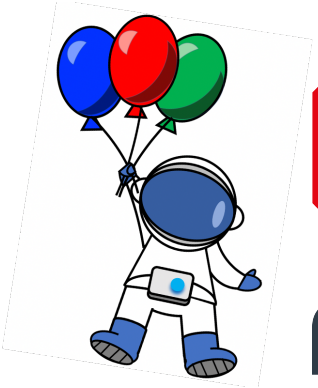
Search for anomalous chiral effects in heavy-ion collisions with ALICE

Chunzheng Wang (for the ALICE Collaboration)

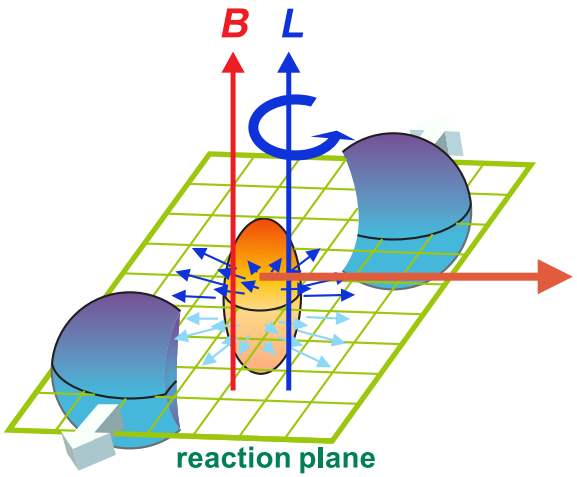
Fudan University, Sept 5, 2023



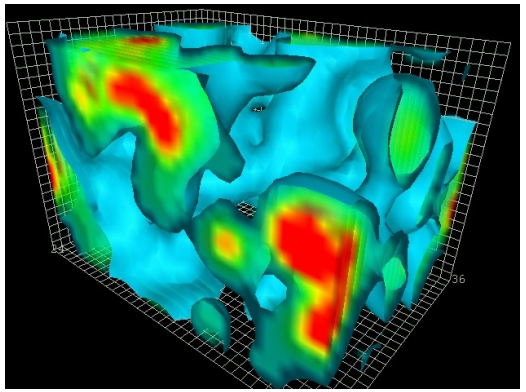
ALICE

FUDAN UNIVERSITY

Anomalous chiral effects in the heavy-ion collisions



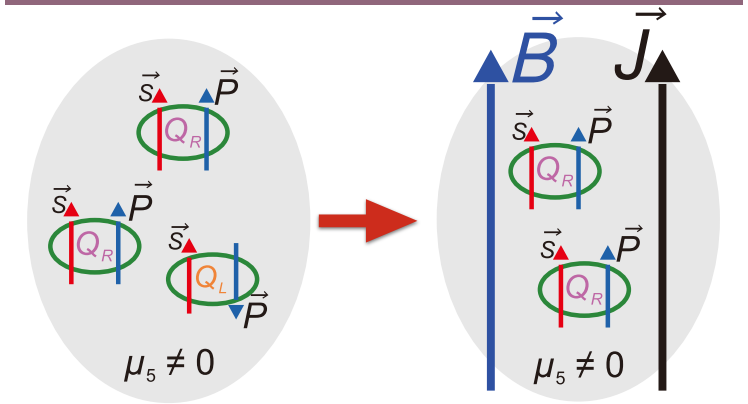
Extremely strong magnetic/vortical field



Credit to Derek B. Leinweber

Chiral symmetry restoration
Non-trivial QCD vacuum

Chiral Magnetic Effect (CME)



Chirality imbalance → Current parallel to the field

$\vec{B}$ → **Chiral Magnetic Effect (CME)**

$$J_V^{\mathrm{CME}} = \frac{\mu_A}{2\pi^2} e\vec{B}$$

$\vec{B}$ → **Chiral Separation Effect (CSE)**

$$J_A^{\mathrm{CSE}} = \frac{\mu_V}{2\pi^2} e\vec{B}$$

→ **Chiral Magnetic Wave (CMW)**

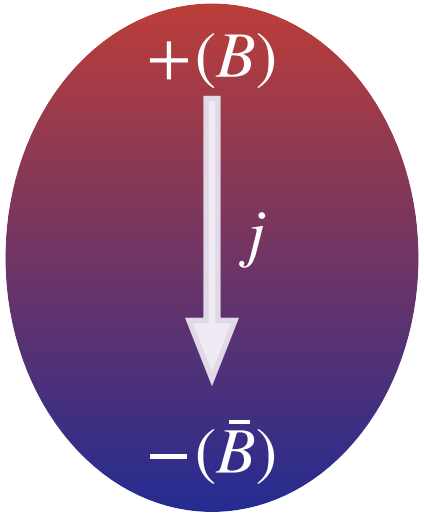
$\vec{\omega}$ → **Chiral Vortical Effect (CVE)**

$$J_V^{\mathrm{CVE}} = \frac{\mu_V \mu_A}{\pi^2} \vec{\omega}$$

- **Local CP/P violation in QCD?**
- **Structure of the QCD vacuum?**

D. Kharzeev, PLB 633, 260 (2006); D. Kharzeev et al., NPA 803, 227 (2008);
K. Fukushima et al., PRD 78, 074033 (2008);
D. Son et al., PRL 103, 191601 (2009); Y. Burnier et al., PRL 107, 052303 (2011);
D. Kharzeev, PRL 106, 062301 (2011); D. Kharzeev et al., PRD 83, 085007 (2011);
D. Kharzeev, PPNP 88, 1 (2016); D. Kharzeev et al., NRP 3, 1 (2021).

Observables of CME/CVE



CME/CVE

Electric/baryonic **Dipole**

Charge/baryon splitting along the reaction plane

S. Voloshin, PRC 70, 057901 (2004)

Observables of CME/CVE

γ correlator:

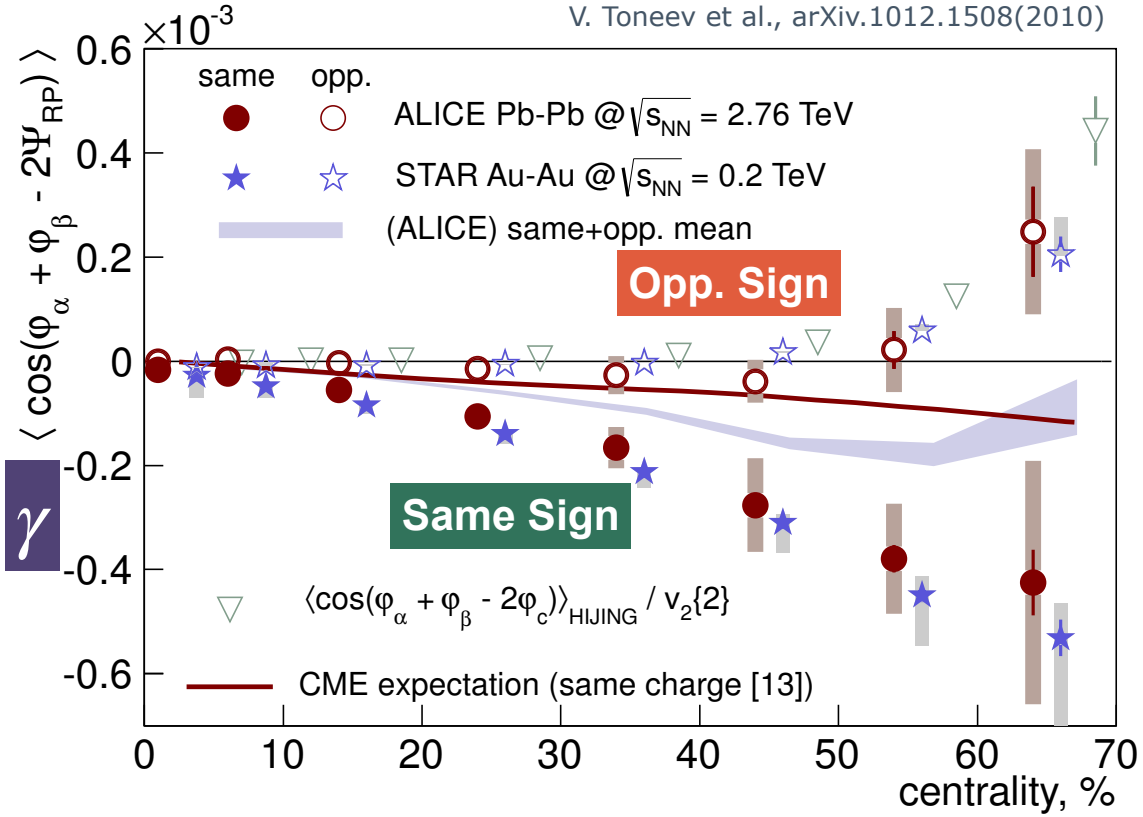
$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle,\ \Delta\gamma = \gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}}$$

δ correlator:

$$\delta = \langle \cos(\phi_\alpha - \phi_\beta) \rangle,\ \Delta\delta = \delta_{\mathrm{OS}} - \delta_{\mathrm{SS}}$$

CME: α, $\beta \rightarrow$ charged hadrons; CVE: α, $\beta \rightarrow$ baryons

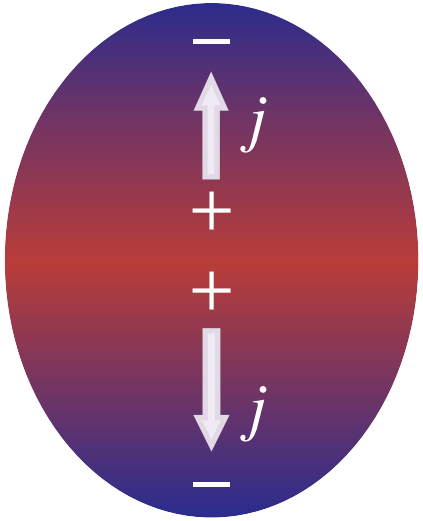
STAR, PRL 103, 251601 (2009)
ALICE, PRL 110, 012301 (2013)
V. Toneev et al., arXiv.1012.1508(2010)



- There is a significant distinction of γ between opposite sign and same sign, which is in line with CME theoretical predictions.

All CME Signal?

