EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCHCERN-EP/80-61
May 8th, 1980A STUDY OF DIMUON EVENTS IN 280 GeV
MUON INTERACTIONS

The European Muon Collaboration

CERN¹- DESY(Hamburg)²-Freiburg³-Kiel⁴-Lancaster⁵-LAPP(Annecy)⁶-Liverpool⁷-
Oxford⁸-Rutherford⁹-Sheffield¹⁰-Turin¹¹- and Wuppertal¹².

J.J. Aubert⁶, G. Bassompierre⁶, K.H. Becks¹², C. Best⁹, E. Böhm⁴,
F.W. Brasse², C. Broll⁶, J. Carr⁹, R.W. Clift⁹, J.H. Cobb⁵, G. Coignet⁶,
F. Combley¹⁰, G.R. Court⁷, J.M. Crespo⁶, P.F. Dalpiaz¹¹, P. Dalpiaz¹¹,
W.D. Dau⁴, J.K. Davies⁸, Y. Déclais⁶, R.W. Dobinson¹, J. Drees¹²,
A. Edwards⁷, M. Edwards⁹, J. Favier⁶, M.I. Ferrero¹¹, J.H. Field^{1a},
W. Flauger², E. Gabathuler¹, R. Gamet⁷, J. Gayler², P. Ghez⁶, C. Gössling²,
J. Haas³, U. Hahn^{3b}, K. Hamacher¹², P. Hayman⁷, M. Henckes¹², H. Jokisch⁴,
J. Kadyk^{6c}, V. Korbel², M. Maire⁶, L. Massonnet⁶, A. Melissinos^{1d},
W. Mohr³, H.E. Montgomery¹, K. Moser³, R.P. Mount⁸, P.R. Norton⁹,
A.M. Osborne¹, P. Payre⁶, C. Peroni¹¹, H. Pessard⁶, U. Pietrzyk¹², K. Rith¹,
E. Schlösser³, M. Schneegans⁶, T. Sloan⁵, W. Stockhausen¹², H.E. Stier³,
J.M. Thénard⁶, J.C. Thompson⁹, L. Urban⁶, H. Wahlen¹, D. Williams⁷,
W.S.C. Williams⁸, S.J. Wimpenny¹⁰.

ABSTRACT

Dimuon production has been observed in 280 GeV μ^+ iron interactions. Cross sections are presented for this process in the kinematic regions covered by the apparatus acceptance. The data are compared with calculations for charm production using a photon gluon fusion model and found to be in a good agreement. Contributions from other known processes are found to be relatively small.

(Submitted to Phys. Letters)

-
- a) now at DESY, Hamburg, Germany
 - b) now at Rheinmetall, Düsseldorf, Germany
 - c) on sabbatical leave from LBL, Berkeley, California, U.S.A.
 - d) on sabbatical leave from Rochester University, Rochester, N.Y., U.S.A.

Dimuon events have been observed previously in both neutrino [1] and muon interactions [2]. In each case the events were interpreted as the production of charmed mesons which decayed semi-leptonically to muons. In this paper we report measurements on the production of dimuons by incident muons from data taken at the same time as those used for our elastic J/ψ analysis [3].

The experiment was performed in the muon beam at the CERN SPS using the EMC forward spectrometer [4]. Fig. 1 shows a diagram of the apparatus. Muons of energy 280 GeV were incident on a 3.75 meter long iron-scintillator target containing 2cm thick iron sheets interspersed with 0.7cm thick scintillator sheets. The target acted as a total absorption calorimeter (STAC) allowing energy measurements of the hadron showers produced by muon interactions. The shower energy measurement has a resolution of $\sigma/E = 0.56 E^{-0.4}$ (E in GeV) as determined from single arm data during this experiment. The momentum of each incident muon was determined to an accuracy of ± 0.7 GeV/c and the angle to ± 0.2 mrad. The spread in momentum of the beam was 8%, FWHM.

