INSTITUTE OF
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ALICE

# Searches for Chiral Magnetic and Chiral Vortical Effects with ALICE

A. Dobrin for the ALICE Collaboration
(Institute of Space Science – INFLPR Subsidiary)

The 8th International Conference on Chirality, Vorticity and Magnetic Field in Quantum Matter

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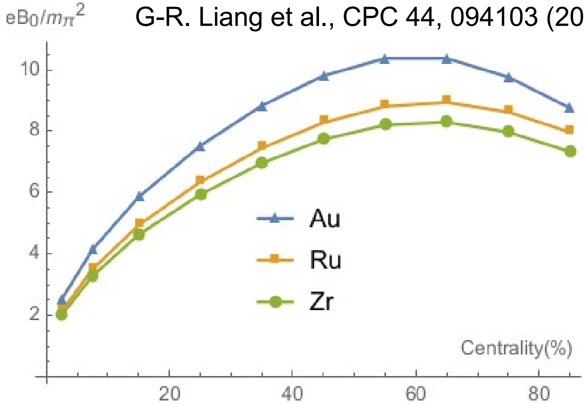
West University of Timisoara

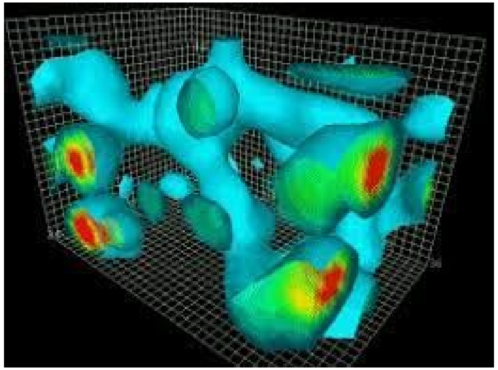
# Chiral effects in heavy-ion collisions



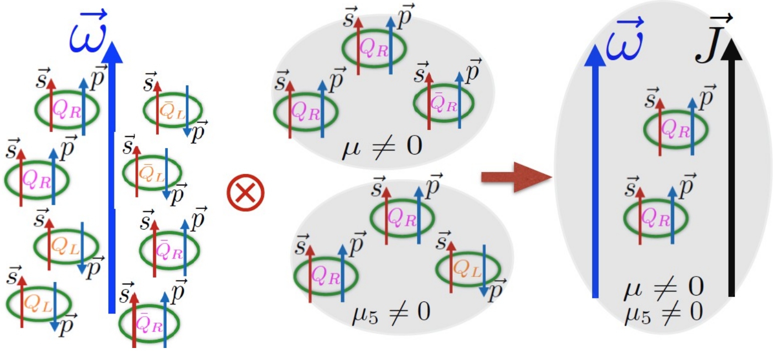
G-R. Liang et al., CPC 44, 094103 (2020)

Strong magnetic field
(B~$10^{15}$ T)

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/



QCD domains with P and CP symmetries locally broken



Electric current along the magnetic field → charge separation

**Chiral Magnetic Effect (CME)**

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

**Chiral Separation Effect (CSE)**

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

**Chiral Vortical Effect (CVE)**

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

**CME + CSE → Chiral Magnetic Wave (CMW)**

D. Kharzeev, PLB 633, 260 (2006); D. Kharzeev et al., NPA 797, 67 (2007); 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 et al, PPNP 88, 1 (2016)

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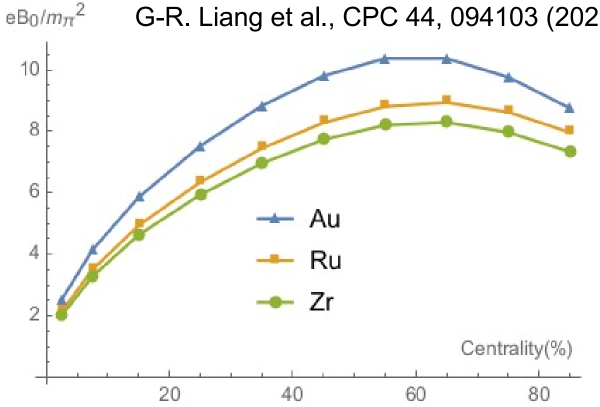

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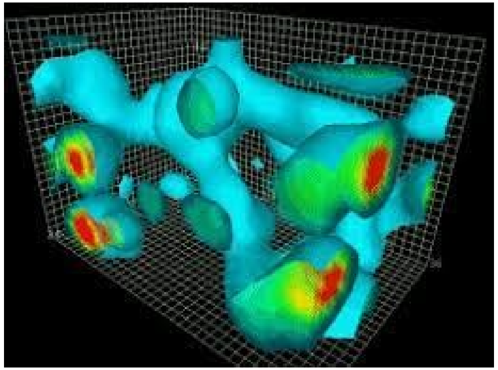

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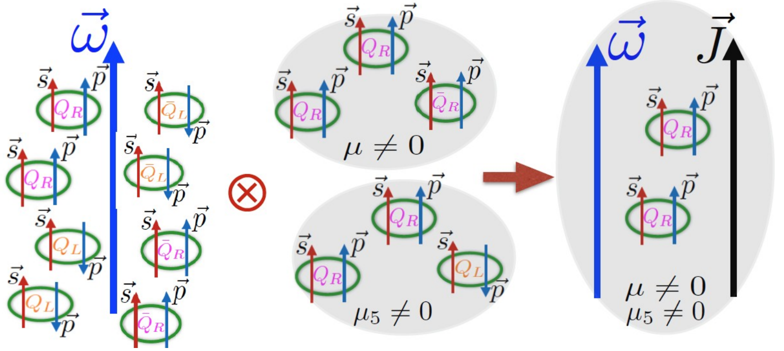

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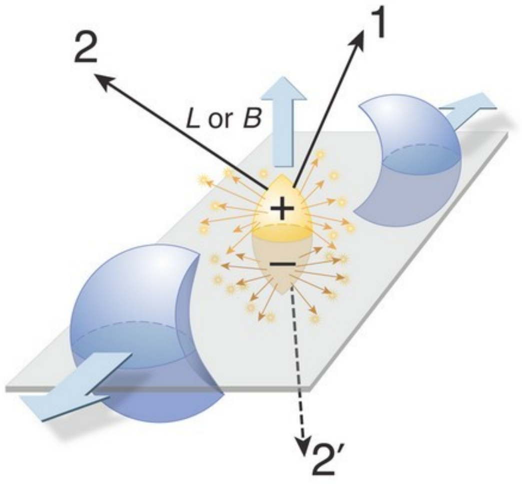
Interpretation of the results complicated by background contributions

# Observables



## CME / CVE

$$\frac{dN}{d\Delta\varphi_\alpha} \sim 1 + 2v_{1,\alpha}\cos(\Delta\varphi_\alpha) + 2a_{1,\alpha}\sin(\Delta\varphi_\alpha) + 2v_{2,\alpha}\cos(2\Delta\varphi_\alpha) + \ldots,$$

2-particle correlator

$$\delta_m = \langle \cos[m(\varphi_a - \varphi_b)] \rangle$$

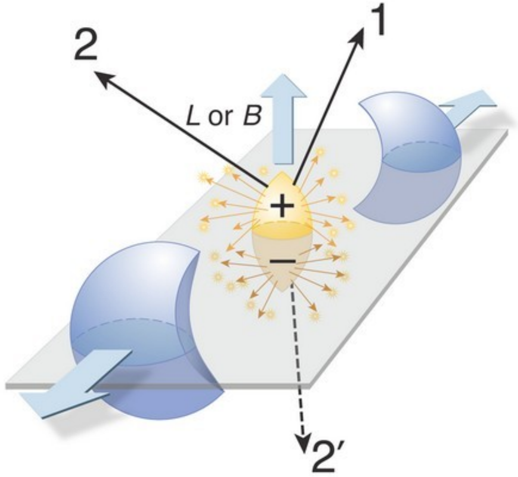
STAR, PRC 81, 054908 (2009)

3-particle correlator

$$\gamma_{m,n} = \langle \cos(m\varphi_a + n\varphi_b - (m+n)\Psi_{|m+n|}) \rangle$$

S. Voloshin, PRC 70, 057901 (2004)

# Observables



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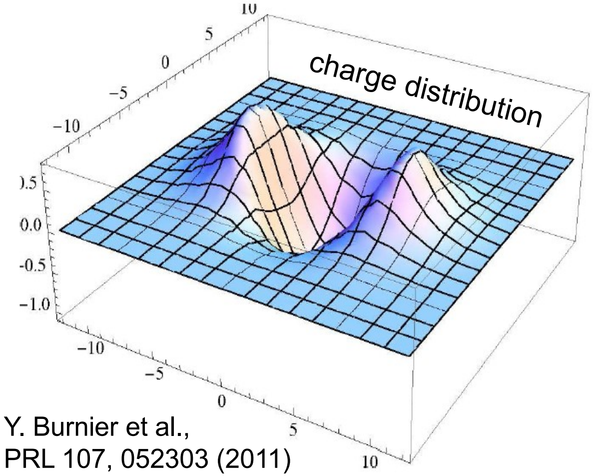
## CMW

Normalized slope $r_n^{Norm}$
of anisotropic flow difference vs. charge asymmetry

$$\Delta v_n^{Norm} = \frac{v_n^- - v_n^+}{(v_n^- + v_n^+)/2} \propto r_n^{Norm} A \qquad A = \frac{N^+ - N^-}{N^+ + N^-}$$

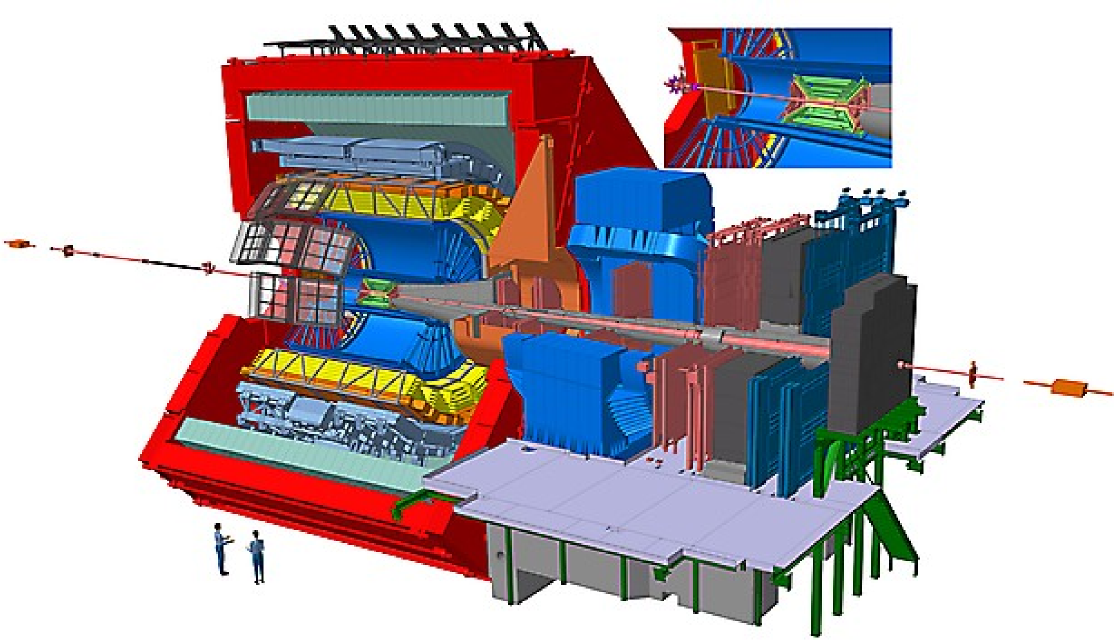
Integral covariance $\Delta \mathrm{IC} = \langle v_n^{\pm} A \rangle - \langle v_n^{\pm} \rangle \langle A \rangle$

S. Voloshin and R. Belmont, NPA 931, 992 (2014)



Y. Burnier et al.,
PRL 107, 052303 (2011)

# A Large Ion Collider Experiment



- Inner Tracking System (ITS)
  - Tracking, vertexing
- Time Projection Chamber (TPC)
  - Tracking, vertexing, particle identification based on specific energy loss, $\Psi_n$
- Time-of-Flight (TOF)
  - Particle identification based on flight time
- V0 detector
  - Triggering, centrality, $\Psi_n$

