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Proposal for Experiments
On High Energy Muons.

Van der Meer has recently proposed (1) the construction of a very intense momentum analysed muon beam. This opens new possibilities in muon physics.

Presently we have considered the following experiments:

- Muon scattering on hydrogen and complex nuclei
- Lepton pair production by muons.

A. General Considerations.

1. **The Beam.**

   The proposed beam consists of a loo m long, straight beam guide and two other sections for the removal of hadrons and momentum analysis, adding up to ~ 5o m. In total the whole device is $\sim$ 15o m long (see fig. 1).

   Two operational posssibilities are considered: the short pulse extraction ($\sim$ 2.2μs.) and the long pulse extraction ($\sim$ loo mS.). The corresponding muon intensities are calculated in ref. (1) (see fig. 2);

   The momentum spread of the beam emerging from the guide is 5%. The angular spread is proportional to the inverse square root of the current in the inner conductor. For example, for muons of 3 Gev/c momentum, using a current of 25 KA, the angular spread is 3o mr.

   The total pion impurity should be $< 10^{-7}$.

2. The Physical Problems.

From a theoretical point of view, the experiments are closely
analogous to those which are being planned with electrons, at *
the large electron synchrotron of DESY. *and C.E.A* In fact one of the main
points of interest consists in testing how far the analogy is
true and to detect if there is any difference in the dynamics
of electrons and muons.

Muon scattering experiments are characterizied by the absence
of Bremsstrahlung background which is present with electrons.
On the other hand, the beam intensity which is obtainable with
muons is smaller, by several orders of magnitude, with respect to
electron beams. *This is reflected in the greater complexity of the*
~~of the~~ experimental apparatus.

1) Muon proton scattering has so far been studied up to $q^2 = 1(Gev/c)^2$
(see ref. (2)). With the proposed beam we can investigate
$d\sigma/dq^2$ up to $q^2 \approx 3(Gev/c)^2$. The curves reported in fig. 4
are examples of the results which can be obtained under the
conditions listed in Table 1. (see fig. 3 for kinematical
notations). The horizontal bars indicate the resolution Δq^2,
in 4-momentum determination, when the momentum of the incident
muon is uncertain within $\frac{\Delta p}{p} \approx 5\%$, which is the natural spread in
the long pulse beam at the exit of the guide.

This Uncertainty probably can be reduced to $\sim 1\%$ by determi-
ning electronically the incident momentum (see sect. B).
The inner cuts in the horizontal bars in fig. 4 indicate the
improved Δq^2 resolution obtainable in this latter case.

Fig. 5a and 5b show the resolution in the missing mass

$$M^{*2} = -(p - p' + P)^2$$

determination at $q^2 = 1(Gev/c)^2$. The familiar quantity

$$E_\gamma = \frac{M^{*2} - M^2}{2M}$$

is used in place of M^{*2}. Fig. 5a and 5b show the discri-
mination obtainable respectively with $\Delta p/p = 5\%$ and 1%.
Fig. 6 shows the same as 5a ($\Delta p/p = 5\%$) at $q^2 = 3(Gev/c)^2$.
A possible extension of the measurements of (μ p) scattering
up to $q^2 = 6(Gev/c)^2$ is being studied and calculations are
being carried out.

2) To our knowledge no <u>experiment on inelastic muon scattering</u> has
been reported. The most recent and complete experiments with
<u>electrons</u>, are those by Hand (3) and by Cone *et al.*(4). Even these
have not produced precise results for large q^2 and the knowledge
of inelastic form factors is still very poor. Again, we refer to
figs. 4,5 and 6, as examples of the accuracy which can be ob-
tained in determining $d^2\sigma/dq^2 dM^{*2}$ under the conditions of table 1

$$(\Delta p/p = 5\% \text{ and } 1\%)$$

Inelastic lepton-photon scattering affords a test of the C_{st} and T_{st}
non-invariance of electromagnetic interactions. If such invari-
ances breaks down, there can be correlations of the type

$$\vec{J} \cdot (\vec{p}_\mu \times \vec{p}_\mu')$$

where J is the spin of the recoiling baryon(5). For example in the
case of N^* production, the detection of the polarization of the
recoiling proton and the angular distribution of the pion are of
interest, even if the interpretation is complicated by possible
effects due to final state ~~strong~~ interactions.

