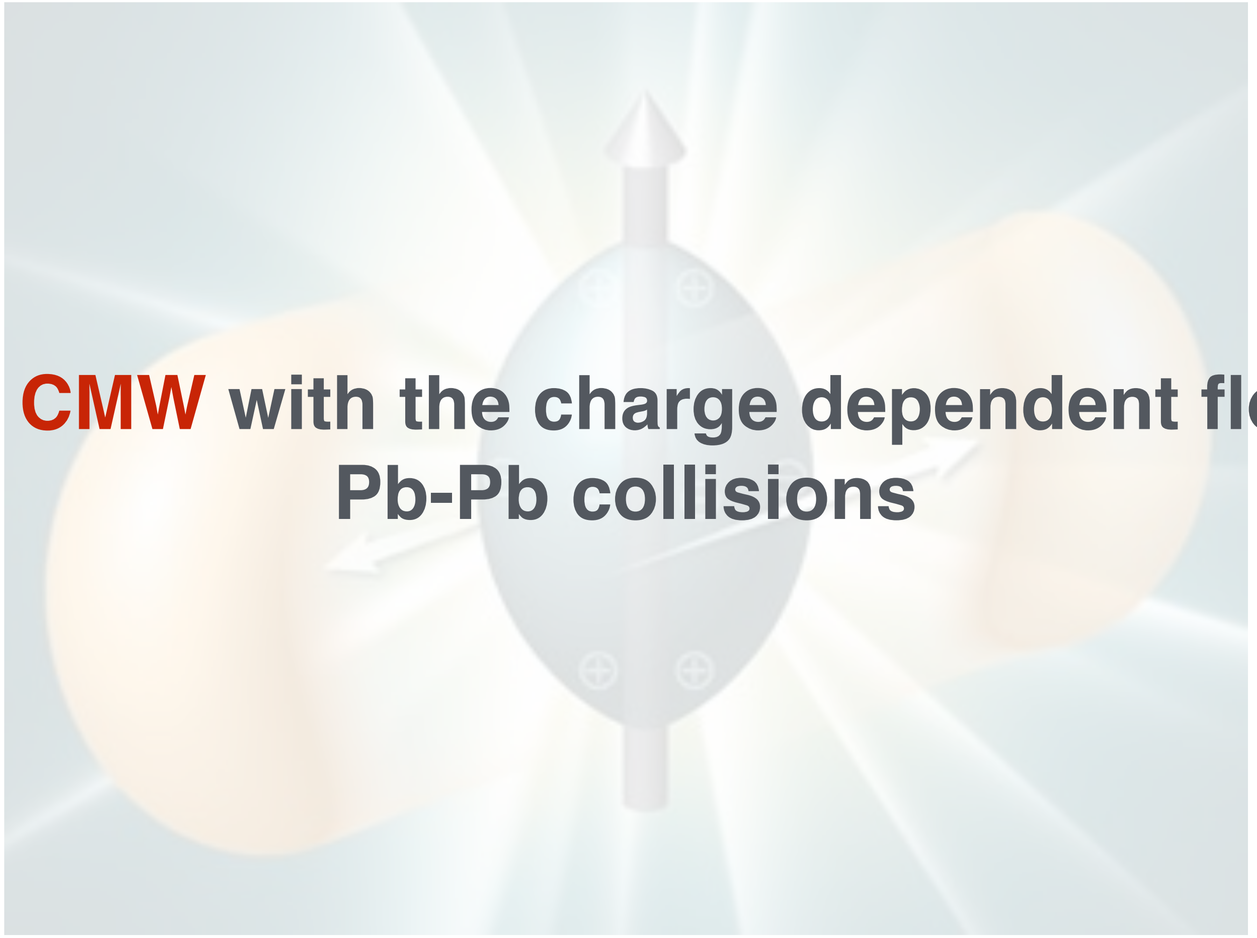
$F_1(v_2) = p_0(1 + p_1(v_2 - \langle v_2 \rangle)/\langle v_2 \rangle)$ to fit both data and model

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

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

Physics Letters B 777, 151 (2018).

PART 2



Search for the CMW with the charge dependent flow at 2.76 TeV Pb-Pb collisions

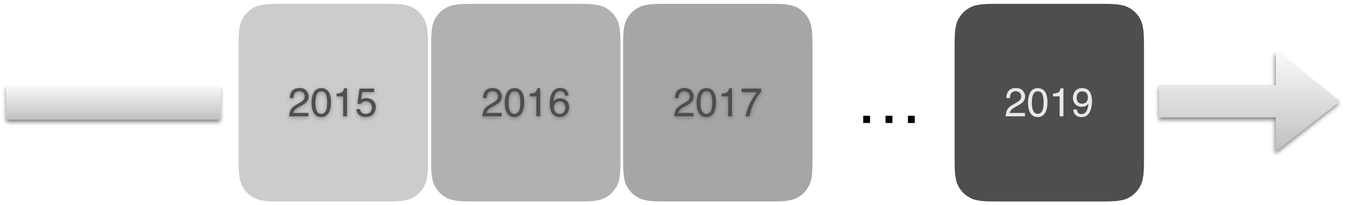
Experimental measurement of CMW (timeline of publication)

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CMS

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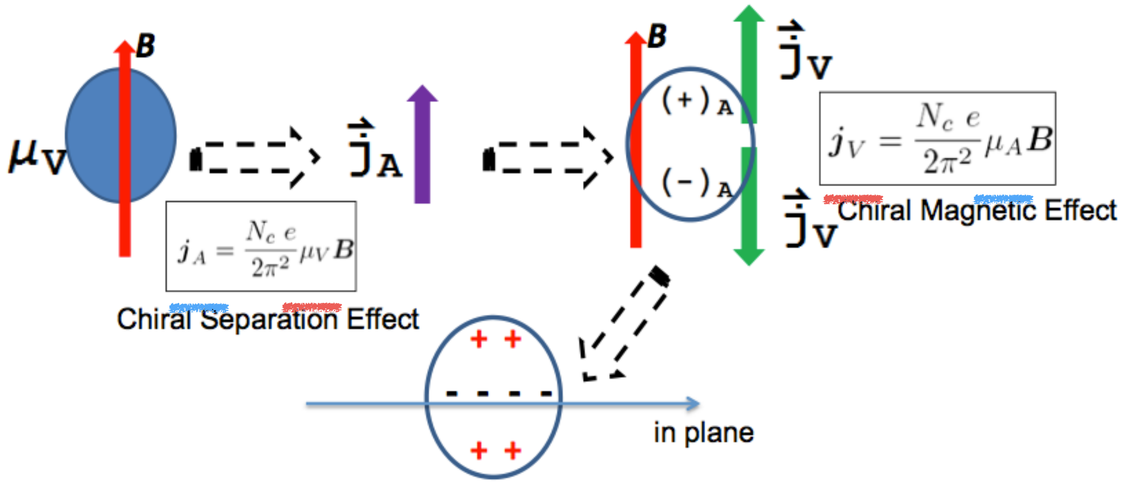
Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
Phys. Rev. C **93**, 044903 (2016).



Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions
Phys. Rev. Lett. 114, 252302 (2015).

Challenges to the chiral magnetic wave using charge-dependent azimuthal anisotropies in pPb and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
arXiv:1708.08901 [nucl-ex]

Measurement of CMW with charge dependent flow



asymmetry in the azimuthal distributions of h+ and h-

$$N_+(\phi) - N_-(\phi) = (\bar{N}_+ - \bar{N}_-)[1 - r\cos(2\phi)] \longleftarrow r \equiv \frac{2q_e}{\bar{\rho}_e}$$

monopole, nonzero net charge density

$$q_e = \int RdRd\phi\cos(2\phi)[j^0_e(R,\phi) - j^0_{e,B=0}(R,\phi)]$$

quadrupole, CMW contribution

$$\bar{\rho}_e = \int RdRd\phi\, j^0_{e,B=0}(R,\phi)$$

$$\frac{dN_\pm}{d\phi} = N_\pm[1 + 2v_2\cos(2\phi)]$$

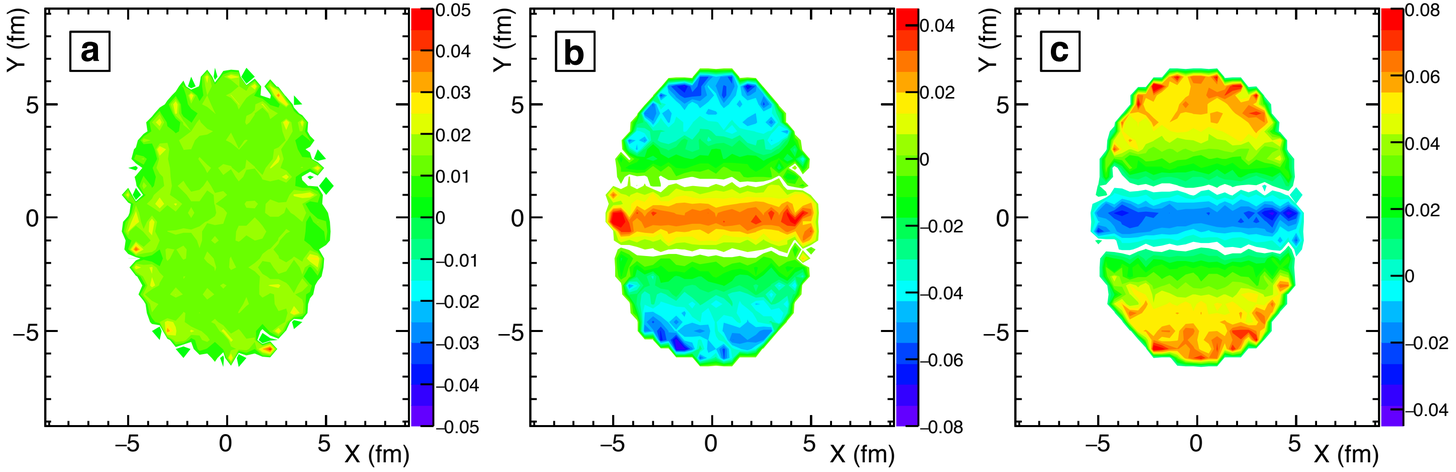
$$\approx \bar{N}_\pm[1 + 2v_2\cos(2\phi) \mp A_\pm r\cos(2\phi)] \longleftarrow A_\pm \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

$$v_2^\pm = v_2 \mp \frac{rA_\pm}{2} \longleftrightarrow \Delta v_2 = v_2^- - v_2^+ \approx rA$$

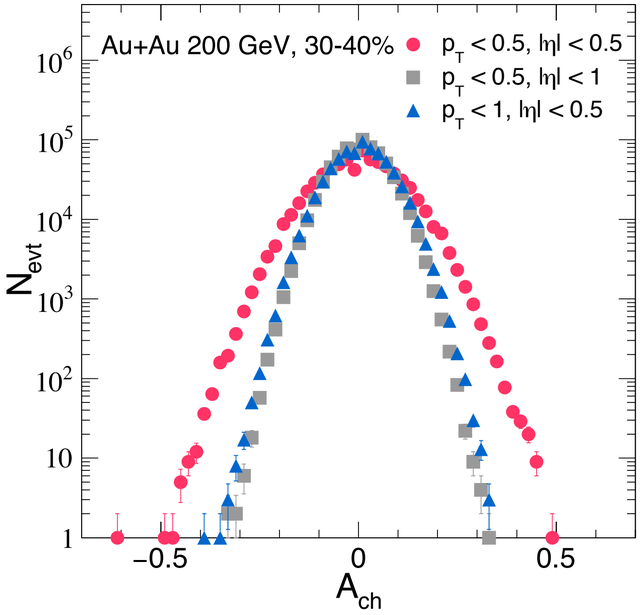
Phys. Rev. Lett. 107, 52303 (2011).

Measurement of CMW with three-particle correlator

AMPT simulation with imported quadrupole



Negative binomial distr.

