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Coherent Multiple Production in Proton-Nucleus Collisions at 200 and 300 GeV/c

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Abstract

Two stacks of the nuclear emulsion were exposed to the 205 and 303 GeV/c proton beams. By following the beam protons, inelastic events induced by proton-nucleus collisions are detected. Then, the mean free path for the coherent production is studied and its energy dependence is discussed. In addition, a feature of the target mass number dependence of the cross section for the inelastic proton-nucleus collision is shown.

1. Introduction

In this article, a study of the coherent processes induced by the proton-nucleus collision is mainly reported. In multiple production processes at the collision of a hadron with a nucleus, there is one type of process not seen in the case of usual single hadron-hadron collision. In this type of collision, called coherent multiple production[1)], the whole nucleons inside the target nucleus collide coherently with the incident hadron. This coherent production consists of diffraction dissociation, in which the target nucleus exchanges no quantum number except angular momentum with the incident hadron, and of Coulomb dissociation, in which the incident hadron is excited by the Coulomb field of the target nucleus. Coherent production is characterized by small momentum transferred to target nucleus, though it is not easy to differentiate between these two types of dissociation. This coherent multiple production process mean free path of proton in nuclear emulsion is studied at 200 and 300 GeV, and its energy dependence is investigated comparing with the other data obtained at lower energy region.

In addition to this, the nuclear mass number dependence of the inelastic cross section for the proton-nucleus collision at 200 and 300 GeV is presented.

2. Experimental procedure

Two emulsion stacks of Ilford K-5 pellicle were exposed to the proton beams at the Fermi National Accelerator Laboratory. Nominal momentum values are 205 and 303 GeV/c, respectively. The exposed beam density is a few times 10^4 particles per cm^2 at 205 GeV/c, and 3×10^3 particles per cm^2 at 303 GeV/c.

Inelastic collision events were scanned by following incident beam tracks. The total track length followed is 1060 m for 205 GeV/c and 526 m for 303 GeV/c. Events detected are classified by N_h, the number of heavily ionizing tracks (grain density larger than 1.4 times of that of plateau value, corresponding to velocity smaller than 0.7 of the light velocity) longer than 3 micron, and n_s, the number of thinly ionizing tracks, and the notation $N_h + n_s$, usually adopted in emulsion work, is used.

The events of the type of 0+1 and 0+2 in which the scattered angle of the proton is less than 5 mrad are excluded. In the 0+2 events, the particle with smaller scattered angle is assumed to be the surviving proton. By this selection of the scattered angle, the elastic events are reasonably excluded. In the elastic scattering at 200 or 300 GeV/c, the scattering angle of 5 mrad gives a condition of $q^2 \gtrsim 1\ (\mathrm{GeV/c})^2$, where q^2 is the squared 4-momentum transfer of the proton. The differential cross section $\frac{d\sigma}{dq^2}$ is proportional to e^{-bq^2} where b value is around 10 at these momenta[2]. Therefore, almost all elastic events are excluded by the 5 mrad cut.

Electromagnetic processes, that is, knock-on and direct electron pair production contaminate the 0+2 and 0+3 events. The electrons with energies less than several tens of MeV are easily identified. The knock-on events with electrons of higher energies are almost completely excluded by the 5 mrad cut. For direct pair production, when necessary, the scattering measurements are performed to identify tracks due to electrons. Thus, in case of 303 GeV/c, 50 direct pairs per 465 m and, in case of 205 GeV/c, 23 direct pairs per 248 m are excluded from apparent 0+3 events. These are not inconsistent with King's result[3].

After correcting these electromagnetic events, the total number of inelastic events, 2976 for 205 GeV/c and 1577 for 303 GeV/c are obtained. The missing rate for the inelastic 0+1 and 0+2 events due to the 5 mrad cut is estimated using the results of the bubble chamber film analyses for proton-proton interactions[4] under the assumption that the cross section for the proton-neutron interaction is the same as the proton-proton one. According to this estimation, the missing rates for these two types of events are sufficiently small.

