SEARCH FOR DCC IN RELATIVISTIC HEAVY-ION COLLISION THROUGH EVENT SHAPE ANALYSIS

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Abstract

Event shape analysis has been used to look for DCC signals in simulated ultra-relativistic heavy-ion collision data at SPS energy. A simple redistribution of particles, with two detectors to detect charged particles and photons, is seen to result in the same flow direction with the flow angle difference peaking at zero. However, events where the neutral pion fraction has been modified according to the DCC probability distribution, show the flow angles in two detectors to be almost 90° apart. The results presented here show that the technique is complementary to the one based on the discrete wavelet transformation. Together the techniques are seen to provide a very powerful tool for DCC search in ultra relativistic heavy ion collision.

1 Introduction

In heavy-ion collisions at ultra-relativistic energies there is a rapid expansion of the collision debris in the longitudinal direction leading to a super cooling of the interior interaction region. This is expected to lead to the formation of unconventionally oriented vacuum structures as allowed by the chiral symmetry [1–3]. These are called the Disoriented Chiral Condensates (DCC). DCC formation results in large fluctuation in the neutral pion fraction. The probability distribution of the neutral pion fraction is characterised by,

\[ P(f) = \frac{1}{2\sqrt{f}} \]  

(1)

where

\[ f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+} + N_{\pi^-}} \sim \frac{N_\gamma/2}{N_\gamma/2 + N_{\text{ch}}} \]  

(2)

\[ N_\gamma \text{ and } N_{\text{ch}} \text{ are multiplicities for photons and charged particles, respectively.} \]

This assumes all charged particles are pions and all photons come from \( \pi^0 \) decay.
Detection of this interesting phenomenon of DCC formation is expected to provide valuable information on the vacuum structure of strong interaction and chiral phase transition. Therefore, it has become a very interesting aspect of heavy ion collision studies and a number of experiments have been planned at RHIC and LHC energies.

In an experiment involving the search of localised DCC one essentially tries to detect a state with a large and localised fluctuation in the ratio of the number of photons to charged particles. In principle there should be regions in the detected phase space where the number $f$ should be very much different from $1/3$. A typical event structure would be very similar to the anti-centauro event as reported by the JACEE collaboration \[4\]. In view of this, a typical experiment would consist of two detectors to detect the charged particles and the photons respectively. These two detectors should have complete overlap in $\eta$ and $\phi$ with as much $\eta$ coverage as possible. From the detected hit patterns of charged and neutral particles one tries to see whether there is any local fluctuation of $f$ indicating the signature of localised DCC.

As far as DCC search goes many analysis methods have been proposed \[1,5–9\]. However, the most attractive method has been the one based on the Discrete wavelet transforms (DWT) proposed by Huang et al. \[6\]. This has the beauty of analysing a spectrum at different length scales with the ability of finally picking up the right scale at which there is a fluctuation. Because of this advantage, although there has been no claim regarding the observation of DCC, the method was successfully applied to filter out interesting events with large photon to charge particle fluctuation in WA98 experiment \[7,8\].

In the present paper, using simulated data, attempts have been made to show the power of yet another analysis technique which has been used successfully for flow analysis in heavy-ion data \[10,11\]. The method is based on the simple fact that localised DCC formation is expected to lead to an event shape anisotropy which is expected to be out of phase for one detector corresponding to the other. In other words it means, whenever there is large number of charge particles recorded in a DCC region in one detector, there should be a depletion in the number of neutral particles in the same zone of the other detector. Therefore, from an event shape analysis using both detectors one can, in principle, look for DCC signals. On the other hand, in the DWT analysis, one tries to look at the neutral pion fraction $f$ at different resolutions constructing what are known as the Father function coefficients (FFC) and Mother function coefficients (MFC). Without DCC, the FFC distribution for simulated generic events has been shown to be a Gaussian. However with DCC, the distribution goes to a non-Gaussian shape with several events appearing in the wings \[7\] The events which lie beyond the generic Gaussian can be picked up as DCC-like events. One can also construct the power spectrum for the FFCs and look
for their variation as a function of the length scale. For generic events with only a statistical fluctuation in the numbers of charged and neutral pions the FFC power spectrum shows a flat curve without a structure at any scale. However, with DCC-like fluctuation, generated over a given domain of phase space, the power spectrum is expected to show an enhancement at scales below the specified domain size.

