Experimental searches for local parity violating effects in heavy ion collisions

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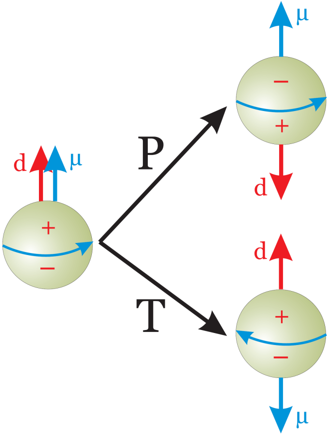
Outline

- Brief introduction
- The CME
- The CMW
- Summary and outlook

Parity in the strong sector

- A non-zero neutron electric dipole moment (nEDM) violates parity
- A non-zero nEDM also violates time reversal, by CPT theorem T-violation implies CP-violation
- However, experiments have consistently found nEDM consistent with zero, upper limit 2.9×10^{-26} *e* cm from C. Baker et al, Phys. Rev. Lett. 97 (2006) 131801
- The observed absence of CP-violation in the strong sector is surprising because of natural CP-violating terms in the QCD Lagrangian



$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} - \frac{\theta g^2}{32\pi^2}F^{a}_{\mu\nu}\tilde{F}^{\mu\nu}_{a} + \overline{\psi}(i\not{D} - me^{i\theta'\gamma_5})\psi$$

Strong CP problem: $0 \leq \bar{\theta} < 10^{-10}$

Topological charge and the $U(1)_A$ anomaly

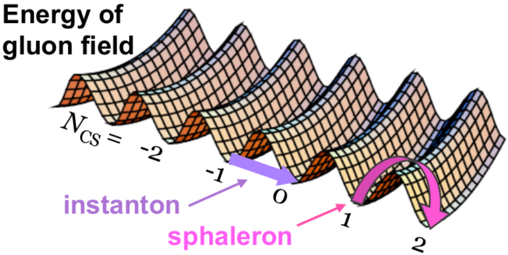
The QCD vacuum is highly non-trivial!

$U(1)_A$ anomaly:

$$\partial_\mu J^\mu_A = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Topological charge:

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



- $Q_w = N_L - N_R$

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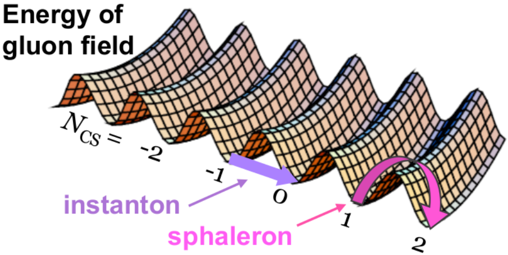


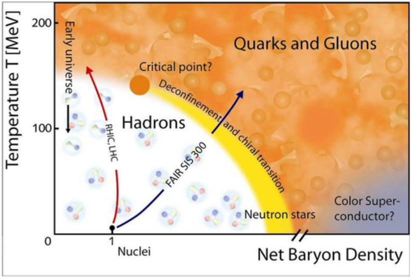
- $Q_w = N_L - N_R$
- Topological charge is the change in Chern-Simons number (N_{CS})
- Instanton: tunneling through barrier (all energies/temperatures, including 0)
- Sphaleron: jumping over barrier (only sufficiently high temperatures/energies)

The goal of heavy ion physics is to create a new state of matter called the quark-gluon plasma, which we hope to create by colliding heavy nuclei at the highest possible energies

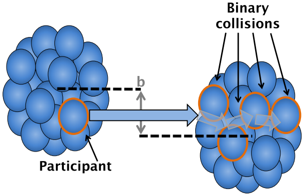
At sufficiently high temperature and/or density, the gauge coupling between quarks and gluons becomes sufficiently weak that deconfinement is achieved

Some basic information about the QGP:

- Particles produced in thermal abundances
- Hydrodynamical models describe the data very well, require fast thermalization at the parton level
- The matter is extremely hot, well in excess of the critical temperature $T_c \approx 150$ MeV (10^{12} K)
  –Stellar coronae 10^6 K
  –Core of white dwarf 10^7 K



- Need to characterize the overlap of the two nuclei
- The most natural choice is impact parameter
- Other things you might like to know are:
  how many nucleons are in the overlap region (N_{part})
  how many nucleon-nucleon collisions occurred (N_{coll})



Centrality	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$
Pb+Pb		
0-5%	382.7 ± 5.1	1685 ± 190
5-10%	329.7 ± 4.6	1316 ± 140
10-20%	260.5 ± 4.4	921 ± 96
20-30%	186.4 ± 3.9	556 ± 55
30-40%	128.9 ± 3.3	320 ± 32
40-50%	85.0 ± 2.6	171 ± 16
50-60%	52.8 ± 2.0	84.3 ± 7
60-70%	30.0 ± 1.3	37.9 ± 3
70-80%	15.8 ± 0.6	15.6 ± 1
p+p	$\equiv 2$	$\equiv 1$

Centrality

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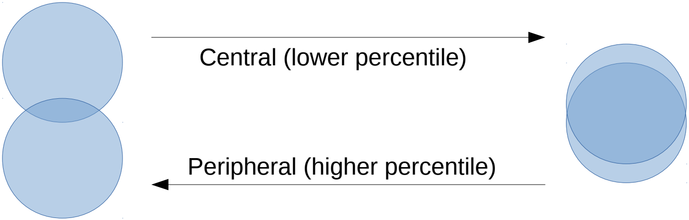
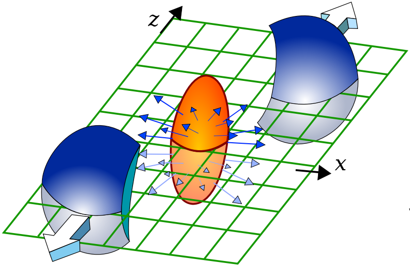
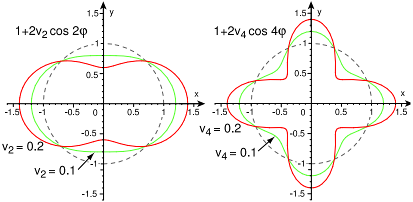


