INSTITUTE OF SPACE SCIENCE
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ALICE

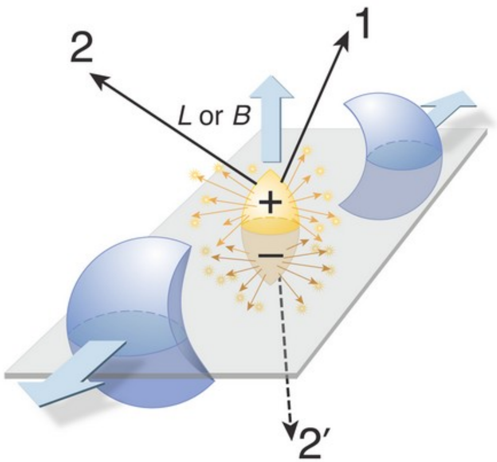
Searches for Chiral Magnetic Effect (CME) and Chiral Magnetic Wave (CMW) in Xe-Xe and Pb-Pb collisions with ALICE

Andrea Danu (for the ALICE Collaboration)
~ Institute of Space Science - RO ~

OUTLINE

- Motivation
- ALICE Detector
- Results
- Summary

Chiral Magnetic Effect (CME) and Chiral Magnetic Wave (CMW)



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    - Allowed by theory but never observed (strong-CP problem)

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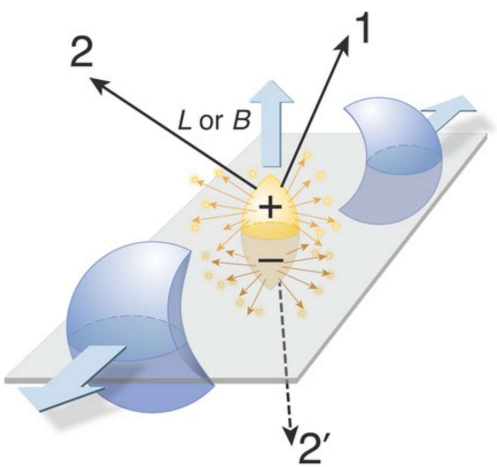

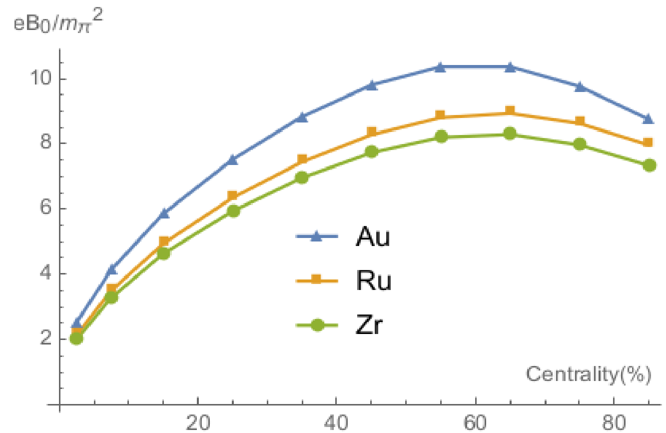

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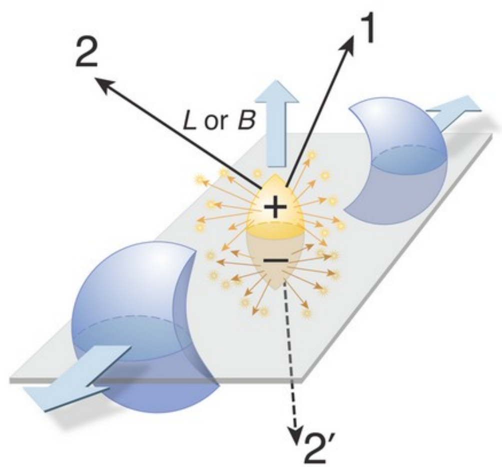

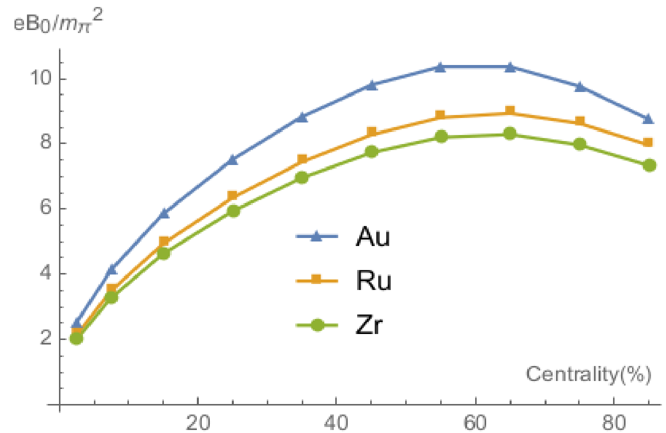

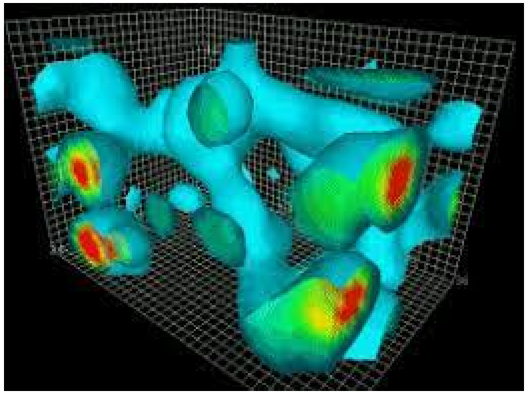

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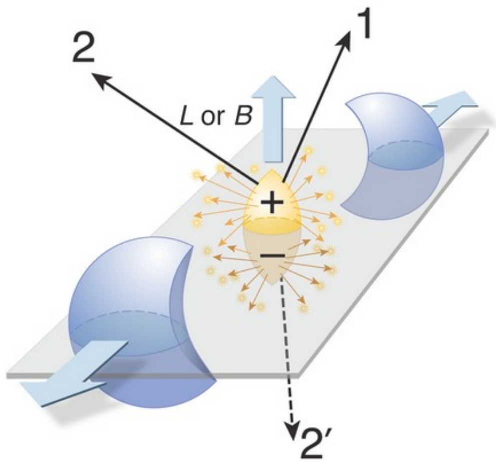

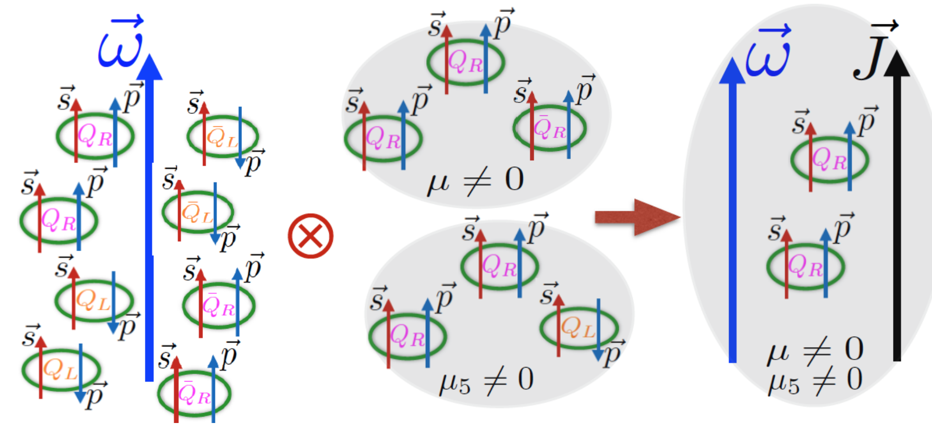

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  - Experimental consequence: charge separation perpendicular to the reaction plane
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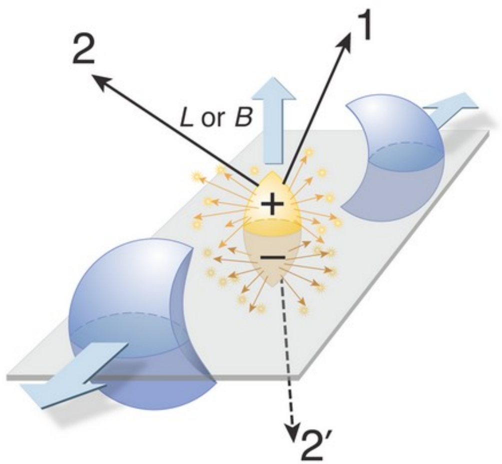

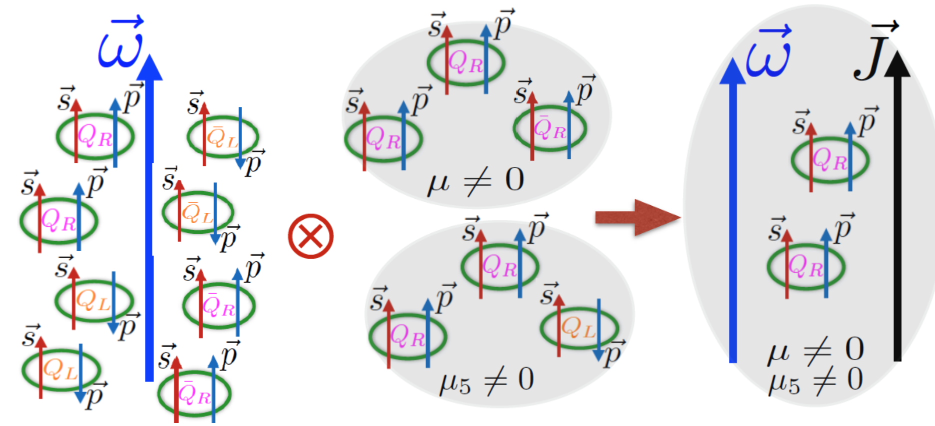

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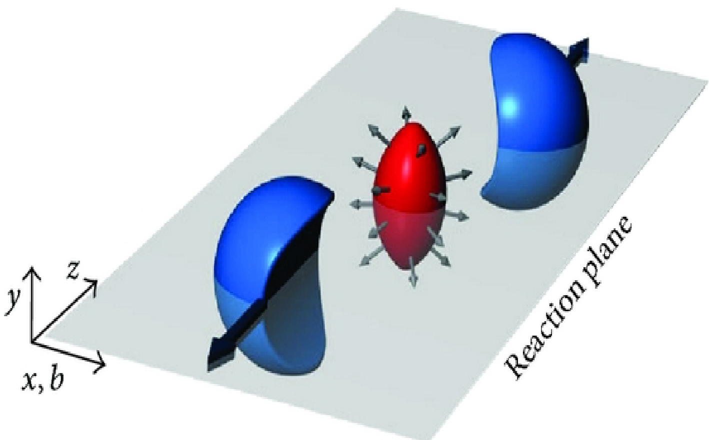
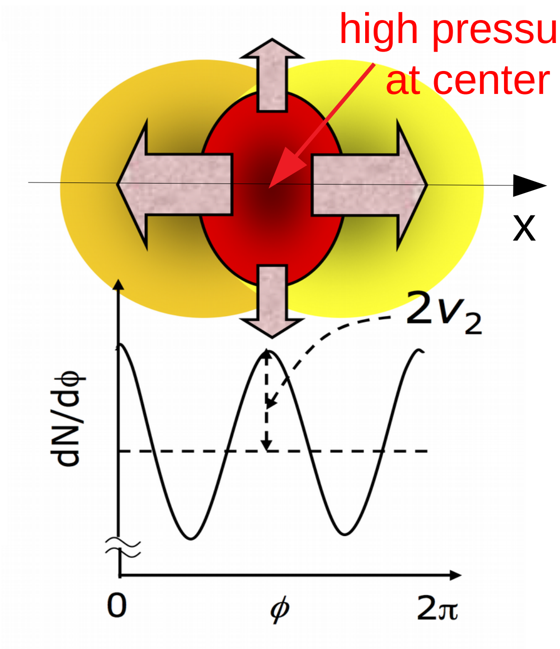
- Chiral Magnetic Effect (CME): interaction of quarks with the QCD domains and B
    - Experimental consequence: charge separation perpendicular to the reaction plane
    - Interpretation of the experimental results is complicated by background contributions

- Chiral Magnetic Wave (CMW): combination of CME and Chiral Separation Effect (CSE)
    - CSE refers to the separation of chiral charge along the axis of the magnetic field