Observables of CMW



CMW

Electric **Quadrupole**

Charge asymmetry dependent v_2

S. Voloshin et al., NPA 931, 992 (2014)

Observables of CMW

Slope r of $\Delta v_2^{\mp}$ vs. A:

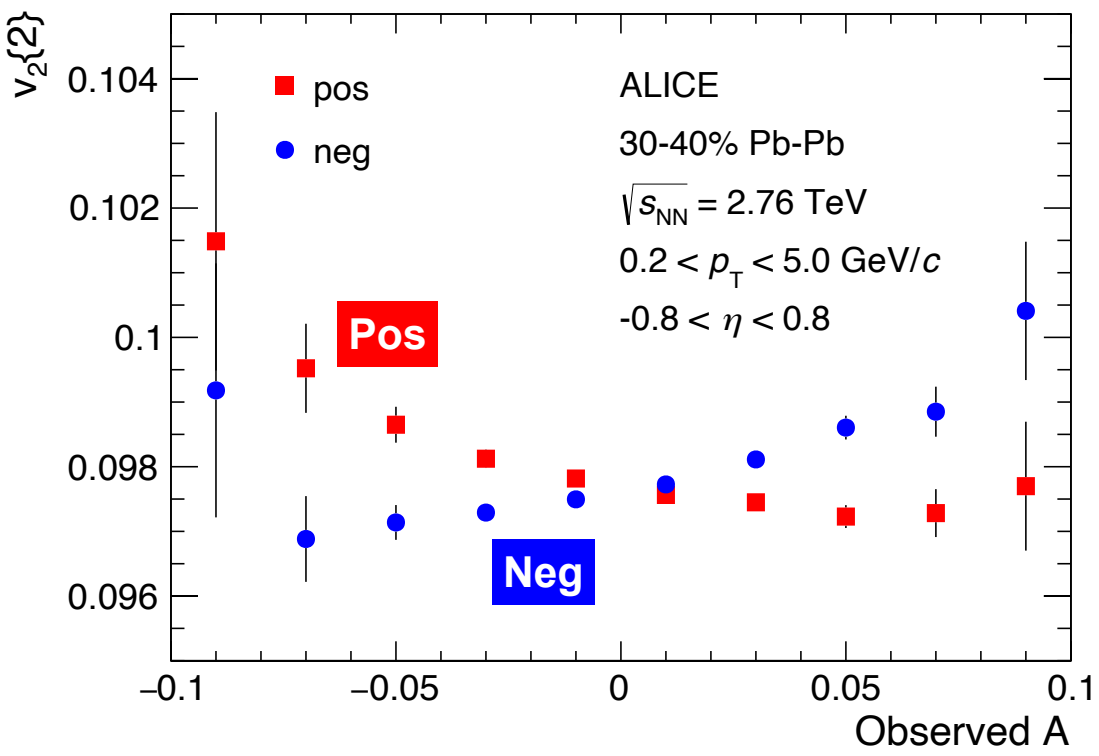
$$\Delta v_2^{\mp} = v_2^{-} - v_2^{+} = rA$$

Integral covariance between $v_2^{\pm}$ and A:

$$\langle v_2^{\pm} A \rangle - \langle v_2 \rangle \langle A \rangle$$

Charge asymmetry $A = (N^{+} - N^{-})/(N^{+} + N^{-})$

ALICE, PRC 93, 044903 (2016)

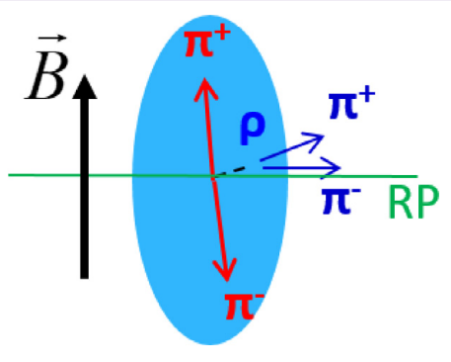


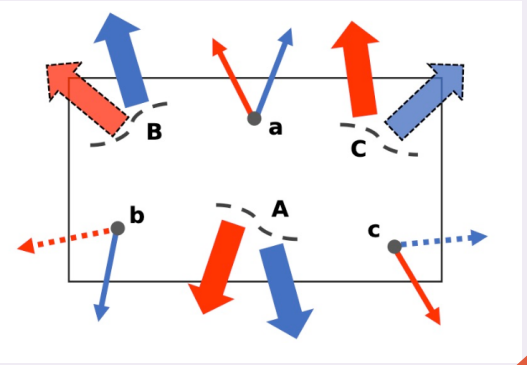
- Different v_2 of positive and negative particles wrt. A have been observed, which is in line with CMW theoretical predictions,

All CMW Signal?

Signal and background

Background





Local Charge Conservation (LCC)
(Momentum space)

Collective flow

Resonances/Clusters…

- Flow channels the initial charge separation (either signal or background) to the final state.

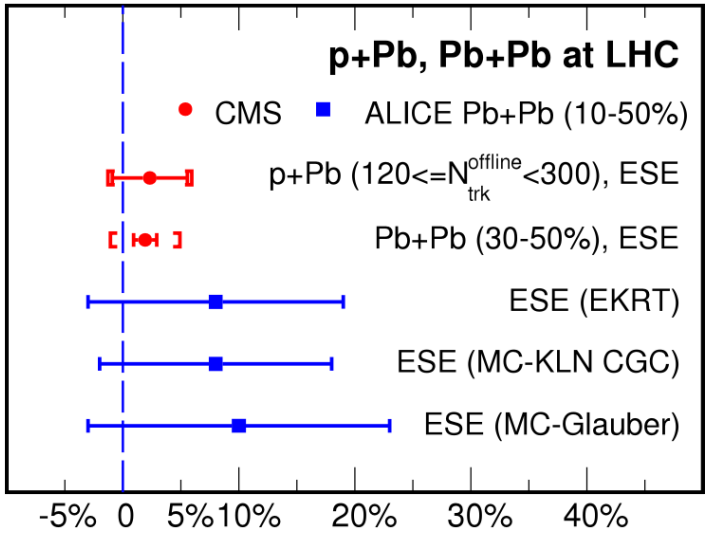
S. Schlichting et al., PRC 83, 014913 (2011); A. Bzdak et al., PLB 726 239243 (2013)
P. Christakoglou et al., EPJC 81, 717 (2021); W. Wu et al., PRC 107, L031902 (2023)

Event shape engineering (ESE)

$$q_2 = Q_2/\sqrt{M} \propto v_2$$

- Select events in different q_2 intervals
- Control the bkg. by controlling v_2 event by event.

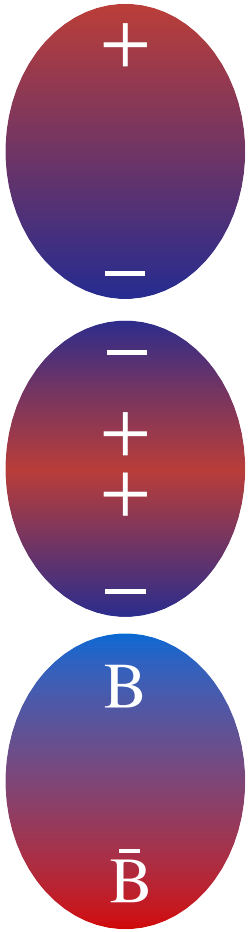
J. Schukraft et al., PLB 719, 394 (2013); F. Wen et al., CPC 42, 014001 (2018)
R. Milton et al., PRC 104, 064906 (2021); C. Wang et al., PLB 820, 136580 (2021)



Background Dominates!

ALICE, PLB 777, 151 (2018); CMS, PRC 100, 064908 (2019)
J. Zhao et al., PPNP 107, 200 (2019); ALICE, JHEP 2020, 160 (2020)

Overview of this report



1.Chiral Magnetic Effect (CME)

Extract the CME fraction by ESE

2.Chiral Magnetic Wave (CMW)

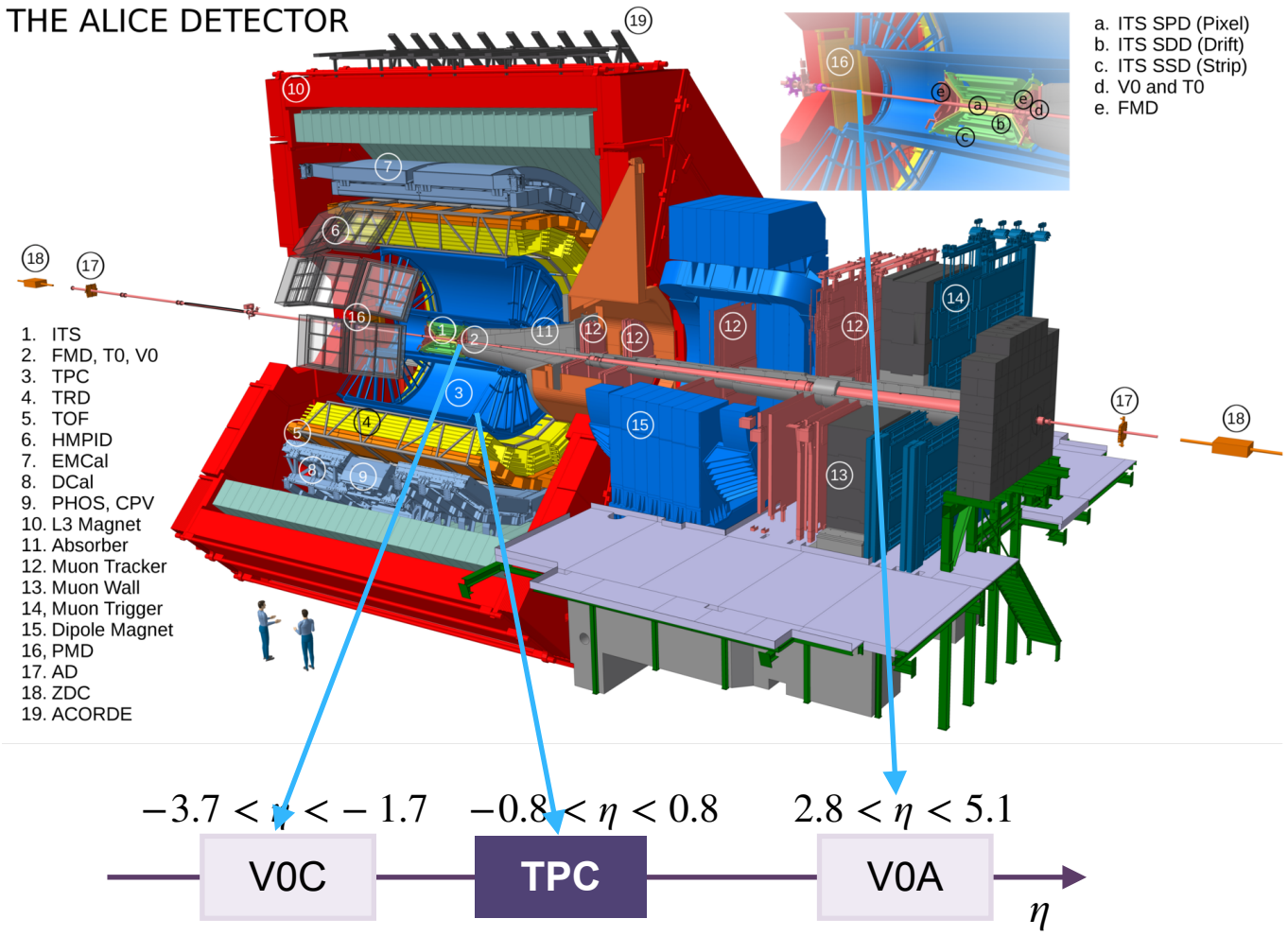
Extract the CMW fraction by ESE

3.Chiral Vortical Effect (CVE)

