PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 55, Nos 1 & 2
July & August 2000
pp. 53–62

Formation of disoriented chiral condensates in relativistic heavy-ion collisions

AJIT M SRIVASTAVA
Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India

Abstract. We present a brief review of the subject of disoriented chiral condensates (DCC). We describe the conventional scenarios for the formation of DCC which have been proposed in the literature. Observable signals, such as fluctuations in neutral to charged pion ratio, are discussed. We then discuss a novel scenario for DCC formation, recently proposed by us, where the entire region of hot partons can get converted into a single large DCC. Our arguments suggest that formation of such large DCC is unlikely in the collision of heavy nuclei, and ultra-high energy hadronic collisions may be better suited for this.

Keywords. Disoriented chiral condensate; pion condensate; quark-gluon plasma; thermal fluctuations.

PACS Nos 25.75.Gz; 12.38.Mh; 12.39.Fe

1. Introduction

Formation and detection of disoriented chiral condensates (DCC) in ultra-relativistic hadronic or heavy-ion collisions is an exciting possibility which has received much attention recently. By DCC one essentially means the formation of a chiral condensate in an extended domain, such that the direction of the condensate is misaligned from the true vacuum direction. Formation of such domains has been proposed by Anselm [1], by Blaizot and Krzywicki [2], and by Bjorken, Kowalski and Taylor [3] in the context of high multiplicity hadronic collisions, and by Rajagopal and Wilczek for relativistic heavy-ion collisions [4]. As the chiral field relaxes to the true vacuum in such a domain, it may lead to coherent emission of pions which will lead to anomalous fluctuations in the ratio of neutral pions to all pions [3,5]. The proposal of ref. [3] was motivated by the Centauro events in cosmic ray collisions [6].

Much of the discussion relating to DCC is in the context of linear sigma model where the basic physics of the formation and decay of DCC can be easily understood. Effective potential in the linear sigma model at finite temperature T is,

$$V_{\text{eff}} = \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 - \frac{\lambda(\sigma^2 + \vec{\pi}^2)}{2}\left(f_\pi^2 - \frac{m_\pi^2}{\lambda} - \frac{T^2}{2}\right) - f_\pi m_\pi^2 \sigma. \quad (1)$$

The last term leads to explicit symmetry breaking and is responsible for non-zero pion mass. We take m_π = 140 MeV, f_π = 94.5 MeV, and $\lambda \simeq 55$ (corresponding to $m_\sigma = 1$

GeV). In the chiral limit there is a second order phase transition with the critical temperature $T_c = \sqrt{2} f_\pi$ ($\simeq 134$ MeV for our choice of parameters). With non-zero quark masses, chiral symmetry is explicitly broken, and is only approximately restored at a temperature $\simeq 115$ MeV in the sense that the saddle point at the chiral angle $\theta = \pi$ disappears above this temperature. Figure 1 shows the shape of the effective potential at $T = 0$.

Explicit symmetry breaking lifts the degeneracy of vacuum and the true vacuum is shown by point P in figure 1. Inside a DCC domain, chiral field does not take value P, and is disoriented in this sense. Due to higher potential energy, this field rolls down towards the true vacuum (P) and oscillates about it resulting in the emission of coherent pions.

2. Conventional scenarios for DCC formation

Bjorken, Kowalski and Taylor suggested DCC formation for high multiplicity hadronic collisions [3]. It was proposed that ultra-high energy hadronic collisions will lead to a rapidly expanding *hot* partonic shell and that in the interior of the shell the chiral field may get misaligned from the true vacuum, resulting in the formation of DCC (figure 2). This was termed as the *baked Alaska* model.

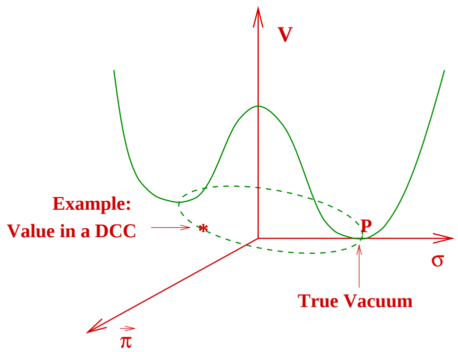

Figure 1. The effective potential for the linear sigma model at $T = 0$.

