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LETTER OF INTENT

to carry out a programme of physics at the S.P.S. to study the electro-magnetic interactions using muons of energy up to 250 GeV

by

The British, French and German and CERN Muon Collaboration

INTRODUCTION

A collaboration has been set up to pursue a programme of physics using a muon beam at the S.P.S. The muon has been chosen as an electromagnetic probe to study the structure of the nucleon because it has been shown that intense beams of up to 10^8 $\mu^{\pm}$/pulse can be produced at the S.P.S., the required purity of the beam can be easily obtained using a hadron filter, and in addition it is highly polarized. In contrast to hadron-hadron scattering, lepton induced reactions have the important feature that it is possible to vary the energy and momentum transfer to the target hadron over a very wide range.

The interest in the field of electromagnetic interaction of hadrons has grown rapidly since the initial results from SLAC showed that the nucleon structure functions W_1 and νW_2 are functions of ν/q^2, rather than ν and q^2 separately(1). It is clearly of interest to determine whether this scaling behaviour still holds in the much larger region of ν and q^2 defined by muons of energy up to 250 GeV. There are many model predictions to explain the behaviour of the cross sections for inclusive, exclusive and multi-particle reactions at high energies and large q^2 for proton, neutron and polarized targets.

The muon can also be used at these energies to test Q.E.D. using the processes of wide angle bremsstrahlung and trident production, and in particular provides a method of searching for heavy leptons and bosons which only couple to the muon. Tests of two photon exchange processes and tests relevant to μ/e universality can be carried out.

At present, two muon experiments are under way at N.A.L.(2,3), and therefore the members of the collaboration feel that they should be in a position to carry out second generation exeriments. It is therefore proposed that the muon beam line should be installed in the North Area since this would allow a high quality muon beam to be set up with few restrictions on space and shielding requirements. We propose that an experimental facility should be set up in the North Area consisting of a forward spectrometer to detect the scattered muon and the forward produced hadrons in conjunction with a detector which is capable of detecting particles at large angles with respect to the primary muon beam. This facility should allow experiments to begin at the end of 1977 when the first beams are brought into the North Area. The present members of this collaboration are not actively engaged in any proposal for an S.P.S. experiment in the West Area.

2. PHYSICS INTEREST

2.1 Muon Proton Scattering

a) $\mu^{\pm} + p \rightarrow \mu^{\pm} +$ anything

(outgoing muon measured)

One of the main interests in studying μ-nucleon interactions comes from deep inelastic scattering. The scaling of the structure functions W_1 and νW_2 can be tested with incident energies up to 250 GeV, and values of ω up to 200. Figure 1 shows contours on the q^2, ν plot for counting rates per 100 hours for 10^8 muons/pulse at 200 GeV in bins of $\Delta q^2 =$ 1 GeV^2 and $\Delta W = 1$ GeV. Cross sections can be measured up to $q^2 = 80\ \text{GeV}^2$ if the virtual photon total cross section behaves like $1/q^2$. If scaling persists, then the shape of the limiting scaling function at high values of ω is important. A measurement of the ratio $R = \sigma_L/\sigma_T$ up to high values of ν and (or) q^2 is important in order to distinguish between quark-parton[(4)] and generalised vector dominance[(5)] models.

b) $\mu^{\pm} + p \rightarrow \mu^{\pm} + $ hadrons

(muon+number and charge of hadrons measured)

One of the first questions to be answered in the detection of final state hadrons is how the multiplicity of hadrons varies with energy and momentum transfer, i.e. does it depend on ω only like $\log \omega$ as for example, in parton models[6]. Another interesting question is the relative size of the contributions from i-prong charged events ($i = 1, 3, 5$ etc. ...).

c) $\mu^{\pm} + p \rightarrow \mu^{\pm}$ + one or more hadrons + anything

(muon + hadron(s) completely measured)

Inclusive distributions of $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ etc. in $x = p^{*}_{\parallel} / p^{*}_{max}$ and $p_{\perp}$ have to be studied as functions of q^2 and W or ω. The measurements can be used to study the strong interaction properties of virtual photons by comparison with those of real photon and hadron-induced reactions. Figure 2 shows as an example, inclusive π^{+} counting rates for $E_{\mu} = 200$ GeV at a large value of q^2 and W. These have been obtained by extrapolation from existing measurements at presently available energies assuming that the normalized invariant cross section $\frac{1}{\sigma_{tot}} \frac{E}{p^{*}_{max}} \frac{d^2\sigma}{dx\, dp_{\perp}^2}$ and the slope in $p_{\perp}$ are independent of q^2 and W.

All measurements which are possible at existing electron accelerators are at values of $q^2 < 3$ GeV^2 and $W < 5$ GeV[7], and do not permit discrimination between many different models of deep inelastic scattering. Particle correlations, inclusive production of pairs of $\pi^{+}\pi^{-}$, $K^{+}K^{-}$, $\bar{p}p$ and the dependence on the invariant mass of these pairs, can give very useful information towards understanding of deep inelastic scattering.

d) $\mu^{\pm} + p \rightarrow \mu^{\pm}$ + exclusive channel

(muon + hadron final state completely measured)