Search for the CVE by the γ and δ correlator

in the Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with ALICE

ALICE experiment



ALICE for anomalous chiral effects

- **High collision energies (TeV)**

→ different μ and B/ω field, with respect to STAR experiment

- **High multiplicity**

→ small fluctuations

- **Good performance of forward detectors**

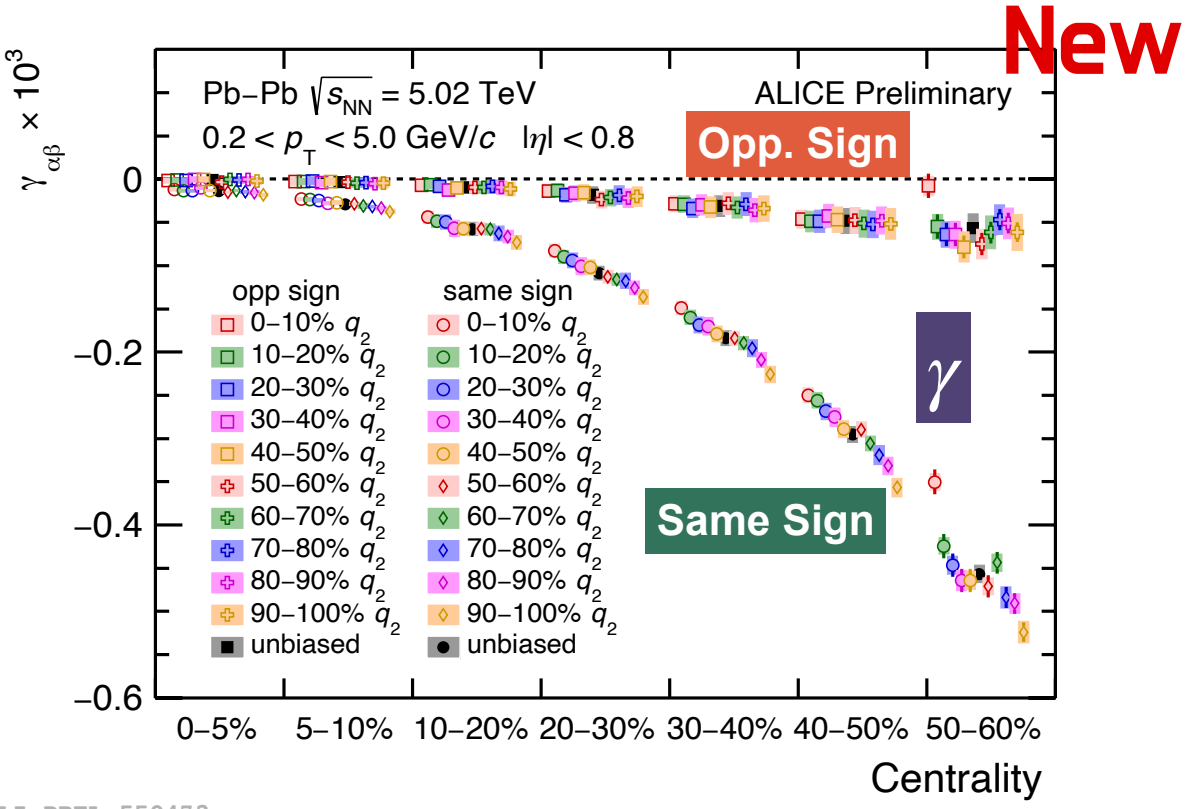
→ good for techniques such as ESE

- **Extensive particle identification (PID) with TOF/TPC**

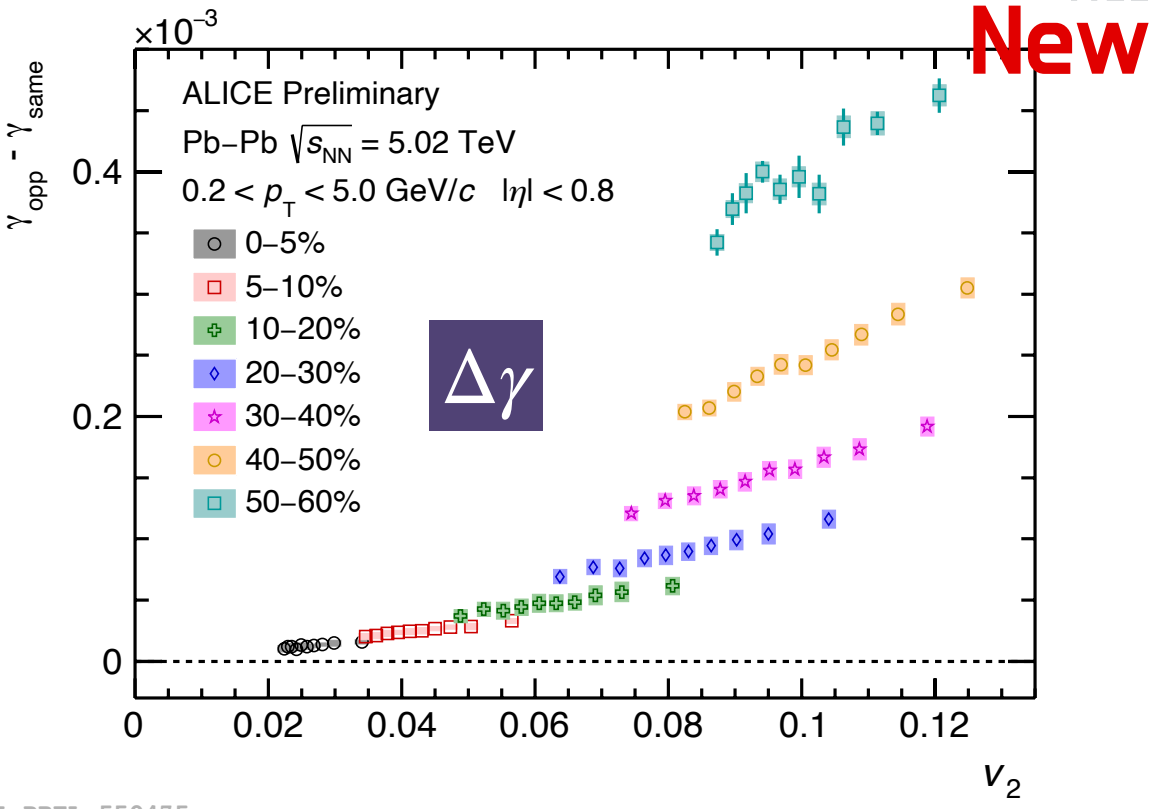
→ appropriate for CVE and PID CME

ALICE, J. Inst. 3, S08002 (2008)
ALICE, J. Inst. 8, P10016 (2013)
ALICE, MPA 29, 1430044 (2014)