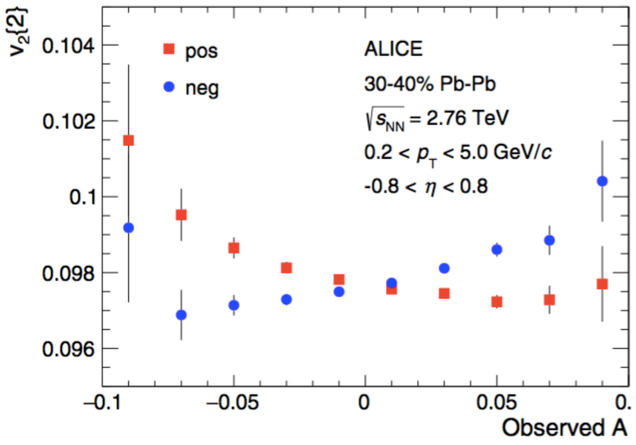


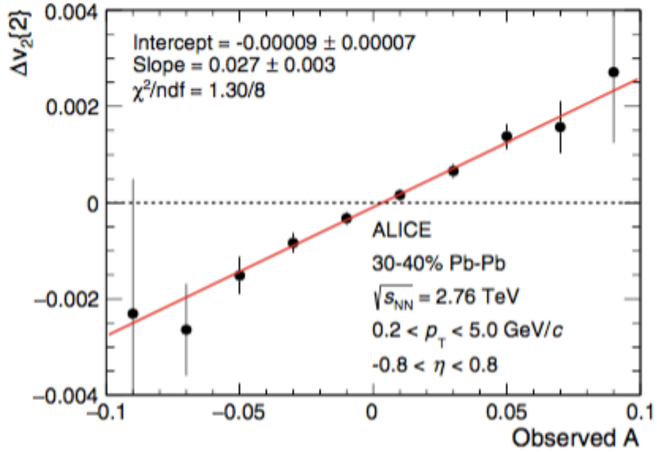
$$\langle v_n^{\pm} A\rangle - \langle A\rangle\langle v_n\rangle = \langle \cos[n(\varphi_1 - \psi_n)]\, A\rangle - \langle \cos[n(\varphi_1 - \psi_n)]\rangle\langle A\rangle \approx \frac{\langle\langle \cos[n(\varphi_1 - \varphi_2)] A\rangle\rangle}{\sqrt{\langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle}} - \sqrt{\langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle}\langle A\rangle$$

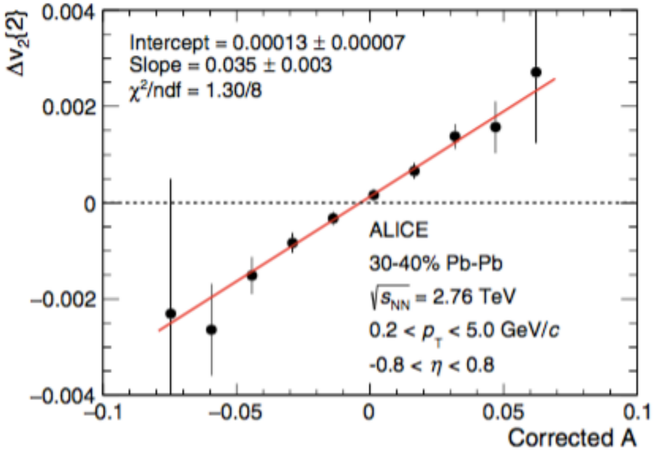
$$\langle v_n^{\pm} q_3\rangle - \langle q_3\rangle_1\langle v_n\rangle = \langle \cos[n(\varphi_1 - \psi_n)]\, q_3\rangle - \langle \cos[n(\varphi_1 - \psi_n)]\rangle\langle q_3\rangle_1 \approx \frac{\langle\langle \cos[n(\varphi_1 - \varphi_2)] q_3\rangle\rangle}{\sqrt{\langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle}} - \sqrt{\langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle}\langle q_3\rangle_1$$

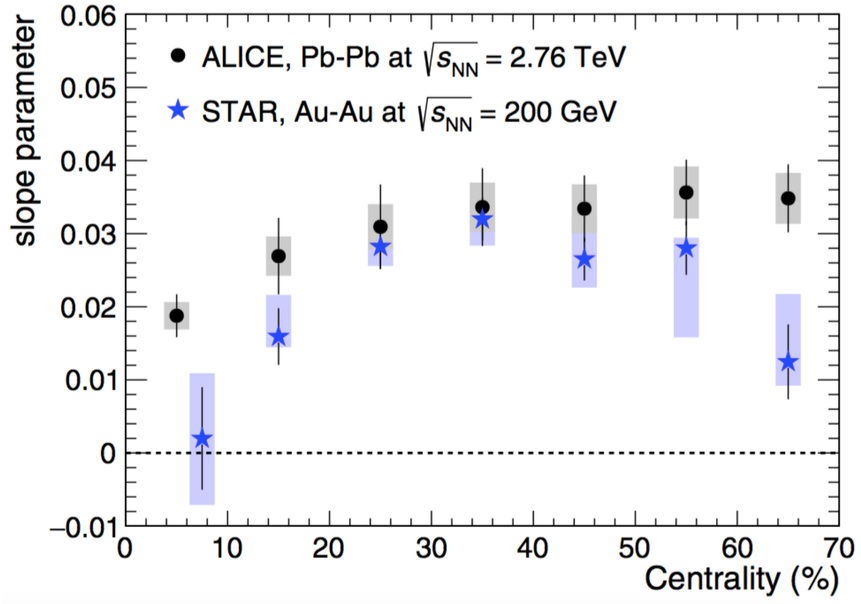
Phys. Rev. C. 93, 044903 (2016)

