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Search for Centauro Events at CDF

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A search was performed for Centauro events in CDF minimum-bias data. Within each event particles are detected and identified as either hadronic requiring $E_T >$ 0.4 GeV, or electromagnetic requiring $E_T > 0.2$ GeV, using calorimeter towers out to $|\eta| < 4.2$. The search for Centauro-like events is based primarily on their unique particle kinematics: particle multiplicities $\sim$ 75, mean $p_T \sim 1.7$, and $\eta \sim 2$. In addition we look for Centauro candidates with unusual hadronic to electromagnetic asymmetry.

1 Introduction

In the early 1970's, unusual cosmic-ray events were detected and named "Centauro"[1] because they appeared to be different beasts in the upper (very little electromagnetic activity) and lower chambers (large hadronic multiplicity). These events appeared to have many more hadronic than electromagnetic (EM) particles (γ or $e^{\pm}$). Seven such events have been observed by two experiments. Assuming that they are produced in nucleon-nucleon collisions, the characteristics of these Centauro events are[1]:

- Hadron multiplicities are between 63-90, with a mean of 75
- $\gamma, e^{\pm}$ multiplicities are between 0 and 4
- Average hadron transverse momentum is 1.75 ± 0.7 GeV
- Mean η of hadrons is centered around 2.2 with $\sigma_\eta \sim 0.7$
- Average total energy is 1740 TeV, $\sqrt{s} \sim$1.8 TeV[a]

Because the rate of high energy cosmic ray events is low, the cross-section for Centauro production must be relatively high in order for them to have been observed. The most optimistic cross-section can be derived from the original observation[1] that Centauros represent 1% of the inelastic cross-section, or $\sigma_{cent} \sim 0.5$ mb at $\sqrt{s} = 1.8$ TeV.

[a] Assuming a cosmic ray particle interacting with a nucleon in the atmosphere.

Although there were many speculations as to why such a large hadronic to electromagnetic (*had-em*) asymmetry would be observed, none are particularly satisfying and the fact remains that this asymmetry is extremely unusual within both cosmic-ray and accelerator data. Theory predicts chiral symmetry during particle production, and most hadronization data appear to be statistically consistent with equal production of π^+, π^-, π^0. In addition, a parameterization of accelerator and cosmic-ray particle production data shows that, independent of the *had-em* asymmetry, the Centauro events are kinematically unusual[2].

One proposed mechanism for producing large *had-em* particle asymmetry has seen great popularity recently[3]. It is assumed that, within very energetic hadron-hadron or heavy-ion collisions, a region of vacuum is produced that has no preferred chiral orientation, i.e. chirally disoriented. When this vacuum expands and cools below some critical temperature, it adjusts (condenses) to the chiral state of the event vacuum by emitting pions. This cluster of emitted pions is therefore called a "Disoriented Chiral Condensate" (DχC), and can provide a large hadronic ($\pi^\pm$) to electromagnetic (γ's from π^0) asymmetry.

There is also a phenomenological interpretation of Centauros as diffractive fireballs[4] that successfully reproduces the kinematics of the cosmic ray events. In this model a nucleon-nucleon collision at $\sqrt{s} \sim 1.8$ TeV can create a diffractive superheated fireball with mass ~ 180 GeV. The decay of this diffractive mass produces ~ 75 hadrons with $< E_T > \sim 1.8$ GeV in the forward region centered around $|\eta| = 2.2$ with a spread $\Delta\eta = \pm 0.7$. This diffractive-fireball interpretation seems to reproduce the kinematics of the observed Centauro events and in fact predicted the η distribution ($\eta = 2.2 \pm 0.7$ Gaussian) of the final state particles before the data were re-analyzed[1]. Within this model the unusual *had-em* asymmetry is assumed to be caused by a phase transition, similar to the DCC hypothesis, due to the superheated fireball conditions. The cross-section for a diffractive event with this mass is predicted to be ~ 0.33mb.

The previous hadron collider searches[5] may have been unable to observe the Centauro events because they only looked in the central rapidity region, or were unable to produce them if the threshold is indeed $\sqrt{s} \sim 1.8$ TeV as estimated.

2 Analysis

We use 3.3 μb^{-1} of beam-crossing (minimum-bias) data taken with the CDF detector during the Tevatron run 1A. There were 273 thousand events with 0 or 1 detected vertex and 167 thousand with 1 vertex. We allowed 0 vertex events to accept any all-neutral final states.

