HADRON PRODUCTION IN DEEP INELASTIC MUON SCATTERING

H.E. Montgomery
European Organisation for Nuclear Research, Geneva, Switzerland
Workshop on Fixed Target Physics at SPS

Report to which the following persons contributed:
J.J. Aubert, C. Benchouk, H. Braun, S.C. Brown, R.W. Clift, G. Coignet,
V. Eckardt, J. Favier, C. Gössling, J. Nassalski, P. Renton, N. Schmitz,

ABSTRACT

Future possibilities of physics with the final state hadron system in muon scattering are considered in the light of work done so far at the SPS and planned for the Tevatron.

1. INTRODUCTION

The physics interest in the study of the hadronic final state in muon scattering is twofold.

(a) - A study of production mechanisms.
(b) - A study of fragmentation and radiative QCD jets.

The existing experiments which are of primary concern when considering muon scattering in the years ≥ 1985 are:

(a) - e⁺e⁻ annihilation
    Petra, Pep

(b) - ν(ν̄)N
    BEBC, Fermilab 15'

(c) - μN
    NA2 (SPS)
    NA9 (SPS)
    NA28 (SPS)
    E665 (Tevatron)

In general lepton scattering is complementary to e⁺e⁻ experiments and there are some aspects of QCD tests which demand data from both. The interest of a comparison with e⁺e⁻ data at similar energies lies not in rivalry but the necessity to confront QCD with a wide spectrum of pertinent data so that a quantitative determination of ostensibly equivalent parameters may be made in different reactions. However, lepton scattering experiments have an advantage in the definition of the parton direction and identity.
Neutrino scattering\(^1\) may be considered in much the same light as muon scattering. Both define the struck parton jet well although the neutrino does marginally better with the diquark system and antineutrinos are the only reliable source of d quark fragmentation functions. However neutrino scattering suffers in general fragmentation and QCD studies from several major defects.

(a) - Lack of energy necessary to separate adequately 1, 2 and 3 parton fragmentation systems.
(b) - Lack of statistics.
(c) - Lack of definition of the momentum and direction of the exchanged virtual boson.
(d) - Lack of charged particle identification.

By far, the most relevant "competition" to any future work at the SPS is provided by the experiment NA2 (SPS), from which illustrative data will be used in this report, by NA9, NA28 (SPS) which are running SPS experiments with a rather complete acceptance and charged particle identification and by E665 which for brevity can be described as the Tevatron version of NA9. Compared to NA2, NA9 and E665 (as presently proposed) have a more complete detection and particle identification system but are lower luminosity experiments partly due to target length limitations and partly due to limitations in the streamer chamber repetition rate.

In the rest of this report we will consider the current physics interests\(^2\) in the light of present data and the possibilities of the above experiments. Following the evident needs a possible apparatus for 1985 will be described. In addition the indirect measurement of $B\bar{B}$ production through its multimuon final states will be considered. This report is by definition a summary and fails to do justice to the detailed work performed by the members of the subgroup which was presented in the parallel sessions of this workshop.

2. QUARK PARTON MODEL

The basis of all discussion of deep inelastic scattering is the Quark Parton Model illustrated in fig. 1. Within this model the production mechanism is expected to be well described by the photon quark interaction and the unknowns under study in hadron production are the various fragmentation functions of quarks $D^q(z)$ and of diquarks $D^{qq}(z)$. In muoproduction for $x_{Bj} < 0.05$, scattering is from the quark antiquark sea (see fig. 2) and there is expected to be essentially an equal number of positive and negatively charged hadrons produced. For higher $x_{Bj}$ the charge 2/3 u quark dominates at the level of 90%. These characteristics can be seen in the data\(^3\) illustrated in fig. 3 where the z weighted distributions are shown for each charge in 3 different $x_{Bj}$ regions.
Fig. 1: Conventional QPM picture of Deep Inelastic lepto production of hadrons

Fig. 2: Fraction of different quarks participating in the scattering as a function of $x_{ Bj}$
Fig. 3: Distributions of positive and negative hadrons as a function of $Z$ for three different $x_{Bj}$ regions in muon scattering.

