Charge Asymmetry Measurements at ALICE

Jim Thomas

for the Alice Collaboration

EMMI / GSI and LBL

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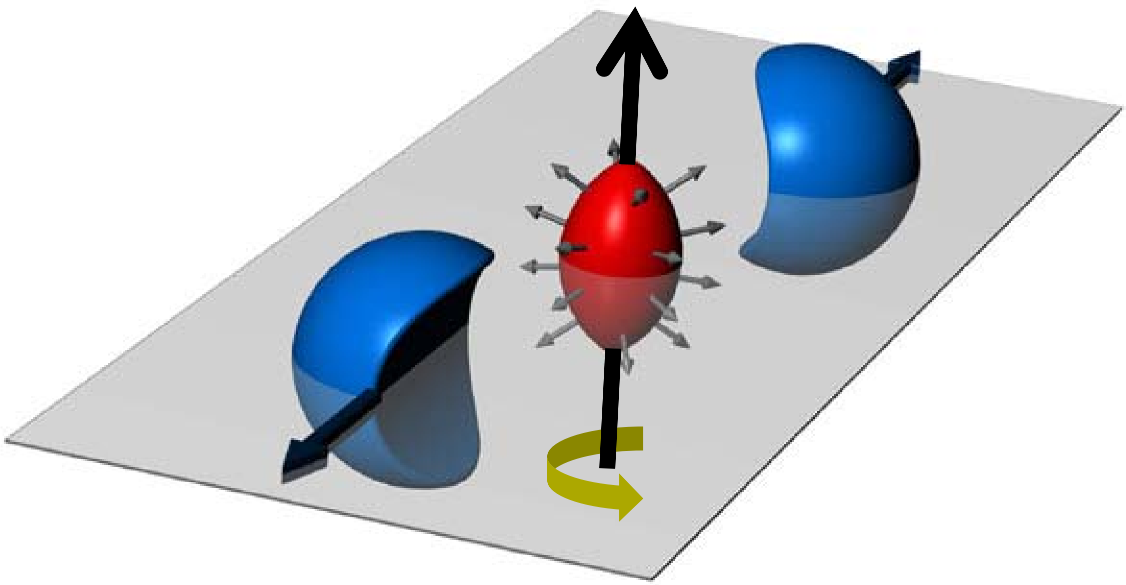
Motivation

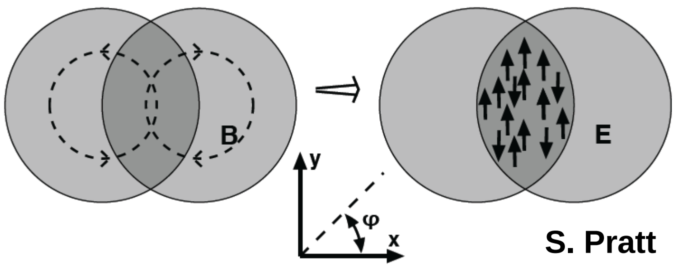
- Kharzeev et al. have suggested that chiral symmetry restoration and parity violation may be observable in HI collisions via charge sensitive cross-sections and particle emission
  - The Chiral Magnetic Effect (Nucl. Phys. A 803 (2008) 227)
  - The Chiral Magnetic Wave (arXiv:1103.1307)

- In this talk, we will explore the Chiral Magnetic Effect (CME)

Chirally restored quarks in large magnetic fields



Electromagnetic charges in motion create an E&M magnetic field (not a color magnetic field)

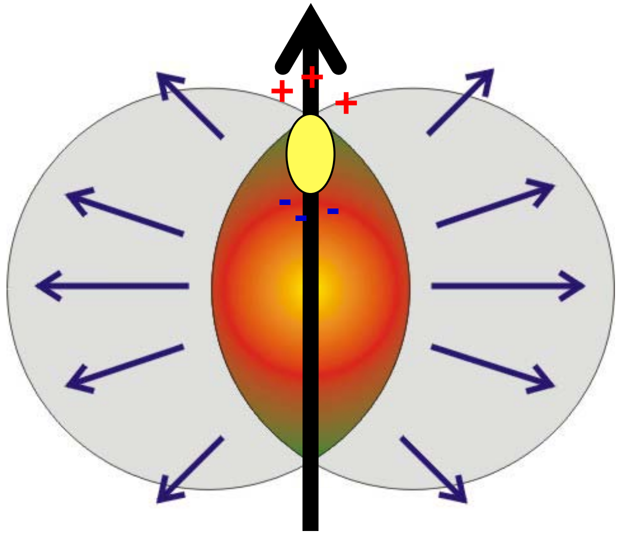


The magnetic fields can reach 10^{18} gauss. Stronger than on the surface of a neutron star.

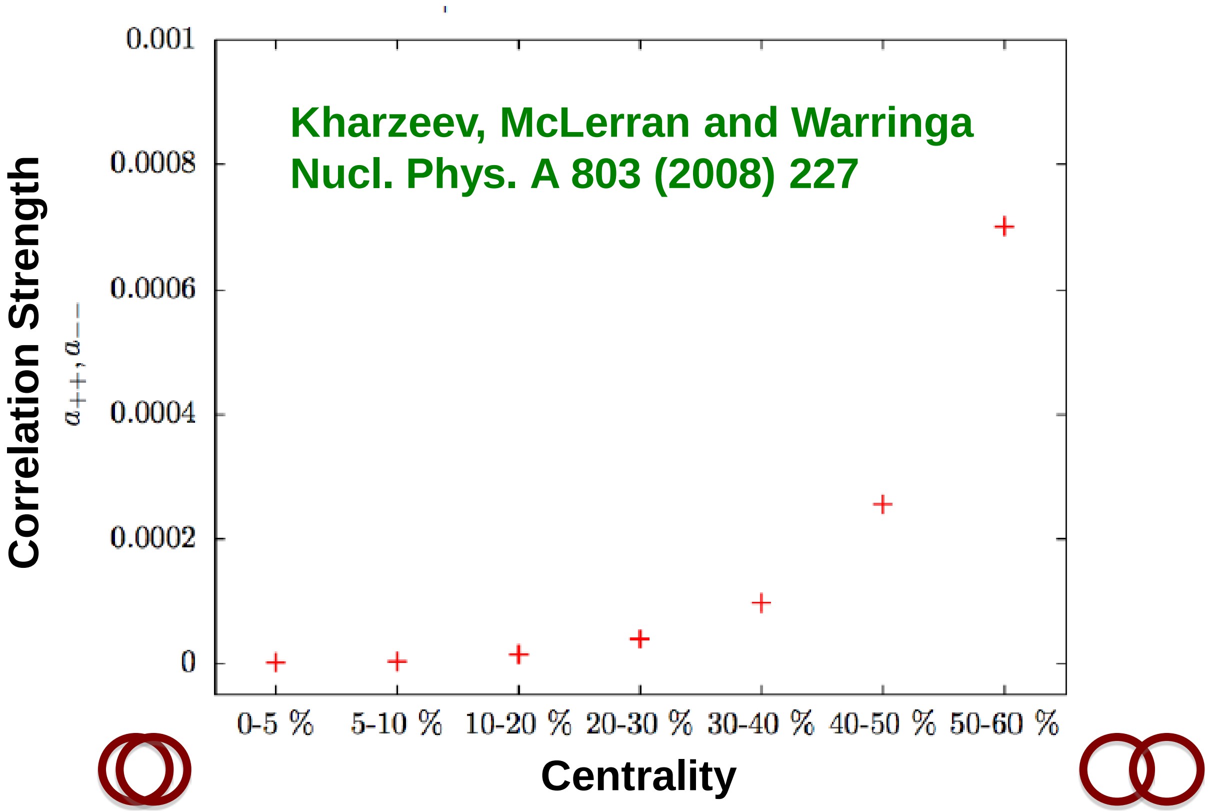
Quarks interact with the magnetic field via their spin

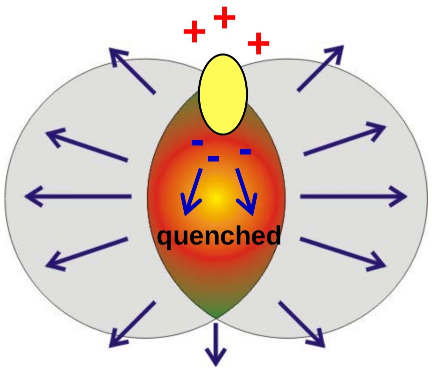
Charge separation wrt the reaction plane will be the result of the CME

The charge-flow asymmetry is too small to be seen in a single event but may be observable with <u>correlation techniques</u>



A Possible Result of the Chiral Magnetic Effect





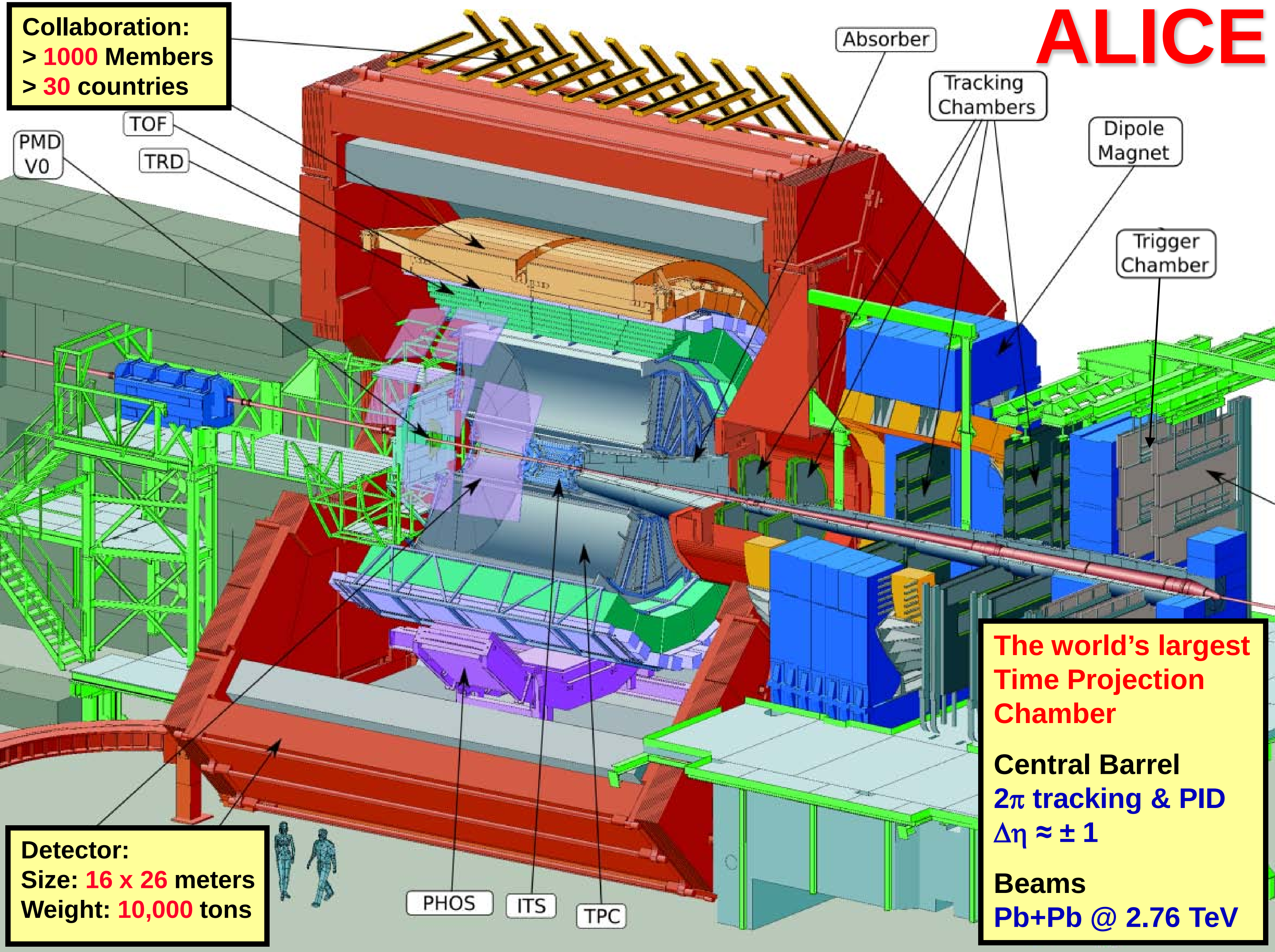
- Theory suggests ++ and -- correlations increase in peripheral collisions
- ++ to +- correlations may be altered due to de-correlation in the medium
  - Kharzeev suggests 'bubble' on edge of collision zone and one side absorbed

The Hypothesis

- **The hypothesis:**
  - **The Chiral Magnetic Effect will cause a separation of charge, above and below the reaction plane**

