Overview of experimental searches for local parity violating effects

Ron Belmont
Wayne State University

ALICE Juniors' Day
CERN
12 March 2015

- Introduction and physics motivation
- The CME
- The CMW
- Summary and outlook

Утро в сосновом лесу

Утро в сосновом лесу

Parity

What is parity?

- In 3 space dimensions, parity is the simultaneous inversion of all three dimensions

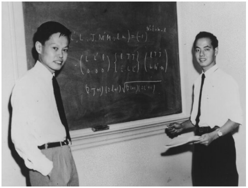
$$P \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

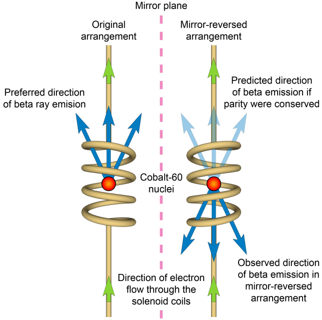
- Scalar quantities (e.g. mass, charge) are P-even
- Vector quantities (e.g. momentum, electric field) are P-odd
- Pseudo-vector quantities (e.g. angular momentum, magnetic field) are P-even
  $\vec{L} = \vec{r} \times \vec{p} \quad \rightarrow \quad \vec{L} = -\vec{r} \times -\vec{p}$
- Parity was long believed to be conserved in all laws of physics
- However...

Parity

Parity violation (weak interactions)

- Proposed by T.D. Lee and C.N. Yang, Phys. Rev. 104, 254 (1956)
- Discovered by C.S. Wu et. al., Phys. Rev. 105, 1314 (1957)





- Electron emission from $^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e + \overline{\nu}_e$ was found to be anti-parallel to the nuclear spin—parity violation
- Pauli was shocked and refused to believe the results, insisting they be repeated
- Wu's experiment was repeatedly confirmed, and she *should* have gotten the Nobel Prize in physics, as Lee and Yang did...

Chirality

What is chirality?

- Chirality is an internal quantum number, equal to $-1(L)$ or $+1(R)$
- For massless particles it is equal to helicity $(\vec{s} \cdot \vec{p})$, for massive particles it is different
- Chirality is a Lorentz invariant, while helicity is not for massive particles
- Helicity and chirality are P-odd, meaning they change sign under parity transformation
- Any state can be written as the sum of the left and right components, i.e. $\psi = \psi_R + \psi_L$
- The chirality operator is the Dirac gamma matrix γ^5 and has eigenvalues of ± 1 $\gamma^5 \psi_R = +\psi_R, \quad \gamma^5 \psi_L = -\psi_L, \quad \gamma^5 \overline{\psi}_R = -\overline{\psi}_R, \quad \gamma^5 \overline{\psi}_L = +\overline{\psi}_L$
- The chiral projection operators can be constructed from γ^5 $P_{R,L} = \frac{1}{2}(1 \pm \gamma^5)$

Chirality

A brief word on notation and terminology

- Typically any vector quantity can be written as the sum of the chiral quantities
- The vector current is the sum of left- and right-handed current
  $J_V^\mu = J_R^\mu + J_L^\mu$
- Typically any axial quantity can be written as the difference of the chiral quantities
- The axial current is the difference of left- and right-handed current
  $J_A^\mu = J_R^\mu - J_L^\mu$
- The same is also true with chemical potentials, number densities, etc.
  $n_V = n_R + n_L, \quad n_A = n_R - n_L$
- Because of the connection to the Dirac gamma matrix γ^5, axial quantities are sometimes denoted with a 5
  $J_A^\mu \leftrightarrow J_5^\mu$

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

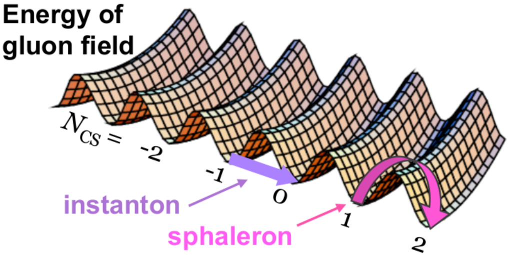
The QCD vacuum is highly non-trivial!