The results on inelastic cross sections and related quantities are tabulated in Table I. The prong number distributions of $0+n_s$ events for both energies are shown in Figs. 1 and 2. Events accompanied by a slow electron or a visible track shorter than 3 micron (recoil nucleus) are named as dirty events and they are shown in Figs. 1 and 2 by the hatched area. Such low energy

electrons or recoil tracks show that the target nucleus received appreciable energy from the incident proton, thus these dirty events can not be the coherent ones. As seen in Figs. 1 and 2, the numbers of clean events at multiplicity of 3, 5 and 7 are systematically larger than neibouring multiplicity. This tendency shows clearly that the above-mentioned coherent multiple production process contributes to these small and odd number multiplicity events.

3. Estimate of number of coherent events

Coherent processes are characterized by the small momentum transfer and this nature can be used as one of the selection criteria of coherent events. In a coherent event, the momentum transfer q, should lie in the region,

$$qR \lesssim 1 ,$$

where R is the nuclear radius of the target.

As in high energy collisions $q_{\parallel} \gg q_{\perp}$,

$$q_{\parallel} \lesssim m_{\pi}/A^{1/3} ,$$

where A is the target mass number.

As shown by Fisher et al.[5], the lower bound of $q_{\parallel}$ can be estimated without knowing the momentum value as,

$$q_{/\!/} \gtrsim \sum_i m_i \cdot \sin\theta_i ,$$

where m_i is the mass and θ_i is the emission angle of the i-th projectile particle.

We define q_{min} given by,

$$q_{min} = \sum_i m_i \cdot \sin\theta_i$$

q_{min} can be obtained for every observed events, and is used for the selection of coherent events. In this calculation, we should determine which particle is projectile proton and give a proper mass value, because in the case of the incident proton, projectile charged particles are usually one proton and even number of pions. We make an assumption that the track with the smallest angle of emission is due to the projectile proton. Even if this assumption does not hold, our purpose is to estimate the lower limit for transferred momentum and this is evidently fulfilled by this assignment of particles. In the case of neutron emission this procedure gives an incorrect result, but this case is fewer than the proton emission case, as the neutron case should have one more charged pion than the proton case.

For light nuclei (C, N, and O) in nuclear emulsion

$$m_\pi / A^{1/3} \approx 0.06 \text{ GeV/c}$$

and for heavy nuclei (Ag and Br)

$$m_\pi / A^{1/3} \approx 0.03 \text{ GeV/c} .$$

Therefore, events with q_{min} smaller than 0.06 GeV/c are considered as possible coherent events. The distributions of q_{min} is shown in Figs. 3 and 4. In the region of q_{min} smaller than 0.06 GeV/c there exist dirty events, and this shows that incoherent events are also included in this q_{min} region. To estimate the number of such events, I, q_{min}-distributions for dirty events and for clean incoherent events are assumed to be similar. Then,

$$I = K \times (\text{No. of dirty events at } q_{min} \leq 0.06 \text{ GeV/c}) ,$$

where,

$$K = \frac{(\text{No. of clean events at } q_{min} > 0.06 \text{ GeV/c})}{(\text{No. of dirty events at } q_{min} > 0.06 \text{ GeV/c})} .$$

For 205 GeV/c, this method of correction was used, but in the case of 303 GeV/c the number of events is not large enough to allow to estimate K. So, instead of K, K' is used, where K' is defined by

$$K' = \frac{(\text{No. of clean events with } n_s \neq 1, 3, 5, 7)}{(\text{No. of dirty events with } n_s \neq 1, 3, 5, 7)} .$$

K' is around 1.40 for both 205 and 303 GeV/c .

Another method is to subtract K' x (No. of dirty events at $q^2_{min} \leq 0.06$ GeV/c) from (No. of clean events at $q^2_{min} \leq 0.06$ GeV/c).

As shown in Table II for the case of 205 GeV/c, these two methods give consistent results.

3. Results and discussions.

Values of the mean free path for proton-nucleus coherent interactions with three and five prongs at 205 and with three prongs at 303 GeV/c are given in Table II, where at 205 GeV/c both values obtained using the above-mentioned K- and K'-correction are shown. As to other coherent events with other multiplicities not listed in Table II, statistics is not enough to derive reliable values.