Particles leaving the target were detected and momentum analysed in the drift chambers, labelled W1-5, and the multiwire proportional chambers, labelled P0-3 in fig. 1. The tracks of particles which traversed the magnetised iron hadron absorber were reconstructed in the drift chambers W6-7 and were associated with muons. Each of the large chambers contained a dead region in the centre through which the beam passed. Secondary particles which remained in the beam region were detected in the small proportional chamber, P0, which were designed to withstand a high particle flux.

The experiment was triggered by the scintillator hodoscopes H1 to H4 shown in fig. 1. The multimuon trigger used for this experiment demanded at least two particles passing through the iron absorber both of which satisfied a broadly smeared lower momentum cut at ~ 15 GeV/c. In addition to avoid triggers from the copious electromagnetic tridents one of the particles was required to have a minimum vertical angle of ± 13 mrad. These requirements were met by forming coincidences between selected

hodoscope elements. A target pointing requirement eliminated most of the unwanted triggers from beam halo. The remainder were rejected by the veto counters V1-3 shown in fig. 1.

The beam intensity was monitored by the small scintillator hodoscope H5. The total number of muons for this experiment was 8×10^{10} corresponding to a total luminosity of $7 \times 10^{37} \text{ cm}^{-2}$.

Events with two reconstructed muon tracks were selected for analysis. Figs. 2a) and b) show the missing energy for the opposite sign pair (+-) and the like sign pair (++). The missing energy is defined as

$$E_{\text{MISS}} = E_{\text{Beam}} - E_1 - E_2 - E_{\text{STAC}}$$

where E_{Beam} is the measured energy of the incident muon, E_1 and E_2 are the energies of the outgoing muons and E_{STAC} is the shower energy measured in the STAC target. The distributions show a peak centred at $\sim 20 \text{ GeV}$ and a large number of events in the +- sample at high missing energy which are ascribed to tridents at low Q^2 . The latter events were found to have an extra track in P0 or a hit in H5. Events with this signature were taken away from the dimuon data sample and formed part of the three muon sample discussed in the following paper [5]. A cut in the vertex position was made to define a fiducial volume in the target, thus eliminating events with interaction vertices less than 5 absorption lengths from the downstream end of the target. Another cut was made to further minimise hadron punch through by rejecting events with more than 2 GeV in the last STAC element.

Figs. 2c) and d) show the missing energy distributions after making these reductions. The peak centred at 20 GeV remains with little residual background. A few tridents remaining at higher missing energy were eliminated by a missing energy cut at 90 GeV. 344 +- and 401 ++ events remained after these cuts. The faster muon was taken to be the scattered muon for the ++ sample. The +- sample, in which ambiguity does not exist, showed that misidentification of the scattered muon occurs in 16% of the events using this criterion. Monte Carlo simulation showed that this ambiguity produced negligible distortion of the spectra.

An acceptance weight was calculated for each event by reading it into a Monte Carlo simulation programme, which generated several hundred events with the same kinematic variables but varying azimuth and vertex position. Kinematic cuts were made on the data to eliminate events with low acceptance (large weight) thus defining the sensitive region of the apparatus. Events were accepted in the range $y (= \nu/E_{\text{Beam}}) < 0.91$, $Q^2 > 1 \text{ (GeV/c}^2\text{)}^2$, scattered muon angle $> 7 \text{ mrad}$, second muon energy $> 16 \text{ GeV}$. 497 events of the total sample survived these cuts. These data events were binned in each kinematic variable and the differential cross sections per bin integrated over all other kinematic variables were calculated by summing the acceptance weights in each bin. It should be stressed that these are not absolute cross sections but rather they are cross sections within the sensitive region defined by the above kinematic cuts. For this reason we label the cross sections σ^{CUT} .

The following normalisation corrections were applied to the data:

1. Dead times, random vetoing and beam hodoscope inefficiencies of $(10 \pm 2)\%$.
2. Random vetoing in P0 and H5 of $(30 \pm 5)\%$.
3. Track reconstruction inefficiency (including chamber inefficiencies) of $(10 \pm 2)\%$ per muon track.
4. Loss of events due to the energy cut on the last STAC element of $(9 \pm 1)\%$.

