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Large Transverse Momentum π^0 Production in $\alpha\alpha$, dd and pp Collisions at the CERN ISR

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Physics Letters B (To be Published)

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ABSTRACT

The invariant cross sections for inclusive high p_T π^0 production in $\alpha\alpha$, dd and pp collisions have been measured in the central rapidity region at the same center-of-mass energy per nucleon pair, $\sqrt{s_{NN}} = 31$ GeV. The transverse momentum range covers $3.2 < p_T < 9.0$ GeV/c. The data show a very clear anomalous nuclear enhancement in $\alpha\alpha$ collisions whereas no such effect is observed in dd collisions.

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Inclusive production of single particles with large transverse momentum has proved to be an excellent probe of the substructure of the nucleon via "hard" scattering. The phenomena are very well described by the QCD-parton approach in which high p_T single particles are the leading fragments of jets produced by a large momentum transfer quasielastic scattering of point-like constituents of the nucleon.[1,2] In this picture, the nucleon is already treated as a composite object. The extension of this process to the collisions of nuclei was thought to be straightforward, since the distance scale of the collision ($\approx 1/p_T$) is so small that the constituents should act independently, thus giving a cross section proportional to the number of constituents in the projectile and target, or proportional to $A_1 \times A_2$ for the collision of two nuclei.[3]

It was therefore quite surprising when the first observation of high p_T inclusive production from proton-nucleus collisions at Fermilab[4] indicated an "anomalous nuclear enhancement." The cross section was proportional to A^α, with $\alpha > 1$, as a function of the atomic weight, A, of the nuclear target. These measurements were extended to higher energies, and to nucleus-nucleus collisions, in light-ion running at the CERN ISR in 1980.[5] The anomalous enhancement persisted[6] and perhaps even increased[7] for $\alpha\alpha$ collisions at ISR energies, but there was no anomalous enhancement for αp dp or dd collisions.[5,6,7,8]

In August 1983, the second and last light-ion run took place at the CERN ISR. This report presents new measurements of inclusive π^0 production, for $p_T > 3.2$ GeV/c, in pp, dd and $\alpha\alpha$ collisions all at the same nucleon-nucleon center-of-mass energy, $\sqrt{s_{NN}} = 31$ GeV. The new $\alpha\alpha$ data have 15 times the integrated luminosity as the previous data,[7] and together with the dd data allow a detailed comparison between light ion and pp interactions at the highest energy available at accelerators. The systematic errors, caused by absolute p_T scale uncertainty and calibration drift, are also much improved for the present data, since all the αα, dd and pp runs were obtained in a two-month interval.

The experiment was performed using the R110 detector (Figure 1) which was basically a full azimuth electromagnetic calorimeter with a system of drift chambers in a magnetic field of 1.4T. Other measurements from this run have already been reported involving multiparticle final states.[9] The inclusive π^0 measurements were made using the two lead-glass modules and the drift chambers. Each module consisted of a front array of 34 blocks, 4 radiation lengths (X_0) thick, with each block intercepting an area approximately 10×50 cm^2, and a back array of 168 blocks, 17 X_0 thick, arranged in 12 rows of 14, with each block intercepting an area 15×15 cm^2. All the blocks were of type SF5 lead glass.[10] The RMS energy resolution was $(4.3/\sqrt{E} + 2)$% where E is in GeV. Apart from the addition of the front arrays, the apparatus is identical to that used in our previous measurement.[7]

Data were collected using a trigger requiring a total energy deposition, in either one of the two lead glass modules, above a threshold which could be varied. A summary of the nominal thresholds and the integrated luminosity used in this analysis is given in Table 1, together with the integrated luminosity from the 1980 ISR run.[7]

