Search for fingerprints of disoriented chiral condensates in cosmic ray showers

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Although the generation of disoriented chiral condensates (DCCs), where the order parameter for chiral symmetry breaking is misaligned with respect to the vacuum direction in isospin state, is quite natural in the theory of strong interactions, they have so far eluded experiments in accelerators and cosmic rays. If DCCs are formed in high-energy nuclear collisions, the relevant outcome are very large event-by-event fluctuations in the neutral-to-charged pion fraction. In this note we search for fingerprints of DCC formation in observables of ultra-high energy cosmic ray showers. We present simulation results for the depth of the maximum ($X_{\text{max}}$) and number of muons on the ground, evaluating their sensitivity to the neutral-to-charged pion fraction asymmetry produced in the primary interaction.

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I. INTRODUCTION

Almost forty years ago exotic, apparently hybrid and unexpected events, dubbed Centauros, were observed in cosmic ray (CR) experiments in emulsion chambers in Chacaltaya by Lattes and collaborators [1]. Those events were very different from what is commonly observed in CRs, exhibiting a large number of hadrons and a small number of electrons and gammas, which suggests the presence of very few rapid-gamma-decaying hadrons. So, a possible imbalance in the number of neutral to charged pions could be envisaged. The nature and reality of Centauro events started a long debate, that includes the re-examination of the original emulsion chamber plates, and is still not resolved [2–5].

Nevertheless, Centauro events were certainly an experimental motivation for the development of the theory of disoriented chiral condensates (DCCs) that started in the early 1990s [6–9]. For a detailed review, see Ref. [10]. Assuming that a given nuclear system could be heated above the critical (crossover) transition region for chiral symmetry restoration, i.e. for temperatures of the order of $180 – 190$ MeV [11], then quenched to low temperatures, the chiral condensate initially melted to zero could grow in any direction in isospin space. Besides the vacuum (stable) direction, it could build up as in a metastable, misaligned pseudo-vacuum state, and later decay to the true, chirally broken vacuum. The fact that DCCs could be formed in high-energy heavy ion collisions stimulated several theoretical advances and experimental searches [10]. Most likely the temperatures achieved in current heavy ion experiments are high enough to produce an approximately chirally symmetric quark-gluon plasma, and the following rapid expansion can cool the system back to the vacuum [12], so that the dynamics of chiral symmetry restoration and breakdown can be described in a quench scenario [9], so that the evolution of the order parameter can be much affected by an explosive behavior that naturally leads to large fluctuations and inhomogeneities [13–17].

Since, by assumption, the order parameter for chiral symmetry breaking, i.e. the chiral condensate, is misaligned with respect to the vacuum direction (associated with the $\sigma$-direction in effective models for strong interactions) in a DCC, this would be a natural candidate to explain the excessive production of hadrons unaccompanied by electrons and photons, suggesting the suppression of neutral pions with respect to charged pions.

Regardless of the outcome of the debate on the nature of Centauro events, DCC formation seems to be a quite natural phenomenon in the theory of strong interactions. However, given its symmetric nature (in isospin space), it should be washed out by standard event averaging methods. So far, there has been no evidence from colliders or CR experiments. Motivated by the possibility of attaining much higher statistics in current ultra-high energy cosmic ray (UHECR) experiments than in the past, so that an event-by-event analysis for very high-energy collisions can in principle be performed, we consider possible signatures of DCC production in CR air showers. If DCCs are formed in high-energy nuclear collisions in the atmosphere, the relevant outcome from the primary collision are very large event-by-event fluctuations in the neutral-to-charged pion fraction, and this could affect the nature of the subsequent atmospheric shower. Very preliminary, yet encouraging results were presented in Ref. [18].

In this paper we search for fingerprints of DCC formation in two different observables of UHECR showers. We present simulation results for the depth of the maximum ($X_{\text{max}}$) and number of muons on the ground, evaluat-
ing their sensitivity to the neutral-to-charged pion fraction asymmetry produced in the primary interaction. To model the effect from the presence of a DCC, we simply modify the neutral-to-charged pion fraction, assuming that the system follows the same kinematics, as will be detailed below. Although this is certainly a very crude description of the dynamics of the primary collision, we believe it captures the essential features that have to be tested in order to verify the feasibility of detecting DCCs in UHECR showers.