- Track selection
  - $0.2 < p_T < 5$ GeV/$c$, $|\eta| < 0.8$

$q_2$ selection

V0C

$-3.7<\eta<-1.7$

$v_n$/CME/CMW/CVE/$\Psi_n$

TPC

$-0.8<\eta<0.8$

$\Psi_n$

V0A

$2.8<\eta<5.1$

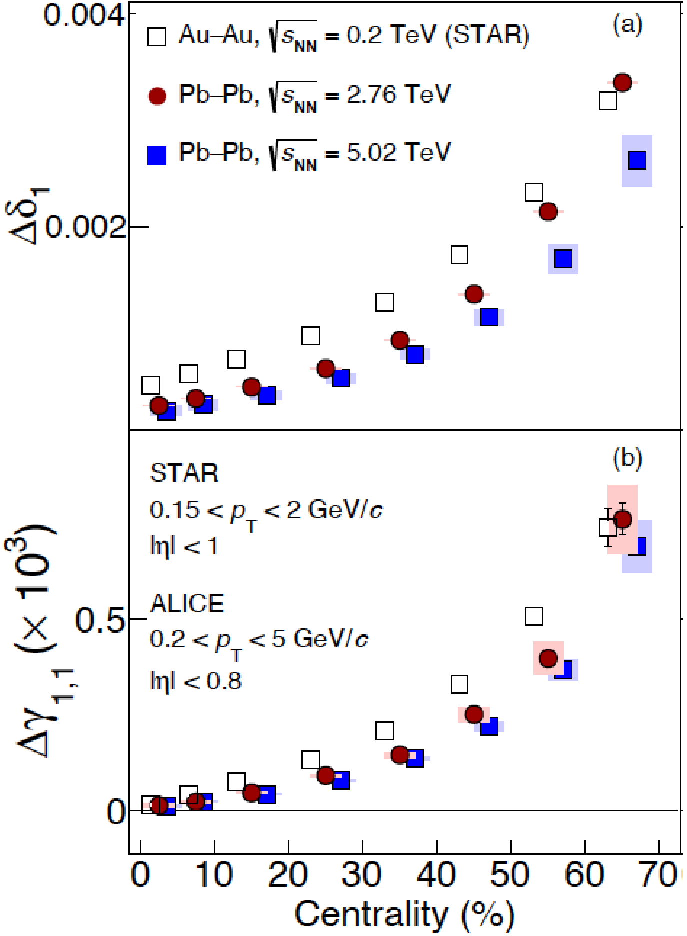
$\eta$

- Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  - ~235M events
- Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV
  - ~1M events

# Chiral Magnetic Effect

# CME @ LHC

ALICE, arXiv: 2211.04384



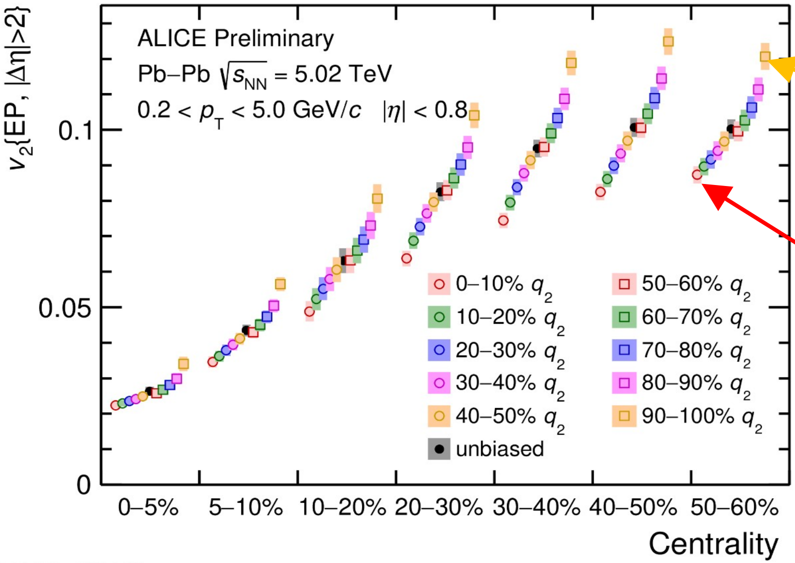
- Strong centrality dependence consistent with naive expectations from CME
- Similar magnitude between RHIC and LHC
  - Different dilution effects (3x larger d$N_{ch}$/d$\eta$ at LHC than at RHIC)
  - Different magnitude of the magnetic field
- Large contribution from background → local charge conservation (LCC) coupled with anisotropic flow

S. Schlichting and S. Pratt, PRC 83, 014913 (2011)

  - Various approaches used to disentangle signal from background
    - Vary the background ($v_2$) → event shape engineering
    - “Killing” the signal (B) → higher harmonics
    - Vary the signal (B) → different collision systems

# Varying the background using event shape engineering

# CME with ESE (I)



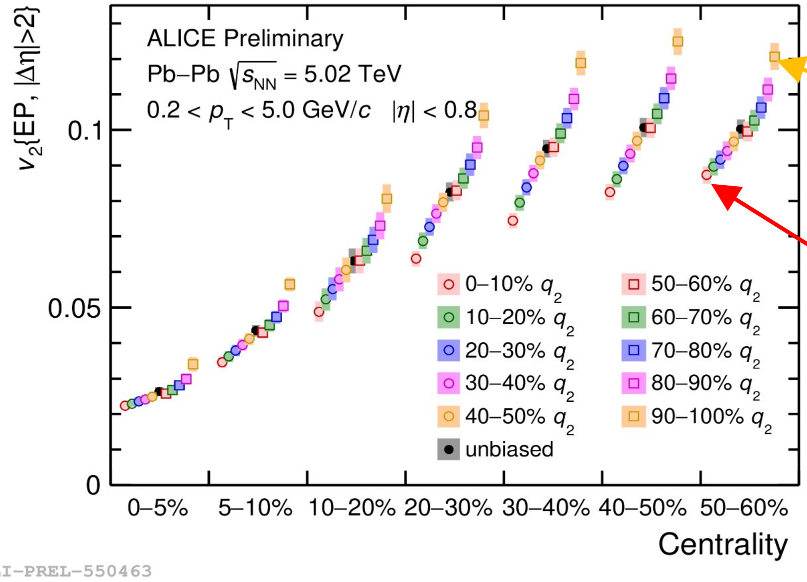
ALI-PREL-550463

Large-$q_2$: 10% high

Small-$q_2$: 10% low

- $q_2^{V0C}$ used to select events with 30% larger or 25% smaller $v_2$ than the average

# CME with ESE (I)



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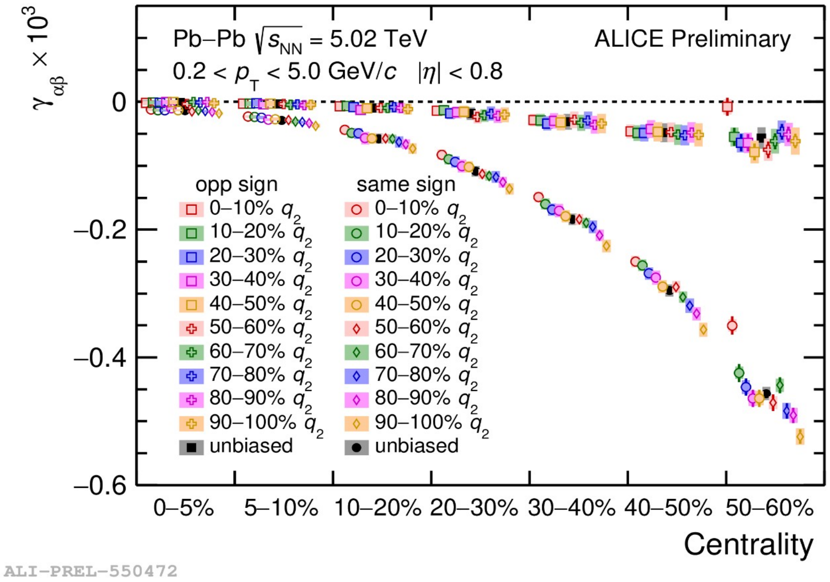
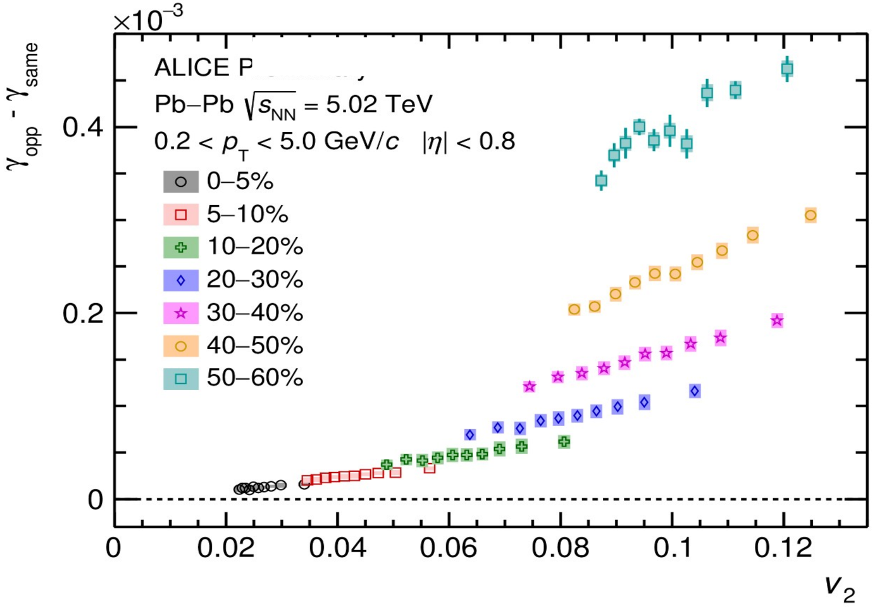


- $q_2^{V0C}$ used to select events with 30% larger or 25% smaller $v_2$ than the average
- $\gamma_{\alpha\beta}$ contains potential CME signal as well as background effects
  - Background contributions are suppressed at the level of $v_2$
- $\gamma_{\alpha\beta}$ depends on the event shape selection in a given centrality bin

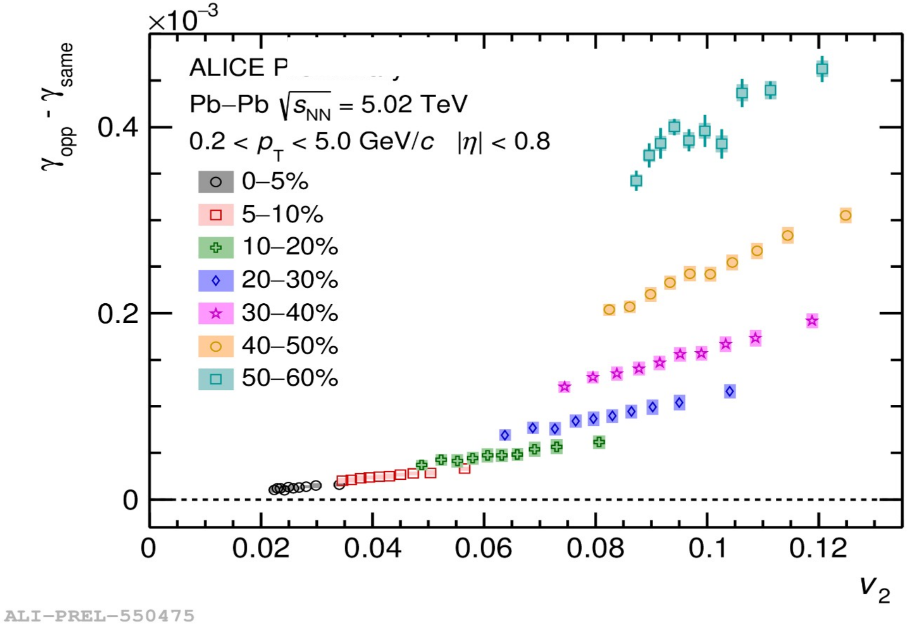
# CME with ESE (II)



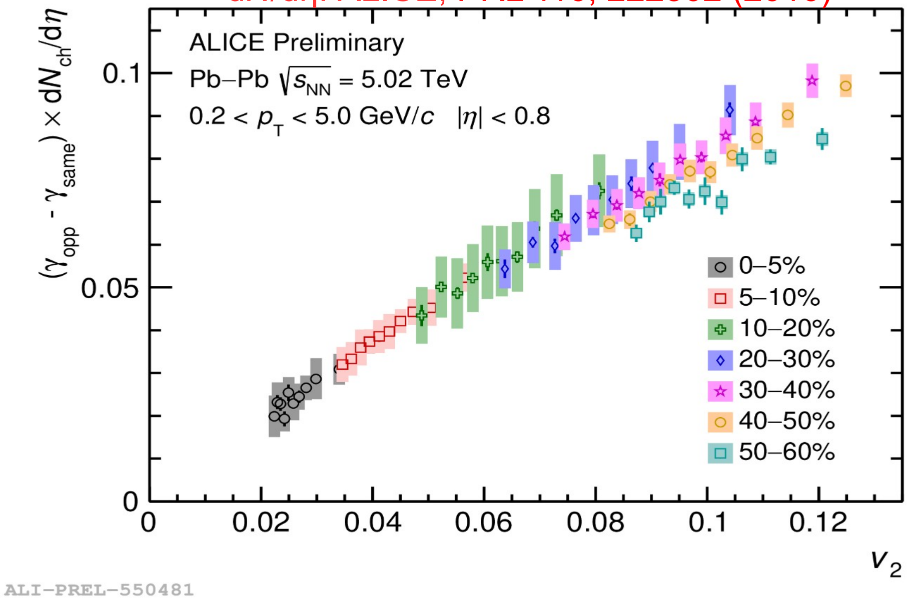
ALI-PREL-550475

- $\gamma_{ab}$ (opp-same) can be used to study the CME
  - Difference is positive for all centrality classes and decreases with centrality and $v_2$ (in a given centrality bin)

