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# Proposal for an Extension of E-363

# Nuclear Size Dependence for Particle Production at Intermediate Transverse Momentum

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## Introduction

Following the discovery of the $\psi$ particles and their proposed interpretation as bound states of charm-anticharm quarks, we proposed E-363 in order to detect the onset of new thresholds for charmed particle production. In the charm scheme of Gaillard, Lee and Rosner[1] the SU4 companions of $\psi$ have masses around 2.2 GeV and their preferred decays lead to final states containing K's. In E-363 we studied the $K/\pi$ ratio at fixed transverse momentum as a function of incident energy in pN collisions. The $p_{3\perp}$ values were chosen in order to maximize the acceptance for K's from charmed meson decays so that the expected signal was an increase in the $K/\pi$ ratio as the incident energy crossed the threshold for production of a pair of the new particles. Data collection for this experiment is now completed and some preliminary results are shown in the attached progress report. We now propose to extend our measurements on particle production using essentially the same apparatus shown in Fig. 1 of the appendix.

## Physics Motivation

With our spectrometer at $\theta_{3\mathrm{Lab}} = 15^{\circ}$ we can distinguish $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ for $0.25 \leq p_{3\perp} \leq 1.6$ GeV/c corresponding to recoil momenta in the lab $1.0 \leq p_{3\mathrm{Lab}} \leq 6.4$ GeV/c. This $p_{3\perp}$ interval covers, for the range $5 \leq \sqrt{s} \leq 25$ GeV, the transition region between the exponential dependence at low $p_{3\perp}$ and the power law dependence at high $p_{3\perp}$. There is a scarcity of data for single particle inclusive production between $\sqrt{s} = 5$ and $\sqrt{s} = 25$ GeV and as Cronin[2] points out this is a region where anomalies in the $p_{3\perp}$ dependence might be expected if one believes that the underlying physics is mundane at the AGS and PS and fundamental at the Fermilab and ISR energies. Although such a general study is interesting in its own right and we intend to carry it out in the proposed extension, we would like to focus our attention on a different effect which was recently reported by Cronin et al.[3] In their study of particle production at $\theta_{3CM} = 90^{o}$ for 300 GeV/c protons incident on Be, Ti and W targets they find a variation of the invariant cross section with atomic number A which is much stronger than the $A^{0.71}$ dependence expected from total cross section measurements on nuclei and interpreted as a shadowing effect by Glauber theory. Cronin et al. parametrize the A dependence by $A^{n(p_{3\perp})}$ and the resulting variation of the exponent n is shown in Fig. 1 for each produced particle species. Not only does n vary with $p_{3\perp}$ but, most unexpectedly, it takes values significantly larger than unity. As pointed out by the authors this implies that the nucleons in the nucleus behave in a cooperative fashion since if they all acted independently and in the absence of shadowing effects, n would be equal to unity.

In a recent publication G. R. Farrar[4] attemps to relate this peculiar nuclear size dependence to the dynamics of quark interactions. The implication of the theory is that n should increase with increasing $p_{3CM}$ of the produced particle saturating in the simplest case at n = 1 for $p_{3CM}$ in the range 1-3 GeV/c. The most interesting prediction is that for s and $p_{3\perp}$ sufficiently large only $p_{3CM}$ of the secondary determines n and not $\theta_{3CM}$, s or $p_{3\perp}$. The measurements of Cronin et al. were made at one energy

(300 GeV/c) and one CM angle ($\theta_{3CM} = 90^\circ$), i.e., the abscissa in Fig. 1 could be either $p_{3\perp}$ or $p_{3CM}$. The independence of n on $\theta_{3CM}$, s and $p_{3\perp}$ remains therefore to be checked. A further point made by Farrar is that no theory involving single or incoherent multiple scattering can lead to n > 1 as clearly indicated by the data of Cronin et al. One suggested explanation involves scattering of a quark from one initial nucleon off a $q\bar{q}$ ($qqq$) state from the nucleus leading to the production of a high momentum meson (baryon). The amplitude for these coherent processes should go as $A^2$ ($A^3$) since the nucleus contains A times as many quarks as a nucleon. Although such terms are expected to be small, since a nucleus looks like a collection of nucleons rather than a collection of quarks, the presence of $A^4$ ($A^6$) terms in the cross section might be detectable for large A. These terms would then provide information on $q$-$q$ interactions at distances large compared to a nucleon diameter. The dynamics of the $q$-$q$ interaction over such distances may in turn be related to the problem of quark confinement.

## Experimental Procedure

We do not propose to make any changes to the experimental apparatus shown in Fig. 1 of the appendix. For $0.25 \leq p_{3\perp} \leq 1.6$ GeV/c ($1.0 \leq p_{3Lab} \leq 6.4$ GeV/c) we can distinguish between $\pi^\pm$, $K^\pm$ and $p^\pm$ by time of flight between T1 and T7 (for $p_{3Lab} < 1.5$ GeV/c) and by using the two threshold $\hat{C}$ counters $\hat{C}1$ and $\hat{C}2$ and the differential $\hat{C}$ counter $D\hat{C}$ (for $p_{3Lab} > 1.5$ GeV/c). The running plan for the $p_{3\perp}$ survey part of the proposed extension is shown in Table 1 and essentially involves completing the gaps in the already existing data from E-363. In addition to the C target we plan to run with Cu and W targets.

In order to answer the questions on the nuclear size dependence described in the previous section we will take advantage of the recoil kinematics at fixed laboratory angle. In Fig. 2 we plot for recoil protons $p_{3CM}$ vs $p_{1\ Lab}$ at $\theta_{3\ Lab} = 15^{\circ}$ and different $p_{3\ Lab}$ values ranging from 2 to 10 GeV/c. We concentrate on recoil protons and antiprotons because they can be identified by our spectrometer for lab momenta up to 11 GeV/c. In Fig. 3 we show $\theta_{3CM}$ vs $p_{1\ Lab}$ for $\theta_{3\ Lab} = 15^{\circ}$ and $2 < p_{3Lab} < 10$ GeV/c. As can be seen from these two figures, as the incident and recoil lab momenta are varied, we cover a wide range of $p_{3CM}$ and $\theta_{3CM}$. In Fig. 4 we plot the exponent n for the nuclear size dependence vs $p_{3Lab}$. Curve a is taken from the data of Cronin et al. shown in Fig. 1. Following these authors we assume that the exponent depends on the $p_{3\perp}$ and species of the outgoing particle, in this case a proton, and not on the incident energy. Curves b, c and d represent transformations of curve a assuming that $p_{3CM}$ rather than $p_{3\perp}$ determines n. As mentioned earlier the abscissa in Fig. 1 can be read either as $p_{3CM}$ or as $p_{3\perp}$.

For our spectrometer at $\theta_{3Lab} = 15^{\circ}$ the transformation between $p_{3\perp}$ and $p_{3CM}$ depends on the incident and recoil momenta as shown in Fig. 2 so that we get curves b, c and d for $p_{1\ Lab} = 100$, 200 and 300 GeV/c respectively. We can now use curves a to d to predict the ratio of $(pW \to pX)/(pC \to pX)$ as a function of $p_{3Lab}$. This is shown in Fig. 5 where curves a to d correspond to n given by curves a to d of Fig. 4. All curves in Fig. 5 are normalized to the same point at $p_{3Lab} = 2$ GeV/c. The striking feature of this figure is that if n depends on $p_{3\perp}$ only we should observe a variation of over a factor of 2 in the ratio as $p_{3Lab}$ increases from 2 to 10 GeV/c. If on the other hand, $p_{3CM}$ is what determines n, the variation, for say 300 GeV/c incident energy, should not exceed 20% as $p_{3Lab}$ goes from 2 to 10 GeV/c. This dramatic difference is independent of the relative normalization between the W and C targets. We have carried out tests with C, Cu and W targets mounted on the same rotating wheel and are confident that we can handle the rates in our detectors and maintain acceptable radiation levels and beam losses.

In conclusion, by taking advantage of the recoil particle kinematics at fixed lab angle we can test whether $p_{3CM}$ or $p_{3\perp}$ is the relevant variable determining n and thus test the theoretical picture outlined in the previous section. An estimate of running time for this part of the proposal is given in Table 2.