In Fig. 5, the mean free paths for the coherent productions at various proton energies obtained so far by emulsion analyses[6,7] are shown. In other analyses, the different selection criterea are adopted except for Ref. 7. Therefore, it needs some caution to compare our results directly with those of other authors, among which the difference between the selection criteria of $\sum_i m_i \sin\theta_i$ and $\sum_i \sin\theta_i$ would be the main problem. A criterion, $\sum m_i \sin\theta_i$ is more strict and expected to give systematically lower number of coherent events than that of $\sum \sin\theta_i$. The difference of the number of coherent events due to these different criteria is

considered to be more serious in the lower multiplicity events. If the selection of $\sum_i \sin\theta_i \leq A^{-1/3}$ (≈ 0.4) is applied to our data, the mean free paths of 0+3 and 0+5 coherent events for 205 GeV/c are $32 \pm {}^{7}_{5}$ m and $76 \pm {}^{30}_{17}$, respectively. By comparing these values with those shown in Table II, it will be said that the difference between two methods is significant in the case of 0+3, but in 0+5 is not so serious. In Fig. 5, therefore, one could see the energy dependence of the mean free path for the 0+5 coherent events as continuing to decrease. For 0+3 events, the selection of $\sum_i m_i \sin\theta_i$ gives systematically longer mean free path than the other, but is better to discuss the absolute value of the mean free path for the coherent events. Fig. 5 shows that the mean free path for 0+3 events at 205 GeV/c is somewhat shorter than that at 303 GeV/c. However, the statistics of the data at 303 GeV/c is not sufficient. Therefore, to draw any tendency on the energy dependence for the 0+3 coherent events at these energies would be reserved until further studies will be finished.

If the inelastic cross section for the proton-nucleus collision is expressed by $\sigma_o A^{\alpha}$ where σ_o is the inelastic cross section for the elementary proton-nucleon collision which is assumed to be the same as that for the proton-proton collision and A is the nuclear mass number, then, the observed mean free path for the inelastic collision λ_{ob} is written as,

$$1/\lambda_{ob} = \sigma_o \sum_i A_i^{\alpha} N_i$$

where N_i is the number of the specific nucleus in unit volume of emulsion. The summation is carried out over the whole nuclei composing the nuclear emulsion. Using this relation, one can derive α-value from the observed λ_{ob}'s to be 0.76 $\pm$ 0.01 for 205 GeV/c and 0.77 $\pm$ 0.01 for 303 GeV/c . These results show that the A-dependence of the inelastic cross section for the proton-nucleus collision at these energies might be somewhat stronger than that shown by $A^{2/3}$.

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Table I

proton momentum	205 GeV/c	303 GeV/c
track length	1060 m	526 m
number of inelastic events	2976	1577
mean free path for inelastic events	35.6±0.7 cm	33.4±0.8 cm
number of $0+n_s$	449	280
mean free path for $0+n_s$	2.36±0.11 m	1.88±0.11 m
mean n_s for $0+n_s$	7.8±0.4	7.8±0.5
mean n_s for clean $0+n_s$	7.0±0.4	7.3±0.6

Table II

coherent events

proton momentum	event type	correction method	number of events	mean free path in m
	0 + 3	K	23 ± 5	$46 \pm {}^{13}_{8}$
2 0 5		K'	14 ± 4	$76 \pm {}^{30}_{17}$
GeV/c	0 + 5	K	17 ± 4	$62 \pm {}^{20}_{12}$
		K'	14 ± 4	$76 \pm {}^{30}_{17}$
3 0 3 GeV/c	0 + 3	K'	10 ± 3	$53 \pm {}^{22}_{13}$

Figure captions.

Fig. 1. n_s distribution for $0+n_s$ events at 205 GeV/c .

Fig. 2. n_s distribution for $0+n_s$ events at 303 GeV/c .

Fig. 3. q_{min} distribution for 0+3 and 0+5 events at 205 GeV/c .

Fig. 4. q_{min} distribution for 0+3 events at 303 GeV/c .