# CME with ESE (II)

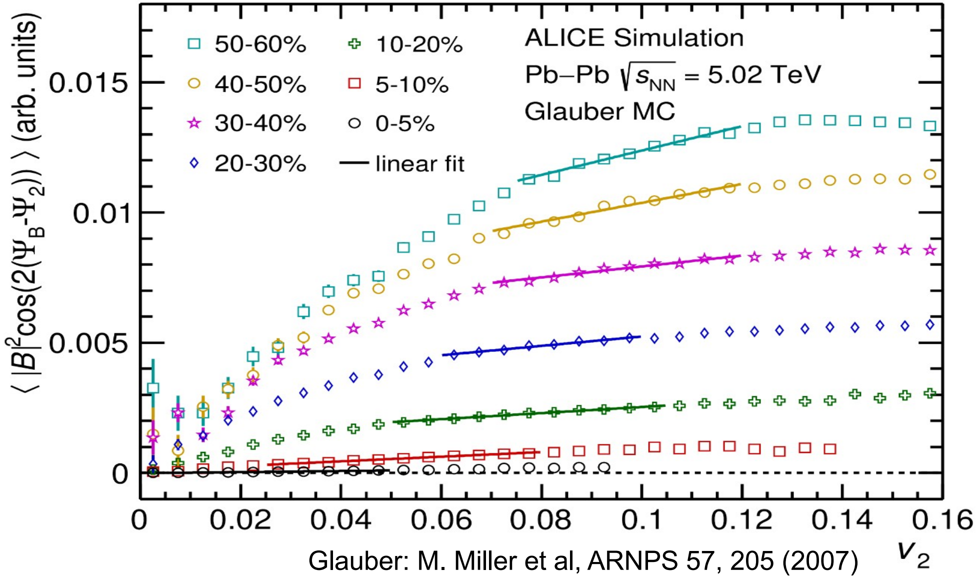


dN/dη: ALICE, PRL 116, 222302 (2016)



- $\gamma_{ab}$ (opp-same) can be used to study the CME
  - Difference is positive for all centrality classes and decreases with centrality and $v_2$ (in a given centrality bin)
  - Difference approximately scales with $v_2$ and multiplicity → mostly background contribution

# Does magnetic field depend on $v_2$ in initial state models?



Glauber: M. Miller et al, ARNPS 57, 205 (2007)

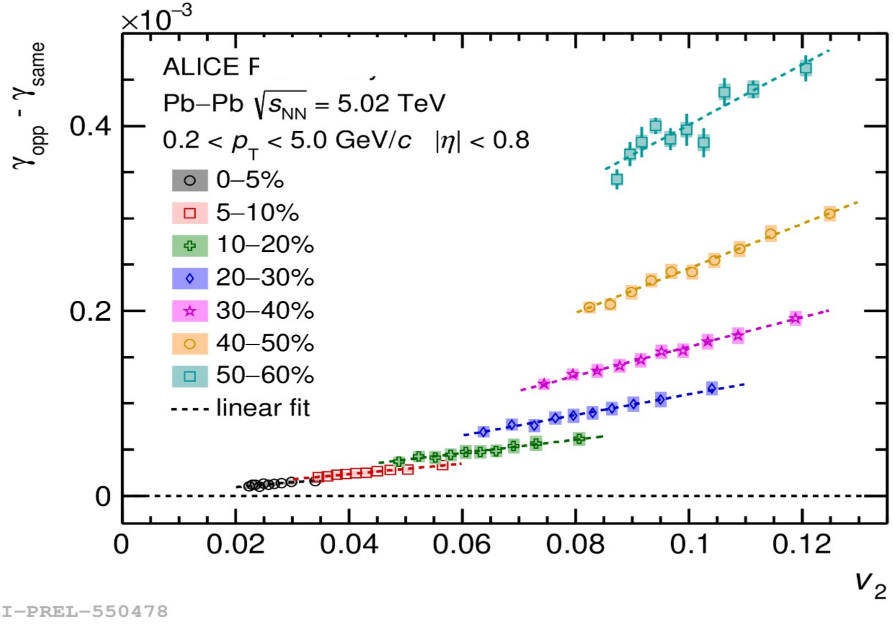
ALI-SIMUL-550490

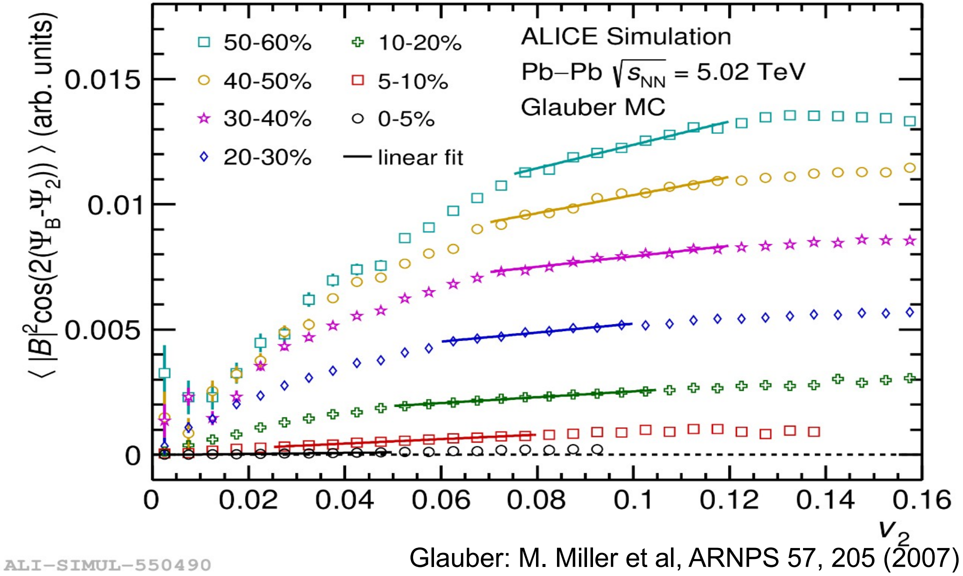
$$eB_s^{\pm}(\tau,\eta,\boldsymbol{x}_\perp) = \pm Z\alpha_{EM}\sinh(Y_0 \mp \eta)\int \mathrm{d}^2\boldsymbol{x}'_\perp \rho_\pm(\boldsymbol{x}'_\perp)[1-\theta_\mp(\boldsymbol{x}'_\perp)] \times \frac{(\boldsymbol{x}'_\perp - \boldsymbol{x}_\perp)\times \boldsymbol{e}_z}{[(\boldsymbol{x}'_\perp - \boldsymbol{x}_\perp)^2 + \tau^2\sinh(Y_0 \mp \eta)^2]^{3/2}}$$

D. Kharzeev et al., NPA 803, 227 (2008)

- Perform a MC Glauber simulation to evaluate the dependence of the CME signal on $v_2$
  - Parameters are tuned to ALICE results
  - Calculate magnetic field at the origin using spectators with the proper time τ=0.1 fm
  - $\langle |B|^2 \cos(2(\Psi_B-\Psi_2))\rangle$, the expected contribution of the CME to $\gamma_{ab}$, shows a strong dependence on $v_2$

# Relating data and models



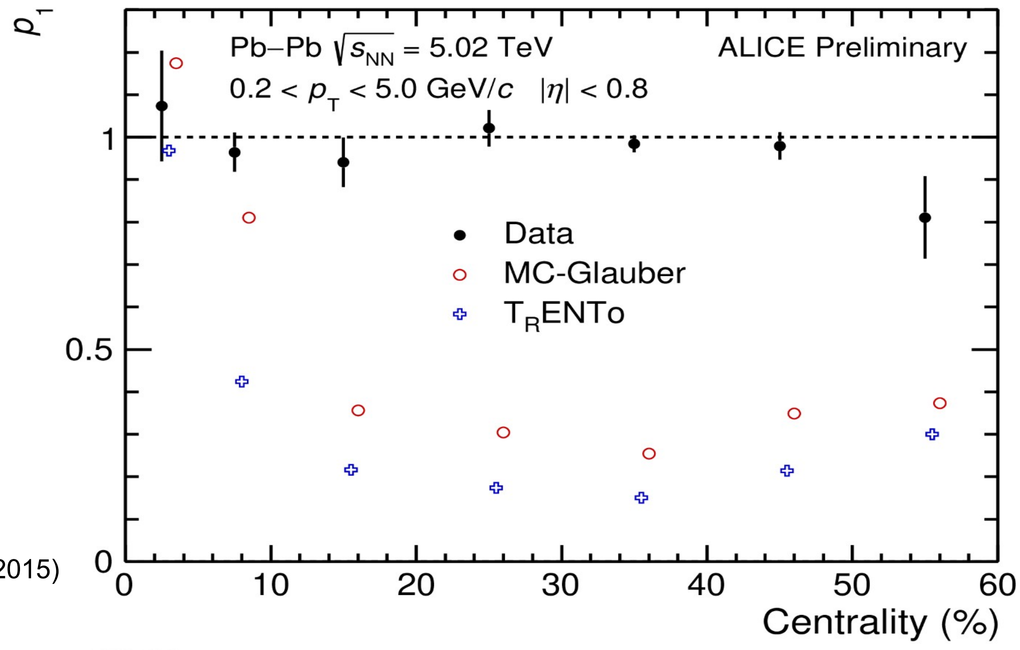


Glauber: M. Miller et al, ARNPS 57, 205 (2007)

- Fit $\gamma_{ab}$ (opp-same) and $\langle |B|^2\cos(2(\Psi_B-\Psi_2))\rangle$ with a linear function to disentangle the potential CME signal from background

$$P_1(v_2) = p_0(1+p_1(v_2-\langle v_2\rangle)/\langle v_2\rangle)$$

# Slopes of data and model fits



Glauber: M. Miller et al, ARNPS 57, 205 (2007)
TRENTO: J. Moreland et al, PRC 92, 011901 (2015)

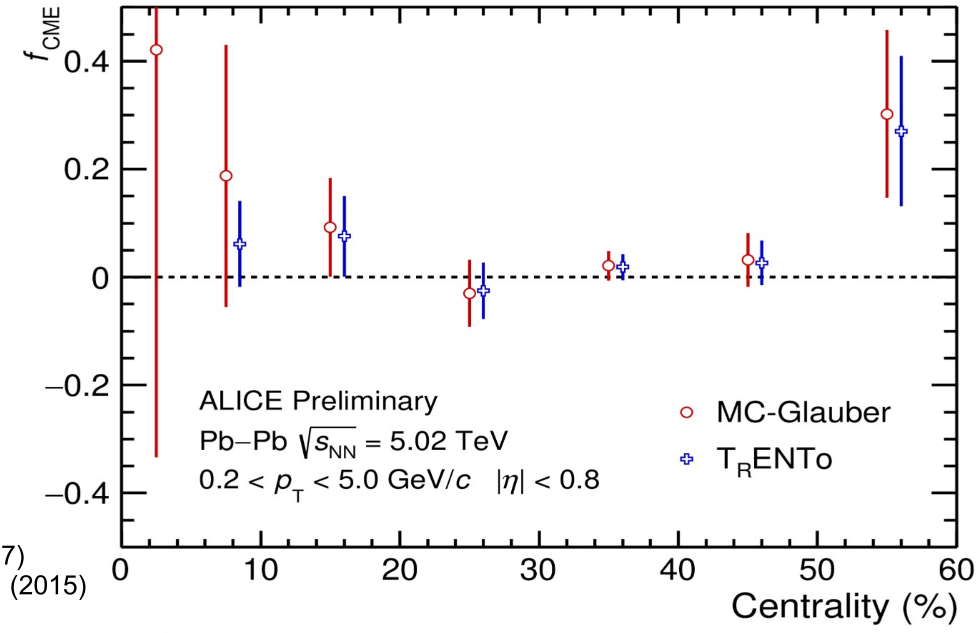
ALI−PREL−550493

- Extract the CME fraction, $f_{\text{CME}}$ relating the slopes of data and model fits according to

$$f_{\text{CME}} * p_{1,MC} + (1 - f_{\text{CME}}) * 1 = p_{1,data}$$

- Assumption: background contribution scales linearly with $v_2$ and the corresponding slope is unity

# CME fraction



Glauber: M. Miller et al, ARNPS 57, 205 (2007)
TRENTO: J. Moreland et al, PRC 92, 011901 (2015)