## References

1. M. K. Gaillard, B. W. Lee, J. Rosner, Fermilab-Pub 74/86-THY, 1974.
2. J. W. Cronin, Talk at SLAC Summer Institute on Particle Physics, 1974.
3. J. W. Cronin et al. Fermi Institute Report EFI74-50, to be published in Phys. Rev. D, (1975).
4. G. R. Farrar, Physics Letters 56B, 185 (1975).

Table 1

| Recoil Momentum GeV/c | Hours Set up time | Hours for Data (negative) | Hours for Data (positive) | Total Hours |
|---|---|---|---|---|
| 1 | 4 | 4 | 4 | 12 |
| 1.5 | 4 | 4 | 4 | 12 |
| 2.0 | 4 | 4 | 4 | 12 |
| 2.5 | 4 | * | 4 | 8 |
| 3.0 | 4 | *+2 | 4 | 10 |
| 3.4 | 4 | * | 6 | 10 |
| 3.8 | 4 | * | *+10 | 14 |
| 4.3 | 4 | 20 | 15 | 39 |
| 4.8 | 4 | 30 | 20 | 54 |
| 5.4 | 4 | *+30 | 20 | 54 |
|  |  |  |  | 225 |

*Data already exist.

Table 2

| Recoil Momentum GeV/c | Hours Set up Time | Hours for Data (negative) | Hours for Data (positive) | Total Hours |
|---|---|---|---|---|
| 7 | 4 | 30 | 20 | 54 |
| 8.5 | 4 | 40 | 25 | 69 |
| 10 | 4 | 50 | 30 | 84 |
| 11.5 | 4 | 60 | 40 | 104 |
|  |  |  |  | 311 |

Total number of hours Tables 1 and 2 = 536.

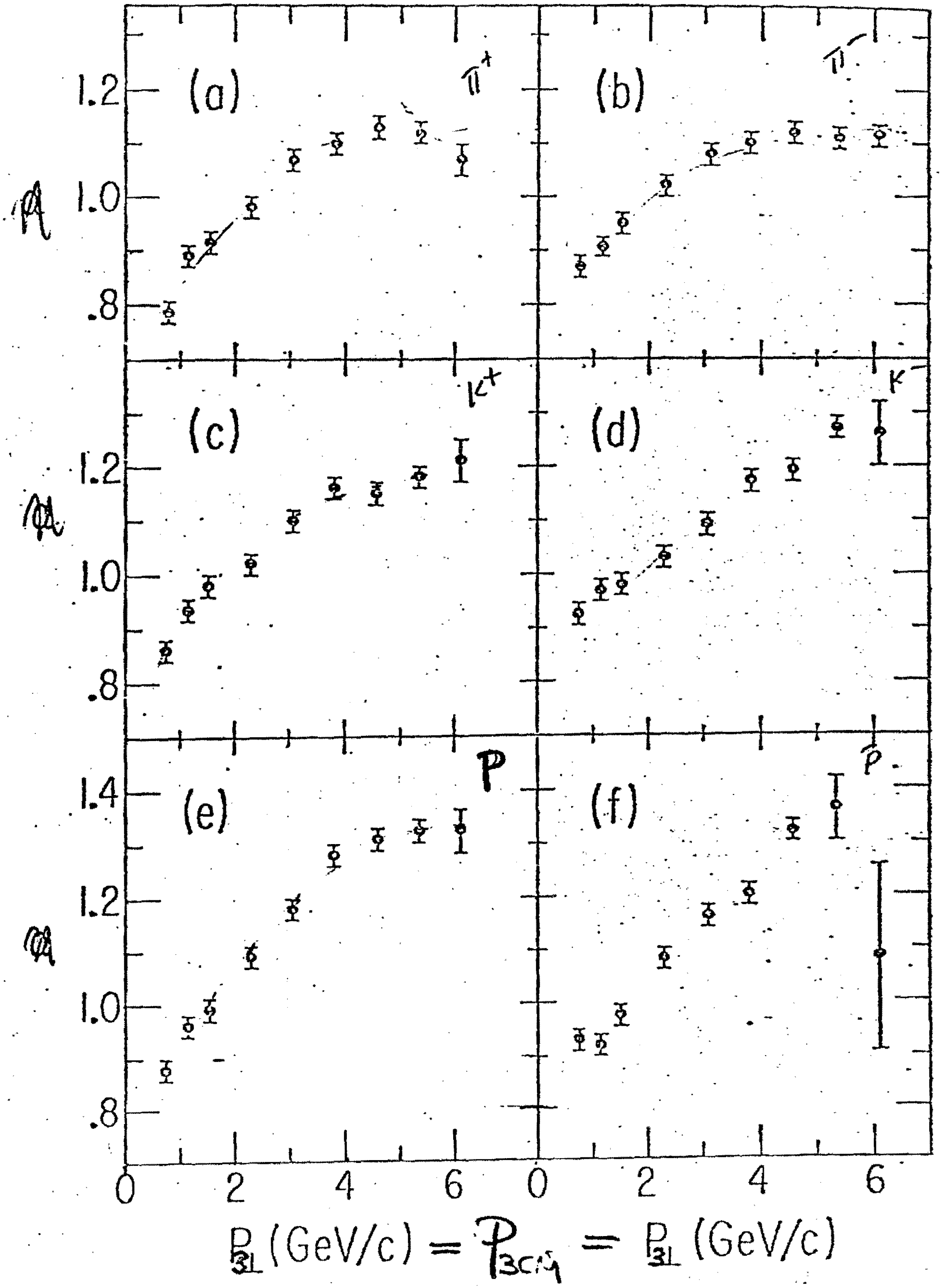
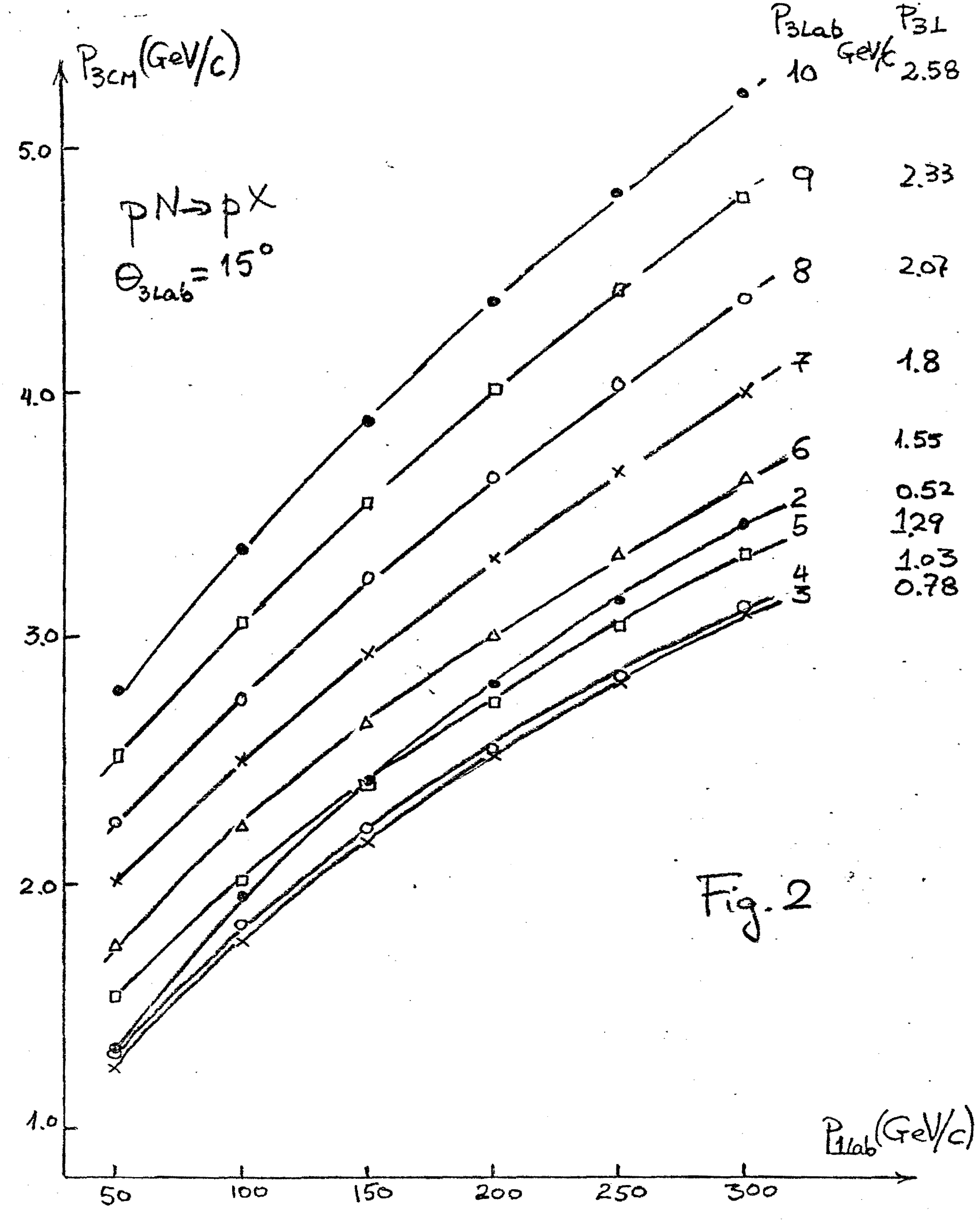