Fig. 5. Energy dependence of the mean free path for coherent productions. ○ and □ are our results. ● and ■ are other authors'.

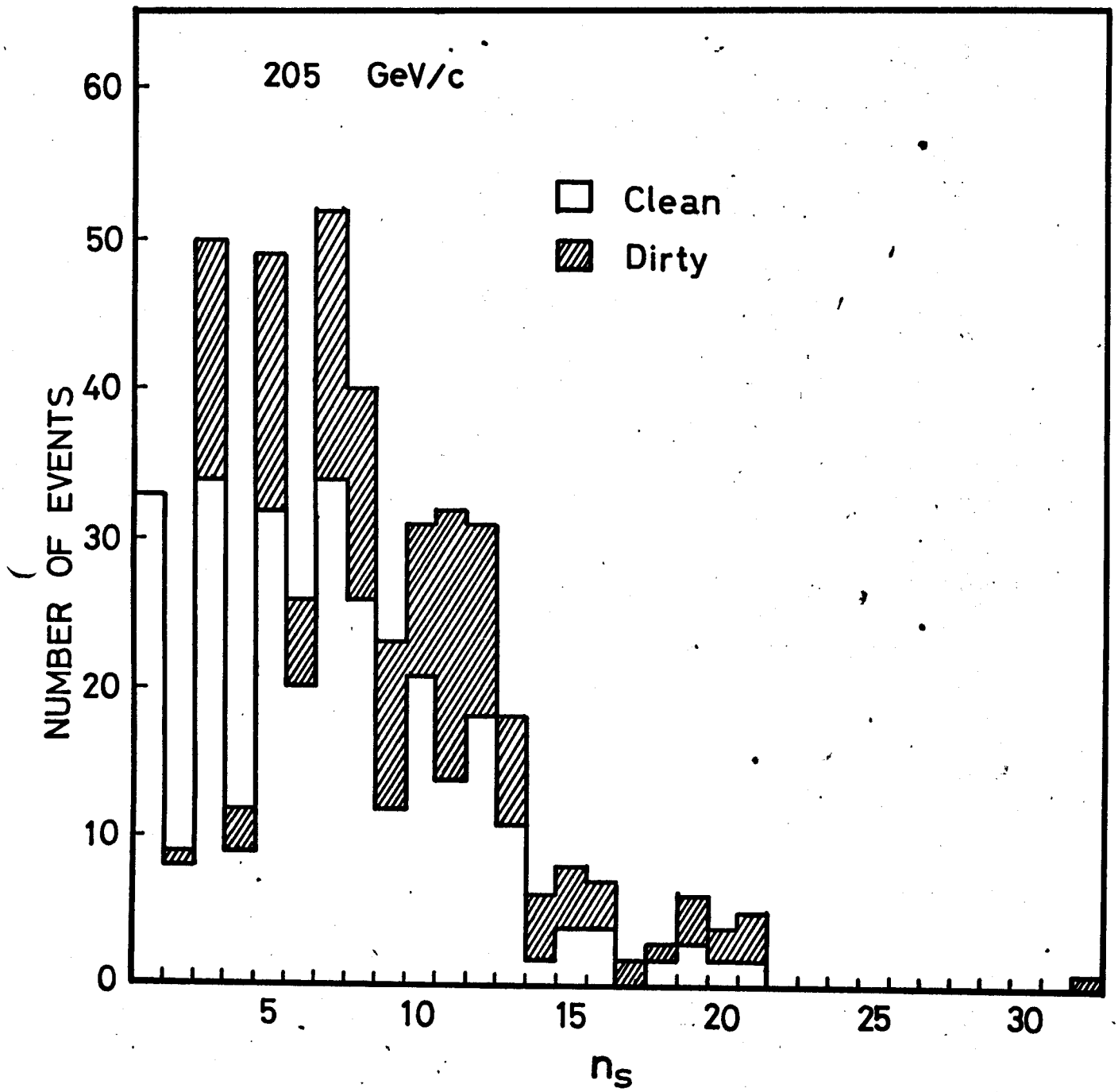
205 GeV/c
Clean
Dirty
NUMBER OF EVENTS
0
10
20
30
40
50
60
5
10
15
20
25
30
n_s