Extract the fraction of CME



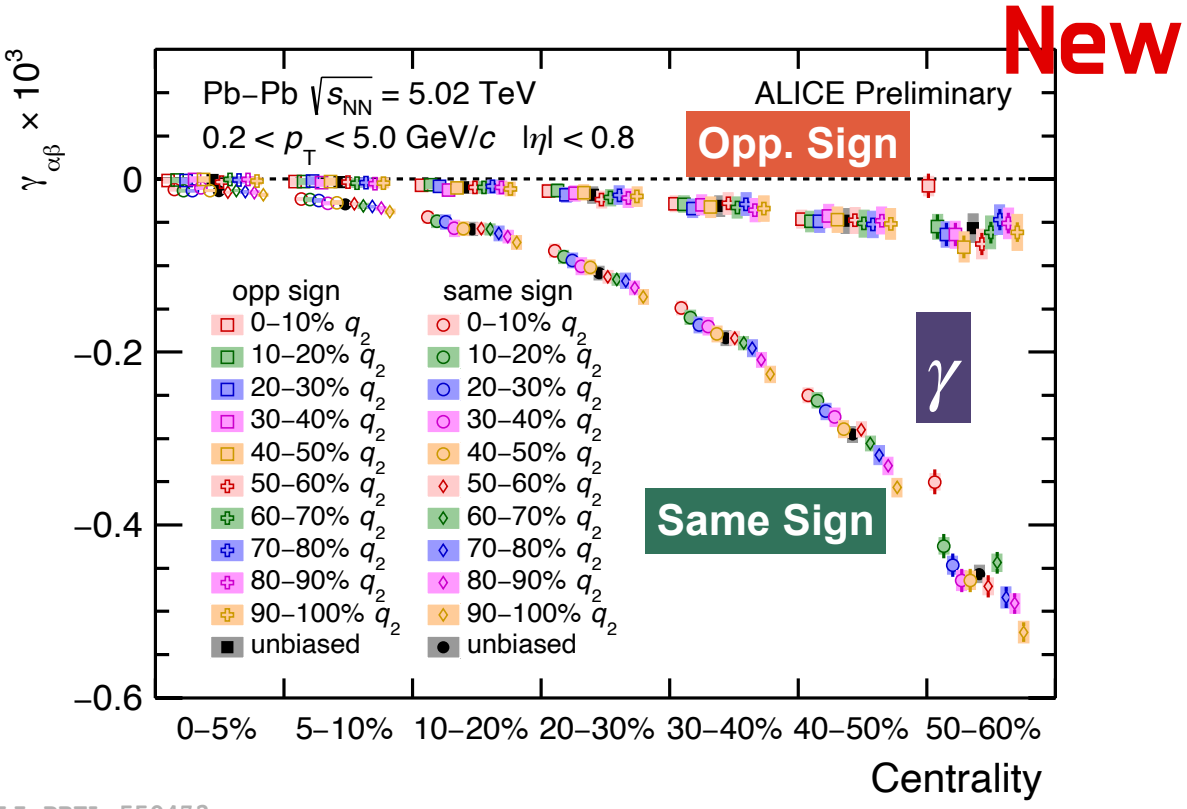
ALI-PREL-550472



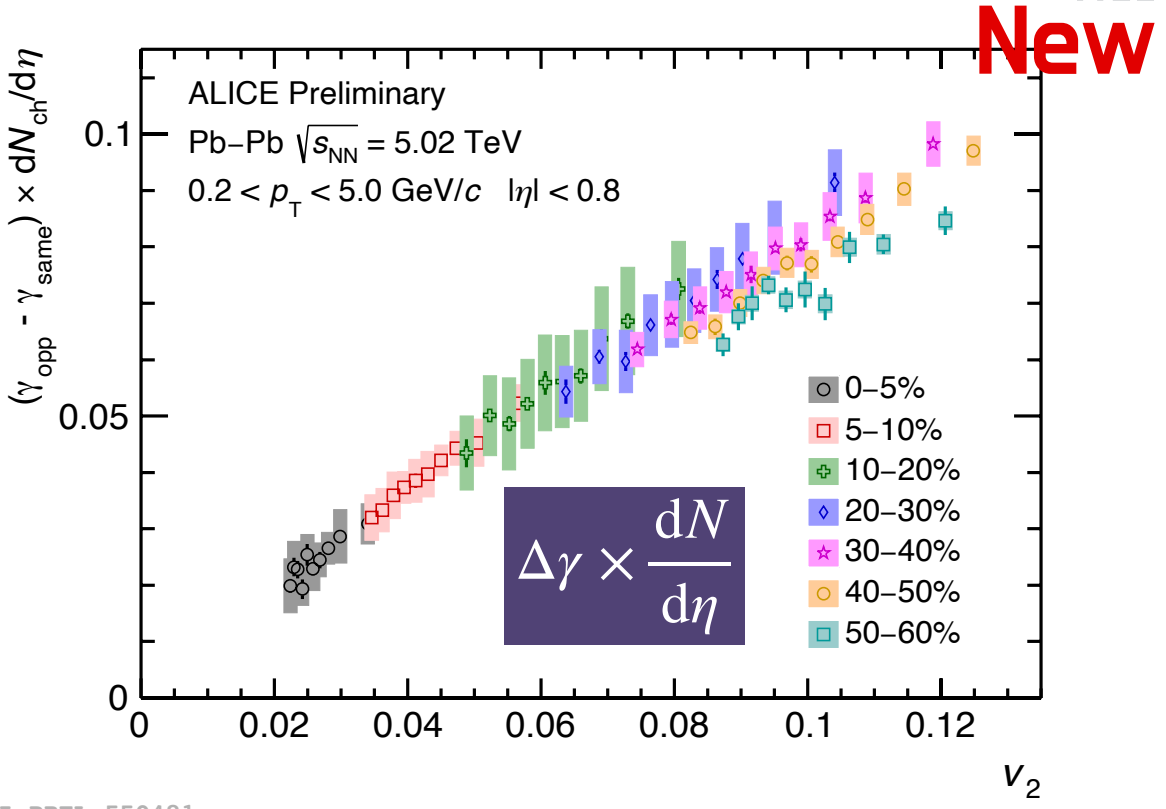
ALI-PREL-550475

- q_2 for ESE is measured by V0C with V0A as the event plane estimator.
- $\Delta\gamma$ is positive for all centrality classes and decreases with centrality and v_2.

Extract the fraction of CME



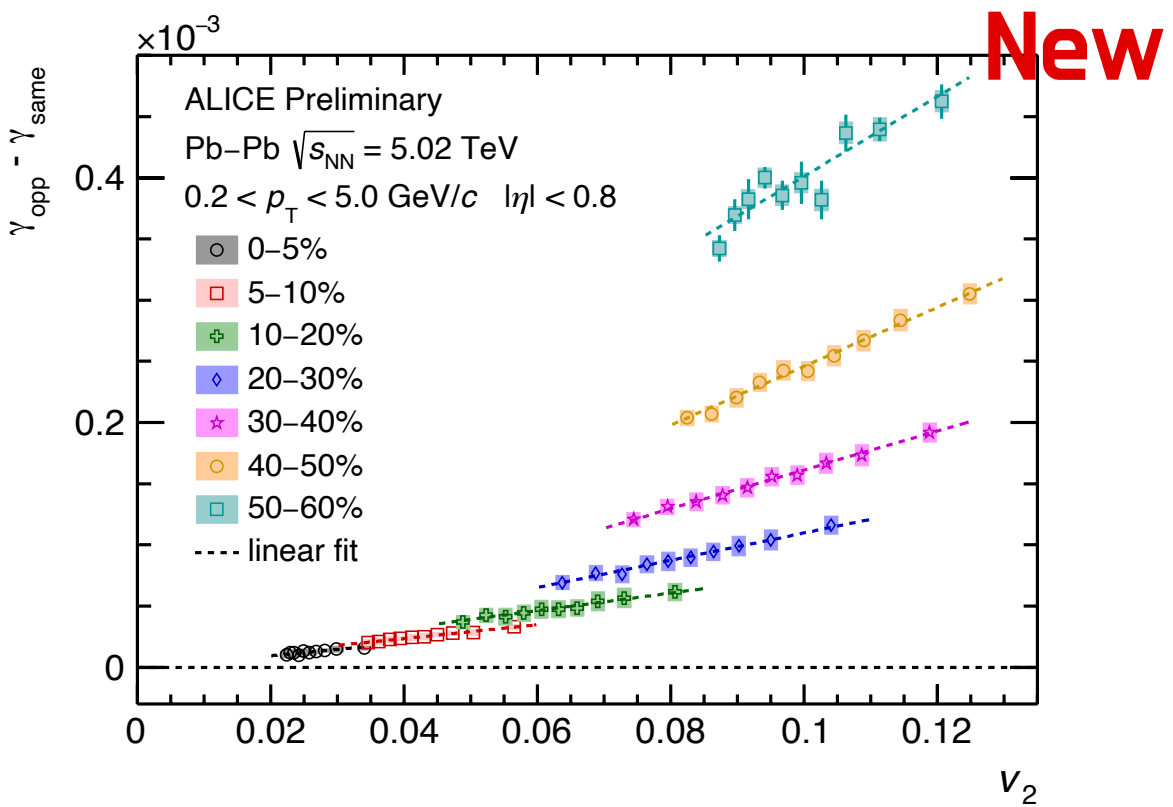
ALI-PREL-550472

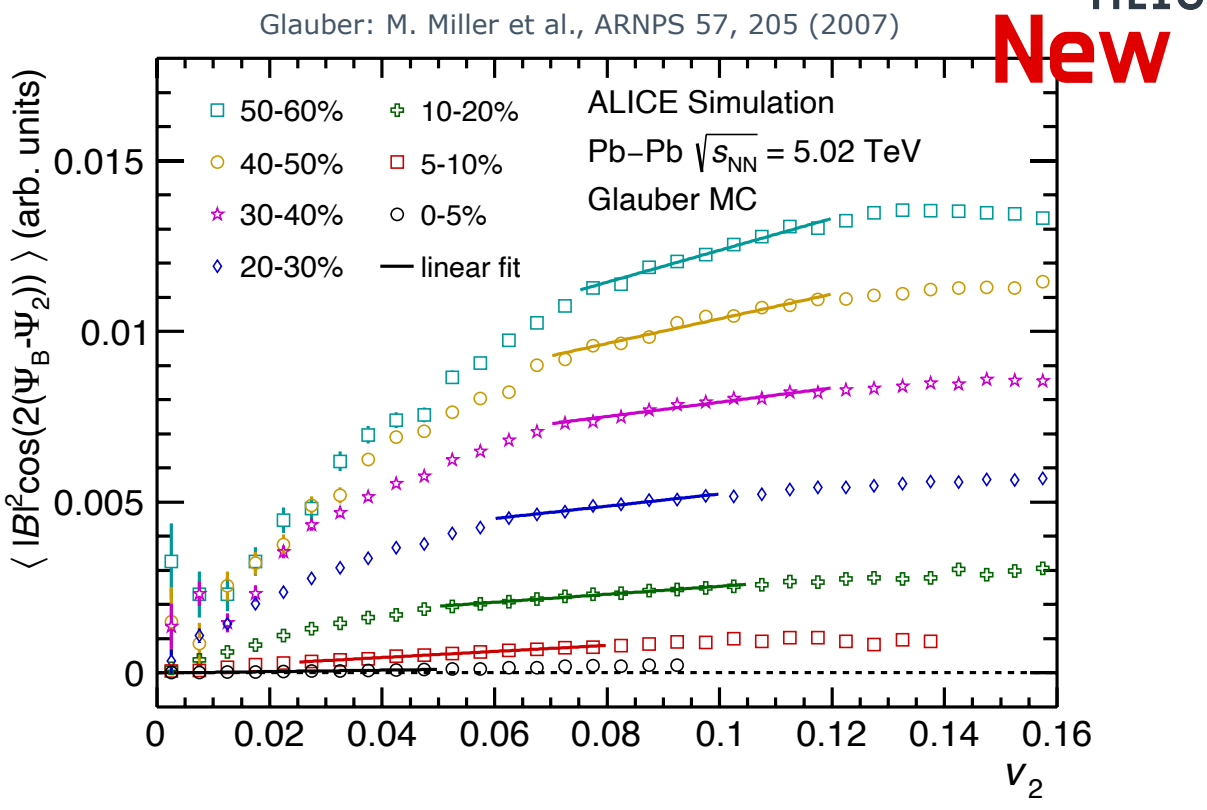


ALI-PREL-550481

- q_2 for ESE is measured by V0C with V0A as the event plane estimator.
- $\Delta\gamma$ is positive for all centrality classes and decreases with centrality and v_2.
- $\Delta\gamma$ approximately scales with v_2 and multiplicity → large background contribution.

