Possibility of DCC formation in pp collisions at LHC energy via reaction-diffusion equation

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Abstract

There are indications of formation of a thermalized medium in high multiplicity pp collisions at LHC energy. It is possible that such a medium may reach high enough energy density/temperature so that a transient stage of quark-gluon plasma, where chiral symmetry is restored, may be achieved. Due to rapid 3-dimensional expansion, the system will quickly cool undergoing spontaneous chiral symmetry breaking transition. We study the dynamics of chiral field, after the symmetry breaking transition, for such an event using reaction-diffusion equation approach which we have recently applied for studying QCD transitions in relativistic heavy-ion collisions. We show that the interior of such a rapidly expanding system is likely to lead to the formation of a single large domain of disoriented chiral condensate (DCC) which has been a subject of intensive search in earlier experiments. We argue that large multiplicity pp collisions naturally give rise to required boundary conditions for the existence of slowly propagating front solutions of reaction-diffusion equation with resulting dynamics of chiral field leading to the formation of a large DCC domain.

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I. INTRODUCTION

Some years ago there was a lot of interest in exploring the very interesting possibility that extended regions, where the chiral field is misaligned from the true vacuum, may form in large multiplicity hadronic collisions or in heavy-ion collisions [1–4]. Such a region was called a disoriented chiral condensate (DCC). A large DCC domain would lead to spectacular signatures such as coherent emission of pions which can be detected [2] as anomalous fluctuations in the ratio $R$ of neutral pions to all pions. Original motivation for DCC came from Centauro events in cosmic ray experiments [2, 5]. However, even after intensive experimental search for DCC, no clear signals were found for its formation. Though it was generally agreed that in a heavy-ion collisions, chiral symmetry breaking transition will necessarily lead to formation of many DCC domains, expected size of such DCC domains was too small, and their numbers too large in any given event, that standard DCC signals were washed out. Indeed, from this perspective, heavy-ion collisions were not ideally suited for the detection of DCC. With a large volume system undergoing chiral symmetry breaking transition, multiple DCC domains necessarily result, and a clean signal of coherent pion emissions becomes very unlikely. In comparison, a pp collision, with a small volume system, could, in principle, lead to a single DCC domain.

We revisit the issue of formation of DCC, this time in the context of (very) large multiplicity pp collisions at LHC energies. Some of the earliest suggestions for DCC formation were actually made in the context of high multiplicity hadronic collisions. One would expect that a pp collisions, with a small volume system, could lead to a single DCC domain with a relatively cleaner signals of coherent pion emission. However, at previously attained energies, it was never clear whether the necessary condition for DCC formation, namely intermediate stage of chiral symmetry restoration, was ever achieved. Further, even if chiral symmetry was restored, the resulting DCC domains would have been too small of order few $\text{fm}^3$, in view of rapid roll down of the chiral field to the true vacuum. This will lead to only few pions from which a clear signal, say of neutral to charge particle ratio, would be hard to detect.

The conditions of chiral symmetry restoration seem much more favorable for the very high multiplicity pp collisions at LHC energy. Indeed there are strong indications that several signals, such as flow, formation of ridge, etc. which have been attributed to a thermalized
medium undergoing hydrodynamic expansion in heavy-ion collisions, may be present in such high energy pp collisions [6]. It is entirely possible that the energy density/temperature of such a medium may cross the chiral transition temperature. This will take care of the requirement of intermediate stage of chiral symmetry restoration for DCC formation. We show in this paper that the problem of rapid roll down of the chiral field to true vacuum is alleviated due to rapid three dimensional expansion of the system which makes reaction-diffusion equation applicable for governing the dynamics of chiral field for this system (with appropriate boundary conditions which, as we will show, naturally arise in these events). The expanding system leads to a DCC domain which stretches and becomes larger due to expansion, without the chiral field significantly rolling down (due to specific properties of solutions of reaction-diffusion equation). Eventually one gets a large DCC domain whose subsequent decay should lead to coherent pion emission.

