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Central Particle Production via Independent Cluster Emission in Hadron-Hadron, Photon-Hadron and e^+e^- Processes

by

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Abstract: Evidence is presented that one and the same central cluster is responsible for inclusive particle production in the central region in hadron-hadron, photon-hadron and e^+e^- processes. It is argued that also two-particle final states appear via a cluster intermediate state which for decay to 90° is independent on charge quantum numbers and which is furthermore controlled by the same parameters as the central cluster responsible for many particle final states.

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Data on two-particle correlations between particles produced in the central region at NAL and ISR energies have lead to the picture of independent emission of central particle clusters [1]. As was emphasized by Pokorsky and Van Hove [2] this leads in a natural way to a unified picture of inelastic particle production at high energies: The fragmentation of an incident hadron proceeds via formation of a leading cluster which subsequently decays whereas secondaries in the central region are produced by central clusters. Asymptotically, in this picture, the leading clusters carry the quantum numbers of the leading particles and the central clusters those of the vacuum. The typical central cluster has a mass $M \lesssim 2$ GeV and it decays into 2-3 charged particles, where the decay is almost isotropic in its rest system. In this framework the exponential cut-off in $p_\perp$ is a property of the cluster.

Taking the existence of clusters seriously one is naturally lead to the expectation that <u>any</u> hadronic final state is produced via an intermediate state consisting of one or more clusters. We emphasize that this should apply irrespective of the initial state and of the energy available and therefore the same clusters as observed in purely hadronic collisions should be produced in photon induced reactions and in e^+e^- annihilation.

In the following we present evidence that the central cluster observed at the ISR is indeed present in electro- and photo-production data and in e^+e^- annihilation. We study the recent Harvard-Cornell data [3] on inclusive electroproduction in the central region and compare with photoproduction data from ref. [4]. Inclusive particle production in e^+e^- annihilation [5,6] is already in a previous publication[7] shown to contain a strong cluster component for particle momenta of less than 1 GeV. Here we show that this cluster can be identified in <u>absolute magnitude</u> with the central ISR cluster.

Two-particle final states in elastic processes show at fixed $p_\parallel$ the same $p_\perp$ cut-off as found in inelastic many particle final states [8]. This is an indication that also two-particle final states are the decay products of a cluster intermediate state. We argue that this cluster has no quantum number dependence at the special point $p_\parallel = 0$. This is checked by comparing the $p_\perp$-distributions at $p_\parallel = 0$ of the elastic processes $\pi^\pm p \to \pi^\pm p$ and $pp \to pp$ with the charge exchange processes $\pi^- p \to \pi^0 n$ and $\gamma_V p \to \pi^+ n$. We note in particlar that in the presently measured $p_\perp$-range the 90° data for two-particle final states are well described by the cluster without any reference to a possible parton interaction.

The first important feature of the cluster model is its <u>factorization property</u>.

Consider the exclusive reaction

$$a+b \longrightarrow c_1 + \cdots + c_n \qquad (1)$$

and assume that the final state appears via an intermediate state which is completely dominated by the production of clusters. Then the cross-section factorizes into the total cross-section, σ_{tot}^{ab} , of the initial state particles (= cross-section for producing an intermediate state) and the decay probability dP that the intermediate state decays into the phase space volume $d^3p_1 \cdots d^3p_n$ in the c.m. system:

$$\frac{d\sigma}{d^3p_1 \cdots d^3p_n} = \sigma_{tot}^{ab} \frac{dP}{d^3p_1 \cdots d^3p_n} . \qquad (2)$$

Thus in this approach the appropriate quantities to consider are distributions normalized by the total cross-section.

The assumption of independent emission of the central cluster implies a further factorization of the decay probability dP in eq. (2). Let us consider a reaction where n_c central particles are produced at the total c.m. energy W via the central cluster, and where one integrates over an arbitrary number of undetected secondaries coming from all other regions of phase space. Assuming that the central cluster (cc) is emitted without correlation to the remaining part of the intermediate state we write

$$\frac{dP_{cc}}{d^3p_1 \cdots d^3p_{n_c}} = C_{n_c}(p_1, \cdots, p_{n_c})\, g(W) . \qquad (3)$$

Here the energy - independent function C_{n_c} describes the n_c particles in the central cluster and g(W) contains the rest of the secondaries. For the one-particle inclusive distribution of a secondary of momentum p coming from the central cluster we then get

$$\frac{dP_{cc}}{d^3p} = g(W) \sum_{n_c=2}^{\infty} \frac{1}{(n_c-1)!} \int d^3p_2 \cdots d^3p_{n_c}\, C_{n_c}(p, p_2, \cdots, p_{n_c}) . \qquad (4)$$

For simplicity all particles are here assumed identical.

The total probability to observe n_c central particles in the final state is given by

$$P^{tot}_{n_c} = g(W)\,\mathcal{P}_{n_c} \equiv \frac{g(W)}{n_c\,!}\int d^3p_1 \cdots d^3p_{n_c}\; C_{n_c}(p_1, \cdots, p_{n_c}) \quad . \tag{5}$$

Using the normalization (see discussion later)

$$\sum_{n_c=2}^{\infty} P^{tot}_{n_c} = 1 \tag{6}$$

eq. (4) is rewritten as (E = energy of observed particle)

$$\frac{E}{\sigma^{ab}_{tot}}\,\frac{d\sigma}{d^3p} = \langle n_{cc}\rangle\, f(p) \tag{7}$$

where $\langle n_{cc}\rangle$ denotes the constant average multiplicity of secondaries produced by the central cluster,

$$\langle n_{cc}\rangle = \sum_{n_c=2}^{\infty} n_c\,\mathcal{P}_{n_c} \Big/ \sum_{n_c=2}^{\infty} \mathcal{P}_{n_c} \tag{8}$$

and the W-independent function $f(p)$ is defined by

$$f(p) = \sum_{n_c=2}^{\infty} n_c \left(E\,\frac{d\,\mathcal{P}_{n_c}}{d^3p}\right) \Big/ \sum_{n_c=2}^{\infty} n_c\,\mathcal{P}_{n_c} \quad . \tag{9}$$

Eq. (7) is of course only relevant for that part of the phase space into which the central cluster particles decay ($p_{\parallel} = 0$, $p_{\perp} \lesssim 1$ GeV). The complete inclusive p - distribution valid in the whole phase space will consist of a sum of terms of the type (7), one for each cluster in the intermediate state.