The exclusive channels $\pi^+ n$, $\rho^o p$, $\Delta^o \pi^+$, $\Delta^{++} \pi^-$, $K^+ \Lambda(\Sigma)$ have revealed interesting effects in the presently accessible kinematical range(7). Some of the reactions, in particular non-diffractive ones, seem to have contributions from longitudinal photons. There are indications that the diffractive reaction $\rho^o p$ decreases faster with q^2 than the total inelastic cross section. It is interesting to see if this general behaviour continues to higher values of q^2 and ν and if the cross section is independent of energy for diffractive processes and behaves like W^{-4} for non-diffractive processes. Figure 3 shows the variation in counting rate in the q^2, ν plane for the reactions $\rho^o p$ and $\pi^+ n$ assuming the energy dependence given above for the diffractive and non-diffractive processes, and that $\sigma(\pi^+ n) \propto \sigma_{tot}(q^2)$ and $\sigma(\rho^o p) \propto \frac{1}{(m_\rho^2 + q^2)^2}$. The rates are integrated over the momentum transfer t, the azimuthal angle around the virtual photon direction and the azimuthal angle of the scattered muon around the incident muon direction.

It is also interesting to study events with higher multiplicities to look for higher mass mesons, e.g. ρ' etc.

2.2. Muon Neutron Scattering

Since the structure functions for the neutron and proton are different, it is interesting to compare the above proton reactions with those from neutron targets. There are sum rule predictions(8) which relate muon scattering cross sections from neutrons and protons with those of corresponding neutrino cross sections, which will have to be tested when neutrino measurements are available.

2.3 $\mu + A \rightarrow \mu$ + anything

(muon completely measured)

Present electron nucleus scattering experiments[9] show that there is no shadowing of the total virtual photon cross section contrary to photoproduction experiments. This situation may change at higher energies as predicted for example by the generalized vector dominance model[10]. Thick targets can be used with muons to enhance the counting rate at very large q^2 enabling a comparison to be made with neutrino reactions.

2.4 $\mu(\uparrow) + p(\uparrow) \rightarrow \mu$ + hadrons

The polarization of the muon in combination with a polarized proton target enables a sensitive search to be made for spin dependent effects as predicted by different models[11] and, for example, allows a sensitive test on the quantum numbers of the nucleon constituents. The spin dependent cross sections are more sensitive to the different models than the spin independent cross section. For bin sizes in W and q^2 three times those shown in Fig. 1 and for 100 hours of running, asymmetries can be determined to within ±0.1 up to a $q^2 \approx 20$ $(\mathrm{GeV/c})^2$ using a 2 litre polarized target. It is also possible to gain new information from exclusive and inclusive hadron production measurements off a polarized target[12].

2.5 2-Photon Exchange, Q.E.D. Tests and e/μ Universality

Tests on 2 photon exchange contributions can be performed by a comparison of μ^+ and μ^- scattering, which is sensitive to the real part of the one photon-two photon exchange interference term. The imaginary part can be obtained from polarization measurements. These tests can be extended to larger values of q^2 or to smaller values of the scattering angle in the presently explored range of q^2.

The validity of Q.E.D. can be tested via wide angle bremsstrahlung for spacelike and timelike lepton propagators up to masses of the virtual lepton of 5 GeV[13]. This process allows a search for heavy leptons to be made. Counting rates for the W.A.B. process are illustrated in fig. 4. Additional tests on Q.E.D. are possible by measuring lepton pairs in addition to the scattered muon since the yield for this reaction is sufficiently large for lepton pairs of mass up to 3 GeV due to the high incident energy[13]. Heavy mesons which couple only to the muon can be detected by looking at Q.E.D. processes.

Experiments, which have been carried out so far, show no significant difference between electron and muon scattering[14]. However, the statistical accuracy can be greatly improved compared with existing experiments due to the much higher muon fluxes. In addition, a much wider range of q^2 and ν can be covered.

3. BEAM REQUIREMENTS

Our proposal requires a muon beam which will give high intensity, low hadron contamination ($<10^{-6}$) and a low halo. Studies have been carried out by groups from CERN, DESY and DNPL and were initially presented at the E.C.F.A. meeting at Tirrenia in 1972[15].

Present Beam Design

For E_μ = 200 GeV, E_p = 400 GeV, 10^{12} interacting protons/pulse, ~7 pulses/min.

a) Intensity: $\sim 1.0 \times 10^8$ for $\left(\frac{\Delta E}{E}\right)_\mu = \pm 10\%$.

b) Beam cross section at target: $\sim 10 \times 10\ \text{cm}^2$

c) Divergence at target: ±3mrd. horizontally (due to momentum analysis)

±0.5 mrad. vertically

d) Halo: ~3% of main muon beam in 4 x 4 m^2.

<0.2% of main muon beam within a circle of 0.5 m. radius around beam.

e) Polarization: 75% for a momentum bite of 10% in both pion and muon beams.

90% for a momentum bite of 4%.

f) Length of decay section: ~650 m.

g) Total beam length: ~1.1 km.

h) Max. energy: 250 GeV (1/3 of muon intensity at 200 GeV).

One of the most critical properties of the muon beam is the muon halo and this must be made as small as possible.

In order to obtain a resolution on the incident muon of the order of 0.1% (F.W.H.M.) as outlined below, it is necessary to have, for example, detectors of 0.2mm spatial resolution 10 metres on either side of a two degree bending system. A resolution of 0.3 mm has been achieved[16] and further development is still possible. The question of the operation of these detectors in high beam intensities is under study, but it is certainly possible to use scintillation counter hodoscopes in experiments where beam momentum resolution is not critical, especially in regions of large q^2.