A further detail of the fragmentation parameters is for example the production ratio between vector and pseudoscalar mesons. Recent data\(^4\) are shown in fig. 4 in which a comparison between $\pi^+$ and $\rho^+$ production is made. At $z = 1$ the data are equal and this provides a measure of $a_V/a_S$ since at $z = 1$ only direct production is possible by definition. The resultant value $a_V/a_S = 1.0 \pm 0.3$ (stat) $\pm 0.4$ (syst) differs from the value 3 expected from spin counting. If this were a mass effect then a measurement of $K^+/K$ would be illuminating. NA9 may provide this measurement for which particle identification is necessary.

Baryon/antibaryon production has been seen to contribute $\approx$ 10% of the hadrons in the fragmentation process however the exact production mechanism is as yet obscure. A clue that gluons may be relevant is provided by some preliminary data\(^4\) on the $p_T$ dependence of the ratio $p/(all +ve)$ and $p/(all-ve)$ shown in fig. 5. These data contain $\approx$ 2000 identified protons and antiprotons and are based on $\approx$ 500k muon scatters from NA2. NA9 will have a better identification but many fewer events and a similar total number of identified protons and antiprotons is expected. One can therefore conclude that a definitive study of baryon production needs good particle identification but also higher statistics than offered by NA9, E665.
Fig. 4: Comparison of production of $\rho^0$ and $\pi^0$ mesons in muoproduction.

Fig. 5: The ratio of (p/all-ve) and ($\bar{p}$/all-ve) hadrons as a function of $P_T^2$. 
3. QCD CORRECTIONS TO FRAGMENTATION
(Report of W. Stockhausen to Parallel Sessions)

Beyond the parton model leading order QCD corrections modify the fragmentation functions $P^B(z)$ such that they acquire a $Q^2$ dependence $P^B_{Q^2}(z, Q^2)$ which is described by a set of Altarelli-Parisi evolution equations. Although scale breaking has been observed in $e^+e^-$ production its interpretation is complicated by the plethora of heavy quark decays. In neutrino scattering $Q^2$ dependence is only seen for $W < 4$ GeV. In muon scattering, data with statistical and systematic errors at the 10% level, exist and the $Q^2$ dependence is seen to be weak. The data are shown in fig. 6 and, in anticipation of the next point, are shown for fixed $x_{Bj}$.

In the hadronic final state, strong next to leading order effects are expected to appear as a breakdown of the factorisation, between the variables $x_{Bj}$ and $z$, which is present in both the QPM and leading order QCD. This appears as an $x_{Bj}$ dependence (fig. 7) of the fragmentation function at fixed $Q^2$. Quantitative model estimates of

![Graphs showing $Q^2$ dependence of fragmentation yields for 5 different $Z$ values in four bins of $x_{Bj}$. The solid curve is a QCD calculation [8] the dashed lines represent the Quark Parton Model.](image)
the QCD corrections have been made and rough agreement with the data is seen, however the large number of independent fragmentation functions which contribute to unidentified hadron data give many degrees of freedom. Furthermore, the data and the models can be reduced (fig. 8) to a dependence on a single variable $W^2$ which, within errors, requires no residual dependence on either $x_{Bj}$ or $Q^2$. Note that this breakdown of factorisation is one of the few observable next to leading order QCD effects, it is not present in $e^+e^-$ annihilation.

In addition to the classical perturbative QCD effects there are expected to be significant higher twist effects. In general these are 'edge of phase space' effects and lead to the dependence of the fragmentation on $y = v/E$. Within the models of Berger this can be understood as the observation of a very high $z$ pion forcing the quarks of the mass shell and thus inducing a non-zero longitudinal photon coupling. Also some recent calculations suggest that observable effects should be present in $\rho^+\rho^-$ production.