Charge asymmetry dependence of v_2 at 2.76 TeV Pb-Pb collisions





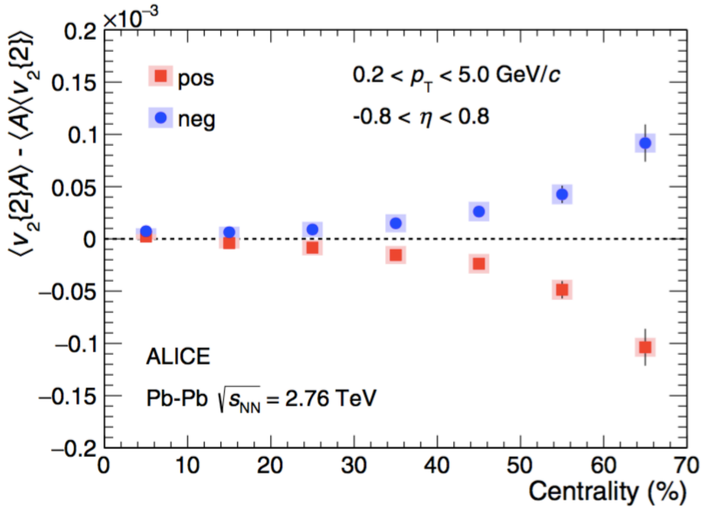


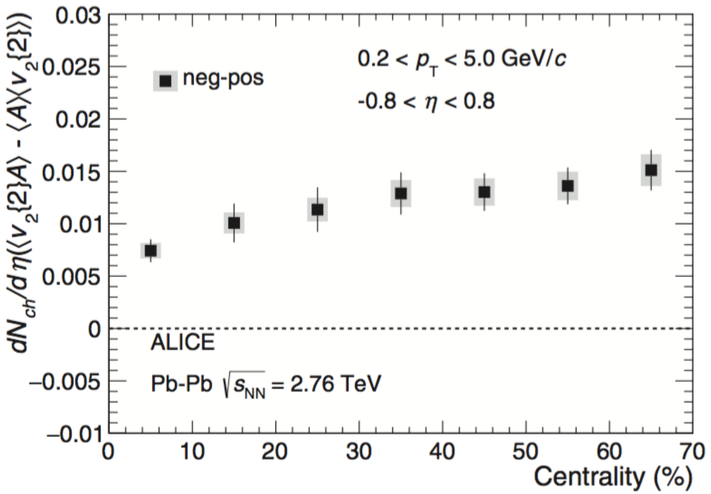


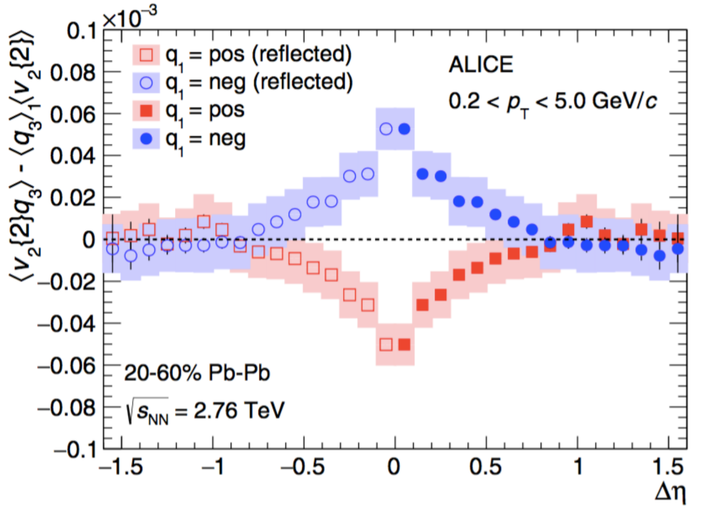
- The linear dependence has been clearly observed at TeV collisions
- At TeV scale, the slopes remain the same, however, with weaker centrality dependence

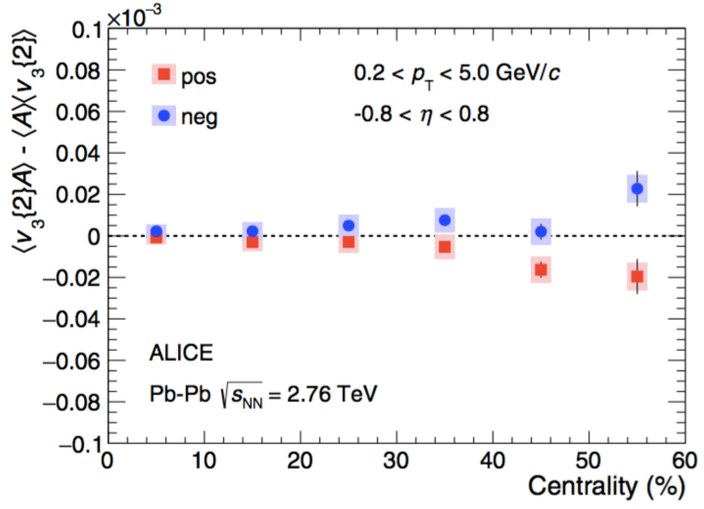
Phys. Rev. C. 93, 044903 (2016)

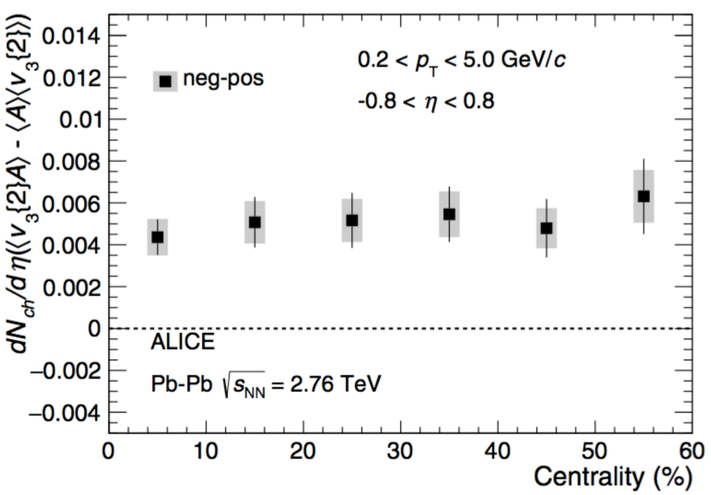
Three-particle correlation at 2.76 TeV Pb-Pb collisions

