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# PROPOSAL TO MEASURE NEUTRINO AND ANTINEUTRINO INTERACTIONS IN A LARGE MAGNETIZED IRON DETECTOR WITH VERY GOOD ACCEPTANCE AND RESOLUTION AT THE TEVATRON

CERN-Dortmund-Fermilab-Heidelberg-Saclay-Warsaw Collaboration

## SUMMARY

A detector which integrates the functions of target, calorimeter and spectrometer is proposed for neutrino studies at the Tevatron. Outstanding properties of this detector are:

1) large useful target mass;
2) very good hadron energy resolution;
3) very good muon momentum resolution; and
4) very good muon acceptance.

The detector would strengthen the Tevatron neutrino program considerably, especially in the measurement of the $Q^2$ dependence of the nucleon structure functions and the search for new types of particles in multimuon processes.

## 1. INTRODUCTION

Electronic neutrino detectors have demonstrated their usefulness in the study of a number of processes, especially inclusive processes on complex nuclear targets and multilepton processes. This success is based on two properties: a) it is possible to construct large iron core magnetic spectrometers which at the same time select muons and measure their momenta with good precision, and b) calorimetric techniques have been developed which measure hadronic shower energies with good precision.

The proposed detector has been used at CERN in the past years and works very well. It integrates the three functions of target, hadron calorimeter, and muon spectrometer; in this way it achieves two distinct advantages: a) the muon acceptance is essentially 100% independent of the place of origin of the event in the detector, and b) the detector can be made indefinitely long and therefore with large target mass, without sacrificing muon acceptance.

The detector is currently being augmented by twelve new modules of improved calorimetric resolution. The improved detector will be exploited until the end of 1982 at the SPS in an effort to improve the precision of the structure functions. We would then wish to extend the work to higher energies at the Tevatron.

## 2. DETECTOR

### 2.1 General

The detector (Fig. 1) consists of magnetized iron toroids, 3.75 m in diameter, instrumented with planes of scintillator and interspersed with triple plane drift chambers. It is integrated in the sense that the toroids serve as neutrino target, hadron calorimeter, and muon analysing magnet.

The "old" part of this detector consists of 19 modules with 75 cm iron thickness each, and has been used at CERN since 1977 (experiment WA1 at the SPS). The new part consists of 12 modules with 50 cm iron thickness each, and is presently under construction and scheduled for completion and use at the SPS early in 1981. The total potential target mass is 1750 tons. The fiducial mass will depend on the measurement in question, but will normally be between 400 and 1000 tons.

Although the diameter and magnetic field are the same for all modules, there are substantial differences. The old modules (Fig. 2) are instrumented with eight horizontal scintillators which traverse and are read out on both sides. The horizontal shower position is determined from the ratio of right and left pulse heights. The uncertainty of the shower position is approximately ±15 cm in both horizontal and vertical dimensions. There are seven modules with 5 cm iron sampling, eight modules with 15 cm sampling, and four modules with only one plane of scintillator, whose function is limited to that of muon momentum analyser.

The new modules (Fig. 3) are instrumented with scintillator strips 15 cm wide, in groups of five with 2.5 cm iron spacing, successive groups being placed alternately horizontally and vertically. Each 50 cm module has 20 scintillator planes, the first and third sets of five consisting of horizontal strips, the second and fourth of vertical strips. The scintillators do not traverse, but there are separate right and left, or up and down elements. The shower position uncertainty for these units will be less than ±5 cm in both vertical and horizontal dimensions, and some information on shower direction and structure will be available.

The precision of the drift chamber measurements is approximately ±1 mm. The new chambers now under construction have one substantial advantage over the old: the signal wires are paired to remove the left-right ambiguity. This will reduce the computer reconstruction time per event, and improve the reconstruction efficiency, which at present is ∿ 95%. It is not yet known what fraction of the chambers will be of the old design and what fraction will be new.

### 2.2 Hadron shower energy resolution

The energy resolution of a sampling calorimeter depends of course on the sampling thickness, roughly inversely with the square root. This is shown in Fig. 4. Some typical pulse height distributions for the new modules are shown in Fig. 5, and the resolution as function of energy in Fig. 6 *). These are approximately:

$$\sigma = \pm 0.6/\sqrt{E},\ \pm 0.8/\sqrt{E} \text{ and } \pm 1.4/\sqrt{E},\ E \text{ in GeV}\ ,$$

for the three types of modules, respectively.

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*) The 2.5 cm results are obtained in a test module 60 cm × 60 cm × 200 cm Fe using the same scintillators and circuits as the new modules.

It is important to notice that calorimetric shower energy determination improves with increasing energy, and very good results, e.g. $\Delta E/E \sim \pm 3\%$ for $E_h = 400$ GeV, can be expected at Tevatron energies.

## 2.3 Hadron shower containment

The efficient containment of the hadron shower is an important advantage of a large, dense target structure. If the target dimensions are not very large compared to the shower size, then either a substantial fraction of the data will have shower containment inadequate for good energy measurement, or the fiducial volume must be substantially reduced, with a consequent event loss rate.

## 2.4 Muon momentum resolution

The precision of the muon momentum measurement is determinant for the precision of the measurement of the structure functions at high $Q^2$. The uncertainty in an iron core magnet has two basic sources: the multiple scattering and the position measurement error. The multiple scattering error $(\Delta p/p)_{ms}$ is independent of momentum, and inversely proportional to the square root of the magnet length. The measurement error due to uncertainties in drift chamber position and measurement, $\sim 1$ mm in the present case, decreases with the $5/2$ power of the length, if account is taken of the fact that the number of drift chambers hit is proportional to the length. Important at the energies of the Tevatron is the fact that the relative measurement error, $(\Delta p/p)_{meas.}$, is proportional to the momentum. At high momenta, therefore, the length of the magnet becomes relatively more important. This can be seen in Fig. 7, where the momentum resolution, and the separate contributions from multiple scattering and measurement, are shown as functions of muon momentum for different lengths of our system. For a track length of five metres the multiple scattering error of approximately 12% can be achieved only for $p_\mu$, less than about 50 GeV, whereas for magnet lengths of 15 to 20 metres the ultimate multiple scattering resolution of 6-7% is achieved even for the highest muon momenta obtainable at the Tevatron. It is an important feature of this apparatus that all muons produced in the first twelve, and best, modules will have a potential measurement length in excess of 20 metres. In this connection, it must also be kept in mind that the muons of a chosen charge are focused towards the axis, and even at the highest energies and momentum transfers possible at the Tevatron, the muons are trapped for the full length of the magnet, so that muon momentum resolutions of ∿ 6% will be obtained up to the highest energies.