- **Lets look at ALICE … and then at the data**

ALICE



Collaboration:
> 1000 Members
> 30 countries

Detector:
Size: 16 x 26 meters
Weight: 10,000 tons

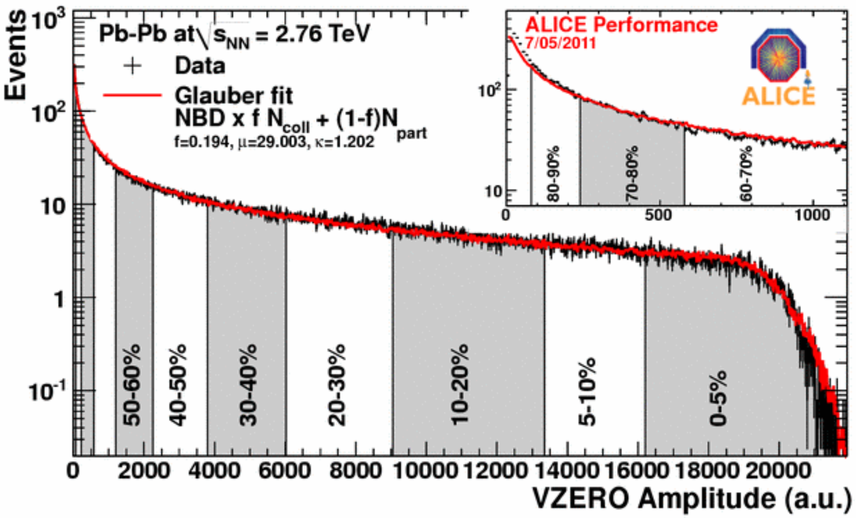
The world's largest Time Projection Chamber

Central Barrel
2π tracking & PID
$\Delta\eta \approx \pm 1$

Beams
Pb+Pb @ 2.76 TeV

Studies in ALICE: Analysis details

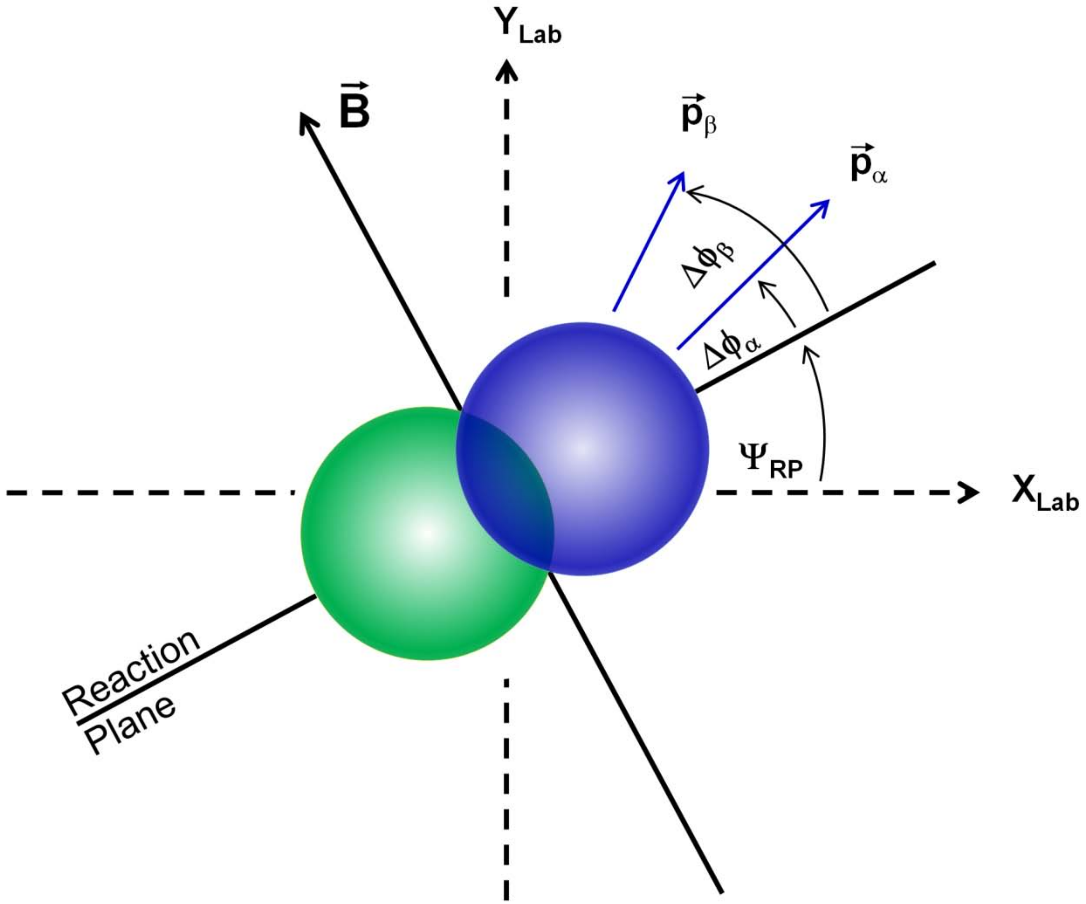
- **50 M Pb-Pb events recorded in Nov-Dec 2010 during the first LHC heavy-ion run**
  - **Event sample split in two sets having different magnetic field polarities (used for the systematic uncertainties)**
- **The trigger consists of the following criteria (at least two out of three):**
  - **two pixel chips hit in the outer layer of the SPD,**
  - **signal in VZERO-A detector,**
  - **signal in VZERO-C detector.**
- **Due to the small magnitude of the potential signal, we need to have the acceptance corrections under control:**
  - **The TPC tracks provide a uniform acceptance with minimal corrections**
- **The centrality was selected using the VZERO magnitude as the default estimator**
  - **Centrality bins: 0-5%, 5-10%, 10-20%, … , 70-80%**
  - **Different centrality estimators (TPC tracks, SPD clusters) investigates**
    - **Results used for the systematic uncertainty**



ALI-PERF-400

Analysis Uses Standard Flow Tools

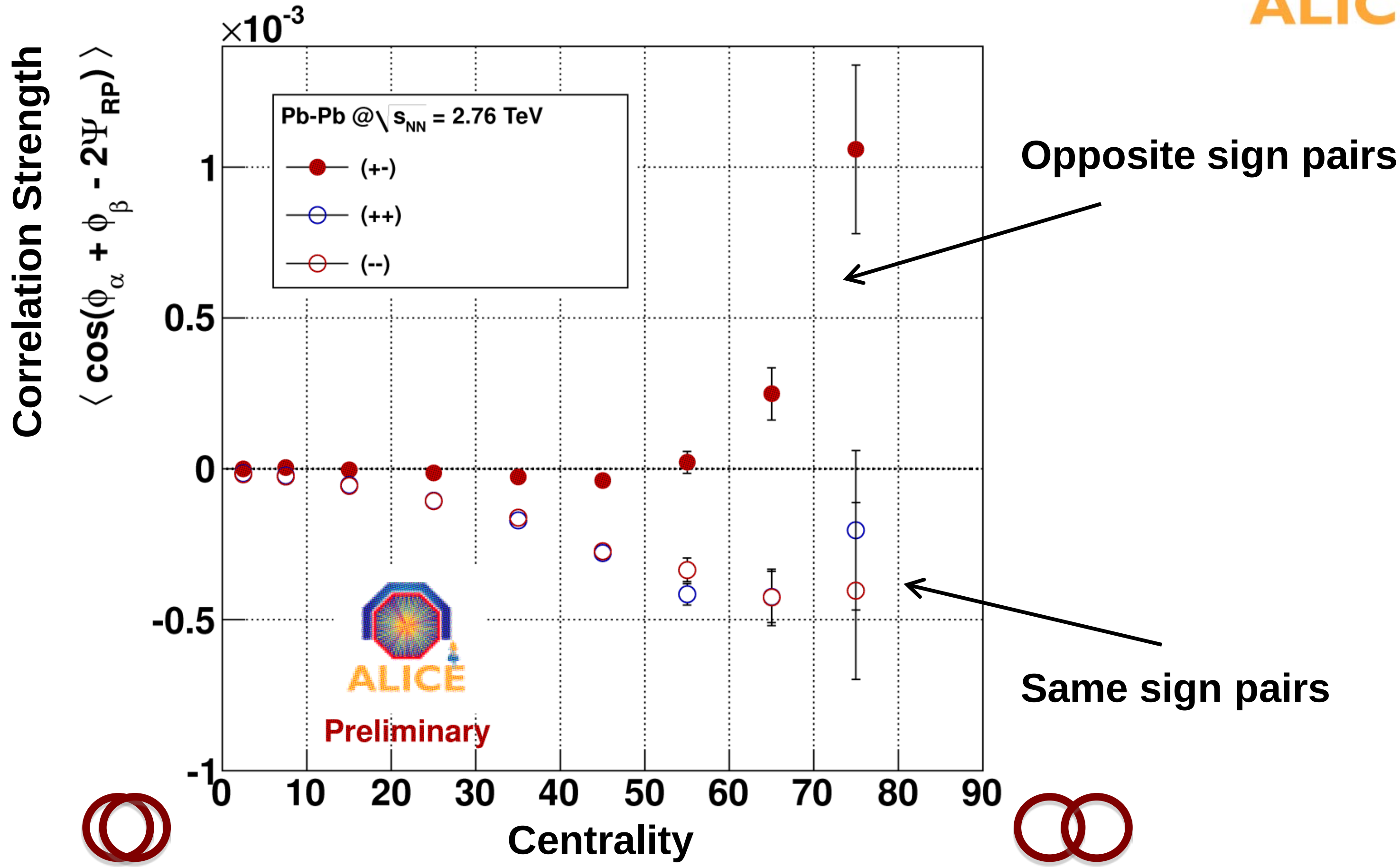
The line between the centers of the nuclei and the beam axis define the reaction plane – the B field axis is expected to be perpendicular to this plane



The observable is a triple correlation: $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$

- **or equivalently** $\left\langle \cos(\phi_i - \phi_k)\ \cos(\phi_j - \phi_k)\ -\ \sin(\phi_i - \phi_k)\ \sin(\phi_j - \phi_k) \right\rangle \ \Rightarrow\ (v_1^2 - a_1^2)\, v_2$
- **If $v_1 \Rightarrow 0$, then $(v_1^2 - a_1^2) * v_2 \ \Rightarrow\ -a_1^2 * v_2$** **Note clever cancellation of the background terms.**

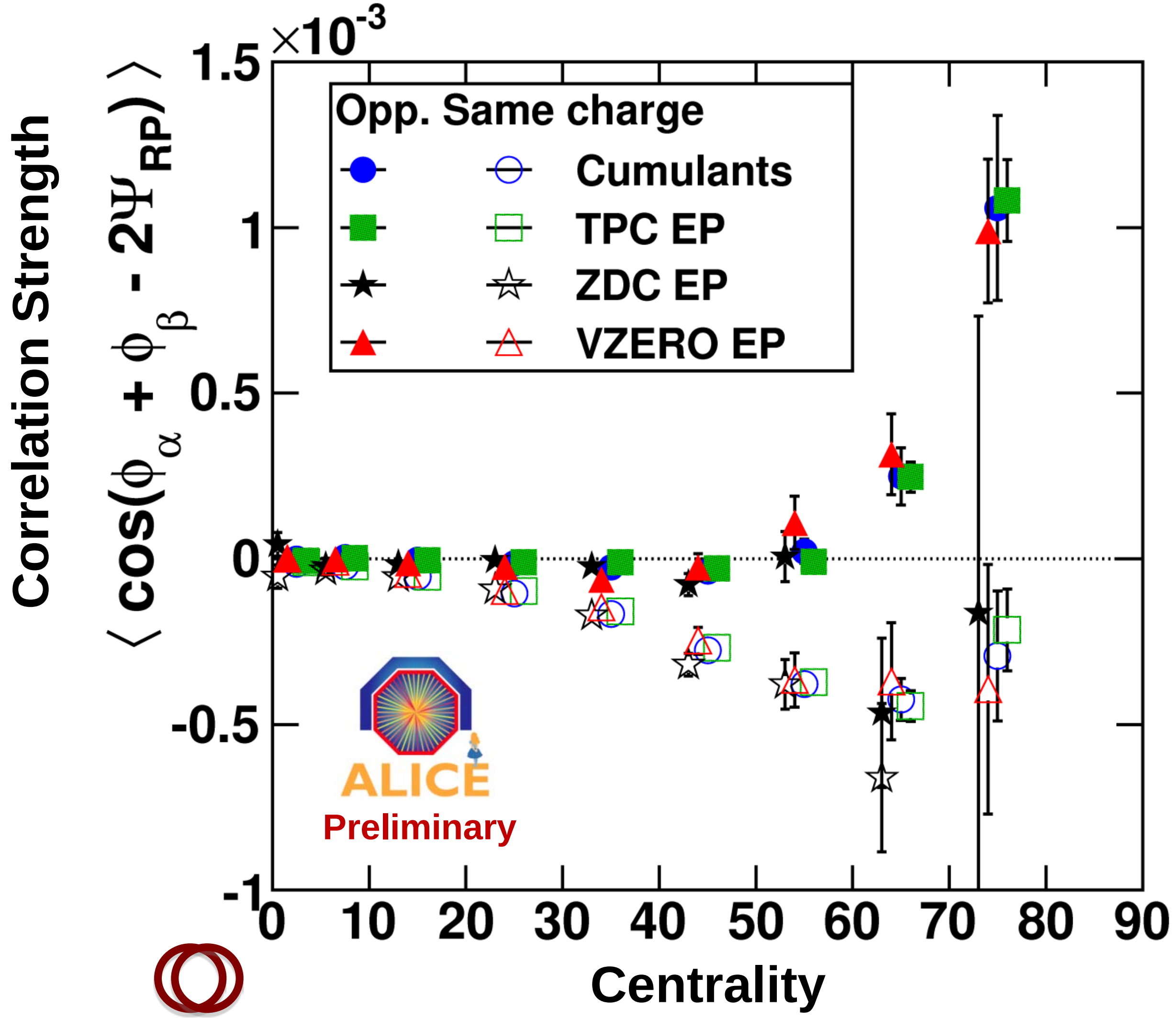
3p Results from ALICE



- Results for (++) and (--) consistent with each other
- The magnitude of the correlations between the same signed charged pairs is larger than the for the opposite charge pairs

