Experimental searches for local parity violating effects in heavy ion collisions

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Outline

- Why are we here?
- Where have we been?
- Where are we now?
- Where are we going?

Утро в сосновом лесу

Утро в сосновом лесу

Parity

What is parity?

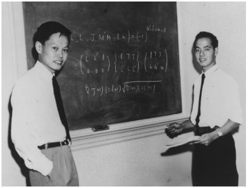
- In 3 space dimensions, parity is the simultaneous inversion of all three dimensions

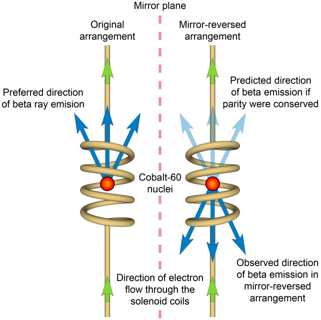
$$P \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

- 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 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)

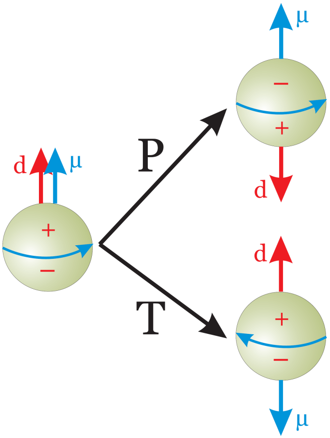




- Electron emission from ${}^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e + \overline{\nu}_e$ was found to be anti-parallel to the nuclear spin—parity violation
- Pauli was shocked and refused to believe the results, insisting they be repeated
- Wu's experiment was repeatedly confirmed, and she *should*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

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 131801 (2006)
- The observed absence of CP-violation in the strong sector is surprising because of natural CP-violating terms in the QCD Lagrangian



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

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

Chirality

What is chirality?

- Chirality is an internal quantum number, equal to $-1(L)$ or $+1(R)$
- For massless particles it is equal to sign of energy times helicity $(p_0\vec{s}\cdot\vec{p}/|p_0 s|)$, for massive particles it is different (and it evolves with time—Higgs)
- 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.
  $n_V = n_R + n_L, \quad n_A = n_R - n_L$
- Symmetry groups can also be represented this way,
  $G_R \times G_L = G_V \times G_A$

Chiral symmetry and breaking

- Chiral symmetry is invariance of the Lagrangian under independent rotations of L and R fermions
- Chiral symmetry is broken whenever there is mixing between L and R

$$m\overline{\psi}\psi = m(\overline{\psi}_R + \overline{\psi}_L)(\psi_R + \psi_L) = m(\overline{\psi}_R\psi_R + \overline{\psi}_L\psi_L + \overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R)$$

- Simplifed QCD Lagrangian with massless quarks:

$$\mathcal{L} = \mathcal{L}_{\text{glue}} + \overline{\psi}_R \not{D} \psi_R + \overline{\psi}_L \not{D} \psi_L$$

- This Lagrangian is unvariant under separate unitary rotations in flavor space for R and L:

$$\overline{\psi}_{R,L}\not{D}\psi_{R,L} \to \overline{\psi}_{R,L}V^{\dagger}_{R,L}\not{D}V_{R,L}\psi_{R,L} = \overline{\psi}_{R,L}\not{D}V^{\dagger}_{R,L}V_{R,L}\psi_{R,L} = \overline{\psi}_{R,L}\not{D}\psi_{R,L}$$

- Rewriting the symmetries:

$$\begin{aligned} U(N_f)_R \times U(N_f)_L &\to SU(N_f)_R \times SU(N_f)_L \times U(1)_R \times U(1)_L \\ &\to SU(N_f)_V \times SU(N_f)_A \times U(1)_V \times U(1)_A \end{aligned}$$

Chiral symmetry and breaking

- In general, there are three categories of symmetry breaking
  –explicit: not actually present in the Lagrangian
  –sponteous: present in the Lagrangian but lost in the equations of motion
  –anomalous: present in the classical theory but lost in quantization
- QCD has explicit chiral symmetry breaking due to the non-zero Higgs masses of the quarks
- QCD has spontaneous chiral symmetry breaking of $SU(N_f)_A$, which is what gives rise to the hadron masses (98% of the mass of the visible universe is due to the spontaneous symmetry breaking)
- QCD has anomalous breaking of $U(1)_A$ symmetry, which is the subject of this talk
- Chiral symmetry summary:

Symmetry	Status	Meaning or effect
$SU(N_f)_V$	Approximate	flavor symmetry, pseudo-Goldstone bosons
$SU(N_f)_A$	Spontaneously broken	98% of nucleon mass
$U(1)_V$	Exact	baryon conservation
$U(1)_A$	Anomalously broken	chiral anomaly

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

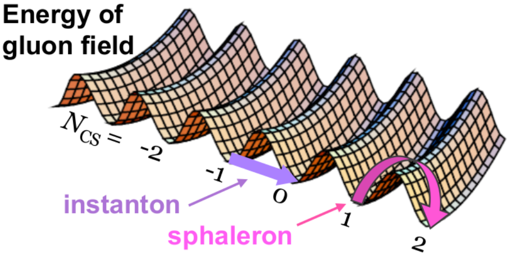
The QCD vacuum is highly non-trivial!

$U(1)_A$ 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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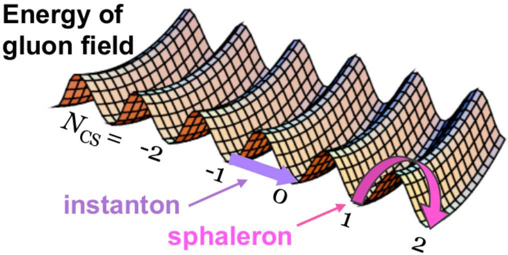
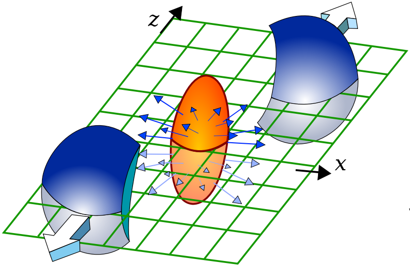
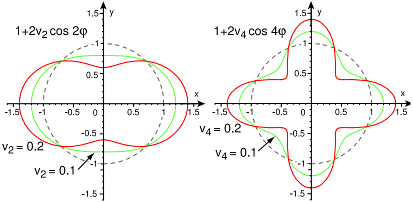


- $Q_w = N_L - N_R$
- Topological charge is the change in Chern-Simons number (N_{CS})
- Instanton: tunneling through barrier (all energies/temperatures, including 0)
- Sphaleron: jumping over barrier (only sufficiently high temperatures/energies)

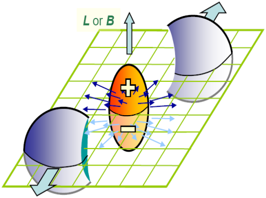
Anisotropic flow



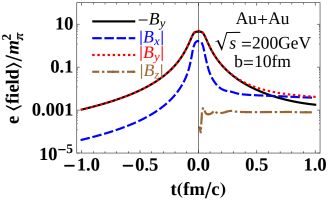


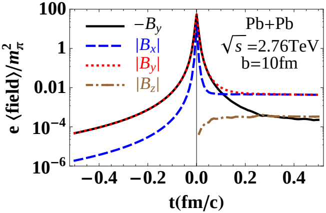
$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\Delta\phi \qquad \Delta\phi = \phi - \psi_{RP}, \quad v_n = \langle \cos n\Delta\phi \rangle$$

- 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



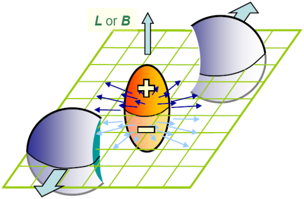
W.-T. Deng and X.-G. Huang
Phys. Rev. C 85, 044907 (2012)

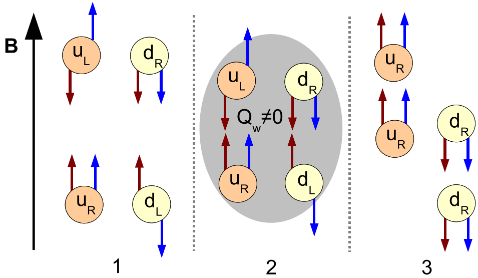




- The spectating nucleons induce a magnetic field in the overlap region
- The peak strength of the magnetic field in conventional units is roughly $10^{17\text{-}18}$ gauss—largest magnetic field in the known universe!
  –MRIs 10^5 gauss
  –Magnetars 10^{15} gauss
- The spectators (nominally) define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

The Chiral Magnetic Effect

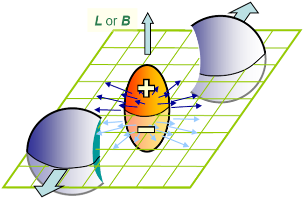


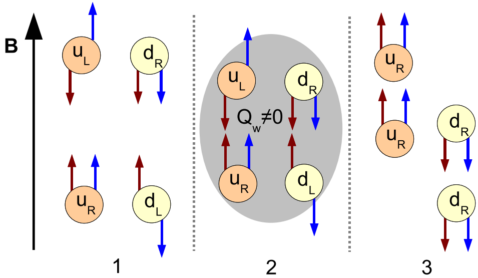


- Chiral imbalance induced by quantum anomaly
  (recall $U(1)_A$ anomaly $\partial_\mu J^\mu_A = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \rightarrow Q_w = N_L - N_R$)
- Alignment of spins by external magnetic field induces electric current of chiral quarks

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

The Chiral Magnetic Effect





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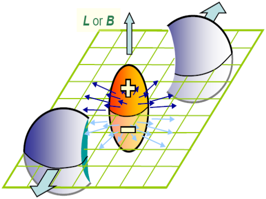
- How to measure?