Fig. 1

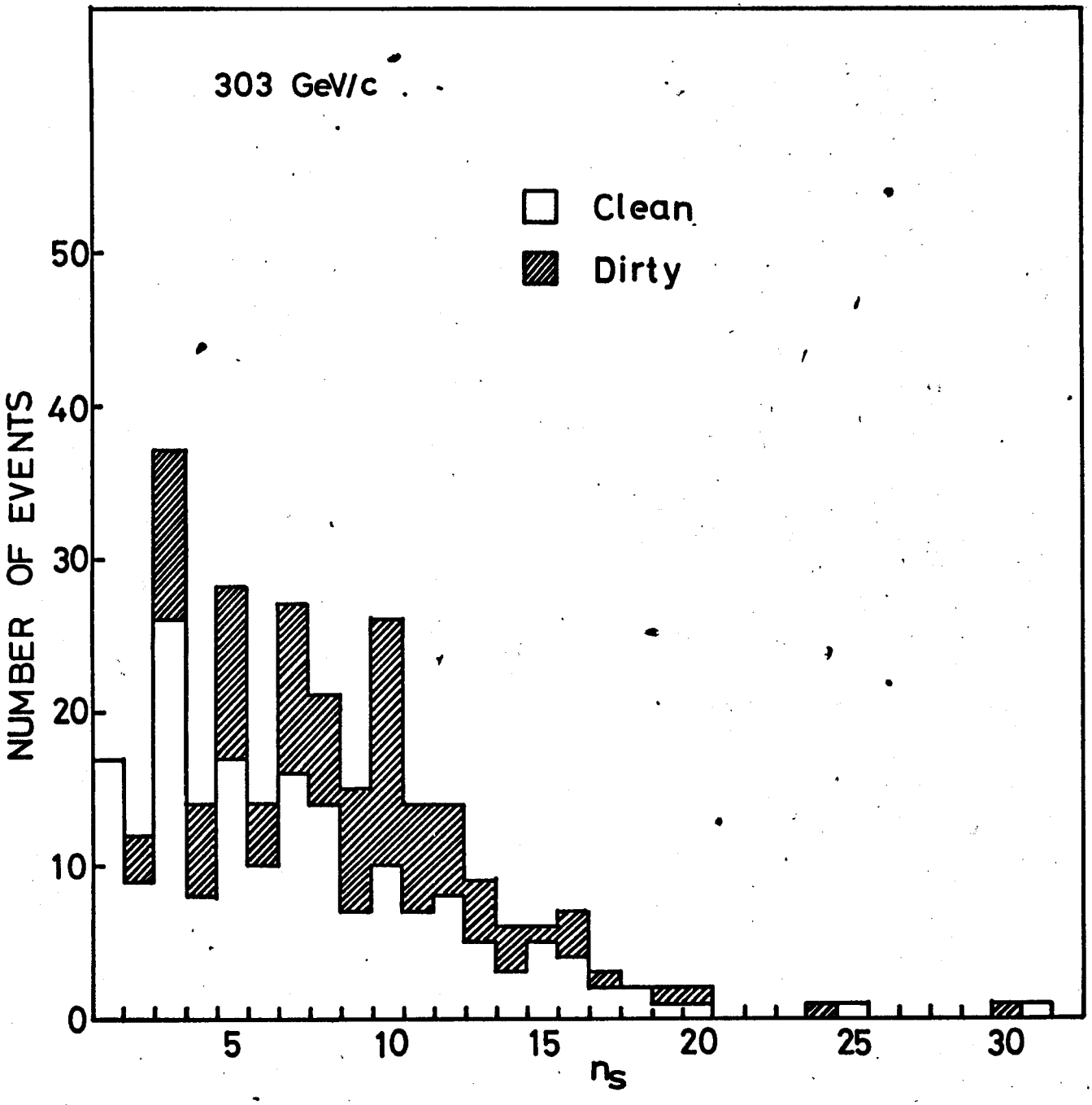
303 GeV/c
Clean
Dirty
NUMBER OF EVENTS
0
10
20
30
40
50
5
10
15
20
25
30
n_s

