Chapter 1

Introduction

1.1 Physics motivation

1.1.1 Disoriented Chiral Condensates

The Lagrangian of QCD (Quantum Chromodynamics [1], the theory of strong interactions) for two quarks (u and d) has isospin symmetry SU(2). In the limit that the quarks are massless, the Lagrangian also has chiral symmetry $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$. That is, if we write the isospin doublet $\Psi = \begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}$ in terms of left- and right-handed fields,

$$\Psi = \frac{1}{2}(1-\gamma_5)\Psi + \frac{1}{2}(1+\gamma_5)\Psi = \Psi_L + \Psi_R, \tag{1.1}$$

where γ_5 is the usual product of gamma matrices of Dirac theory, then the Lagrangian is symmetric under $\Psi_L \leftrightarrow \Psi_R$. The spontaneous breaking of this chiral symmetry in the QCD ground state is accompanied by a massless Goldstone boson [2], the pion. In the real world, the quarks are light but not massless, and the QCD Lagrangian has an approximate chiral symmetry which is explicitly broken, giving the pion a small mass.

Spontaneous chiral symmetry breaking is often described by the linear sigma model [3], in which there is a scalar field σ of isospin 0 and a vector pion field $\vec{\pi}$ of total isospin 1. The Lagrangian can be written as

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \vec{\pi} \partial^\mu \vec{\pi} + \partial_\mu \sigma \partial^\mu \sigma) - \frac{\lambda}{2}(\vec{\pi}^2 + \sigma^2 - {f_\pi}^2)^2, \tag{1.2}$$

and the potential is minimized for $\sigma^2 + \vec{\pi}^2 = {f_\pi}^2$. The symmetry is broken when a particular minimum is chosen. In order to break chiral symmetry, but not isospin symmetry, the minimum chosen is that for which the σ field acquires a vacuum expectation value: $\langle\sigma\rangle = f_\pi$, $\langle\vec{\pi}\rangle = 0$. A term can be added to the Lagrangian in order to break the chiral symmetry explicitly, such as $f_\pi m_\pi^2 \sigma$ or $-\frac{1}{2} m_\pi^2 \vec{\pi}^2$, but it is unclear experimentally which of these terms is realized in nature [4].

The ordinary vacuum has chiral order parameter in the σ direction (it has no isospin). A disoriented chiral condensate (DCC) is a piece of vacuum which is disoriented from the σ direction to a direction with $\vec{\pi}$ components. When the DCC domain makes contact with the ordinary vacuum, it coherently radiates pions with isospin determined by the direction of disorientation in order to restore the σ direction. For example, if the disorientation were in the π^0 direction, π^0's would be emitted. There has been much theoretical work done recently on DCC and other mechanisms for coherent semiclassical radiation of pions in high-energy collisions of hadrons and of heavy ions [5]-[16].

The distinctive signature of DCC is that the pions produced when the DCC domain makes contact with the outside vacuum have a neutral fraction $f = N_{\pi^0}/(N_{\pi^+} + N_{\pi^-} + N_{\pi^0})$ distributed according to

$$P(f)df = \frac{1}{(2\sqrt{f})}df \tag{1.3}$$

in the limit of large numbers of pions. This neutral fraction distribution is common to some other mechanisms which produce coherent final states [13]-[14], [17]-[19]. The proof of this has been given in terms of quantum mechanical coherent state arguments [10], but can be seen easily with a geometrical argument. The vacuum condensate has equal probability of having an order parameter oriented in any direction in $(\sigma, \vec{\pi})$ space. If we define θ as the polar angle relative to the π^0-axis, quantum-mechanical arguments give $f = \cos^2\theta$, and $P(f)\,df = P(\cos^2\theta)\,d(\cos\theta)$. We have $df/d(\cos\theta) = 2\sqrt{f}$, so that $P(f)\,df = (1/2\sqrt{f})\,df$. In generic particle production, that is, production by (observed) mechanisms other than DCC, producing a pion of any given charge is equally likely due to isospin symmetry, so that f is binomially distributed with mean $\langle f \rangle = \frac{1}{3}$. Note that the $1/(2\sqrt{f})$ distribution also has a mean of $\langle f \rangle = \frac{1}{3}$, but that the distributions are quite different; in particular, the probability of producing pions with a small or large neutral fraction is much higher for DCC than for generic production (Fig. 1.1).

