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PRODUCTION OF CHARMED PARTICLES IN 250 GeV μ^+ -IRON INTERACTIONS

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Abstract

Dimuon and trimuon events produced by the interaction of 250 GeV muons in an iron target have been studied and are shown to originate predominantly from charm production. The data are used to measure the contribution of charm to the nucleon structure function F_2 . The cross sections for real photoproduction ($Q^2 = 0$) of charm in the current fragmentation region are derived as a function of photon energy and are found to be $\sim 0.6\%$ of the total, hadronic photoproduction cross section in this energy range. The measured cross sections are found to be well represented by the photon-gluon fusion model. The charmed quark fragmentation function is obtained by using this model to fit the measured decay muon energy distribution and is found to be well represented by $\exp(1.6 \pm 1.6)Z$. The data are used to study the momentum distribution of the gluons in the nucleon. An upper limit of 1.4% (90% confidence level) is set on the branching ratio $D \rightarrow \mu\nu$ and a model dependent upper limit on the branching ratio $F \rightarrow \mu\nu$ is derived.

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Introduction

Measurement of the muoproduction of open charm is interesting as it can be used to investigate both the production mechanism for heavy quarks and the sub-structure of the nucleon. In particular, as shown below, it may be used to study the momentum distribution of the gluons inside the nucleon. The measurements are also necessary in order to understand fully the scaling violations which arise in deep inelastic muon scattering from the threshold effects in charm production. These effects must be understood quantitatively when fitting the measured evolution of the nucleon structure function F_2 to obtain the QCD scale parameter Λ .

In previous publications [1] dimuon and trimuon events from 280 GeV μ^+ -iron interactions were shown to be dominantly caused by open charm production in which the charmed particles decayed semileptonically to muons. This was demonstrated by the relatively large observed missing energy in the final state which was assumed to be carried away by unseen neutrinos from the decay. In addition, allowing for the different acceptance in each process, the ratio of the yields of the trimuon events to the dimuon events was consistent with the known semileptonic branching ratio for D mesons. Thus the dimuons originated mainly from the semileptonic decay of one charmed hadron and the trimuons from the decay of two charmed hadrons.

In this paper new data are presented on the muoproduction of open charm, studied through dimuon and trimuon events produced by 250 GeV μ^+ interactions in an iron-scintillator target calorimeter (STAC). The data come from a second experimental run with a factor ~ 5 higher luminosity than that reported in [1]. The higher statistical precision allows the cross sections to be determined as a function of two variables, eg. Q^2 and ν , so that the contribution of charm to the nucleon structure function, F_2 , may be measured.

Throughout this paper the following kinematic quantities are used:

$$-Q^2 = 4\text{-momentum transfer to the virtual photon} = (p_\mu - p'_\mu)^2$$

where p_μ and p'_μ are the incident and scattered muon 4-vectors,

$$v = \frac{p \cdot q}{M},$$

where $q = p_\mu - p'_\mu$ is the 4 vector of the virtual photon, M is the proton mass, and p is the 4 vector of the target nucleon;

$$Z_\mu = E_{\mu 1} / v,$$

$$Z_{\mu\mu} = (E_{\mu 1} + E_{\mu 2}) / v,$$

where $E_{\mu 1}$ and $E_{\mu 2}$ are the decay muon energies in the laboratory frame and

$$x = \frac{Q^2}{2Mv}.$$

The production mechanism for charm can be described in terms of two types of theoretical model, namely, the photon-gluon fusion model and the struck quark model. The photon-gluon fusion model [2] (Fig. 1a) is a first order QCD calculation, higher order processes being neglected. The virtual photon couples to a charmed quark of charge $\frac{2}{3}e$. The gluon couples to the charmed quark with a running coupling constant which is assumed to scale as $Q^2 + \hat{s}$ [18],

$$\alpha_s = \frac{12\pi}{25 \ln \frac{Q^2 + \hat{s}}{\Lambda^2}}$$

where $\hat{s}$ is the energy squared of the $c\bar{c}$ pair in the photon-gluon rest frame and Λ is the QCD scale parameter. Each charmed quark is assumed to fragment to a D meson where the D meson acquires a fraction Z_D of the charmed quark's momentum. One or both of the D mesons is then assumed to decay semileptonically to produce a dimuon or trimuon event respectively.