This paper is organized as follows. In Section II we briefly review some characteristics of DCCs, especially the Baked-Alaska scenario and the inverse square root distribution of the neutral pion fraction. In Section III the method for the simulation is presented. We use CORSika [19], a program for detailed simulation of extensive air showers initiated by high-energy cosmic ray particles. In Section IV we show and discuss our results. Section V contains our conclusions.

II. DCC FEATURES AND THE NEUTRAL PION FRACTION DISTRIBUTION

It is widely believed that for high enough energy densities, achieved e.g. by increasing dramatically the temperature, strong interactions becomes approximately chiral (it would be an exact symmetry only if current quarks were strictly massless), so that the chiral condensate, which is the order parameter for that transition, essentially vanishes. On the other hand, for low temperatures the chiral condensate acquires a non-vanishing value and breaks spontaneously the chiral symmetry of (massless) QCD [20].

In a given model, one can construct an effective potential for the chiral condensate degrees of freedom and study the mechanism of chiral symmetry restoration and breakdown. If we restrict our analysis to two flavors of light quarks, up and down, that can be easily accomplished by the linear sigma model coupled to quarks [21]. In that case, the effective degrees of freedom are pions, $\pi^a$, and the sigma, $\sigma$. In the high-temperature limit all field expectation values vanish, whereas in the vacuum one has $\langle \pi^a \rangle = 0$ and $\langle \sigma \rangle = f_\pi$, where $f_\pi$ is the pion decay constant.

The physical picture we have in mind is a very high-energy heavy ion collision that will create a hot quark-gluon plasma where chiral symmetry is approximately restored. As the plasma is quenched to low temperatures by expansion, the system will evolve to the vacuum emitting a large number of pions. However, the evolution can proceed along many different paths in chiral space before it finally reaches the true vacuum, i.e. it can “roll” into different directions, and the ratio of neutral to charged pions produced depends strongly on the chosen metastable state in each event. In other words, the misalignment of the vacuum is reflected in the distribution of produced pions, generating a coherent state and an anomaly in the ratio of charged to neutral pions. This effect will be, of course, washed out by event averages.

A more intuitive physical picture for the formation of DCCs, the Baked-Alaska scenario, was proposed by Bjorken and collaborators [7, 22, 23]. Consider a high-multiplicity collision at high energy. Before hadronization, most of the energy released at the collision point is carried away by the primary partons at nearly the speed of light. This hot and thin expanding shell isolates the relatively cold interior from the outer vacuum. As the state evolves, the interior cools down and what was before a global minimum becomes a local maximum. The symmetry is spontaneously broken and one of the pseudo-vacua should be chosen, with a slight preference for the true vacuum. However, if the lifetime of the shell is short enough, the quark condensate in the interior might be rotated from its ordinary direction, since it costs relatively little energy, $\epsilon \sim f_\pi^2 m_\pi^2 \approx 20$ MeV/fm$^3$ [10]. When the hot shell hadronizes, the reorientation induced by the external contact is reflected in the produced pions, which will be coherent and present fluctuations in an event-by-event analysis.

Assuming that the correlated region is large enough to be described semiclassically, one can use the linear sigma model with explicit symmetry breaking for the description of the dynamics [24]. Quantitatively, one can represent the shell of this fireball as the source of these excitations of pions:

$$\langle \sigma \rangle = f_\pi \langle \pi^a \rangle = J^a(x),$$

where $a$ is the isospin index. A spherically expanding shell is represented by

$$J^a(x) = J^a(t) \Theta(t-t_0) \delta(t-r),$$

with initial radius $r_0 = t_0$, where $t_0$ is the time where the expansion starts. After the hadronization, the currents $J^a(t)$ vanish and the fields $\pi^a$ decay towards the vacuum into freely propagating pions. So, the pion emission is characterized by the state

$$|\vec{J}\rangle = \mathcal{N} \exp \left( \sum_{a=1}^{3} \int \frac{d^3k}{(2\pi)^3} J^a(k) c^a(\vec{k}) \right) |0\rangle,$$

where $\mathcal{N}$ is a normalization factor, and the sum is over isospin directions $a = 1, 2, 3$. The creation operator of a pion with momentum $\vec{k}$ and isospin component $a$ is $c^a(\vec{k})$ and $J_a(\vec{k})$ is the 4-dimensional Fourier transform of the source $J^a(x)$ at $k^0 = \sqrt{\vec{k}^2 + m_\pi^2}$.