It is conjectured that such a condensate may be formed in hadron-hadron collisions with high transverse energy and a large multiplicity (number of particles produced). As the collision debris expands outward at almost the speed of light, it may form a hot, thin shell, the cool interior of which would be separated from the outside vacuum and could conceivably have a chiral order parameter which is disoriented from the σ direction. When the shell hadronizes, the interior condensate makes contact with the outside vacuum and radiates pions.

1.1.2 Centauro/anti-Centauro

Cosmic ray experiments have found evidence for hadronic events which can be interpreted as having an anomalously large or small fraction of pions which are neutral and may therefore be related to DCC. Centauro events have been observed in emulsion chambers by the Chacaltaya-Pamir Collaboration [20, 21] and are characterized by a large number (~ 100) of charged particles and almost no electromagnetic energy, which implies no π^0's, since their immediate decay produces two photons. The center-of-mass (cm) energies are on the order of a TeV or larger. Further interpretation of the events is controversial. What is measured can be related to the transverse momentum, e.g., $k_\gamma \langle p_T \rangle = 0.35 \pm 0.15\,\mathrm{GeV}$ for Centauro I, but the gamma ray inelasticity k_γ is not known. The value is usually quoted as $k_\gamma \sim 0.2 - 0.4$ with the lower and upper values preferred for nucleons and pions, respectively. Most analyses assume that the hadrons produced in Centauros events are nucleons. However, if we want to interpret Centauros as being related to DCC, the hadrons should be pions, and therefore it is possible that the p_T is low ($\langle p_T \rangle \approx 0.875 \pm 0.375$ GeV with a large systematic uncertainty), which is referred to as Chiron behavior. It has been suggested (Ref. [22] based on data from Ref. [21]) that these events may be diffractive.[1] Taking the view that Centauros are diffractive fireballs recoiling against a proton or anti-proton, but that pions rather than nucleons are produced, boosting these events to the lab frame of Fermilab Tevatron collisions, Centauros would be expected to occur at $\eta \sim 3.5 - 4.5$.[2] (As will be discussed in Sec. 2.2, the acceptance of the MiniMax detector covers precisely this region.)

[1]Diffractive processes [23] are thought of as involving the exchange of a colorless object called a pomeron, but are not well understood. In single diffraction, either the incoming proton or anti-proton is dissociated, while the other remains intact and typically has a low transverse momentum and a longitudinal momentum almost that of the initial beam. Both hadrons are dissociated in double diffraction.

[2]We work in what is called "lego space" where ϕ is the azimuthal angle and η is the pseudorapidity which is defined in terms of θ, the angle from the beam axis, as $\eta = -\ln \tan \frac{\theta}{2}$. Therefore, the region explored by central detectors which look transverse to the beam covers small η, while η gets infinitely large in the beam direction. An advantage to using the pseudorapidity is that η has a simple transformation under boosts in the beam direction. Also, the density of particles produced in a collision is uniform over a large region of lego space.

Events with a large neutral fraction are referred to as anti-Centauros. Such cosmic ray events have been reported by the JACEE Collaboration [24], which uses balloon-borne detectors. An example is the event shown in Fig. 1.2. The leading cluster contains about 32 photons and only 1 charged particle. A possibly distinct cluster has about 54 photons and 17 charged particles. The collision occurred within the detector with a cm energy greater than 200 GeV and Chiron behavior was exhibited.

However, the interpretation of these cosmic ray events is controversial, and observations of this type of event under controlled conditions, such as in a collider environment, where they could be better understood, would be very useful. Several collider experiments have unsuccessfully looked for large Centauro-like domains. CDF has conducted such a search at the Tevatron ($\sqrt{s} = 1.8$ TeV), and has reported no evidence for Centauros or anti-Centauros [25]. However, the CDF search only covered the region $|\eta| \lesssim 3$ and only looked at particles with $p_T \gtrsim 400$ MeV, and therefore might not be expected to observe such phenomena. The UA5 Collaboration ruled out large Centauro domains going out to larger η [26, 27], but at cm energies no greater than 900 GeV, whereas the necessary cm energy is expected to be larger. UA1 also conducted a search at relatively low energies and in the central region, and found no evidence [28].

