Charge dependent flow measurements and the search for the Chiral Magnetic Wave in ALICE

Ron Belmont
Wayne State University
On behalf of the ALICE Collaboration

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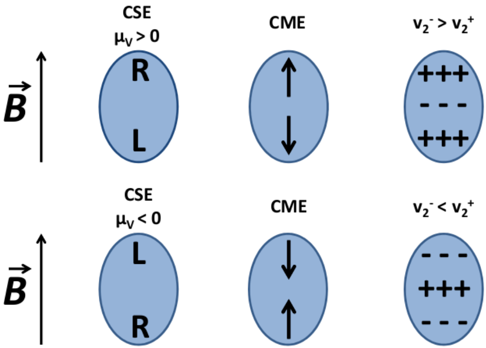
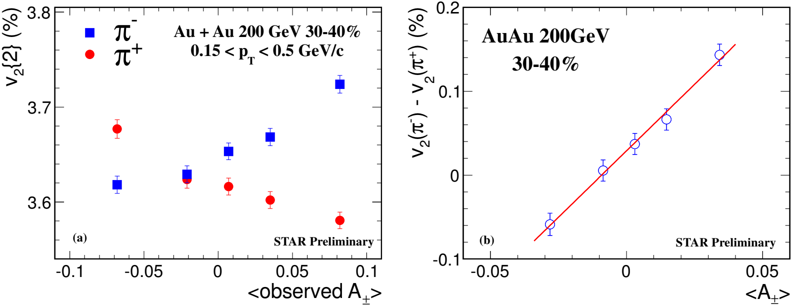
Physics Motivation: the Chiral Magnetic Wave



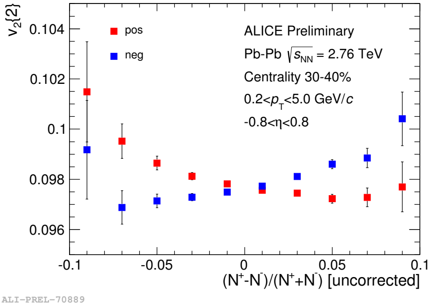
- Coupling between Chiral Magnetic Effect (CME) and Chiral Separation Effect (CSE) leads to wave propagation of electric quadrupole moment, which leads to charge dependence of elliptic flow
- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

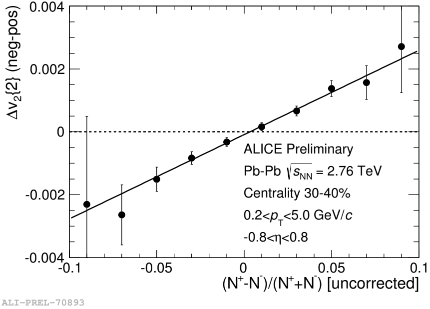
STAR results on $v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality



- STAR preliminary, arXiv:1211.3216
- Charge asymmetry $A_{\pm} = A = (N^+ - N^-)/(N^+ + N^-)$
- Note change in y-axis scale on right plot—correction for efficiency/acceptance
- Qualitatively consistent with CMW picture

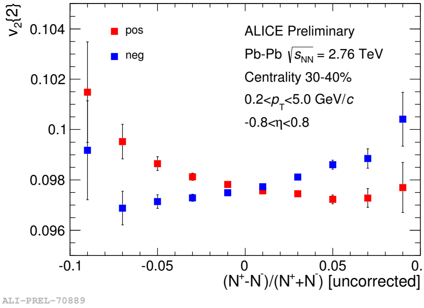
$v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality in ALICE

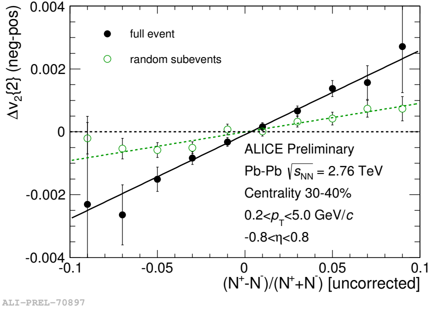




- Strong, clear signal
- Qualitatively consistent with STAR results

$v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality in ALICE





- Strong, clear signal
- Qualitatively consistent with STAR results
- Using random subevents with half the track population weakens signal
- Observable has significant efficiency dependence

Proposal for new measurement: 3-particle correlator

$v_2^{\pm}$ and Δv_2 vs A

- Interesting! But requires efficiency correction due to negative binomial sampling