(a)
π+
(b)
π−
(c)
K+
(d)
K−
(e)
P
(f)
p̄
A
A
A
1.2
1.0
.8
1.2
1.0
.8
1.4
1.2
1.0
.8
0
2
4
6
0
2
4
6
P3L (GeV/c) = P3cm = P3L (GeV/c)

Fig.1 (ref-3)



$P_{3CM}$ (GeV/c)
$P_{3Lab}$ GeV/c
$P_{3\perp}$
pN → pX
$\theta_{3Lab} = 15°$
10 2.58
9 2.33
8 2.07
7 1.8
6 1.55
2 0.52
5 1.29
4 1.03
3 0.78
5.0
4.0
3.0
2.0
1.0
50
100
150
200
250
300
$P_{1Lab}$ (GeV/c)

Fig. 2

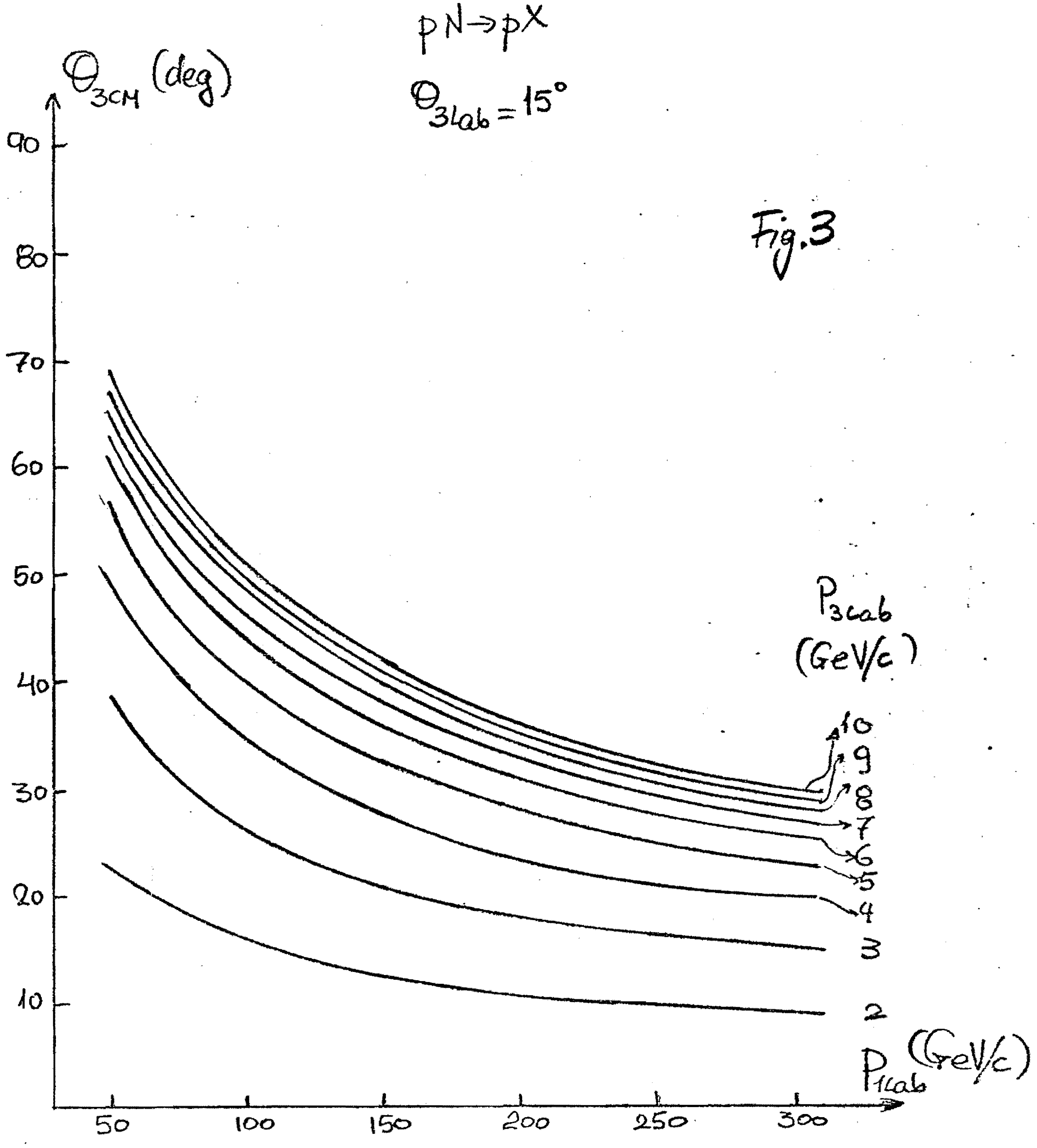


Fig.3

$pN \to pX$
$\Theta_{3lab} = 15°$
$\Theta_{3CM}$ (deg)
90
80
70
60
50
40
30
20
10
$P_{3lab}$ (GeV/c)
10
9
8
7
6
5
4
3
2
$P_{1lab}$ (GeV/c)
50
100
150
200
250
300

