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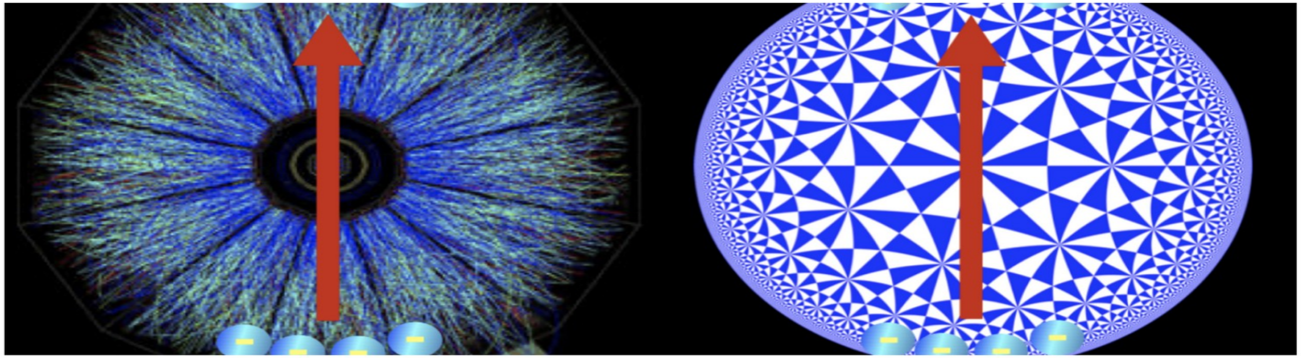
ALICE

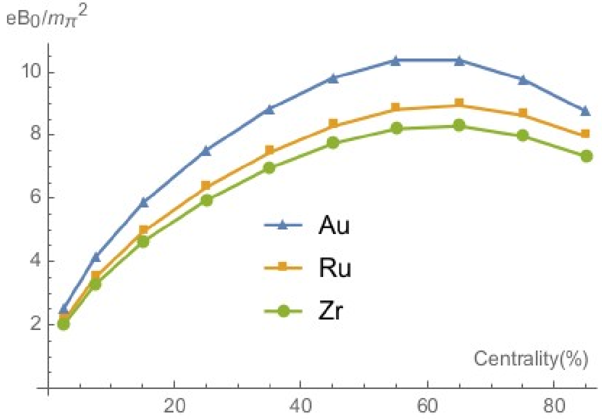
Searching for the Chiral Magnetic Effect with ALICE

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

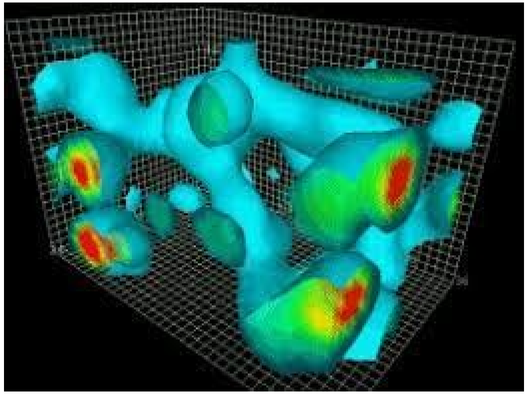
HOLOGRAPHIC PERSPECTIVES ON CHIRAL TRANSPORT



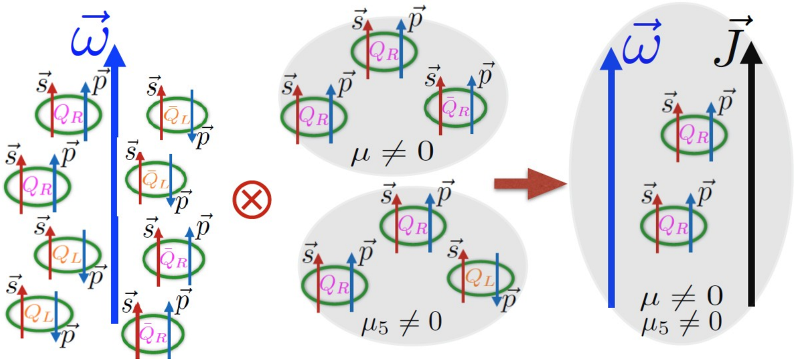
Chiral Magnetic Effect (CME)



G-R. Liang et al., arxiv 2004.04440



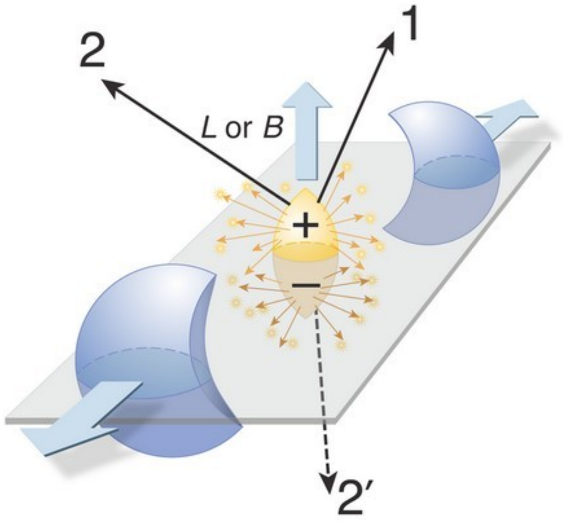
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/



D. Kharzeev, PLB 633, 260 (2006)
D. Kharzeev et al., NPA 797, 67 (2007)
D. Kharzeev et al., PRD 83, 085007 (2011)
D. Kharzeev et al, PPNP 88, 1 (2016)

- **Heavy-ion collisions**: strong magnetic field (B~10^{15} T)
- **Theory**: QCD domains with P and CP symmetries locally broken
- **CME**: electric current along magnetic field
  - Charge separation perpendicular to the reaction plane
- Interpretation of the results complicated by background contributions

Observables



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

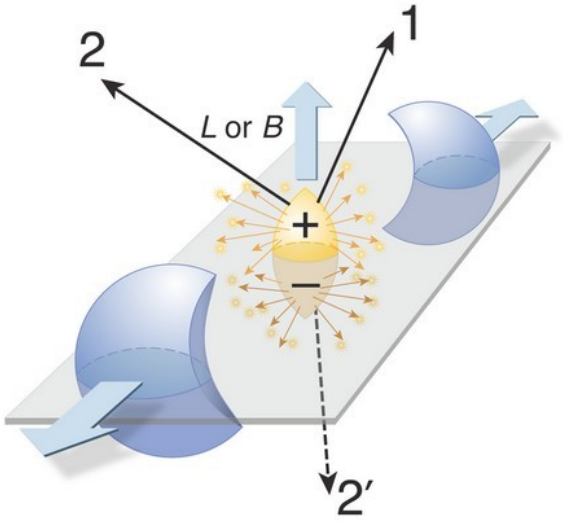
2-particle correlator

STAR, PRC 81, 054908 (2009)

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

$$\langle \cos(\varphi_a - \varphi_b) \rangle = \langle \cos[(\varphi_a - \Psi_{RP}) - (\varphi_b - \Psi_{RP})] \rangle$$
$$= \langle \cos(\Delta\varphi_a - \Delta\varphi_b) \rangle = \langle v_{1,a} v_{1,b} \rangle + \langle a_{1,a} a_{1,b} \rangle + B_{in} + B_{out}$$

Observables



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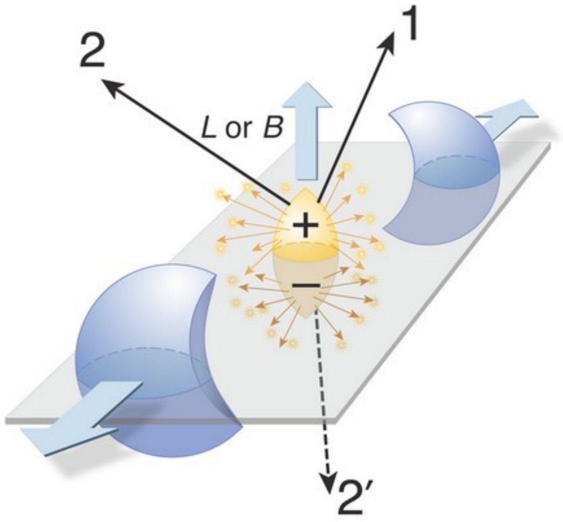
3-particle correlator

S. Voloshin, PRC 70, 057901 (2004)

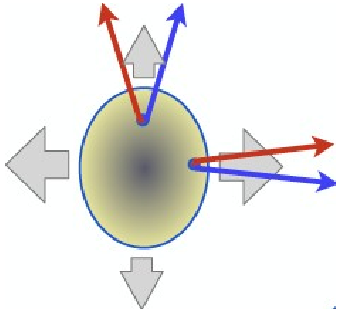
$$\gamma_{m,n} = \langle \cos(m\varphi_a + n\varphi_b - (m+n)\Psi_{|m+n|}) \rangle$$

$$\langle \cos(\varphi_a + \varphi_b - 2\Psi_{RP}) \rangle = \langle \cos[(\varphi_a - \Psi_{RP}) + (\varphi_b - \Psi_{RP})] \rangle$$
$$= \langle \cos(\Delta\varphi_a - \Delta\varphi_b) \rangle = \langle v_{1,a} v_{1,b} \rangle - \langle a_{1,a} a_{1,b} \rangle + B_{in} - B_{out}$$

Observables



“Flowing clusters”



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

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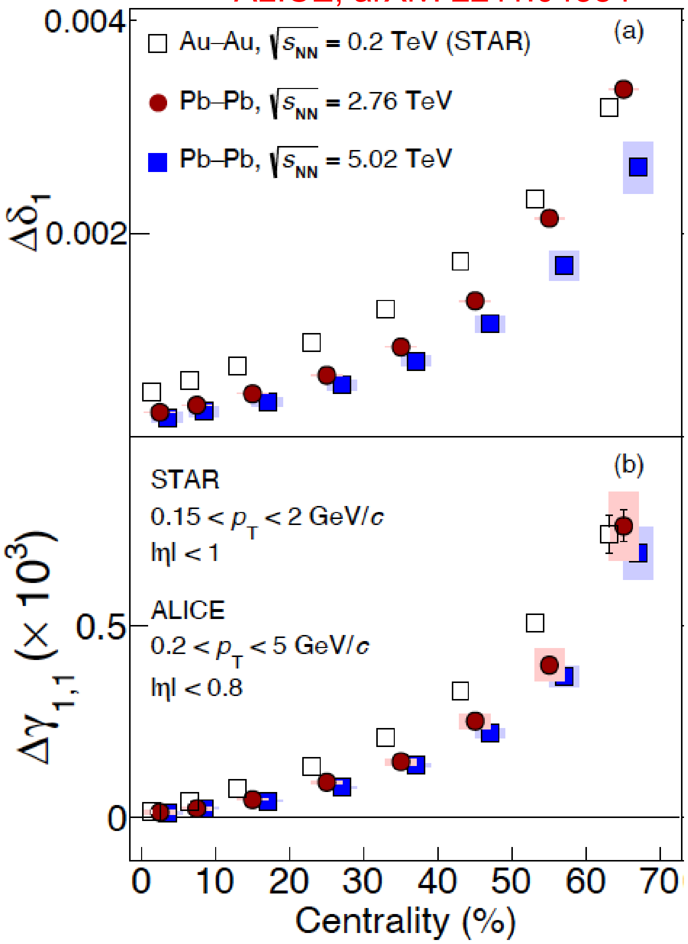
$$= \langle \cos(\Delta\varphi_a - \Delta\varphi_b) \rangle = \langle v_{1,a} v_{1,b} \rangle - \langle a_{1,a} a_{1,b} \rangle + B_{in} - B_{out}$$