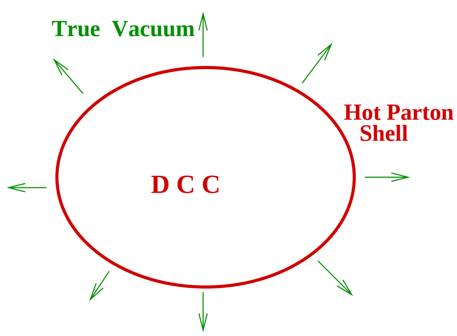

Figure 2. The baked Alaska model of DCC formation.

Possibility of DCC formation in the context of relativistic heavy-ion collisions was first proposed by Rajagopal and Wilczek who argued that a non-equilibrium dynamics during the chiral symmetry breaking phase transition may produce DCC domains [4]. It is important to appreciate that the most essential ingredient in almost all the models of DCC formation is the assumption of an intermediate, thermalized state with temperatures higher than T_c so that chiral symmetry is (approximately) restored. Such a state is very natural in the context of heavy-ion collisions, but may not be so natural for p–p collisions, or for cosmic ray collisions. Therefore, it is important to understand whether it is possible to *disorient* the chiral vacuum without invoking such an intermediate state. For example in the baked Alaska scenario discussed in ref. [3], it is not clear how the parton shell can disorient the vacuum without invoking thermal equilibrium. If thermal equilibrium is assumed, then it is not clear why one should not get multi domain formation in the interior of the shell. (Though, in this context, see ref. [7].)

If one assumes the existence of a thermalized, (approximately) chirally symmetric intermediate state, then DCC formation naturally happens as the system cools down through T_c. In the chiral limit, spontaneous breaking of chiral symmetry for temperatures below T_c implies that one particular point on the vacuum manifold S^3 will be chosen as the vacuum state in a given region of space, with all points on S^3 being equally likely. One may expect this to essentially hold true even in the presence of small pion mass. This will lead to a sort of domain structure in the physical space where each domain will have the chiral field aligned in a given direction, but the directions in different domains vary randomly, see figure 3.

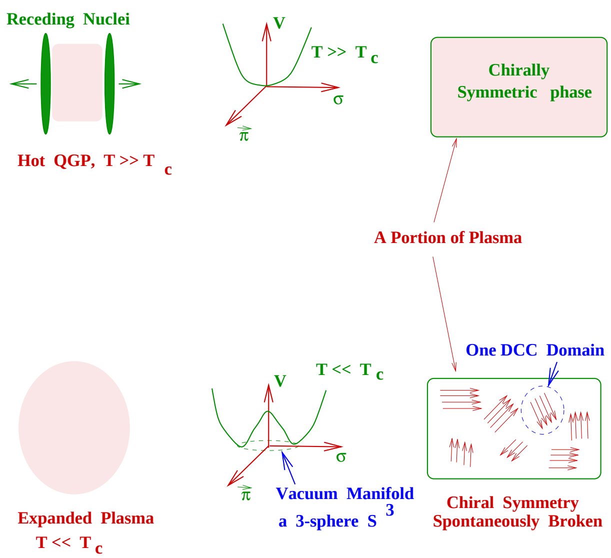

Figure 3. Domain formation in the chiral limit. Top figure shows the situation when chiral symmetry is restored at high temperatures. Vacuum expectation value of the chiral field is zero. Bottom figure shows the spontaneously broken case at low temperatures. Domain like regions form where the magnitude of the chiral field is uniform, but its direction in the vacuum manifold S^3 (denoted here by the arrow) varies from one domain to another. The direction is uniform inside a given domain.

This essentially summarizes the conventional picture of the formation of DCC domains. Formation of this type of domain structure in a phase transition has been extensively discussed in the context of topological defects in condensed matter physics and also in particle physics models of the early Universe. For an equilibrium, second order phase transition one expects [4] maximum size of domains to be of the order of m_π^{-1}. For such small domains, dramatic signals like fluctuation in the ratio *R* of neutral pions to all pions will not be observable. However, it has been suggested that in a non-equilibrium transition coherent pion emission may be observable [4], see also ref. [8] in this context. The amplification of long-wavelength pion modes due to parametric resonance, leading to larger DCC domains, has been discussed in ref. [9]. The effects of fluctuations on the growth of DCC domains, in the conventional picture, have been extensively studied in refs [10,11]. More recently, similar investigations, for the case of spherical expansion of the plasma, have been carried out in ref. [12]. Especially in the annealing scenario [13] it is suggested that reasonably large DCC domains of sizes as large as 5 fm may form. The issue of initial conditions for these scenarios, appropriate at high temperatures, has been discussed in refs [14], see also ref. [15] in this context.