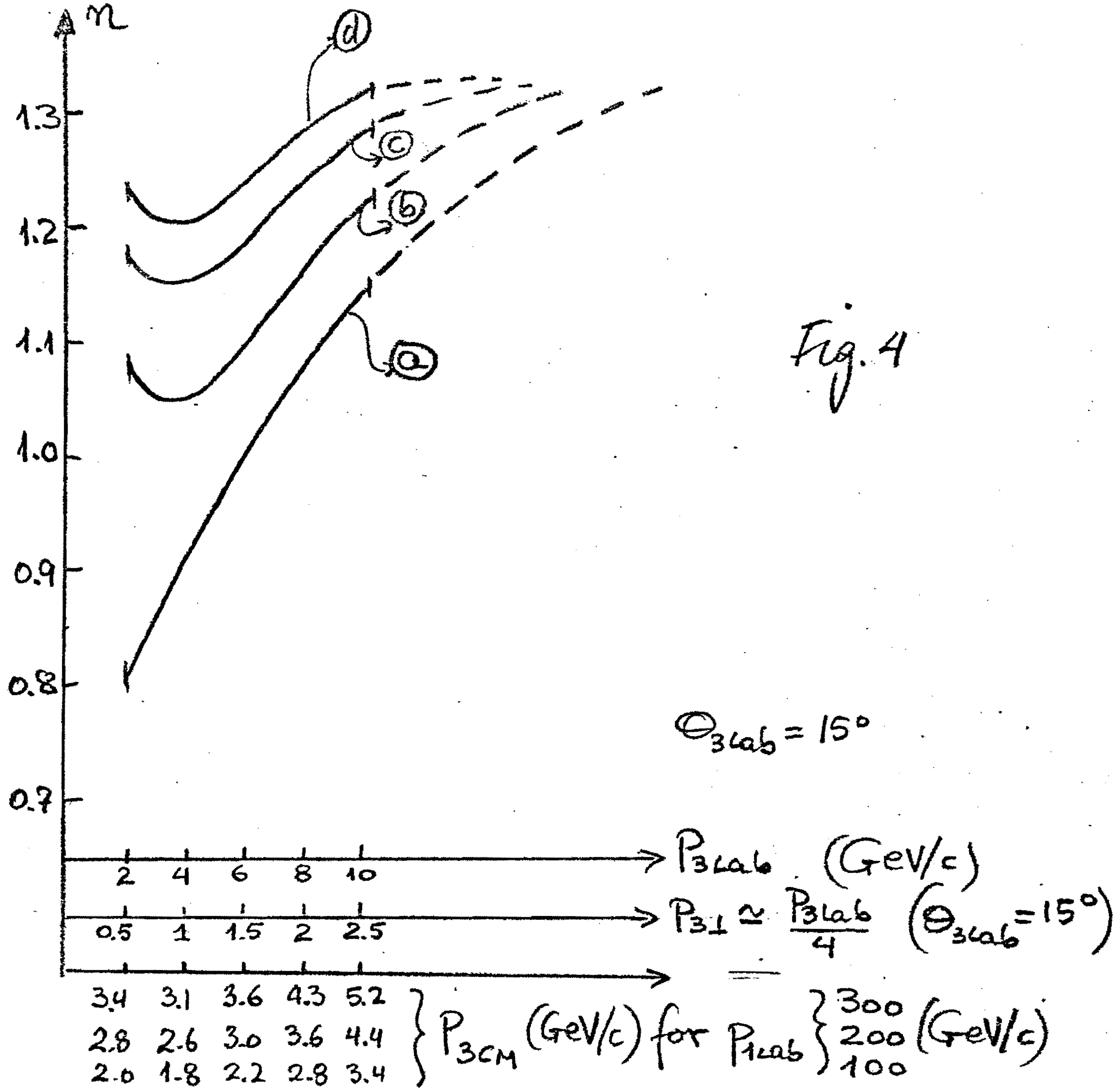


Fig. 4

ⓐ n for p Nucleus → pX from Cronin et al. (ref 3) assuming $p_{3\perp}$ to be the relevant variable. We also assume that n depends only on $p_{3\perp}$ and not on the incident energy

ⓑ, ⓒ, ⓓ n for p Nucleus → pX assuming $P_{3CM}$ to be the relevant variable. The transformation $P_{3\perp} \to P_{3CM}$ depends on $P_{1lab}$ so that we get curves b, c and d for 100, 200, 300 GeV/c respectively

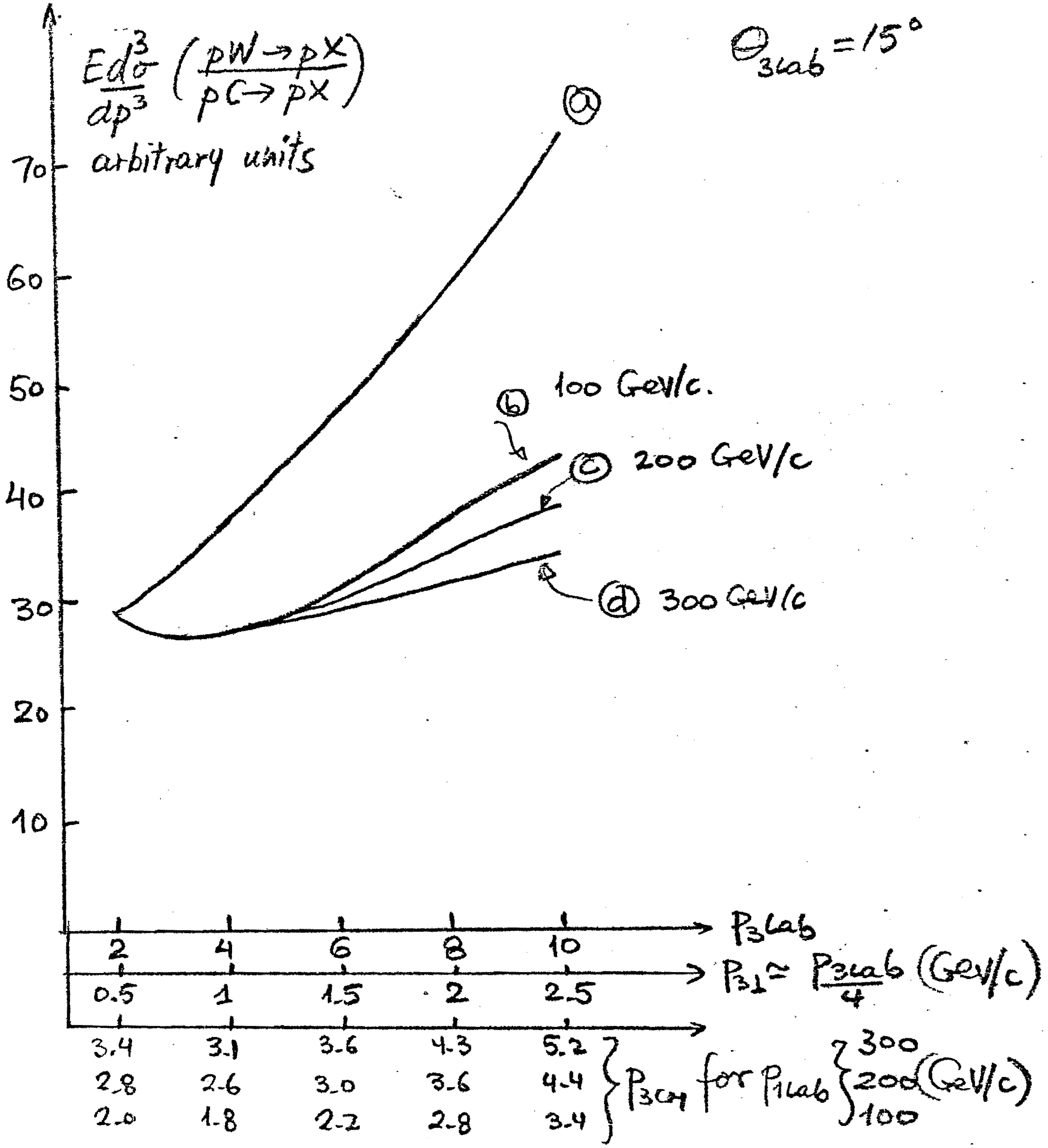

$\frac{E d^3\sigma}{dp^3} \left( \frac{pW \to pX}{pC \to pX} \right)$
arbitrary units
$\Theta_{3lab} = 15°$
70
60
50
40
30
20
10
ⓐ
ⓑ 100 GeV/c.
ⓒ 200 GeV/c
ⓓ 300 GeV/c
$P_{3lab}$
2 4 6 8 10
$P_{3\perp} \simeq \frac{P_{3lab}}{4}$ (GeV/c)
0.5 1 1.5 2 2.5
3.4 3.1 3.6 4.3 5.2
2.8 2.6 3.0 3.6 4.4
2.0 1.8 2.2 2.8 3.4
$P_{3cm}$ for $P_{1lab}$ 300 200 100 (GeV/c)

Fig. 5

## Appendix

## Progress Report on E-363

Between January and April we measured K/π ratios as a function of incident energy at $\theta_{lab} = 15^\circ$ and recoil momenta of 5.4, 3.8, 3.4 and 3.0 GeV/c. A second spectrometer arm at $\theta_{lab} = 12^\circ$ was installed in March in order to study K/π coincidences. The present experimental setup is shown in Fig. 1 and some representative results on $K^-/\pi^-$ and $\bar{P}/\pi$ ratios in the $15^\circ$ arm are shown in Figs. 2 and 3.