Anisotropic flow

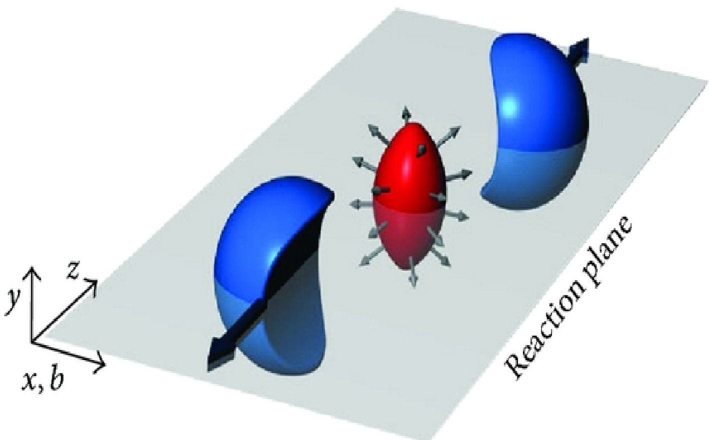


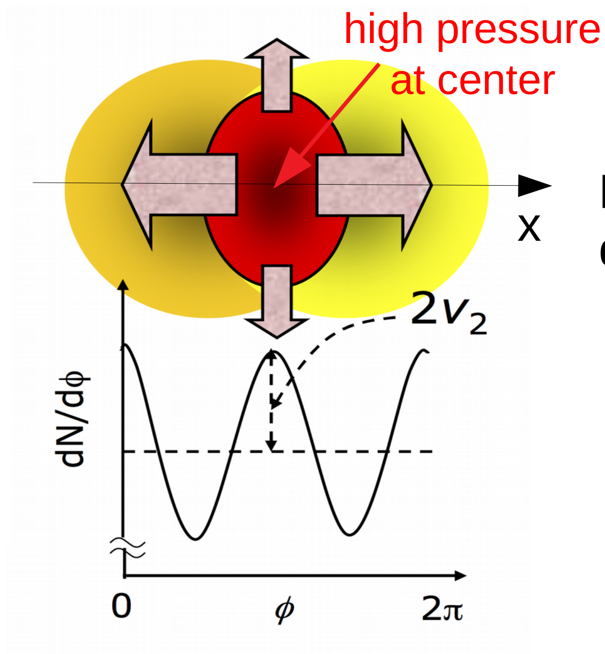


Pressure gradients (larger in the x direction) push bulk “out” → “flow”

More, faster particles seen in the x-direction

Anisotropic flow





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$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\varphi-\Psi_n\right)\right)\right)$$

- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions
  - v_n quantify the event anisotropy

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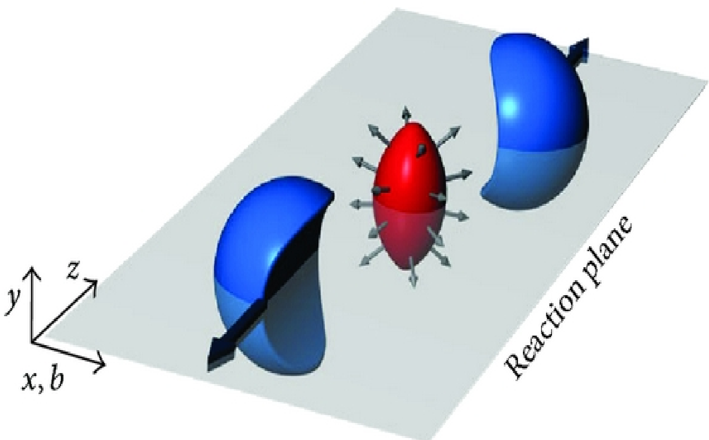

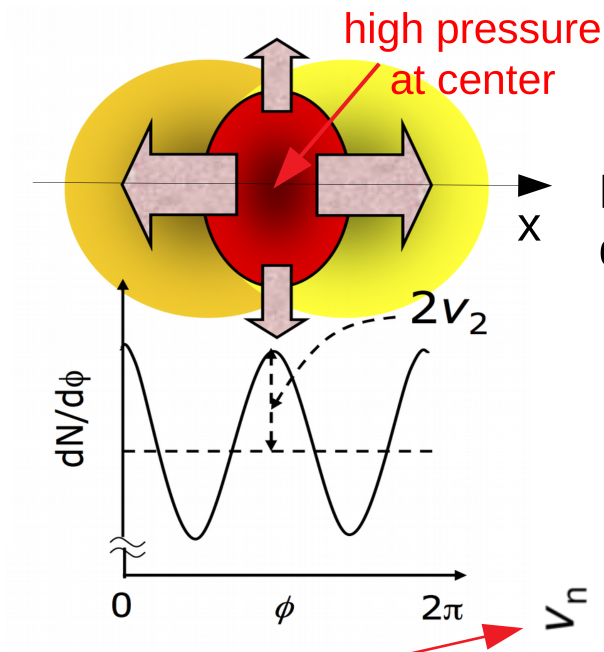

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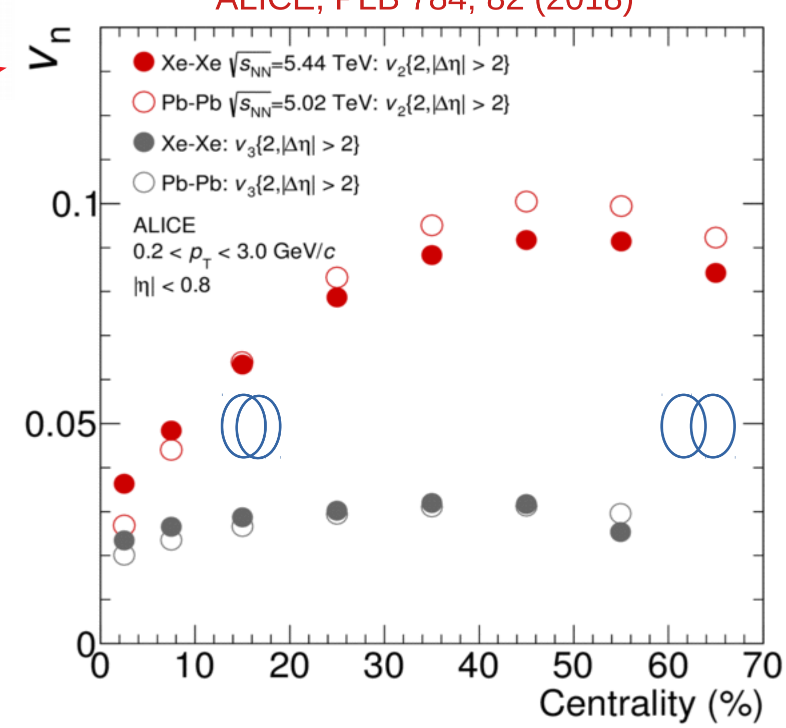
ALICE, PLB 784, 82 (2018)



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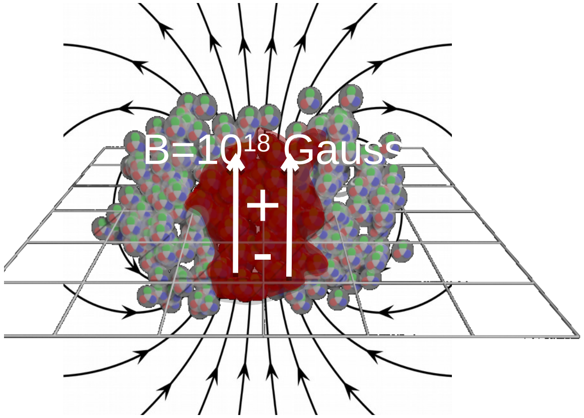
- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions
  - v_n quantify the event anisotropy
- Characterize key QGP properties like viscosity
  - Nearly perfect fluid: $1/4\pi < \eta/s < 3/4\pi$

Observables for CME and CMW

charge separation



- CME

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

  - 2-particle correlator

$$\delta_{ab} = \langle\cos(\varphi_a - \varphi_b)\rangle \approx \langle a_{1,a} a_{1,b}\rangle + B_{\mathrm{in-plane}} + B_{\mathrm{out-plane}}$$

  - 3-particle correlator

$$\gamma_{ab} = \langle\cos(\varphi_a + \varphi_b - 2\Psi_2)\rangle \approx -\langle a_{1,a} a_{1,b}\rangle + B_{\mathrm{in-plane}} - B_{\mathrm{out-plane}}$$

  - B_{in} and B_{out} denote background contributions projected onto Ψ_2 and perpendicular to it

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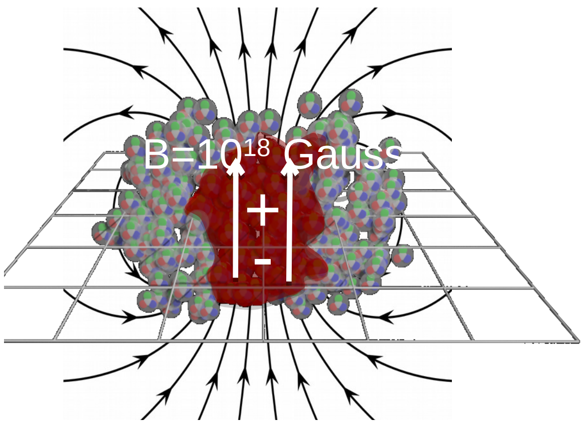

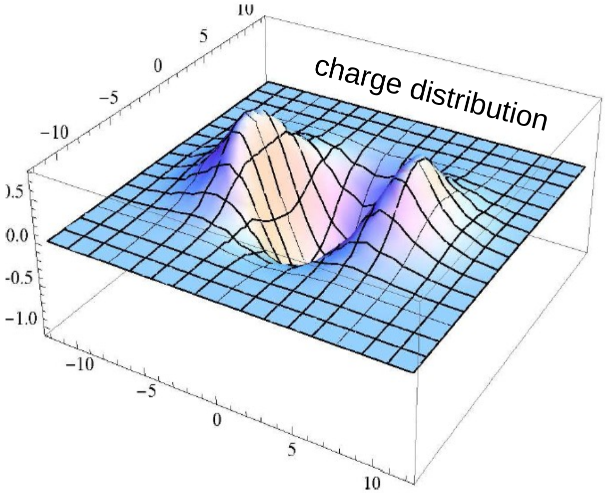

Y. Burnier et al.,PRL 107, 052303 (2011)

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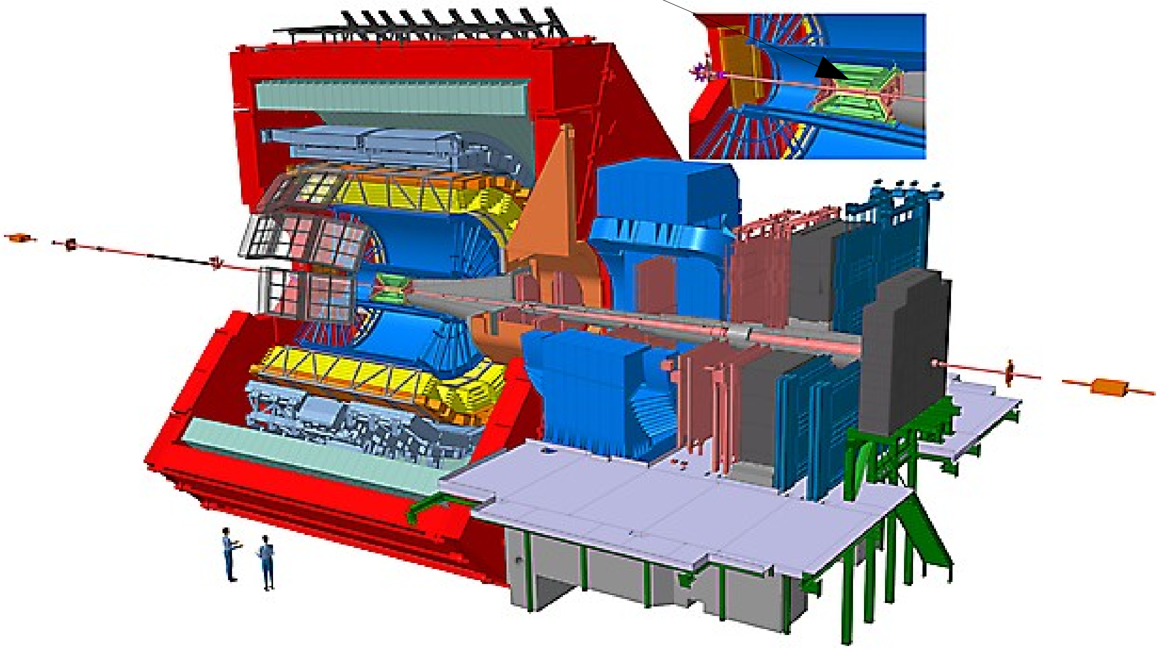
- CMW
  - Anisotropic flow difference vs charge asymmetry

$$\Delta v_n = v_n^+ - v_n^- = r_{\Delta v_n}^{Norm} A_\pm \qquad A_\pm = \frac{N_+ - N_-}{N_+ + N_-}$$