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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The CME correlator

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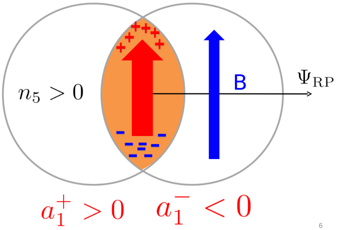

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- Positive particles should go above the reaction plane $a_1^+ > 0$
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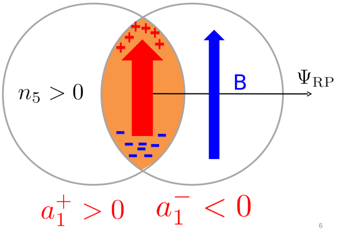

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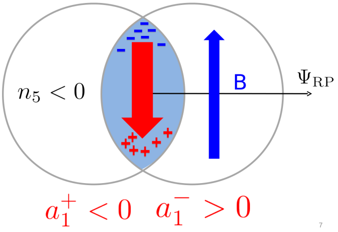

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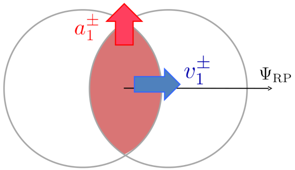
- However...
- Q_w fluctuates about $\langle Q_w \rangle = 0$, so the CME current changes sign event by event, and therefore $\langle a_1^\pm \rangle = 0$

The CME correlator

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

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



- 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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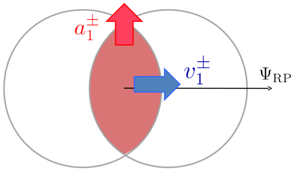

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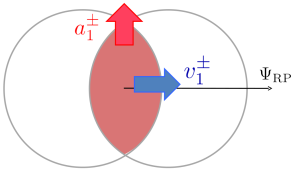

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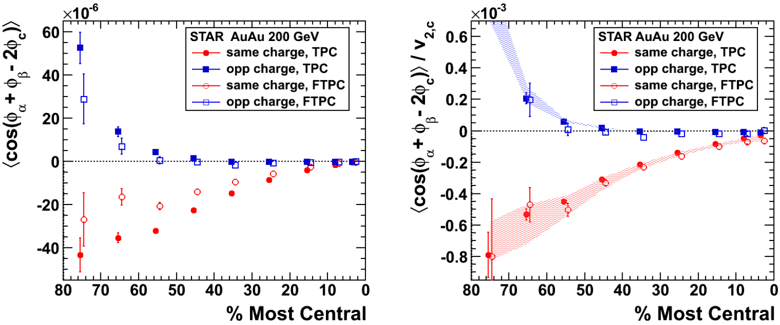
- Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = -\langle a_{1,a} a_{1,b} \rangle$
- However...
- RP dependent backgrounds remain
- If dipole fluctuations, $\langle v_1 v_1 \rangle \neq 0$

Intermission

Where have we been?

The first CME results (STAR)

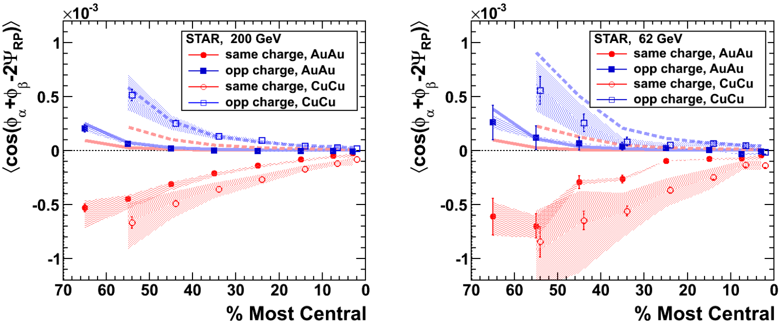
STAR, Phys. Rev. C 81, 054908 (2010)



- 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

The first CME results (STAR)

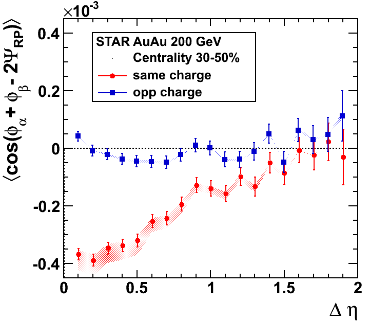
STAR, Phys. Rev. C 81, 054908 (2010)

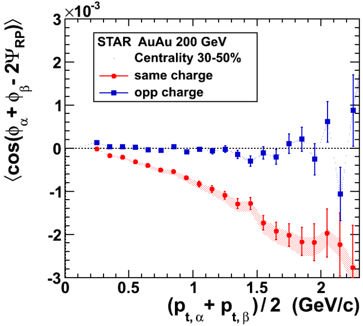


- Strong negative correlation for same sign in both Au+Au and Cu+Cu
- Positive correlation of opposite sign for Cu+Cu despite being absent in Au+Au
  –Medium in Cu+Cu is small enough that some opposite sign correlation remains?

The first CME results (STAR)

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

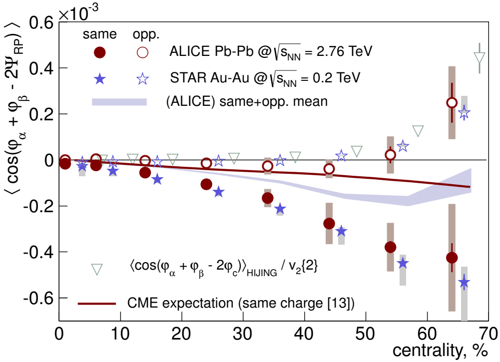




- No opposite sign correlation in Au+Au for any $\Delta\eta$ or any $\bar{p_T}$
- Same sign correlation gets strong for smaller $\Delta\eta$ and larger $\bar{p_T}$
  –The behavior in $\Delta\eta$ matches naïve expectations, different for $\bar{p_T}$

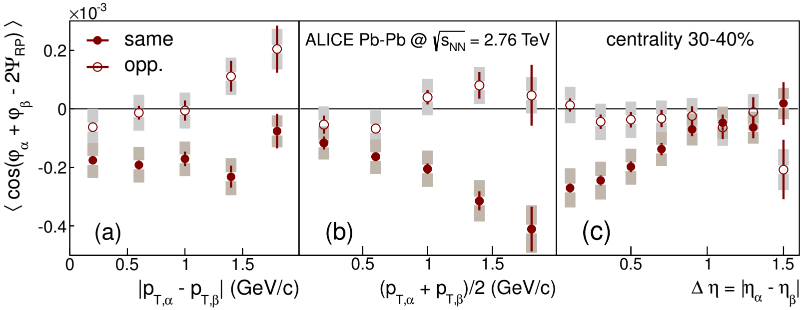
ALICE results on the CME

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

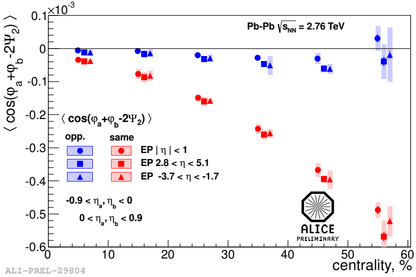
ALICE, Phys. Rev. Lett. 110, 012301 (2013)

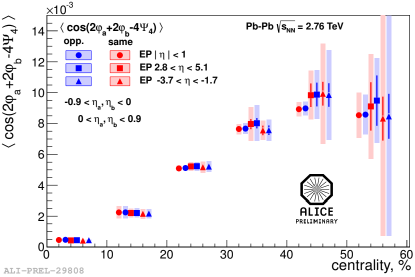


- ALICE results consistent with STAR results for both $\Delta\eta$ and $\bar{p_T}$

ALICE results on the CME

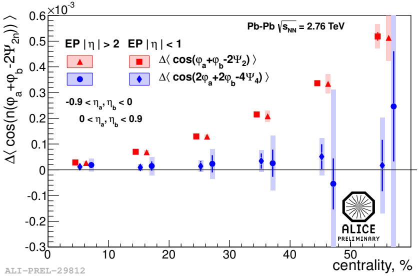
Y. Hori, Nucl. Phys. A 904-905, 475c-479c (2013)





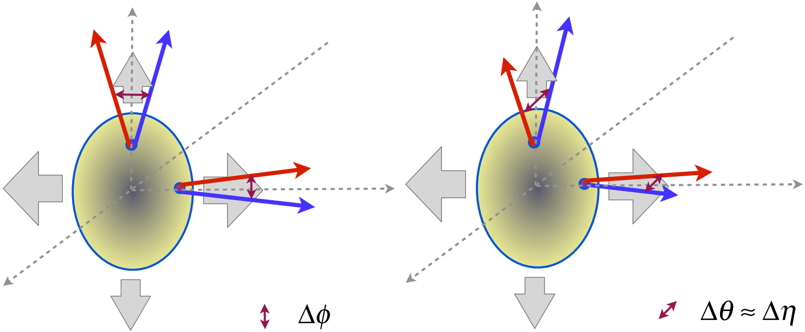
- Double harmonic correlator should have no CME signal, only backgrounds

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



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

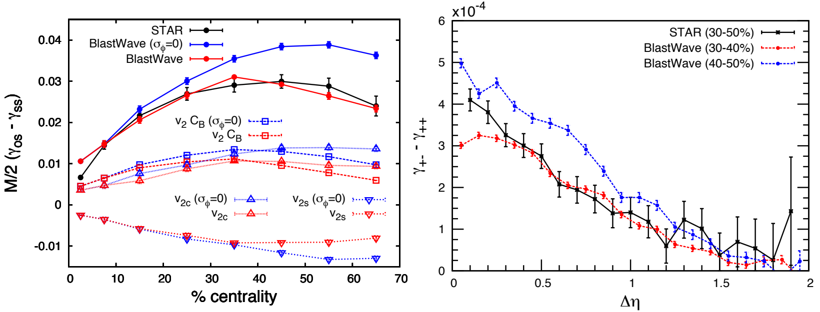
Backgrounds



- 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 background
- Simple and intuitive mechanism for generating charge-dependent angular correlations