Extract the fraction of CME

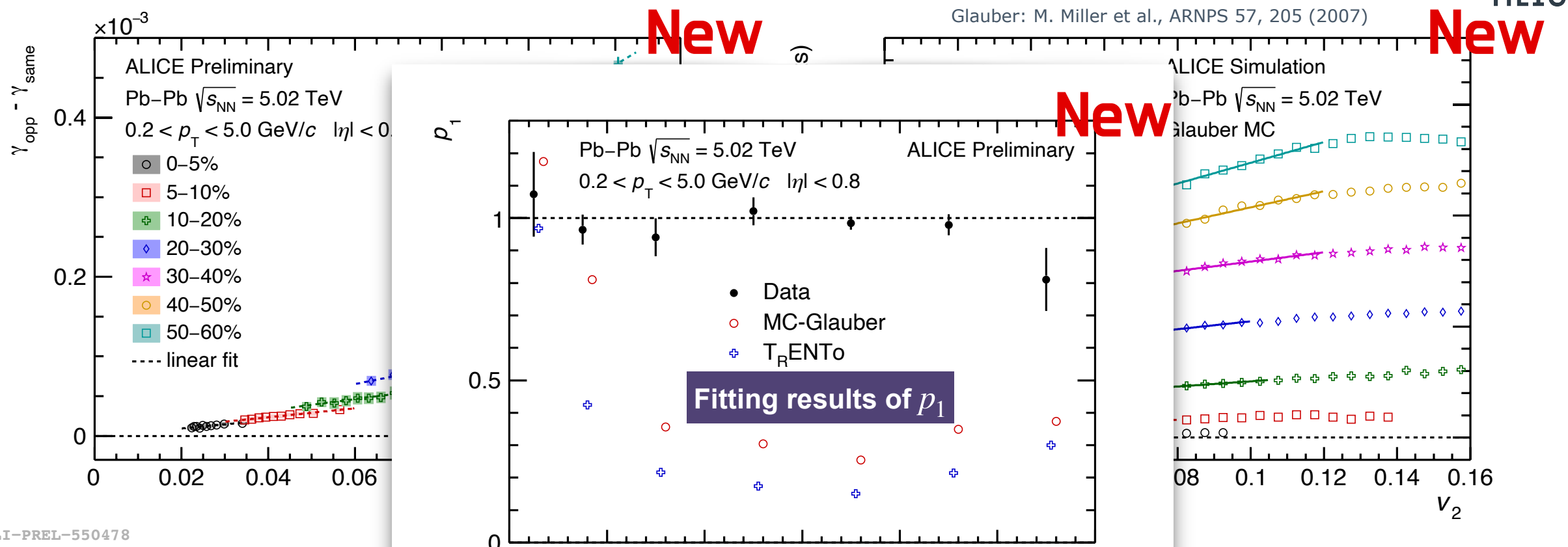


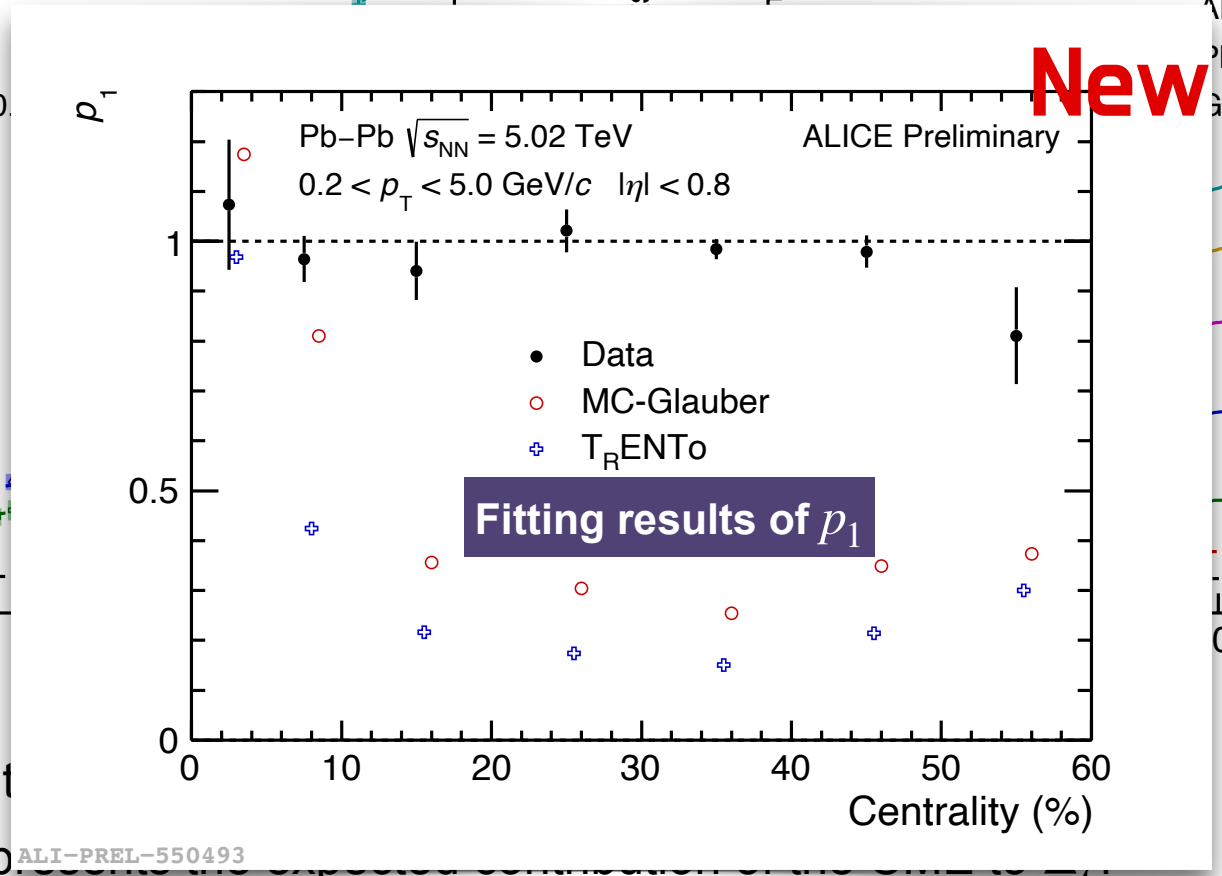


- Perform a MC simulation to evaluate the **dependence of the CME signal on v_2.**
- $\langle |B|^2 \cos(2(\Psi_B - \Psi_2)) \rangle$ represents the expected contribution of the CME to $\Delta\gamma$.
- Fit $\Delta\gamma$ and $\langle |B|^2 \cos(2(\Psi_B - \Psi_2)) \rangle$ with a linear function to disentangle the CME signal from the background.

$$f(v_2) = p_0 \left[1 + p_1 \frac{v_2 - \langle v_2 \rangle}{\langle v_2 \rangle} \right].$$

Extract the fraction of CME





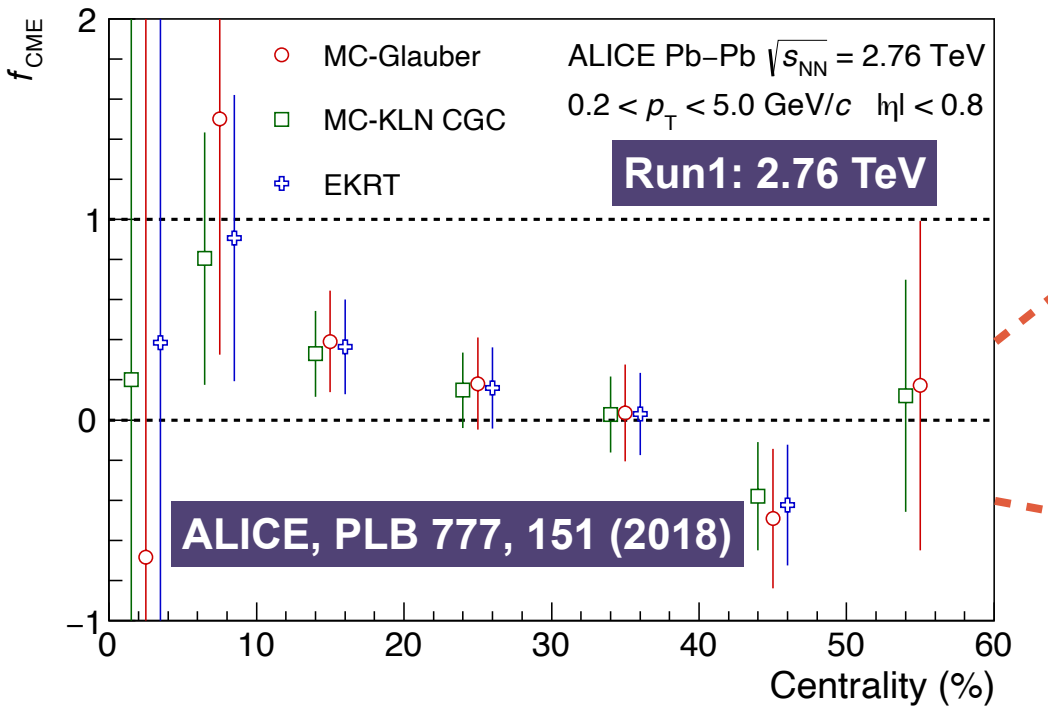
- Perform a MC simulation t
- $\langle |B|^2 \cos(2(\Psi_B - \Psi_2)) \rangle$ rep
- Fit $\Delta\gamma$ and $\langle |B|^2 \cos(2(\Psi_B - \Psi_2)) \rangle$ with a linear function to disentangle the CME signal from the background.

