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

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ABSTRACT

We have searched for charge 1/3 and charge 2/3 particles produced with large transverse momentum in 400 GeV proton-Cu collisions. At 6.15 GeV/c transverse momentum 4.9×10^4 positive and 1.5×10^4 negative unit-charged 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 1/3 particles are 5.1×10^{-39} and 8.8×10^{-39} cm^2 GeV^{-2}, respectively. For charge 2/3 positive and negative 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 et al.[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 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 ±5%, was set to accept unit charge (e) particles of lab momentum 80 GeV/c ($P_\perp$ = 6.15 GeV/c). The respective lab momenta for charge 1/3 e and charge 2/3 e particles are 27 GeV/c ($P_\perp$= 2.05 GeV/c) and 53 GeV/c ($P_\perp$ = 4.10 GeV/c).

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 this experiment, on the charge) of the particle. For unit-charged 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 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 1/3 and 8.0 GeV/c^2 for charge 2/3, assuming quarks are produced in pairs via the process $p + N \rightarrow N + N + q + \bar{q}$.

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 9 vertical elements and a bank of 3 horizontal 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 grams/cm^2.

The event trigger was a threefold coincidence $A_2 \cdot A_3 \cdot A_4$. Each trigger counter was sensitive to a pulse height 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 1/3 e particles of mass ≤ 10 GeV/c^2 and by 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 1/20 of the average signal for unit-charge particles in the struck counter. However, due to 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 1/3 e particles. Using the pulse height information from the trigger counters A_2 - A_4, we determined the first normalized moment $M_1 = 1/3 \sum_{i=2}^{4} \left(\frac{dE/dx}{\langle dE_1/dx \rangle}\right)_i$ for each accepted event. The average square deviation, M_2 was also calculated. Typical distributions of $\frac{dE_1}{dx}$ and M_1 are given in Figs. 2a and 2b, respectively. Events which reconstructed to within 3 cm from the target in the horizontal 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 <u>none</u> with values of M_1 and M_2 compatible with those expected from a particle of charge 1/3 e or 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% C.L. 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 $\left(E \frac{d\sigma}{dp^3}\right)_e$ 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 1/3 or 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-charged particles in extrapolating to the cross section per nucleon. The results are shown in Table 1.

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 ISR by Fabjan _et al._[3] and by Alper _et al._[3] As some theoretical models consider the high $p_\perp$ pions to be the daughters of fragmenting quarks, we have also plotted in Fig. 3, for comparison with our limits on free quarks, the differential spectrum of π^+ produced at $\theta_{c.m.} \approx 90°$ by 400 GeV protons.

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

We thank Fermilab for allowing us to make this search.

References

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Table Caption

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

Figure Captions

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 to A_4 for one run.

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

TABLE 1

	$(E \frac{d\sigma}{dp^3})_e$ (cm^2 GeV^{-2}) $p_\perp$ = 6.15 GeV/c	N (events)	$(E \frac{d\sigma}{dp^3})_{\frac{1}{3}e}$ (cm^2 GeV^{-2}) $p_\perp$ = 2.05 GeV/c	$(E \frac{d\sigma}{dp^3})_{\frac{2}{3}e}$ (cm^2 GeV^{-2}) $p_\perp$ = 4.10 GeV/c
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}