    - Normalized slope $r_{\Delta v_n}^{Norm}$

A Large Ion Collider Experiment



- Inner Tracking System (ITS)
  - Tracking, triggering, vertexing

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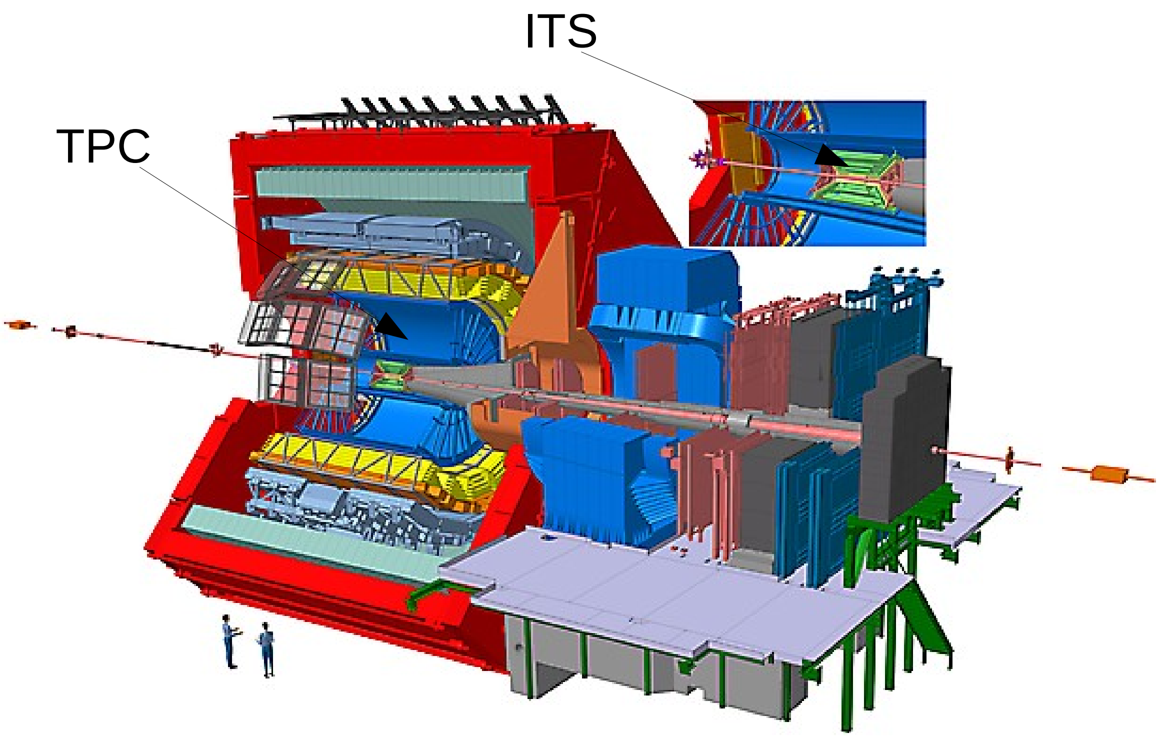

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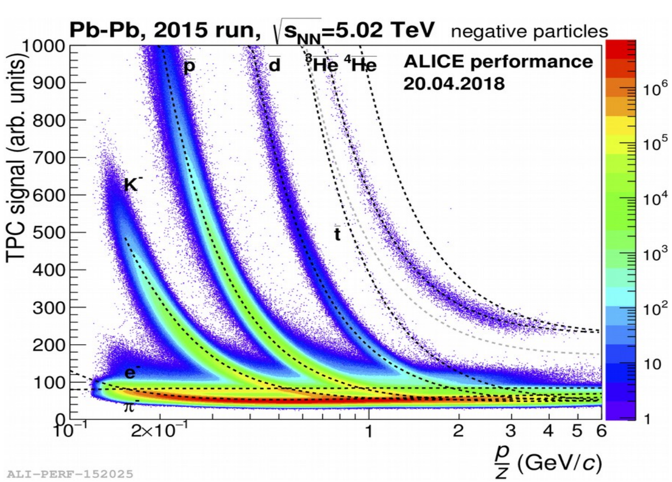
  - Tracking, vertexing, particle identification based on specific energy loss



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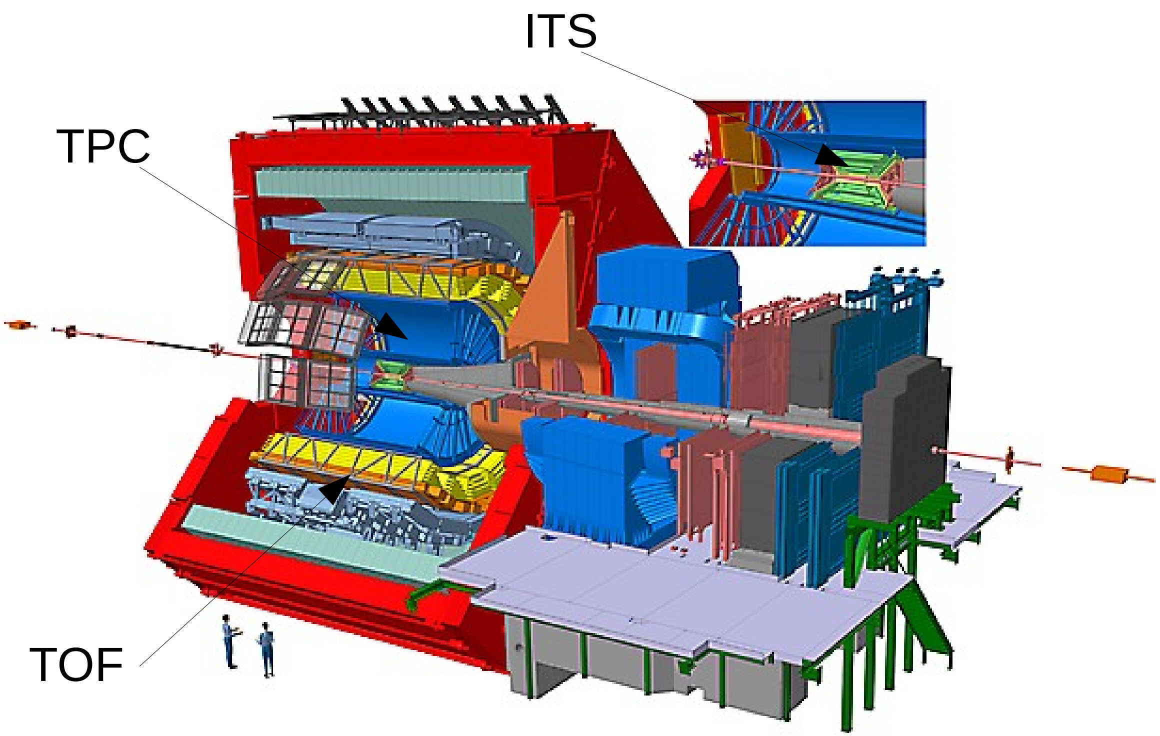

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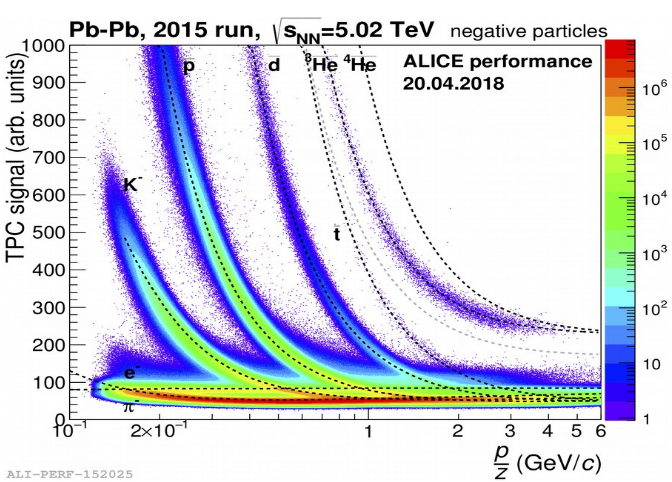

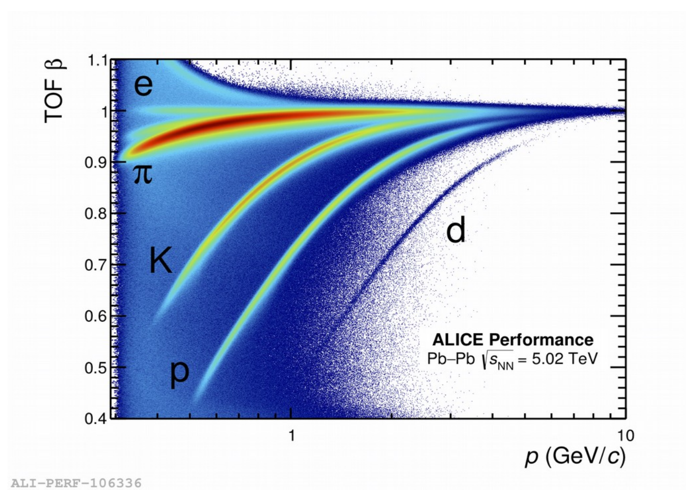

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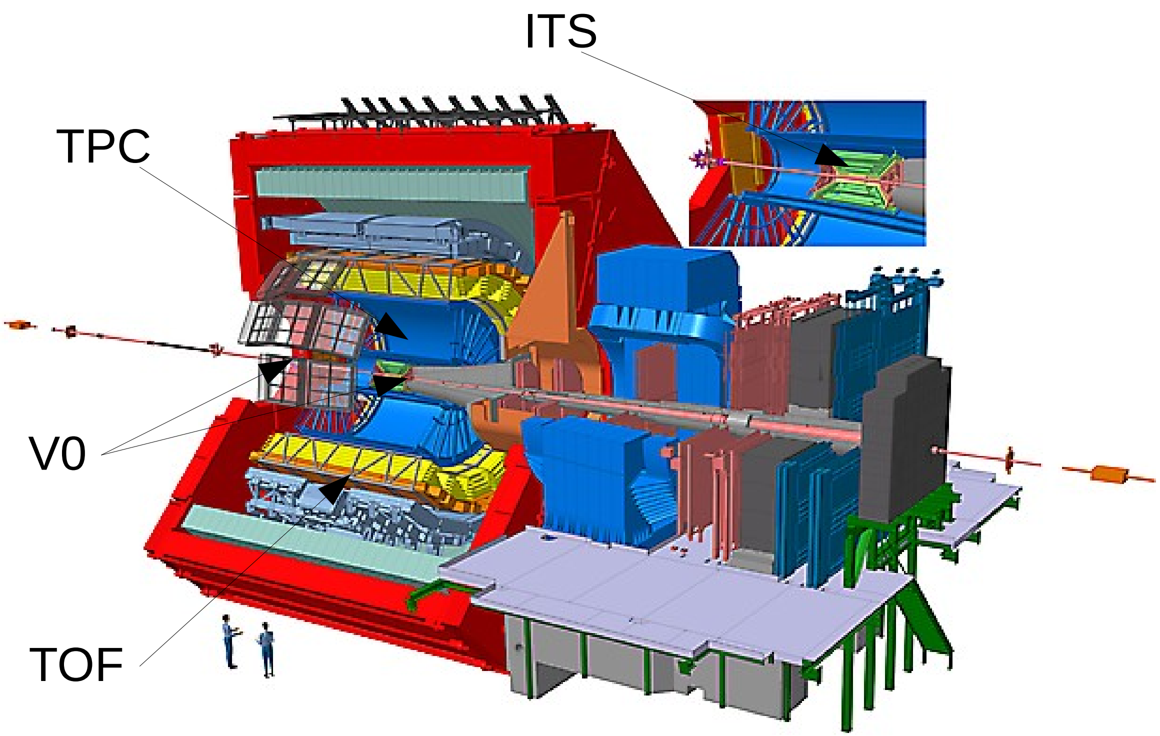

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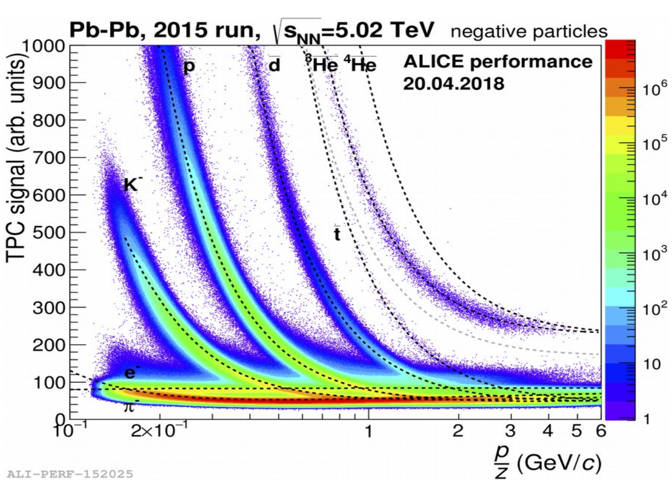
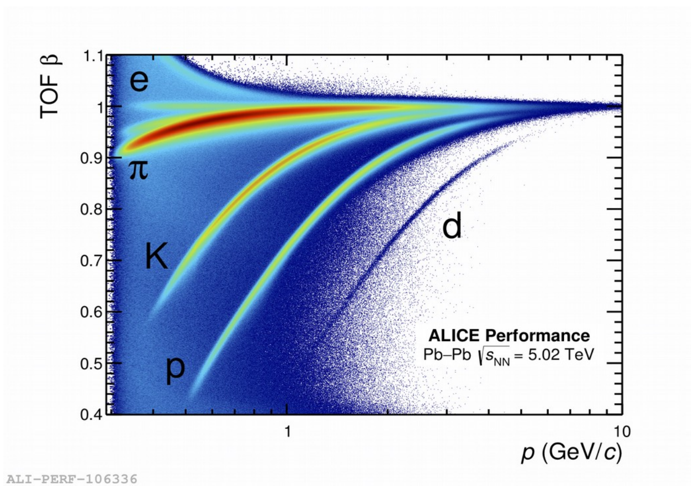
- V0
  - Triggering, centrality and ψ_2 determination





