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A NEW SEARCH FOR RELATIVISTIC PARTICLES WITH FRACTIONAL
ELECTRIC CHARGE AT THE CERN $p\bar{p}$ COLLIDER

The UA2 Collaboration

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ABSTRACT

We report on a search for relativistic particles with fractional electric charge at the CERN $p\bar{p}$ collider, using a telescope of scintillation counters to detect particles with anomalously low ionization. Since no event survives the selection criteria, upper limits on quark production are deduced from this experiment. At 90 % confidence level and in the limit of very light quarks with charge $\pm 1/3$ and $\pm 2/3$ they are $2.8 \cdot 10^{-6}$ and $5.6 \cdot 10^{-5}$, respectively, per single charged particle. These limits increase rapidly with increasing quark mass and are nearly two and one order of magnitude better than previously measured by UA2.

1. INTRODUCTION

Although the idea of an absolute confinement of quarks is very compelling within the context of quantum chromodynamics, there is no theoretical principle which forbids the existence of free quarks. Since the liberation of free quarks may require a large energy, it is important to search for it whenever a new centre of mass energy domain is reached [1, 2]. Therefore, during the first two running periods (1981 and 1982) of the CERN $p\bar{p}$ collider at a centre of mass energy of 540 GeV, the UA2 detector included an experimental set-up to detect events with anomalously low ionization. Results from data corresponding to an integrated luminosity of $75 \mu\text{b}^{-1}$ collected during the 1981 run have already been published [1]. This letter reports on a new search for relativistic particles with fractional charge in a data sample collected during the 1982 running period with two orders of magnitude larger integrated luminosity. The nature of the detector, and limitations of the analysis method, imply that such particles could not be observed if they had abnormally large interaction cross sections in matter, or if they were produced in association with other particles at small angles to them.

2. QUARK DETECTORS AND TRIGGER CONDITIONS

The UA2 detector [3] included in its early phase of operation a wide angle spectrometer [4], which was later replaced by calorimeters better suited to the experimental programme made possible by the increased collider luminosity [5]. A small part of this wide angle spectrometer was equipped with two scintillator hodoscopes, the front and back quark counters. These counters were used to search for charged particles associated with abnormally low ionization densities. The quark counters (Figure 1) covered a solid angle of ≈ 27 msr at nearly 90° from the beam line and were inserted in the middle of the large lead glass array of the wide angle spectrometer. Particles produced in a $p\bar{p}$ collision and aiming at the quark counters traversed in sequence the following elements: the central vertex detector [6], the magnetic field volume, a stack of 12 drift chamber planes, a scintillator hodoscope (WF), a 2 cm thick iron plate, another scintillator hodoscope (WB), the front quark counter and the back quark counter.

The front quark counter, made of five scintillators (Q1 to Q5), and containing two veto counters to reject particles which produce Čerenkov radiation in the light guides, has been described elsewhere [1].

The back quark counter (Figure 1) consists of three consecutive layers of NE110 scintillator, each 45 cm thick and 0.7 m^2 in area. Each layer is made of three blocks on top of each other. Each block (Q6 to Q14) is viewed through an air light guide by an XP2041 photomultiplier (PM). The anode signals of each of the nine PM's are measured by 10-bit analog-to-digital converters and the timings of the summed signals of the three PM's of a same layer are measured in time-to-digital converters. The timing information can be used to reject background from beam-gas collisions.

The stability of each PM gain and its calibration in terms of ionization density were monitored throughout the experiment with a light flasher system and minimum ionizing particles.

Two triggers were used to select events containing low ionization density candidates in the quark counters. Both were the result of coincidences between scintillator signals (from the quark counters and the WF counters facing them), with conditions (Table 1) imposed on their amplitudes A measured in terms of minimum ionizing particle equivalent (mip). Trigger 1, which was used to the search for quarks with charge $\pm 1/3$, required explicitly the presence of signals with $0.05 < A < 0.4$ and included in addition a coincidence with a minimum bias signal [7] characteristic of non-diffractive $p\bar{p}$ interactions. As a result its rate was very low, of the order of 0.01 Hz for a luminosity of $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$. Trigger 2 required simply a minimum bias signal and the presence of signals with $A > 0.05$ in all scintillator layers, with no upper limit on their amplitudes. This latter trigger was used to the search for quarks with charge $\pm 2/3$ and for monitoring and calibration purposes. Its rate was deliberately limited to 0.03 Hz by introducing an external dead time.

A total number of 21'244 (161'684) events were collected using trigger 1 (2), corresponding to an integrated luminosity of 14.8 (3.6) nb^{-1} .