We have thus seen that it is consistent, within the framework of independent cluster emission, to consider the inclusive one-particle distribution of a secondary coming from the central cluster without making any reference to the rest of the typical final state and to the energy W of the collision. For this conclusion to hold we do however need the normalization condition (6), which means that any intermediate state contains a central cluster. At ISR some slow increase with energy is observed in the inclusive cross-sections at 90^{o} [9].

For the pions and kaons this increase is somewhat too big to be accounted for by the rise in the total cross-section, σ_{tot}^{pp} ,and we interprete this as due to a small violation of eq. (6) which vanishes with increasing energy. The correction due to this effect is at present energies estimated to be $\lesssim$ 10% (see e.g. ref. [10] for a parametrization of the energy dependence)*).
In e^+e^- annihilation we do not expect any violation of (6). It seems here in the one-photon approximation reasonable to assume that there is always a central cluster in the intermediate state near to the origin in phase space.

In the following discussion of inclusive distributions we are mainly interested in the decay properties of the central cluster for $p_\perp \lesssim 1$ GeV at the point $p_\parallel = 0$, where we assume the function $f(p)$, eq. (9), to be cut off exponentially in $p_\perp$ +)

$$f(p_\parallel = 0, p_\perp) = C\, e^{-2 r p_\perp} \qquad (10)$$

Then we predict the following universal inclusive distribution for a hadron h produced by the central cluster in the reaction a + b → h + X:

$$\frac{E_h}{\sigma_{tot}^{ab}} \frac{d\sigma_h}{d^3p}\bigg|_{p_\parallel = 0} = N_h\, e^{-2 r_h p_\perp} \qquad (11)$$

Here the W independent normalization constant $N_h \equiv C_h \langle n_{cc}^h \rangle$ as well as the average central cluster multiplicity $\langle n_{cc}^h \rangle$ and the radius r_h depend only on the type of the detected hadron h.

The cluster distribution (11) compares for $p_\perp \lesssim 1$ GeV well with the observed distributions at the ISR from where one obtains [8,9] **)

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*) We neglect in the whole discussion the strong energy dependence of $\bar{p}$ production. This may be due to pair creation and contributes a negligible part to the total cross - section.

+) A priori there is no reason to use eq. (10) instead of the thermodynamic form $e^{-E/kT}$ with a temperature $T \approx 160$ MeV[11]. The inclusive proton data at the ISR, however, clearly prefer the form (10).

**) If nothing else is stated we use units $\hbar = c = 1$ GeV.

$r_\pi \simeq 3$, $N_{\pi^\pm} \simeq 5$, $r_K \simeq 2.5$, $N_{K^\pm} \simeq 0.3$, $r_p \simeq 2$, $N_p \simeq 0.1$. Since pion production dominates we can obtain an estimate for the constant $C_{\pi^\pm}$ from the charged multiplicity sum rule, $C_{\pi^\pm} \simeq 3.5$, which in turn leads to the following properties of the central cluster: average charged multiplicity $\langle n_{cc} \rangle_{ch} \simeq 2.9$, average central cluster mass $\langle M_{cc} \rangle \simeq 1.75$ GeV and average energy per charged central cluster particle, $\langle E_{cc} \rangle_{ch} \simeq 0.41$ GeV. Thus we conclude that central particle production at the ISR for $p_\perp \lesssim 1$ GeV proceeds via formation of a relatively light central cluster *) with an average mass of 1.75 GeV, constant average number of about 4.3 pions and with the universal pion distribution ("<u>cluster distribution</u>")

$$\frac{E_\pi}{\sigma_{tot}} \frac{d\sigma_\pi}{d^3p}\Big|_{p_\parallel = 0} \simeq 5\, e^{-6 p_\perp} \tag{12}$$

The basic contention is now that the distribution (12) appears also in other reactions.

Of special interest is the case of e^+e^- annihilation. Here it has previously been assumed [13)14)] that all secondaries come from one single cluster. In models with an approximately energy independent momentum cut-off this immediately implies (because of energy conservation) that $\frac{E}{\sigma_{tot}} \frac{d\sigma}{d^3p}$ is <u>proportional</u> to the total c.m. energy W (E, p = energy, momentum of observed particle, σ_{tot} = total hadronic e^+e^- annihilation cross-section). This feature is f. ex. observed in the thermodynamical model for $W \gtrsim 3$ GeV [13)]. The SPEAR data [5)], however, violate this prediction at low p ($p \lesssim 0.8$ GeV) in the whole measured energy range $3.0 \leq W \leq 7.4$ GeV, where $\frac{E}{\sigma_{tot}} \frac{d\sigma}{d^3p}$ is <u>energy independent</u>. This is seen on Fig. 1 where we compare the charged particle distributions from SPEAR with the contribution from the <u>central</u> cluster only, eq. (11). The full line corresponds to the estimate, see eq. (11), $\sum_h N_h \simeq N_{\pi^+} + N_{\pi^-} \simeq 10\ GeV^{-2}$ and the slope is chosen as the average radius $\langle r \rangle = \frac{1}{3}(r_\pi + r_K + r_p) = 2.5\ GeV^{-1}$. Here we assume an isotropic cluster decay.

In this discussion we have been concerned only with the small $-p$ component

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*) Direct evidence for the existence of a low mass central cluster with small charged multiplicity has recently been found at the ISR [12)].

in the $e^+ e^-$ inclusive distributions. The large- p component , which on Fig. 1 is seen as the deviation from the cluster distribution, was studied in ref. [7] and shown to have features compatible with the usual parton ideas [15].

