Fermi National Accelerator Laboratory

FERMILAB-Pub-85/103-E
7180.605

A-DEPENDENCE OF THE INCLUSIVE PRODUCTION OF HADRONS WITH HIGH TRANSVERSE MOMENTA*

Y. B. Hsiung,[3] Y. Sakai,[6a] J. A. Crittenden,[3] M. R. Adams,[7] C. N. Brown,[4]
G. Charpak,[2] S. Childress,[4] G. Coutrakon,[7b] D. A. Finley,[4]
H. D. Glass,[7] R. Gray,[8] Y. Hemmi,[6] J. R. Hubbard,[1] A. S. Ito,[4]
D. E. Jaffe,[7] A. M. Jonckheere,[4] H. Jöstlein,[4] D. M. Kaplan,[3c]
J. Kirz,[7], L. M. Lederman,[4] A. Maki,[5] Ph. Mangeot,[1] R. L. McCarthy,[7]
K. Miyake,[6] T. Nakamura,[6] R. Orava,[4d] A. Peisert,[1e] R. E. Plaag,[8]
J. E. Rothberg,[8] J. P. Rutherfoord,[8] F. Sauli,[2] S. R. Smith,[4f]
K. Sugano,[4g] K. Ueno,[4h], and K. K. Young[8]

July 1985

[1] CEN Saclay, Gif-sur-Yvette, France
[2] CERN, Geneva, Switzerland
[3] Columbia University, New York, New York 10027 USA
[4] Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA
[5] KEK, Ibaraki-ken, Japan 305
[6] Kyoto University, Kyoto, Japan 606
[7] State University of New York, Stony Brook, New York 11794 USA
[8] University of Washington, Seattle, Washington 98185 USA

[a] Now at KEK, Ibaraki-ken, Japan 305
[b] Now at Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA
[c] Now at Florida State University, Tallahassee, Florida 32306 USA
[d] Now at University of Helsinki, SF-00171, Helsinki-17, Finland
[e] Now at Max Planck Institute, D-8 Müchen-40 Federal Republic of Germany
[f] Now at Columbia University, New York, New York 10027 USA
[g] Now at Argonne National Laboratory, Argonne, Illinois 60439 USA
[h] Now at University of Rochester, Rochester, New York 14627 USA

---

*Submitted to Phys. Rev. Lett.

A-Dependence of the Inclusive Production of Hadrons with High Transverse Momenta

Y.B. Hsiung[3], Y. Sakai[6a], J.A. Crittenden[3], M.R. Adams[7],
C.N. Brown[4], G. Charpak[2], S. Childress[4], G. Coutrakon[7b],
D.A. Finley[4], H.D. Glass[7], R. Gray[8], Y. Hemmi[6], J.R. Hubbard[1],
A.S. Ito[4], D.E. Jaffe[7], A.M. Jonckheere[4], H. Jöstlein[4],
D.M. Kaplan[3c], J. Kirz[7], L.M. Lederman[4], A. Maki[5], Ph. Mangeot[1],
R.L. McCarthy[7], K. Miyake[6], T. Nakamura[6], R. Orava[4d],
A. Peisert[1e], R.E. Plaag[8], J.E. Rothberg[8], J.P. Rutherfoord[8],
F. Sauli[2], S.R. Smith[4f], K. Sugano[4g], K. Ueno[4h], K.K. Young[8]
(Fermilab Experiment 605)

[1] CEN Saclay, Gif-sur-Yvette, France
[2] CERN, Geneva, Switzerland
[3] Columbia University, New York, New York 10027
[4] Fermilab, Batavia, Illinois 60510
[5] KEK, Ibaraki-ken, Japan 305
[6] Kyoto University, Kyoto, Japan 606
[7] State University of New York, Stony Brook, New York 11794
[8] University of Washington, Seattle, Washington 98185