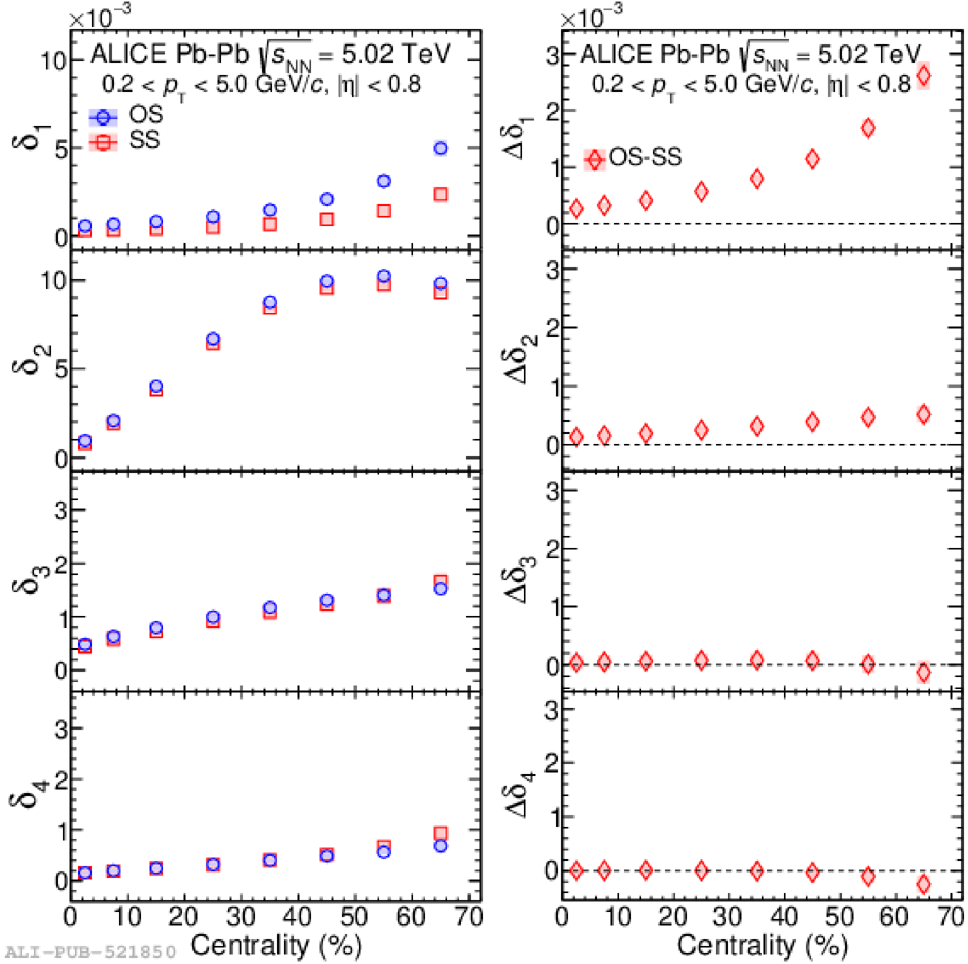
ALI−PREL−550496

- CME fraction in 0–5% is currently statistically limited
- Combining the points from 5–60% gives
  - $f_{CME}$ (Glauber) = 0.028 ± 0.021 → 6.4% at 95% C.L.
  - $f_{CME}$ ($T_R$ENTo) = 0.025 ± 0.018 → 5.5% at 95% C.L.

# “Killing” the signal using higher harmonics

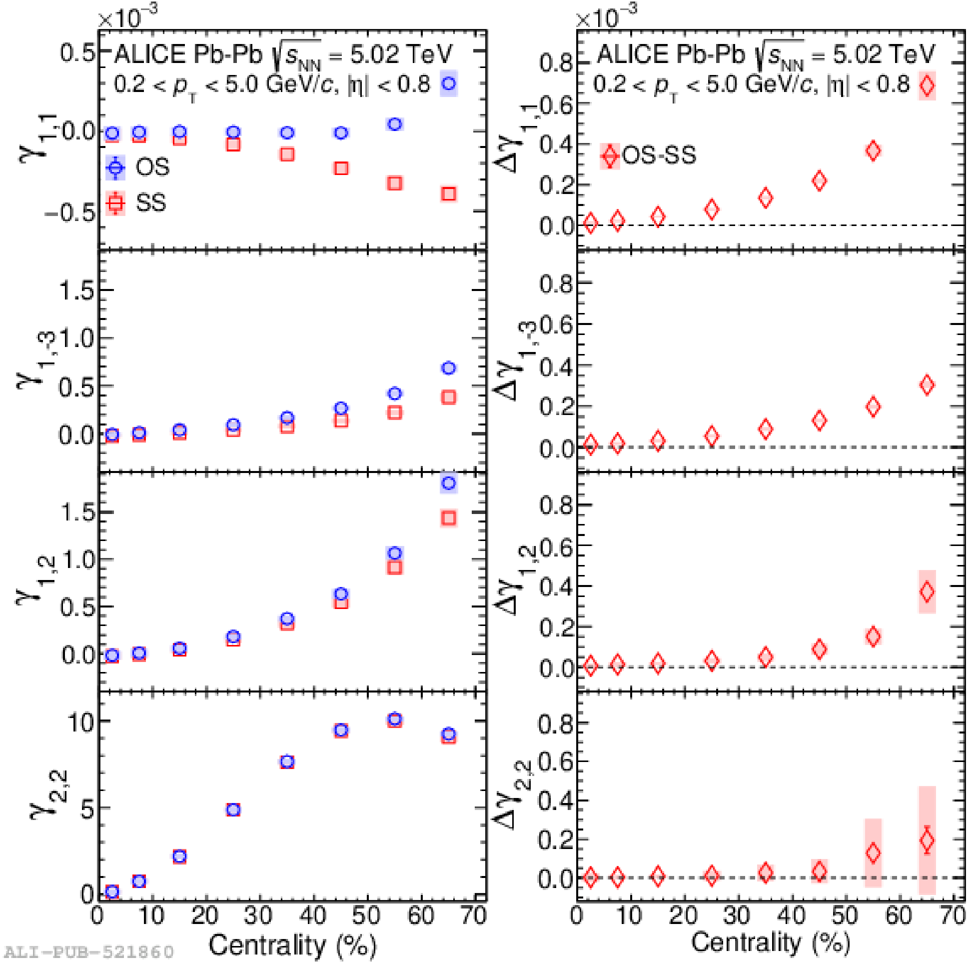
ALICE, JHEP 09, 160 (2020)

# 2-particle correlators



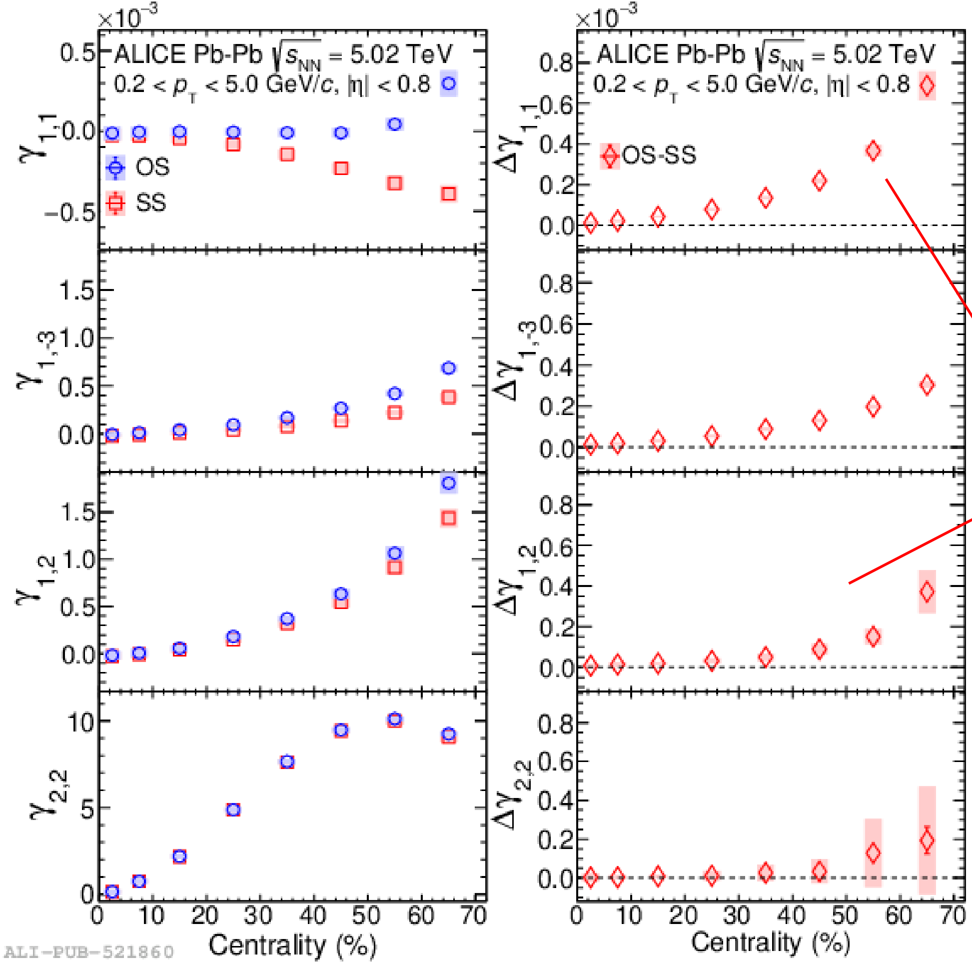
- Weak charge dependence, except $\delta_1$
  - Dominated by background effects → constrain background in $\gamma_{1,1}$

# 3-particle correlators



- $\gamma_{1,1}$ and $\gamma_{1,-3}$ sensitive to CME
- $\gamma_{1,2}$ and $\gamma_{2,2}$ probe only the background
- Significant charge dependence, except $\gamma_{2,2}$
  - Increases from central to peripheral collisions

# 3-particle correlators

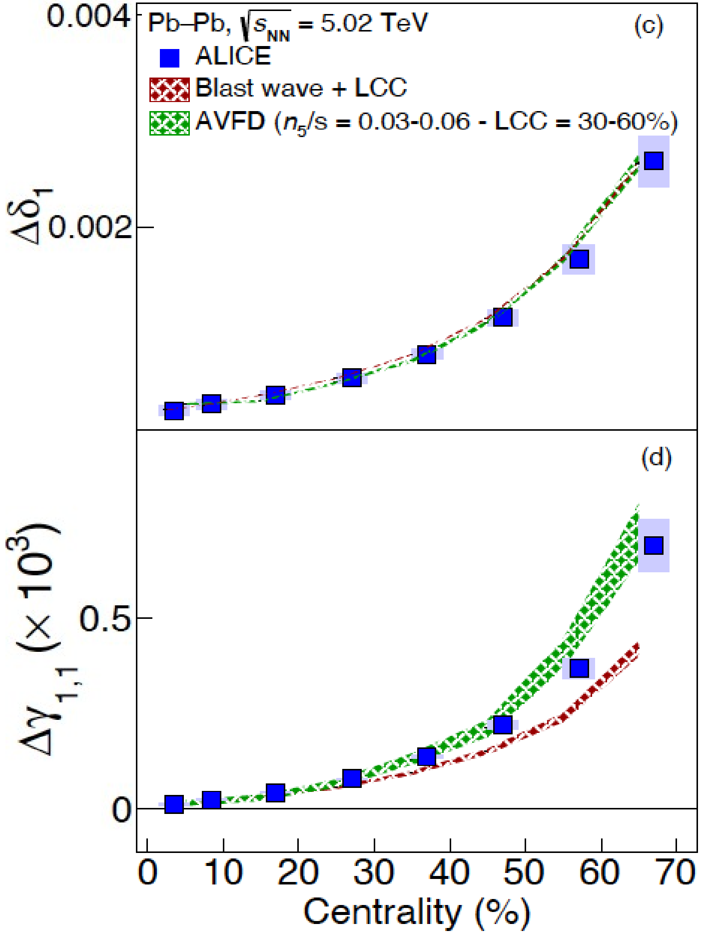


- $\gamma_{1,1}$ and $\gamma_{1,-3}$ sensitive to CME
- $\gamma_{1,2}$ and $\gamma_{2,2}$ probe only the background
- Significant charge dependence, except $\gamma_{2,2}$
  - Increases from central to peripheral collisions
- $\gamma_{1,1}$ and $\gamma_{1,2}$ used to estimate the background contribution to $\gamma_{1,1}$

$$\Delta\gamma_{1,1} \approx \kappa_2 v_2 \Delta\delta_1$$
$$\Delta\gamma_{1,2} \approx \kappa_3 v_3 \Delta\delta_1 \longrightarrow \Delta\gamma^{\mathrm{Bkg}}_{1,1} \approx \Delta\gamma_{1,2} \times \frac{v_2}{v_3}\frac{\kappa_2}{\kappa_3}$$
$$\Delta\gamma_{2,2} \approx \kappa_4 v_4 \Delta\delta_2$$

# Model comparisons

ALICE, arXiv: 2211.04384



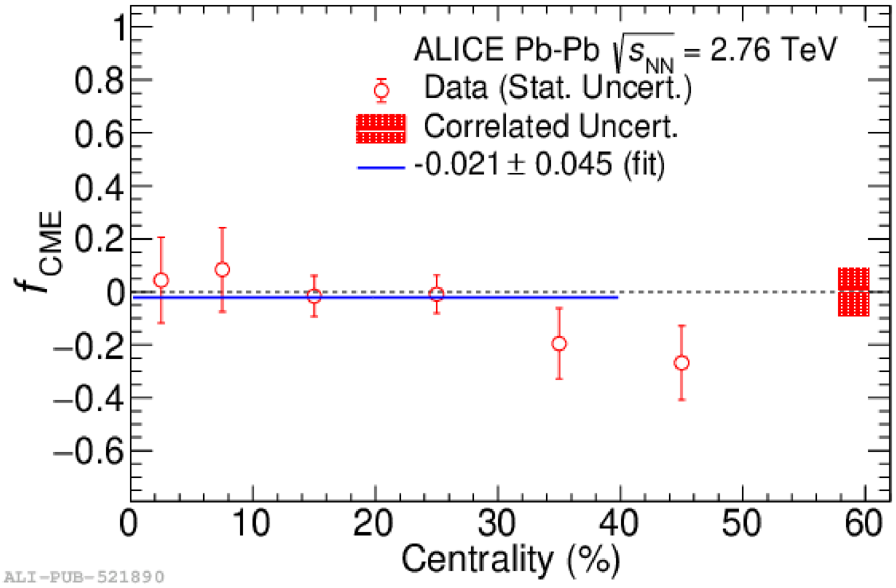
- Blast-Wave + Local Charge Conservation (LCC)
  - Tune the parameters in each centrality class to reproduce $v_2$ and $p_T$ spectra of π, K, p
  - Tune the number of sources emitting balancing pairs
  - Underestimates $\Delta\gamma_{1,1}$ by up to ≈40%
    - Disagreement increases from central to peripheral collisions

