NAL PROPOSAL No. 325

Scientific Spokesman:

J. W. Cronin
Enrico Fermi Institute
University of Chicago
Chicago, IL 60637

PH: 312 - 667-4700

STUDY OF DI-MUON PRODUCTION AT HIGH TRANSVERSE MOMENTA

J. W. Cronin and Henry Frisch
University of Chicago

P. A. Piroué
Princeton University

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ADDENDUM TO NAL PROPOSAL 325

THE MULTI-HOLE SPECTROMETER (MHS)

J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute
University of Chicago, Chicago, Illinois 60637

and

J. P. Boymond, P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories
Princeton University, Princeton, New Jersey 08540

August 12, 1974

We have given further consideration to the study of high mass dimuon events. In the original Proposal 325 (E-300 Addendum), we suggested using the east end of the pit being built for Adair (E-48). (We assume the reader has also read the E-300 Addendum). At the time of writing this note (August 1, 1974), the exact location of the pit is still uncertain. In addition, we have done more detailed calculations on muon background and find that a wide detector transverse to the muon direction is far from optimum. For the small angle muons there is insufficient thickness to suppress the μ background from π and K decay, while at larger angles, the desired muons do not have sufficient range. Thus,in this note we propose an alternative scheme which, on the one hand, is an escalation, but, on the other hand, is far superior and sensibly designed.

One should recall that E-100 was the first experiment at FNAL to successfully measure direct muons. Our results are now published (Phys. Rev. Letters 33, 114, 1974). We are most eager to continue this work in a modest but significant way. We realize that there are many muon experiments approved or proposed. We are still behaving as scientists, trying to follow up on a discovery with a reasonable next step, given the limitations of our location and apparatus.

It is well known that the invariant π and K production cross sections are functions only of $p_\perp$ in the central region (x = 0.) Thus, if one builds a detector parallel to the proton beam, the decay muons must penetrate a fixed amount of transverse shielding independent of angle with respect to the incident beam. We have designed a detector which has a fixed $p_{\perp}$ = 1.5 GeV/c cutoff for muons.

The detector is a set of 10 6' x 4' x 1' liquid scintillation counters, each placed in a 4' diameter 17' deep hole. The 10 holes are placed along a line 19' displaced from the incident beam direction. One has 15' of transverse earth shielding which corresponds to a 1.5 GeV/c cutoff in transverse momentum. The holes,which begin at 140' from the target, increase in distances from another in geometric progression with a factor 1.166 in distance from one to another.

Figure 1 shows a layout of this "Multi-Hole Spectrometer" (MHS). The spacing of the detectors is such that each has a 1' overlap with its neighbors for muons that travel in a straight line from the target. This overlap assures that no muon can scatter around a detector. In the center of mass of a 300 GeV pp collision, the detector subtends a polar angle of 45° to 120°. It subtends an azimuthal angle of 18°.

As in our previous proposal, we plan to interrogate the multi-hole spectrometer each time a direct muon is detected in our E-100 spectrometer. Given a direct muon in the spectrometer from parton-anti-parton annihilation, we expect to observe the other muon in the MHS with a probability of 0.8 or greater.

We are also eager to operate such a detector in coincidence with identified hadrons in the spectrometer. We would be eager to find out if direct muons are produced in coincidence with hadrons. In particular, people speculate these days that charmed particles might be produced in pairs in ordinary collisions. They are expected to have a finite branching ratio to $K\mu\nu$. Hence, one might observe K,μ coincidences--the K coming from one charmed particle in the pair and the muon from the other of the pair.

Such a device cannot measure the $\mu\mu$ mass accurately. It can however measure the minimum mass which is given by $M_{\mu\mu} \gtrsim (p_{\perp}^{s} + 1.5)$ GeV/c^2 where $p_{\perp}^{s}$ is the transverse momentum setting of the spectrometer and 1.5 is the transverse momentum cutoff of the MHS. If the RMS transverse momentum of $M_{\mu\mu}$ is less than .5 GeV/c, then the dimuon mass resolution is $\Delta M_{\mu\mu}/M_{\mu\mu} \sim 0.1$.

A steel hadron absorber 6" wide and 72" long is placed on the west side of the beam. Figure 2 shows the arrangement of the absorber close to the target. It moves in a transverse direction to the beam for a distance between 0.5" and 2" from the beam. This varies the decay distance for π's and K's by a factor 4. For μ's at .040 mrad the distance varies between (12.5" + λ) and (50" + λ) where λ is the attenuation length in steel measured to be 6.8" in the last experiment. For μ's at .150 mrad the decay distance varies between (3.3" + λ) and (13.3" + λ).

We have calculated the singles rates in the detectors for the absorber close position using the measured invariant cross sections on a heavy target. The rates from π and K decay are found to be $\sim$ 500 μ's/ft^2/10^{12} interacting protons. This is, then, 1.2×10^4 μ's/pulse for one detector and 1.2×10^5 for the entire system. Assuming a 500 msec effective spill, the chance coincidence probability for the entire system is 4×10^{-3}, and 5×10^{-4} for a given detector. This sets a limit on the sensitivity of the apparatus. One notes that the insertion of 12" additional transverse shielding will increase the sensitivity by a factor 5. This could easily be done by inserting a solid steel drawer in position 2D of the target box.