The cross sections for the ++ and +- samples were equal within the statistical accuracy and the two samples were therefore combined to give the totals for both signs of the second muon. Fig. 3 shows the measured differential cross sections in Q^2 , W (the virtual photon-nucleon c.m. energy), p_T^2 (the transverse momentum of the second muon relative to the virtual photon) and z (the ratio E_2/ν where E_2 is the second muon energy). There is an overall systematic error estimated to be $\pm 15\%$ which is not included in figs. 3 and 4. Radiative corrections were neglected in deriving these cross sections.

The smooth curves labelled π , K decays shown in fig. 3 represent calculations of the contributions to the cross sections from π and K decays produced in hadron showers from deep inelastic scattering [6]. The

mean neutrino energy from the decay calculation is 8.7 GeV which is lower than the mean missing energy observed in the data. A curve is also drawn in the z distribution to represent the asymmetric trident contribution where one muon has low energy and is outside the acceptance [7]. This shows that the events at high z can be accounted for by this process. Further contributions to the cross sections from the following sources were estimated (the numbers in brackets are upper limits expressed as fractions of the observed total cross section):

1. An incident muon undergoing bremsstrahlung of a real photon which interacts to produce a shower of hadrons, one of which decays to a muon ($<1\%$).
2. Production of low mass vector mesons which decay to two muons with one μ outside the acceptance ($<1\%$).
3. Production of hadrons by a deep inelastic scattering event with one of the hadrons in the resulting shower producing an inclusive dimuon event [8] with one muon undetected ($<0.5\%$).
4. Electromagnetic production of τ leptons one of which decays to a muon ($<0.5\%$).

None of these processes contributes significantly to the observed rates and we conclude that the dimuons are produced from another source. The large value of the mean missing energy also indicates that energetic neutrinos are produced by prompt decay rather than by π and K decay. The most likely particles which promptly decay to muons and neutrinos are members of the charmed particle family.

The data were therefore compared to models for charmed meson production. Curves are shown in fig. 3 which represent the calculated cross sections from a struck quark model. In this model the charmed quark density in the sea was taken from the parametrisation of Buras and Gaemers [9] and used to calculate the cross section for virtual photon-quark scattering. The c quark was assumed to be ejected, carrying the energy of the virtual photon, and to fragment to a D meson which subsequently decayed to a μ . It was assumed that the fragmentation

function for the c quark to D meson was constant (i.e. flat in z) and that the D meson would decay to a muon with a 10% branching ratio [10]. The weak interaction form factor for the decay was assumed to be 1.0 and the decay mode to be $K^*\mu\nu$ or $K\mu\nu$ with equal probabilities. The same cuts were placed on the model as in the data to calculate the cross sections in the sensitive region. It can be seen that the model predicts cross sections which are larger than the measured values suggesting that there is less charmed sea than previously thought [9].

To facilitate comparison with other models the data were corrected for the background contribution due to π and K decays, which is at the level of 20% of the total observed cross section. It can be seen from fig. 3 that this background preferentially populates the low p_T^2 region. Thus in order to reduce the background to $\sim 10\%$ and hence the significance of the uncertainty in its calculation, events with $p_T^2 < 0.25 \text{ (GeV/c)}^2$ were excluded from further comparisons. Also, to eliminate the remaining tridents, events with $z > 0.6$ were rejected.