$U(1)_A$ anomaly:

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

Topological charge:

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



- $Q_w = N_L - N_R$

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

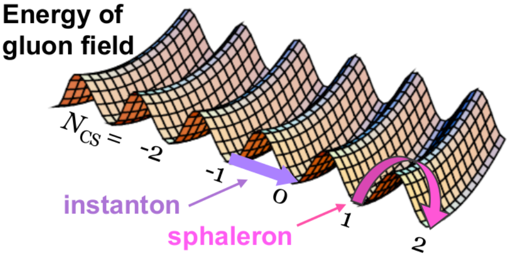
The QCD vacuum is highly non-trivial!

$U(1)_A$ anomaly:

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

Topological charge:

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

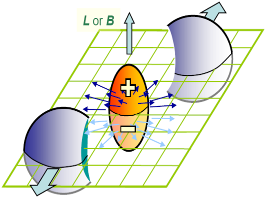


- $Q_w = N_L - N_R$
- Topological charge is the change in Chern-Simons number (N_{CS})
- Instanton: tunneling through barrier (all energies/temperatures, including 0)
- Sphaleron: jumping over barrier (only sufficiently high temperatures/energies)

A brief history of parity violation in QCD in a few references

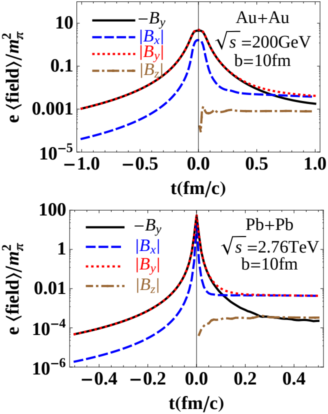
- Earliest papers on general features in QFT
  T.D. Lee, Phys. Rev. D 8, 1226 (1973)
  T.D. Lee and G.C. Wick, Phys. Rev. D 9, 2291 (1974)
  P.D. Morley and I.A. Schmidt, Z. Phys. C 26, 627 (1985)
- First paper suggesting local P-violation in QCD
  D. Kharzeev, R.D. Pisarski, and M.R.G. Tytgat, Phys. Rev. Lett 81, 512 (1998)
- First paper suggesting an experimental search
  D. Kharzeev, Phys. Lett. B 633, 260 (2006) [note: posted to arXiv in 2004]
- First paper suggesting a specific observable
  S.A. Voloshin, Phys. Rev. C 70, 057901 (2004)
- First paper invoking the name "chiral magnetic effect"
  D.E. Kharzeev, L.D. McLerran and H.J. Warringa, Nucl. Phys. A 803, 227 (2008)
- First experimental papers reporting the CME search
  STAR, Phys. Rev. Lett. 103, 251601 (2009)
  STAR, Phys. Rev. C 81, 054908 (2010)
- First ALICE paper reporting the CME search
  ALICE, Phys. Rev. Lett. 110, 012301 (2013)

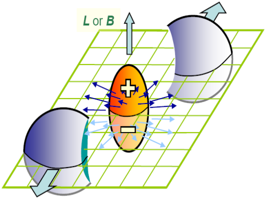
The magnetic field in heavy ion collisions

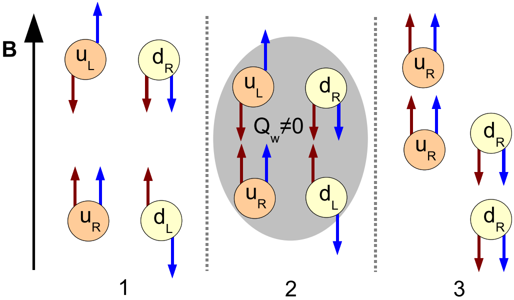


- The spectating nucleons induce a magnetic field in the overlap region
- The magnetic field is stronger but shorter lived at higher energies