It is clear that in this field the confrontation with QCD is not yet really discriminative. Advances are possible in muon physics since the systematic errors on the measurement of $v$ are adequate however the charged pions must be identified to reduce the number of fragmentation functions in the model calculation and to avoid problems from "mass effects". NA9 will not have high enough statistics nor will E665. This is a clear field for a new experiment, run with high luminosity, at several different energies to look at the $y$ dependence as well.
4. PRODUCTION FROM HIGH A NUCLEI

(Report from C. Coignet to Parallel Session)

4.1 How does fragmentation work?

As sketched in fig. 9, fragmentation, in the laboratory frame, is expected to take place over a long distance of the order of z 100 Pm. If this is the situation then differences in the hadrons produced from different nuclei provide information on the nature of confinement and the interaction of fragmenting quarks with nuclear matter. Within the model of Bialas and Bialas\textsuperscript{11)} there is a relationship

\[
\frac{1}{N} \left( \frac{dN}{dz} \right)_{A_2} \quad \text{high } z \quad \text{high } \gamma_{\text{cms}} \quad \frac{d^eff}{q^N}\
\]

Data have been presented by NA2\textsuperscript{4)} on a comparison between hadrons produced on Hydrogen, Carbon and Copper targets. A publication on these data is in preparation but they, surprisingly for some people, indicated that the fragmenting quark at high energies takes little note of its surroundings, this is illustrated by plots as a function of \( y \) and \( p_T^2 \) in figs. 10 and 11. There are also more recent ideas\textsuperscript{12)} which might expect enhancement of the parton reinteraction probability if gluons are emitted.
Fig. 9: Sketch of virtual photon interaction with a quark in a nucleus

4.2 Nature of the photon interaction

The detection and study of the hadronic debris resulting from lepton scattering on nuclei has been strongly advocated\(^{13}\) as a means to study the nature of the virtual photon interaction. This line of thought has been given new impetus by the observation\(^{14}\) of the anomalous behaviour of the ratio between iron and deuterium nuclei. If indeed this phenomenon can be related to an increase of the \(q\bar{q}\) sea then an increase in the production of strange and charm meson pairs would be expected for high \(A\). On the other hand if the effect is related exclusively to virtual pion states a change in the \(K/\pi\) ratio would be expected.

The presently approved program within the NA28 proposal is for \(\sim 10\) days exploratory work with high \(A\) nuclei. If these were used with \(\chi_e^{13}\) in the streamer chamber at 20 atmos they would yield \(\sim 10\) K deep inelastic events. These would not provide a study of anything but the gross features. A "reasonable" experiment with a series of high pressure targets (\(Xe^{13}, Kr^{84}, Ar^{84}, Ne^{20}, He^{4}\)) would consist of \(\sim 50-60\) days running, with a resultant \(\sim 20\) K statistics on several targets. It would not be necessary to modify the present NA29 apparatus.

5. QCD JETS

The conventional diagrams relevant to QCD jet production are shown in fig. 12. In any discussion of jets it should be remembered that the QCD process e.g. fig. 12 a) is a bremsstrahlung type of process peaked at zero degrees and therefore any observation of jets is necessarily in the tails of various kinematic distribution \((p_t^2)\). The behaviour of \(p_t^2\) with kinematics is expected to be given by\(^{15}\)

\[
\langle p_t^2 \rangle \propto \alpha_s(Q^2) \cdot W^2,
\]
Fig. 10: Comparison of hadron yields from hydrogen copper and carbon targets as function of c.m.s. rapidity ($y^*$) for two different ranges in $v$.

Fig. 11: As fig. 10 but as function of $p_t^2$. 

- 75 -
the dependence on $W^2$ coming from the phase space for gluon emission, such behaviour is observed\textsuperscript{16}). In contrast the $p_T$ associated with the fragmentation of any parton is not expected to change and this is the limiting resolution. (Unfortunately our apparatus is not sensitive to direct partons). Given these contrasting behaviours it is clear that there is an advantage in going to high energies. This is illustrated in fig. 13 where the tails in $\sum_{\text{in}} p_T^2$ are compared for two different data sets with a mean $W$ differing by a factor 2. The tail is clearly much more pronounced in the higher energy data set. In this higher energy range it is then possible (fig. 14)\textsuperscript{17}) to observe jet like energy flow structures if a $p_T^2$ cut is applied to the data.