Whenever possible, it is advisable to experiment on nuclear targets
rather than on free nucleons. In fact, for the same number of events
the target would be much more compact and - as a consequence- the
geometry of the recording apparatus reduced in proportion.

3) <u>Lepton Pair Production by Muons.</u>
Recently Brodsky and Ting (6) have made a theoretical study of
electron pair production by muons. They have determined kinema-
tical configurations which will insure that either diagrams with
"time-like" or "space-like" protons will give the dominant con-
tribution to the cross-section and at the same time give a pro-
duction rate which make triple coincidence experiments possible.
They select configurations whereby (A) , the pair is detected sym-
metrically with respect to the muon scattering plane and (B) the
total momentum of the three final leptons is in the incident
μ-direction. (A) insures vanishing interference contribution be-
tween spacelike and timelike diagrams, (B) insures that the mo-
mentum transfer to the nucleus is minimised for fixed lepton

energies and polar angles. The cross section is then nearly proportional to Z^2. Feasible event rates for a muon beam can thus be obtained from a high Z target.

Timelike diagrams dominate the cross section for large muon scattering angles in ~~which~~ wide ranges of the kinematics; the cross section is nominally 10^{-32} cm^2/ (Mev)^2 (sr)^3 at $p = 10\ GeV/c$ $Z = 10$ for $t = (100\ (MeV/c)^2$ in the ranges $\Delta\theta_1 \asymp \Delta\theta_2 \asymp \Delta\theta_3 \asymp 20\ \mu rad$, $\Delta\phi_2 \simeq \Delta\phi_3 \simeq 40°$, $\Delta E_1 \asymp \Delta E_2 \asymp \Delta E_3 \simeq 1\ GeV$,

giving a rate of 2.10^{-7} per incident muon. Timelike momentum transfers up to 1 (Gev/c)^2 will give feasible rates.

An important test of $\mu - e$ universality in the timelike region can also be performed by measuring three muons in the final state, taking into account mass differences and statistics. An "equilateral" configuration has been considered, in which the three leptons intersect in a plane perpendicular to the incident direction points which form the vertices of an equilateral triangle. Brodsky and Ting are calculating the cross section for this configuration. Finally we note that three muons in the final state afford a test of the muon statistics. Also a study of the spectrum of the "odd" muon $(\mu^+ \mu, \mu^+ \mu^- \mu^-$ configurations or vice-versa) will give information.

4) Finally, it is also relevant to remark that the study of muon interactions both on hydrogen and complex nuclei, is of interest in connection with the neutrino experiment, on the basis of the Conserved Vector current theory.

B. The Experimental Set-up.

We have considered a number of experimental set-ups appro-
piate to the different experiments discussed in the previous
sections.
The relevant points are the following:

1. A momentum analysis of the primary beam emerging from the
   guide is considered necessary for some of the experiments
   ~~routed~~ discussed above. We believe that, using a system of scintilla-
   tors and magnetic field, the momentum of each muon can be
   determined to 1% accuracy and its direction known to $\sim$1 mr.
   This implies the use of the long pulse beam ($\sim$0.1 S).

2. The momentum and angle determination of the final products
   will be carried out by a wirechamber-magnet system - al-
   though arranged on a different geometry. For experiments
   on a hydrogen target we are also considering the use of a pulsed
   magnetic field, cylindrically symmetric, which will allow a
   detection of events over an azimuthal angle $\varphi = 2\pi$ around the
   target.

3. The recording apparatus may require a computer on line.
   Calculations to determine the details of the apparatus are
   in progress.