Proposal for new measurement

- $\langle \cos(n(\varphi_1 - \varphi_2))q_3 \rangle$
  - $\langle \cos(n(\varphi_1 - \varphi_2)) \rangle = v_n^2$
  - q_3 is charge of third particle (event averaged q_3 is same as A)
- Factorize to remove charge independent flow contribution: $\langle \cos(n(\varphi_1 - \varphi_2))q_3 \rangle - \langle q_3 \rangle \langle \cos(n(\varphi_1 - \varphi_2)) \rangle$
- Deviations from 0 $\rightarrow$ charge dependent flow
- We use 2-particle Q-cumulant to calculate $\langle \cos(n(\varphi_1 - \varphi_2)) \rangle$ $c_n\{2\}$ integral, $d_n\{2\}$ differential

Features of new measurement

- Efficiency correction not needed
- Both integral and differential measurements can be done
- Possibility for easier and better comparisons across experiments

Experimental details

Detector subsystems:

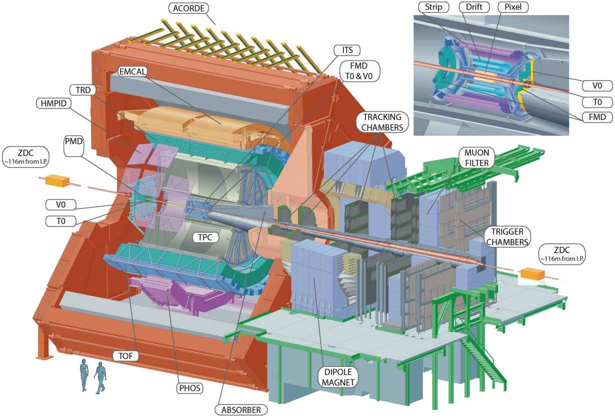
- ITS: vertex, tracking
- V0A+C: trigger, centrality
- TPC: centrality, tracking

Data sample:

- Year 2010 data set
- Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- $\approx$ 12 M events analyzed

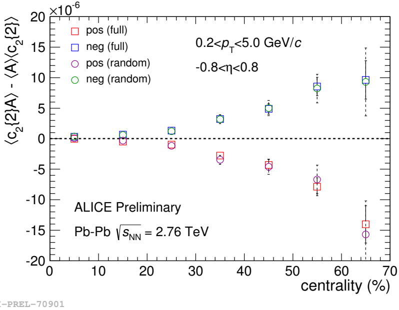
Track selection:

- $0.2 < p_T < 5.0$ (GeV/c)
- $-0.8 < \eta < 0.8$
- $0 < \varphi < 2\pi$

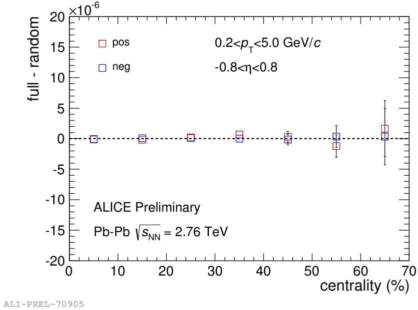


3-particle correlator: efficiency independent

Full and Random together

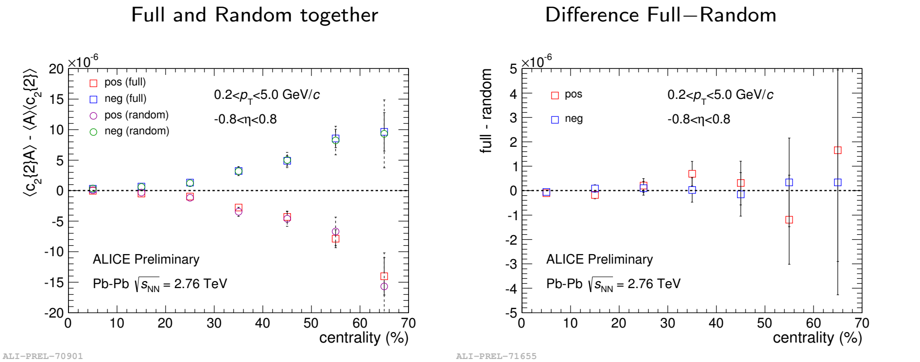


Difference Full−Random



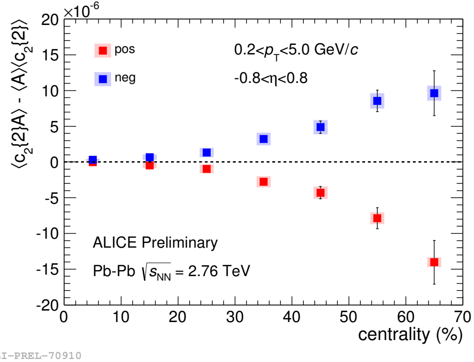
- The correlator is identical when using random subevents (half the tracks are selected randomly), indicating it is unaffected by detector efficiency