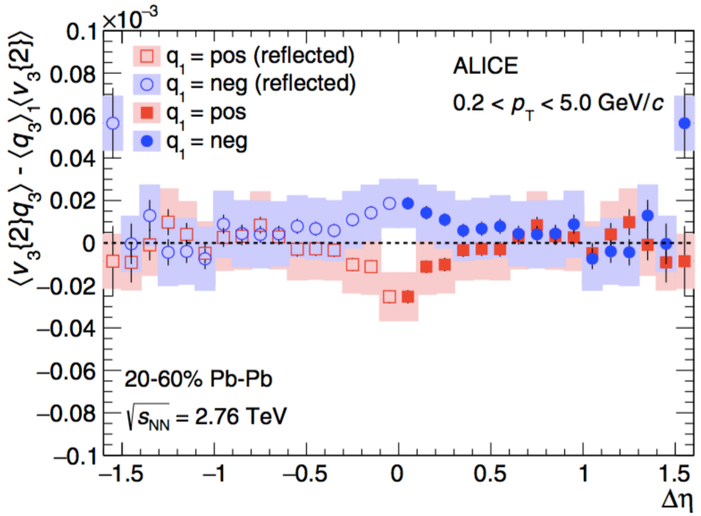










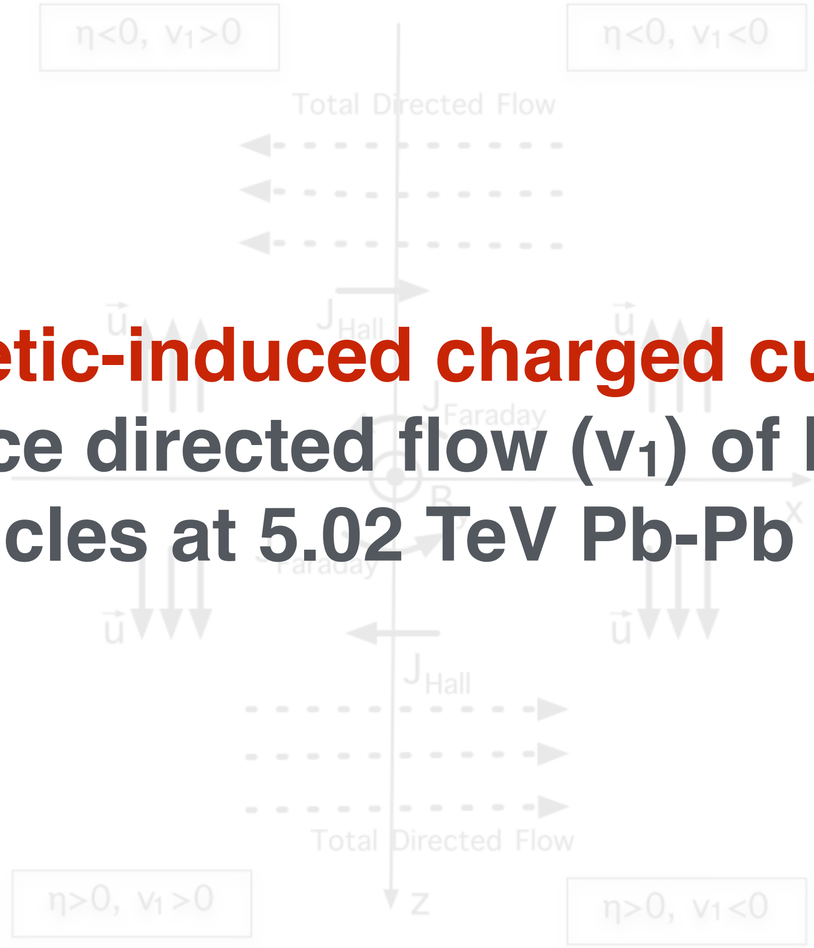


Phys. Rev. C. 93, 044903 (2016)

Summary I

- The ALICE measurements of the anomalous chiral effects (CME, CMW) have been reviewed
- New insights of the observables are provided. Collaboration with the theorists is important.
- Such studies not only help us to search for the chiral anomaly but also improve the knowledge of the collectivity of the QGP

PART 3

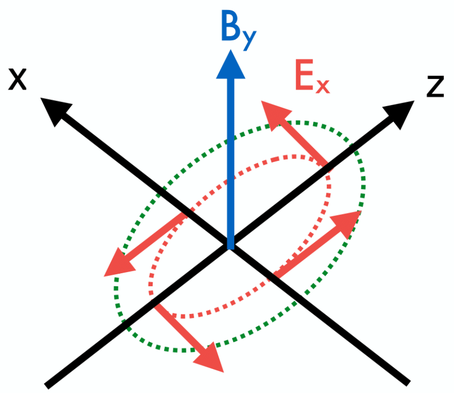


Search for magnetic-induced charged currents with the charge dependence directed flow (v_1) of light and heavy-flavour particles at 5.02 TeV Pb-Pb collisions

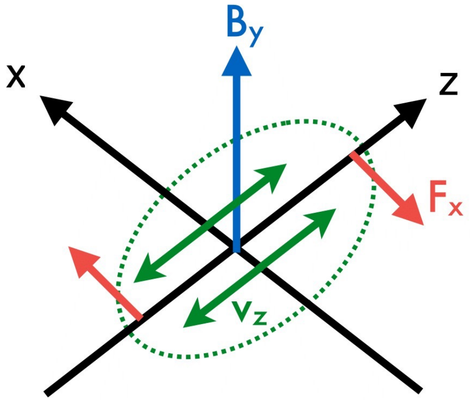
Magnetic-induced charged currents

- 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)