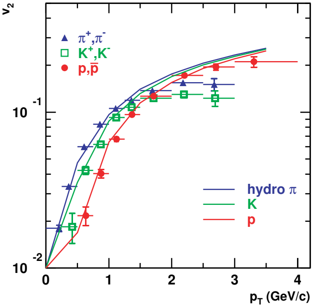
Anisotropic flow

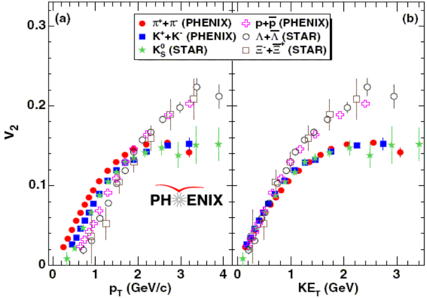




$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\Delta\phi \qquad \Delta\phi = \phi - \psi_{RP}, \quad v_n = \langle \cos n\Delta\phi \rangle$$

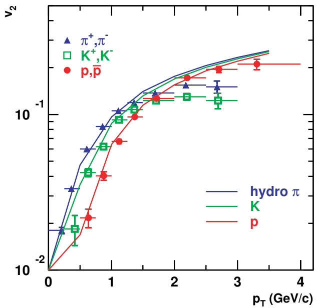
- Collisions that are not fully overlapping have azimuthally non-uniform shape
- Initial state spatial anisotropy creates pressure gradients that drive final state momentum anisotropy—the anisotropic flow builds up early and self quenches
- Azimuthal distribution of particles can be described as Fourier series with coefficients v_n (Voloshin and Zhang, Z. Phys. C70 (1996) 665-672)
  –dominant term is v_2 (called elliptic flow)
- Note that ψ_n can be different from ψ_{RP}, but for now we don't need to worry about this complication

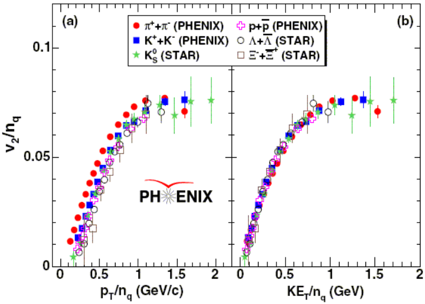




- Hydrodynamics models describe the data well at low transverse momentum p_T
- Mass splitting from common flow velocity, plotting vs transverse kinetic energy $KE_T = \sqrt{p_T^2 + m^2} - m$ makes them line up
- At higher p_T baryons and mesons group together...

Elliptic flow





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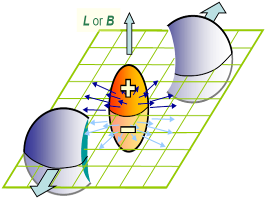
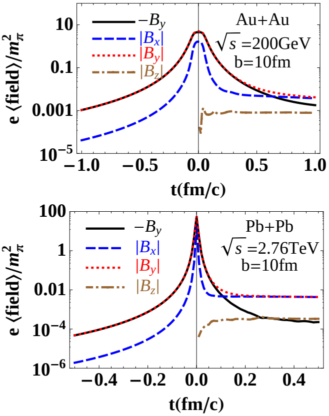
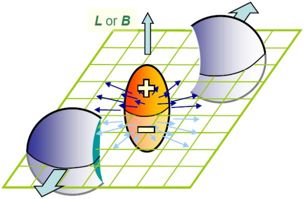
- At higher p_T baryons and mesons group together...
- ...scaling with the number of constituent quarks n_q groups all particles together –Seen as "smoking gun" for QGP formation

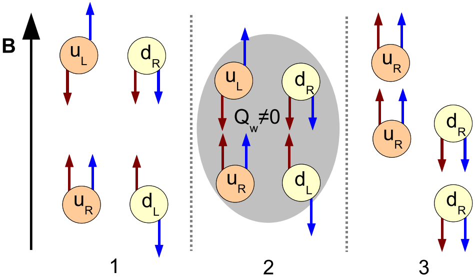


W.-T. Deng and X.-G. Huang
Phys. Rev. C 85, 044907 (2012)



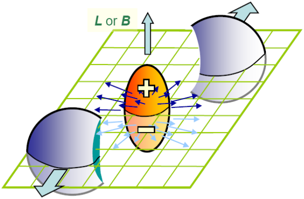
- The spectating nucleons induce a magnetic field in the overlap region
- The peak strength of the magnetic field in conventional units is roughly $10^{17\text{-}18}$ gauss—largest magnetic field in the known universe!
  –MRIs 10^5 gauss
  –Magnetars 10^{15} gauss
- The spectators define both the magnetic field and the geometry (recall earlier slide), so $\psi_B = \psi_{RP}$

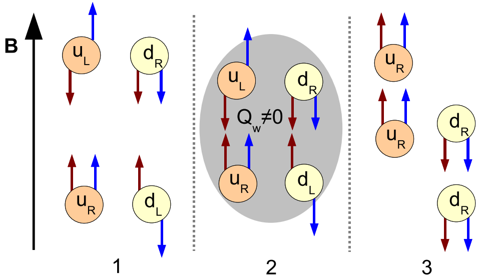




- Chiral imbalance induced by quantum anomaly
  (recall $U(1)_A$ anomaly $\partial_\mu J^\mu_A = \frac{g^2}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \rightarrow Q_w = N_L - N_R$)
- Alignment of spins by external magnetic field induces electric current of chiral quarks

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





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

- How to measure?

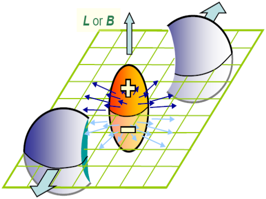
The CME correlator

The standard Fourier expansion (Voloshin and Zhang, Z. Phys. C70 (1996) 665-672)

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\Delta\phi \qquad \Delta\phi = \phi - \psi_{RP}, \quad v_n = \langle \cos n\Delta\phi \rangle$$

The Fourier expansion including P-odd sine terms

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} [v_n \cos n\Delta\phi + a_n \sin n\Delta\phi] \qquad a_n = \langle \sin n\Delta\phi \rangle$$



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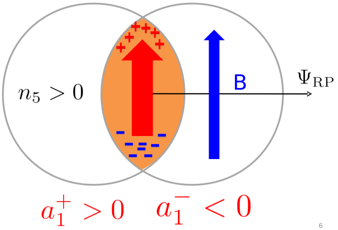

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- Positive particles should go above the reaction plane $a_1^+ > 0$
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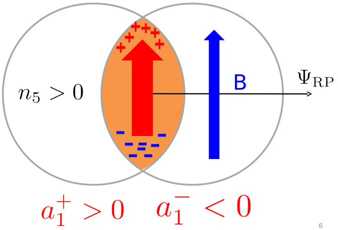

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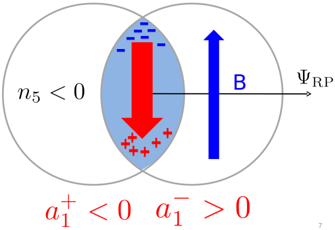