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



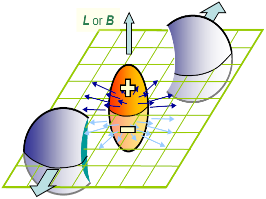


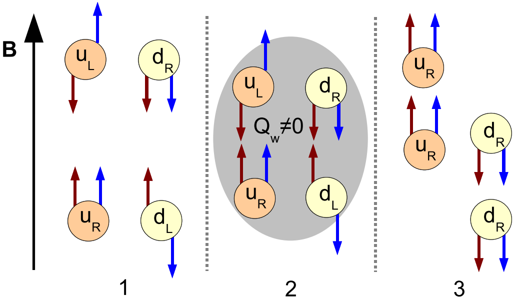


- Chiral imbalance induced by quantum anomaly (recall $Q_w = N_L - N_R$) leads to electric current when quark spins are aligned by an external magnetic field

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

The Chiral Magnetic Effect





- Chiral imbalance induced by quantum anomaly (recall $Q_w = N_L - N_R$) leads to electric current when quark spins are aligned by an external magnetic field

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

- How to measure?

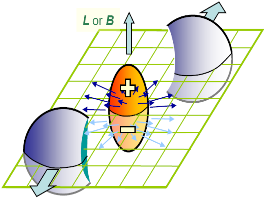
The CME correlator

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

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

The Fourier expansion including P-odd sine terms

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



- Normally we ignore sine terms, but now we need them

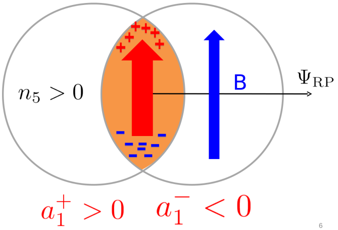
The CME correlator

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

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

The Fourier expansion including P-odd sine terms

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



- Normally we ignore sine terms, but now we need them
- Positive particles should go above the reaction plane $a_1^+ > 0$
- Negative particles should go below the reaction plane $a_1^- < 0$

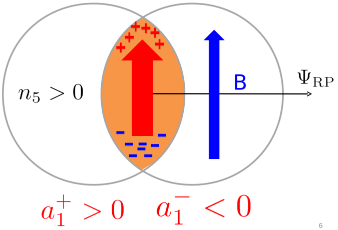
The CME correlator

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

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

The Fourier expansion including P-odd sine terms

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



- Normally we ignore sine terms, but now we need them
- Positive particles should go above the reaction plane $a_1^+ > 0$
- Negative particles should go below the reaction plane $a_1^- < 0$
- However...

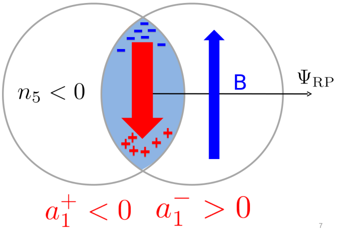
The CME correlator

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

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

The Fourier expansion including P-odd sine terms

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

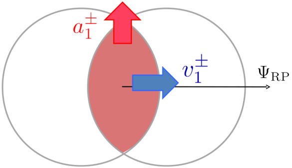


- Normally we ignore sine terms, but now we need them
- Positive particles should go above the reaction plane $a_1^+ > 0$
- Negative particles should go below the reaction plane $a_1^- < 0$
- However...
- Q_w fluctuates about $\langle Q_w \rangle = 0$, so the CME current changes sign event by event, 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)

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

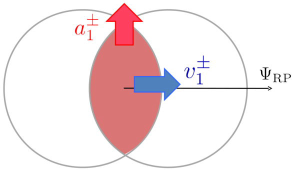


- Backgrounds uncorrelated with RP cancel
- Same sign $\langle a_1^{\pm}a_1^{\pm}\rangle > 0$
- Opposite sign $\langle a_1^{\pm}a_1^{\mp}\rangle < 0$
- Directed flow is rapidity-odd, $\langle v_1 v_1\rangle \approx 0$
- Optimistically, $\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle = -\langle a_{1,a}a_{1,b}\rangle$

The CME correlator

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

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

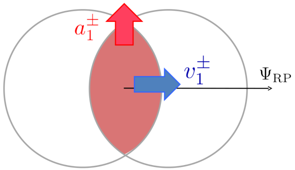


- Backgrounds uncorrelated with RP cancel
- Same sign $\langle a_1^{\pm}a_1^{\pm}\rangle>0$
- Opposite sign $\langle a_1^{\pm}a_1^{\mp}\rangle<0$
- Directed flow is rapidity-odd, $\langle v_1v_1\rangle\approx 0$
- Optimistically, $\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle=-\langle a_{1,a}a_{1,b}\rangle$
- However...