Kapusta and Vischer [16] discussed the case of DCC formation for the first order transition case. They calculated the probability of forming a bubble with disoriented chiral field inside and estimated the roll down of the chiral field during the bubble expansion. Recently, Scavenius and Dumitru have proposed that a first order transition can naturally lead to quench like scenario which can then lead to growth of DCC domains [17].

3. Signals of DCC

The most dramatic, and hence most discussed, signature of DCC is the distribution for the ratio of neutral pions to all pions

$$f = \frac{n_{\pi_0}}{n_{\pi_0} + n_{\pi_\pm}}. \tag{2}$$

If pions are incoherently produced that the probability distribution of f will be a Gaussian, peaked at the value 1/3. Let us now consider the case when all the pions are produced from a single DCC. By taking the number of pions of a given Cartesian isospin to be proportional to π_i^2, i being that component of isospin, and by assuming that all points on the vacuum manifold S^3 are equally likely as initial condition, one can easily show that the probability distribution for f is given by [4],

$$P(f) = \frac{1}{2\sqrt{f}}. \tag{3}$$

This distribution differs markedly from the Gaussian expected for incoherently emitted pions, especially for lower values of f. Probability for very small value of f is essentially negligible for incoherent pions, while it can be substantial for the DCC case. Significant departures from the value 1/3 for f can then provide the cleanest evidence for the formation of a DCC.

It is clear, though, that if the pions were coming from several DCC domains, then the probability distribution will get modified. As the number of DCC domains becomes large, one will again recover the Gaussian distribution centered at 1/3. This makes it difficult to experimentally detect signal from each DCC domain [18]. Though, we may point out that the width of the Gaussian will directly depend on the DCC size and hence may provide a somewhat indirect evidence for DCC formation. Several methods for statistical analysis of the data have been proposed incorporating similar considerations. An interesting technique to identify the DCC signal from multi domain structure utilizes the wavelet method [19].

It seems clear that it is not easy to get large DCC domains in typical experimental situations. If the domains are only 2–3 fm size, or smaller (which seems quite plausible), then it may become very difficult to detect this signal. For example, a DCC domain of radius 3 fm will lead to only about 30 pions. Though, it may still be possible to separate out the DCC signal due to the fact that DCC pions will be expected to have very low P_T.

Many other signals have also been proposed for the detection of DCC. It has been suggested that DCC formation may lead to the amplification in isospin violating effects which may survive even in the situation of multi domain formation [20]. Other suggestions include the effect on the transverse momentum distribution of pions [21], increase in dilepton yield due to soft pion modes in DCC [22], two pion correlations arising from the squeezed state description of DCC [23], etc. Enhancement of baryon–antibaryon production resulting from disordered multiple DCC domain formation has also been proposed [24]. Here one focusses on the *junctions* of different DCC domains, instead of the interior of a domain itself. An important aspect of this signal is that the total yield of baryons and antibaryons is directly proportional to the number of DCC domains. Thus, this signal is stronger for smaller DCC domains.

4. Thermal fluctuations and Ginzburg regime

We now turn to the consideration of thermal fluctuations of correlated domains, in regards to these scenarios [25]. It is well known from the studies of domain formation in condensed matter systems and also in particle theory models of the early Universe (in the context of topological defect formation) that the picture of well defined domains makes sense only for temperatures below, what is known as, the Ginzburg temperature $T_{\rm G}$. This temperature can be thought of as the one above which a domain of correlation length size can easily fluctuate to the symmetric phase by thermal effects. Essentially, thermal fluctuations become dominant above this temperature and mean field description breaks down. Only when such fluctuations become sufficiently suppressed, can one talk about a well defined domain with the order parameter field taking well defined value inside the domain (and hence classical evolution etc.).