In the struck quark model (Fig. 1b) a charmed quark in the nucleon sea is ejected by a virtual photon. In this quark-parton picture the fractional momentum of the charmed quark of mass M_c will be

$$\xi = \frac{Q^2 + M_c^2}{2Mv}$$

The ejected charmed quark is then assumed to fragment to a charmed hadron which can then decay semileptonically to a muon. In order to make quantitative calculations in this model the form of the distribution of the charmed quarks in

the nucleon sea, $C(\xi)$, was taken to be that given by Buras and Gaemers [3]. Recently it has been proposed that an additional long-lived, intrinsic charm component of the nucleon exists [4]. This component would be expected to contribute to muoproduction of open charm at large values of x and also give a threshold rise in the total value of F_2 in this region [5].

Comparisons are made between the data presented here and the predictions of the struck quark and photon-gluon fusion models. As in [1] good agreement is found between the photon-gluon fusion model and these data whereas in general the agreement with the struck quark model is much poorer. These new data have already been used to set limits on the intrinsic charm content of the nucleon [6].

As the photon-gluon fusion model gives a good representation of the data the fragmentation of the charmed quark is studied using this model. In reference [1] the charmed quarks were assumed to fragment into observable hadrons by a mechanism in which light quark-antiquark pairs were shared between the charmed quarks, a process best viewed in the photon-gluon rest frame. Gavai and Roy [7] showed that the data in [1] could be consistent with the charmed quarks fragmenting by sharing light quark-antiquark pairs with the residual nucleon, a mechanism best viewed in the nucleon's rest frame. Both these modes of fragmentation are investigated, and the fragmentation function is studied. Various models exist for the fragmentation function of the charmed quark [8]. All predict that this fragmentation function will be harder than that observed for light quarks [9].

In order to investigate the parameters of the photon-gluon fusion model, fits were performed of the model to the data. The fitting procedure showed that the model predictions are most sensitive to the gluon momentum distribution of the nucleon, $G(\eta)$, where η is the fraction of the momentum of the nucleon carried by the gluon. This momentum distribution is studied in detail.

I. Apparatus

The experiment was performed in the M2 muon beam at the CERN SPS using the EMC forward spectrometer and an iron target calorimeter (STAC). The data were taken concurrently with, and with the same trigger as the J/ψ production

experiment described in the previous paper [10] which contains brief details of the apparatus. A more complete description of the apparatus is given in ref. [11]. It is important for the experiment reported here to have a good measurement of the missing energy in order to determine the energy carried away by neutrinos. The missing energy is defined as

$$E_{\text{MISS}} = E_{\text{Beam}} - \sum E_{\mu} - E_{\text{STAC}} \quad (1)$$

where E_{Beam} is the energy of the beam muon, $\sum E_{\mu}$ is the total energy of the outgoing muons in the dimuon and trimuon events and E_{STAC} is the energy of the shower measured in the STAC target. Thus good energy resolution is required on the shower energy measurement as well as accurate calibration of the STAC, the beam momentum spectrometer and the forward spectrometer.

The STAC was calibrated using showers from single arm deep inelastic scattering events (taken concurrently [12] with the data reported here) in which neutrino production is expected to be rare. The beam momentum calibration was checked in separate experimental runs and found to be accurate to ± 0.75 GeV/c. In these runs the beam muons were steered into the live regions of the EMC forward spectrometer and their measured momenta were compared to the values obtained from the beam spectrometer stage. The forward spectrometer calibration was checked using the observed mean value of the J/ψ mass from data taken with a liquid deuterium target [11].

