Proposal for Experiments
on High Energy Muons.

Van de 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 100 m long, straight beam guide and two other sections for the removal of hadrons and momentum analysis, adding up to 50 m. In total the whole device is ~150 m long (see fig. 1).

Two operational possibilities are considered: the short pulse extraction (~2.2 μs) and the long pulse extraction (~100 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 30 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. 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 characterized 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 the experimental apparatus.

1) Muon proton scattering has so far been studied up to $q^2 = 1 (\text{Gev/c})^2$ (see ref. (2)). With the proposed beam we can investigate $d\sigma/dq^2$ up to $q^2 \approx 3 (\text{Gev/c})^2$. 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 $\Delta q^2$, in 4-momentum determination, when the momentum of the incident muon is uncertain within $\frac{40}{p} \approx 5\%$, which is the natural spread in the long pulse beam at the exit of the guide.

This uncertainty probably can be reduced to $1\%$ determining electronically the incident momentum (see sect. B).

The inner cuts in the horizontal bars in fig. 4 indicate the improved $\Delta q^2$ resolution obtainable in this latter case.

Fig. 5a and 5b show the resolution in the missing mass determination at $q^2 = 1 (\text{Gev/c})^2$. The familiar quantity

$$E_y = \frac{M^2 - M_y^2}{2M}$$

is used in place of $M^2$. Fig. 5a and 5b show the discrimination obtainable, respectively with $\frac{\Delta p}{p} = 5\%$ and $1\%$.

Fig. 6 shows the same as 5a ($\Delta p = 5\%$) at $q^2 = 3 (\text{Gev/c})^2$.

A possible extension of the measurements of $\mu p$ scattering up to $q^2 = 6 (\text{Gev/c})^2$ is being studied and calculations are being carried out.
2) To our knowledge no experiment on inelastic muon scattering has been reported. The most recent and complete experiments with electrons, 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 obtained in determining $d^2 \sigma /dq^2 dM^2$ under the conditions of table 1

$$\frac{4\pi}{\rho^2} = 5\% \text{ and } 1\%$$

Inelastic lepton-proton scattering affords a test of the $C_{se}$ and $T_{se}$ non-invariance of electromagnetic interactions. If such invariances break down, there can be correlations of the type

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

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 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) Lepton Pair Production by Muons.

Recently Brodsky and Ting (6) have made a theoretical study of electron pair production by muons. They have determined kinematical configurations which will insure that either diagrams with "time-like" or "space-like" protons will give the dominant contribution to the cross-section and at the same time give a production rate which make triple coincidence experiments possible.

They select configurations whereby (A), the pair is detected symmetrically with respect to the muon scattering plane and (B) the total momentum of the three final leptons is in the incident $\mu$-direction. (A) insures vanishing interference contribution between spacelike and timelike diagrams, (B) insures that the momentum 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 ranges of the kinematics; the cross section is nominally \( \text{10}^{-32} \text{ cm}^2 \) \( \text{(Mev)}^2 \) \( \text{(sr)}^3 \) at \( p = 10 \text{ GeV/c} \), \( Z = 10 \) for \( t = (0.1 \text{ MeV/c})^2 \) in the ranges \( \Delta \theta_1 \times \Delta \theta_2 \times \Delta \theta_3 \times 20 \text{ rad} \), \( \Delta \phi_2 \times \Delta \phi_3 \leq 40^\circ \), \( \Delta E_1 \times \Delta E_2 \times \Delta E_3 \geq 1 \text{ GeV} \), giving a rate of \( \text{10}^{-7} \) per incident muon. Timelike momentum transfers up to \( 1 \text{ (Gev/c)}^2 \) will give feasible rates.

An important test of muon 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 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 (\( \mu^+ \mu^- \) 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 appropriate 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 discussed above. We believe that, using a system of scintillators and magnetic field, the momentum of each muon can be determined to $1\%$ accuracy and its direction known to $\sim 1\text{ mrad}$. This implies the use of the long pulse beam ($\sim 0.1\text{s}$).

2. The momentum and angle determination of the final products will be carried out by a wirechamber-magnet system — although arranged in a different geometry. For experiments on a hydrogen target we are considering the use of a pulsed magnetic field, cylindrically symmetric, which will allow a detection of events over an azimuthal angle 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 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 1/2 years from the moment of approval by NERC.

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

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Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Primary muon momentum</td>
<td>$P_\mu = 3$ GeV/c</td>
</tr>
<tr>
<td>Angular spread at exit from the guide</td>
<td>$\Delta \alpha = 1.5$ degrees</td>
</tr>
<tr>
<td>Momentum spread at the exit from the guide</td>
<td>$\Delta P_\mu / P_\mu = 5$ o/o</td>
</tr>
<tr>
<td>Length of the target of liquid hydrogen</td>
<td>$1$ m</td>
</tr>
<tr>
<td>Muon flux (long extraction) in $\frac{\Delta P}{P} &lt; 5%$</td>
<td>$10^6 \mu$/pulse of $3 \times 10^9$ protons</td>
</tr>
<tr>
<td>Precision in the determination of the scattered momentum</td>
<td>$\Delta P_\mu' / P_\mu' = 2$ o/o</td>
</tr>
<tr>
<td>Precision in the determination of the angle of scattering</td>
<td>$\Delta \theta = 1/2$ degree</td>
</tr>
<tr>
<td>Azimuthal acceptance of the detector</td>
<td>$\Delta \phi = 2 \pi$</td>
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<td>Minimum angle of scatter</td>
<td>$\phi &gt; 20^\circ$</td>
</tr>
<tr>
<td>Exposure</td>
<td>$10^7$ pulses</td>
</tr>
</tbody>
</table>
References.

1. S. Van de Meer, NPA/Int. 65-12 (See also Cern 62-12 by the same author).
4. B.A. Cone et al, P.R.L.
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 of the differential cross sections, under the conditions listed in table 1. The horizontal bars indicate the error in $q^2$ determination (see text).

Fig. 5. Mass resolution obtainable under the conditions of table 1 at $q^2 = 1 \text{ (GeV/c)^2}$ and

\[
E_y = \frac{M^2}{2M} \hspace{1cm} (\text{see text})
\]

Fig. 5a: $\Delta p / p = 0.05$

Fig. 5b: $\Delta p / p = 0.01$

Fig. 6. Mass resolution obtainable under conditions of table 1 at $q^2 = 3 \text{ (GeV/c)^2}$ and $\Delta p / p = 0.05$
FIG. 1 (FROM S. VAN DER MEER, REF(1))
\[ \frac{dN}{dp_\mu} \text{ per incoming proton} \]

**SHORT PULSE (≤2 ms)**

\( i = 100 \text{ kA} \)

**TOTAL** \( 2.6 \times 10^{-3} \) **MUONS PER PROTON**

**LONG PULSE (100 ms)**

\( i = 25 \text{ kA} \)

**TOTAL** \( 2.4 \times 10^{-4} \) **MUONS PER PROTON**

**FIG. 2** (FROM VAN DER MEER, REF.11)
\[ Q_v^2 = 1 \left( \frac{\text{Gev}}{c} \right)^2 \]
Fig. 5b

\[ Q^2 = 1\text{(GeV/c)}^2 \]

\[ (\Delta \theta = 10^\circ) \]
Fig. 6

\[ Q^2 = 3 \left( \frac{\text{GeV}}{c} \right)^2 \]

\[ (\Delta \Theta = 10^\circ) \]