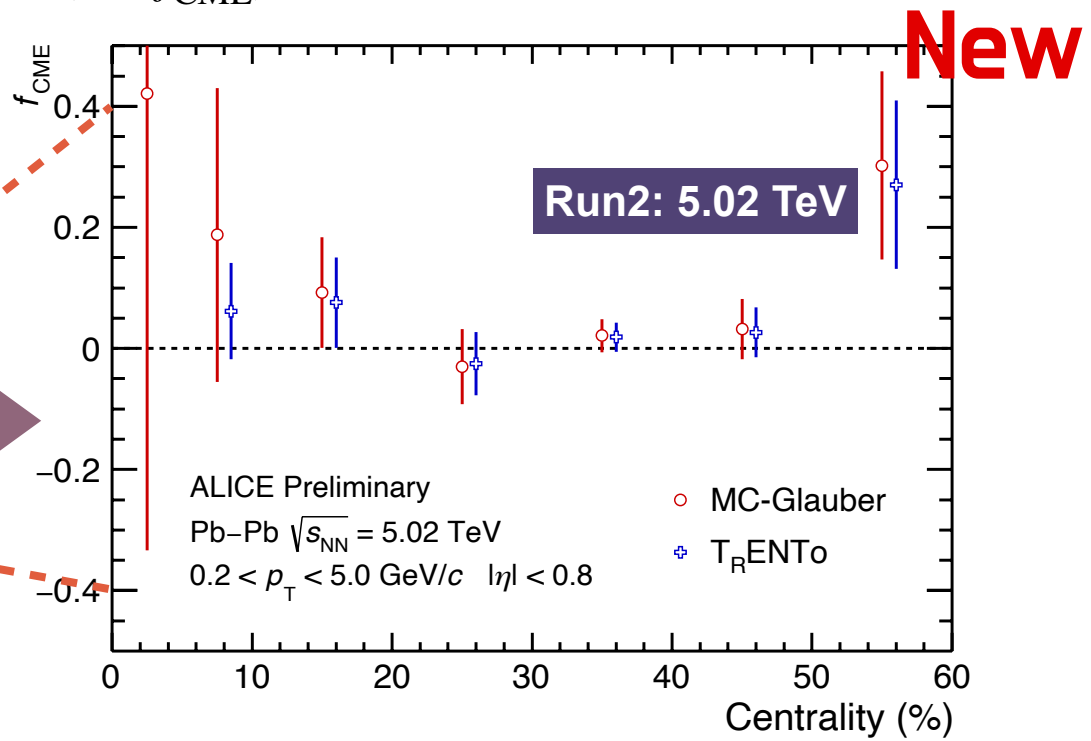
$$f(v_2) = p_0 \left[1 + p_1 \frac{v_2 - \langle v_2 \rangle}{\langle v_2 \rangle} \right].$$

Extract the fraction of CME

- **Assumption:** background contribution scales linearly with v_2.
- Extract the CME fraction f_{CME} by $p_{1,\mathrm{data}} = f_{\mathrm{CME}} p_{1,\mathrm{MC}} + (1 - f_{\mathrm{CME}})$

Glauber: M. Miller et al., ARNPS 57, 205 (2007)
EKRT: H. Niemi et al., PRC 93, 024907 (2016)
TRENTO: J. Moreland et al., PRC 92, 011901 (2015)
KLN: H. Drescher et al., PRC 76, 041903 (2007)



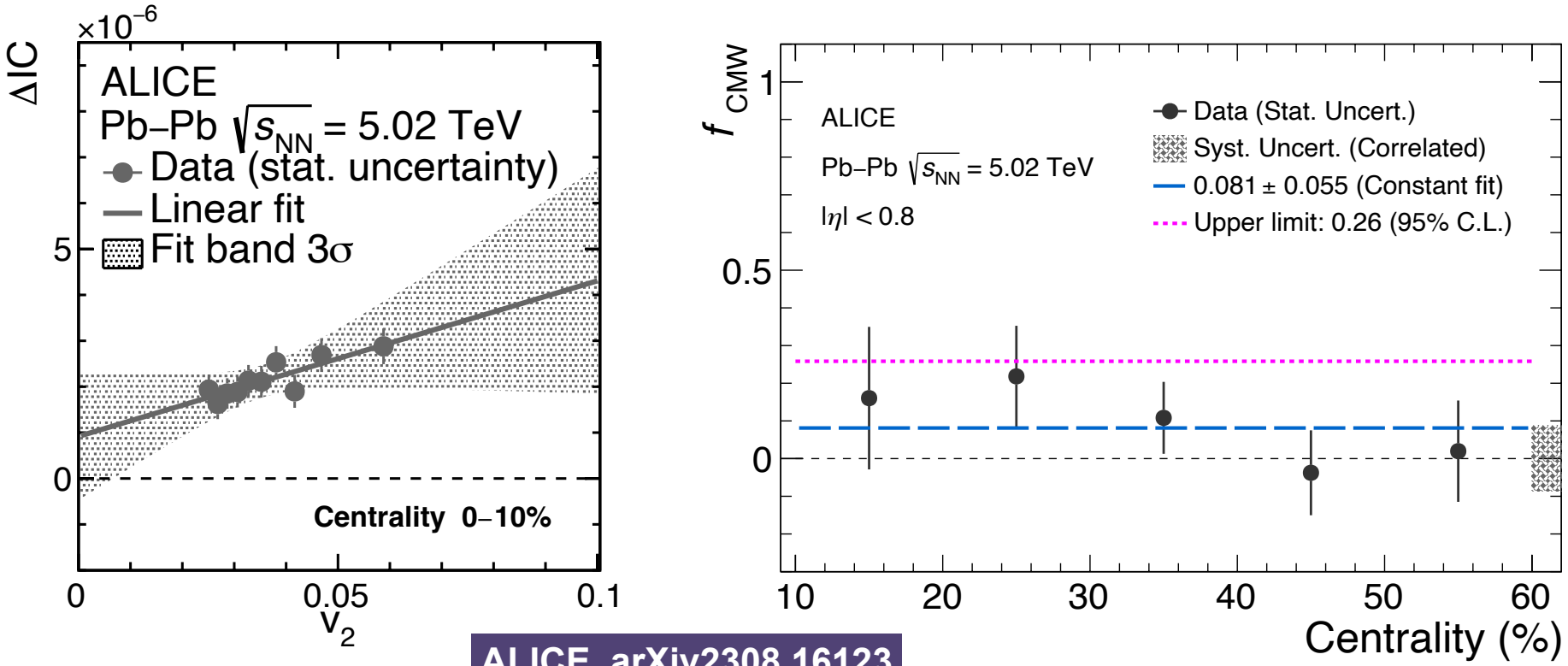


2.76 TeV, 10–50% centrality
$f_{\mathrm{CME}}(\mathrm{Glauber}) = 0.102 \pm 0.129$, 33% at 95% C.L.
$f_{\mathrm{CME}}(\mathrm{KLN}) = 0.076 \pm 0.104$, 26% at 95% C.L.
$f_{\mathrm{CME}}(\mathrm{EKRT}) = 0.084 \pm 0.114$ 29% 95% C.L.

5.02 TeV, 5–60% centrality
$f_{\mathrm{CME}}(\mathrm{Glauber}) = 0.0276 \pm 0.0213$, 6.4% at 95% C.L.
$f_{\mathrm{CME}}(\mathrm{T_R ENTo}) = 0.0245 \pm 0.0179$, 5.5% at 95% C.L.

The upper limit has been further constrained.