4. EXPERIMENTAL FACILITIES

a) Basic Requirements

The apparatus should be able to detect the scattered muon over a large range of longitudinal momentum (15-200 GeV) and scattering angles of up to 10°. Here, the maximum transverse momentum of the muon is ≈ 5 GeV (fig. 1). The apparatus should be capable of distinguishing a muon from a hadron and triggering on the scattered muon. The system should be capable of measuring hadrons with longitudinal momentum up to about 200 GeV and with transverse momentum up to several GeV; particle identification should be possible up to 100 GeV. It is necessary to have a determination of the total hadron centre of mass energy and of the missing mass better than m_{π} for the exclusive channels outlined in section 2.1.d, since it is essential at these higher energies to ensure that one or more pions, e.g. π^{o}, have not been produced in association with the exclusive channels. This requires that the incident and scattered muon as well as the detected hadrons are well determined. To achieve a resolution of less than m_{π} a momentum resolution of 0.1% is necessary for measurements with primary energies up to 120 GeV. With higher primary energies up to 250 GeV a momentum resolution of 0.2% is sufficient, if W is restricted in this case to values greater than 5 GeV. Radiative corrections broaden the missing mass resolution for muon scattering only slightly ($<m_{\pi}$). For the inclusive reactions outlined in section 2 only a modest resolution is required.

b) The Forward Spectrometer

The forward spectrometer will consist of a series of magnets of identical dimensions distributed along the primary beam. As the momentum of the particle increases, it has a smaller scattering angle with respect to the incident beam direction and therefore sees more magnetic field. Spectrometers of this type have already been considered for muon experiments[17] and for hadron induced reactions[18]. A possible arrangement of the forward spectrometer is illustrated in fig. 5, where the magnetic length and the length of the lever arms have been optimised with respect to magnet costs, and space for Cerenkov counters has been obtained. A rough estimate of the different momentum ranges in which hadrons (π, K and p) can be separated using threshold Cerenkov counters is also illustrated in fig. 5.

The spectrometer consists of three stages adapted to the momentum ranges indicated in fig. 5 and in order to achieve the required resolution, each trajectory is measured at at least four positions by sets of chambers W_1 - W_8 giving spatial resolution of 0.15 mm. The angular acceptance of the spectrometer is approximately ±4.5 degrees in the vertical and ±9 degrees in the horizontal plane. The magnetic length of the three sections are 2,4 and 8 Tm and the acceptances of the three stages in the q^2, ν plane with the limitation of $\Delta W < m_\pi$ are shown in fig. 6. However, without this limitation, the acceptance in ν and q^2 is that of fig. 1. Photons (π^o) can be identified using shower hodoscopes (S) and the hadrons are absorbed in the iron of the magnets with iron defining apertures and in the iron at the end of the spectrometer. The H hodoscopes may be used to define the muon trajectories through the iron.

A possible muon trigger for scattering between 0.5 to 9.0 degrees is defined by a double coincidence $(T_i + T_{i+3})$ i = 1, 2, 3 among the hodoscopes T_1 to T_6. The number of events detected by this system is approximately 200 events per 10^8 incident muons. Triggers from pions produced in the target decaying before reaching absorber could be suppressed by requiring only one muon in the trigger.

Accidental events will be reduced by the use of halo veto counters. Another source of spurious triggers is muon-electron scattering. Because the muon is scattered by less than 5 milliradians, this trigger can be eliminated by requiring a minimum vertical scattering angle.

c) Large Angle Detector

The large angle detector should provide momentum analysis for particles which do not enter the forward spectrometer. Two possible magnetic systems have been considered - a solenoid, giving a field parallel to the beam direction and a dipole magnet, giving a transverse field direction.

A dipole magnet has been chosen for the target detector since most of the particles outside the acceptance of the forward spectrometer have $p_{\parallel} > p_{\perp}$. Furthermore, the solenoid, although offering in principle, a direct measurement of $p_{\perp}$ imposes limitations on detector space for a given cost and does not lend itself easily to particle identification. The transverse field bends the low momentum particles away from the forward spectrometer, and facilitates the use of lever arms for precise momentum measurements.

The approximate size of the usable field (1-1.5 T) volume should be 2 x 2m^2 with a gap of 1 m giving an energy determination of for example ~1% at 3 GeV. A large C-type magnet with the beam entering through a hole in the return yoke appears to satisfy most of the detection requirements. Trajectories will be measured by wire chambers inside and outside the field volume. In addition, the magnet should have sufficiently free access over a large fraction of 4π for particles to enter Cerenkov detectors, dE/dx and time of flight counters. The magnet should be designed in such a way that it will be possible to insert other devices when required, e.g. streamer chamber.

d) Polarized Target

The collaboration proposes that a large volume polarized target (2 litres) is built, which is capable of being polarized parallel and anti-parallel to the incoming beam direction. The physics which can be done with the polarized muon beam and polarized target combination is extremely interesting and could be one of the early experiments.

The construction and design of such a target is under consideration and various schemes have been proposed to overcome the severe technical problems which are inherent in the manufacture of a large target.

5. CONCLUSIONS

In order to be in a position to start the experimental programme outlined above in 1977 in the North Area the muon collaboration requires:

a) A high quality muon beam.

b) A magnetic spectrometer to detect particles in a forward cone of 10 degrees with very good momentum resolution.

c) A vertex detector (dipole magnet) for particles produced at large angles.

d) A large volume polarized target.