Figs. 4 show the data, corrected as described above. The curves are the results of a QCD calculation using the photon-gluon fusion model for $c\bar{c}$ production [11]. For this calculation the running coupling constant of QCD was used with $\Lambda = 0.5 \text{ GeV}$. The mass of the charmed quark was taken to be 1.5 GeV. The conventional gluon distribution

$$\eta G(\eta) = 3(1-\eta)^5$$

was used, where η is the fraction of the nucleon's momentum carried by the gluon. It was assumed that each c quark would fragment to a D meson which then decayed to a μ as in the struck quark model described above. The predictions of the model are essentially unchanged if we assume that the c quark fragments into a charmed baryon providing that the $\Lambda_c \rightarrow \mu$ branching ratio is the same as that for $D \rightarrow \mu$. Again the same kinematic cuts were applied to the model as to the data. The agreement in both shape and normalisation between the model and the data is impressive. Furthermore, the model predicts a mean neutrino energy of 18.0 GeV in agreement with the observed mean missing energy of $(19.7 \pm 3.0) \text{ GeV}$.

To summarize measurements have been presented of the cross section in a defined kinematic region for dimuons arising from 280 GeV positive muons interacting with iron. The kinematics of the events indicate that they are attributable to charmed meson decay. If this hypothesis is assumed the data are well represented by the photon gluon fusion model for $c\bar{c}$ production. However, if the data are interpreted in terms of the struck quark model, the charmed quark content of the sea is lower by a factor of ~ 5 than that of reference [9].

We should like to thank all our colleagues at our home institutions and at CERN who have helped in the performance of this work.

REFERENCES

- [1] J.G.H. de Groot et al., Phys. Lett. 86B (1979), 103.
N. Armenise et al., Phys. Lett. 86B (1979), 115.
- [2] D. Bauer et al., Phys. Rev. Letters 43 (1979), 1551.
- [3] J.J. Aubert et al., Phys. Lett. 89B (1980), 267.
- [4] J.J. Aubert et al., Nucl. Instr. and Methods (to be published).
- [5] J.J. Aubert et al., Phys. Lett. (to be published), CERN-EP/80-62
- [6] Two independent calculations were made giving identical results. One of the calculations used the shower Monte Carlo programme described by A. Grant, Nuclear Instruments and Methods 131 (1975), 167. The second programme used the parametrised multiplicities of p-p scattering data from M. Antinucci et al., Lettere al Nuovo Cimento 6 (1973), 121. In this case pions and kaons were assumed to produce multiplicities similar to protons.
- [7] We thank D.Y. Bardin, J.I.N.R.(Dubna), for making available to us his programme for the calculation of QED tridents.
- [8] K.J. Anderson et al., Phys. Rev. Letters 37 (1976), 799.
R. Cassell et al., SLAC-PUB-2408 (1979).
- [9] A.J. Buras and K.J.F. Gaemers, Nucl. Phys. B132 (1978), 249.
- [10] A compilation of the branching ratios to electrons averaged over $D^\pm$ and D^0 is given by R.H. Schindler, SLAC-219 (1979). We assume that the muon branching ratio is the same.
- [11] M. Glück and E. Reya, Phys. Lett. 79B (1978), 453 and 83B (1979), 98.
J.P. Leveille and T. Weiler, Nucl. Phys. B147 (1979), 147.
The model calculations were based on the formulae in the appendix of the latter paper.

Figure Captions

- Fig. 1 : Layout of the apparatus showing a schematic dimuon event.
- Fig. 2 : Missing energy for $\mu^+\mu^-$ and $\mu^+\mu^+$ events. The smooth curve labelled single arm shows the observed missing energy distribution in deep inelastic single muon scattering events.
- Fig. 3 : Differential cross sections in the defined kinematic region $y < 0.91$, $Q^2 > 1 (\text{GeV}/c^2)^2$, $\theta_{\mu 1} > 7 \text{ mrad}$, $E_{\mu 2} > 16 \text{ GeV}$.
- Fig. 4 : Differential cross sections in the kinematic region as in fig. 3, corrected for the π , K decay background and with the additional cuts of $p_T^2 > 0.25 (\text{GeV}/c)^2$, $z < 0.6$. The curves are the calculated absolute values from the photon gluon fusion model [11] in the same defined kinematic region.

FIG. 1

FIG. 2

FIG. 3

FIG. 4