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MULTIPLICITY DISTRIBUTIONS IN p-α AND α-α COLLISIONS IN THE CERN ISR

The Axial Field Spectrometer Collaboration

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ABSTRACT

Measurements of charged particle multiplicity distributions in the central rapidity region in p-p and p-α, and α-α collisions are reported. They are better fitted to the "wounded nucleon" than to the "gluon string" model. The average transverse momenta, for all three reactions, are identical up to very high multiplicities.

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This paper reports on measurements of charged particle multiplicity distributions and mean transverse momenta obtained with the Axial Field Spectrometer at the I8 intersection at the ISR, in the study of ultra-relativistic ($\sqrt{s} >> m_p$) p-α and α-α collisions. We compare the results with models on both the quark-gluon and nucleon level. Measurements were also made of p-p interactions at $\sqrt{s}$ = 31.5, 44, and 63 GeV. The 31.5 GeV p-63 GeV α and 63 GeV α-63 GeV α collisions studied had the same nucleon-nucleon cm energy as $\sqrt{s}$ = 44 and 31.5 GeV p-p collisions respectively. We report measurements of the multiplicity distributions and of the mean transverse momenta of particles produced in the central region as a function of multiplicity, to obtain tests of models of particle production.

The apparatus used for this study [1] consisted of a cylindrical (barrel) scintillator hodoscope with 44 elements each covering 8^0 in azimuthal angle ϕ and 0.96 m long at a radius of 18 cm. This was surrounded by a cylindrical drift chamber with 42 layers of wires between r = 20 cm and r = 80 cm, 1.4 m long and covering the full azimuth apart from two holes of $\Delta\phi = 16^0$ each. The chamber was situated in a magnetic field ∿ 5 kG parallel to the beam axis. Surrounding the downstream beam pipes at 4.5 m from the intersection were placed 4-quadrant scintillator hodoscopes covering $1.2^0 < \theta < 6^0$.

Data were taken with a "minimum bias" trigger [2] requiring at least one hit in the barrel counters surrounding the intersection or a beam-beam coincidence (BBC) between at least one of the quadrant scintillators on each side of the intersection. The multiplicity distributions were obtained from tracks reconstructed in the drift chamber, which accepted tracks in a laboratory pseudorapidity range of approximately $|\eta| < 1.6$. Its axis bisected the 14^0 crossing angle of the intersecting beams, which gives a small difference between η and η_{cm}.

The analysis program searched for and fitted tracks over the full chamber with requirements on the number of space points (≥ 9) and the χ^2 of the track fit. Tracks were required to originate from a fiducial region around the beam crossing "diamond". In addition, if a vertex was found, the tracks were required to fall on that vertex. (Events where no vertex was found were dominated by single track events). We then formed the charged track multiplicity distributions by counting tracks with $|\eta| < 0.8$, the region in which the acceptance is uniform (and track densities are observed to be flat) in η_{cm} and uniform in ϕ apart from the two 16^0 holes mentioned above. (We cut on $|\eta| < 1.6$ region initially to maximize the number of events with the vertex constraint). Zero multiplicity events occur as a result of this contraction, and hence do not represent the full contribution of zero multiplicity events with our trigger. 90% of the accepted tracks have > 17 measurements, the average being 36.

Predictions of the p-α and α-α multiplicity distributions from p-p multiplicity distributions are made by convolutions derived from the p-p multiplicity distributions, and depend on the zero and unit multiplicity intensities ($m = 0,1$). Also, tests of KNO scaling [3] depend strongly on the mean multiplicity, which in turn is sensitive to $m = 0,1$. Single tracks in the drift chamber, without a BBC trigger, can arise from beam-gas events and they lack the strong constraint of a clean vertex present for $m \geq 2$. To test whether these under-constrained single tracks indeed arise from p-p inelastic events we have compared those that did have a BBC with those that only possessed a barrel hodoscope hit. The distribution of events in x, y and z about the centre of the intersection diamond would give evidence for beam-gas interactions or other spurious tracks. These distributions appear to be almost indistinguishable in the two samples.

Zero multiplicity events arising from the rapidity range contraction are not used in the analyses. To estimate the true zero multiplicity contribution we use an extrapolation procedure. As we shall see later it is useful to define a multiplicity amplitude, A, which has the property that a twofold convolution of this amplitude yields the observed p-p multiplicity distribution. We have chosen the form $A = (1 + Bm) \exp(-Cm)$ for this amplitude function and determined B and C from a fit to our observed p-p data for $m \geq = 1$. We then extrapolate our observed multiplicity distribution to get a measure of the $m = 0$ intensity. Fig. 1 shows the result of applying this procedure to the 44 and 63 GeV data. The fits are good, with $\chi^2/\text{d.f.} = 0.9$ in both cases: see Table 1. We next use these data to construct a KNO function of the form $(1+az+bz^2)$ $\exp(-cz)$ with $z = m/M$ and M the mean multiplicity (including 0). Fig. 2 shows this function with the 44 and 63 GeV data [4].

The $\sqrt{s}$ = 31.5 GeV p-p data obtained in this experiment were, unfortunately, not obtained close in time to the α-run but after barrel counters of different acceptance and efficiency had been installed and the beam counters repositioned. The data do not show good KNO scaling with the 44 and 63 GeV pp data, and the mean multiplicity $\langle m\rangle$ is slightly higher (see Table 1). This is due to a loss of low multiplicity ($m \leq 2$) events in the 31.5 GeV data, the reason not being fully understood. The shape of the multiplicity distribution for $m \geq 3$ fits well with the other energies (χ^2/df = 14/14), as shown in Fig. 2, where $\langle m\rangle$ has been left as a free parameter for the 31.5 GeV data. We therefore assume that the correct 31.5 GeV pp multiplicity distribution can be obtained by using the KNO function in Fig. 2 with the mean determined by the fit at higher multiplicities, i.e. ignoring the first three 31.5 GeV p-p points in Fig. 2.