B_{in} and B_{out} background contributions projected onto Ψ_{RP} and perpendicular to it

$$B_{in} - B_{out} \propto v_{2,cluster} \langle \cos(\varphi_a + \varphi_b - 2\varphi_{cluster}) \rangle$$

CME @ LHC

ALICE, arXiv: 2211.04384

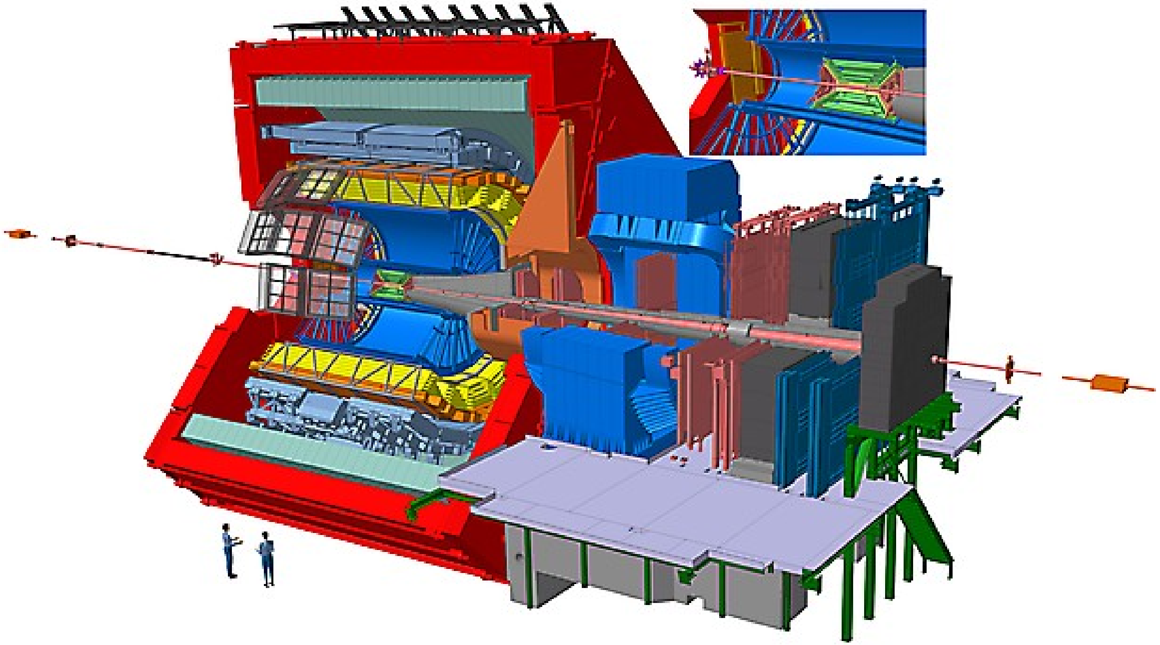


- Strong centrality dependence consistent with naive expectations from CME
- Similar magnitude between RHIC and LHC
  - Different dilution effects (3x larger $dN_{ch}/d\eta$ at LHC than at RHIC)
  - Different magnitude of the magnetic field
- Large contribution from background → local charge conservation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

A Large Ion Collider Experiment



- Inner Tracking System (ITS)
  - Tracking, triggering, vertexing
- Time Projection Chamber (TPC)
  - Tracking, vertexing, Ψ_n
- V0 detector
  - Triggering, centrality, Ψ_n

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

q_2 selection | v_2/CME/Ψ_n | Ψ_2

V0C | TPC | V0A

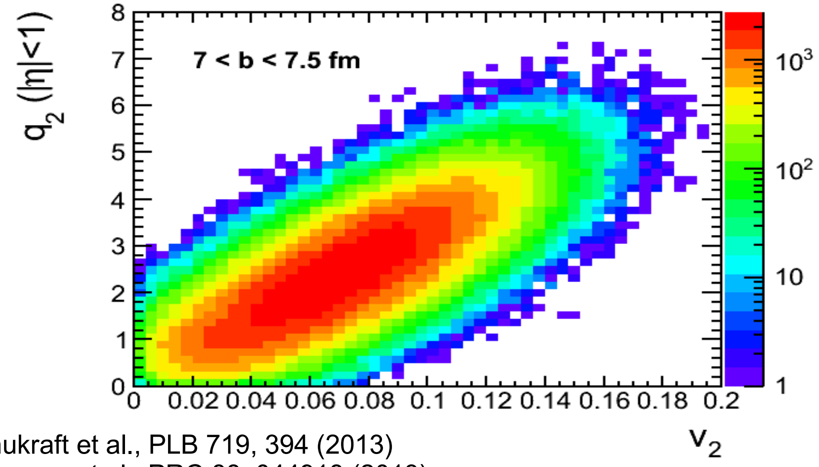
$-3.7<\eta<-1.7$ | $-0.8<\eta<0.8$ | $2.8<\eta<5.1$ | η

- Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
  - ~12.5M events
- Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ~60M events
- Xe–Xe at $\sqrt{s_{NN}}$ = 5.44 TeV
  - ~1M events

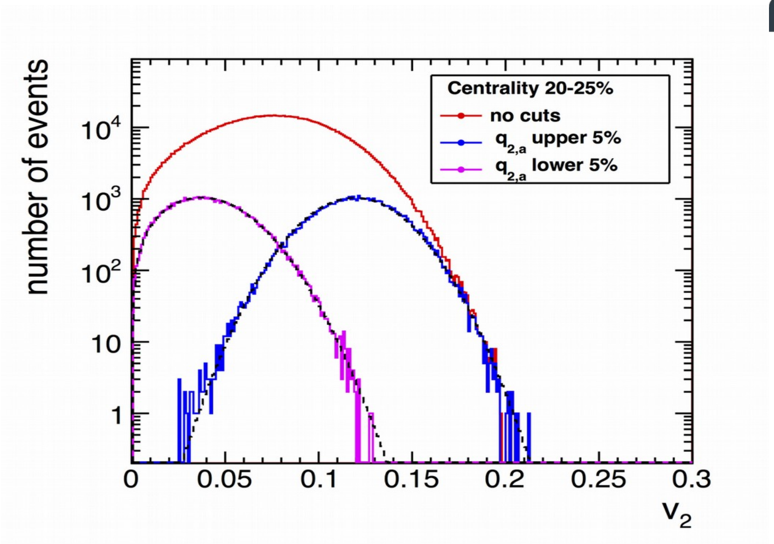
Varying the background using event shape engineering

ALICE, PLB 777, 151 (2018)

Event Shape Engineering (ESE)



J. Schukraft et al., PLB 719, 394 (2013)
H. Petersen et al., PRC 88, 044918 (2013)
P. Huo et al., PRC 90, 024910 (2014)



- Select events with similar centralities and different shapes based on the event-by-event flow/eccentricity fluctuations

Flow vector

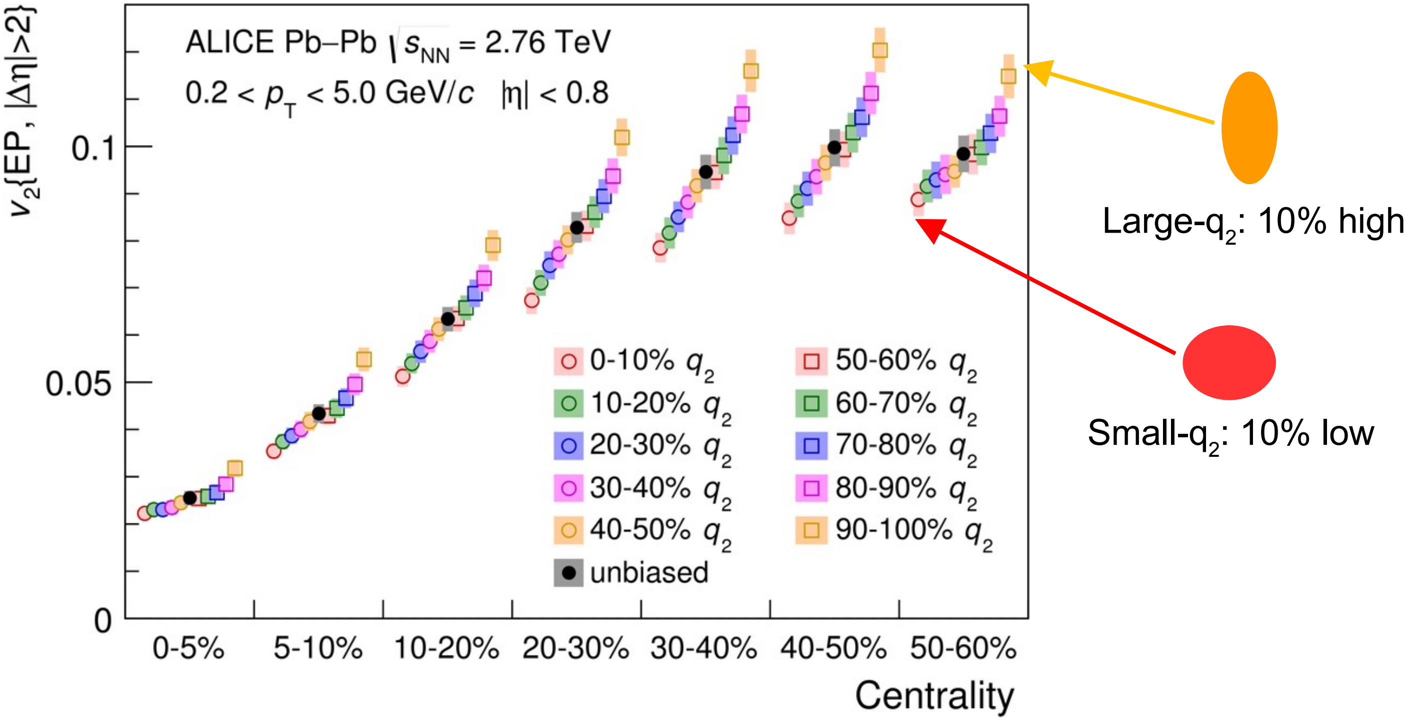
$$Q_{n,x}=\sum_i \cos(n\varphi_i)$$
$$Q_{n,y}=\sum_i \sin(n\varphi_i)$$