In the present case we have carried out simulation of DCC-like and pure flow-type events and have applied the technique of event shape analysis which distinguishes very clearly both class of events. In case of simulated DCC-like events, particularly when their fraction in a large number of events is comparatively small, the present method, together with that based on DWT, has been found to be successful in finding out DCC-type signature.

2 Modeling DCC and event anisotropy

For DCC production, a procedure which is similar to the one employed in [5] has been followed. VENUS 4.12 event generator [12] has been used for the simulation of DCC type events at SPS energy (\(Pb\) on \(Pb\)). In this, the charge of the pions is interchanged pairwise (\(\pi^+\pi^- \leftrightarrow \pi^0\pi^0\)), in a selected \(\eta - \phi\) zone according to the DCC probability distribution as given in equation (1) event by event. Finally the \(\pi^0\)s are allowed to decay.

For the present study, DCC events have been simulated in a range 3.0 \(\leq\) \(\eta\) \(\leq\) 4.0 with a domain size having \(\Delta \phi = 90^\circ\). For the analysis 20,000 events were generated. A similar amount of VENUS events were also generated for comparison. However, to simulate what happens in a true experimental situation it is also necessary to include detector related effects. For photon and charge particle detection the detection efficiencies were taken to be about 70 \(\pm\) 5\% and 95 \(\pm\) 2\% respectively. It is also known that charged particles sometimes lead to photon-like signals and such a contamination in an experimental situation can be as high as 25 \% [13]. Following this, it was decided to include a 25 \% charged particle contamination in the photon signal. Finally, we have also prepared several sets of data with different DCC fractions (10 \(-\) 100 \%) mixing generic VENUS and DCC type events in an appropriate manner.

To introduce event anisotropy in every event, a simple toy model has been employed. Here the distributions for both charged and neutral particles are generated from VENUS, distorted according to a procedure as given below. First of all a flow direction is selected at random, distributed uniformly between 0\(^\circ\) and 360\(^\circ\). About each flow direction, corresponding to a given event, a Gaussian particle distribution, with a \(\sigma\) of 10\(^\circ\) is generated by picking VENUS generated particles at random. Here
the charge conservation in every localised region is ensured since all three types of particles are selected with equal probability.

Constructed as above, both localised DCC and simple event anisotropy (indicating flow) are modeled in different events and the results were analysed using the standard flow analysis as employed elsewhere [11]. In the present study the method of Fourier analysis with n=2 (elliptic flow) has been employed.

3 Method of analysis

The particle distribution in a given detector can be written as a set points \((\eta_i, \phi_i, i = 1, N)\) showing the hit pattern in the detector.

In the second order elliptic flow, for each event, one tries to construct the sums

\[
X = \Sigma \cos(2\phi_i) \\
Y = \Sigma \sin(2\phi_i)
\]

The flow angle \(\Phi\) is determined from these two sums using the expression

\[
\Phi = \frac{1}{2} \tan^{-1}(Y/X)
\]

In the absence of any detector imperfections and other geometrical effects, the distribution of \(\Phi\), taken over a large number of events is expected to be flat without any peaks or bumps spread over 0° to 180°. This is because the flow direction varies randomly from event to event. However, when the events are realigned, with respect to the flow angle in each event, one can see the characteristic peaks (at 0 and 180°) in the azimuthal distribution of particles.

In case of two detectors with the same phase space \((\eta-\phi)\) coverage, one detecting photons and other detecting charged particles the situation is very interesting. If there is genuine flow in a particular event both detectors would show the effect in terms of \(\Phi\) angles getting aligned in the same direction. Therefore the distribution of \(\Psi(=\Phi_1 - \Phi_2)\), the difference between the flow angles, as obtained for the two detectors is expected to be peaking at zero. However, in case of DCC being prominent in a particular region, there will be more photons detected in one detector. The other detector is expected to show less charged particles in the same region of phase space. Therefore an event shape analysis is expected to show two flow angles for both detectors which will be out of phase (with n=2 the angular difference is expected to
peak at $90^\circ$). This is the most important result based on which the present analysis is carried out.

4 Results and Discussions

Results shown in Fig.1 (a-c) correspond to the case with only DCC in which one can notice (Fig. 1 a) a clear peak for the angle between the event planes for the two detectors, $\Psi$, at $90^\circ$. Figs. 1 b and c show the angle between the event planes as obtained for two sub-events in each of the detectors separately. It is important to notice that both detectors show "flow", but one with respect to the other clearly shows an anti-flow type behavior. In the same figure we have also presented the data corresponding to pure VENUS events for comparison. One can notice there is neither any signature of flow nor DCC-like fluctuation.

