

## OBSERVING DISORIENTED CHIRAL CONDENSATES\*

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### ABSTRACT

We speculate that, in very high energy hadronic collisions, large fireballs may be produced with interiors which have anomalous chiral order parameters. Such a process would result in radiation of pions with distinctive momentum and isospin distributions, and may provide an explanation of Centauro and related phenomena in cosmic-ray events. The phenomenology of such events is reviewed, with emphasis on the possibility of observing such phenomena at Fermilab experiment T-864 (MiniMax), or at a Full Acceptance Detector (FAD) at the SSC.

### 1. Introduction

The vacuum is a very complicated place. As understood in quantum field theory, it can carry long-range order parameters, and thus it may be possible to study coherent phenomena associated with the alteration of the properties of the vacuum over long distances [1].

The first question one might ask is: "suppose that one does disorient the vacuum over some region of spacetime. How would one know?" We address this question in the context of the vacuum of the strong interactions [2-8]. This is almost degenerate owing to the approximate  $SU(2)_L \times SU(2)_R$  chiral symmetry. This symmetry is spontaneously broken in a way analogous to what is supposed to occur in the Higgs sector. This phenomenon is described by the chiral fields

$$\Phi = \sigma + i\vec{\tau} \cdot \vec{\pi} \Leftrightarrow q_L \bar{q}_R,$$

where

$$q = \begin{pmatrix} u \\ d \end{pmatrix}$$

and

$$\langle \Phi \rangle = \langle \sigma \rangle = f_\pi \neq 0.$$

The fields  $(\sigma, \vec{\pi})$  form an  $O(4)$  4-vector.

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Now suppose that in some region of spacetime the vacuum orientation differs, and is tilted into one of the pion directions

$$\langle \sigma \rangle = f_\pi \cos \theta \quad \langle \vec{\pi} \rangle = f_\pi \hat{u} \sin \theta .$$

If we neglect the interface between this region and the exterior, it costs relatively little energy,

$$\Delta E = \frac{1}{2} \mu_\pi^2 \langle \pi^2 \rangle = \frac{1}{2} \mu_\pi^2 f_\pi^2 \sin^2 \theta = (10 \text{ MeV}/fm^3) \sin^2 \theta,$$

arising from the pion mass in the effective Hamiltonian, to disorient the vacuum.

How might such a region be formed? Consider high-multiplicity, high transverse energy collisions at collider energies. The collision debris from such an interaction will expand outward at essentially the speed of light for a considerable distance before hadronization occurs. At intermediate times, it is thus plausible that the geometry is that of a ‘hot’, relatively thin shell surrounding a ‘cool’ interior. (While this picture has support even in the case of ideal hydrodynamic expansion [9], the opposite extreme of free-streaming, without local thermodynamic equilibrium is closer to the picture we have in mind.) Since the interior is protected from the exterior by the hot shell, there seems little reason to expect the interior orientation to be the same as the exterior.

These qualitative arguments can be made a little more substantive by appealing to a linear sigma-model description of the dynamics. The basic point is that if the interior is ‘cold’, and initially in a symmetric state, long-wavelength fluctuations will grow while short wave-length fluctuations will be suppressed due to the instability of the meta-stable state. Of course, eventually the finite mass of the pion will restore the interior to the ‘true’ vacuum, but numerical simulations suggest that excursions to ‘disoriented chiral condensates’ (dcc) may be possible [6-8]. Evidently, there are still many uncertainties and much work to do!

Eventually, after hadronization, the surface tension will cause the bubble of chiral condensate to collapse. The interior vacuum will align itself with the vacuum of the rest of the universe, radiating pions in the process. If the bubble of condensate is large enough to be semi-classical, then one can study the evolution of the condensate using the equations of motion of the sigma model. This process has a distinctive signature: it will be coherent, and event-by-event, of a given (cartesian) isospin. In events in which the deflection of the vacuum is in the  $\pi^0$  direction, the produced pions will be neutral; in other events in which the orientation is orthogonal to the  $\pi^0$  direction, the particles will be charged.

One can make a specific prediction for the distribution of the neutral fraction of such pions fairly easily. A priori, it is equally probable that the condensate will be disoriented towards any of the (cartesian) isospin directions. Remembering that the fields represent probability amplitudes, it follows that

$$P(f)df = \frac{df}{2\sqrt{f}},$$

where  $f$  is the fraction of the pions which are neutral [3].