II. Data Reduction

In order to select dimuon and trimuon events which originate from charm production certain cuts must be applied to the data to eliminate background processes such as QED trident production.

a) Cuts applied to the dimuon events

Of the events with a momentum analysed beam track 59762 were detected with two fully reconstructed muon tracks in the spectrometer and a well fitted vertex. The histograms labelled cut 0 in fig. 2 show the missing energy distributions for these events. Both distributions show a peak centred at ~ 15 GeV with a number of events at higher missing energy which are ascribed to

QED tridents with one undetected muon usually remaining in the beam region. Cuts were applied to the data to minimise the backgrounds from this process. Table I shows in detail the cuts applied together with the numbers of events surviving in each case.

Events with a third muon in the beam region were found to have an extra hit in the downstream hodoscope H5 or an extra track in the proportional chamber P0 (see fig. 4 of ref. [10]). Events with this signature were removed (cuts 1 and 2 in Table I). The QED trident background (mainly elastic) was further reduced by demanding a shower energy E_{STAC} of at least 30 GeV (cut 3 in Table I). The histograms labelled cut 3 in fig. 2 show the missing energy distributions after applying these cuts. The peak centred at ~ 15 GeV remains and the background from QED tridents has almost disappeared. Events were selected with missing energy in the range $-90 \text{ GeV} < E_{\text{MISS}} < 90 \text{ GeV}$ (cuts 4 and 5, Table I). This eliminated the majority of the residual QED tridents and also eliminated a contamination arising at large, apparent, negative missing energy due to two separate single arm muon scattering events within the sensitive time window of the apparatus. Corrections ($\sim 20\%$) were applied to the data for random vetoing in H5 and P0. These were estimated from the number of events in the peak at ~ 15 GeV above the smooth background before and after applying the H5 and P0 selections (cuts 1 and 2).

Events were selected in the upstream 2.8m of the target (cut 6, Table I) leaving at least 5 absorption lengths of material in the target downstream from the interaction vertex. This minimised contamination from $\pi^\pm$ and $K^\pm$ mesons leaking from the shower in the target calorimeter and decaying to muons in the forward spectrometer region. In addition, it ensured that the whole hadronic shower was absorbed in the STAC so that a reliable energy measurement could be made. The remaining events were then tested for consistency with having caused a trigger. Some false triggers were due to extra hits from δ rays and showers produced in the hadron absorber upstream of the trigger hodoscopes (H3, H4). Events were rejected if the two reconstructed muons could not have directly produced a trigger (cut 7, Table I). This rejected from the sample events whose trigger efficiency is difficult to calculate.

It was not possible to identify the scattered muon uniquely for the $\mu^+ \mu^+$ (++) sample and the following prescription was adopted. The

scattered muon was taken to be the faster track if this track had momentum greater than 80 GeV or if the ratio of the faster to slower track momenta was greater than 1.8. Otherwise the track with the smaller angle to the incident muon direction was taken. Studies of the $\mu^+\mu^-$ (+-) events where ambiguity does not exist and Monte Carlo simulation showed that the scattered muon will be misidentified in 12% of the ++ events using this prescription. This effect was included in all Monte Carlo simulation of the data.

Kinematic cuts were applied to the data to avoid regions where the acceptance was either small or changing rapidly. Dimuon events were selected with $Q^2 > 1 \text{ GeV}^2$, $60 < \nu < 220 \text{ GeV}$ and decay muon momentum greater than 16 GeV (cuts 9-11, Table I). 1493 ++ and 1374 +- events remained after all these selections. A more complete description of this analysis can be found in reference [13].

b) Cuts applied to the trimuon events

Trimuon events were fully reconstructed if all three muons were outside the beam region of the drift chambers W3-W7. This was the case for muons of momentum less than $\sim 120 \text{ GeV}$ or angle to the beam direction of $\geq 15 \text{ mrad}$. Often the scattered muon from events at low ν and low Q^2 was not fully reconstructed. However the direction of such muons was determined by the two small proportional chambers P0 in the beam upstream of the spectrometer magnet, and their momentum could be computed for known energy balancing processes such as QED trident production.

A total of 41571 events of the type $\mu^+\text{Fe} \rightarrow \mu^+\mu^+\mu^-X$ were found, 2060 of which were fully reconstructed events. Apparatus cuts were applied as detailed in Table II. A momentum cut of 10 GeV was applied to all muons (cut 1). Each event was checked for consistency with having caused the trigger (cut 2). Events were rejected if they did not originate from the upstream 2.8 meter fiducial volume of the target or did not have a momentum analysed beam track (cut 3).

