The 5th China LHC Physics Workshop

Experimental searches for the anomalous chiral effect and the strong magnetic field in heavy-ion collisions

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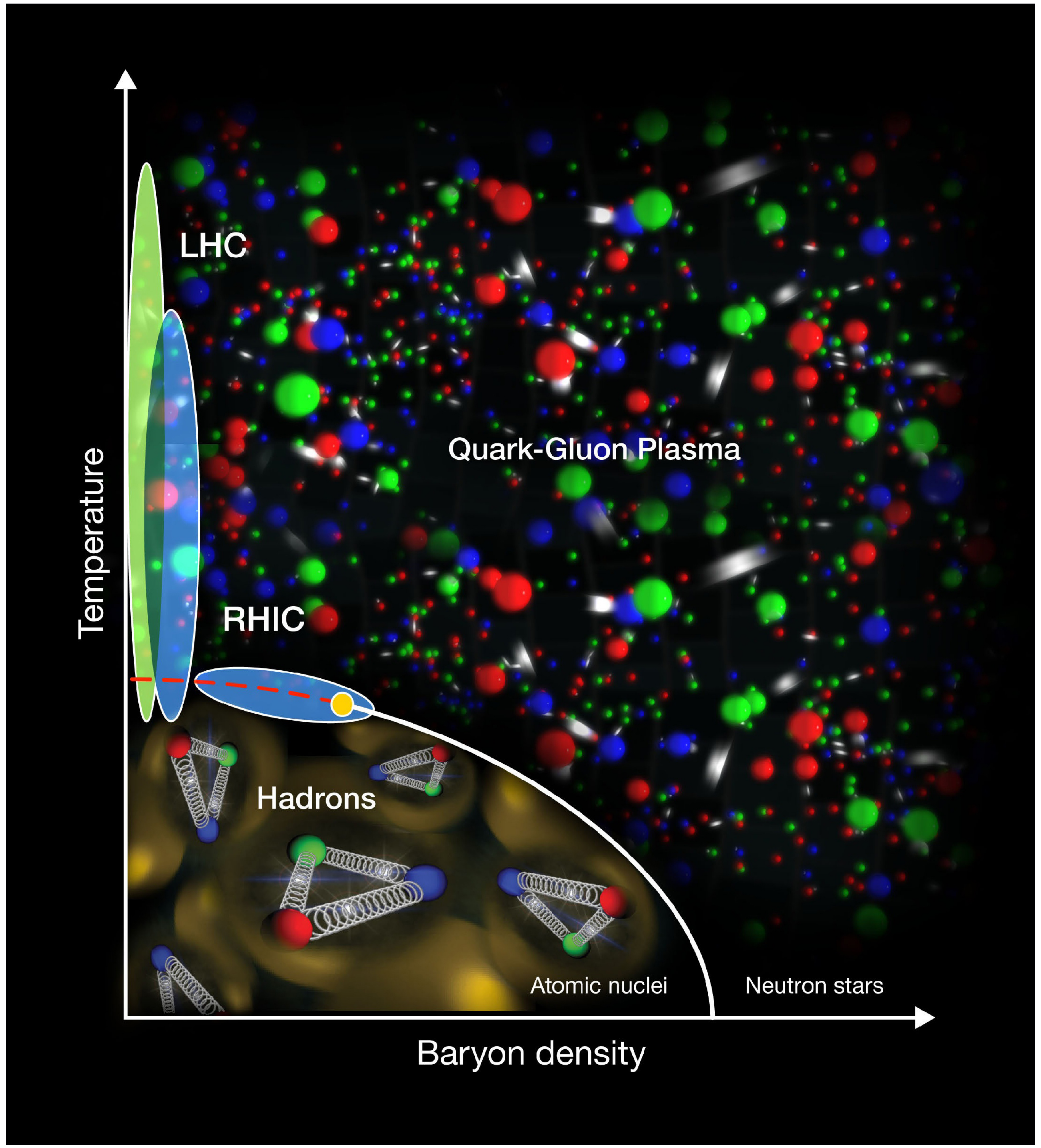
November 2019

Outline

- Magnetic field in heavy-ion collisions and the novel phenomena
- Experimental search for the anomalous chiral effect
  - Chiral Magnetic Effect
  - Chiral Magnetic Wave
- Magnetic-induced charged currents

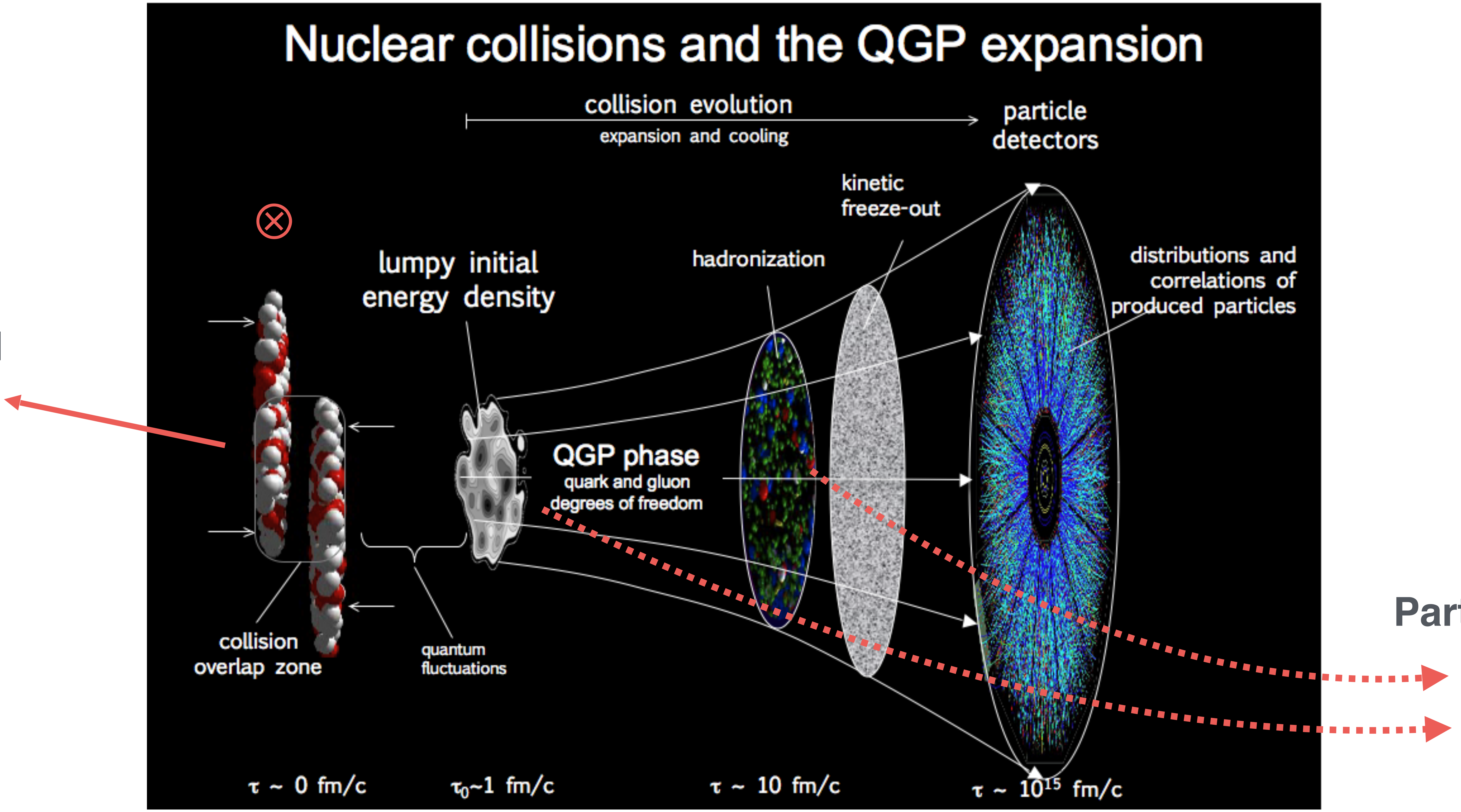
Heavy-ion collisions and Quark Gluon Plasma



- State of matter in quantum chromodynamics (QCD) which exists at extremely high temperature and/or density
- Asymptotically free strong-interacting quarks and gluons, which are ordinarily confined by color confinement inside atomic nuclei/hadrons

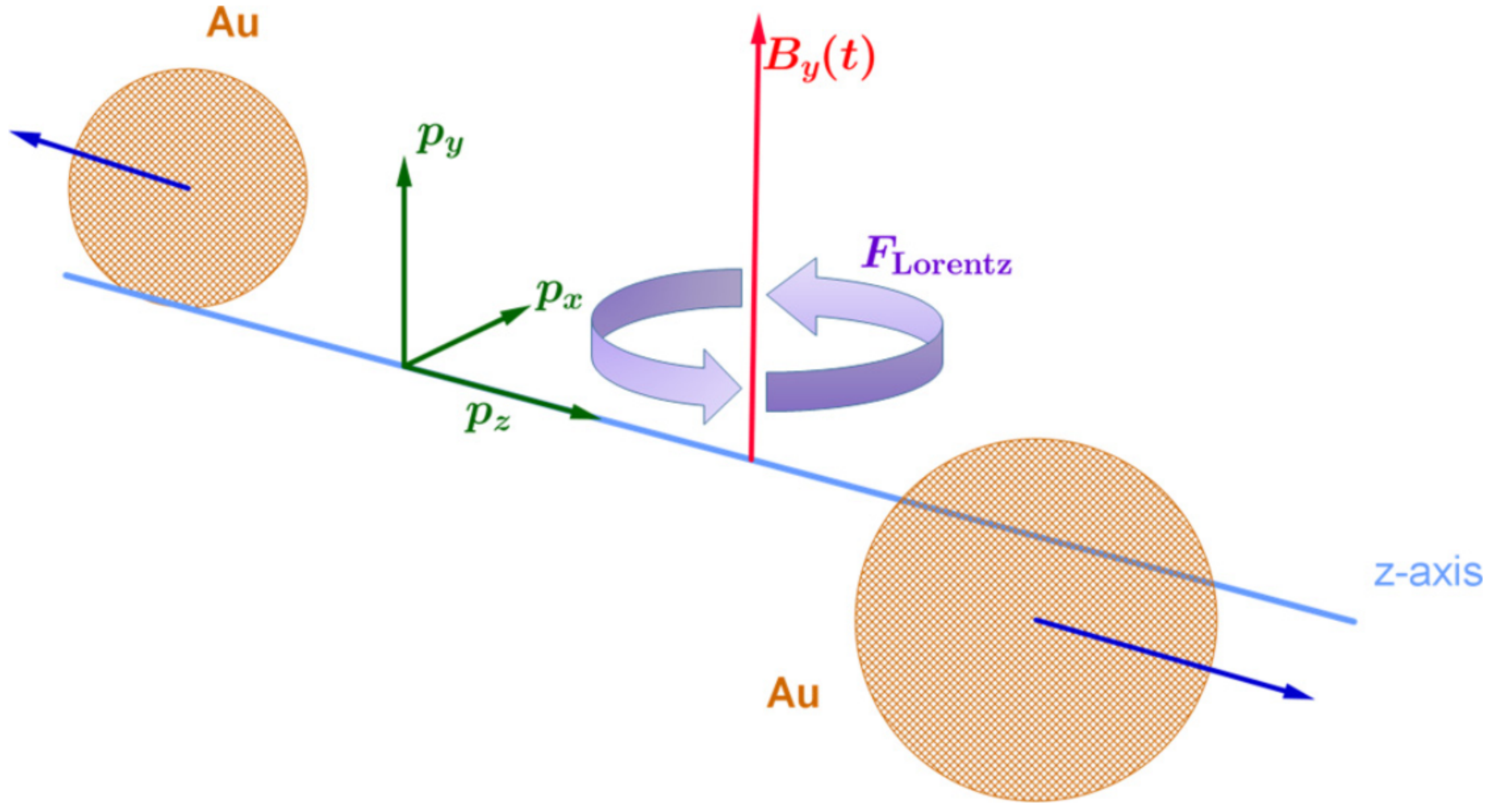
Heavy-ion collisions and Quark Gluon Plasma

Magnetic field



Particles emitted

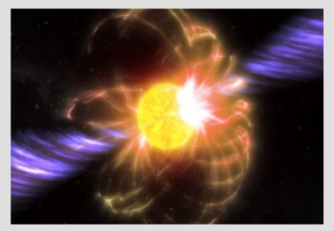
Strong magnetic field in HIC



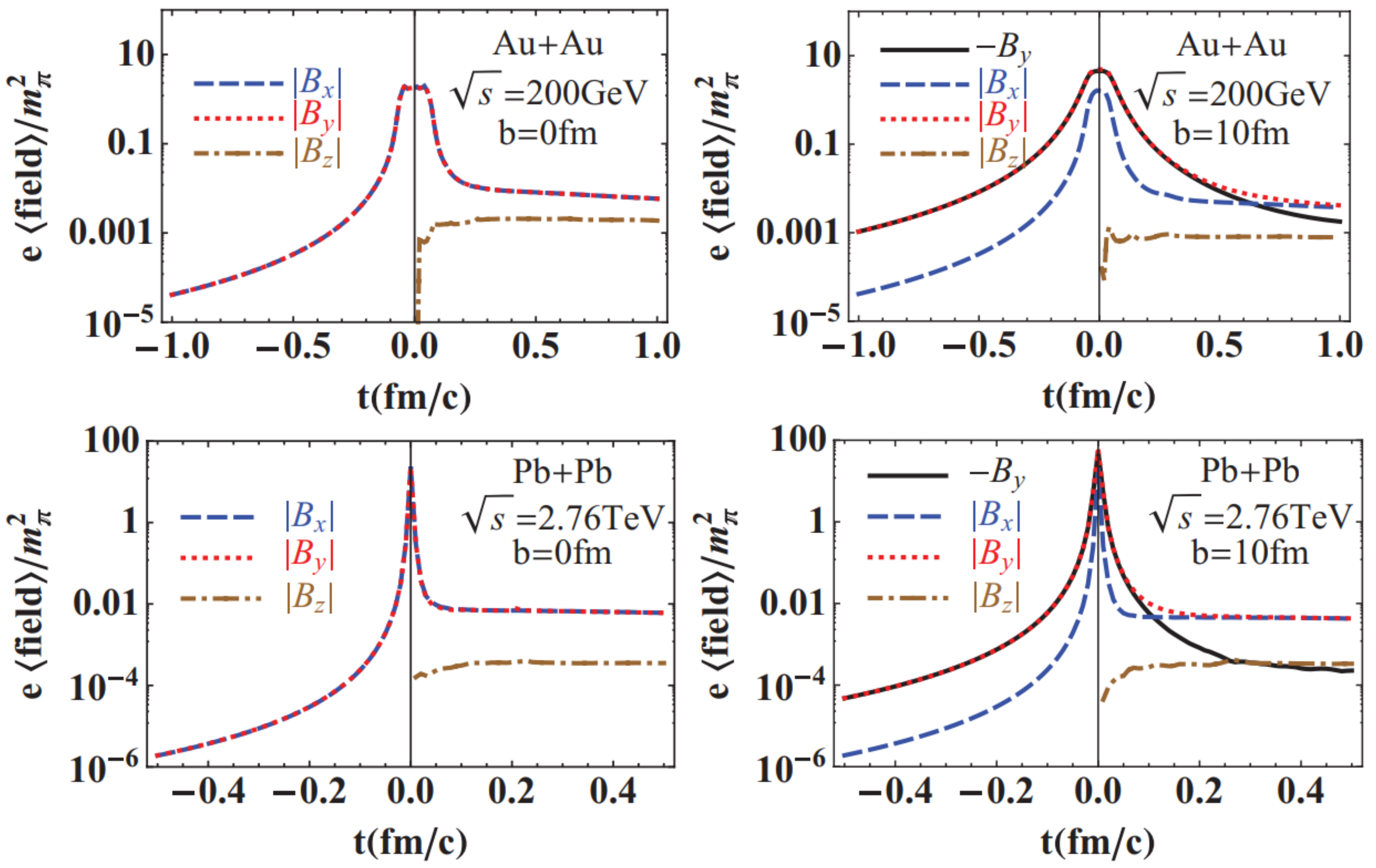
- Thinking — human brain: 10^{-12} Tesla
- Earth's magnetic field: 10^{-5} Tesla
- Refrigerator magnet: 10^{-3} Tesla
- Loudspeaker magnet: 1 Tesla
- Levitating frogs: 10 Tesla
- Strongest field in Lab: 10^{3} Tesla
- Typical neutron star: 10^{6} Tesla
- Magnetar: $10^{7...10}$ Tesla
- Heavy-ion collisions: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

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

Destructive explosion



Phys. Rev. C 85, 044907 (2012).

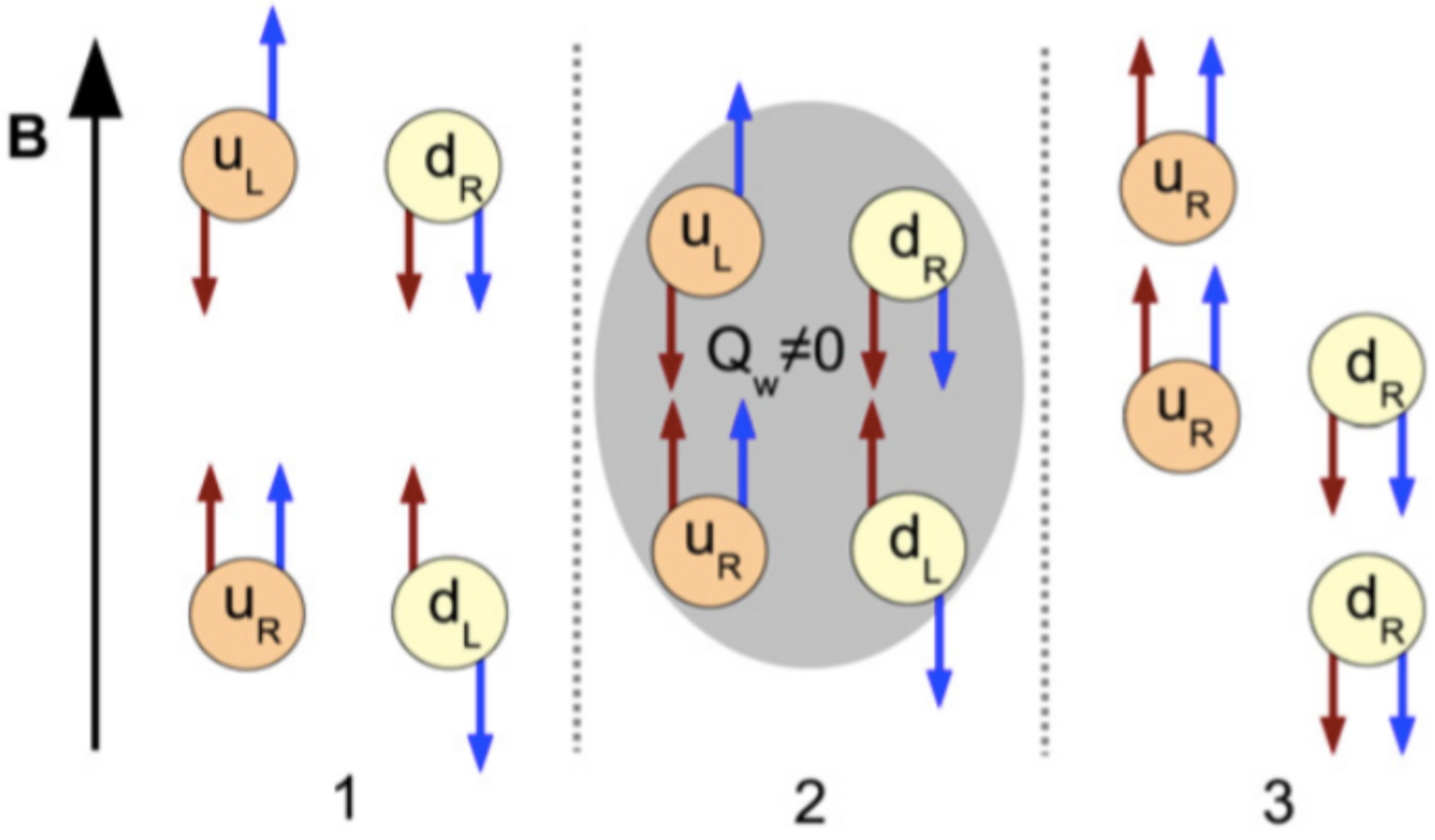


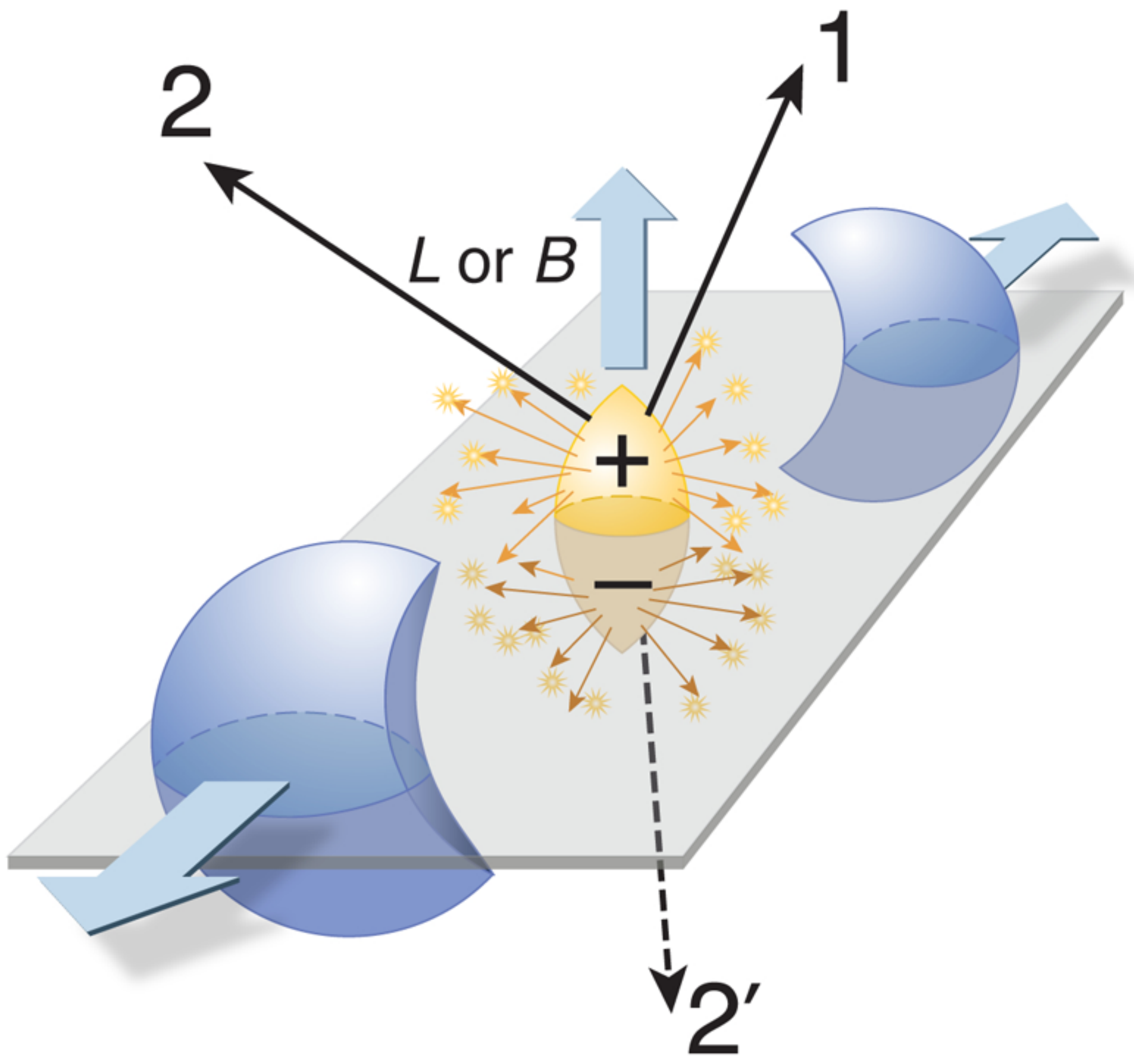
Possible response to the magnetic field in HIC

- Deflection and polarization of the dileptons
- Coherent production
- Collective motions of direct photons
- Associated emission of jet (low momentum photons)
- Anomalous chiral effect
- Synchrotron radiation from quarks

Chiral Magnetic Effect

Nuclear Physics A 803, 227 (2008).