The number of pions follows a Poisson distribution with average

$$\pi^a(\vec{k}) = \langle \vec{J} | c^a(\vec{k}) c^a(\vec{k}) | \vec{J} \rangle = |J^a(\vec{k})|^2,$$

and the number of pions produced per unit phase space
is approximately given by \[10\]

\[
\frac{dN_{\pi}^{(j)}}{d^{3}k} \approx \frac{|J^{a}(\vec{k})|^{2}}{(2\pi)^{3}}.
\] (5)

Statistically, one expects that the magnitude and the chiral orientation of the source $J^{a}(\vec{k})$ will fluctuate event by event for each mode. Let us assume that the vacuum orientation is tilted into one of the pion directions, i.e.:

\[
\langle \sigma \rangle = f_{\pi} \cos \theta, \quad \langle \bar{\pi} \rangle = f_{\pi} \sin \theta \, \hat{u},
\] (6)

so that all relevant modes of chiral condensate point in the same direction $\hat{u}$ in isospin space:

\[
\vec{J}_{DCC}(\vec{k}) = J(\vec{k})\hat{u}.
\] (7)

In generic models of production the neutral pion fraction, defined as

\[
f \equiv \frac{N_{\pi^{0}}}{N_{\pi^{0}} + N_{\pi^{+}} + N_{\pi^{-}}},
\] (8)

is a binomial distribution with average $\bar{f} = 1/3$. In this way, in the limit of large numbers $N_{\pi^{+}}$, the probability of all pions being charged is very small. However, if pions are the product of a DCC decay, this probability is not negligible. In fact, if there is no privileged isospin direction, the vector $\hat{u}$ can point in any direction within the unit sphere. Then:

\[
f_{DCC} = \cos^{2} \theta,
\] (9)

where $\theta$ is the angle between the unit vector $\hat{u}$ and the $\pi^{0}$ direction. So, one finds the following well-known distribution for the neutral pion fraction [7,8]:

\[
dP = d(\cos \theta) = \left(\frac{1}{2 \cos \theta} \right) d(\cos^{2} \theta) = \frac{df}{2\sqrt{f}}.
\] (10)

The probability of less than 10% of pions be neutral, for instance, is $\sim 30\%$.

### III. DCC SIMULATIONS

The conditions of a high temperature initial state followed by a rapid cooling stage are both possible to happen in heavy ion collisions at the very high energies like those accessible at RHIC and to be reached at the LHC, as well as in UHECR collisions in the top of the atmosphere. The large aperture of a detector like that of the Pierre Auger Observatory [24] (combining shower sampling at ground level and longitudinal shower profile reconstruction) has been providing high quality data and unprecedented statistics in the field [25,27]. Therefore, even though the formation of a DCC is probably rare, we believe it is worth studying the implications of such events to the physics of showers generated by UHECR.

The neutral pion fraction distribution, Eq. (10), is at the basis of our strategy to search for DCC fingerprints in UHECR showers. Therefore, any investigation to measure the impact caused by the presence of a DCC should assess the sensitivity of a given observable with respect to the neutral pion fraction produced in the primary interaction. This fraction determines the initial distribution of particles between the electromagnetic and hadronic components of the showers. In this paper, we consider two observables which are usually measured by UHECR detectors: the slant depth in the atmosphere (defined as the integral of the atmosphere density along the shower axis $\int \rho dx$ and expressed in units of $g/cm^{2}$) at which the shower reaches its maximum development, $X_{\text{max}}$, and the number of muons on the ground $N_{\mu}$. It is known that the parameter $X_{\text{max}}$ is affected by the first interaction cross-section and its associated multiplicity and inelasticity [5].

If DCCs really exist, the conditions for them to be produced should include not only high energy densities, but the regions where such densities are achieved should not be small as well, since DCCs are considered “macroscopic” space-time regions where the chiral parameter is not oriented in the same direction as the vacuum. With those requirements in mind, we have chosen to work with Fe initiated showers at 10$^{19}$ eV. Then, central collisions are privileged over peripheral ones by selecting events with a large number of participating nucleons ($N_{\text{part}} > 40$) which, in turn, should lead to a higher multiplicity in the first interaction.