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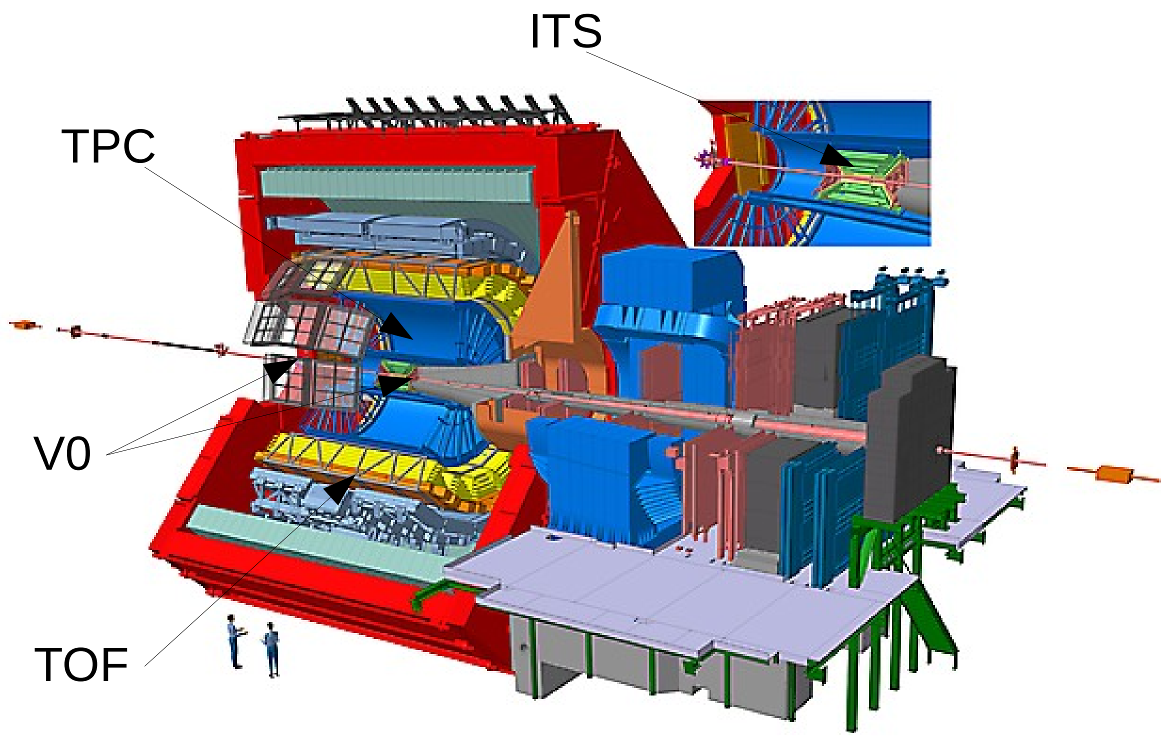

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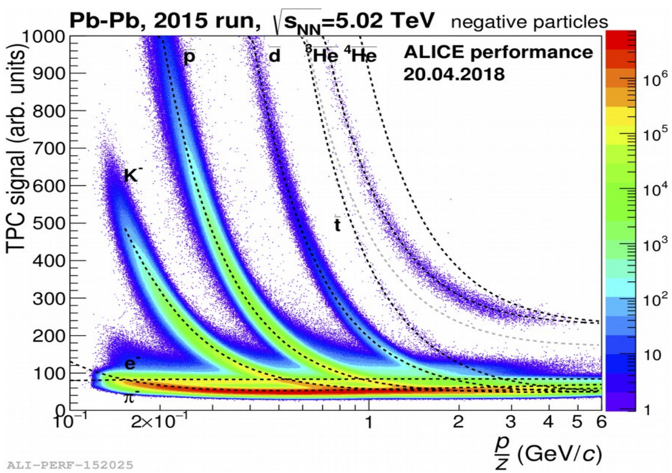
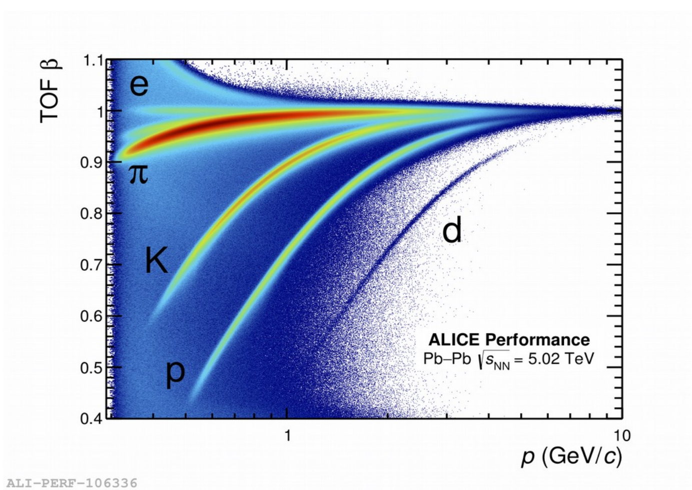


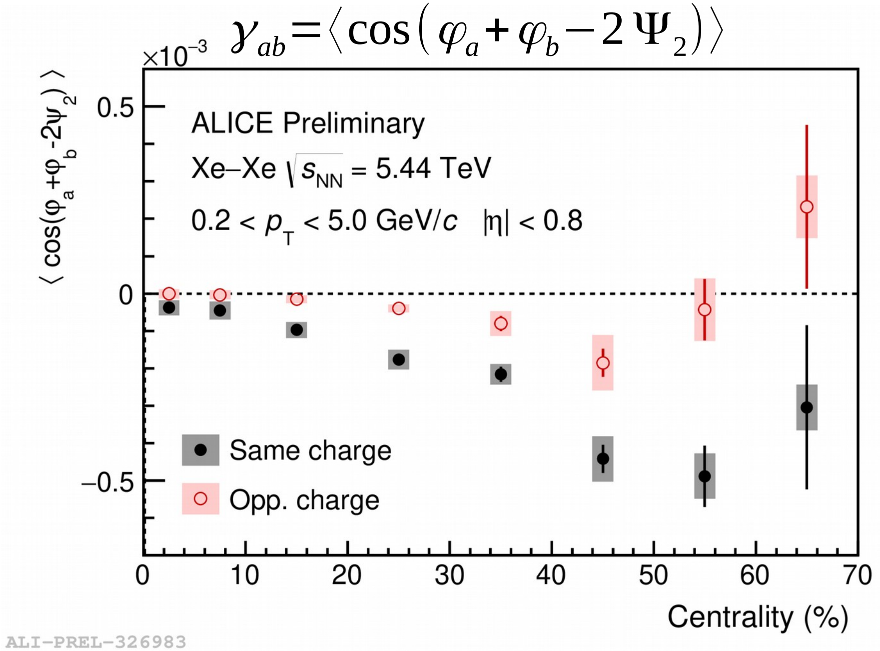


- Track selection
  - $|\eta| < 0.8$
  - $0.2 < p_T < 5$ GeV/c

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

CME in Xe-Xe and Pb-Pb collisions

2- and 3-particle correlators in Xe-Xe collisions: centrality dependence



- γ_{ab}: stronger correlation for opposite charge pairs compared to same charge → charge separation

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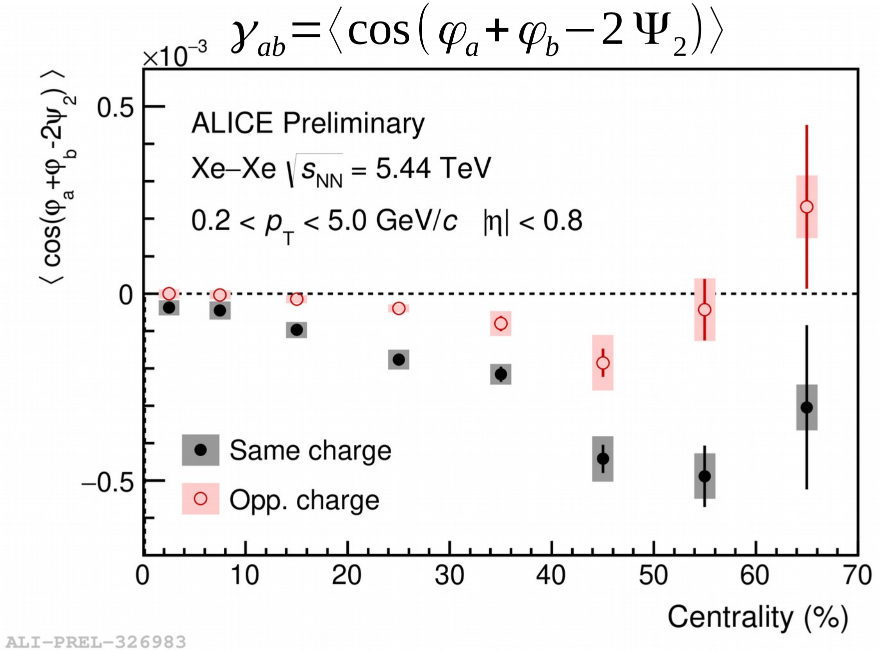