3-particle correlator: efficiency independent



- The correlator is identical when using random subevents (half the tracks are selected randomly), indicating it is unaffected by detector efficiency

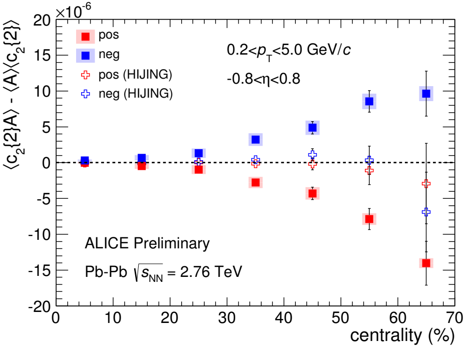
3-particle correlator: 2^{nd} harmonic



What causes the increased charge separation as the collisions become more peripheral?

- Peripheral → stronger magnetic field → stronger CMW effect?
- Central → more combinatoric pairs → trivial dilution of local charge conservation (LCC) effects?
- Dependence on magnitude of v_2 or dN/dy?
- Some combination of these (and possibly other) effects?

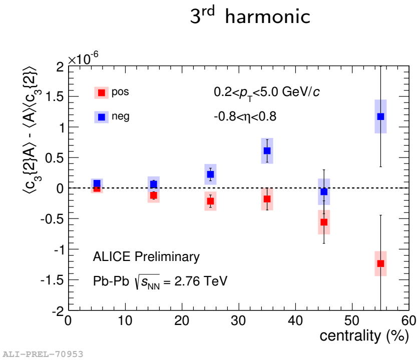
3-particle correlator: comparison to HIJING

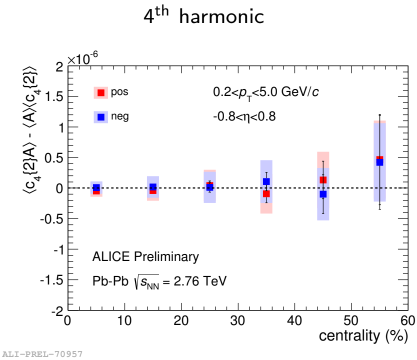


ALI-PREL-70914

- No observed effect in HIJING
- Note that HIJING has 3 particle correlations like 3 body decays

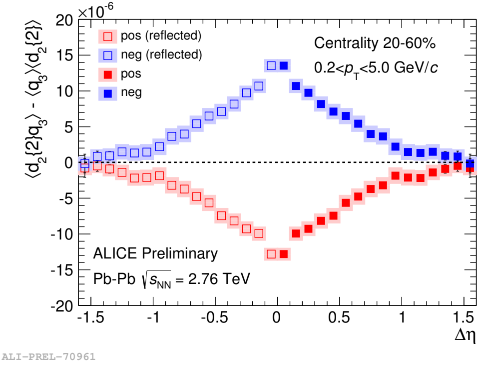
3-particle correlator: higher harmonics





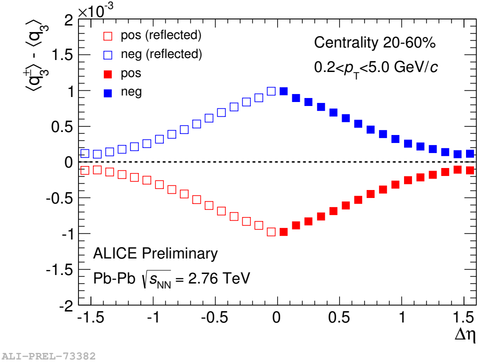
- CMW quadrupole expected to affect only 2nd harmonic, LCC expected to affect all harmonics
- Small effect for 3rd harmonic, no observed effect for 4th harmonic
  —Note y-axis scale reduced by $\times 10$ compared to 2nd harmonic
- Higher order multipole effects for CMW or harmonic interference? LCC only?