Lest one worry that we are violating conservation of isospin in this argument, we note that it has a quantum mechanical analog. For simplicity, let us consider restricting the quantum mechanical amplitude describing the system to a single spacetime mode, and projecting onto a number basis. If the system started as an isosinglet, for instance, then this must be reflected in each element of the expansion of the amplitude: each such element must be annihilated by the isospin generators. It follows that such a state of (sharp) isospin zero must have an even number of pions in it, and must be of the form

$$|\psi\rangle = C_0^{(N)}(2a_+^\dagger a_-^\dagger - (a_0^\dagger)^2)^N |0\rangle,$$

where the  $a_i^\dagger$  are the pion creation operators. From this, it is possible to determine the probability for seeing  $2n$  neutral pions out of  $2N$  total pions in such a state [6,10]:

$$P(n, N) = \frac{(N!)^2 2^{2N} (2n)!}{(n!)^2 2^{2n} (2N+1)!}.$$

Using Stirling's approximation, it follows that  $P(n, N) \sim 1/\sqrt{n/N}$  in the limit that both  $n$  and  $N$  become large, thus recovering the  $1/\sqrt{f}$  found above.

This distribution is significantly different from the distributions normally expected in multiparticle production, even for fairly small values of  $N$ . In conventional multiparticle production, the distribution should be strongly peaked about  $f = 1/3$ . It is obvious that a high percentage of dcc's would produce events with anomalously small neutral fractions; by the same token, there would also be a significant number of events with anomalously large neutral fractions. We illustrate this by comparing the isosinglet dcc distribution with a binomial distribution with the same mean for  $N = 6$  in figures 1(a) and 1(b).

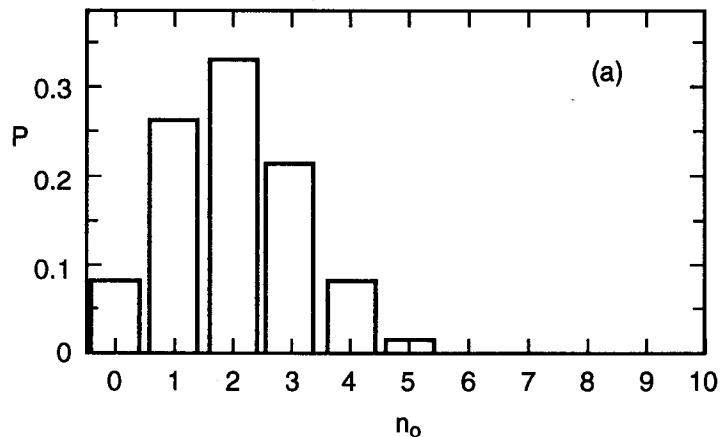


Figure 1 (a). Probability distributions of the number of neutral pions for total multiplicity  $N=6$  for the binomial distribution.

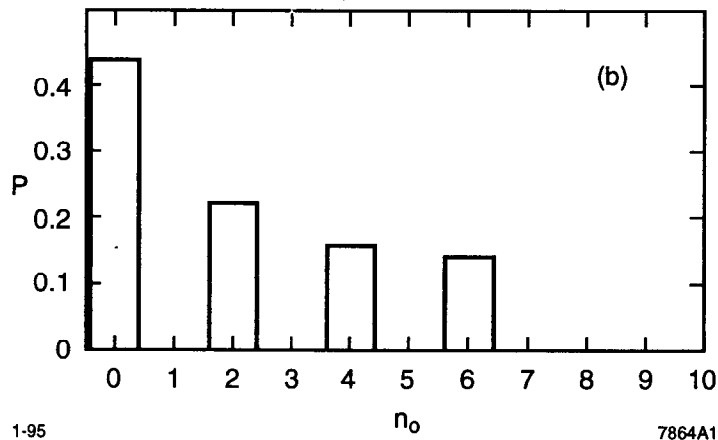


Figure 1 (b). Probability distributions of the number of neutral pions for total multiplicity  $N=6$  for the isosinglet dcc distribution.

Before turning to the question of production mechanisms, it is appropriate to pause for inspiration from cosmic ray experiments.

## 2. Are Centauro's Signals of Disoriented Chiral Condensates?

Centauro events are cosmic ray events exhibiting [11]:

- Large ( $\sim 100$ ) numbers of hadrons;
- Little apparent electromagnetic energy and hence, no  $\pi^0$ 's;
- 'High' hadronic  $p_t$ , reported as  $k_\gamma \langle p_t \rangle = 0.35 \pm .15 \text{ GeV}$ , where  $k_\gamma$  is the gamma-ray inelasticity.