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- Positive particles should go above the reaction plane $a_1^+ > 0$
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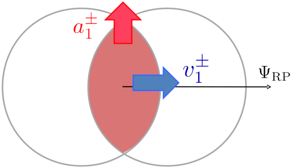
- However...
- Q_w fluctuates about $\langle Q_w \rangle = 0$, so the CME current changes sign event by event, and therefore $\langle a_1^{\pm} \rangle = 0$

The CME correlator

What to do? Measure 2 particle correlation with respect to the reaction plane (Voloshin, Phys. Rev. C 70 (2004) 057901)

$$\begin{aligned}\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle &= \langle\cos\Delta\phi_a\cos\Delta\phi_b\rangle-\langle\sin\Delta\phi_a\sin\Delta\phi_b\rangle\\ &= [\langle v_{1,a}v_{1,b}\rangle+B_{in}]-[\langle a_{1,a}a_{1,b}\rangle+B_{out}]\end{aligned}$$



- Backgrounds uncorrelated with RP cancel
- Same sign $\langle a_1^\pm a_1^\pm\rangle > 0$
- Opposite sign $\langle a_1^\pm a_1^\mp\rangle < 0$
- Directed flow is rapidity-odd, $\langle v_1 v_1\rangle \approx 0$
- Optimistically, $\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle = -\langle a_{1,a}a_{1,b}\rangle$

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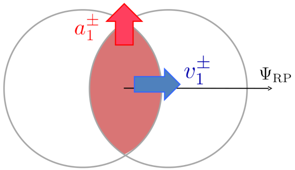

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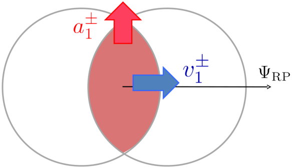

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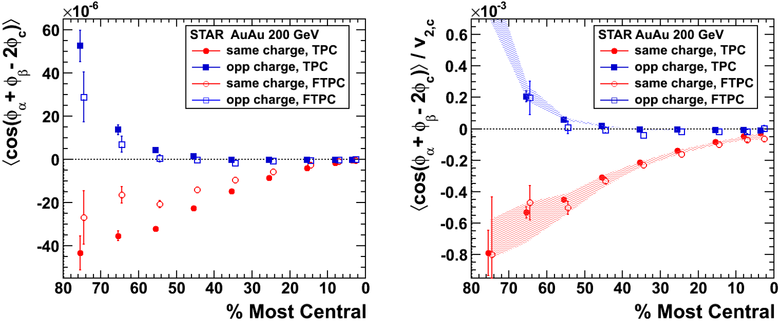
- Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP})\rangle = -\langle a_{1,a} a_{1,b}\rangle$
- However...
- RP dependent backgrounds remain
- If dipole fluctuations, $\langle v_1 v_1\rangle \neq 0$

The first CME results (STAR)

STAR, Phys. Rev. C 81, 054908 (2010)



- Strong negative correlation for same sign, consistent with CME expectation
- Essentially no correlation of opposite sign
  –Possible explanation: the large medium destroys the opposite sign correlation

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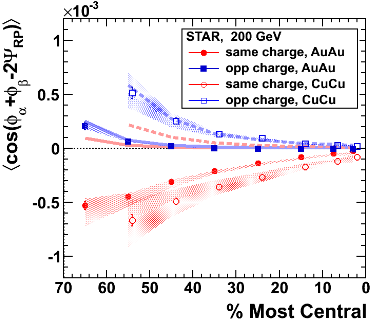

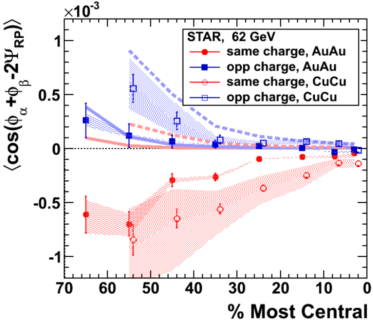

- Strong negative correlation for same sign in both Au+Au and Cu+Cu
- Positive correlation of opposite sign for Cu+Cu despite being absent in Au+Au
  –Medium in Cu+Cu is small enough that some opposite sign correlation remains?

The first CME results (STAR)

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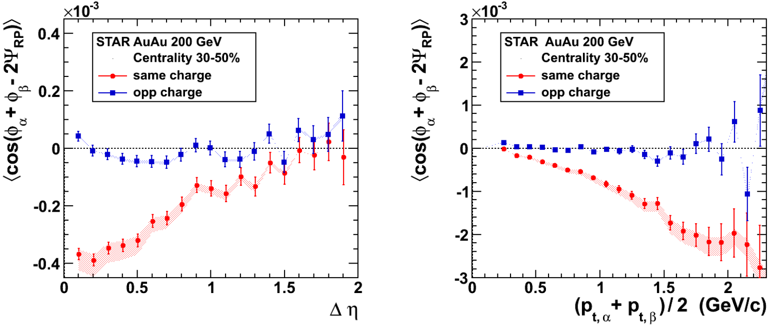
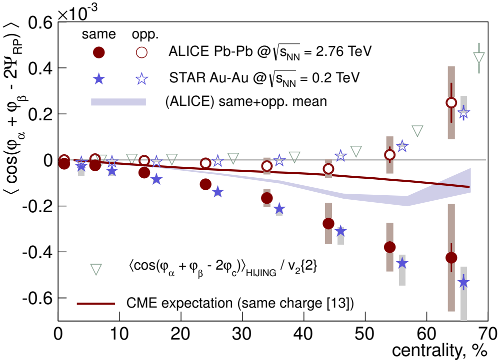


- No opposite sign correlation in Au+Au for any $\Delta\eta$ or any $\bar{p_T}$
- Same sign correlation gets strong for smaller $\Delta\eta$ and larger $\bar{p_T}$
  –The behavior in $\Delta\eta$ matches naïve expectations, different for $\bar{p_T}$

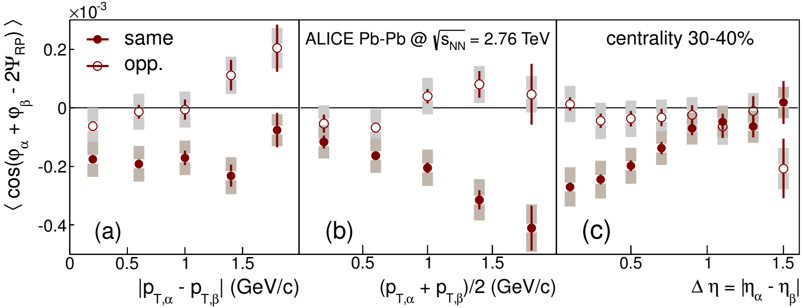
ALICE results on the CME

ALICE, Phys. Rev. Lett. 110, 012301 (2013)