Inclusive electro- and photoproduction is not in a trivial way compatible with the energy independent form (12). The integrated distribution for π^- photoproduction at $p_{\parallel} = 0$ is in ref. [16] shown to be consistent with a $1/\sqrt{W}$ approach to the asymptotic limit and the recently reported data [3] for electroproduction of pions at $p_{\parallel} = 0$ show a considerable energy dependence , which becomes stronger with increasing $p_{\perp}$, and the $p_{\perp}$ distribution at fixed W is inconsistent with (12) even in shape. It is,however, interesting that if these data are considered at fixed values of the missing mass M rather than at fixed W we find that the data agree both in shape and magnitude with (12) even at the very low value M = 3.1 GeV, see Figs. 2,3.*) This choice of variables is inspired by the work of refs. [8] which indicates that the cluster has a simple interpretation in the transverse position (impact parameter) plane. A way of understanding the advantage of keeping M, rather than W, fixed is the following. If we let $p_{\perp}$ increase at fixed W and $p_{\parallel} = 0$ we approach the end of phase space and we get near to the 2-particle distribution which is considerably different from the inclusive one-particle distribution. It is therefore to be expected that (12) is inappropriate for the inclusive $p_{\perp}$ distribution at fixed and low values of W. Keeping on the other hand M fixed we stay at a fixed distance to the end of phase space and with M big enough we avoid behaviours special to the end of the phase space.

We now describe our results for processes with two particles in the final state. According to our general hypothesis also these processes proceed via an intermediate state which we might again call a cluster. It is, however, clear that this cluster cannot be the typical central cluster. First of all this two-particle cluster necessarily has the total energy of the initial state and secondly it might be charged. In ref. [17] the possibility was discussed that energy dependence in two -to-two processes is related to charge flow between forward and backward hemispheres. Generalizing this result to hold in the whole kinematical region we get that charge exchange processes and elastic

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*) The data of ref. [3] are presented at fixed W. Also reported is a parametrization of the energy dependence of the normalized π^+ spectra. Since the presented π^+ and π^- data are consistent with each other and with the photoproduction data [4] for π^- production at W = 3.1 GeV we have assumed the same energy dependence of the normalized cross-sections in all cases on Figs.2,3.

processes are the same at $p_{\parallel} = 0$, where no charge transfer takes place. In other words the decay of the cluster does not depend on quantum numbers at the special point $p_{\parallel} = 0$. Although the two-particle cluster necessarily is in the tail of the mass distribution of cluster production we therefore expect that the decay is controlled by the same parameters (i.e. production radii) as those describing the typical central cluster. If the two particles coming from the cluster are produced exactly as the one particle in an inclusive process, eq. (11), without any other correlation than the necessary momentum conservation constraint, then the $p_{\perp}$-distribution for the process a + b→c + d is written as

$$\frac{1}{\sigma^{ab}_{tot}} \frac{d\sigma}{dt}\bigg|_{p_{\parallel}=0} \simeq A\, e^{-2(r_c+r_d)\,p_{\perp}} \quad . \tag{13}$$

Here we have anticipated the result that the normalization A phenomenologically as a first approximation turns out to be independent not only on a and b but also on c and d . Eq. (13) is on Figs. 4-7 checked with data for a variety of elastic and quantum number exchange processes with the normalization

$$A = 31.6 \ GeV^{-2} \quad . \tag{14}$$

On Fig. 4 we compare eqs (13,14) with elastic π^+p data. Also shown is the unnormalized cross-section $d\sigma/dt$. It is seen that normalizing with $\sigma^{\pi^+p}_{tot}$ leaves a much simpler distribution. Not shown are the elastic π^-p data which however compare very well with the π^+p data. The rather poor K^+p elastic data at 90° are consistent with eqs. (13,14). Elastic pp data are shown on Fig. 5.

To illustrate that the cluster decay at $p_{\parallel} = 0$ is really independent on the initial state and on the charges of the final state particles we show on Figs. 6,7 the normalized cross-sections for $\pi^-p\to\pi^0n$ *) and $\gamma_V p\to\pi^+n$ compared with eqs. (13,14).

We note that in all two-particle cases, even at large $p_{\perp}$, there seems to be no need for the power behaviour of the type $p_{\perp}^{-N}$ which is usually associated with parton interactions [21].

To summarize we have shown that not only for inclusive distributions but also for two-particle final states the simple idea of cluster emission gives a good description of central particle production.

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*) For simplicity we neglect here that eq. (13) due to time reversal invariance should be symmetric in initial and final state labels. Symmetrizing the normalizing total cross-section introduces corrections of the order of $\lesssim$ 15%.

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Figure Captions

Fig. 1: Normalized inclusive charged particle distributions in e^+e^- annihilation compared with the cluster distribution as discussed in the text. Data from ref. [5].

Fig. 2: Normalized data on $\gamma_v p \to \pi^+ X$ [3] compared with the cluster distribution, eq. (12).