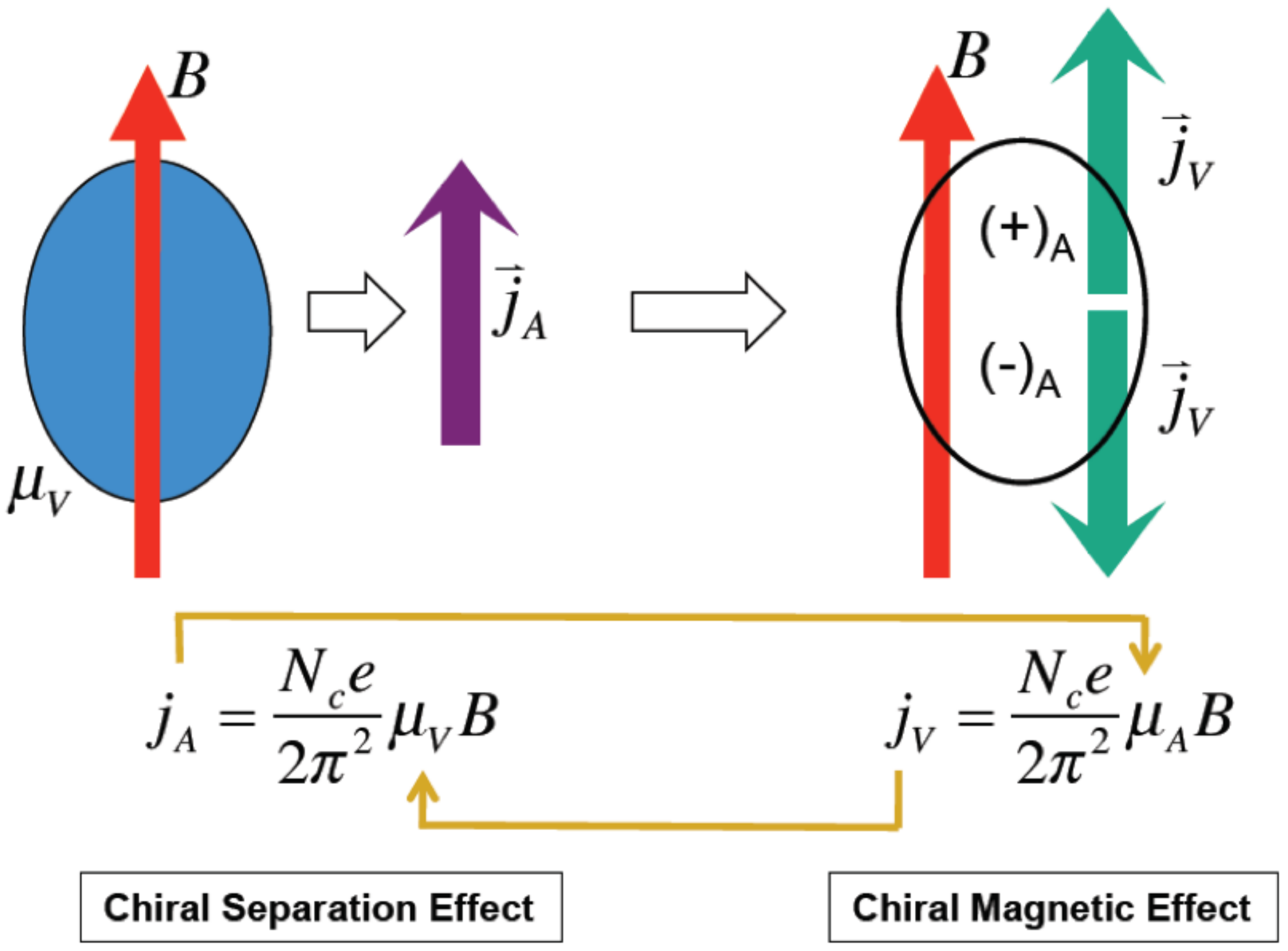


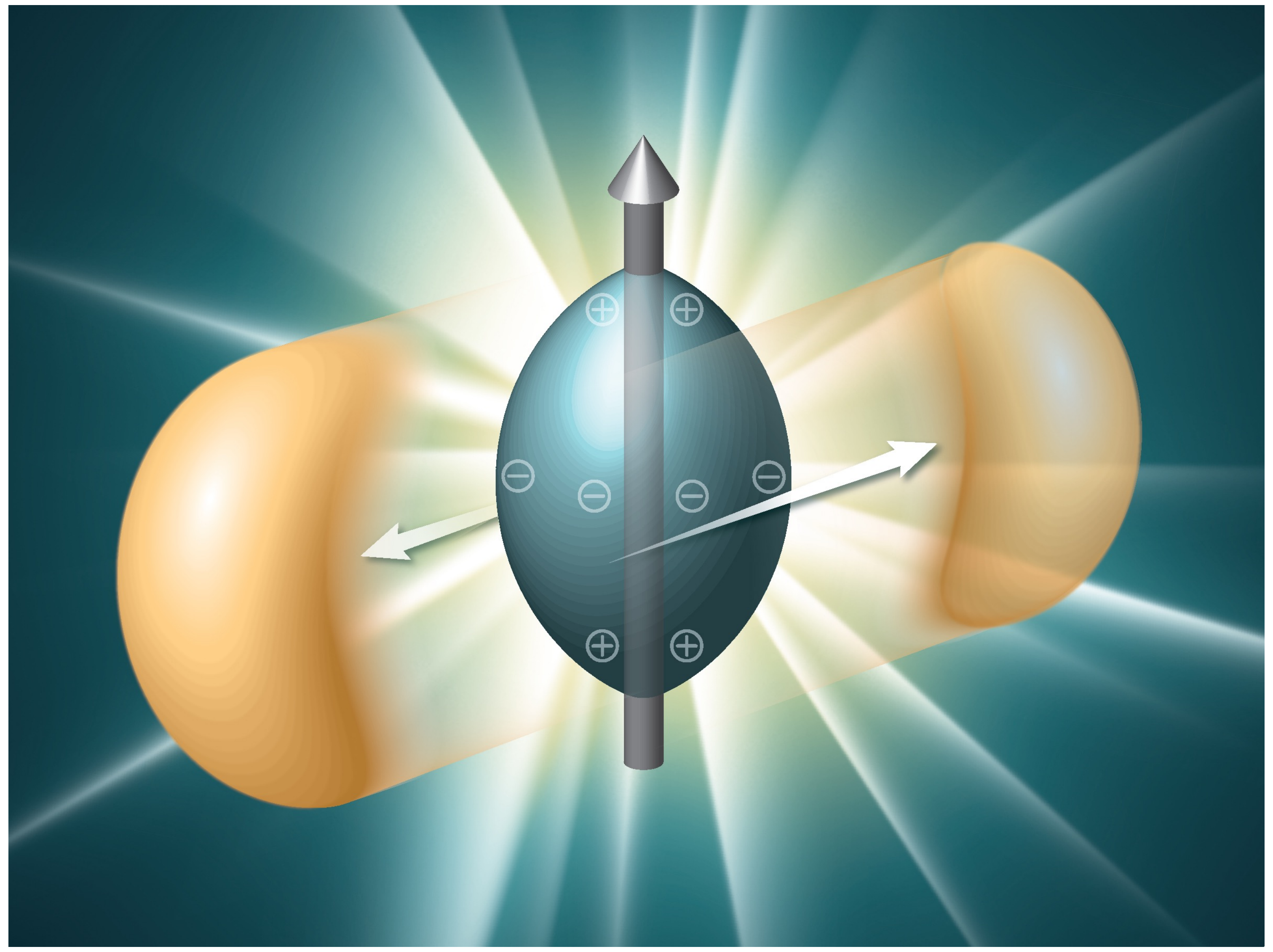


Novel topological effect of QCD

$$\vec{\mathbf{J}} = \sigma_5 \vec{\mathbf{B}} \qquad \sigma_5 = \frac{Qe}{2\pi^2}\mu_5$$

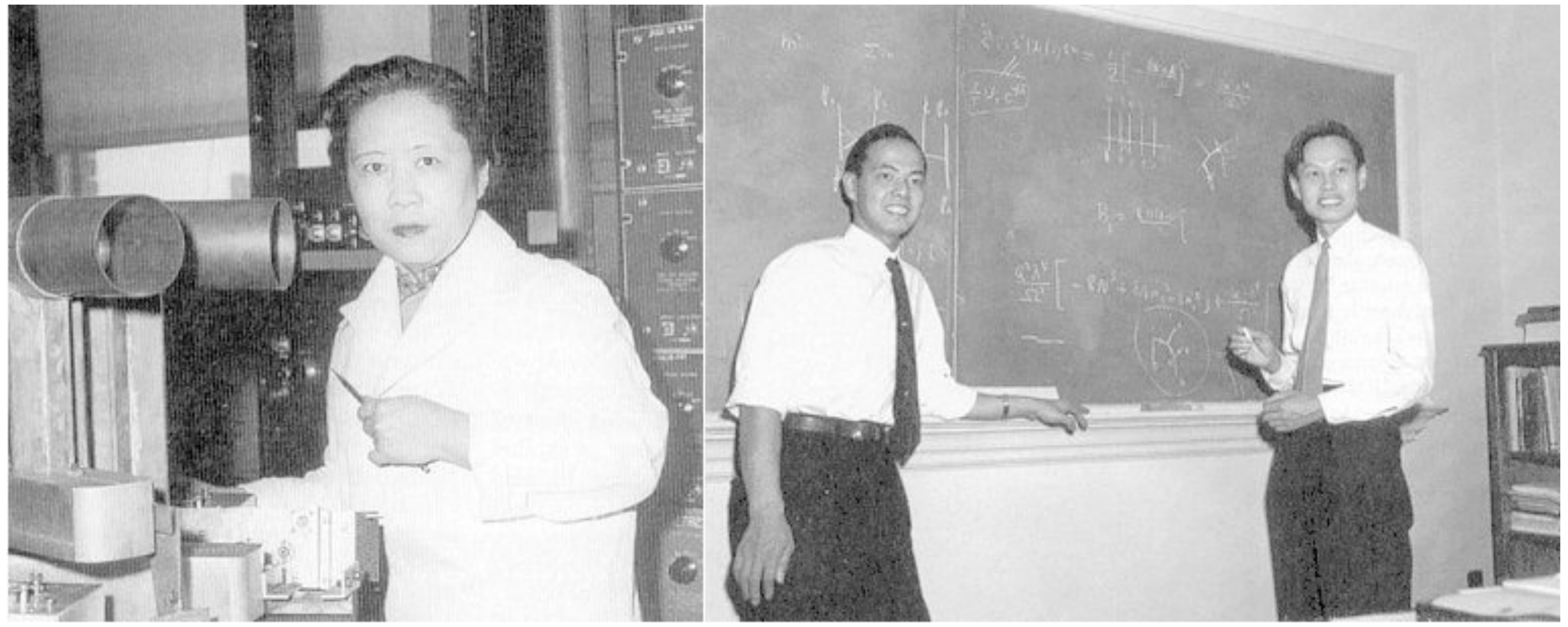
Chiral Magnetic Wave





Phys. Rev. Lett. 107, 052303 (2011).

Possible P/CP violation in strong interactions



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

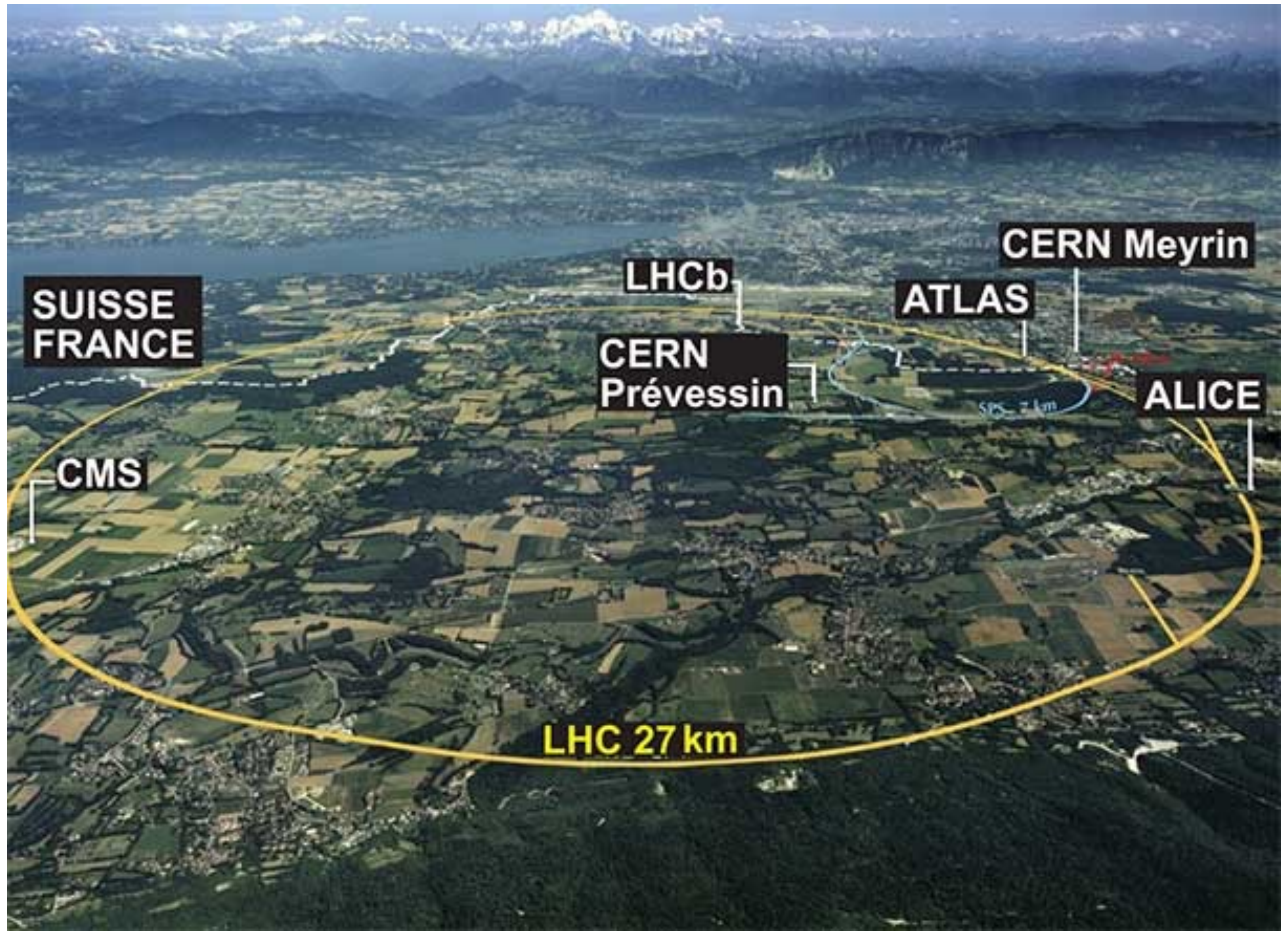
The discovery of CP violation in 1964 in the decays of neutral kaons resulted in the Nobel Prize in Physics in 1980 for its discoverers James Cronin and Val Fitch

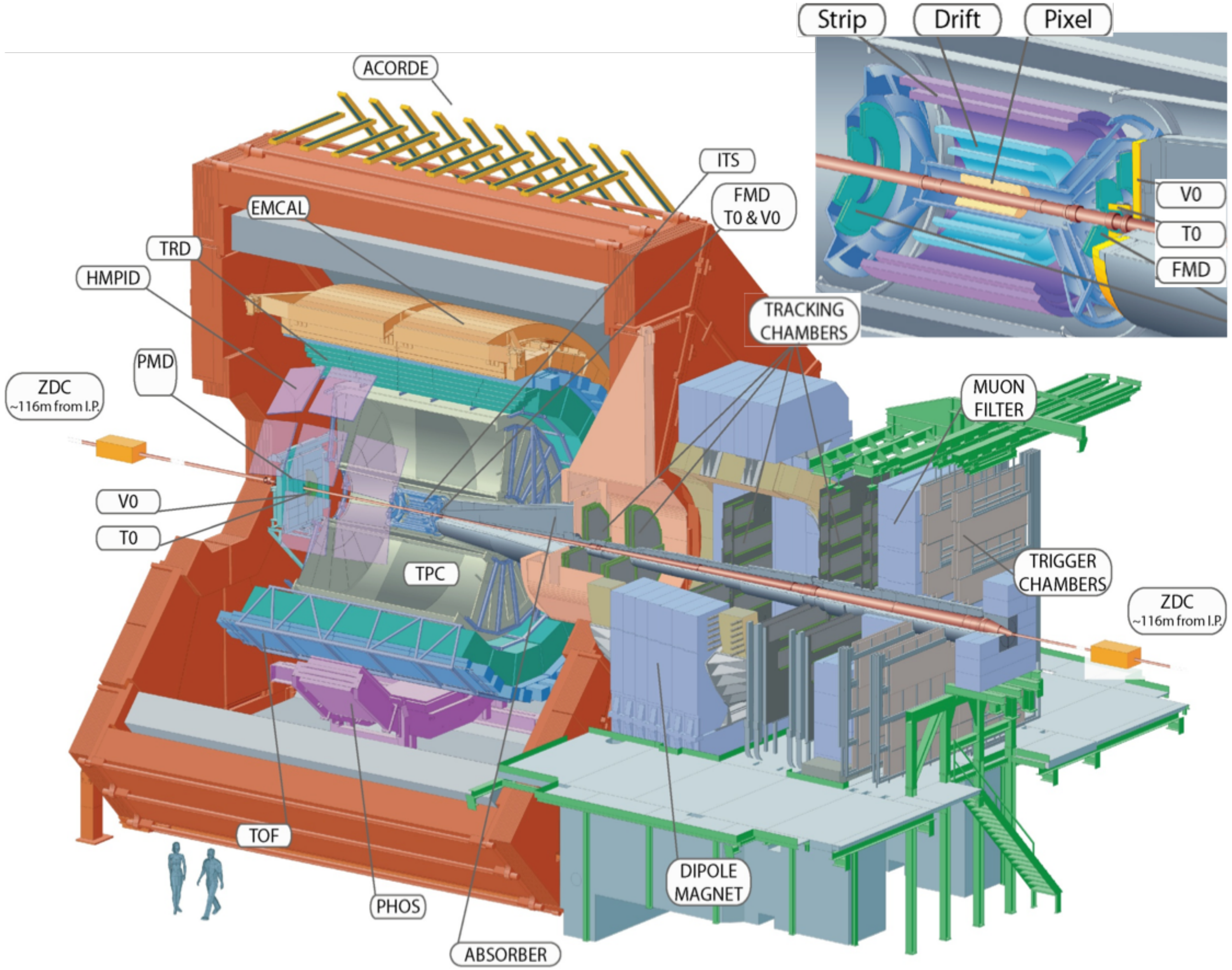
Why is the strong nuclear interaction CP-invariant?