6. EQUIPMENT REQUIRED FROM CERN

The muon collaboration requests from CERN:

a) The muon beam.

b) The magnets for the forward spectrometer.

c) Participation in the development of a large volume polarized target.

The collaboration will provide the remainder of the equipment. This includes the entire detection system, electronics, computers, etc., and the dipole magnet for the large angle detector. Discussions are underway to organize the sharing of responsibility for this equipment.

FIGURE CAPTIONS

Fig. 1 Kinematical range in q^2 and ν accessible with 10^8 μ/pulse and 200 GeV muons incident on a 1 metre H_2 target. For the counting rates fits to existing electron and photoproduction data have been used (19).

Fig. 2 Inclusive counting rate of pions as function of $x = p^*_\mu / p^*_{max}$ for E_μ = 200 GeV, W = 16 GeV and q^2 = 35 GeV^2, integrated over $p_\perp$. The scale of longitudinal (with respect to virtual photon) laboratory momentum is also indicated. For the calculation of the counting rate the inclusive invariant structure function $F(x, p_\perp)$ was used as measured at present energies (20) and the total cross section from (19).

Fig. 3 Counting rates for the reactions $\gamma_V p \to \pi^+ n$ and $\gamma_V p \to \rho^o p$ in the q^2, ν plane with assumptions as described in the text.

Fig. 4 Counting rates for the reaction $\mu p \to \mu p \gamma$ as a function of the invariant mass $M(\mu\gamma)$.

Fig. 5 Schematic layout of forward spectrometer.

Fig. 6 Approximate acceptance in q^2 and ν of the three stages of the forward spectrometer with the resolution in the total hadronic mass $\Delta W < m_\pi$ for E_μ = 200 GeV on the left side and the extension to E_μ = 250 GeV on the right side. Section 1 corresponds to the section with the last four magnets of the spectrometer.