[a] Now at KEK, Ibaraki-ken, Japan 305

[b] Now at Fermilab, Batavia, Illinois 60510

[c] Now at Florida State University, Tallahassee, FL 32306

[d] Now at University of Helsinki, SF-00170, Helsinki-17, Finland

[e] Now at Max Planck Institute, D-8 München-40
Federal Republic of Germany

[f] Now at Columbia University, New York, NY 10027

[g] Now at Argonne National Laboratory, Argonne, IL 60439

[h] Now at University of Rochester, Rochester, NY 14627

We present new data on the A-dependence of the inclusive production of high-transverse-momentum hadrons, both singles and symmetric pairs. These data qualitatively support the hypothesis that the observed A-dependence results from multiple scattering of quarks and gluons within the target nucleus.

Approximately ten years ago a Chicago-Princeton collaboration[1] (CP) found that single hadron production at large transverse momentum (p_T) varies as A^{α} with $\alpha > 1$. Here A is the number of nucleons (atomic weight) in the target nucleus. Early explanations of this collective effect were unsuccessful, partly because of the strong dependence observed on the quantum numbers of the final hadron. Multiple scattering at the quark level, however, can cause a strong quantum number dependence[2], and recent detailed calculations[3] using constituent multiple scattering have proved reasonably successful in reproducing the observed A-dependence of single mesons and symmetric meson pairs[4].

We present here single hadron and symmetric hadron pair data from Fermilab Experiment 605. Our apparatus (Fig. 1) is a magnetic pair spectrometer[5] using drift chambers and multiwire proportional chambers to track particles over an aperture covering approximately 0.5 steradians near 90° in the proton-nucleon center-of-momentum frame. A calorimeter[6] was used to reject background and trigger the experiment on hadrons. A ring-imaging Cherenkov counter[5] was used to identify these hadrons up to mementa of 200 GeV/c over half of the spectrometer aperture. Data were read out using the Nevis Data Transport System[7] and recorded on magnetic tape. Cross sections from these data will be presented elsewhere[8].

We used the 400 GeV/c primary proton beam at an intensity of typically 5×10^9 protons/second incident on the three targets described in Table 1. After traversing the target, noninteracting beam protons and low p_T secondaries were buried in a dump located in our upstream spectrometer magnet. Positive and negative hadrons with large p_T were accepted simultaneously, above and below the beam dump. The upstream magnet deflected the remaining low p_T charged particles out of the aperture and focused the particles of interest onto our detector. The dump was configured so that neutral particles originating in the target could not exit the upstream magnet.

The dominant singles rates were caused by low energy photons generated presumably by π^0-initiated showers in the coils of the upstream magnet. Resulting chamber rates were high (up to 50 megahertz per plane) but, through the use of heavy redundancy, tracks were cleanly reconstructed in the presence of our uncorrelated photon background. Each hadron track was defined by 29 projective measurements (18 wire chamber measurements, 5 scintillation counter measurements, 6 calorimeter measurements) in addition to its ring-imaging Cherenkov measurements. Comparison of track momentum (measured using our downstream magnet) to track energy (measured by our calorimeter) indicates that spurious tracks are not present in our data (less than 1% of the sample). This statement is independent of the hadron's p_T.

The efficiency of each component of our system was measured by observing the fraction of tracks reconstructed with that component missing. On average 15.5 of 18 chambers recorded a hit along a given track whereas our reconstruction algorithm requires a minimum of 12 hits. Our reconstruction efficiency was calculated using the measured efficiency of each element in the reconstruction algorithm. This calculation was checked by a Monte Carlo calculation which indicated that correlations among the chamber inefficiencies are negligible. The reconstruction efficiency remained adequate while the data discussed here were recorded (typically 95% per track). The track reconstruction efficiency is independent of target to an accuracy of a few per cent. Particle yields have been corrected for reconstruction inefficiency on a run by run basis.