After an off-line check of the trigger condition, events were required to have at least three charged tracks with a reconstructed vertex inside the well-defined beam intersection region. Neutral clusters were defined as isolated distributions of energy which occupied at most 3 × 3 adjacent blocks in the back array, plus the associated front array blocks. In addition, cuts were made on the ratio of energy deposited in the front and back arrays in order to reduce background from charged hadrons. Consistency was required between the energy measured with 200 nsec and 400 nsec ADC gates. For each cluster an estimated energy loss in the iron and magnetic coils[9,11] was added and the center-of-mass (c.m.) transverse momentum p_T was calculated, assuming a π^0 coming from the vertex. The individual γ-rays from π^0 decays were not resolved. In order to ensure a uniform acceptance and to avoid possible trigger inefficiencies near the threshold, the final corrected transverse momentum was required to be well above the nominal threshold, and the c.m. rapidity y and azimuth angle ϕ were required to be within the fiducial regions $|y| < 0.40$, (0.55) and $|\phi|$, $(|\pi-\phi|) < 0.33$, (0.43) radians for the two modules. The difference in the c.m. solid angles reflects the non-zero crossing angle of the beams in the ISR. Since there were no significant systematic differences in the data from the two modules, the invariant cross sections were computed by combining the results from both modules, treating them as a single detector.

The invariant cross sections $E\, d^3\sigma/dp^3$ for π^0 production in $\alpha\alpha$ dd and pp collisions at nucleon-nucleon c.m. energy $\sqrt{s_{NN}} = 31$ GeV as a function of p_T are shown in Figure 2 and given in Table 2. In addition to the statistical errors shown, there is a systematic uncertainty of ±5% in the absolute p_T scale. However, the relative p_T scale uncertainty for the 3 data sets is estimated to be less than ±0.5%, and the relative normalization uncertainty ±2%. It should be noted that (as in our previous publications[7,11]) the cross sections here are not for reconstructed π^0's, but for single clusters in the lead glass consistent with the decays $\pi^0 \to \gamma\gamma$, $\eta^0 \to \gamma\gamma$ and possibly direct single γ production.[12] No correction was applied to the data for the η^0 and possible direct photon contributions. The data are in good agreement with previous measurements.[6,7,8,11]

The solid lines on Figure 2 are fits of the data for each type beam to the empirical expression

$$\frac{E\, d^3\sigma}{dp^3} = A\, p_T^{-n}\; e^{-bx_T}$$

This expression is convenient to use because it gives a logarithmic derivative which changes linearly with p_T. Although cast in the popular scaling form,[11] with $x_T = 2\, p_T/\sqrt{s}$, the fit parameters A, n and b (Table 3) are highly correlated and should not be compared naively with fits to data at several values of $\sqrt{s}$ which can, in fact, separate the p_T and x_T dependences.[11]

In Figure 3, the ratios of the measured $\alpha\alpha$ and dd cross sections to the fit of the pp data, R($\alpha\alpha$/pp-fit) and R(dd/pp-fit), are shown as a function of p_T, as well as the ratio of the pp data to the fit. The $\pm 1\sigma$ variations of the pp fit are indicated by the dashed lines. The $\alpha\alpha$/pp ratio shows no marked

p_T dependence over the measured range, $3.7 \leq p_T \leq 9.0$ GeV/c, but clearly exhibits the "anomalous enhancement," with $\langle R \rangle = 23.8 \pm 0.4$, a factor of 1.5 greater than $A^2 = 16$. At the lower values of p_T, $3.7 \leq p_T \leq 5.0$ GeV/c, the data are in excellent agreement with previous measurements;[6,7] but for $p_T > 5$ GeV/c the ratio remains constant or possibly decreases for the present data whereas the previous measurement[7] suggested a continuous rise to values approaching 40. It must be emphasized that the present data are much more reliable than the previous result[7] since the pp and $\alpha\alpha$ cross sections were measured directly at the same $\sqrt{s_{NN}}$ within a short period of time, while the previous publication[7] used an indirect method to relate the p_T scale calibration of the $\alpha\alpha$ data to that of the pp comparison data taken over a year earlier (Table 1).

In marked contrast to R($\alpha\alpha$/pp-fit), R(dd/pp-fit) shows no evidence of an "anomalous enhancement" and is consistent within the systematic errors with a constant value of $\langle R \rangle = 3.7 \pm 0.2$ over the range $3.2 \leq p_T \leq 9.0$ GeV/c. At the larger values of transverse momentum the uncertainty of the pp fit is the dominant systematic error. Thus it is preferable to compare directly the $\alpha\alpha$ and dd measurements as shown in Figure 4. This new ratio of hard scattering data in isotopic spin zero nuclei, one very tightly bound and one very loosely bound, should be a fertile testing ground for nuclear effects.