We have consulted a contractor (Case, Roselle, Ill.) for the price of holes. The contractor stated $1500/per hole for 10 4' diameter 17' deep holes lined with corregated steel. The additional cost to place a cover on each hole and a Sears-Roebuck sump inside may cost NAL $500/hole. Our detector cost is estimated to be $1000 each (4 665PM's, 24 cu. ft. liquid scintillator, and a rough aluminum tank.)

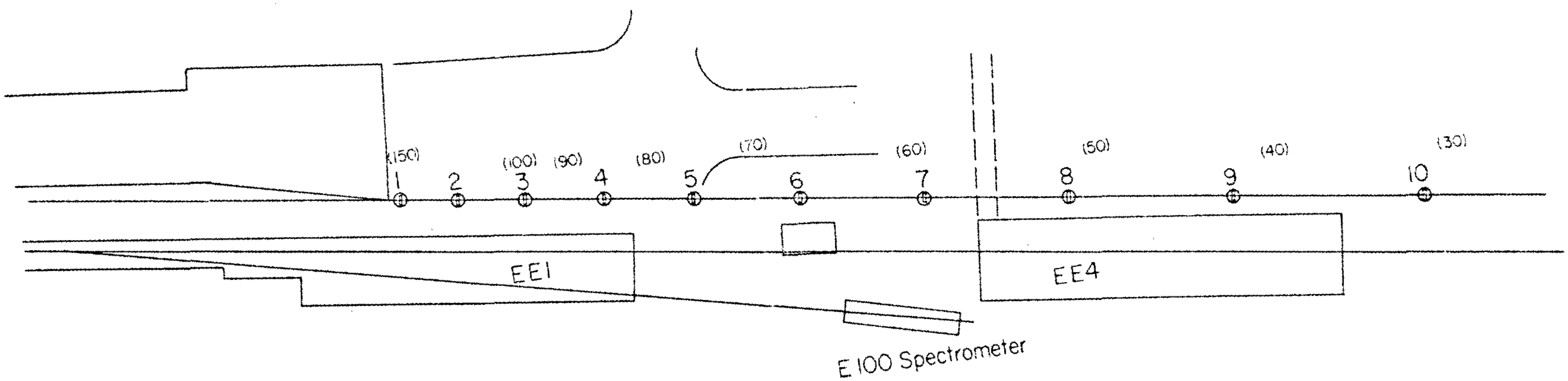
In order to make the MHS less unsightly, we have considered more decorative covers which may enhance the beauty of the site. Figure 3 shows several disguises which might be appropriate.

FIGURE CAPTIONS

Figure 1. The experimental layout. The numbers in parenthesis are angles measured from the beam line in milliradians.

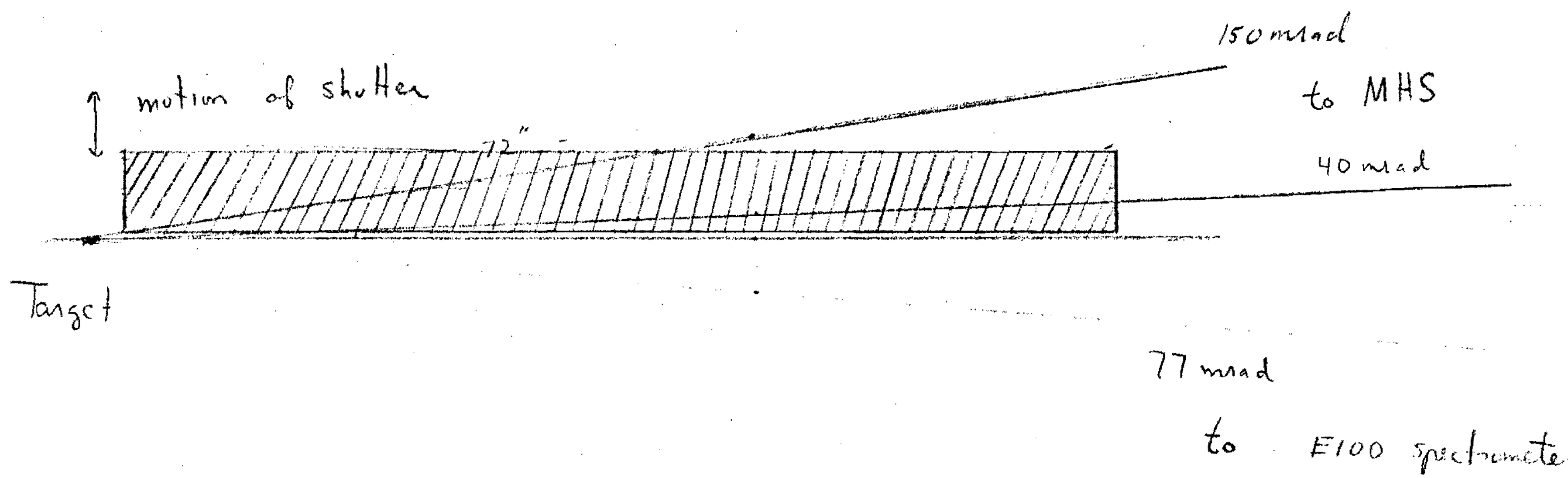
Figure 2. The moveable shutter for the second arm.

