T864 (MINIMAX): A SEARCH FOR DISORIENTED CHIRAL CONDENSATE AT THE FERMILAB COLLIDER

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A small test/experiment has been performed at the Fermilab Collider to measure charged particle and photon multiplicities in the forward direction, $\eta \approx 4.1$. The primary goal is to search for disoriented chiral condensate (DCC). The experiment and analysis methods are described, and preliminary results of the DCC search are presented.

1 Introduction

In this talk I will describe the status of a small test/experiment (T864 (MiniMax)) designed to search for disoriented chiral condensate (DCC) and performed over the last three years at the TeVatron collider. The origins of MiniMax go back earlier to an initiative designed to provide the SSC with a full-acceptance detector (FAD). [1] During the associated workshop activity, it was acutely realized that some of the physics goals were accessible already at Fermilab. A collaboration was created (MAX) and their proposal was considered in the fall of 1992 by the Fermilab program committee, but was rejected. We decided not to give up, reduced the scope considerably, and on April 1, 1993, resubmitted the revised MiniMax proposal. It was conditionally approved by the director in late May of that year.

The experimental goals of MiniMax are as follows:

1. Demonstrate that experimentation in the far-forward direction in collider mode is feasible.

2. Search for the anomalies (Centauro, anti-Centauro (JACEE)) reported by the cosmic-ray community in this region of phase space.

3. Search for disoriented chiral condensate.

4. Contribute to general multiparticle-production phenomenology.

[a]See the MiniMax web pages *http://fnmine.fnal.gov* for more information about the experiment, including a collaboration list, beautiful pictures, and links to papers and transparency copies from talks.

2 Physics

The primary motivation for our enterprise has been the search for DCC. By DCC we mean a piece of strong-interaction vacuum with a rotated value of its chiral order parameter. The QCD vacuum contains a boson condensate, like the Higgs sector of electroweak theory. This condensate arises as a consequence of the spontaneous breaking of the chiral $SU(2) \times SU(2) = O(4)$ symmetry of QCD. The collective excitations of this condensate are the pions (Goldstone bosons), and would be strictly massless were the chiral symmetry exact. The condensate transforms as a 4-vector $(\sigma, \vec{\pi})$ and in ordinary vacuum points in the sigma direction. But perhaps in the interior of high-energy collision fireballs the orientation is different. If so, the piece of disoriented vacuum will eventually decay into true vacuum, and the decay products will be a pulse of coherent semiclassical pion field carrying the quantum numbers of the disoriented vacuum. In particular all decay pions in a given event will have the same (Cartesian) isospin. This feature leads to the basic signature for DCC searches, namely large fluctuations in the fraction of produced pions which are neutral:

$$f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+} + N_{\pi^-}} \ . \tag{1}$$

If the orientation of the chiral order parameter is random event-by-event, then

$$\frac{dN}{df} = \frac{1}{2\sqrt{f}} \ , \tag{2}$$

which is very different from the conventional wisdom, as embodied in Monte-Carlo event generators.

The cosmic ray evidence on Centauro and anti-Centauro events serves as a motivation for this idea. The cosmic-ray observations are sensitive to particles produced in the forward direction at large cms pseudorapidities. This has also served as motivation for the choice of acceptance for the MiniMax experiment. The experiment is sensitive to the same leading-particle region as the JACEE event described by Lord and Iwai,[2] and we have used that event as a prototype of what might be out there waiting to be observed.

While there has been a great deal of theoretical interest in DCC production,[3] there still is not enough development to create production models appropriate to our experimental needs. We have done a small amount of work ourselves, but have been too busy with the experiment to go very far in that direction. At present the operational MiniMax definition of DCC is as follows:

DCC is a cluster of pions with near-identical momenta and a distribution of neutral fraction which follows the DCC inverse-square-root rule. Consequently, in the DCC rest frame the pions have low kinetic energy and the mass of the DCC "snowball" will be only slightly larger than N times the pion mass, with N the multiplicity of the pion cluster. A very important parameter is the mean kinetic energy of these pions in the DCC rest frame. It can be expected to be quite small, perhaps no larger than the pion rest mass, provided the proper time of the DCC decay process is relatively large, leading to a large emission volume or area.