In addition to the Centauro events, a class of hadron-enriched events has also been reported [12]. Cosmic ray events with  $\sum E_{tot} \geq 100 \text{ TeV}$  are presented on a scatter plot of the number of hadrons

$N_h$  versus the fraction  $Q_h = \sum E_h^\gamma / (\sum E_h^\gamma + \sum E_\gamma)$  of the visible energy which these hadrons constitute. When compared with Monte-Carlo simulations of families based on models of the strong interactions, and assuming that cosmic ray primaries are predominantly protons, there are far too many ( $\sim 20\%$ ) events in regions not populated by the Monte-Carlo. These events show fluctuations in hadron number and/or energy fraction.

Before continuing, it is probably necessary to briefly review the status of candidate Centauro events. The 5 'classic' Centauro events were seen in the two-storeyed emulsion chamber experiment of the Brazil-Japan collaboration, located at 5220 m at the Chacaltaya observatory in Bolivia. At least two additional candidate Centauro events have also been seen in Chacaltaya chambers. At least one additional candidate has been seen in the Pamir emulsion chamber experiment. On the other hand, it is claimed that Centauros have not been observed in emulsion chambers at Mt. Kanbala (5500 m, China-Japan Collaboration) or at Mt. Fuji (3750 m., Mt. Fuji Collaboration), despite comparable cumulative exposures [13]. More precisely, the China-Japan collaboration reports an upper limit of the fraction of such events among hadron families with energy greater than 100 TeV to be 3% at the 95% confidence level. This appears to be a limit incompatible with the rate at which Chacaltaya has observed Centauros. This comparison may be too glib, however, because of differences in emulsion chamber design and data analysis. Of particular importance may be the differing techniques for separating hadronic showers from others.

The two groups are similarly divided on the (non)observation of the more general class of hadron-enriched events mentioned above. In this context, the debate (which has been going on for over a decade) seems to reduce to a question of whether the data signal a change in the composition of cosmic ray primaries at these energies, or whether they signal a change in the hadronic interactions.

If these events are real, might they be signals of the formation of disoriented chiral condensates?

We begin with the characteristic feature of Centauro's and the hadron-enriched events: anomalously large amounts of energy in the hadron component. The suppression of  $\pi^0$ 's which this implies is often taken to indicate a suppression of pions altogether. The argument is basically statistical: one would ordinarily expect the neutral fraction to be given by essentially a binomial distribution, resulting in events sharply peaked about 1/3. As we have seen above, however, the distribution for an isospin-zero coherent state of pions is  $\sim 1/\sqrt{f}$ , with  $f \sim 0$  being the most probable fraction. (Note, however, that we still have  $\langle f \rangle = 1/3$ .) Thus, one is tempted to interpret the classic Centauro

events as signals of a disoriented chiral condensate.