We will not attempt to give any arguments in the favor of chiral symmetry restoration in these high multiplicity pp events at LHC, and just refer the reader to the literature where evidence for the possibility of a thermalized medium in such collisions has been discussed [6]. We will only focus on the evolution of chiral field in such a system. Starting from a chirally symmetry phase (after some very early stage of rapid thermalization of partons produced in a central pp collision), rapid 3-dimensional expansion will quickly set in. This is due to the small size of the system resulting from pp collision, compared to heavy-ion collisions where longitudinal expansion phase lasts for significant time. Resulting rapid cooling of system will lead to chiral symmetry breaking with the chiral field achieving some value in the vacuum manifold. With explicit symmetry breaking term for the chiral effective potential being small, any value in the vacuum manifold will be (roughly) equally likely, leading to formation of a domain where chiral field is likely to be initially misaligned from the true vacuum. This will be a DCC domain. Standard estimates for such a domain (from earlier investigations) lead to typical size of coherence length of order 1 fm. The field will also roll down to the true vacuum rapidly in time of order few fm. It is very hard to detect such a DCC domain as this will lead to very small number of coherent pions.

This is where the role of reaction-diffusion equation become important. Reaction-diffusion equations [7–9], are usually studied for biological systems, e.g. population genetics, and chemical systems. Interestingly, typical solution of such equations, with appropriate boundary conditions, consists of a traveling front with well defined profile, quite like the profile
of the interface in a first order transition case \cite{7,9}. This happens even when the underlying transition is a continuous transition or a crossover. In a previous work we have demonstrated that such propagating front solutions, separating the two QCD phases, exist for chiral phase transition and confinement-deconfinement (C-D) transition in QCD even when the underlying transition is a cross-over or a continuous transition \cite{10}. We utilize the fact that the only difference between the field equations in relativistic field theory case and the reaction-diffusion case is the absence of second order time derivative in the latter case. Thus, correspondence between the two cases is easily established in the presence of strong dissipation term leading to a dominant first order time derivative term. Such a dissipative term arises due to plasma expansion in the form of the Hubble term. Further, we had argued that the required boundary conditions for the existence of such a traveling front naturally arise in the context of relativistic heavy-ion collision experiments (RHICE).

We extend that analysis \cite{10} to the case of high multiplicity pp collisions at LHC energy. As we are interested in the formation of DCC, we focus here on the chiral transition. We argue that here also appropriate boundary conditions naturally arise which are suitable for the existence of propagating front solutions. One important difference between the analysis in \cite{10} and the present case is that previously we considered propagating front solutions separating chirally symmetric phase from the chiral symmetry broken phase. Here, in view of our focus on DCC formation, we consider the situation when the (approximate) chiral symmetry is spontaneously broken after an early stage of chiral symmetry restoration. We then consider the interior of the system to be such that chiral field is disoriented there from the true vacuum, while it lies in the true vacuum outside. This constitutes the initial profile of the chiral field which gives the appropriate boundary conditions for the existence of propagating front solutions for the reaction-diffusion equation. We study evolution of this profile as the system undergoes rapid 3-dimensional expansion. The other requirement for the applicability of reaction-diffusion approximation for this case is presence of strong dissipation. This is automatically satisfied due to dissipation term (the Hubble term) arising from 3-dimensional spherical expansion (as well as due to coupling of the chiral field with other field modes).

We will show that the propagating front solution delays the roll down of the chiral field in the interior of the region towards the true vacuum. At the same time rapid expansion stretches the interior to a size of several fm radius before the field significantly rolls down
towards the true vacuum. Resulting system constitutes a large, single, DCC domain which should lead to relatively clear signal of coherent pion emission (e.g. in terms of the distribution of neutral to charged pion ratio).

We mention that in this paper we have ignored the effects of thermal fluctuations. Such fluctuations are important and they will lead to some variations in the chiral field within a domain. However, in our model DCC formation results after chiral symmetry breakdown when the system undergoes rapid 3-dimensional expansion, hence rapid cooling. Thus, presumably, thermal fluctuations will remain under control. Main point is that large DCC domain here results starting from a single small domain which stretches by rapid expansion and the only role thermal fluctuations can play is to fluctuate the field of this single DCC domain around the average disoriented value. These considerations have to be augmented with considerations of the quantum decay of the DCC domain into pions which will put final limit on the growth of DCC domains in our model.