- 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

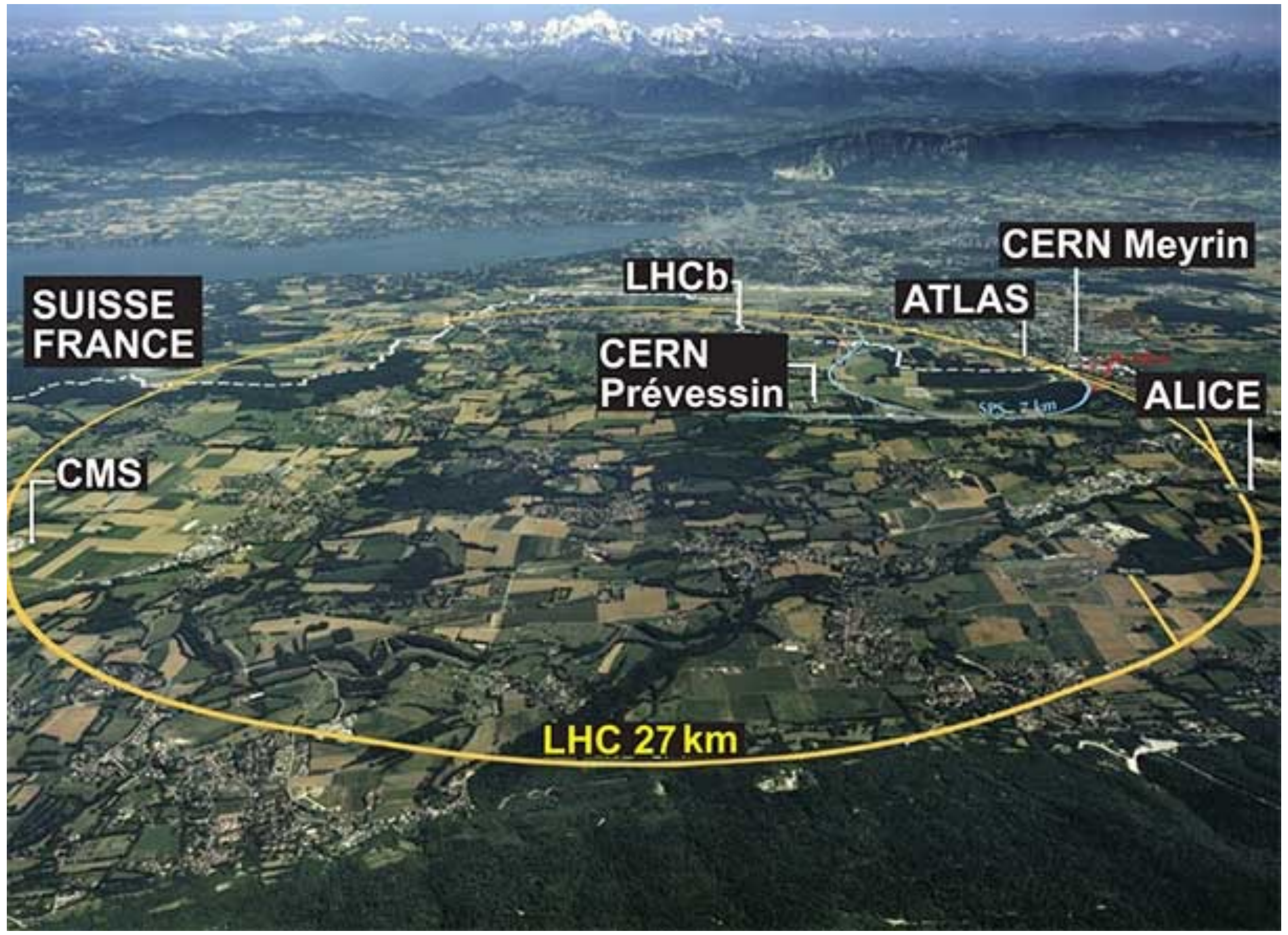
A Large Ion Collider Experiment



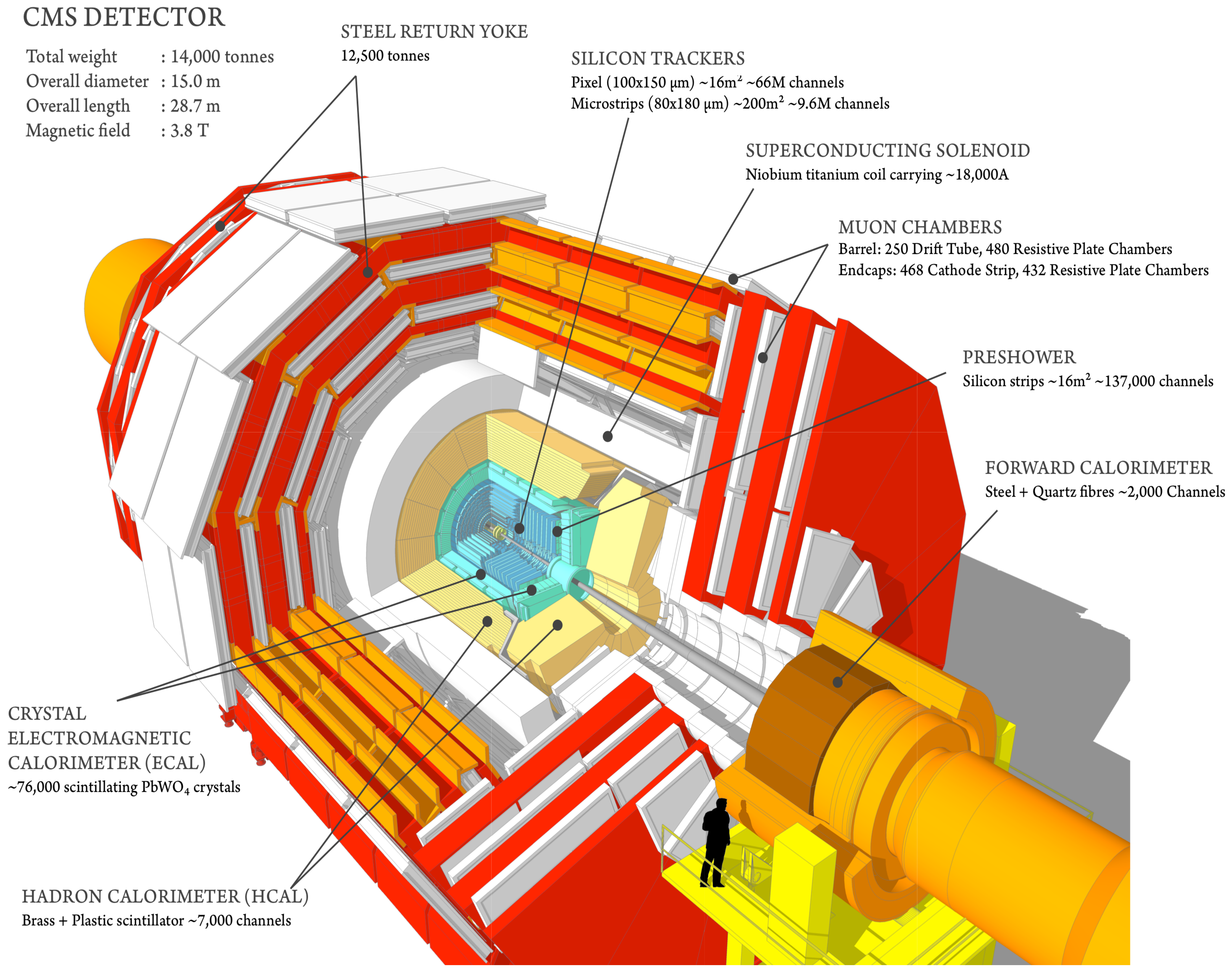


41 countries, 177 institutes, 1800 members

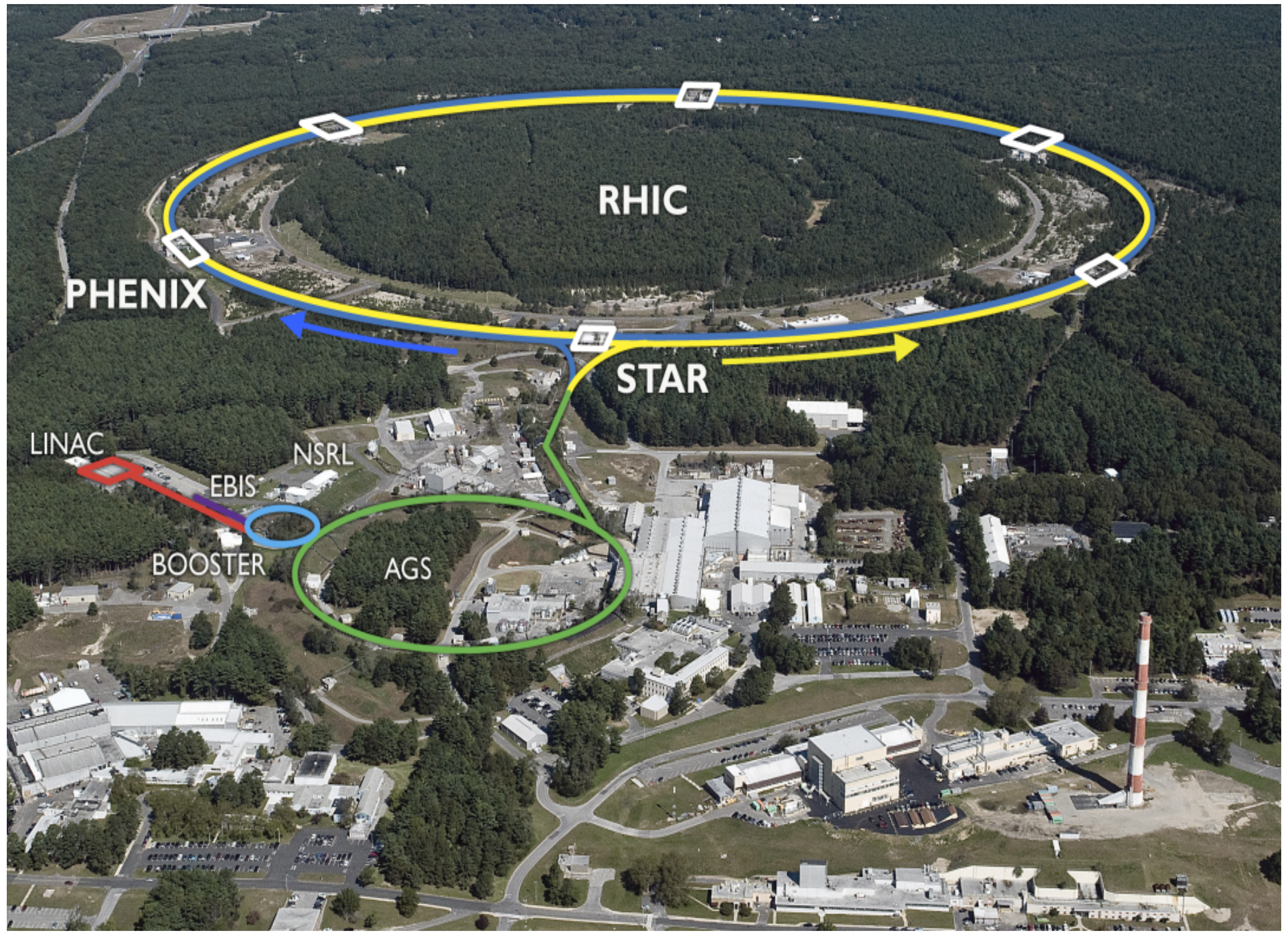
Compact Muon Solenoid



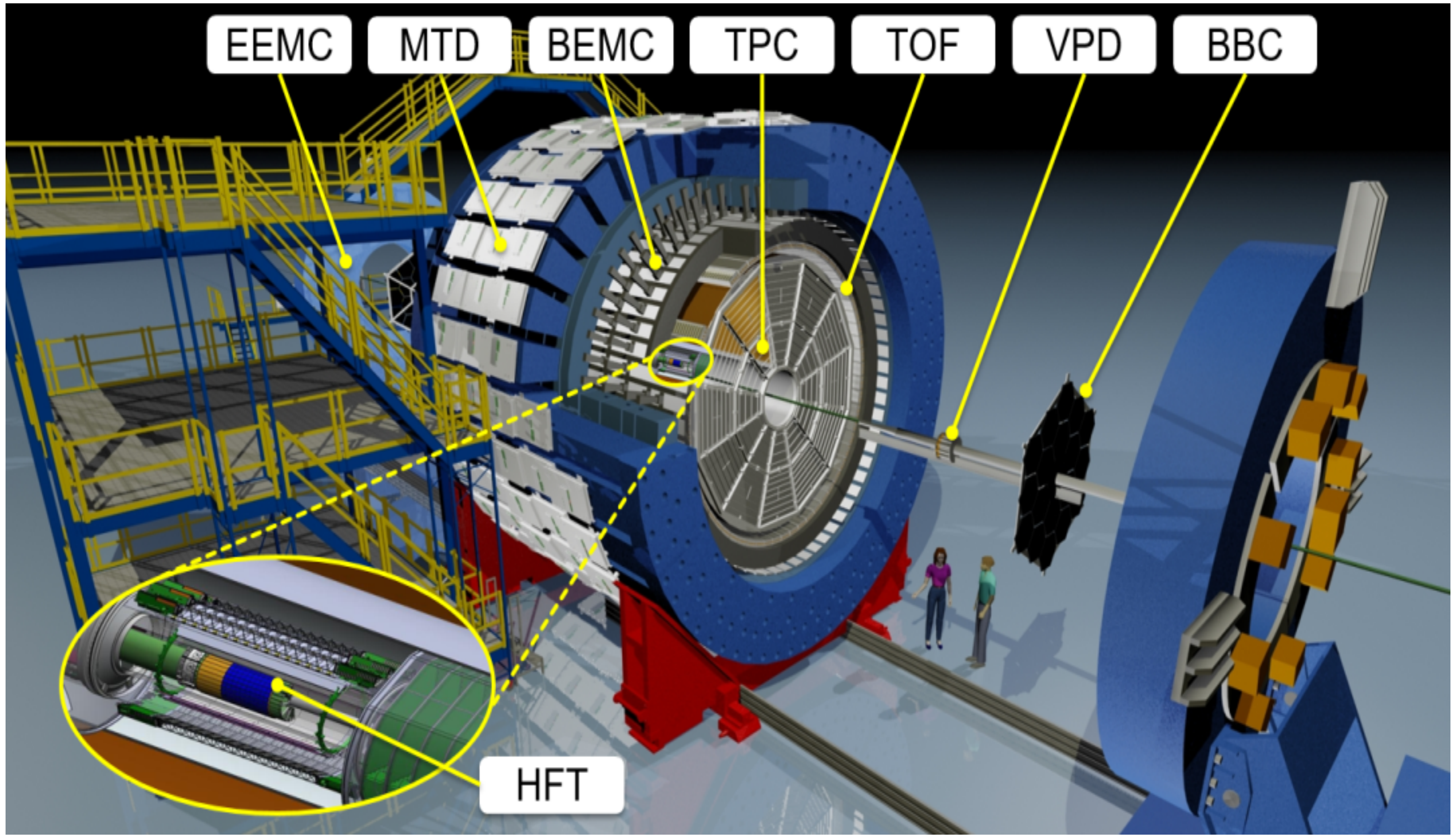
45 countries, 198 institutes, 2100 members



Solenoidal Tracker at RHIC



14 countries, 65 institutes, 668 members



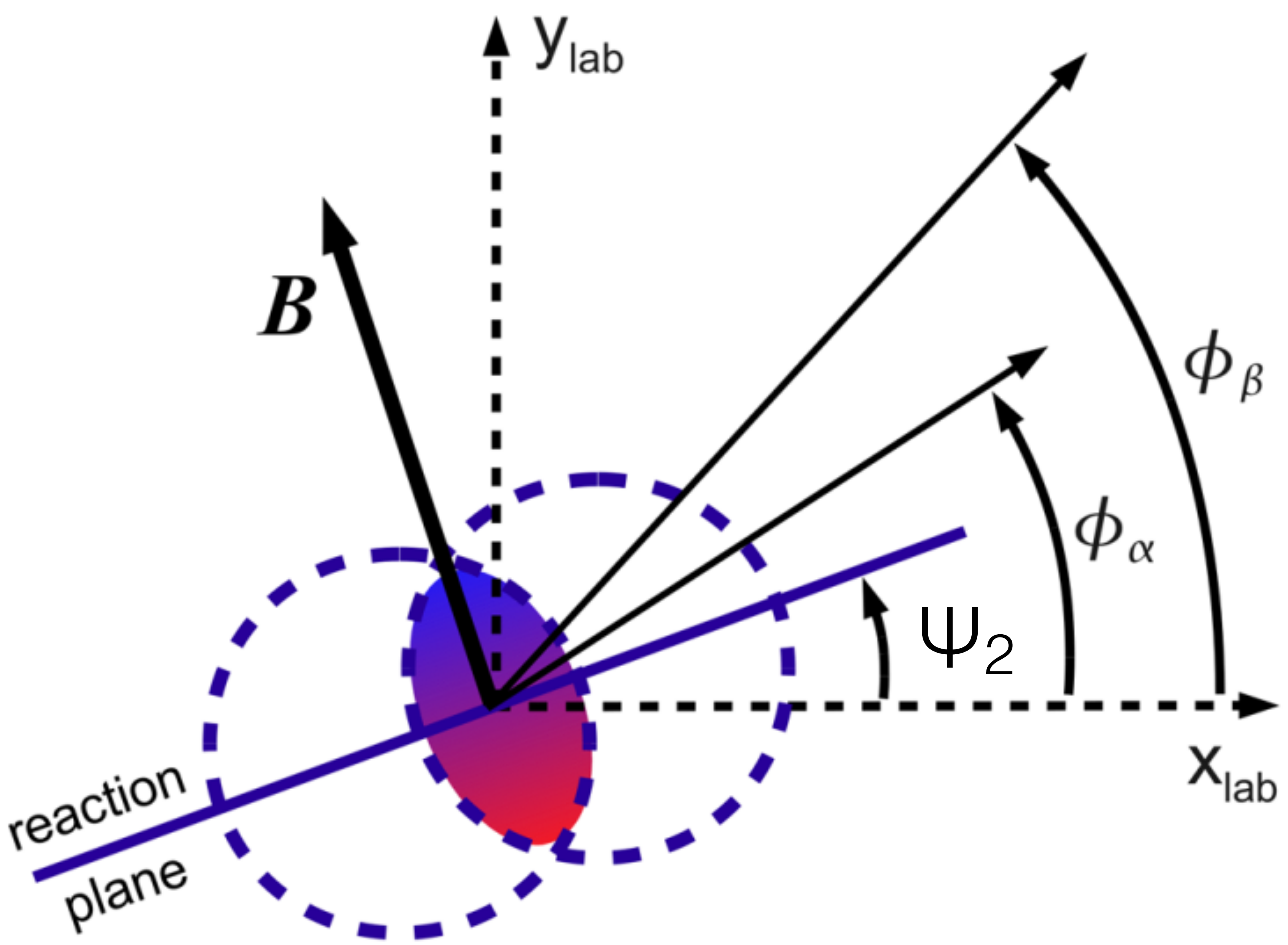
Strong magnetic field & chiral anomaly in HIC

- **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**
  - ✓ LHC: Pb-Pb, p-Pb, Xe-Xe at 2.76 TeV, 5.02 TeV, 5.44 TeV
  - ✓ RHIC: Au+Au, p(d)+Au, U+U, Isobaric at BES (7-62 GeV), ~200 GeV
- **Particle of interest**
  - ✓ Inclusive charged particles
  - ✓ Identified particles: π, K, p, heavy-flavour, etc at various kinematic windows (p_T, η, etc)

Experimental measurement of CME

- Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation
  STAR Collaboration, Phys. Rev. Lett. 103, 251601 (2009).
- Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions
  STAR Collaboration, Phys. Rev. C 81, 054908 (2010).
- Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  ALICE Collaboration, 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
  STAR Collaboration, Phys. Rev. C 88, 064911 (2013).
- Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au+Au Collisions at RHIC
  STAR Collaboration, Phys. Rev. Lett. 113, 052302 (2014).
- Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 200 GeV
  STAR Collaboration, Phys. Rev. C 89, 044908 (2014).
- Observation of Charge-Dependent Azimuthal Correlations in p-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect
  CMS Collaboration, Phys. Rev. Lett. 118, 122301 (2017).
- Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider
  CMS Collaboration, Phys. Rev. C 97, 044912 (2018).
- Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  ALICE Collaboration, Physics Letters B 777, 151 (2018).

Measurement of CME with two- and three-particle correlations



$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \cdots$$
$$+ 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \cdots,$$

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

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

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

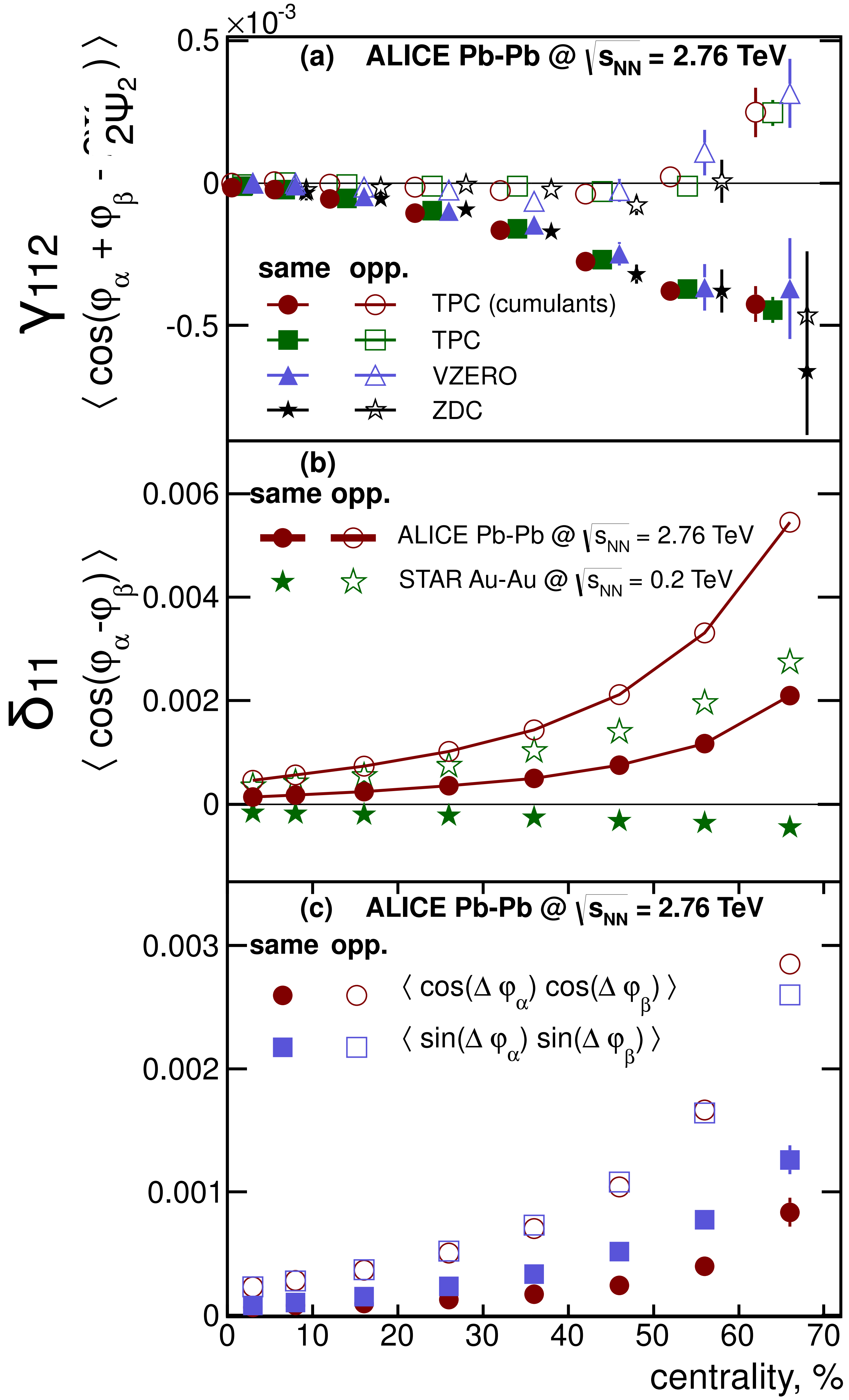
$\gamma_{132} \equiv \langle\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle$

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

…

- ✓ 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



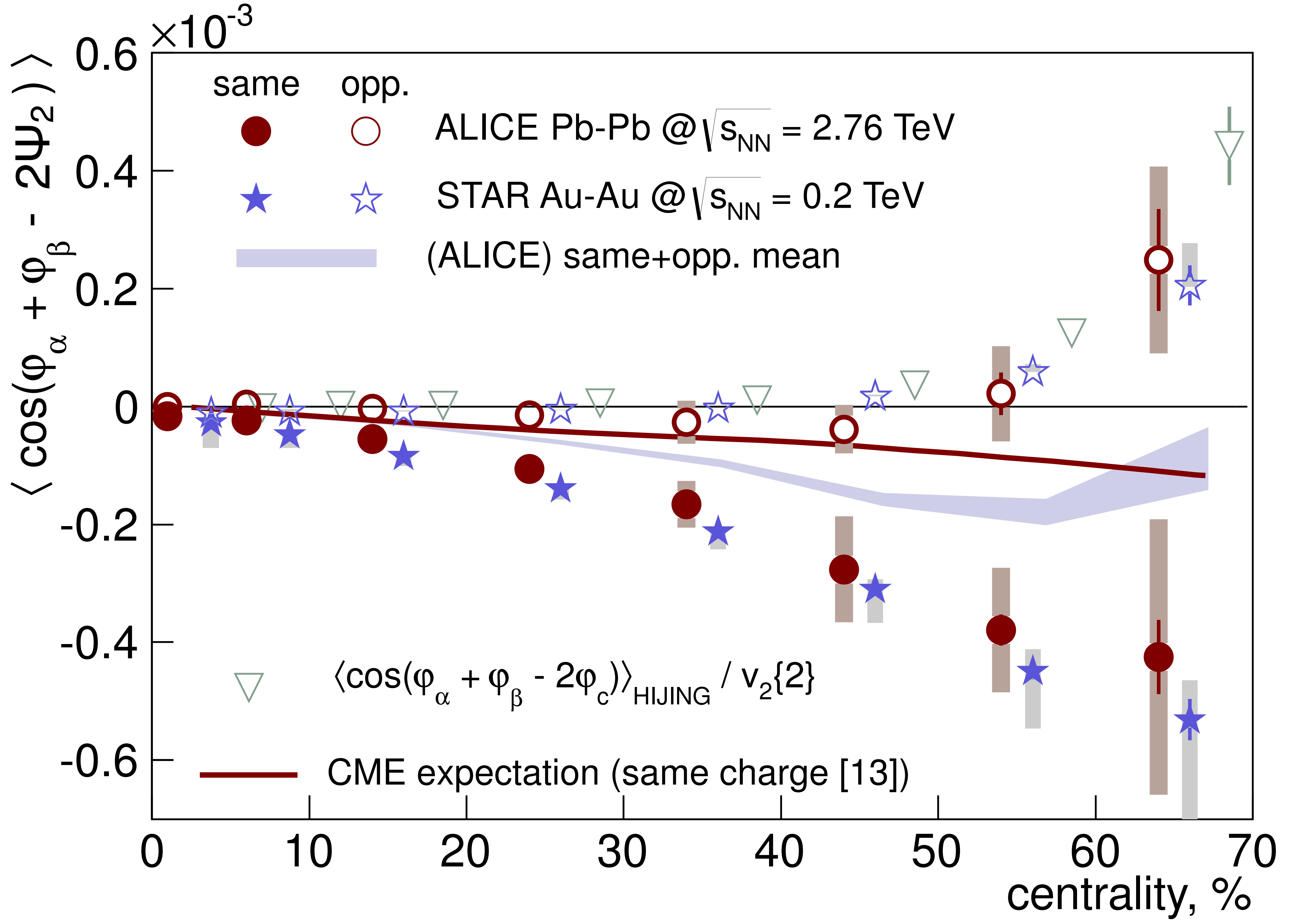
Phys. Rev. Lett. 110, 012301 (2013).