C. Practical Considerations.

The site. From a preliminary discussion with G. Munday *and L. Hoffman.*
it appears that the best location of the beam and of the
experimental area *may be either on the North or on the South* ~~is on the west~~ side of the East Hall.
This question is being studied further.

The Time Scale. We estimate that the preparation of the
experiment will take 1/2 years from the moment of appro-
val by NPRC.

The Budget for the Beam. The cost of the beam guide, in-
cluding power supply but excluding buildings and shiel-
ding, is estimated to be 1.4 M.S.F. . We are not yet in a
position to state the cost of the recording apparatus.

X. de Bouard
R. Felst
C. Franzinetti
R. Mermod
P. Scharff
S. Van der Meer
M. Vivargent
H. Wachsmuth
T.R.Willits
K.Winter
H.Yoshiki

Cern, 2nd February 1966

Table I

Primary muon momentum : $P_\mu = 3$ Gev/c

Angular spread at exit from the guide : $\Delta\alpha = 1.5$ degrees

Momentum spread at the exit from the guide : $\Delta P_\mu/P_\mu = 5$ o/o

Length of the target of liquid hydrogen : 1 m

Muon flux (long extraction) in $\frac{\Delta\rho}{\rho} = 5\%$: 10^6 μ/pulse of $3 \cdot 10^{11}$ protons

Precision in the determination of the

scattered momentum : $\Delta P_\mu'/P_\mu' = 2$ o/o

Precision in the determination of the

angle of scattering : $\Delta\theta = 1/2$ degree

Azimuthal acceptance of the detector : $\Delta\varphi = 2\pi$

Minimum angle of scatter : $\theta > 20^\circ$

Exposure : 10^7 pulses

References.

1. S. Van de Meer, NPA/Int. 65-12 (See also Cern 62-12 by the same author).
2. R. Cool and al, P.R.L, 1965.
3. L.N. Hand, P.R. $\underline{129}$, 1834, 1963
4. B.A. Cone et al, P.R.L.
5. N. Christ and T.D. Lee, Phys. Rev.
6. S.J. Brodsky and S.C.C. Ting, Prepriny Dec. 1965

Fig. 1.   The beam guide proposed by S.Van de Meer (ref. 1)

Fig. 2.   Expected muon intensity (from ref.1)

Fig. 3.   Kinematics.

Fig. 4.   Typical errors which could be obtained in the determination ot the differential cross sections, under the conditions listed in tabl e 1. The horizonyal bars indicate the error in q^2 determinµ tion (see text) .

Fig. 5.   Mass resolution obtainable under the conditions of table 1

at $q^2 = 1 (Gev/c)^2$ and

$$Fig\ 5a: \quad \Delta p/p = 0.05$$
$$Fig\ 5b: \quad \Delta p/p = 0.01$$

$$E_\gamma = \frac{M^{*2} - M^2}{2M} \ (see\ text)$$

Fig. 6.   Mass resolution obtainable under conditions of table 1
at $q^2 = 3 (Gev/c)^2$ and $\Delta p/p = 0.05$