We recorded events which exceeded a calorimeter-pulse-height threshold. The efficiency of this trigger requirement was monitored as a function of track position and momentum using prescaled hadron events triggered with a lower threshold. The energy deposited in horizontal segments of the calorimeter was recorded for each track, using analog-to-digital converters. This information was used to calculate the calorimeter trigger efficiency for each event. We have performed the analysis presented here requiring various minimum values of this trigger efficiency. Our results are independent of this minimum value as it ranges from 50% to 95%. Hence we conclude that any target dependence of our trigger efficiency was sufficiently small that it does not affect these results. Our trigger included a scintillation-counter five-fold coincidence in roads, in addition to the calorimeter requirement.

The rate of incident protons interacting in the target was monitored by a 4-counter telescope oriented at 90° in the laboratory frame with respect to the incident beam. The calibration of the relative number of monitor counts expected per incident proton on each target was carried out using a secondary emission monitor (SEM) which was positioned upstream of our target. The targets were thin slabs about 1mm high (Table 1) but much wider than the beam. Typically 70% of the beam passed through the target. This targeting fraction was measured periodically buy moving the target vertically to scan the beam profile. Uncertainties in this procedure affect all α measurements presented here by less than ± .03 (limit of error). Since this uncertainty does not affect point-to-point comparisons (it shifts all measurements of α by the same amount), we do not include it in the error bars shown below. Data were taken in cycles of the three targets, with a run on each target lasting approximately one hour.

Corrections have been applied for absorption of primary protons and secondary hadrons in the targets.

The three targets have slightly different acceptances and resolutions in p_T due to their differing lengths and mutiple scattering properties. We have simulated these differences via Monte Carlo methods. Resulting corrections to α, included below, are generally smaller than 0.01 in magnitude, but become as large as .02 near the edges of our acceptance for the bins shown.

The data from the three targets are consistent with the form

$$\text{yield/(luminosity per nucleus)} = \text{constant} \times A^{\alpha}$$

(average $\chi^2 = 1.80$ for one degree of freedom). In Fig. 2 we show our measurements of α for π^+ and K^+ production, compared to earlier Chicago-Princeton measurements[1] and the calculation of Lev and Petersson[3]. Their constituent-mulitple-scattering (CMS) model does show a rise in α as p_T varies from 2 to 4 GeV/c (to an α value which is affected by regularization of singularities[3]) but does not show the drop suggested by the CP data near p_T = 6 GeV/c. A drop at high p_T seems difficult to reconcile with a CMS explanation[9]. In Fig 2c, in order to bring as much information as possible to bear on this point, we show α for all positive[10] single hadrons, comparing our results to those of Chicago-Princeton[11] and those of the Columbia-Fermilab-Stony Brook (CFS) group[4]. Our data show little or no drop in α near p_T = 6 GeV/c. The error bars represent the total point-to-point RMS errors. Note that our systematic normalization uncertainty quoted above and indicated in Fig. 2c could improve the agreement between our results and the CP results to the point of marginal consistency but will not change the shape of our α versus p_T curve since we measure the yields from each target at all p_T values simultaneously (unlike CP).

In comparing our data to CP data we should note that we cover a relatively broad range in center-of-momentum production angle. The bulk of our data are in the range $-0.3<\cos\theta^*<0.3$ whereas CP data cover $-0.12<\cos\theta^*<-0.09$. If we restrict our data to the range $-0.1<\cos\theta^*<0.0$, the agreement with CP improves slightly as our statistical accuracy deteriorates.

In Fig. 3 we plot α for h^+h^- pairs (without regard to particle type) versus mass, in comparison to data from CFS[4], the Fermilab-Michigan-Purdue (FMP) group[12], and a recent Serpukhov experiment [13]. Our data points show only statistical errors since these are dominant. A small correction (~3%) has been made to our pair rates to subtract accidentals. All data shown, with the exception of FMP, are consistent with $\alpha \approx 1$ for hadron pairs (summed over net p_T). This result is expected within the CMS model[3] and indicates that symmetric pairs (which dominate the present data) result from single hard constituent collisions. A single collision tends to produce a hadron pair with a net p_T near 0 since the net p_T of the pair is limited by the p_T's of the incident constituents.