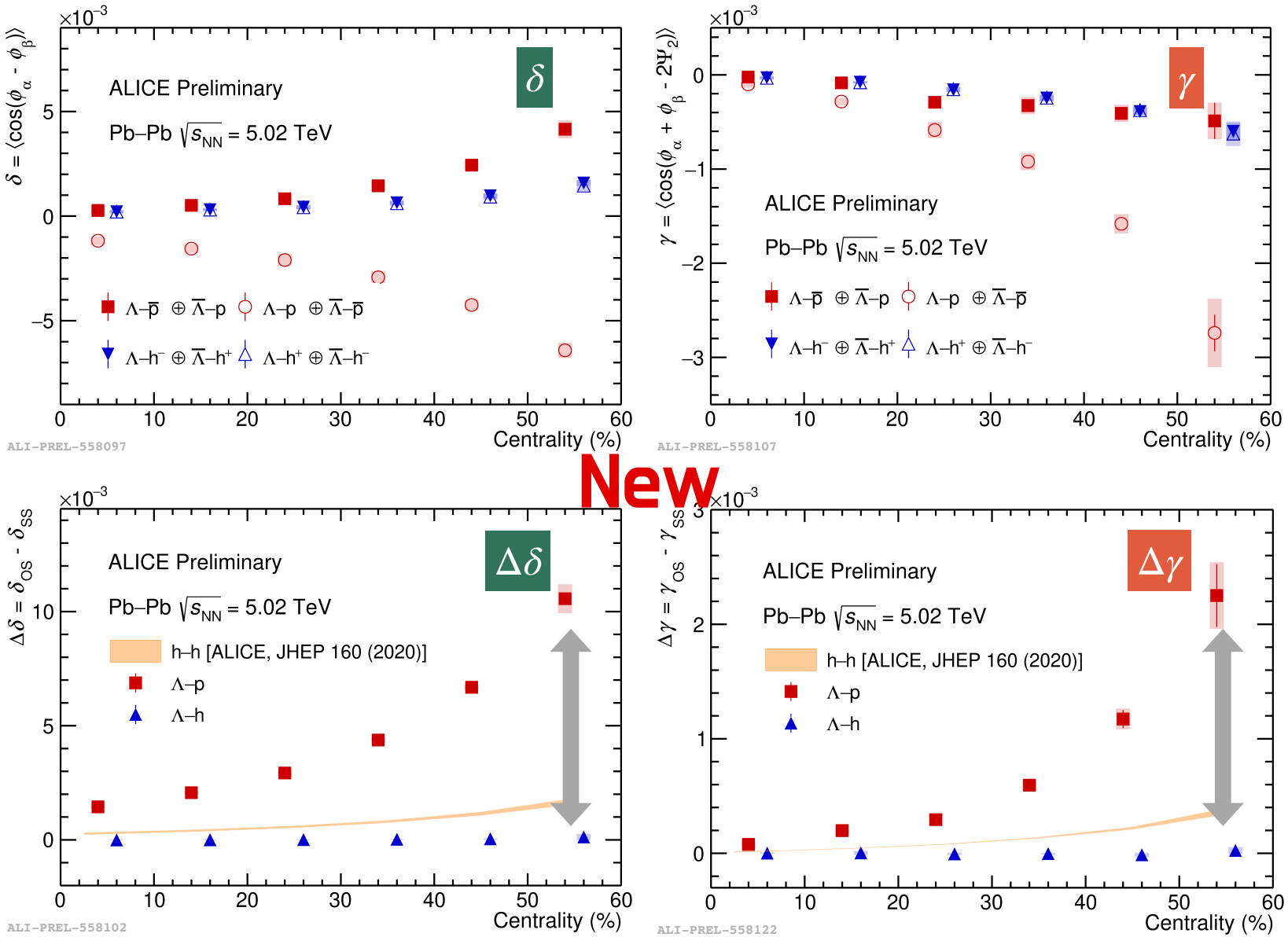
Extract the fraction of CMW



ALICE, arXiv2308.16123

- Integral covariance ($\Delta\mathrm{IC}$) approximately scales with v_2 → large background contribution. C. Wang et al., PLB 820, 136580 (2021)
- CMW fraction extracted by $f_{\mathrm{CMW}} = b/[a\langle v_2\rangle + b]$, where a, b taken from the linear fitting $\Delta\mathrm{IC}(v_2) = av_2 + b$.
- CMW fraction for 10–60% centrality: $f_{\mathrm{CMW}} = 0.081 \pm 0.055$, 26% at 95% C.L., 38% at 99.7% C.L.
- A universal LCC background for CME+CMW is established by W. Wu et al., PRC 107, L031902 (2023).

Search for the CVE

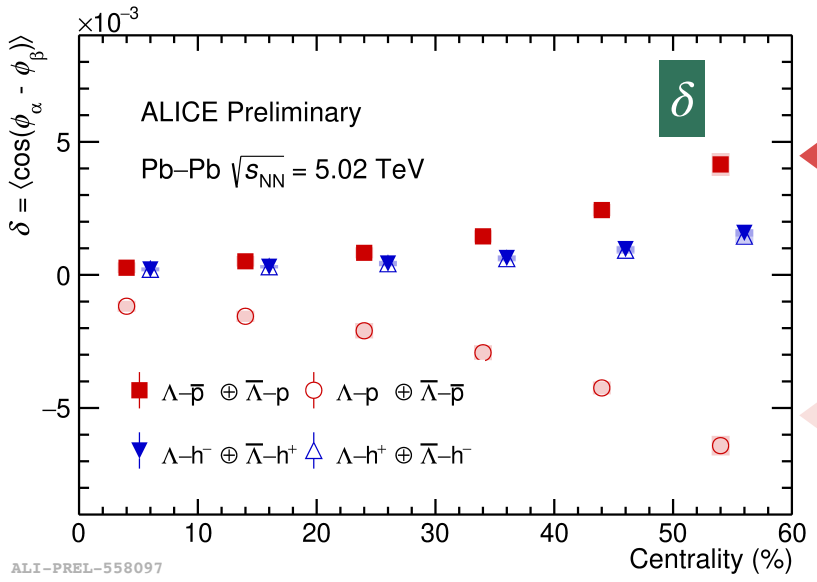


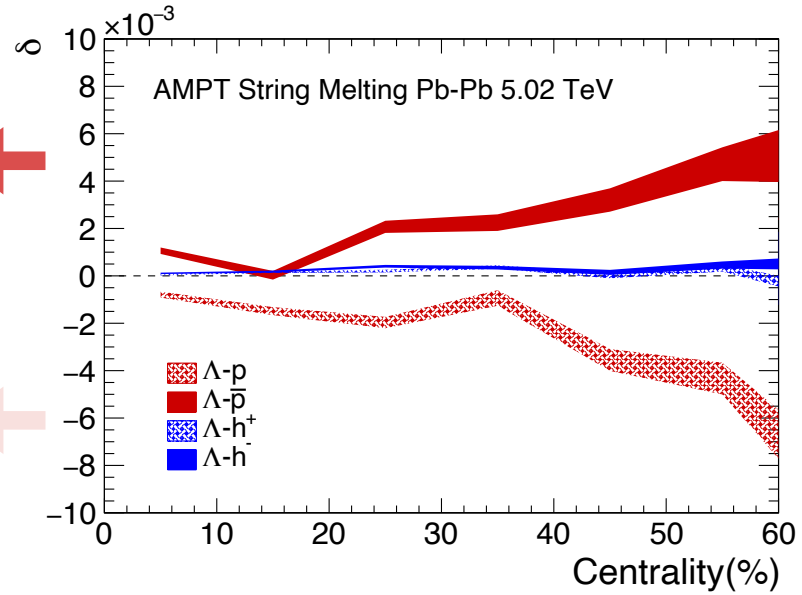
- Choosing neutral baryon $\Lambda(\bar{\Lambda})$ to avoid ambiguity from CME
- Λ reconstructed by $\Lambda \rightarrow \pi p$
- γ, δ extracted by invariant mass method

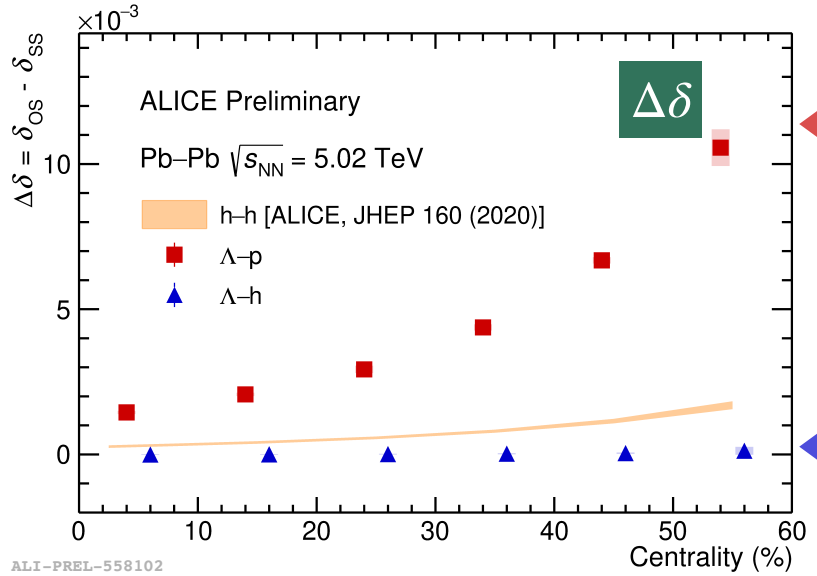
N. Borghini et al., PRC 70, 064905 (2004)

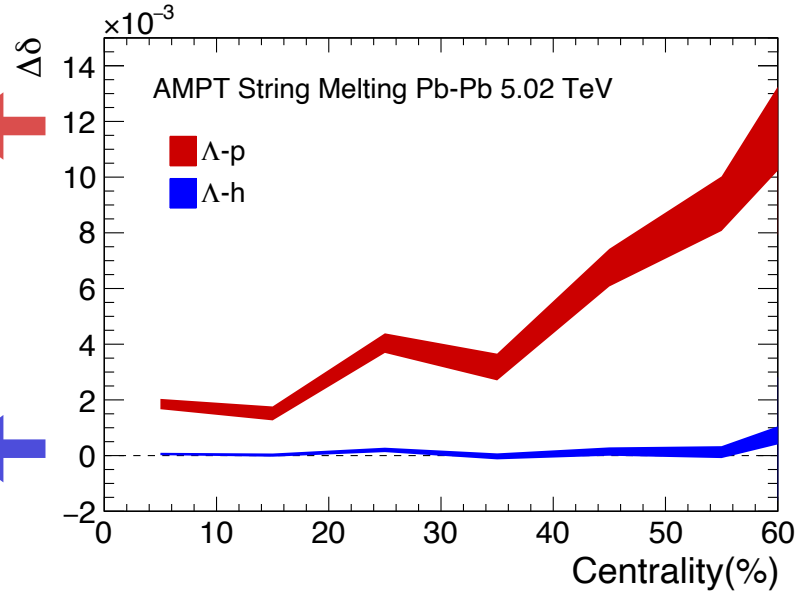
- Significant δ and γ separation of Λ–p, approximately 10 times larger than h–h (CME).
- Separation of Λ–h is near zero.
- $\Delta\delta$, $\Delta\gamma$ of Λ–p increasing with centrality.