3. DATA ANALYSIS

The method of data analysis closely follows that of Ref. 1. In a first step we reject events in which the presence of low ionization densities can be ascribed to spurious sources. These include:

- i) Particles crossing light guides of the front quark counters. They are rejected by excluding events with signals from the veto counters.
- ii) Soft electrons and photons leaking sideways from an electromagnetic shower produced in one of the two columns of lead glass blocks adjacent to the quark counters. They are rejected by excluding events in which a signal is measured in one of these two lead glass columns.
- iii) Events associated with interactions in the iron plate, either with stray particles or with particles entering or leaving the quark counters through the sides, are excluded by demanding a hit pattern consistent with the expected geometry: one and only one WF, and one and only one WB, must give signals and these signals may not exceed 0.7 mip for trigger 1; at most one charged particle track pointing to the quark counters may be measured in the drift chambers. For trigger 2, at least three out of eight signals from WF, Q_1 to Q_5 and the first two layers of the back quark counters must give signals which may not exceed 0.7 mip.

For each event, the pulse heights of the signals measured in the WF and front quark counters are corrected for their dependences on the position and angle of the particle impact. For events with no charged particle track observed in the drift chambers, the impact point is evaluated from the pulse height asymmetry of the top and bottom PM's of the WF and front quark counters.

The most probable ionization I_0 for an event of trigger type 1 or 2 is calculated from the pulse heights I_i ($i = 1$ to 7 or 1 to 8) measured in WF, in the five scintillators of the front quark counter and in the first or two first layers of the back quark counter. We use a maximum likelihood procedure minimizing the function:

$$\psi(I_0) = -1/n \sum_{i=1}^n \ln P(I_i, I_0)/P(I_0, I_0) , \quad (n = 7 \text{ or } 8)$$

where $P(I_i, I_0)$ is the probability density to measure an ionization I_i when the most probable value is I_0 . The functional dependence of $P(I_i, I_0)$ is chosen to be either Landau or Poisson; the function giving the larger likelihood is chosen. Events with $\text{Min}(\psi) > 2.2$ are rejected as being inconsistent with a unique I_0 value. Test beam data show that 95 % of minimum ionizing particles satisfy such a cut.

The distribution of I_0 for the events of the two trigger samples which satisfy the selection criteria are shown in Figure 2.

4. RESULTS

We find no candidate satisfying $I_0 < 0.7$ mip for either trigger mode.

In order to extract upper limits on the ratio R of the quark yield around 90° to that of particles with unit electric charge, the relative detection efficiency must be evaluated. For this purpose we use a Monte Carlo programme [1] to produce quarks of various masses m and electric charges equal to $\pm 1/3$ and $\pm 2/3$. The momentum distribution is taken of the form $p_\perp \exp(-Bm_\perp)$, where $m_\perp = (p_\perp^2 + m^2)^{1/2}$ and $B = 5 \text{ Gev}^{-1}c^2$, which is typical of thermodynamical models [8] and is verified experimentally for a variety of known particles at the CERN $p\bar{p}$ collider [4,9]. The particles are traced through the magnetic field and the ionization energy loss in each traversed scintillator is calculated according to appropriate distributions. The Monte Carlo generated events are subject to the same selection criteria as used for the experimental data. The isolation constraint resulting from the requirements that no other charged particle points to the quark counters and that no energy is measured in the adjacent lead glass columns is not explicitly taken into account in the Monte Carlo simulation. If the particles produced in association with a free quark had the same distributions as in minimum bias events this constraint would result in an acceptance loss of less than 5 %.

Figure 3 shows the 90 % confidence level upper limits for the ratio R , the number of quarks per single charged particle as a function of the quark mass m for both $\pm 1/3$ and $\pm 2/3$ electric charges. They reach $2.8 \cdot 10^{-6}$ and $5.6 \cdot 10^{-5}$ respectively in the limit of very light quarks but increase rapidly with increasing quark mass. These limits are only valid under the assumption that free quarks have the same interaction length as ordinary hadrons (the amount of material between the interaction region and the second and third layer of the back quark counter is ≈ 85 and 130 g cm^{-2} respectively).

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FIGURE CAPTIONS

1. Schematic view of the experimental set-up: a) side view;
b) top view.
2. Distributions of the most probable ionization I_0 for all events having $\psi < 2.2$ and passing the selection criteria.
3. The 90 % confidence level upper limits on R , the number of quarks per single charged particle as a function of m .
The labels $1/3$ and $2/3$ refer to the absolute values of the quark charges.

TABLE 1
Trigger conditions

Trigger	WF (2 counters)	WB (2 counters)	Front quark counters (5 layers)	Back quark counters (3 layers)
1	at least one with $A > 0.03$	not in trigger	at least 3 with $0.05 < A < 0.4$	1. layer with $0.05 < A < 0.4$ 2. layer with $A > 0.05$
2			all 5 with $A > 0.05$	all 3 with $A > 0.05$

Fig. 1(a) Side view of the experimental apparatus

Fig. 1(b) Top view of the experimental apparatus

Fig. 2

Fig. 3