For all simulations presented in this work, we have used CORSIKA 6.617 [13] with the interaction models Sibyll 2.1 [28] and GHEISHA 2002d [29], for high and low energy processes, respectively. The DCC-like shower simulation chain is as follows: Large $N_{\text{part}}$ collisions are selected and their first secondaries (mostly pions and kaons) separated; after, some of the neutral pions in this sample are converted into charged ones; the resulting particle list is then inserted back into CORSIKA to proceed with usual cascade development through the atmosphere. Such a procedure was performed for several $\pi^{0}$ fractions and 2 different zenith angles. The first interaction slant depth ($X_{0}$) distribution for DCC-like showers will therefore be the same as for normal Fe initiated showers in central collisions. This is a valid assumption, since the DCC formation process takes place during a subsequent cooling stage of the initial hot plasma, with the first interaction cross section being the same as in a Fe-nucleus collision. We believe that even though the simulation approach adopted here is simplified, the essential features of the process are being taken into account.

1 For brevity, from now on we should refer to the slant depth as simply depth. However, the reader should be aware that in the literature the term depth may be used to refer to the integral of the atmosphere density along the vertical and not along the shower axis.
For comparison, proton initiated showers as well as normal Fe initiated ones were also generated. For the normal Fe case, we have produced both a sample rich in central collisions and another sample with all the centralities. For each shower we extract the value of $X_{\text{max}}$ and the number of muons on the ground.

**IV. DISCUSSION OF RESULTS**

From now on we shall identify our DCC-like Fe initiated showers by Fe+DCC. Fig. 1 shows the $X_{\text{max}}$ distribution of a vertical shower ($\theta = 0$) corresponding to an extremely asymmetric situation ($f = 0$), that is, where all the initially produced $\pi^0$s are converted into $\pi^+/\pi^-$. For the distribution of Eq. (10), sharply peaked at $f = 0$, the probability for less than 1% of $\pi^0$s being produced is 10%. Four types of showers: normal Fe (central collision: Fe-Central), Fe (all centralities), Fe+DCC and proton initiated are shown. On can clearly see that both samples generated from a central collision have smaller than average $X_{\text{max}}$, since the higher the multiplicity in the first interaction the faster is the subsequent cascade development in the atmosphere. And there is essentially no difference between the Fe-Central and the Fe-DCC samples in terms of $X_{\text{max}}$, which might indicate that the early stage where the $\pi^0$ population is depleted together with the higher interaction probability due to the large multiplicity allow for a complete recovery of these particles in the subsequent interactions. Nonetheless, it is clear that one should look at low $X_{\text{max}}$ events when searching for DCCs signatures, and this property is independent of the initial $\pi^0$ fraction.

![Figure 1](image1.png)  
**Figure 1:** Normalized $X_{\text{max}}$ distributions for vertical showers initiated by Fe (central collision), Fe+DCC, Fe and proton with $E = 10^{19}$ eV.

Another feature which can be appreciated in Fig. 1 is the smaller $X_{\text{max}}$ fluctuations for Fe-DCC and Fe-Central as compared to those of proton and Fe with all centralities. This is to be expected, since the fluctuations in $X_{\text{max}}$ have basically two components: the ones in the first interaction slant depth $X_0$ (which, in turn, depends on the interaction cross-section) and those introduced by the cascade growth up to the maximum. The latter depends on the initial shower size (the multiplicity), in average being smaller for high multiplicity events, i.e. those found in the central collisions.

![Figure 2](image2.png)  
**Figure 2:** Normalized distributions of the number of $\mu^+ + \mu^-$ on the ground for vertical showers initiated by Fe (central collision), Fe+DCC, Fe and proton with $E = 10^{19}$ eV.

The muon number distributions on the ground for the same showers described above are shown in Fig. 2. As expected, increasing the number of initial charged pions will lead to a corresponding larger density of muons on the ground as the products of the charged pions decay.