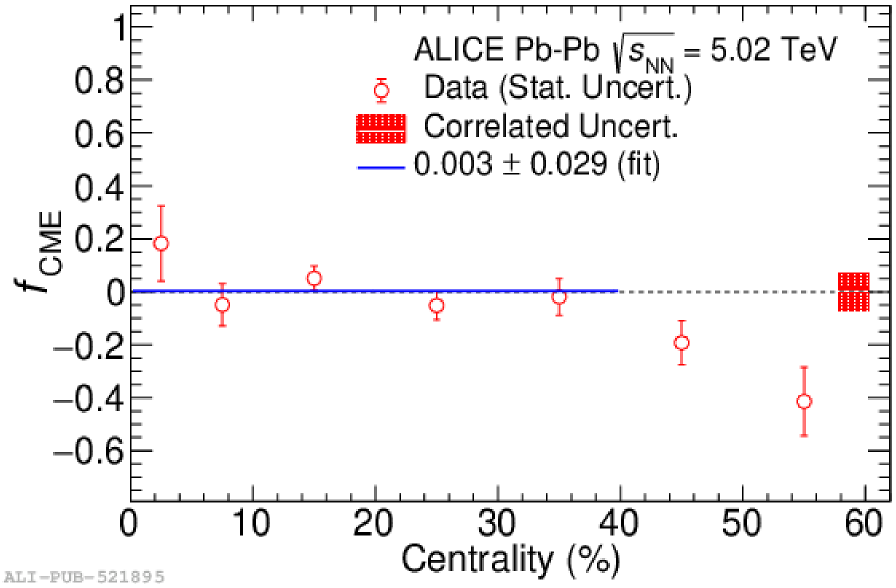
P. Christakoglou et al., EPJC 81, 717 (2021)

- Anomalous Viscous Fluid Dynamics (AVFD)
  - EbyE IC + E/M fields (field lifetime as input)
  - Tune the parameters in each centrality class to reproduce $v_2$ and multiplicity
  - Good agreement with data points
    - Non-zero values for signal

S. Shi et al., AP 394, 50 (2018)
Y. Jiang et al., CPC 42, 011001 (2018)

# CME fraction





- Consistent with 0 for 0–40% and then becomes negative
- Combining the points from 0–40%
  - $f_{CME}^{2.76\ TeV}$ = -0.021 ± 0.045 → 18% at 95% C.L.
  - $f_{CME}^{5.02\ TeV}$ = 0.003 ± 0.029 → 15% at 95% C.L.

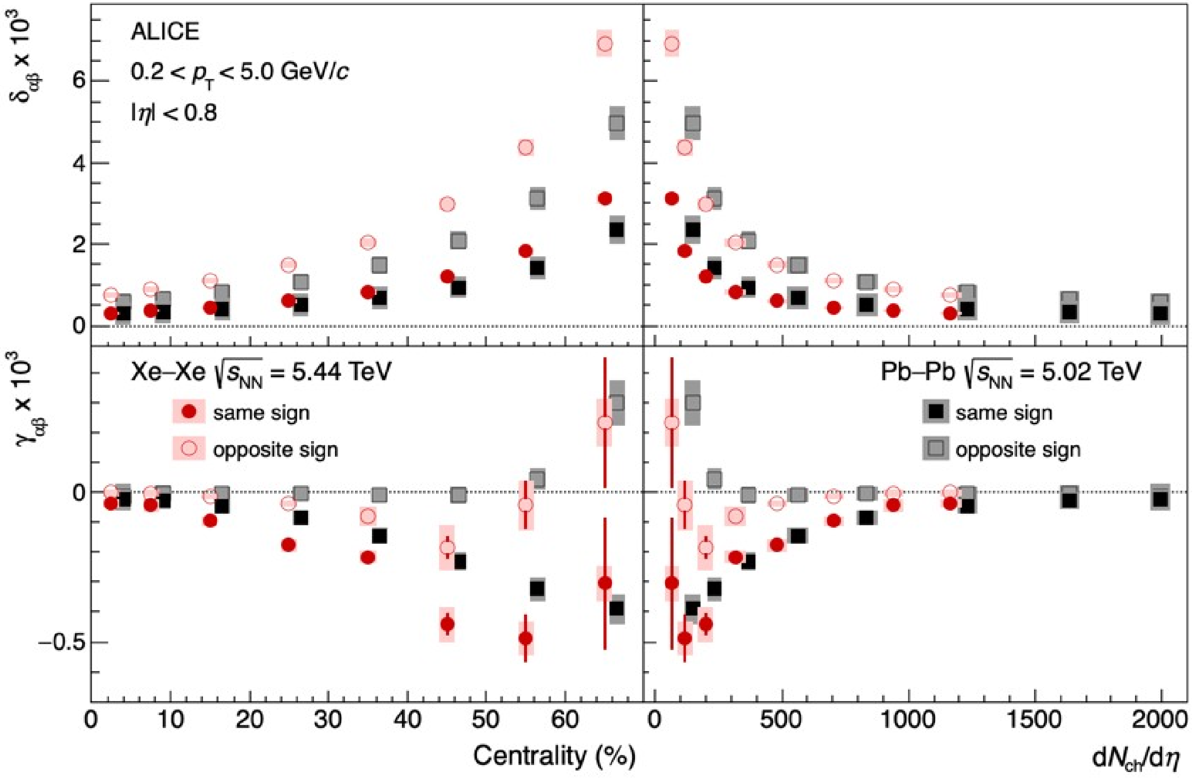
$$f_{\mathrm{CME}} = 1 - \frac{\Delta\gamma_{1,1}^{\mathrm{Bkg}}}{\Delta\gamma_{1,1}}$$

Assumption: $\kappa_2 \approx \kappa_3$

# Varying the signal using different collision systems: Xe–Xe vs Pb–Pb collisions

ALICE, PLB 856, 138862 (2024)

# CME in Xe–Xe and Pb–Pb collisions

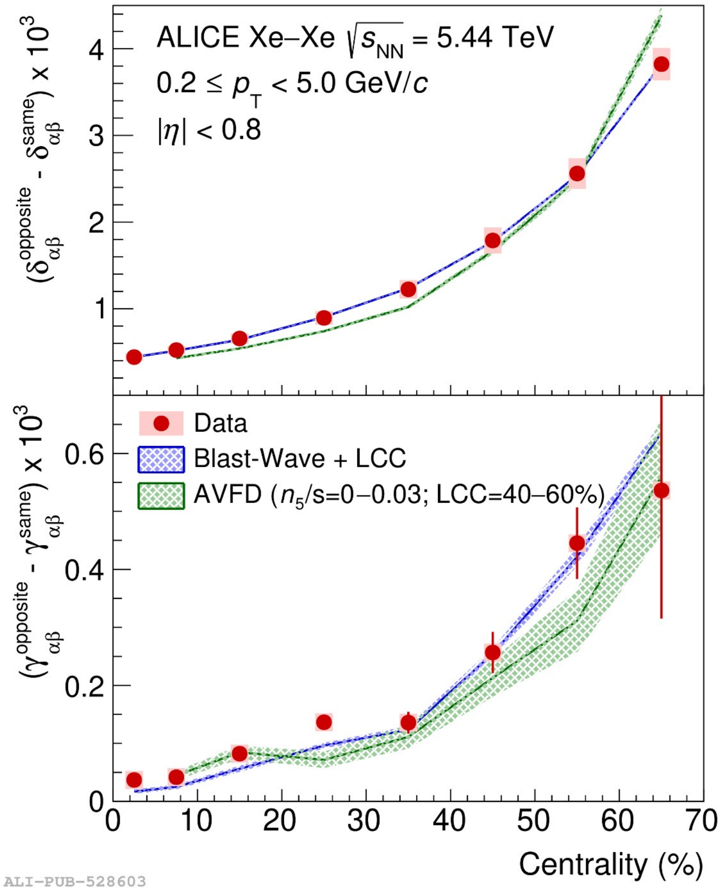


ALICE, JHEP 09, 160 (2020)

ALICE, PRL 116, 222302 (2016)
ALICE, PLB 790, 35 (2019)

- Strong dependence on the charge
- Qualitatively similar centrality dependence
  - Larger magnitude in Xe–Xe than in Pb–Pb collisions
    - Dilution effects arising from different number of particles (CME ~ 1/M)
- Similar values in Xe–Xe and Pb–Pb collisions within uncertainties (vs $dN_{ch}/d\eta$)

# Model comparisons



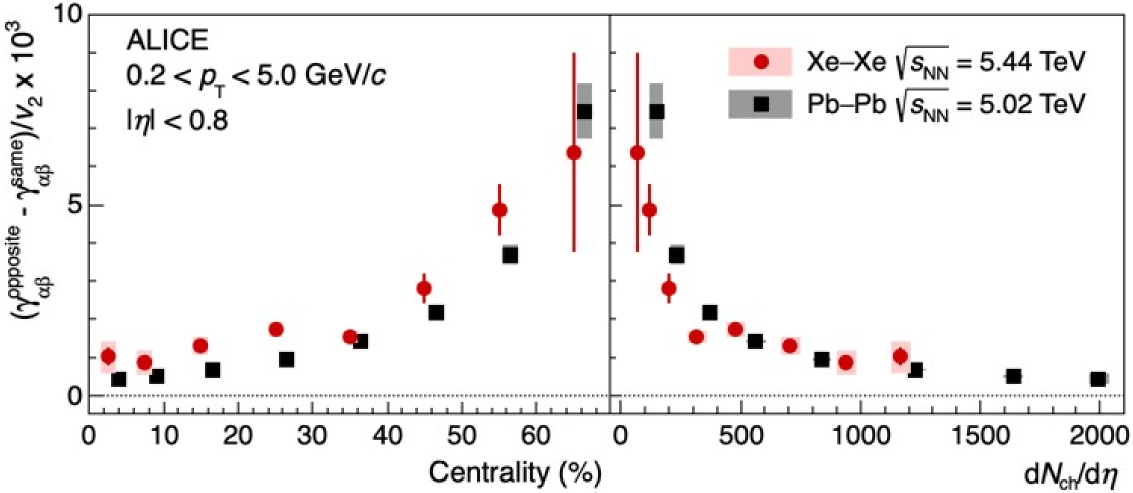
- Blast-Wave + Local Charge Conservation (LCC)
  - Describes fairly well the measured data points
    - Background dominates measurements
    - Not observed in Pb-Pb collisions

- Anomalous Viscous Fluid Dynamics (AVFD)
  - Good agreement with data points
    - Signal consistent with zero

P. Christakoglou et al., EPJC 81, 717 (2021)

S. Shi et al., AP 394, 50 (2018)
Y. Jiang et al., CPC 42, 011001 (2018)

# CME fraction in Xe–Xe and Pb–Pb collisions



- $\gamma_{ab}$ (opp-same) can be used to study CME
  - Similar values in Xe–Xe and Pb–Pb collisions (vs $dN_{ch}/d\eta$) → large background contribution

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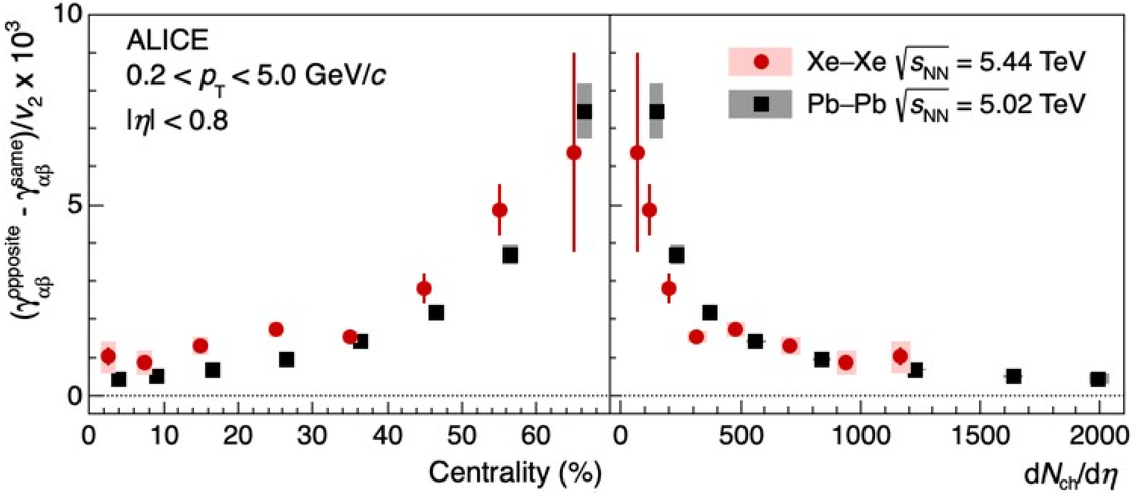
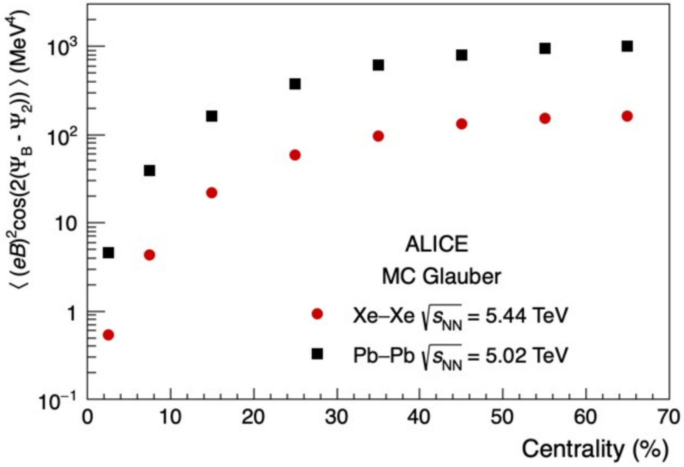