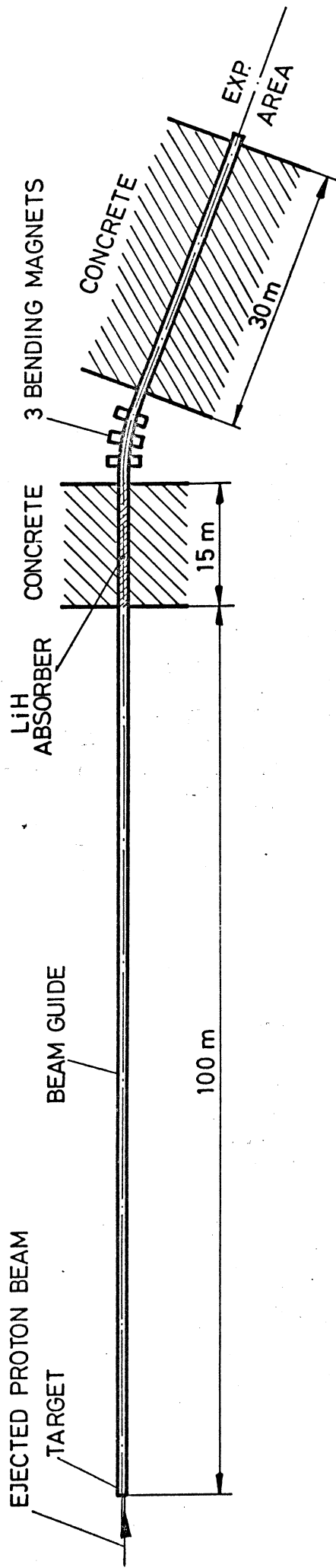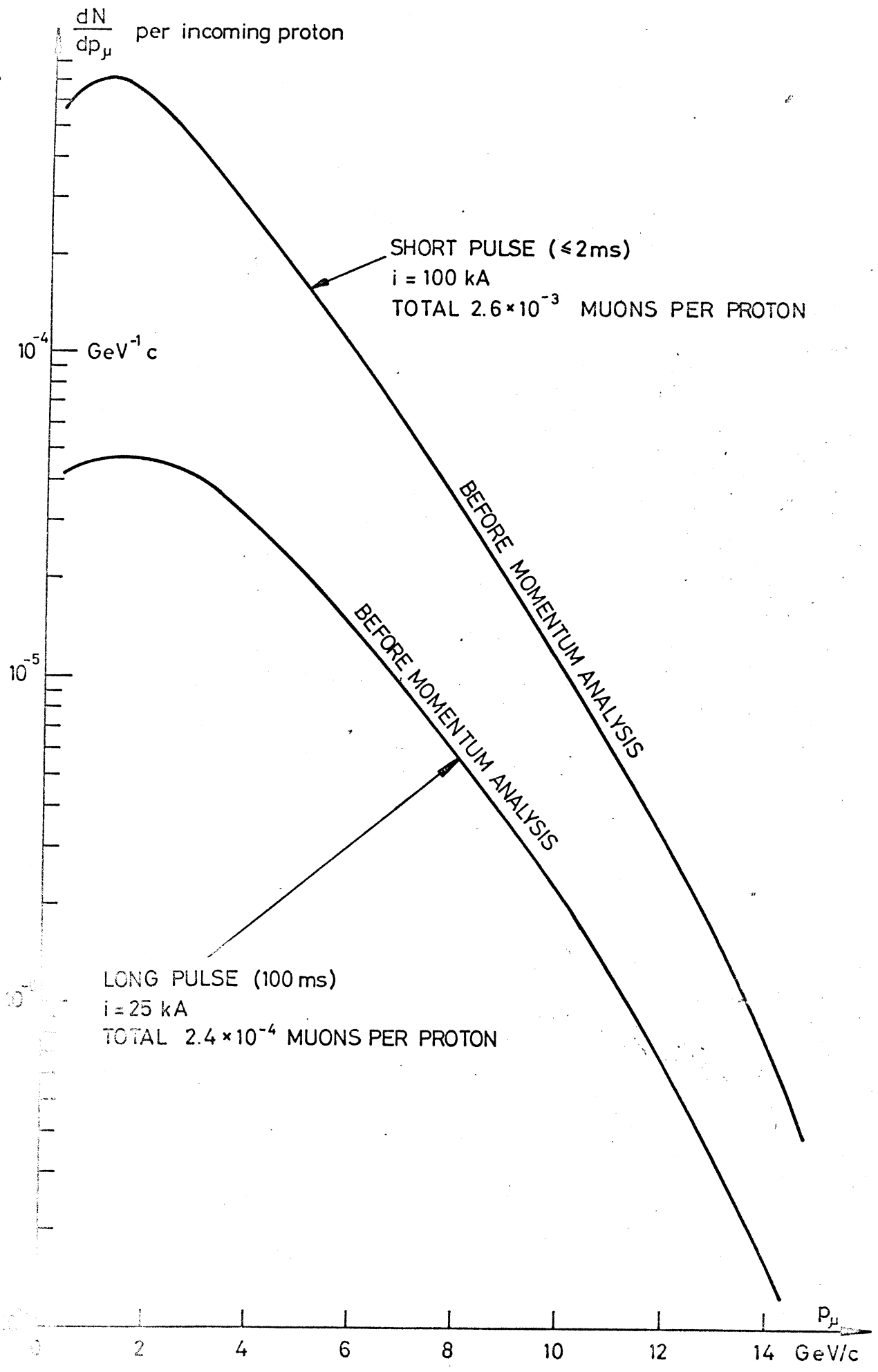FIG. 1   (FROM S. VAN DER MEER, REF[1])