→

q_n distribution

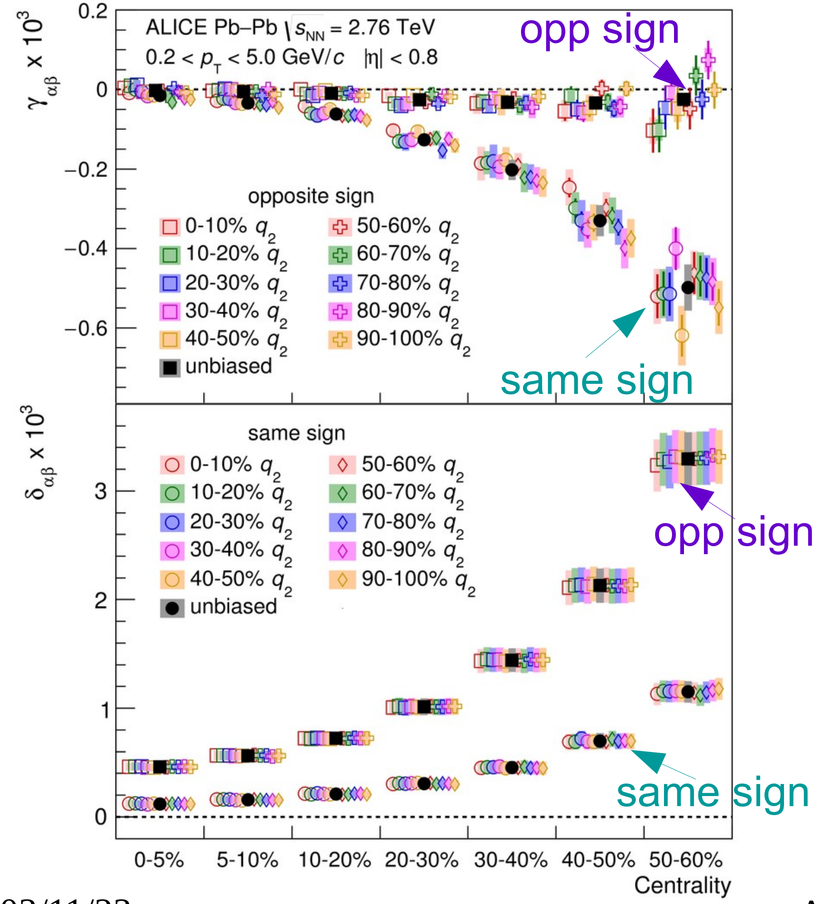
$$Q_n=Q_{n,x}, iQ_{n,y}$$
$$q_n=|Q_n|/\sqrt{M}$$

ESE in ALICE



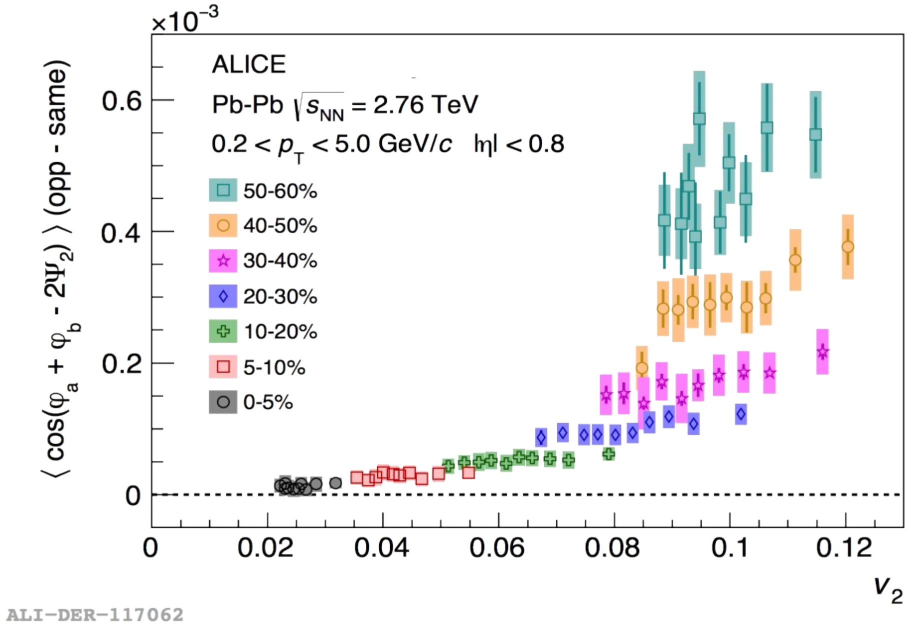
- q_2^{V0C} used to select events with 25% larger or 20% smaller v_2 than the average
- v_2 is measured with event plane method to be consistent with CME measurements
  - Non-flow is greatly suppressed by the large separation in rapidity between the TPC and the V0A ($|\Delta\eta|$>2.0)

CME with ESE (I)



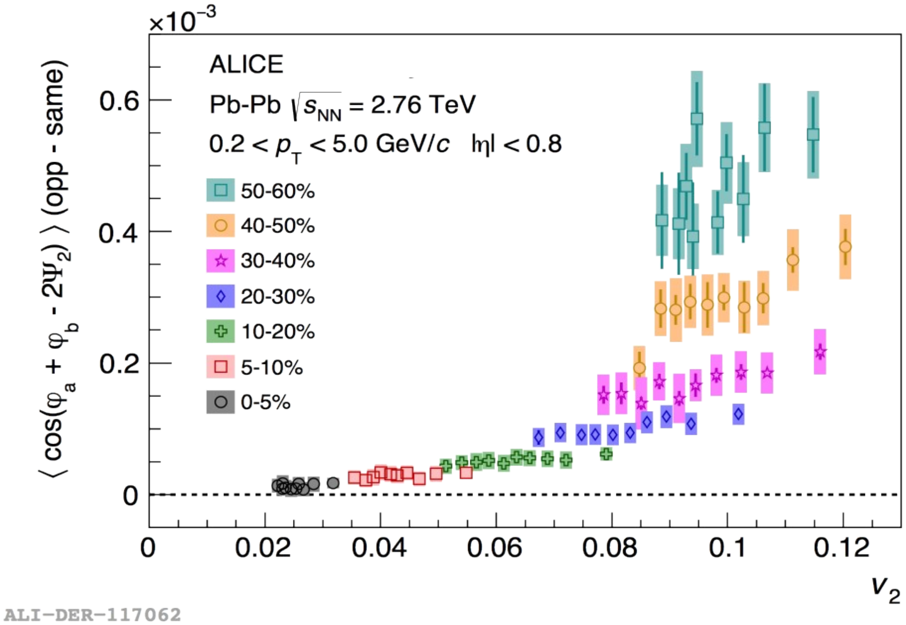
- Correlators contain potential CME signal as well as background effects
  - Background contributions in γ_{ab} are suppressed at the level of v_2
- γ_{ab} depends weakly on the event shape selection in a given centrality bin
- δ_{ab} shows similar values for ESE and unbiased in a given centrality bin → large non-flow contribution

CME with ESE (II)

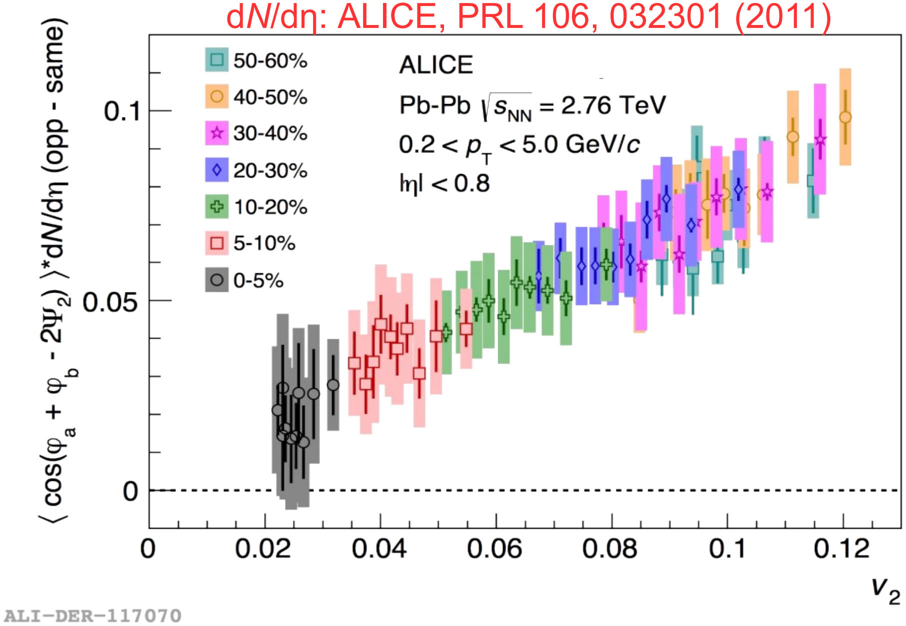


- γ_{ab} (opp-same) can be used to study the CME
  - Difference is positive for all centrality classes and decreases with centrality and v_2 (in a given centrality bin)

CME with ESE (II)

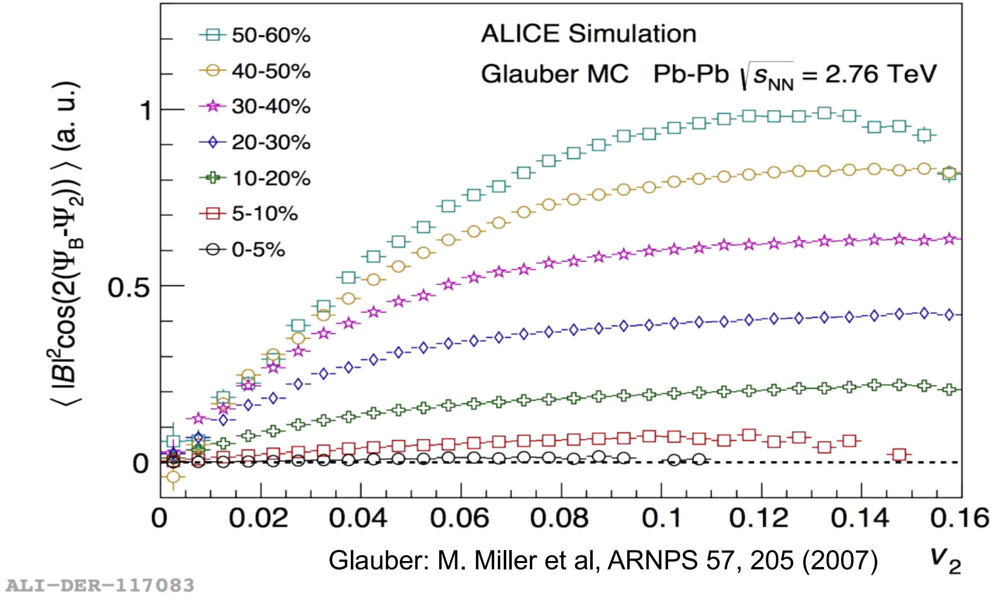


dN/dη: ALICE, PRL 106, 032301 (2011)



- γ_{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?