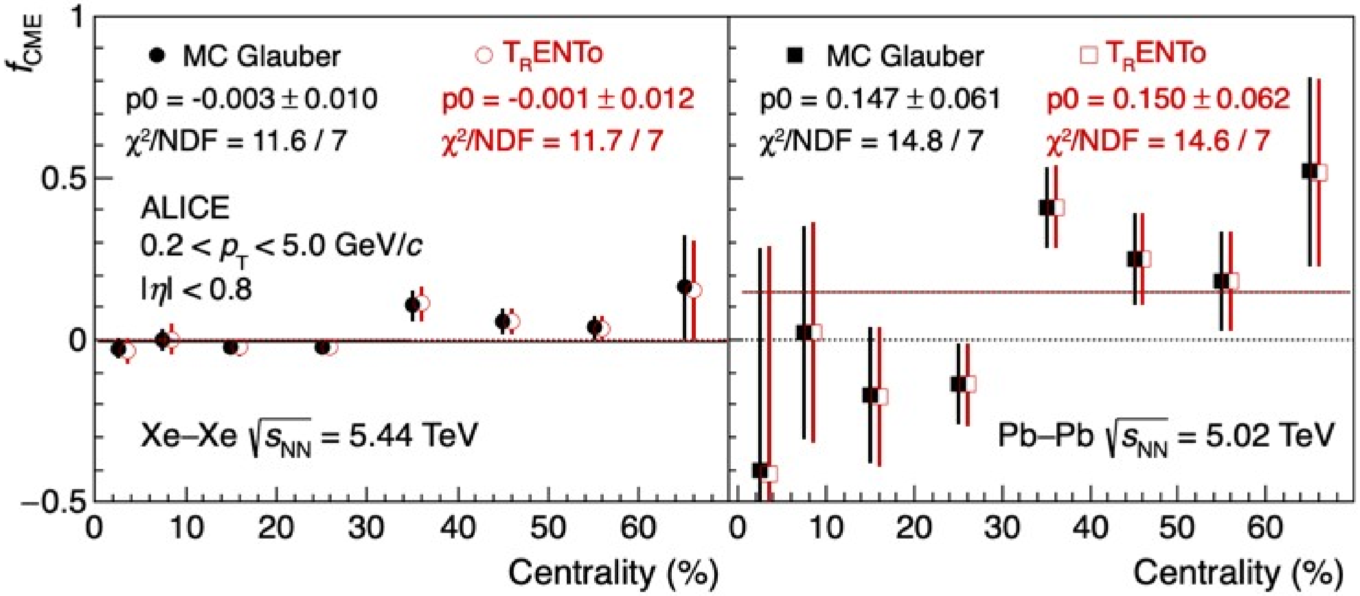
- $\gamma_{ab}$ (opp-same) can be used to study CME
  - Similar values in Xe–Xe and Pb–Pb collisions (vs d$N_{ch}$/d$\eta$) → large background contribution

- CME fraction extracted using a two-component approach
  - Assumption: both signal and background scale with d$N_{ch}$/d$\eta$
    - d$N_{ch}$/d$\eta$ used to compensate for dilution
  - <$|B|^2\cos(2(\Psi_B-\Psi_2))$> from MC simulations

$$(\mathrm{d}N_{ch}/\mathrm{d}\eta)^{Xe}\Delta\gamma_{ab}^{Xe} = sB^{Xe} + b v_2^{Xe}$$
$$(\mathrm{d}N_{ch}/\mathrm{d}\eta)^{Pb}\Delta\gamma_{ab}^{Pb} = sB^{Pb} + b v_2^{Pb}$$

$$f_{CME} = \frac{sB}{sB + b v_2}$$

# CME fraction in Xe–Xe and Pb–Pb collisions



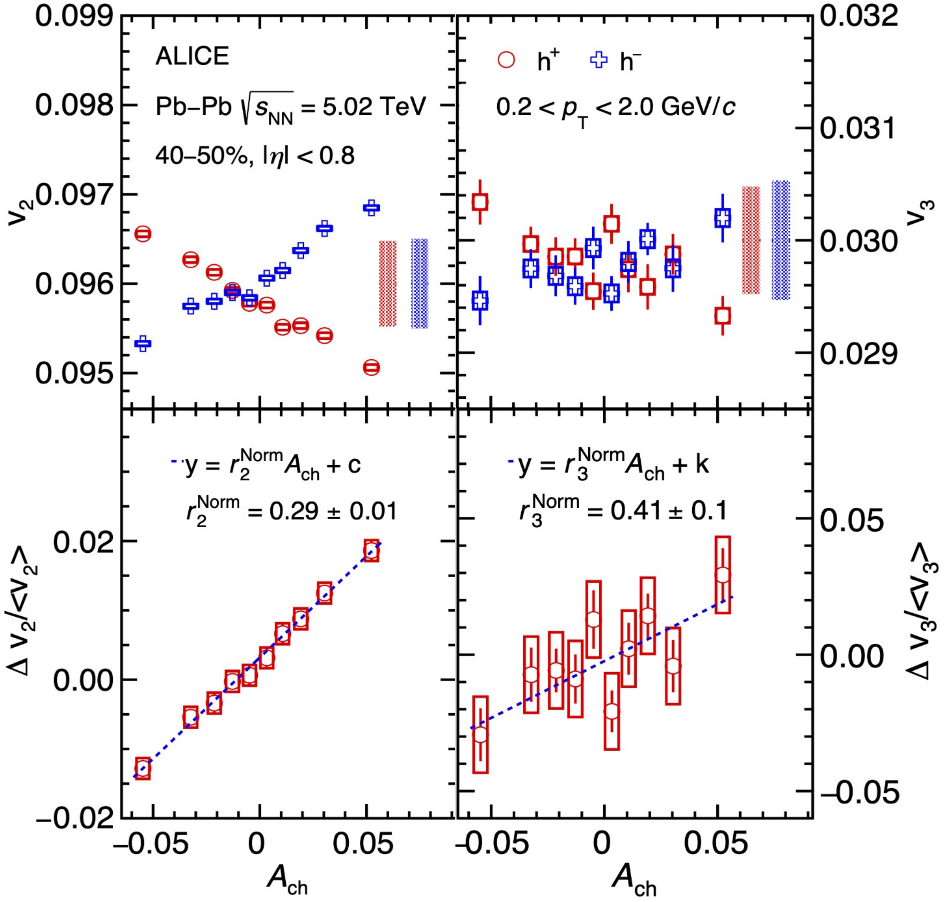
- Consistent with 0 for 0–30% and then becomes positive
- Combining the points from 0–70%
  - $f_{CME}^{Xe}$ = -0.003 ± 0.010 → 2% at 95% C.L.
  - $f_{CME}^{Pb}$ = 0.147 ± 0.061 → 25% at 95% C.L.

$$f_{\text{CME}} = \frac{s\,B}{s\,B + b\,v_2}$$

# Chiral Magnetic Wave

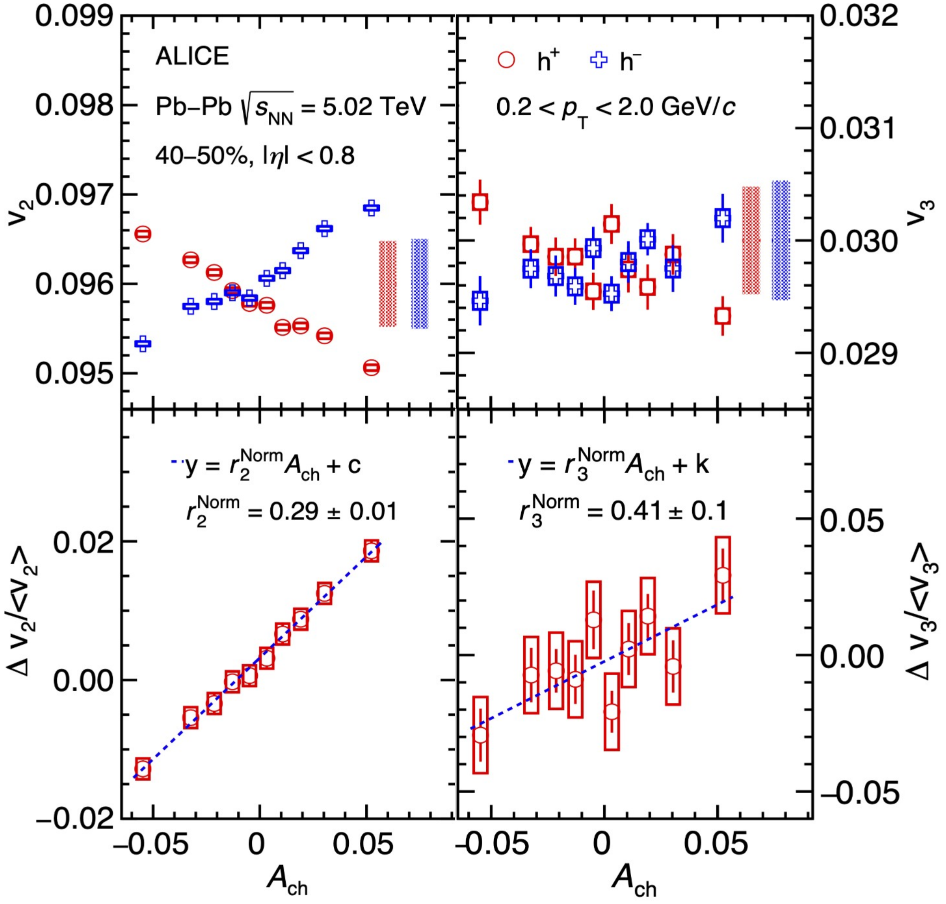
ALICE, JHEP 12, 067 (2023)