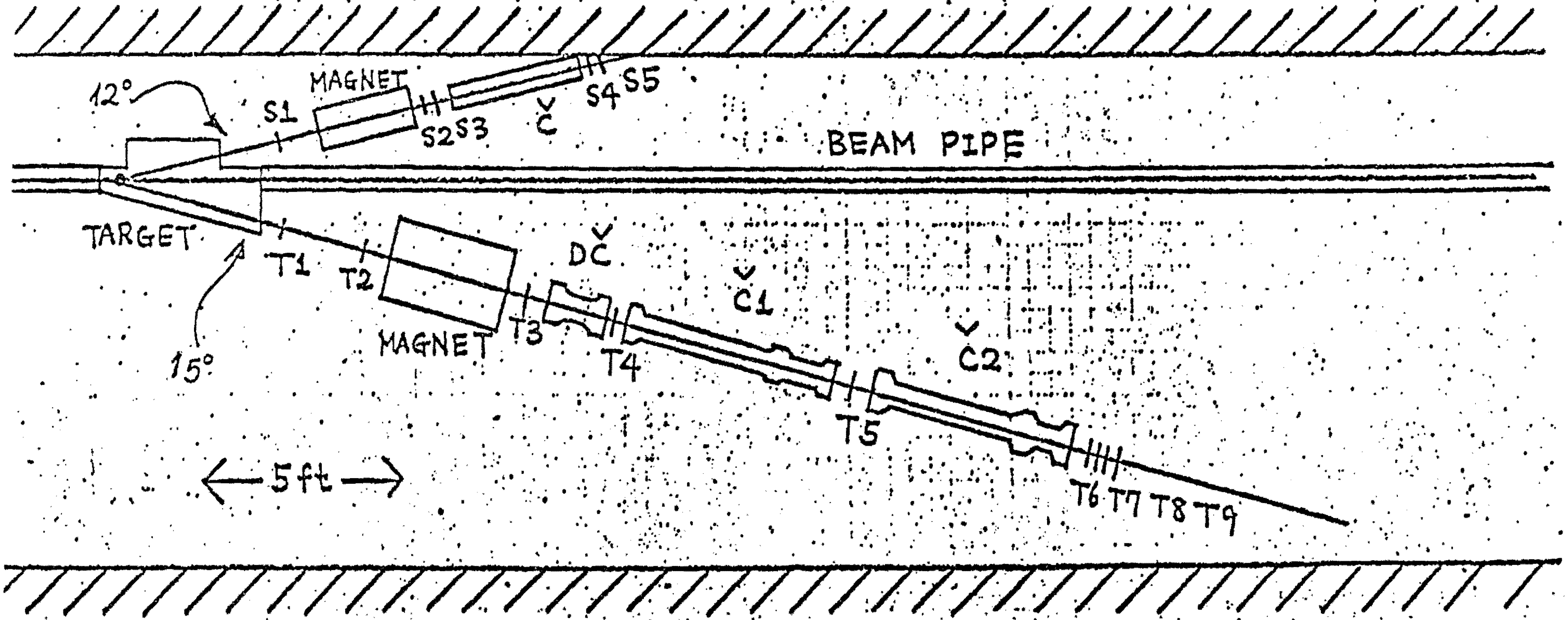
Some short runs with both arms tuned for Kπ coincidences of invariant mass around 2.2 GeV/c were taken in late March. The very low coincidence rate (∿ 2/hour) of which 50% was accounted for by accidentals (measured simultaneously by delaying one arm with respect to the other by one RF period) lead us to abandon further running in this mode in order to complete the K/π ratio measurements.

During these measurements in the $15^\circ$ arm we accepted $\pi^-$ events in the $12^\circ$ arm. This allowed us to normalize different momentum runs for K's and π's in the $15^\circ$ arm to the same number of $\pi^-$'s in the $12^\circ$ arm and thereby obtain information on the $p_\perp$ dependence for $K^-$ and $\pi^-$ production as a function of incident energy. Furthermore we spent some time collecting data with the $15^\circ$ arm polarity reversed which were also normalized to $\pi^-$ at 2 GeV/c in the $12^\circ$ arm. The resulting antiparticle/particle ratios as a function of incident energy are shown in Figs. 4 to 6.

In conclusion, at the present level of statistical accuracy, we observe no deviations from a smooth rise with energy for all measured ratios. Such deviations could have occurred as a result of opening of new thresholds for charmed particle production. We are now in the process of setting model dependent cross section limits on such processes.

E 363

Fig 1



$$\text{Event} \equiv T = T1 \cdot T2 \cdot T3 \cdot T4 \cdot T5 \cdot T9$$

$$\pi = T \cdot \check{C}1 \cdot \check{C}2$$

$$K = T \cdot D\check{C} \cdot \overline{\check{C}1} \cdot \check{C}2$$

- beam ... accelerating proton of intensity ~$10^{13}$/cycle and energy varying from 9 GeV to 380 GeV
- target --- 6μ Carbon filament
- magnet ... select momentum up to 6 GeV/c with 4 % bite ~~and~~ bend vertically by 4.2° to improve angular resolution

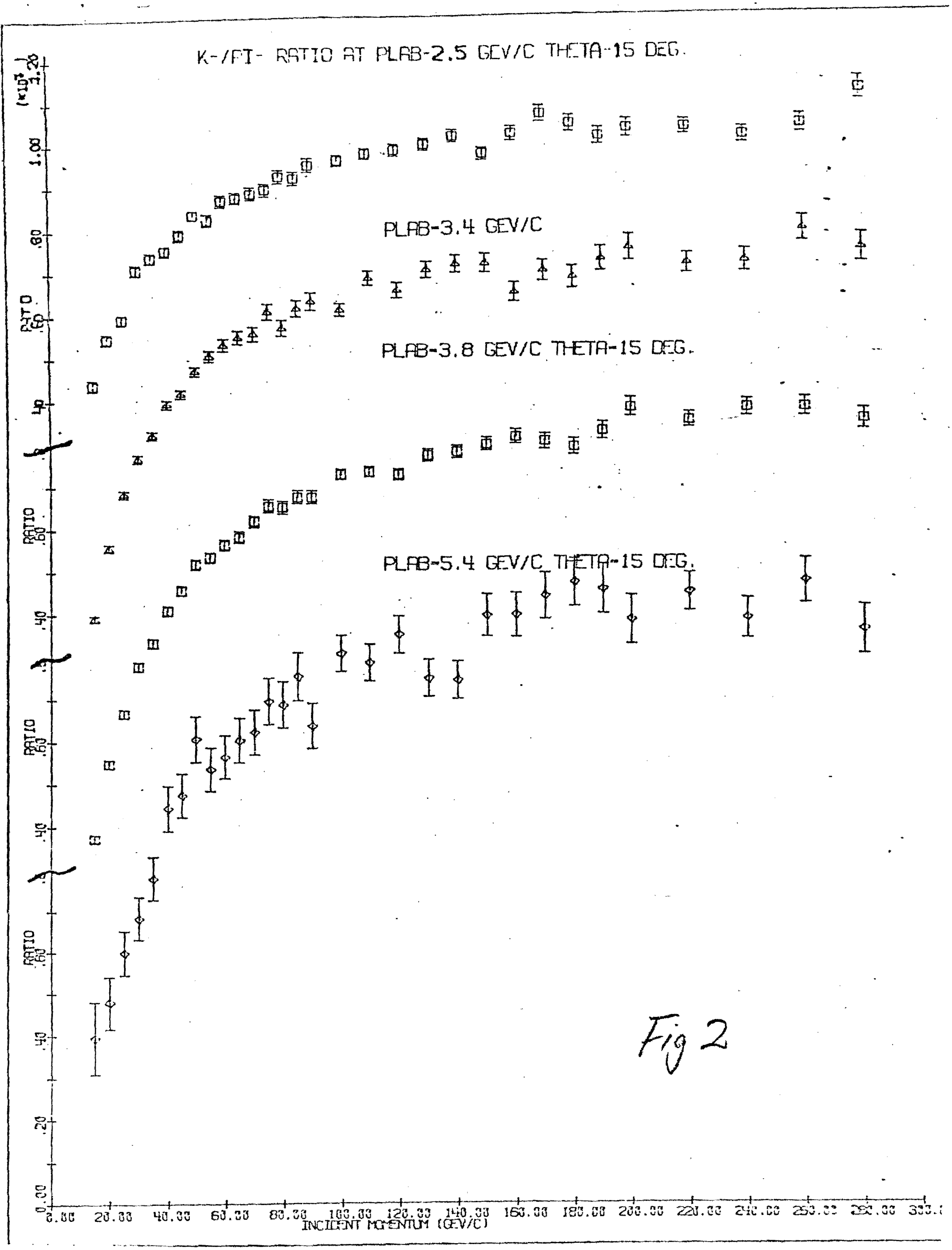

K-/PI- RATIO AT PLAB-2.5 GEV/C THETA-15 DEG.
PLAB-3.4 GEV/C
PLAB-3.8 GEV/C THETA-15 DEG.
PLAB-5.4 GEV/C THETA-15 DEG.
(x10-3)
1.20
1.00
.80
RATIO .60
.40
RATIO .60
.40
RATIO .60
.40
RATIO .60
.40
.20
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
INCIDENT MOMENTUM (GEV/C)