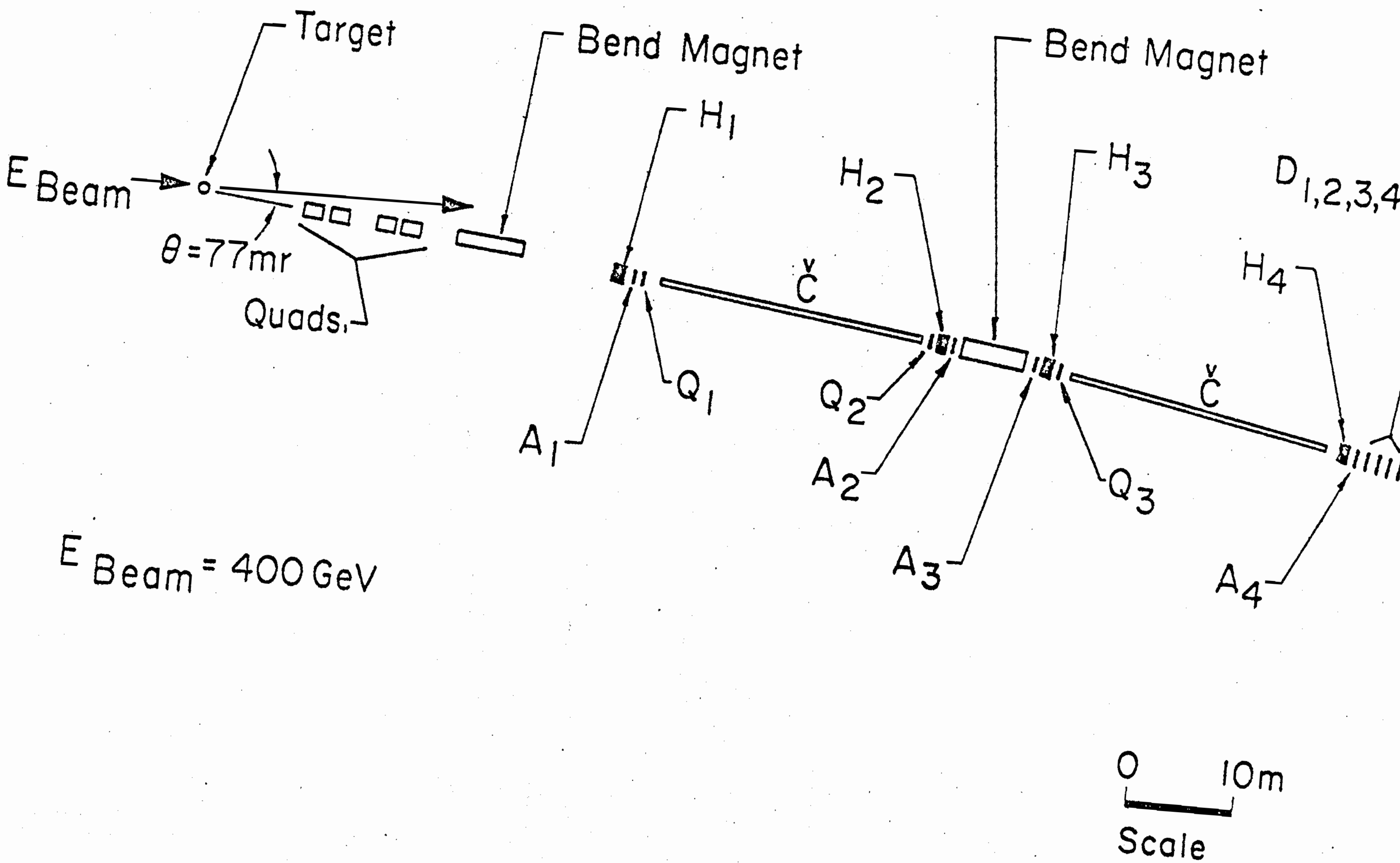
Target
Bend Magnet
Bend Magnet
H_1
E_{Beam}
H_2
H_3
$D_{1,2,3,4}$
θ=77mr
Č
H_4
Quads.
Q_1
Q_2
Č
A_1
A_2
Q_3
A_3
A_4
E_{Beam} = 400 GeV
0
10m
Scale