1.1.3 Multiplicity distributions

Very little is known about particle production in the forward direction because this region has not been well studied. The distribution of charged particles in lego space has been reported by experiments such as CDF [29] and UA1 [30] for the central region ($|\eta| \lesssim 3$). Measurements of $dN_{ch}/d\eta$ were made for larger η by UA5 [27], and by P238 [31] at the CERN Sp$\bar{\text{p}}$S collider for proton-anti-proton collisions at center-of-mass energy $\sqrt{s} = 630$ GeV. The distribution of photons $dN_\gamma/d\eta$ in the forward direction is even less well known; UA5 observed photons at $\sqrt{s} \leq 900$ GeV [27, 32]. MiniMax, which was able to observe both charged particles and photons in the region $3.3 < \eta < 4.5$ at $\sqrt{s} = 1.8$ TeV, therefore had the potential to make measurements in a previously unexplored region.

Figure 1.3 shows a plot of $dN_{ch}/d\eta$, averaged over typical collisions at Tevatron energies, from the event generator PYTHIA. The distribution in the central region is taken from measured values, and these are extrapolated to the forward region. Note that the mean number of charged particles varies by only about 0.5 (about 13%) in the region $|\eta| < 4$. Since there is no preferred azimuthal direction, the distribution in ϕ is also uniform.

1.2 Conceptual design of MiniMax

With the primary goal to search for DCC, the MiniMax detector should be able to observe both charged particles and photons simultaneously. If we take seriously the interpretation of Centauros and anti-Centauros given in Sec. 1.1.2, the detector should cover the forward region $3.5 < \eta < 4.5$, and be sensitive to low-p_T particles. The smallest coverage which would be expected to be sufficient for observing such events is $\Delta\eta\Delta\phi = 1$. Further considerations include the restricted area around the beampipe due to the main ring and the floor, and the lack of funding for the experiment. In order to achieve "minimal maximum acceptance" (hence the name MiniMax), the detector was designed as a telescope of multi-wire proportional chambers (MWPC's) along the beampipe, with converter inside the telescope. Thus, charged particles can be observed in the chambers before and after the converter, and photon conversions in the chambers behind the converter.

In the absence of a magnetic field, the energy of the particles can only be determined using calorimetry. For this reason, and to observe photons which do not convert inside the telescope, an electromagnetic calorimeter was placed behind the MWPC telescope.

If Centauros are diffractive and are related to DCC, then DCC might be more likely to be produced in diffractive interactions than in non-diffractive ones. In order to test this conjecture, diffractive events must be identified. Scintillator and hadronic calorimetry were used to detect leading anti-protons and anti-neutrons from diffractive events.

A picture of the original design for the MiniMax detector is shown in Fig. 1.4.

A brief note on the similarity between MiniMax and UA5 is in order, although the details of the UA5 experiment did not play a role in the design of the MiniMax detector. UA5 was an experiment at the CERN proton–anti-proton collider (Sp$\bar{\text{p}}$S) and ran from 1981-1982 and in 1985, during which time collisions at $\sqrt{s}$ = 546, 200, and 900 GeV were studied. The detector consisted of two streamer chambers, $600 \times 125 \times 50$ cm^3, on opposite sides of the beampipe, in which charged particles left tracks which were photographed for analysis by well developed techniques. For the runs at $\sqrt{s}$ = 546 GeV, photons were detected through conversions in lead-glass plates, approximately 1 X_0 thick, located inside the streamer chambers near the sides. In later runs, a lead converter plate (2 mm of lead supported by an aluminum box with walls 1 mm thick), placed between the beam pipe and the upper streamer chamber, was used instead. The beampipe was elliptical with mean dimensions 6×15.2 cm^2. Combining this transverse distance of the chambers from the beam axis with the length of the chambers, UA5 was able to observe particles at pseudorapidities up to $|\eta| \approx 5$. UA5 published results on many important studies, including multiplicity and pseudorapidity distributions and correlations for charged particles and photons, strangeness production (e.g. K's, Λ's, and Ξ's, observed through decays), diffractive dissociation, and a search for Centauros. Reference [27] is a comprehensive report on these studies at $\sqrt{s} = 546$ GeV. The Monte Carlo simulations created and used by UA5, which include non-diffractive and diffractive event generators, along with a Centauro generator, are described in Ref. [33].