Fig. 2

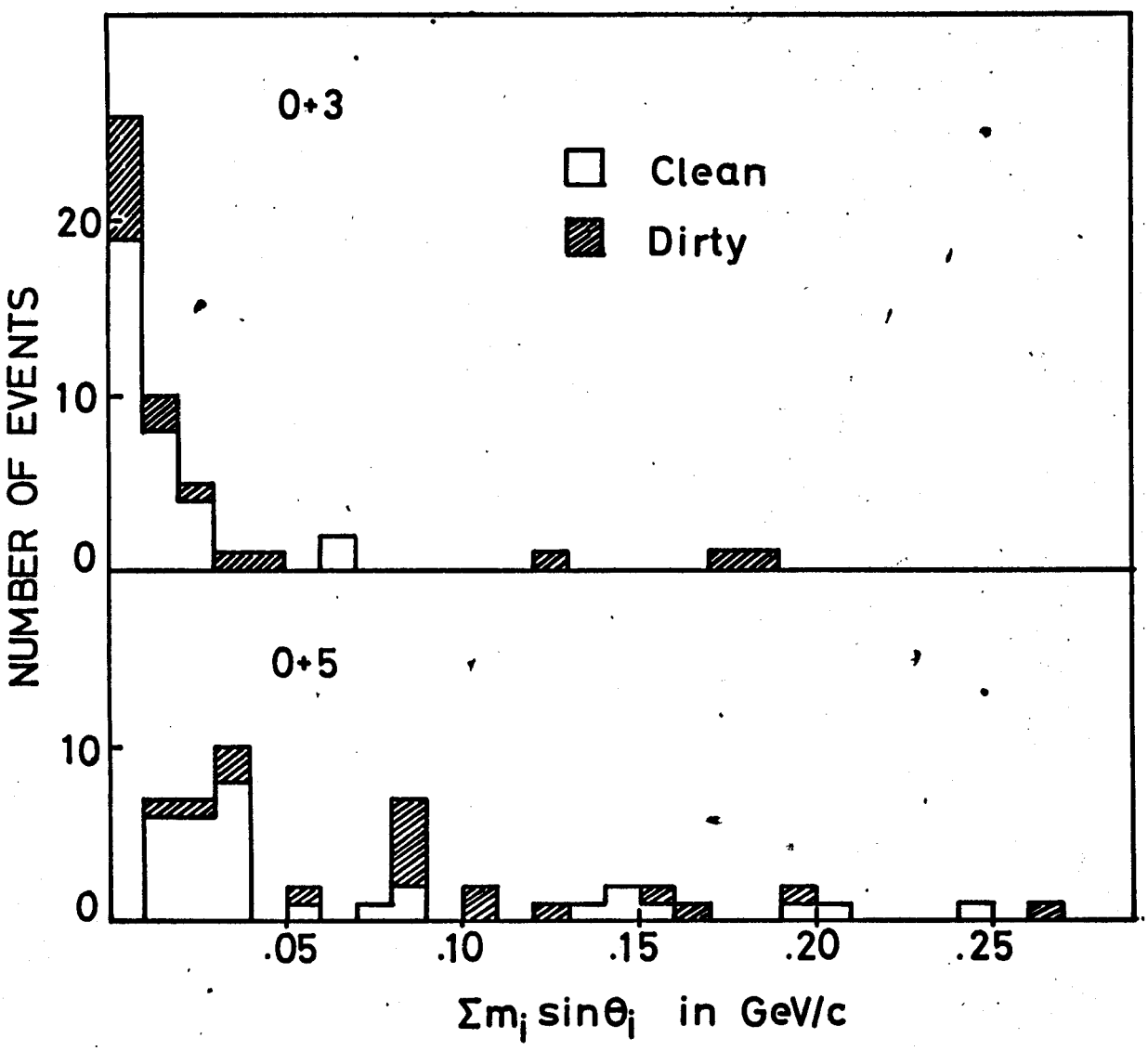
0+3
Clean
Dirty
20
10
0
NUMBER OF EVENTS
0+5
10
0
.05
.10
.15
.20
.25
$\Sigma m_i \sin\theta_i$ in GeV/c