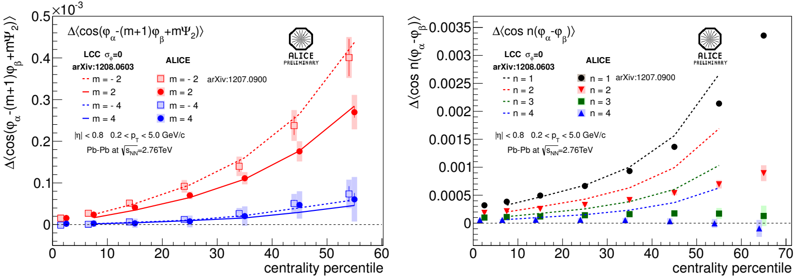
Backgrounds

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



- 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, 475c-479c (2013)



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

Intermission

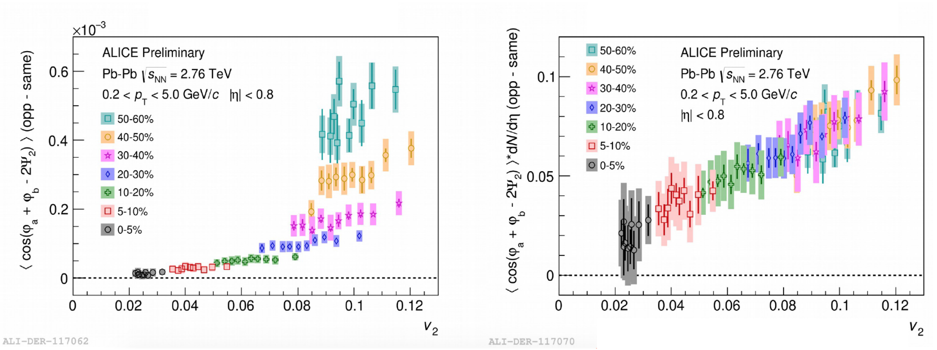
Where we've been:

- Observation of signals "qualitatively consistent" with CME
- Surprisingly large signal at LHC... why?
- Determination that there is significant background contamination (we are trying to measure a P-odd effect with a P-even observable)

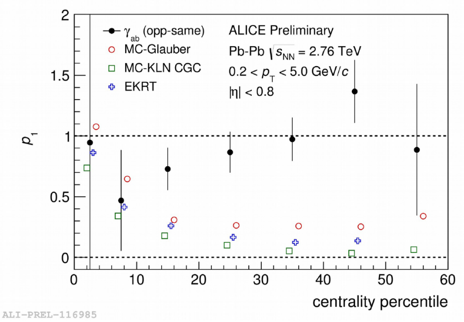
Where are we going? Towards quantitative assessment of backgrounds

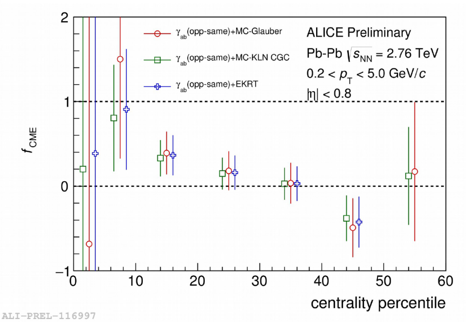
- One approach: adjust background (e.g. event shape engineering)
- Another approach: adjust signal (e.g. small systems, isobars)

CME observable with event shape engineering at the LHC



- Event shape engineering: categorize events by size of v_2 in each centrality class
- $\Delta\gamma$ (left panel) and $\langle dN_{ch}/d\eta\rangle\Delta\gamma$ (right panel) as a function of v_2 (different v_2 categories for each centrality)
- $\langle dN_{ch}/d\eta\rangle\Delta\gamma$ vs v_2 is almost perfectly linear: signal dominated by background

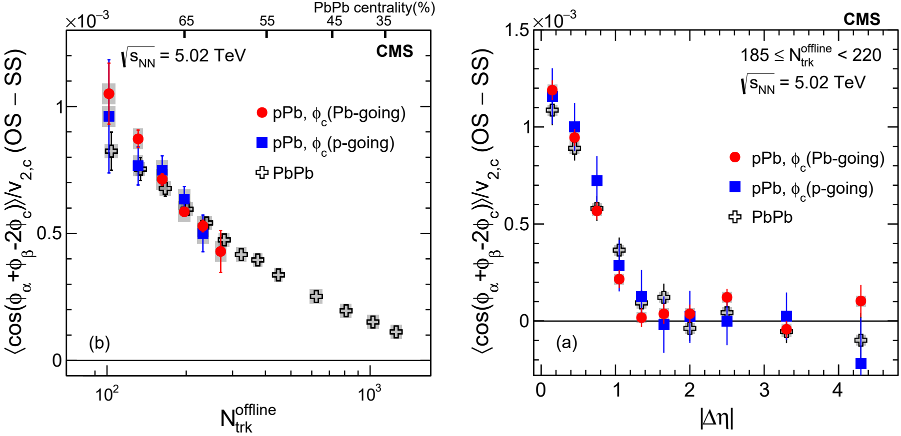




- Determine $\langle\cos(2(\psi_B - \psi_2))\rangle$ from initial conditions models
- Assume functional form: $P_1(v_2) = p_0(1 + p_1(v_2 - \langle v_2\rangle)/\langle v_2\rangle)$
- $f_{CME}\, p_1^{MC} + (1 - f_{CME}) = p_1^{data}$
- f_{CME}—Glauber: 0.102 ± 0.129, KLN: 0.076 ± 0.101, EKRT: 0.084 ± 0.114

CME observable in p+Pb collisions at the LHC

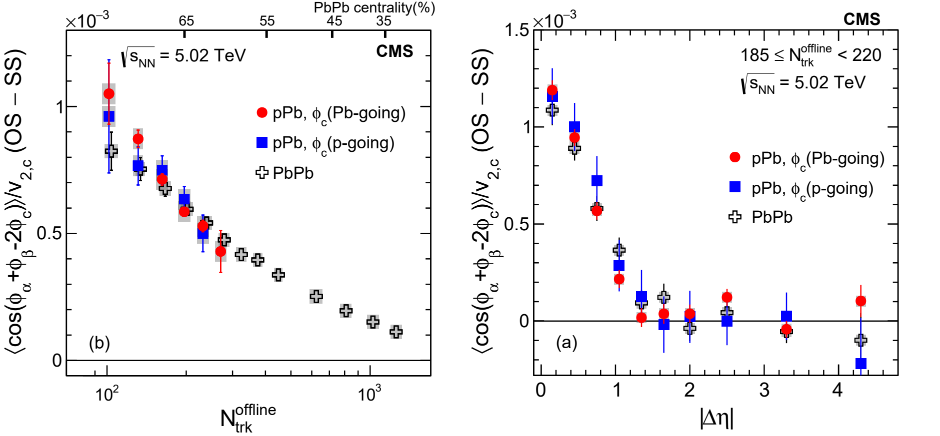
CMS, Phys. Rev. Lett. 118, 122301 (2017)



- *Striking* similarity between p+Pb and Pb+Pb (OS−SS)
- No CME signal expected in p+Pb
- CME correlator heavily dominated by backgrounds

CME observable in p+Pb collisions at the LHC

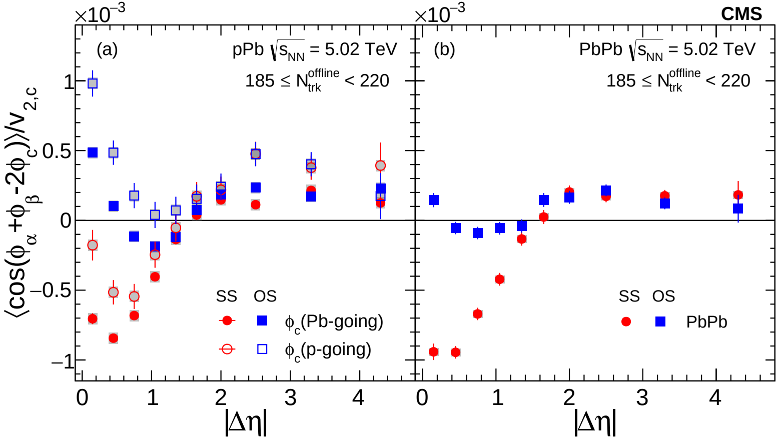
CMS, Phys. Rev. Lett. 118, 122301 (2017)



- *Striking* similarity between p+Pb and Pb+Pb (OS−SS)
- No CME signal expected in p+Pb
- CME correlator heavily dominated by backgrounds
- But...

CME observable in p+Pb collisions at the LHC

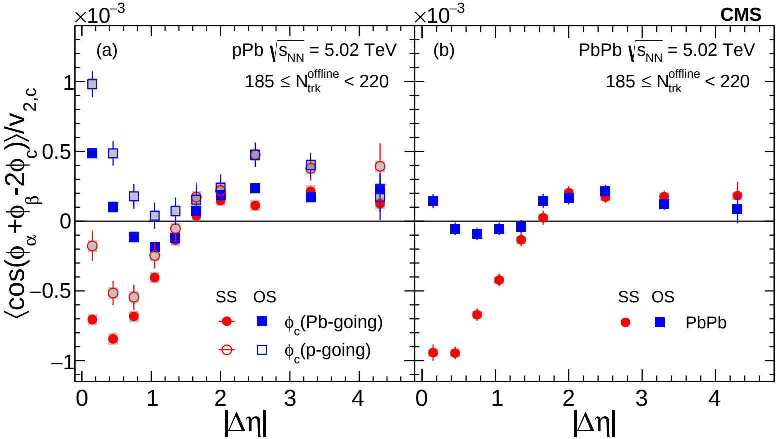
CMS, Phys. Rev. Lett. 118, 122301 (2017)



- OS and SS are more different in p+Pb vs Pb+Pb than you'd expect for identical physics

CME observable in p+Pb collisions at the LHC

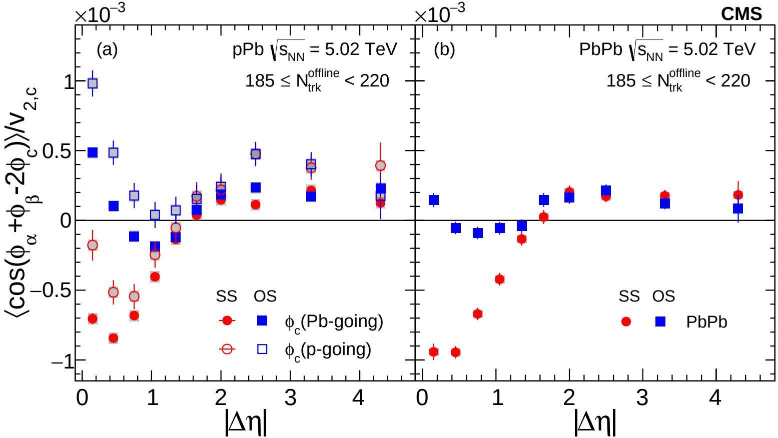
CMS, Phys. Rev. Lett. 118, 122301 (2017)



- OS and SS are more different in p+Pb vs Pb+Pb than you'd expect for identical physics
- What does that mean?