Figure 3. Possible decorative covers to the MHS.



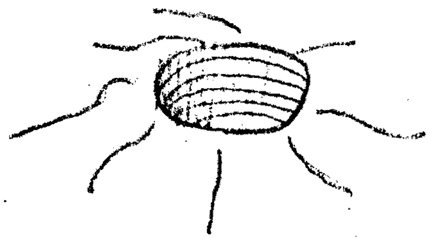
(150)
(100)
(90)
(80)
(70)
(60)
(50)
(40)
(30)
1
2
3
4
5
6
7
8
9
10
EE1
EE4
E 100 Spectrometer

Figure 1

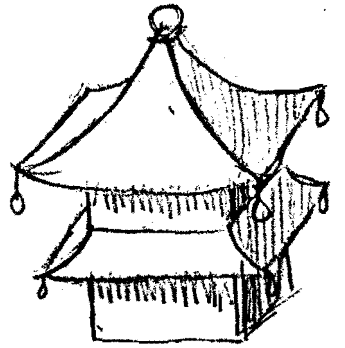


150 mrad
to MHS
motion of shutter
72"
40 mrad
Target
77 mrad
to E100 spectrometer

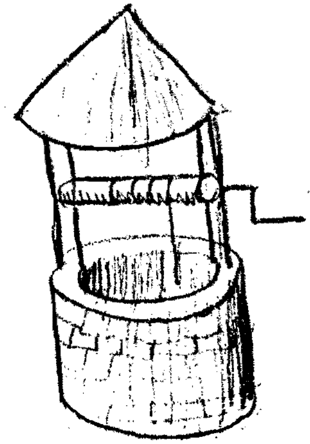
Fig 2



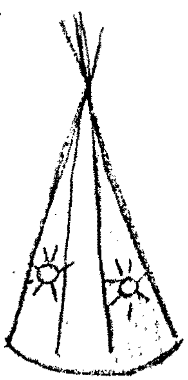
Ugly Exposed Hole



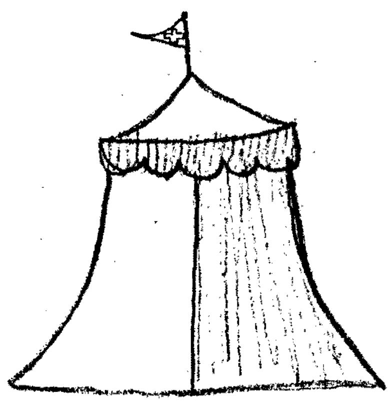
Chinese Pagoda



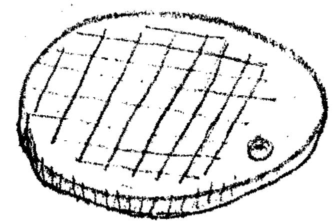
Wishing Well



Tepee



Jousting Tent



Manhole

or Missle silo

Fig 3

325

THE UNIVERSITY OF CHICAGO
CHICAGO · ILLINOIS 60637
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
January 17, 1977

RECEIVED
JAN 19 1977
DIRECTORS OFFICE
FERMILAB

Professor Edwin L. Goldwasser
Director's Office
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Il. 60510

Dear Ned:

In this letter we are requesting additional running time beyond our present high mass dimuon program which is scheduled to end approximately on February 14, for the purpose of searching for quarks at high $P_\perp$. At Chicago, Guiseppe Cocconi and Keith Olive have searched through our E-300 data taken last winter for charge 2/3e quarks. A paper describing these results is enclosed, which shows that for high $P_\perp$ the invariant cross section for quark production is $\lesssim 10^{-6}$* of the corresponding invariant pion production cross section.

We have calculated our sensitivity for a quark search with a running time of 100 hours. With 1.5×10^{12} 400 GeV protons/pulse on a 40% interaction length target, we can set an upper limit for the cross section of 2/3e quarks of 9×10^{-40} cm^2-GeV^{-2} at $P_\perp = 3.07$ GeV/c and for 1/3e quarks of 3×10^{-39} cm^2-GeV^{-2} at $P_\perp = 1.54$ GeV/c. These are a factor of 10^{-8} and 10^{-10} of the π production cross section at the same transverse momentum. The exact run plan we will propose is still under discussion. A higher $P_\perp$ might be more appropriate for 1/3e quarks.

We will require about three days of preparation for this run since we have to make our scintillation counters and hodoscopes sensitive to 1/9 ionization. We also plan to add four additional counters so that we will have eleven ionization samples of a given particle.

