\textbf{\Phi-measure and Disoriented chiral condensates}

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\section*{Abstract}
Fluctuations in the ratio of neutral to charged pions arising due to formation of disoriented chiral condensates (DCC) are discussed using the \Phi-measure. The properties of the measure for various cases of DCC and non-DCC are discussed. The effect of detector efficiencies and other experimental factors are presented. Application of the \Phi-measure to simulated data, within the context of a simple DCC model are also discussed.

In heavy-ion collisions, there is rapid expansion of collision debris along the longitudinal direction, leading to supercooling of the interior interaction region. This may result in the formation of domains of unconventionally oriented vacuum configurations as allowed by chiral symmetry called as disoriented chiral condensates (DCC) \cite{1}. Detection of these would provide important informations on the vacuum structure of the strong interaction and the nature of chiral phase transition. To have a system in which chiral symmetry is restored in the laboratory and to be able to study the above features is one of the main goals of ultra-relativistic heavy-ion collision experiments.

It has been predicted that DCC formation is associated with large event-by-event fluctuations in the neutral to charged pion ratio. The probability of the neutral pion fraction \cite{2,3}, \( f \), is

\begin{equation}
P(f) = 1/2 \sqrt{f} \quad \text{where} \quad f = N_{\pi^0}/N_{\pi},
\end{equation}

\( N_{\pi^0} \) and \( N_{\pi} \) being the total number of neutral pions and the total number of pions respectively. The corresponding distribution for non-DCC events is a gaussian with \( <f> = 1/3 \). It can easily be seen that for events with DCC there is a strong anti-correlation in the production of neutral to charged pions. Several theoretical calculations regarding various aspects of DCC exists.
in literature, starting form the probability of DCC production [4] to life time of DCC [5]. Although there is an absence of a dynamical model of DCC, still the theoretical calculations are encouraging with respect to formation of DCC in heavy-ion collisions.

A typical experiment, looking for DCC would consist of two detectors, one to detect charged pions and other to detect photons from the decay of π⁰’s. They must have a common η-ϕ overlap with η coverage as much as possible. From the detected hit patterns one tries to see if there is any fluctuation in f, which would indicate presence of DCC-type fluctuations. Typical event structures would be similar to the anti-Centauro events reported by the JACEE collaboration [6]. Results from other cosmic ray experiments have not ruled out the possibility of a DCC formation mechanism [7]. As far has accelerator based experiments are concerned, several experiments have attempted to look for DCC by colliding hadrons and heavy-ions. Hadron-hadron collision experiments like UA1 [8], UA5 [9], D0, CDF [10] and MINIMAX [11], having √s from 540 GeV to 1.8 TeV, have so far reported null results. Heavy-ion collision experiments like WA98 [12,13] and NA49 [14] at CERN SPS have so far put upper-limits on DCC production. In future several experiments have planned to look for this interesting phenomena at RHIC [15] and LHC [16].

Several techniques have been developed to look for DCC. These includes Nγ vs. Nch correlation [13], “robust” variables [11] and those based on multi-resolution analysis techniques such as discrete wavelet transformations [13]. It must be mentioned that it is important to have the right variable or method to look for fluctuations which are exotic. The importance of this in general has already been emphasized by some of the recent calculations [17]. One of the important observables for looking at fluctuations is the Φ-measure [18]. It has been developed specifically to remove the influence of trivial geometrical fluctuations and the effect of averaging over many particle sources. It’s utility in looking for fluctuations in transverse momentum, azimuthal fluctuations [19] and studying chemical fluctuations [20,21] has been shown. More recently the usefulness of Φ in studies of charge fluctuations have been demonstrated and it has been shown to have some advantages over other techniques [22]. Its limitations have also been discussed [23]. In this letter we try to see the usefulness of Φ-measure for looking at DCC-type fluctuations.

First we briefly recall some of the basic equations related to Φ-measure in general and then study its properties for a DCC-type fluctuation. The Φ-measure for a system of particles is defined as,

\[
\Phi \stackrel{\text{def}}{=} \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\langle z^2 \rangle}.
\]

(2)

z is the single-particle variable, \( z \stackrel{\text{def}}{=} x - \overline{\tau} \), with \( \overline{\tau} \) being the probability
(averaged over events and particles) that a produced particle is of the sort of interest, say it is $\pi^0$. One easily observes that $\overline{\tau} = 0$. While $Z$ is the event variable, which is a multi-particle analog of $z$, defined as $Z \overset{\text{def}}{=} \sum_{i=1}^{N}(x_i - \overline{\tau})$, where the summation runs over particles from a given event. By construction $< Z >= 0$, where $< ... >$ represents averaging over events.