The remaining sample of 15511 (1187 fully reconstructed) originated mainly from QED production as shown below. For these events the scattered muon was taken as the faster μ^+ if the ratio of the μ^+ momenta was greater than 1.5, otherwise the smaller angle μ^+ was selected. Monte Carlo studies

showed that with this method the misidentification of the scattered muons was 8%. This effect was included in all Monte Carlo simulation of the data.

The invariant mass distribution, $M_{\mu\mu}$, of the produced muon pair is shown in fig. 3. The smooth curve is the calculated absolute yield expected from QED tridents*. This yield was calculated by tracking Monte-Carlo events through the apparatus including chamber and reconstruction efficiencies. The QED weights of the accepted events in each bin were added and the total weight multiplied by the experimental luminosity gave the predicted yield in each bin. The typical acceptance for QED tridents with mass > 1 GeV was 1%. The predicted curve agrees well with data in the range $M_{\mu\mu} > 1$ GeV, except in the region where J/ψ production is dominant. This shows that the majority of the trimuon events originate from QED trident production. In the region $M_{\mu\mu} < 1$ GeV there is some disagreement between the data and the prediction. However, in this region contributions are expected from ρ and ω decays to $\mu^+\mu^-$ and these mass peaks will be smeared by the experimental resolution.

Trimuon events originating from charm would be produced with extra hadrons and therefore would be highly inelastic. To study the inelastic trimuon signal the 1187 events with three fully reconstructed muon tracks were selected. Fig. 4(a) shows the $Z_{\mu\mu}$ distribution of these muon pairs for the mass intervals $M_{\mu\mu} < 1$ GeV and $1 < M_{\mu\mu} < 2.5$ GeV. The dashed curves are the predicted yields of QED trident events where the effects of bremsstrahlung have been included. There is a large excess of highly inelastic events at low $Z_{\mu\mu}$ above that expected from QED processes. Such inelastic events are expected with large electromagnetic showers from radiative corrections to elastic QED trimuon production and with hadronic showers from charm production.

To separate hadronic and electromagnetic showers, samples of each measured concurrently in the apparatus have been studied. The hadronic sample consisted of small angle muon scatters accumulated using a beam transmission trigger. The fraction of the total shower energy deposited in the element containing most

* We thank D.Y. Bardin for making his programme to calculate QED tridents available to us. The results of this programme agreed with an independent calculation by Ganapathi and Smith [14].

energy and the number of elements firing downstream of the maximum were used to characterise the showers. For a perfect calorimeter this fraction should be large for electromagnetic and small for hadronic, while the length should be short for electromagnetic and long for hadronic. Showers of energy less than 20 GeV could not be distinguished and such events were rejected from further analysis. They are mainly inelastic tridents. Each event was weighted according to its probability to have a hadronic shower. Above 180 GeV the showers were found to be dominantly electromagnetic and such events were rejected. Fig. 4(b) shows the $Z_{\mu\mu}$ distribution of events weighted by this procedure showing that QED tridents are much reduced by the weighting procedure and give a negligible background for $Z_{\mu\mu} < 0.5$. A cut of $Z_{\mu\mu} < 0.5$ was therefore made to select the highly inelastic events and to reject the remaining trident, leaving a final sample of 201 (149 weighted) events with $M_{\mu\mu} < 1$ GeV and 83 (63 weighted) events with $1 < M_{\mu\mu} < 2.5$ GeV. These were the candidates for charm production.

III. Identification of the Events

Fig. 5(a) shows the missing energy distribution for the trimuon events with $M_{\mu\mu} < 1$ GeV and 5(b) with $1 < M_{\mu\mu} < 2.5$ GeV. The distribution in fig. 5(a) shows a peak centred at zero with a long positive missing energy tail. The number of events in the peak centred at zero is consistent with that expected from the photoproduction of ρ mesons detected through the decay $\rho \rightarrow \mu^+ \mu^-$. Therefore, to isolate a clean sample of charm candidates only events with $M_{\mu\mu} > 1$ GeV were retained. Fig. 5(b) shows that a large missing energy, mean value 31 ± 4 GeV, is associated with these high mass events, indicating the presence of neutrinos in the final state.