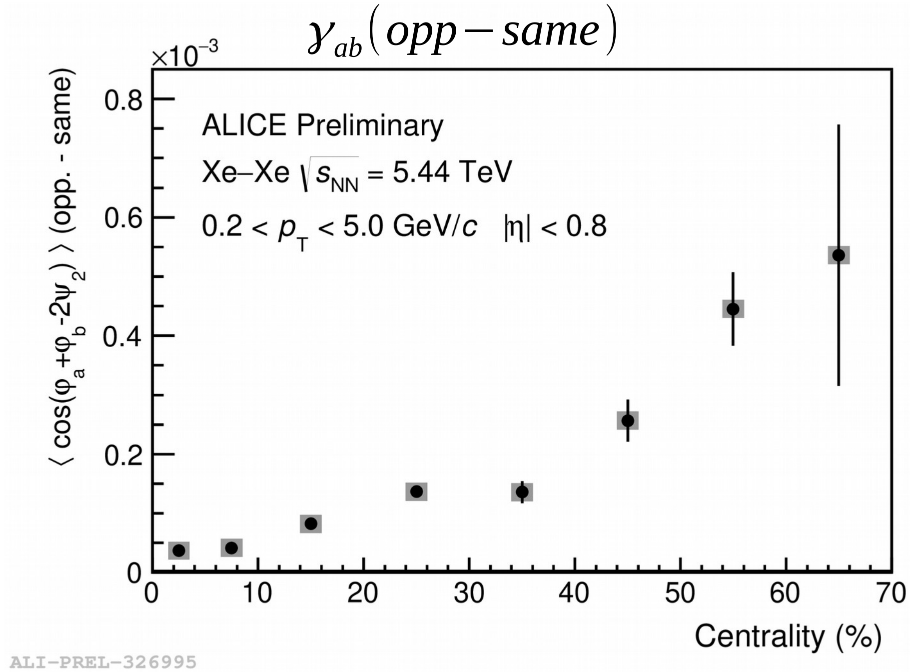

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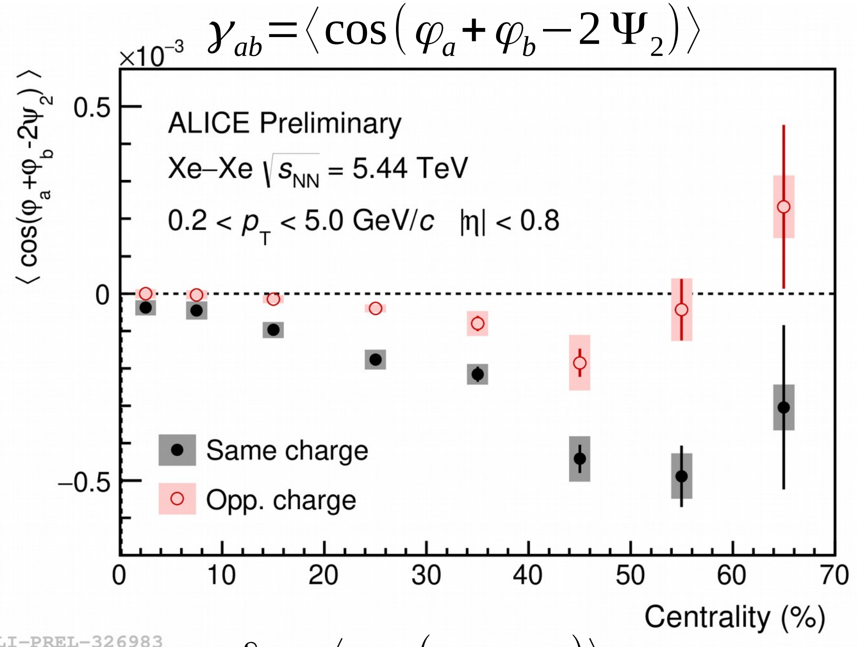
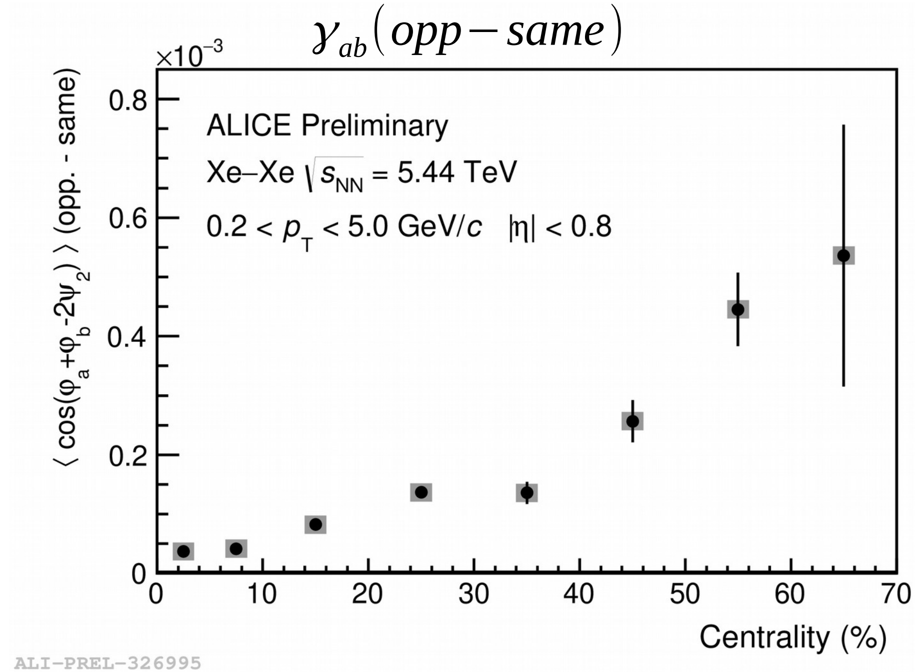
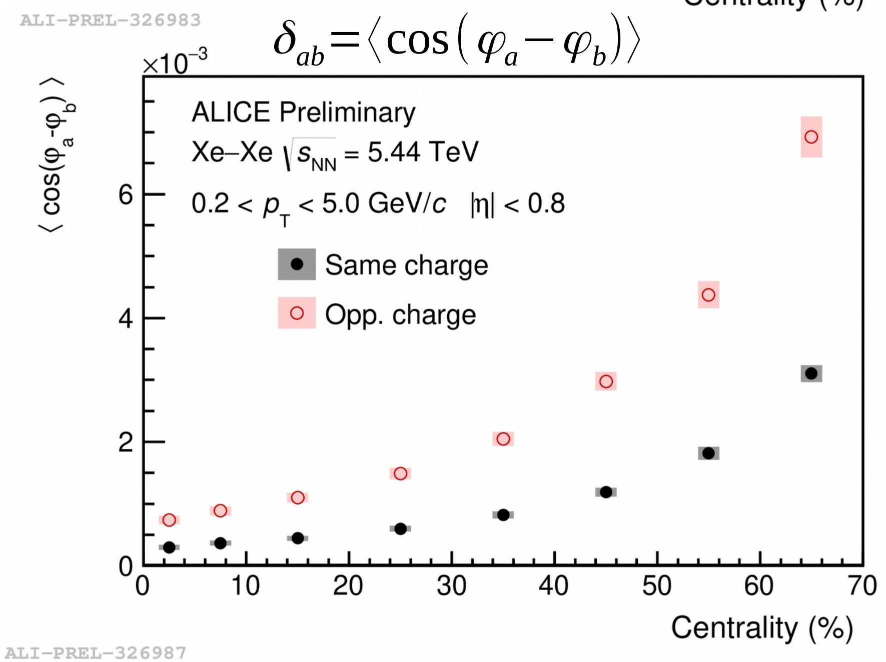


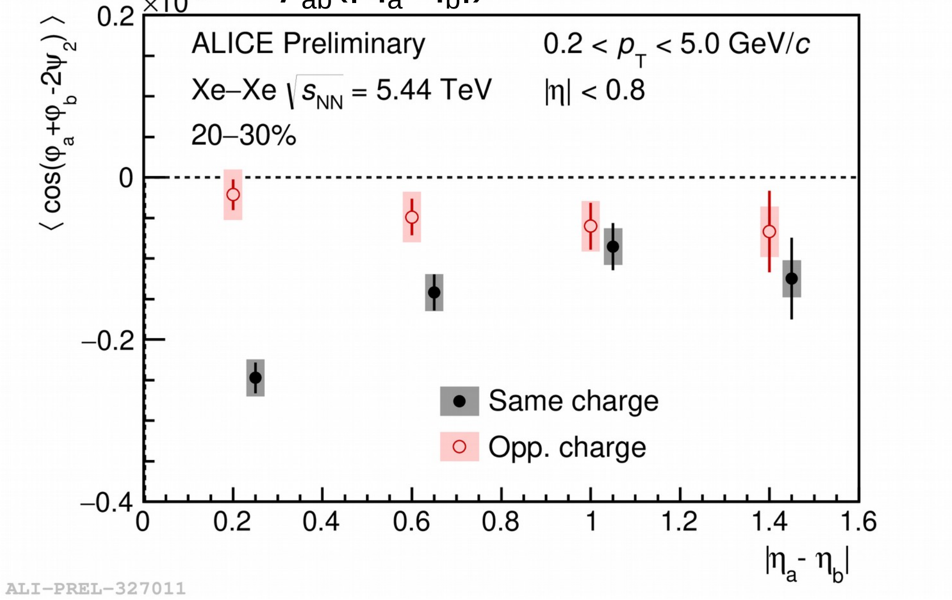




- γ_{ab}: stronger correlation for opposite charge pairs compared to same charge → charge separation
- γ_{ab}(opp-same): indication of charge separation
- δ_{ab}: stronger correlation for opposite charge pairs compared to same charge → background dominates

3-particle correlator in Xe-Xe collisions: differential analysis

$\gamma_{ab}(|\eta_a-\eta_b|)$



- $\gamma_{ab}(|\eta_a-\eta_b|)$: strong dependence for same charge pairs and weak for opposite charge pairs

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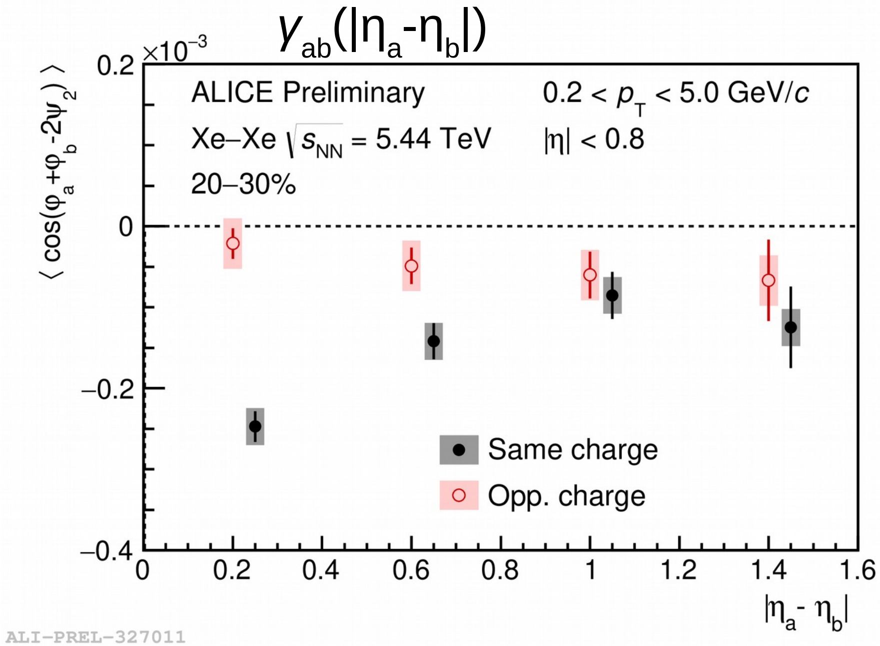

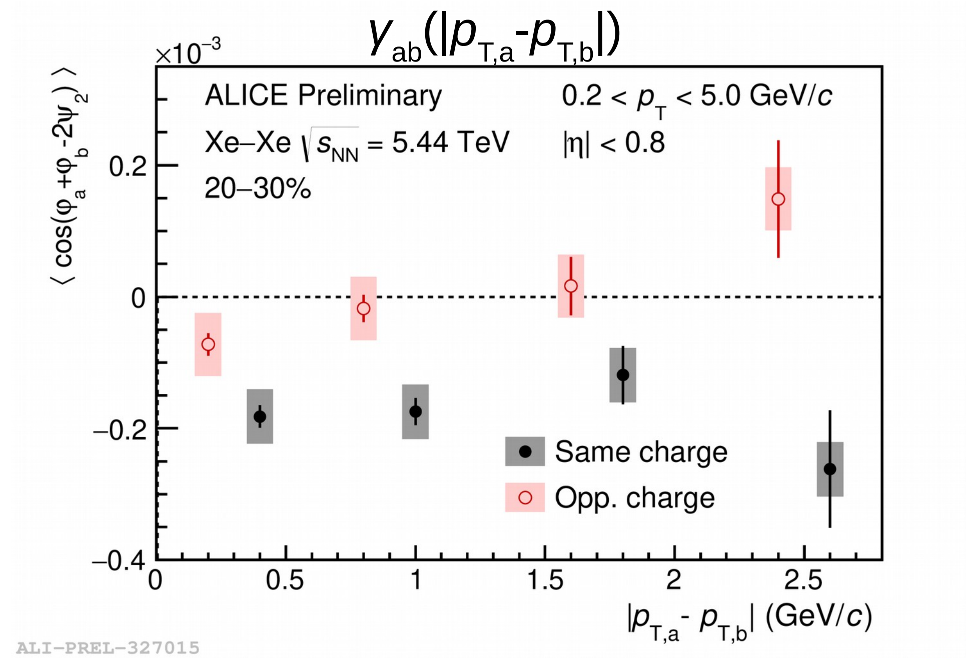

- $\gamma_{ab}(|\eta_a-\eta_b|)$: strong dependence for same charge pairs and weak for opposite charge pairs
- $\gamma_{ab}(|p_{T,a}-p_{T,b}|)$: no dependence for same charge and strong dependence for opposite charge pairs

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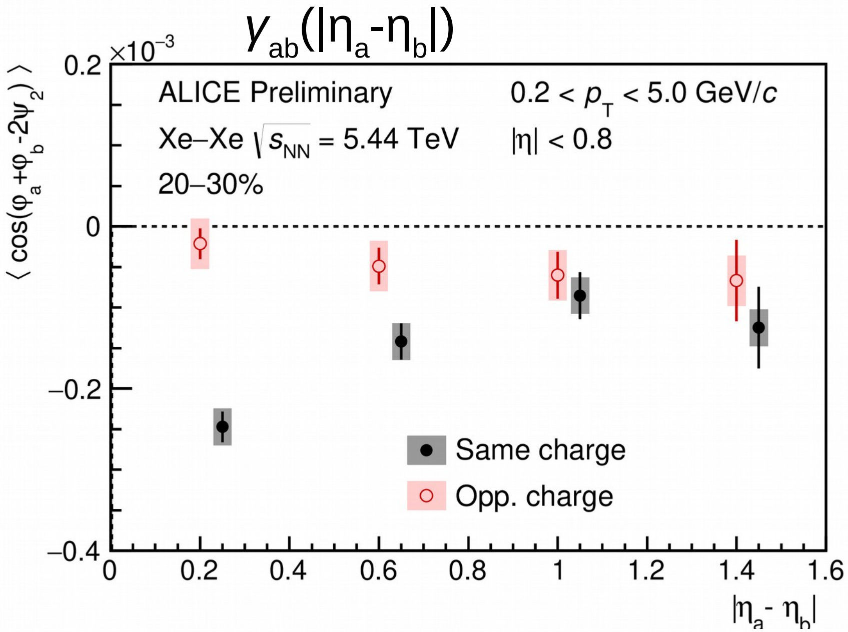