As discussed in Ref. [20] one can compute $\Phi$ for the system of particles of two sorts, $a$ and $b$, e.g. $\pi^0$ and $\pi^{\pm}$. $x_i = 1$ when $i$–th particle is of the $a$ type and $x_i = 0$ otherwise. The inclusive average of $x$ and $x^2$ would then be given as

$$\overline{x} = \sum_{x=0,1} xP_x = P_1 ,$$

$$\overline{x^2} = \sum_{x=0,1} x^2P_x = P_1 ,$$

where $P_1$ is the probability (averaged over particles and events) that a produced particle is of the $a$ sort. Thus,

$$P_1 = \frac{< N_a >}{< N_a > + < N_b >} ,$$

with $N_a$ and $N_b$ being the numbers of particles $a$ and $b$, respectively, in a single event. One immediately finds that $\overline{\tau} = 0$ while

$$\overline{\overline{\tau}} = P_1 - P_1^2 = \frac{< N_a > < N_b >}{< N >^2} ,$$

(3)

where $N = N_a + N_b$ is the multiplicity of all particles $a$ and $b$ in a single event.

As the event variable $Z$ is defined as $N_a - \overline{\tau}N$, one gets

$$< Z >= < N_a > - \overline{\tau} < N >= 0 ,$$

$$< Z^2 >= < N_a^2 > - 2 \overline{\tau} < N_a N > + \overline{x^2} < N^2 > .$$

Which leads to

$$< Z^2 > < N >^2 = < N_b >^2 < N_a^2 > + < N_a >^2 < N_b^2 > - 2 < N_a > < N_b > < N_a N_b > ,$$

then

$$\frac{< Z^2 >}{< N >} = \frac{< N_b >^2}{< N >^3} (< N_a^2 > - < N_a >^2 )$$

$$+ \frac{< N_a >^2}{< N >^3} (< N_b^2 > - < N_b >^2 )$$

$$- 2 \frac{< N_a > < N_b >}{< N >^3} (< N_a N_b > - < N_a > < N_b > ) .$$

(4)
The fluctuation measure $\Phi$ as given in Eqn. (2) is completely determined by Eqns. (3, 4). Now we identify $N_a = N_{\pi^0}$ and $N_b = N_{ch} = N_{\pi^+} + N_{\pi^-}$.

If $N_\pi = N_{\pi^0} + N_{ch}$ is the total pion, then we can write $N_{\pi^0} = f N_\pi$ and $N_{ch} = (1 - f) N_\pi$. Where $f$ is the fraction of neutral pion out of total number of pions in a given event. With this we get,

$$z^2 = < f > (1 - < f >)$$  \hspace{1cm} (5)

In order to calculate $\frac{< Z^2 >}{< N_\pi >}$, we consider the following equations.

$$< \delta N_{\pi^0}^2 > = < f^2 > + < \delta N_\pi^2 > + < N_\pi^2 > + < \delta f^2 > + 2 < N_\pi > < f > < \delta N_\pi \delta f >$$  \hspace{1cm} (6)

$$< \delta N_{ch}^2 > = < (1 - f)^2 > + < \delta N_\pi^2 > + < f^2 > - 2 < N_\pi > < (1 - f) > < \delta N_{\pi} \delta f >$$  \hspace{1cm} (7)

$$< \delta N_{\pi^0} \delta N_{ch} > = < f > < (1 - f) > < \delta N_\pi^2 > - < N_\pi > < f > < \delta N_{\pi} \delta f > + < N_\pi > < (1 - f) > < \delta N_{\pi} \delta f >$$  \hspace{1cm} (8)

where, $< \delta N > = N - < N >$ and $< \delta N^2 > = < N^2 > - < N >^2$.

Using Eqn. 6, Eqn. 7 and Eqn. 8 in Eqn. 4 one can easily get the expression for $\frac{< Z^2 >}{< N_\pi >}$ as

$$\frac{< Z^2 >}{< N_\pi >} = < N_\pi > < \delta f^2 >$$  \hspace{1cm} (9)

A small assumption is involved in the above derivation, that the fluctuations in $N_\pi$ is small and the term $\frac{< \delta N_{\pi^0}^2 >}{< N_\pi >} + \frac{< N_{\pi^0}^2 >}{< N_\pi >} \sim N_\pi$.