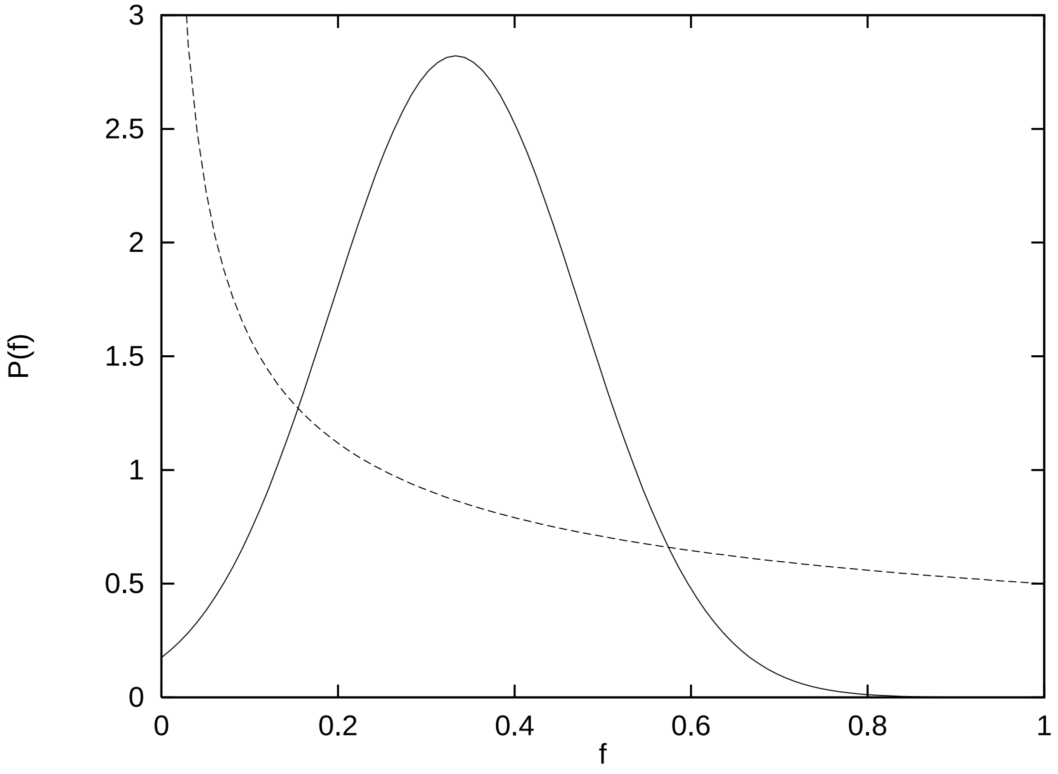

Figure 1.1: Binomial and DCC neutral fraction distributions.