Results shown in Figs. 1 (d-f) show the same plots for flow type events which have no DCC-like fluctuation. Here, the individual detectors are seen to show the same effect as one with respect to the other.

In Fig.2 we have presented event shape analysis results for 20000 events having different fractions of DCC-type fluctuation ranging from 10 % to 100 %. One can notice that the expected peak around $90^\circ$ gets weaker as DCC fraction decreases. This is primarily because of an overwhelming majority of generic events that contribute uniformly to the $\Psi$ distribution over the entire angular range. So in order to look for any DCC-like signature one has to suppress the contribution of these events filtering out the interesting DCC-like ones.

In Fig.3 we have shown the FFC distribution for pure generic and pure DCC-like events at scale $j = 1$. We find that the FFC distribution for DCC-like events is broader in comparison to that for generic events. In fact, one can show that there is pile up of a large number of events within the width of the generic distribution with decrease in the fraction of DCC-like events. But it is those events that lie beyond the width of the generic distribution, about which some definite conclusion regarding their DCC-like nature can be made. In such a case, when a fraction of the events contain the DCC type signal, it is very difficult to notice their signature using the power spectrum analysis [7] which employs the event averaging procedure. This is because the interesting events lying beyond the width of the generic distribution, contributing significantly to the power spectrum, are overwhelmingly outnumbered by those lying within the width.

A simple method to filter out the contribution of a great majority of non-DCC type events is to apply a cut on the width of the FFC distribution and consider the events lying above the cut. With this in view, in the present case, we have applied
a cut of $\pm 1.5\sigma$ in the FFC distribution. The $\Psi$ Distribution of the filtered events for the case of 25% of DCC-like events is shown in Fig.4. One can clearly notice the peaking at $\Psi = 90^\circ$ indicating a DCC-like signature. The pure VENUS events with the same cut in their FFC distribution are also shown for comparison. They are seen to contribute uniformly over the entire angular range.

This clearly shows that the DWT and the event shape analysis applied together can be a very powerful method for the search of DCC. However, one needs to judiciously use an appropriate cut on the FFC distribution to filter out a great many uninteresting effects. Before concluding, a word must be mentioned regarding the errors. One can notice, the spectral distribution shows a histogram where the error in the entry at every angle goes as $\sqrt{N}$. By filtering out a large number of events, which are mostly distributed uniformly over the entire angular range, one essentially reduces the background although the statistical errors increase slightly.

5 Conclusion

In the present paper it has been demonstrated that the technique of event shape analysis can be very effectively employed to look for the signature of DCC formation in relativistic heavy ion collision data. Here, in the absence of any rigorous theoretical model to simulate DCC formation, an isospin fluctuation has been introduced locally on the VENUS generated events to generate a charged to neutral pion asymmetry. At least for the case with a single, large, DCC domain, it seems to be a very effective technique for looking at DCC signature. However, in cases where only a certain fraction of the events are expected to be of DCC type, together with the technique of DWT which provides a first hand filter, the present technique provides a very powerful probe for DCC signal.

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**Figure Captions**

**Fig.1:** The distribution of $\Psi$ for simulated DCC(a-c) and flow(d-f). (a) shows anti-correlation between event planes determined for charged particle and photon detectors. (b) and (c) show correlations between event planes obtained considering two sub events for the photon and charged particle detectors respectively. The dotted lines in figures (a-c) show the distributions for generic VENUS events. In case of flowy events (d) shows correlation between event planes obtained from the two detectors. (e) and (f) are same as (b) and (c).

**Fig.2:** The distribution of $\Psi$ for simulated DCC and VENUS with varying DCC fractions (a) 100 % of the events DCC (b) 75 % of the events DCC (c) 50 % of the events DCC (d) 25 % of the events DCC (e) 15 % of the events DCC (f) 10 % of the events DCC

**Fig.3:** FFC distribution for simulated generic VENUS and pure DCC-like events. The solid and the dotted lines correspond to the DCC-like and VENUS events respectively.

**Fig.4:** The distribution of $\Psi$ as obtained from the two detectors excluding events lying within 1.5 sigma of the FFC distribution of VENUS. The dotted lines shows the distribution of $\Psi$ as above but for pure VENUS events. Errors though not shown are of the order of $\sqrt{N}$ at every point.
fig. 2
Fig. 3
fig. 4