Thus we request three calendar days of check-out time at 5×10^{11} protons/pulse and 100 hours of data taking time at 1.5×10^{12} protons/pulse. You must realize that this run is the 'swan song' of a now venerable apparatus. We would be most sad if quarks were really there and we missed them.

Proposal # 325
Master
Do File
RRW
THG
PPO
RDO
— response

Sincerely yours,

Jim

James W. Cronin
for the Chicago-Princeton Group

JWC/pjf
Enclosure

* Note: 10^{-6} was obtained for each of 12 different measurements. To achieve greater sensitivity we will concentrate on only one or possibly 2 points.

Search at FNAL for Quarks Produced with Large Transverse Momentum

D. Antreasyan, G. Cocconi,[†] J. W. Cronin, H. J. Frisch, K. Olive,

and M. J. Shochet

The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

and

L. Kluberg,[‡] P. A. Piroué, and R. L. Sumner

Princeton University, Princeton, New Jersey 08540

The data taken last year in experiment E-300 (Dependence on Atomic Numbers of Inclusive Spectra at large $p_\perp$),[1] have been searched for quarks of charge $\frac{q}{e} = \pm \frac{2}{3}$.

A spectrometer analyzed the secondaries produced in various targets by protons of 300 and 400 GeV, at a lab. angle of 77 mr, i.e., at center of mass angles $\theta_{c.m.} \simeq 90°$ (see Fig. 1).

In order to identify the quarks, the pulse height produced by the accepted particles is measured in seven plastic scintillator counters, $A_1 - A_4$, $D_2 - D_4$, and the seven pulse heights are compared with those produced in the same counters by identified particles of unit charge ($\pi^{\pm}$ mesons, $K^{\pm}$ mesons, protons).

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† Visitor from CERN, Geneva, Switzerland.

‡ On leave from Ecole Polytechnique, Paris, France.

An event, to be recorded, requires a trigger consisting of a coincidence $A_2 \cdot A_3 \cdot A_4$, with pulses in each counter $\geq \frac{1}{5} < \frac{dE_1}{dx} >$, where $< \frac{dE_1}{dx} >$ is the average pulse height produced by a particle of charge 1e.

In order to be accepted and further analyzed in our quark search, the event giving rise to a trigger has to satisfy the following conditions:

1. Each of the four pairs of hodoscopes H_1, H_2, H_3, H_4 placed next to counters A_1 - A_4 (see Fig. 1), must have at least one of the seventeen vertical and at least one of the five horizontal elements giving a signal of amplitude $\geq \frac{1}{5} < \frac{dE_1}{dx} >$.

2. Assume that the signals are due to a charged particle with the polarity and the momentum expected from the spectrometer settings. Then the elements triggered in the hodoscopes must define a trajectory compatible with that of a particle emitted from a fiducial region contained within the target and bent only by the dipoles and the quadrupoles of the spectrometer.

3. The pulses in the trigger counters must arrive in a time succession compatible with that due to a particle moving with speed $\beta = 1 \pm 5.10^{-2}$ ($\Delta t \lesssim 5$ ns). This condition is satisfied, at the momenta explored, by particles of mass $\lesssim 10$ GeV.

The data were taken in various runs, each run characterized by the primary energy E_0, the nature of the target, the sign and the momentum, p_1, accepted by the spectrometer for charge 1e particles.

In each run, quark candidates are selected as follows:

1. Utilizing accepted events, the average pulse height for charge 1e particles is measured for each of the seven counters A_1, A_2, A_3, A_4, D_2, D_3, D_4 and called $< \frac{dE_1}{dx} >_i$, i = 1, 2 . . . 7.

2. Using the information from the first four counters, for each accepted event the first normalized moment

$$M_1 = \frac{1}{4} \sum_{i=1}^{4} \left(\frac{dE/dx}{<dE_1/dx>}\right)_i$$

is determined, as well as the average square deviation, M_2.

Typical distributions of $\frac{dE_1}{dx}$ and M_1 are given in Fig. 2 and Fig. 3.

3. The events for which $M_1 < 0.65$ are considered quark candidates, and the pulse heights of the remaining three counters, D_2, D_3, D_4 are used for an estimate of M_1 and M_2.

4. Also, the position of the particle at the target, as deduced from the hodoscopes, is reanalyzed to eliminate marginal cases.

These selection criteria are sufficient to reach the conclusion that, from a total number of more than 1,400,000 accepted events, none emerges with values of M_1 and M_2 compatible with those expected from a particle of charge $\pm\frac{2}{3}$ e. Actually, in no case a consistent first moment $M_1 < 0.6$ has been observed.

In order to establish upper limits for $\frac{2}{3}$ e quark production cross section, we use the following criteria.

1. For each primary proton energy and spectrometer polarity, data are grouped according to the value of $p_\perp$, independent of the target nature (H_2, Be, Cu, Ti, W). The total sum of events accepted is called N, and is due to π mesons, K mesons and protons. The target nature is neglected because, as shown by the results of Experiment E-300,[1] the packing of the nucleons in nuclei does not affect, at least in first-approximation, the production of large $p_\perp$ secondaries.