It is very advantageous for us in the MiniMax experiment to search for DCC produced with high transverse velocity. When this occurs the products of the DCC "snowball" are boosted into a "coreless jet" which occupies a quite limited region of (lego) phase space. Even this limited region is at least as large as the MiniMax lego acceptance. However, for experiments with large acceptance, the question of (lego) coherence length will enter. It is not clear that, even if DCC is produced over all of (lego) phase space, the chiral order parameter will point in a common direction. The characteristic length may be no larger than one or two lego units, and attention will have to be paid to this problem in experiments with acceptance large compared to MiniMax.

In any case, for us the important parameters for the simulation of DCC are the distribution of multiplicity N, the rest-frame kinetic-energy distribution, the DCC transverse-velocity distribution, and to some extent the pseudorapidity distribution.

3 History and Description of the Apparatus

The location in space of the MiniMax experiment was at the C0 collision region of the Fermilab TeVatron proton-antiproton collider. The C0 region is precisely halfway between D0 and CDF (B0), the experiments responsible for the top-quark discovery. The MiniMax location in time coincided with the top-quark data-acquisition period (1993-1996). From proposal submission to removal and dismantling of the apparatus, the time interval was just under three years. The location of the experiment in fiscal space was near the imaginary axis.

The location in phase space is illustrated in Fig. 1. The heart of the apparatus consisted of a 24-plane MWPC tracking telescope, backed up with a 28-element lead-scintillator electromagnetic calorimeter. Behind the eighth MWPC plane was placed a remotely movable lead converter. In most runs the lead thickness was chosen to be 1 X_0 which allowed photon conversion products to be detected via tracking information in the rear 16 MWPC planes. Trigger scintillator was embedded in the telescope as well, at the position of the lead and just in front of the calorimeter. The lego acceptance of this telescope was a circle of radius 0.65 centered at pseudorapidity $\eta = 4.1$ in the proton

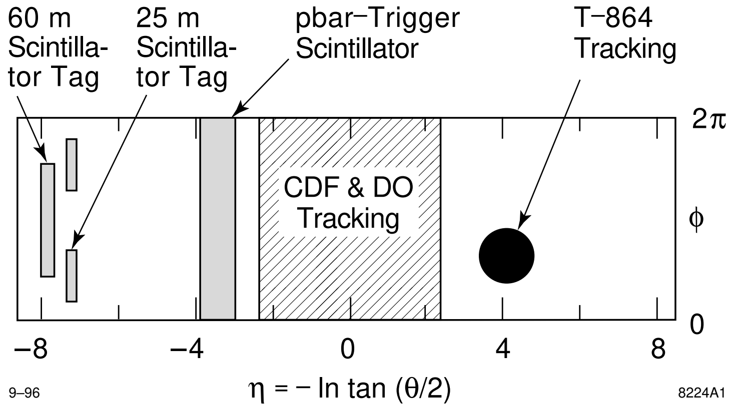

Figure 1: MiniMax lego acceptance.

hemisphere.

In addition, an 8-element trigger hodoscope was placed around the beam in the antiproton hemisphere at $\eta \approx -3.0$. Much further upstream were placed additional counters designed to tag events with leading antinucleons. Two 10 cm $\times$ 10 cm hadron calorimeter modules (plus some pieces of scintillator) were placed astride the beampipe 25 meters upstream in the antiproton direction. One of the calorimeters was sensitive to 400 GeV antiprotons produced in the collision and swept into the the calorimeter by accelerator magnets; the other was sensitive to antineutrons produced at zero degrees. Despite the poor containment, these detectors provide quite clean tags for the production of antibaryons of $x_F \approx 0.5$. Even further upstream, at 60 meters in the antiproton direction, scintillator was placed adjacent to the beampipe. These were sensitive to $\bar{p}$'s of $x_F \approx 0.85 - 0.90$ which were swept by the machine magnets into the beampipe in the proximity of the scintillators. All these upstream tags were, under most of our running conditions, very pure. The evidence for this comes from the multiplicity distribution of the $\eta = -3$ trigger hodoscope, which shows high sensitivity to the nature of the tag and/or trigger.

In this short report it is not possible to describe in much detail the actual operating conditions. While it was anticipated that creating a clean trigger would be difficult, this turned out to be straightforward. The background rate from beam halo/beam-gas interactions was in most of our production running lower that 1 percent and well understood. The trigger cross section was 35–40 mb, out of a total nondiffractive, inelastic proton-antiproton cross section of 50

mb. Luminosity was determined from the D0 luminosity monitors, the known ratio of the machine beta-functions at C0 and D0, and the known values of the individual bunch intensities.