## 2.5 Muon angular resolution

The limitations on the muon angular resolution are the result, on the one hand, of the multiple scattering, which contributes an error of approximately 0.014 GeV/$E_\mu$ and the measurement error, which is ∿ 1.4 mrad. Of these two, except for the case of small x and high $Q^2$, the multiple scattering error is the larger and contributes an error in $\Delta x/x$ of ∿ 0.2 GeV/$\sqrt{(1-y)Q^2}$, independent of x. This error would be somewhat smaller in a medium with smaller atomic number; however, the contribution of the hadron energy errors and muon momentum errors to $\Delta x/x$ are the greater, except at very small $Q^2$ and x, and not a great deal may be gained by improving the muon angular resolution.

## 2.6 Muon acceptance

Since the target serves simultaneously as muon analysing magnet, the muon acceptance is essentially complete, independent of x, y, $Q^2$, and neutrino energy. Furthermore, since the muons of a particular sign are focused towards the axis, these muons are trapped and the measurement error, which is only dependent on track length, is then also independent of these variables. This large muon acceptance facilitates the systematically correct determination of the structure functions.

Since the muon angle is proportional to the square root of $Q^2$, the muon acceptance of a divided function detector is particularly disadvantageous at large $Q^2$, whereas for the integrated function detector also the high $Q^2$ region is measured without problem.

The integrated feature of the proposed detector also results in good acceptance for multimuons although here the "wrong sign" muons are defocused, and leave the magnet rather quickly, typically after 5-10 modules. Nevertheless, the sign measurement and (10-15)% momentum measurements are possible also for these in almost all cases.

One limitation of this technique applies to low-energy muons. Because the muons must first appear outside the hadron shower, and must then traverse a sufficient number of modules to survive track reconstruction programs and permit momentum measurement, 4-5 GeV seems to be a minimum muon energy for systematic work. This limits the y region which can be covered at the high y end to $y \lesssim [1 - (6\ \mathrm{GeV}/E_\nu)]$. At high neutrino energies this is not serious for the determination of structure functions. It is more unpleasant for multimuons, where the loss imposed by this cut is important.

### 2.7 Time resolution, data acquisition capacity, and triggering system

The detector is equipped with a buffer of 40 events capacity; only 2 to 2.5 microseconds are needed from the time of trigger to storage in this buffer. We therefore regularly record several events even in a 23 μs short spill beam, and up to forty in a 2 millisecond medium spill beam. This capability, which is made possible by the use of drift chambers rather than spark chambers, has two important advantages:

a) The trigger can be loose, and therefore closer to being bias free.

b) It is possible to get large data samples in intense beams, such as wide band beams.

The trigger system is conventional, except perhaps for the capability of using wire chamber information to reject events before they are entered into the buffer. This so-called "delayed trigger" is used routinely to select multimuon events in the wide band beam.

## 3. PURPOSE OF THE EXPERIMENT

### 3.1 Anticipated physics at the Tevatron

The capability of the proposed detector is limited to the detection and energy measurement of the hadron showers and the detection, energy, and angular measurement of muons; the physics possibilities are limited consequently. In the low-energy past, the experimentation with our type of detector has divided itself into the following classes:

1) Study of inclusive features of the charged current, such as total cross-sections and structure functions.

2) Study of neutral current total cross-sections, y distributions, V-A character of neutral current.

3) Study of multimuon events: their origin, nature of the GIM current, strange sea structure function, search for heavy leptons and flavours.

4) The search for new types of neutrinos in beam dump experiments.

This pattern may be the same at the Tevatron. In any case, it is not possible to predict the changes in this pattern at this time.

### 3.2 Nucleon structure functions

In neutrino and antineutrino scattering the three structure functions $F_1(x,Q^2)$, $F_2(x,Q^2)$, and $F_3(x,Q^2)$ can be determined, in contrast to muon or electron scattering, in which $F_3$ cannot be measured. Furthermore, $F_3(x,Q^2)$ is particularly interesting since, on the one hand, it has a simple interpretation as valence quark distribution and, on the other hand, its $Q^2$ evolution in QCD is predicted independently of assumptions about gluons. In the language of the quark parton model, the quark and antiquark constituent distributions of the nucleon can separately be measured. In addition, the strange quark distribution can be isolated in the measurement of opposite sign dimuon events, and their interpretation via the GIM mechanism for charm production.

The new energy will extend the $Q^2$ domain by a factor of two. Although this is not an enormous extension on a logarithmic scale, it can nevertheless be expected to be important, since, as has recently been repeatedly emphasized, the QCD predictions become increasingly unambiguous with increasing $Q^2$ and it is the evolution over a large $Q^2$ domain which is interesting in the light of the theory. The extension of the $Q^2$ domain is therefore important.

The most interesting structure function from the point of view of QCD comparison is probably $F_3(x,Q^2)$. However, also the quark-antiquark sea may eventually permit important contact between theory and experiment. The sea is measured directly in antineutrino scattering at large y. Since here the rates are low, the wide band beam capabilities of our detector are particularly advantageous. The sea is the domain of small x, and the $Q^2$ dependence of the sea involves all the basic ingredients of QCD. Tevatron energies will be most welcome in this small x region, since $Q^2$, being proportional to x, is unpleasantly small at present energies. The quadrupole triplet beam which is foreseen would be ideally suited for this work.