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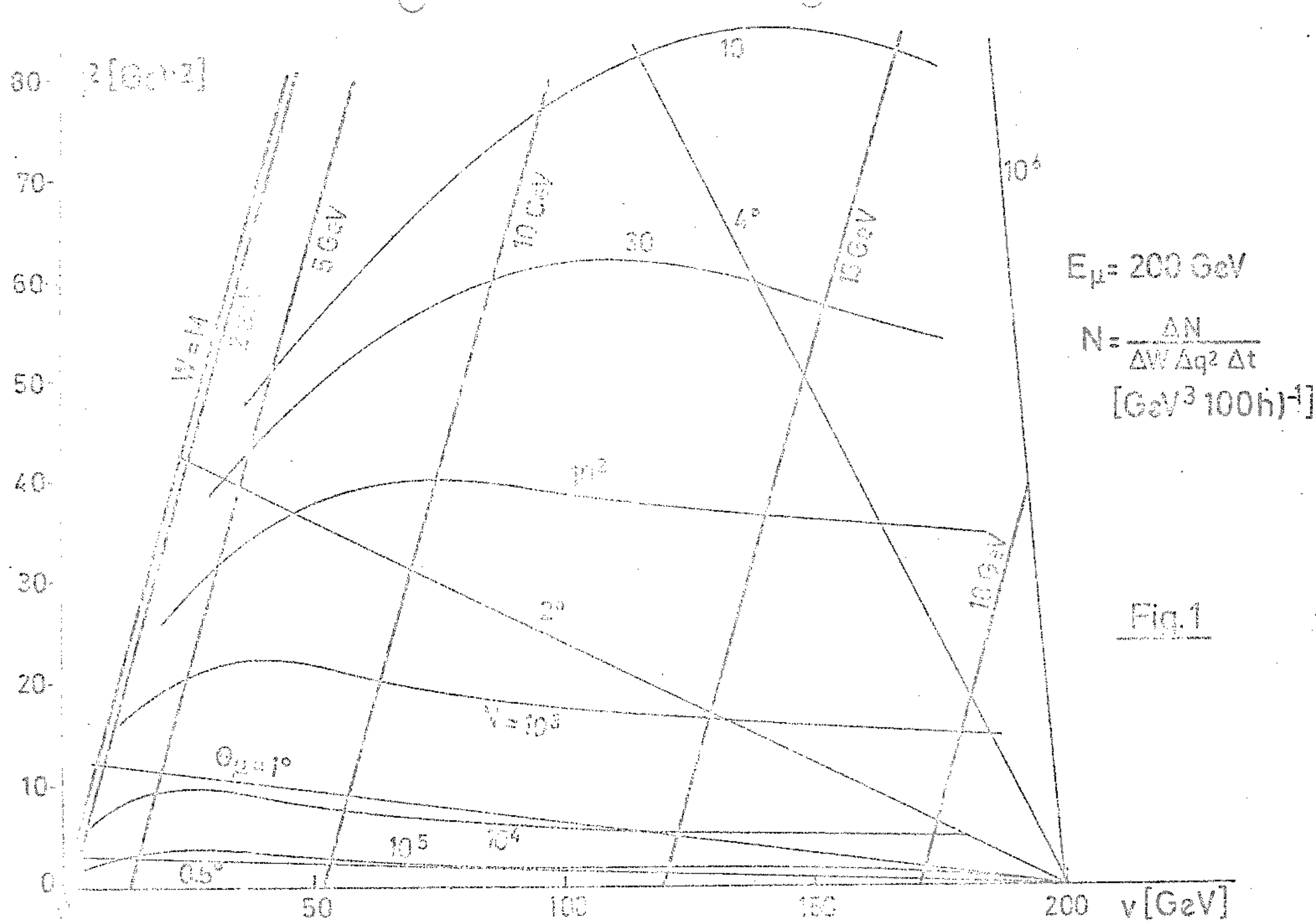
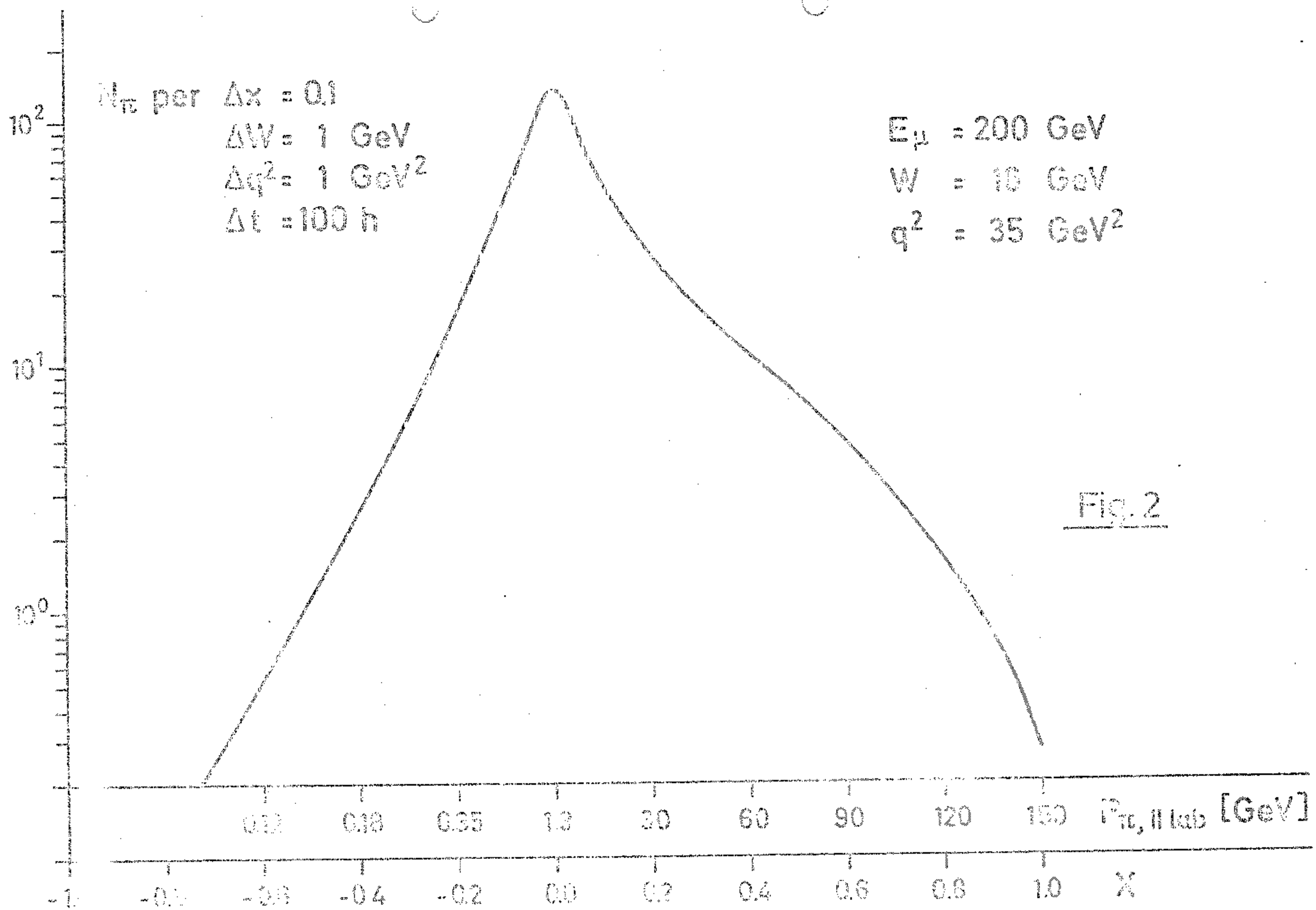