Fig. 1

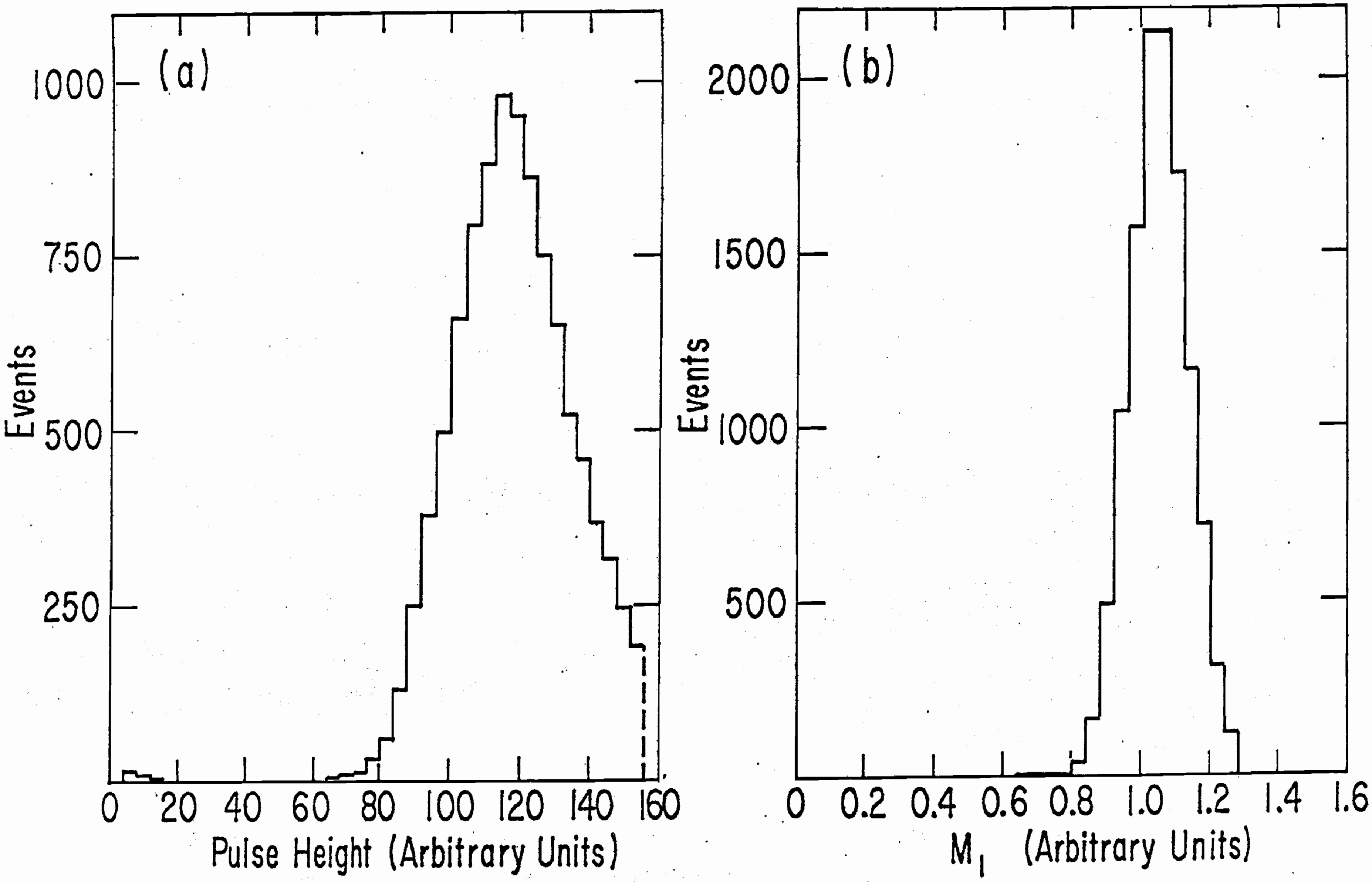
(a)
1000
750
500
250
Events
0
20
40
60
80
100
120
140
160
Pulse Height (Arbitrary Units)
(b)
2000
1500
1000
500
Events
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
M_1 (Arbitrary Units)