$\dfrac{dN}{dp_\mu}$ per incoming proton

10^{-4} — GeV^{-1}c

SHORT PULSE ($\leqslant$2ms)
i = 100 kA
TOTAL 2.6×10^{-3} MUONS PER PROTON

BEFORE MOMENTUM ANALYSIS

10^{-5}

BEFORE MOMENTUM ANALYSIS

LONG PULSE (100 ms)
i = 25 kA
TOTAL 2.4×10^{-4} MUONS PER PROTON

2   4   6   8   10   12   14   GeV/c

p_μ

FIG. 2 (FROM VAN DER MEER, REF[1])

FIG. 3

Fig 4

q^2 (GeV/c)^2

$\dfrac{d\sigma}{dq^2}$ nb$\Big/$(GeV/c)^2

f^{-2}

(90°)

(60°)

(45°)

(30°)

(20°)

2nd res.

FROM ELECTRON DATA
EXTRAPOLATED USING
ROSENBLUTH FORMULA

ROSENBLUTH FORMULA (ELASTIC)

(E_μ = 3 GeV)

100   75   50   25

4   3   2   1   0

10   100
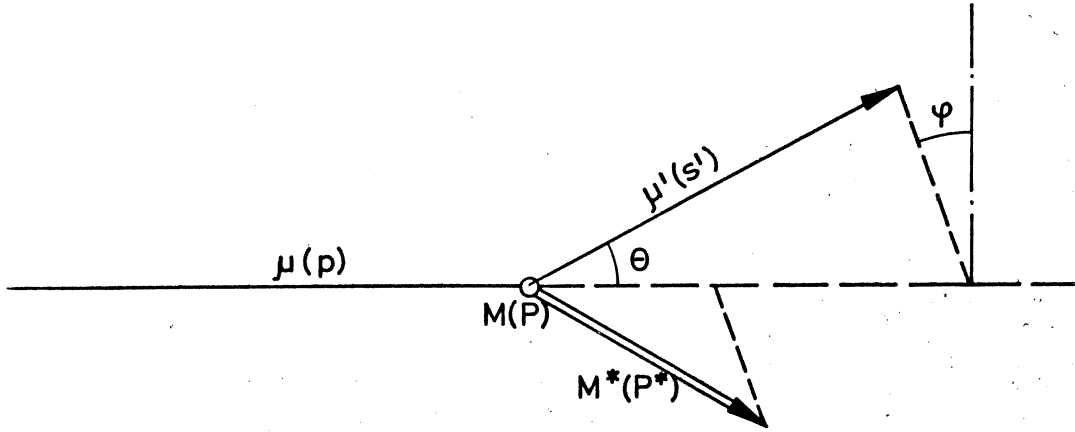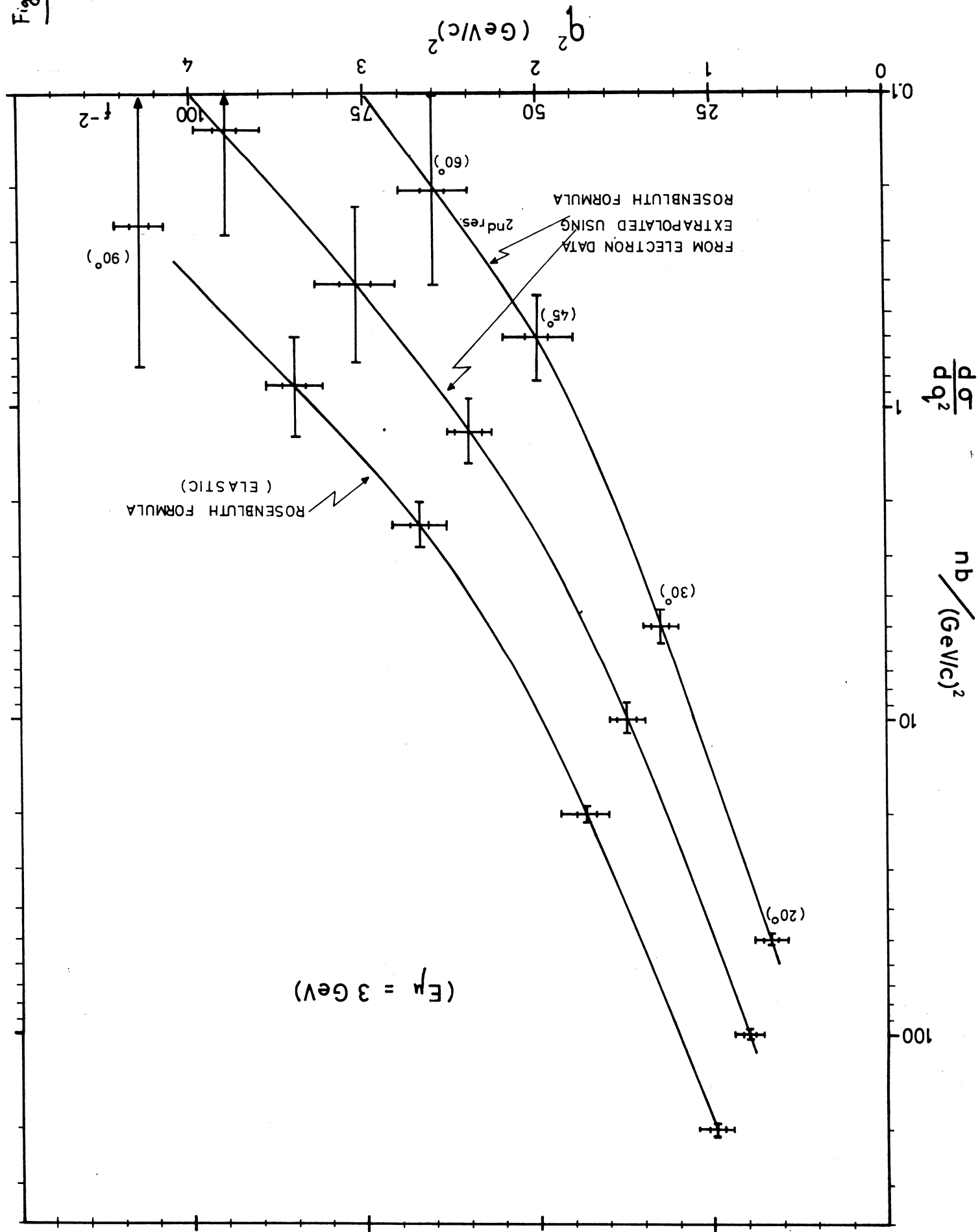
Fig. 5a

$Q_\nu^2 = 1 \dfrac{(Gev)^2}{c}$

$\dfrac{d\sigma}{dE_\gamma}$ Arbitrary units

E_γ (Gev)