2. If the zero number of quarks observed emerges from a Poisson distribution, then the 90% confidence upper limit for the production cross section is obtained by assuming that 2.3 quarks were present while the total number of accepted events was N.

3. The upper limit for the differential cross section is then given by the expression:

$$\left(E\frac{d\sigma}{dp^3}\right)_{\frac{2}{3}e} = \left(\frac{3}{2}\right)^2 \frac{2.3}{N} \left(E\frac{d\sigma}{dp^3}\right)_{1e}$$

where $\left(E\frac{d\sigma}{dp^3}\right)_{1e}$ is the differential cross section for the production of charged particles measured in the same conditions in Experiment E-300. The results are to be found in Table 1.

A summary of the quark searches around $\theta_{c.m.} = 90°$ is given in Fig. 4, where, besides those of the present search at 400 GeV, are also given the limits obtained at the ISR by Fabjan et al.[2] and by Alper et al.[3] In Fig. 4 is also plotted the differential spectrum of π^+ produced at $\theta_{c.m.} = 90°$ by 400 GeV protons, a good reference for appreciating the effectiveness of the searches.

As a conclusion, our search has the following merits:

1. It explores more deeply a region, that of large $p_\perp$ at $\theta_{c.m.} \simeq 90°$, where the scattered quarks should have the greatest chance of breaking loose from the strings that the theoreticians are inventing for limiting their freedom.

2. The clean, zero background obtained indicates that the E-300 spectrometer has not been pushed to its limit in its discrimination of quarks against ordinary particles. An exposure to a total number

of primary protons 10 - 100 times greater than the present one (where 3% of ~2.5 10^{17} protons interacted in the targets) would measure proportionally smaller cross sections.

3. Easy adjustments of the phototube voltages and of the discriminators would permit, with the present apparatus, also the detection of quarks with charge $\pm\frac{1}{3}$ e.

REFERENCES

[1] D. Antreasyan et al., Phys. Rev. Lett. 38, 137 (1977); D. Antreasyan et al., Phys. Rev. Lett. 38, 140 (1977); L. Kluberg et al., submitted to Phys. Rev. Lett.

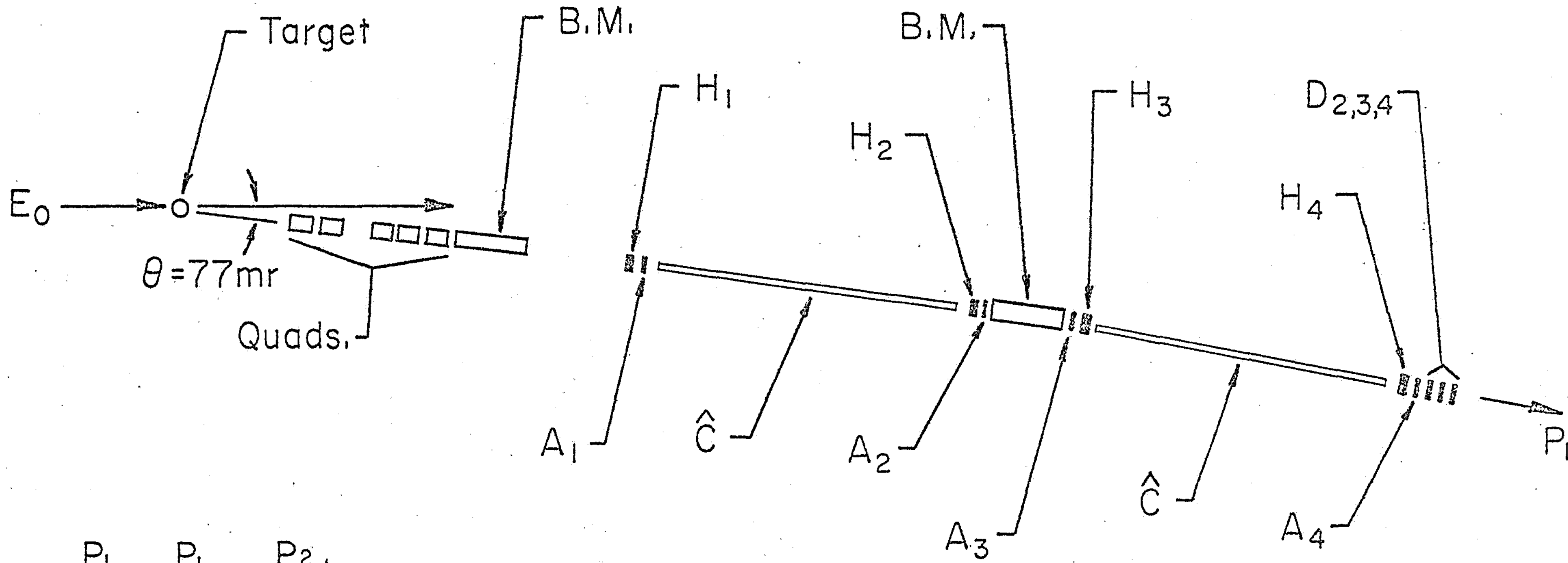
[2] C. W. Fabjan et al., Nucl. Phys., B101, 349 (1975).