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

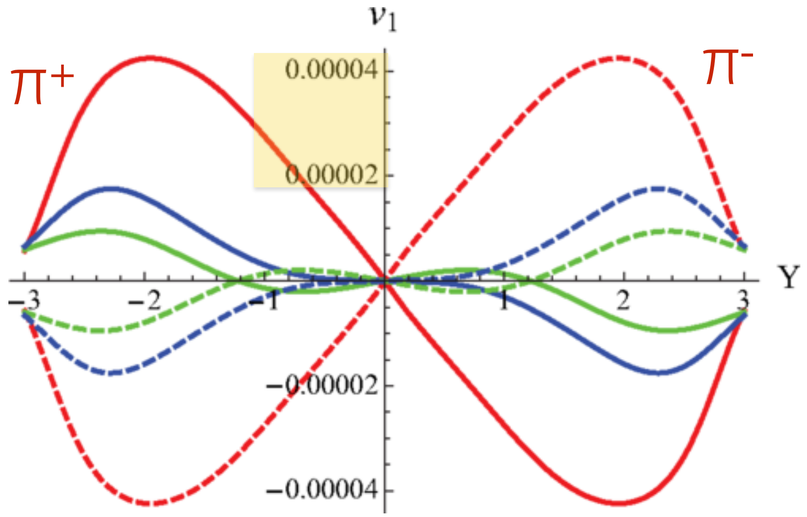


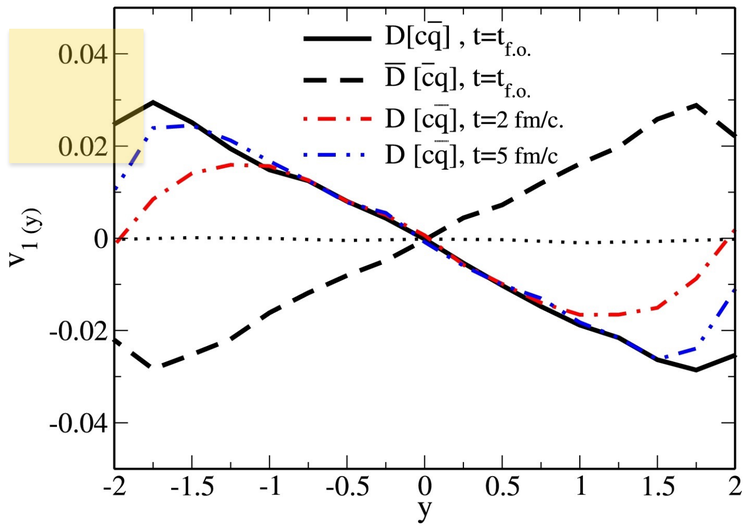
$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

- 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

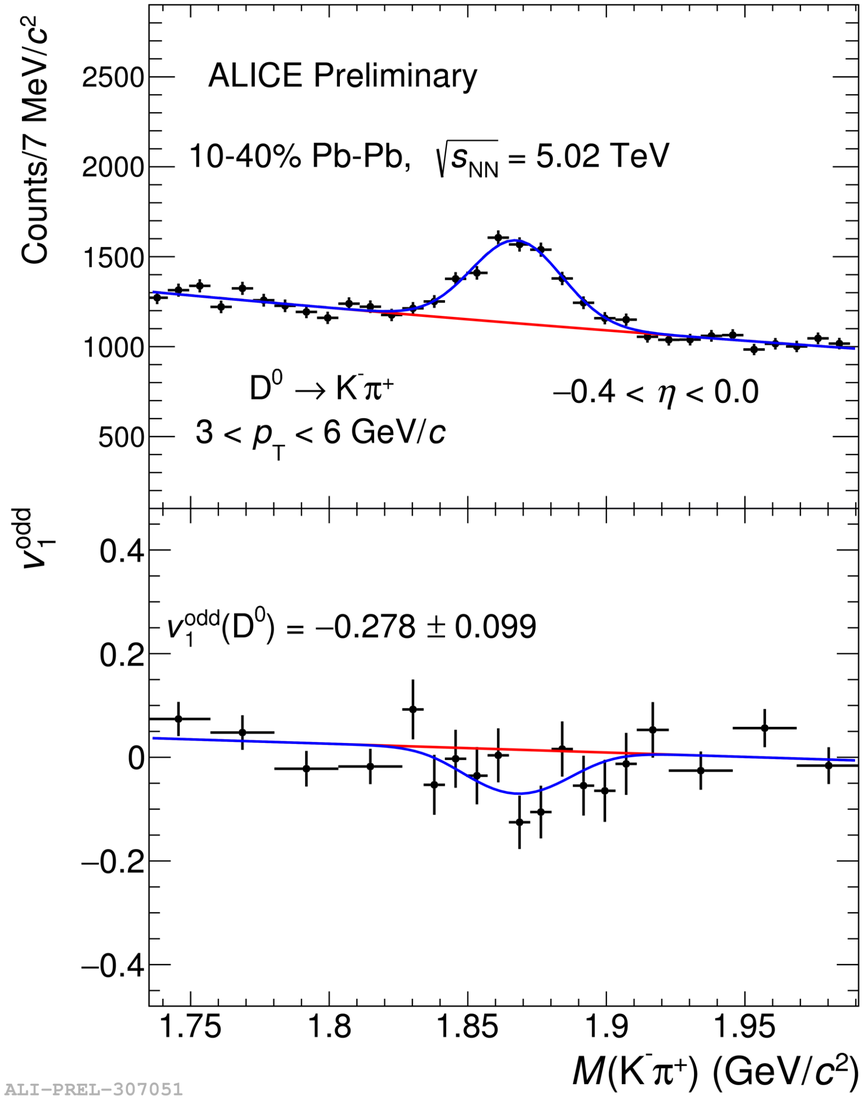




Phys. Rev. C 89, 054905 (2014).
Phys. Lett. B 768, 260 (2017).

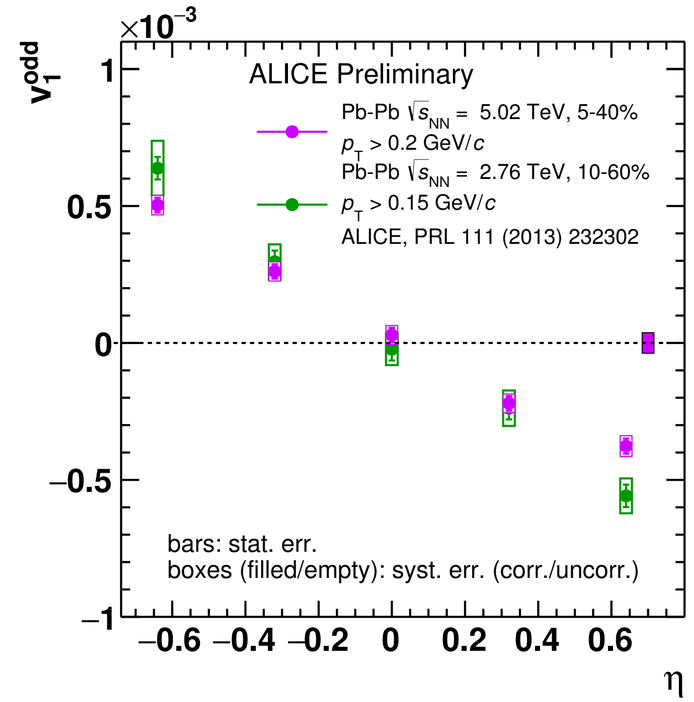
- Charge-dependent v_1 of light and heavy-flavour particles
  - ✓ Formation time ~ 0.1 fm/c, comparable to the time scale when B is maximum
  - ✓ The kinetic relaxation time of charm is similar to the QGP lifetime
  - ✓ Possible larger v_1 of charm quarks compared to light quarks (~10^3)
- Rapidity-odd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