Particles are defined as a minimal cluster of calorimeter towers, $\Delta\eta =$

0.20 (two towers) by $\Delta\phi = 0.26$ (one tower in Central and three in Plug and Forward calorimeters). The summed towers are identified as either hadronic (presumably $\pi^{\pm}$) requiring $E_T > 0.4$ GeV, or electromagnetic (presumably γ from π^0) requiring $E_T > 0.2$ GeV. This identification relies on tracking, the ratio of hadronic to electromagnetic energy, and the longitudinal energy deposit within the compartments of the Plug and Forward EM calorimeters. The CDF detector has been described in detail elsewhere[6].

We define the hadronic to electromagnetic asymmetry significance as $A_{had-em} = \sqrt{N_{tot}} \times (N_{had} - N_{em})/N_{tot}$, which is the conventional asymmetry weighted by $\sqrt{N_{tot}}$, where $N_{tot} = N_{had} + N_{em}$, so higher multiplicities have more significance. Figure 1 shows data and Monte Carlo distributions of the asymmetry significance using the sum of all hadronic and electromagnetic (EM) particles in each event. Both distributions in Fig. 1 are well described by a Gaussian. The data and Monte Carlo asymmetry distributions are similar to each other and fit fairly well to Gaussians with mean ~ 0 and $\sigma \sim 1$. This is consistent with hadronic and EM particle production described by Binomial statistics with approximately equal probability of $\pi^{\pm}$ and γ. The data asymmetry distribution with dijet-like events suppressed is also shown superimposed (dashed histogram). The dijets bias the distribution towards large hadronic asymmetries because a jet composed of π^0's and $\pi^{\pm}$'s is identified as many hadronic particles. Figure 2 shows a dijet event display that produced a high hadronic multiplicity.

3 Centauro Monte Carlo

In order to determine our sensitivity to Centauro events, we used a toy Monte Carlo to generate these exotic events. The Centauro events were statistically distributed assuming:

- uniform multiplicity probability between 63-90 particles;
- uniform mean η between $1.7 < \overline{|\eta|} < 2.7$;
- Gaussian particle η's with $\sigma = 0.7$;
- Gaussian particle $(\pi^0, \pi^{\pm})$ p_T's with mean 1.75 and $\sigma = 0.25$ GeV;
- three samples of all $\pi^{\pm}$, all π^0, and an even mixture.

A simple detector parameterization used the measured $\pi^{\pm}$ detection efficiency and particle mis-identification probability, then determined the Centauro-window η, multiplicity, mean E_T, and *had-em* asymmetry for the generated events. The Centauro Monte Carlo was used to determine the acceptance of various cuts on the data distributions.

4 Results

The Centauro analysis determines the η-region with maximum particle multiplicity ("Centauro-window") within $\Delta\eta = 2$ and summed over ϕ for each event. Centauro candidates are selected based on the hadronic+EM multiplicity, mean particle E_T, and mean η of the Centauro-window. These candidates are then analyzed for signs of unusual *had-em* asymmetry.

Figure 3a shows the particle multiplicity (N) versus mean particle E_T for all events. Although there are events with relatively high N and mean E_T, they appear to be part of the continuum. The events with very large mean E_T look like dijet events (back-to-back clusters). Figure 3b shows the same plot when the Centauro-window is non-central, $|\eta| > 1.3$. There are 6 events above the 83% Monte Carlo acceptance cuts on N and E_T. Figure 3c shows that the multiplicity is much higher for events with central Centauro-windows, presumably because the particle detection is more efficient in the Central calorimeter and jets tend to be more central.

The distribution of *had-em* asymmetry of the particles within the Centauro window is shown in Fig.3d. There is no evidence of a unusually high hadronic or EM asymmetry tail. Although the observed Centauros were all hadronic, in order to investigate any *had-em* asymmetry we considered all-$\pi^\pm$ (Centauro), all-π^0 (anti-Centauro), and $\frac{2}{3}\pi^\pm - \frac{1}{3}\pi^0$ (symmetric) final states.

5 Conclusions

All the events in the tails of the distributions shown in Fig. 3 have been scanned. Dijet events where both jets have similar and non-central η, like the one shown in Fig. 2, tend to mimic the Centauro characteristics, i.e. high hadronic multiplicity and high mean E_T. Besides this dijet background, there is no evidence for Centauro-like events in our data. We therefore place a 95% confidence level (CL) upper limit on the Centauro production cross-section based on various assumptions. The 95% CL upper limit is calculated by determining the number of Centauro candidates (N_{cand}) passing a set of cuts, scaling this up to the 95% CL upper limit on the number of candidates ($N_{cand}^{95\%} = N_{cand} + 1.64 * \sqrt{N_{cand}}$), and then using the Monte Carlo acceptance (ϵ_{MC}) and integrated luminosity ($\mathcal{L} \sim 3.3\mu b^{-1}$): $\sigma_{cent} < N_{cand}^{95\%}/(\epsilon_{MC}\mathcal{L})$.