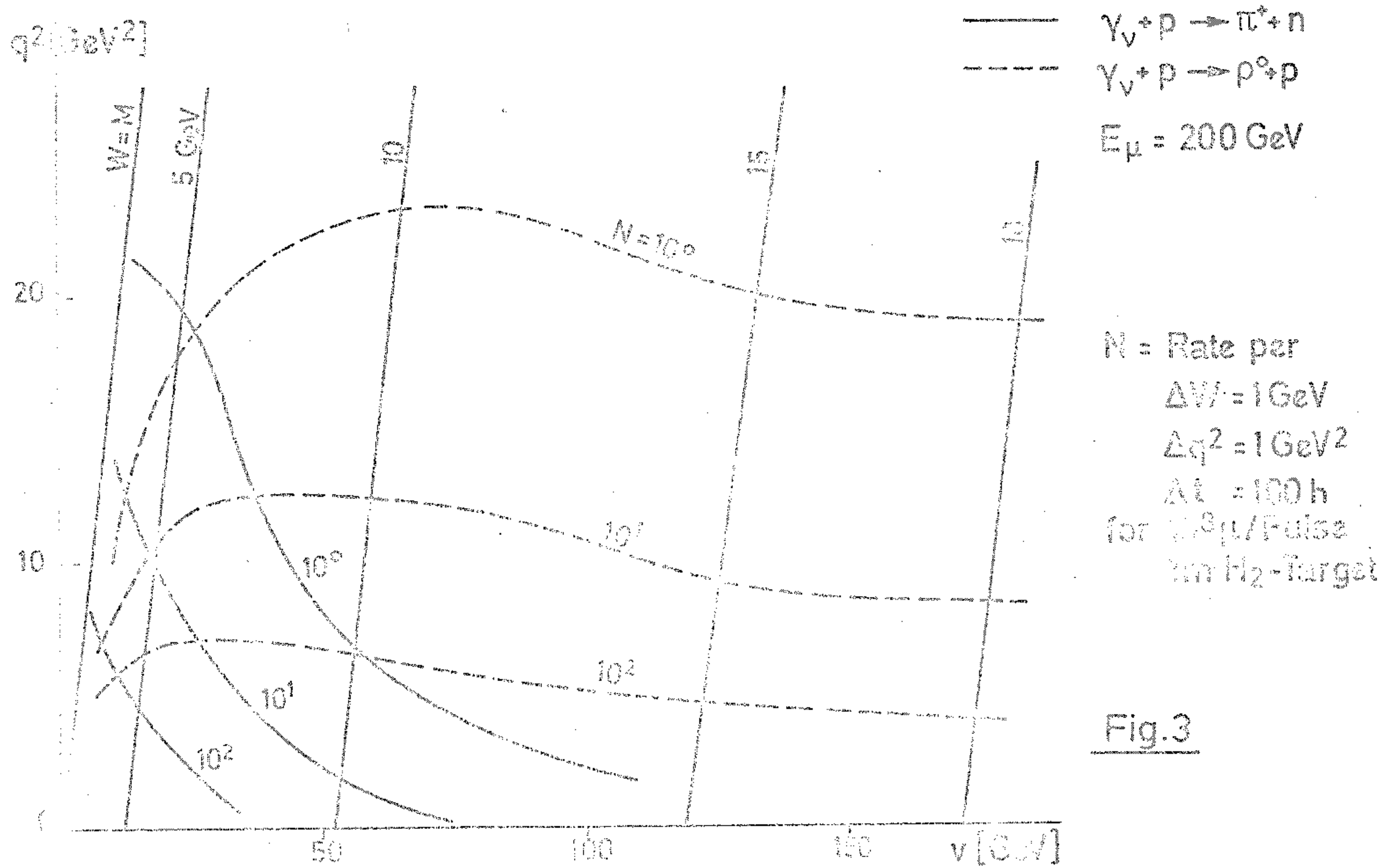
E_μ = 200 GeV
N = ΔN / (ΔW Δq² Δt)
[GeV³ 100h)⁻¹]
ν [GeV]
0
50
100
150
200
10-
20-
30-
40-
50-
60-
70-
80-
W = M
5 GeV
10 GeV
15 GeV
19 GeV
10
30
10⁴
4°
2°
N = 10³
10⁴
10⁵
0.5°

Fig. 1



N_π per Δx = 0.1
ΔW = 1 GeV
Δq^2 = 1 GeV^2
Δt = 100 h
E_μ = 200 GeV
W = 16 GeV
q^2 = 35 GeV^2
10^2
10^1
10^0
0.18
0.35
30
60
90
120
150
$P_{\pi,\parallel lab}$ [GeV]
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
x