The CME correlator

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

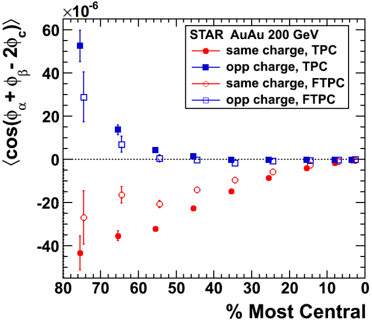
$$\begin{aligned}\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle &= \langle\cos\Delta\phi_a\cos\Delta\phi_b\rangle - \langle\sin\Delta\phi_a\sin\Delta\phi_b\rangle \\ &= [\langle v_{1,a}v_{1,b}\rangle + B_{in}] - [\langle a_{1,a}a_{1,b}\rangle + B_{out}]\end{aligned}$$

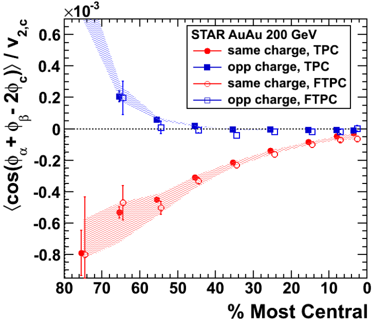


- Backgrounds uncorrelated with RP cancel
- Same sign $\langle a_1^{\pm}a_1^{\pm}\rangle > 0$
- Opposite sign $\langle a_1^{\pm}a_1^{\mp}\rangle < 0$
- Directed flow is rapidity-odd, $\langle v_1 v_1\rangle \approx 0$
- Optimistically, $\langle\cos(\phi_a+\phi_b-2\psi_{RP})\rangle = -\langle a_{1,a}a_{1,b}\rangle$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

The first CME results

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

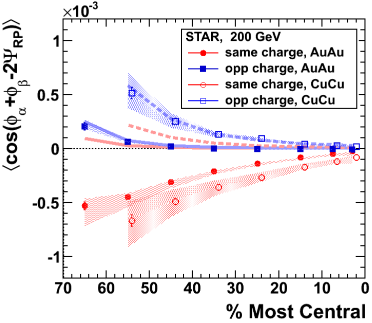


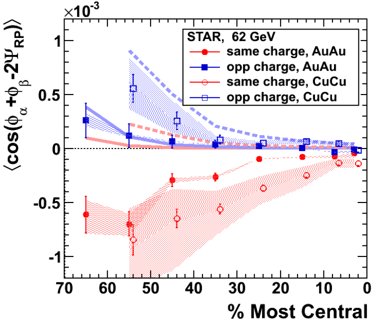


- Strong negative correlation for same sign, consistent with CME expectation
- Essentially no correlation of opposite sign
  –Possible explanation: the large medium destroys the opposite sign correlation

The first CME results

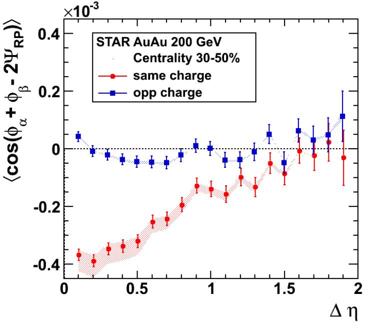
STAR, Phys. Rev. C 81, 054908 (2010)

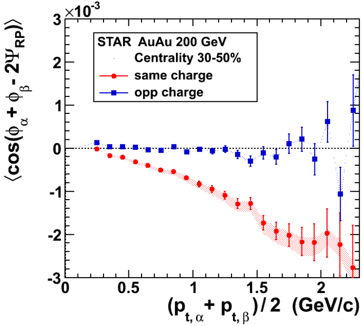




- Strong negative correlation for same sign in both Au+Au and Cu+Cu
- Positive correlation of opposite sign for Cu+Cu despite being absent in Au+Au
  –Medium in Cu+Cu is small enough that some opposite sign correlation remains?