The measured p-α and α-α multiplicity distributions appear in Fig. 3 along with the 44 GeV p-p data and the 31.5 GeV (KNO modified) p-p data. One sees from these plots that the α-α distribution differs much more from the p-p distribution at the corresponding $\sqrt{s}$ than does the p-α distribution.

It is known that KNO scaling works extremely well, even up to $\sqrt{s}$ = 540 GeV [5], in p-p and $\bar{p}$-p collisions. Thus an interesting first investigation is the determination of whether or not the p-α and α-α data show "KNO-like scaling". By this we mean whether the pα and αα data have the same functional form as the pp data when plotted in the variables of Fig. 2, not whether the α data itself scales with energy. We have fit the p-α and α-α data to the KNO function derived from the 44 and 63 GeV p-p data. The fits are carried out for $m \geq 2$ since $m = 0$ is not measured and the $m = 1$ events without vertex fits may be less reliable than events with $m \geq 2$. The mean multiplicity and overall normalization are varied in the fit. While the χ^2/d.f. for the 44 and 63 GeV data to the KNO function was 0.4, the value obtained for the p-α data was 1.1 and for the α-α data was 3.8. The data were fitted over the multiplicity interval 2-20 corresponding to a range of intensities of 1000:1 (see Fig. 3). This implies that although the KNO functions for pα and $\alpha\alpha$ are similar to that for pp collisions, the $\alpha\alpha$ data show systematic departures. These are shown in Fig. 4a as a plot of the χ^2, multiplied by the sign of the deviation "fit-data", vs the multiplicity. Apparently the α-α data do not show good KNO-like scaling. (Because the α-α multiplicity, differs more from the p-p multiplicity than does the p-α multiplicity, the α-α data provides a more sensitive test of KNO-like scaling). If multiple interactions are the source of the higher multiplicities observed in nuclear interactions one would not expect to find KNO-like scaling.

The nuclear multiplicity distributions can also provide tests for various models of multiparticle production in the central region. In this letter we describe tests of two models. The first model attempts to go directly from the measured nucleon-nucleon data to the p-α and α-α data. In this "wounded nucleon" model (WNM) [6] the basic assumption made is that each "struck" nucleon contributes to the central multiplicity independent of the number of times that it has been struck. This assumption has been tested in the fragmentation region in p-nucleus interactions [7] accounting for the A independence of the multiplicity in the proton fragmentation region and the $A^{1/3}$ dependence in the nucleus fragmentation region. In this work we apply the wounded nucleon model for the first time to the central multiplicity distribution.

The basic assumptions in testing this model are:

1) we use the best known ^{4}He nucleon distribution [8] and a Monte Carlo simulation to compute a_n, the number of times n nucleons are wounded;

2) an inelastic p-p cross section, σ^*, is used for all hadron-hadron scatters, except that it is treated as a free parameter, the computation yielding the weights a_n (σ^*);

3) the effects on the multiplicity distribution of final state rescattering of the hadronization products are neglected;

4) pion absorption and production resulting from cascading are neglected. This is consistent with the assumption that the hadronization time, at these relativistic energies, is much

longer than the interaction time since the Lorentz dilation factor (γ) of the projectile in the α rest frame exceeds 500;
5) we assume that the multiplicity distribution contributed by n wounded nucleons is obtained from the convolution of n multiplicity amplitudes, A_n (m).

Table 1 shows the results of our fits, to the p-α and α-α data, of the calculated multiplicity distribution $\Sigma\ a_n\ (\sigma^*)\ A_n(m)$. Fig. 4b shows, for the α-α data, the χ^2, including the sign, to illustrate the quality of the fit. Table 2 presents the extracted value of σ^*. Our geometry is insensitive to diffractive events. Therefore our values of σ^* should be compared with the non-diffractive inelastic p-p cross-section. Both the p-α and α-α distributions are well reproduced by reasonable and equal values of σ^*, in good agreement with the recent result of 26.3mb for the inelastic minus diffractive p-p cross section [9].

The errors assigned to σ^* are the result of studies of systematic errors and are approximately three times the statistical errors. We have investigated many cuts in the data to search for systematic errors:

1) We find that the same values of σ^* and χ^2/d.f. are obtained when the data are fitted over a multiplicity range starting at m = 2, 3, 4 or 5. Inclusion of m = 1 in the p-α data and α-α data doubled the χ^2/d.f. and dropped σ^* by 2-3 mb. Thus we use the m = 2-20 interval for our reported values;
2) splitting the pseudo-rapidity interval into the ranges $-0.8 < \eta < 0$ and $0 < \eta < 0.8$ gave identical results;
3) an arbitrary 10% change in the m = 0 multiplicity in the KNO modified data at 31.5 GeV produced a shift of about 1 mb.

Table 3 shows the values of a_n for our best fits to the number n of wounded nucleons.