A crude estimate for the value of $T_{\rm G}$ can be obtained by equating the temperature to the energy density difference $\triangle V(T)$ between the bottom of the effective potential and the top of the central bump (in figure 1) times the volume of a region of size correlation length. For the correlation length we can take m_π^{-1}. We get

$$m_\pi^{-3} \triangle V(T) \simeq T, \tag{4}$$

where $\triangle V(T)$ can be calculated from eq. (1). An interesting aspect for the case of chiral transition is that the bottom of the potential is tilted. Thus the value of $T_{\rm G}$ (obtained by the above equation) will depend on the chiral angle θ. Here we mention that we are using the term Ginzburg temperature $T_{\rm G}$ to denote the temperature for the onset of thermal fluctuations destabilizing a DCC domain with certain specific value of θ. Thus, the true value of $T_{\rm G}$, in the sense of defining the critical regime where fluctuations are dominant, will correspond to the value of $T_{\rm G}$ at $\theta = \pi$. Using eq. (4), we find that the value of $T_{\rm G}$ is around 0.7 $T_{\rm c}$, see ref. [25].

There are two important points to be noted here. First, note that these values of $T_{\rm G}$ are significantly lower than the value of $T_{\rm c}$. It will take a long time for the system to cool down to this temperature from $T = T_{\rm c}$ (e.g. for the longitudinal expansion case temperature is proportional to $\tau^{-1/3}$). At this temperature the bottom of the effective potential is not that flat any more and the roll down of the chiral field will be much faster than what has been assumed in ref. [13]. The net result will be that the resulting DCC domain will not be as large. For, example, even though m_σ is small at $T_{\rm c}$, it can grow by a factor of about four when temperature drops to a value near 0.6$T_{\rm c}$, see ref. [4]. The resulting DCC domain may also then be smaller by a factor of two or so.

Second point is that, for any temperature above $T_{\rm G}$, regions of correlation length size (say $\simeq m_\pi^{-1}$) can easily fluctuate to chirally symmetric state. This has an interesting implication that DCC domains can form (if these domains can grow later) even in relatively lower energy heavy-ion collisions where the temperature of the system never rises to $T_{\rm c}$, but only rises up to $T_{\rm G}$. Unfortunately, this also implies that detection of DCC, though interesting by itself, will not imply that quark–gluon plasma phase (or, more precisely, chirally symmetric phase of matter) has been detected. A hot hadronic gas, in the spontaneously broken phase of chiral symmetry, can still lead to formation of DCC as long as its temperature reaches a value near $T_{\rm G}$, see ref. [25].

5. Formation of a single large DCC domain

We now discuss a novel possibility where a truly large, single, domain of DCC can form [26]. In our model, the entire region of hadronic system (or QGP, depending on the maximum temperature reached) gets converted to a single DCC domain which can have diameter as large as 14 fm (for gold nucleus). The main idea of our model is that during the rapid heating of the initial parton system, the chiral field is driven towards the value zero due to a rapidly changing effective potential. If heating is fast enough, and the maximum temperature reached is large enough, then the field picks up enough energy to overshoot the zero of the field and goes to the opposite point on the vacuum manifold. That is, starting from the true vacuum with chiral angle being zero, the field ends up at chiral angle = π. Most importantly, this happens for the entire region being heated up. The end result being that the entire region of the QGP ends up with chiral field being maximally disoriented, with the chiral angle being (close to) π. Eventually the field will roll down from there, emitting coherent pions in the process.

Due to thermal fluctuations, there will be some variation in the chiral angle over the entire DCC. We require that this variation remains relatively small, compared to the average disorientation of the chiral field from the true vacuum. We find that if the maximum temperature of the plasma is too large, or the rate of expansion too slow (e.g. in the longitudinal expansion model), then thermal fluctuations become dominant. Thermal fluctuations remain small only when spherical expansion is assumed even at very early stages of the plasma evolution. For that case we find allowed values of T_0 to lie roughly in the range 200–400 MeV, the lower bound arising due to the fact that for small T_0 the chiral field does not overshoot at all. Such values of T_0 are small compared to the maximum QGP temperatures expected in central events in the heavy-ion collisions involving very heavy nuclei at LHC and RHIC. This suggests that in such experiments, or for that matter, even in present heavy-ion experiments, observing a large DCC is more likely if one explores a range of centrality in selecting events, so that the possibility will be larger for the plasma temperature to lie in the allowed range for some events. Requirement of early three dimensional expansion suggests that possibility of a large single DCC domain may be larger for very energetic collisions of smaller nuclei, or even hadron–hadron collisions. In this sense, Tevatron may indeed be a good place to look for DCC [27]. This is, in some sense, consistent with what one expects from Centauro events where very heavy nuclei are not involved in the collision.