At the present time there is still a lot to learn about QCD jet structures, among the questions for Deep Inelastic Scattering are:

(a) How does the diquark target jet behave as a function of $W^2$ for $W^2 > 100 \text{ GeV}^2$? This should be answered by NA9.

(b) How does the event structure vary as a function of $W^2$ up to energies equal to that of Petra and Pep? This can be answered by E665 at CMS energies up to $W^2 = 1400 \text{ GeV}^2$ but not at the SPS where the limiting muon energy is 325 GeV.

(c) What are the flavour and charge properties of the jet structures. This will be difficult in either of NA9/E665 as presently concieved because of lack of statistics.

(d) How do the jet structures behave in topology, flavour etc. as a function of $x_{Bj}$? Can the transition from $qg \rightarrow \bar{q}q$ be seen?

Again as for (c) NA9 and E665 seem to be short of statistics and there appears to be a clear case for an improved high luminosity, good particle identification muon experiment.
Fig. 13: $\sum_{\text{out}} p_T^2$, $\sum_{\text{in}} p_T^2$ for two data sets with different energy compared with Quark Parton and QCD model calculations.

Fig. 14: Distribution of energy flow (a) with no cut on $p_T^2$ (b) with cut of $p_{T\text{max}}^2 > 2 \text{ GeV}^2$
6. HEAVY FLAVOUR PRODUCTION

(Report of C. Gössling to Parallel Sessions)

Charm production by muons is well described by the photon gluon fusion model which is based on the diagram shown in fig. 12(b). The experimental studies have been performed by the NA2\textsuperscript{18}) and BFP\textsuperscript{19}) experiments at SPS/FNAL energies. The technique detects the semi-leptonic charm decays via observation of extra final state muons and uses a calorimetric target to signal the missing neutrino energy. The only bar to the measurement of the upsilon production and of bottom hadron production is luminosity. The extension of this proven technique to the heavier quark systems has been studied in the working group and a report prepared\textsuperscript{20}) which is included after this contribution. The proposed apparatus will of course be sensitive to exotic unexpected multimuon final states and would provide a limit on the production of super symmetric photino particles\textsuperscript{21}).

The direct detection via hadron decay has been considered and rejected. It does not provide the statistics required for a study of production and fragmentation.

7. PHOTON DETECTION

7.1 Single Photon Production

Measurements of π⁺ production\textsuperscript{22}) are strongly complementary to charged hadron production. Single photons (not products of π⁺ decay) are complete jets in themselves. In muon scattering the interference between the Bethe-Heitler and Compton amplitudes fig. 15 is proportional to the cube of the muon charge and is therefore different for μ⁺ and μ⁻. Analysis of NA2 data is at present under way. It is necessary to await the results before judging on a future program.

7.2 2 γ Physics

(Report of G. Smadja to Parallel Sessions)

In principle very forward π⁺/η⁺ production can proceed by the Primakoff effect (fig. 16) in which the virtual photon (Q²) interacts with the Coulomb field of a heavy nucleus. Since Q² < 0 it is necessary to go to high energies to satisfy the coherence conditions. At lower energies the technique has been used at Q² = 0 to determine the π⁺/η⁺ lifetime\textsuperscript{23}).