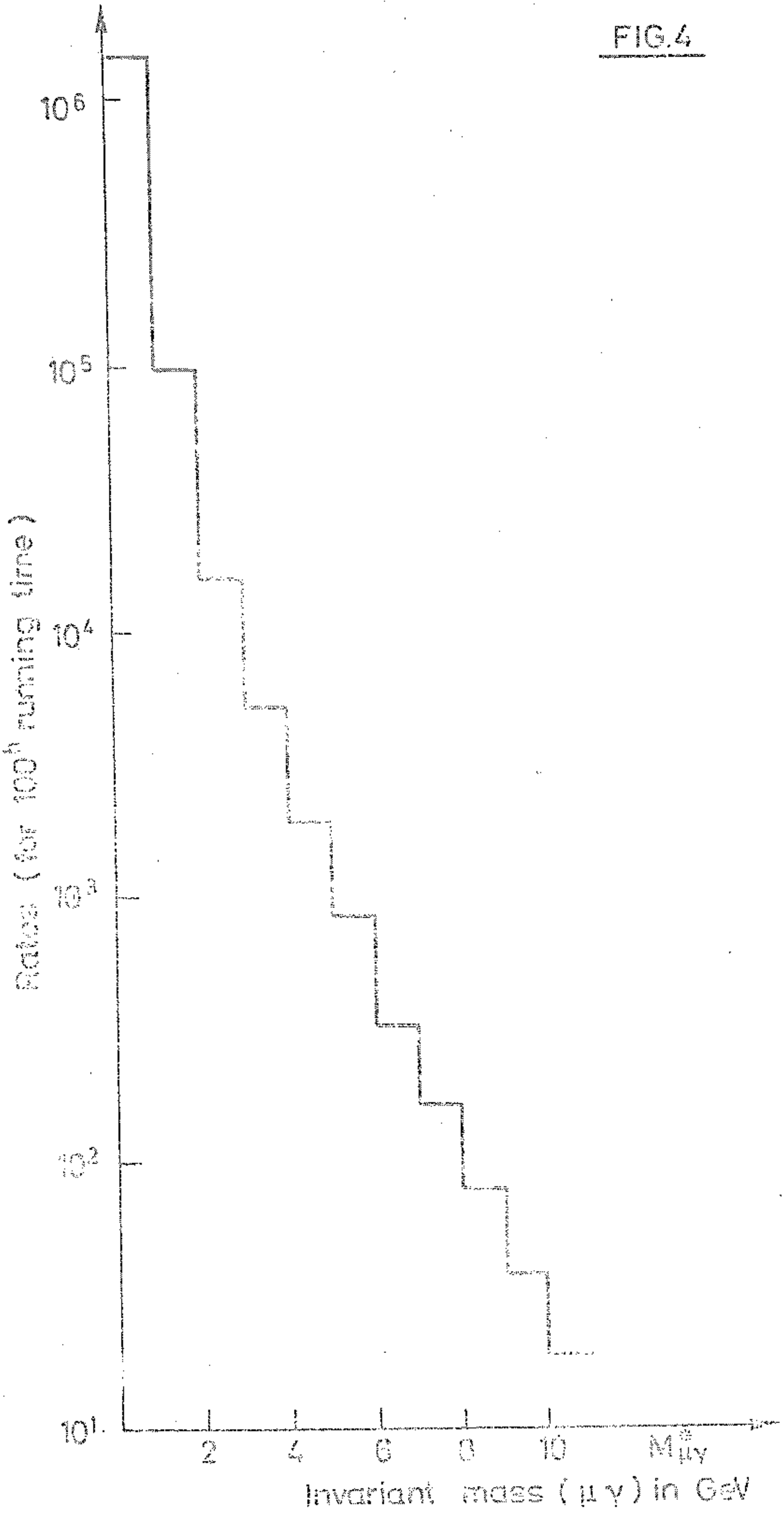
Fig. 2



q² [GeV²]
20
10
50
100
150
ν [GeV]
W = M
5 GeV
10
15
N = 10⁰
10¹
10²
10⁰
10¹
10²
γ_v + p → π⁺ + n
γ_v + p → ρ⁰ + p
E_μ = 200 GeV
N = Rate per
ΔW = 1 GeV
Δq² = 1 GeV²
Δt = 100 h

Fig.3

FIG.4



Rates (for 100h running time)
10^6
10^5
10^4
10^3
10^2
10^1
2
4
6
8
10
M*μγ
Invariant mass (μγ) in GeV