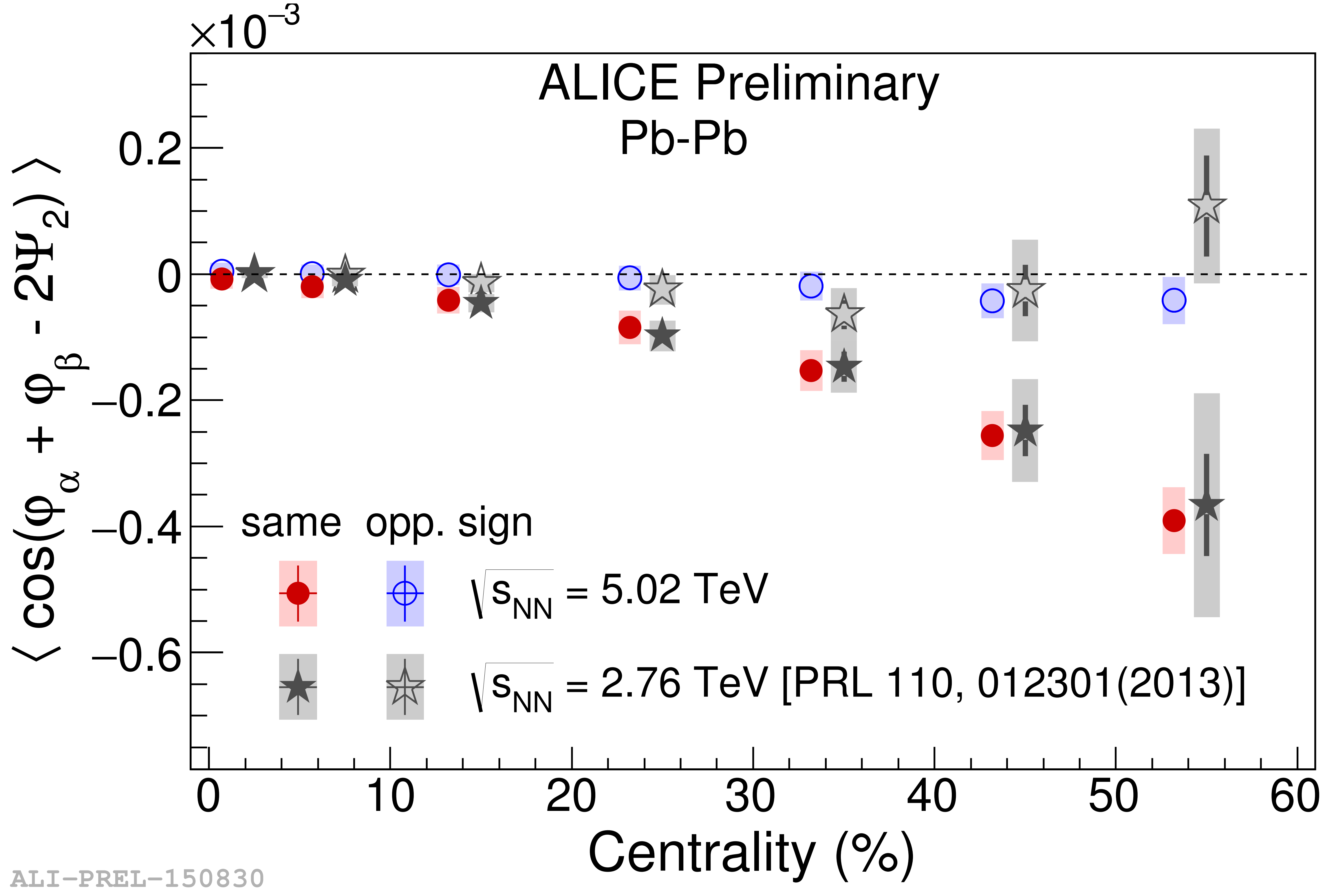
- Good agreement between various γ_{112} obtained with the EP estimated from different detectors

- 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 behavior for OS between <cos cos> and <sin sin> terms

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



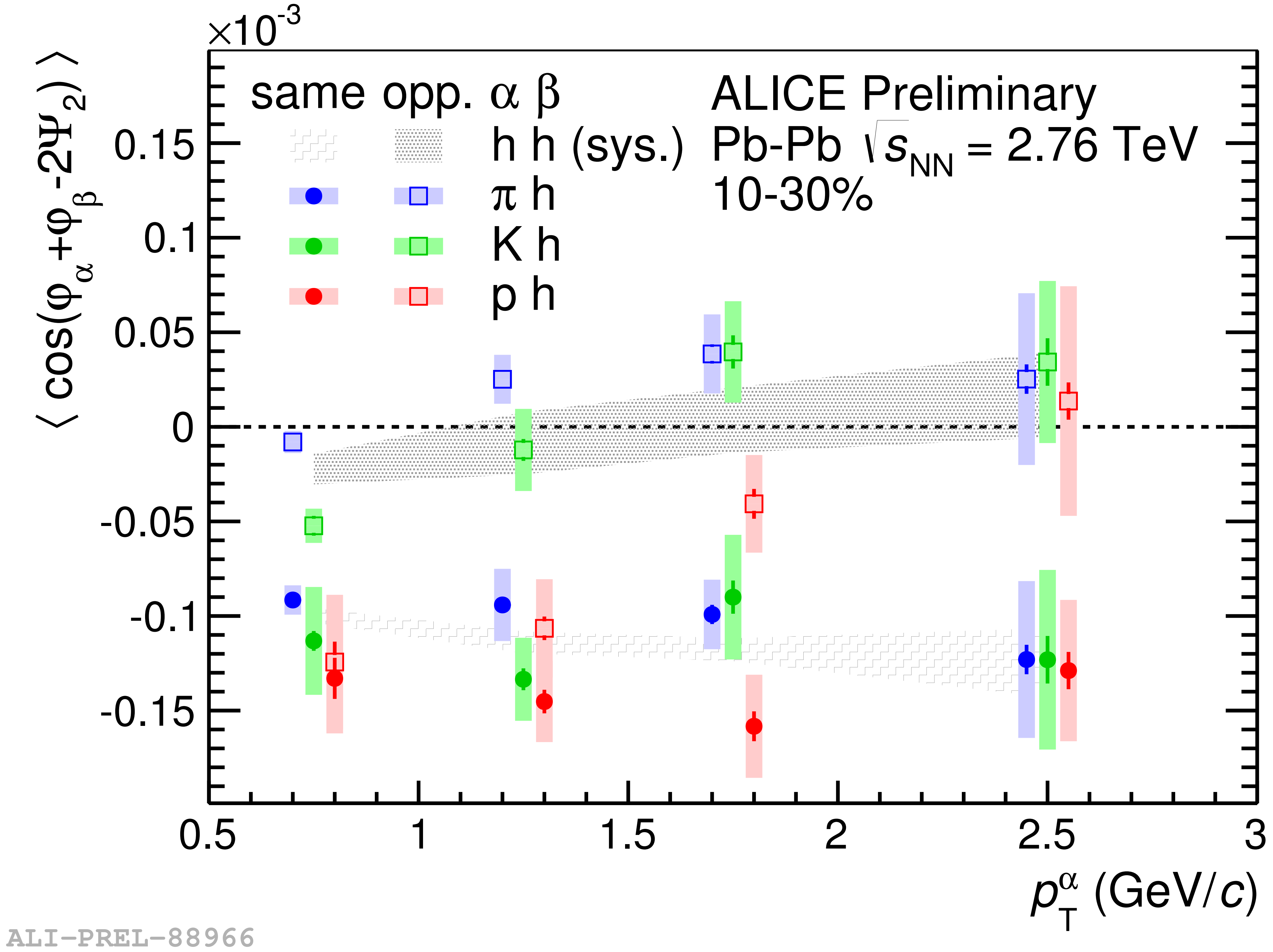


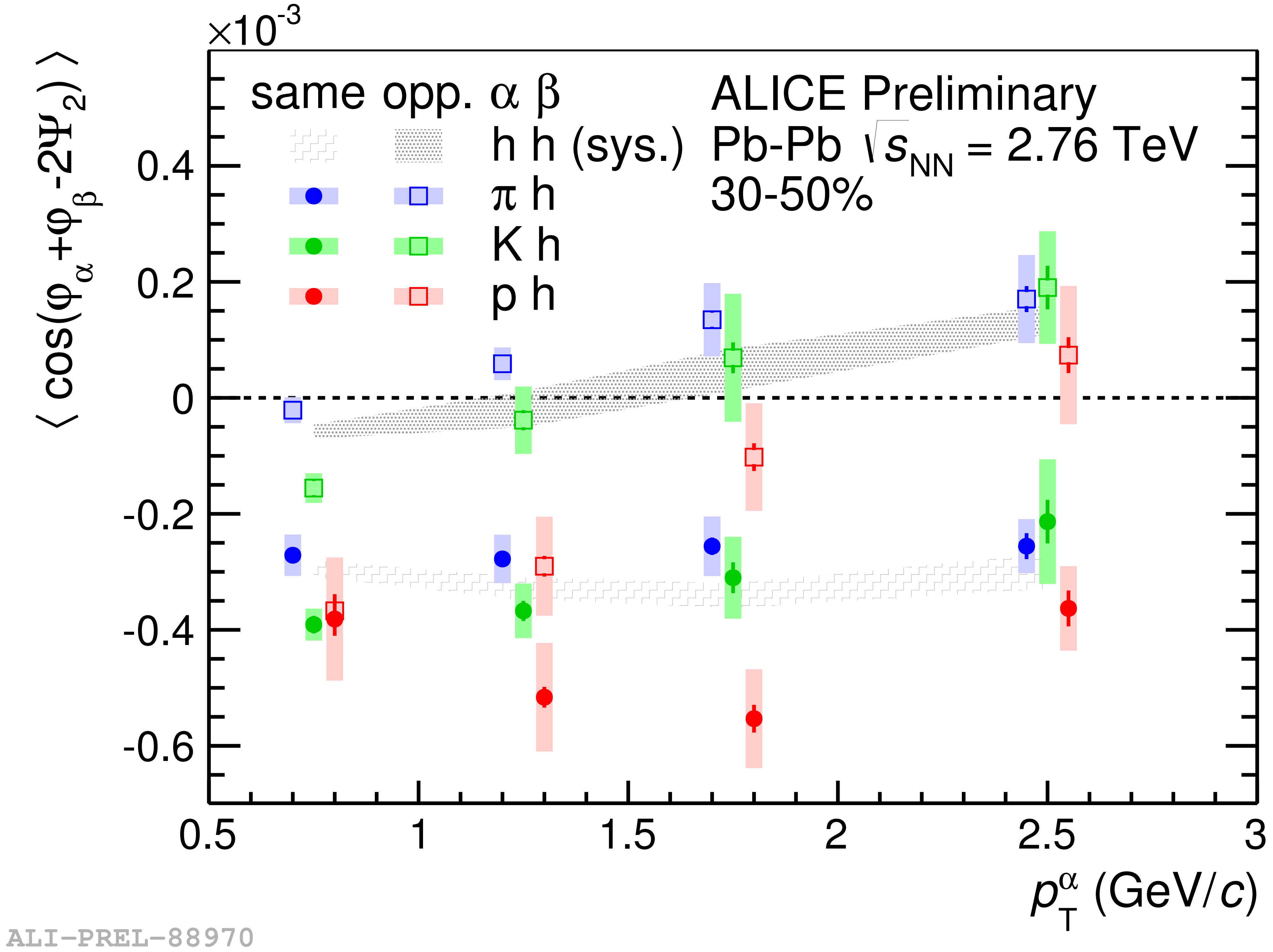
- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

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

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

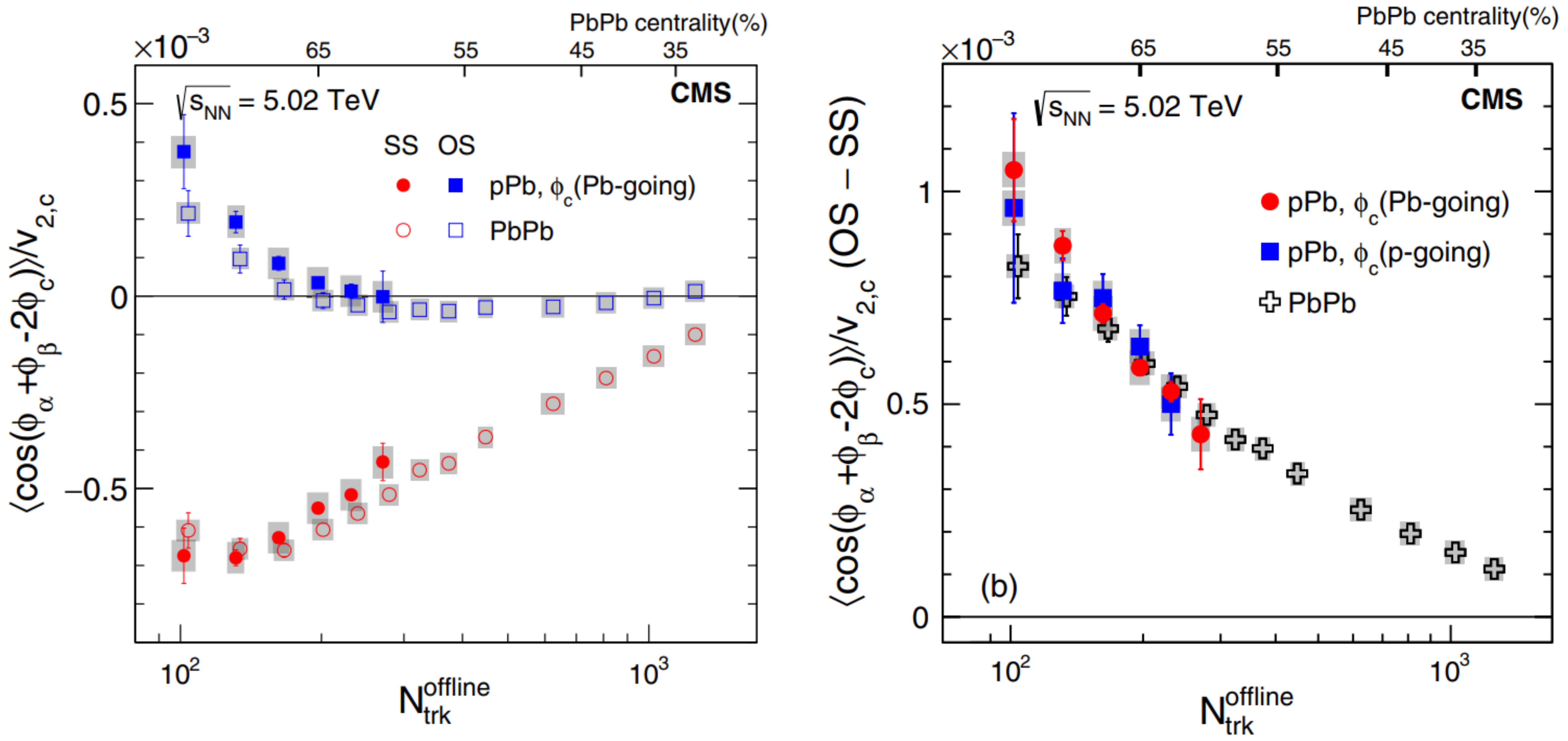
γ_{112} with identified particles at 2.76 TeV Pb-Pb collisions





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

Big **challenge** from small system collisions



Agreement for pPb and PbPb collisions observed, possibly indicating a common underlying mechanism (**background**) that generates the observed correlation

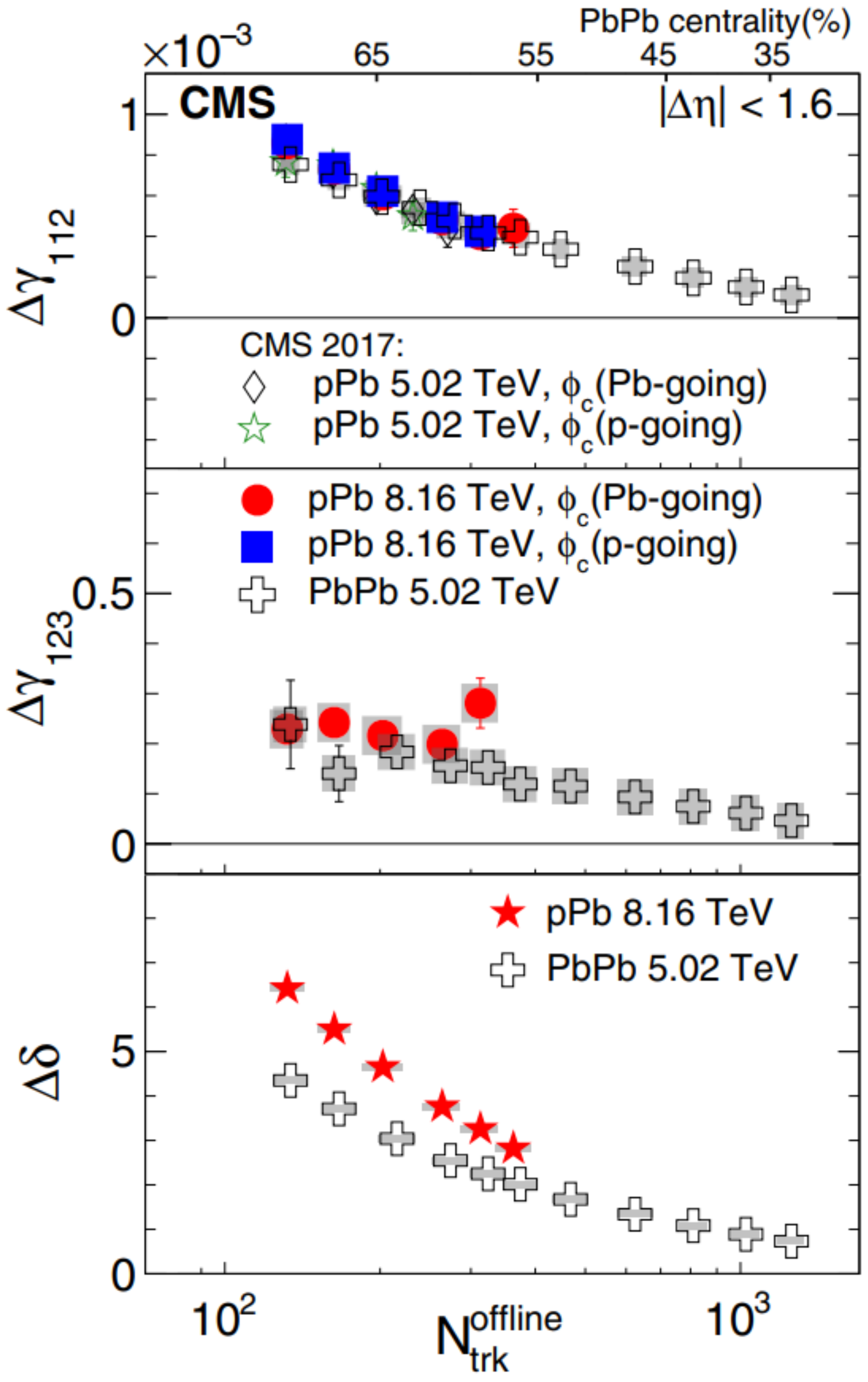
More checks on background – collective flow

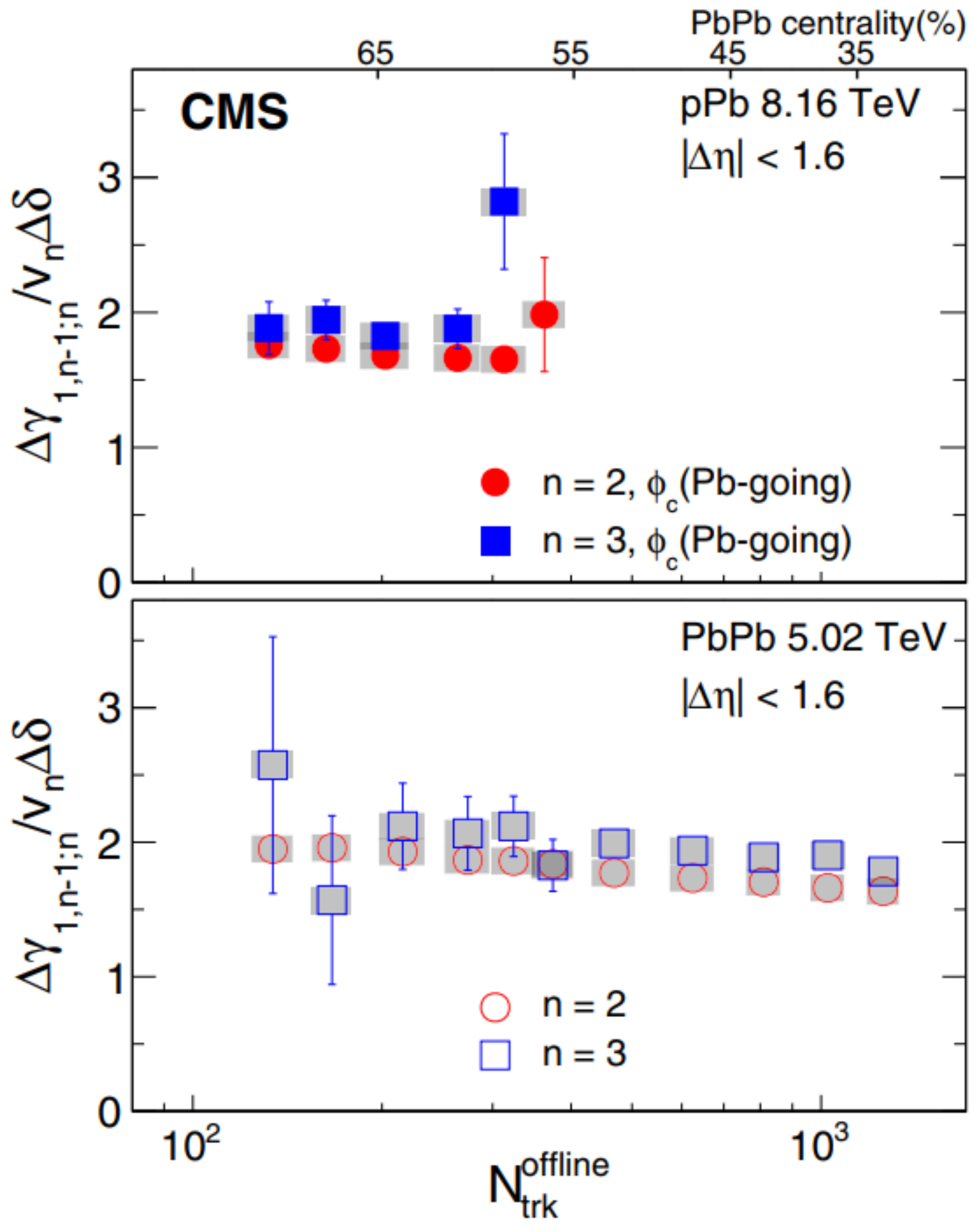
$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$
$$= \langle \cos(\phi_\alpha - \Psi_2) \cos(\phi_\beta - \Psi_2) \rangle$$
$$- \langle \sin(\phi_\alpha - \Psi_2) \sin(\phi_\beta - \Psi_2) \rangle$$
$$\gamma_{112}^{\text{bkg}} = \kappa_2 \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 2(\phi_\beta - \Psi_{\text{RP}}) \rangle = \kappa_2\, \delta\, v_2$$

$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$
$$\gamma_{123}^{\text{bkg}} = \kappa_3 \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 3(\phi_\beta - \Psi_3) \rangle$$
$$= \kappa_3\, \delta\, v_3,$$

If pure background:

$$\frac{\Delta\gamma_{112}}{\Delta\delta\, v_2} \approx \frac{\Delta\gamma_{123}}{\Delta\delta\, v_3}$$

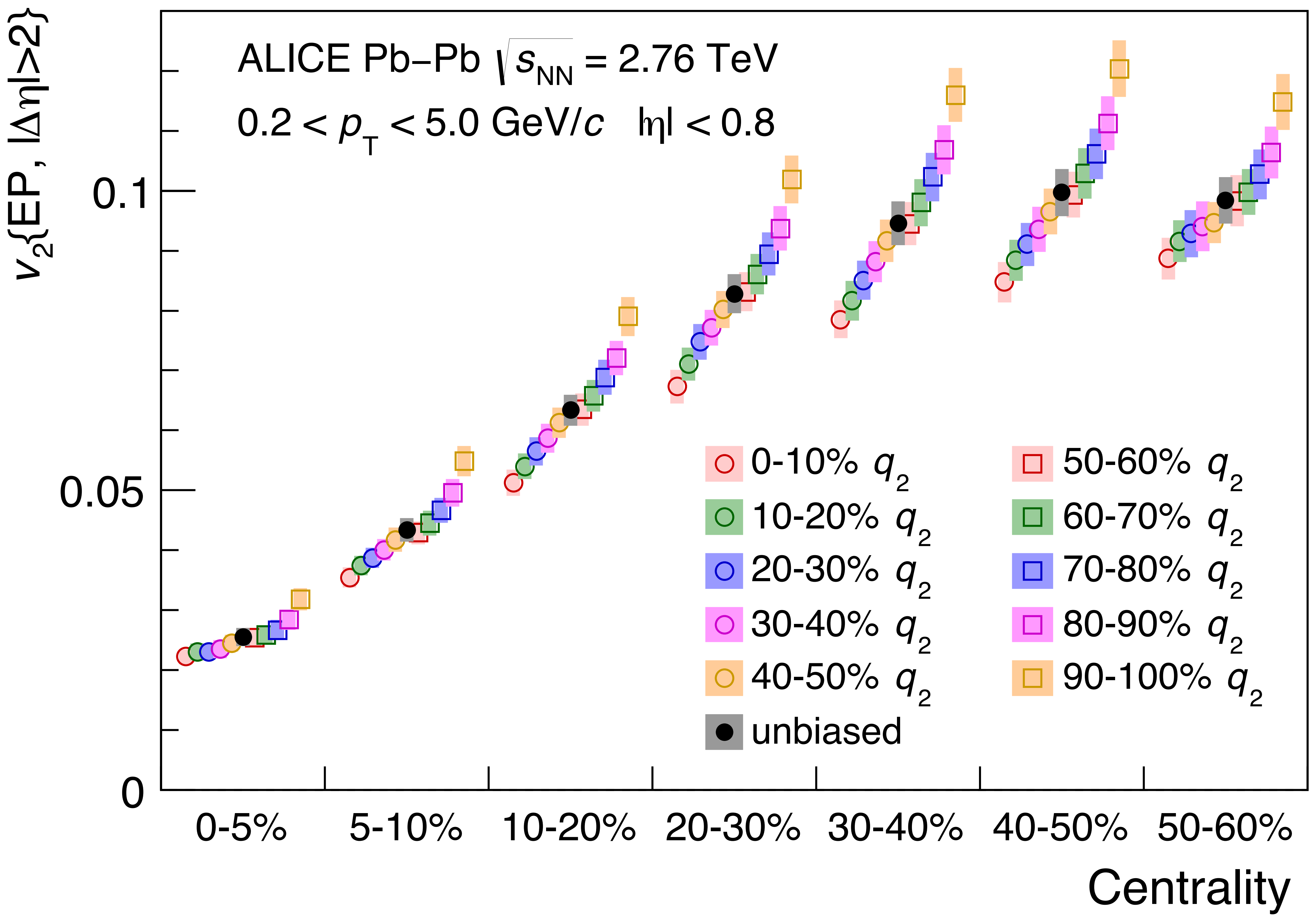




Strikingly similar behavior, which challenges the CME interpretation

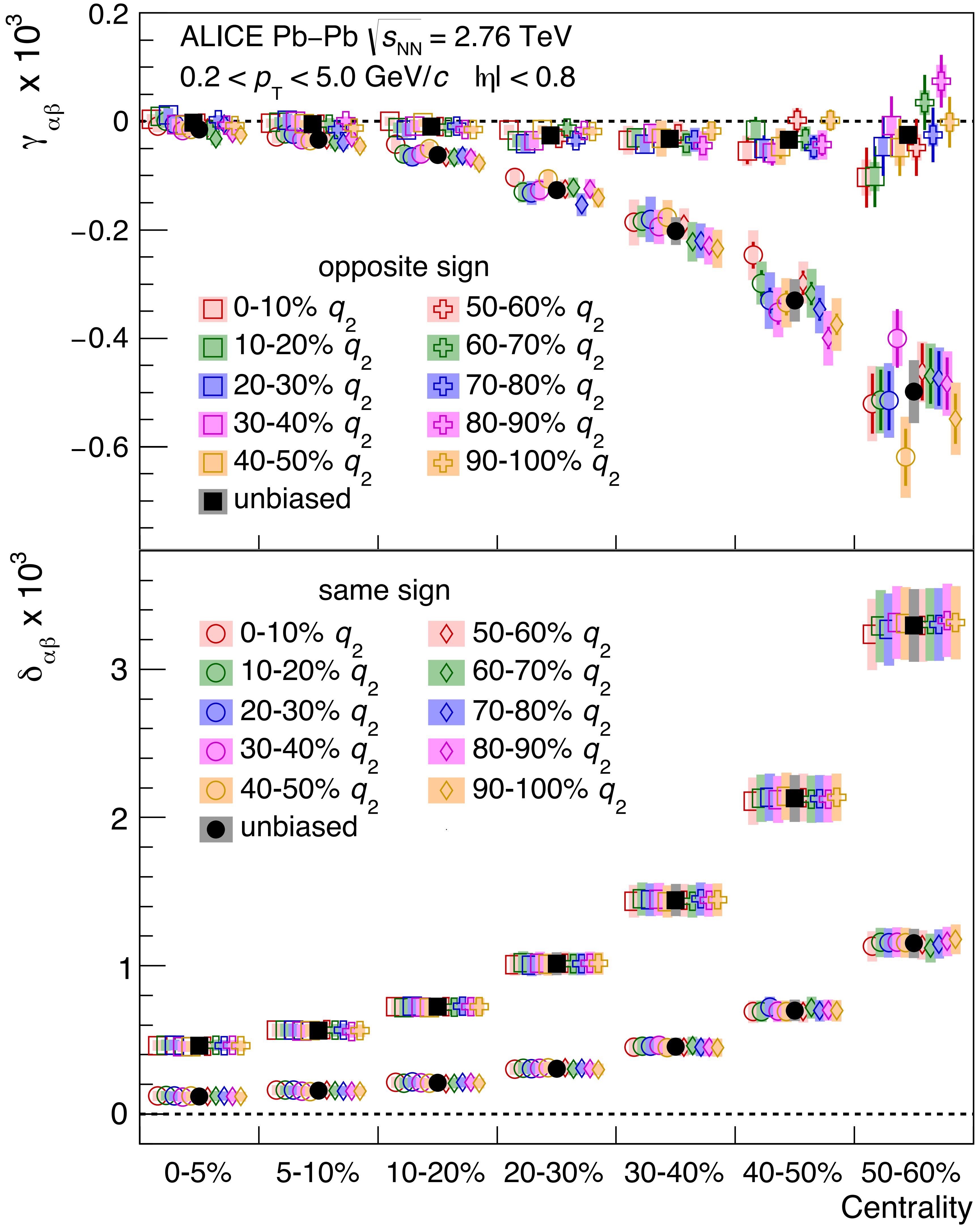
Event Shape Engineering

Physics Letters B 777, 151 (2018).