We now discuss the evolution of chiral field during heating and cooling of plasma in this model. In the beginning, system is at zero temperature with the chiral field being at the true vacuum (i.e. with chiral angle $\theta = 0$ with $< \sigma >= f_\pi$ and $< \pi_i >= 0$). If chiral field overshoots the central barrier to the opposite point on S^3 (i.e. $\theta = \pi$), it will sit at that saddle point until some fluctuation de-stabilizes it. More naturally, one will expect some pionic components to develop during overshooting, so chiral field will end up at some point close to $\theta = \pi$ on the vacuum manifold S^3.

To take care of thermal fluctuations, we evolve chiral field using the following Langevin equations [28]

$$\ddot{\Phi}_i \ + \ (\frac{\eta}{\tau} \ + \ \eta')\dot{\Phi}_i \ = \ -\frac{\partial V(\tau)}{\partial \Phi_i} \ + \ \xi_i(\tau), \tag{5}$$

where Φ_i represents components of the chiral field with $\Phi_i = \pi_i$ for $i = 1,2,3$ and $\Phi_4 = \sigma$. $V(\tau)$ is the effective potential (eq. (1)) with temperature T being time dependent. $\eta = 1$ for linear expansion and $\eta = 3$ for spherical expansion. η' is the friction coefficient due to coupling to the heat bath. $\xi_i(\tau)$ represents Gaussian white noise term with

$$\langle \xi_i(\tau) \rangle = 0,$$

$$\langle \xi_i(\tau_1), \xi_j(\tau_2) \rangle = \frac{2T}{\mathcal{V}} \eta' \delta_{ij} \delta(\tau_1 - \tau_2). \tag{6}$$

$\mathcal{V}$ is the volume of the region over which the chiral field is being evolved by above equations. We take $\eta' \sim 1$–4 fm^{-1}, and $\mathcal{V} \sim 5$ fm^3 (radius ~ 1 fm).

Now, the initial system of hadrons is at $T = 0$. Eventually the system achieves thermal equilibrium with a temperature $T = T_0$, and T starts decreasing due to expansion. What happens in the initial stage between $T = 0$, and $T = T_0$? Presumably the most natural approach is to think of the initial system of partons as being completely out of equilibrium which then thermalizes due to interactions. As thermalization proceeds, the system approaches a state in (quasi) equilibrium with a well defined temperature, which is the maximum temperature of the QGP. Thus, in this picture, at any instant during this intermediate stage, the system does not have a well defined temperature.

Unfortunately, it is hard to do any calculations within this picture, as one has to deal with a non-equilibrium system, which is approaching an equilibrium state. We assume a simplified picture wherein we think of the initial system of partons at zero temperature which is getting heated up, finally reaching the temperature T_0 of the QGP. In this picture, at any instant, one has a well defined temperature which first increases to a maximum value of T_0, and thereafter starts decreasing due to continued plasma expansion. Thus we take the system starting with $T = 0$, initially heating to $T = T_0$ (when interactions and secondary particle production dominate over expansion), subsequently cooling according to $T \sim \tau^{-\eta/3}$ (η = 1 (3) for linear (spherical) expansion). We take different types of temperature evolution for the heating stage and study the evolution of the chiral field due to the changing effective potential, see figure 4. DCC formation happens whenever σ field overshoots to the opposite side of S^3.

We see here that there are cases when σ field overshoots the central barrier and settles on the other side, eventually rolling down to the true vacuum. This corresponds to the formation of DCC. (We mention here that in this model also, DCC formation is possible even when $T_0 < T_c$. This again raises the issue, as we discussed above, whether DCC can be taken as a signal for chiral symmetry restoration.) Figure 5 shows parametric plot of the magnitude of $\vec{\pi}$ vs. σ, showing the evolution of the chiral field in the presence of thermal fluctuations. Here we have plotted different trajectories, difference arising due to the random nature of the noise term in eq. (5).