CME observable in p+Pb collisions at the LHC

CMS, Phys. Rev. Lett. 118, 122301 (2017)



- OS and SS are more different in p+Pb vs Pb+Pb than you'd expect for identical physics
- What does that mean?
- Are we sure there's no signal in p+Pb?

How to calculate B-field

Start with the Biot-Savart Law for moving point charges:

$$\vec{E} = \frac{e}{4\pi\varepsilon_0} \frac{1 - v^2/c^2}{(1 - v^2 \sin^2\theta/c^2)^{3/2}} \frac{\hat{r}}{r^2},$$
$$\vec{B} = \frac{1}{c^2}[\vec{v} \times \vec{E}],$$

where $\sin\theta = |\hat{r} \times \hat{v}|$. Take $\sin\theta = 1$ (true at $t = 0$).

$$\begin{aligned} \vec{E} &= \frac{e}{4\pi\varepsilon_0} \frac{1 - v^2/c^2}{(1 - v^2/c^2)^{3/2}} \frac{\hat{r}}{r^2} \\ &= \frac{e}{4\pi\varepsilon_0} \gamma \frac{\hat{r}}{r^2} \end{aligned}$$

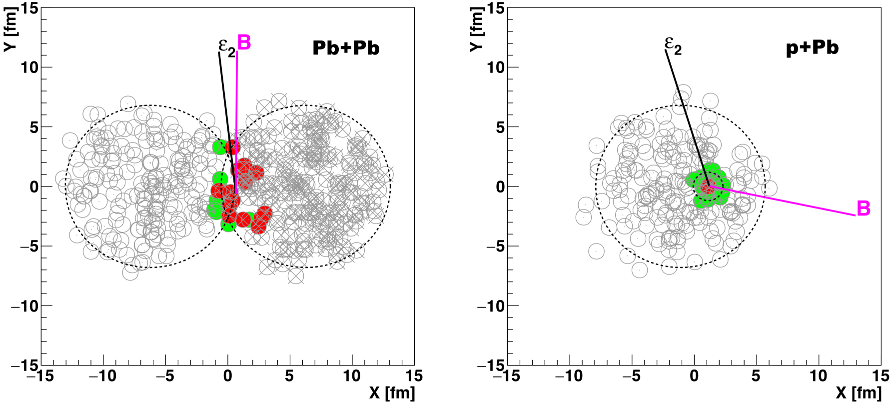
Since $\hat{r} \equiv \hat{E}$ and we've set $\sin\theta = 1$, we have $\vec{v} \times \vec{E} = v\vec{E}$, so we get

$$\begin{aligned} \vec{B} &= \frac{v}{c^2}\vec{E} \\ &= c\frac{e\mu_0}{4\pi}\beta\gamma\frac{1}{r^2}\hat{r}. \end{aligned}$$

Pick a point (or region to average over) for evaluation, plug and chug constants, profit!
Theorists like to give $\hbar eB/c^2$—10^{15} Tesla $\leftrightarrow$ 3.04 m_π^2

Magnetic field calculations for Pb+Pb and p+Pb at the LHC

R. Belmont and J.L. Nagle, arXiv:1610.07964 (accepted by Phys. Rev. C)



- Pb+Pb: impact parameter, ψ_2, and ψ_B appear strongly correlated
- p+Pb: impact parameter, ψ_2, and ψ_B appear uncorrelated

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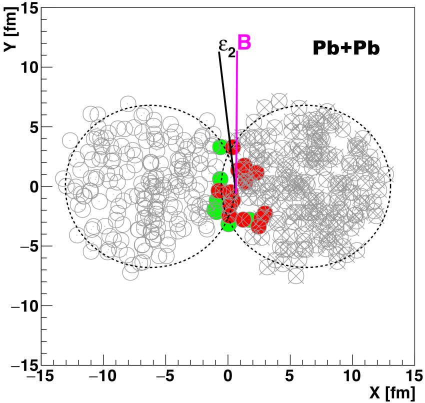
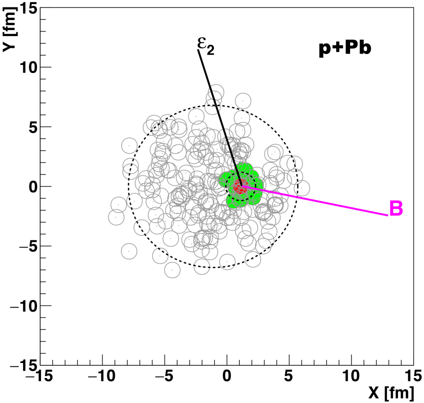
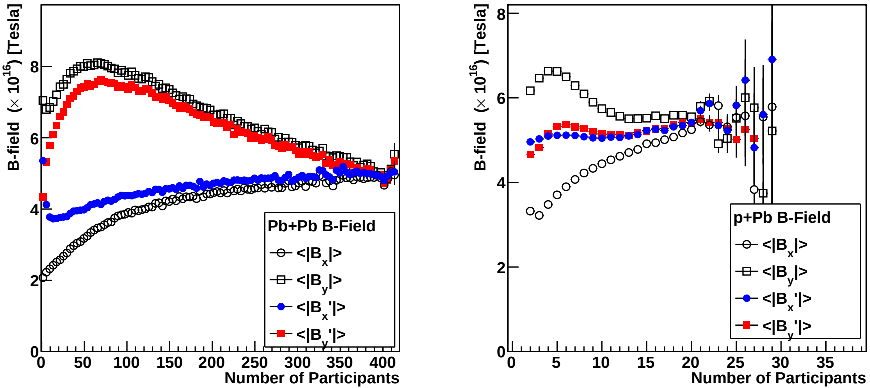




- Pb+Pb: impact parameter, ψ_2, and ψ_B appear strongly correlated
- p+Pb: impact parameter, ψ_2, and ψ_B appear uncorrelated
- Take away: so, yes, we're pretty sure there's no signal in p+Pb...

Magnetic field calculations for Pb+Pb and p+Pb at the LHC

R. Belmont and J.L. Nagle, arXiv:1610.07964 (accepted by Phys. Rev. C)



- Very strong magnetic fields in both cases ($\sim 150\ m_\pi^2$ for central collisions)
- Impact parameter along x, ψ_2 along x'
- Average x' and y' components equal means no correlation between ψ_2 and ψ_B

Magnetic field calculations for Pb+Pb and p+Pb at the LHC

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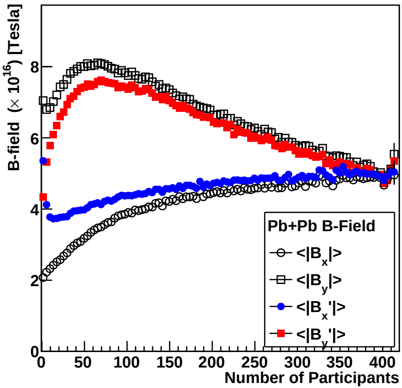
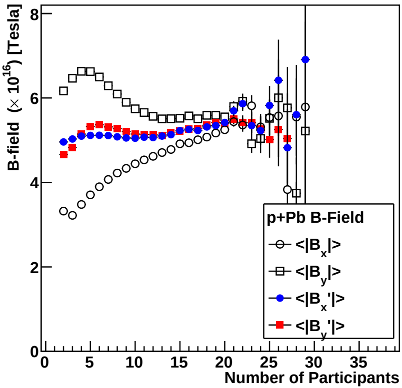


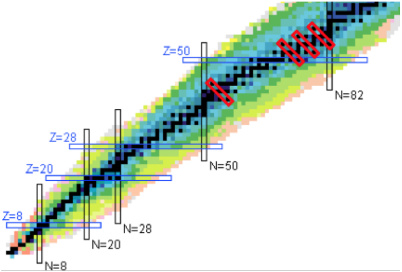


- Very strong magnetic fields in both cases ($\sim 150\ m_\pi^2$ for central collisions)
- Impact parameter along x, ψ_2 along x'
- Average x' and y' components equal means no correlation between ψ_2 and ψ_B
- Take away: okay now we're *really* sure there's no signal in p+Pb

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

Why isobars?