The data acquisition system ran at about 50 Hz, and in the production running in 1995 and early 1996 about 8 million events were recorded.

The tracking system (about 3000 wires) and its readout performed well, with wire efficiencies well above 95 percent. The main difficulty is that the background levels in the chambers, originating from secondaries from real proton-antiproton collision products, were quite large. The mean occupancy per wire ranged from 10 percent to 30 percent depending upon location. The distribution of background hit density follows a simple rule: directly proportional to the distance from the luminous region and inversely proportional to the distance from the beam axis. Despite this large occupancy, we have in the late runs, comprising over half the data set, been able to reconstruct tracks in all but the last few percent of the events, thanks to the simple geometry and the large number of planes.

Simulations of the physics and detector response have been developed. PYTHIA is used as the event generator for generic events.[4] In addition a DCC event generator has been created, using the definitions of DCC described in Section 2. The particles so created are tracked via GEANT [5] through the detector. The main sources of background (*e.g.* floor, beampipe, apparatus material, etc.) are included. While the results of the simulation agree well with early data taken with the original beampipe, later data taken after the beampipe designed for the experiment was installed in early 1995 do not agree. The simulation underestimates the observed background by nearly a factor two; this discrepancy remains not understood.

Track-finding algorithms are still under development. At present, two different combinatorial trackers are in use. Separate track segments are constructed for the front eight planes and the back sixteen, with matching then performed at the position of the lead. As mentioned above the track-finding efficiency remains high for all but the last few percent or so of the data set. There are many candidate algorithms for finding γ's. Our present definition for a gamma conversion candidate is at least one track originating at the lead which points toward the luminous region. The simulations are used to estimate the efficiency of these algorithms. For the γ's, the efficiency is about 65 percent per conversion above a gamma laboratory energy of 3 GeV; below that the efficiency drops off rapidly.

4 Analysis Strategy

There are many obstacles for the MiniMax experiment to overcome in trying to infer the presence or absence of DCC in the data. There is no momentum information for charged tracks and γ's. Not all charged tracks are pions. Neutral pions are not reconstructed; indeed most of the time only one of the two γ's enter the quite limited MiniMax acceptance. Only half of the γ's convert in the lead. Efficiencies are of course not 100 percent, and they may be correlated, in particular, with multiplicity or background level. Nevertheless we have reason to believe that a meaningful analysis still can be done.

The main reason for our cautious optimism is that we have identified robust observables which are insensitive to most (but of course not all) of the aforementioned problems.[6] Our raw data consist of a table of probabilities $P(n_{\rm ch}, n_\gamma)$ for finding per event $n_{\rm ch}$ charged tracks and n_γ converted γ's. It is, as is not uncommon in such analyses, convenient to trade in this table for the table of bivariate normalized factorial moments constructed from the generating function for P:

$$G(z_{ch}, z_\gamma) = \sum z_{ch}^{n_{ch}}\, z_\gamma^{n_\gamma}\, P\left(n_{ch}, n_\gamma\right) \ . \tag{3}$$

We then try to relate this generating function to the ideal one describing the production of pions, generic or DCC. Most models of pion production (including our DCC model) assume some parent distribution $P(N)$ for producing N pions, followed by a binomial distribution for the partition into charged and neutral pions. We call this hypothesis generic pion production.

$$p(n_{ch}, n_0) = P(N)\binom{N}{n_0} f^{n_0}(1-f)^{n_{ch}} \qquad N = n_{ch} + n_0 \qquad f \approx \frac{1}{3} \ . \tag{4}$$

From these equations, it is easy to work out that the bivariate generating function describing production of charged and neutral pions is obtained from the single-variable generating function for the parent pions by replacing the pion fugacity variable z by a linear combination of the fugacities for the charged and neutral pions, weighted by the assumed neutral fraction $f \cong 1/3$. That is, if

$$G(z) = \sum z^N P(N) \tag{5}$$

then

$$G(z_{ch}, z_0) = G(f z_0 + (1-f)\, z_{ch}) \ . \tag{6}$$

Furthermore if the efficiency $\epsilon_{\rm ch}$ for finding a charged track from a parent charged pion and the efficiencies ϵ_0, ϵ_1, ϵ_2 for our finding 0, 1, or 2 γ's respectively are uncorrelated with multiplicity or environment, then the generating function for the MiniMax observables as defined above will be again obtained by replacing the pion fugacities by weighted fugacities: [7]

$$\begin{aligned} z_{ch} &\rightarrow \epsilon\, z_{ch} + (1-\epsilon) \\ z_0 &\rightarrow \epsilon_0 + \epsilon_1 z_\gamma + \epsilon_2 z_\gamma^2 \;. \end{aligned} \tag{7}$$