The paper is organized in the following manner. In Sec. II, we provide a brief review of DCC formation. Sec. III reviews basic physics of reaction diffusion equations where we discuss that the dynamics of chiral order parameter for chiral symmetry breaking transition with dissipative dynamics is governed by one such equation, specifically, the Newell-Whitehead equation [10]. Sec.IV discusses the basic physics of our model and Sec.V presents results for the DCC formation. Conclusion are presented in section VI.

II. DISORIENTED CHIRAL CONDENSATE

Formation of disoriented chiral condensates (DCC) in laboratory experiments was intensively investigated some time ago. DCC refers to the formation of a chiral condensate in an extended domain, such that the direction of the condensate is misaligned from the true vacuum direction. It is expected that as the chiral field relaxes to the true vacuum in such a domain, it will lead to coherent emission of pions. A motivation for the formation of such domains came from Centauro events in cosmic ray collisions [5]. It was suggested in ref[2] that the anomalous fluctuations in neutral to charge pion ratio observed in the Centauro (and anti-Centauro) events in cosmic ray collisions, could be due to the formation of a large region of DCC. This was termed as the Baked Alaska model in ref[2]. Formation of DCC was extensively investigated in high multiplicity hadronic collisions as well as in heavy-ion
A natural framework for the discussion of the formation of DCC is the linear sigma model as this provides a simple way to model chiral symmetry restoration at high temperatures. Formation of DCC naturally happens as the temperature drops down through the critical temperature, and the chiral field picks up random directions in the vacuum manifold in different regions in the physical space. We will work within the framework of linear sigma model with the Lagrangian density given by,

$$L = \frac{1}{2} \partial_\mu \Phi \partial^\mu \Phi - V(\Phi, T) \quad (1)$$

where the finite temperature effective potential $V(\Phi, T)$ at one loop order is given by [11],

$$V = \frac{m_\sigma^2}{4} \left( \frac{T^2}{T_c^2} - 1 \right) |\Phi|^2 + \lambda |\Phi|^4 - H\sigma \quad (2)$$

Here the chiral field $\Phi$ is an $O(4)$ vector with components $\Phi = (\vec{\pi}, \sigma)$, and $T$ is the temperature. Values of different parameters is taken as $m_\sigma = 600\text{ MeV}$, $\lambda \simeq 4.5$, $H = (120\text{ MeV})^3$ and $T_c \simeq 200\text{ MeV}$.

FIG. 1: Effective potential for the chiral field $\Phi$. $P$ denotes the true vacuum on the (approximately degenerate) vacuum manifold while $*$ marks the value of the chiral field inside a DCC domain which is disoriented from the true vacuum direction.

In the chiral limit, spontaneous breaking of chiral symmetry (for $T < T_c$) implies that
the vacuum corresponds to some specific point on the vacuum manifold $S^3$ with all points on $S^3$ being equally likely. This is not the situation in the presence of explicit symmetry breaking, as there is a unique vacuum state as shown in Fig.1. However, one may expect that this preference for the true vacuum may be insignificant during very early stages in a rapidly cooled system, due to small pion mass. Thus, as the temperature drops below $T_c$, one expects that the chiral field will assume some arbitrarily chosen value in the (approximately degenerate) vacuum manifold within a correlation size domain. If this value differs from the true vacuum direction (as marked by $\ast$ in Fig.1) then this domain will correspond to a DCC which will subsequently decay by emission of coherent pions as the chiral field rolls down to the true vacuum. This essentially summarizes the conventional picture of the formation of a DCC domain.

III. REACTION-DIFFUSION EQUATION FOR CHIRAL TRANSITION

There is a wide veracity of reaction-diffusion equations, see, e.g. ref.[7, 8]. Previously we discussed [10] specific equations which can be identified with the field equations for the chiral transition and the C-D transition in QCD in strong dissipation limit, leading to slowly moving propagating front solutions. We then showed that in different situations in relativistic heavy-ion collisions, with realistic dissipation, propagating front solutions of these equations still persist, making the dynamics of the relevant transitions effectively like a first order phase transition. Here, we will recall the case of chiral transition from ref.[10] and adopt it for the situation for the evolution of field inside a DCC domain.