- Different Z means different B-field (change signal)
- Same A means same multiplicity (fix background)
- Similar shape means similar v_2 (fix background)



Requirements $\Delta Z = 4$ and non-zero abundance

Low Z nucl	High Z nucl	B^2 ratio
$^{96}_{40}$Zr	$^{96}_{44}$Ru	1.21
$^{124}_{50}$Sn	$^{124}_{54}$Xe	1.17
$^{130}_{52}$Te	$^{130}_{56}$Ba	1.16
$^{136}_{54}$Xe	$^{136}_{58}$Ce	1.15

- Lighter pairs offer higher B^2 ratio (good)
- Heavier pairs offer higher multiplicity
  —better EP resolution (good), more detector occupancy (bad)
- Which is the best is non-trivial, but Zr/Ru is the run plan

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

Nuclear structure is more important than previously thought in heavy ions

- Most nuclei are not spherical, and the deviations from sphericity can vary widely
- Ellipticity shape parameter β_2 affects the initial eccentricity ε_2 in heavy ion collisions and therefore the measured v_2
- Recent STAR results: v_2 much higher in ultra-central U+U compared to ultra-central Au+Au
- Deformation may also affect B-field

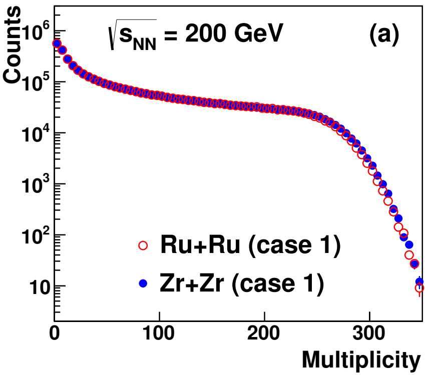
Possible problem: Zr/Ru are not spherical, may not have the same shape, shape parameters not especially well-known

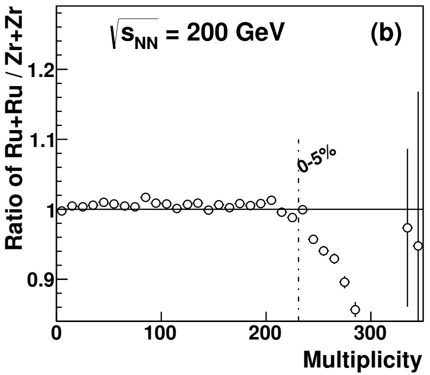
- Case 1: $\beta_2[^{96}_{40}\text{Zr}] = 0.080$, $\beta_2[^{96}_{44}\text{Ru}] = 0.158$
- Case 2: $\beta_2[^{96}_{40}\text{Zr}] = 0.217$, $\beta_2[^{96}_{44}\text{Ru}] = 0.053$

Opportunity: measure v_2 in ultra-central Zr+Zr and Ru+Ru to determine relative β_2

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

CME Task Force Report, arXiv:1608.00982





Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter

- Solution 1: Multiplicities are identical except for very central

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

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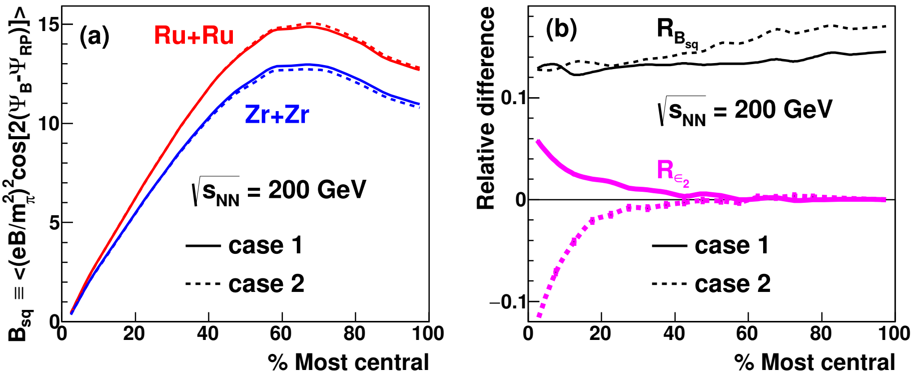

Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter

- Solution 1: Multiplicities are identical except for very central
- Solution 2: B-field and eccentricity aren't so different

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

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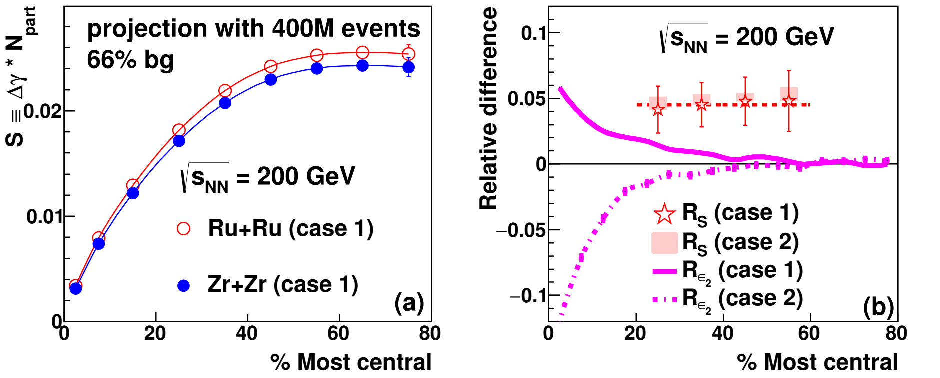
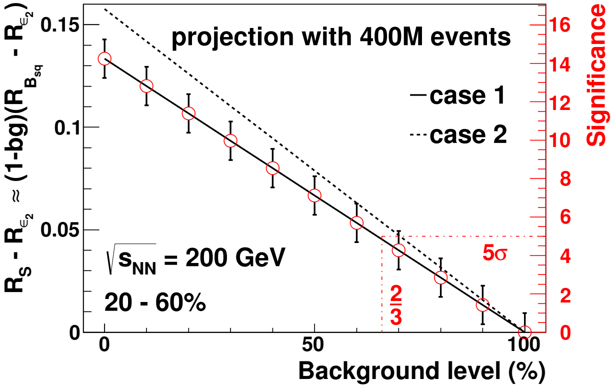


Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter

- Solution 1: Multiplicities are identical except for very central
- Solution 2: B-field and eccentricity aren't so different
- Solution 3: Expected signal difference stronger differences in ε_2

Isobaric collisions: let's pretend to be nuclear physicists for a few minutes

CME Task Force Report, arXiv:1608.00982



If we have 400M events for Zr+Zr and Ru+Ru:

- If 100% CME: 16σ separation between Zr+Zr and Ru+Ru
- If 33% CME: 5σ separation between Zr+Zr and Ru+Ru
- If 20% CME: 3σ separation between Zr+Zr and Ru+Ru

Good news! Latest run plan is 3.5 weeks for each: anticipate 1.2B events for each

Intermission

Where we've been and where we are:

- Observation of signals "qualitatively consistent" with CME
- Surprisingly large signal at LHC... why?
- CMS results on p+Pb and Pb+Pb: some of the details need to be sorted out, but the implications are clear: CME contribution to observed signal at LHC is very, very small

Where are we going?

- The situation at RHIC energies may be very different, where the field is weaker but longer lived
- Isobaric collisions in 2018 will hopefully shed significant light on the matter

The Chiral Magnetic Wave

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

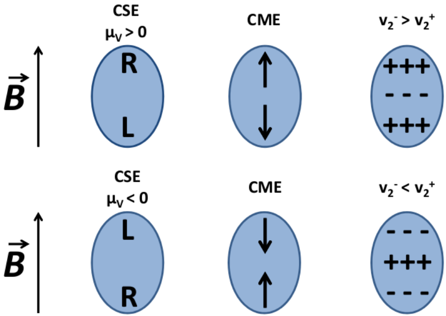
The Chiral Magnetic Wave

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

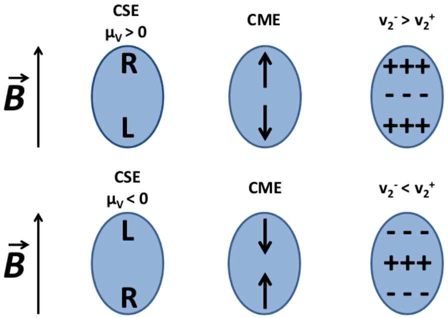
$$\frac{dQ}{d\Delta\phi} = Q[1 - r_e \cos(2\Delta\phi)]$$

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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- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)

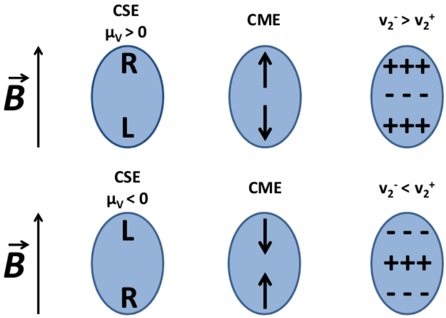
The Chiral Magnetic Wave

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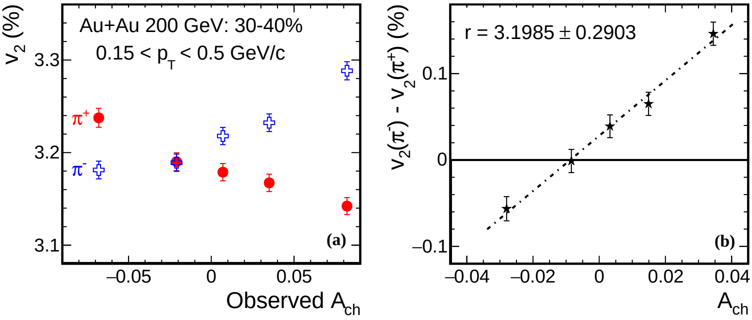
STAR results on $v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality

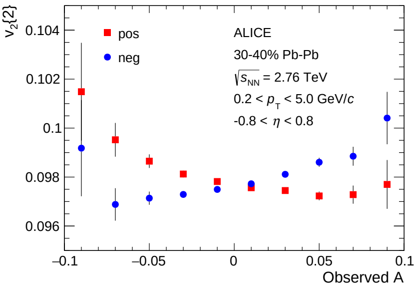
STAR, Phys. Rev. Lett. 114, 252302 (2015)

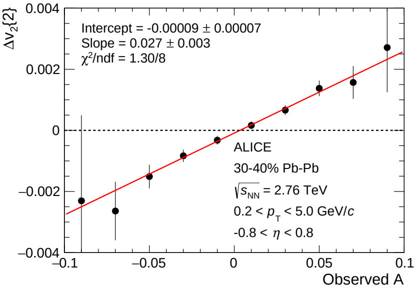


- Charge asymmetry $A_{ch} = A = (N^+ - N^-)/(N^+ + N^-)$
- Note change in x-axis scale on right plot—correction for efficiency/acceptance
- Qualitatively consistent with CMW picture