Comparison with AMPT model



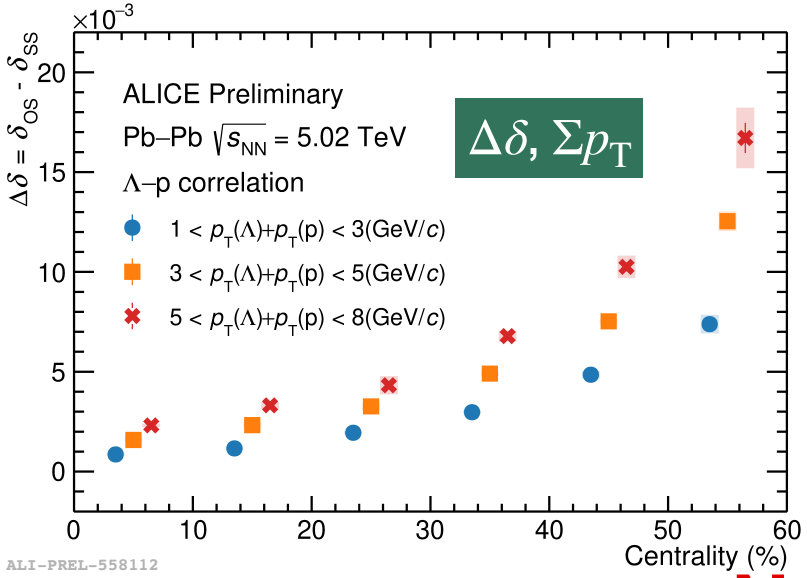


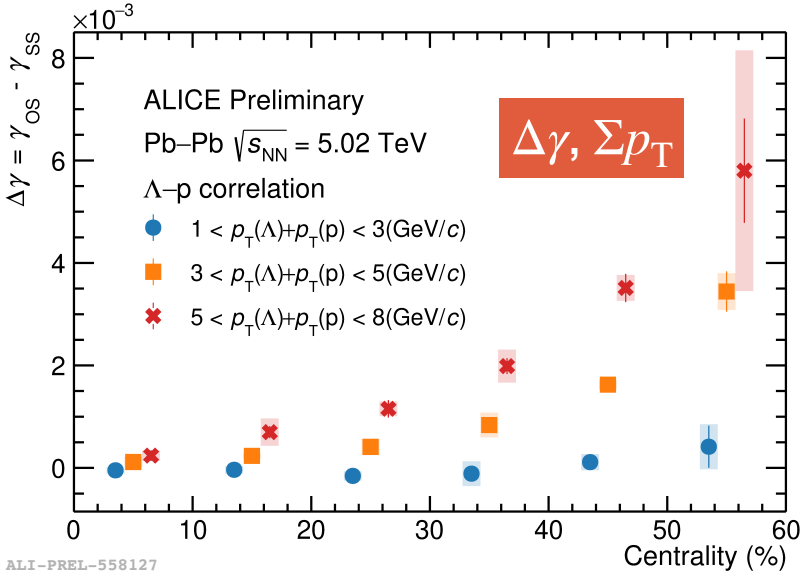




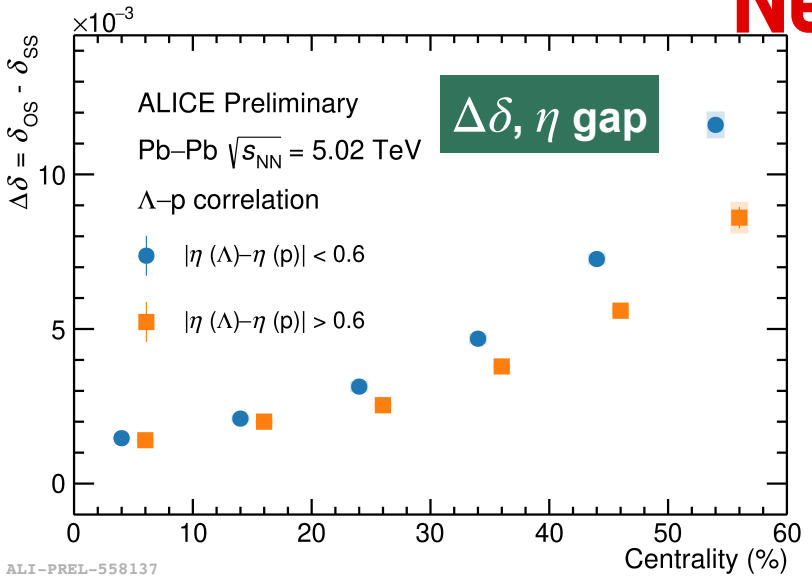
- The AMPT model, which has no CVE but partially contains the local baryon conservation (LBC), can reproduce δ, $\Delta\delta$ correlators, however, fails for $\Delta\gamma$ correlators
- Urgent need for advanced models such as AVFD+LBC…

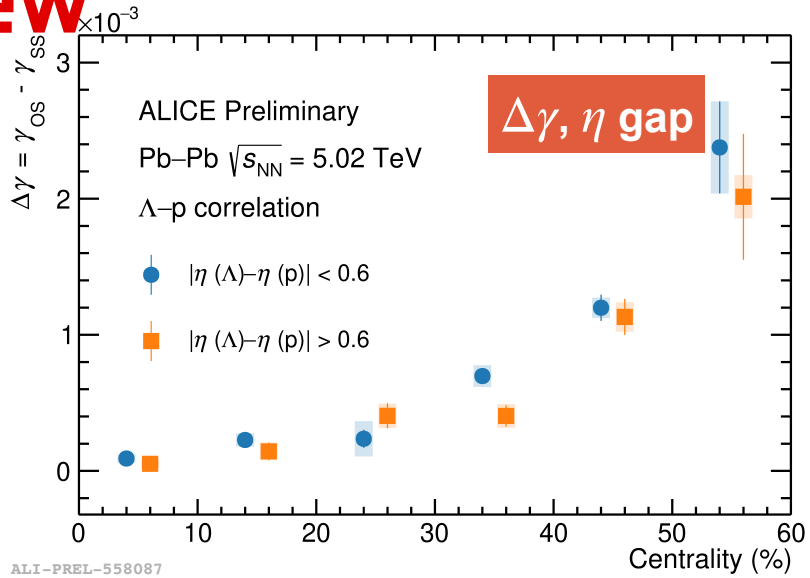
Observables in different kinematics regions





New



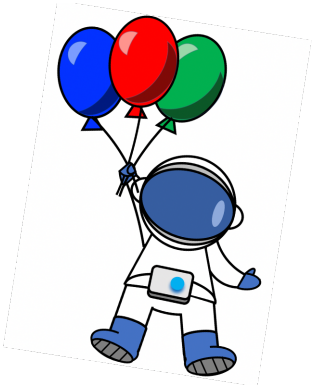


- Larger Σp_T leads to larger $\Delta\delta$ and $\Delta\gamma$
- Larger η gap leads to small $\Delta\delta$ but moderate $\Delta\gamma$
- Helpful to understand subtle mechanism and establish the theoretical interpretation

Summary

Anomalous chiral effects (CME, CMW, CVE) are studied in Pb—Pb $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collisions with ALICE

- Event shape engineering has been successfully applied to extract CME/CMW signals with ALICE. The upper limit of CME is further constrained.
  - Contribution from CME/CMW signal is close to zero within the error at TeV scale.
- First measurements of CVE with ALICE. δ and γ correlators of Λ–p show a non-trivial behavior. They also show hierarchy in different kinematics regions.
  - Theoretical inputs are highly desired to disentangle the CVE signal and the background.

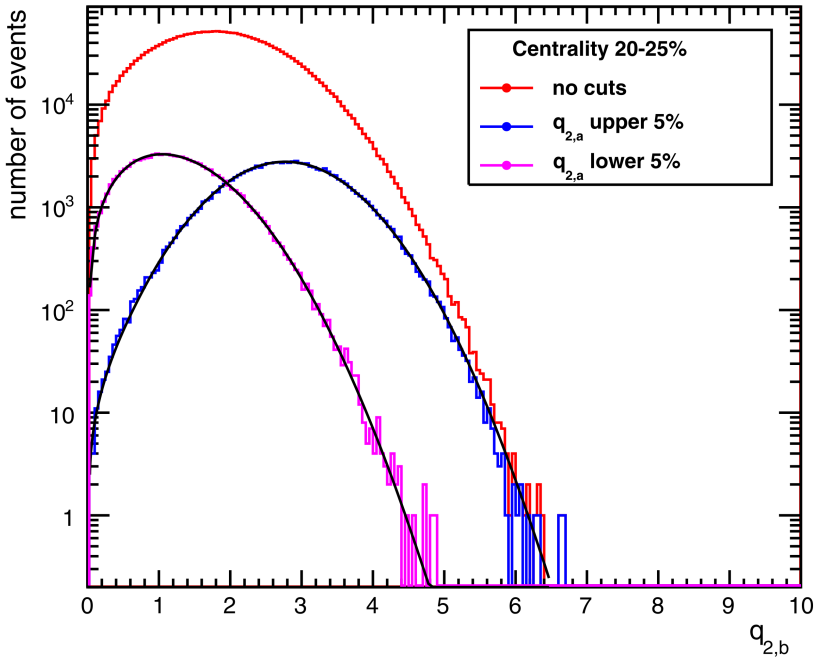


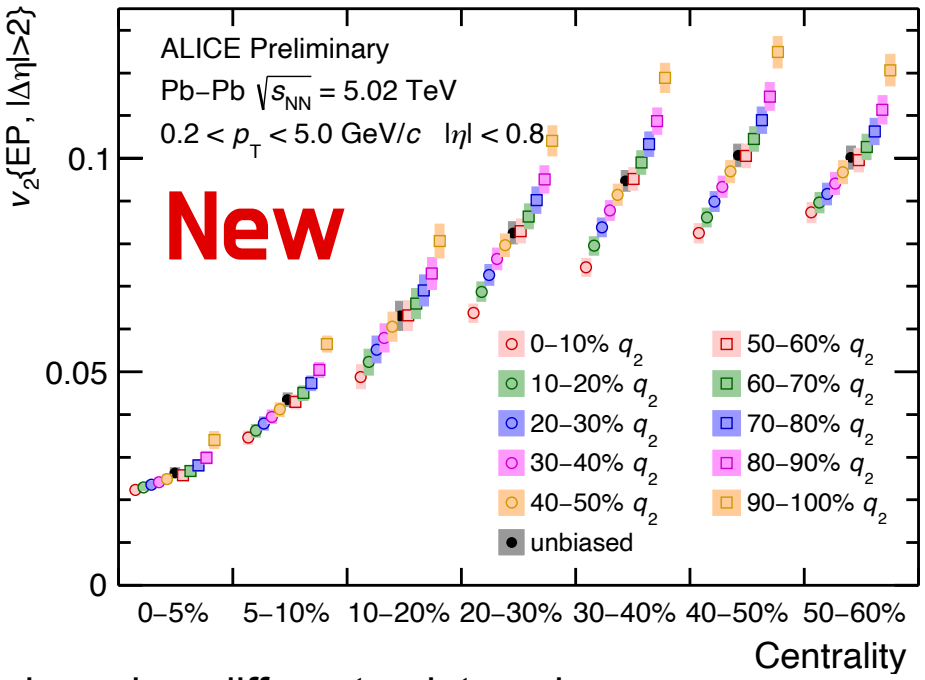
Thank you for your attention!

Back Up

Event shape engineering

J. Schukraft et al., PLB 719, 394 (2013)





Event Shape Engineering

$$\vec{Q}_2 = [\Sigma\cos(2\phi), \Sigma(\sin 2\phi)]$$

$$q_2 = Q_2/\sqrt{M}$$

- Select events based on different q_2 intervals.
- Essentially select events using **event-by-event flow fluctuations**.
- Better to use **different samples** to calculate and observable to avoid auto-correlation. (TPC for observables, while V0C for q_2 in ALICE)

- Way to disentangle the v_2 related background and signal in CME/CMW measurement.

Observables in different kinematics regions