3-particle correlator vs $\Delta\eta$



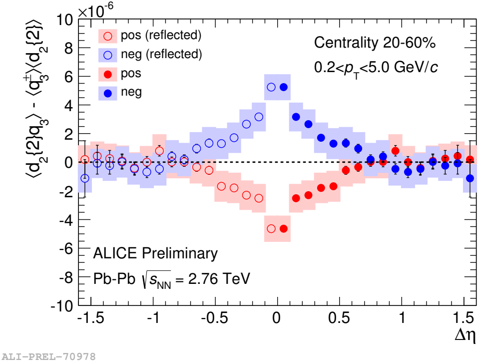
- We can directly measure the η range and dependence of the charge dependent effect
- LCC and CMW correlations may have different η ranges, providing an additional experimental constraint
- This observable best (but not only) way to compare across experiments with different η acceptance

Understanding mean charge vs $\Delta\eta$



- $\langle q_3 \rangle$ denotes mean charge
- $\langle q_3^{\pm} \rangle$ denotes mean charge depending on charge of particle 1 q_1
- The mean charge of the third particle is significantly affected by the charge of the first particle (e.g. LCC, balance function)
- How does this affect the three particle correlator?

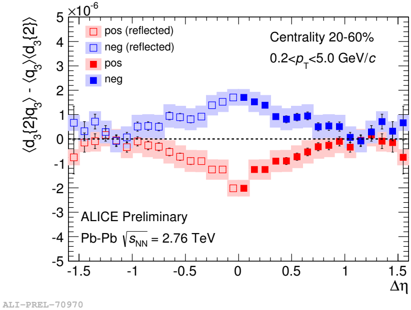
3-particle correlator vs $\Delta\eta$



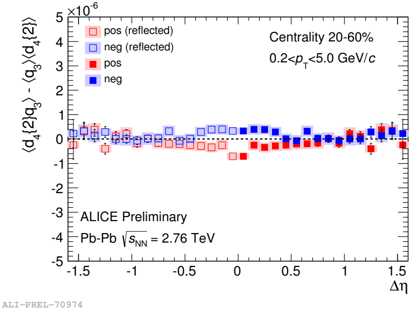
- The observed effect has a large contribution from the dependence of q_3 on q_1
- Both the strength and range are significantly reduced, but a pronounced charge dependent effect remains
- How much contribution from charge conservation has been removed? Is there some way to remove all LCC effects leaving only CMW?

3-particle correlator vs $\Delta\eta$ for higher harmonics

3rd harmonic



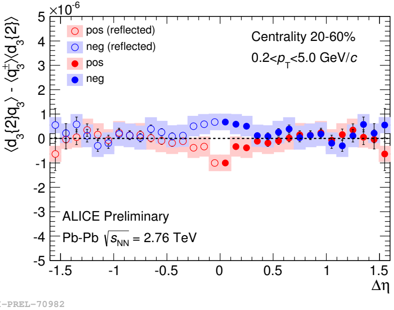
4th harmonic



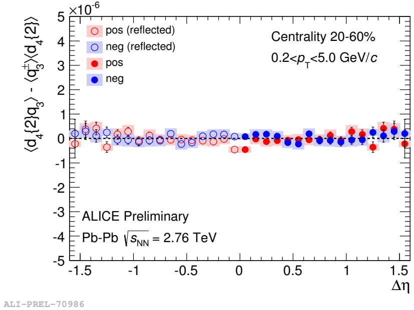
- Charge *independent* subtraction
- Moderate effect for 3rd, minimal effect for 4th

3-particle correlator vs $\Delta\eta$ for higher harmonics

3rd harmonic



4th harmonic



- Charge *dependent* subtraction
- Very little effect for either

Conclusion and Outlook

- Integrated 3 particle correlator has strong centrality dependence
  —LCC and dilution? CMW and B-field strength? Magnitude of v_2, dN/dy? Other?
- Differential 3 particle correlator directly measures the η range, providing additional constraints
- Selection on q_1 for subtraction influences the differential correlator
  —How much of the LCC effect has been removed? Input from theory needed!
- Differential correlator is the best (though not only) way to compare across experiments with different η acceptance
- Small but non-negligible charge dependence of third harmonic
  —Higher order multipole moments of P-violating effects, interference from flow harmonics? LCC only?
- Danke schön!

Additional material

Physics Motivation: the Chiral Magnetic Wave

Chiral Magnetic, Separation Effect:

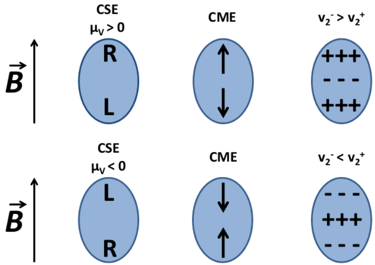
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B}, \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$

Thermodynamics:

$$\vec{J}_V = \frac{N_c e}{2\pi^2}\chi\rho_A \vec{B}, \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\chi\rho_V \vec{B}$$