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

ALICE, Phys. Rev. C 93 044903 (2016)

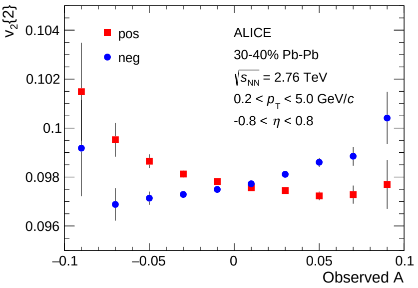


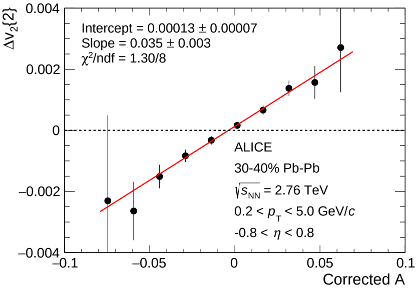


- Strong, clear signal
- Qualitatively consistent with STAR results

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

ALICE, Phys. Rev. C 93 044903 (2016)





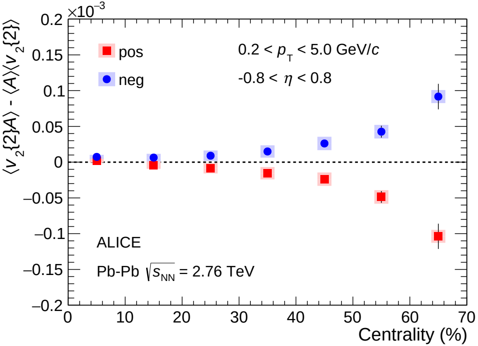
- Strong, clear signal
- Qualitatively consistent with STAR results
- Necessary to make correction

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 $\langle q_3\rangle_{\mathrm{event}} \equiv A$
- 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: 2nd harmonic

ALICE, Phys. Rev. C 93 044903 (2016)



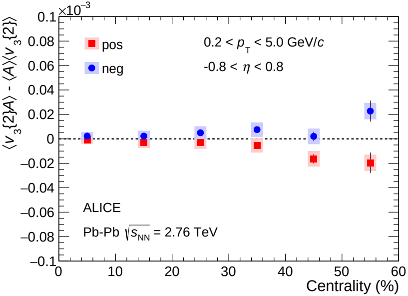
What causes the increased charge separation as the collisions become more peripheral?

- 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?

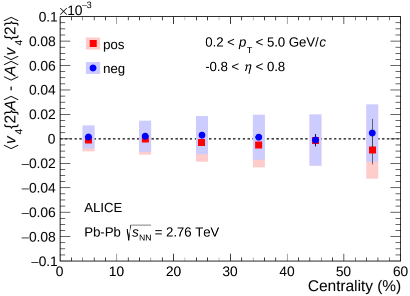
3-particle correlator: higher harmonics

ALICE, Phys. Rev. C 93 044903 (2016)

3rd harmonic



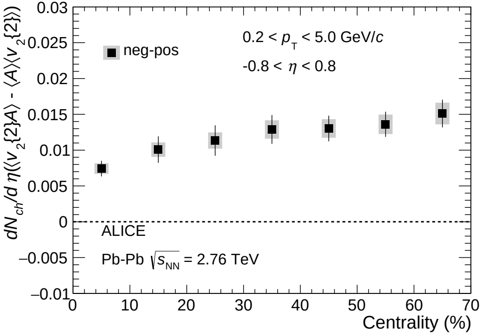
4th harmonic



- 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 $dN_{ch}/d\eta$

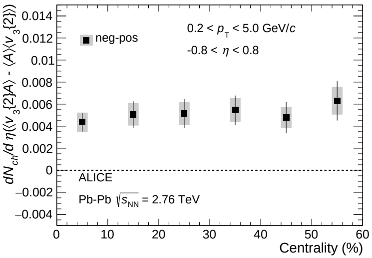
ALICE, Phys. Rev. C 93 044903 (2016)



- 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, Phys. Rev. C 93 044903 (2016)



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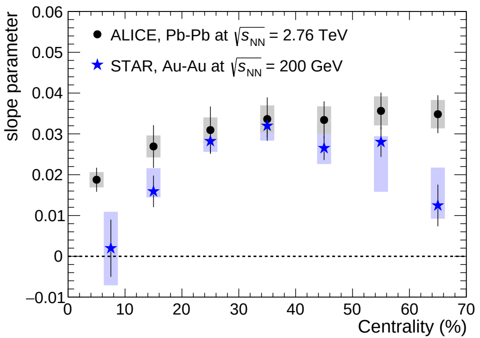
- Note that the σ_A^2 must be the true variance, so the observed σ_A^2 must be efficiency corrected
- As with the direct measurement of v_2 vs A, the evaluation of the slope parameter in this way depends on corrections from Monte Carlo

Estimating the slope parameter from the integral correlator

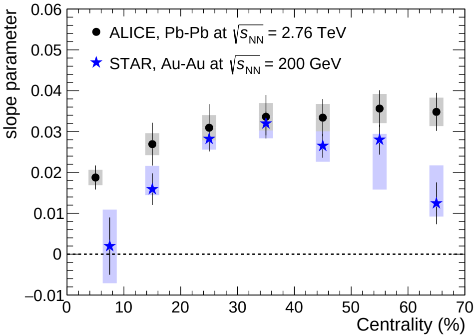
ALICE, Phys. Rev. C 93 044903 (2016)



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

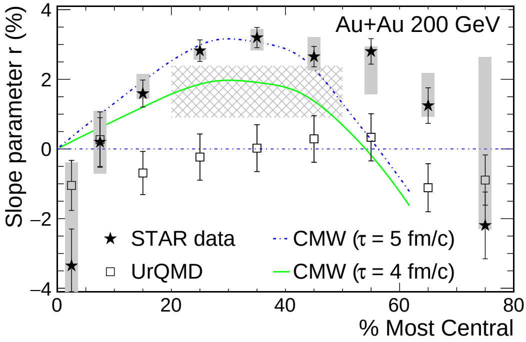
Estimating the slope parameter from the integral correlator

ALICE, Phys. Rev. C 93 044903 (2016)



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

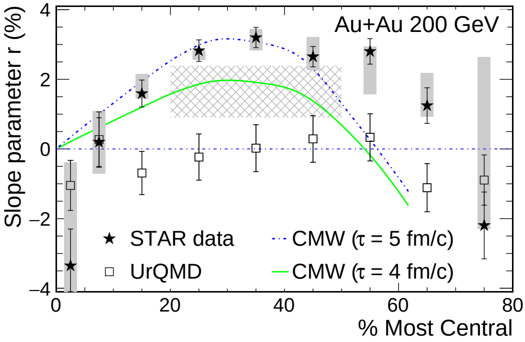
STAR, Phys. Rev. Lett. 114, 252302 (2015)



- Very good agreement between theory and experiment

Slope parameter measurement by STAR

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



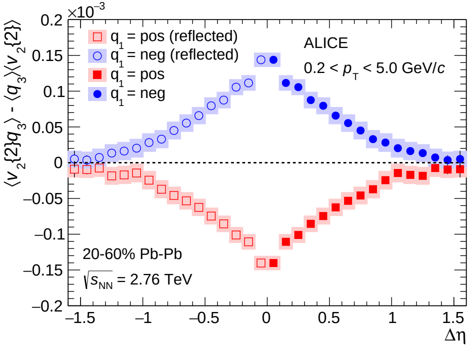
- Very good agreement between theory and experiment
- (Almost too good...)

Intermission

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

3-particle correlator vs $\Delta\eta$

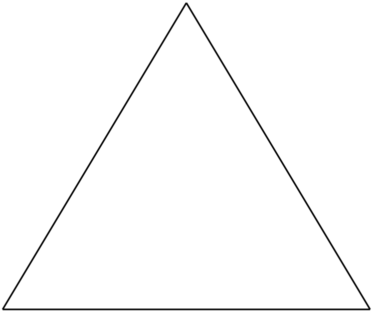
ALICE, Phys. Rev. C 93 044903 (2016)



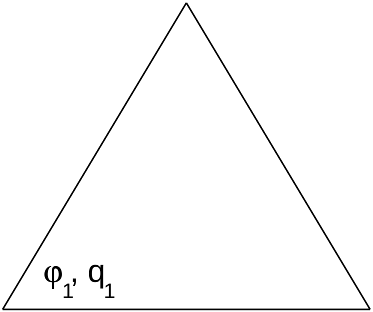
- Generalizing from A to q_3 as discussed, we can measure the correlator as a function of the separation between particles 1 and 3, $\Delta\eta = \eta_1 - \eta_3$
- Doing so we can directly measure the η range and dependence of the charge dependent effect
- LCC and CMW correlations may have different 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



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



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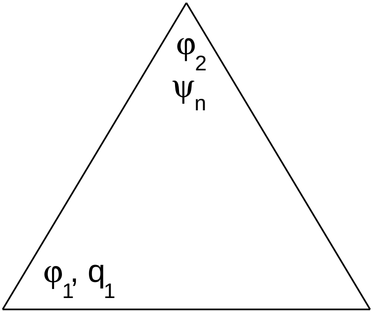

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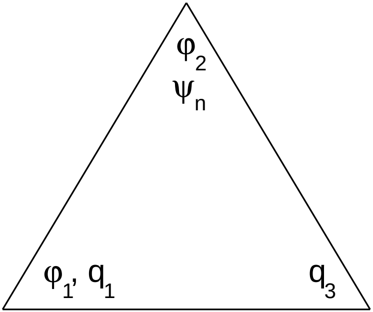

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- 1 is the particle of interest, and we consider both ϕ_1 and q_1
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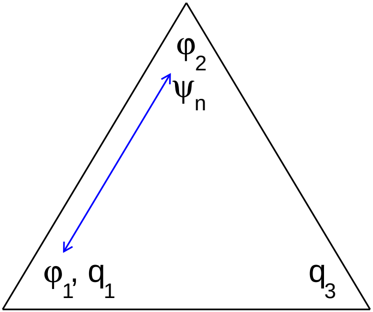
- 3 is the charged particle
- The correlation between 1 and 2 is the harmonic coefficient