[3] B. Alper et al., Phys. Lett. 46B, 265 (1975).

Table 1

$p_\perp$ ($\frac{2}{3}e$)		300 GeV $(E\frac{d\sigma}{dp^3})_{1e}$	300 GeV N	300 GeV $(E\frac{d\sigma}{dp^3})_{\frac{2}{3}e}$	400 GeV $(E\frac{d\sigma}{dp})_{1e}$	400 GeV N	400 GeV $(E\frac{d\sigma}{dp^3})_{\frac{2}{3}e}$
2.05	+	$8.6\ 10^{-32}$	168,333	$2.65\ 10^{-36}$	$1.32\ 10^{-31}$	403,962	$1.70\ 10^{-36}$
	-	4.5	178,883	1.30	0.70	335,534	1.08
2.57	+	$5.0\ 10^{-33}$	41,190	$6.30\ 10^{-37}$	$8.1\ 10^{-33}$	76,679	$5.47\ 10^{-37}$
	-	2.5	49,398	2.63	4.3	43,013	5.18
3.07	+	$4.5\ 10^{-34}$	42,874	$5.43\ 10^{-37}$	$8.4\ 10^{-34}$	13,317	$3.27\ 10^{-37}$
	-	1.7	16,416	5.37	3.9	31,017	0.65
3.59	+	$4.4\ 10^{-35}$	5,620	$4.06\ 10^{-38}$	$9.6\ 10^{-35}$	6,304	$7.89\ 10^{-38}$
	-	1.5	2,333	3.33	4.0	8,239	2.51
4.10	+	$3.9\ 10^{-36}$	1,583	$1.28\ 10^{-38}$	$1.51\ 10^{-35}$	1,285	$6.11\ 10^{-38}$
	-	1.24	698	0.92	0.46	2,276	1.05
4.61	+	$3.5\ 10^{-37}$	140	$1.29\ 10^{-38}$	$2.46\ 10^{-36}$	353	$3.61\ 10^{-38}$
	-	1.0	92	0.56	0.67	223	1.56

Momenta in GeV and cross sections in $cm^2\ GeV^{-2}$.



P_1	$P_{1\perp}$	$P_{\frac{2}{3}\perp}$
40	3.08	2.05
50	3.85	2.57
60	4.61	3.07
70	5.38	3.59
80	6.15	4.10
90	6.91	4.61
	GeV	