- ALICE results consistent with STAR results
- Naïve expectation is for weaker correlation due to shorter B-field lifetime

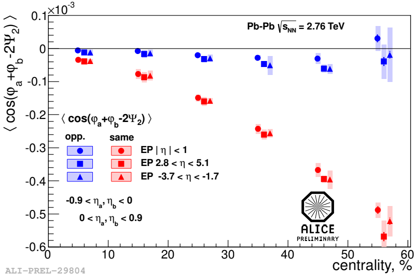
ALICE, Phys. Rev. Lett. 110, 012301 (2013)

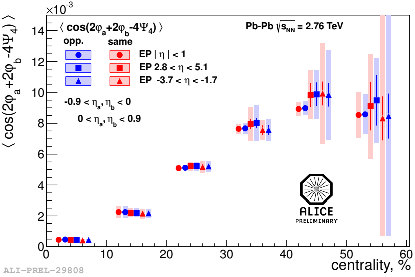


- ALICE results consistent with STAR results for both $\Delta\eta$ and $\bar{p_T}$

ALICE results on the CME

Y. Hori, Nucl. Phys. A 904-905 (2013) 475c-479c





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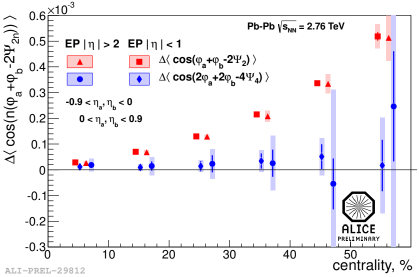
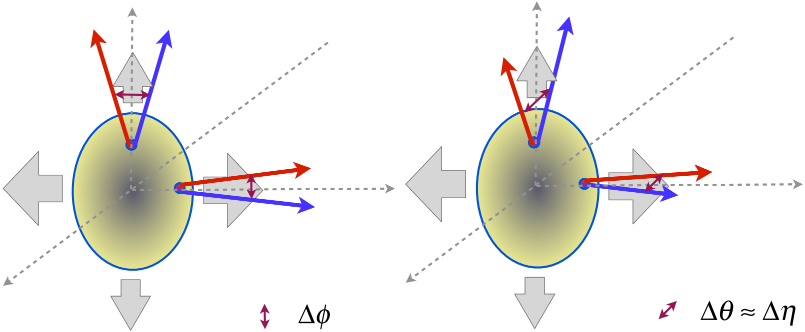


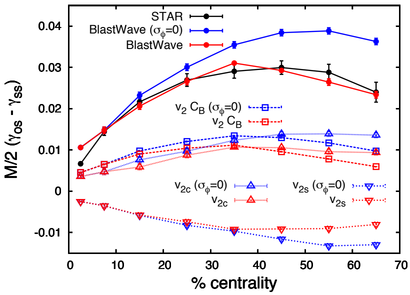
- Double harmonic correlator should have no CME signal, only backgrounds
- Difference between same sign and opposite sign consistent with zero

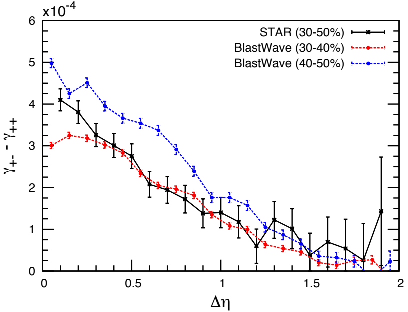
Backgrounds



- LCC: local charge conservation—charges are created in $\pm$ pairs at a single space-time point
- Angle between pairs is collimated by the radial+anisotropic flow backround
- Simple and intuitive mechanism for generating charge-dependent angular correlations

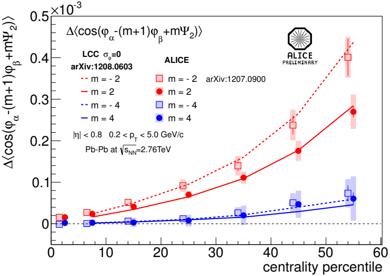
S. Schlichting and S. Pratt, Phys. Rev. C 83 (2011) 014913

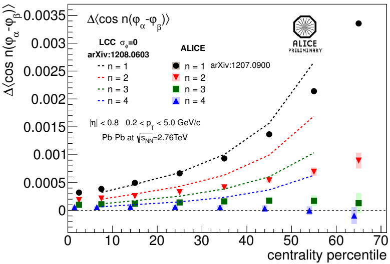




- Construct a simple model of LCC+flow using the Blastwave model
- Results show very good agreement with STAR CME correlator results (OS-SS)
- However, the absence of OS correlation and the strong SS correlation is not explained in this (simple) model
- This may indicate that the CME correlator results contain a combination of background and new physics

Y. Hori, Nucl. Phys. A 904-905 (2013) 475c-479c





- Tuning the model parameters to match the CME correlator results creates a significant mismatch between model and data two particle correlations

The chiral separation effect—an invitation to the chiral magnetic wave

Before moving on to the chiral magnetic wave, we need to briefly discuss the chiral separation effect (CSE)

- D.T. Son and A.R. Zhitnitsky, Phys. Rev. D 70, 074018 (2004)
- M.A. Metlitski and A.R. Zhitnitsky, Phys. Rev. D 72, 045011 (2005)
- Quantum anomalies at finite vector charge density drives the following relation

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

- This effect, an axial current proportional to a vector chemical potential, is called the chiral separation effect (CSE)
- It is readily apparent that there is a strong relationship to the CME

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

- And with that, onward to the chiral magnetic wave

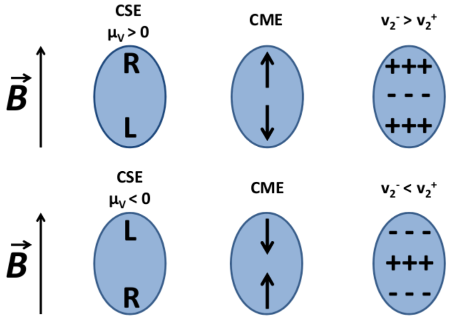
The Chiral Magnetic Wave

Chiral Separation Effect

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

Chiral Magnetic Effect

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



- CSE leads to separation of chiralities at opposite poles
- CME currents point in opposite directions, leading to electric quadrupole
- Gorbar, Miransky, and Shovkovy, Phys. Rev. D83, 085003 (2011)
- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)