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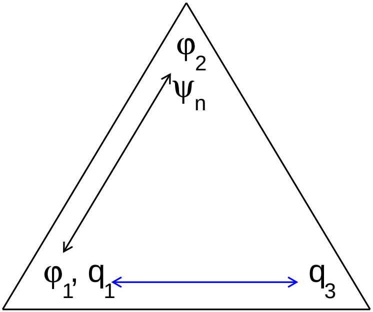

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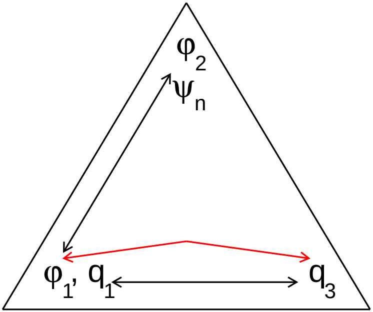
- Both correlations must be fully taken into account to get at potentially new physics



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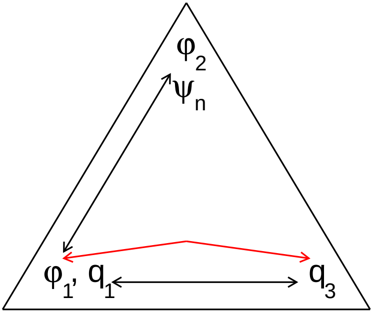
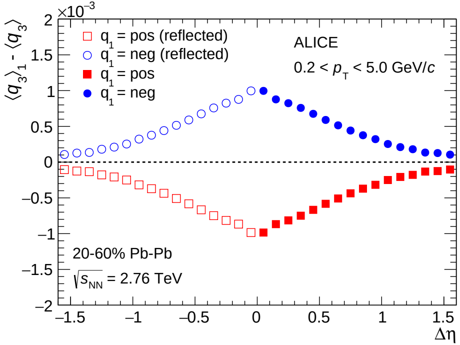


  - When removing the charge correlation between 1 and 3, all reducible correlations have been removed and the correlator is a cumulant $\langle\langle\cos(n(\phi_1 - \phi_2))q_3\rangle\rangle$
  - S.A. Voloshin and R. Belmont, Nucl. Phys. A 931 (2014) 992-996

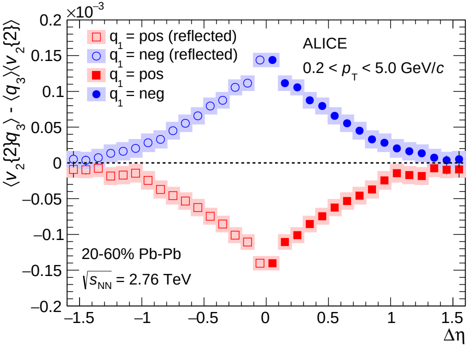
Understanding mean charge vs $\Delta\eta$

ALICE, Phys. Rev. C 93 044903 (2016)



- $\langle q_3 \rangle$ 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?

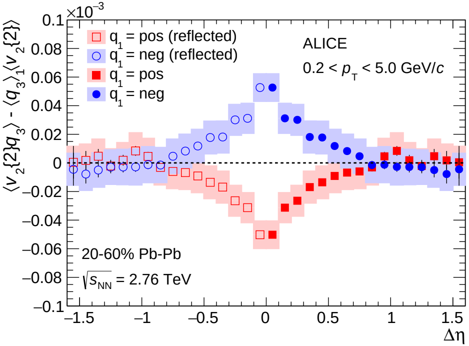
ALICE, Phys. Rev. C 93 044903 (2016)



- Charge independent subtraction (charge correlation not considered)

3-particle correlator vs $\Delta\eta$

ALICE, Phys. Rev. C 93 044903 (2016)



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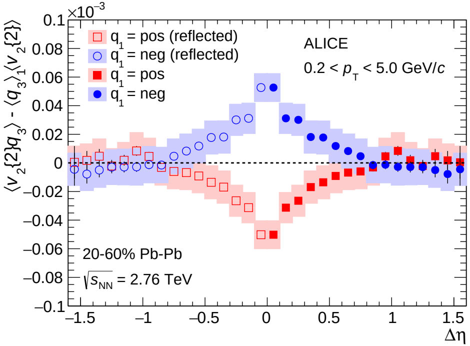
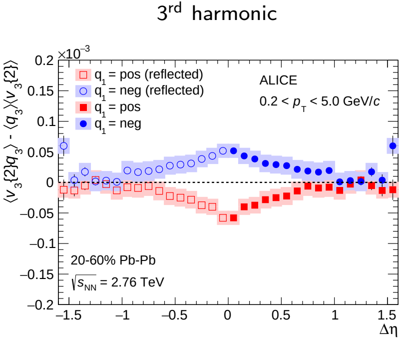
ALICE, Phys. Rev. C 93 044903 (2016)

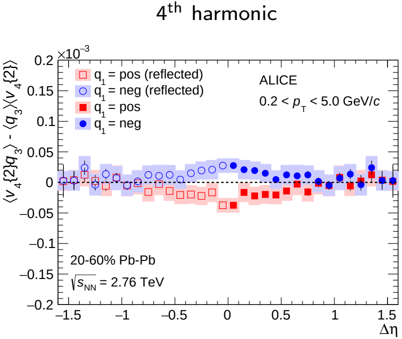


- Charge dependent subtraction (charge correlation considered)
- The observed effect has a large contribution from the dependence of q_3 on q_1
- Both the strength and range are significantly reduced, but a pronounced charge dependent effect remains
- How much contribution from charge conservation has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

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

ALICE, Phys. Rev. C 93 044903 (2016)



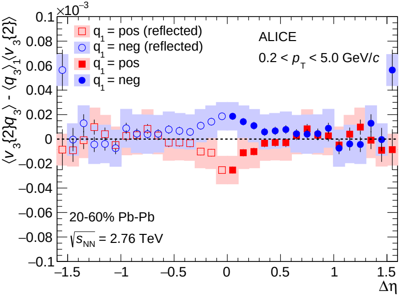


- Charge *independent* subtraction
- Moderate effect for 3rd, minimal effect for 4th

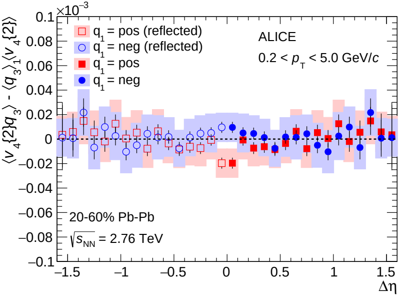
3-particle correlator vs $\Delta\eta$ for higher harmonics

ALICE, Phys. Rev. C 93 044903 (2016)

3rd harmonic



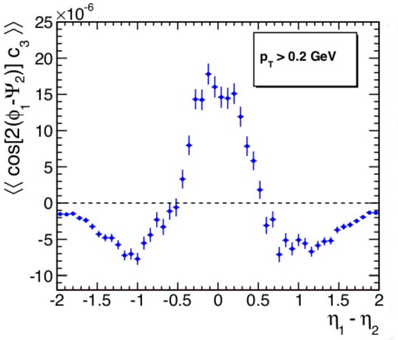
4th harmonic



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

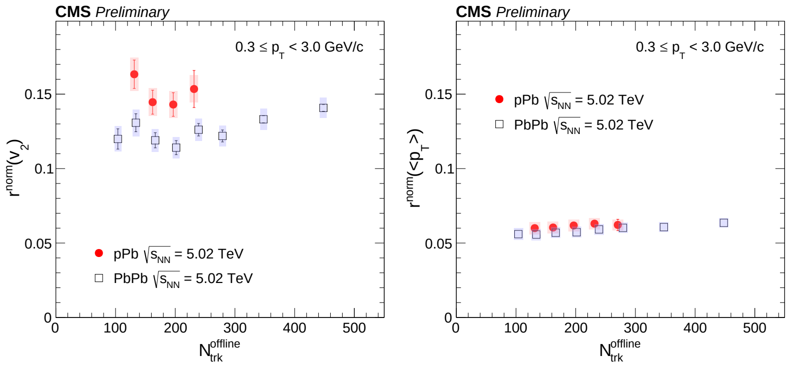
Backgrounds

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—combination of background and new physics?
- In any case, it's clear the CMW observables are susceptible to to backgrounds just like the CME

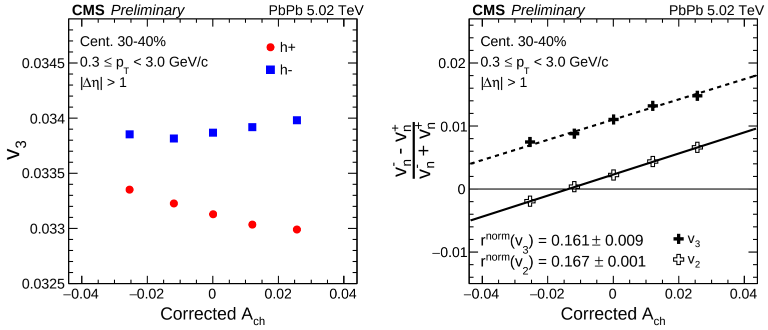
CMS, QM2017



- As with CME, no CMW contribution to known observables in p+Pb

CMS results on CMW in p+Pb

CMS, QM2017



- As with CME, no CMW contribution to known observables in p+Pb

Intermission

Where we've been and where we are:

- Observation of signals "qualitatively consistent" with CMW (sound familiar?)
- Surprisingly large signal at LHC... why? (sound familiar?)
- CMS results on p+Pb and Pb+Pb: some of the details need to be sorted out, but the implications are clear: CMW contribution to observed signal at LHC is very, very small (sound familiar?)

Where are we going?