At the present time, the "anomalous nuclear enhancement" in inclusive single particle production at large transverse momentum is reasonably well understood theoretically as being caused by smearing of the steeply falling hard scattering p_T spectrum due to multiple scattering of the constituents in the nucleus.[13,14] This mechanism also explains the observed features of the production in nuclei of two back-to-back high p_T hadrons.[15]

The new measurements of R(αα/pp-fit) presented here are in good agreement with the constituent-multiple-scattering model[13] and preclude other mechanisms which have been investigated.[16] These data together with the new measurements of R(dd/pp-fit) greatly extend the range in transverse momentum of inclusive single particle production in nuclei and should enable calculations of the "anomalous enhancement" to be further refined and improved.

We would like to thank the staff and management of CERN, in particular those of the PS, ISR and DD Divisions, for their assistance in the successful operation of this experiment. We are grateful to R. Gros for the excellent maintenance of our apparatus, and to M.-A Huber for her dedicated secretarial and data-management work. We also acknowledge the assistance of A.M. Smith of the CERN EF Division.

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Figure Captions

Figure 1: A view of the apparatus along the beam axis. Iron shielding around the lead glass is not shown.

Figure 2: Invariant cross sections for the reactions $p + p$, $d + d$, $\alpha + \alpha \rightarrow \pi^0 + \text{anything}$ at $\sqrt{s_{NN}} = 31$ GeV. The solid lines are fits to the data for each type beam.

Figure 3: Ratio of the measured data to the pp fit for each type beam. The 2 points at the highest p_T for each beam have been combined. In addition to the statistical errors shown, there is a systematic error resulting from the $\pm1\sigma$ variation of the pp fit.

Figure 4: Ratio of the measured cross sections for inclusive π^0 production in $\alpha\alpha$ and dd collisions at $\sqrt{s_{NN}} = 31$ GeV as a function of p_T.

Table 1
Integrated Luminosities and Nominal Thresholds

	Nominal Threshold GeV	Integrated Luminosity 1983	1980
$\alpha\alpha$	3.5, 4.0, 5.0	$0.91 \times 10^{35} cm^{-2}$	$6.0 \times 10^{33} cm^{-2}$
dd	3.0, 4.0, 5.0	$4.00 \times 10^{35} cm^{-2}$	--
pp	3.0, 4.5	$5.02 \times 10^{35} cm^{-2}$	$1.9 \times 10^{36} cm^{-2}$ (June 1979)

Table 2

Invariant Cross Sections for the Reactions

pp, dd, $\alpha\alpha \rightarrow \pi^0$ + anything at $\sqrt{s_{NN}}$ = 31 GeV

p_T (GeV/c) \ Beams	$E\frac{d^3\sigma}{dp^3}$ (cm^2c^3/GeV^2) pp	dd	$\alpha\alpha$
3.42	(1.89 ± 0.05)-32	(6.67 ± 0.23)-32	
3.84	(6.41 ± 0.37)-33	(2.17 ± 0.16)-32	(1.47 ± 0.04)-31
4.22	(2.01 ± 0.15)-33	(7.58 ± 0.45)-33	(5.41 ± 0.16)-32
4.72	(6.42 ± 0.63)-34	(2.35 ± 0.24)-33	(1.46 ± 0.06)-32
5.23	(1.97 ± 0.10)-34	(6.71 ± 0.51)-34	(4.23 ± 0.22)-33
5.73	(6.37 ± 0.55)-35	(2.55 ± 0.13)-34	(1.47 ± 0.06)-33
6.23	(2.21 ± 0.31)-35	(9.64 ± 0.73)-35	(5.31 ± 0.36)-34
6.73	(6.80 ± 1.70)-36	(3.46 ± 0.42)-35	(1.73 ± 0.20)-34
7.23	(3.94 ± 1.25)-36	(1.15 ± 0.24)-35	(5.47 ± 1.13)-35
7.73	(1.47 ± 0.74)-36	(6.30 ± 1.70)-36	(1.34 ± 0.55)-35
8.42	(1.70 ± 1.70)-37	(1.03 ± 0.46)-36	(1.13 ± 0.34)-35

Table 3

Parameters of the Fits Shown in Figure 2

$$E \frac{d^3\sigma}{dp^3} = A\, p_T^{-n}\, e^{-bp_T/15.5}$$

(p_T in GeV/c)