The Chiral Magnetic Wave

Azimuthal distribution of charges

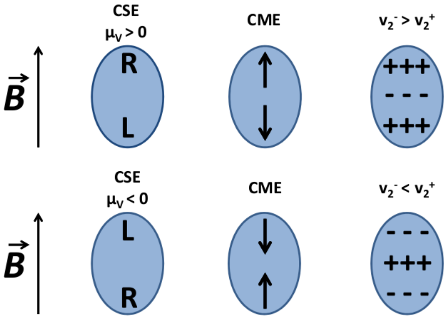
$$\frac{dQ}{d\Delta\phi} = Q[1 - r_e \cos(2\Delta\phi)]$$

Definition of charge asymmetry A

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

Azimuthal distribution of particles

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



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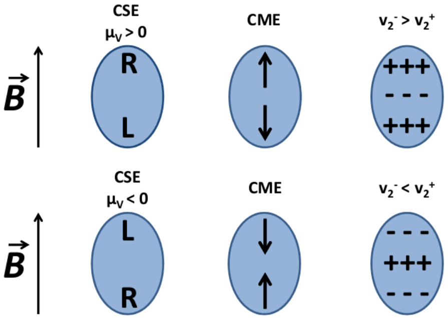
The Chiral Magnetic Wave

v_2 of charged particles

$$v_2^{\pm} = v_2 \mp \frac{r_e A}{2}$$

Definition of Δv_2

$$\Delta v_2 \equiv v_2^{-} - v_2^{+} = r_e A$$



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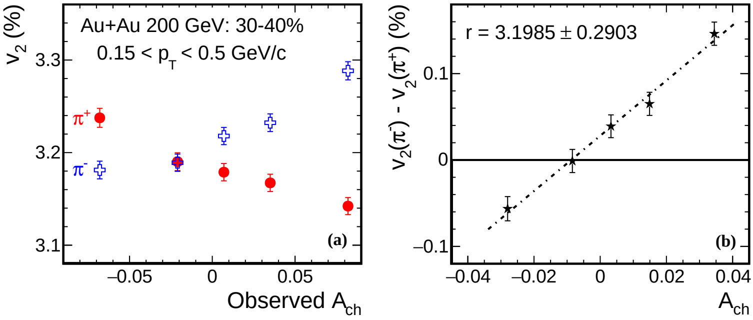
STAR results on $v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality

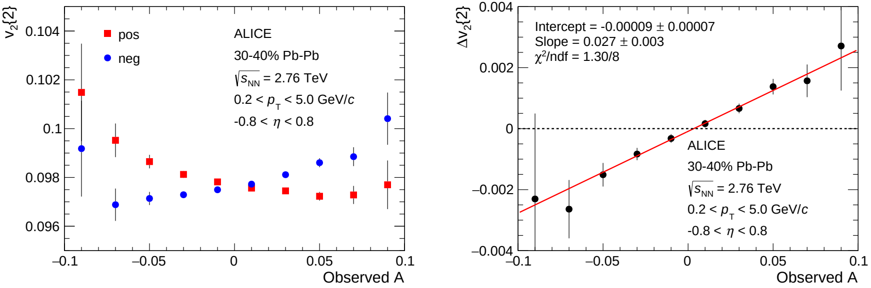
STAR, Phys. Rev. Lett. 114, 252302 (2015)



- Charge asymmetry $A_{ch} = A = (N^+ - N^-)/(N^+ + N^-)$
- 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

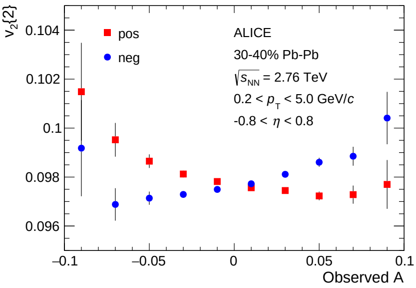
ALICE, arXiv:1512.05739 (submitted to PRC)

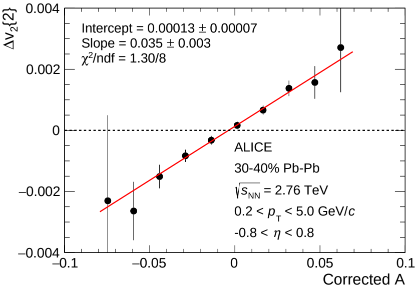


- Strong, clear signal
- Qualitatively consistent with STAR results

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

ALICE, arXiv:1512.05739 (submitted to PRC)





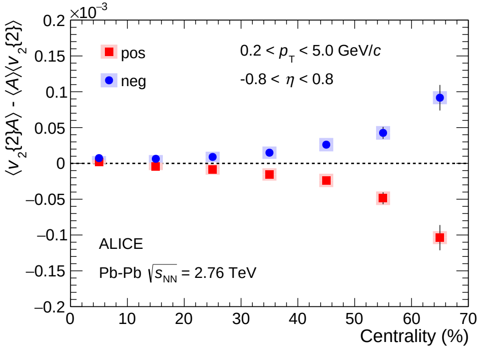
- Strong, clear signal
- Qualitatively consistent with STAR results
- Necessary to make correction

Proposal for new measurement: 3-particle correlator

- v_2 as a function of A is very interesting, but requires efficiency correction (due to binomial sampling)
- So what else can we do? Measure the covariance: $\langle v_2 A\rangle - \langle v_2\rangle\langle A\rangle$
- A fundamental feature of statistics is that the covariance between two variables is independent of sample size, i.e. no efficiency correction for this measure is needed (we call it a "robust observable")
- It is both straightforward and very useful to generalize to arbitrary harmonic v_n
- Since v_n is a 2-point correlation, this is a 3-point correlation
- Can also generalize A to the charge of a third particle q_3, since $\langle q_3\rangle_{\text{event}} \equiv A$
- We have then $\langle v_n A\rangle - \langle v_n\rangle\langle A\rangle$ and $\langle v_n q_3\rangle - \langle v_n\rangle\langle q_3\rangle$ as observables to evaluate

3-particle correlator: 2^{nd} harmonic

ALICE, arXiv:1512.05739 (submitted to PRC)

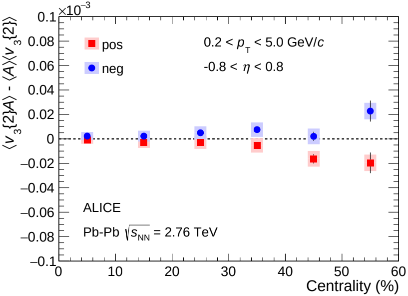


What causes the increased charge separation as the collisions become more peripheral?