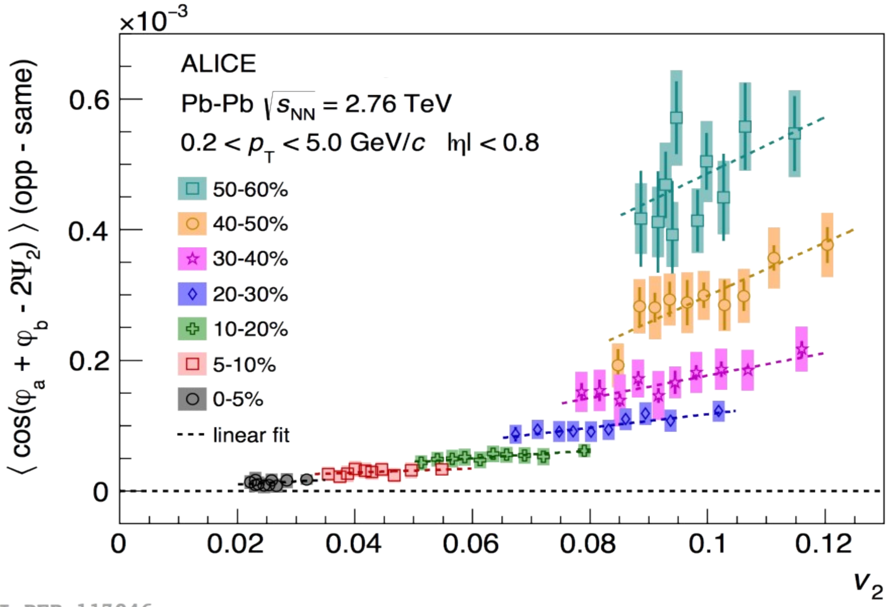
Glauber: M. Miller et al, ARNPS 57, 205 (2007)

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

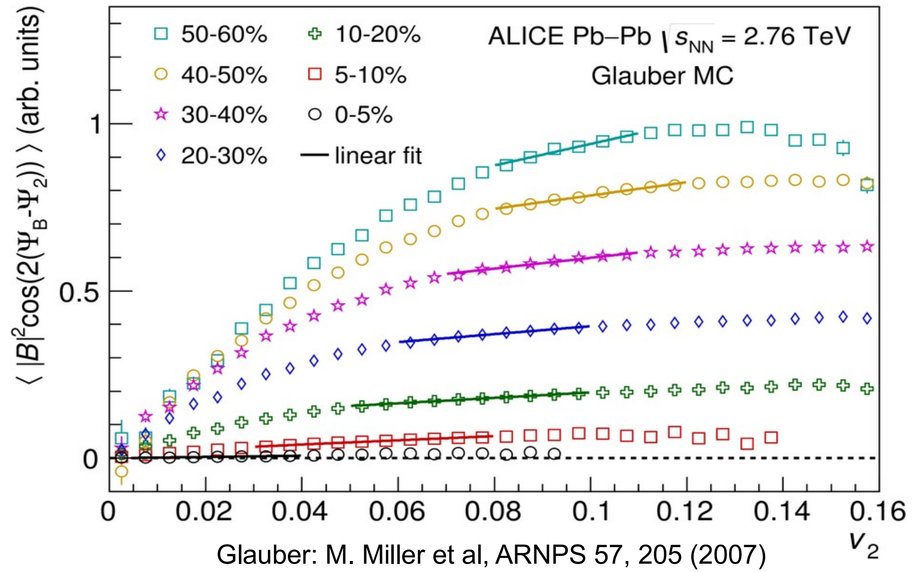
D. Kharzeev et al, NPA 803, 227 (2008)

- 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 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 γ_{ab}, shows a strong dependence on v_2

Relating data and models



ALI−DER−117046

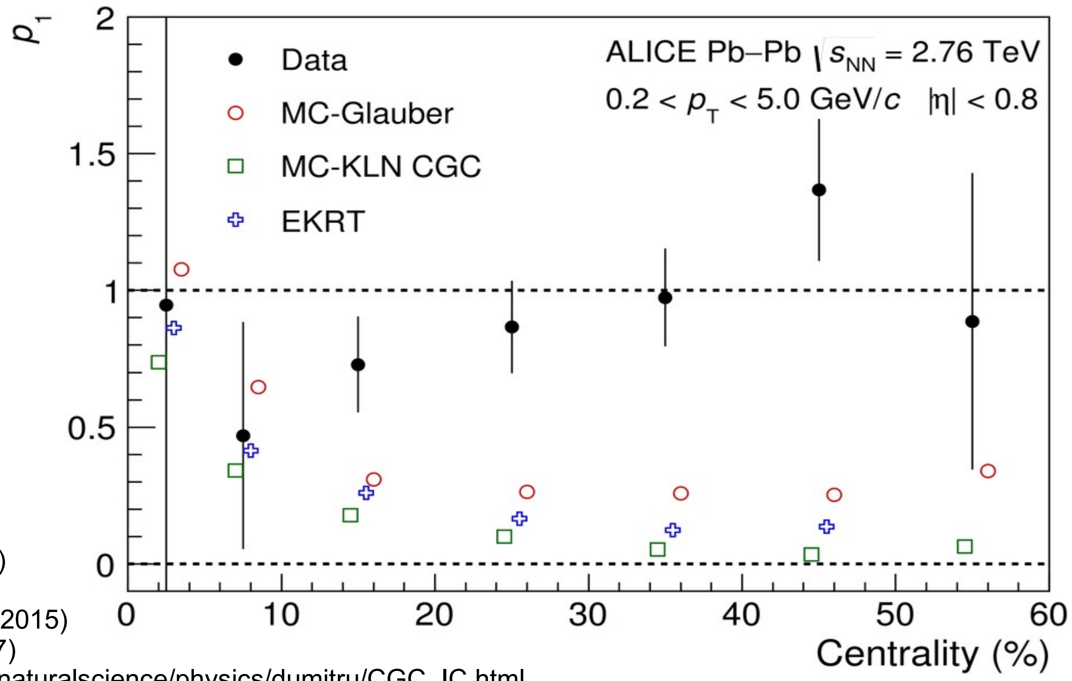


Glauber: M. Miller et al, ARNPS 57, 205 (2007)

- Fit γ_{ab} (opp-same) and $<|B|^2\cos(2(\Psi_B-\Psi_2))>$ 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



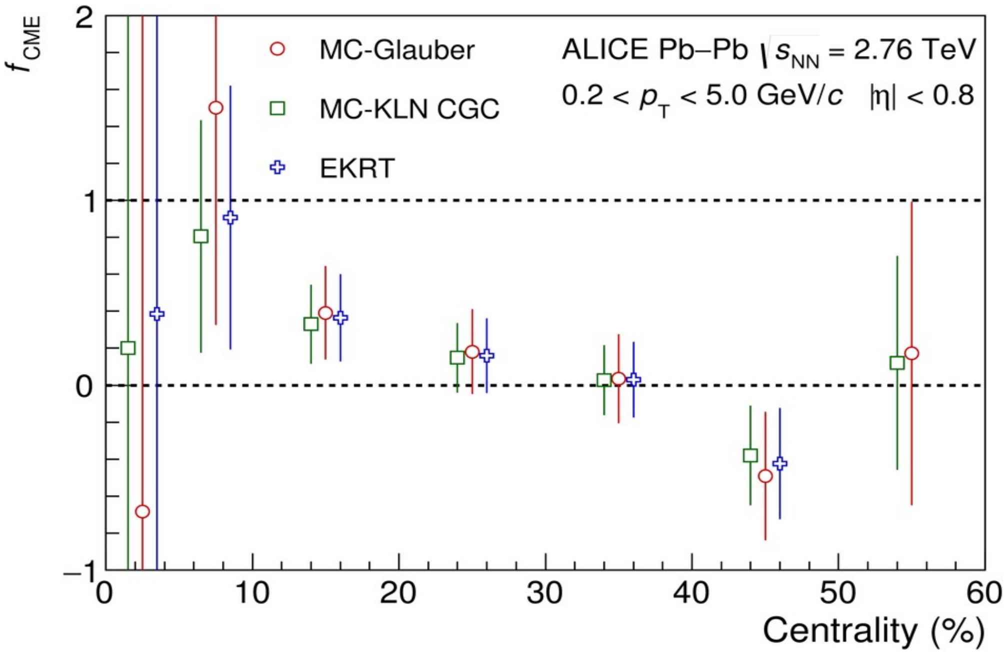
Glauber: M. Miller et al, ARNPS 57, 205 (2007)
EKRT: H. Niemi et al, PRC 93, 024907 (2016)
TRENTO: J. Moreland et al, PRC 92, 011901 (2015)
KLN: H. Drescher et al, PRC 76, 041903 (2007)
mckt code v.32, http://faculty.baruch.cuny.edu/naturalscience/physics/dumitru/CGC_IC.html