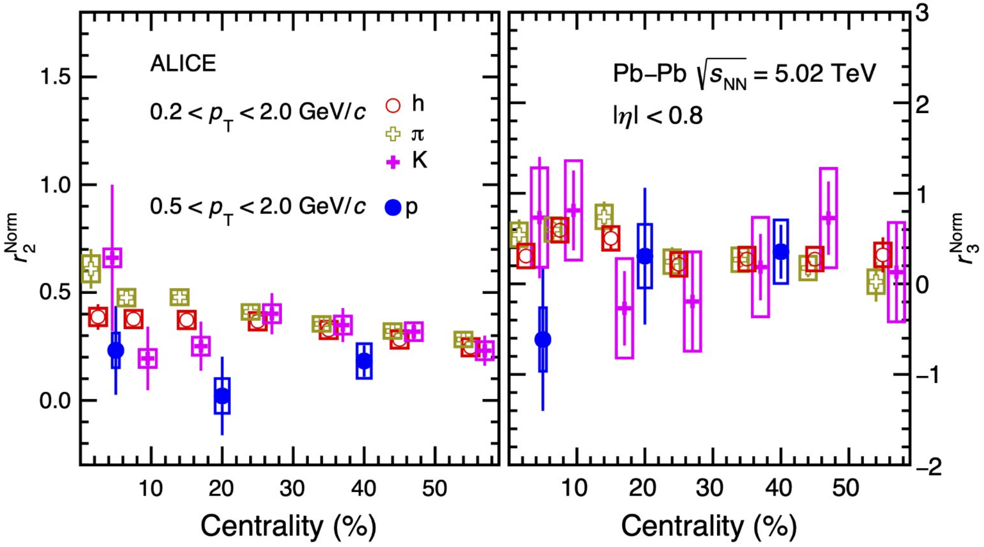
# $v_2$ and $v_3$ vs. $A$



- Finite $r_n^{Norm}$

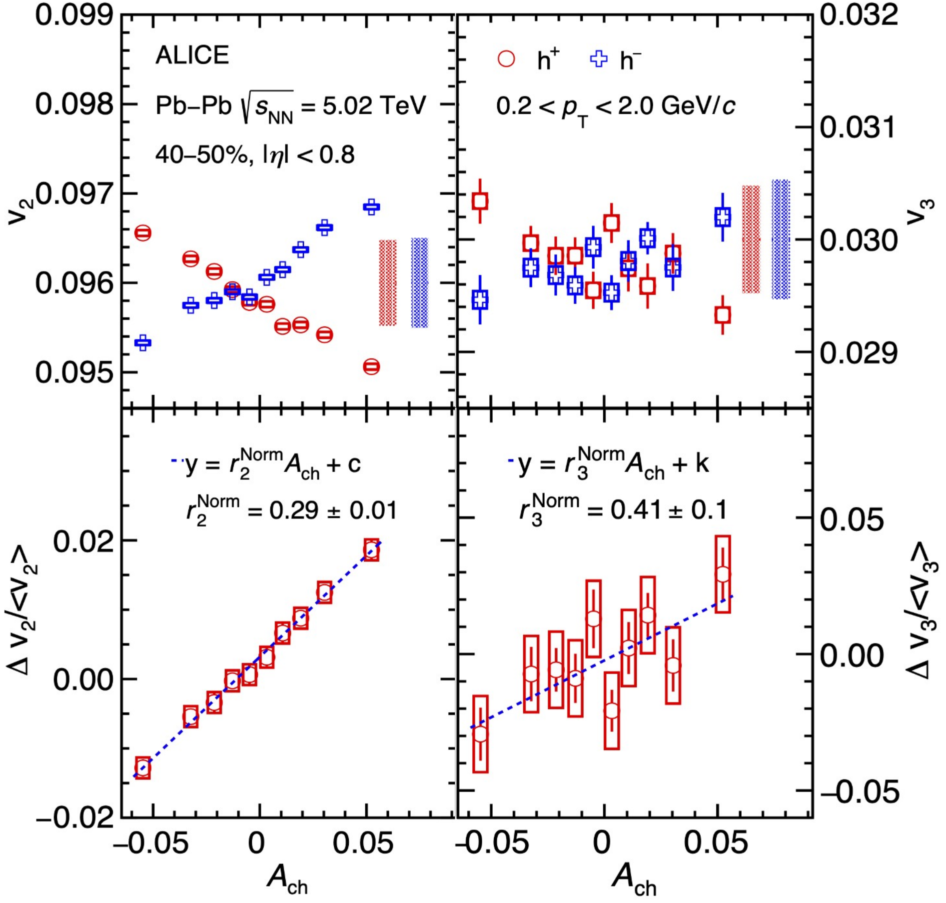
# $v_2$ and $v_3$ vs. $A$

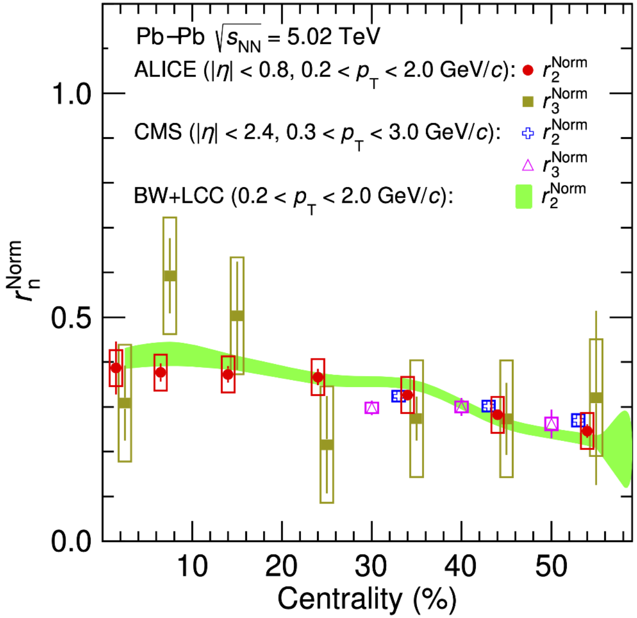




- Finite $r_n^{\rm Norm}$
- $r_2^{\rm Norm}$ consistent with $r_3^{\rm Norm}$
  - No particle type dependence

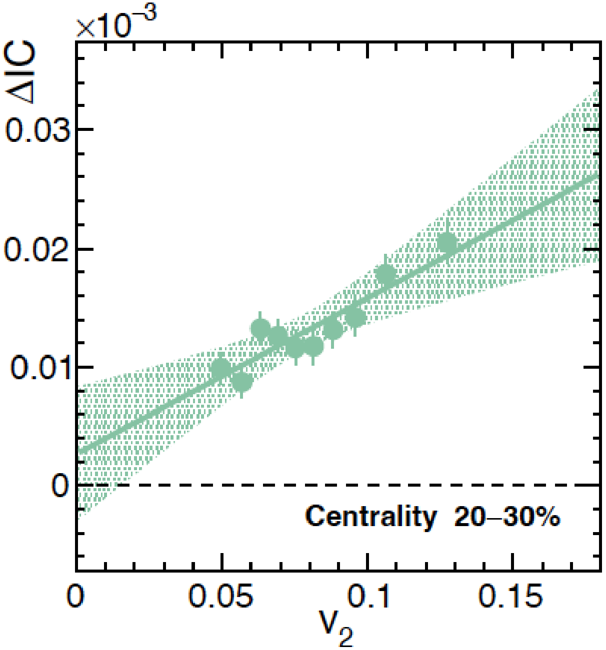
# $v_2$ and $v_3$ vs. $A$

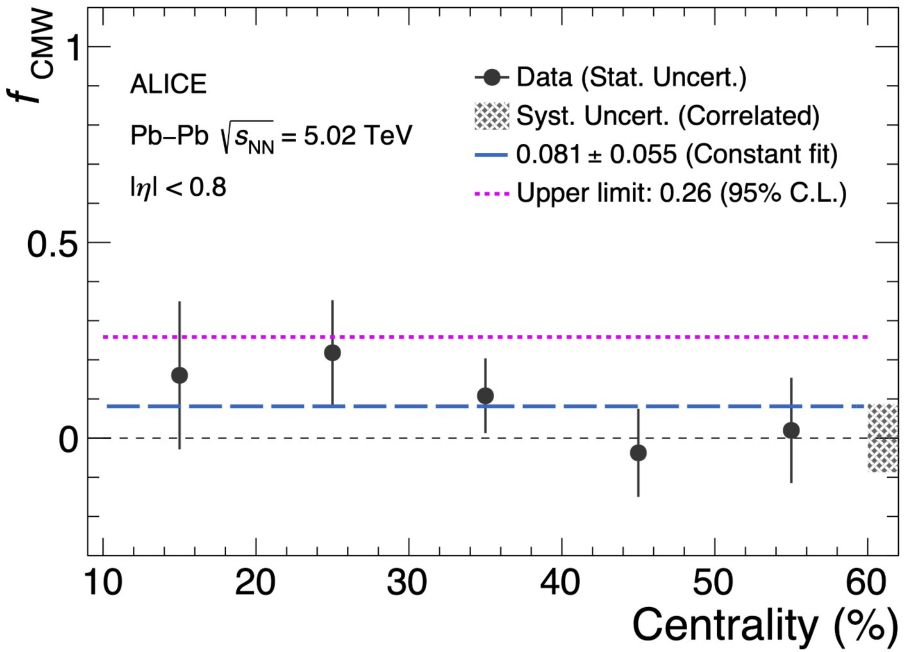




- Finite $r_n^{Norm}$
- $r_2^{Norm}$ consistent with $r_3^{Norm}$
  - No particle type dependence
- Good agreement with CMS results and BW calculations

# CMW fraction





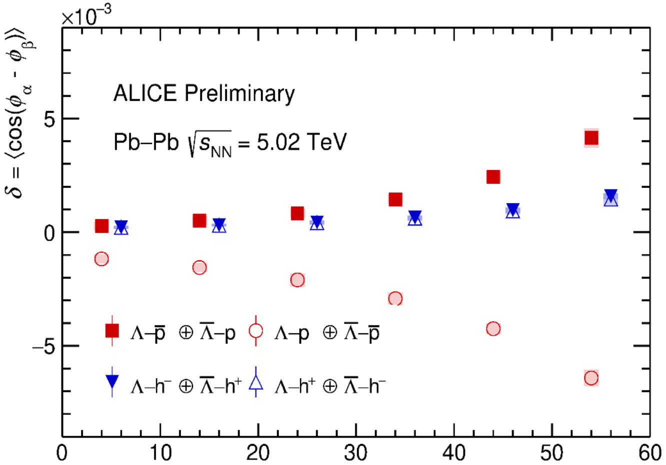
- ΔIC approximately scales with $v_2$ → large background contribution
- $f_{\mathrm{CMW}}$ extracted by fitting ΔIC vs. $v_2$ with a linear function $av_2+b$
- Combining the points from 10–60 %
  - $f_{\mathrm{CMW}} = 0.081 \pm 0.055$ → 26% at 95% C.L.

$$f_{\mathrm{CMW}} = \frac{b}{a\langle v_2\rangle + b}$$

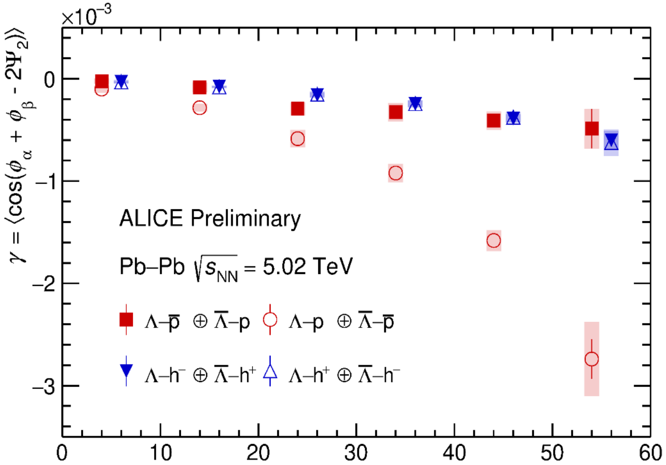
C. Wang et al., PLB 820, 136580 (2021)

# Chiral Vortical Effect

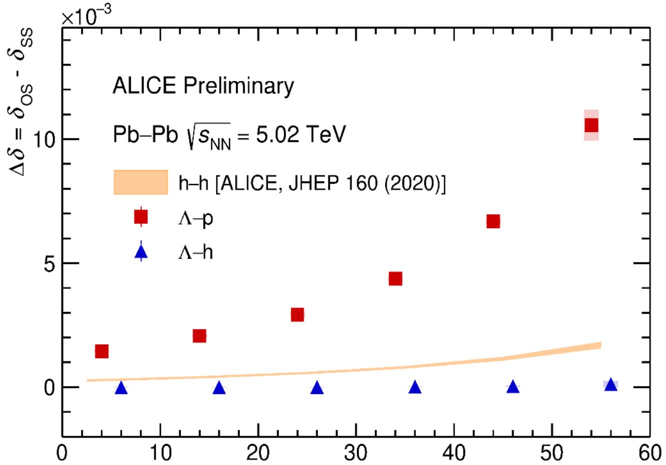
# CVE



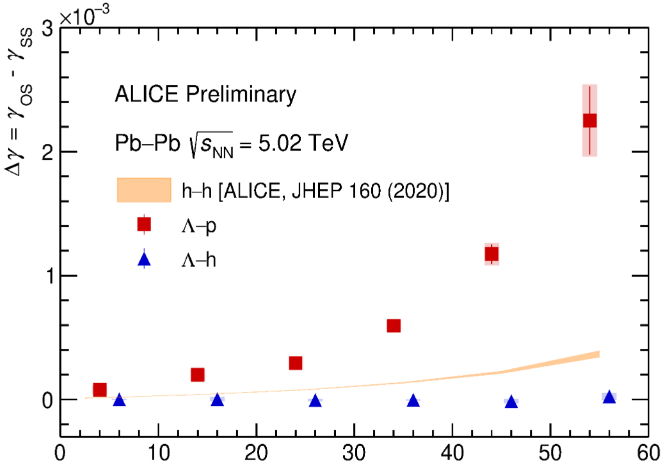
ALI-PREL-558097



ALI-PREL-558107



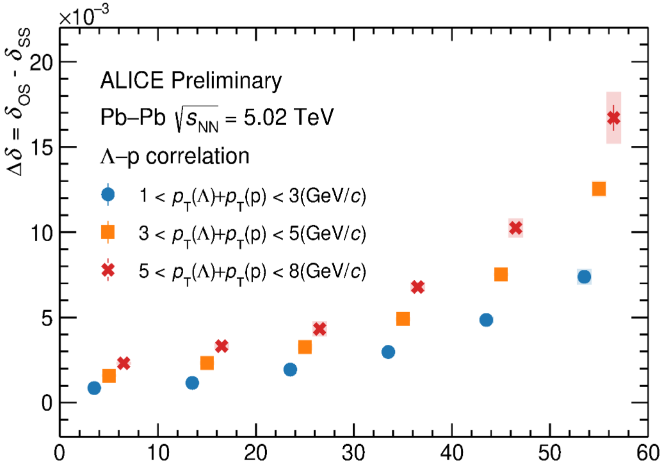
ALI-PREL-558102



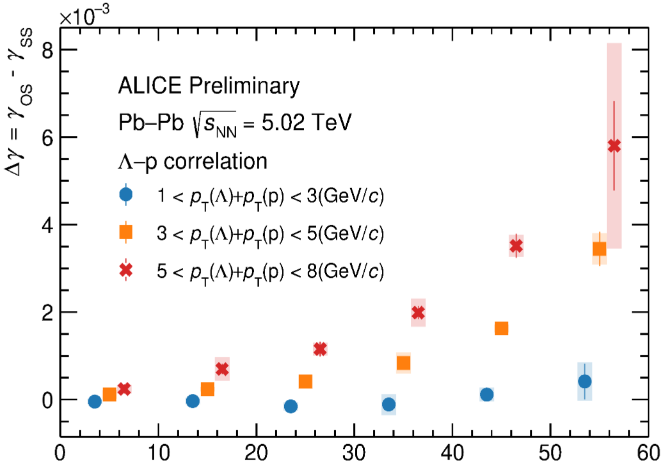
ALI-PREL-558122

- Avoid CME ambiguity by using Λ baryon (Λ → πp)
- Significant δ and γ separation of Λ–p
  - ~10 times larger than CME
  - Increasing with centrality
- Close to zero δ and γ separation of Λ–h