0 10 m

EXPERIMENT E 300

$E_0 = 300\text{-}400$ GeV

Fig. 1

Typical Distribution of the Pulse Heights from Counter A_1

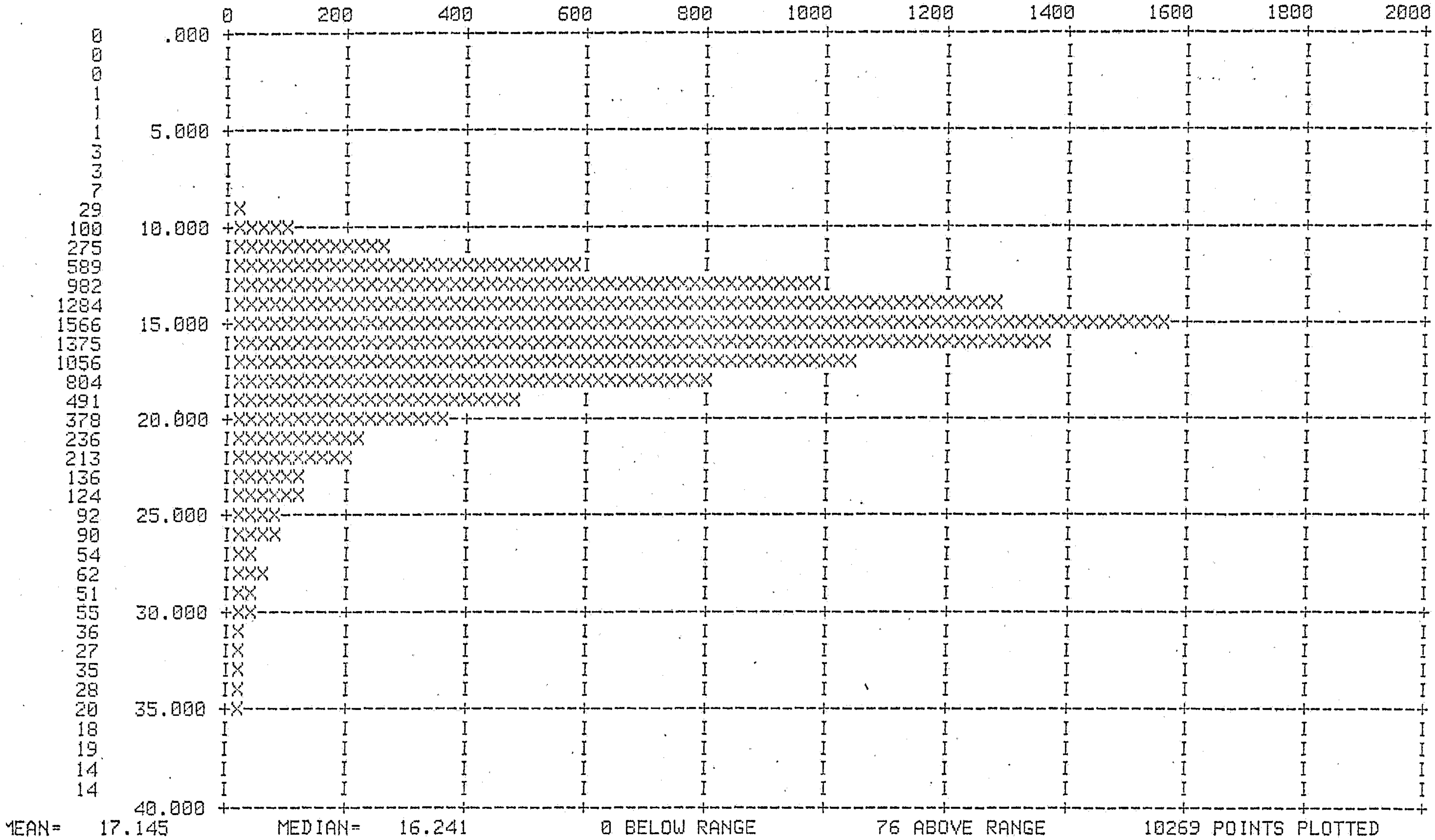


Fig. 2

Typical Distribution of Normalized First Moment, M_1, from Counters A_1, A_2, A_3, A_4

