Search for Quarks Produced with Large Transverse Momentum in 400-GeV Proton-Nucleus Collisions

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We have searched for charge-$\frac{1}{3}$ and charge-$\frac{2}{3}$ particles produced with large $p_\perp$ in 400-GeV proton-Cu collisions. At $p_\perp = 6.15$ GeV/c, 4.9×10^4 positive and 1.5×10^4 negative unit-charge particles provided the normalization; no fractionally charged particles were found. The 90%-confidence-level upper limits for the invariant production cross sections per nucleon for positive and negative charge-$\frac{1}{3}$ particles are 5.1×10^{-39} and 8.8×10^{-39} cm^2 GeV^{-2}, respectively; for charge-$\frac{2}{3}$ particles the respective limits are 1.3×10^{-39} and 2.2×10^{-39} cm^2 GeV^{-2}.

In the years since the original suggestion of the existence of fractionally charged particles by Gell-Mann[1] and Zweig,[2] there have been many unsuccessful searches for quarks produced at accelerators[3] or by cosmic rays,[4] or for quarks trapped in matter.[4] Recently new evidence for fractional charge has been reported by LaRue, Fairbank, and Hebard.[5]

We have searched at Fermilab for particles with charge smaller than unity produced with large transverse momentum ($p_\perp$) in 400-GeV proton collisions with a copper target. The motivation was that a quark might be physically knocked out of a nucleon in a high-$p_\perp$ collision; previous searches have not explored the high-$p_\perp$ region.

The experiment utilized the Chicago-Princeton spectrometer previously used for measurements of high-$p_\perp$ hadron[6] and direct lepton[7] production (see Fig. 1). The 100-m-long single-arm spectrometer was located at an angle of 77 mrad relative to the incident proton beam. The data presented were taken during a period of two weeks,

with 400-GeV protons hitting a 7.5-cm-long Cu target (40% absorption) at a rate of 5×10^{11} per pulse. The spectrometer, which has a momentum acceptance of $\pm 5\%$, was set to accept unit-charge (e) particles of lab momentum 80 GeV/c ($p_\perp = 6.15$ GeV/c). The respective laboratory momenta for charge-$\frac{1}{3}e$ and charge-$\frac{2}{3}e$ particles are 27 GeV/c ($p_\perp = 2.05$ GeV/c) and 53 GeV/c ($p_\perp = 4.10$ GeV/c).
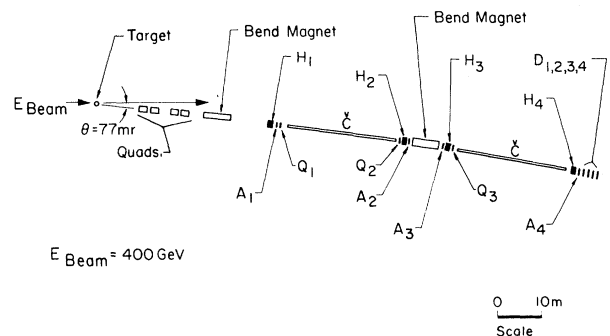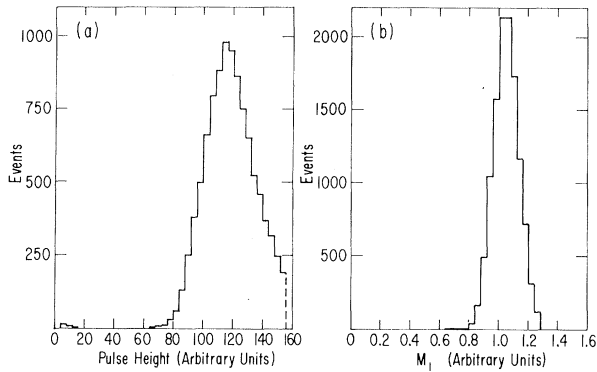

FIG. 1. Schematic of the spectrometer.

FIG. 2. (a) Typical distribution from one run of the pulse height in counter A_4. (b) Typical distribution in the first moment of the counters A_2-A_4 for one run.

For highly relativistic particles the 77-mrad laboratory angle corresponds to 96° in the c.m. frame of an incident proton and a single nucleon in the target. As the corresponding c.m. angle depends on the velocity of the particle, it depends on the mass and the momentum (and therefore, in in this experiment, on the charge) of the particle. For unit-charge particles of mass 2 GeV/c^2, the c.m. angle is 100°; for mass 5.0 GeV/c^2, it is 116°. For charge-$\frac{1}{3}$ particles of masses 2 GeV/c^2 and 5 GeV/c^2 the angles are 123° and 164°, respectively.

The maximum mass which one could detect in this geometry is 6.3 GeV/c^2 for charge $\frac{1}{3}$ and 8.0 GeV/c^2 for charge $\frac{2}{3}$, assuming quarks are produced in pairs via the process $p+N \to N+N+q+\bar{q}$

Seven plastic scintillation counters A_1-A_4, and Q_1-Q_3 (see Fig. 1) were used to measure the ionization of particles traversing the spectrometer. Four scintillation-counter hodoscopes H_1-H_4, each consisting of a bank of nine vertical elements, gave spatial information on the trajectory. The pulse heights produced in all of the above counters were recorded for each event. The total amount of material traversed by the particles in the spectrometer was 17 g/cm².

The event trigger was a threefold coincidence

$A_2 \cdot A_3 \circ A_4$. Each trigger counter was sensitive to a pulse height $\frac{1}{20}$ of the average pulse height $\langle dE_1/dx\rangle$ produced by a particle of unit charge in that counter. The trigger logic was such that only particles moving with $\beta > 0.94$ were accepted. This condition is satisfied, at the momenta explored, by charge-$\frac{1}{3}e$ particles of mass ≤ 10 GeV/c^2 and by charge-$\frac{2}{3}e$ particles of mass ≤ 19 GeV/c^2.