As we mentioned in the introduction, we will consider the case of high multiplicity pp collisions at LHC energy, assuming that the resulting partonic system undergoes a rapid 3-dimensional expansion. We take the field equations for the chiral field (from Eq.(1)) to be,

$$\ddot{\phi} - \nabla^2 \phi + \eta \dot{\phi} = -4\lambda \phi^3 + m(T)^2 \phi + H$$

$$m^2(T) = \frac{m^2 \sigma}{2} \left(1 - \frac{T^2}{T_c^2}\right)$$

Here $\Phi$ is taken to be along $\sigma$ direction only which we represent by $\phi$. This is for the sake of establishing correspondence with the reaction-diffusion equation. Later, when we consider the case of DCC, we will consider other components of the chiral field $\Phi$ as well. In
the above equation, the time derivatives are w.r.t the proper time $\tau$. The dissipation term $\eta$ is not a constant for expanding plasma. For the early stages in a heavy-ion collisions one normally takes Bjorken 1-D scaling solution case with $\eta = 1/\tau$, which eventually turns into a 3-dimensional spherical expansion for which $\eta = 3/\tau$. For the present case of pp collision, due to small system size, one expects 3-dimensional expansion to be applicable from very early stages (after time of order 1 fm). Hence, later on when we discuss the case of DCC, we will take $\eta = 3/\tau$.

Exact correspondence of the above equation with the reaction-diffusion equation was established in ref.[10] by neglecting the explicit breaking of chiral symmetry (i.e. $H = 0$ in Eq.(1)) and by considering the extreme dissipative case of large, constant, value of $\eta$ so that one could neglect the $\ddot{\phi}$ term. With rescaling of the variables as, $x \to m(T)x$, $\tau \to m(T)^2 \eta \tau$, and $\phi \to 2\sqrt{\lambda/m(T)}\phi$, the resulting equation is found to be,

$$\dot{\phi} = \nabla^2 \phi - \phi^3 + \phi$$  \hspace{1cm} (4)

This equation, in one dimension with $\nabla^2 \phi = d^2\phi/dx^2$, is exactly the same as the reaction-diffusion equation known as the Newell-Whitehead equation [7,8]. In that context, the term $d^2\phi/dx^2$ is identified as the diffusion term while the other term on the right hand side of Eq.(4) is the so called reaction term (representing reaction of members of biological species for the biological systems). Non-trivial traveling front solutions for the Newell-Whitehead equation arise with suitable boundary conditions, namely $\phi = 0$ and 1 at $x \to \pm \infty$. The analytical solution with these boundary conditions has the form,

$$\phi(z) = [1 + exp(z/\sqrt{2})]^{-1}$$  \hspace{1cm} (5)

where $z = x - v\tau$. $v$ is the velocity of the front [8] and has the value $v = 3/\sqrt{2}$ for this solution.

One can see from the general form of these reaction-diffusion equations, that such traveling front solutions will exist when the underlying potential allows for non-zero order parameter in the vacuum state, along with a local maximum of the potential [7,8]. The corresponding values of the order parameter provide the required boundary conditions for the propagating front solution. In ref.[10] we were interested in the dynamics of chiral symmetry breaking transition, hence we considered the two boundary values of the chiral field
to be the true vacuum value and the one corresponding to the central maximum of the potential, respectively. For the case with non-zero value of $H$ as in Eq.(3), the value of chiral field at one boundary was taken to be the (true) vacuum expectation value $\phi = \xi$ while the other boundary field value corresponded to the shifted central maximum of the potential as $\phi = \phi_0$ (see, Fig.1). The propagating front solution in Eq.(5), suitably modified for these changed boundary conditions is \[10\],

$$
\phi(z) = -\frac{(\xi - \phi_0)}{A_0}[1 + \exp\left(\frac{m(T)(|z| - R_0)}{\sqrt{2}}\right)]^{-1} + \xi
$$

(6)

where the normalization factor $A_0 = [1 + \exp(-\frac{m(T)R_0}{\sqrt{2}})]^{-1}$. Here, we have restored the original, unscaled, variable $z$. $|z|$ was used in order to have symmetric front on both sides of the plasma for the 1-d case with $R_0$ representing the width of the central part of the plasma. For the 3-dimensional case, $|z|$ is replaced by the radial coordinate $r$. (Also, for the present case of pp collisions, we will multiply $m(T)$ by 3 to represent a sharper variation of $\phi$ initially. Note, this will be just a suitable choice of initial profile and proper solution of propagating front will result quickly when the initial profile is evolved by the field equations.)