Fig. 3

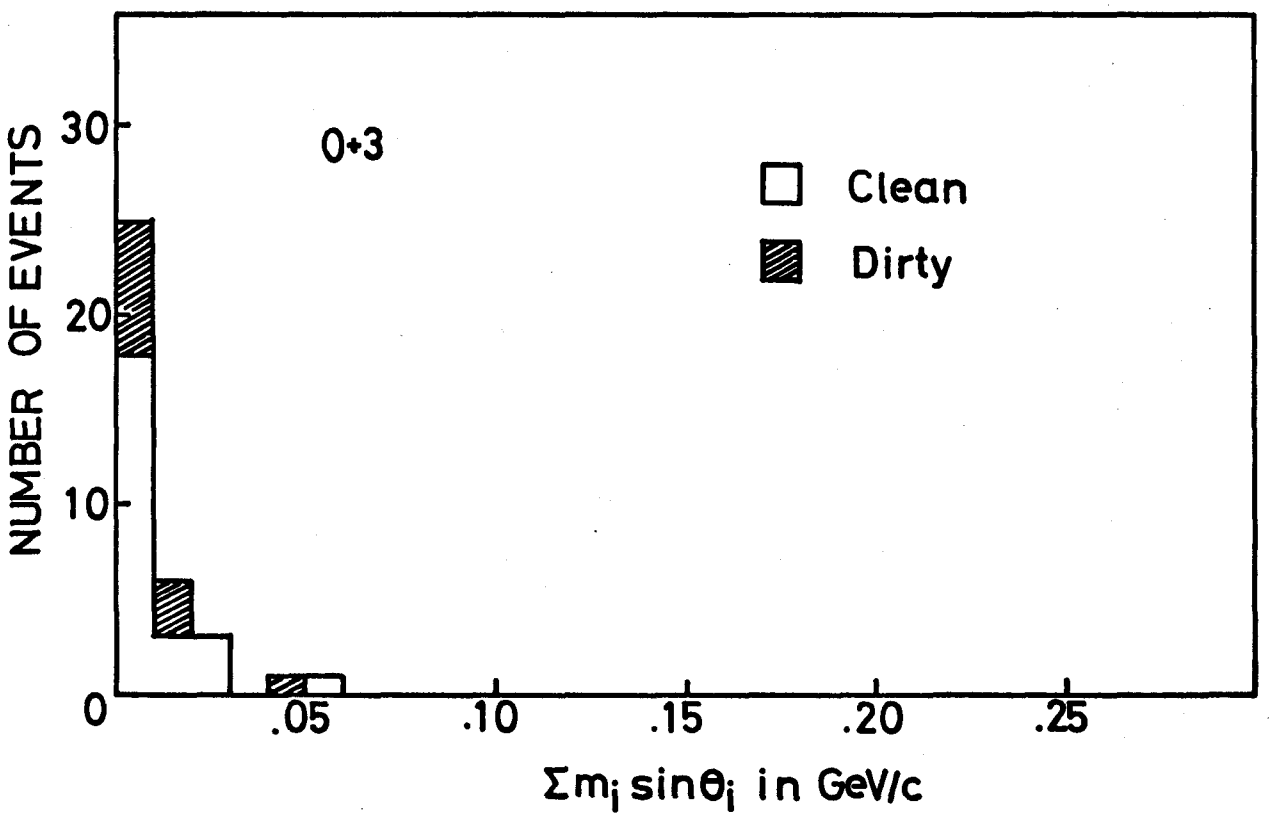
NUMBER OF EVENTS
30
20
10
0
0+3
Clean
Dirty
.05
.10
.15
.20
.25
Σm_i sinθ_i in GeV/c