We now turn to the comparison of our data with the predictions of the "gluon string model" (GSM) of Bialas and Czyz [10]. In this model only one quark in each nucleon produces a string in p-p interactions. In p-nucleus interactions multiple scattering of a quark produces strings that collapse into one, and different quarks within a nucleon produce separate strings only if they collide with quarks from different nucleons. We use the same Monte Carlo as used for the WNM for counting the number of strings, choosing at random which of the quarks has been struck. This method bypasses the need to employ a quark-quark cross section with the appropriate shadowing to reproduce the p-p cross section. The same p-p multiplicity distribution used in the WNM analysis is used for the single string contribution, n strings requiring an n-fold convolution of the p-p multiplicity distribution. As shown in Table 2 the χ^2 is much poorer than in the WNM in each test. In the case of the α-α data, where the WNM and GSM differ most, the cross section, σ^* is unrealistically low. Fig. 4b shows the χ^2 comparisons; those for the GSM are large and show a systematic rather than statistical variation about the fitted function.

From measurements in the fragmentation region in p-nucleus interactions it has been observed that the multiplicity is not given by the product of the p-p multiplicity and the number of scatters but rather by the number of wounded nucleons; it is generally believed that this is connected with the time dilation of the hadronization, the nuclear scatterings occuring before hadronization. Since the time evolution is not well understood for particles emitted into the central region we have also tested this multiple scattering model (MSM) on our central multiplicity p-α distributions. It fails completely, yielding a $\sigma^* =$ 6.6 mb and a χ^2/d.f. of 60/17 (Table 2). Thus it appears that the hadronization time in the central region cannot be short compared with the time between collisions.

As a final test of the additivity of the interactions we compared the momentum spectra of the particles after transformation to the c.m. We show in Fig. 5 the mean transverse momentum of particles emitted in $|\eta| < 1.6$ vs multiplicity. We employed the momentum range $0.08 < p_T < 2.0$ GeV/c. (Since our object was to compare the p-p, p-α, and α-α data we used the full rapidity range for maximum statistics. The mean p_T is not corrected for spectrometer acceptance effects [11]). In order to get good statistical accuracy for the high multiplicity points we used an electronic trigger on barrel counter multiplicities > 19. These and minimum bias data are combined in Fig. 5. We also find no differences between the $<p_T>$ values for the three separate p-p energies studied.

These data provide the first experimental test of the identity of the transverse momentum spectra in p-p, p-n, and n-n interactions at ISR energies, the differences being less than 0.5%. They also show that there is very little correlation between multiplicity and the p_T distribution, Fig. 5 showing that $<p_T>$ is independent of n at the 2% level.

We conclude that our measured central multiplicity distributions in ultrarelativistic p-α and α-α interactions are well fitted using the p-p cross sections, the best ^{4}He wave function and the "wounded nucleon model". Multiple scattering models such as this should not show KNO-like scaling to pp data, and this is consistent with our observations. Furthermore we have already shown experimentally [12], in a model independent way, that very high central multiplicity α-α collisions appear to arise from four independent nucleon-nucleon collisions. This view gains further support from the equality of $<p_T>$ for $p_T < 2$ GeV/c in p-p, p-α, and α-α interactions over a wide range of multiplicities.

Thus it appears that, within the accuracy of the measurements reported in this paper, low p_T nuclear interactions at these very high energies can be understood on the basis of independent nucleon interactions with no need to invoke the underlying quark-gluon structure.

REFERENCES

[1] H. Gordon et al., Nucl. Instrum. Methods 196 (1982) 303.
O. Botner et al., Nucl. Instrum. Methods 196 (1982) 315.

[2] Approximately 95% of the p-p inelastic cross section is seen by this "minimum bias" trigger at $\sqrt{s}$ = 44 GeV.

[3] Z. Koba, H.B. Nielsen, and P. Olesen, Nucl. Phys. B 40 (1972) 317.

[4] We have also studied the extrapolation to zero multiplicity by another fitting procedure, fitting the p-p multiplicities directly to the form M $(1 + az + bz^2) \exp(-cz)$, and find that these fits also give KNO scaling and almost identical intensities for m = 0 (< 7% difference in the $\sqrt{s}$ = 44-63 comparison on the KNO plot.) Our background studies using the BBC showed that we could attribute at most 5% of the single tracks to unexplained background.

[5] G. Arnison et al., Phys. Lett. 107B (1981) 320.

[6] A. Bialas, M. Bleszynski and W. Czyz, Nucl. Phys. B111 (1976) 461.

[7] W. Busza et al., Phys. Rev. Lett. 34 (1975) 836.

[8] R.F. Frosch et al., Phys. Rev. 160 (1967) 874; we have employed their three parameter Fermi model for our nucleon spatial distribution:
$\rho(r)/\rho(0) = (1 + ar^2/c^2) / (1 + \exp((r-c)/f))$;
c = 1.008F; f = 0.327 F; a = 0.445.

[9] K. Goulianos, H. Sticker and S.N. White, Phys. Rev. Lett. 48 (1982) 1454.

[10] A. Bialas and W. Czyz, Proceedings of the Workshop on Future Relativistic Heavy Ion Experiments, May (1981);
A Bialas, W. Czyz and L. Lesniak, Z. Phys. C.13 (1982) 147.

[11] T. Akesson et al., Phys. Lett. 108B (1982) 58.

[12] T. Akesson et al., Phys. Lett. 110B (1982) 344.

FIGURE CAPTIONS

Fig. 1: Fits of the $\sqrt{s}$ = 44 and 63 p-p data to the two-fold convolution of the amplitude function (1 + Bm) exp (-Cm).

Fig. 2: Comparison of the $\sqrt{s}$ = 44 and 63 GeV data with the fitted KNO function. (Smooth line: KNO; open circles: 44 GeV; x's: 63 GeV; Closed circles: 31.5 GeV data fitted to the KNO function for $m \geq 3$.)