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

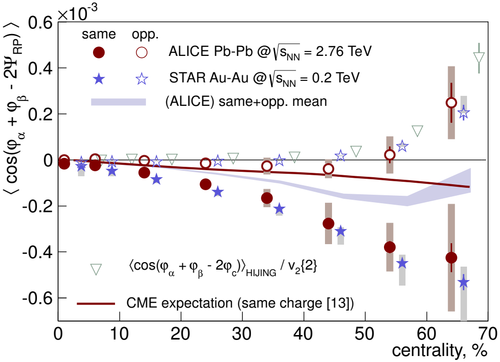




- No opposite sign correlation in Au+Au for any $\Delta\eta$ or any $\bar{p_T}$
- Same sign correlation gets strong for smaller $\Delta\eta$ and larger $\bar{p_T}$
  –The behavior in $\Delta\eta$ matches naïve expectations, different for $\bar{p_T}$

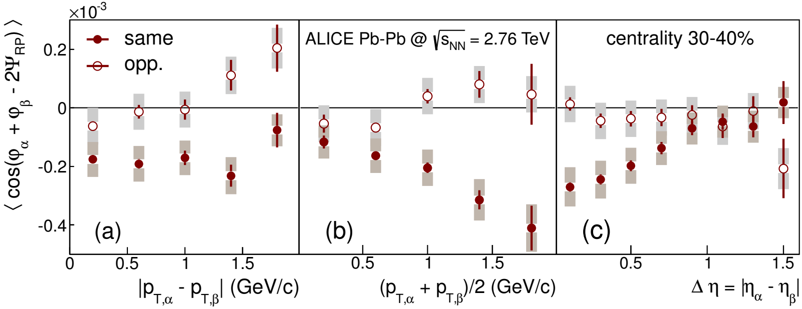
ALICE results on the CME

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



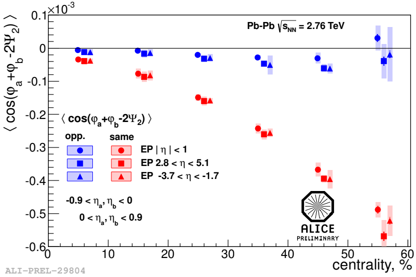
- ALICE results consistent with STAR results
- Naïve expectation is for weaker correlation due to shorter B-field lifetime

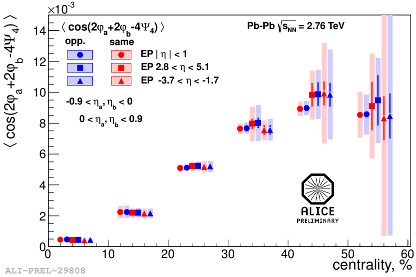
ALICE, Phys. Rev. Lett. 110, 012301 (2013)



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

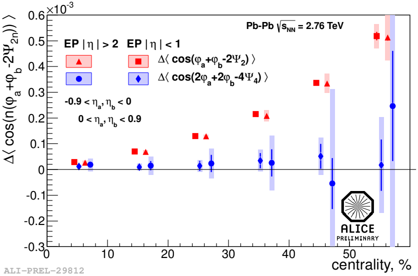
ALICE results on the CME





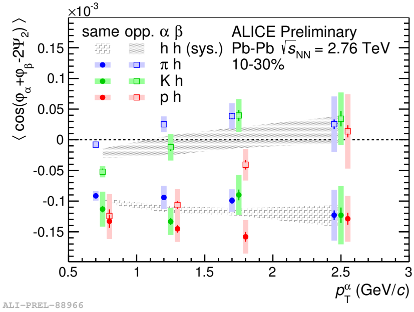
- Double harmonic correlator should have no CME signal, only backgrounds