Fig. 4

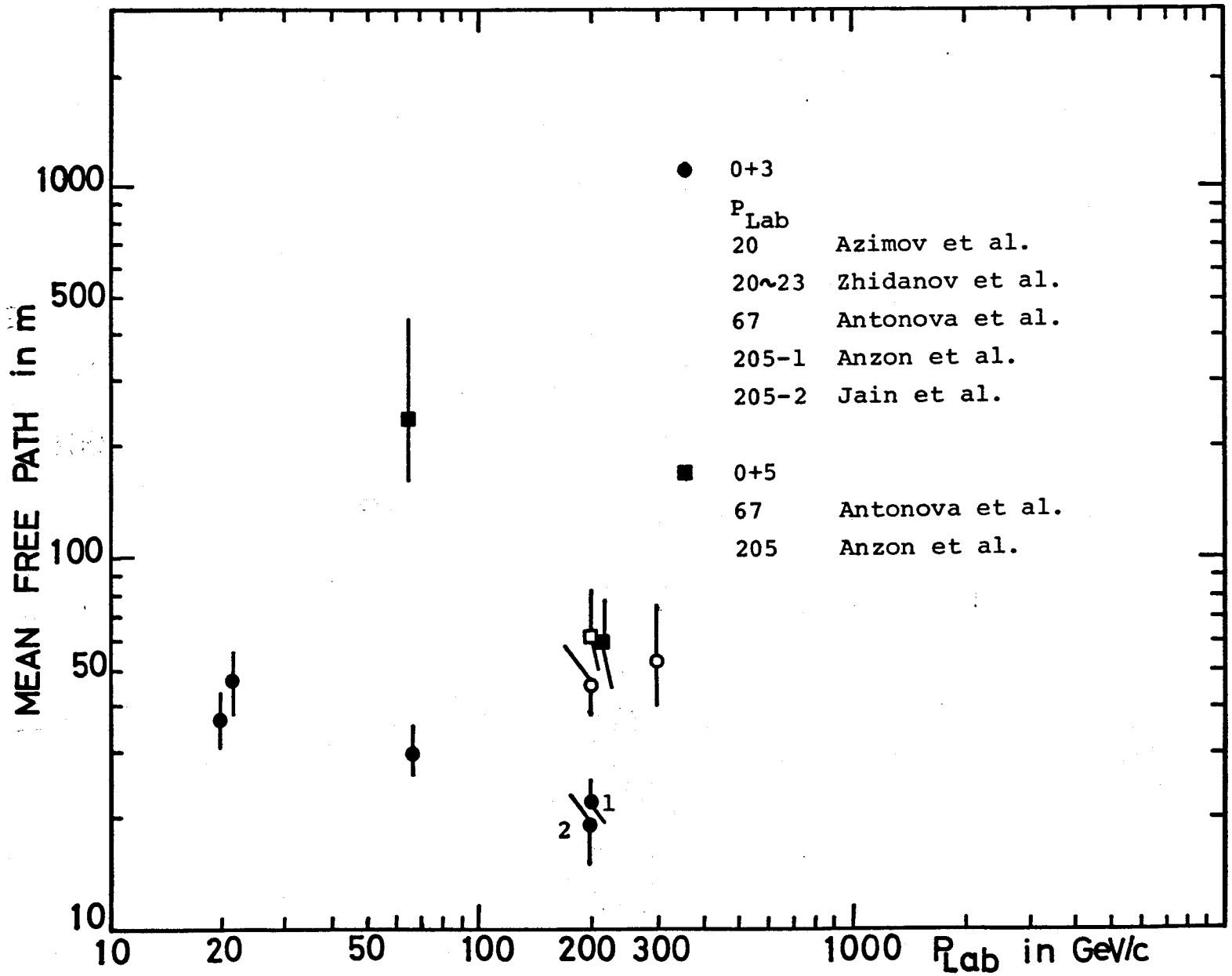
MEAN FREE PATH in m
1000
500
100
50
10
10
20
50
100
200
300
1000
P_{Lab} in GeV/c
0+3
P_{Lab}
20 Azimov et al.
20~23 Zhidanov et al.
67 Antonova et al.
205-1 Anzon et al.
205-2 Jain et al.
0+5
67 Antonova et al.
205 Anzon et al.
1
2

Fig. 5