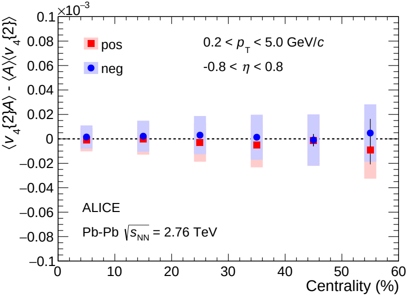
- Peripheral $\rightarrow$ stronger magnetic field $\rightarrow$ stronger CMW effect?
- Central $\rightarrow$ more combinatoric pairs $\rightarrow$ trivial dilution of local charge conservation (LCC) effects?
- Dependence on magnitude of v_2 or dN/dy?
- Some combination of these (and possibly other)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

ALICE, arXiv:1512.05739 (submitted to PRC)

3rd harmonic



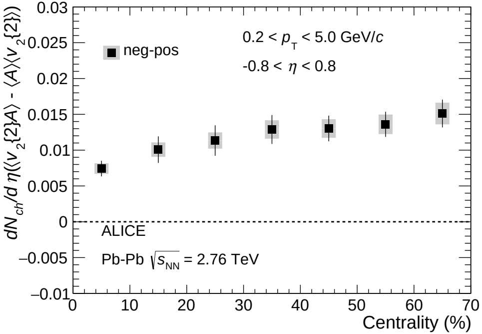
4th harmonic



- 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 reduced y-axis scale compared to 2nd harmonic
- Higher order multipole effects for CMW or harmonic interference? LCC only?

Multiplication with $dN_{ch}/d\eta$

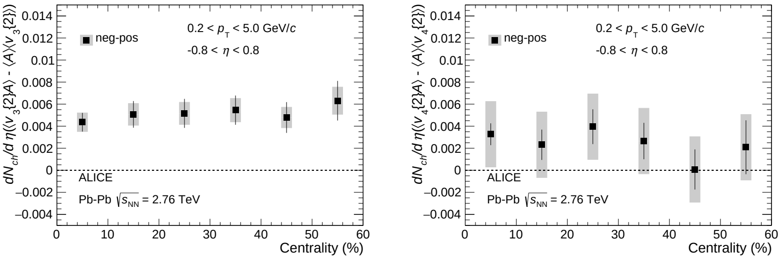
ALICE, arXiv:1512.05739 (submitted to PRC)



- Trivial correlations are inversely proportional to N
- Multiplication of 2nd harmonic three-particle correlator by $dN_{ch}/d\eta$ shows correlation that still increases as the collisions become more peripheral
- This may indicate that correlation contains a non-trivial component

Multiplication with $dN_{ch}/d\eta$

ALICE, arXiv:1512.05739 (submitted to PRC)



- Trivial correlations are inversely proportional to N
- Multiplication of 3rd and 4th harmonic three-particle correlator by $dN_{ch}/d\eta$ shows correlation that is roughly flat with centrality
- This may indicate a different nature of the correlation depending on the harmonic number

Estimating the slope parameter from the integral correlator

- Recall the integral correlator $\langle v_2 A\rangle - \langle A\rangle\langle v_2\rangle$
- Hypothesis: $v_2^{\pm} = \bar{v}_2 \mp rA/2$
- Plug and chug, rewrite to get

$$\langle v_2^{\pm} A\rangle - \langle A\rangle\langle v_2^{\pm}\rangle \approx \mp r \left(\langle A^2\rangle - \langle A\rangle^2\right)/2 = \mp r\sigma_A^2/2.$$

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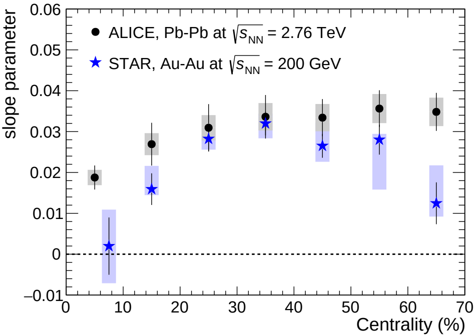
- Plug and chug, rewrite to get

$$\langle v_2^{\pm} A\rangle - \langle A\rangle\langle v_2^{\pm}\rangle \approx \mp r\left(\langle A^2\rangle - \langle A\rangle^2\right)/2 = \mp r\sigma_A^2/2.$$

- Note that the σ_A^2 must be the true variance, so the observed σ_A^2 must be efficiency corrected
- As with the direct measurement of v_2 vs A, the evaluation of the slope parameter in this way depends on corrections from Monte Carlo

Estimating the slope parameter from the integral correlator

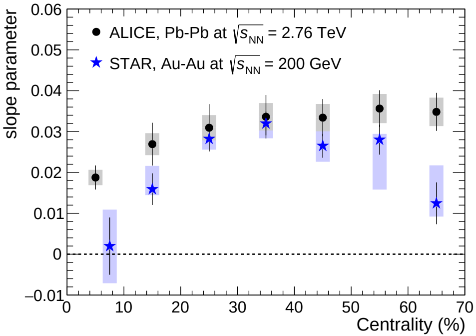
ALICE, arXiv:1512.05739 (submitted to PRC)



- Reasonable agreement with STAR for mid-central collisions
- Weaker overall centrality dependence

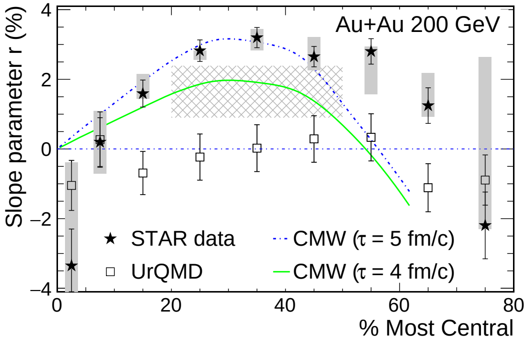
Estimating the slope parameter from the integral correlator

ALICE, arXiv:1512.05739 (submitted to PRC)



- Reasonable agreement with STAR for mid-central collisions
- Weaker overall centrality dependence
- But is agreement with STAR really to be expected?