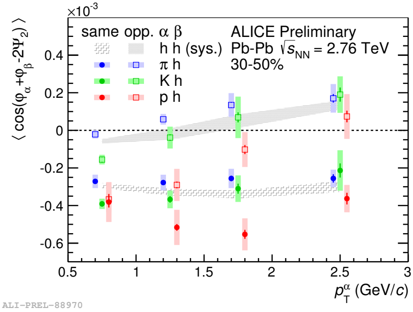
ALICE results on the CME



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

ALICE results on the CME





- Measurements of different species may help disentangle background sources
- Mesons (π and K) similar to unidentified particles, protons different
  –PID dependence stronger for opposite sign correlator
- Input from theory needed to fully understand backgrounds and PID dependence

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

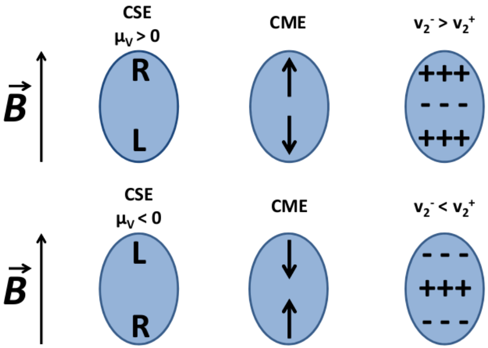
$$\vec{J}_A = \frac{N_c e}{2\pi^2} \mu_V \vec{B}$$

- 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

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

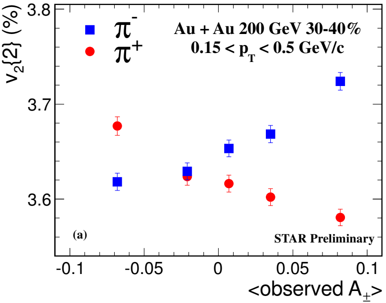
- And with that, onward to the chiral magnetic wave

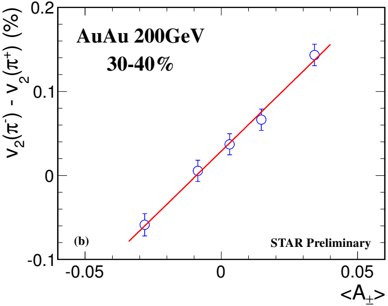
The Chiral Magnetic Wave



- CSE leads to separation of chiralities at opposite poles
- CME currents point in opposite directions, leading to electric quadrupole
- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

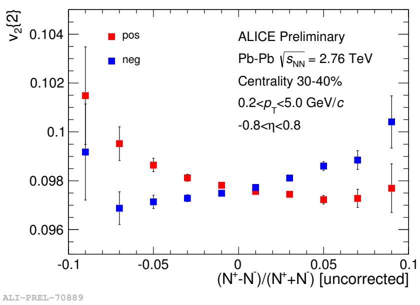
STAR results on $v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality

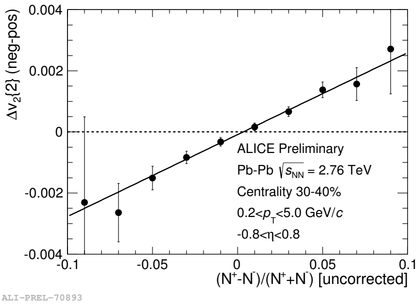




- STAR preliminary, arXiv:1211.3216
- Charge asymmetry $A_\pm = A = (N^+ - N^-)/(N^+ + N^-)$
- Note change in x-axis scale on right plot—correction for efficiency/acceptance
- Qualitatively consistent with CMW picture

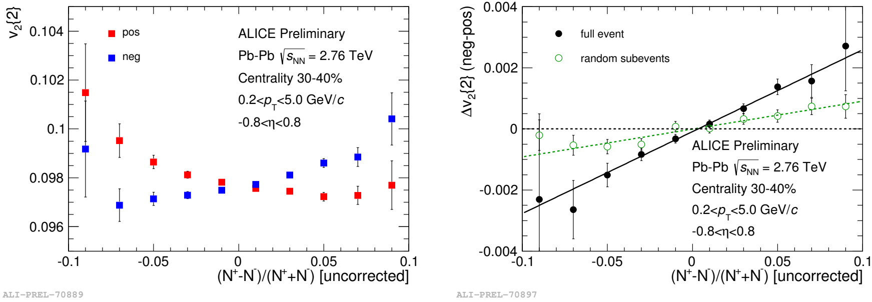
$v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality in ALICE