Fig.5b

$$\frac{d\sigma}{dE_\gamma}$$
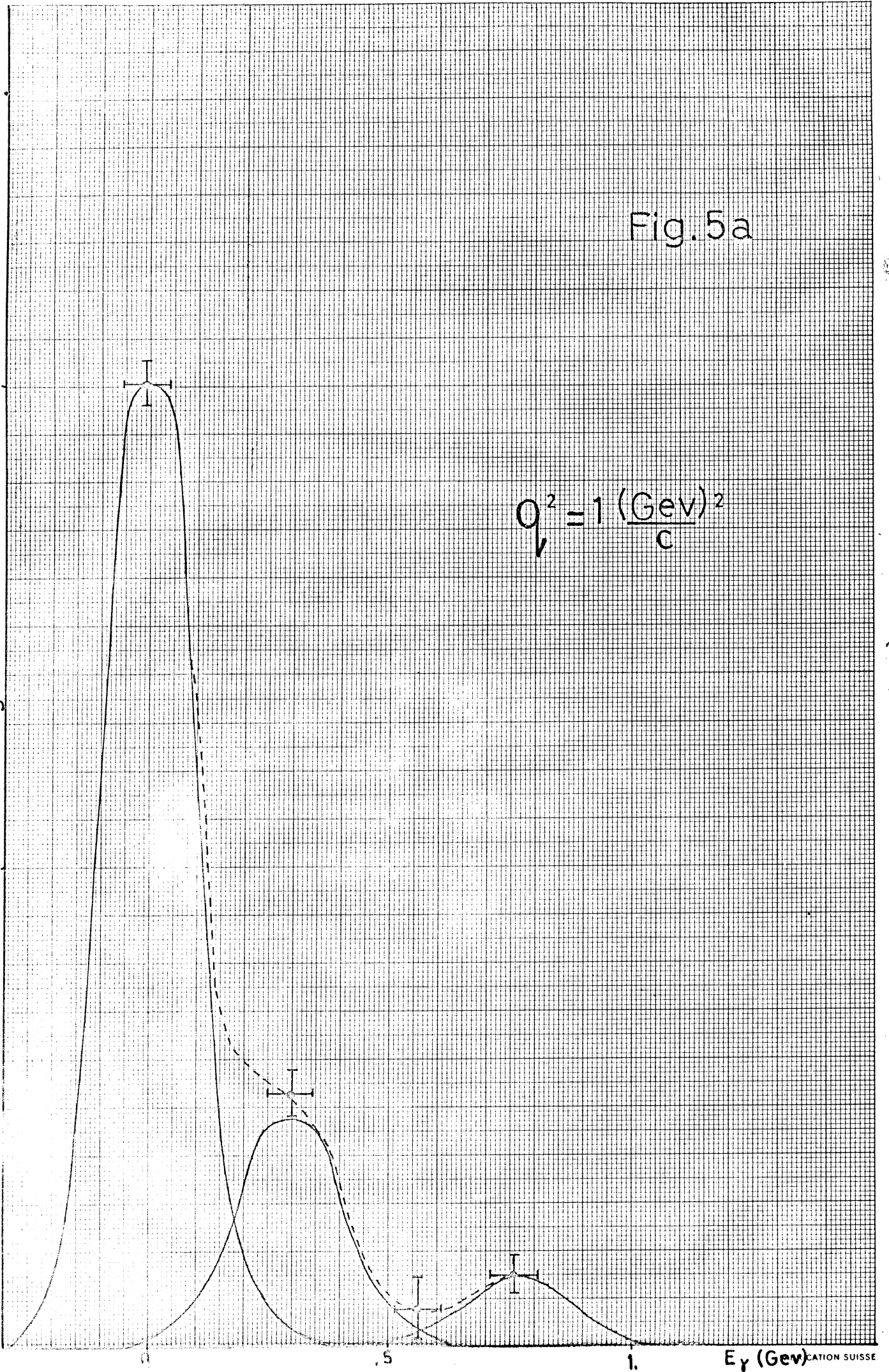
$$q^2 = 1(GeV/c)^2$$
$$(\Delta\theta = 10°)$$

Arbitrary units

200

150

100

50

0

0.5

1.0

E_γ (GeV)

FABRICATION SUISSE

Fig.6

$Q^2 = 3 \left(\dfrac{Gev}{c}\right)^2$

$(\Delta\theta = 10°)$

Arbitrary units

E_γ (Gev)