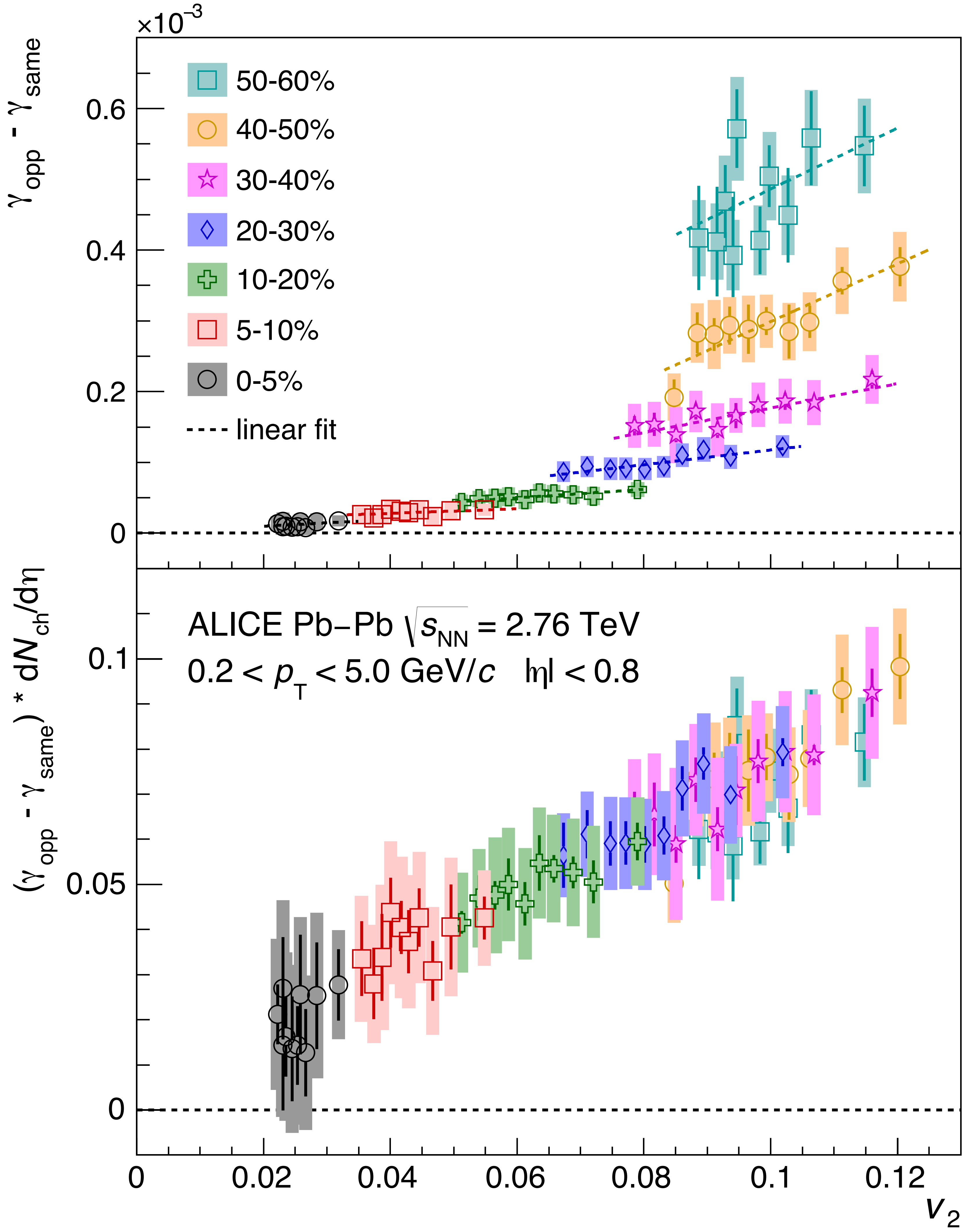
- Events with the desired initial spatial anisotropy (or v_2) can be experimentally selected by q_2
  - ✓ Help to disentangle eccentricity and v_2 related backgrounds from the potential CME signal

γ_{112} and δ_{11} after ESE



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

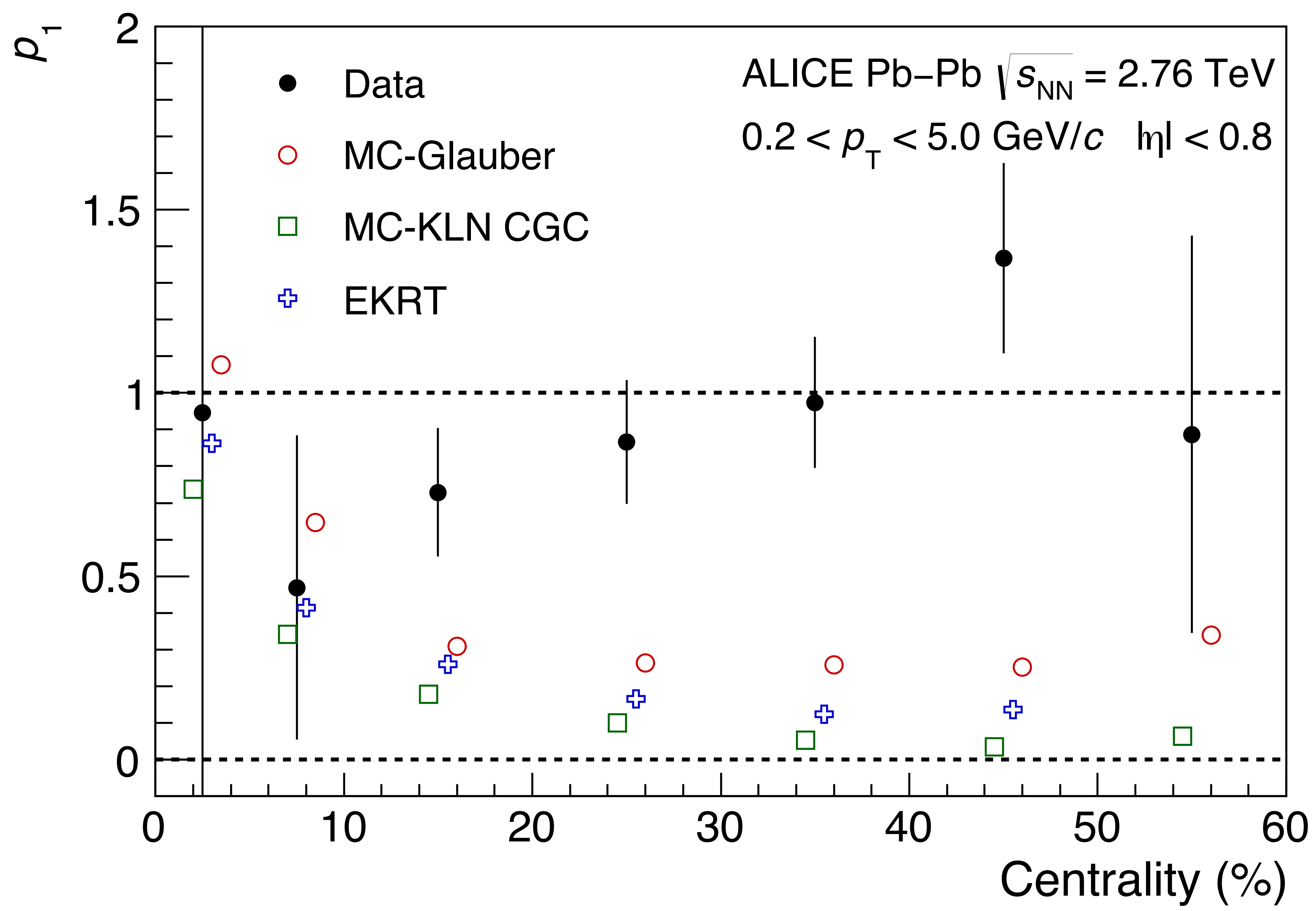
$\Delta\gamma_{112}$ after ESE

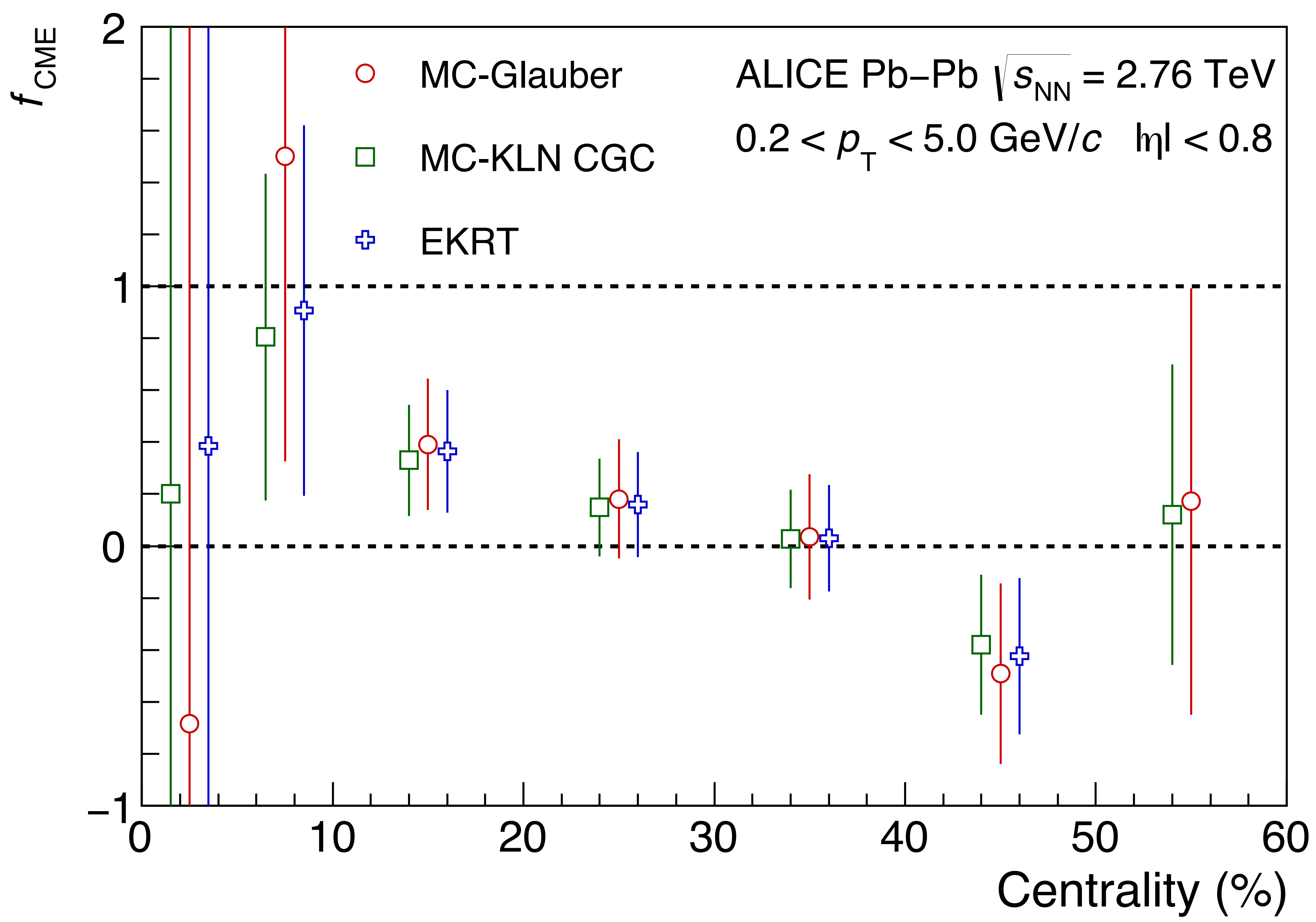


- $\Delta\gamma_{112}$ is positive for all centralities
- The magnitude decreases for more central collisions and with decreasing v_2 (in a given centrality bin)
- After scaling by $dN_{ch}/d\eta$, $\Delta\gamma_{112}$ is approximately proportional to v_2

- 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





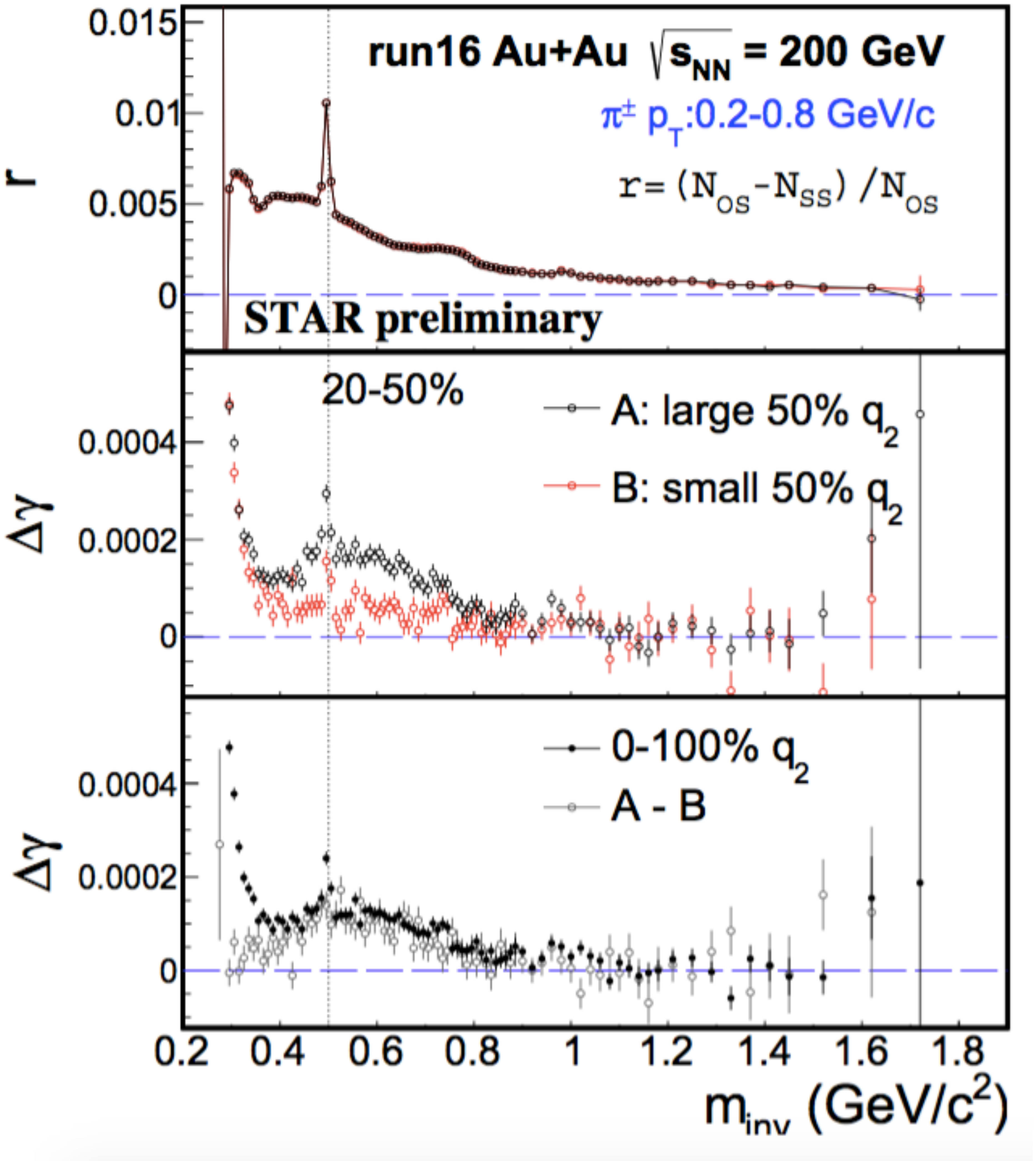
$F_1(v_2) = p_0 (1 + p_1 (v_2 - \langle v_2 \rangle)/\langle v_2 \rangle)$ to fit both data and model

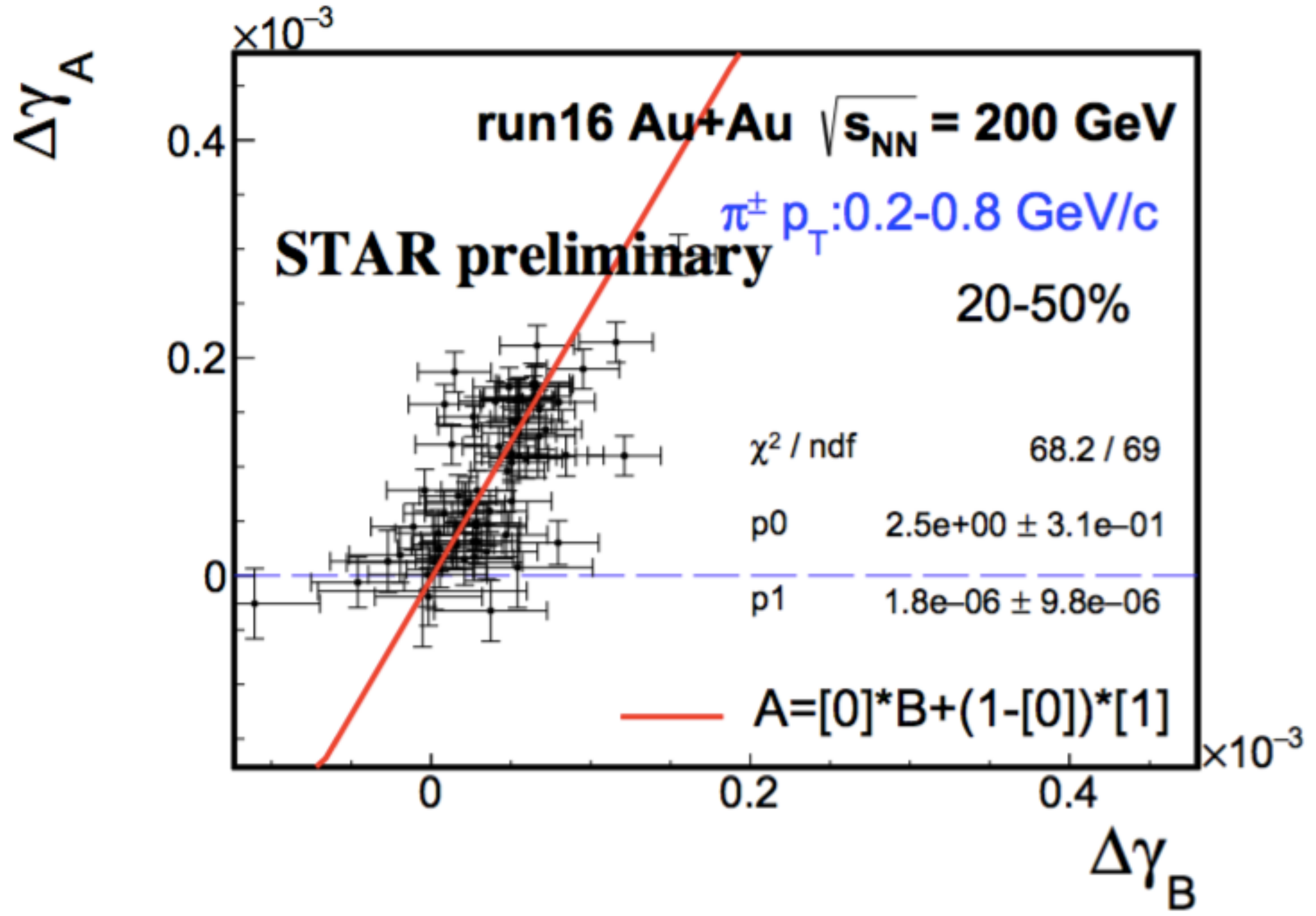
$f_{CME} \times p_{1,MC} + (1 - f_{CME}) \times 1 = p_{1,data}$ ➔ $f_{CME} = \Delta\gamma^{CME} / (\Delta\gamma^{CME} + \Delta\gamma^{Bkg})$

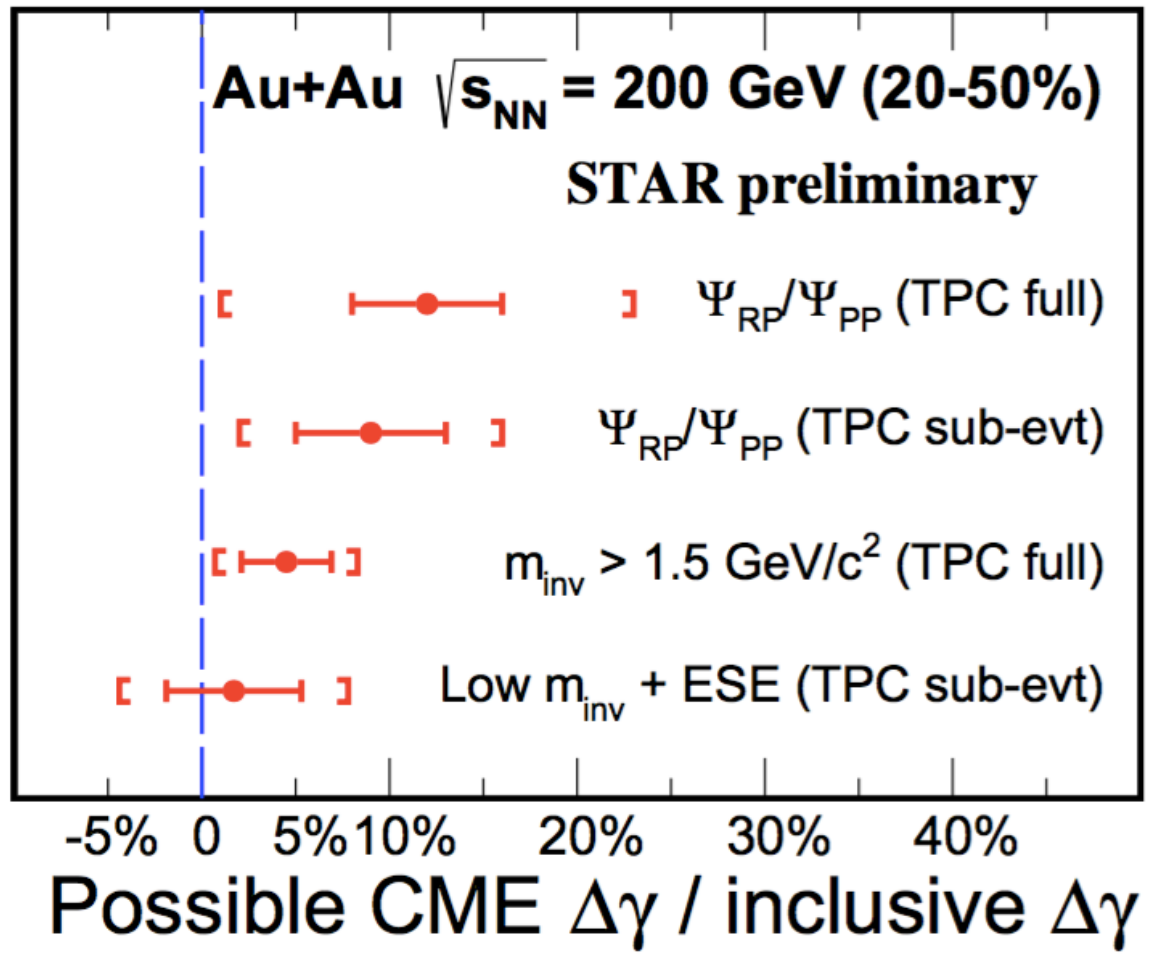
At semi-central collisions (10–50%) f_{CME} ~26% - 33% at 95% C.L.