Fig. 3: Relative number of events vs multiplicity, normalized to unity, for p-p, p-α, and α-α data in the cm pseudorapidity range $|\eta| < 0.8$. The 31.5 GeV points are those obtained from the KNO fit.

Fig. 4: Comparisons of data fits to several models.
a) χ^2 (including the sign of the deviation) vs multiplicity resulting from best fits to p-p derived KNO function. (Closed circles: p-α; Open circles: α-α)
b) χ^2 (including the sign of the deviation) vs multiplicity resulting from best fits of the α-α data to the wounded nucleon model (closed circles) and the gluon string model (open circles). Note the different scales for a) and b).

Fig. 5: Mean transverse momenta, $\langle p_T \rangle$, vs multiplicity for p-p (squares), p-α (open circles) and α-α data (closed circles) for the pseudorapidity range: $|\eta| < 1.6$. $\langle p_T \rangle$ is calculated for two multiplicity bins and plotted at the highest m; only error bars $\geq 0.5\%$ are shown.

Particles		pp		pp		pp		pα			αα	
√s nn		31.5 GeV		44 GeV		63 GeV		44 GeV			31.5 GeV	
No.Events		25569		38181		16140		44591			39985	
	Data	KNO	Data	CAF	Data	CAF	Data	WNM	KNO	Data	WNM	KNO
INT		3-15		1-18		1-17		2-20	2-20		2-20	2-20
χ^2		14.1		12.5		14.3		15.5	19.4		48.3	68.0
<m>	2.92	2.66	2.78	2.82	2.84	2.88	3.22	3.34	3.27	3.97	4.28	4.16
D	2.22	2.23	2.35	2.34	2.44	2.43	2.70	2.69	2.69	3.41	3.41	3.36
<m'>	3.27	3.13	3.28	3.28	3.36	3.36	3.74			4.60		
B	0.59 ± 0.05		0.54 ± 0.04		0.42 ± 0.05							
C	0.83 ± 0.01		0.79 ± 0.01		0.74 ± 0.01							

Table 1: Parameters and fits to the data

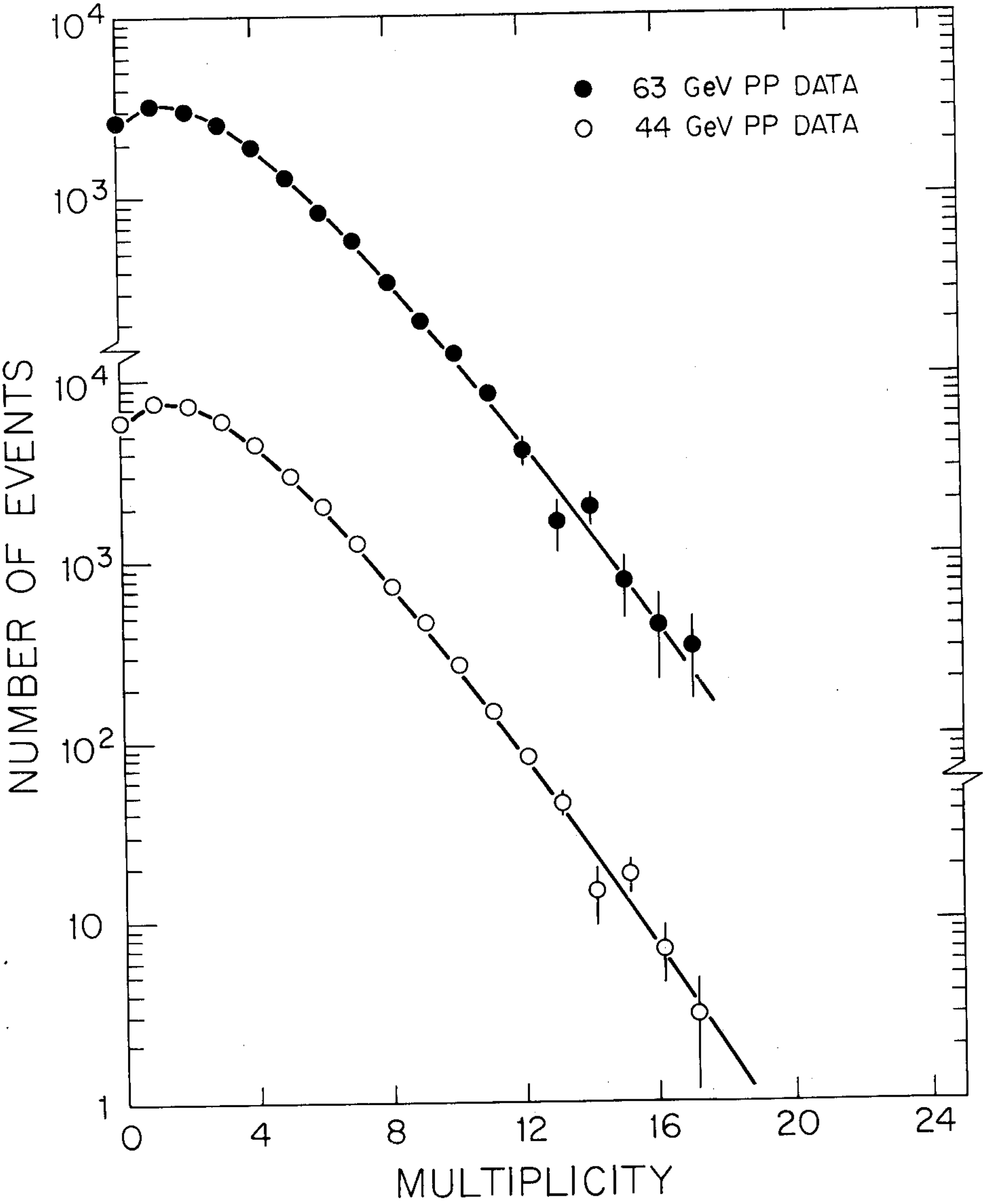
<m>	Mean multiplicity including m = 0
D	Dispersion corresponding with <m'>
<m'>	Mean multiplicity for m $\geq$ 1
INT	Multiplicity range used for fit
KNO	Fit to the KNO function at 44 and 63 GeV
WNM	Fit to the Wounded Nucleon model
CAF	Convoluted Amplitude function