In ref.\[10\] we had calculated numerical solutions for the full Eq.(3), retaining the $\ddot{\phi}$ term. Correspondence with the analytical solution was achieved by considering a large, constant, value of $\eta$ which resulted in propagating fronts of the same form as discussed in literature for reaction-diffusion equations. Subsequently we relaxed this assumption of constant $T$ and studied proper time dependence of $T$ and $\eta$ for expanding QGP (still retaining the assumption of uniform temperature for studying front propagation as with spatially varying $T$ the effective potential also has to vary spatially and correspondence with reaction-diffusion equation becomes more complicated). We showed that the propagating front solution still exists with little modifications.

IV. DCC FORMATION VIA THE REACTION-DIFFUSION EQUATION

In the present work we are considering the situation of the evolution of the disoriented chiral field after chiral symmetry breaking transition. Thus the two boundary conditions for the propagating front solution have to be appropriately modified. The basic picture of DCC formation in this case will be taken as follows. In a high multiplicity pp collision, we will assume that a thermalized medium is created and that temperature/energy density of
this medium reaches sufficiently large value so that the (approximate) chiral symmetry is restored during very early stages. Due to very small size of the initial system, it undergoes 3-dimensional spherical expansion after a very short time of order 1-2 fm. This leads to rapid cooling of the system and the chiral symmetry is spontaneously broken. This is the starting point of our calculation, with initial profile of the chiral field in the interior of the system assuming some arbitrarily chosen value on the (approximately degenerate) vacuum manifold. We will consider the case of maximal disorientation when the field in the center of the parton system takes value at the saddle point opposite to the true vacuum on the vacuum manifold. Outside the system the chiral field was always in the true vacuum and we will assume that it continues to have close to the same value in somewhat interior regions as well (where temperature could be taken to develop similar value as the central temperature). This sets the two boundary conditions for the initial profile of the chiral field and we study whether an initial profile with such boundary conditions can lead to a propagating front solution. (We mention that for the sake of numerically integration of the differential equation, we need to fix the boundary conditions at \( r = 0 \) and for large \( r \). However, the initial profile taken has a plateau for small \( r \) hence the field is allowed to roll down freely in the region away from \( r = 0 \). Indeed, such a profile with the same boundary conditions shows rapid roll down for the symmetry restored potential where one does not expect any propagating solution. Also, for one dimensional case, we consider the chiral field to have symmetric profile about \( x = 0 \) and the boundary conditions are only fixed for large \( |x| \) with \( x = 0 \) point free to evolve via the differential equation. Exactly same results of propagating front solution are still obtained on both sides of \( x = 0 \).)

The profile of the chiral field in between the two boundary values (as discussed above) is taken to lie on the vacuum manifold and we choose this profile, for simplicity, to remain in the \( \sigma - \pi_3 \) plane. In such a DCC domain, the decay of the field will lead to emission only of neutral pions. If we had chosen the field to remain in any plane of \((\pi_1, \pi_2, \sigma)\), it would lead to emission only of charged pions. For a more general possibility, appropriate distribution of neutral and charged pions will be obtained.

Note that it is not immediately obvious that such boundary conditions should lead to a propagating front solution. For reaction-diffusion equations, the corresponding boundary condition is set for a local maximum of the potential, and not for a saddle point. However, it appears that the importance of maximum of the potential is in delaying the roll down of
the field from that point due to vanishing field derivative. In that situation, a saddle point
will also satisfy this requirement and propagating front solution should result. As we will
see, this intuition seems correct and we do find propagating solutions with this new type
of boundary conditions. We have checked that if the field at that boundary is taken even
close to the saddle point (say, within 10-20%), slowly propagating front still results and our
results remain essentially unaffected.