Figures 5(c) and (d) show the missing energy distributions for the final samples of dimuon events. Again there is a large positive missing energy (mean value 19 ± 2 GeV). Figs 5(c) and (d) also show an absolute Monte-Carlo calculation using the hadronic shower development as given in [15] in order to calculate the missing energy distribution from π and K decays. This background

* Several models for the hadron shower were tried besides that of Grant [15]. The quoted systematic error was obtained by studying the variations in the prediction of these models.

process contributes a fraction $(14 \pm 7)\%$ * of the dimuon events (with a mean missing energy due to neutrinos of 7 GeV) and 1% of the trimuon events. The dimuon data were corrected for the calculated π/K decay background in order to determinate the cross sections. As shown in [1] all other background processes are small.

The large observed mean missing energies in figs. 5(b)-(d) indicate prompt, weak decay of heavy quark states rather than the decay of π and K mesons. The fact that the mean missing energy for the trimuons is roughly a factor two higher than that in the dimuons suggests that two heavy quarks states are decaying semileptonically in the trimuon events and only one in the dimuon events. Furthermore, after correcting for the different acceptances in each process (described below), the ratio of the yields of the trimuon events to the dimuon events is $(7 \pm 3)\%$ consistent with the known semileptonic branching ratios of the D mesons [16]. This indicates that the selected dimuon and trimuon events originate predominantly from the production and semileptonic decays of charmed D mesons.

IV. Results

a) Comparison of the measured distributions with the photon-gluon fusion model

Fig. 6 shows the observed distributions of the dimuon events in Q^2 , ν and p_T^2 , where p_T is the transverse momentum of the secondary muon relative to the virtual photon direction. Fig. 7 gives the distributions for the trimuon events in Q^2 , ν , p_T^2 and $\Delta\phi$, where p_T is the transverse momentum of the muon pair relative to the virtual photon and $\Delta\phi$ is the difference in the azimuthal angles of the secondary μ^+ and μ^- around the virtual photon direction. The latter distribution shows that the μ^+ and μ^- tend to be produced on opposite sides of the virtual photon direction.

These data are compared to the predictions of the photon-gluon fusion model for charm production [2] using the formulae of Leveille and Weiler. The smooth curves in figs. 6 and 7 are the absolute predictions of this model in which the value of the QCD scale parameter Λ is taken to be 0.5 GeV and the gluon

momentum distribution from counting rules [17] to be

$$G(\eta) = \frac{3(1 - \eta)^5}{\eta} \quad (2)$$

The charmed quark mass was taken to be 1.5 GeV*. In the range $4M_C^2 < \hat{s} < 4M_D^2$ where M_D is the mass of the D meson, $\frac{1}{6}$ of the cross section was assumed to be lost to bound charm (J/ψ) production and the rest to be open charm [18], the necessary mass change occurring during hadronisation and by flavour exchange with the recoiling hadronic system. The charmed quarks were assumed to fragment to a D meson with a fragmentation function $\exp(AZ_D)$, where A was chosen to be 1.6 (see below) and Z_D is the ratio of the D meson momentum to the charmed quark momentum in the laboratory frame. The effects of different fragmentation functions on the normalisation of the smooth curves is discussed below. The weak interaction form factors for the decay were taken to be 1.0 and the semileptonic decay modes of the D meson to be $K_{\mu\nu}^*$ and $K_{\mu\nu}$ with equal probability. The mean semileptonic branching ratio of the D meson to muons was assumed to be 8.2% [16].

