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

QCD Chirality Workshop
Los Angeles
21 January 2015

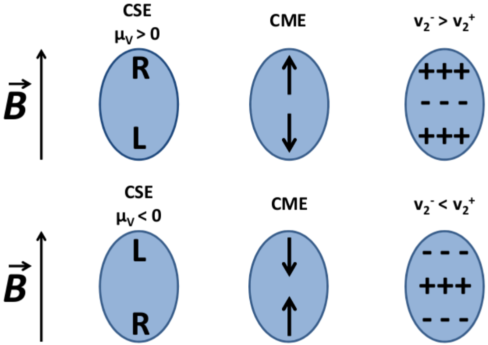
Outline

- Physics motivation
- Previous results on CMW
- Proposal for new observable
- Experimental details
- Results
- Conclusions and outlook

Утро в сосновом лесу

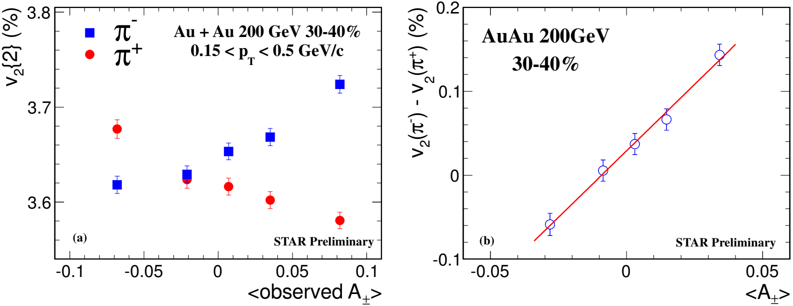
Утро в сосновом лесу

Physics Motivation: the Chiral Magnetic Wave



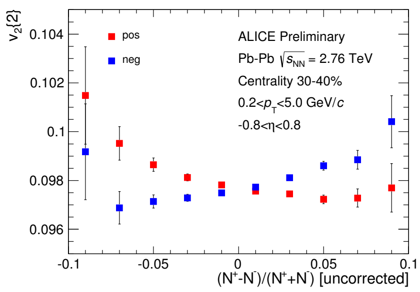
- Coupling between Chiral Magnetic Effect (CME) and Chiral Separation Effect (CSE) leads to wave propagation of electric quadrupole moment, which leads to charge dependence of elliptic flow as a function of charge asymmetry
- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao,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

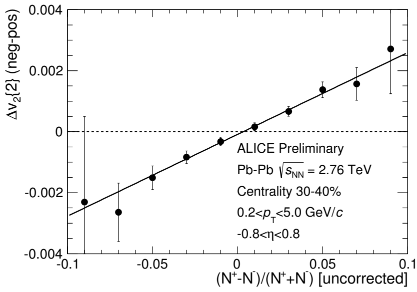
STAR results on $v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality



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

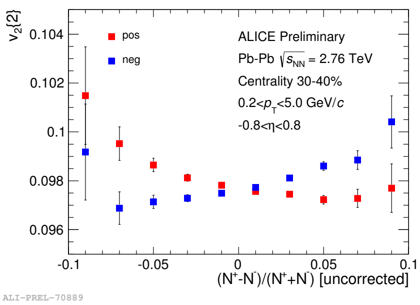
$v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality in ALICE

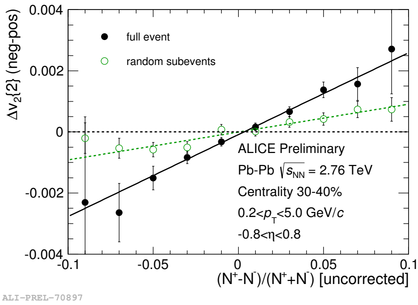




- Strong, clear signal
- Qualitatively consistent with STAR results

$v_2^{\pm}$ 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 as a function of A is very interesting, but requires efficiency correction due to negative binomial sampling
- So what else can we do? Measure the covariance! $\langle v_2 A\rangle - \langle v_2\rangle\langle A\rangle$
- v_2 is a 2-point correlation, so this is a 3-point correlation
- Can also generalize A to the charge of a third particle q_3, since $\langle q_3\rangle_{\mathrm{event}} \equiv A$
- Putting it together, the general 3-point correlator is

$$\langle\cos(n(\varphi_1 - \psi_n))q_3\rangle - \langle q_3\rangle\langle\cos(n(\varphi_1 - \psi_n))\rangle$$