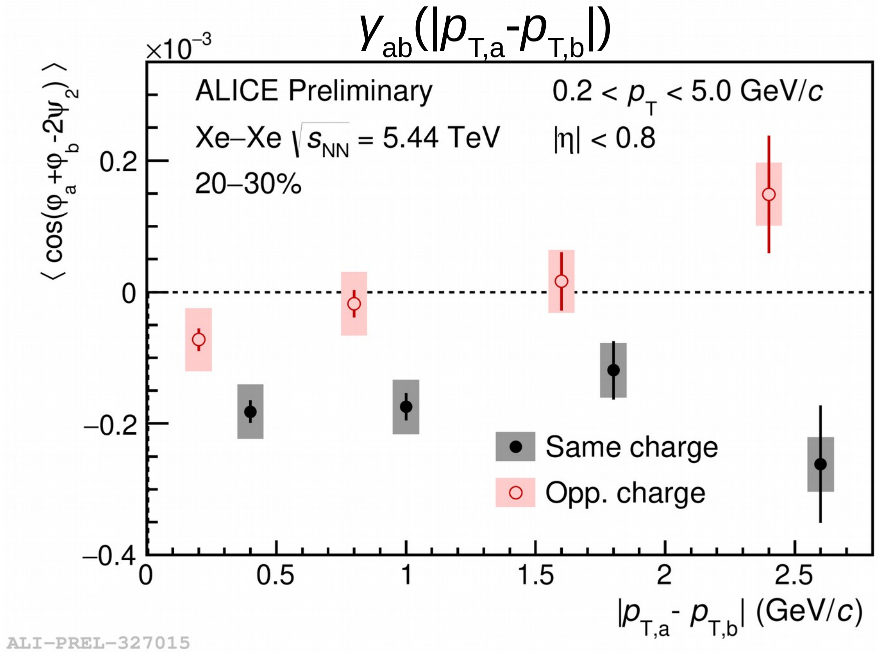

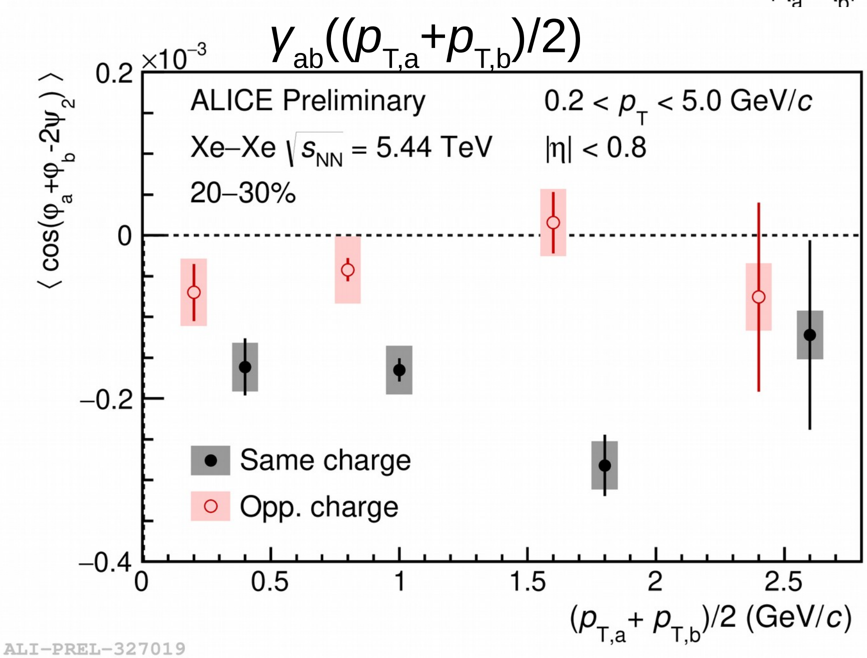

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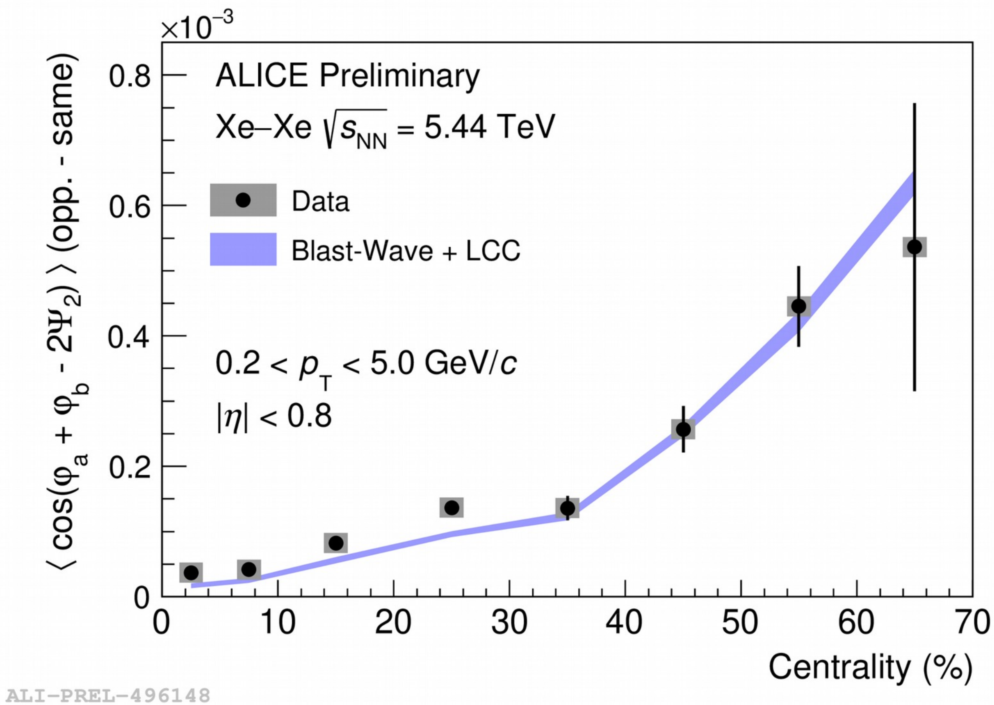
- $\gamma_{ab}(|p_{T,a}-p_{T,b}|)$: no dependence for same charge and strong dependence for opposite charge pairs
- $\gamma_{ab}((p_{T,a}+p_{T,b})/2)$: strong correlation for same charge pairs and weak for opposite charge pairs

3-particle correlator in Xe-Xe collisions: model comparison



- 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
  - Describes fairly well the measured data points
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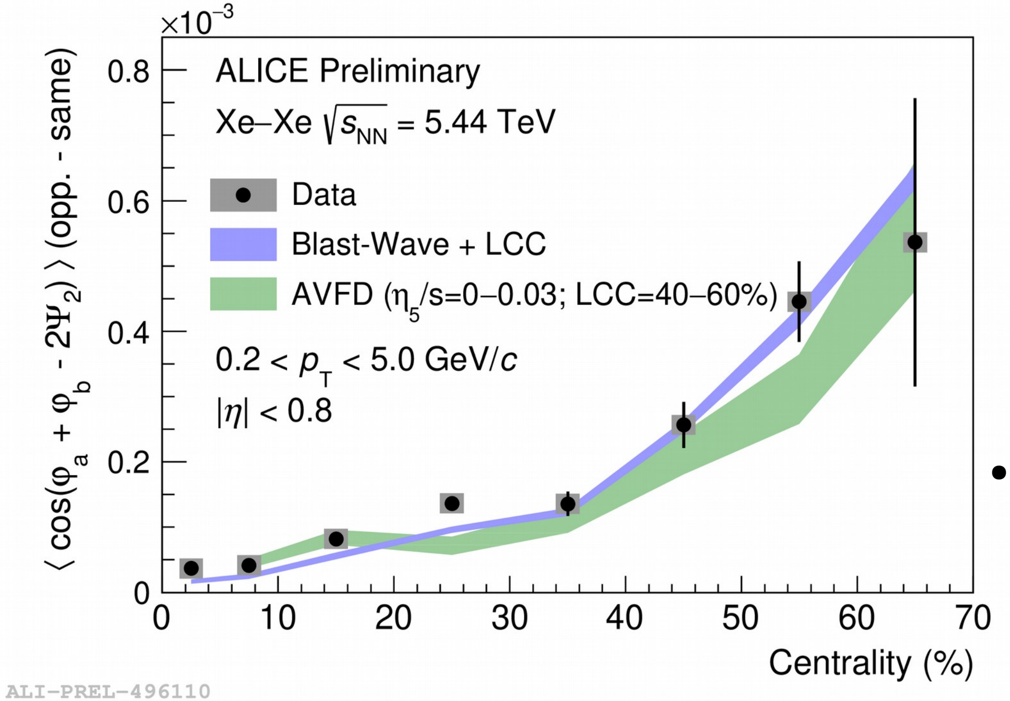

S. Shi et al., Annals Phys. 394, 50 (2018)
Y. Jiang et al., CPC 42 (2018) 011001

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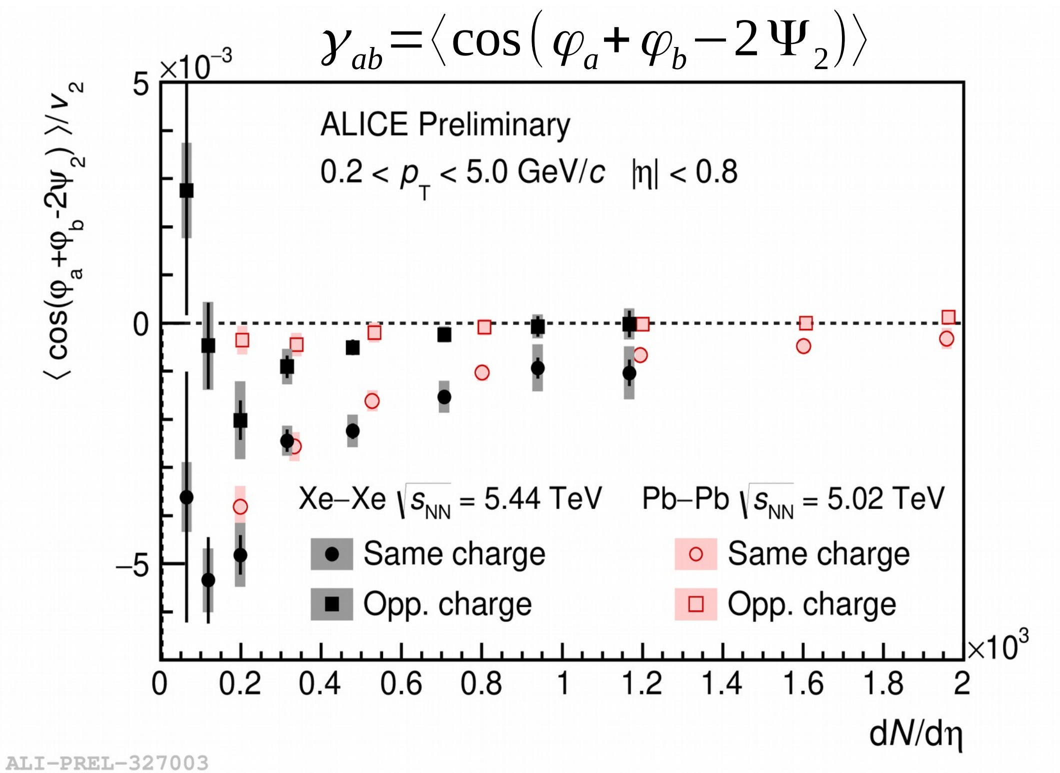
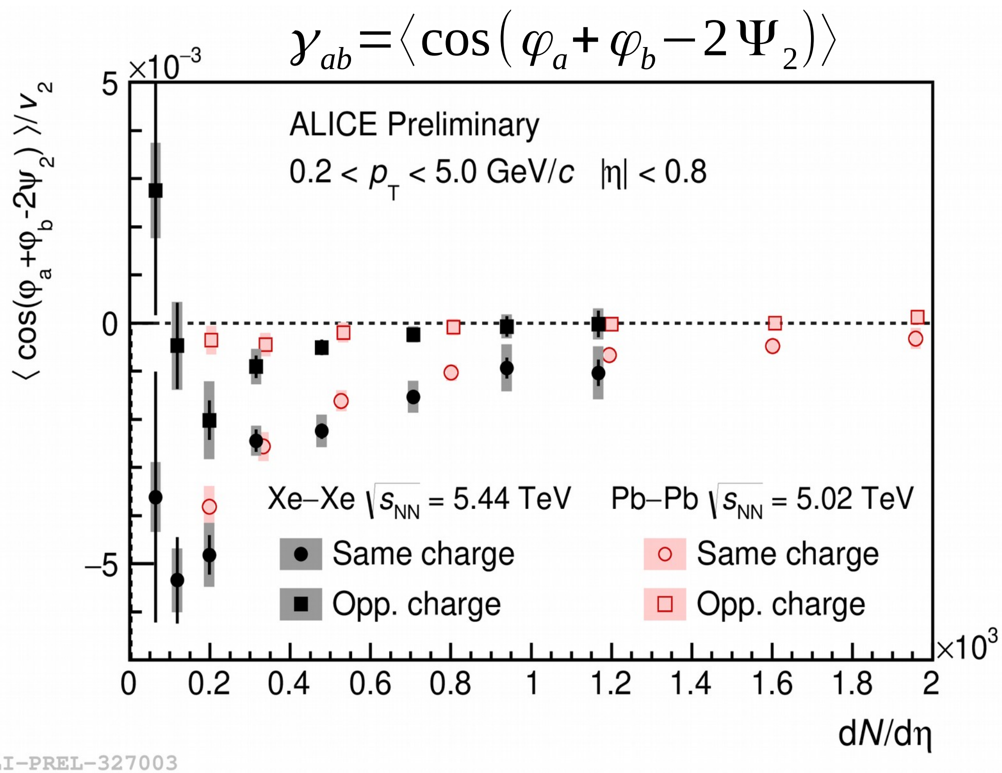
- Anomalous Viscous Fluid Dynamics (AVFD)
  - EbyE IC + E/M fields (field lifetime as input)
  - Tune the parameters in each centrality class to reproduce v_2 and multiplicity (arXiv: 2106.03537)
  - Good agreement with data points
    - *Signal consistent with zero*