Different trajectories in figure 5 represent different parts of the DCC domain. If all parts correspond to rolling down roughly along one side of S^3, we will have approximate DCC and hence coherent pions. This is the same situation as for any large DCC. Importantly, we find that for large T all trajectories do not overshoot. Also pionic component are too large for large T, implying that DCC is not well defined. We find that this happens if T_0 is too large and for linear expansion (i.e. for slow cooling thermal fluctuation are always dominant). This leads us to important conclusion that such large DCC is expected to form only when T_0 lies in a window, roughly 200 MeV to 400 MeV, and with spherical expansion. Requirement of spherical expansion at very early stages suggests that heavy ions at LHC, RHIC are not suitable for large DCC. $p - p(p - \bar{p})$ collisions should be better suited for large DCC formation. This also seems consistent with Centauro events where heavy nuclei are not expected to be involved.

An interesting possibility of DCC formation in this model arises when chiral field in the entire DCC forms a patch around $\theta = \pi$, Subsequently, field rolls down covering S^3. This is like forming a huge Skyrmion like configuration. Evolution of this configuration leads to interesting signal due to the simple fact that for Skyrmion, spatial variation of the field is correlated with field variation in the internal space. This leads to well defined spatial variation of pion distribution since the ratio R of neutral to all pions depends only on one angle on S^3, say ϕ (see, ref. [26]). As the large Skyrmion collapses, it should acquire standard spherically symmetric configuration due to energetic reasons (as seen in texture simulations for structure formation in cosmology). Such a configuration has ϕ (and hence R) constant in conical shells about the axis connecting North and South poles. If we assume spherical expansion, (which seems reasonable for late stages) then (low P_T) pions will come out radially. For data collection, one can assume some North pole around collision point, and then collect pions in conical shells. This can be repeated with changing position of North pole over a full 4π range. For one choice of North pole, one should start getting pions of fixed R in each conical shell. In fact this seems an interesting method of analysis of particle distributions as it should detect any axially symmetric phenomenon (which leaves imprint on low P_T pions). It is straightforward to adapt this method for fixed target experiments by taking projections of conical shells.

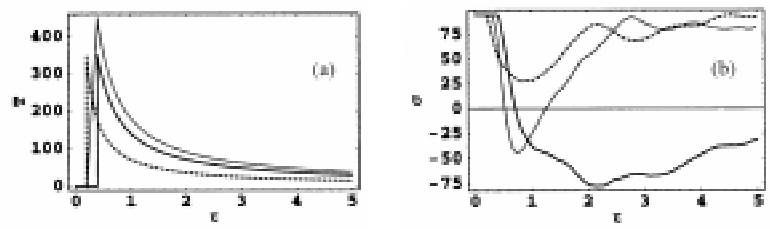

Figure 4. (**a**) shows the evolution of temperature and (**b**) shows corresponding evolution of σ field. τ is in fm and T and σ are in MeV.

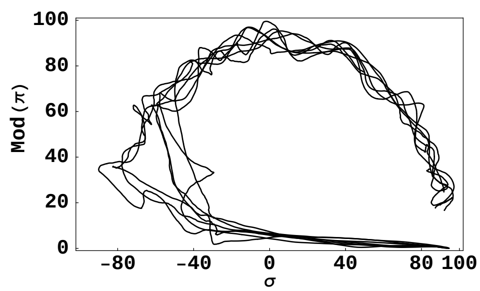

Figure 5. Parametric plot of the magnitude of $\vec{\pi}$ vs. σ (in MeV).

6. Conclusions

In conclusion, DCC is an exciting possibility to be probed in high energy colliders. DCC size is still the most crucial issue. There are variety of models which present possibilities for the formation and detection of DCC. An important point we have discussed here is that DCC detection may not necessarily mean the detection of an intermediate chirally symmetry phase. This is because DCC can form by thermal fluctuations at temperatures below T_c. Also, we have discussed a new possibility of forming truly large DCC where almost the entire hot region may convert to a single DCC. We have also discussed an interesting phenomenon where spatial distribution of pions shows systematic variations due to the formation of non-trivial DCC structure. To detect this we propose a method of data analysis which can be useful in general and may detect any axially symmetry phenomenon which leaves imprints on low P_T pions.

Acknowledgement

I would like to thank the organizers and other participants for a great workshop.