### 3.3 Longitudinal structure function: $q_L(x,Q^2)$

In a phenomenological description, the existence of the longitudinal structure function is due to the transverse momentum of the quarks inside the nucleon. This can be separated roughly into two contributions: the "primordial" transverse momentum and the "dynamic" contribution due to hard gluon bremsstrahlung, according to the expression:

$$R(x,Q^2) = \frac{q_L(x,Q^2)}{F_2(x,Q^2)} \approx \underset{\text{primordial}}{a\,\frac{\langle p_T^2\rangle}{Q^2}} + \underset{\text{dynamic}}{b\,\frac{(1-x)}{\ln Q^2/\Lambda^2}}\ .$$

The "dynamic" contribution can be predicted in QCD for higher values of $Q^2$ and is supposed to become dominant at small values of x and moderate values of $Q^2$.

Tevatron energies will be very useful also here, again because an increase in the $Q^2$ range will help in sorting out the two contributions.

### 3.4 Propagator effect

It would, of course, be important to see some sign of the intermediate boson. With the present value of $\sin^2 \theta_w$ the $W^\pm$ mass is expected to be (77 ± 3) GeV. With 800 GeV protons it should be possible to produce reasonable results up to $Q^2 \approx 500\text{–}600\ \text{GeV}^2$, so that propagator effects of the order of 15–20% are expected. These should be both measurable and distinguishable from logarithmic scaling violation effects. So if the W has not been discovered before, it should be possible to see the W mass via the propagator effect at the Tevatron.

### 3.5 Multimuons

#### a) Search for new particles

Heavy leptons or flavours, if they exist, are expected to give discernable signals in the multimuon channels. Such signals could not only be useful in the process of establishing the existence of such particles, but may be expected to give experimental information on the weak interaction of these objects, just as the dimuon data have been very useful in confirming the magnitude, V-A, and flavour character of the weak interaction of charmed quarks (GIM current).

### b) $Q^2$ dependence of strange sea

The strange sea structure function is measured directly in the production of dimuons (charm) by antineutrinos. The accumulation of large event numbers in wide band beams makes it possible to study the evolution also of this structure function with $Q^2$. The extension of the $Q^2$ domain made possible by the higher energies of the Tevatron will be important.

### c) $p_T$ and fragmentation dependence on $Q^2$ for charm

The $Q^2$ variation of these parameters, interesting in the frame of QCD, can be studied.

### d) Vector meson production by neutral currents

The production of high mass vector mesons can be detected via their $\mu^+\mu^-$ decay, and the comparison of these cross-sections with the corresponding photoproduction cross-sections is of interest. The processes are extremely rare in neutrino interactions, but the large detector proposed here, with its essentially complete muon detection efficiency, gives a powerful possibility.

## 3.6 Beam dump experiments and search for new neutrinos

Beam dump experiments improve very much with increasing energy. The background of $\pi$ and K decay neutrinos diminishes, and the acceptance for all types of neutrinos increases because of the Lorentz contraction. The higher energy is important also in the production of the higher mass hadrons which are the possible parents of new types of neutrinos. These facts, combined with the substantially improved geometry planned for the Tevatron beam dump experiments, will greatly increase the sensitivity of these experiments with respect to those which have been done so far, so that one may hope for some new results.

The proposed detector would certainly be the best imaginable for the detection of multimuon events, so that it could very well contribute to the discovery of something new. However, it is not suited either to the search for $\tau$ neutrinos, since it is insensitive to missing neutrinos, nor can it be used to measure $\overset{(-)}{\nu}_e$ reactions, since it cannot distinguish electrons.

However, if the detector were combined with a front end which can measure the hadron shower direction, this might be very powerful in the $\tau_\nu$ search.

## 4. THE TEAM

The team is an evolution of the CERN-Dortmund-Heidelberg-Saclay Collaboration, strengthened by groups from Fermilab and Warsaw. A larger American participation would be advantageous and we would welcome it. Probably, if the experiment is mounted at Fermilab, additional American collaborators would materialize. In this connection we would like to mention that discussions are in progress with W.Y. Lee, Columbia University, concerning the desirability of the addition of a low Z active target detector in front of the detector proposed here. Our apparatus would constitute the muon spectrometer for the addition. This would extend the physics possibilities into the regions of ν-e scattering, τ neutrino search, and structure functions at very small x. If both of these experiments are approved, the two teams will combine into one.

The present collaborators are as follows:

| | | |
|---|---|---|
| CERN: | Physicists: | J. de Groot, J. Knobloch, J. May, P. Palazzi, F. Ranjard, D. Schlatter, J. Steinberger, H. Taureg, W. von Rüden, H. Wahl, J. Wotschack |
| | Engineers: | C. Bertuzzi, M. Schmitt |
| | Technicians: | 11 |
| DORTMUND: | Physicists: | F. Eisele, P. Klasen, K. Kleinknecht, B. Pszola, D. Pollmann, B. Renk, H.J. Willutzki |
| | Technicians: | 3 |
| FNAL: | Physicists: | J.P. Berge, R. Hanft, F.A. Nezrick |
| HEIDELBERG: | Physicists: | F. Dydak, T. Flottmann, C. Geweniger, V. Hepp, J. Krolikowski, K. Tittel, M. Vysocansky |
| | Engineer: | W. Heyde |
| | Technicians: | 6 |
| PEKING: | Physicists: | J.T. He, T.Z. Ruan, W.M. Wu |
| SACLAY: | Physicists: | G. Guyot, J.-P. Merlo, B. Peyaud, J. Rander, J. Rothberg, J.-P. Schuller, R. Turlay |
| | Engineers: | C. Lechevin, A. Patoux |
| | Technicians: | 7 |

WARSAW: Physicists: H. Abramovicz, K. Doroba, A. Para, M. Szczekowski, M. Szeptycka

Technicians: 7.

## 5. BEAMS AND FLUXES

### 5.1 General

We wish at first to make several points which are perhaps self-evident:

1) We are not proposing a specific experiment, but a number of measurements extending over a period of several years and which must evolve as new physics is learned.