Clear charge separation effect is seen at LHC energies

Systematic Effects: Different event plane methods

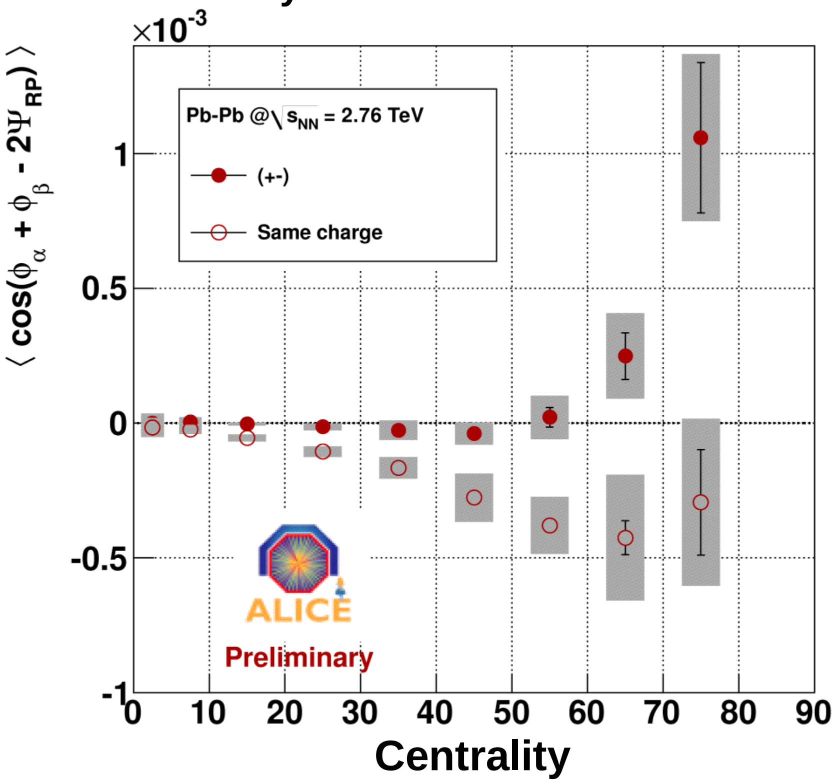


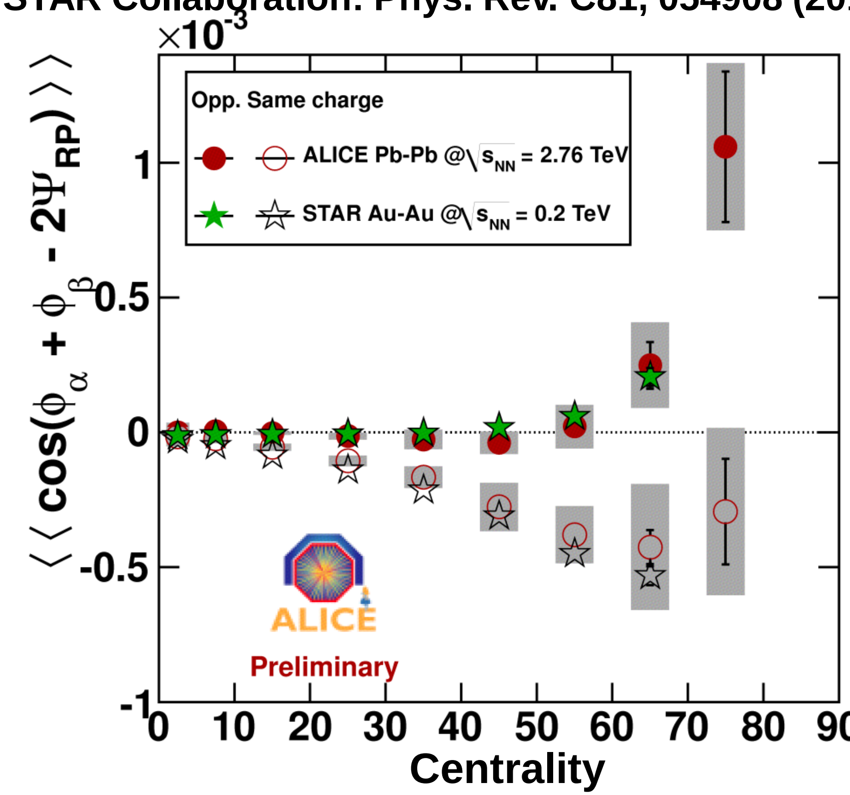
Good agreement between the four methods

Integrated 3-particle correlator: LHC .vs. RHIC

Stat. error: error bars
Syst. error: shaded area

STAR Collaboration: Phys. Rev. Lett. 81, 251601 (2009)
STAR Collaboration: Phys. Rev. C81, 054908 (2010)



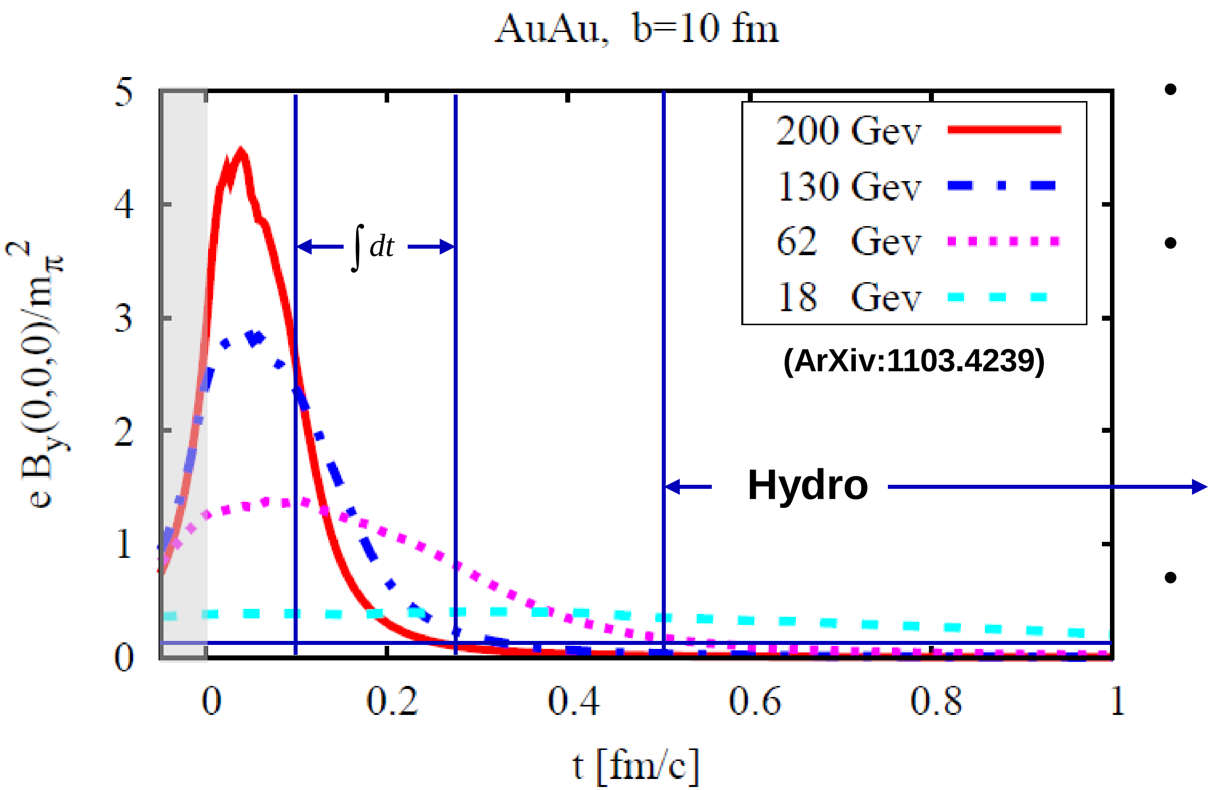


- **Most theories predict a smaller effect at LHC energies compare to RHIC**
  - **The energy scaling depends on the t_0 of the application of the magnetic field**
  - **But may also be constant vs $\sqrt{s}$ if $t_0 \approx 0$, or flux is pinned by the plasma**

LHC Results nearly identical to results at RHIC

Scaling from RHIC to the LHC

- **Presumably, the domain size for topological charge fluctuations grows at higher energies … but the effect of the spectator's magnetic field goes down more dramatically (this is not intuitively obvious)**



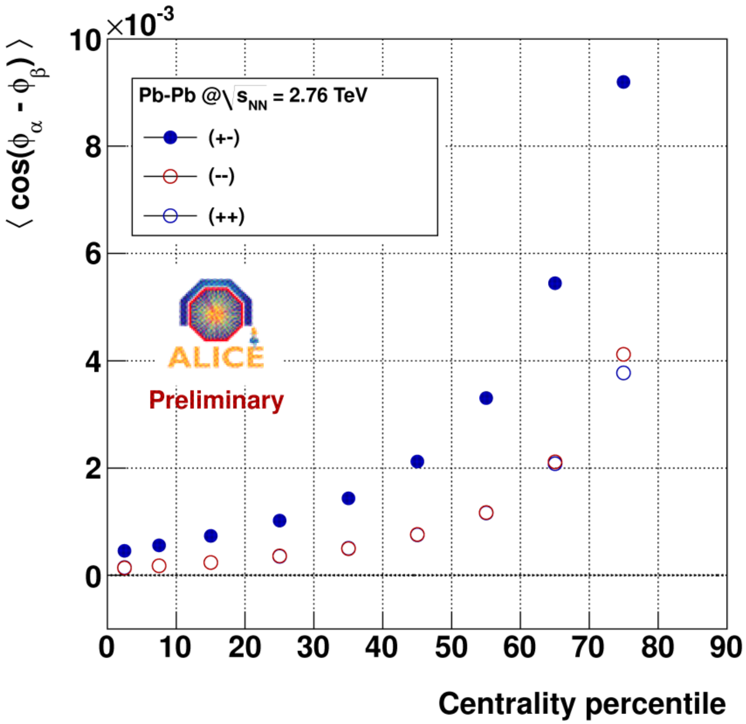
- **When $\tau > R / \sinh(Y_0)$**

$$eB_s \approx Z\alpha_{EM} \exp(-2Y_0)\frac{4b}{\tau^3}$$

- **Min τ: is when $c\tau$ is less than size of Lorentz contracted nucleus; or alternatively < 1/Qsat**
  - **Time scale for evolution of classical fields ~0.1 to 0.2 fm/c**
- **Min Field: B field > 0.2 m_π^2**
  - **Min field required for formation of landau levels with fermions**

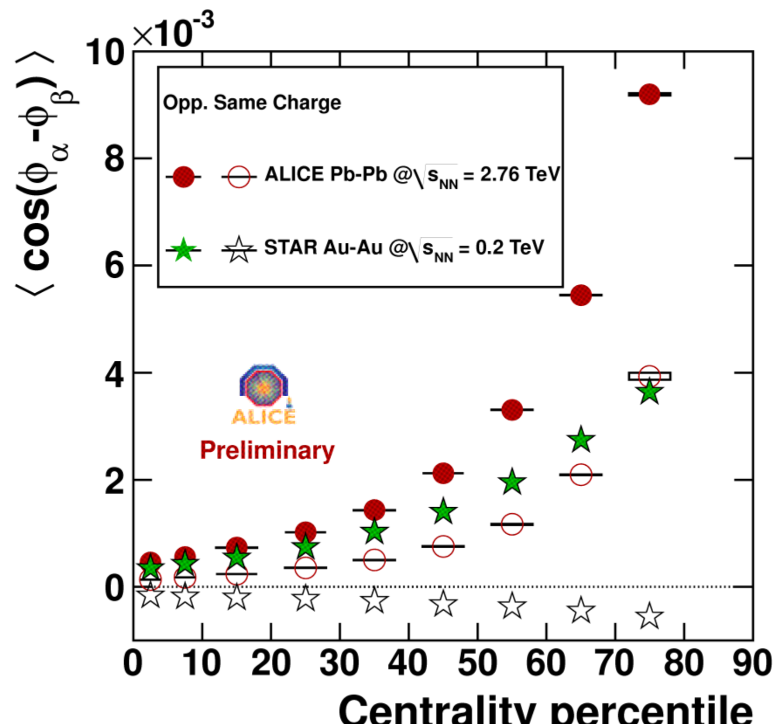
- **At 2.76 and 5.52 TeV, the beam rapidities are 7.98 and 8.68**
  - **Thus, the time integral over the region of interest diminishes the CME effect at higher energies … ~ 1/√s according to Voronyuk et al. (ArXiv:1103.4239)**