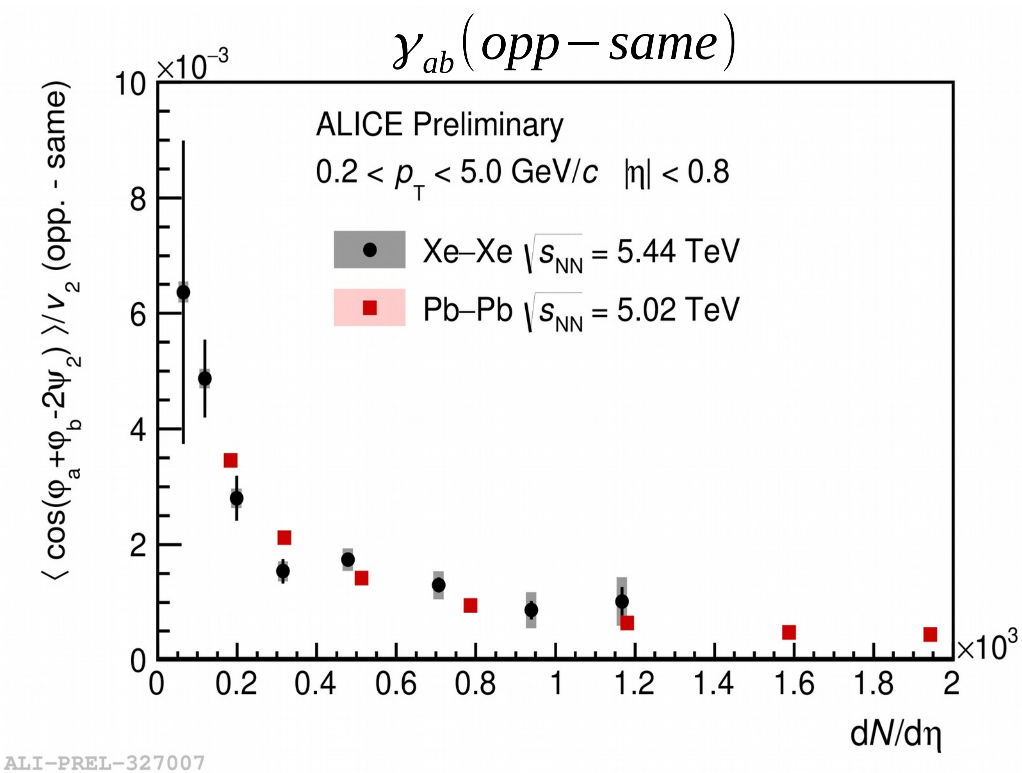
3-particle correlator: Xe-Xe vs Pb-Pb measurements



- γ_{ab} in Xe-Xe collisions has similar values as in Pb-Pb collisions when divided by v_2, except for peripheral collisions

3-particle correlator: Xe-Xe vs Pb-Pb measurements

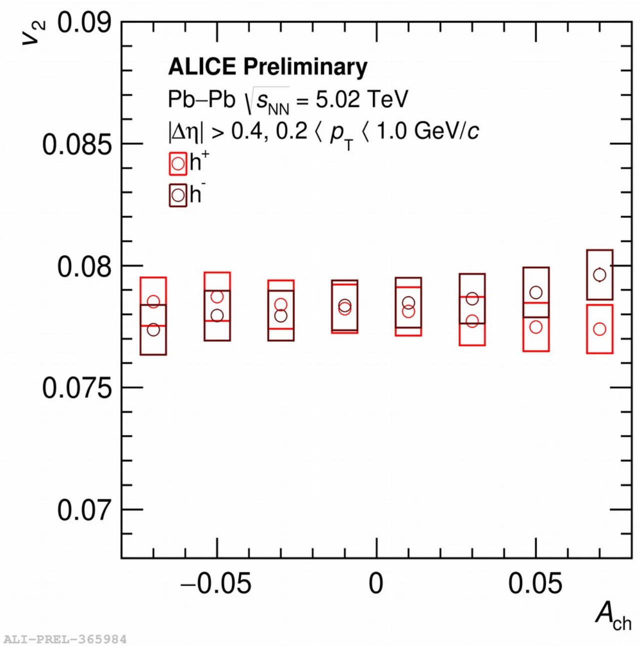


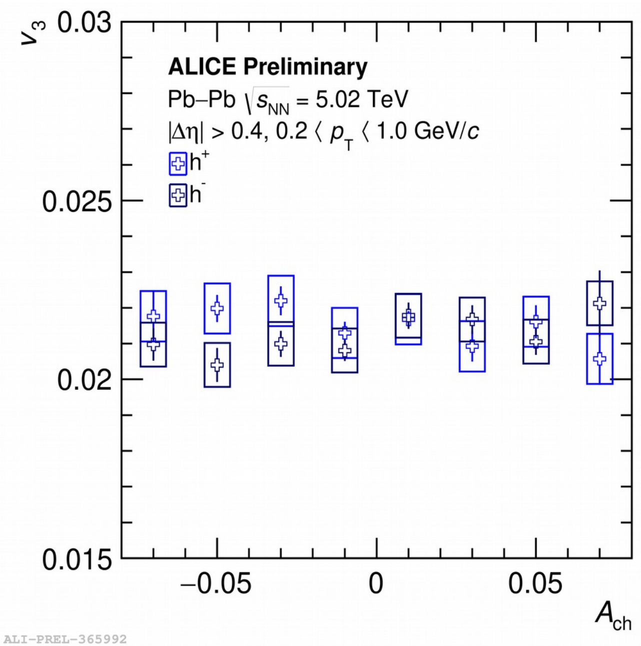


- γ_{ab} in Xe-Xe collisions has similar values as in Pb-Pb collisions when divided by v_2, except for peripheral collisions
- γ_{ab} (opp-same) in Xe-Xe collisions has similar values as in Pb-Pb collisions within uncertainties → background dominates

CMW in Pb-Pb collisions

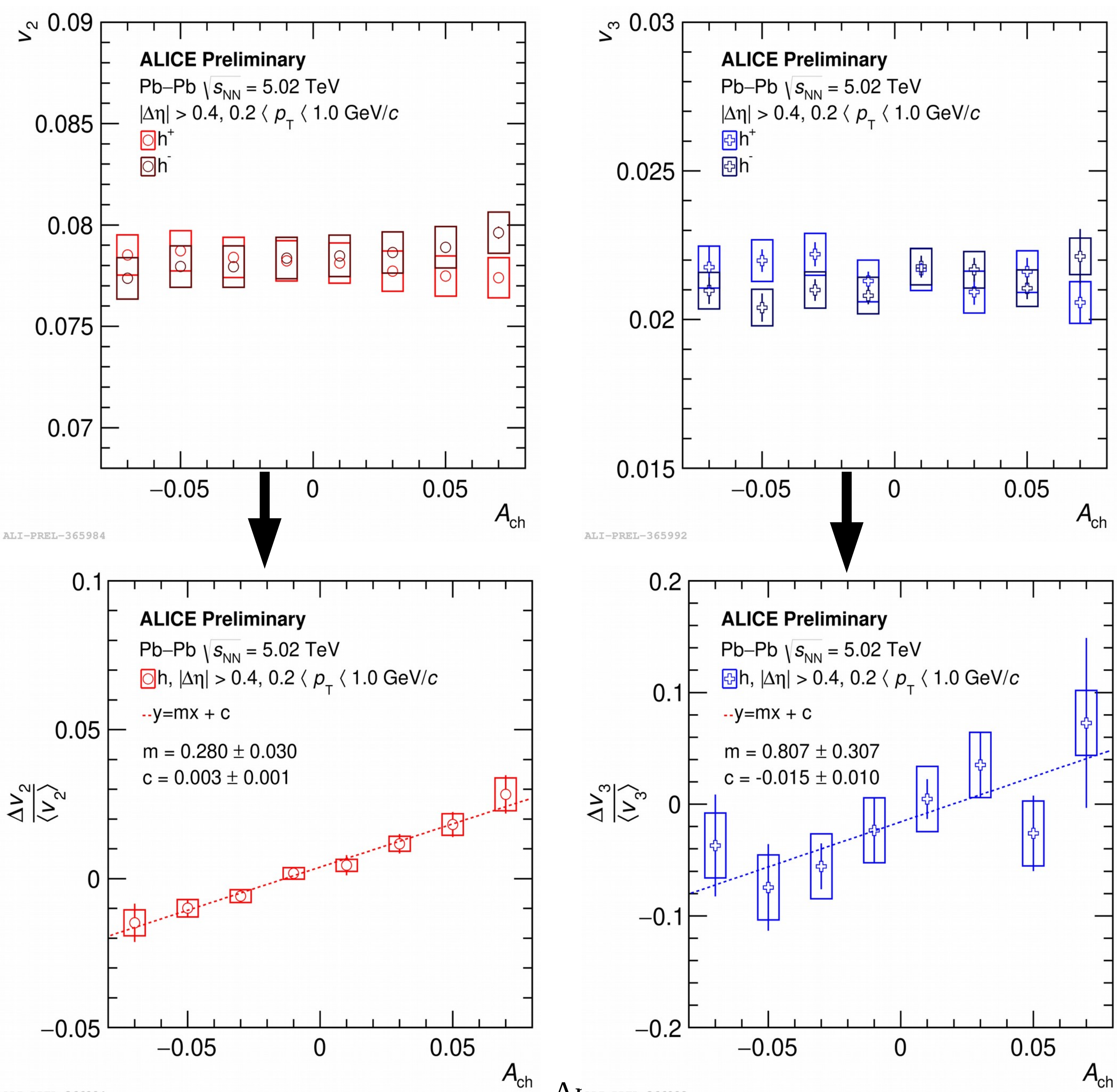
Search for CMW: v_2 and v_3 vs A_{ch} for charged hadrons (40-50 % centrality)





$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

Search for CMW: v_2 and v_3 vs A_{ch} for charged hadrons (40-50 % centrality)



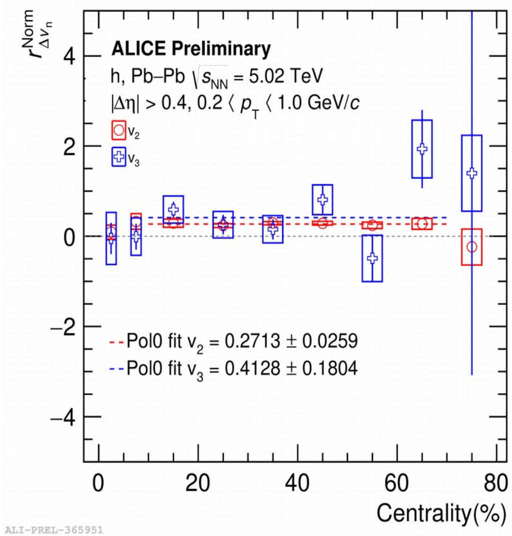
$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$r^{Norm}_{\Delta v_n} = \frac{d\left(\frac{\Delta v_n}{\langle v_n \rangle}\right)}{d A_{ch}}$$

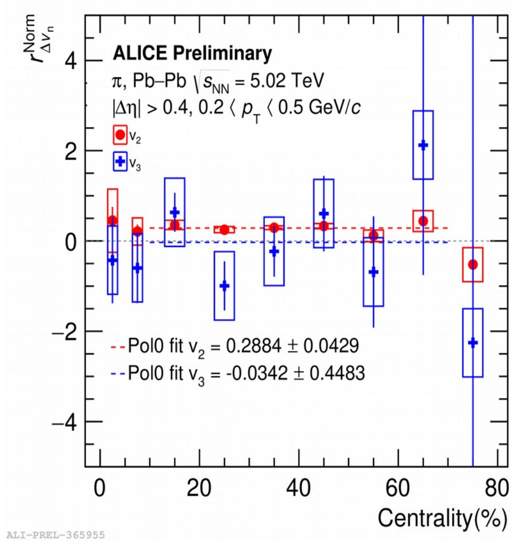
Finite $r^{Norm}_{\Delta v_2}$ and $r^{Norm}_{\Delta v_3}$ is observed