Reaction	Fit	σ*(mb)	χ^2/d.f.
p-α	WNM	25 ± 4	15/17
α-α	WMN	20 ± 5	48/17
p-α	GSM	14	47/17
α-α	GSM	11	267/17
p-α	MSM	6.6	60/17

Table 2: The values of the p-p cross sections, σ*, extracted from the fits, and the χ^2/d.f.

	a_2	a_3	a_4	a_5	a_6	a_7	a_8
p-α	1.00	.31±.03	.10±.02	.013±.01			
α-α	1.00	.42±.06	.32±.05	.21±.05	.13±.05	.06±.03	.012±.01

Table 3 : The relative numbers of wounded nucleons from our best fits. The assigned errors are determined from the errors in Table 2



● 63 GeV PP DATA
○ 44 GeV PP DATA
NUMBER OF EVENTS
10^4
10^3
10^4
10^3
10^2
10
1
MULTIPLICITY
0
4
8
12
16
20
24

Fig. 1

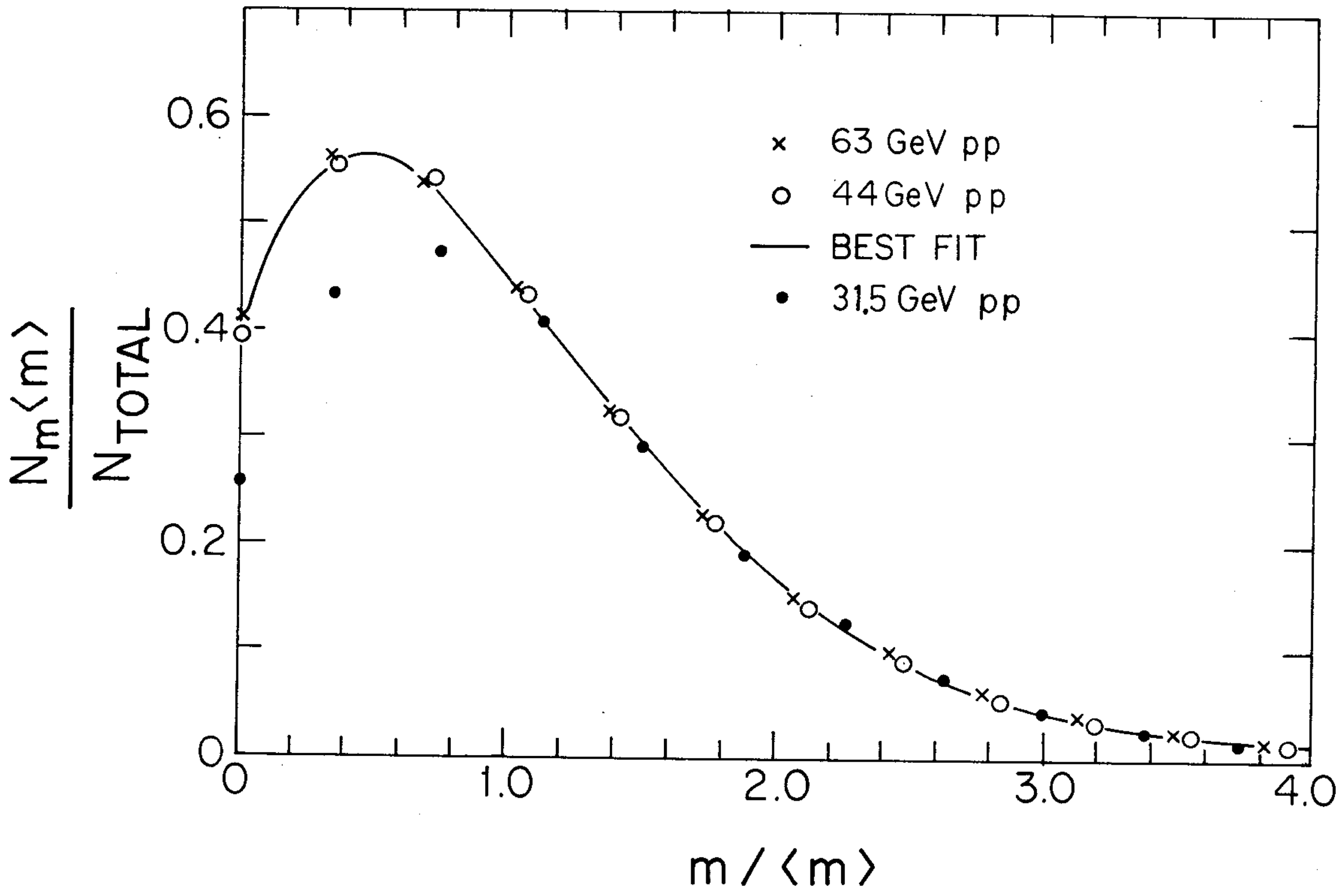

63 GeV pp
44 GeV pp
BEST FIT
31.5 GeV pp
$\frac{N_m \langle m \rangle}{N_{TOTAL}}$
0.6
0.4
0.2
0
0
1.0
2.0
3.0
4.0
$m / \langle m \rangle$

