parity non-conservation OR momentum & charge conservation

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Parity Violation

\[ \vec{E}_a \cdot \vec{B}_a \]
- fluctuates randomly, but same sign with flux tube
- fluctuates as \( 1/N_{\text{tubes}} \)
- fluctuations span large rapidity range
Parity Violation (Fluctuation)
(numerous papers by Kharzeev et al)

$\vec{E}_a \cdot \vec{B}_a$ couples to electromagnetic $\vec{E} \cdot \vec{B}$

Inside flux tube, E and B fields can rotate into one another
Parity Fluctuations

- B fields add coherently
- E fields cancel in participant region

Coupling to flux tubes generates non-zero $E_y$
Parity Fluctuations

\[ E_y \neq 0 \]

\[ \langle \sin \phi_1 \sin \phi_2 \rangle_{\text{same sign}} - \langle \sin \phi_1 \sin \phi_2 \rangle_{\text{opp sign}} > 0 \]

OR EQUIVALENTLY

\[ \langle \cos(\phi_1 + \phi_2) \rangle_{\text{opp sign}} - \langle \cos(\phi_1 + \phi_2) \rangle_{\text{same sign}} > 0 \]
Measurements of three particle correlations have been presented for heavy ion collisions have been presented for same charge correlations without postulating a negative signal as shown by the triangles in Fig. g and i. These calculations also predict a prominent role in particle production is played by clusters. For the correct sign of fake signal to be created in the true reaction plane, these calculations also predict a prominent role in particle production is played by clusters. Same sign and opposite sign should have yielded opposite results.

From STAR

STAR, 200 GeV
- red circles: same charge, AuAu
- blue squares: opp charge, AuAu
- red circles: same charge, CuCu
- blue squares: opp charge, CuCu

Same sign & opposite sign should have yielded opposite results
I. Correlations that separate charge

* Consider:

\[ \gamma_p \equiv \left\langle \cos(\phi_i + \phi_j) \right\rangle_{+-} - \left\langle \cos(\phi_i + \phi_j) \right\rangle_{ss} \]

* Parity Fluctuations
* Local Charge Conservation + Elliptic Flow
* Fluctuating Initial Conditions & E-Field
* HBT
Estimate Magnitude of Parity Signal

- Let $|E| = |B|$ in each tube,
  \[ \gamma_p \sim \frac{\Delta p^2}{\langle p_t \rangle^2} \left( \frac{\Delta p}{N_{\text{tubes}}} \right) \sim 0 \text{ MeV} \]
  \[ \Delta p \approx 40 \text{ MeV} \]
  \[ E_y \neq 0 \]

- Signal of Correct Size

- Only fraction of charges existent at $\tau = 0.2$ fm/c (reduce by $\approx 1/10$)

- Particles absorbed and rethermalized (reduce by $\approx 1/20$)

- $E$ should be less by $\approx e/2\pi$ (reduce by 1000)

- Contribution 4-6 orders of magnitude too low
Fluctuating IC

Monte-Carlo Calculations give contribution that is too small by $\approx \frac{1}{1000}$
Correlations from HBT

* Both Coulomb and Bose Differ between same- and opposite sign
* Since charge is conserved, must consider pair-wise correlations
* Messy calculation
* Appears to small by $\approx 1/100$
Correlations from Local Charge Conservation

- Balancing Charge has similar $y$, $p_t$, $\phi$
- Charge Balance Functions
  \[ B(\Delta y) \equiv \frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_+} \]
- Correlations Equally Feasible
Balance Functions

DATA: STAR PRL, 2004
Blast-Wave: Cheng et al, PRC 65, 2004
$B(\Delta \phi)$

Charged Particles

STARS Preliminary

Dip from HBT
Radial flow more dominant for central collisions
Relation to $B(\Delta \phi)$

$$\gamma_P = \frac{2}{M^2} \int \, d\phi \, d\Delta \phi \, \frac{dM}{d\phi} \, B(\phi, \Delta \phi) \left[ \cos 2\phi \cos \Delta \phi - \sin 2\phi \sin \Delta \phi \right]$$

probability for charge observed at $\phi$ to have balancing particle emitted at $\phi + \Delta \phi$

Three Contributions

1. $\langle c_b \rangle \equiv \frac{1}{M} \int \, d\phi \, d\Delta \phi \, \frac{dM}{d\phi} \, B(\phi, \Delta \phi) \cos \Delta \phi$

2. $v_{2c} \equiv \frac{1}{M} \int \, d\phi \, d\Delta \phi \, \frac{dM}{d\phi} \left[ B(\phi, \Delta \phi) \cos 2\phi \cos \Delta \phi - \frac{v_2 \langle c_b \rangle}{2\pi} \right]$