Using Eqn. 5 and Eqn. 9 in Eqn. 2, the $\Phi$-measure can be defined as,

$$\Phi = \sqrt{< N_\pi > < \delta f^2 >} - \sqrt{< f > (1 - < f >)}$$  \hspace{1cm} (10)

Let us now consider its properties within three simple models of the multiplicity distribution.
**Non-DCC case** - It is known from $pp$ experiments [24] that the produced pions have their charge states partitioned binomially with mean of $f$ at $1/3$. The fluctuation in $f$ is inversely proportional to the total number of pions given by $< \delta f^2 > = < f > (1 - < f >)/N_\pi$. Then one can easily see that,

$$\Phi_{\text{non-DCC}} = 0$$

(11)

**Non-DCC but $N_{\pi^0}$ and $N_{ch}$ are correlated** - If $N_{\pi^0}$ and $N_{ch}$ are assumed to be correlated in such a way that there are no DCC-type fluctuations in the events. The neutral pion fraction, which is defined by the ratio $N_{\pi^0}/N_\pi$, is assumed to be strictly independent of the event multiplicity. Then, $f = \alpha$, where $\alpha$ is a constant smaller than unity. Then $< \delta f^2 > = 0$ and $\Phi$-measure is given as

$$\Phi = -\sqrt{\alpha(1 - \alpha)}.$$  

(12)

**DCC case** - For the DCC case, the probability distribution is given by Eqn. (1). Using this, one can easily see that $< f > = 1/3$, as in the non-DCC case, while $< \delta f^2 > = 4/45$. So the $\Phi$-measure is given as

$$\Phi_{DCC} = \sqrt{< N_\pi > 4/45} - \sqrt{2/9}$$

(13)

For a typical case, where the total pion multiplicity, $N_\pi$, in the experiment is 300, we find for the DCC case the above $\Phi$-measure is about 4.7.

This is a result where all the pions observed are of DCC origin. However a more realistic case [25] would be to include pions from non-DCC sources as well.

**Background pions** - In a given event pions can originate both from a DCC source and from other non-DCC sources, even in a DCC event. In such a case the probability distribution for the neutral pion fraction, $P(f)$ [26], is given as,

$$P(f) = \int df_{DCC} df_{\text{non-DCC}} P(f_{DCC}) P(f_{\text{non-DCC}})$$

$$\delta(f - \beta f_{DCC} - (1 - \beta)f_{\text{non-DCC}})$$

(14)

where $\beta$ corresponds to fraction of DCC pions out of a total number of pions $N_\pi$, produced in the event. $f_{DCC}$ and $f_{\text{non-DCC}}$ correspond to the neutral pion fraction for pions from DCC and non-DCC sources in the event, respectively. With the presence of non-DCC pions, one can see, the neutral pion fraction
can no longer start from zero nor can reach the full value of unity, the range depending upon the fraction of non-DCC pions present in the sample. For various values of $\beta$, and total number of non-DCC pions, $(1 - \beta)N_\pi$, the above equation can be evaluated easily to obtain the final $f$ distribution from which one can get the resultant fluctuation, $< \delta f^2 >$. Knowing $< \delta f^2 >$ the $\Phi$-measure can be easily estimated. The results obtained for an average total number of 300 pions in an event, are shown in Fig. 1. One can see that the value of $\Phi$-measure, decreases with decrease in the fraction of DCC pions.

**Multiple domains** - It is possible that in an event multiple domains of DCC are formed. In such a case the total probability distribution of the neutral pion fraction is the average value of $P(f)$ over all of the domains. This can be written as

$$P_m(f) = \int df_1 \cdots df_m \delta(f - \frac{f_1 + \cdots + f_m}{m}) P_1(f_1) \cdots P_m(f_m)$$  \hspace{1cm} (15)$$

where, $m$ is the number of domains. It can be shown that the resultant probability distribution approaches a gaussian centered at $1/3$ with the standard deviation $\sim 1/\sqrt{m}$. This means $< \delta f^2 > \sim 1/m$, so that $\Phi$, reduces as the

![Fig. 1. Variation of $\Phi$-measure as a function of the pion fraction ($\beta$) from a DCC origin. The plot is obtained for an average pion multiplicity of 300.](image)
number of domains increases in an event.

\[ \Phi_{\text{multi-DCC}} \sim \sqrt{< N_{\pi} > / m} - \sqrt{2/9} \]  

(16)

However, by carrying out this analysis by dividing the \( \eta - \phi \) phase space to appropriate bins this effect can be reduced.