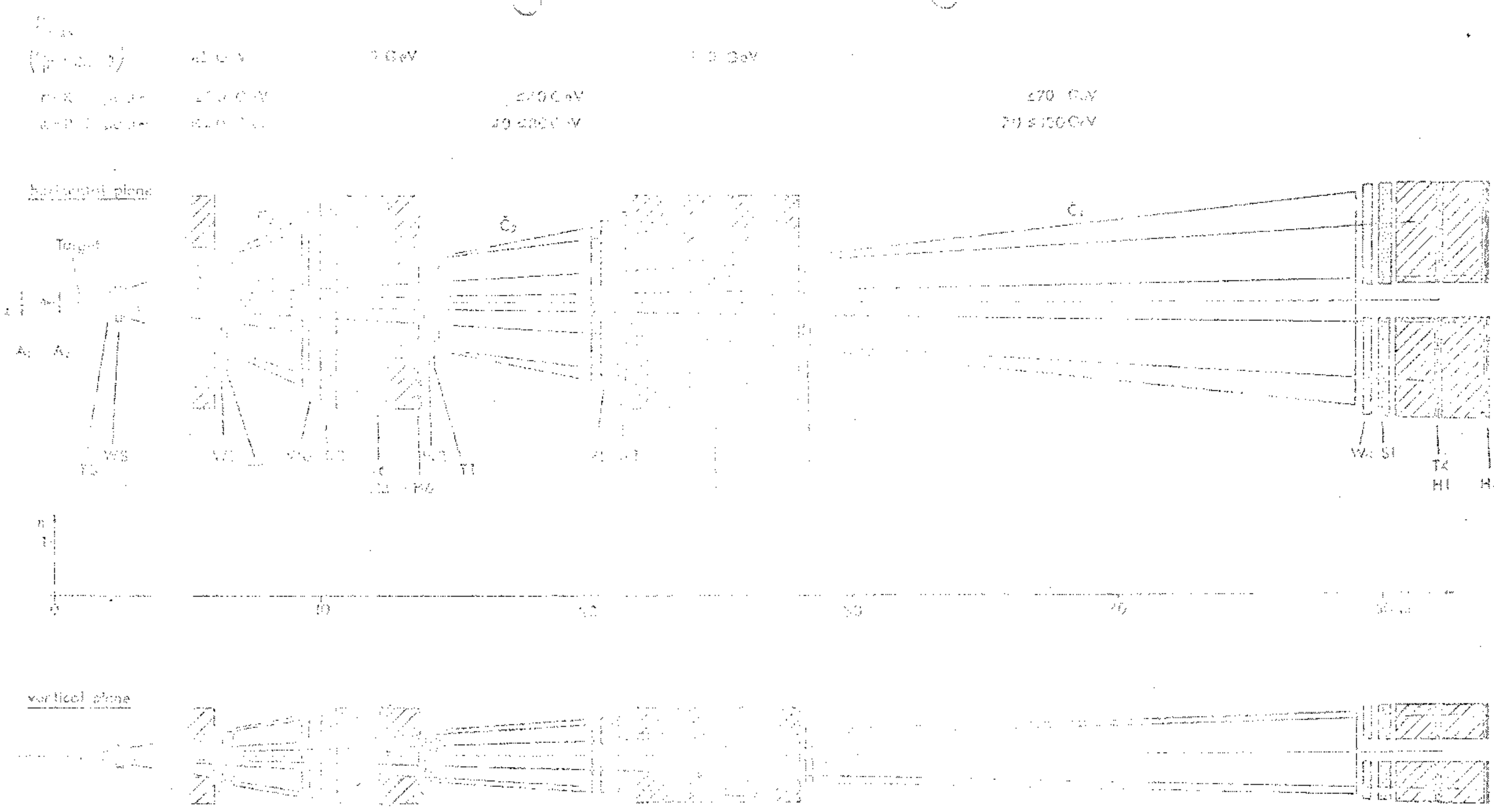
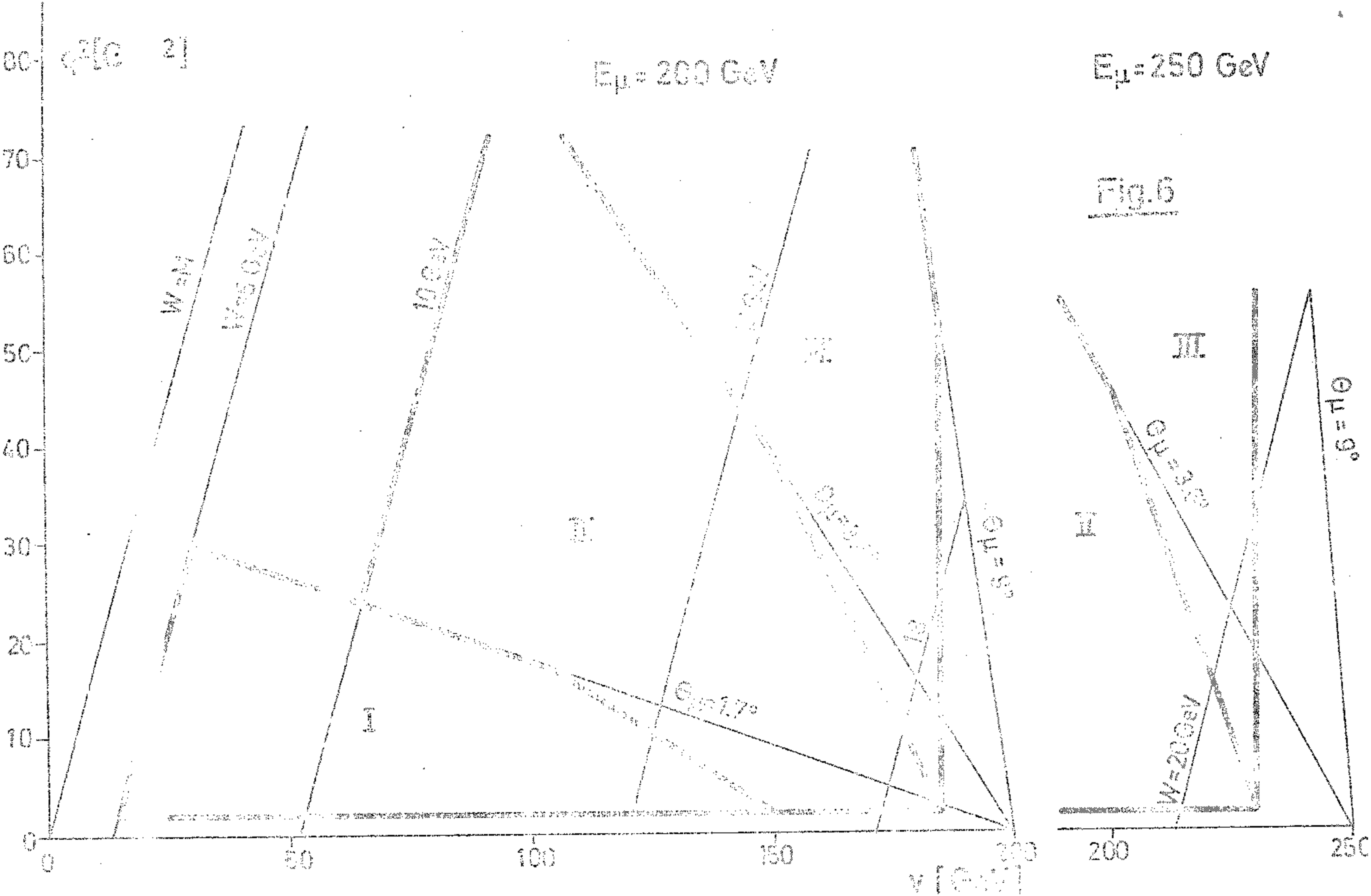

horizontal plane
Target
Č2
Č1
vertical plane
T Trigger
A Antitrigger
W Wire chamber
H Hodoscope
S Shower hodoscope

Fig. 5



E_μ = 200 GeV
E_μ = 250 GeV
W = M
10 GeV
Θ_μ = 1.7°
Θ_μ = 9°
Θ_μ = 3.5°
W = 20 GeV
I
II
III
0
10
20
30
40
50
60
70
80
0
50
100
150
200
250

Fig. 6