2–particle correlations: Centrality dependence



- Correlations between opposite charges are positive and large
- Correlations of same charged pairs are also positive and have a smaller magnitude
- Results between (++) and (--) are consistent

- Similarity to STAR: the magnitude of the opposite charged pairs is larger than the same charged ones.
- Difference with STAR:
  - Sign of the same charged correlations
  - Strength of the correlations



Comparison of 2 and 3 particle correlators

- **2p:** $$\left\langle \cos\left(\phi_\alpha - \phi_\beta\right)\right\rangle \approx \left\langle P \right\rangle + C_{in-plane} + C_{out-plane}$$

- **3p:** $$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle \approx -\left\langle P \right\rangle + C_{in-plane} - C_{out-plane}$$

- **STAR's 2p correlations have opposite sign for the (±) and (++,--) correlations**
  - **Combination of 2p and 3p results may suggest in-plane emission of particles**
  - **However, non-flow effects may invalidate this suggestion**

- **ALICE 2p data have the same sign for the (±) and (++,--) correlations and also a larger magnitude compared to STAR**
  - **Combination of 2p and 3p results may suggest out-of-plane emission of particles**
  - **However, non-flow effects may (and probably do) invalidate this suggestion**

2p results are extremely valuable but non-flow effects need to be understood before firm conclusions can be drawn from the combination of 2p and 3p results

Summary

- **Charge asymmetric emission of particles wrt the reaction plane has been seen in Pb+Pb collisions by using both a 2-particle and a 3-particle (P-even) correlator**
- **The results from the 2-particle correlator studies show that:**
  - **the sign of the correlation is the same for same-sign and opposite-sign pairs at the LHC and thus not in agreement with what was observed by STAR at $\sqrt{s_{NN}}$ = 0.2 TeV**
- **The results of the 3-particle correlator indicate that:**
  - **the centrality dependence of the signal illustrates a remarkable agreement in both the magnitude and sign with the results reported by STAR at $\sqrt{s_{NN}}$ = 0.2 TeV**
  - **the signal has a hadronic width of one unit in η**
  - **the signal increases with increasing pair p_T**
  - **doesn't have any obvious contribution from short range correlations (i.e. HBT)**
- **The combined results suggest that there is a change in the correlation pattern between LHC and RHIC energies (larger out-of-plane than in-plane correlations)**
- **Our results may be consistent with the systematic effects expected by the CME, however simple models predict a smaller 3p signal at LHC energies due to CME**

Theory is challenged by the latest findings, we are looking forward to the feedback from the community!

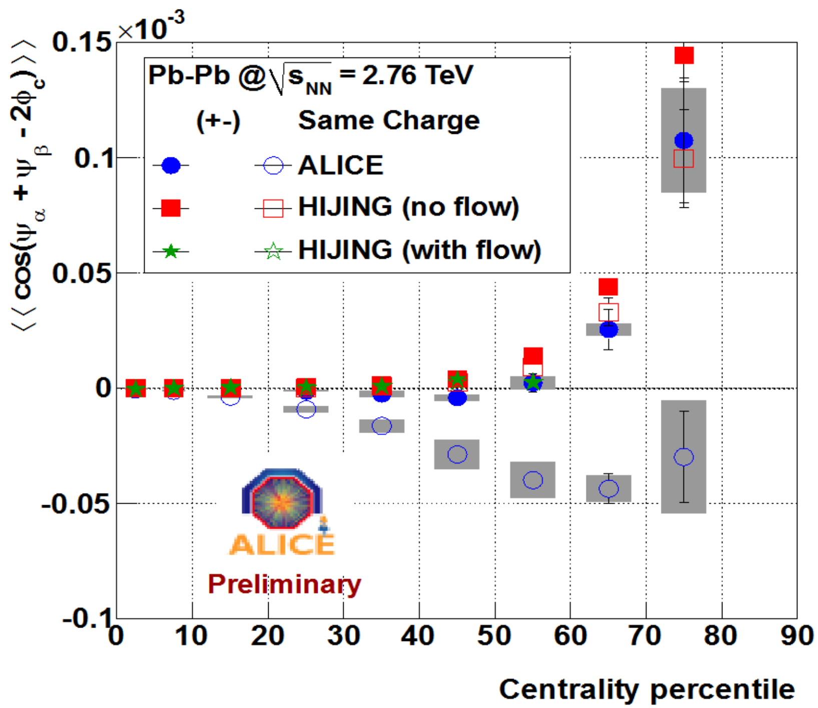
Backup Slides

Time Scale for processes relevant to CME

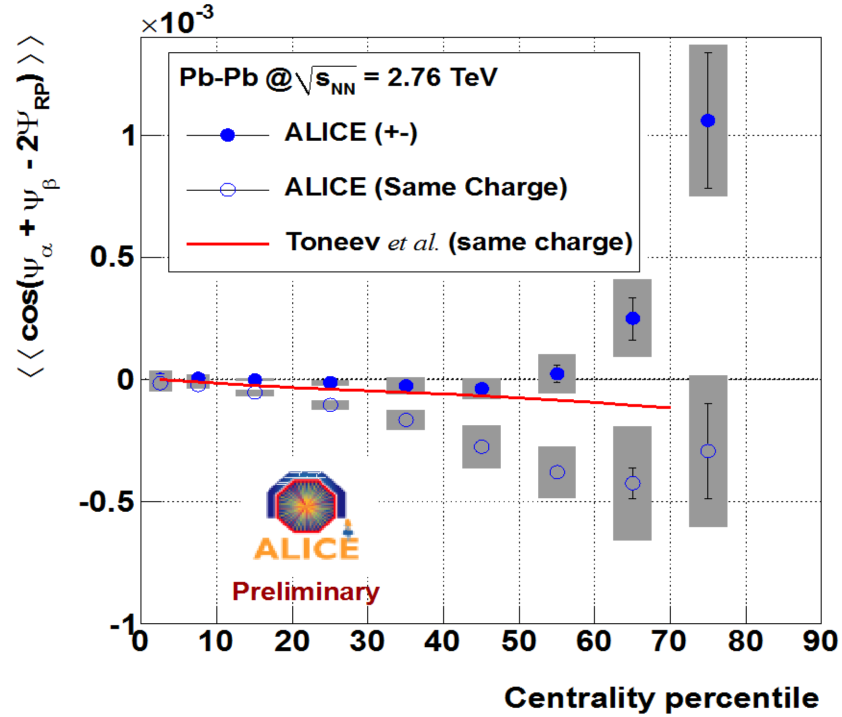
- Three things are required if the Chiral Magnetic Effect is to be seen
  - Chiral Symmetry restoration (≅ formation of a QGP)
  - Topological charge changing transitions
  - Large magnetic field
- There is a characteristic time scale for each of these processes.
  - Normally, we think in terms of the Hydro era ⇒ Freezeout, but the magnitude of the B field evolves more rapidly than that.
- Approximate time scale for mid-peripheral HI collisions:
  - 0.0 fm/c — B field is already large and growing
  - 0.1 — Passing of the two Lorentz contracted heavy ions; time scale for the evolution of classical fields
  - 0.2 — B field is rapidly falling and almost unimportant; non-equilibrium processes dominate
  - 0.3 — B field below threshold for fermion Landau levels on domain walls
  - 0.5 — Hydrodynamic era begins, equilibrium begins
  - 2 to 10 — Chiral symmetry restoration ends, QGP formation ends
  - 10 to 20 — Freezeout

Integrated 3-p correlator: Compared to models

S. A. Voloshin, Phys. Rev. C 70, 057901 (2004).



V.D. Toneev and V. Voronyuk, arXiv:1012.1508v1 [nucl-th]



- **HIJING points consistent with the (+-) data points**
  - **HIJING w & w/o flow consistent**
- **HIJING points scaled with the square of the multiplicity, consistent with the idea of having the correlations originating from emerging clusters (jets, resonances)**

- **Toneev et al. are the only published predictions for LHC energies (@4.5 TeV)**
- **According to the authors the magnitude should roughly scale with 1/√s**
  - **Applied in the figure to convert the prediction to √sNN = 2.76 TeV**

$$\langle\langle \cos(\psi_a + \psi_b - 2\phi_c) \rangle\rangle \equiv \langle\langle \cos(\psi_a + \psi_b - 2\Psi_{RP}) \rangle\rangle \cdot v_{2,c}$$

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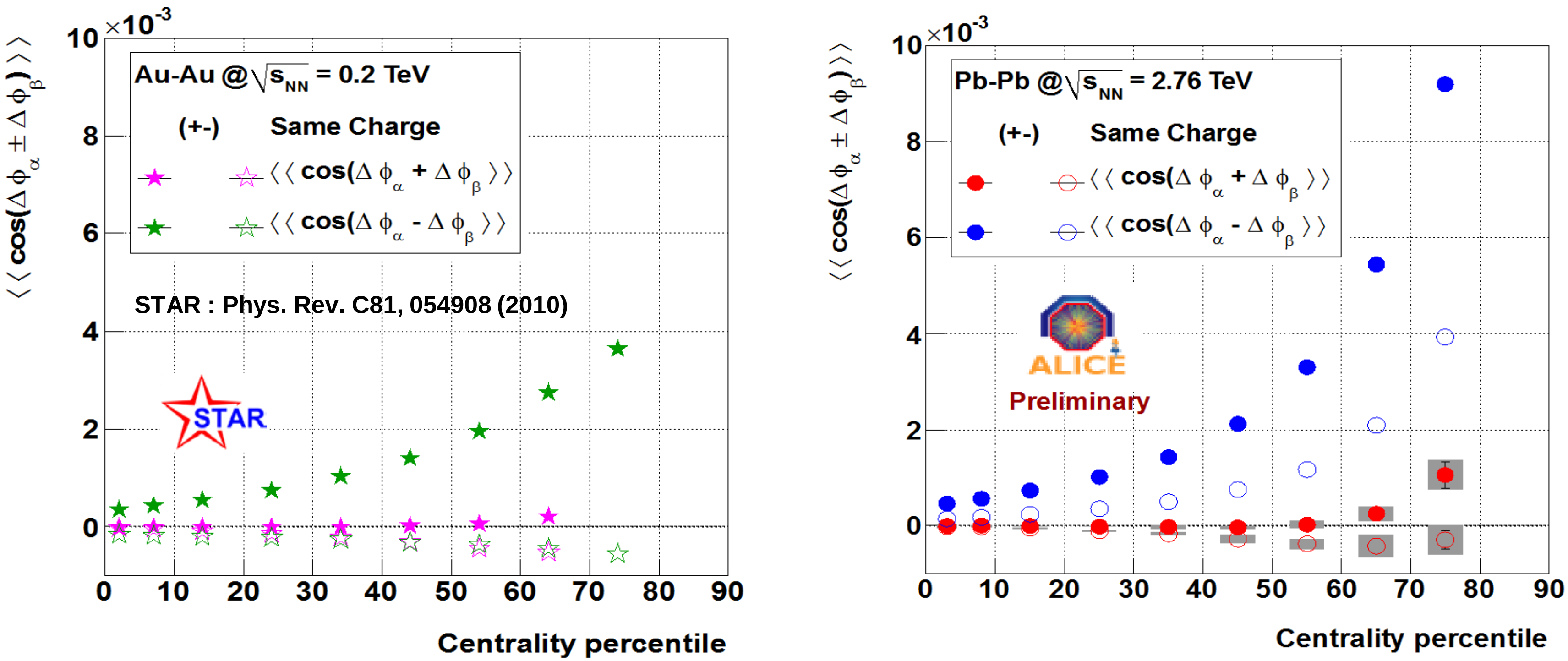
Comparison of 2 and 3 particle correlators

$$\langle\cos(\phi_\alpha - \phi_\beta)\rangle \approx \langle P\rangle + C_{in-plane} + C_{out-plane}$$

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \approx -\langle P\rangle + C_{in-plane} - C_{out-plane}$$



- STAR's 2-particle correlations for same charged pairs have the same magnitude as the points coming from the 3-particle correlation analysis.
  - Larger magnitude of the correlations in-plane than out-of-plane?
- ALICE data demonstrate a larger magnitude but also a change in sign
  - Larger magnitude of the correlations out-of-plane than in-plane?
  - Differences in the correlations vs reaction plane between energies?