2) The dominant interest must be at the highest energies. The lower energy regions should be well explored at that time.

3) We do not expect neutrino physics to be the centre of interest at the Tevatron, we rather expect it to be the $\bar{p}p$ collider, and consequently we believe that the running time and protons devoted to neutrino work will be limited. It is important that all neutrino users make an effort to be compatible for the various exposures.

### 5.2 Narrow band (dichromatic) beams

We believe that extensive experiments with both neutrinos and antineutrinos from more or less conventional 500-600 GeV momentum selected hadron beams are important to determine the structure functions, including the search for the propagator effect, and to check the $Q^2$ evolution of the neutral current.

### 5.3 Wide band beams or sign-selected high band beams

Such beams are important in the study of rare processes, such as

a) multimuon reactions and the search for new leptons or flavours, and

b) the smaller components of structure functions such as the antiquark sea, and large x and $Q^2$ behaviour.

### 5.4 Beam dump

At the Muon and Neutrino Workshop of 1979 large interest was shown in a new generation of beam dump experiments in which the higher energy of the Tevatron is combined with shorter beam path length, and therefore higher fluxes. The main emphasis was put on trying to detect τ neutrinos.

Our detector offers little possibility for distinguishing $\nu_\tau$ and $\nu_\mu$ or $\nu_e$. Nevertheless, we would wish to participate in a high-intensity, high-energy beam dump experiment, since, on the one hand, the CERN beam dump experiments left more than one question unclear (for instance, the ratios of prompt $\nu_\mu$ and $\bar{\nu}_\mu$, as well as prompt $\nu_\mu$ to $\nu_e$), and on the other hand, there is always the possibility that new phenomena will turn up with higher energy and intensity.

### 5.5 Beam monitoring devices

The neutrino spectra and absolute intensities are of course basic to all systematic neutrino cross-section measurements. We would wish to participate in the design and construction of neutrino beam monitoring devices. In particular, we could offer to furnish a Čerenkov counter of the type pioneered at CERN, suitable for particle ratio measurements in narrow band beams up to the highest Tevatron energies. Furthermore, we might help in the design and construction of some device for measuring absolute muon fluxes in the shield.

## 6. TIME SCALE AND INSTALLATION

The construction of the new modules is in progress. Installation at the CERN SPS is expected to be completed early in 1981, and the remainder of that year, as well as the year 1982, will be devoted to accumulating data with the improved detector, up to the highest energies available at the SPS, hopefully up to ∿ 400 GeV neutrino energy.

If this proposal is approved, the apparatus should then be shipped to Fermilab and installed during 1983, so that we should be ready to participate in the Fermilab program early in 1984.

Shipment, and especially installation at Fermilab, are substantial undertakings. We have not made serious studies of these problems.

## Figure captions

Fig. 1 : Layout of the entire apparatus, consisting of magnetized target calorimeter modules interspersed with drift chamber.

Fig. 2 : "Old" modules and their instrumentation.

Fig. 3 : "New" modules and their instrumentation.

Fig. 4 : Calorimetric hadron energy resolution as function of the sampling thickness.

Fig. 5 : Some energy resolution curves obtained with a test calorimeter using the geometry and circuits of the new modules.

Fig. 6 : Measurement of energy resolution versus energy for pions and electrons obtained in test calorimeter using geometry of the new modules.

Fig. 7 : Multiple scattering, measurement and combined uncertainties of the muon momentum measurement as functions of muon momentum for several muon track lengths in the proposed detector.