D^0 v_1 extraction

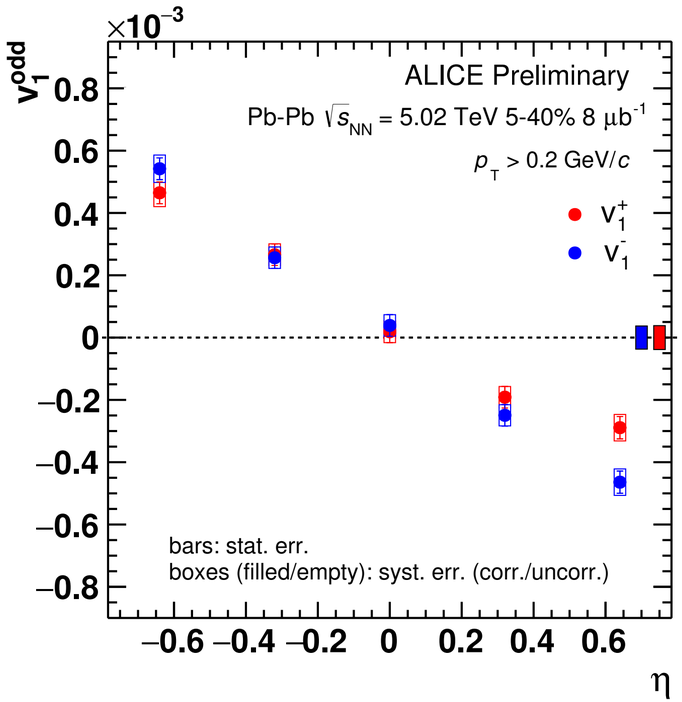


- D^0 mesons and their antiparticles are reconstructed in the central rapidity region from their charged hadronic decay channels D^0 ➔ $K^-\pi^+$
- $v_1^{odd}(D^0)$ extracted from a simultaneous fit to the invariant mass and to the $v_1^{odd}(M)$ distributions

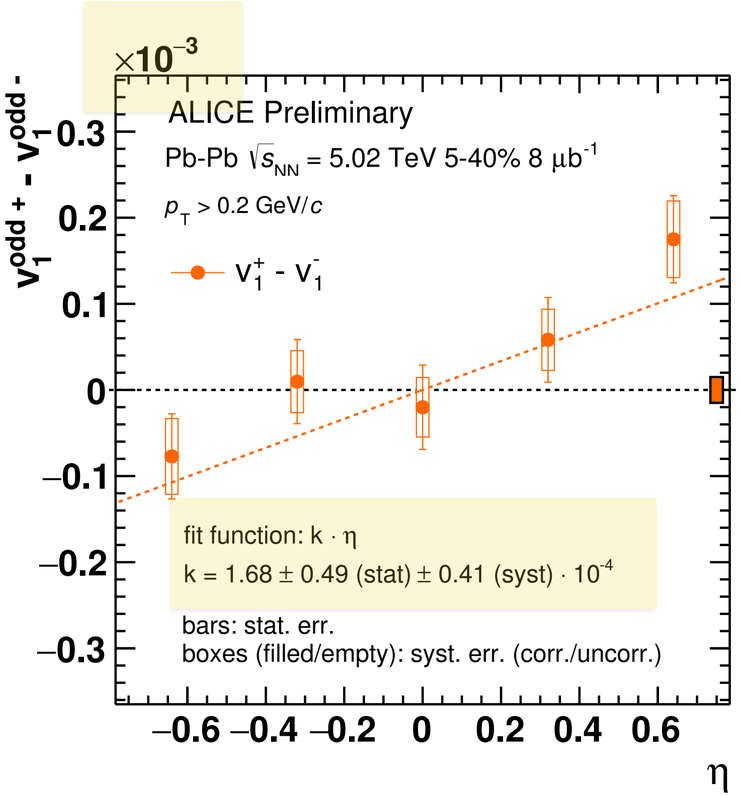
Charge dependence v_1 of charged hadrons at 5.02 TeV