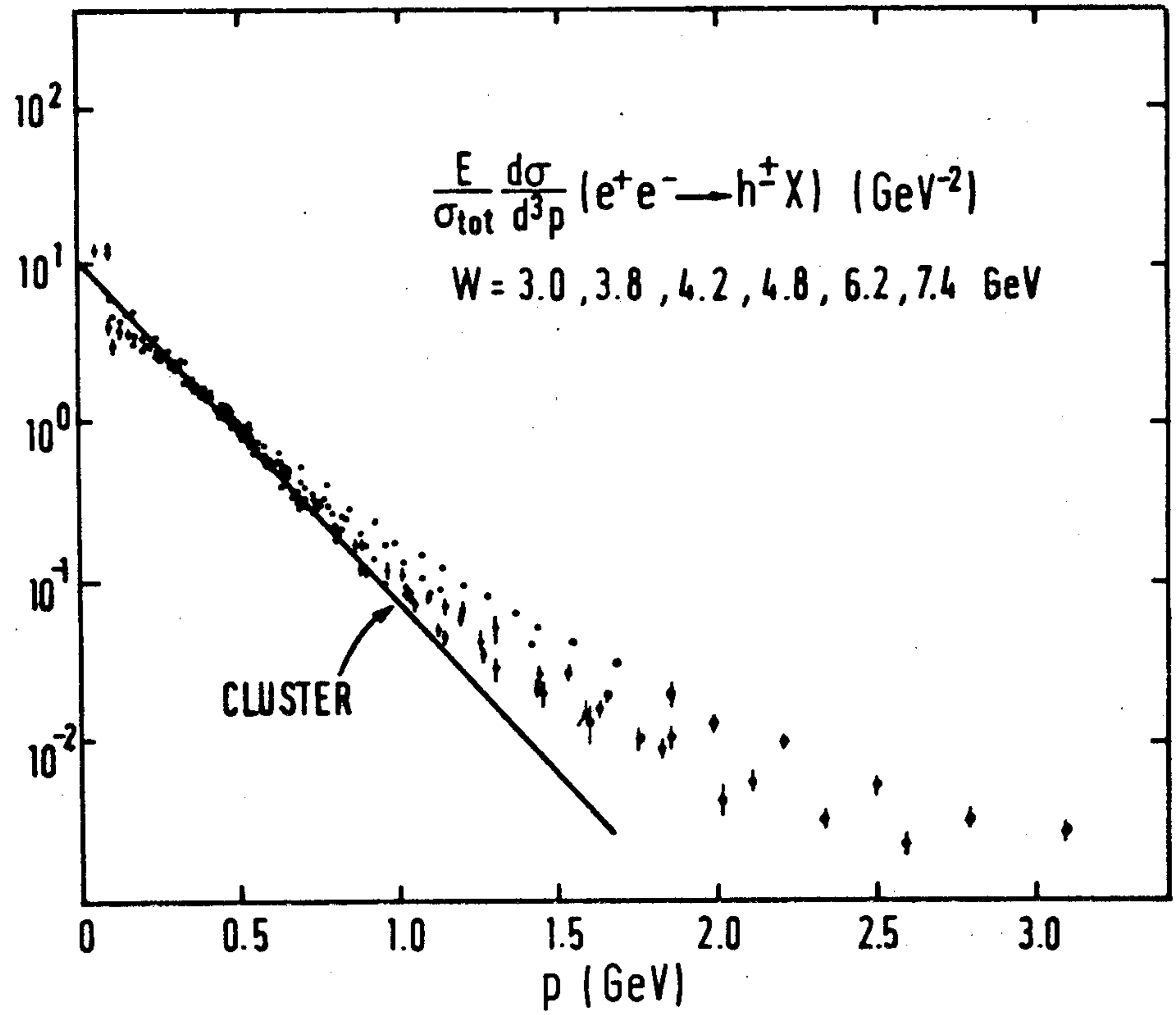
Fig. 3: Normalized data on $\gamma_v p \to \pi^- X$ at $Q^2 = 1.2$ [3] and at $Q^2 = 0$ GeV^2 [4] compared with the cluster distribution, eq. (12).

Fig. 4: Normalized elastic $\pi^+ p$ data [18] compared with the cluster distribution, eqs. (13,14). The grey band indicates the unnormalized $d\sigma/dt$.

Fig. 5: Normalized elastic pp data [19] compared with the cluster distribution, eqs. (13,14).

Fig. 6: Normalized πN charge exchange data [18] compared with the cluster distribution, eqs. (13,14).

Fig. 7: Normalized data on $\gamma_v p \to \pi^+ n$ compared with the cluster distribution, eqs. (13,14). The normalizing total cross-section was taken from ref. [20].



$\frac{E}{\sigma_{tot}}\frac{d\sigma}{d^3p}(e^+e^- \to h^\pm X)$ (GeV^{-2})
W = 3.0 , 3.8 , 4.2 , 4.8 , 6.2 , 7.4 GeV
CLUSTER
10^2
10^1
10^0
10^{-1}
10^{-2}
0
0.5
1.0
1.5
2.0
2.5
3.0
p (GeV)