References

[1] A A Anselm, *Phys. Lett.* **B217**, 169 (1989)
[2] J-P Blaizot and A Krzywicki, *Phys. Rev.* **D46**, 246 (1992)
[3] J D Bjorken, K L Kowalski and C C Taylor, preprint SLAC-PUB-6109, presented at the 7th Les Rencontres de Physique de la Vallee d'Aoste: Results and Perspectives in Particle Physics, La Thuile, Italy, 7–13 March 1993
[4] K Rajagopal and F Wilczek, *Nucl. Phys.* **B399**, 395 (1993); *Nucl. Phys.* **B404**, 577 (1993)
[5] J P Blaizot and D Diakonov, *Phys. Lett.* **B315**, 226 (1993)
[6] C M G Lattes, Y Fujimoto and S Hasegawa, *Phys. Rep.* **65**, 151 (1980)
L T Baradzei *et al*, *Nucl. Phys.* **B370**, 365 (1992), and references therein
[7] M Suzuki, *Phys. Rev.* **D54**, 3556 (1996)
[8] S Gavin, A Gocksch and R D Pisarski, *Phys. Rev. Lett.* **72**, 2143 (1994)
[9] D I Kaiser, *Phys. Rev.* **D59**, 117901 (1999)
H Hiro-Oka and H Minakata, *Phys. Rev.* **C61**, 044903 (2000)
[10] F Cooper, Y Kluger, E Mottola, and J P Paz, *Phys. Rev.* **D51**, 2377 (1995)
[11] D Boyanovsky, H J de Vega and R Holman, *Phys. Rev.* **D51**, 734 (1995)
D Boyanovsky, M D'Attanasio, H J de Vega and R Holman, *Phys. Rev.* **D54**, 1748 (1996)
[12] M A Lampert, J F Dawson and F Cooper, *Phys. Rev.* **D54**, 2213 (1996)
[13] S Gavin and B Müller, *Phys. Lett.* **B329**, 186 (1994)
M Asakawa, Z Huang and X N Wang, *Phys. Rev. Lett.* **74**, 3126 (1995)
[14] J Randrup, *Phys. Rev.* **D55**, 1188 (1997)
D Molnar, L P Csernai and Z I Lazar, *Phys. Rev.* **D58**, 114018 (1998)
[15] A Krzywicki and J Serreau, *Phys. Lett.* **B448**, 257 (1999)
[16] J I Kapusta, and A P Vischer, *Z. Phys.* **C75**, 507 (1997)
J I Kapusta, A P Vischer and R Venugopalan, *Phys. Rev.* **C51**, 901 (1995)
[17] O Scavenius and A Dumitru, *Phys. Rev. Lett.* **83**, 4697 (1999)
[18] WA98 Collaboration: T Nayak *et al*, *Nucl. Phys.* **A638** 249c (1998)
WA98 Collaboration: M M Aggarwal *et al*, *Phys. Lett.* **B420**, 169 (1998)
T D Cohen and C K Chow, nucl-th/9903029
[19] Z Huang, I Sarcevic, R Thews and X N Wang, *Phys. Rev.* **D54**, 750 (1996)
[20] T D Cohen, *Phys. Lett.* **B372**, 193 (1996)
[21] F Cooper, Y Kluger and E Mottola, preprint, LBL-38585 (1996)
[22] Z Huang, M Suzuki and X N Wang, *Phys. Rev.* **D50**, 2277 (1994)
V Koch, J Randrup, X-N Wang and Y Kluger, nucl-th/9712061
[23] H Hiro-Oka and H Minakata, *Phys. Lett.* **B425**, 129 (1998)
[24] J I Kapusta and A M Srivastava, *Phys. Rev.* **D52**, 2977 (1995)
[25] S Digal and A M Srivastava, *Mod. Phys. Lett.* **A13**, 2369 (1998)
[26] S Digal, R Ray, S Sengupta and A M Srivastava, hep-ph/9805227, *Int. J. Mod. Phys.* (in press)
[27] MiniMax Collaboration: J D Bjorken, for the collaboration, hep-ph/9610379
[28] T S Biro and C Greiner, *Phys. Rev. Lett.* **79**, 3138 (1997)
C Greiner, Z Xu, and T S Biro, hep-ph/9809461