Events were generated by Monte Carlo and weighted according to the photon-gluon fusion model. The secondary muons were tracked through the apparatus and the weights of the accepted events in the same bins as the data were added. The predicted number of events in each bin for the smooth curves of figures 6 and 7 was obtained by multiplying the accepted weight per bin by the measured luminosity. The Monte Carlo events included full simulation of ionisation energy losses [19] and multiple scattering during the tracking of the secondary muons through the calorimeter target, detectors and the hadron absorber. The effect of events from outside the range of the cuts being smeared into the range was simulated by generating the input Monte Carlo events over a wide kinematic range. For example, the dimuon events were generated in the range $0.03 < Q^2 < 200 \text{ GeV}^2$. Negligible numbers of events generated outside this range were smeared into the region of measurement. The accepted Monte Carlo events were subjected to the same analysis procedures as the data. Thus all the effects of the misidentification of the scattered muon in the ++ dimuon and trimuon samples were included.

* Similar curves in shape and normalisation are obtained if a quark mass of 1.35 GeV and A of 0.3 GeV are used.

It can be seen from figures 6 and 7 that the photon gluon fusion model gives a good representation of the data over the whole of the measured range.

b) Determination of the charmed quark fragmentation function

Fig. 8 shows the event distribution (not corrected for acceptance) in Z_μ for the dimuons and $Z_{\mu\mu}$ for the trimuons. Smooth curves, normalised to the same total numbers of observed events, are drawn for fragmentation in the photon-gluon centre of mass frame and the laboratory frame with a flat fragmentation function in each. It can be seen that flat fragmentation in the laboratory frame gives better agreement with the data than flat fragmentation in the photon-gluon rest frame. Furthermore, a fragmentation function could not be found which would give an acceptable fit in the centre of mass frame as the observed spectrum was too soft. This supports the hypothesis of Gavai and Roy [7] that fragmentation of the charmed quarks is more likely to occur by light quark-antiquark exchange to the residual nucleon rather than by exchange between the charmed quark pair (as discussed in the introduction).

A fit was performed to the shape of the dimuon Z_μ distribution using a fragmentation function of the form $\exp(AZ_D)$, where A was a free parameter. Monte Carlo events were generated and weighted using the photon-gluon fusion model. The accepted Monte Carlo events were read into a fitting programme (CERN-MINUIT) and reweighted with the exponential fragmentation function. The free parameter in the exponent was adjusted to minimise χ^2 between the observed and the normalised predicted distributions. The fit was performed in the range $0 < Z_\mu < 0.4$ as at higher Z_μ the data are contaminated with a background from asymmetric electromagnetic trident production. This background arises when one muon from a QED trident event either stops or has very low momentum and the other muon takes a large fraction of the energy of the virtual photon*. The best fit obtained was $\exp(1.6 \pm 0.6)Z_D$ with a χ^2 of 6.0 for 5 degrees of freedom where the error is statistical only. The best fit value of A was insensitive to the value of α_s in the photon-gluon fusion model but was quite sensitive to the assumed value of the quark mass, M_c , and the assumed gluon momentum distribution. By using extreme values of these parameters (e.g. $\eta G(\eta) \propto (1-\eta)^3$ or $\eta G(\eta) \propto (1-\eta)^7$ for the gluon distribution) and

* This background was worse at high Z_μ in the data of [1] where events were not rejected with $E_{STAC} < 30$ GeV.

refitting, the systematic error on A was deduced. The best fit fragmentation function was determined to be $\exp(1.6 \pm 1.6) Z_D$, where the error now includes the uncertainties in the model parameters. As can be seen from fig. 8(b) the fragmentation function obtained from the dimuon data is consistent with the trimuon $Z_{\mu\mu}$ distribution. However, because the value of Z_μ is always less than Z_D there is an absence of data to constrain the fit for $Z_D \approx 0.2$. Thus we cannot exclude the possibility that the fragmentation function rises at small Z_D . In addition we cannot exclude a fragmentation which turns over and decreases as Z_D tends to 1. Nevertheless the data show that the charmed quark fragmentation is considerably harder than light quark fragmentation as expected theoretically [8].

c) Cross sections in a kinematic range of high acceptance

As the photon-gluon fusion model gives a good representation of the data in Figures 6-8 it was used to model the acceptance of the apparatus. Monte Carlo events were generated and weighted as described above and binned in the same manner as the data. The ratio of the accepted weight in each bin to the generated weight gives the apparatus efficiency in that bin. For these acceptances the fitted fragmentation function $\exp 1.6 Z_D$ in the laboratory frame was used. Radiative corrections were applied to the data using the equivalent radiator approximation [20].