The process has been recently calculated\textsuperscript{24}). It has been shown that the hadronic wave functions involved in the form factor F\textsubscript{π⁺γ}(Q²), fig. 17a, and the conventional charged pion form factor F\textsubscript{π⁺}(Q²), fig. 17 b, are related such that a measurement of the strong coupling is obtained which is independent of the uncalculable functions.

\[ a_8 (Q^2) = \frac{1}{4\pi Q^2} \frac{F_\pi (Q^2)}{[F_{π⁺γ}(Q^2)]^2} \]
"Single"

\[
\begin{array}{c}
\mu \rightarrow \gamma \\
q \gamma \\
\end{array}
\quad
\begin{array}{c}
\mu \rightarrow \gamma \\
q \gamma \\
\end{array}
\]

Fig. 15: Interference of Bethe-Heitler and Compton diagrams for single photon production.

\[
F_{\pi Y}(Q^2)
\]

Fig. 16: Sketch of Primakoff process.

\[
F_{\pi Y}(Q^2)
\]

\[
F_{\pi Y}(Q^2)
\]

\[
\gamma \rightarrow \pi^0
\]

\[
\gamma \rightarrow \pi^+
\]

Fig. 17: The form factors $F_{\pi Y}$ and $F_\pi$ calculated using factorization between QCD and the hadronic wave functions $\phi$. 
Highish values of $Q^2$ are required but as shown in fig. 18 the experiment is statistically feasible out to $Q^2 > 2 \text{ GeV}^2$. $F_\pi(Q^2)$ is known out to several GeV$^2$.

The technical problem is to operate the photon detector as close as possible to the muon beam. It is conceivable that this type of extension might provide some competition for $e^+e^-$ storage rings in the field of 2 photon physics.

8. THE APPARATUS

In section 3 and 5 it was pointed out that the current NA9 experiment and the E665 experiment at Fermilab (as presently conceived) failed to satisfy the need for good statistics in the study of fragmentation and jet production. The limitations come from the target length 1 m and the repetition rate of the SC which limit final physics samples for ~1 year running to 50-100 K events.

Fig. 18: Yield of events from the Primakoff process as a function of $Q^2$. The statistical errors are indicated.
The obvious question as to whether a significant factor in luminosity (5–10) can be achieved with a modern design for a detector and with a larger target has been considered. The answer presented in an accompanying document [25] is unequivocally positive.

The solution presented involves a TPC as a vertex detector and ring imaging Cerenkov counters for charged particle identification. The total cost in a preliminary estimate would be $1/10 of 1 Lep detector and the construction time \( \approx 2 \) years. The solution studied is probably not unique and may not be the best but demonstrates clearly that the technology is not a limitation.

9. CONCLUSIONS

We have considered hadron production by muons in the light of existing experiments. The fields examined and conclusions presented in the report are:

- QCD corrections to fragmentation – high statistics, good particle identification required – needs new experiment.

- Study of Quark fragmentation mechanism using nuclear targets – needs \( \approx 1 \) year SPS dedicated running – no new experiment required.

- Study of QCD jets – while study of \( W^\pm \) dependence requires Tevatron E665 a detailed high statistics study is also required with good particle identification either at Tevatron or SPS.

- Heavy flavour production – Extension of current calorimeter/muon detection techniques to bottom quark system needs luminosity and good calorimeter.

- Photon detection provides access to interesting 2\( \gamma \) production mechanisms.

- The high luminosity good particle identification experiment alluded to above is eminently practical.

As a final conclusion it seems clear that hadron production by muons has shown its worth in comparison to a priori competitive experiments. It seems to be a suitable candidate for membership of the club of second phase SPS experimental physics.
REFERENCES

1) A detailed comparison between muon-anti-neutrino scattering was prepared in the working group by P. Rention, N. Schmitz and W. Wittek and was presented to the common muon/anti-neutrino parallel session by W. Wittek.

2) For recent reviews of Hadron Production in Muon Scattering, see:


12) G. Ingelman, Private Communication.

13) For a review of the situation for nuclear targets see


17) EMC, J.J. Aubert et al., Phys. Lett. 100B (1981) 433 (see also Ref. 2)).


20) R.W. Clifft et al., A Study of Beauty and Charm Muoproduction at the SPS.
    See these proceedings.

21) J. Ellis and D.V. Nanopoulos, Search for Photinos using high energy muon beams,

22) EMC, J.J. Aubert et al., in preparation, see also ref. 4).


25) H. Braun, "Ideas for a high luminosity muon physics detector with complete
    particle identification". See these proceedings.