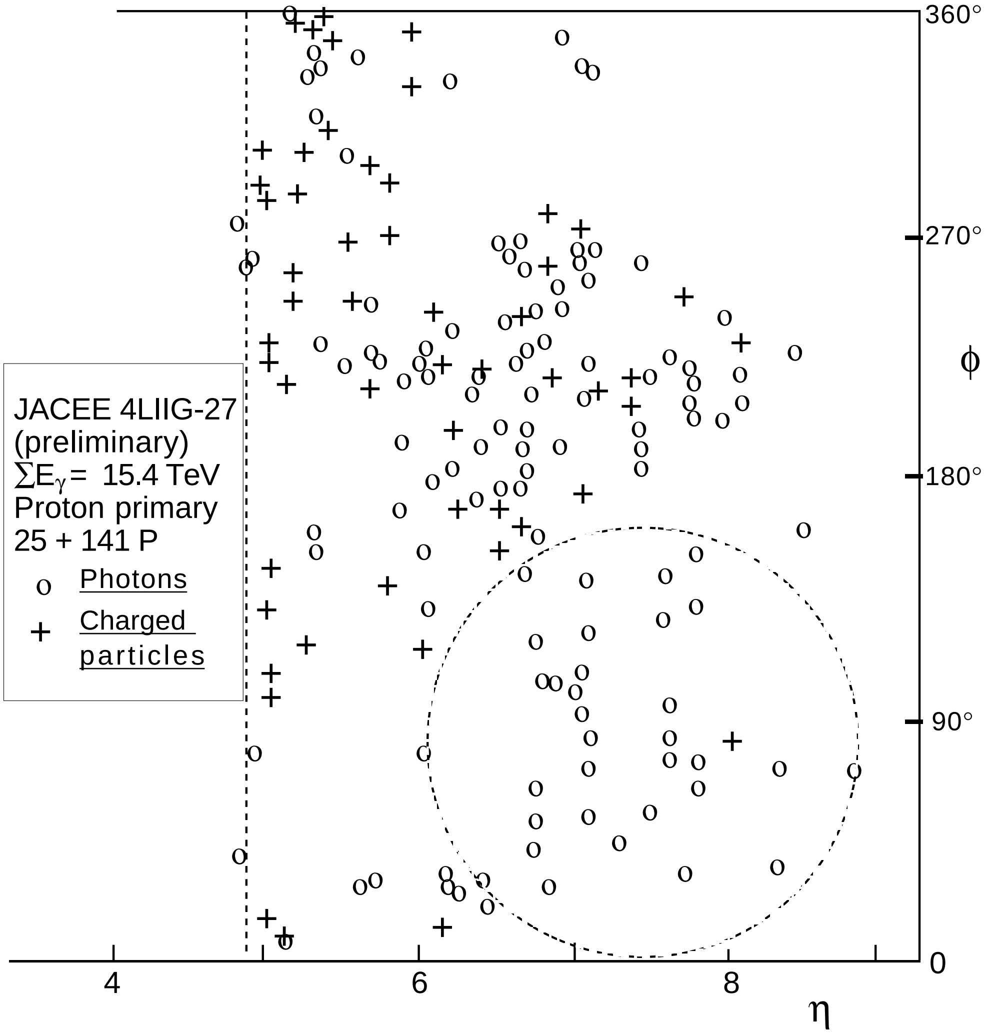

Figure 1.2: JACEE event

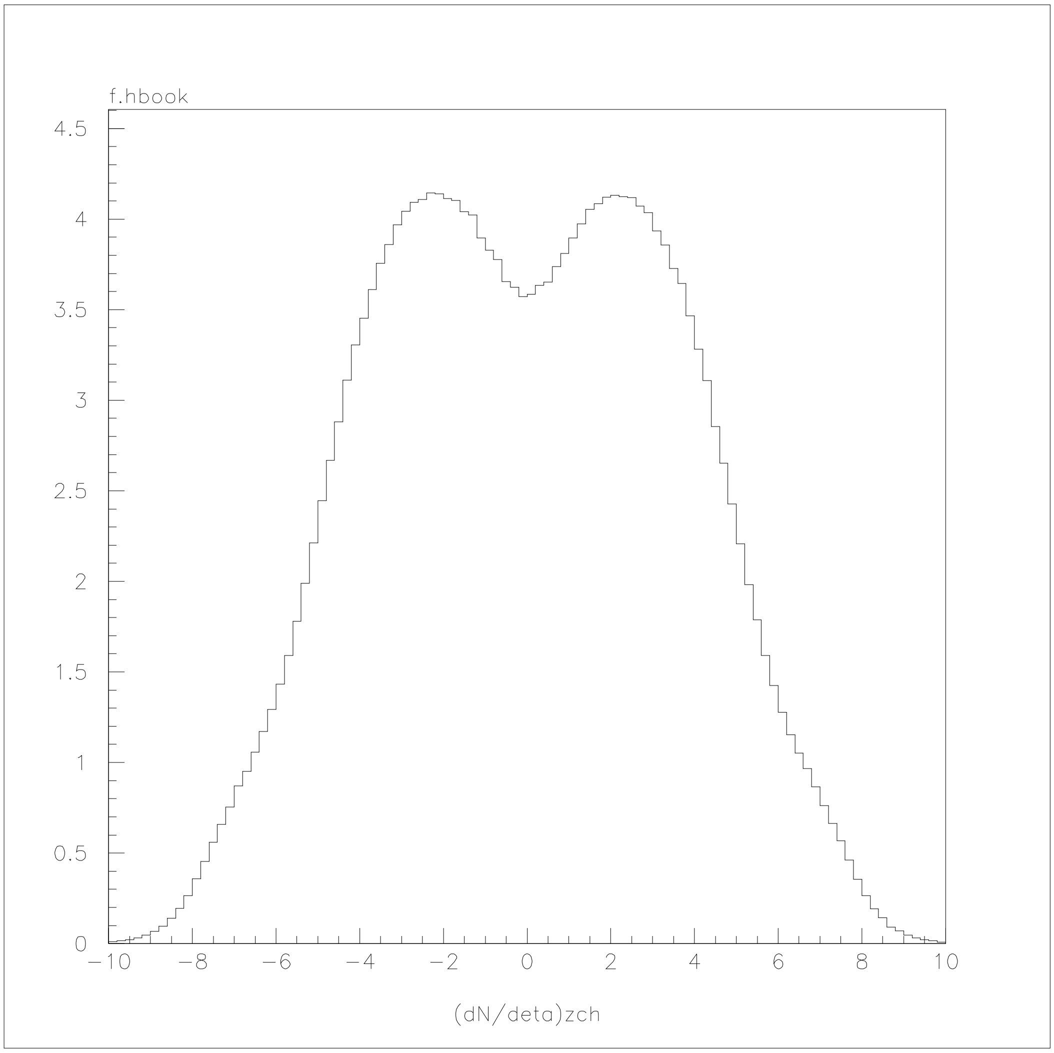

Figure 1.3: Charged multiplicity distribution $dN_{ch}/d\eta$ for non-single diffractive inelastic PYTHIA events at $\sqrt{s} = 1.8$ TeV.

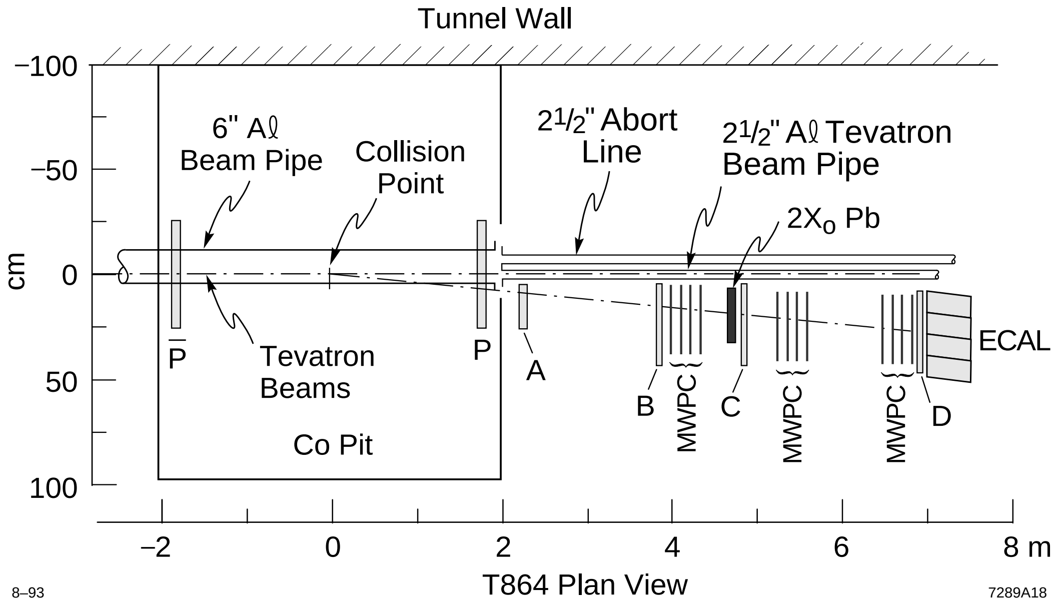

Figure 1.4: Original design of the MiniMax detector.