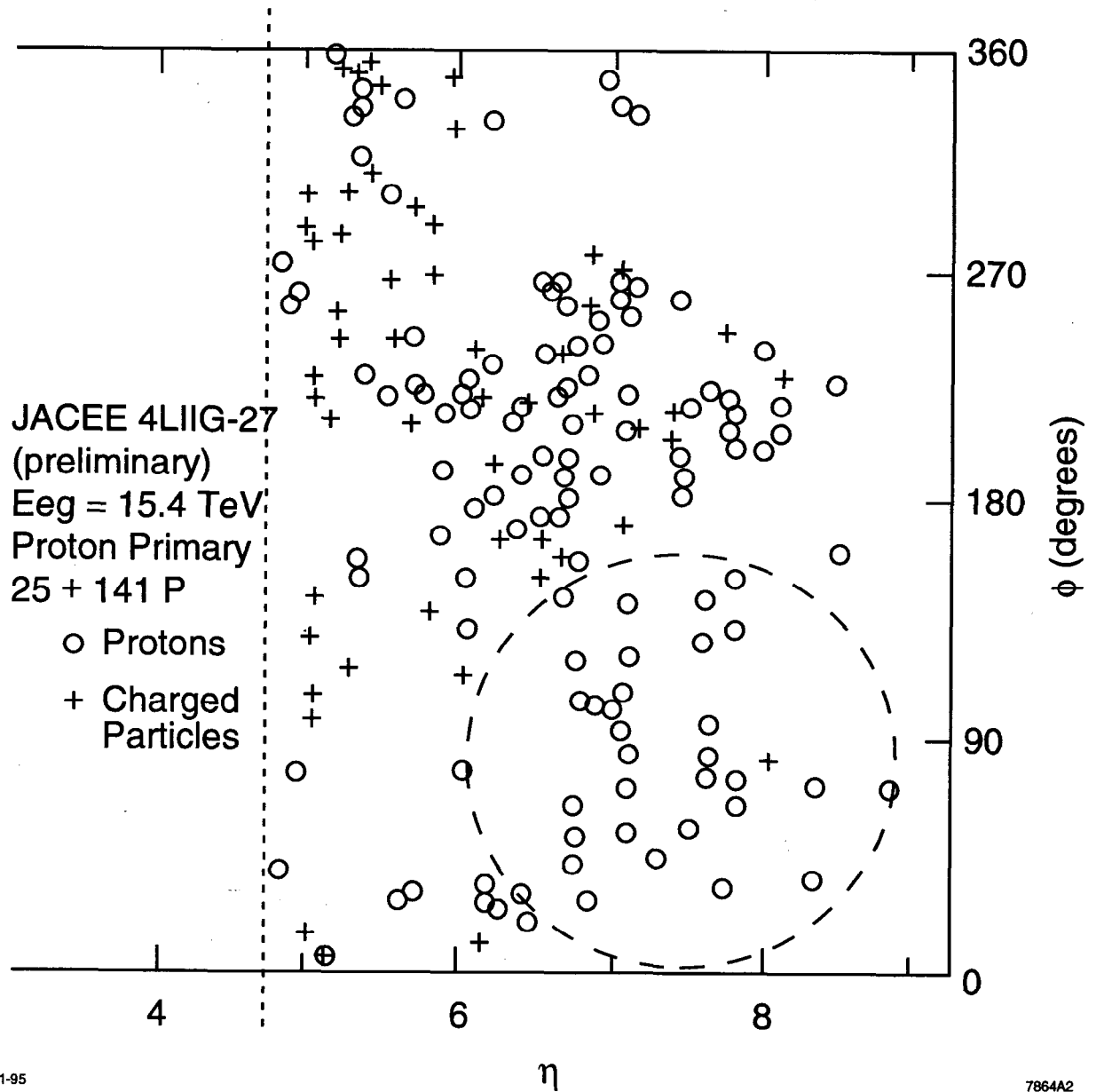


Figure 2. JACEE event [14] showing the leading particles  $\eta > 5$ . At lower rapidities the photon detection efficiency becomes small.

But what about the other end of the dcc distribution, where we expect events with an anomalously large neutral fraction? The JACEE collaboration has observed interesting candidate events [14], one of which we display in Figure 2. It is initiated by a single charged primary, and the collision occurs within the detector. Almost all the leading particles are photons. The  $\gamma$ 's appear to cluster into two groups. The leading cluster, indicated by the circle, consists of about 32  $\gamma$ 's with  $\langle p_t \rangle \approx 200$  MeV and only one accompanying charged particle. A possibly distinct cluster has three times as many  $\gamma$ 's as charged hadrons (about 54  $\gamma$ 's versus about 17 charged). This event is one out of a sample of 70 or so. The  $\gamma$ /charged ratio for the generic sample is unity; normal events are seen! However the events are found in the emulsion by scanning for the leading photon showers. So there is a "trigger bias" in favor of a large neutral fraction.

There have been three systematic searches for Centauros at the CERN collider at  $\sqrt{s} = 540$  GeV [15],  $\sqrt{s} = 546$  GeV [16], and  $\sqrt{s} = 900$  GeV [17] and all have yielded negative results. The UA5 Centauro searches [16, 17] definitively ruled out Centauros up to energies of  $\sqrt{s} = 900$  GeV; the experiment was rather inefficient in detecting photons, particularly in the forward direction, and provides no limits on anti-Centauros. The simplest reconciliation of these experiments with the cosmic ray events is that the experimental energies are below the threshold for the Centauro mechanism, which can be argued, on the basis of the analysis of the cosmic ray data, to be near or above Tevatron energies [6, 17, 18]. Nothing like Centauros have been seen so far at Fermilab, although a systematic search among minimum bias events has yet to be carried out. In this context, Goulios [18] has pointed out that at the Tevatron the  $\eta$ -distribution of a diffractively produced Centauro is such that events of this type would not have been observed in the 1988-89 run, in which data were collected requiring a coincidence between two scintillation counter arrays covering the region  $3.24 < |\eta| < 5.90$  on both sides of the interaction region. In any case, it appears to be very difficult for either CDF or D0 to efficiently count both low  $p_t$  charged particles and low  $p_t$  photons in the forward direction as dcc interpretation of the cosmic ray data suggests may really be required.