FIG. 1

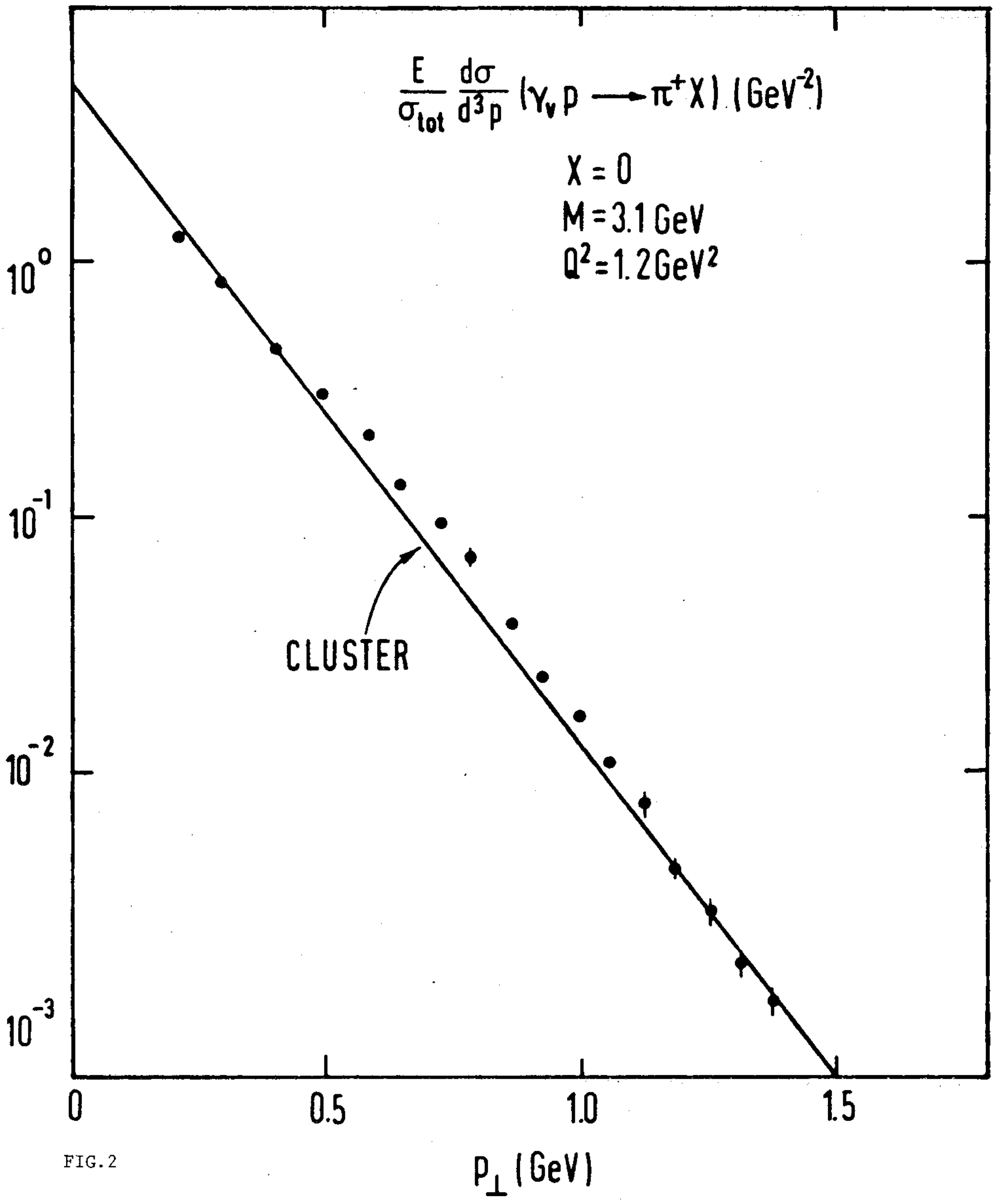