Fig 2

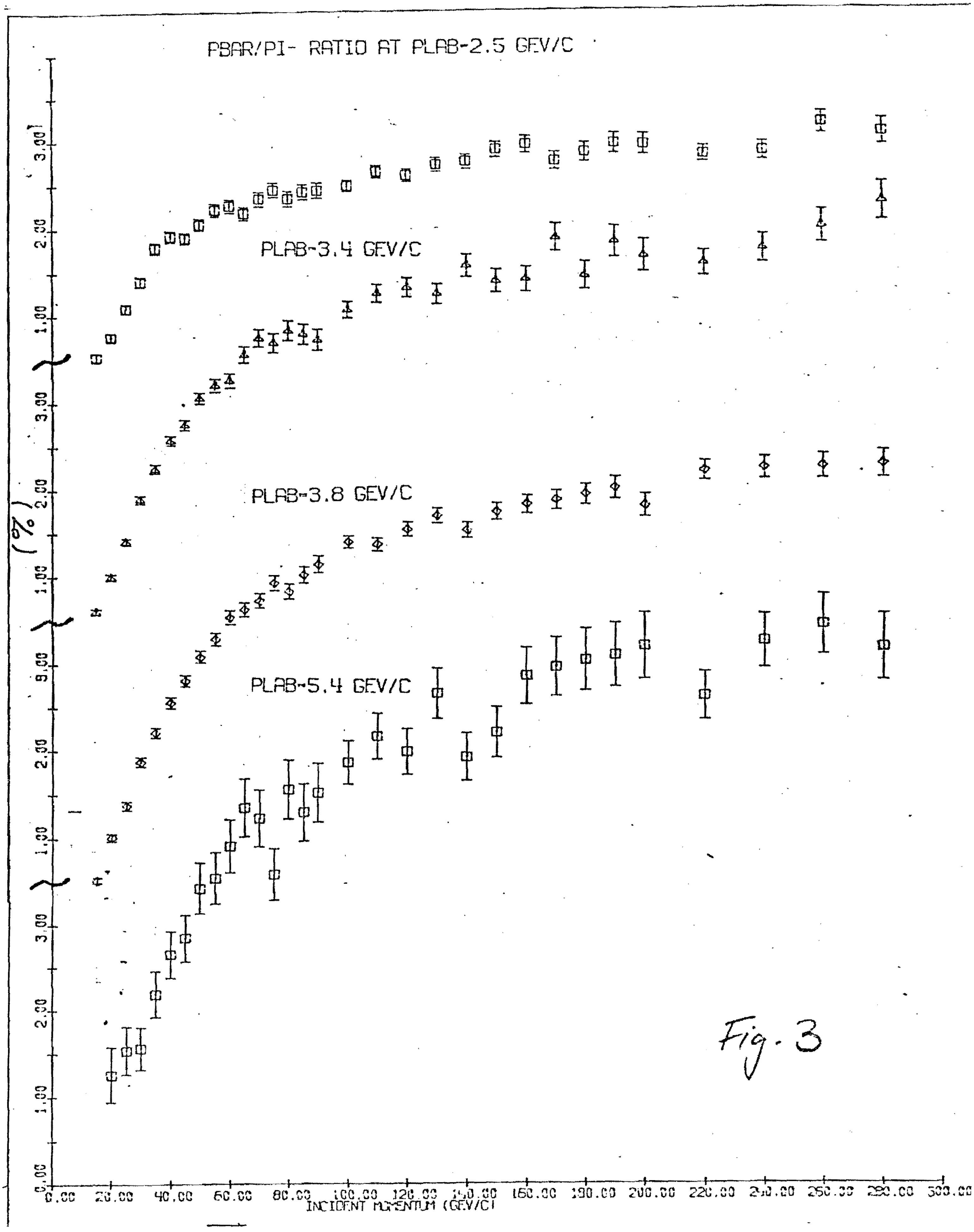
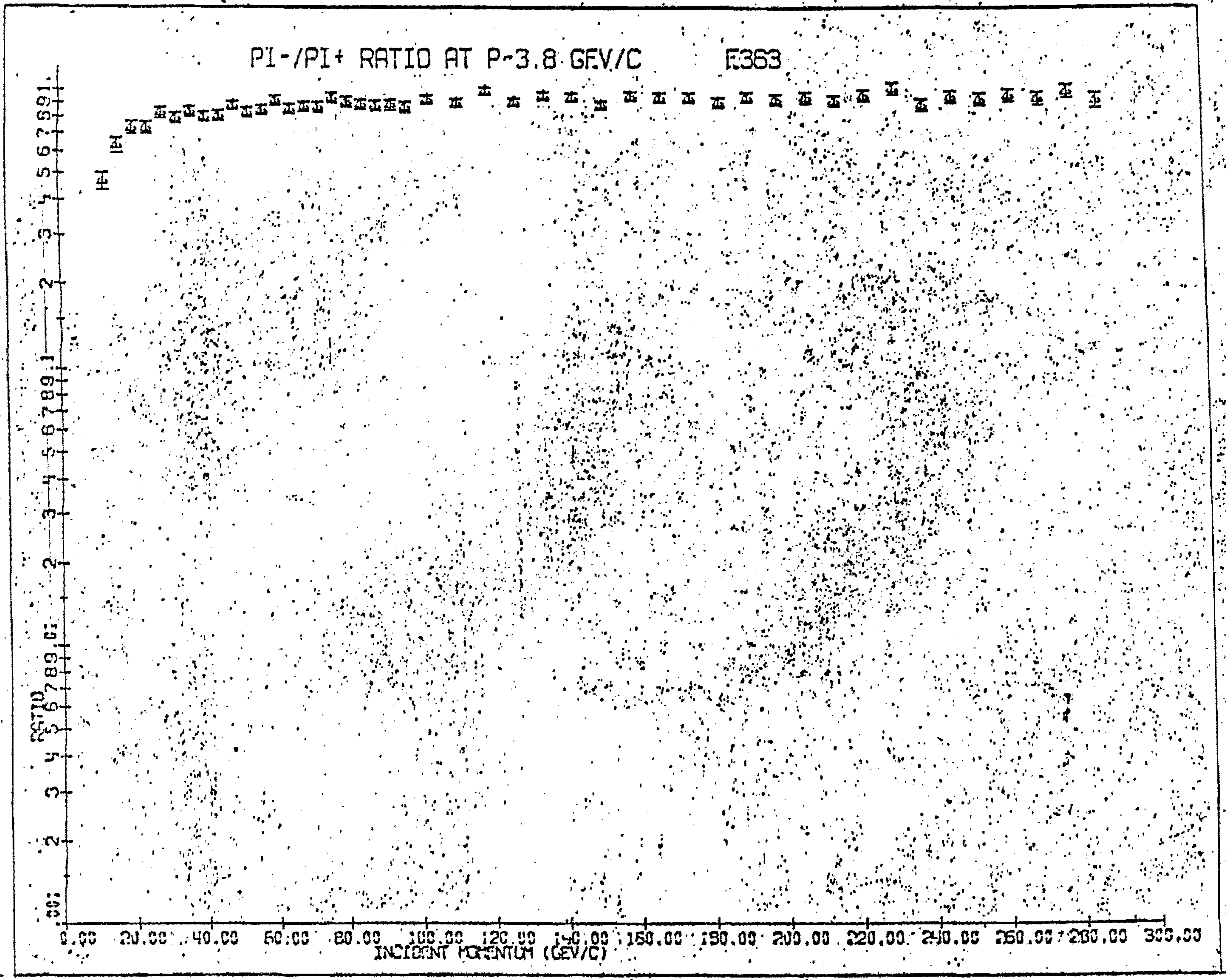

PBAR/PI- RATIO AT PLAB-2.5 GEV/C
PLAB-3.4 GEV/C
PLAB-3.8 GEV/C
PLAB-5.4 GEV/C
(%)
0.00
1.00
2.00
3.00
1.00
2.00
3.00
1.00
2.00
3.00
1.00
2.00
3.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
INCIDENT MOMENTUM (GEV/C)

Fig. 3

Fig 4


PI-/PI+ RATIO AT P-3.8 GEV/C
E363
RATIO
.01
2
3
4
5
6
7
8
9
0.1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7
8
9
1
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
INCIDENT MOMENTUM (GEV/C)

(Fig 5)