Full Fourier Transform of the Invariant Yield

$$f(\phi) = \frac{b_0'}{2} + \sum_{n=1}^{\infty} \left(a_n' \sin(n\phi) + b_n' \cos(n\phi) \right)$$

where

$$a_n' = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \sin(n\phi) \, d\phi \quad \text{for} \quad n = 1, 2, \ldots$$

$$b_n' = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\phi) \cos(n\phi) \, d\phi \quad \text{for} \quad n = 0, 1, 2, \ldots$$

If we want to test if parity is conserved then we should keep the extra terms

$$E \frac{dN^3}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + \underline{2a_1 \sin(\Delta\phi)} + 2b_1 \cos(\Delta\phi) + \underline{2a_2 \sin(2\Delta\phi)} + 2b_2 \cos(2\Delta\phi) + \ldots \right)$$

where

$$a_n = \pi a_n' = \sum_i \sin(n(\phi_i - \Psi_R)) , \qquad b_n = \pi b_n' = \sum_i \cos(n(\phi_i - \Psi_R))$$

The standard HI flow analysis assumes a = 0 and assigns $b_n \equiv v_n$

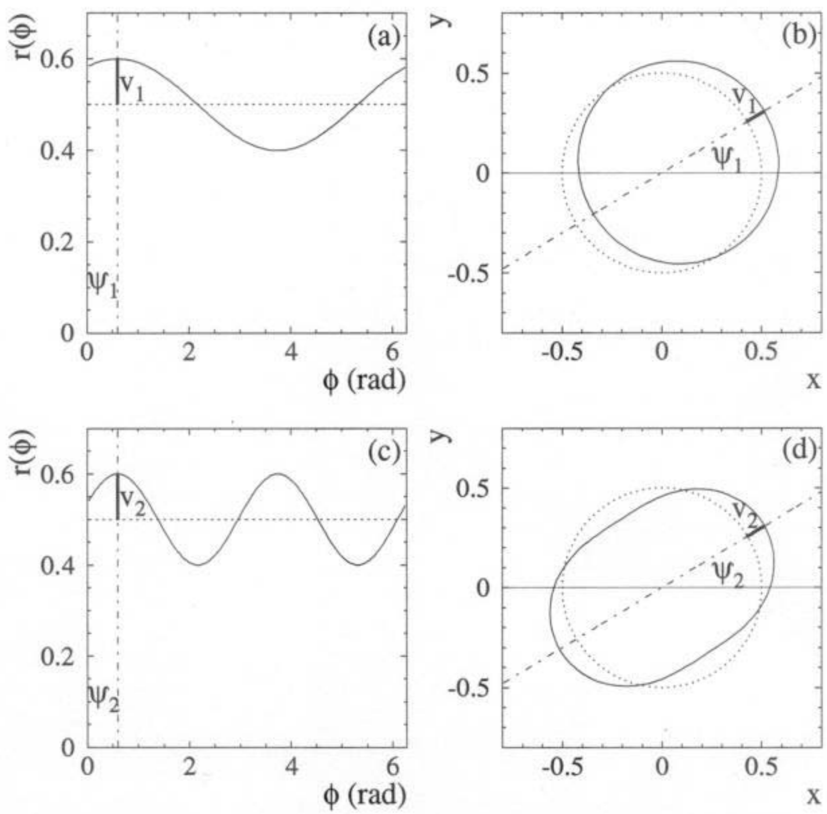
Interpreting Flow – order by order

n=1: Directed Flow has a period of 2π (only one maximum)

– v_1 measures whether the flow goes to the left or right – whether the momentum goes with or against a billiard ball like bounce. For collisions of identical nuclei, symmetry forces v_1 to be an odd function of η

n=2: Elliptic flow has a period of π (two maximums)

– v_2 represents the elliptical shape of the momentum distribution. It is an even function of η for identical nuclei



Perform a Fourier Transform to isolate the coefficients

If parity is conserved, sin() terms drop out

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2a_1\sin(\Delta\phi) + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + 2v_4\cos(4\Delta\phi) + \ldots\right)$$

isotropic | parity non-conserving | directed | elliptic | higher order terms

The Experimental Observable

- The coefficients for the Fourier expansion of the invariant yield are

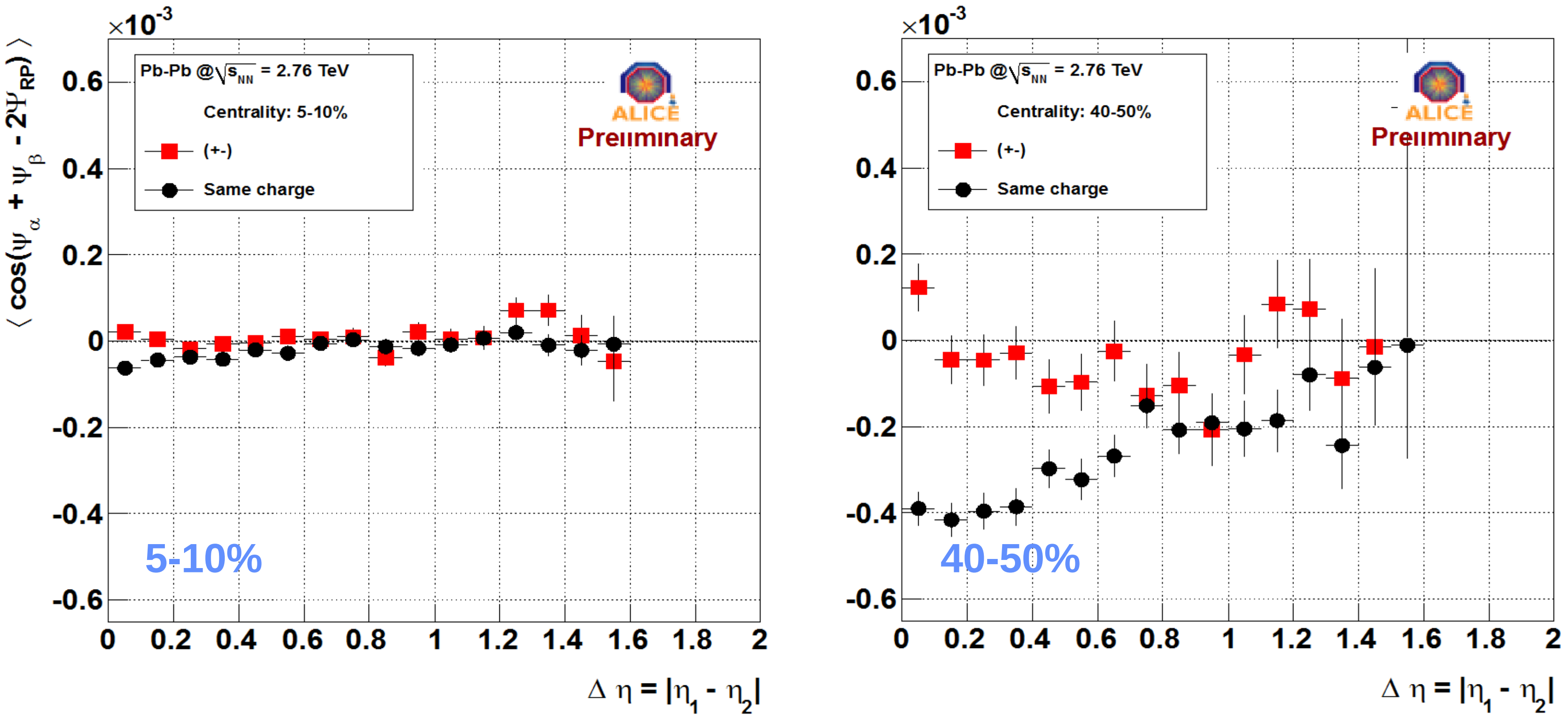
$$v_n \equiv \langle \cos(n(\phi - \Psi_R)) \rangle \quad \text{or} \quad v_n^2 = \langle \cos(n(\phi_i - \phi_j)) \rangle$$

  – where the average is taken over all particles in the event and ψ_R is the known reaction plane angle (e.g. from the ZDC if we are using TPC data)
  – The second method is a true two particle correlation (many details left out)

- Under certain assumptions v_1 is directed flow
  – Note that a 'normal' v_1 measurement for pions in a Pb-Pb reaction has an intrinsic symmetry that suggests weighting by sign(η)
  – Don't do this. We are looking for charge flow that goes up/down so choose to do the sum without sign(η) weighting and thus the 'normal' v_1 will cancel out. (See next bullet). This assumes symmetric η acceptance.

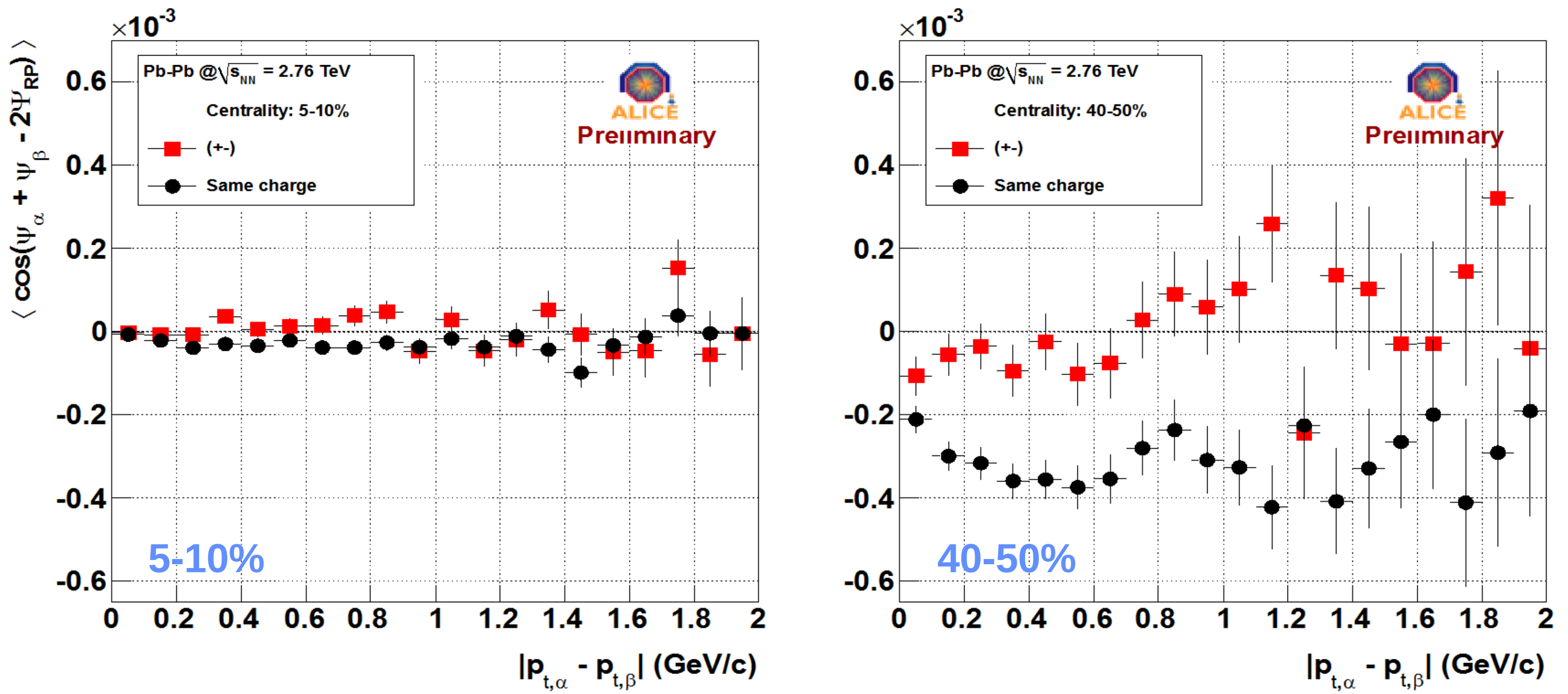
- A clever observable: $\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle$ … a triple correlation
  – Mixed Harmonics: $\langle \cos(\phi_i - \phi_k)\cos(\phi_j - \phi_k) - \sin(\phi_i - \phi_k)\sin(\phi_j - \phi_k) \rangle = (v_1^2 - a_1^2)\, v_2$
  – Measure $(v_1^2 - a_1^2) * v_2$ because v_2 is large and it amplifies the parity non-conserving signal, a_1, while preserving reasonable statistical errors.
  – The signal is parity odd, but the observable $(v_1^2 - a_1^2) * v_2$ is even. Best way to measure charge sensitive flow because $v_1 \Rightarrow 0$ and $(v_1^2 - a_1^2) * v_2 \Rightarrow -a_1^2 * v_2$