The upshot of all of this is that we regard the interpretation of the cosmic ray events in terms of dcc's as rather speculative. Nevertheless, we believe that this interpretation opens an avenue towards an experimental search for this phenomena.

### 3. How to find Disoriented Chiral Condensates

These cosmic ray data, if they are signals of dcc's, indicate that

the signal is rather clean in the forward direction. We now turn to the question of where one should look in an accelerator environment, using these events as a guide.

Centauro I was close enough to the Brazil-Japan emulsion chamber that the position of the interaction vertex could be determined by the angular divergence of the showers in the detector. What was measured is

$$\frac{\langle E_h^{(\gamma)} R_h \rangle}{H} = k_\gamma \langle p_t \rangle = 0.35 \pm 0.15 \text{ GeV},$$

where  $E_h^\gamma$  is the portion of a hadron's energy which is converted to (visible) electromagnetic energy,  $R_h$  is the distance of the hadron from the center of the event, and  $H$  is the height of production of the hadron. In order to determine  $p_t$ , however, one needs to know the value of the gamma-ray inelasticity,  $k_\gamma$ . The value of  $k_\gamma$  is usually quoted as  $k_\gamma \sim 0.2-0.4$ , with the lower end being preferred for nucleons, while the higher end is preferred for pions. Direct measurement of  $k_\gamma$  in emulsion chambers is impossible because of the high energy threshold ( $\sim 1 \text{ TeV}$ ). As a result, estimates are based on extrapolating accelerator data or on Monte-Carlo simulations. These seem to indicate that one should use  $k_\gamma \sim 0.4$  or larger [19]. We would thus estimate that  $\langle p_t \rangle \sim 0.875 \pm 0.375 \text{ GeV}$ , with large systematic uncertainty.

Note that most analyses of the Centauro events have followed the Japan-Brazil collaboration and have used  $k_\gamma = 0.2$ , based on the assumption that the hadrons are nucleons.

So where should one look for such events at the Tevatron? To really answer this question, one needs a better understanding of the overall event structure than is possible either from our theoretical speculations or from the Centauro data. In particular, we know essentially nothing about the central-region production of Centauros since the Chacaltaya detector is only sensitive to hadrons with typical hadronic transverse momenta for pseudorapidities of  $\eta \sim 9$  or greater. However, we can use the data to put upper limits on the central rapidity a Centauro fireball would have at the Tevatron.

For this purpose, we assume that Centauros are diffractive fireballs, recoiling against a proton or antiproton. This interpretation (with, however, the identification of the hadrons as nucleons) has been argued by K. Goulios [18]. Under such assumptions, the center of the Centauro fireball would be located at

$$\theta \sim \frac{\langle p_t \rangle}{(E/\langle N \rangle)}$$

where  $E = 900 \text{ GeV}$  is the Tevatron beam energy and  $\langle N \rangle = 75$  is the estimated mean multiplicity of the Centauro fireballs. Using the above estimate for  $p_t$  based on the assumption that the fireball is composed



of pions, we find that the central rapidity of a Centauro fireball at the Tevatron is

$$\eta_c \approx 3.3 \pm 0.5.$$

This number is essentially consistent with the JACEE event which we have suggested as an example of an anti-Centauro fluctuation. In this event, the photons have  $\langle p_t \rangle \sim 0.2 \text{ GeV}$ . The rapidity densities are comparable to those of the Centauro events, and thus we would estimate from this event that  $\eta_c \sim 4.1$  were it produced at the Tevatron.

Thus we conclude that in order to definitively search for Centauro events at the Tevatron, under the assumption that they represent signals of dcc's, one should be sensitive to fireballs of rapidity at least as high at  $\eta \sim 4$ .

Having discussed *where* one should look, we next turn to the question of *how* one should look for these events.