- 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 $\langle q_3\rangle_{\text{event}} \equiv A$
- Putting it together, the general 3-point correlator is

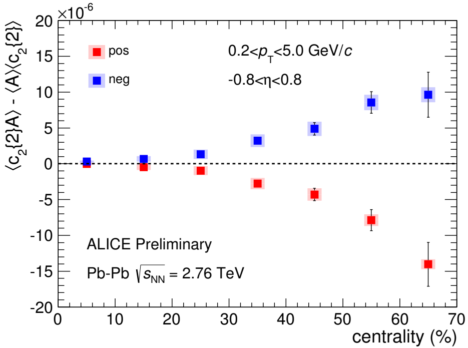
$$\langle \cos(n(\phi_1 - \psi_n))q_3\rangle - \langle q_3\rangle\langle \cos(n(\phi_1 - \psi_n))\rangle$$

- Can construct similar correlator with cumulant instead

$$\langle \cos(n(\phi_1 - \phi_2))q_3\rangle - \langle q_3\rangle\langle \cos(n(\phi_1 - \phi_2))\rangle$$

- 2-particle Q-cumulants used to calculate $\langle \cos(n(\phi_1 - \phi_2))\rangle$
  $c_n\{2\}$ integral, $d_n\{2\}$ differential

3-particle correlator: 2nd harmonic



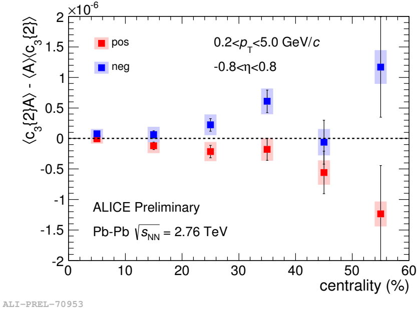
ALI-PREL-70910

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

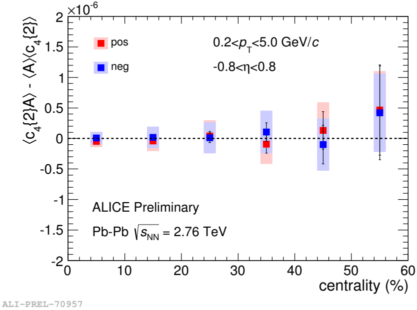
- Peripheral → stronger magnetic field → stronger CMW effect?
- Central → more combinatoric pairs → trivial dilution of local charge conservation (LCC) effects?
- Dependence on magnitude of v_2 or dN/dy?
- Some combination of these (and possibly other) effects?

3-particle correlator: higher harmonics

3rd harmonic



4th harmonic

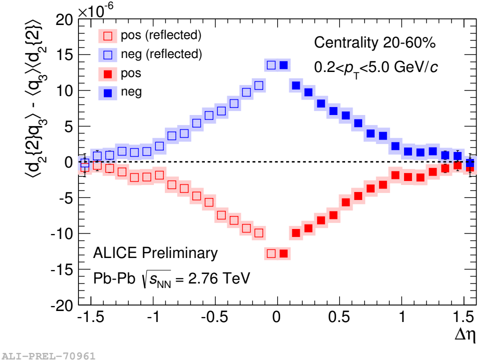


- CMW quadrupole expected to affect only 2^{nd} harmonic, LCC expected to affect all harmonics
- Small effect for 3^{rd} harmonic, no observed effect for 4^{th} harmonic
  —Note y-axis scale reduced by $\times 10$ compared to 2^{nd} harmonic
- Higher order multipole effects for CMW or harmonic interference?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

Intermission

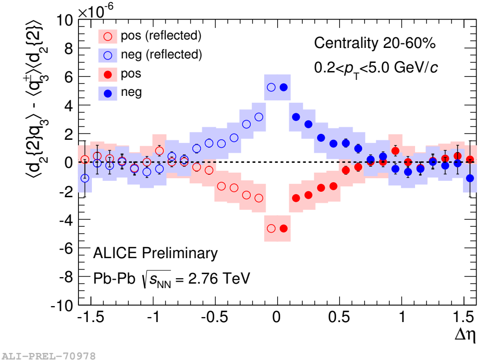
- What kind of differential studies can we do with this correlator?