- Similar correlator reported in this analysis

$$\langle\cos(n(\varphi_1 - \varphi_2))q_3\rangle - \langle q_3\rangle\langle\cos(n(\varphi_1 - \varphi_2))\rangle$$

- We use 2-particle Q-cumulant to calculate $\langle\cos(n(\varphi_1 - \varphi_2))\rangle$
  $c_n\{2\}$ integral, $d_n\{2\}$ differential

Experimental details

Detector subsystems:

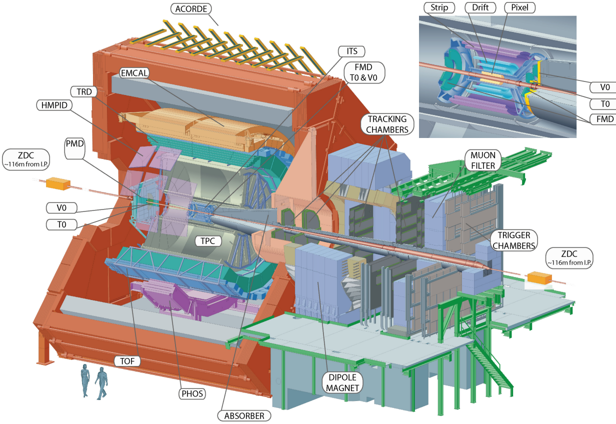
- ITS: vertex, tracking
- V0A+C: trigger, centrality
- TPC: centrality, tracking

Data sample:

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

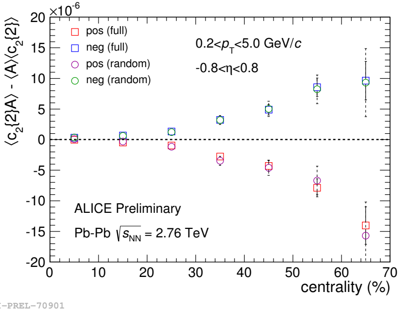
Track selection:

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

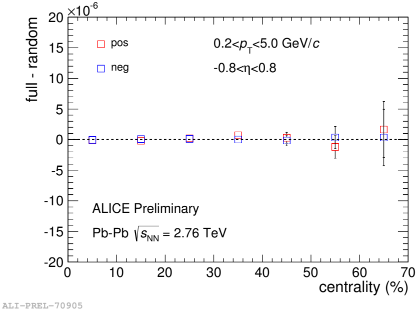


3-particle correlator: efficiency independent

Full and Random together



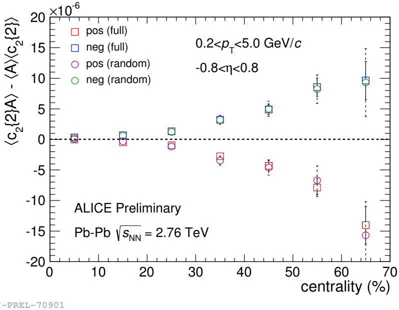
Difference Full−Random



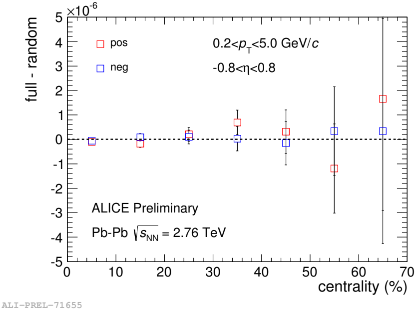
- The correlator is identical when using random subevents (half the tracks are selected randomly), indicating it is unaffected by detector efficiency