Fig. 2

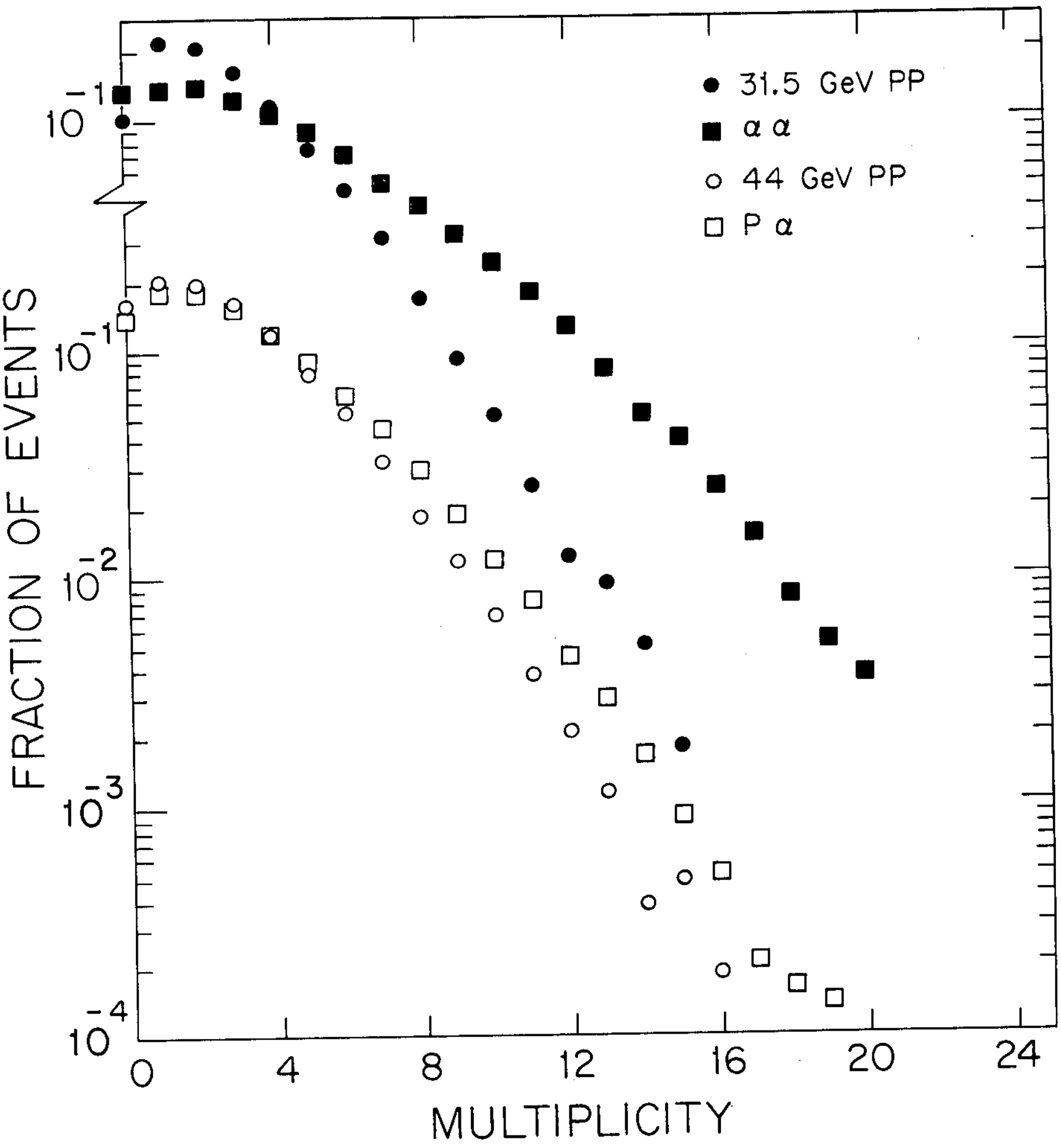

● 31.5 GeV PP
■ αα
○ 44 GeV PP
□ Pα
FRACTION OF EVENTS
10^-1
10^-1
10^-2
10^-3
10^-4
0
4
8
12
16
20
24
MULTIPLICITY

Fig. 3

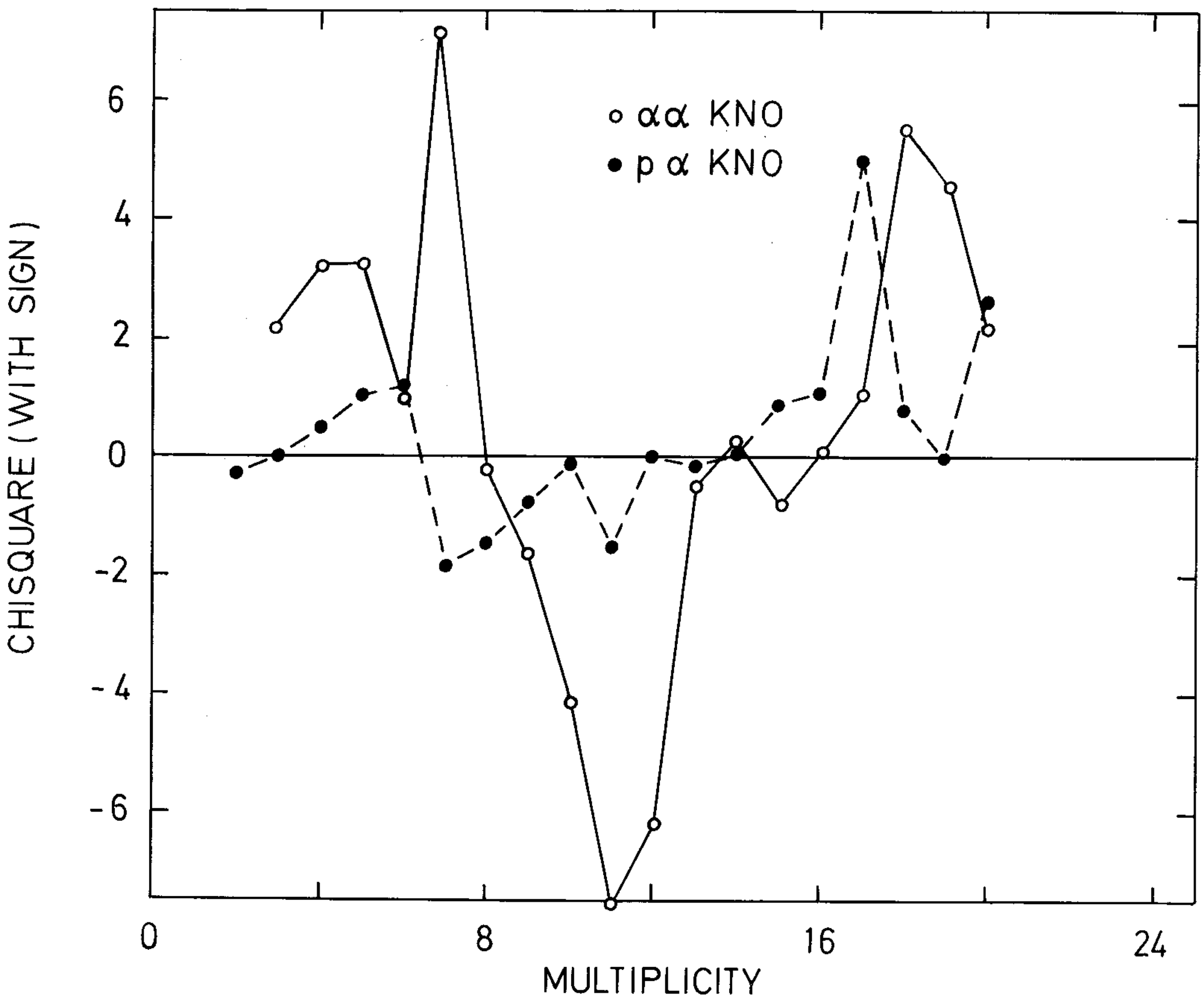