Table 1 shows the 95% CL limit derived for kinematic and asymmetry cuts and assuming an all-$\pi^\pm$ (Centauro), all-π^0 (anti-Centauro), or mixed final state. With a kinematic cut on the multiplicity and $|\eta| > 1.3$, the upper limits are at the 10μb level, while the rate of Centauros in Cosmic Rays was originally thought to be 500μb (1% of inelastic) and the diffractive fireball prediction is 330μb. Although less efficient, the cut on asymmetry alone is inconsistent with expectations, and sets a very restrictive limit on the all-π^0 final state. This analysis does not consider the possibility that the Centauro decays to protons and neutrons.

Table 1: Centauro Production Cross-Section Upper Limits

Selection Criteria	all-$\pi^{\pm}$		all-π^0		$\frac{2}{3}\pi^{\pm}$, $\frac{1}{3}\pi^0$ mix	
	N_{cand}	ϵ_{MC}	N_{cand}	ϵ_{MC}	N_{cand}	ϵ_{MC}
$N \oplus \overline{\lvert\eta\rvert} > 1.3$	32	85%	9	85%	9	70%
95% CL upper limit σ_{cent}	15 μb		5.6 μb		6.8 μb	
$A_{h-e} > 3.5\ \pi^{\pm}; < -5.0\ \pi^0$	129	90%	0	100%		
95% CL upper limit σ_{cent}	48 μb		0.91 μb			

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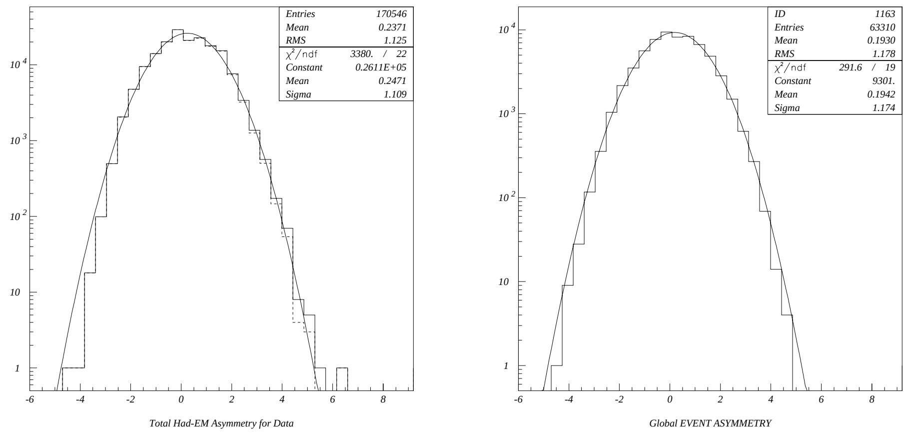

Figure 1: Asymmetry A_{had-em} per Event in Data (left) and Monte Carlo (right), with Gaussian fit (the effect of suppressing dijets is shown superimposed).

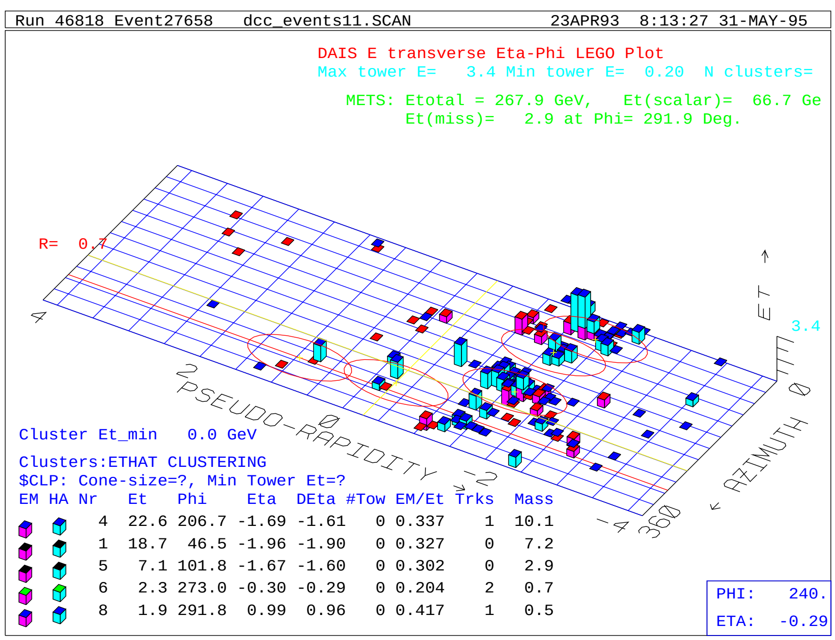

Figure 2: Centauro Candidate tagged as Dijet.