Fig. 2

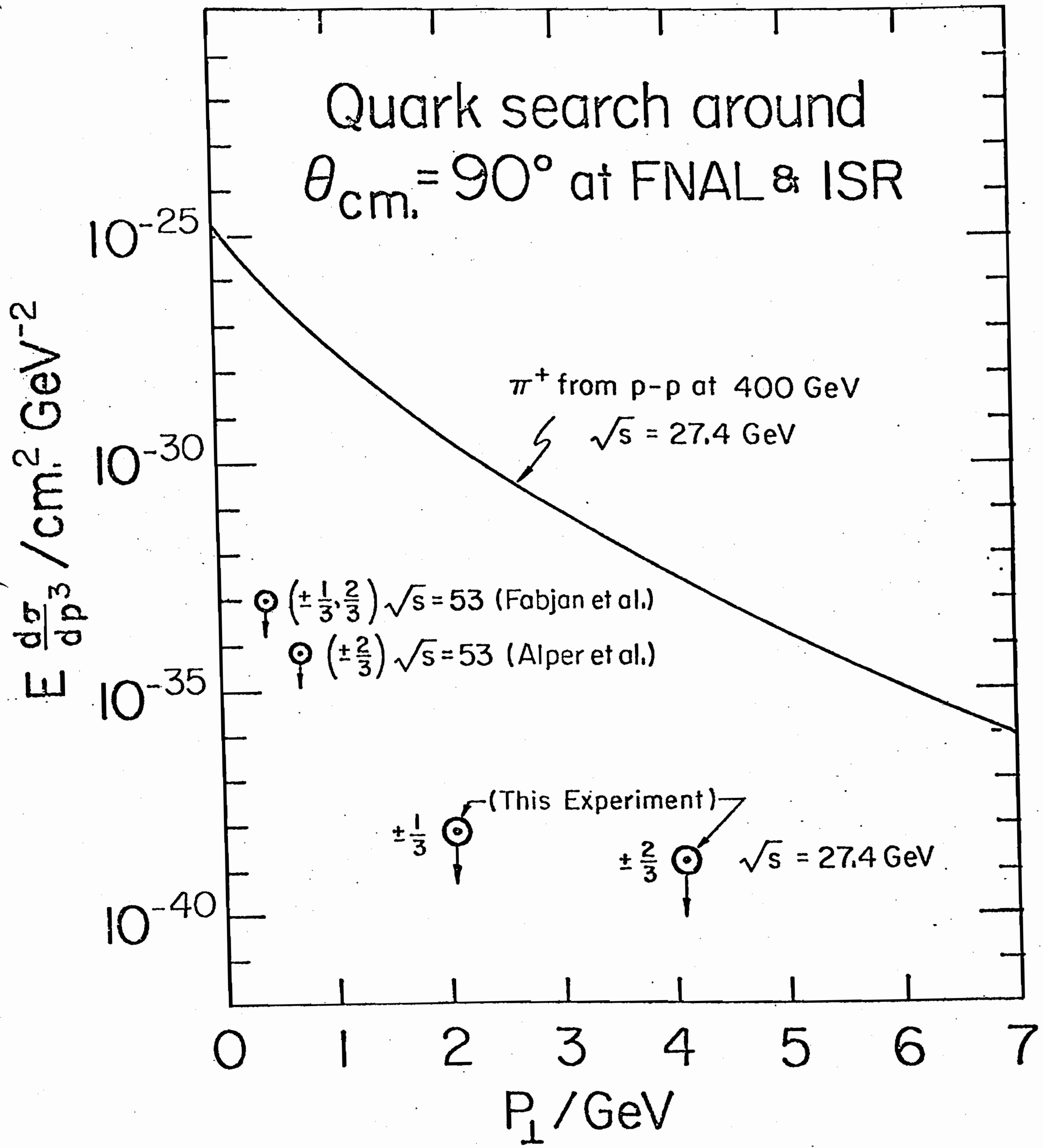
Quark search around
$\theta_{c.m.}$ = 90° at FNAL & ISR
π^+ from p-p at 400 GeV
$\sqrt{s}$ = 27.4 GeV
$(\pm\frac{1}{3}, \frac{2}{3})$ $\sqrt{s}$ = 53 (Fabjan et al.)
$(\pm\frac{2}{3})$ $\sqrt{s}$ = 53 (Alper et al.)
(This Experiment)
$\pm\frac{1}{3}$
$\pm\frac{2}{3}$
$\sqrt{s}$ = 27.4 GeV
10^{-25}
10^{-30}
10^{-35}
10^{-40}
$E\frac{d\sigma}{dp^3}$ /cm.^{2} GeV^{-2}
0 1 2 3 4 5 6 7
$P_\perp$ / GeV

Fig. 3