For fixed mass, the CMS picture[3] expects α for h^+h^- pairs to rise versus net p_T as the pair enters the region which can be most easily reached by multiple scatters. The present data are limited in net p_T due to the acceptance of our upstream magnet. Hence we cannot verify the rise versus net p_T previously observed by CFS (who used two seperate spectrometers). However, if we define p_{out} for a pair as the component of the lower-p_T hadron's momentum perpendicular both to the beam and the higher-p_T hadron's momentum, we see in Fig. 4 that α does appear to rise as p_{out} increases. We expect such a rise[14] within the CMS picture, because of the limited p_T's of the incident constituents mentioned above.

In summary we have made three measurements which qualitatively support the constituent-multiple-scattering model of the A-dependence of hadron production at high p_T:

(1) α for single hadrons shows little or no drop as a function of p_T over the range $4 < p_T < 8$ GeV/c.

(2) α for h^+h^- pairs summed over net p_T is consistent with 1 in the region $8 <$ mass < 12 GeV/c^2.

(3) α for pairs rises with p_{out}.

We gratefully acknowledge the many hours of dedicated work given to this research effort by support staff from our collaborating institutions and Fermilab. This work was supported by the National Science Foundation, the Department of Energy, the Commissariat a l'Energie Atomique, and the US - Japan agreement in High Energy Physics.

References

1. D. Antreasyan et al., Phys. Rev. D19, 764 (1979).
References to prior work are given in this paper.

2. A. Krzywicki et al., Phys. Lett. 85B, 407 (1979).

3. M. Lev and B. Petersson, Z. Phys. C - Particles and Fields 21, 155 (1983).

4. R.L. McCarthy et al., Phys. Rev. Lett. 40, 213 (1978).

5. M. Adams et al., NIM 217, 237 (1983).

6. Y. Sakai, Memoirs of the Faculty of Science, Kyoto University,
Series of Physics, Astrophysics, Geophysics and Chemistry, 36, 401 (1985).

7. J.A. Crittenden et al., IEEE Transcations on Nuclear Science NS-31, 1028 (1984).

8. J.A. Crittenden et al., in preparation. See also
Y. Sakai, Ph.D. thesis Kyoto University (1984)
Y.B. Hsiung, Ph.D. thesis Columbia University (1985)
J.A. Crittenden, Ph.D. thesis Columbia University (1985)

9. A slow decrease in α is predicted on the basis of the EMC effect by T. Ochiai, S. Daté and H. Sumiyoshi, Rikkyo University Preprint, RUP-85-4, Tokyo 171, Japan.

10. These data were taken during our test run, during which the primary beam hit our target at an angle with respect to the spectrometer axis, favoring the acceptance of positive hadrons. The statistical precision of our negative hadron data is poor compared to the precision of our positive data. The statistical precision of our π^+ data is poor compared to the precision of our h^+ data because our Cherenkov counter only covered half our aperture and was inoperative during a portion of the test run.

11. We use α values and particle ratios quoted in reference 1 to calculate the CP α values for h^+ shown in Fig. 2c.

12. D.A. Finley et al., Phys. Rev. Lett. 42, 1031 (1979).

13. V.V. Abramov et al., JETP Lett. 38, 352 (1983),
translation from Pisma Zh. Eksp. Teor. Fiz. 38, No. 6, 296-299.

14. A value of $\alpha < 1$ at $p_{out} = 0$, as favored by our data, is not expected in reference 3. This aspect of our data may favor reference 9.