**Neutral pion decay.** - The neutral pions decay to photons \( (\pi^0 \rightarrow 2\gamma) \), before they reach the detectors. For such a case one can take \( N_{\pi^0} = 2N_\gamma \). Then carrying out the analysis similar that done for arriving at Eqn. 10, one obtains

\[ \Phi_\gamma = \sqrt{4 < N_\pi > < \delta f^2 > - 2 < f > (1 - < f >)} \]  

(17)

This shows decay introduces a finite value of \( \Phi \) even for non-DCC, of the order of 0.27

**Detector effects** - We know that the measurement of any observable in an experiment is affected by the efficiency of the detector. The effect of this can be seen easily through the following calculation. Consider the efficiency of detecting photons is \( \epsilon_1 \) and that for charged pions is \( \epsilon_2 \). Then we have, \( N_{\gamma}^{\exp} = \epsilon_1 N_\gamma \) and \( N_{ch}^{\exp} = \epsilon_2 N_{ch} \). Photon multiplicity measurements are also affected by charged particle contamination. But true \( N_\gamma \) can be obtained from the measured \( N_{\gamma-\text{like}} \) using the relation [27]

\[ N_\gamma = \frac{p_\gamma}{\epsilon_\gamma} N_{\gamma-\text{like}} \]  

(18)

where, \( \epsilon_\gamma \) is the photon counting efficiency, \( p_\gamma \) is the purity of the photon sample obtained from detector simulations. For convenience one can define \( \frac{p_\gamma}{\epsilon_\gamma} \) as \( \epsilon_1 \). Then following the simple statistical analysis and assuming that the fluctuation in efficiencies are independent of multiplicity (for simplicity and may indeed be true if the analysis is carried out in narrow bins in centrality) and fluctuations in efficiencies are small, we find

\[ \Phi_{\exp} = 2\epsilon_1 \epsilon_2 \sqrt{< N_\pi > < \delta f^2 > + < N_\pi > < f >^2 < (1 - f) >^2 E} 
- \sqrt{2\epsilon_1 \epsilon_2 < f > (1 - < f >)} \]  

(19)

where, \( E = \frac{<\delta\epsilon_1^2>}{<\epsilon_1^2>} + \frac{<\delta\epsilon_2^2>}{<\epsilon_2^2>} \).

Let us consider an experiment where the average total detected pion multiplicity is 300. Taking typical values of relative fluctuation \( (\sigma/\text{mean}) \) in efficiencies, to be \( \sim 3\% \) [28], we have \( <\delta\epsilon_1>^2/<\epsilon_1>^2 \) and \( <\delta\epsilon_2>^2/<\epsilon_2>^2 \)
both to be about 0.0009. Together they introduce an error 0.0027. Then the term \( < N_\pi > < f >^2 < 1 - f >^2 \left[ \frac{<\delta e^2_1>}{<e^2_1>^2} + \frac{<\delta e^2_2>}{<e^2_2>^2} \right] \) \( \sim 0.04 \) which is very small compared to \( < N_\pi > < \delta f^2 > \) so may be for simplicity neglected. Hence \( \Phi_{exp} \) can be now written as,

\[
\Phi_{exp} = 2\epsilon_1\epsilon_2\sqrt{< N_\pi > < \delta f^2 >} - \sqrt{2\epsilon_1\epsilon_2 < f > (1 - < f >)}
\]

(20)

So knowing the efficiency and purity of the detected multiplicity sample, one can estimate the value of \( \Phi_{exp} \).