Chiral basis:

$$\vec{J}_L = -\frac{N_c e}{2\pi^2}\chi\rho_L \vec{B}, \quad \vec{J}_R = \frac{N_c e}{2\pi^2}\chi\rho_R \vec{B}$$



- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

Physics Motivation: the Chiral Magnetic Wave

Azimuthal distribution of charges:

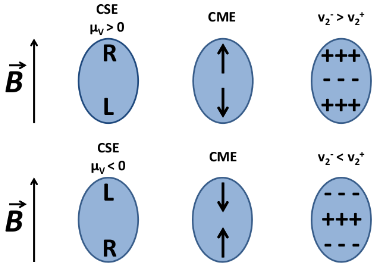
$$\frac{dQ}{d\phi} = Q[1 - r_e \cos(2\phi)]$$

Definition of charge asymmetry A:

$$A = \frac{Q}{N^{total}} = \frac{N^+ - N^-}{N^+ + N^-}$$

Azimuthal distribution of particles:

$$\frac{dN^\pm}{d\phi} = N^\pm[1 + (2v_2 \mp r_e A)\cos(2\phi)]$$

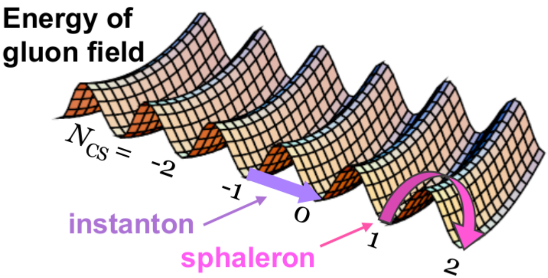


- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

Physics Motivation: Topological Charge

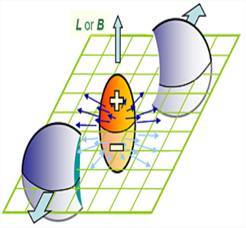
QCD vacuum is highly non-trivial!
Topological charge, winding number, Chern-Simons number:

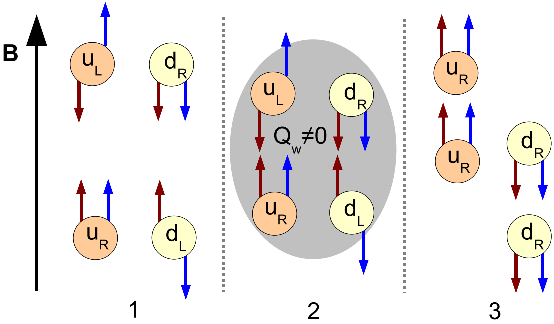
$$Q_w = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \in \mathbb{Z}.$$



- Instanton: tunneling through barrier (all energies/temperatures, including 0)
- Sphaleron: jumping over barrer (only sufficiently high temperatures/energies)

Physics Motivation: the Chiral Magnetic Effect





- Kharzeev, McLerran, and Warringa, Nucl. Phys. A803, 227 (2008)
- Presence of non-zero topological charge causes some chiralities to flip example: $Q_w = -1 \Rightarrow L \rightarrow R, R \rightarrow R$
- Problem: Q_w fluctuates about 0, electric dipole averages to 0

Methodology—Direct Cumulants

- Definition of flow vectors

$$
\begin{aligned}
Q_{n,x} &= \sum_{i=1}^{M} \cos n\varphi_i = \Re\ Q_n \\
Q_{n,y} &= \sum_{i=1}^{M} \sin n\varphi_i = \Im\ Q_n
\end{aligned}
$$

- Direct cumulant method for integral flow

$$
\begin{aligned}
\langle \cos(n(\varphi_1 - \varphi_2)) \rangle &= \frac{Q_n Q_n^* - M}{M(M-1)} \\
&= c_n\{2\}
\end{aligned}
$$

- The flow coefficients can be calculated as $v_n = \sqrt{c_n\{2\}}$
- In this analysis, particles 1 and 2 are always selected to be the same charge

Methodology—Direct Cumulants

- Definition of single particle flow vectors

$$u_{n,x} = \cos n\varphi_i = \Re\, u_n$$
$$u_{n,y} = \sin n\varphi_i = \Im\, u_n$$

- Direct cumulant method for differential flow

$$\langle \cos(n(\varphi_1 - \varphi_2)) \rangle = \frac{u_n Q_n^* - 1}{M - 1} = d_n\{2\}$$

- The flow coefficients can be calculated as $v_n = d_n\{2\}/\sqrt{c_n\{2\}}$
- In this analysis, the charge of particle 1 is selected while particle 2 is allowed to be from either charge