More checks on background – Invariant mass

Nuclear Physics A 982, 535 (2019).







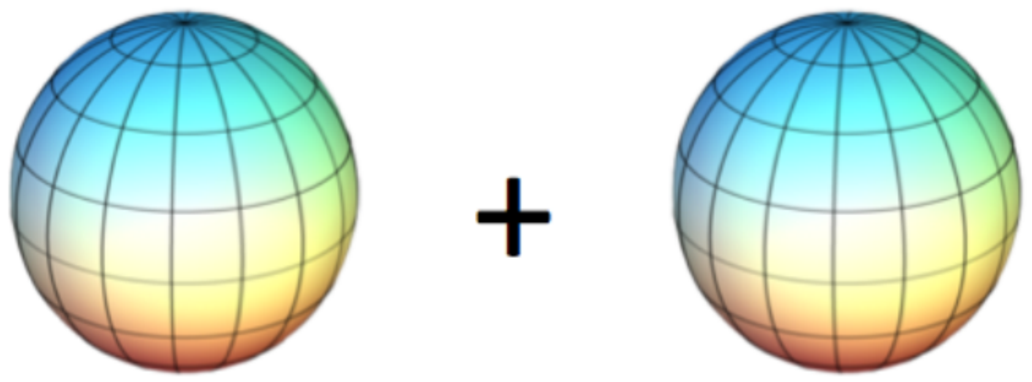
Charge separation measurements by the γ_{112} are contaminated by major backgrounds arising from resonance decay correlations coupled with the elliptical anisotropy

Current knowledge of CME

- γ correlator has been used to investigate charge separation for a decade, and it's clear that the flow driven background can not be eliminated. Other possible backgrounds also exist.
- Different techniques have been tested by different experiments at various collision systems.
- Current consensus: CME component in $\gamma < 10\%$
- Important and urgent task: new observables

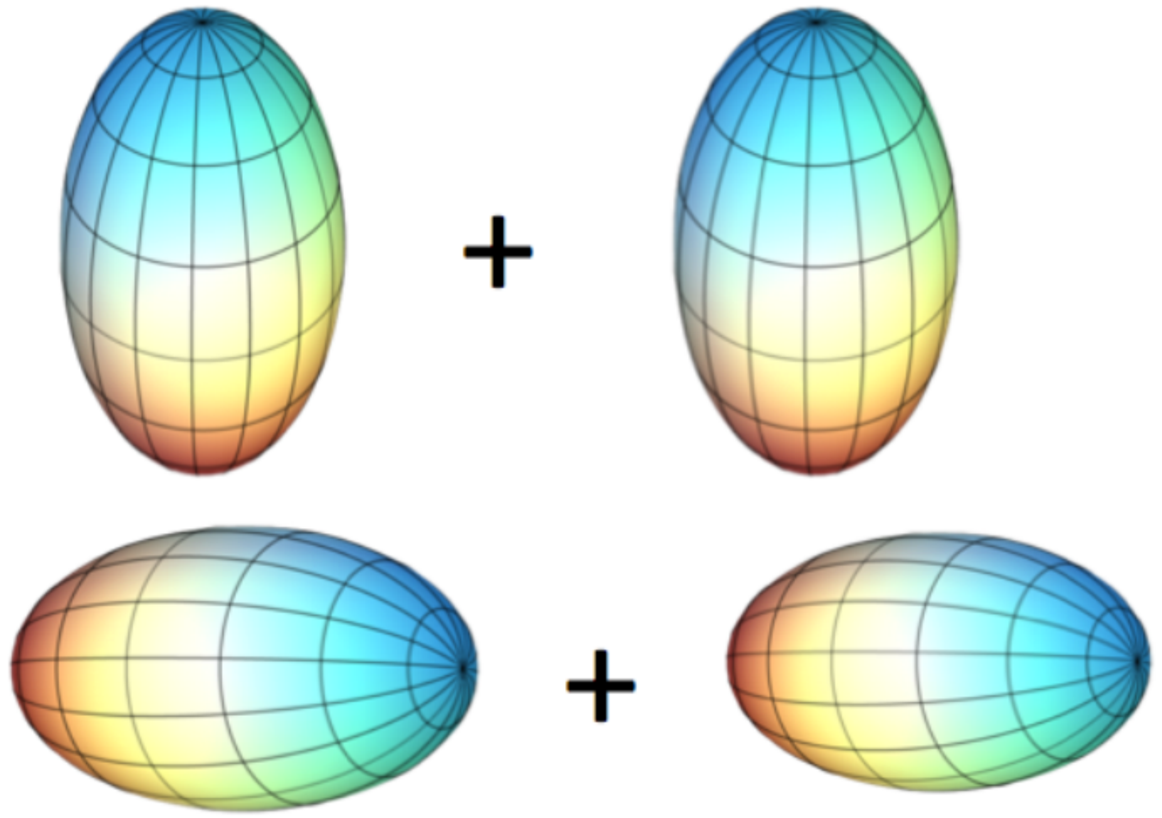
Beyond the observables

- Collisions of deformed nuclei



$^{197}_{79}\mathbf{Au}$

$^{208}_{82}\mathbf{Pb}$



RHIC 2012

$^{238}_{92}\mathbf{U}$

Finite v_2 + no B field
In most central collisions
(body-body)

- Isobars: different chemical elements that have the same number of nucleons. For example, $^{96}_{44}\mathbf{Ru}$ (Ruthenium) and $^{96}_{40}\mathbf{Zr}$ (Zirconium): up to 10% variation in B field

RHIC 2018

Observable	$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ vs $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$
Flow	$\approx$
CME	$>$
CMW	$>$
CVE	$\approx$

Experimental measurement of CMW

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

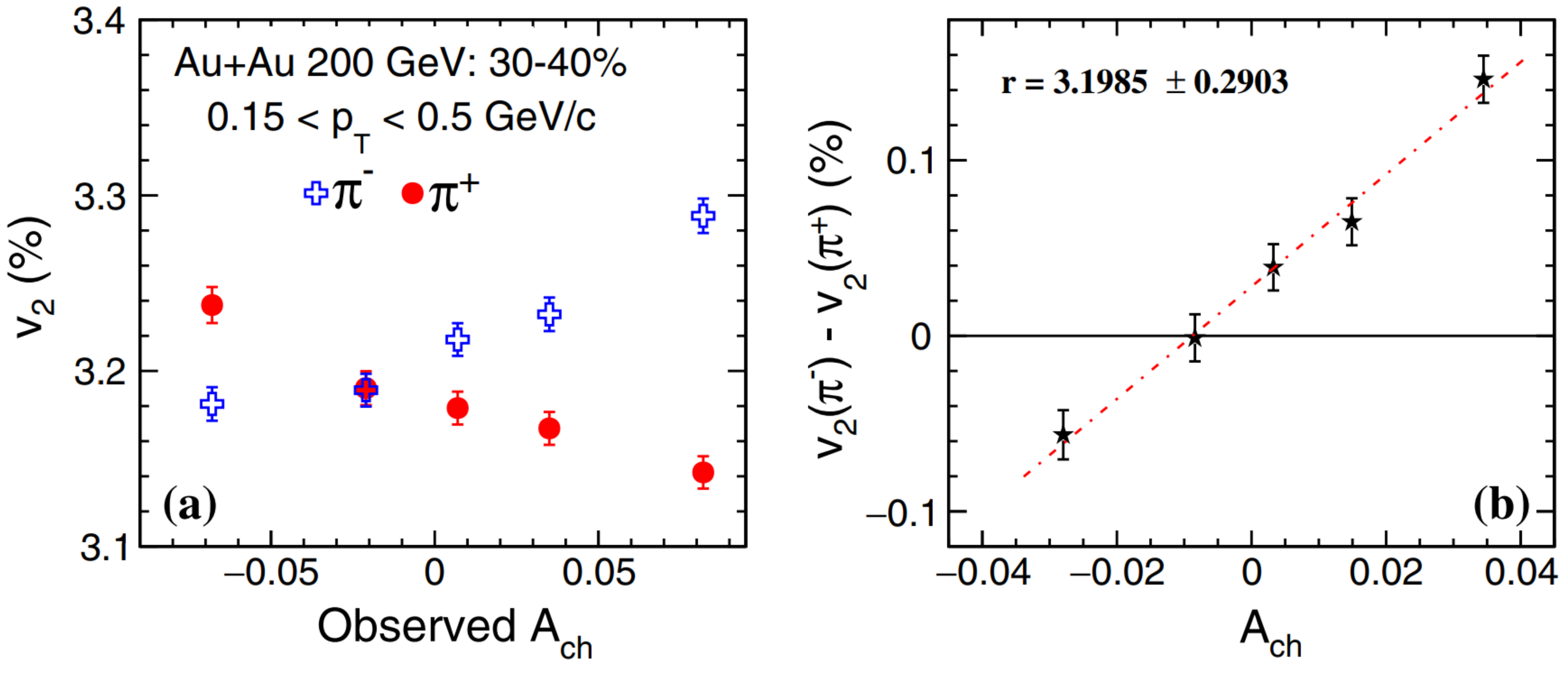
- Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at √sN N = 2.76 TeV
  ALICE Collaboration, Phys. Rev. C 93, 044903 (2016).

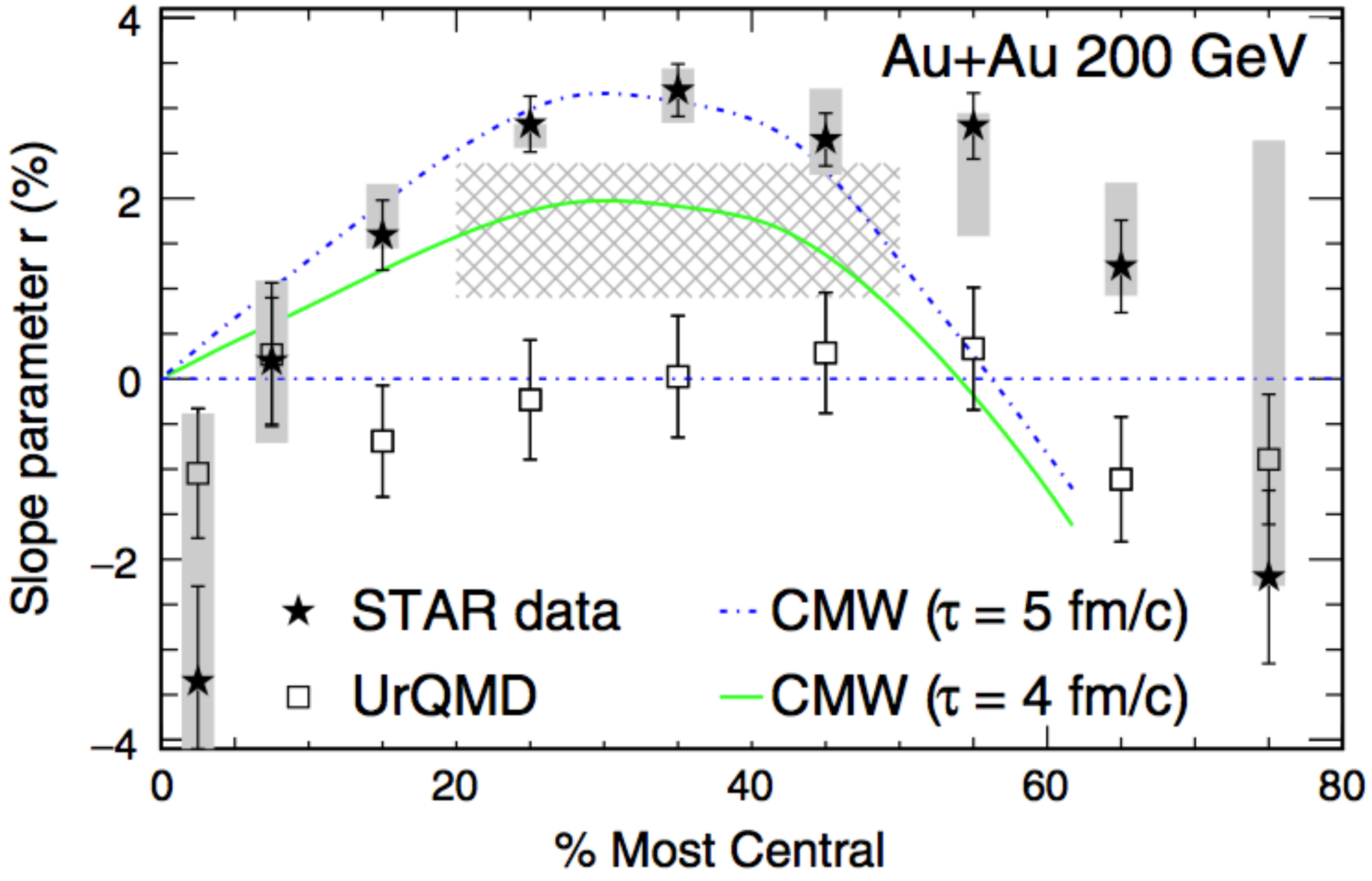
- Challenges to the chiral magnetic wave using charge-dependent azimuthal anisotropies in pPb and PbPb collisions at psNN = 5.02 TeV
  CMS Collaboration, ArXiv:1708.08901 [Nucl-Ex] (2017).

Measurement at RHIC-STAR

$$\frac{dN_\pm}{d\phi} = N_\pm[1 + 2v_2\cos(2\phi)]$$
$$\approx \bar{N}_\pm[1 + 2v_2\cos(2\phi) \mp A_\pm r\cos(2\phi)]$$

$$\Delta v_2 = v_2^- - v_2^+ \approx r A$$



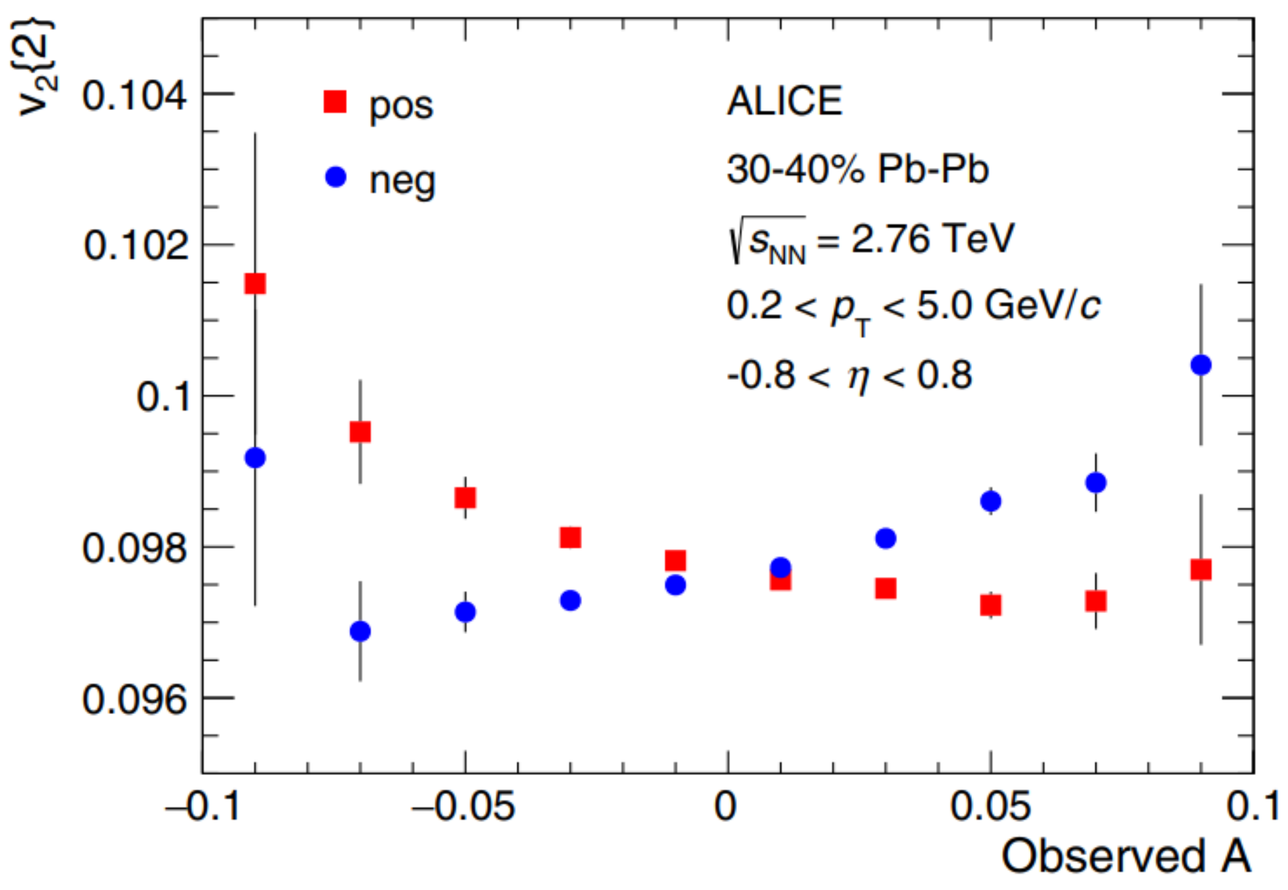


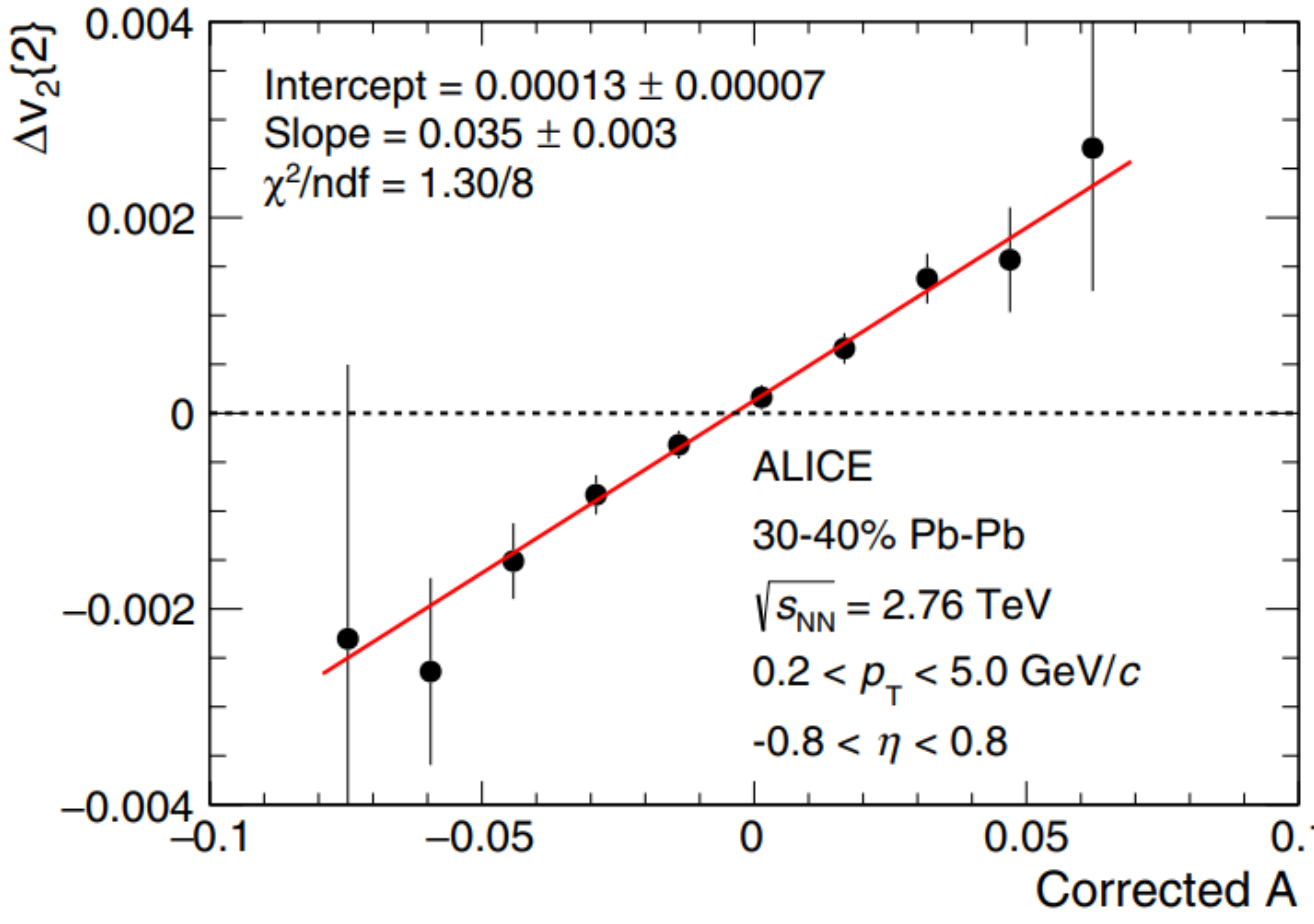
The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation