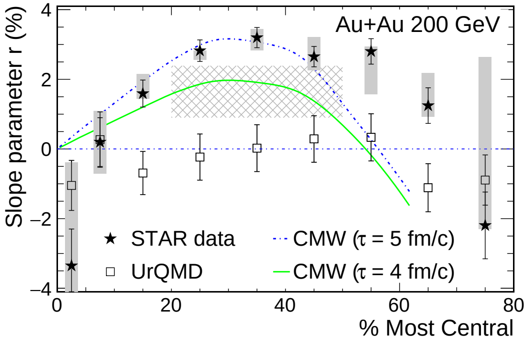
STAR, Phys. Rev. Lett. 114, 252302 (2015)



- Very good agreement between theory and experiment

Slope parameter measurement by STAR

STAR, Phys. Rev. Lett. 114, 252302 (2015)



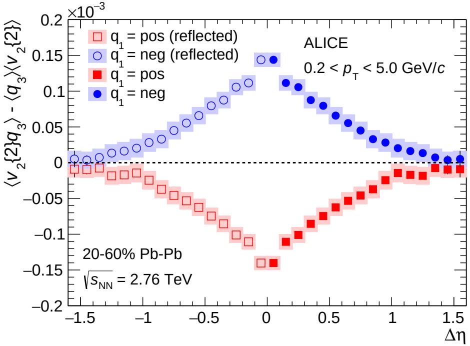
- Very good agreement between theory and experiment
- (Almost too good...)

Intermission

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

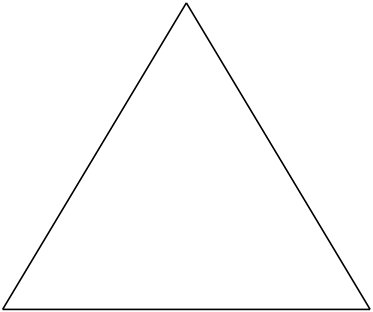
3-particle correlator vs $\Delta\eta$

ALICE, arXiv:1512.05739 (submitted to PRC)



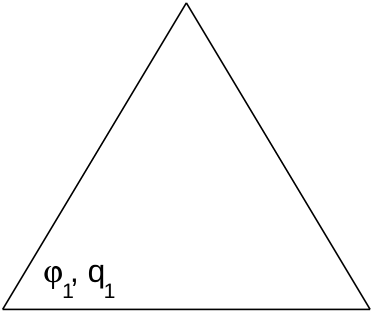
- Generalizing from A to q_3 as discussed, we can measure the correlator as a function of the separation between particles 1 and 3, $\Delta\eta = \eta_1 - \eta_3$
- Doing so we can directly measure the η range and dependence of the charge dependent effect
- LCC and CMW correlations may have different η ranges, providing an additional experimental constraint
- However, we're missing something very important...

- Let us examine the three particles more carefully



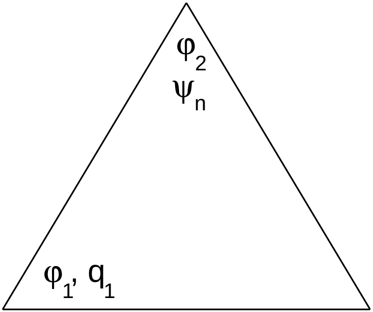
3-particle correlator: a closer look

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



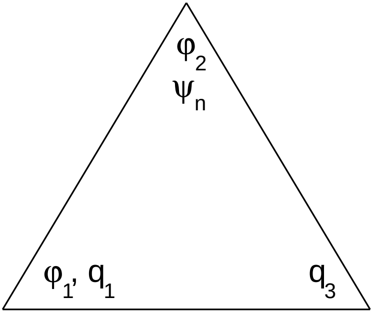
3-particle correlator: a closer look

- 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



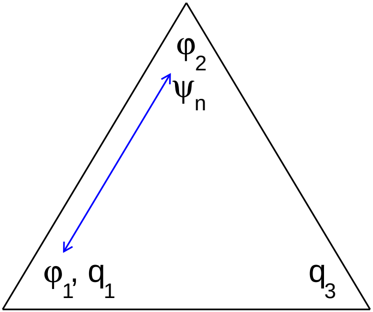
3-particle correlator: a closer look

- 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



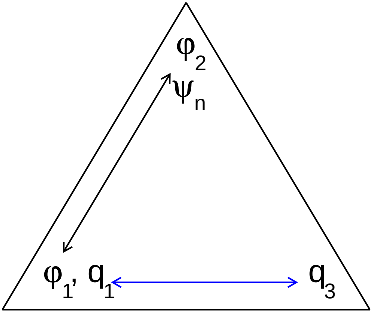
3-particle correlator: a closer look

- 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
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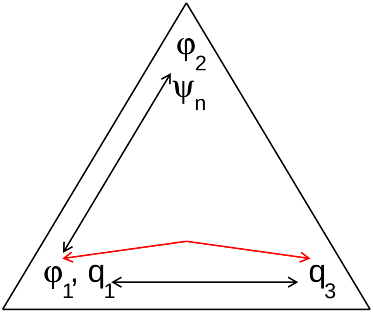
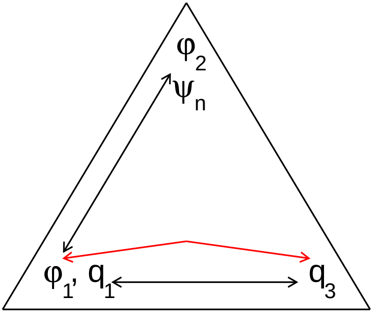
- The correlation between 1 and 2 is the harmonic coefficient
- The correlation between 1 and 3 is the balance function
- Both correlations must be fully taken into account to get at potentially new physics



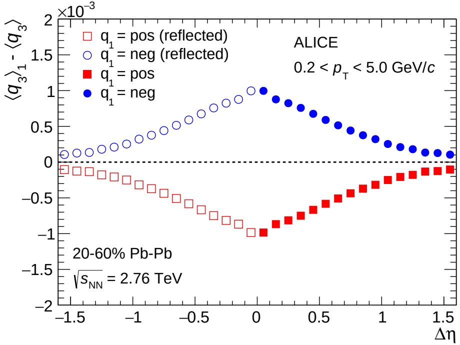
3-particle correlator: a closer look

- 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 $\langle\langle\cos(n(\phi_1 - \phi_2))q_3\rangle\rangle$
    - S.A. Voloshin and R. Belmont, Nucl. Phys. A 931 (2014) 992-996



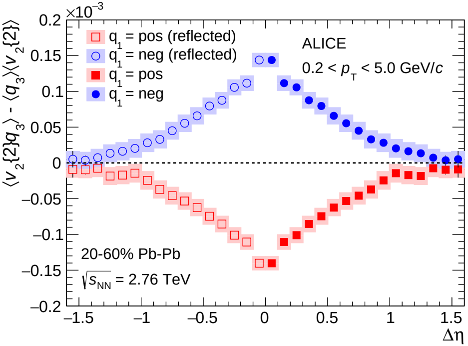
Understanding mean charge vs $\Delta\eta$

ALICE, arXiv:1512.05739 (submitted to PRC)



- $\langle q_3 \rangle$ denotes mean charge (i.e. independent of q_1)
- $\langle q_3 \rangle_1$ denotes mean charge depending on 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?