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

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

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

CME fraction

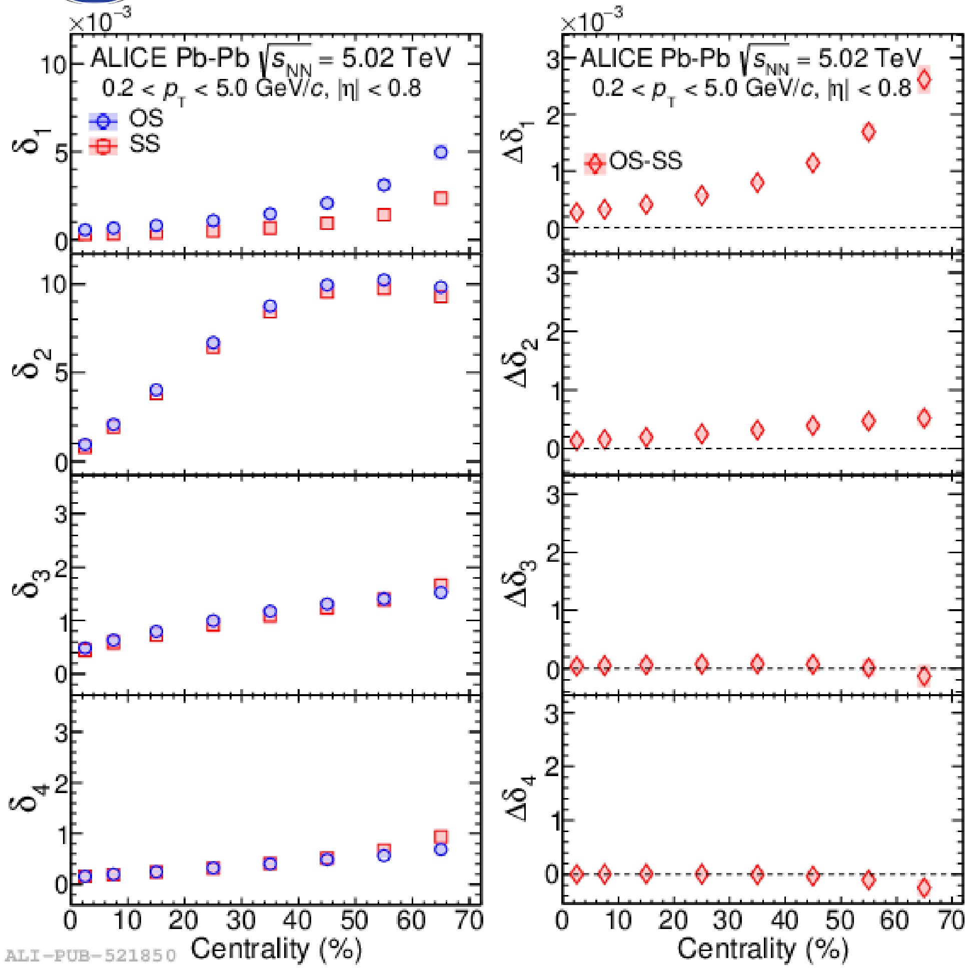


- CME fraction in 0-10% and 50-60% is currently statistically limited
- Combining the points from 10-50% gives
  - f_{CME} (Glauber) = 0.10 ± 0.13 → 33% at 95% C.L.
  - f_{CME} (KLN) = 0.08 ± 0.10 → 26% at 95% C.L.
  - f_{CME} (EKRT) = 0.08 ± 0.11 → 29% at 95% C.L.

“Killing” the signal using higher harmonics

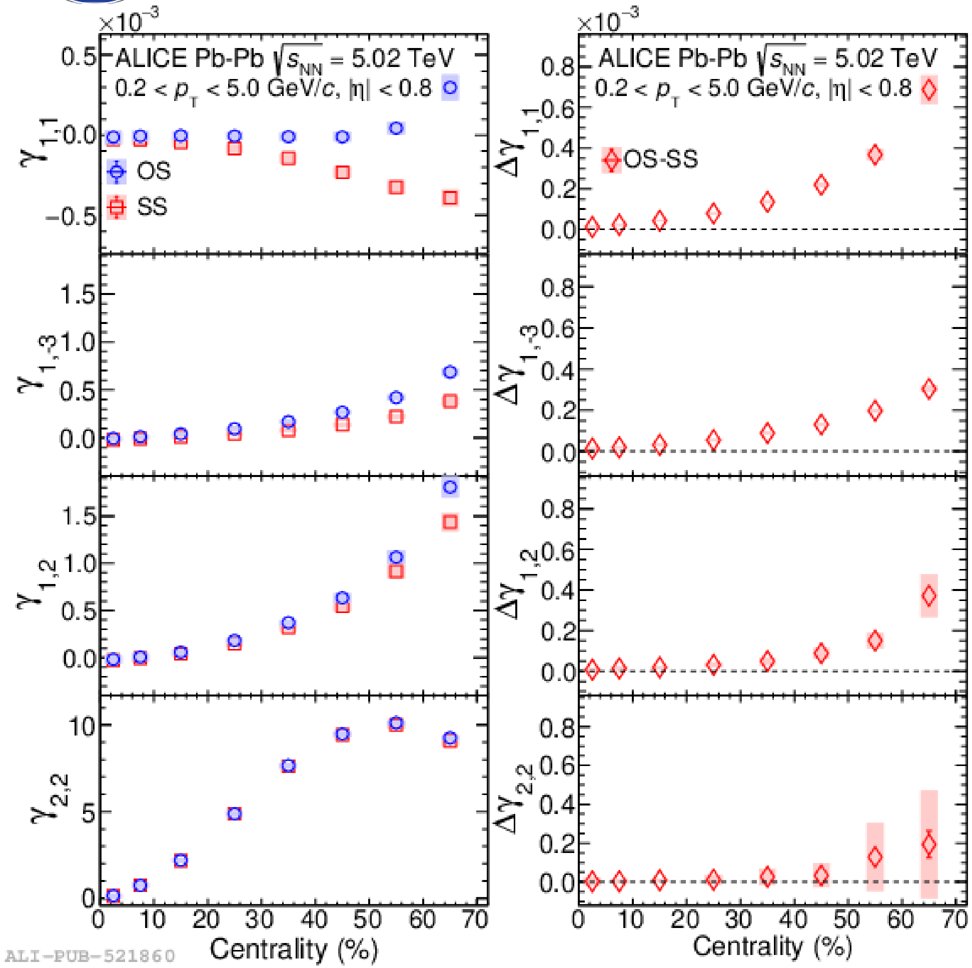
ALICE, JHEP 09, 160 (2020)

2-particle correlators



- Weak charge dependence, except δ_1
  - Dominated by background effects → constrain background in $\gamma_{1,1}$
- δ_1 qualitatively consistent with balance function results

3-particle correlators

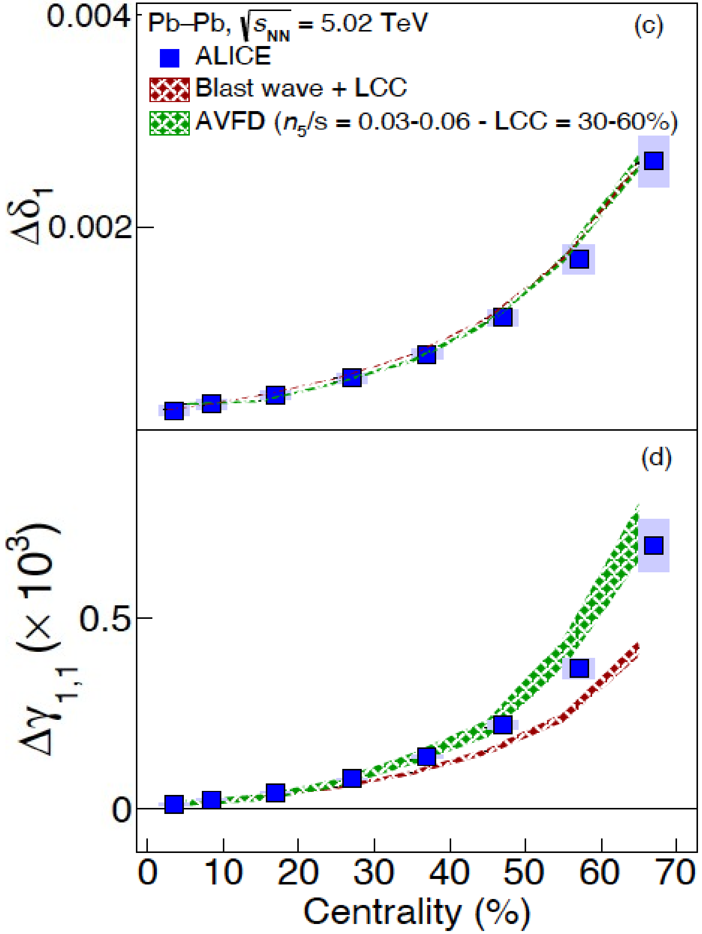


- $\gamma_{1,1}$ and $\gamma_{1,-3}$ sensitive to CME
- $\gamma_{1,2}$ and $\gamma_{2,2}$ probe only the background
- Significant charge dependence, except $\gamma_{2,2}$
  - Increases from central to peripheral collisions
- $\gamma_{1,1}$ and $\gamma_{1,2}$ used to estimate the background contribution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

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

Model comparisons

ALICE, arXiv: 2211.04384



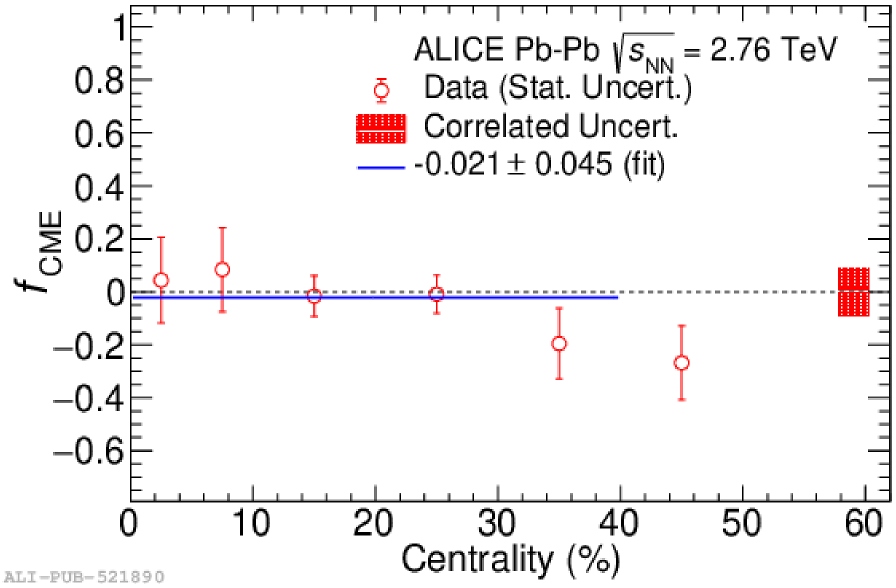
- Blast-Wave + Local Charge Conservation (LCC)
  - Tune the parameters in each centrality class to reproduce v_2 and p_T spectra of π, K, p
  - Tune the number of sources emitting balancing pairs
  - Underestimates $\Delta\gamma_{1,1}$ by up to ≈40%
    - Disagreement increases from central to peripheral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

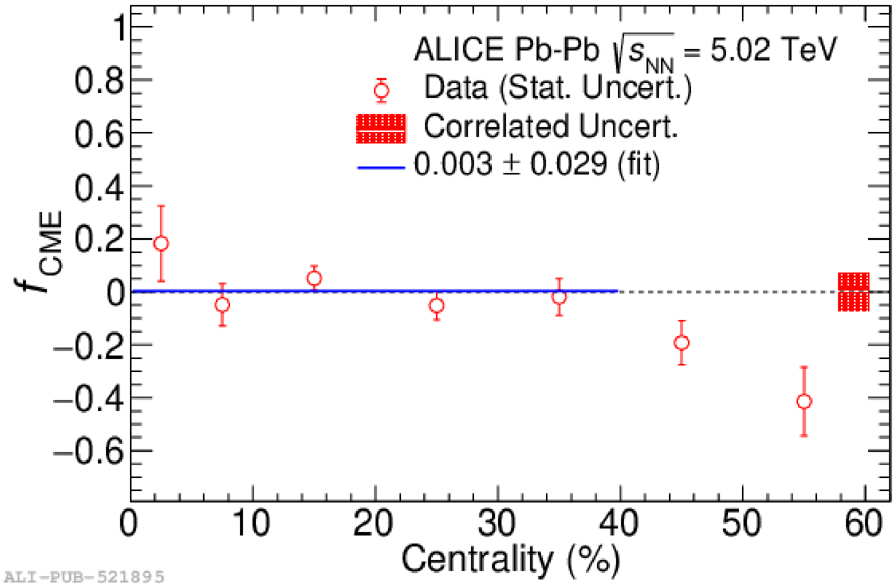
P. Christakoglou et al., EPJC 81, 717 (2021)

- 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.