3. $v_{2s} \equiv \frac{1}{M} \int \, d\phi \, d\Delta \phi \, \frac{dM}{d\phi} \, B(\phi, \Delta \phi) \sin 2\phi \sin \Delta \phi$
$v_2 \langle c_b \rangle$

more pairs in-plane than out-of-plane (elliptic flow)

\[
v_2 \langle c_b \rangle \equiv \frac{v_2}{M} \int d\phi \ d\Delta \phi \ \frac{dM}{d\phi} \ B(\phi, \Delta \phi) \ \cos \Delta \phi
\]

\[
v_{2c} \equiv \frac{1}{M} \int d\phi \ d\Delta \phi \ \frac{dM}{d\phi} \left[ B(\phi, \Delta \phi) \cos 2\phi \cos \Delta \phi - \frac{v_2 \langle c_b \rangle}{2\pi} \right]
\]
$V_{2s}$

balancing charge more likely to be found towards in-plane than out-of-plane (elliptic flow)

$$v_{2s} \equiv \frac{1}{M} \int d\phi \ d\Delta \phi \ \frac{dM}{d\phi} \ B(\phi, \Delta \phi) \ \sin 2\phi \ \sin \Delta \phi$$
Blast-Wave Calculation

- STAR parameterization
  (STAR, PRC 72, 14904 (2005))
- Add Charge Conservation
- Correct for efficiency and acceptance

(Cheng, et al., PRC 69 054906 (2004))
Normalizing $B(\Delta \phi)$

* Multiply model $B(\Delta \phi)$ by $\approx 0.4$ to reproduce experimental normalization (accounts for efficiency and percentage of balanced charge outside acceptance)
RESULT

- Readily explains result
- Perfect locality too extreme for peripheral collisions

\[ \gamma_{pM/2} \]

\(%\) centrality
More Differentially

0-5% centrality

B(Δφ)

Δφ

20-30% centrality

B(Δφ)

Δφ

40-50% centrality

B(Δφ)

Δφ

STAR Blast Wave
Charge Separation: Lessons

- Look at Differential Observables!!!! (Ghosts of Intermittencies Past)

- Beware Non-Quantitative Predictions

Fluctuating Parity or IC
II. Correlations not related to charge separation

* Consider:

\[ \langle \cos(\phi_i + \phi_j) \rangle_{ss} \]

* Momentum Conservation
Momentum Conservation

\[ \langle \cos(\phi_1 + \phi_2) \rangle = \frac{\sum_{i<M,j<M,i\neq j} (\cos \phi_i \cos \phi_j - \sin \phi_i \sin \phi_j)}{M^2} \]

\[ \sum_i \cos \phi_i = \sum_i \sin \phi_i \approx 0 \]

Assume all particles have same \( p_t \)

\[ \langle \cos(\phi_1 + \phi_2) \rangle \approx -\frac{\sum_{i<M,j<M,i\neq j} (\cos 2\phi_i)}{M^2} \]

\[ \langle \cos(\phi_1 + \phi_2) \rangle_{\text{same sign}} \approx -\frac{v_2}{3M_+} \]

If \( v_2 \) were weighted with \( p_t^2 \), result would be model independent

\[ \langle \cos(\phi_1 + \phi_2) \rangle' = \frac{\sum_{i\neq j} p_{t,i} p_{t,j} \cos(\phi_i + \phi_j)}{M \langle p_t^2 \rangle} = \frac{v_{2'}}{M} \]
Momentum Conservation  
(momentum "bath" from spectators)

initial, uncorrelated & isotropic

\( \vec{p}_i = \vec{k}_i + \vec{q}_i \)

final momentum

from local scatterings

\[ \sum_i \vec{q}_i = 0 \]

Since \( \vec{k} \) doesn't contribute to \( v_2 \), result holds:

\[ \langle \cos(\phi_1 + \phi_2) \rangle_{\text{same sign}} = -\frac{v_2}{M} \]
Charge Conservation Magnifies Momentum

* For every positive particle with momentum $p_x$, there exists a negative particle with similar momentum

* Include (1/3) of momentum balance from neutrals -> nearly twice as much momentum to balance

$$\langle \cos(\phi_1 + \phi_2) \rangle_{\text{same sign}} = -f_P \frac{2v_2}{3M} (1 + \langle \cos \Delta \phi_{\text{balance}} \rangle)$$
Putting "knowns" to left

\[
\frac{3M}{2v_2} \frac{\langle \cos(\phi_1 + \phi_2) \rangle_{\text{same sign}}}{(1 + \langle \cos \Delta \phi_{\text{balance}} \rangle)} \approx -f_P
\]
To Reduce Model Dependence

\[ \langle \cos(\phi_1 + \phi_2) \rangle'_{ss} \equiv \sum_{i \neq j} p_{t,i} p_{t,j} \cos(\phi_i + \phi_j) \]

\[ \frac{M \langle p_t^2 \rangle}{\langle p_t^2 \rangle} \]

\[ \approx f_p \frac{2v_2'}{3M} (1 + \langle \cos \Delta \phi_{BAL} \rangle) \]

* Other contributions: Differential quenching, HBT...
Conclusions

* $\gamma_p \equiv \langle \cos(\phi_i + \phi_j) \rangle_{+} - \langle \cos(\phi_i + \phi_j) \rangle_{ss}$ explained by charge conservation + elliptic flow

* no evidence for parity fluctuations

* same-sign correlations are open question, but significant contribution comes from p-conservation

* charge/momentum conservation effects are interesting in their own right!!!
bonus slides