3-particle correlator: efficiency independent

Full and Random together

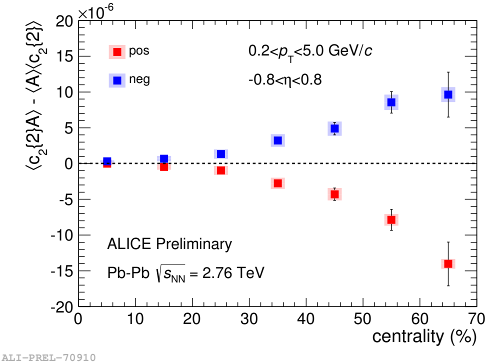


Difference Full−Random



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

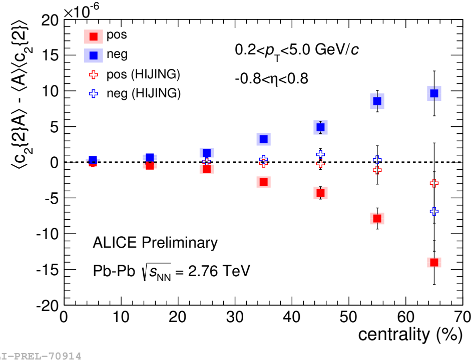
3-particle correlator: 2nd harmonic



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?

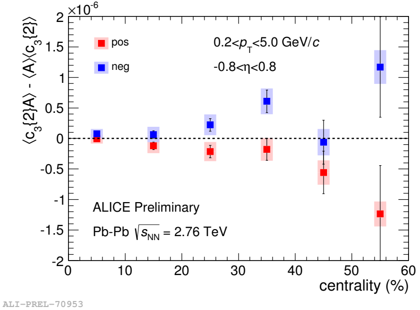
3-particle correlator: comparison to HIJING



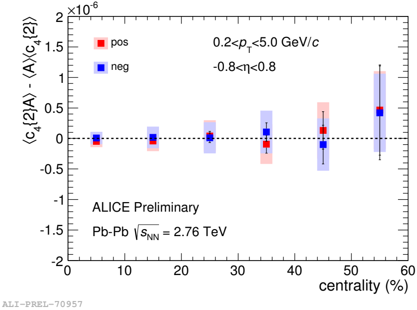
- No observed effect in HIJING
- Note that HIJING has 3 particle correlations like 3 body decays

3-particle correlator: higher harmonics

3^{rd} harmonic



4^{th} harmonic

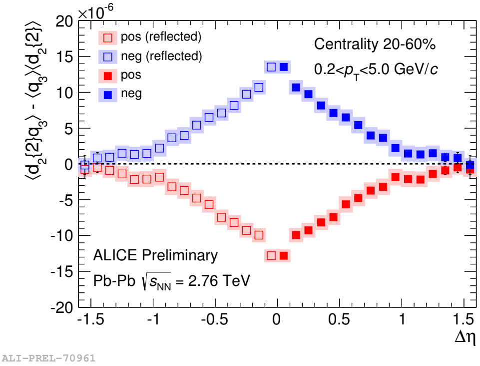


- CMW quadrupole expected to affect only 2^{nd} harmonic, LCC expected to affect all harmonics
- Small effect for 3^{rd} harmonic, no observed effect for 4^{th} harmonic
  —Note y-axis scale reduced by $\times 10$ compared to 2^{nd} harmonic
- Higher order multipole effects for CMW or harmonic interference?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

Intermission

- What kind of differential studies can we do with this correlator?

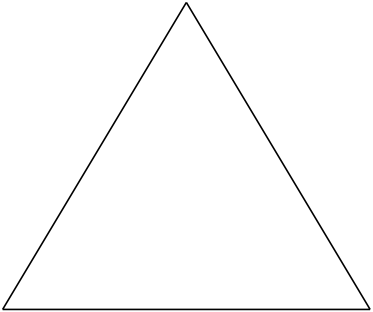
3-particle correlator vs $\Delta\eta$



- Generalizing from A to q_3 as discussed, we can measure the correlator as a function of the separation between particles 1 and 3, $\Delta\eta = \eta_1 - \eta_3$
- Doing so 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
- However, we're missing something very important...