3-particle correlators: Differential analysis in Δη



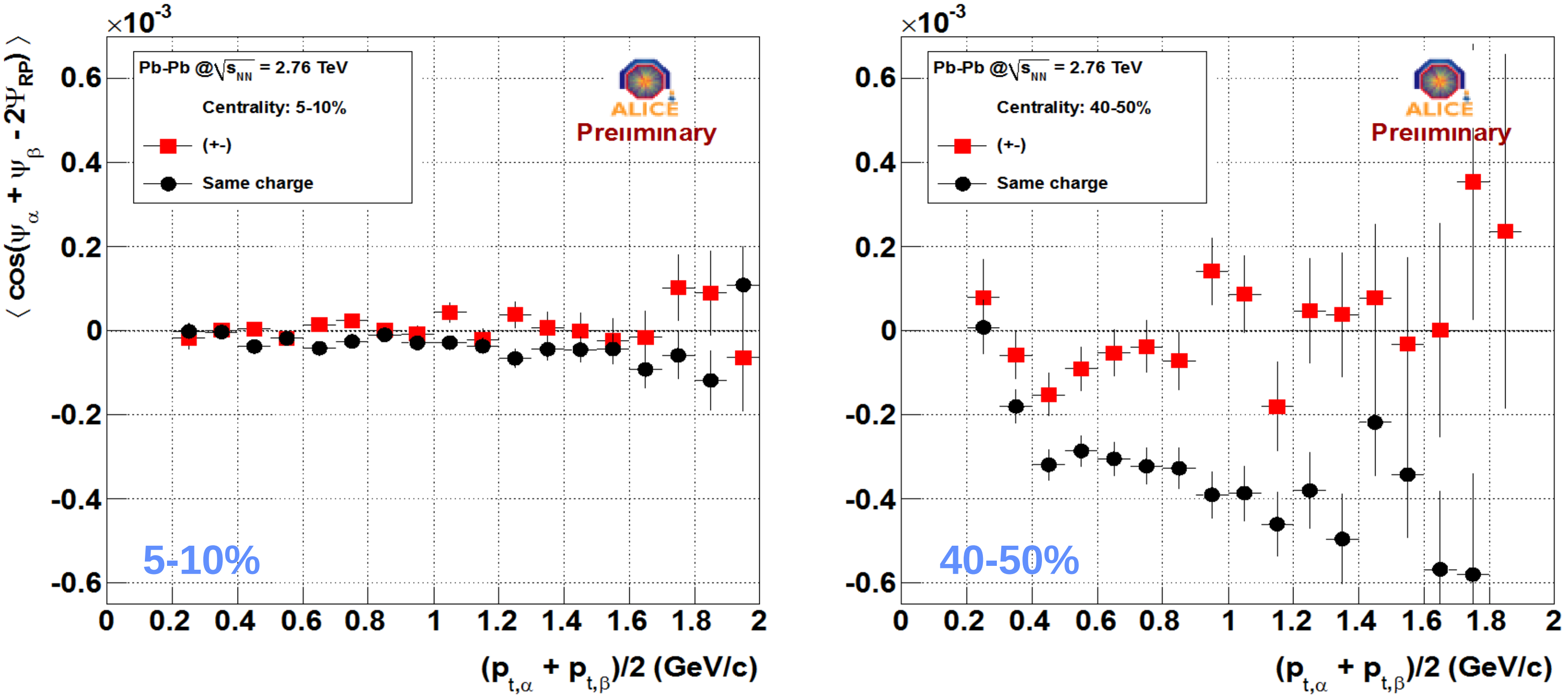
- Correlations between opposite charges are smaller than the ones with same charges
- Charge separation starting to develop when moving away from the most central bins
- Correlation width ~ $\Delta\eta = |\eta_\alpha - \eta_\beta| \sim 1$

3 particle correlators: Differential analysis in Δp_T



- Correlations not localized in small values of Δp_T
  - Correlation from short range correlations of same/opposite charges limited?

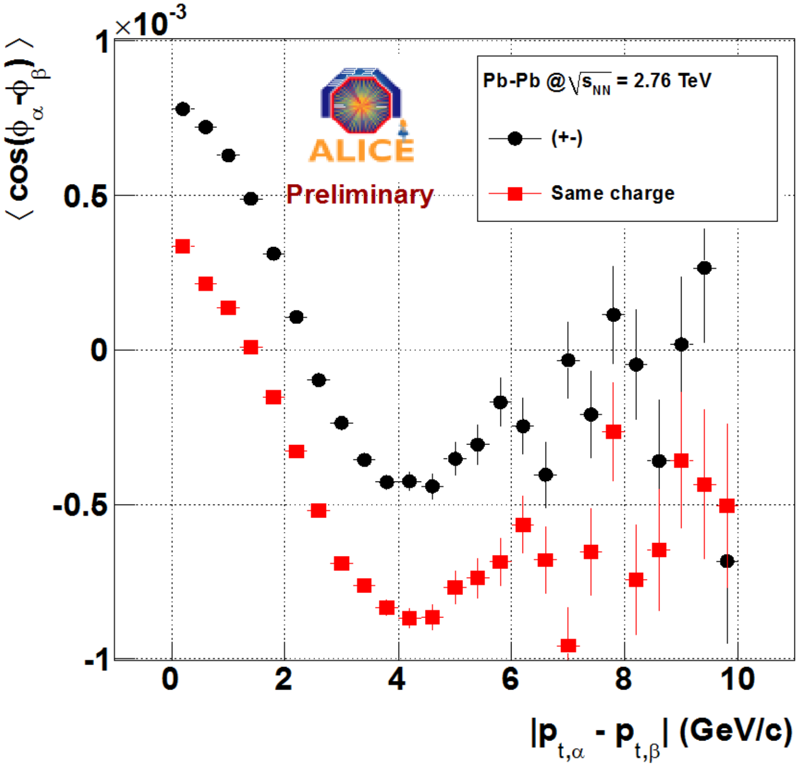
3 particle correlators: Differential analysis in Σp_T



- **Correlations of same charges have larger signal with increasing transverse momentum of the pair contrary to the expectation from theory (i.e. signal localized at the low p_T region**

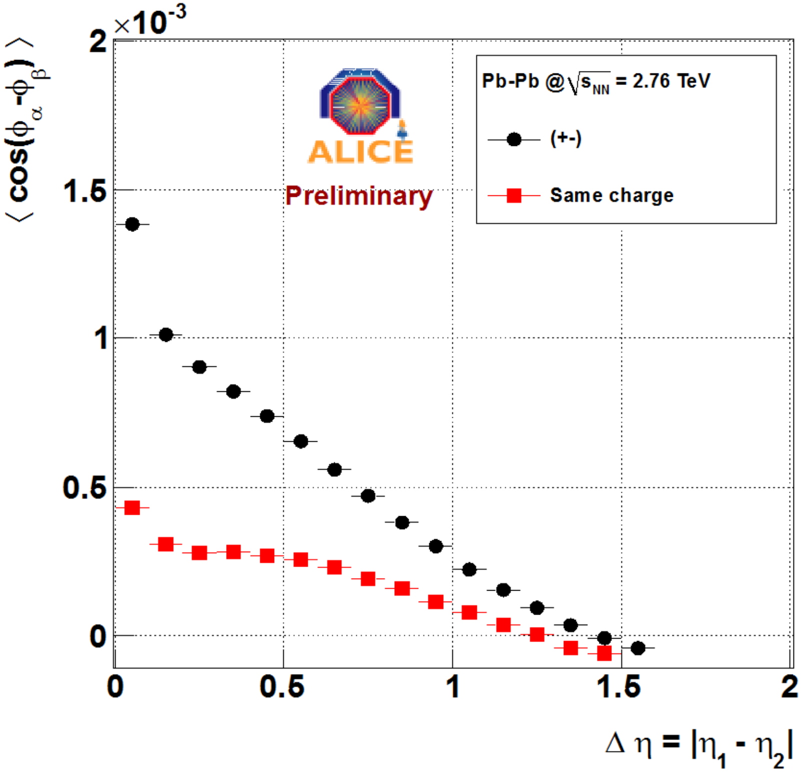
D. Kharzeev *et al.*, Nucl. Phys. A803, 227 (2008)

2–particle correlations: Differential analysis



- Correlations have the same behavior regardless of the charge combination.
- Change of sign @ ~2 GeV/c
- Change of physics @ ~5 GeV/c in Δp_T

- Correlations localized in η
- Different charge combinations have the same correlations in sign but not in magnitude.



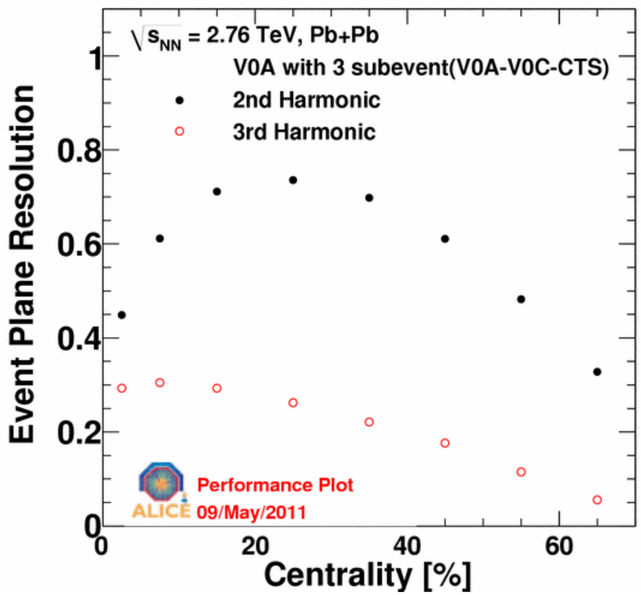
Different methods: event plane estimation

$$Q_{n,y} = \sum_i w_i \cdot \sin(n\phi_i)$$

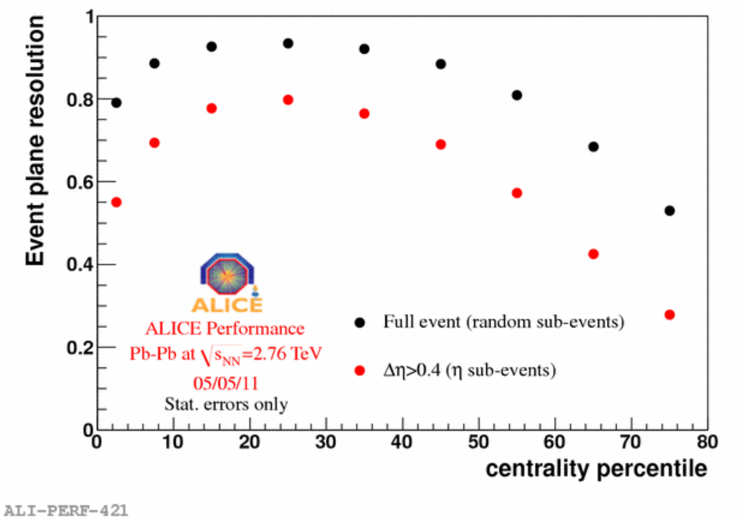
$$Q_{n,x} = \sum_i w_i \cdot \cos(n\phi_i)$$

$$\Psi_n = a\tan 2\left(\frac{Q_{n,y}}{Q_{n,x}}\right)/n$$

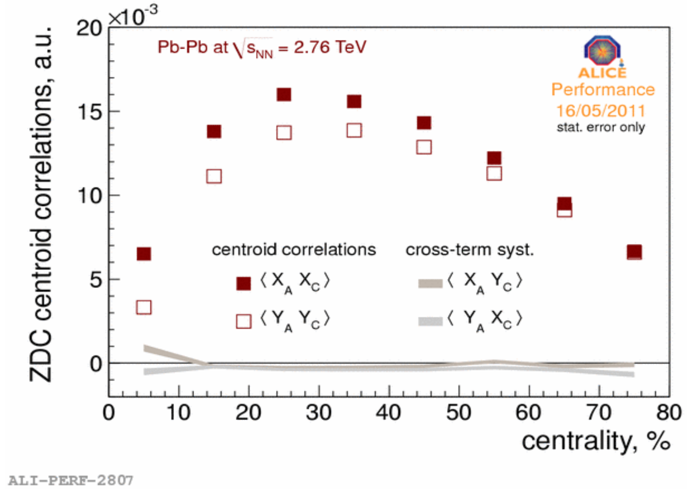
VZERO



TPC



ZDC

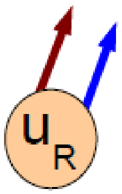


Quarks interact with the B field via their spin

- **Assume: chiral symmetry is restored in a QGP**
- **Assume: quark masses drop to ~0 after chiral symmetry restoration**

In chiral limit:

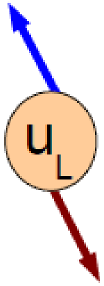
Particles/Antiparticles
with right-handed helicity



have spin and momentum parallel

In chiral limit:

Particles/Antiparticles
with left-handed helicity



have spin and momentum anti-parallel

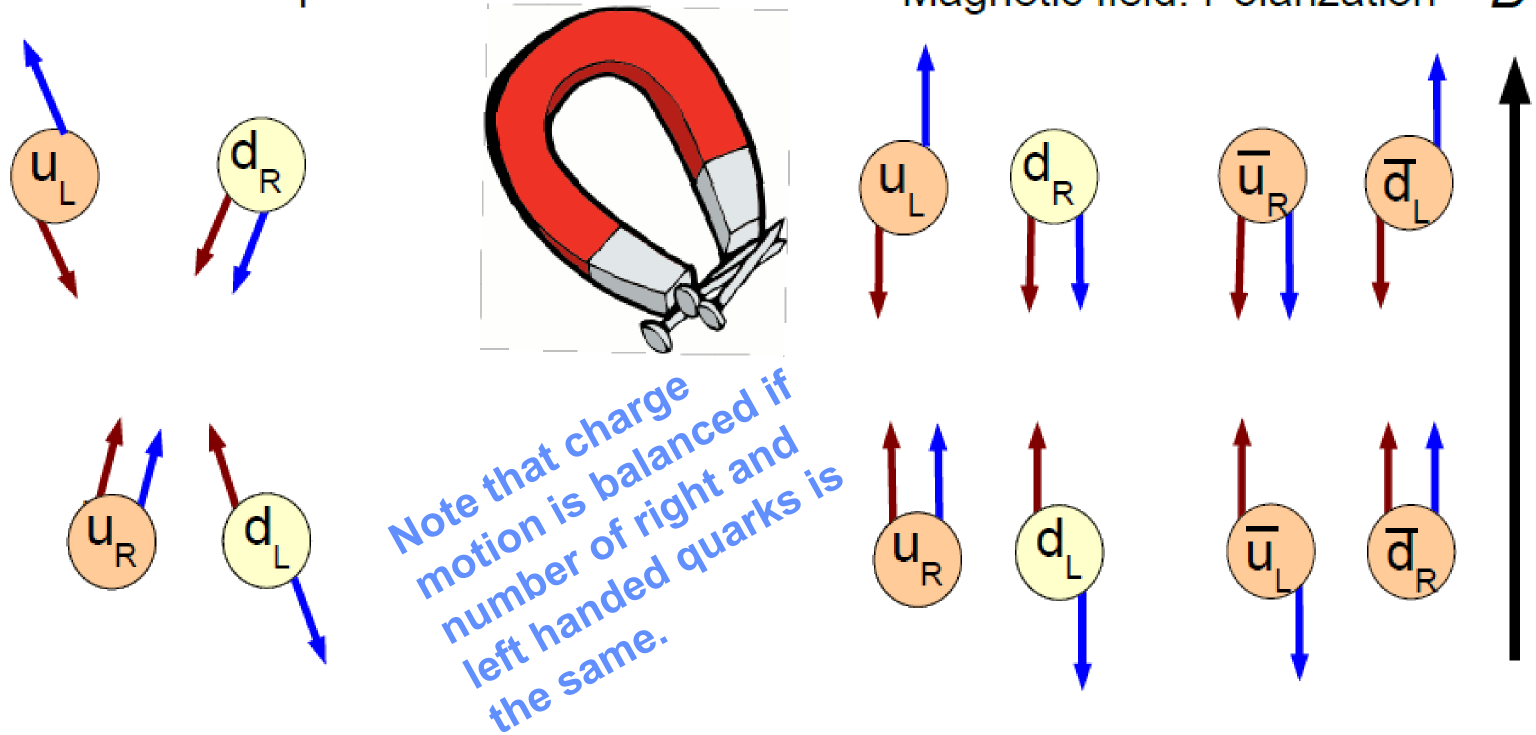
- **Chirality and helicity are the same for massless particles … so in the limit of zero mass, it is easy to define chirality (not so easy for non-zero mass).**

How does the B field affect the Quarks?

A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization

Magnetic field: Polarization B



The momenta of the quarks align along the magnetic field

A quark with right-handed helicity will have momentum opposite to a left-handed one

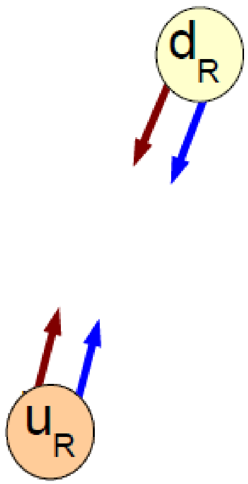
In this way the magnetic field can distinguish between right and left

H. Warringa

How does the Magnetic field affect Chirality?

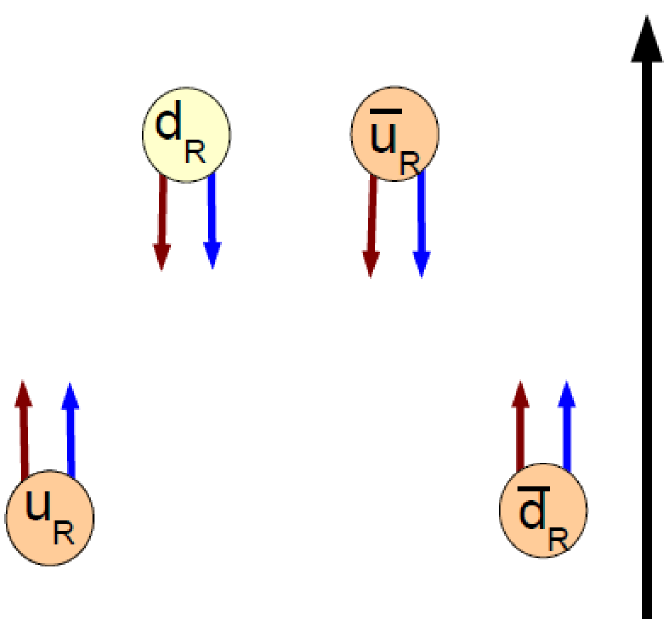
A magnetic field will align the spins, depending on their electric charge

No Magnetic Field: No polarization



Topological Charge fluctuations can create an excess of right, or left handed quarks. Note that right handed quarks move symmetrically up or down based on charge.

Magnetic field: Polarization



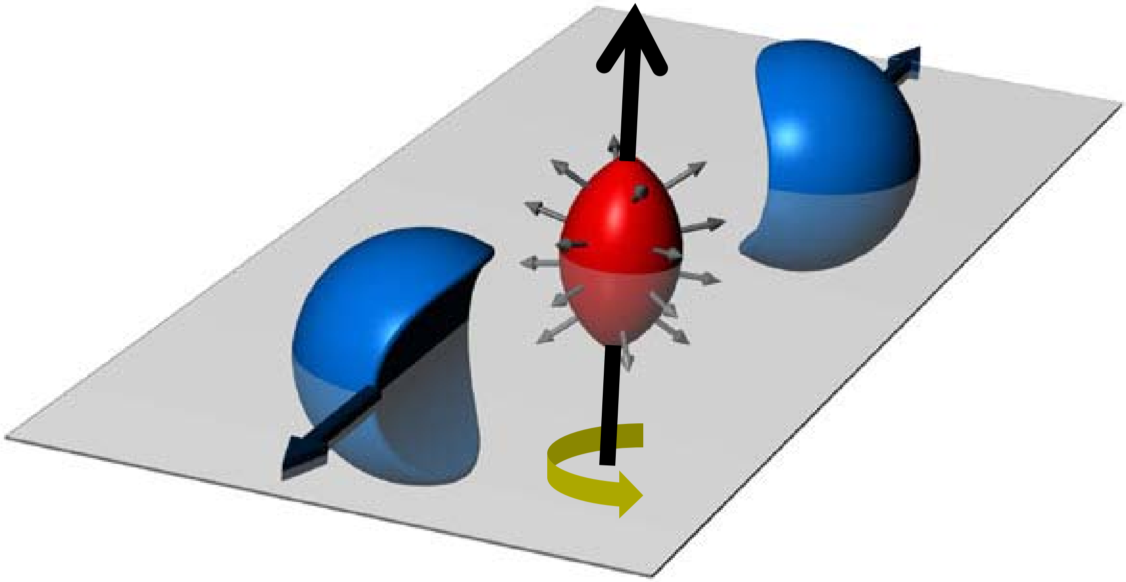
Positively charged particles move parallel the magnetic field

Negatively charged particles move to antiparallel to magnetic field

<u>An electromagnetic current is created along the magnetic field</u>

H. Warringa

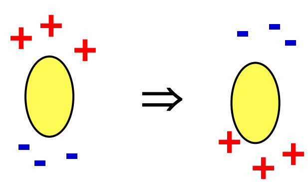
Separation of Charge wrt the reaction plane



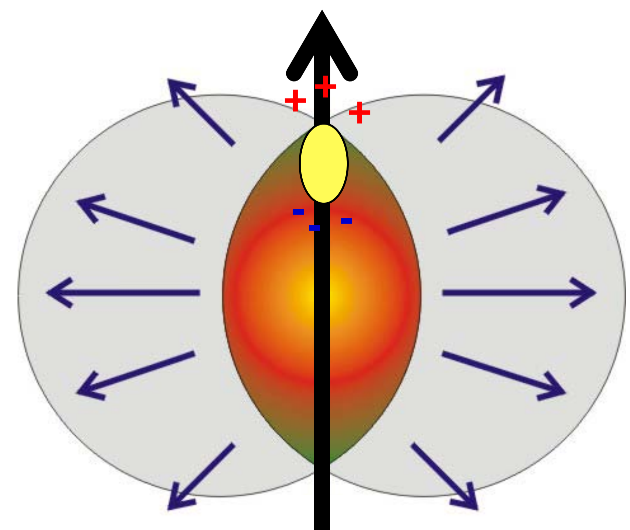
If a chirally restored bubble is created in a heavy ion collision, the positively charged quarks will go up … then hadronize … and yield an excess of positive pions above the plane

Unfortunately, it could be just the opposite in the next event depending on the topological charge in the bubble

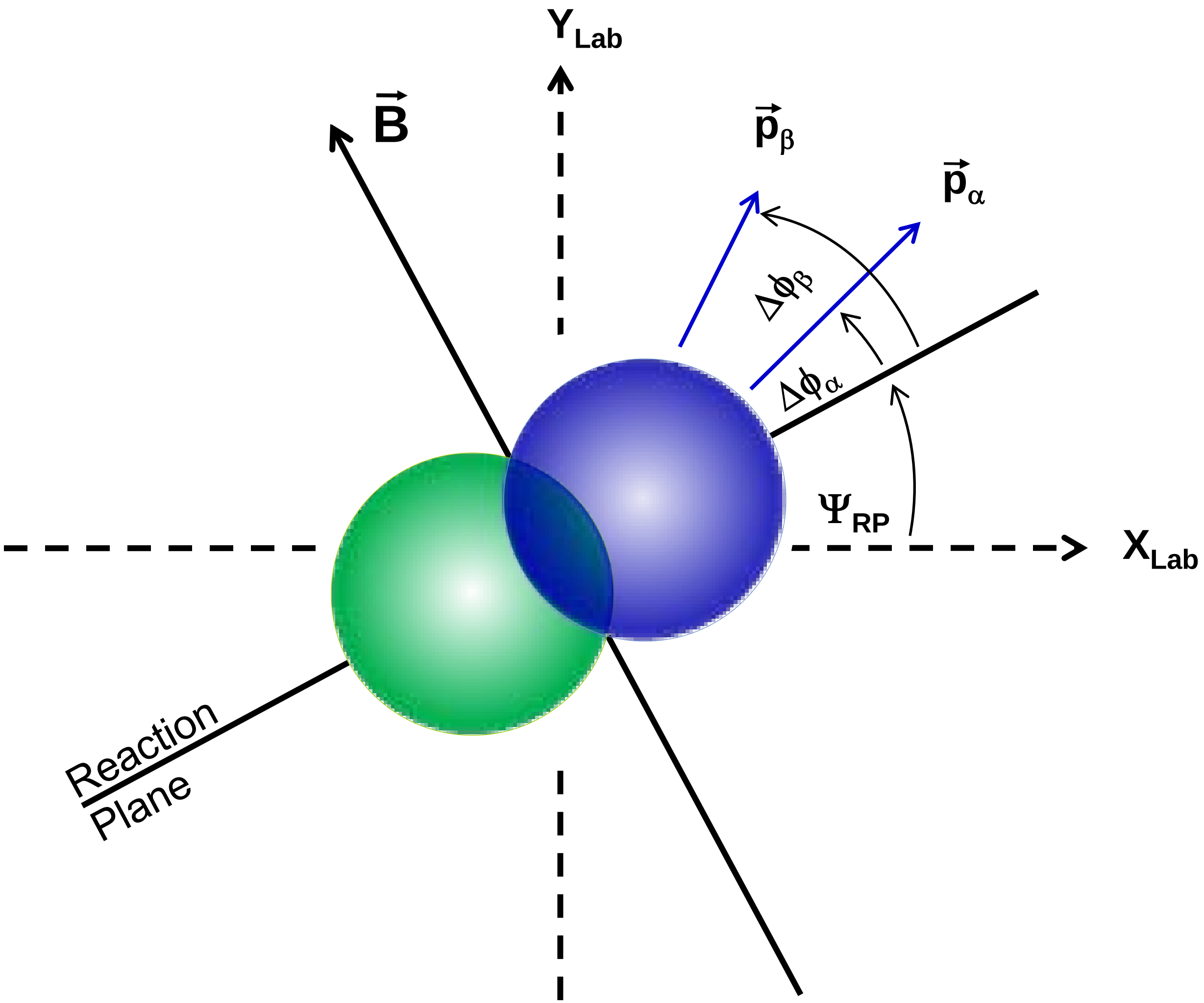
- The signal is manifestly parity odd
  $x \Rightarrow -x$, $p \Rightarrow -p$
  but the observable will be even



- The charge-flow asymmetry is too small to be seen in a single event but may be observable with <u>correlation techniques</u>