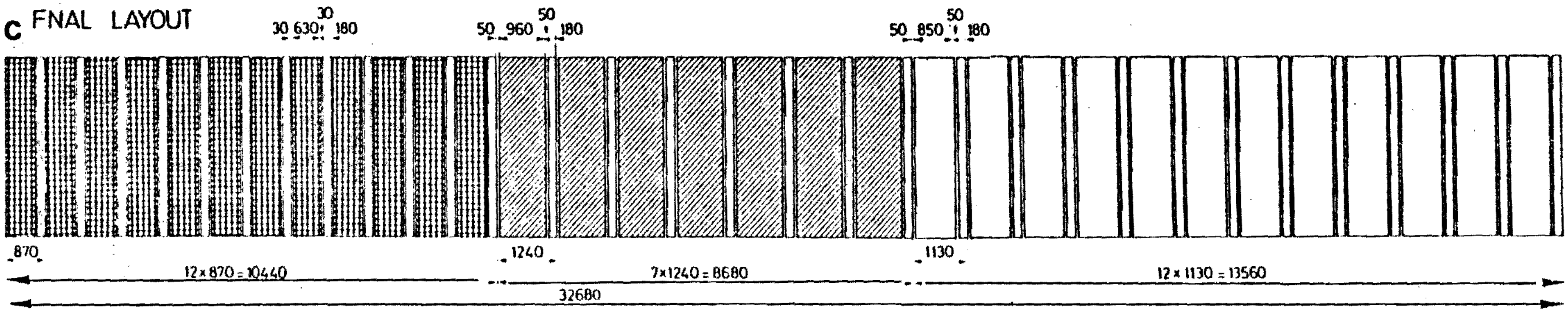

C
FNAL LAYOUT
30
30 630 180
50
50 960 180
50
50 850 180
870
1240
1130
12×870 = 10440
7×1240 = 8680
12×1130 = 13560
32680

Fig. 1

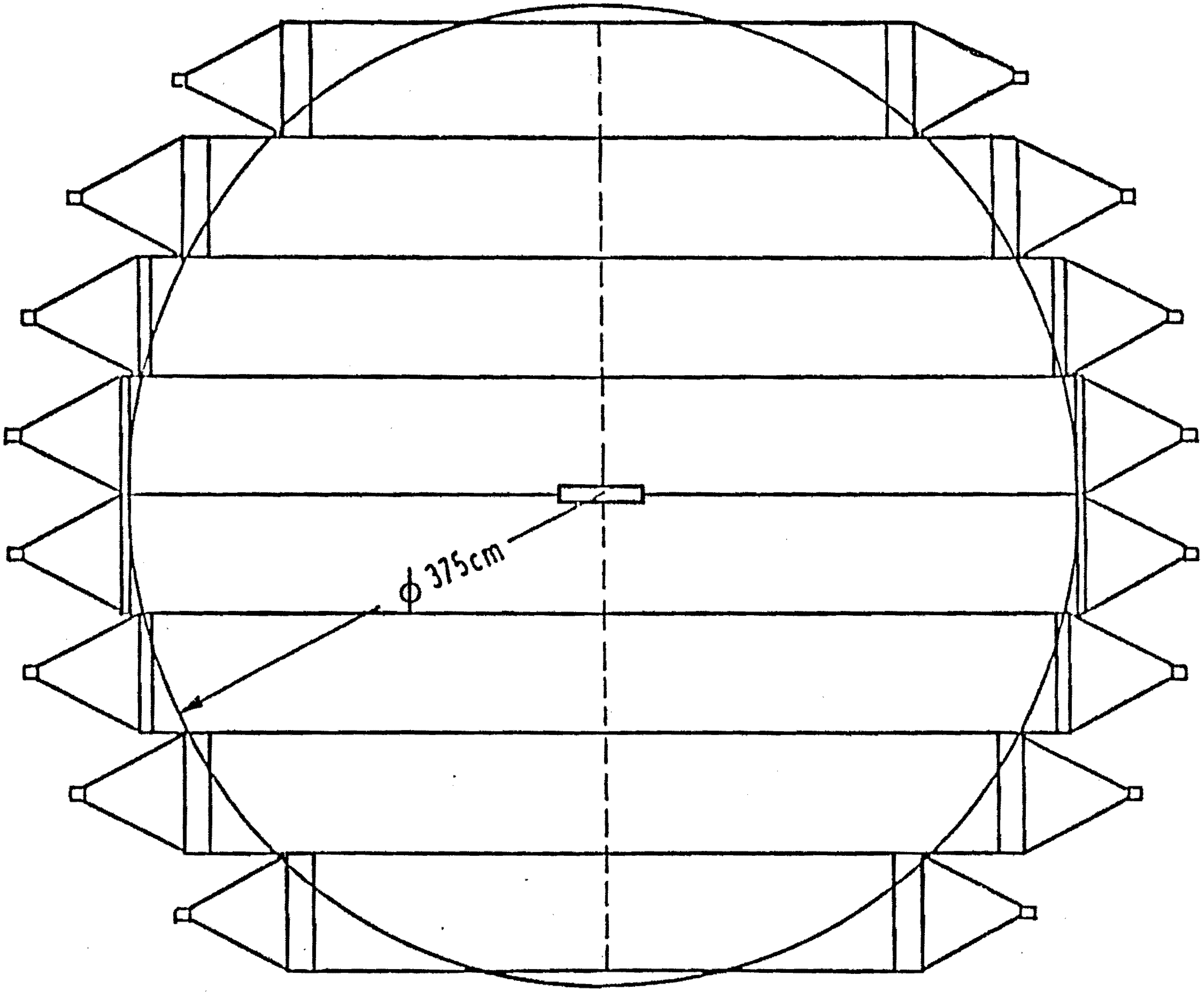


Fig. 2