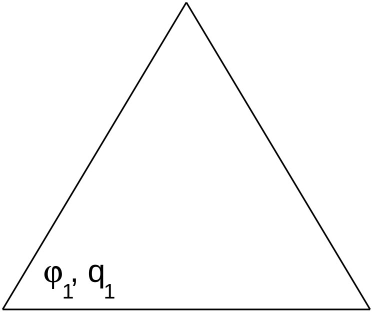
3-particle correlator: a closer look

- Let us examine the three particles more carefully



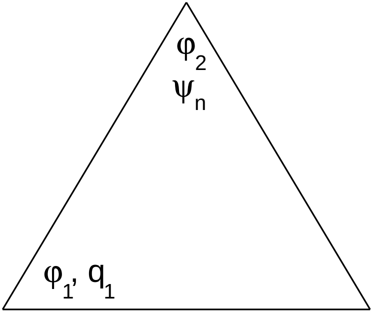
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1



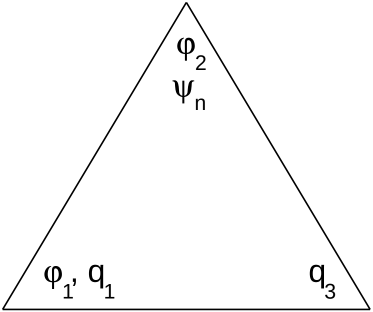
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1



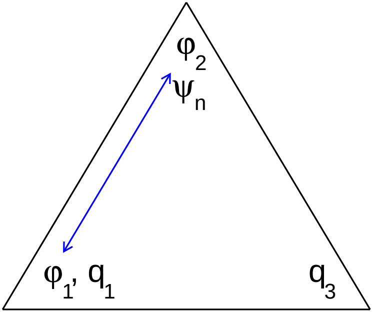
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1
- 3 is the charged particle



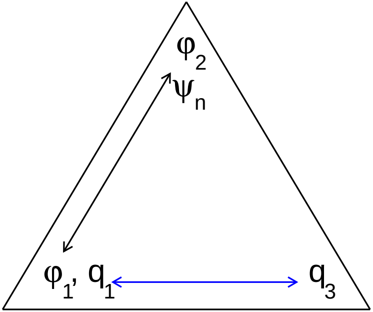
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1
- 3 is the charged particle
- The correlation between 1 and 2 is the harmonic coefficient



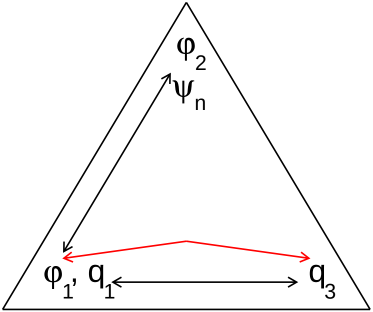
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1
- 3 is the charged particle
- The correlation between 1 and 2 is the harmonic coefficient
- The correlation between 1 and 3 is the balance function



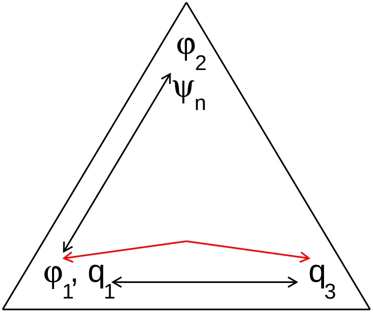
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1
- 3 is the charged particle
- The correlation between 1 and 2 is the harmonic coefficient
- The correlation between 1 and 3 is the balance function
- Both correlations must be fully taken into account to get at potentially new physics



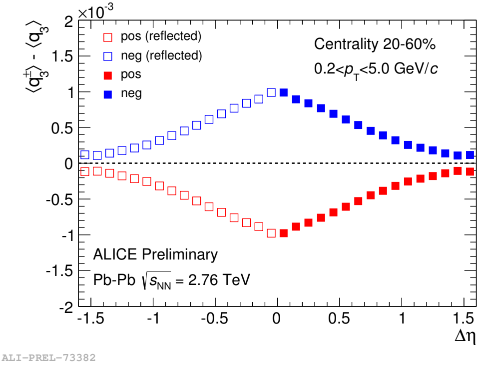
3-particle correlator: a closer look

- Let us examine the three particles more carefully
- 1 is the particle of interest, and we consider both φ_1 and q_1
- 2 is the reference particle for estimating the flow of particle 1
- 3 is the charged particle
- The correlation between 1 and 2 is the harmonic coefficient
- The correlation between 1 and 3 is the balance function
- Both correlations must be fully taken into account to get at potentially new physics