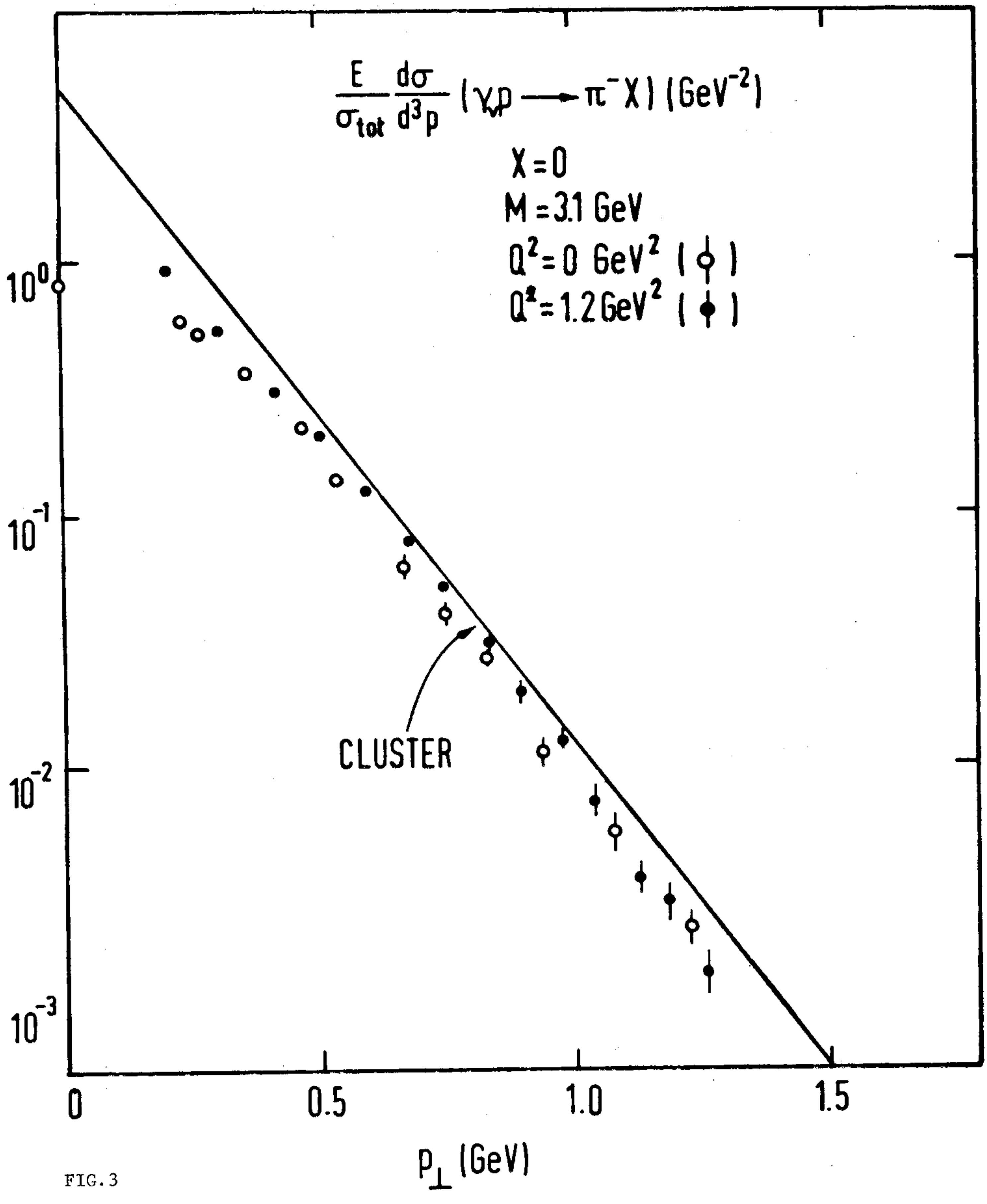
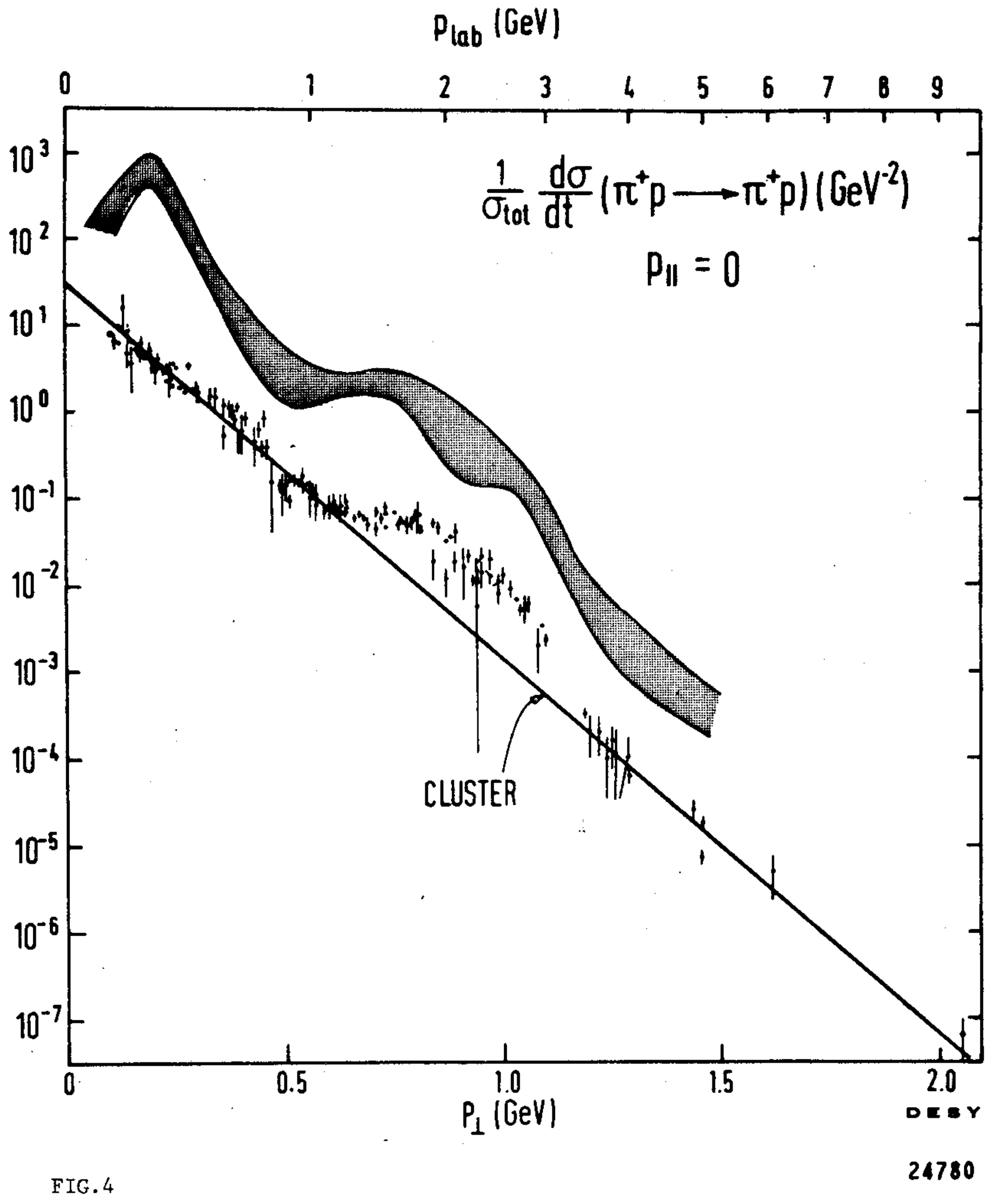