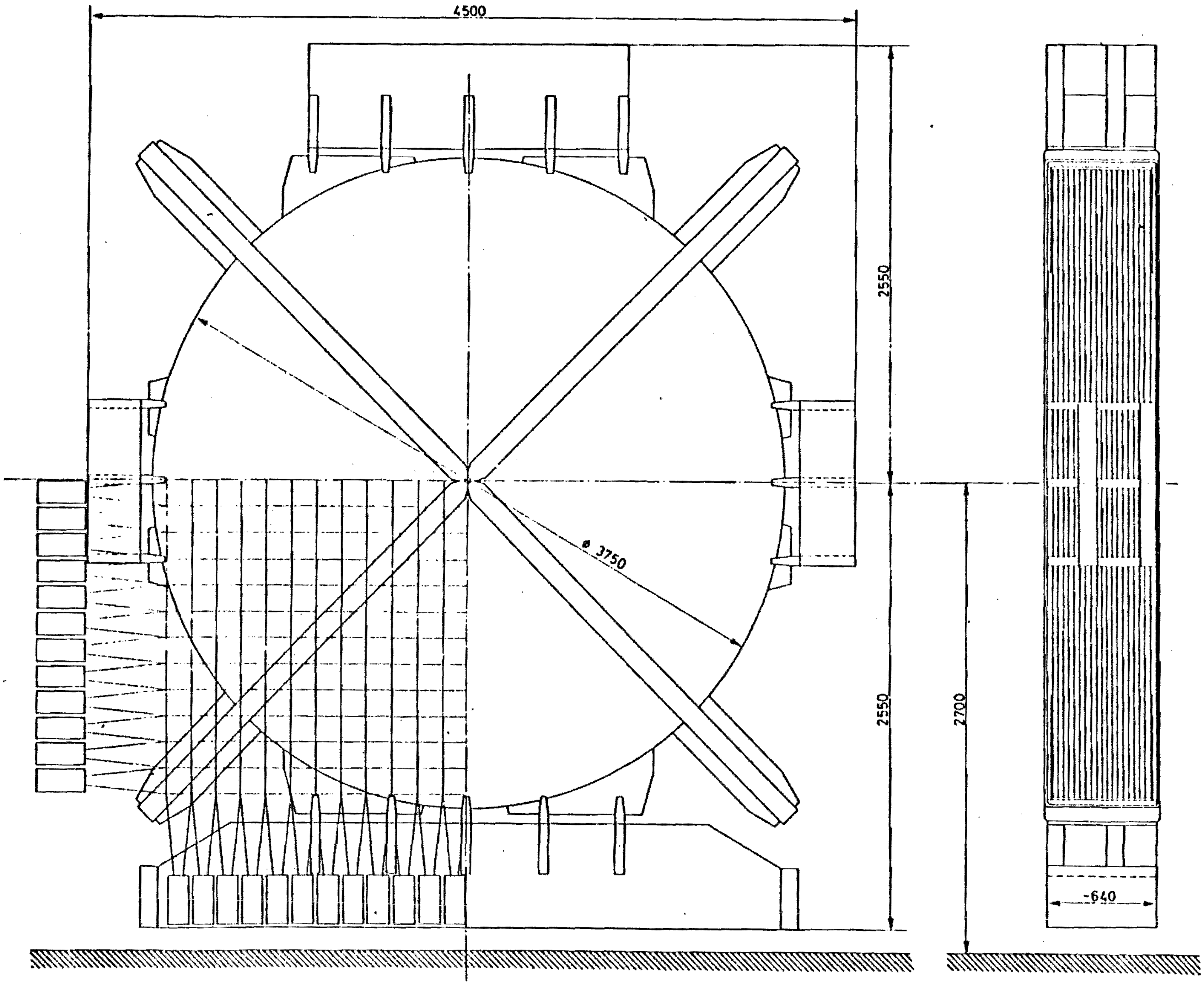


Fig. 3

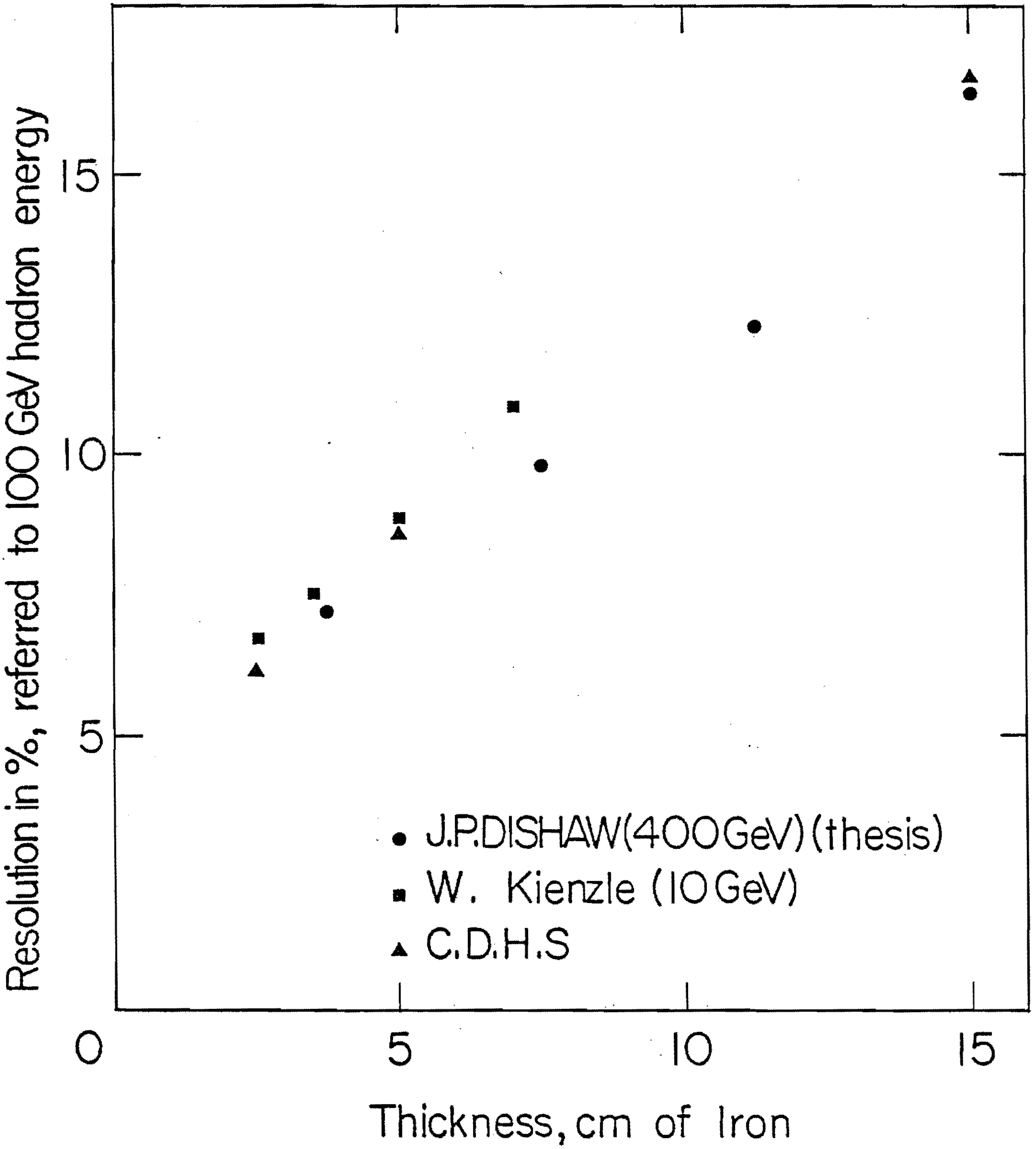

Resolution in %, referred to 100 GeV hadron energy
15
10
5
0
5
10
15
Thickness, cm of Iron
● J.P.DISHAW(400GeV)(thesis)
■ W. Kienzle (10GeV)
▲ C.D.H.S