A useful way to assess the sensitivity of the dcc Centauro signature is to calculate the probability of observing an event with neutral fraction  $f$  smaller than some fixed value. For the anti-Centauro signature, one calculates the probability for observing  $f$  larger than some fixed value. In both cases, it is useful to study this as a function of the total pion multiplicity. Any contamination from conventional processes (which we illustrate using the binomial distribution) will fall off exponentially with increasing  $N$ , while the disoriented condensate part will give a constant contribution. So in principle one would search for a break in the falling exponential.

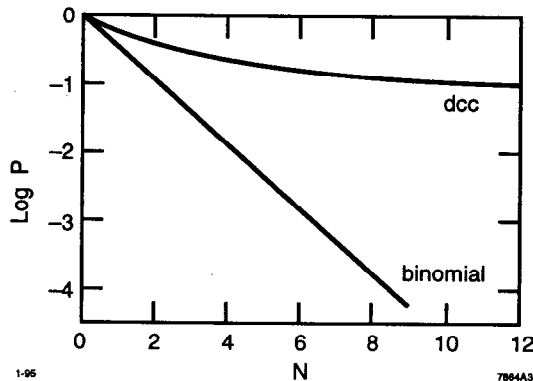


Figure 3.  $\text{Log}_{10}$  of the probability of finding anti-Centauro-like configurations ( $f > 0.9$ ) as a function of total multiplicity  $N$ . The top line represent  $P(f > 0.9)$  for a dcc while the lower line depicts  $P(f > 0.9)$  for the binomial distribution.

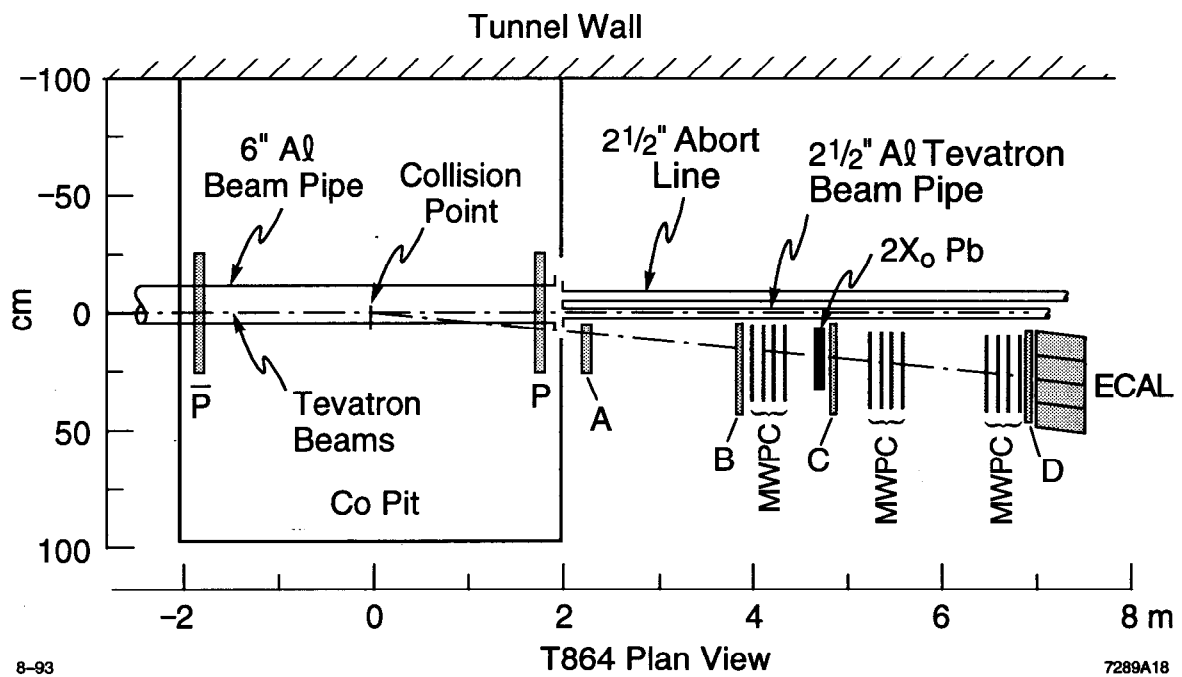
One observation which is useful in assessing how large the acceptance of a detector should be is that both the Centauro events and the JACEE event have multiplicity densities which are large compared compared to those of typical hadronic events. Just cutting on multiplicity is likely to enrich the sample rather dramatically.