Table 1. Targets

material	Be	Cu	W
density (g/cm^3)	1.85	8.96	19.3
length (cm)	10.18	2.578	1.306
height (mm)	0.996	0.914	1.059
A	9.01	63.54	183.8
intergrated luminosity			
per nucleon (10^{39} cm^{-2})	0.222	0.317	0.276
per nucleus (10^{41} cm^{-2})	2.46	0.499	0.150

Figure Captions

1. Fermilab Experiment 605.
2. The power α of the A-dependence is plotted versus p_T for a) π^+, b) K^+ and c) h^+ (all positive hadrons). The curves are from reference 3.
3. The power α of the A-dependence is plotted versus mass for h^+h^-, unlike-sign dihadrons. All data shown were taken with 400 GeV/c protons incident except the Serpukhov points (70 GeV/c.).
4. The power α of the A-dependence is plotted versus p_{out} for h^+h^-, unlike-sign dihadrons.

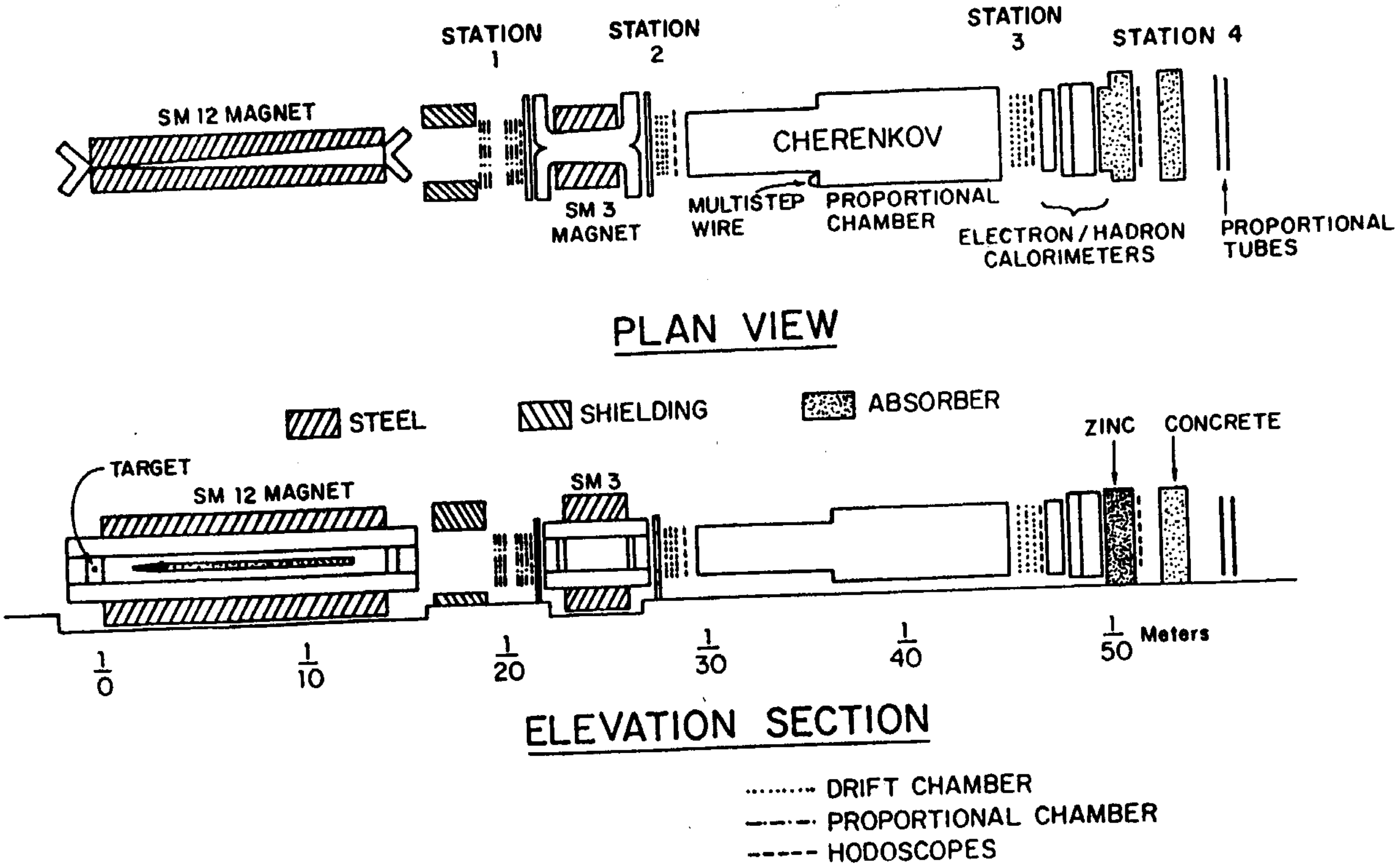
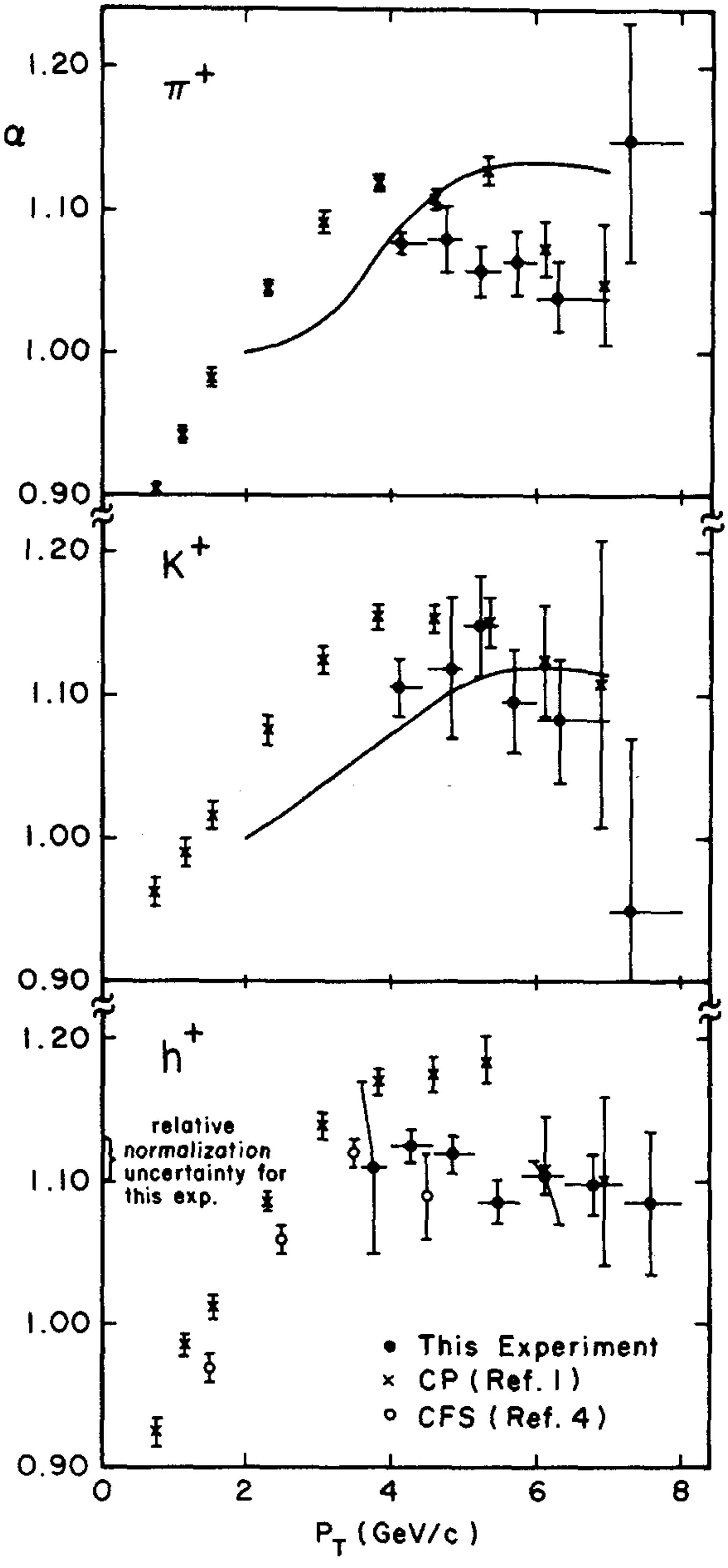