Fig. 4

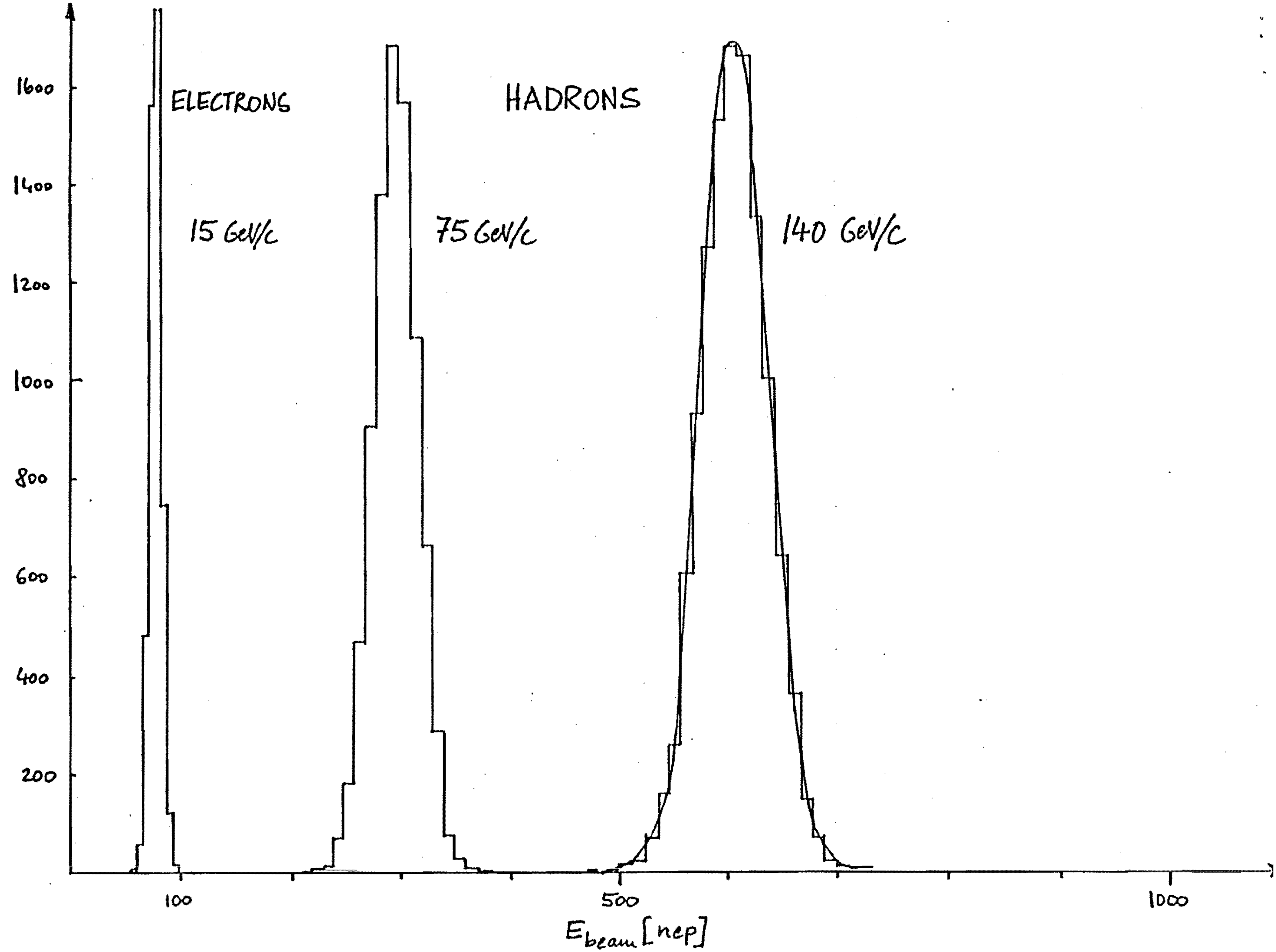
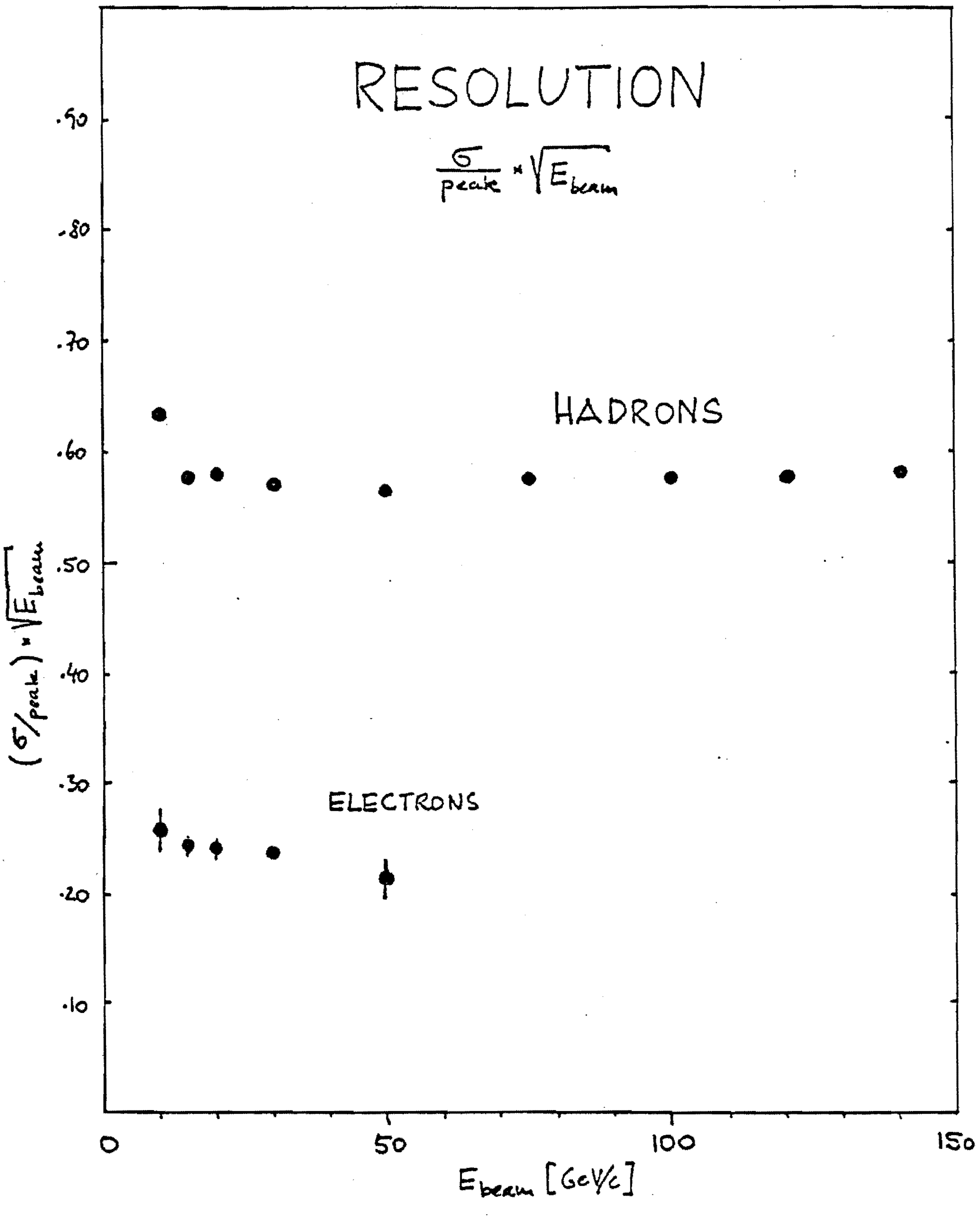