ALI-PREL-130184



ALI-PREL-129681

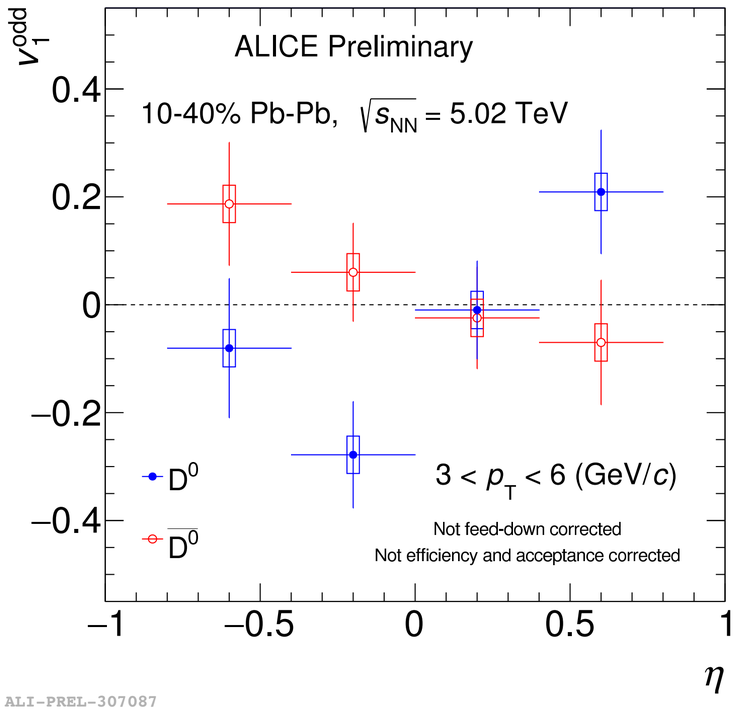


ALI-PREL-129689

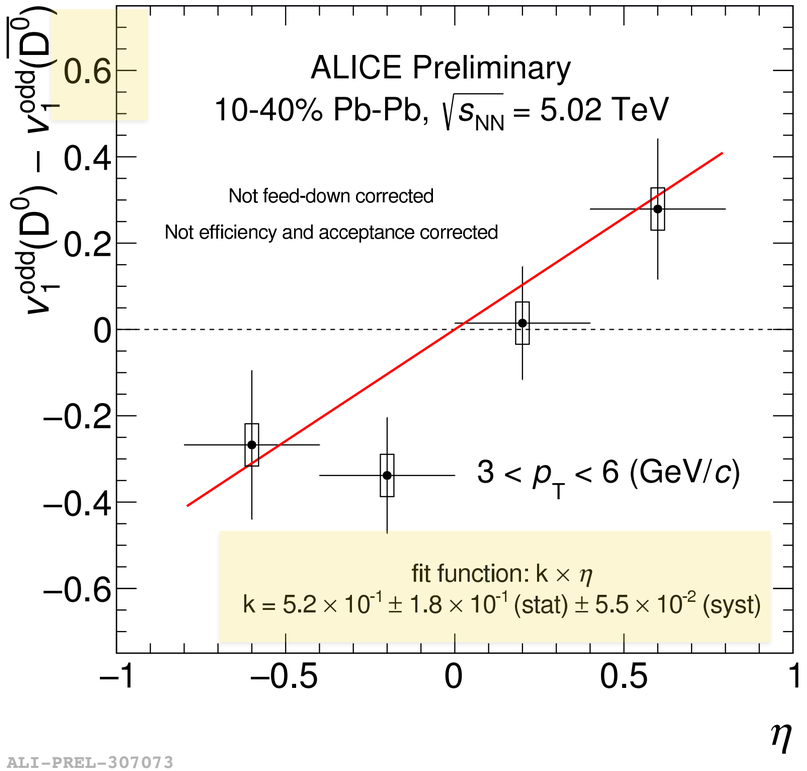
- dv_1^{odd}/dη slightly decreases at 5.02 TeV

- 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).

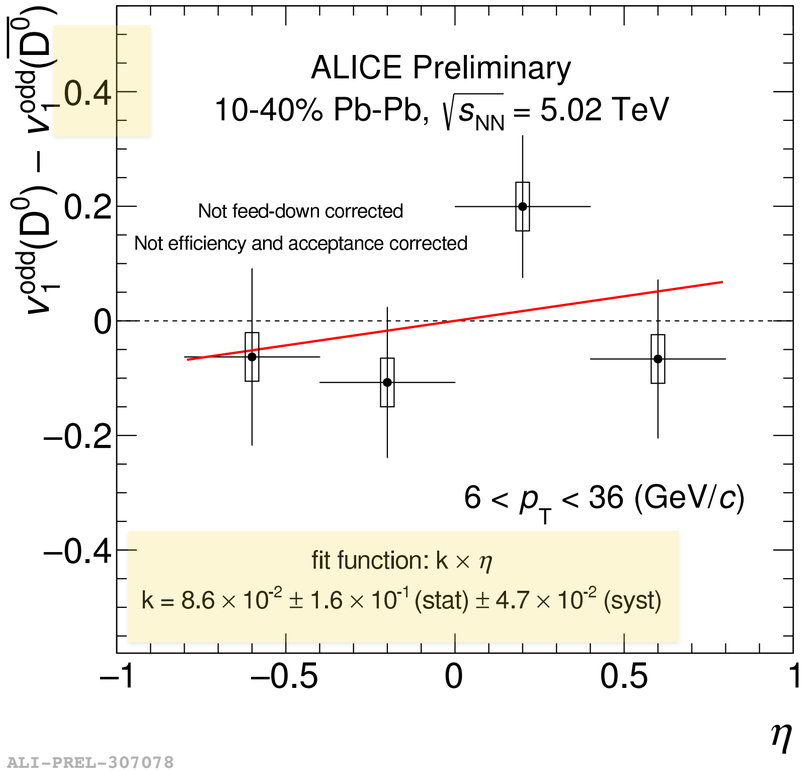
Charge dependence v_1 of D^0 mesons



ALI-PREL-307087



ALI-PREL-307073

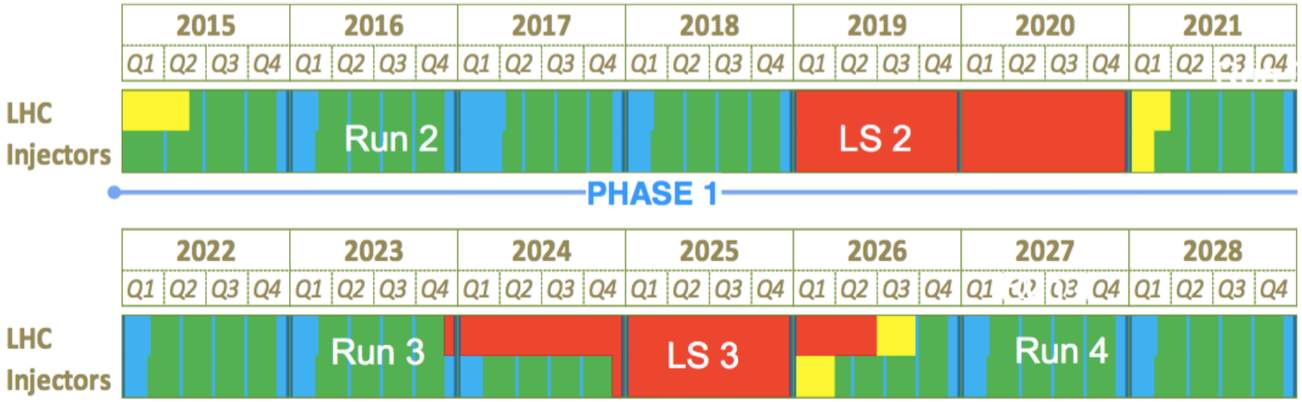


ALI-PREL-307078

- 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 II

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



Thank you for your attention!
谢谢!