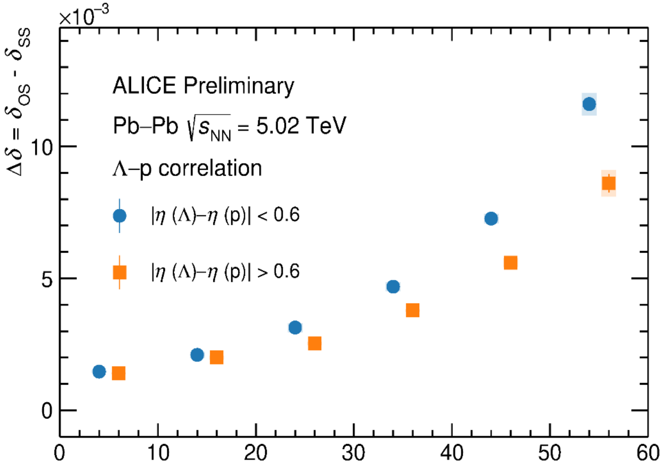
# CVE: differential analysis



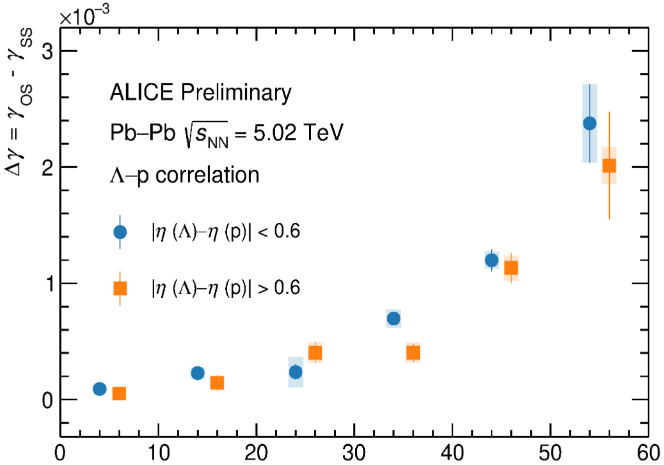
ALI-PREL-558112



ALI-PREL-558127



ALI-PREL-558137

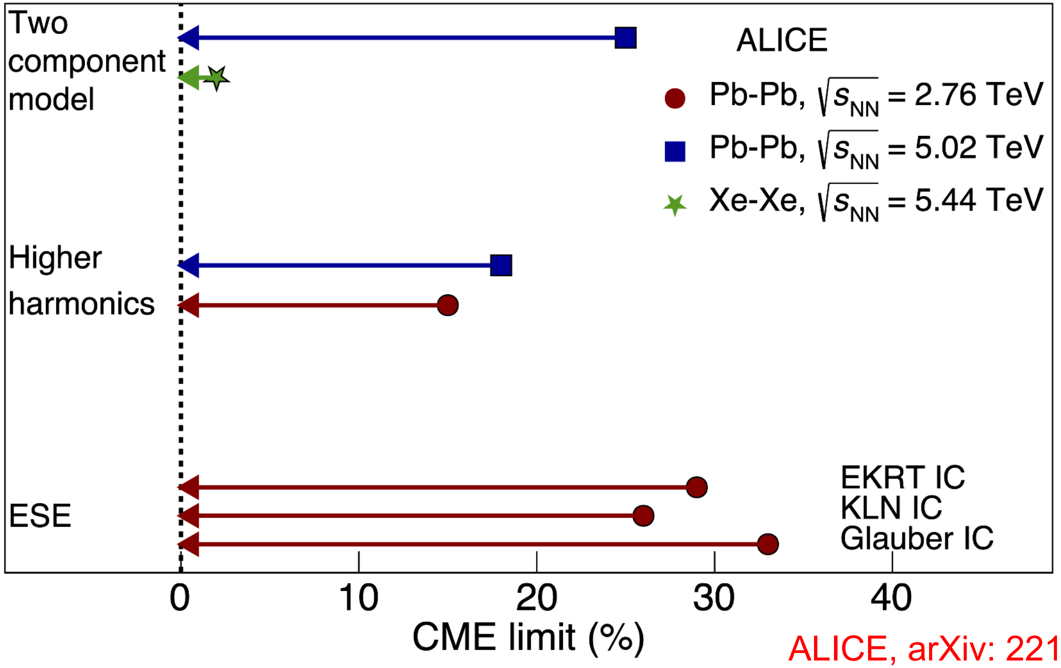


ALI-PREL-558087

- Larger $\Delta\delta$ and $\Delta\gamma$ for larger $\sum p_T$
- Larger $\eta$ gap → small $\Delta\delta$
  - Non-flow contributions?
- Larger $\eta$ gap → moderate $\Delta\gamma$
- Constrain theoretical models

# Summary

- Anomalous chiral searches performed in different collision systems
  - Background dominates the measurements
  - Different approaches used to separate the signal from the background

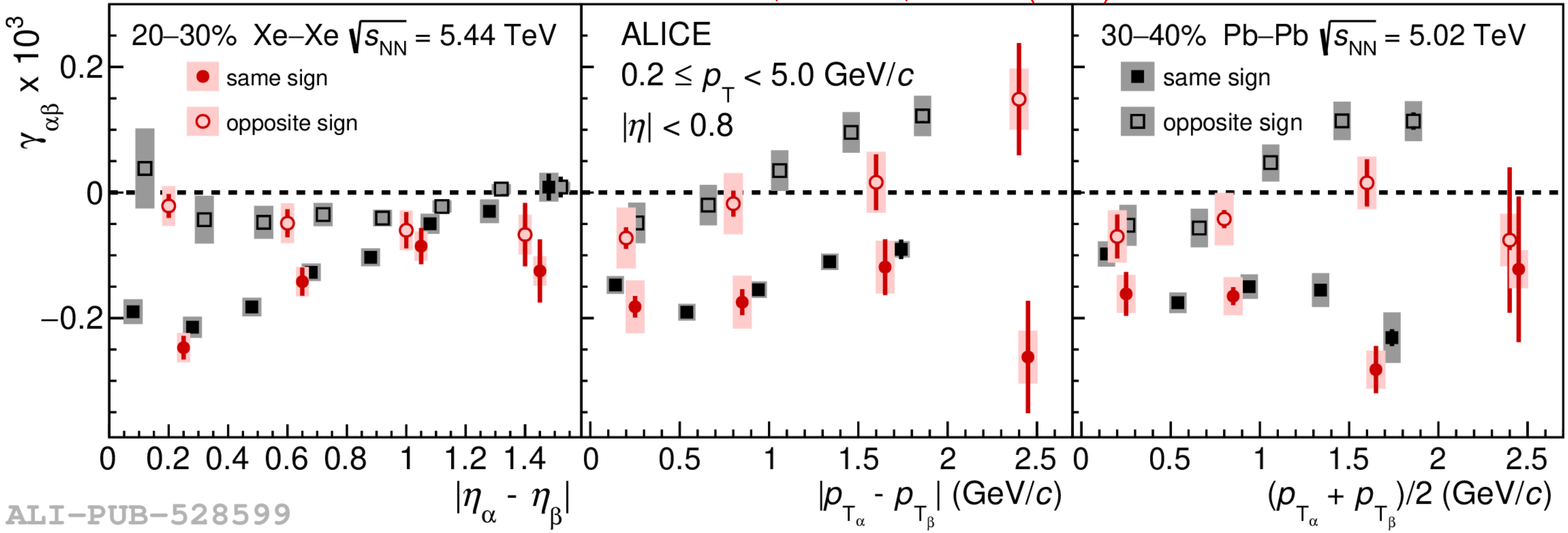


ALICE, arXiv: 2211.04384

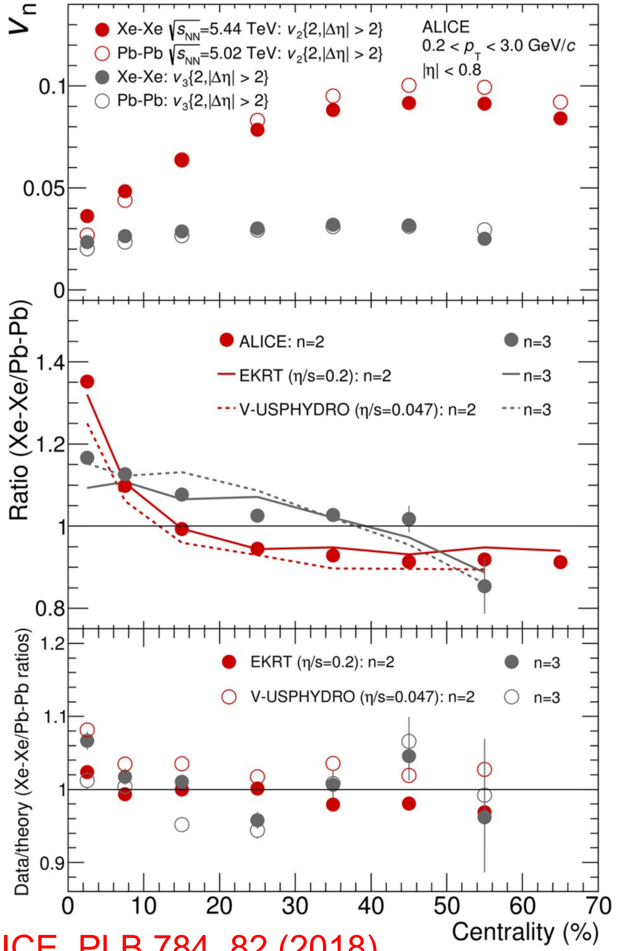
# Backup

# 3-particle correlator: differential results in Xe–Xe and Pb–Pb collisions

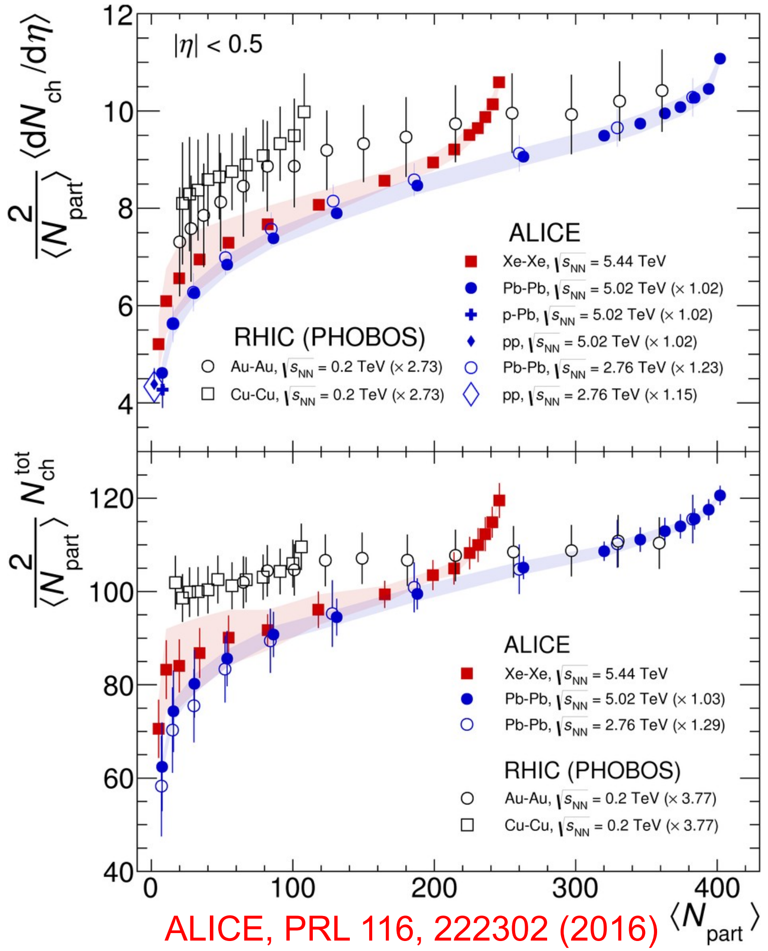
ALICE, PLB 856, 138862 (2024)



# $v_2$ and d$N_{ch}$/d$\eta$ in Xe–Xe and Pb–Pb collisions



ALICE, PLB 784, 82 (2018)



ALICE, PRL 116, 222302 (2016)
ALICE, PLB 790, 35 (2019)