Beam	A (cm^2c^3/GeV^2)	n	b	χ^2/d.o.f.
pp	$6.58 \pm 0.39 \times 10^{-32}$	5.59 ± 1.14	18.91 ± 4.0	5.0/8
dd	$0.24 \pm 0.01 \times 10^{-30}$	6.6 ± 0.8	15 ± 3	5.2/8
$\alpha\alpha$	$1.9 \pm 0.2 \times 10^{-30}$	6.3 ± 1.0	17 ± 3	9.9/7

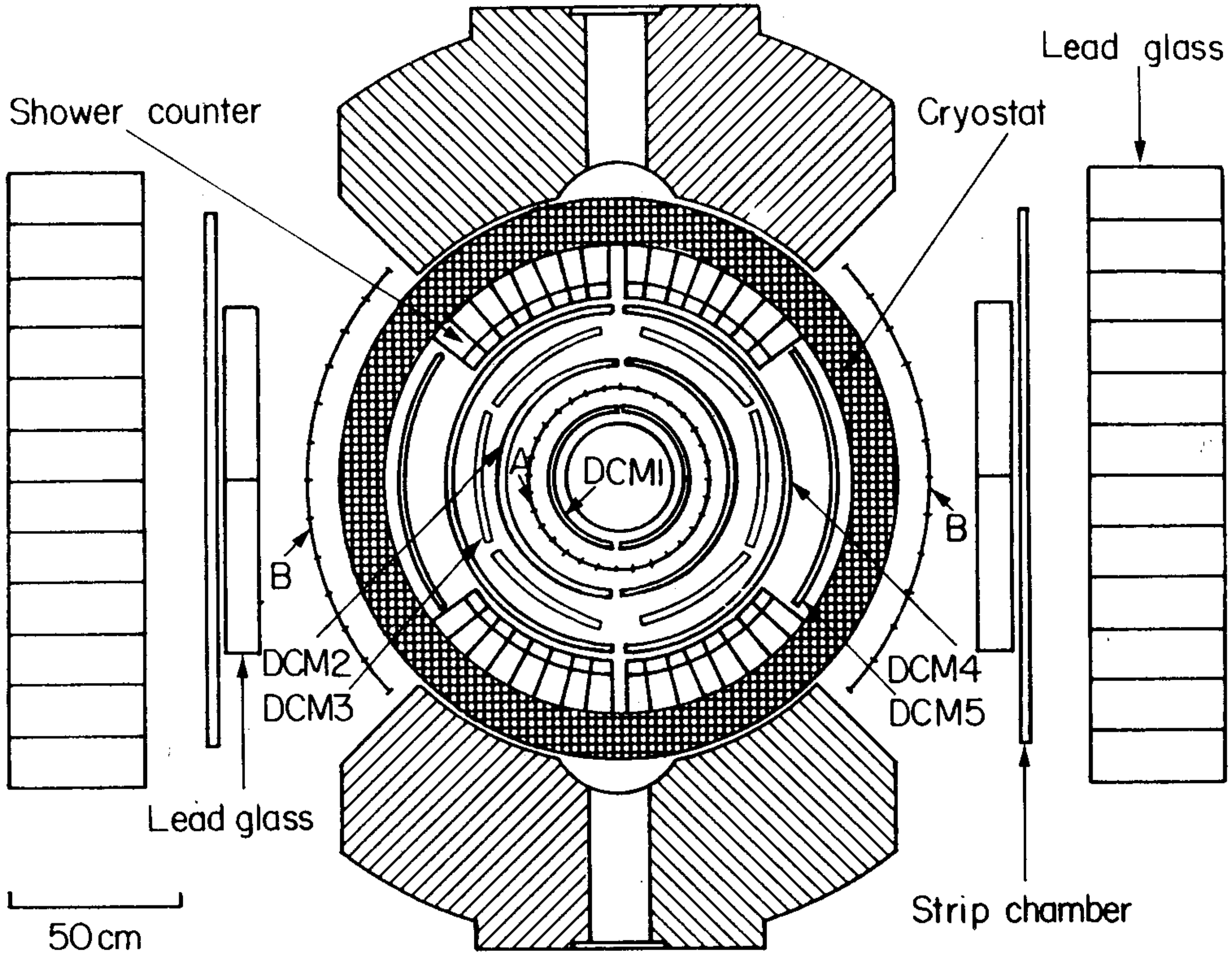

Lead glass
Shower counter
Cryostat
DCMI
A
B
B
DCM2
DCM3
DCM4
DCM5
Lead glass
Strip chamber
50cm