In order to be analyzed, the event giving rise to a trigger was required to have one and only one count in each horizontal or vertical hodoscope bank, with a pulse-height amplitude greater than $\frac{1}{20}$ of the average signal for unit-charge particles in the struck counter. However, because of a high counting rate in H_1, two counts were allowed in the horizontal bank of this hodoscope. Only events which were consistent with a continuous trajectory reconstructing satisfactorily to the target were considered in the analysis: In the circumstance of two hits in H_1, the track which best gave a continuous trajectory was used.

The efficiency of the counters and hodoscope elements for detecting particles of fractional charge was evaluated by determining the average number, $\langle n_1\rangle$, of photoelectrons produced by the passage of unit-charge particles from the shape of the dE_1/dx distribution ($\langle n_1\rangle \approx 60$). For each element the efficiency for detecting fractionally charged particles was determined by comparing the expected signal with that necessary to trigger the electronics. In this evaluation, the number of photoelectrons was assumed to be Poisson distributed. The overall conclusion is that all elements were nearly 100% efficient, even for charge-$\frac{1}{3}e$ particles. Using the pulse-height information from the trigger counters A_2-A_4, we determined the first normalized moment

$$M_1 = \frac{1}{3}\sum_{i=2}^{4}\left(\frac{dE/dx}{\langle dE_1/dx\rangle}\right)_i$$

for each accepted event. The average square deviation M_2 was also calculated. Typical distributions of dE_1/dx and M_1 are given in Figs. 2(a) and 2(b), respectively. Events which reconstructed to within 3 cm from the target in the horizontal

TABLE I. Input numbers and the limits on the cross sections determined from this experiment.

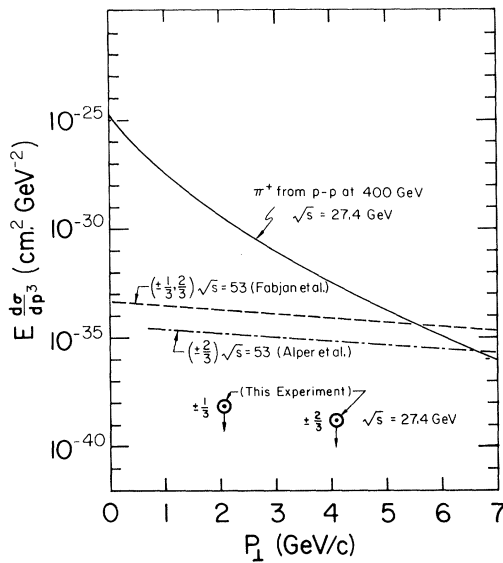|	$(E\,d\sigma/dp^3)_e$, $p_\perp = 6.15$ GeV/c (cm² GeV⁻²)	N (events)	$(E\,d\sigma/dp^3)_{e/3}$, $p_\perp = 2.05$ GeV/c (cm² GeV⁻²)	$(E\,d\sigma/dp^3)_{2e/3}$, $p_\perp = 4.10$ GeV/c (cm² GeV⁻²)
Positive	1.21×10^{-35}	49 181	5.1×10^{-39}	1.3×10^{-39}
Negative	0.63×10^{-35}	14 823	8.8×10^{-39}	2.2×10^{-39}

FIG. 3. The limits on the invariant cross sections vs $p_\perp$ from this search and previous high-energy searches.

and 0.3 cm in the vertical, and for which $M_1 < 0.75$, were considered quark candidates.

From a total number of more than 60 000 accepted events, we find *none* with values of M_1 and M_2 compatible with those expected from a particle of charge $\frac{1}{3}e$ or $\frac{2}{3}e$. In fact, no event was observed with a satisfactory target position and trajectory with a first moment $M_1 < 0.6$.

The 90%-confidence-level upper limit for the differential cross section for quark production is given by the expression

$$\left(E\frac{d\sigma}{dp^3}\right)_q = \left(\frac{e}{q}\right)^2 \frac{2.3}{N}\left(E\frac{d\sigma}{dp^3}\right)_e,$$

where $(E d\sigma/dp^3)$ is the differential cross section per nucleon for the production of unit-charge particles measured with the same spectrometer in a previous experiment,[1] q/e is the fractional charge of the quark (e.g., either $\frac{1}{3}$ or $\frac{2}{3}$), and N is the number of unit-charge particles detected. The factor $(e/q)^2$ comes from the momentum factor in the invariant phase-space element. We have used the measured atomic-number dependence of the cross sections[6] for unit-charge particles in extrapolating to the cross section per

nucleon. The results are shown in Table I.

A summary of the quark searches around $\theta_{c.m.} = 90°$ is given in Fig. 3, where the limits obtained in the present search at 400 GeV are given along with those obtained at the intersecting storage rings by Fabjan et al.[3] and by Alper et al.[3] Since some theoretical models consider the high-$p_\perp$ pions to be daughters of the fragmenting quarks, we have also plotted in Fig. 3, for comparison with our limits on free quarks, the differential spectrum of π^+ produced at $\theta_{c.m.} \simeq 90°$ by 400-GeV protons.

In conclusion, in a kinematical region not previously explored (high $p_\perp$) we find no charge-$\frac{1}{3}$ candidates at a level of approximately 10^{-9} of the pions produced at the same $p_\perp$, and no charge-$\frac{2}{3}$ candidates at a level of approximately 10^{-6}.

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