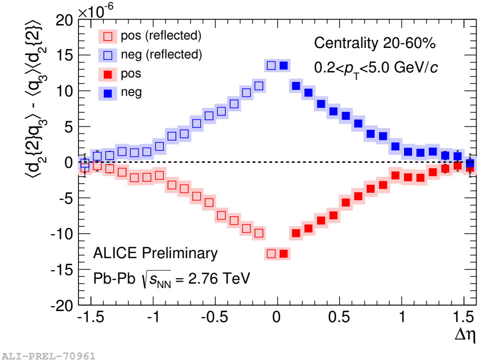
  - When removing the charge correlation between 1 and 3, all reducible correlations have been removed and the correlator is a cumulant $\langle\langle\cos(n(\varphi_1 - \varphi_2))q_3\rangle\rangle$
  - S.A. Voloshin and R. Belmont, arXiv:1408.0714

Understanding mean charge vs $\Delta\eta$



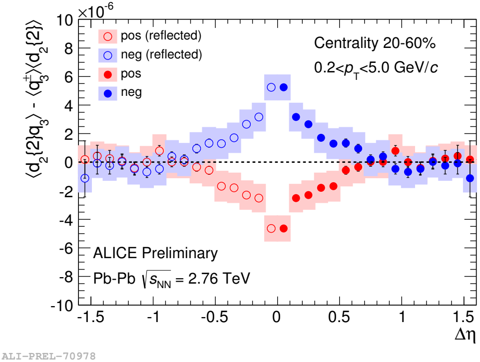
- $\langle q_3 \rangle$ denotes mean charge (independent of q_1)
- $\langle q_3^{\pm} \rangle$ denotes mean charge depending on charge of particle 1 q_1
- The mean charge of the third particle is affected by the charge of the first particle due to charged pair production (the balance function)
- How does this affect the three particle correlator?

3-particle correlator vs $\Delta\eta$



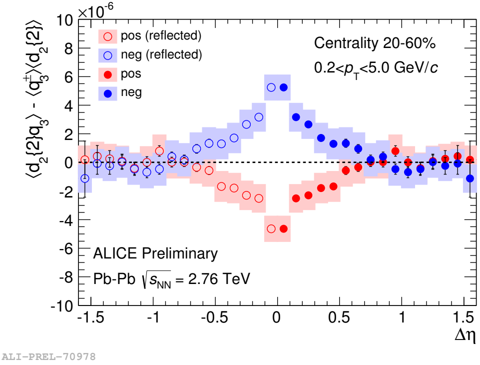
- Charge independent subtraction (charge correlation not considered)

3-particle correlator vs $\Delta\eta$



- Charge dependent subtraction (charge correlation considered)

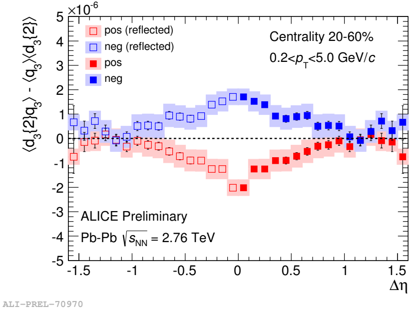
3-particle correlator vs $\Delta\eta$



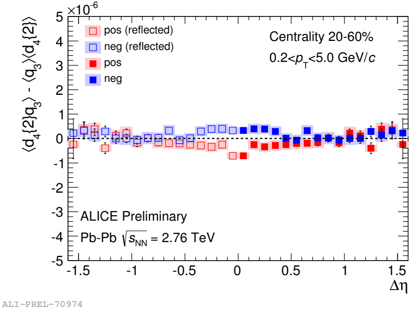
- Charge dependent subtraction (charge correlation considered)
- The observed effect has a large contribution from the dependence of q_3 on q_1
- Both the strength and range are significantly reduced, but a pronounced charge dependent effect remains
- How much contribution from charge conservation has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