$\frac{E}{\sigma_{tot}} \frac{d\sigma}{d^3p} (\gamma_v p \longrightarrow \pi^+ X)$ (GeV^{-2})
X = 0
M = 3.1 GeV
Q^2 = 1.2 GeV^2
CLUSTER
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.5
1.0
1.5
$p_\perp$ (GeV)

FIG.2



$\frac{E}{\sigma_{tot}} \frac{d\sigma}{d^3p} (\gamma_v p \longrightarrow \pi^- X)$ (GeV^{-2})
X = 0
M = 3.1 GeV
Q^2 = 0 GeV^2
Q^2 = 1.2 GeV^2
CLUSTER
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.5
1.0
1.5
$p_\perp$ (GeV)

FIG.3



p_{lab} (GeV)
0
1
2
3
4
5
6
7
8
9
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dt} (\pi^+ p \longrightarrow \pi^+ p)$ (GeV^{-2})
$p_{\parallel} = 0$
CLUSTER
0
0.5
1.0
1.5
2.0
$p_{\perp}$ (GeV)
DESY
24780

FIG.4

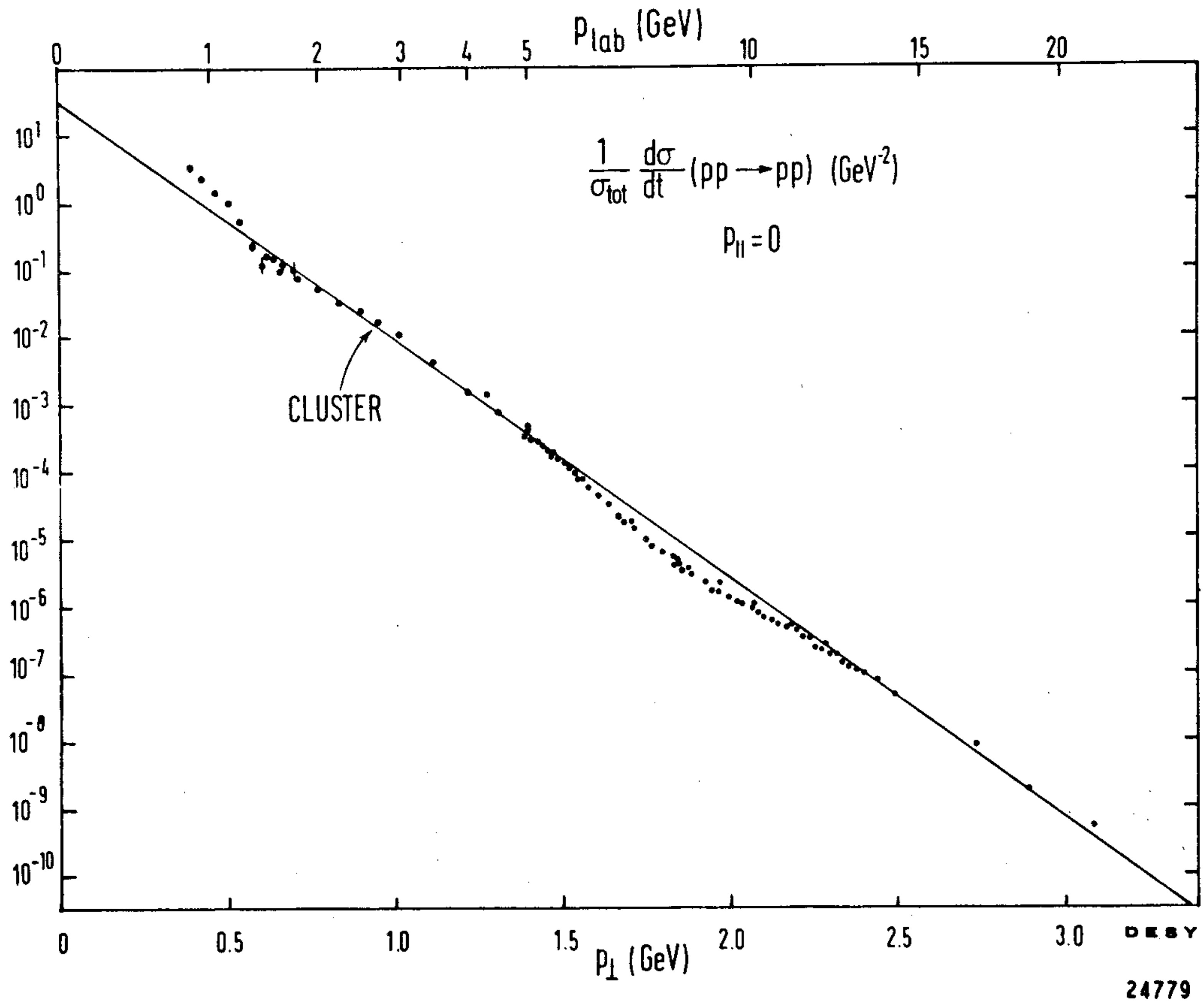
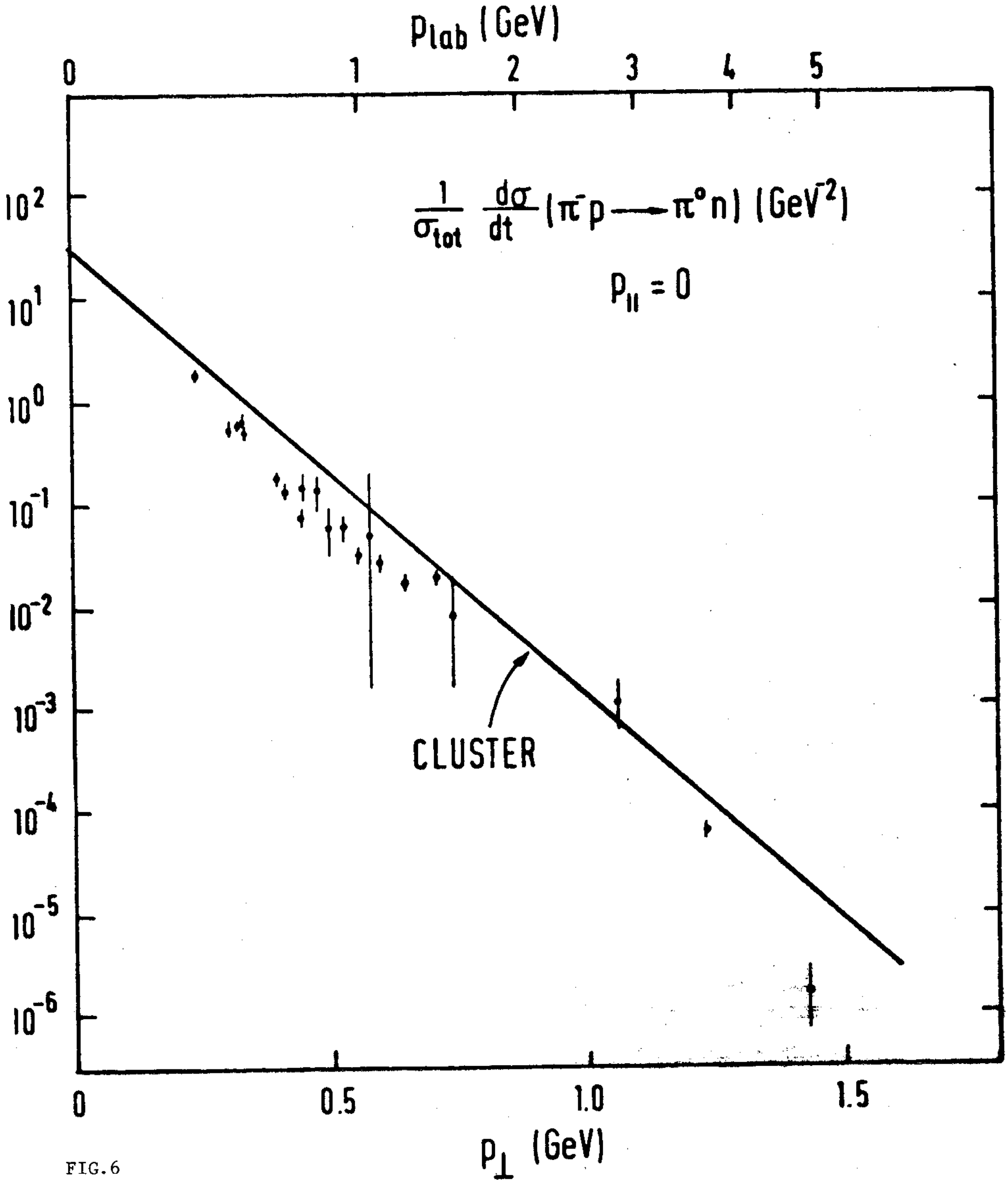