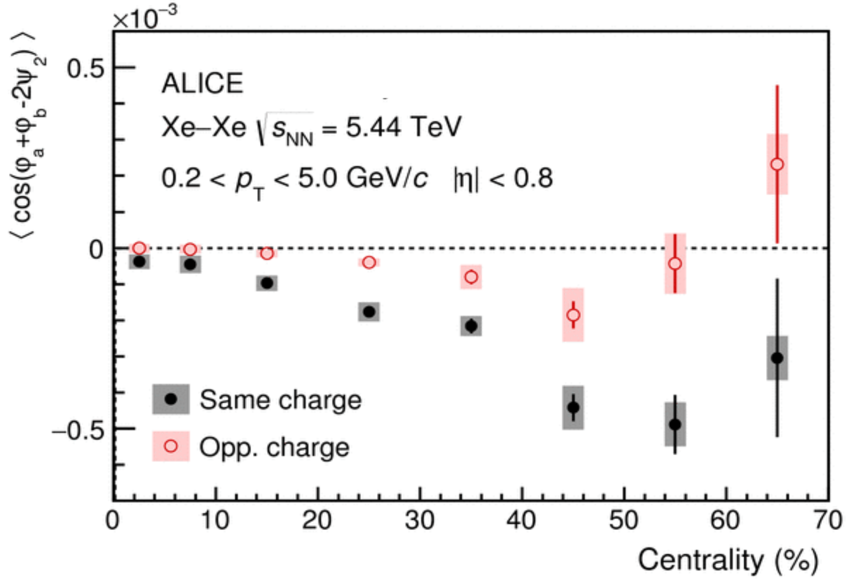
$$f_{\mathrm{CME}} = 1 - \frac{\Delta\gamma_{1,1}^{\mathrm{Bkg}}}{\Delta\gamma_{1,1}}$$

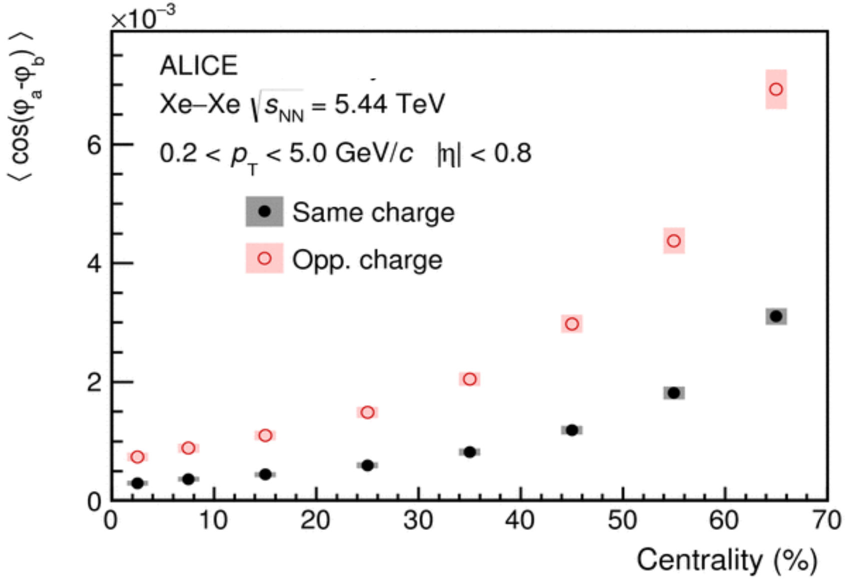
Assumption: $\kappa_2 \approx \kappa_3$

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

ALICE, arXiv: 2210.15383

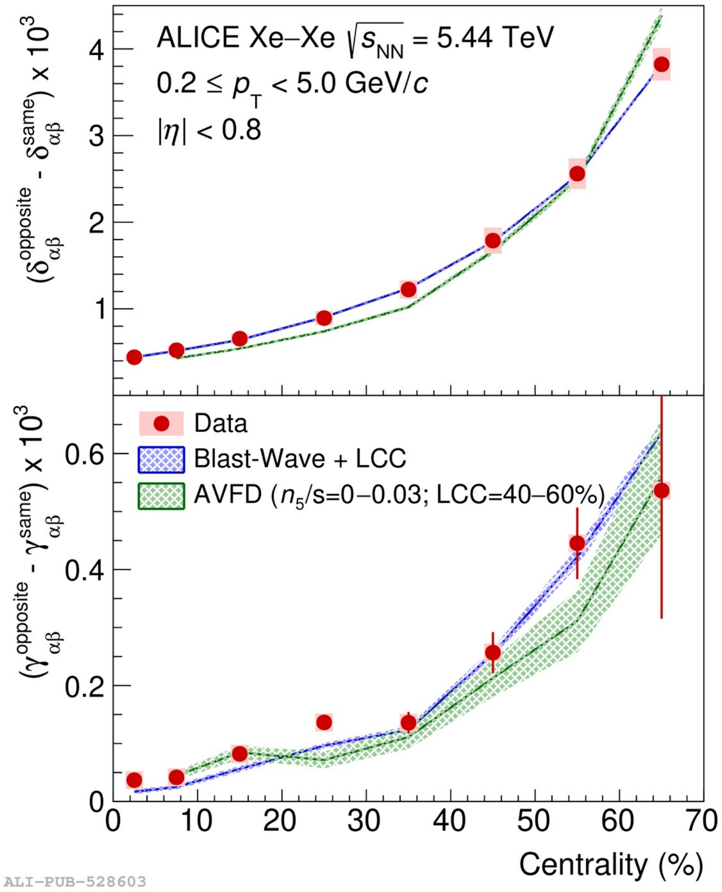
CME in Xe–Xe collisions





- γ_{ab}: consistent with charge separation
- δ_{ab}: background dominates

Model comparisons

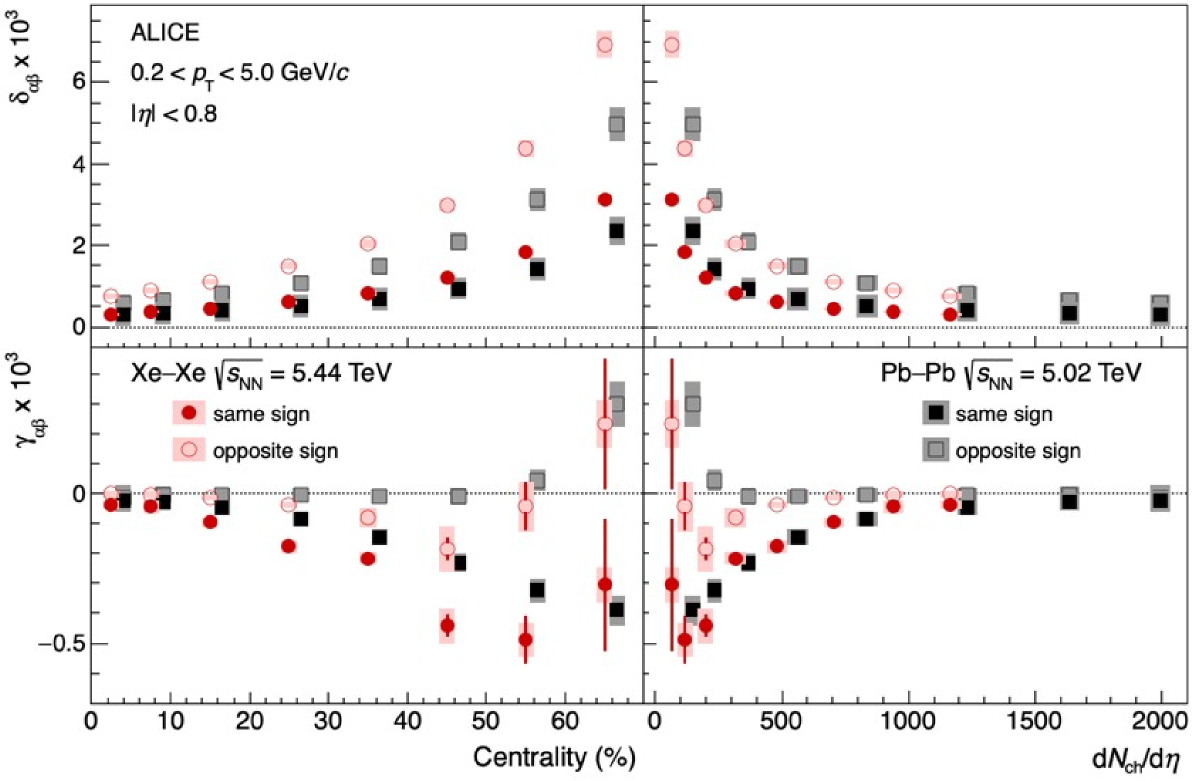


- Blast-Wave + Local Charge Conservation (LCC)
  - Tune the parameters in each centrality class to reproduce v_2 and p_T spectra of π, K, p
  - Tune the number of sources emitting balancing pairs
  - Describes fairly well the measured data points
    - Background dominates measurements
    - Not observed in Pb-Pb collisions
- 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
    - 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 in Xe–Xe and Pb–Pb collisions

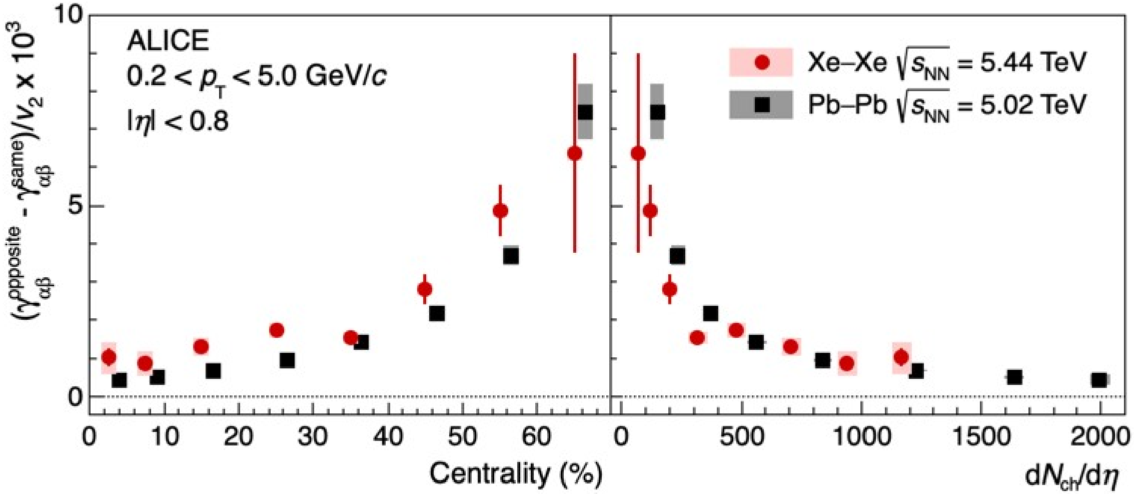


ALICE, JHEP 09, 160 (2020)