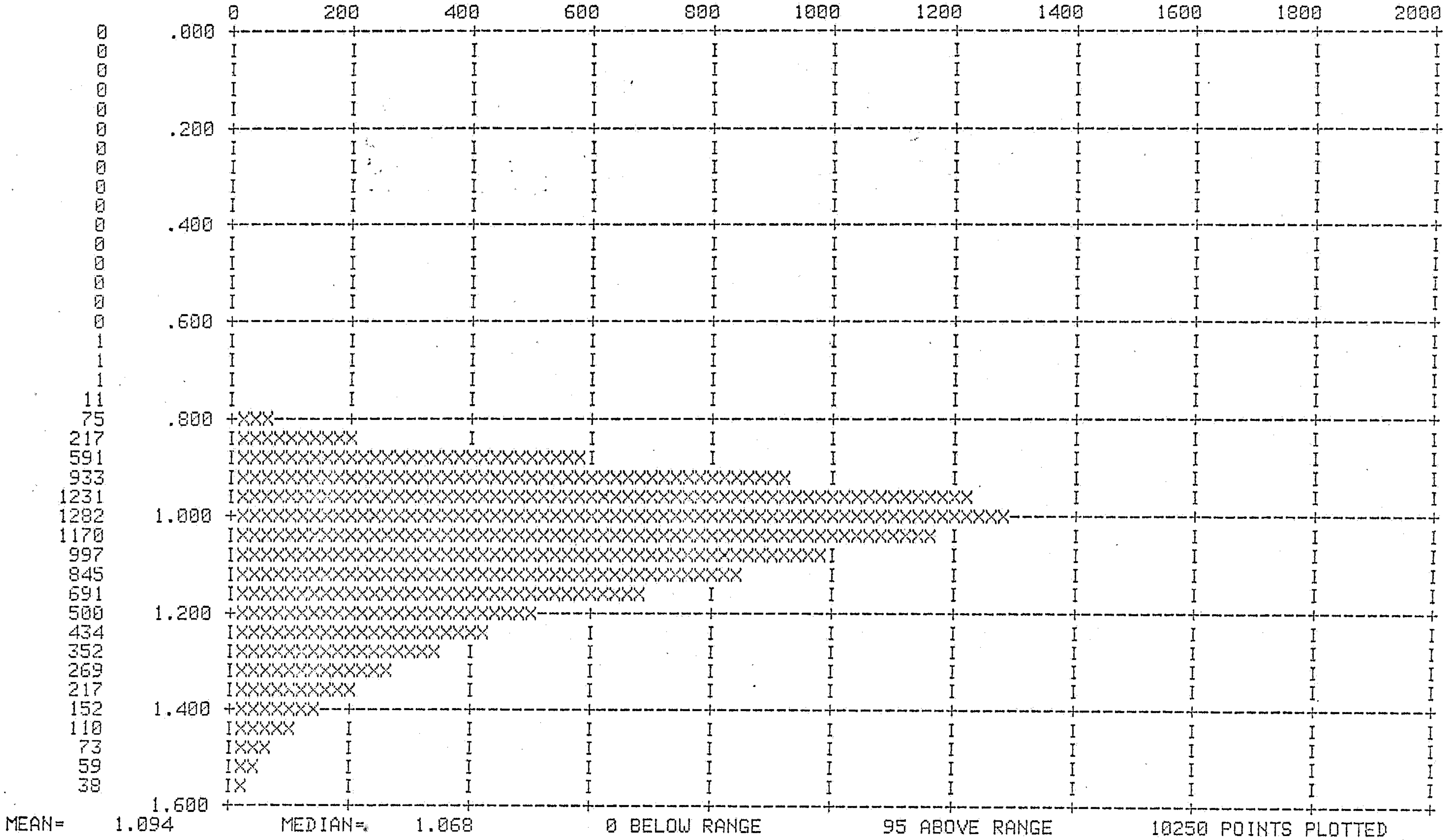
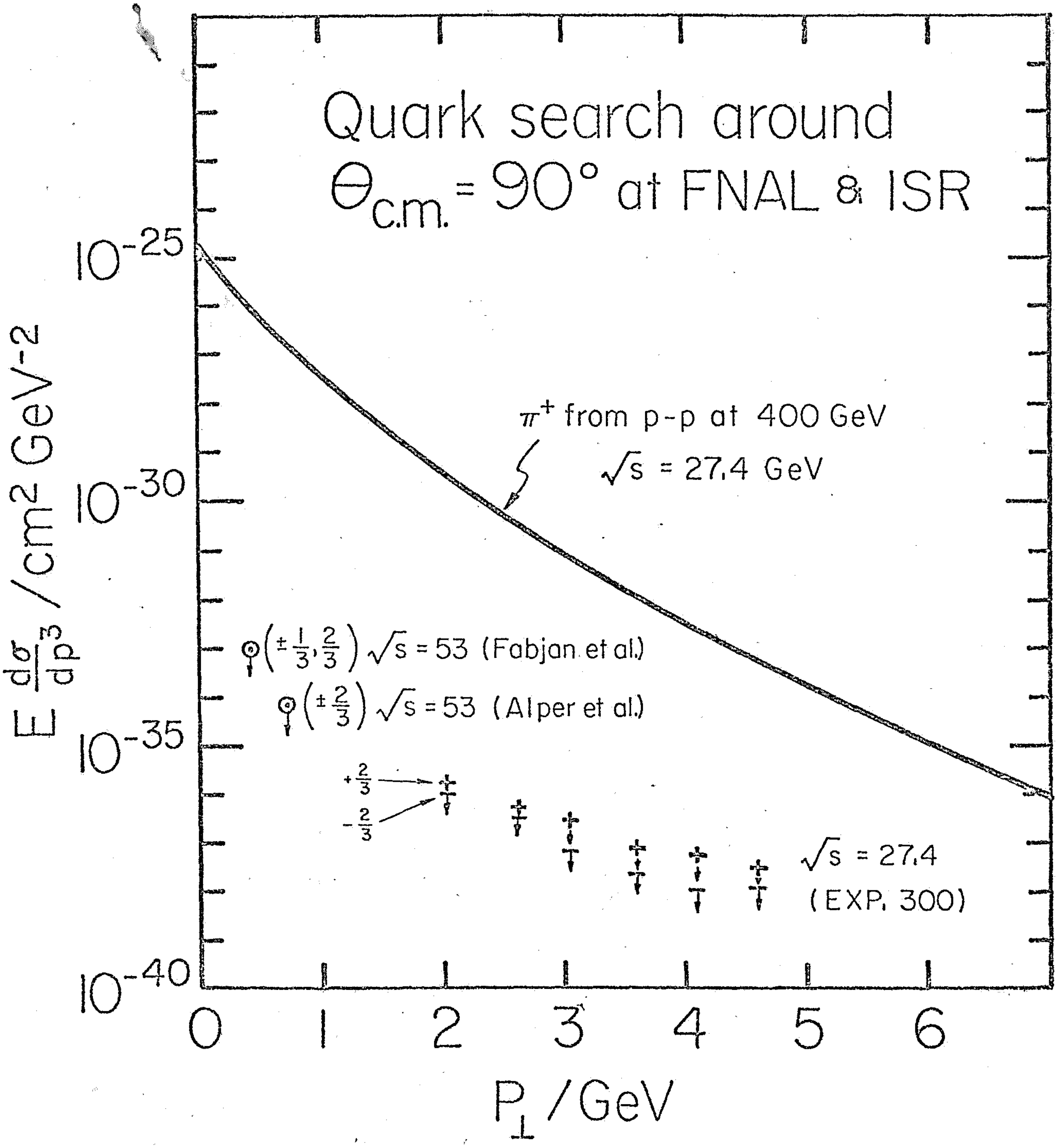


Fig. 3



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.)
$+\frac{2}{3}$
$-\frac{2}{3}$
$\sqrt{s}$ = 27.4
(EXP. 300)
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
$P_\perp$ /GeV

Fig. 4