Application to simulated data - We have discussed above many factors that possibly affect the detection of DCC-type fluctuations in data. Now lets apply the \( \Phi \)-measure to simulated data and observe the sensitivity of the measure to detection of DCC-type fluctuations. Another advantage of applying it to simulated data, is that it can form a guidance for application of this to actual data in future. Simulated events were generated using VENUS 4.12 [29] event generator with default parameters. 15K VENUS events with impact parameter less than 3 \( fm \) was generated for this study. We have compared the observed effect to simulation results based on a simple DCC model [12,30]. We assume the formation of a single DCC domain of a given size lying within the limited coverage (\( \eta = 3-4 \), and full azimuthal) of a hypothetical detector system, consisting of a photon multiplicity detector and a charged particle multiplicity detector. In this model the output of the VENUS 4.12 event generator has been suitably modified to accommodate such a domain, characterized by percentage of pions being DCC type. To introduce DCC in a certain fraction of pions out of the total pions in an event, the charge of the pions is interchanged pairwise (\( \pi^+\pi^- \leftrightarrow \pi^0\pi^0 \)), according to the DCC probability as given by Eqn. (1). After allowing the \( \pi^0 \)'s to decay, all the particles are passed through the realistic detector responses. The efficiency of charged particle detection was taken to be 90\% ± 5\% [31]. The photon counting efficiency and purity of photon sample was taken to be same and 70\% ± 5\% [27]. The average number of photons detected are 372 and the average number of charged particles detected are 456.

First we study the effect of number of pions being DCC-type. As discussed above and shown in Fig. 1, the value of \( \Phi \) decreases as the number of non-DCC pions in a given event increases. Here we study the same in a realistic scenario using simulated data. We introduce DCC for different fractions of pions being DCC-type (\( \beta \)) in an event. This is done following the method discussed above. Then we calculate the quantity, \( \Phi - \Phi_{normal} \). Where \( \Phi \) is the measure of fluctuation for a given DCC pion fraction (\( \beta \)) and \( \Phi_{normal} \) is the measure of fluctuation for normal or non-DCC type events (detector and decay effects included). The variation of \( \Phi - \Phi_{normal} \) as a function of \( \beta \) is shown in Fig. 2. From the Fig. 2 we find that the fluctuations decreases with decrease
with DCC pion fraction, which is consistent with the theoretical calculation shown in Fig. 1. The statistical error on $\Phi$ measure was calculated by taking different number of non-DCC type events (1000, 2000, \ldots, 10000) then finding the maximum variation in $\Phi$ value for these sets. It was calculated to be 0.006. From this we find that such a typical experiment as discussed in the generating simulated data, will be able to detect DCC-type fluctuation, if the number of pions in an event being DCC-type is above $\sim 3\%$.

Secondly, we know that all events in a given heavy-ion reaction cannot be of DCC type. The effect of this has been studied for a fixed number of pions being DCC-type. For simplicity, we have assumed that for DCC type events the percentage of DCC-type pions out of the total number of pions is 25%. Then we have varied the number of events being DCC-type ($\alpha$) out of the total number of events in an given ensemble of events, to study the effect of DCC event fraction ($\alpha$) on $\Phi$-measure. The results have been presented as $\Phi - \Phi_{normal}$ vs. $\alpha$ and are shown in Fig. 3. We find that the value of $\Phi - \Phi_{normal}$ decreases with decrease in $\alpha$, which is along expected lines. Keeping in mind the above mentioned statistical error on $\Phi$-measure, we find that for DCC pion fraction ($\beta$) of 0.25, the measure is sensitive to more than 1% of events being DCC-type out of a given ensemble of events. Similar calculations can be done for different values of $\beta$, but not discussed here, as the aim here is to demonstrate the utility of this widely used observable for DCC-type of studies.
Summary - We have discussed the utility and sensitivity of $\Phi$-measure for looking at DCC-type fluctuations. We have studied the properties of $\Phi$-measure for three different simple models of multiplicity distributions. Then we discussed the effect of various factors affecting the DCC-type fluctuations on $\Phi$-measure. These include the existence of background or non-DCC type pions in addition to those from DCC origin in an event, possible existence of multiple domains of DCC, decay of neutral pion to photons and the detector effects like efficiency and purity. We have then discussed extensively the variation of $\Phi$ with fraction of pions being DCC type ($\beta$) and fraction of events being DCC type ($\alpha$), within the framework of a simple DCC model. From the study using simulated data from VENUS and incorporating realistic detector effects, we found that for a typical example, such a measure is sensitive to DCC-type fluctuations with $\beta$ greater than 0.03 and for a $\beta = 0.25$, it is sensitive to DCC-type fluctuation with $\alpha$ greater than 0.01. With this study we have demonstrated that $\Phi$-measure is a sensitive observable to look for DCC-type fluctuations, while it preserves its other properties, which has made it a powerful measure in event-by-event studies.

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