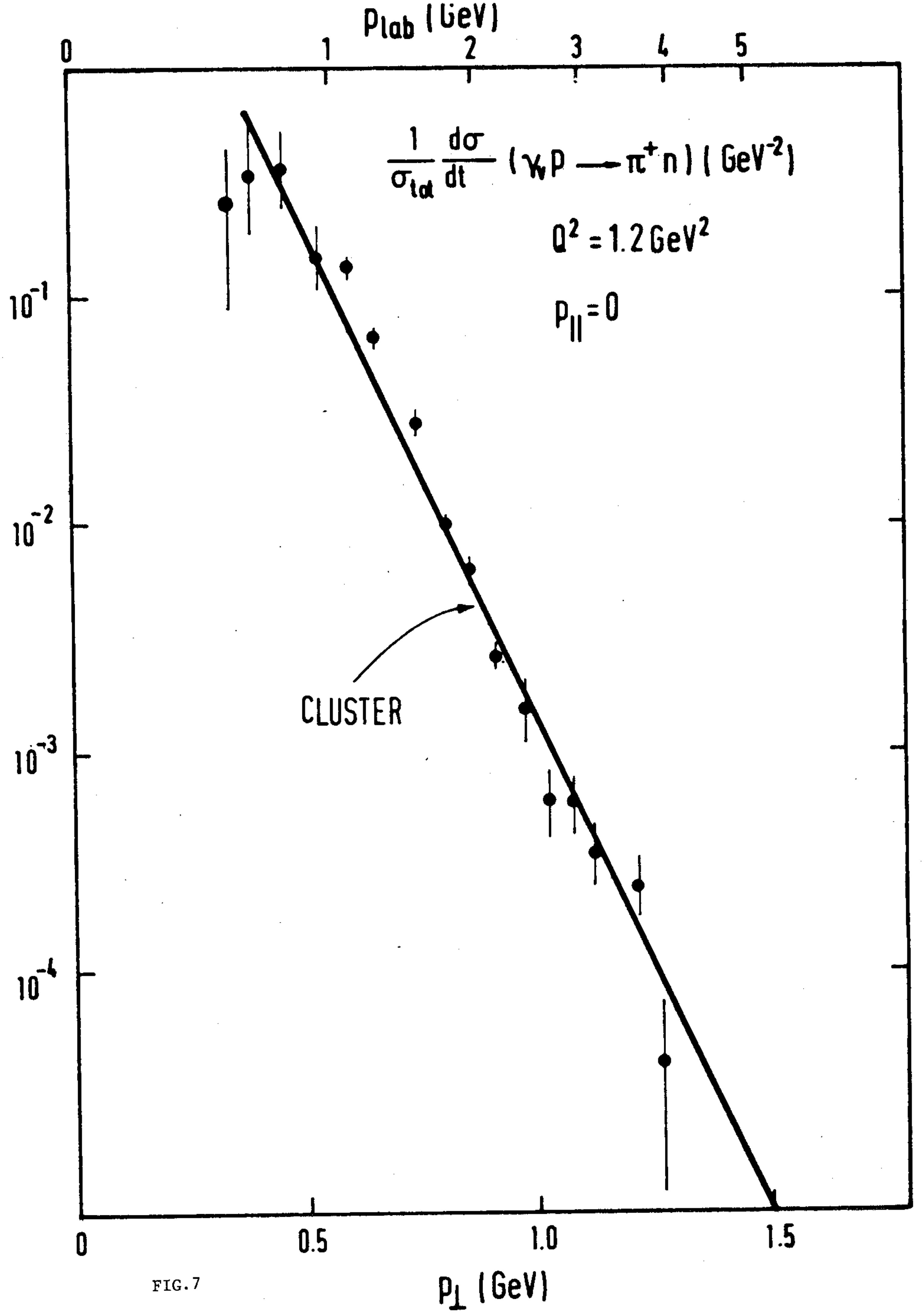

p_{lab} (GeV)
0
1
2
3
4
5
10
15
20
$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dt}(pp \rightarrow pp)$ (GeV^{-2})
$p_{\parallel} = 0$
CLUSTER
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
0.5
1.0
1.5
2.0
2.5
3.0
$p_{\perp}$ (GeV)
DESY
24779

FIG.5



p_{lab} (GeV)
0
1
2
3
4
5
$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dt} (\pi^- p \longrightarrow \pi^0 n)$ (GeV^{-2})
$p_{\parallel} = 0$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
CLUSTER
0
0.5
1.0
1.5
$p_{\perp}$ (GeV)

FIG.6



p_{lab} (GeV)
0
1
2
3
4
5
$\frac{1}{\sigma_{tot}}\frac{d\sigma}{dt}(\gamma_v p \to \pi^+ n)$ (GeV^{-2})
$Q^2 = 1.2\ GeV^2$
$p_{\parallel} = 0$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
CLUSTER
0
0.5
1.0
1.5
$p_{\perp}$ (GeV)

FIG.7