Normalized slope for charged hadrons and pions: centrality dependence

$h^{\pm}$



$\pi^{\pm}$

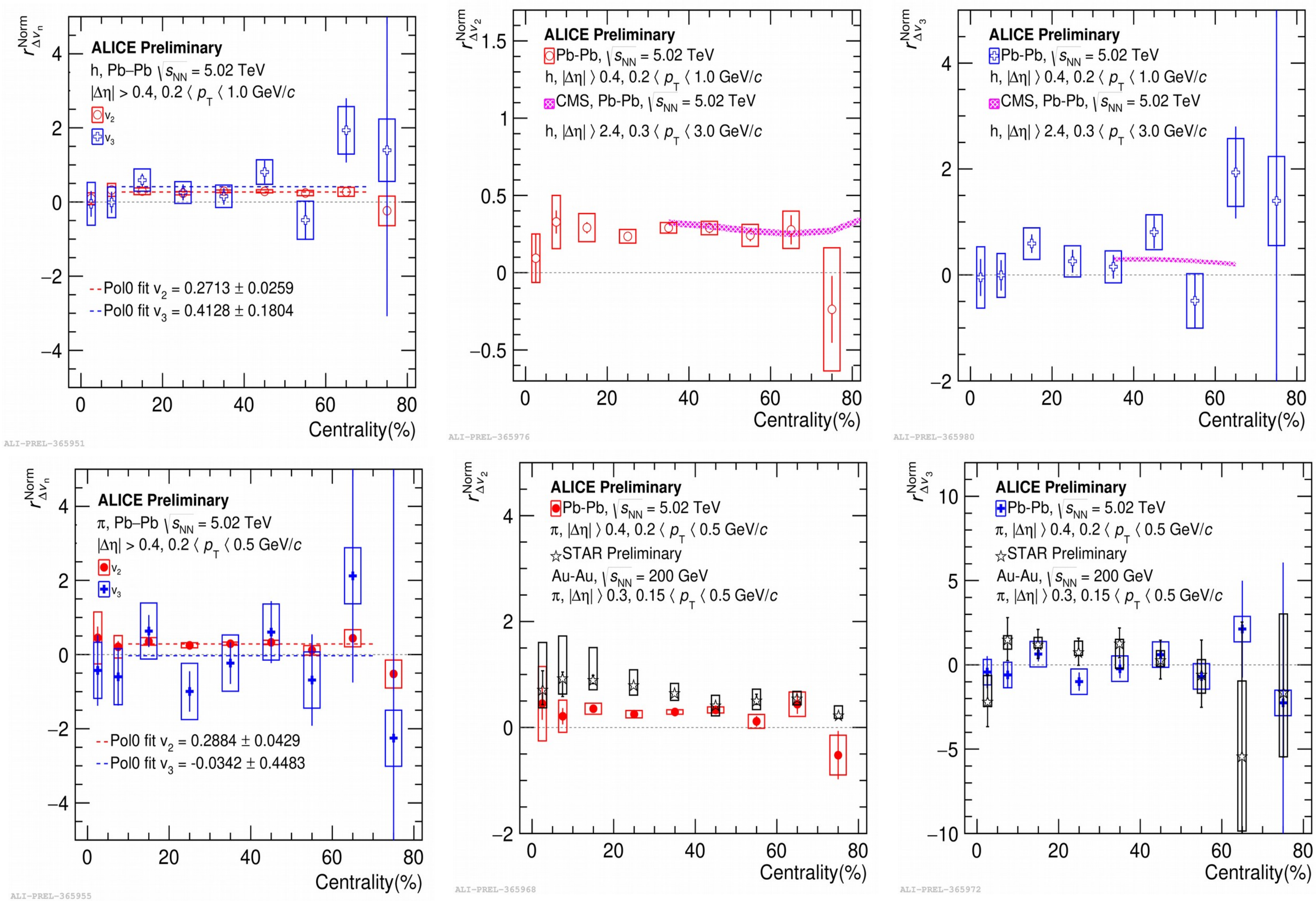


- $r^{Norm}_{\Delta v_2}$ is compatible with $r^{Norm}_{\Delta v_3}$

Comparison with CMS and STAR results

h±

π±



CMS

STAR

CMS Collab., PRC 100, 064908 (2019)
STAR Collab., PRL 114, 252302 (2015)

- $r^{Norm}_{\Delta v_2}$ is compatible with $r^{Norm}_{\Delta v_3}$
- Good agreement with CMS and STAR results

Summary

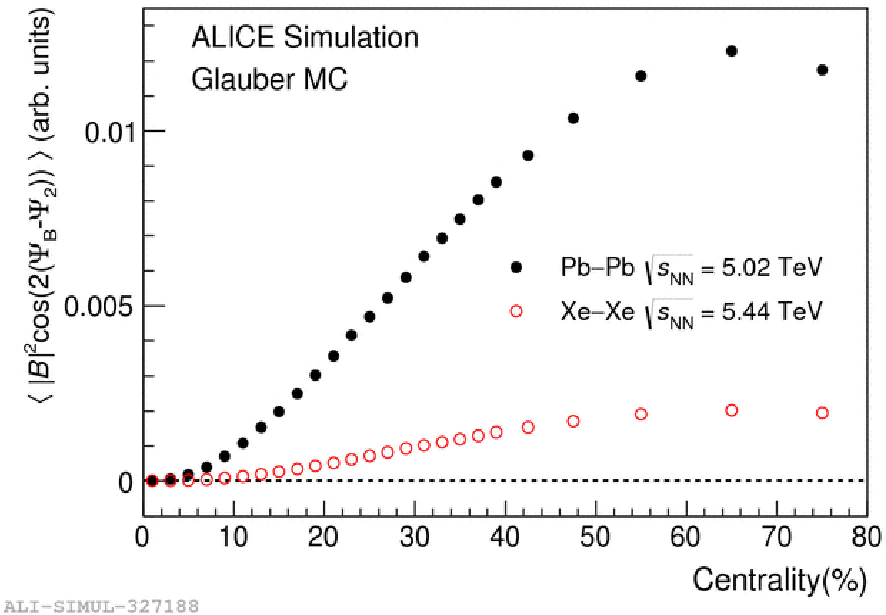
- First measurement of CME in Xe-Xe collisions
  - γ_{ab} consistent with charge separation
  - γ_{ab} (opp-same) similar values as in Pb-Pb collisions
    - Large background contribution
    - Reproduced by background model (BW+LCC) and AVFD with signal values consistent with 0

- Measurements of normalized Δv_2 and Δv_3 slope of charged hadrons and pions in Pb-Pb collisions
  - $r^{Norm}_{\Delta v2}$ is compatible with $r^{Norm}_{\Delta v3}$
  - Good agreement with CMS and STAR results

Backup

Glauber +B configurations

- Perform Glauber simulations tuned to ALICE data
  - MC Glauber v3.2 from TGlauberMC
    - Pb-Pb: σ = 67.6 mb
    - Xe-Xe: σ = 68.4 mb, $\beta_2 = 0.18$, $\beta_4 = 0$
    - 1M events for each configuration
  - Centrality determination using simulated V0M multiplicity → NBD distributions (f*Npart + (1-f)*Ncoll)
    - NBD and f parameters from ALICE public notes
- B determination from proton spectators (arxiv:0711.0950)

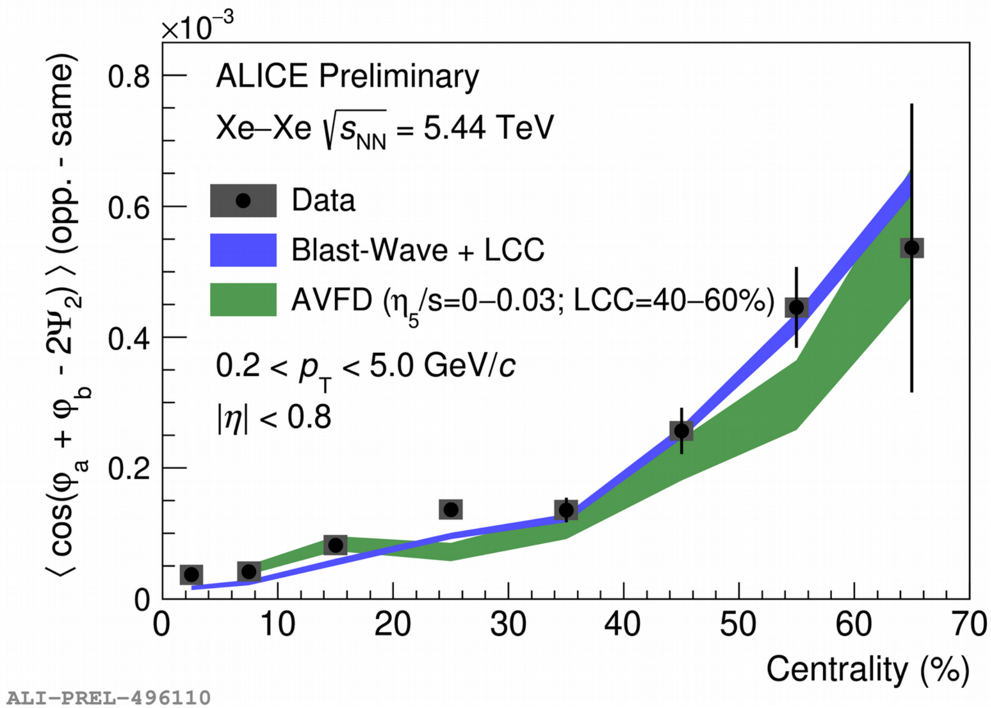


$$e\boldsymbol{B}_s^{\pm}(\tau,\eta,\boldsymbol{x}_\perp) = \pm Z\alpha_{EM}\sinh(Y_0 \mp \eta)\int \mathrm{d}^2\boldsymbol{x}'_\perp \rho_\pm(\boldsymbol{x}'_\perp)[1-\theta_\mp(\boldsymbol{x}'_\perp)] \times \frac{(\boldsymbol{x}'_\perp - \boldsymbol{x}_\perp)\times \boldsymbol{e}_z}{[(\boldsymbol{x}'_\perp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

- τ = 0.1 fm
- Y_0 = 8.672 (Xe-Xe) and 8.592 (Pb-Pb)
- x = y = 0 fm

Expected smaller CME contribution in Xe-Xe than in Pb-Pb collisions

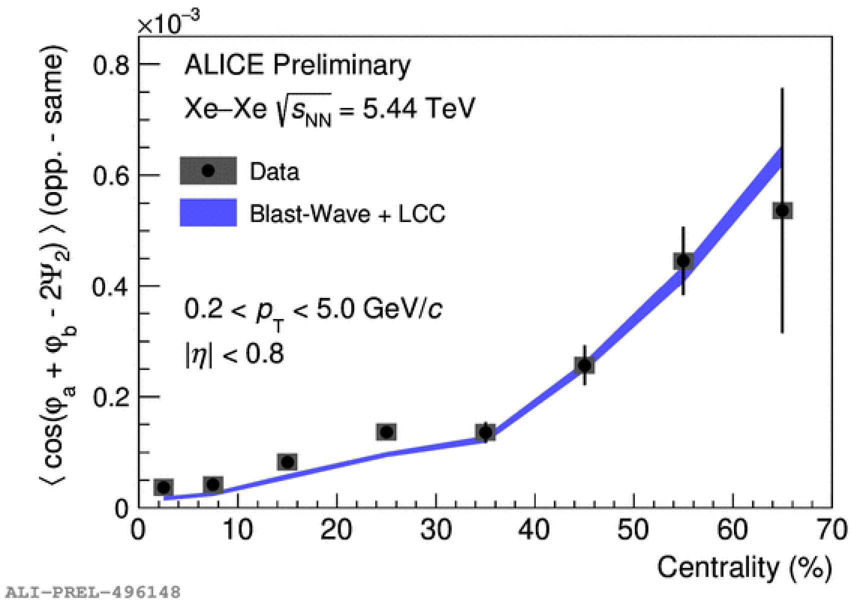
3-particle correlator in Xe-Xe collisions: model comparison

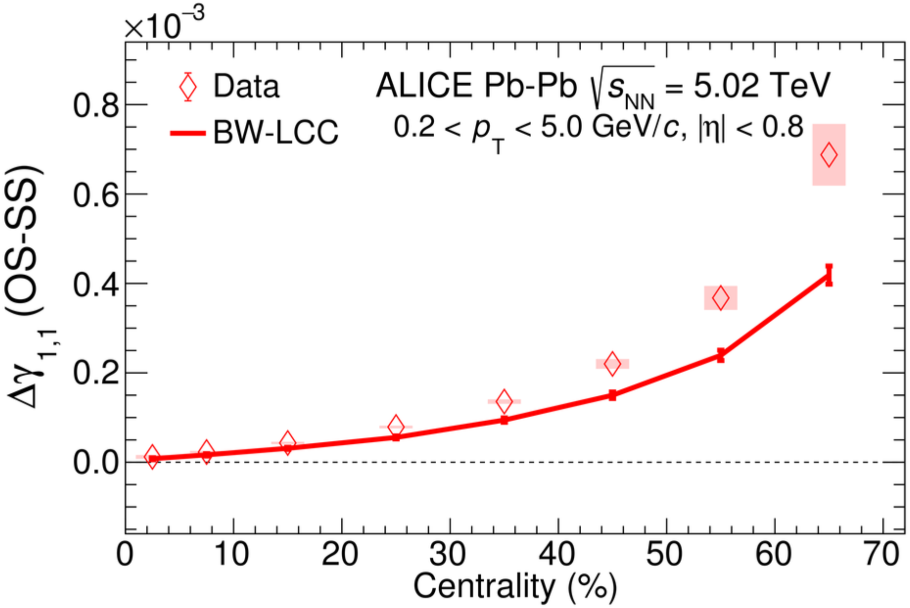


S. Shi et al., Annals Phys. 394, 50 (2018)
Y. Jiang et al., CPC 42 (2018) 011001

- 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
  - Each source generates *M* particles of opposite charge
    - *M* depends on centrality
    - Randomly oriented with the same boost
  - 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)
    - Anomalous transport → CME signal
    - VISH2+1 → hydro evolution
    - Hadronisation + LCC
    - UrQMD
  - Tune the parameters in each centrality class to reproduce v_2 and multiplicity (https://arxiv.org/abs/2106.03537)
  - Good agreement with data points
    - *Signal consistent with zero*

Model calculation: BW+LCC





ALICE Collab, JHEP 160 (2020)