- The situation at RHIC energies may be very different, where the field is weaker but longer lived (sound familiar?)
- According to CME task force: the CMW is not sensitive enough to the B-field for differences to be observable in RHIC 2018 isobar running
- I strongly encourage other experiments to use the correlator we developed in ALICE—seeing the pseudorapidity dependence could make a real difference

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!

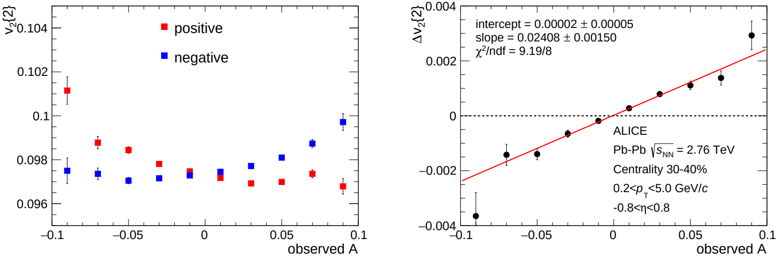
Additional material

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.H.G. Tytgat, Phys. Rev. Lett 81, 512 (1998)
- First paper discussing possible experimental searches
  S.A. Voloshin, Phys. Rev. C 62 044901 (2000)
- First paper suggesting an experimental search for a specific effect
  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)

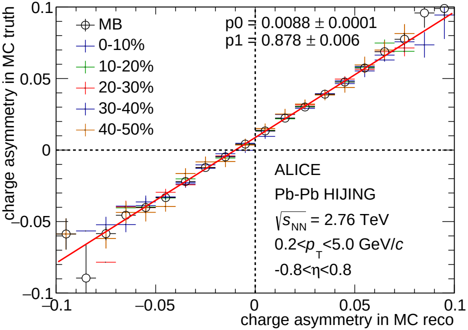
Measuring the slope parameter—direct method

ALICE, Phys. Rev. C 93 044903 (2016)



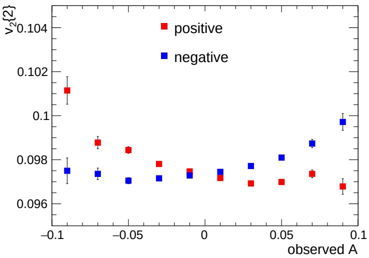
- As discussed before, our Δv_2 vs A results are qualitatively consistent with CMW expectations and published STAR results
- An efficiency correction is required, and we decided to go ahead and do that for reasons I'll get to in a few slides...

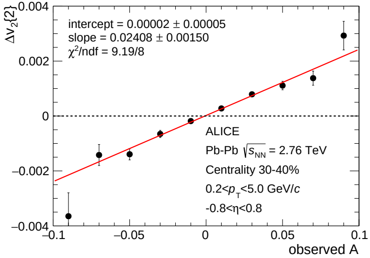
Support for ALICE, Phys. Rev. C 93 044903 (2016)



- We use HIJING simulations of Pb+Pb collisions at 2.76 TeV
- We look at particle level A (true) as a function of track level A (observed) to determine the correction
- The observed A is then corrected to achieve the true A

Support for ALICE, Phys. Rev. C 93 044903 (2016)

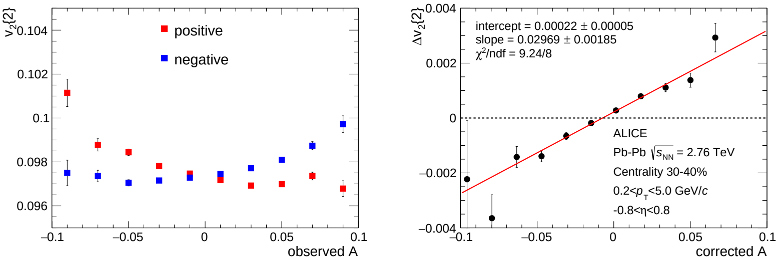




- As shown before, we see results qualitatively consistent with CMW expectations

Measuring the slope parameter—direct method

Support for ALICE, Phys. Rev. C 93 044903 (2016)

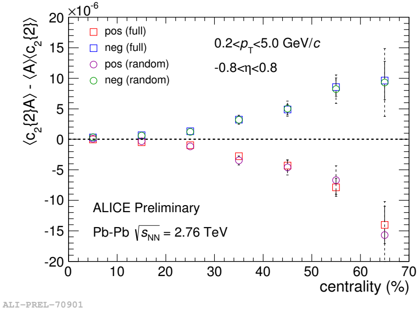


- As shown before, we see results qualitatively consistent with CMW expectations
- The MC correction has a relatively modest effect

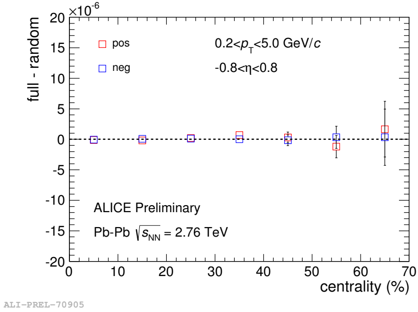
3-particle correlator: efficiency independent

R. Belmont, Quark Matter 2014

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

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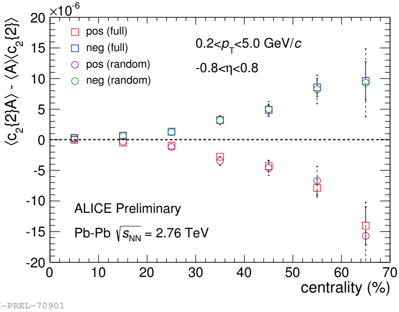

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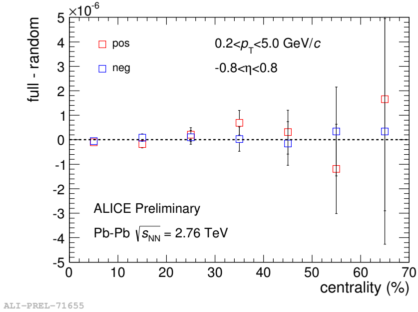

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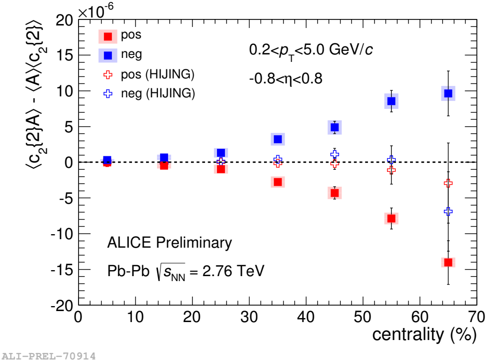
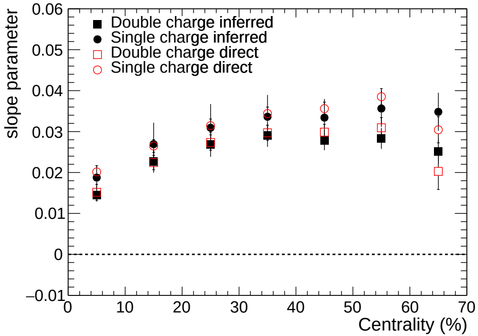
3-particle correlator: comparison to HIJING



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

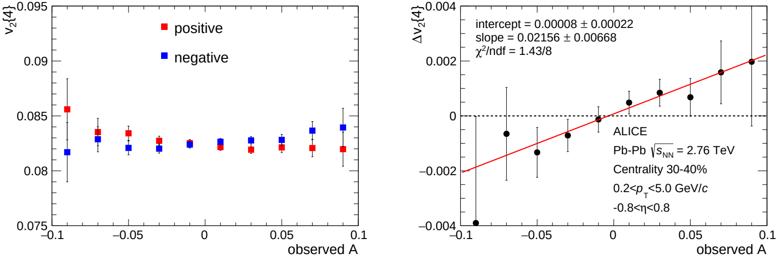
Estimating the slope parameter from the integral correlator

Support for ALICE, Phys. Rev. C 93 044903 (2016)



- Excellent agreement between inferred slopes and direct slopes
- This justifies both the method for inference of slope and the estimate of $\langle v_2\{2\}A\rangle$ as $\langle c_2\{2\}A\rangle/\sqrt{c_2\{2\}}$

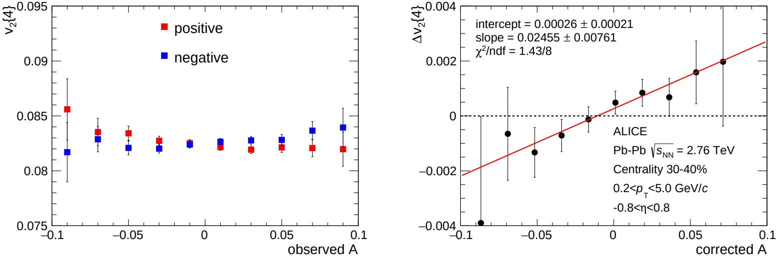
ALICE, Phys. Rev. C 93 044903 (2016)



- $v_2\{4\}$ is significantly lower than $v_2\{2\}$ due to removal of non-flow and different dependence on fluctuations
- But the slope obtained from Δv_2 is quite similar

Higher order cumulants—$v_2\{4\}$

ALICE, Phys. Rev. C 93 044903 (2016)



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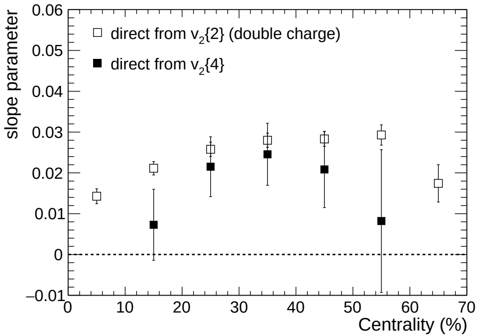
Higher order cumulants—$v_2\{4\}$

SALICE, Phys. Rev. C 93 044903 (2016)



- For mid central collisions there is excellent agreement between the slopes measured with $v_2\{2\}$ and $v_2\{4\}$
- This may go a long way towards separating trivial and non-trivial effects