Fig. 1

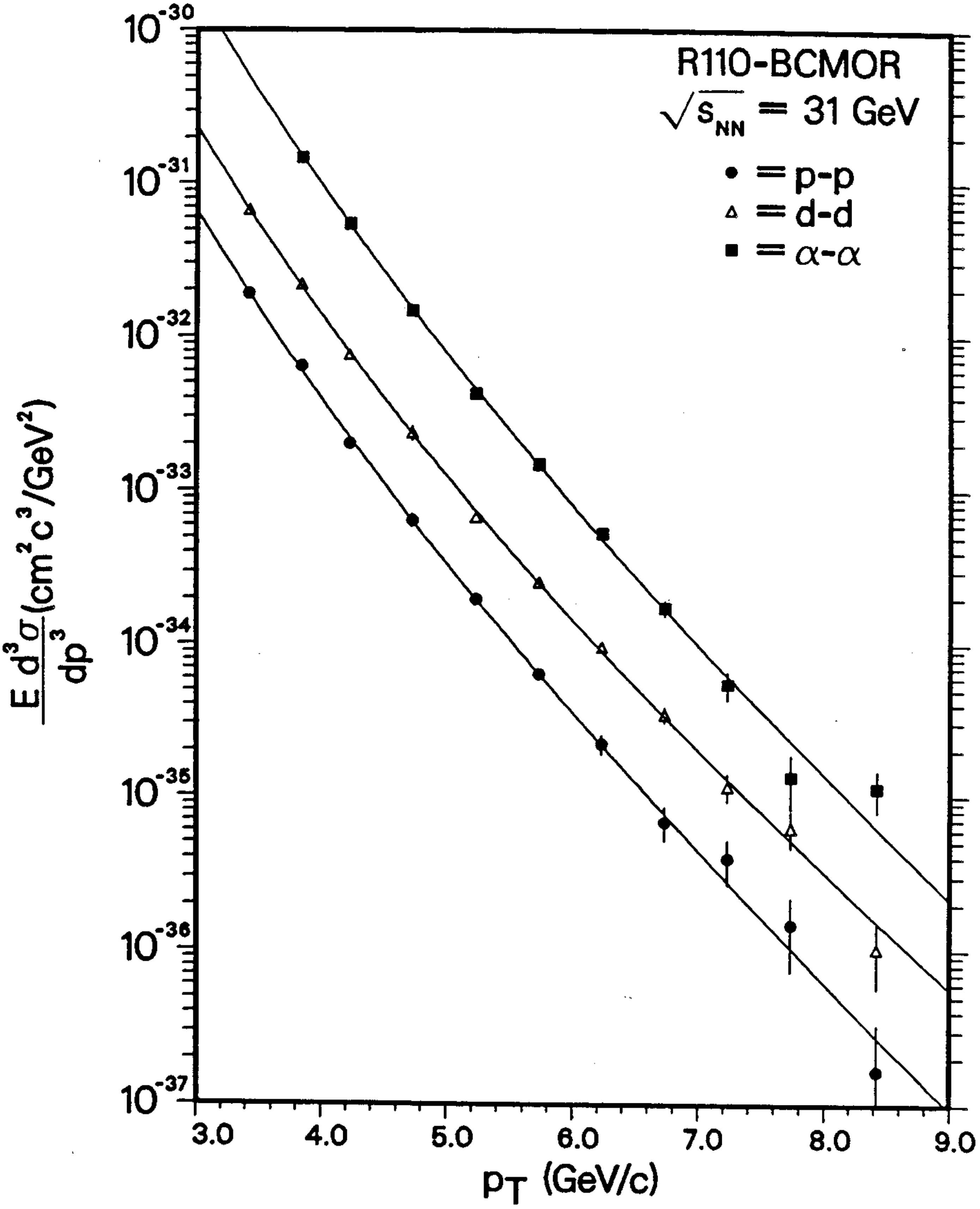

R110-BCMOR
$\sqrt{s_{NN}} = 31$ GeV
● = p-p
△ = d-d
■ = α-α
$\frac{E\,d^3\sigma}{dp^3}$ (cm^{2}c^3/GeV^2)
p_T (GeV/c)
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
3.0
4.0
5.0
6.0
7.0
8.0
9.0