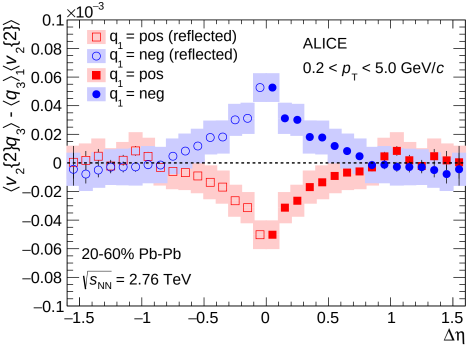
ALICE, arXiv:1512.05739 (submitted to PRC)



- Charge independent subtraction (charge correlation not considered)

3-particle correlator vs $\Delta\eta$

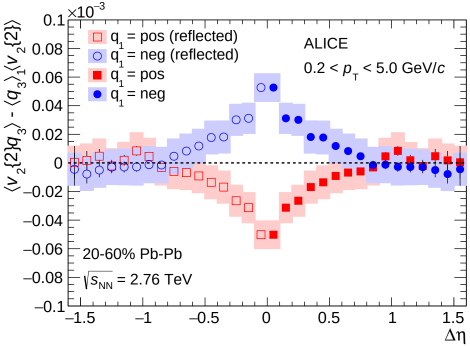
ALICE, arXiv:1512.05739 (submitted to PRC)



- Charge dependent subtraction (charge correlation considered)

3-particle correlator vs $\Delta\eta$

ALICE, arXiv:1512.05739 (submitted to PRC)

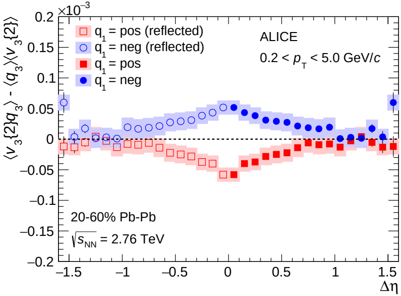


- Charge dependent subtraction (charge correlation considered)
- The observed effect has a large contribution from the dependence of q_3 on q_1
- Both the strength and range are significantly reduced, but a pronounced charge dependent effect remains
- How much contribution from charge conservation has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

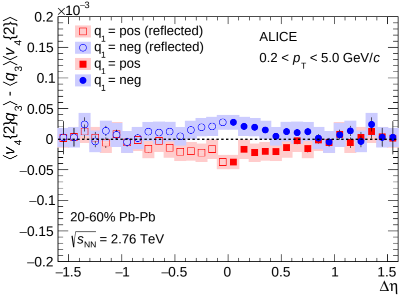
3-particle correlator vs $\Delta\eta$ for higher harmonics

ALICE, arXiv:1512.05739 (submitted to PRC)

3rd harmonic

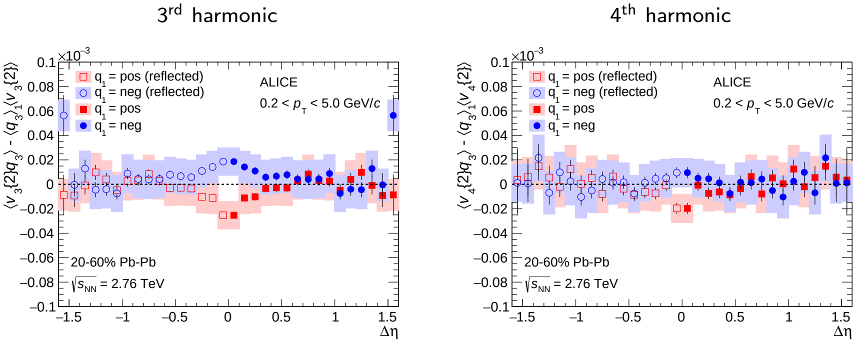


4th harmonic



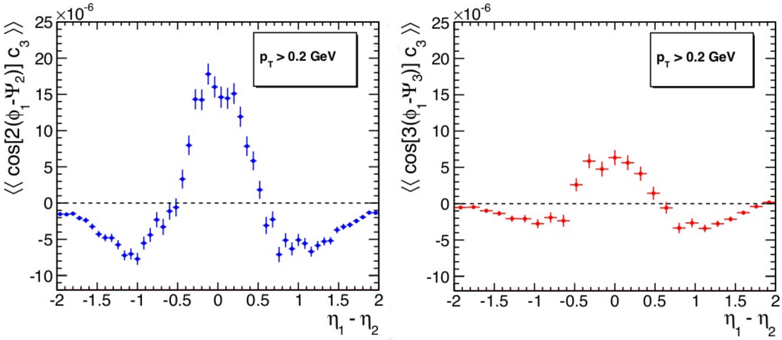
- Charge *independent* subtraction
- Moderate effect for 3rd, minimal effect for 4th

ALICE, arXiv:1512.05739 (submitted to PRC)



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

S.A. Voloshin and R. Belmont, Nucl. Phys. A 931 (2014) 992-996



- Construct a simple model of LCC+flow using the Blastwave model
- Results for the CMW correlator qualitatively and semi-quantitatively match the experimental results
- Note that the magnitude of the side "dips" very closely matches experiment, while the magnitude at $\Delta\eta \approx 0$ is lower
- This may indicate that the CMW correlator results contain a combination of background and new physics

Summary

- Local parity violation is a fundamental feature of QCD
- In an important sense, it *must* be there, but that doesn't mean it's present in the heavy ion collisions we can measure
- In fact there are several key issues
- Does the magnetic field live long enough?
- Are the quarks formed early enough?
- Neither of those questions has been addressed yet, though work is ongoing to try to answer them
- Presence of B-field can be evinced by charge and rapidity dependent v_1
- Presence of quarks can be evinced by charge dependent v_1 in A+B collisions
  Can do this in Cu+Au collisions at RHIC, see e.g. T. Niida QM2015

Summary

- The biggest issue (of course) is understanding the backgrounds
- At the current time, the only viable candidate for background to the CME and CMW observables is local charge conservation on top of strong flow
- The current modeling gets some observables right but others wrong, this is very important work, and studies are ongoing
- Promising avenue of investigation: anomalous hydrodynamics, which embeds the LPV effects in a realistic hydrodynamical medium
- There's no smoking gun yet, but there's always more work to do

Final thoughts

"The optimist regards the future as uncertain."—Eugene Wigner

Final thoughts

"The optimist regards the future as uncertain."—Eugene Wigner

Thank you!

Additional material