1600
1400
1200
1000
800
600
400
200
ELECTRONS
HADRONS
15 GeV/c
75 GeV/c
140 GeV/c
100
500
1000
$E_{beam}$ [nep]

Fig. 5



RESOLUTION
$\frac{\sigma}{\text{peak}} \times \sqrt{E_{beam}}$
HADRONS
ELECTRONS
.90
.80
.70
.60
.50
.40
.30
.20
.10
$(\sigma/_{peak}) \times \sqrt{E_{beam}}$
0
50
100
150
$E_{beam}$ [GeV/c]

Fig. 6

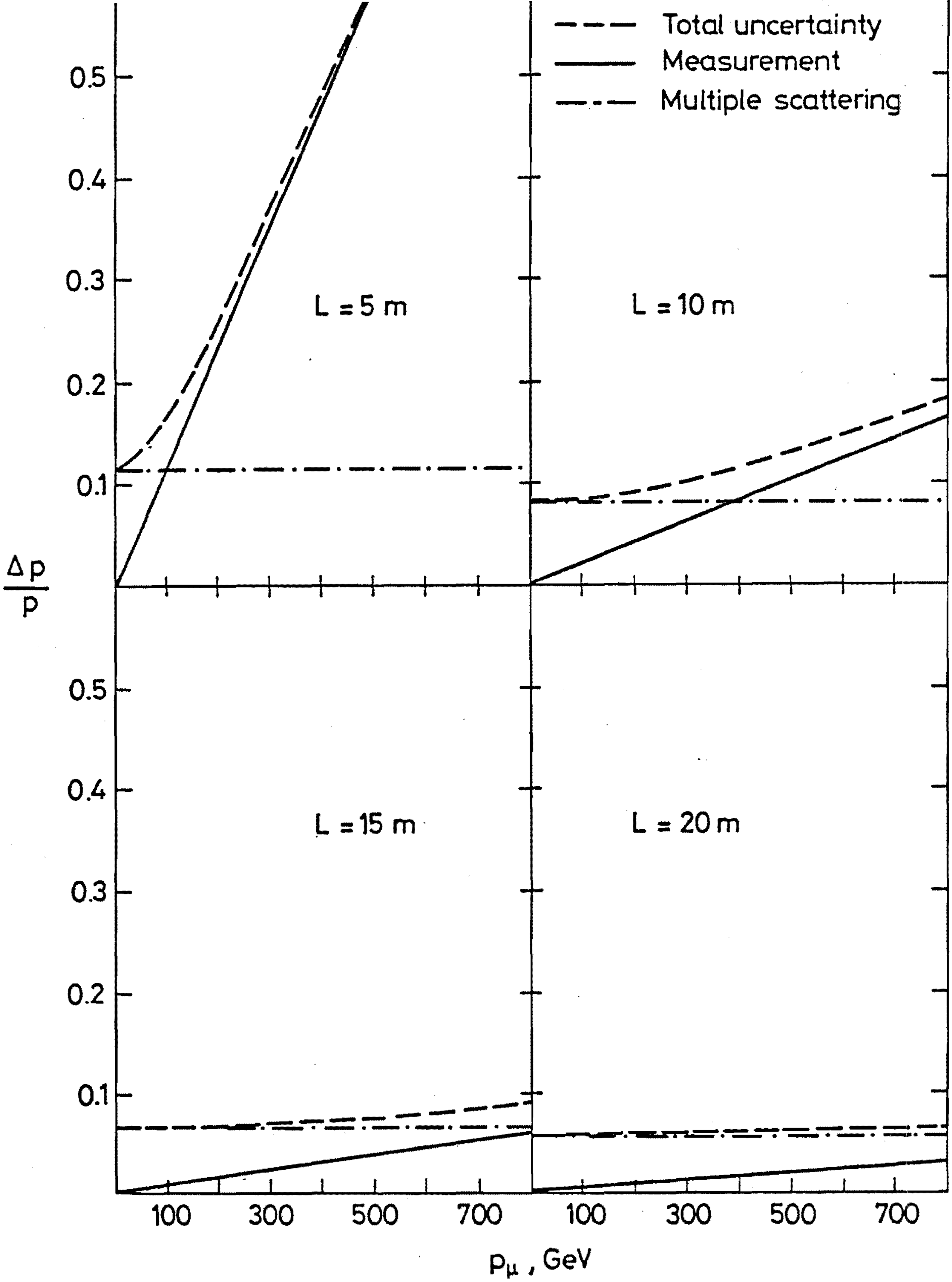

Total uncertainty
Measurement
Multiple scattering
0.5
0.4
0.3
0.2
0.1
Δp/p
L = 5 m
L = 10 m
L = 15 m
L = 20 m
100
300
500
700
pμ , GeV

Fig. 7