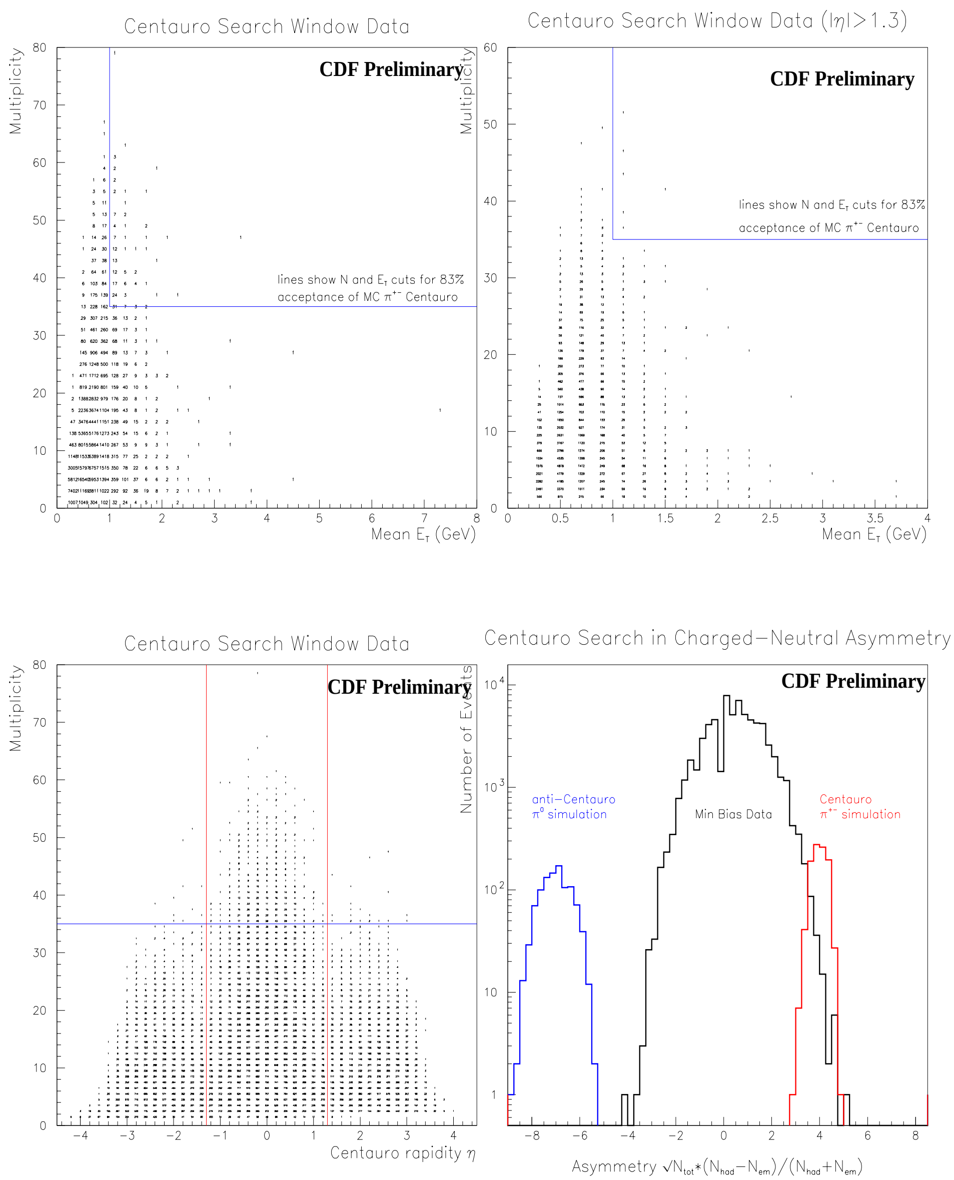

Figure 3: Centauro Window: N vs $\bar{E_T}$ all events (a: top-left), $|\eta| > 1.3$ (b: top-right), N vs η (c: bot-left), and asymmetry (d: bot-right).