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

3[rd] harmonic

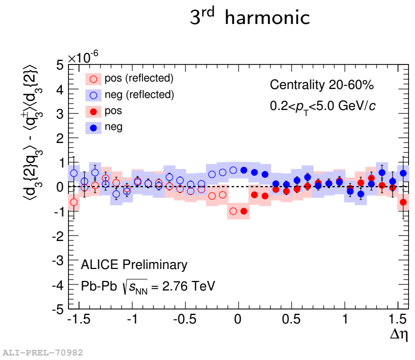


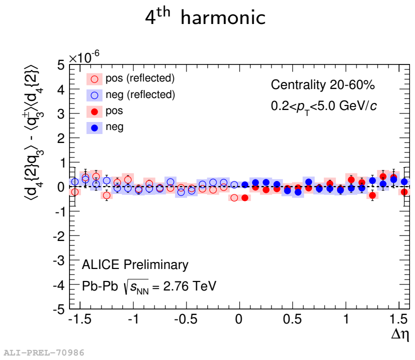
4[th] harmonic



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

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





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

Summary

- 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?

Outlook

Use of identified particlces

- The three-particle correlator can be analyzed with identified particles—and not just the flow particle but any particle or all three particles
- PID of first particle could be used to examine whether there's any flavor or mass dependence of the observed effect
- PID of second and third particles may also be interesting to study
- The current data may not have enough statistics for a detailed PID study, but LHC Run-II is coming soon

Cross-experiment comparisons

- This correlator guarantees "fair" comparisons across experiments
- CMS and ATLAS can measure the differential correlator to larger delta eta
- STAR can (and should!) analyze this correlator for all available RHIC energies, as they have done with the CME correlator

Additional material

Physics Motivation: the Chiral Magnetic Wave

Chiral Magnetic, Separation Effect:

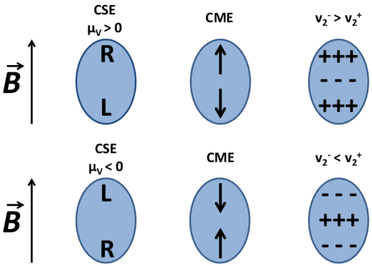
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A\vec{B}, \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V\vec{B}$$

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:

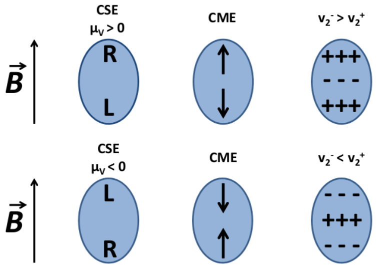
$$\frac{dQ}{d\varphi} = Q[1 - r_e \cos(2\varphi)]$$

Definition of charge asymmetry A:

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

Azimuthal distribution of particles:

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

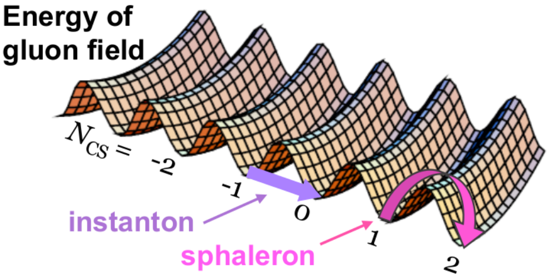


- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

Physics Motivation: Topological Charge

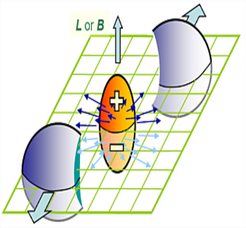
QCD vacuum is highly non-trivial!
Topological charge, winding number, Chern-Simons number:

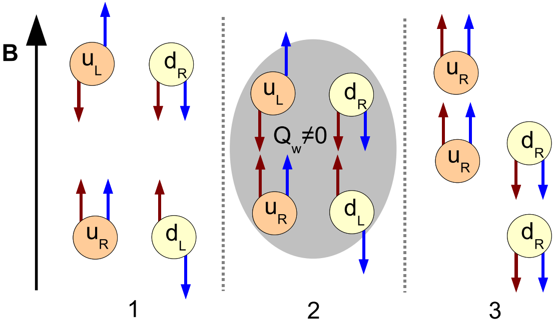
$$Q_w = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \in \mathbb{Z}.$$



- 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: $Q_w = -1 \Rightarrow L \to R, R \to R$
- Problem: Q_w fluctuates about 0, electric dipole averages to 0

Methodology—Direct Cumulants

- Definition of flow vectors

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

- Direct cumulant method for integral flow

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

- 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