○ αα KNO
● pα KNO
CHISQUARE (WITH SIGN)
6
4
2
0
-2
-4
-6
0
8
16
24
MULTIPLICITY

Fig. 4a

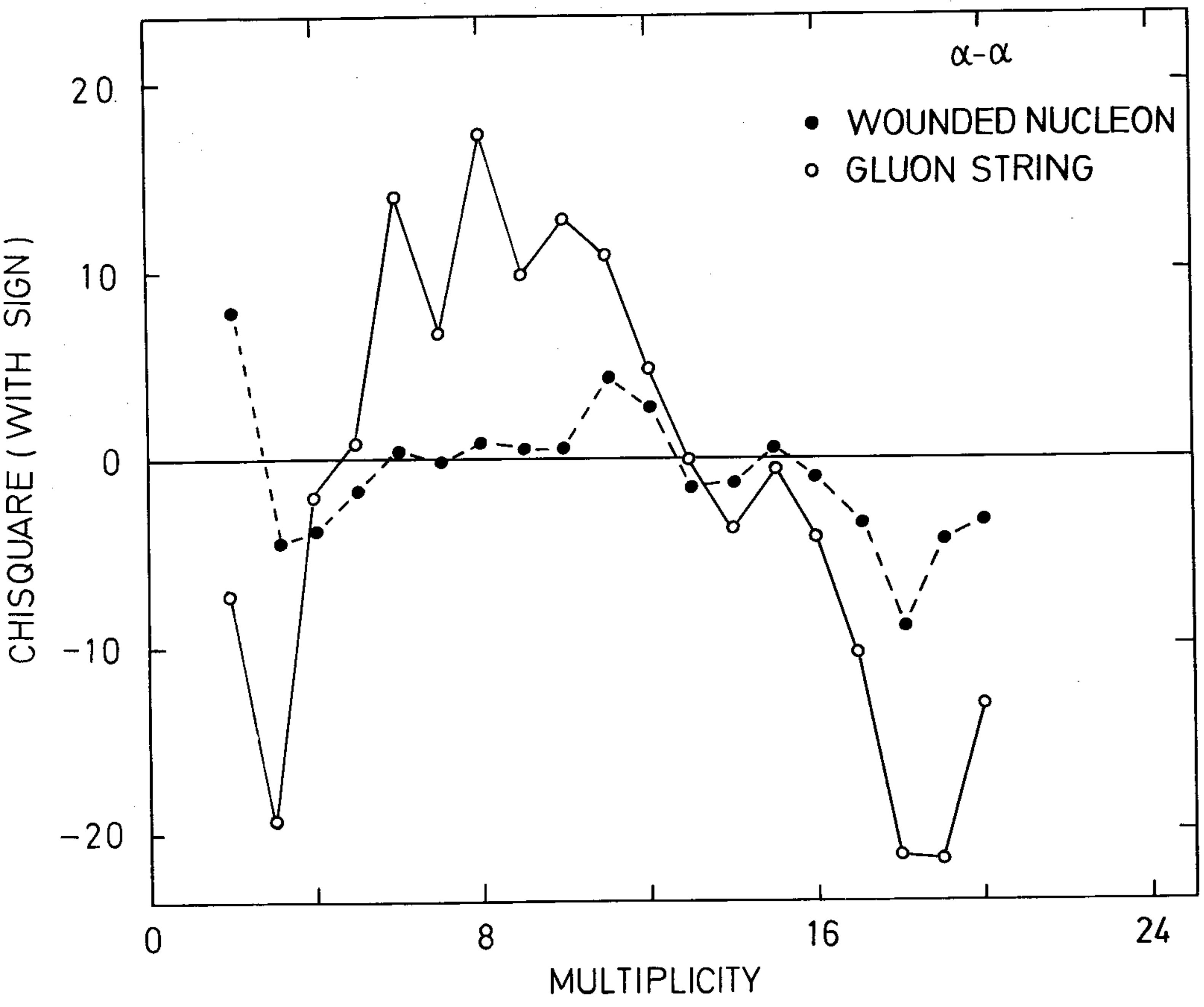

α-α
● WOUNDED NUCLEON
○ GLUON STRING
CHISQUARE (WITH SIGN)
20