The main consequence of these convolutions is that, within the above assumptions, the generating function for the MiniMax bivariate moments is actually only a function of a single variable, not two, if the underlying production dynamics is generic. Therefore there must be many relations between the elements of the array of bivariate factorial moments measured by MiniMax, if generic production prevails. And it turns out that many of these relations are independent of the efficiency factors introduced above. Especially robust variables turn out to be ratios of the normalized bivariate factorial moments. For example, the quantities

$$R_{ij} = \frac{F_{ij}}{F_{i+j,0}} \tag{8}$$

with

$$F_{ij} = \frac{1}{\langle n_{ch}\rangle^i \langle n_\gamma\rangle^j} \left(\frac{\partial}{\partial z_{ch}}\right)^i \left(\frac{\partial}{\partial z_\gamma}\right)^j G(z_{ch}, z_\gamma)\Bigg|_{z_{ch}=z_\gamma=1} \tag{9}$$

can all be shown to equal unity when $j = 1$, if efficiencies are uncorrelated and the pion production is generic. In general, the remaining R_{ij} depend only on one additional parameter, proportional to the probability that both γ's from a parent π^0 are detected.

What happens if the production mechanism is not generic, but DCC? Then one can work out, not quite as easily as for generic production, Eq. (4), that all one has to do is to take the binomial distribution with neutral fraction f and integrate f over the inverse-square-root weight to get the DCC distribution. This leads to a MiniMax bivariate generating function which depends nontrivially on two variables. But again when calculating the above ratios R_{ij} the uncorrelated efficiency factors do not appear, and the values of the R_{ij} are nowhere near unity. For example,

$$R_{i1} = \frac{1}{(1+i)} \;. \tag{10}$$

Therefore the direct extraction of the R_{ij} from the data is our starting strategy. As will be seen in the next section, the results are sensible. The omitted effects, such as correlated efficiencies, etc. then are attacked as perturbations on this first order analysis, with PYTHIA/GEANT simulations being the main tool for assessment of their importance.

Table 1: Values of r_{ij} from the data and Monte Carlo

r_{ij}	PYTHIA and GEANT	pure DCC	DCC and GEANT	Data
r_{11}	$1.01 \pm .02$	0.500	$0.56 \pm .01$	$0.98 \pm .01$
r_{21}	$1.02 \pm .05$	0.333	$0.40 \pm .03$	$0.99 \pm .02$
r_{31}	$1.09 \pm .14$	0.250	$0.34 \pm .05$	$1.03 \pm .04$

5 Results

The charged-particle multiplicity distribution is smooth and is reasonably fit with a negative-binomial form with a k-parameter in the neighborhood of 3. The value of $dN/d\eta$ at $\eta = 4$, as estimated from the raw data, is about 3, consistent with a smooth extrapolation of UA5 data. Errors in these numbers are dominated by systematic effects, which require more study to determine. Therefore we do not choose to quote detailed numbers at this time; overall efficiency determinations and normalizations will be the business of the late, not early, analysis program.

As described in the previous section, our efforts have been concentrated on the DCC search via the factorial-moment robust variables, where the absolute efficiencies play a less central role in the first-order analysis. The very preliminary values of the low-order R_{ij}'s is given in Table I, together with the expectations from simulations for generic and/or pure DCC pion production. These results show no significant dependence upon running conditions, including the presence or absence of the $x_F = 0.5, 0.9$ tags. Detailed limits on the fraction of DCC allowed by the data must await better understanding of systematic errors, as well as more detailed modeling of DCC production mechanisms, but it appears that we are already sensitive to 10–20 percent DCC admixtures.

6 Outlook

The basic goals of the MiniMax experiment are being met. Good data on charged-particle and converted-photon spectra have been acquired, and a preliminary search for DCC carried out. A search for unusual events such as Centauro and JACEE has also been made. Nothing singular has been seen, but firm conclusions depend upon validating our estimates of detection efficiency, especially for converted photons. We should in the future be able to contribute to the study of intermittency, and will attempt to measure the momentum spectra of K_S's and Λ's.

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