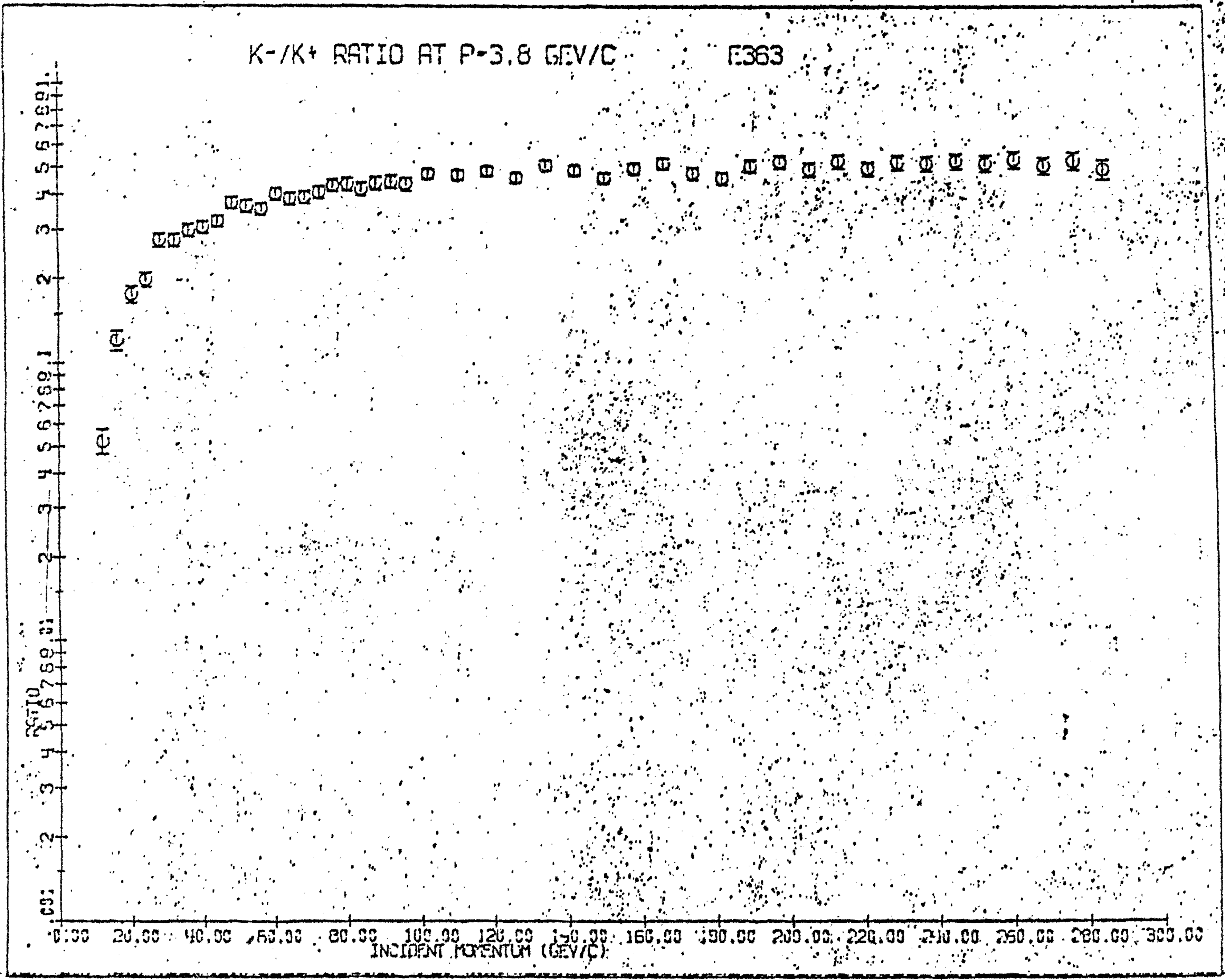
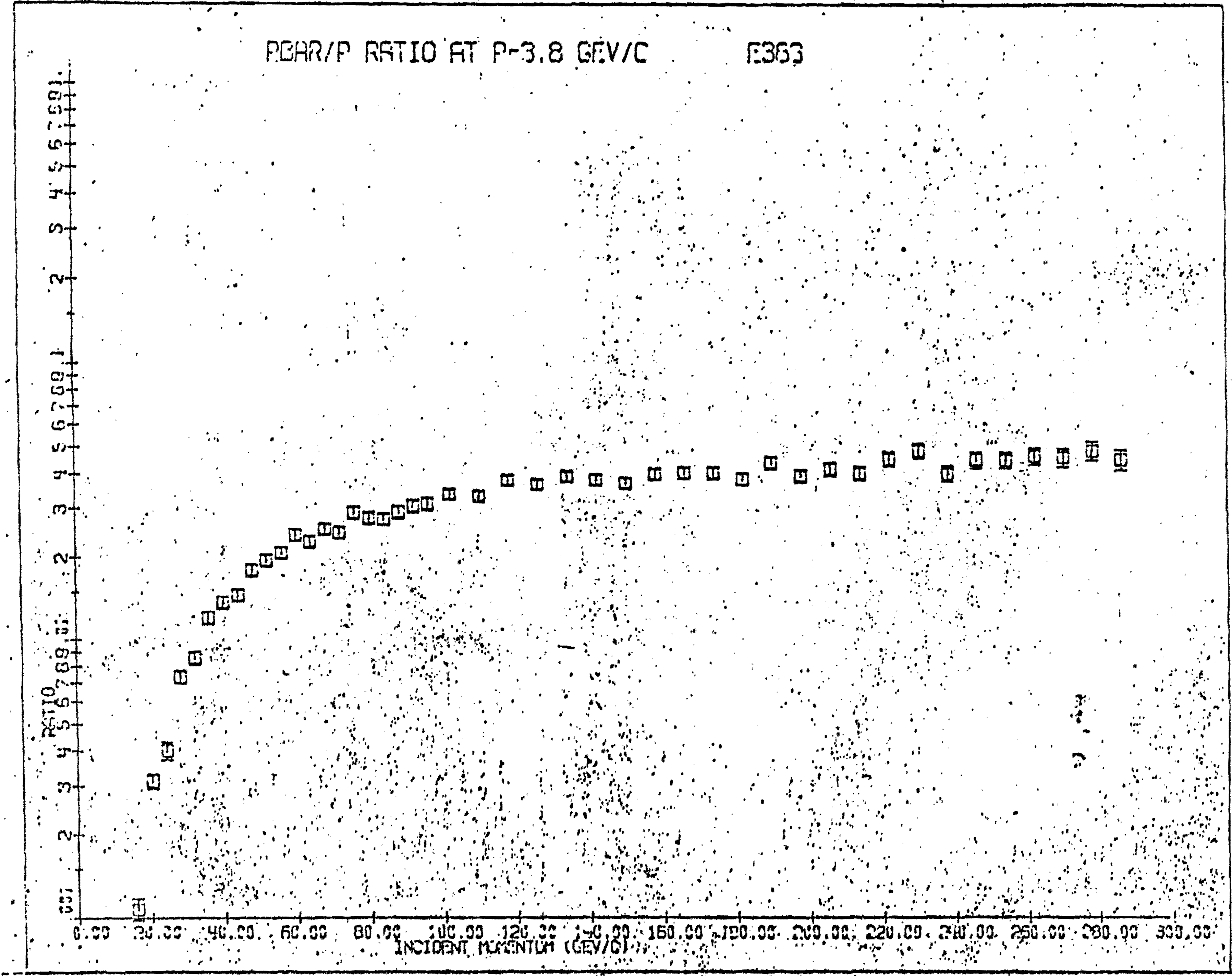

K-/K+ RATIO AT P=3.8 GEV/C
E363
RATIO
1.
.1
.01
.001
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
INCIDENT MOMENTUM (GEV/C)