As one combines both pieces of information ($X_{\text{max}}$ and $N_\mu$), one finds a good separation between the Fe-DCC...
Figure 4: Depth of the maximum versus number of $\mu^+ + \mu^-$ on the ground for showers with $\theta = 38$ degrees initiated by Fe (central collision), Fe+DCC, Fe and proton with $E = 10^{19}$ eV for different $\pi^0$ fractions: $f=0.0$ (top left), 0.25 (top right), 0.50 (middle left), 0.75 (middle right) and 1.0 (bottom left). Bottom right: merit factor (Eq. 11) as a function of $f$.

A fit to the binned $X_{\text{max}} \times N_{\mu}$ distribution provides $(1.96 \pm 0.13) \times 10^{-6}$ g/cm$^2$/muon.

sample and all the other populations, as can be seen from Fig. 3. When collisions with all the centralities are allowed, iron showers exhibit a positive correlation between $X_{\text{max}}$ and $N_\mu$. The correlation is such that showers reaching maximum development at increasingly larger slant depths produce, in turn, a higher muon density at ground level, due to the decrease in the attenuation in the atmosphere from $X_{\text{max}}$ to the ground.

Whereas for Fe-Central showers one sees no correlation between $X_{\text{max}}$ and $N_\mu$, for the case of Fe-DCC showers, instead, a small anti-correlation of about 1.96 g/cm$^2$/10$^6$ muons is present$^2$, as can be seen from Fig. 3. Such an inverted correlation can be understood remembering the additional correlation between $X_{\text{max}}$ and the multiplicity in the first interaction, with low $X_{\text{max}}$ events corresponding, in average, to high multiplicity. As we convert neutral pions to charged ones, high multiplicity (small $X_{\text{max}}$) events show a larger muon density on the ground as compared to low multiplicity ones (large $X_{\text{max}}$).

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$^2$ A fit to the binned $X_{\text{max}} \times N_\mu$ distribution provides $(1.96 \pm 0.13) \times 10^{-6}$ g/cm$^2$/muon.
V. CONCLUSIONS

The recent increase in quality and statistics of UHECR data brings the possibility to look for exotic phenomena as well as rare phenomena within the Standard Model. Among the latter, DCCs have been predicted about twenty years ago, yet never detected due to their elusive character.

In this paper, using air shower simulations, we searched for fingerprints of DCCs formed in ultra-high-energy ($E \sim 10^{19}$ eV) central iron collisions in the upper atmosphere. In particular, we studied the influence of the DCC formation on the observables $X_{\text{max}}$ and $N_\mu$, via the asymmetry in the neutral-to-charged pion ratio in the primary collision. For comparison, we considered also regular air showers generated by protons and iron.

Since DCCs are expected to be formed in central collisions, which lead to smaller than average values of $X_{\text{max}}$ (a difference of about 40 g/cm$^2$ as compared to iron, for instance), one should concentrate searches within this region of shower depth. For the same reason, if DCC events are present they should yield small fluctuations in $X_{\text{max}}$. However, based only on the behavior of this observable one can not distinguish between an iron shower and a central collision and one produced in the presence of a DCC.

The formation of DCCs is associated with large event-by-event fluctuations in the ratio of neutral to charged pions, $f$. In particular, for $f$ large or small as compared to 1/3, one should expect a sizable change in the muon density on the ground, especially for vertical showers. This fact was noticed in the preliminary study of Ref. [18]. In the extreme case of $f = 0$, where DCC events lead to muon-rich showers, we showed that this signature distinguishes between the cases of iron (even for central collisions) and a DCC event. For large $f$, one can also separate these two cases due to the large depletion of muons on the ground. Even in this case, the signature is not contaminated by proton events.

For vertical showers, there is a clear anti-correlation between $X_{\text{max}}$ and $N_\mu$. This comes about since there is a correlation between $X_{\text{max}}$ and the first interaction multiplicity, as was discussed in the previous section. This behavior is not expected in a regular iron shower. In fact, for iron, due to atmospheric attenuation, one would expect a positive correlation.

Even though the analysis presented here is very simplified, it has the advantage of providing a setup that is totally under control for simulations, and we believe it contains the essential ingredients of the phenomena considered. Nevertheless, a more realistic study, that should contain a description of the dynamics of DCC formation, especially its dependence on energy, is certainly necessary.

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