For the present case of 3-dimensional expansion, with spherical symmetry, will use the
field equations in spherical polar coordinates,

\[
\ddot{\Phi}_i - \frac{d^2 \Phi_i}{dr^2} - \frac{2}{r} \frac{d \Phi_i}{dr} + \frac{3}{\tau} + \eta'(T) \dot{\Phi}_i = -4\lambda |\Phi|^2 \Phi_i + m(T)^2 \Phi_i + H \delta_{i4}
\]  

(7)

where \(\Phi_i\) denote components of the O(4) vector \(\Phi\). For this 3-dimensional expansion case,
the temperature is taken to vary with proper time as,

\[
T(\tau) = T_0 \frac{\tau_0}{\tau}
\]  

(8)

The initial value of the temperature for field evolution is taken to be \(T = T_0 = 150\ \text{MeV}\),
at proper time \(\tau = \tau_0 = 2\ \text{fm}\). This stage corresponds to chiral symmetry broken phase.
The system is assumed to have reached a value larger than the critical temperature at an
earlier stage which allows for the chiral field to become disoriented after the transition. Here,
we have introduced a new dissipation parameter \(\eta'(T)\), in addition to the Hubble damping
coefficient \(3/\tau\) \[12\] \[13\]. \(\eta'\) represents dissipation due to coupling to the heat bath, or due to
other field modes (which could be fields other than the chiral field, or even high frequency
modes of the chiral field itself). The value of this dissipation parameter has been discussed
in literature (see, e.g. ref. \[12\] \[13\] and references therein). We mention that inclusion of \(\eta'\)
is not essential in our model of DCC formation as Hubble damping itself can be very large
at sufficiently early times. However, from general considerations, one will always expect
such an additional damping, and it certainly helps for getting a slow moving propagating
front leading to a large DCC domain. We will first take \(\eta' \propto T^2\) with the initial value
\(\eta' = 10\ \text{fm}^{-1}\) at \(\tau = \tau_0\). Subsequently we will also consider the case with constant, time
independent, \(\eta' = 20\ \text{fm}^{-1}\) and \(40\ \text{fm}^{-1}\). We consider these larger dissipation cases to allow
for the possibility of the chiral field coupling to other field modes, and to show that larger
dissipation can lead to much larger increase in DCC domain size in this model.
V. RESULTS

We now present results of field evolution via Eq.(7). The initial profile of the chiral field, at \( \tau = \tau_0 = 2 \text{ fm} \), is shown in Fig.2a. Solid curve shows the profile of the \( \sigma \) field which interpolates between the true vacuum value \( \sigma = 75.18 \text{ MeV} \) and the saddle point opposite to the true vacuum where \( \sigma = -49.25 \text{ MeV} \) (with \( \vec{\pi} = 0 \) at both these boundaries). Interpolating profile of \( \sigma \) is taken in accordance with Eq.(6) (for the 3-dimensional case with radial coordinate \( r \) as discussed there), with \( \phi_0 \) and \( \xi \) suitably replaced by the boundary conditions for the present case. Further, the chiral field is taken to lie everywhere on the (approximately degenerate) vacuum manifold, hence the \( \vec{\pi} \) field also varies in between the two boundary points, as shown by the dashed curve for \( \pi_3 \) in Fig.2a. This is fundamentally different from the case of chiral transition considered in our previous work where pion field was taken to be zero all along the profile of \( \sigma \) which interpolated between the true vacuum and the central maximum of the potential. We again mention that the choice of the chiral field to lie entirely in the \( \sigma - \pi_3 \) plane is just an example. Such a DCC will decay by emitting neutral pions. One could take a more general variation, in which case an appropriate distribution of neutral and charged pions will result.

We have taken the radius of the system to be about 2.5 fm assuming that the initial dense parton system in the pp collision would have undergone some expansion by the time this stage is achieved at \( \tau_0 = 2 \text{ fm} \). This initial profile is evolved using Eq.(7). Note that Eq.(7) is written in comoving coordinates. As the system is undergoing 3-dimensional scale invariant expansion, the physical distances have to be obtained by multiplying with the appropriate scale factor. For this purpose we have taken the velocity of the plasma at comoving distance \( r \) to be proportional to \( r \), with some maximum velocity at the boundary of the region (which we take as a sample value to be 0.9). Plots at subsequent stages are shown in Figs.2b-d with the x axis denoting the physical distance. This is where we see the importance of the front solution of the reaction-diffusion equation. Normally one would have expected that the field from the saddle point will roll down towards the true vacuum in a time scale of couple of fm within the whole system of size 2-3 fm. However, the front solution delays this roll down dramatically. The field retains its value close to the saddle point in a significant region for a long duration of time (due to slow motion of the front).