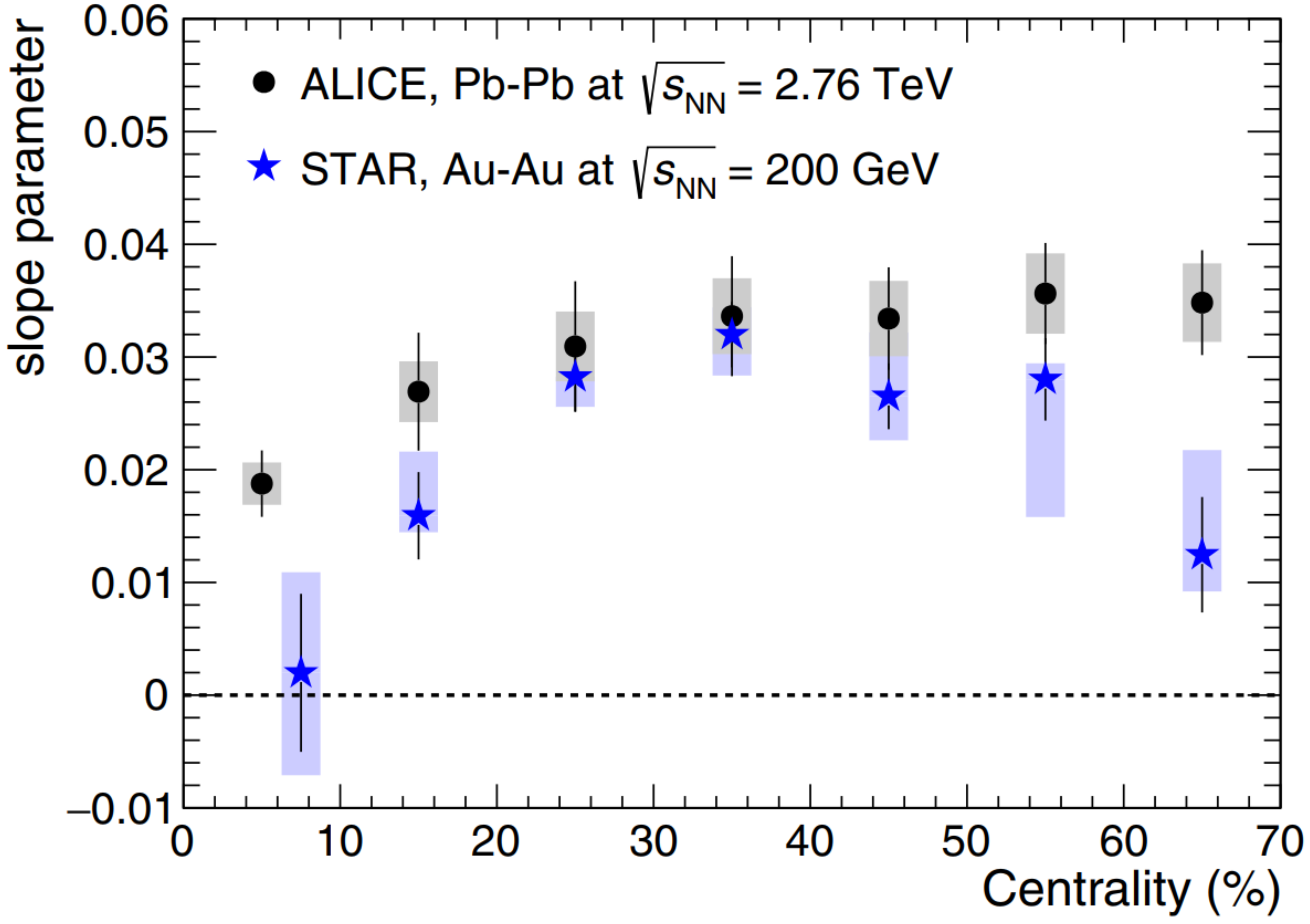
Measurement at LHC-ALICE

$$\frac{dN_\pm}{d\phi} = N_\pm[1 + 2v_2\cos(2\phi)]$$
$$\approx \bar{N}_\pm[1 + 2v_2\cos(2\phi) \mp A_\pm r\cos(2\phi)]$$

$$\Delta v_2 = v_2^- - v_2^+ \approx r A$$



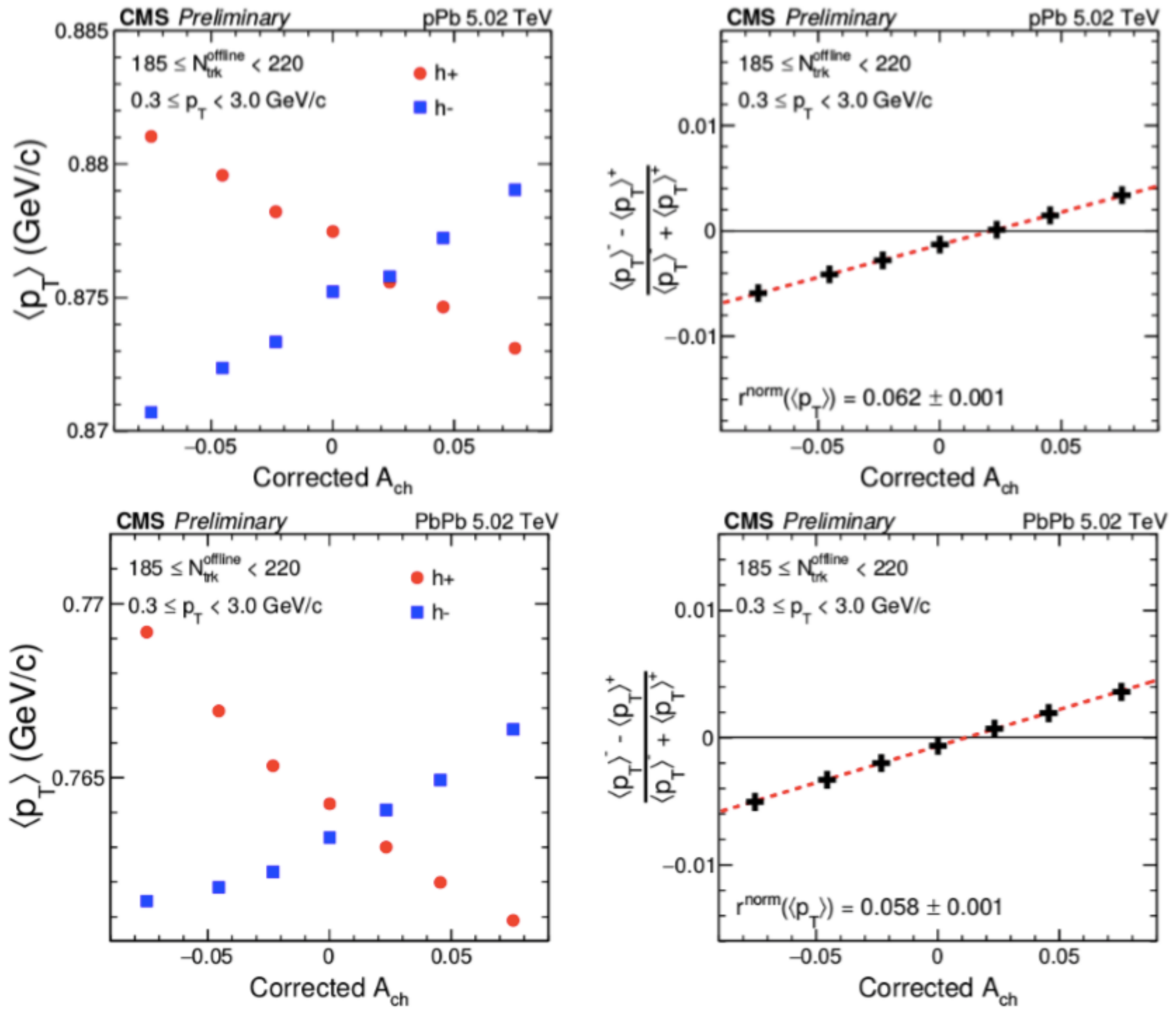


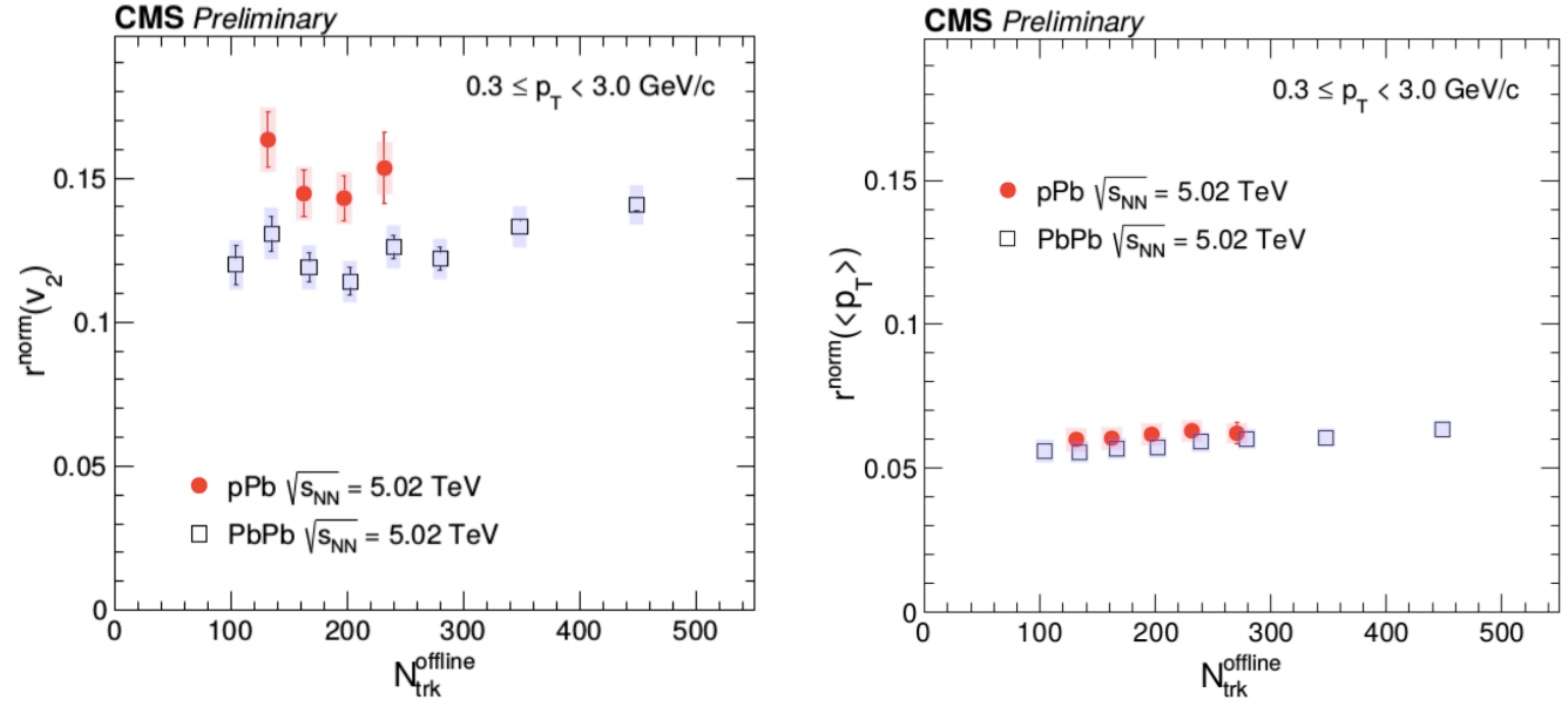


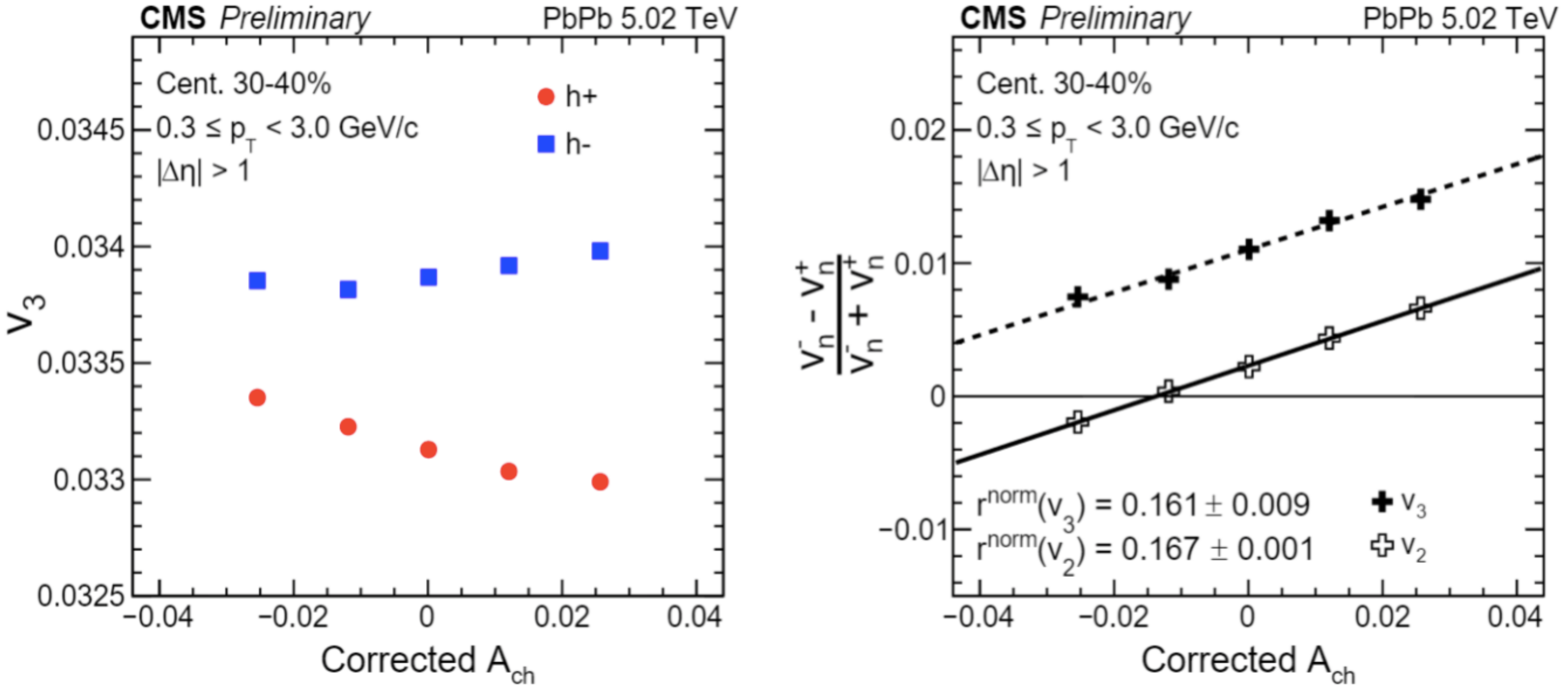
The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation

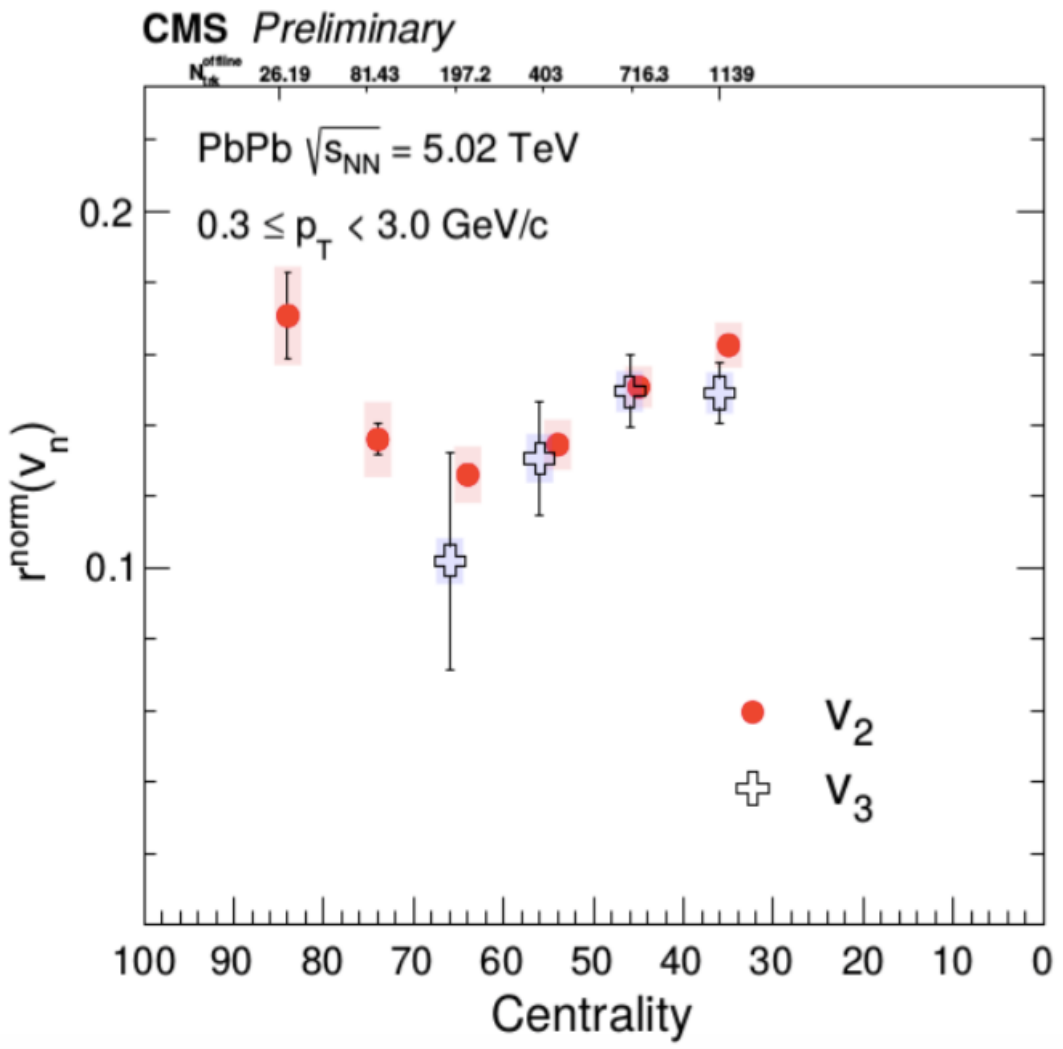
Challenge (again!) from small system collisions

$V_{2,3} \sim p_T \sim A_{ch}$









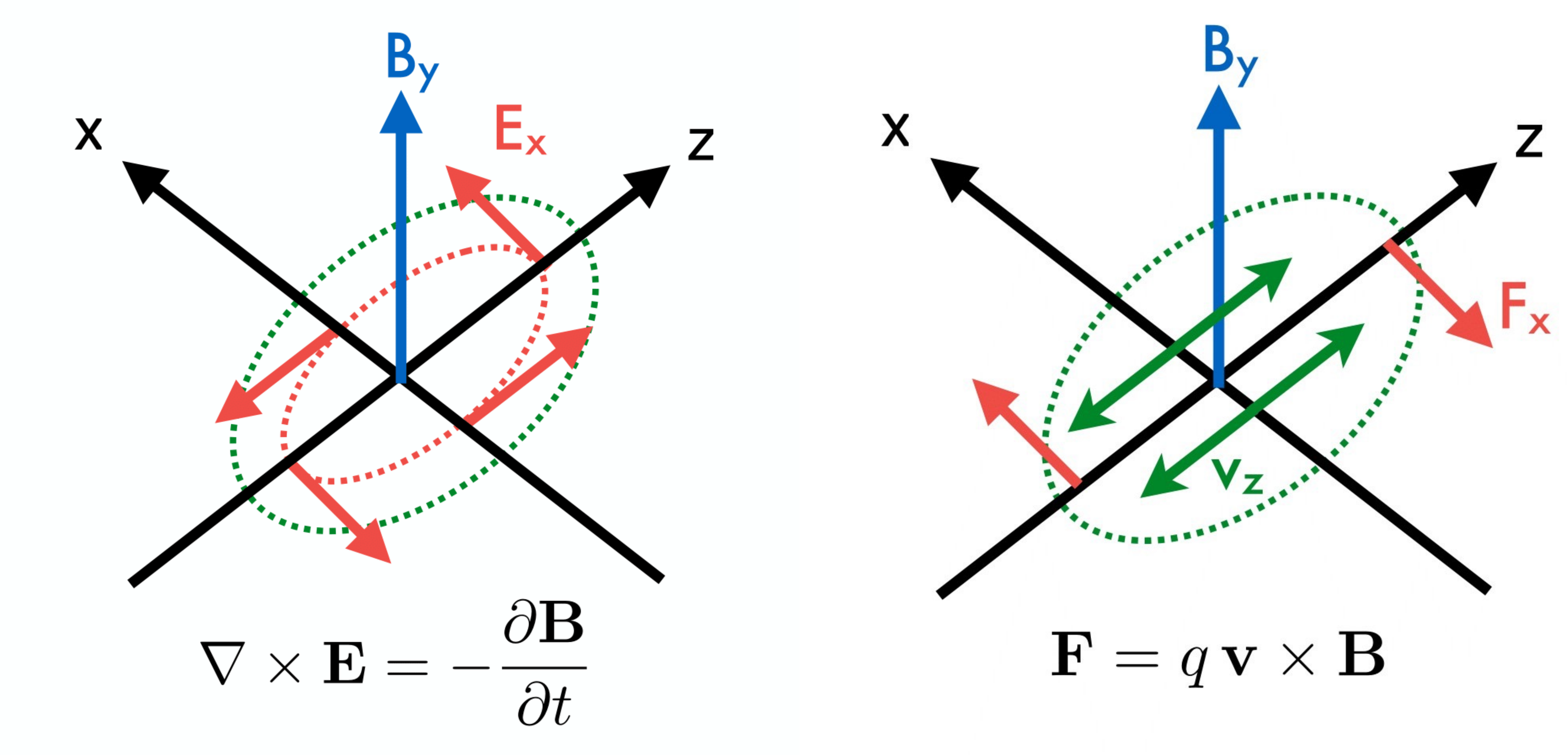
Strikingly similar behavior, indicating a common background that generates the observed correlation and challenging the CMW interpretation

Current knowledge of CMW

- CMW couldn't exist alone without CME, however, the observables are quite different
- Important and urgent task: how to understand the background, new observables

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)

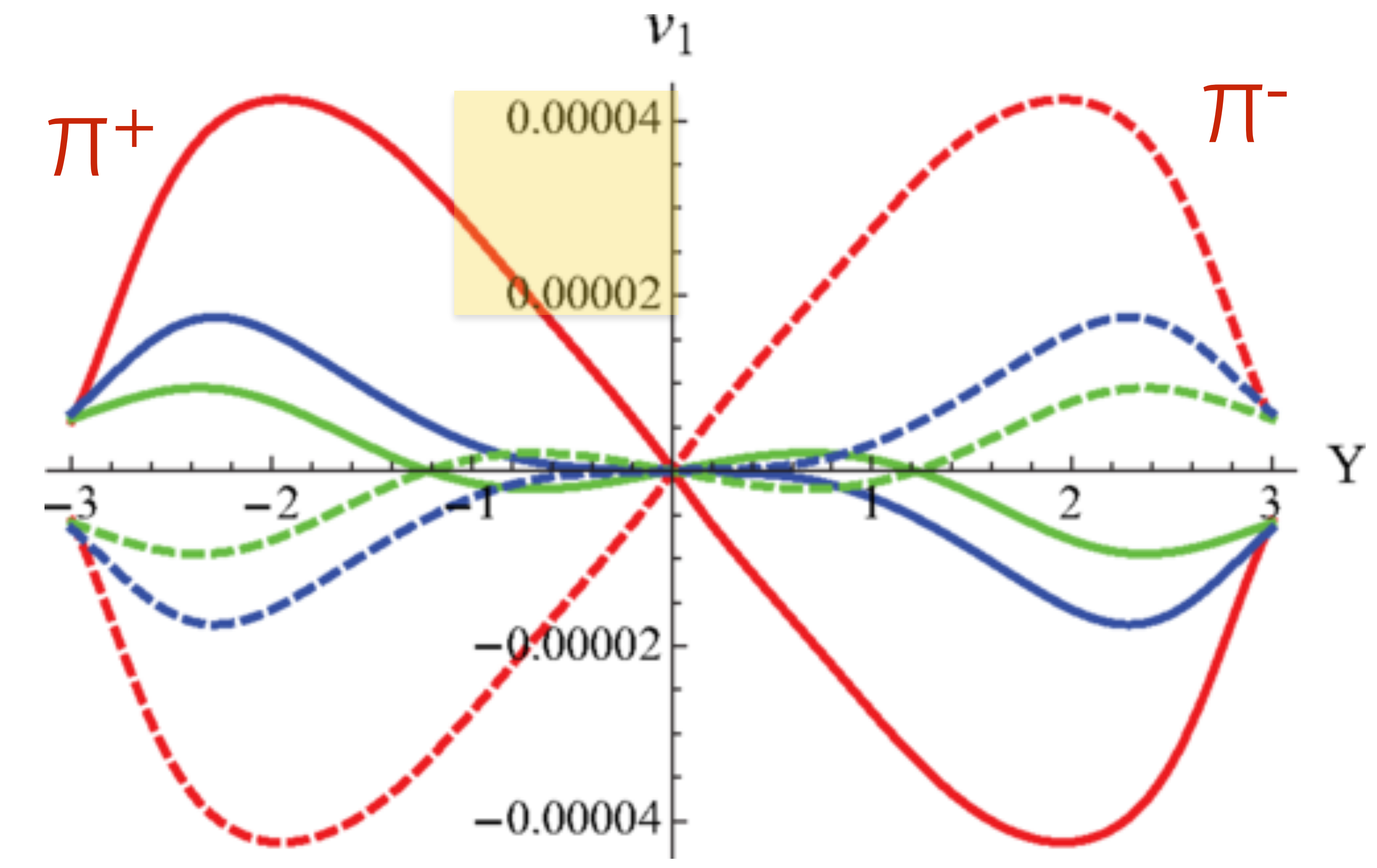


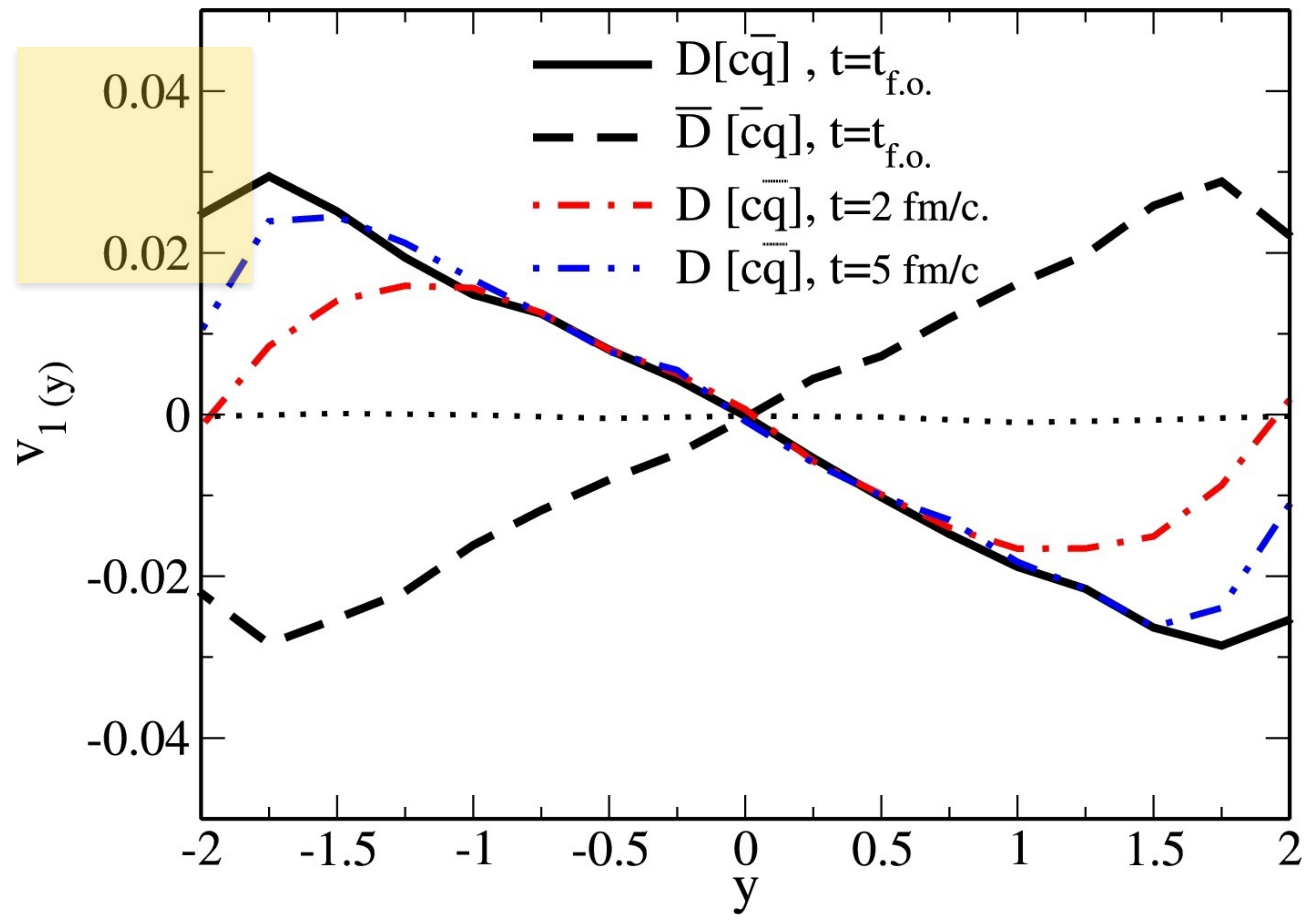
- Charged currents owing to the combination of
  - ✓ Electric field induced by decreasing B (Faraday effect)
  - ✓ Lorentz force on moving charges (Hall effect)