STATION 1
STATION 2
STATION 3
STATION 4
SM 12 MAGNET
SM 3 MAGNET
CHERENKOV
MULTISTEP WIRE
PROPORTIONAL CHAMBER
ELECTRON / HADRON CALORIMETERS
PROPORTIONAL TUBES
PLAN VIEW
STEEL
SHIELDING
ABSORBER
TARGET
SM 12 MAGNET
SM 3
ZINC
CONCRETE
0
10
20
30
40
50
Meters
ELEVATION SECTION
DRIFT CHAMBER
PROPORTIONAL CHAMBER
HODOSCOPES

Figure 1

Figure 2



α
π+
K+
h+
1.20
1.10
1.00
0.90
relative normalization uncertainty for this exp.
● This Experiment
× CP (Ref. 1)
○ CFS (Ref. 4)
0
2
4
6
8
P_T (GeV/c)

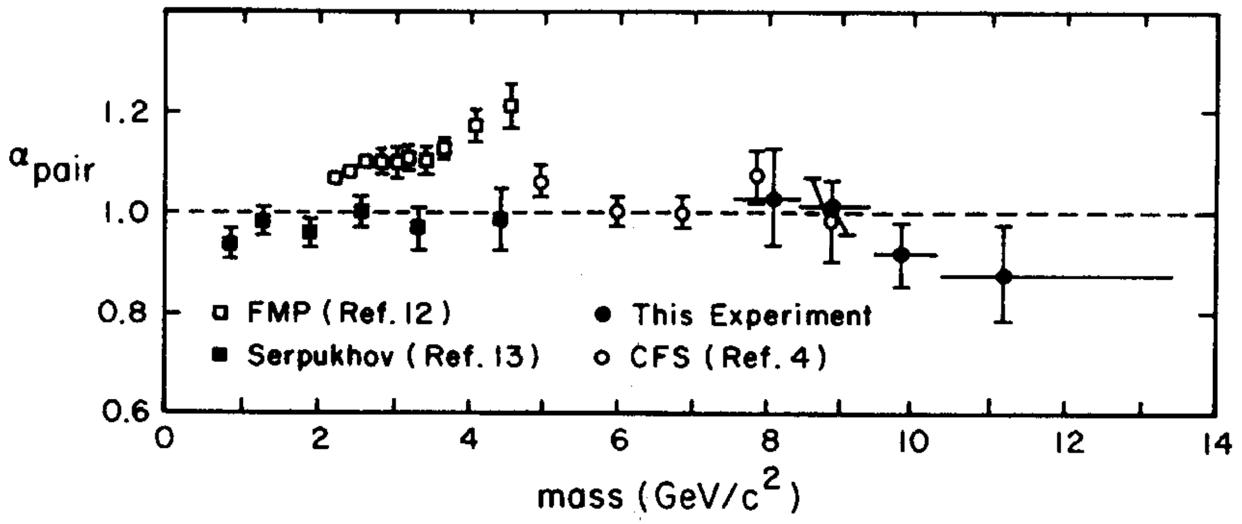

α_{pair}
1.2
1.0
0.8
0.6
0
2
4
6
8
10
12
14
mass (GeV/c^2)
□ FMP (Ref. 12)
■ Serpukhov (Ref. 13)
● This Experiment
○ CFS (Ref. 4)