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

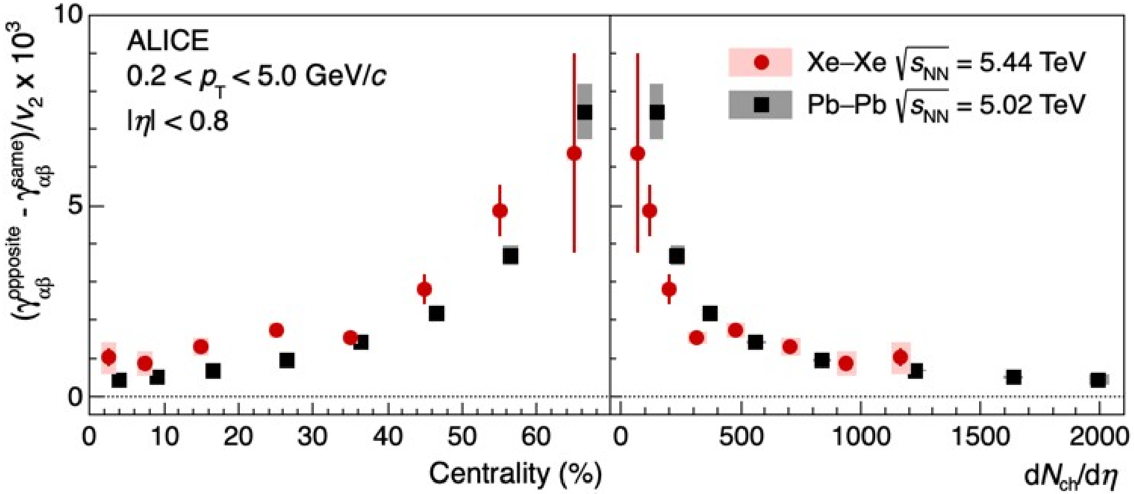
- Strong dependence on the charge
- Qualitatively similar centrality dependence
  - Larger magnitude in Xe–Xe than in Pb–Pb collisions
    - Dilution effects arising from different number of particles (CME ~ 1/M)
- Similar values in Xe–Xe and Pb–Pb collisions within uncertainties (vs $dN_{ch}/d\eta$)

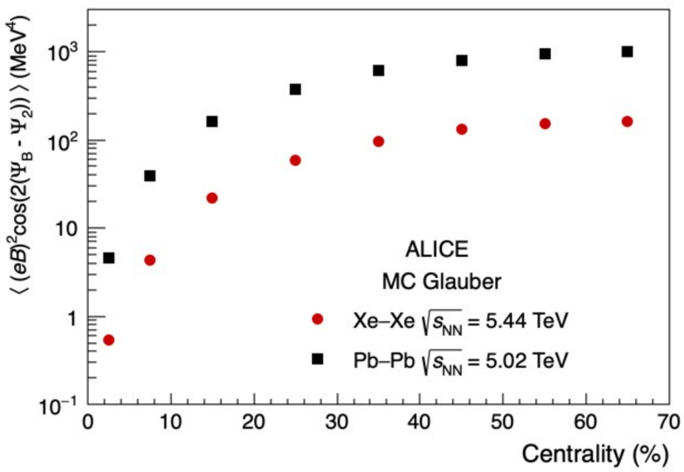
CME fraction in Xe–Xe and Pb–Pb collisions



- γ_{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

CME fraction in Xe–Xe and Pb–Pb collisions



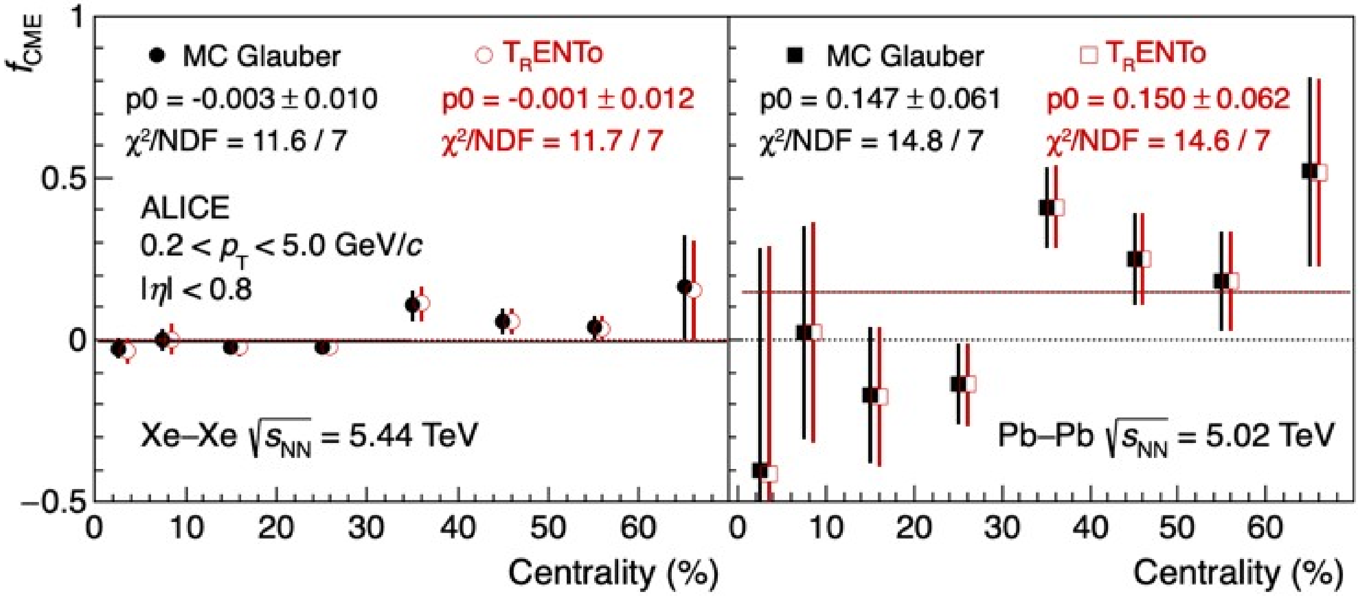


- γ_{ab} (opp-same) can be used to study CME
  - Similar values in Xe–Xe and Pb–Pb collisions (vs dN_{ch}/dη) → large background contribution
- CME fraction extracted using a two-component approach
  - Assumption: both signal and background scale with dN_{ch}/dη
    - dN_{ch}/dη used to compensate for dilution
  - <$|B|^2\cos(2(\Psi_B-\Psi_2))$> from MC simulations

$$(dN_{ch}/d\eta)^{Xe}\Delta\gamma_{ab}^{Xe} = sB^{Xe} + bv_2^{Xe}$$
$$(dN_{ch}/d\eta)^{Pb}\Delta\gamma_{ab}^{Pb} = sB^{Pb} + bv_2^{Pb}$$

$$f_{CME} = \frac{sB}{sB + bv_2}$$

CME fraction in Xe–Xe and Pb–Pb collisions

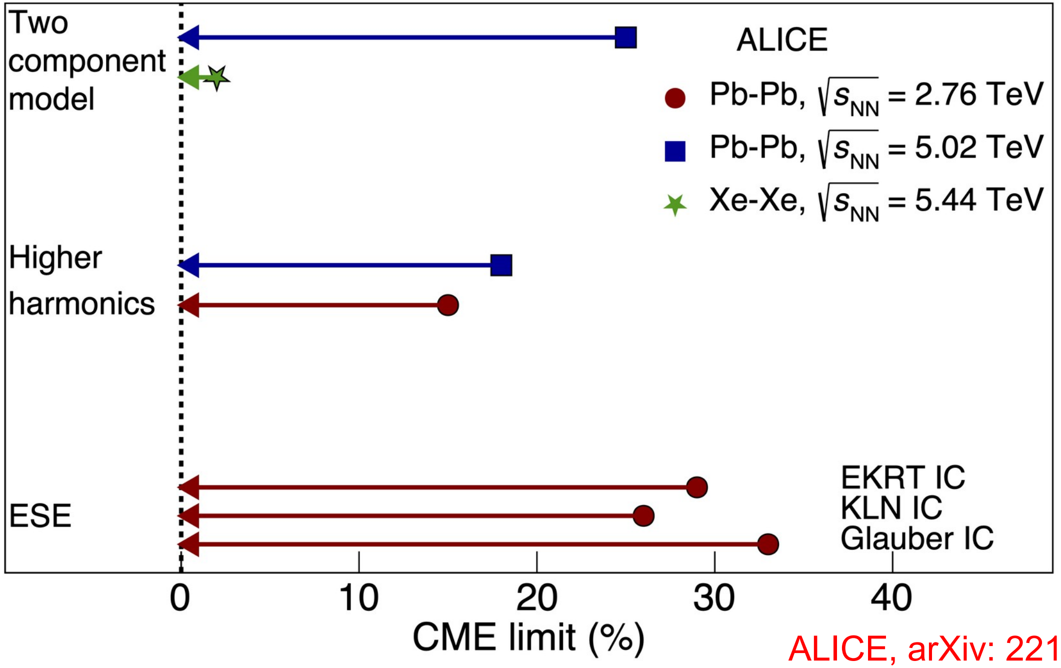


- Consistent with 0 for 0-30% and then becomes positive
- Combining the points from 0-70%
  - f_{CME}^{Xe} = -0.003 ± 0.010 → 2% at 95% C.L.
  - f_{CME}^{Pb} = 0.147 ± 0.061 → 25% at 95% C.L.