- 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



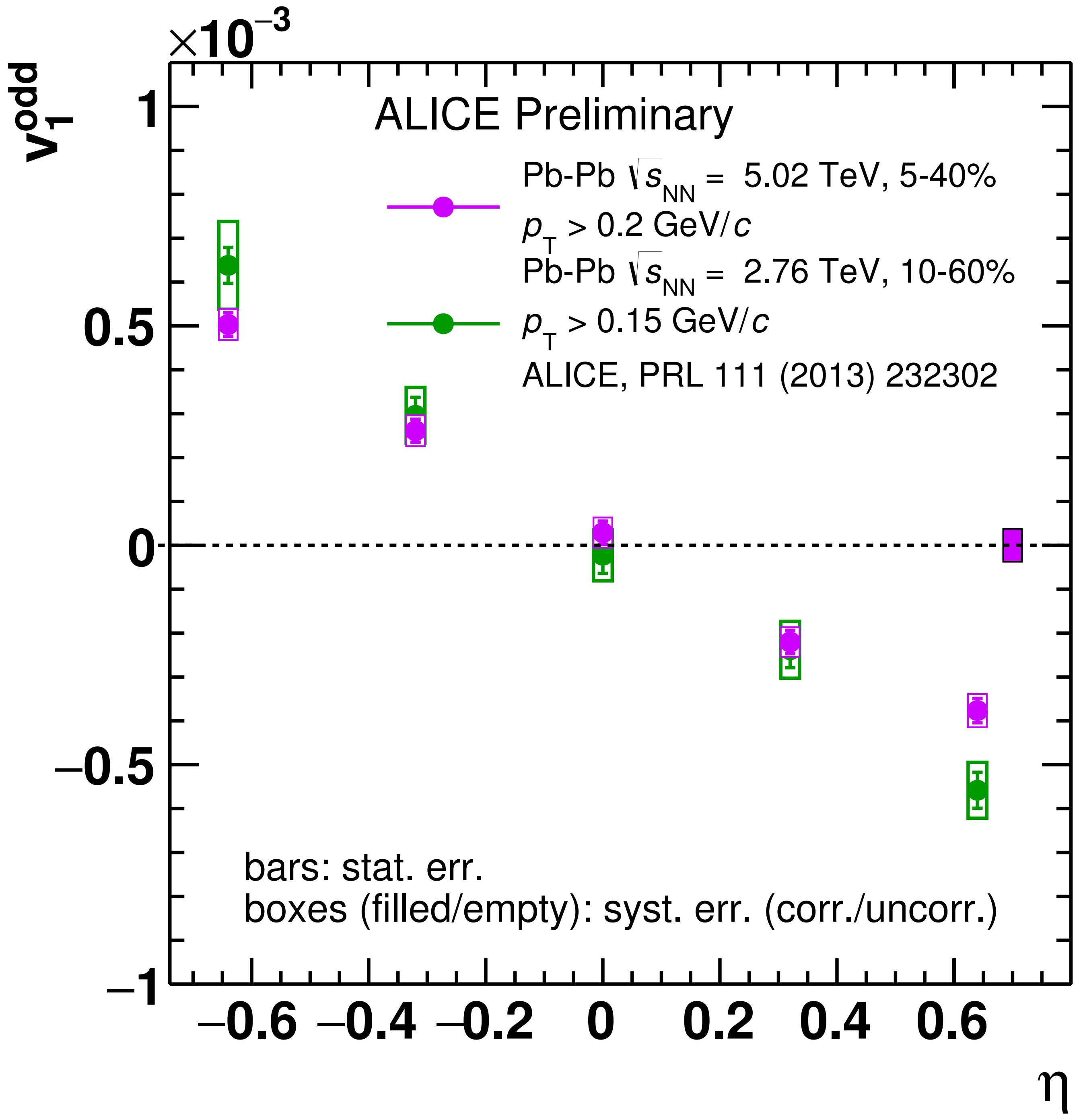


Phys. Rev. C 89, 054905 (2014).
Phys. Lett. B 768, 260 (2017).

- 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

Charge dependence v_1 of charged hadrons at 5.02 TeV



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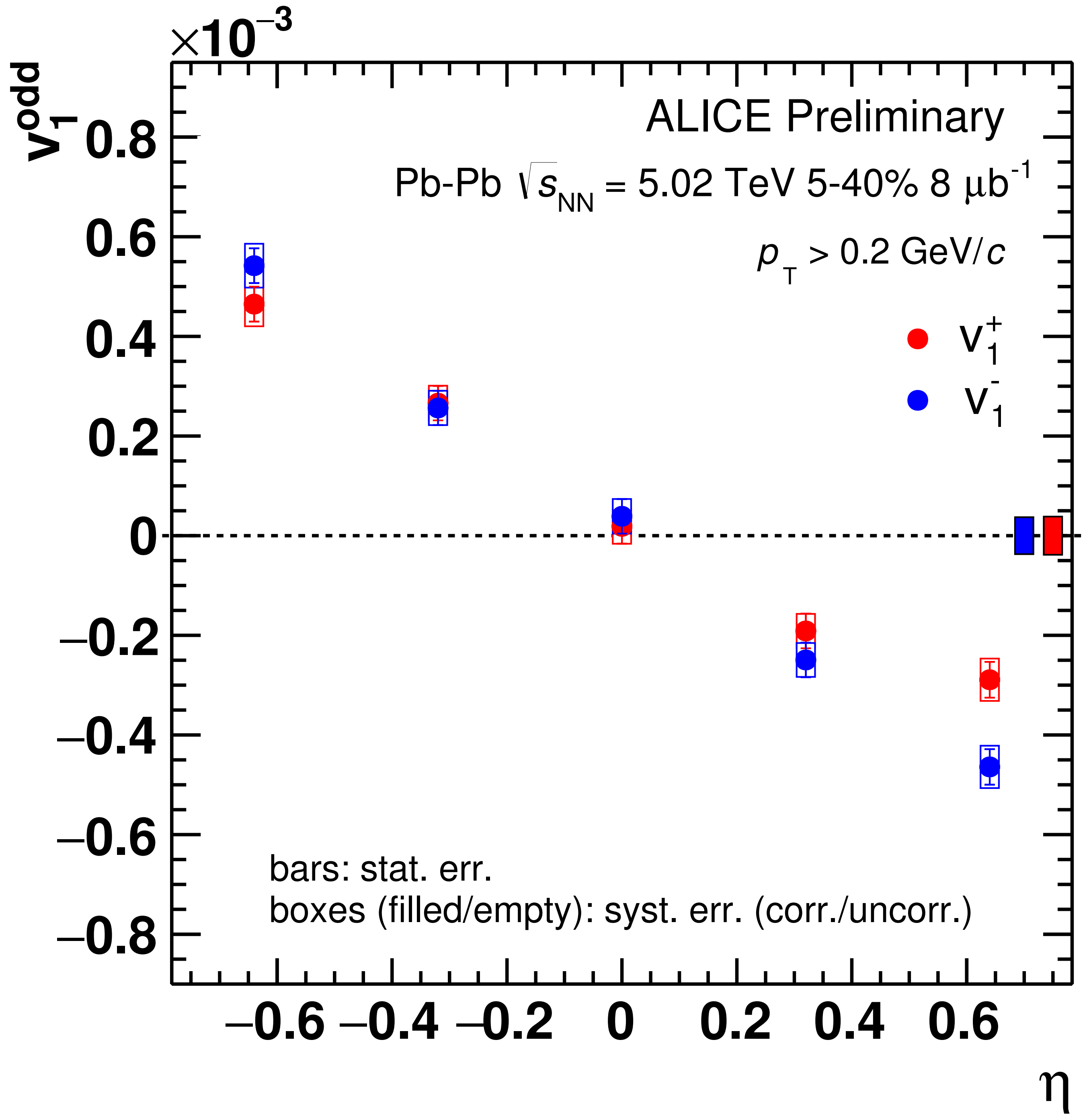
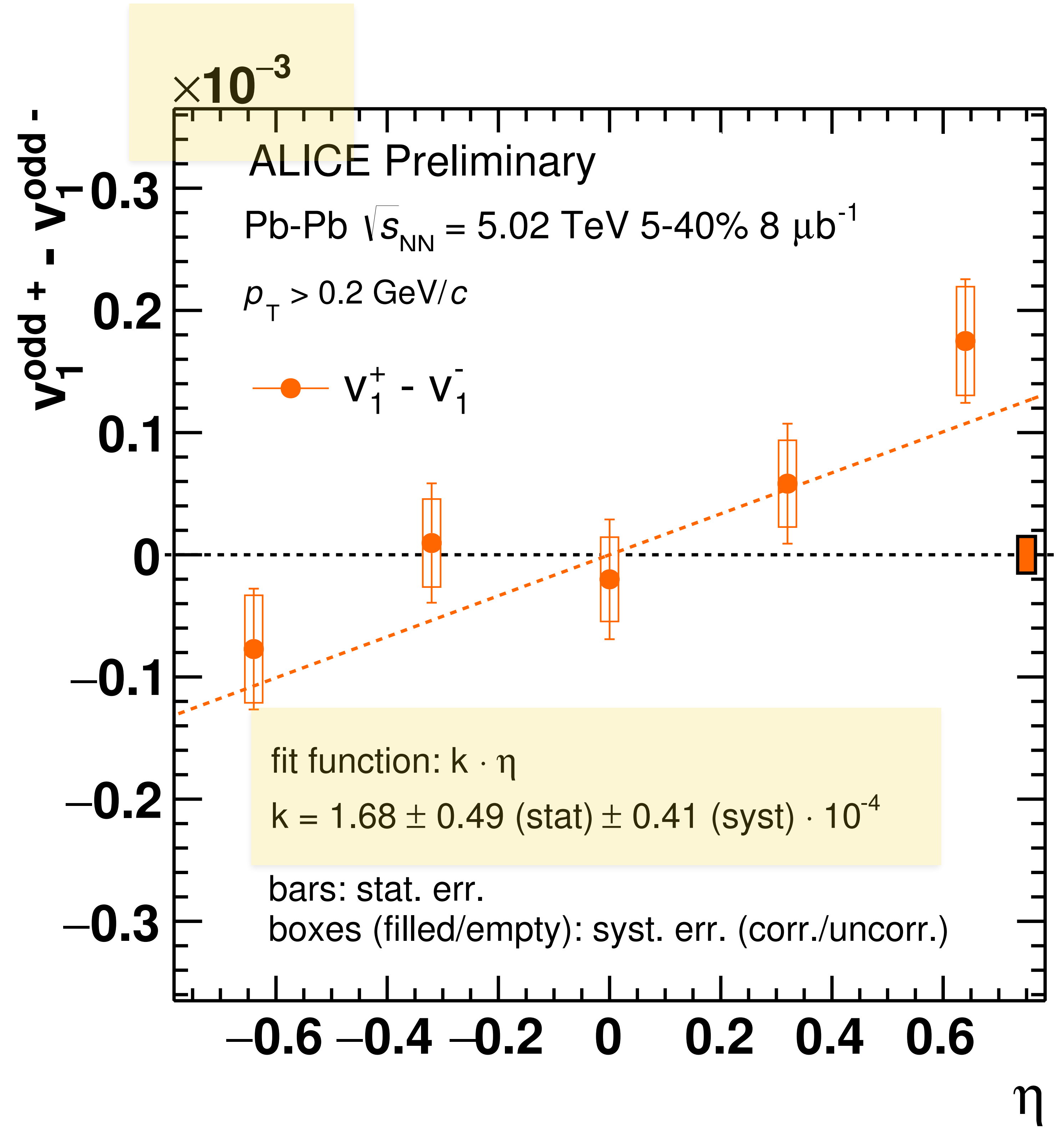


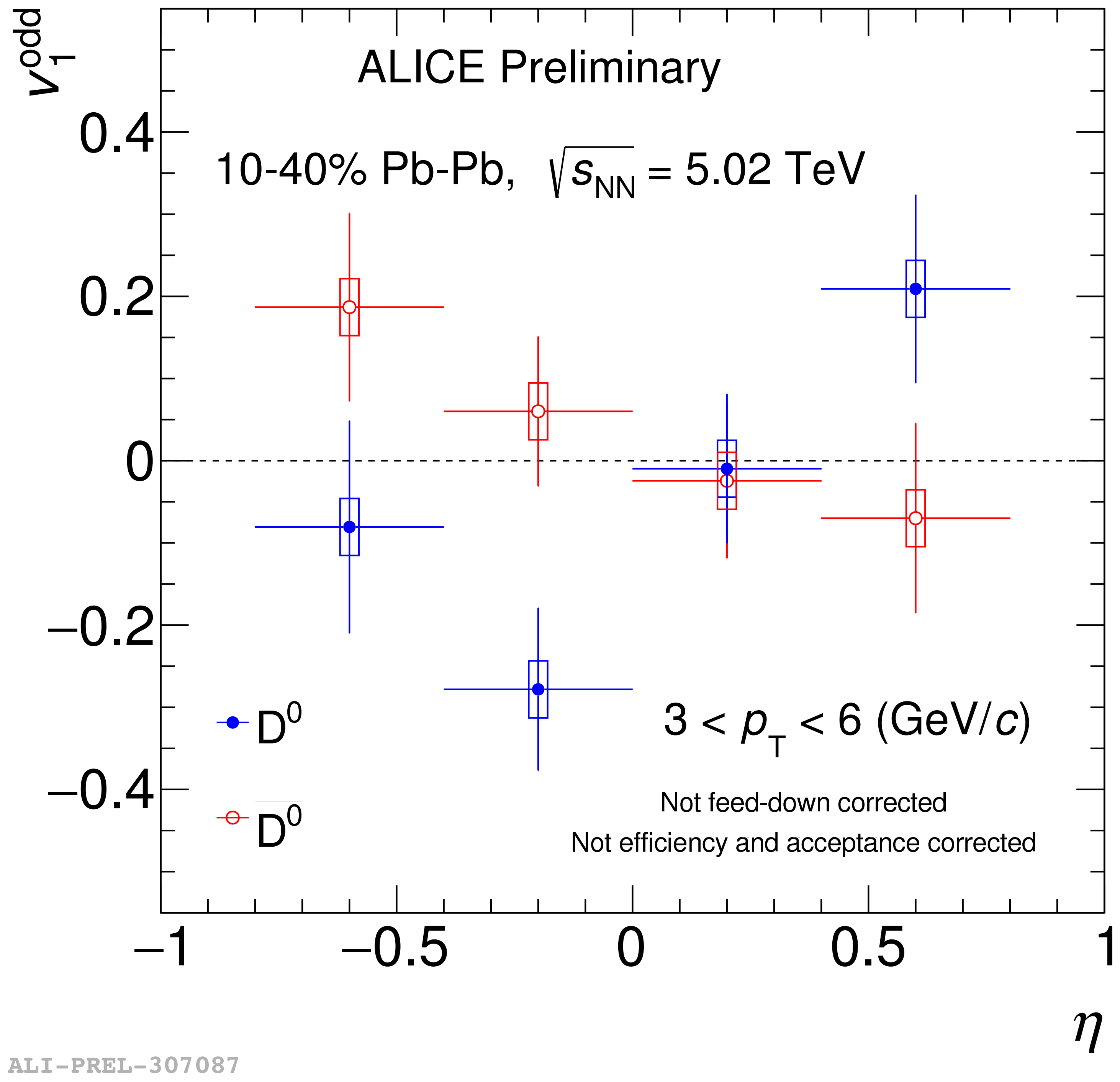
ALI-PREL-129681

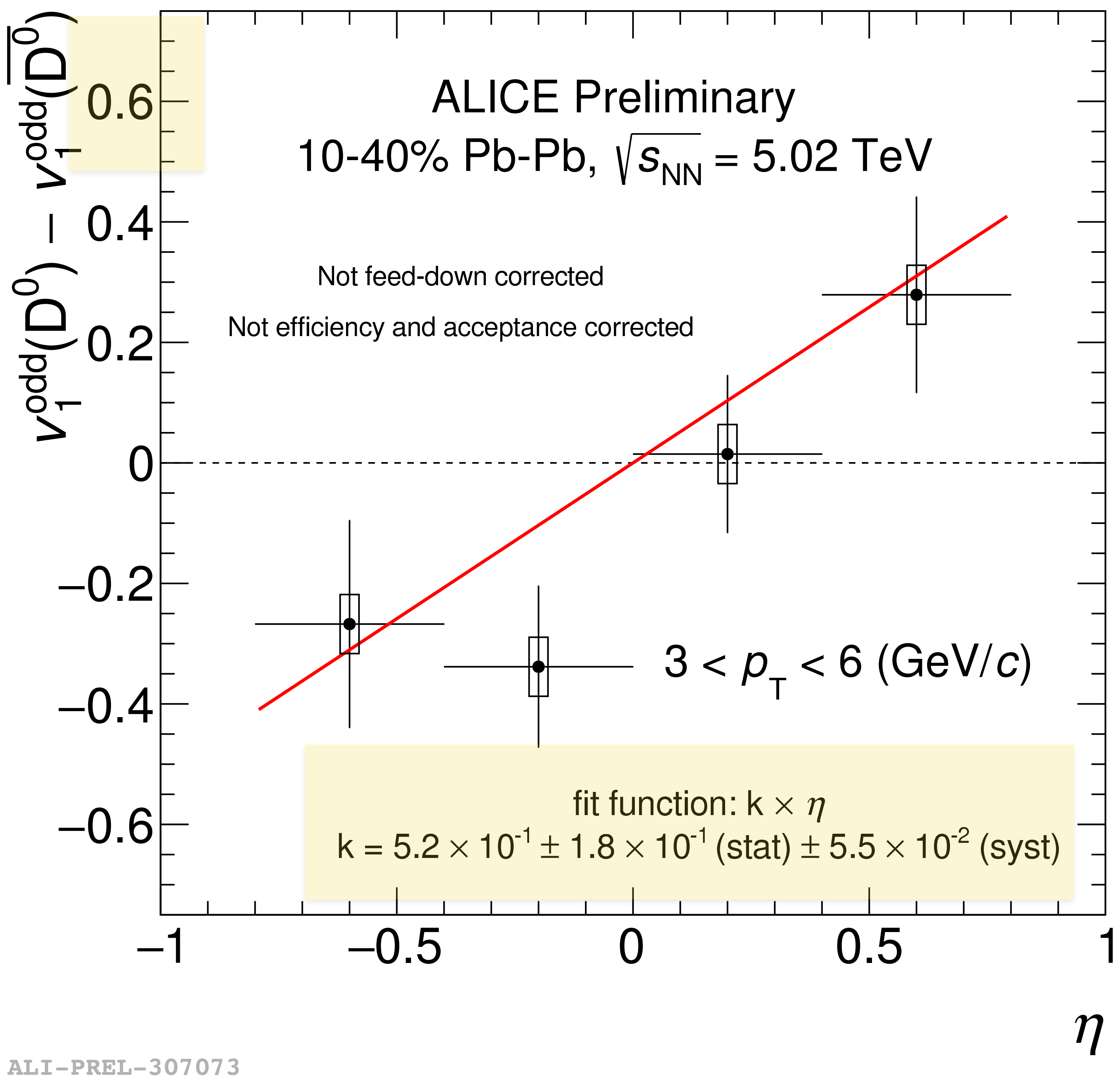


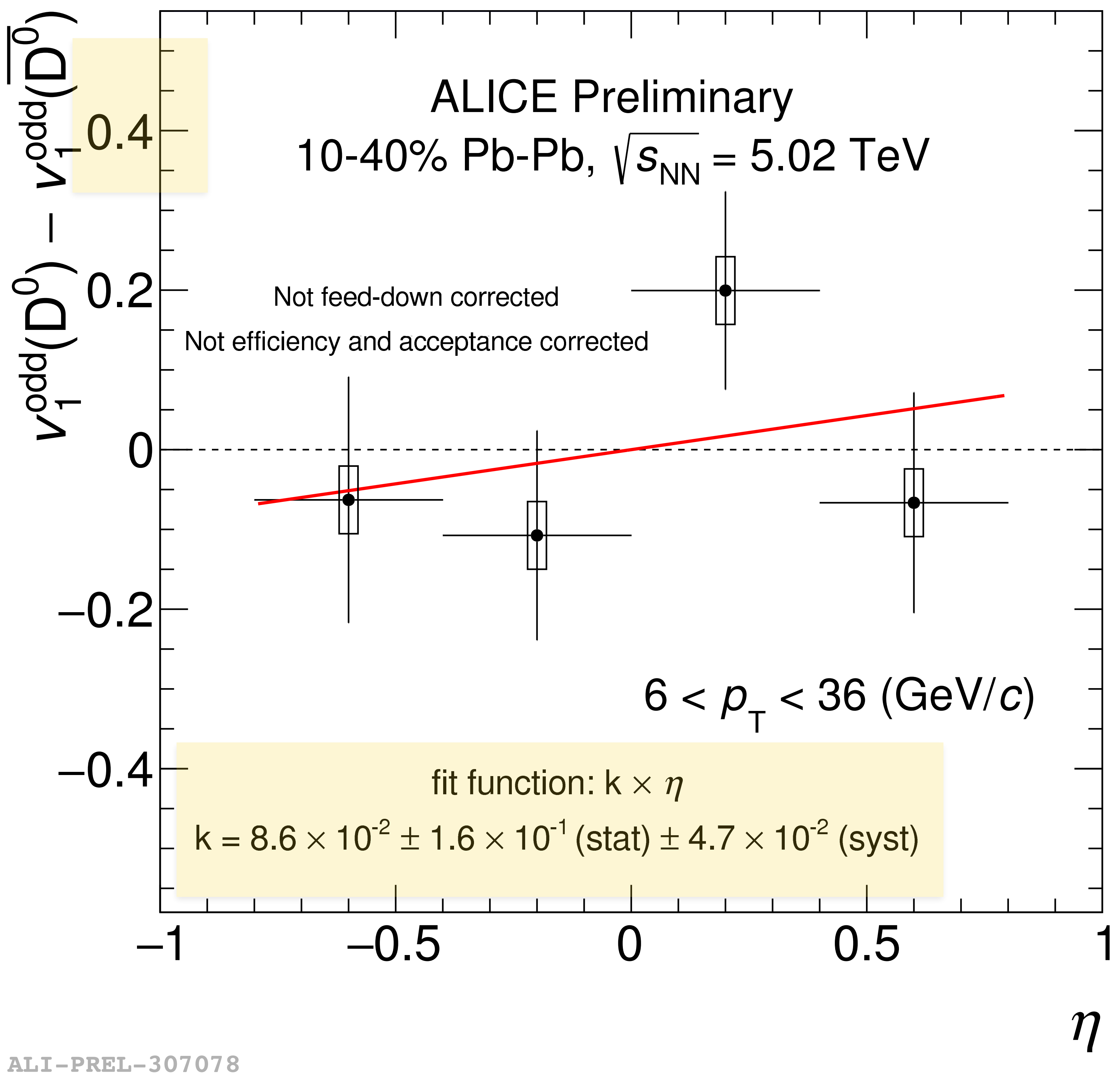
ALI-PREL-129689

- 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

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

- How can we experimentally detect the intense electromagnetic field?
- How can we correctly capture the signal of the anomalous chiral effects, if they exist in QGP?
- 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!