Fig 8



PBAR/P RATIO AT P=3.8 GEV/C E363

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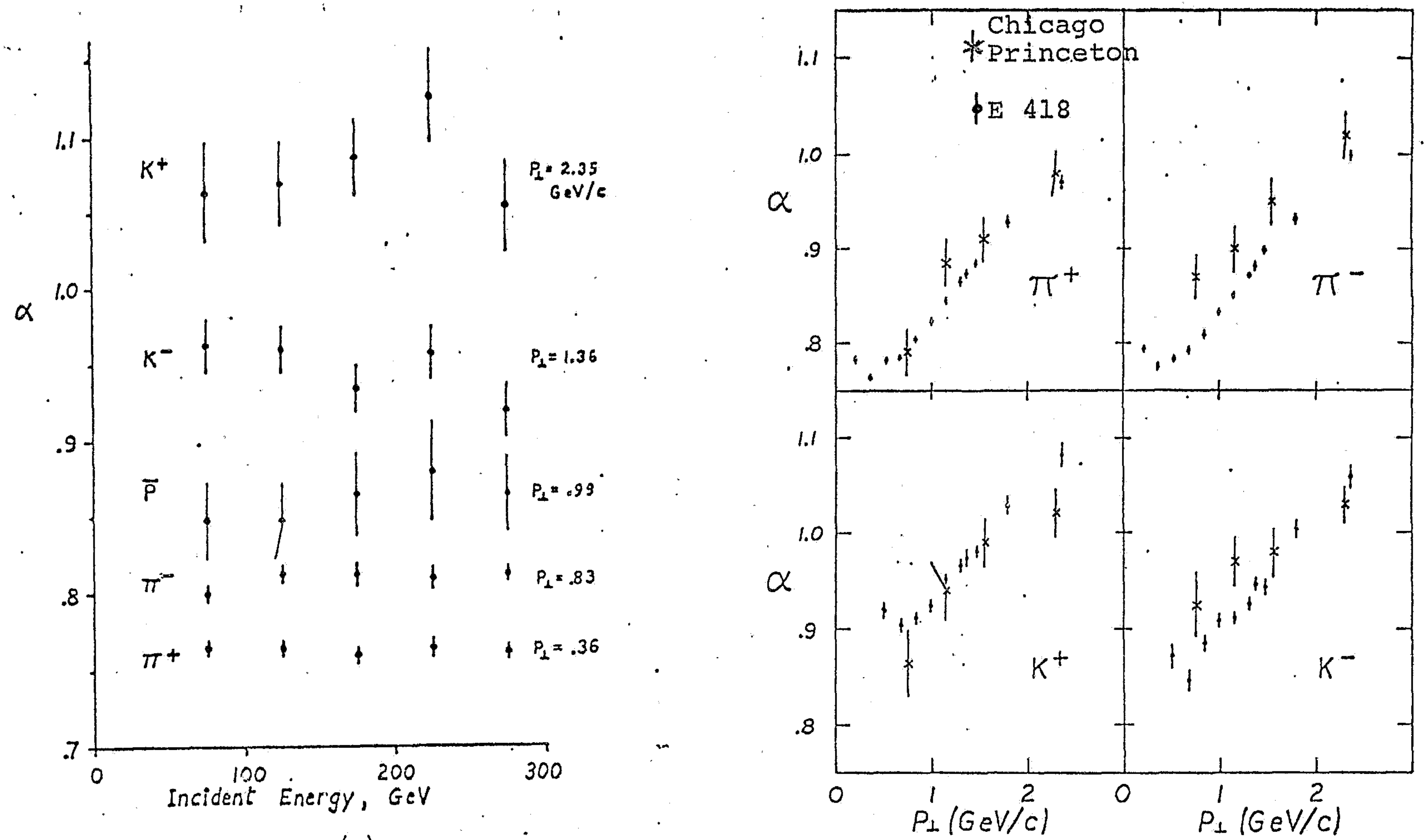
Experiment 418: Proposal to Study the S, $P_T$ and A Dependence of $\pi^\pm$, $K^\pm$ and $P^\pm$ Production for Proton-Nucleon Collisions.

Proposed May 1975
Completed October 1975

During the summer of 1975 we used the apparatus of E-363 to study particle and antiparticle production as a function of S, $P_T$ and A. We focused our attention on the nuclear size dependence of large momentum transfer inclusive scattering and found that the data parameterized as $A^\alpha$ were in good agreement with the Chicago-Princeton results for all secondary particles with the exception of protons. We found that the exponent $\alpha$ increases with $P_T$ from 0.7 to 1.3 for different produced particle momenta and species. The value of the exponent appears to be only a function of $P_T$ and doesn't vary with incident energy (see attached figures). The data are in disagreement with the parton model notion which suggested that at high $P_T$ the exponent $\alpha$ should only be a function of $P^*$. This is particularly dramatic for antiproton production as can be seen in the second attached figure. Our results were reported by P. Goldhagen (Rutgers) at the Washington Meeting, April 26-29, 1976 and an article is in preparation for submission to Physical Review Letters.

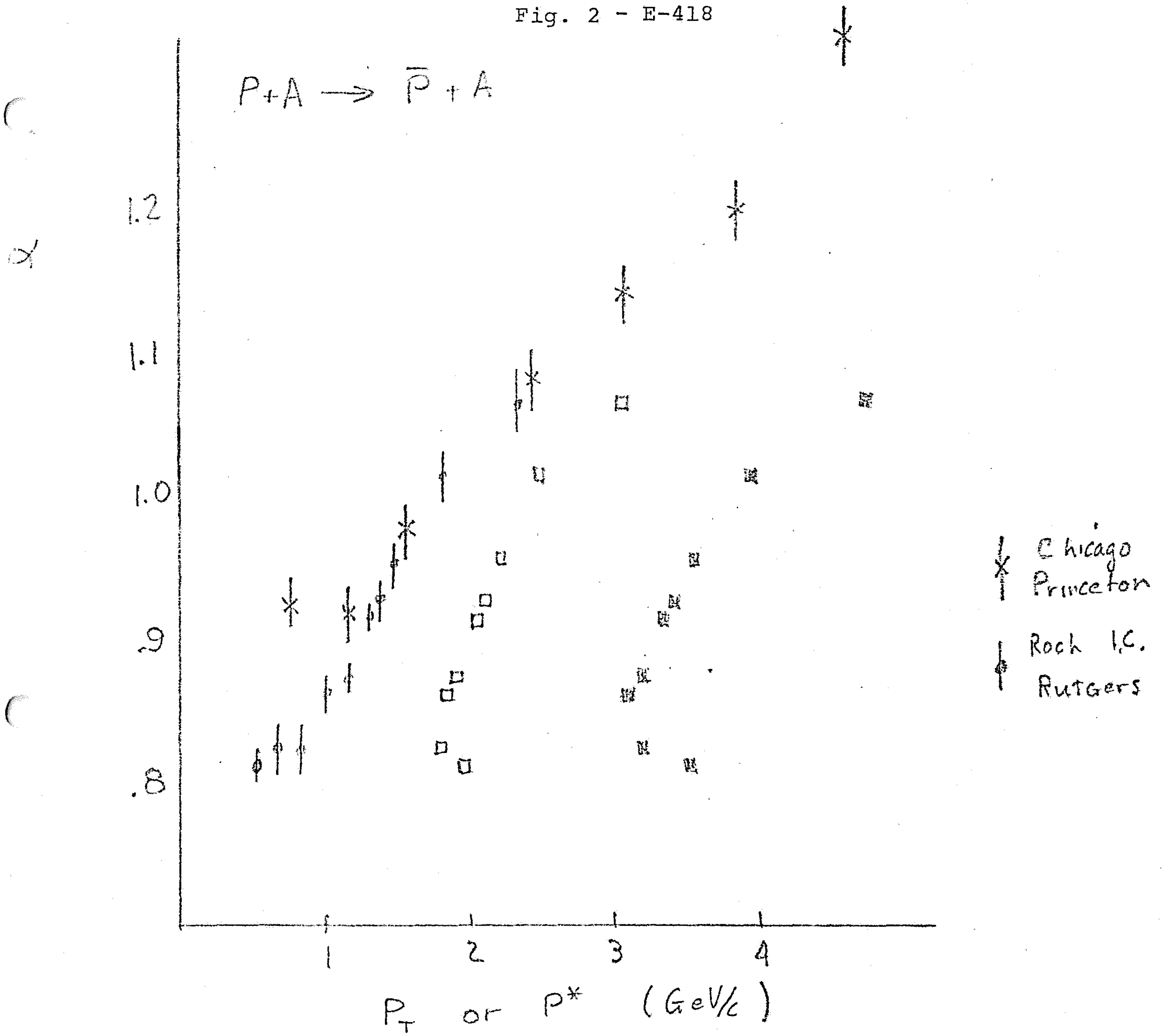
Fig. 1 - E-418



(a) (b)

Results from E418 (A-dependence of inclusive particle production). Fig. 1a shows lack of energy dependence of the exponent α(in $A^\alpha$) for five particle species. Fig. 1b shows $p_T$ dependence. Closed circles are E418 data, x's are data of the Chicago Princeton group.

Fig. 2 - E-418



Atomic number dependence of $\bar{P}$ yields.. The solid points are our data from all energies averaged together plotted vs. $P_\perp$. The open squares indicate where the 100 GeV points would lie if the data were plotted vs. $P^*$. The closed squares indicate the corresponding positions for 300 GeV.