10
0
−10
−20
0
8
16
24
MULTIPLICITY

Fig. 4b

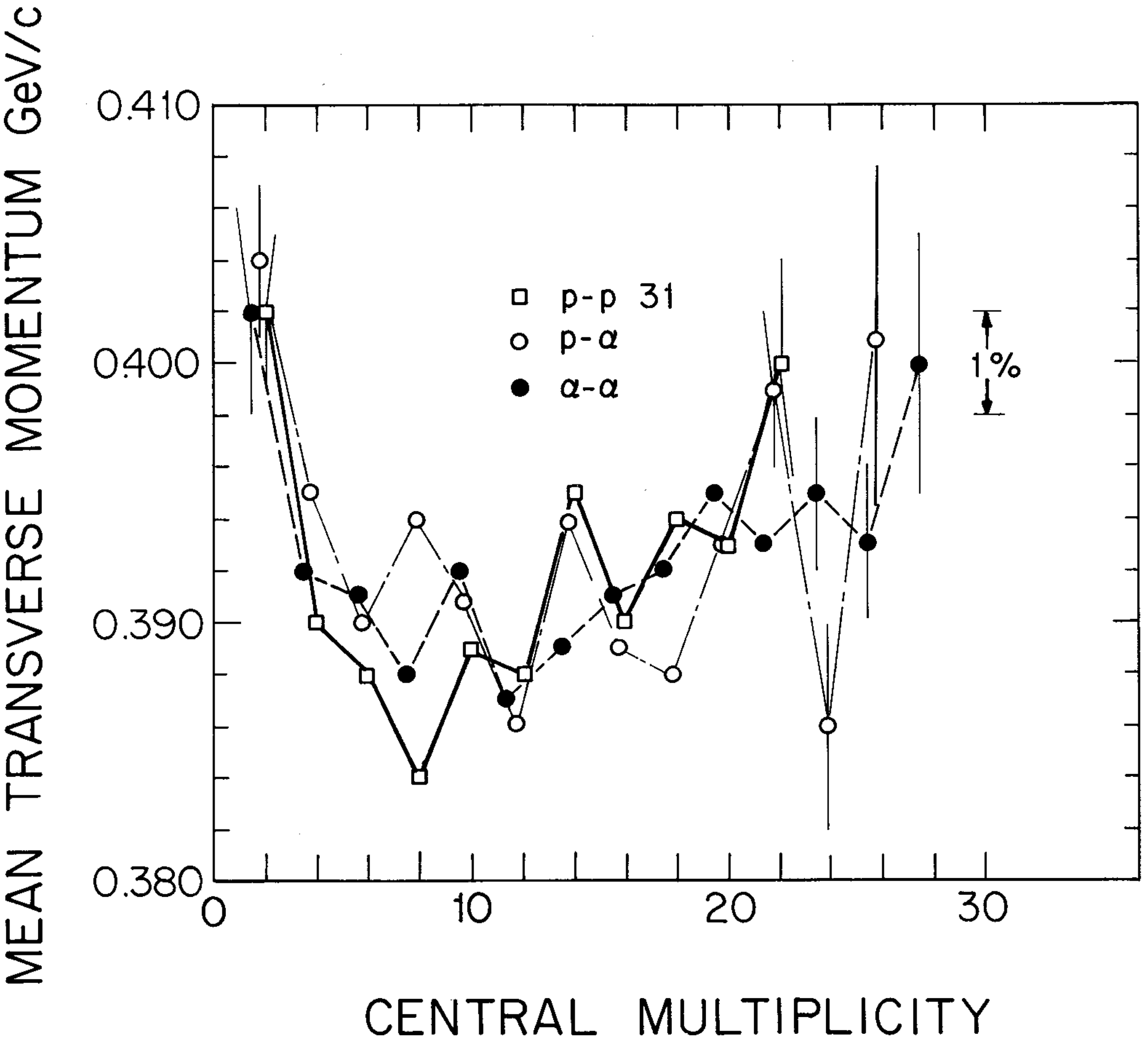

MEAN TRANSVERSE MOMENTUM GeV/c
0.410
0.400
0.390
0.380
0
10
20
30
CENTRAL MULTIPLICITY
□ p-p 31
○ p-α
● α-α
1%

Fig. 5