Fig. 2

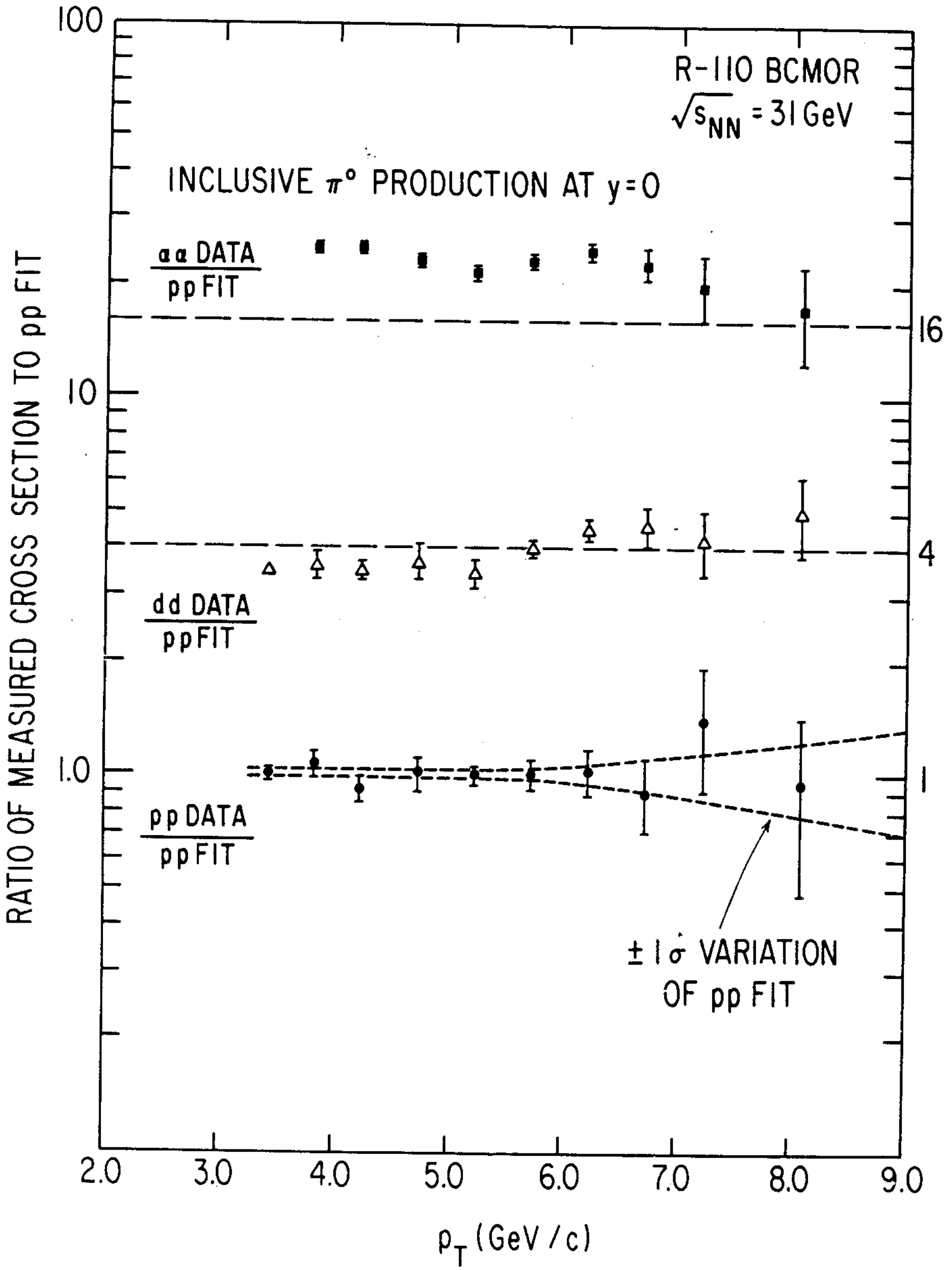
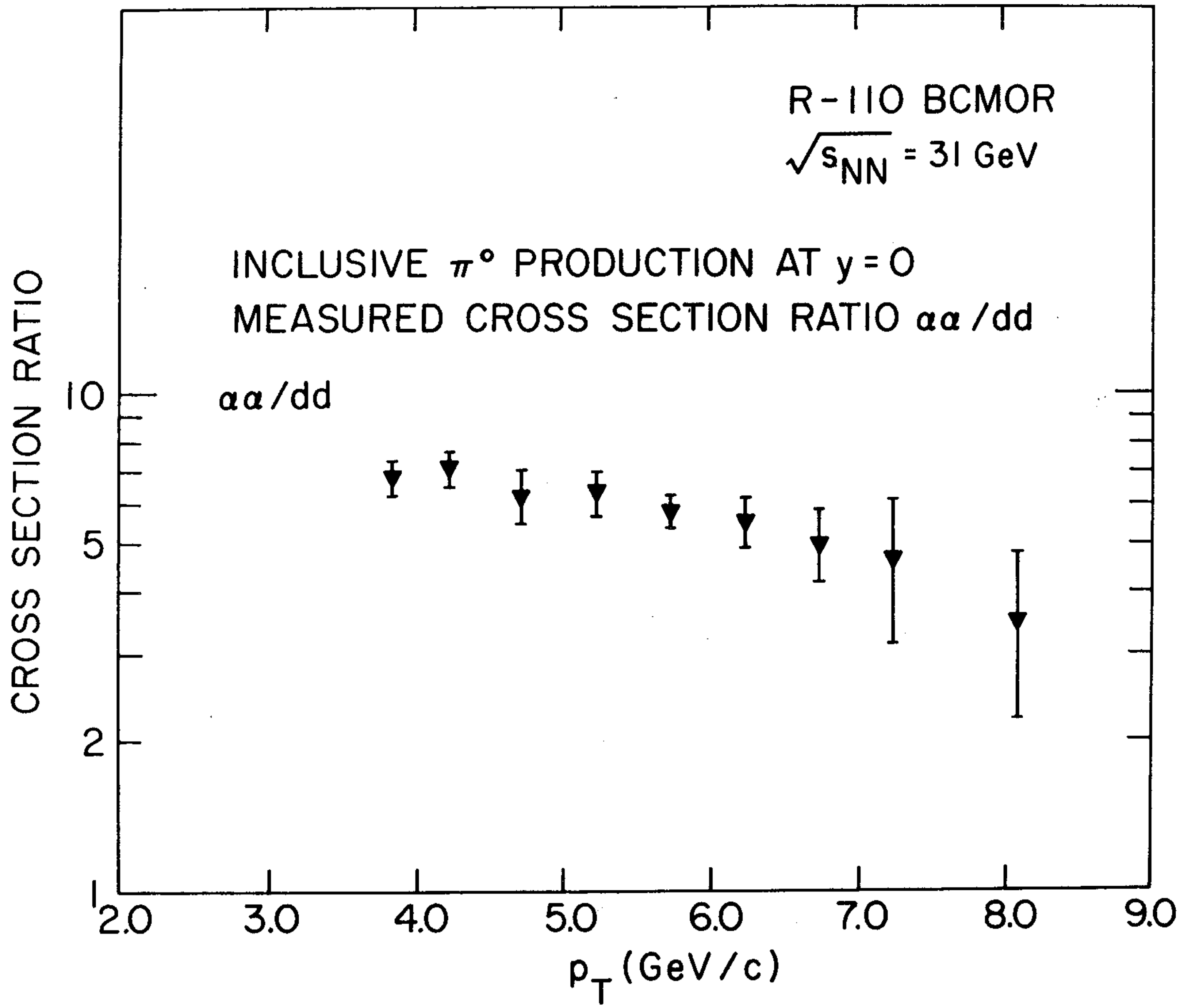

R-110 BCMOR
$\sqrt{s_{NN}}$ = 31 GeV
INCLUSIVE π^0 PRODUCTION AT y=0
αα DATA / pp FIT
dd DATA / pp FIT
pp DATA / pp FIT
16
4
1
± 1σ VARIATION OF pp FIT
100
10
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
RATIO OF MEASURED CROSS SECTION TO pp FIT
p_T (GeV/c)

Fig. 3



R - 110 BCMOR
$\sqrt{s_{NN}}$ = 31 GeV
INCLUSIVE π° PRODUCTION AT y = 0
MEASURED CROSS SECTION RATIO αα /dd
αα /dd
CROSS SECTION RATIO
10
5
2
1
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
p_T (GeV/c)

Fig. 4