#### **4. T-864 (MiniMax): A Chiral Condensate Search at the Tevatron**

The highest hadron collider energies are essential. However, at the Fermilab Tevatron, it appears to be very difficult for CDF or D0 to count both low- $p_t$  charged particles and low- $p_t$  photons efficiently, particularly in the far-forward direction. This experiment was part of the agenda of a proposal for a Maximum Acceptance Detector ("MAX", Fermilab P-864, Bjorken and Longo co-spokesmen [20]) at the Tevatron which, however, was rejected. Consequently, a small test program to initiate the study of this physics (T-864, "MiniMax", J. Bjorken and C. Taylor co-spokesmen [21]) has been proposed and approved for installation at the C0 collision area of the Tevatron during the current summer shutdown.

T-864 is a simple, staged test program of very modest scope, cost, and impact on the laboratory which responds to the suggestion of the Fermilab Physics Advisory Committee that it "hopes that efforts will continue to develop possible methods for exploring the large rapidity regime." The experiment will initially investigate the background environment in the forward direction at the C0 collision area with a minimal "maximum acceptance" detector (MiniMax). This will be done initially in noncollider mode in the far forward direction using only MWPC tracking elements and a simple scintillator-based triggering system. Pending successful completion of the initial test program, MiniMax will then carry out studies of charged particles and gamma rays in the fiducial region defined by the MWPC telescope. Physics goals include both generic multiparticle production studies and, of course, a disoriented chiral condensate search. Both studies will proceed in non-collider mode initially, with requests for short collider runs following the successful completion of the initial program. (Under normal operating conditions of the Tevatron, electrostatic separators prevent collisions from occurring in the C0 hall.)

Because of the aggressive schedule (proposed in April, approved in May, installed by October of this year), limited resources, and constraints from the C0 physical environment, MiniMax is designed to be extremely flexible, in the hope that we will be able to opportunistically exploit short unscheduled shutdowns of the Tevatron to modify the apparatus. Figure 4 is a schematic diagram of the MiniMax detector.