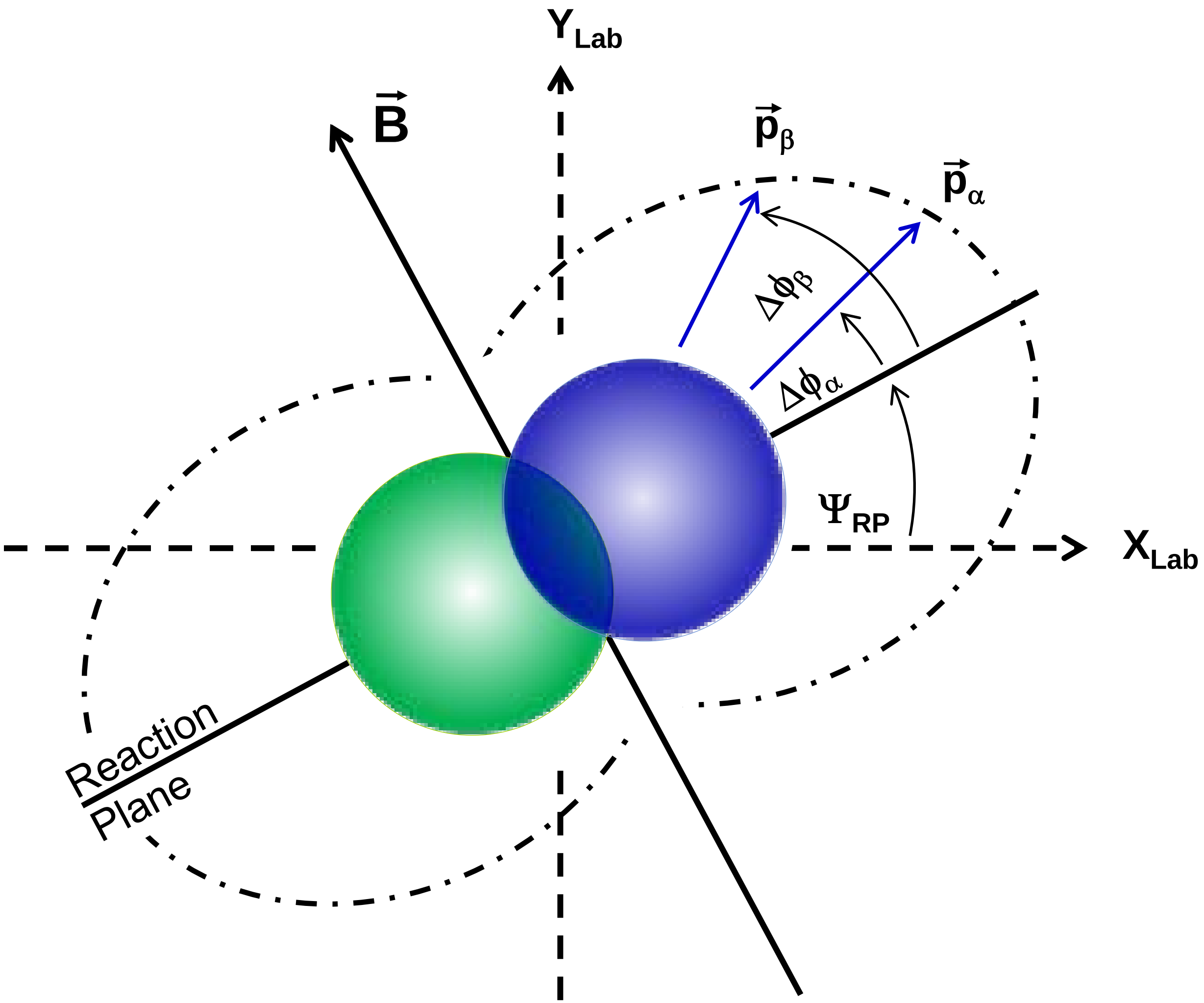


Analysis Uses Standard Flow Tools



- **The line between the centers of the nuclei and the beam axis define the reaction plane – perpendicular to angular momentum vector and B field**

Analysis Uses Standard Flow Tools



- The line between the centers of the nuclei and the beam axis define the reaction plane – perpendicular to angular momentum vector and B field

Looking for new physics – Strong Parity Violation

- **The conventional point of view**
  - "Parity is conserved in the strong and electromagnetic interactions"
    - See, for example, Perkins "Introduction to High Energy Physics"

- **The less-conventional point of view**
  - In the vicinity of a deconfining phase transition, the QCD vacuum can possess meta-stable domains leading to P and CP violation.
    - See, for example, Kharzeev, Pisarski, and Tytgat PRL 81, 512 (1998).

Thanks to wonderful talks given by Harmen Warringa at BNL, Sergei Voloshin QM and Evan Finch CPOD

Explicit P and CP violation is allowed in QCD

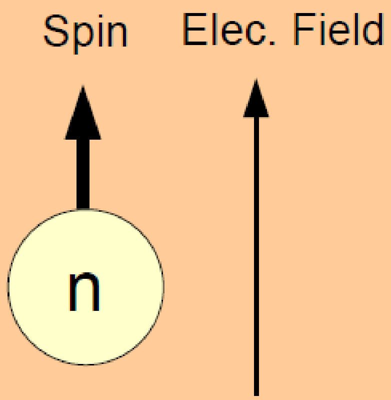
- **A very simple addition to the bare QCD Lagrangian is interesting**
  - $L_{QCD} \rightarrow L_{QCD} + \delta L$

Adding the theta term breaks P- and CP- explicitly

$$L_{QCD} \rightarrow L_{QCD} + \theta \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

This term gives rise to a neutron EDM

Experiment: $|\theta| \leq 10^{-10}$



- **Why is θ so small?**
  - **Perhaps due to Peccei-Quinn symmetry … which would imply the existence of axions.**

An old but still interesting problem …

Implicit P and CP violation is (also) allowed in QCD

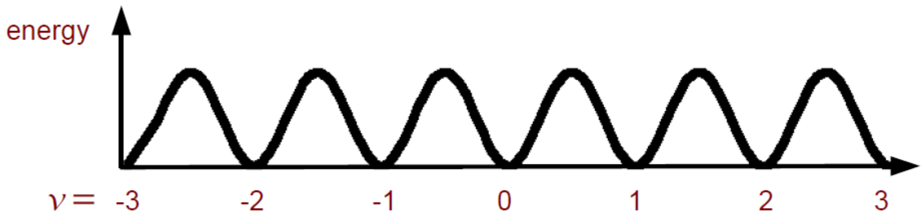
- **Vafa and Witten ('84) showed that if $\theta = 0$ then P and CP violation are not possible**
  - **Theorem valid for ground state QCD at zero temperature and zero density**

- **Heavy Ion Collisions aren't representative of ground state QCD**

- **Possibilities for implicit P and CP violation in QCD**
  - **Finite temperature**
  - **Finite density**
  - **Metastable vacua**
  - **Out of equilibrium**
  - **All of these are possible in a heavy ion collisions where, by hypothesis, Axial symmetry and Chiral symmetry are in transition.**

Summary: Hot QCD allows for Parity Violation

QCD has an infinite number of vacua which can distinguished by a winding number $\nu = 0, \pm 1, \pm 2, \ldots$



$$Q_w = \frac{g^2}{8\pi^2} \int d^4x\, \vec{E}_a \cdot \vec{B}_a = 0, \pm 1, \pm 2, \ldots$$

In chiral limit (m=0): $[N_L - N_R]_{t=\infty} - [N_L - N_R]_{t=-\infty} = 2 N_f Q_w$

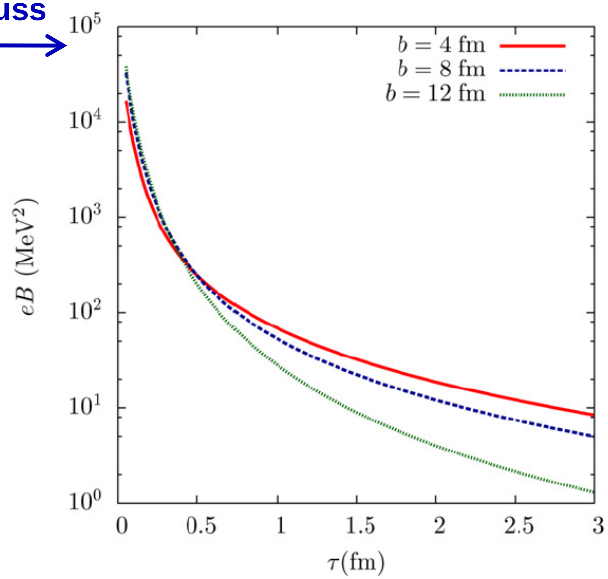
- **Moving from one vacuum state to another is the result of changing the topological charge of the system**
- **Topological charge flips helicity and thus counts the difference between the number of right and left handed quarks (a consequence of the axial Ward identity)**

- **What every experimentalist likes to see in a theory publication …**
  - **"The consequences and magnitude of these effects are subject to experimental study and verification"**
    - **Kharzeev, McLerran, and Warringa arXiv:0711.0950 and Nucl. Phys. A803 (2008) 227.**

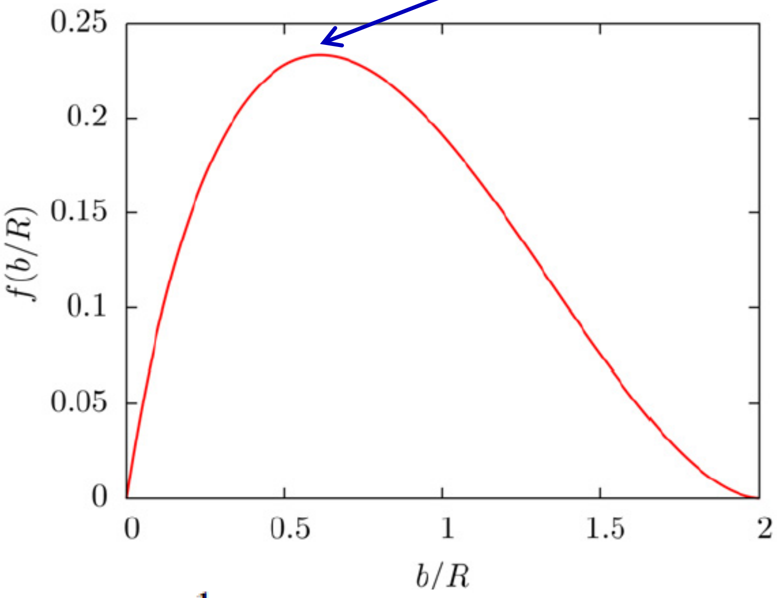
From a humble experimentalist's point of view … the theory appears to be fully vetted; these CP and P violating domains almost certainly occur in ultra-relativistic HI collisions. The question is whether the effects are large enough to be observed …

Prospects for ALICE and the LHC

- **Presumably, the domain size for topological charge fluctuations grows at higher energies … but the effect of the participant's magnetic field goes down as exp(-Y_0/2) (surprise!)**



Peak at mid-centrality



$$eB_p \approx cZ\alpha_{\mathrm{EM}} \exp(-Y_0/2) \frac{1}{R^{1/2}\tau^{3/2}} f(b/R)$$

- **At 2.76 and 5.52 TeV, the beam rapidities are 7.98 and 8.68**
  - **Thus, the exponential attenuation diminishes the effect particpant contribution by a factor of 5, and spectator contribution by more …**

Magnetic Field Thoughts (from RHIC to LHC)

- **The magnetic field according to Kharzeev is**

$$e\vec{B}_s^{\pm}(\tau,\eta,\vec{x}_\perp) = \pm Z\alpha_{\mathrm{EM}} \sinh(Y_0 \mp \eta) \int \mathrm{d}^2\vec{x}'_\perp \, \rho_\pm(\vec{x}'_\perp)[1-\theta_\mp(\vec{x}'_\perp)] \times \frac{(\vec{x}'_\perp - \vec{x}_\perp)\times \vec{e}_z}{[(\vec{x}'_\perp - \vec{x}_\perp)^2 + \tau^2 \sinh(Y_0 \mp \eta)^2]^{3/2}},$$

- **For $\tau > R / \sinh(Y_0)$ we find that the denominator is $\approx \tau^3$, so**

$$e B_s \approx Z\alpha_{\mathrm{EM}} \exp(-2Y_0) \frac{4b}{\tau^3}$$

- **but for $0 < \tau < R / \sinh(Y_0)$, the field is approximately constant and independent of Y_0 . Since this initial field is so strong, the integral over time from 0 to particle freezeout (very late time) is nearly the same for all beam energies. However, the time integral from 0.2 fm/c to freezeout is strongly dependent on $e^{-Y0} = m/\sqrt{S}$**
- **Scaling according to Kharzeev $\approx (1/\sqrt{S})^2$, Toneev $\approx 1/\sqrt{S}$, but also possible that B field is frozen into plasma (this happens in classical E&M plasmas) so no scaling at all.**

notes

- total time: 15 minutes
- add CME introduction
- add ALICE introduction (TPC, ZDC, etc.)
- discuss energy scaling (a la Toneev)
- discuss Koch et al. 2 particle expectations; ALICE vs STAR
  - This is the one real difference between ALICE and STAR results
- cut, cut, cut … you only have 15 minutes !!

- Ilya & Panos comments:
  - In some theories, the signal may not be reduced at LHC
  - Flow fluctuations may lead to baseline shift (Teaney & Yan) See plot in paper draft … not approved but can say there is a shift
  - Koch ignored non-flow – so misleading conclusion about in plane versus out of plane
  - Cut figures 5 and 6, and reduce differential plots
  - Note that I have ignored non-flow in stating the conclusions about in-plane and out-of-plane pre-dominance. This is work for the future with higher order correlations