Figure 3

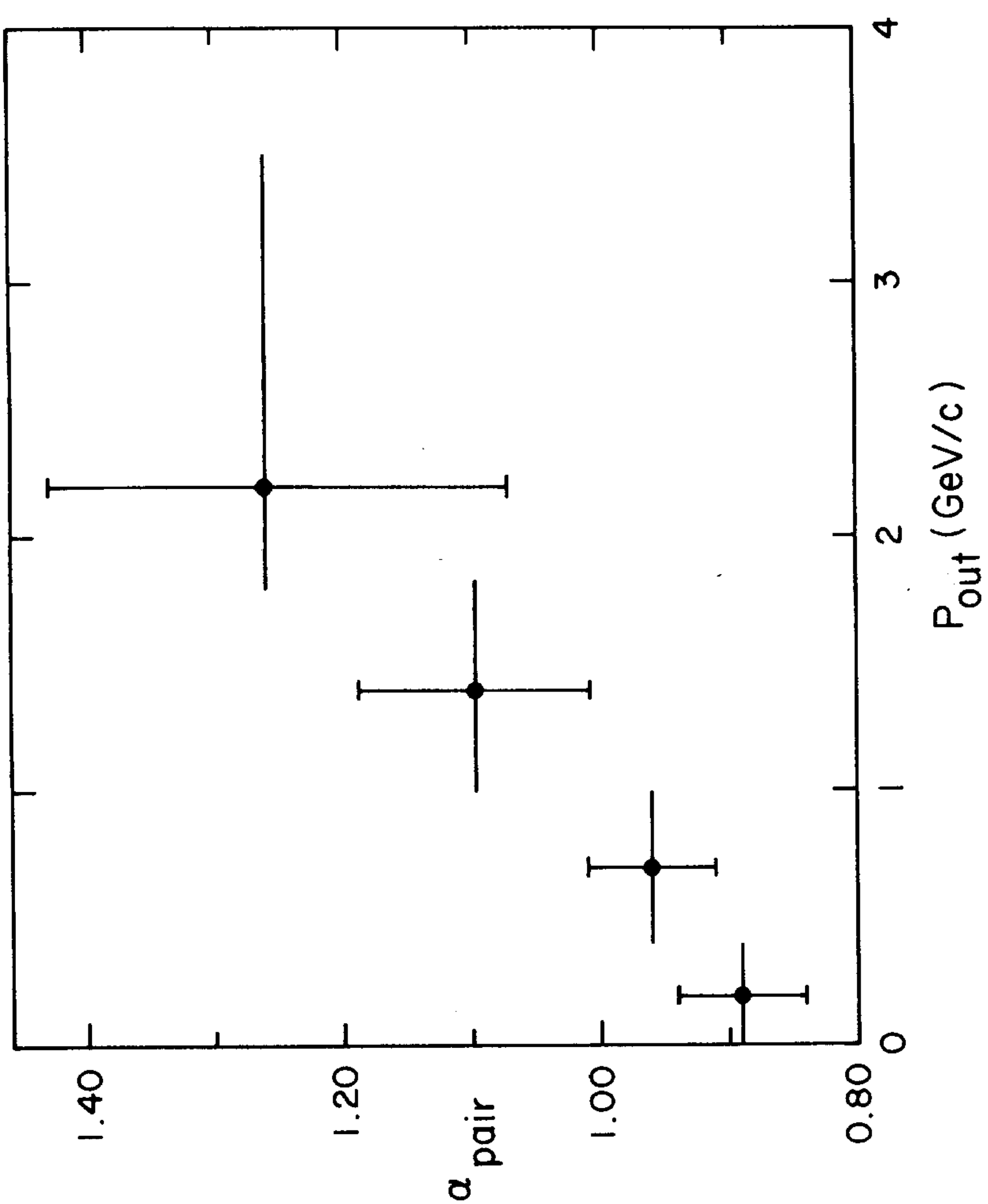


Figure 4