3-particle correlator vs $\Delta\eta$



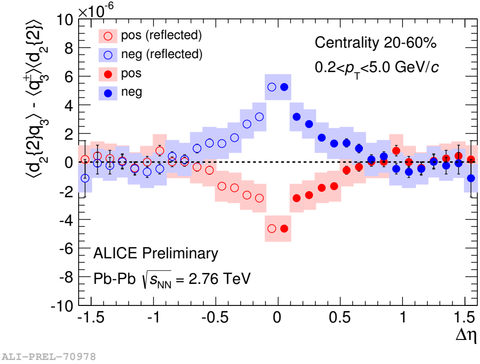
- Charge independent subtraction (charge correlation not considered)

3-particle correlator vs $\Delta\eta$



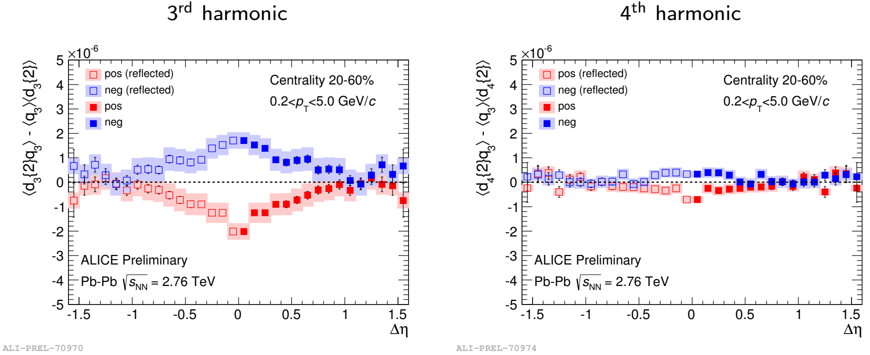
- Charge dependent subtraction (charge correlation considered)

3-particle correlator vs $\Delta\eta$



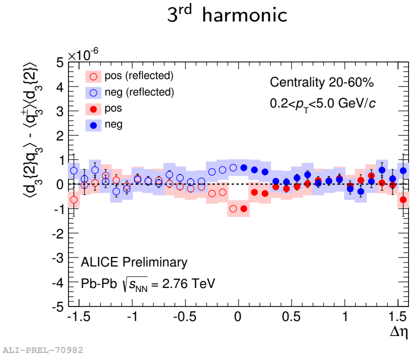
- Charge dependent subtraction (charge correlation considered)
- The observed effect has a large contribution from the dependence of q_3 on q_1
- Both the strength and range are significantly reduced, but a pronounced charge dependent effect remains
- How much contribution from charge conservation has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

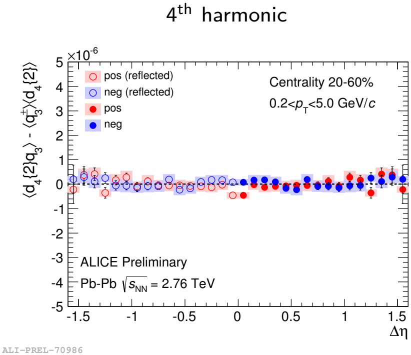
3-particle correlator vs $\Delta\eta$ for higher harmonics



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

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





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

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
  Very promising recent work in the Flow PAG on this
- Presence of quarks can be evinced by charge dependent v_1 in A+B collisions
  Can do this in Cu+Au collisions at RHIC, results coming soon

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 radial flow
- The current modeling gets some observables right but others wrong
- Promising avenue of investigation: anomalous hydrodynamics, which embeds the LPV effects in a realistic hydrodynamical medium
- There's no smoking gun yet, but the results we have already are promising, and there's much more to be done