During this period, rapid expansion of the plasma stretches the whole system, thereby
stretching the region where the chiral field is close to the saddle point, hence disoriented. This leads to a DCC domain which is expanding and getting bigger without the chiral field in the interior rolling down towards the true vacuum. This is shown in Fig.2b (for the $\sigma$ field) and Fig.2c (for $\pi_3$). Note that stretching of a DCC domain costs energy and this should be properly accounted for by calculating back reaction of DCC stretching on the expanding plasma. However, for ultra relativistic pp collisions the expanding parton system will have very large kinetic energy, and the effects of back reaction of stretching of DCC domain will not be significant for the time scales considered here. Fig.2b shows the $\sigma$ field profile (dashed curve) at $\tau = 4$ fm clearly showing that the DCC domain (the region where the field is significantly disoriented from the true vacuum) has almost doubled in size. This means multiplication in number of coherent pions by a factor of 8 (compared to the number expected from the DCC domain of initial parton system size) when the DCC eventually decays. Fig.2d shows the situation at $\tau \simeq 7.2$ fm when the chiral field has significantly rolled down towards the true vacuum. One can say that the decay of DCC domain has set in by this stage. Eventually the DCC domain decays with chiral field rolling down to the true vacuum.

We now consider case of larger dissipation with constant $\eta'$. Figs.3a,b show the stages corresponding to the stages in Fig.2b,c,d for the case with constant $\eta' = 20$ fm$^{-1}$. Figs.3c,d show similar stages for constant $\eta' = 40$ fm$^{-1}$. We note significant increase in the stretching of DCC domains. In fact by $\tau = 7.2$ fm the fields have still not started significantly deviating from the disoriented value. We do not show plots for large $\tau$ because, as mentioned above, the decay of DCC domain by thermal fluctuations as well as quantum effects will limit the growth of DCC domain. It is not clear if such large and (quasi) constant values of $\eta'$ can be realistic. However, its significant effect on the formation of large DCC domains may be taken as a strong motivation for finding arguments/situations where such strong dissipation may be justified/applicable.

We had shown in ref.\cite{10} that the propagating front solutions we obtain are very robust and almost independent of the initial profile of the front taken. Thus our results obtained here are not very sensitive to the exact initial profile of the chiral field taken. A different profile would still lead to similar qualitative features of the evolution of the parton system and hence a DCC domain.
VI. CONCLUSIONS

We conclude by pointing out the important features of our analysis. We focus on high multiplicity pp collisions at LHC energy as potentially important for possible formation of single DCC domains. This is in contrast to heavy-ion collisions where necessarily one gets
FIG. 3: (a) and (b) show the profiles of the chiral field at the same stages as in Fig.2b,c and Fig.2d (starting with the same initial profiles as in Fig.2a). $\eta'$ is taken as constant for this case with value $20 \text{ fm}^{-1}$. Comparison with Fig.2 shows that DCC domain stretches to a much larger size in this case. (c) and (d) show similar stages as in (a) and (b), but now with even larger $\eta' = 40 \text{ fm}^{-1}$. We see much larger DCC domain resulting here.

multiple DCC domains where clean signature of coherent pions becomes difficult to detect. The problem of small size for pp collision (hence small DCC domain) is circumvented by showing the existence of slowly moving fronts governed by reaction-diffusion equation. This delays the roll down of the disoriented chiral field to the true vacuum significantly, while the system undergoes rapid three dimensional expansion. This leads to stretching of the initial DCC domain to a size of several fm which can lead to relatively clean signals of coherent pion emission.

Specific assumptions made in our model, such as the value of dissipation constant, initial profile, etc. are not expected to significantly change the main aspects of our results. In view of our previous results in ref.[10], the existence of slowly moving propagating front results under varied conditions and with widely different initial profiles. This is in complete
contrast to the usual expectation that the field should rapidly roll down to the true vacuum. Thus, high multiplicity pp collisions at LHC energy may be an ideal place to look for the long sought signatures of disoriented chiral condensates. The considerations presented here are about classical evolution of the chiral field in an expanding domain. As we mentioned above, considerations of thermal fluctuations and quantum decay of the DCC domain into pions will put the final constraint on the growth of DCC domains in our model.

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