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

Summary

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

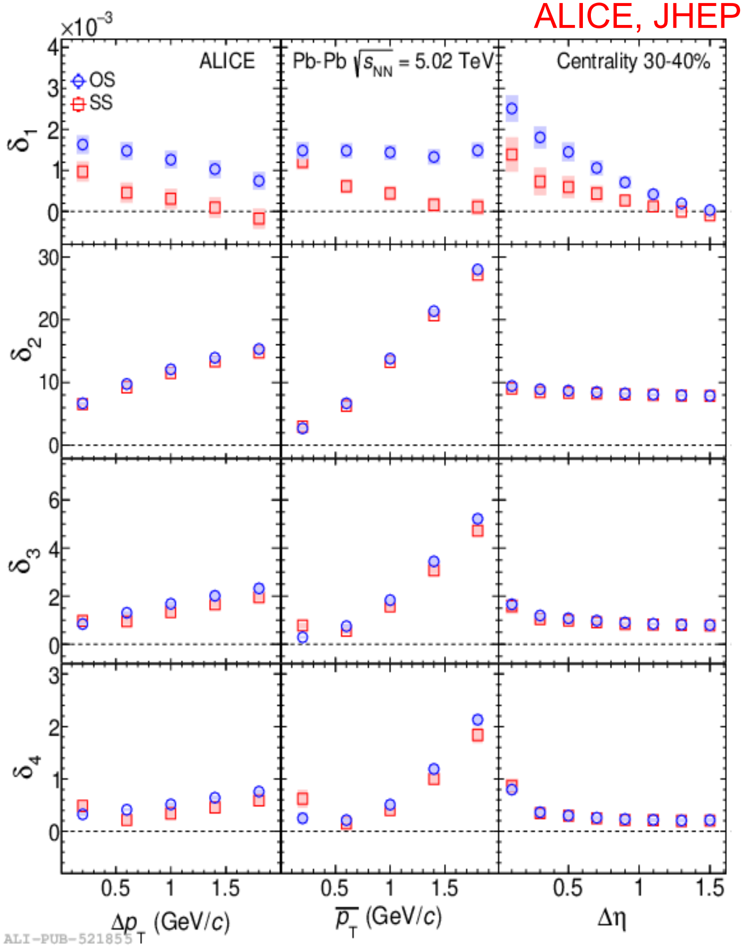


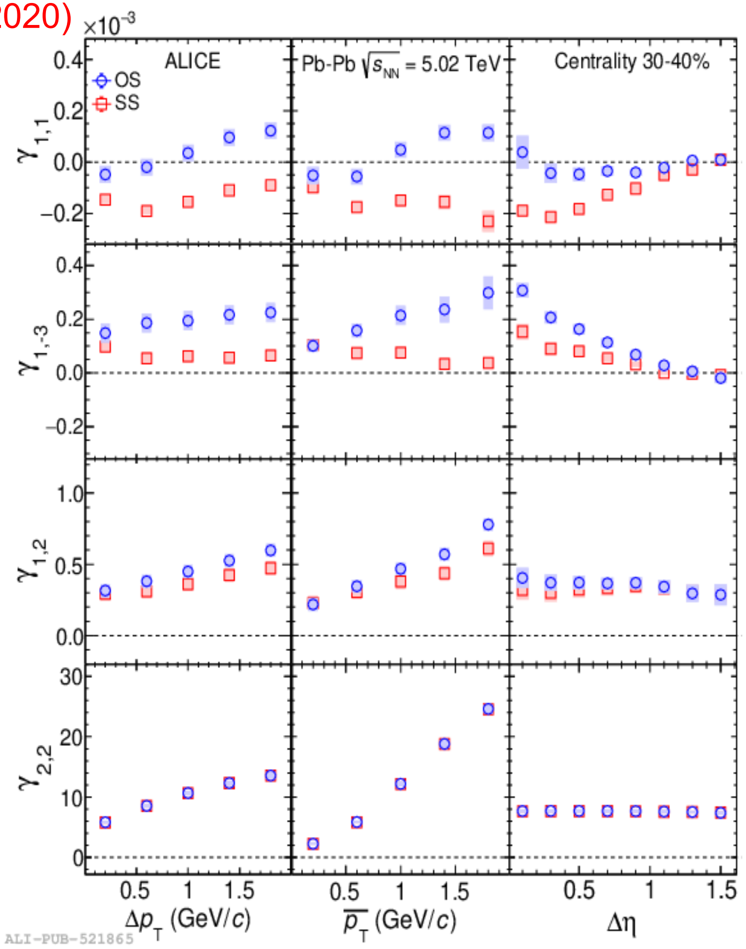
ALICE, arXiv: 2211.04384

Backup

2- and 3-particle correlators: differential results

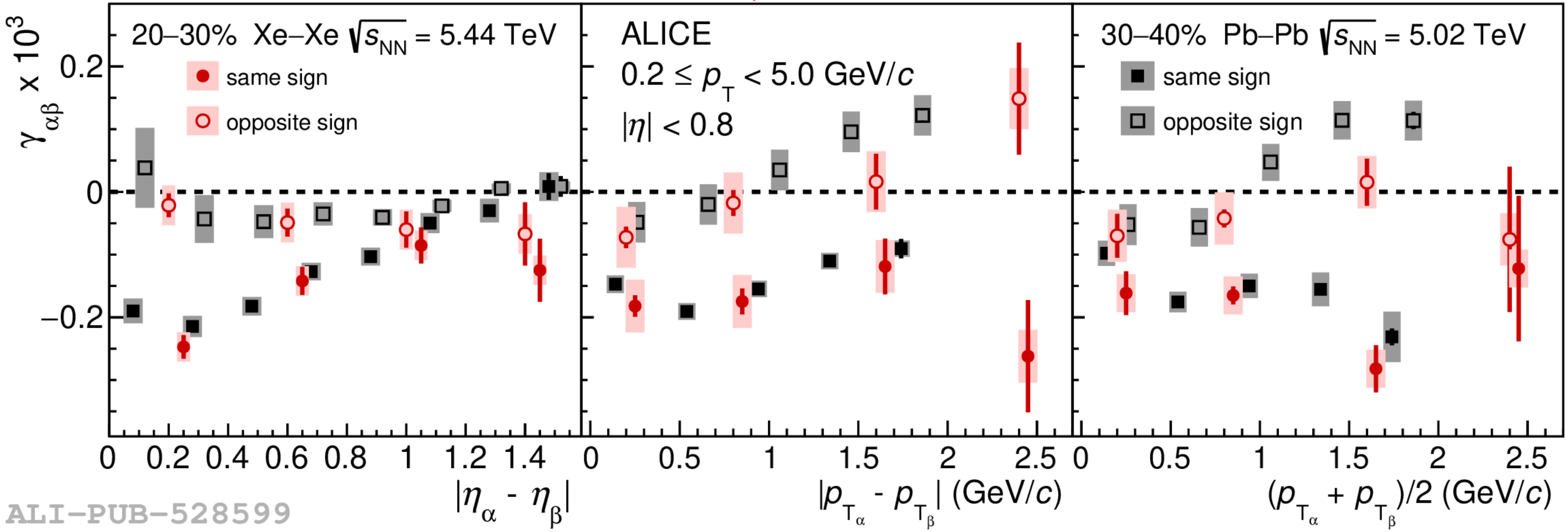
ALICE, JHEP 09, 160 (2020)



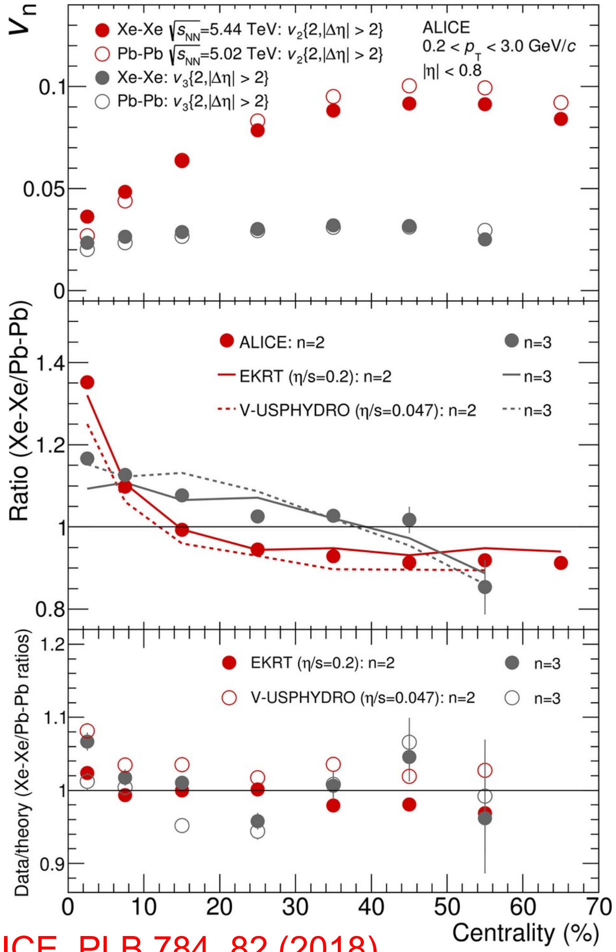


3-particle correlator: differential results in Xe–Xe and Pb–Pb collisions

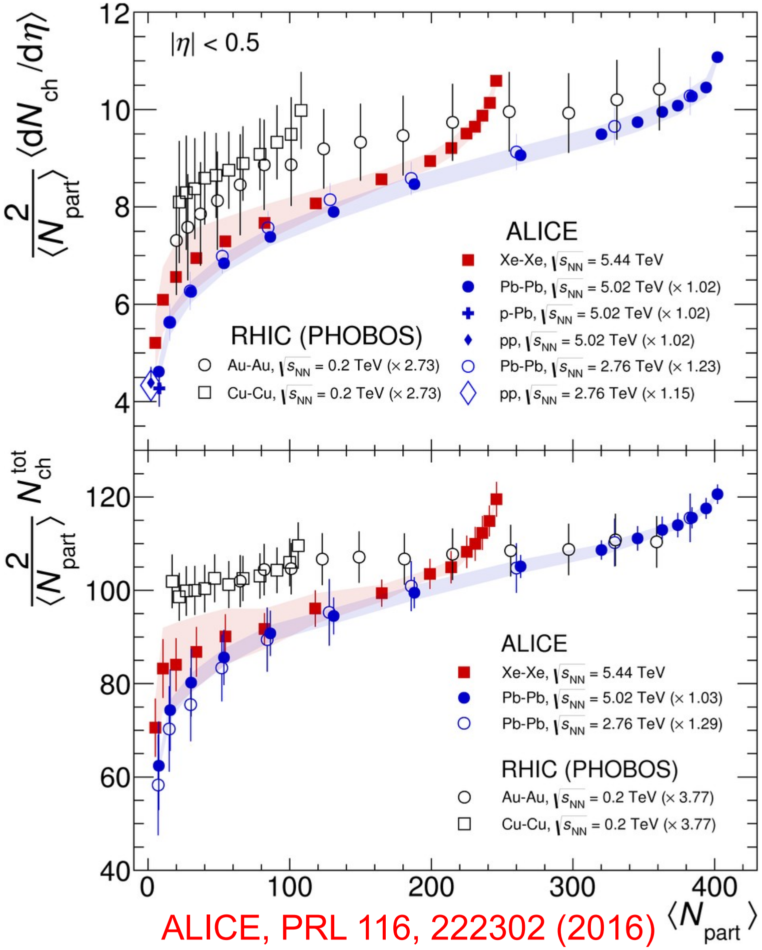
ALICE, arXiv: 2210.15383



v_2 and dN_{ch}/dη in Xe–Xe and Pb–Pb collisions



ALICE, PLB 784, 82 (2018)



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