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Figure 4(a). T864 Plan View

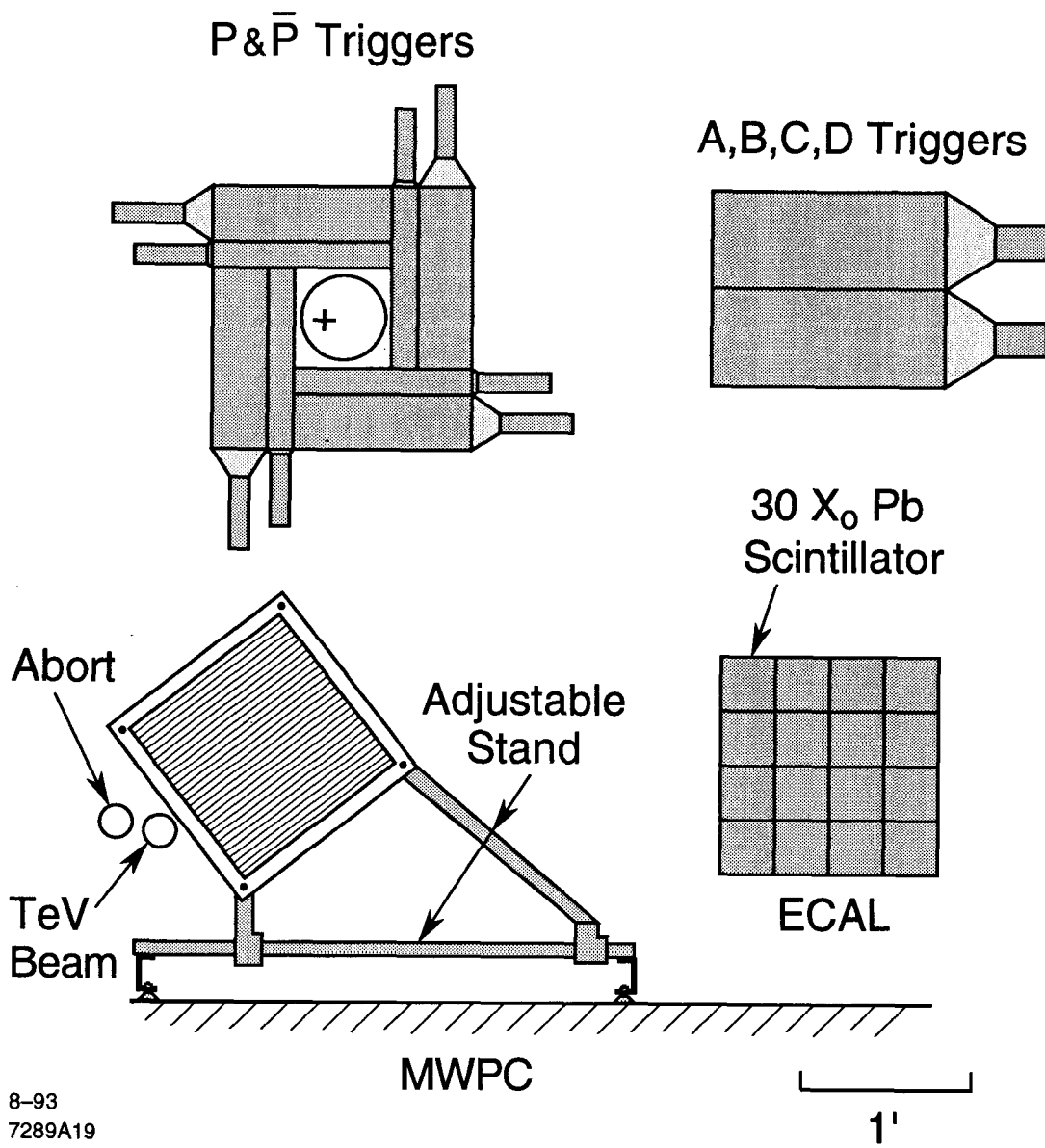


Figure 4(b). T864 details (beam's eye view)

The heart of the detector is a telescope of approximately 12 multi-wire proportional chambers with wire spacings of 2.5 mm and with an active area of about 32 cm x 32 cm, pointed towards the nominal collision vertex, located 5-6 meters away from the collision point. Approximately 2 radiation lengths of converter will be placed midway through the telescope. This converts 80% of the incident photons while leaving 93% of the charged tracks noninteracting and should be adequate for the statistical study of the dcc's.

The MWPC's will be mounted on frames which allow easy change of position both along the beam pipe, and in position and orientation relative to the beam pipe. This flexibility should enable us to understand the background environment, and will also permit us to survey a larger range of pseudorapidities than a fixed geometry would allow.

In first approximation, each plane will have a different orientation, permitting the efficient use of a Hough transform algorithm for reconstructing charged tracks and locating the vertex. Monte-Carlo simulations indicate that this strategy is robust in the presence of backgrounds arising from showers originating in the beampipe near the detector elements.

The triggering system builds on the experience of E-735, which previously occupied the C0 collision hall. In addition to scintillator placed 2 m upstream and downstream of the collision point, there will be scintillator hodoscopes before and in the middle of the tracking telescope. There will also be a lead-scintillator stack at the back of the telescope. The trigger logic is designed to be versatile; the rough intention is to operate with as loose a trigger as possible. The total channel count for the trigger is approximately 70.

How sensitive might we be? Monte-Carlo studies based on Pythia indicate that events such as the JACEE event are extremely unusual according to conventional wisdom, even as seen by such a limited acceptance as that of the MiniMax detector. If such events occur, and if the MiniMax detector performs well and can be well understood, it should be possible to draw significant conclusions from the data. A sensitivity limit of one such event per 10,000 minimum bias events would seem to be a conservative goal.

#### 4. Future Directions

It is clear that there is a good deal of additional work to be done, both experimentally and theoretically.

On the theoretical side, while the plausibility of the formation of chiral condensates has been explored in various idealized situations [22-26], there is substantial room for improvement. Even within the

context of the various idealizations, the implications of the finite pion mass have not been adequately investigated, nor has the question of estimating the domain size of chiral condensate been fully answered. While the long-term development of this physics will necessarily be data driven, there is much that can and should be done now.

On the experimental side, there are a number of directions which should be pursued in the coming years. While MiniMax will be able to do an initial survey of the large rapidity regime at the Tevatron, it may make sense to follow this up with a Maximum Acceptance Detector in the future. Similar studies should be complemented by work in the large rapidity regime at RHIC, where the conditions of the cosmic ray events may be more nearly matched in proton-nucleus collisions. Finally, we believe that it is extremely important that large-rapidity physics issues such as those considered here be on the agenda of the SSC and LHC. Indeed, most of the work described in this paper began in support of the initiative to build a Full Acceptance Detector (FAD) at the SSC.

The large-rapidity regime is one in which we have few reliable theoretical tools and insufficient data, but what we have learned so far is extremely tantalizing. Onward!

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