The $+-$ cross sections were larger by $13 \pm 10\%$ than the $++$ cross sections for the dimuon events where the quoted error is mainly systematic. The difference was mainly in normalisation, there being little systematic variation in the measured kinematic variables. This difference could be ascribed to the c quark fragmenting to a charmed baryon for some fraction of the events [21]. It was neglected and the summed cross sections are given below.

Figure 9 and Table III give the differential cross sections for dimuon production in the range $Q^2 > 1 \text{ GeV}^2$, $60 < \nu < 220 \text{ GeV}$ and $p_\mu^{\text{Decay}} > 16 \text{ GeV}$. In this kinematic region the acceptance of the apparatus is relatively large ($\sim 18\%$) and no model extrapolation into insensitive regions is required. Thus the quoted cross sections in Table III are insensitive to the assumptions made in the photon-gluon fusion model and the fragmentation process. As the quoted cross sections are for dimuon production they are also independent of the semileptonic branching ratio for D meson decay. The errors quoted in Table III

are the statistical errors. The systematic errors are $\pm 11\%$ and arise mainly from the uncertainties in applying the trigger consistency check in the software ($\pm 5\%$) and correction for π/K decay ($\pm 7\%$).

The dash-dotted curves in fig. 9 labelled SQ show the predictions of the struck quark model using the values of $C(\xi)$ from the parameterisation of Buras and Gaemers [3]. In this model the internal transverse momentum, k_T , of the struck charmed quark in the nucleon was assumed to be zero. The calculated decay muon p_T distribution arises solely from the decay of the D meson. In order to reproduce the observed p_T distribution the struck charmed quark would require $\langle k_T \rangle \sim 2.8$ GeV which is much larger than the value measured for light quarks [22]. It is also difficult to explain the observed Z_μ distribution in this model. The SQ curves in fig. 9 were calculated using a flat fragmentation function for the charmed quark. To obtain a reasonable representation of the shape of the Z_μ distribution a fragmentation function of the form $\exp(-4Z_D)$ would be required. This is a much softer distribution than one would expect for heavy charmed quarks [8]. Furthermore, the fact that a significant rate of trimuon events is observed is in contradiction with a struck quark model as one decay muon would stay in the target fragmentation region and not be observed in this experiment. Thus even if a $C(\xi)$ distribution were chosen which would reproduce the normalisation and shape of the v and Q^2 distributions in Fig. 9, there would be severe difficulties in this model.

The dashed curves labelled PGF in fig. 9 are the absolute calculated cross sections using the photon-gluon fusion model with the same parameters as above. It can be seen that this model gives a good representation of the data in both shape and normalisation. The observed p_T^2 distribution arises quite naturally in this model due to the angular distribution of the parent quarks in the photon-gluon rest frame.

The solid curves in fig. 9 labelled IC are for a struck quark model in which the charmed quark density $C(\xi)$ is given by the intrinsic charm model of Brodsky et al. [4]. The x distribution of the dimuon data has already been used to set limits on the intrinsic charm content of the nucleon [6] assuming that the data is a mixture of the photon-gluon fusion process and struck quarks from an intrinsic charm component.

d) Absolute cross sections for charmed particle production in the current fragmentation region

As the photon-gluon fusion model gives a good representation of the data in the sensitive region of the apparatus it was used to calculate the acceptance over the whole kinematic range. The absolute cross sections for the muoproduction of open charm were then determined taking the average semileptonic branching ratio of the D meson to be 8.2% [16]. All the cross sections presented are for the current fragmentation region as the apparatus for this experiment is insensitive for Feynman $x_F \lesssim 0.1$.

Tables IV (a) and (b) and fig. 10 show $\sigma(\gamma^*N \rightarrow c\bar{c}X)$, the total photon-nucleon cross sections for open charm production as a function of Q^2 and v from the dimuon and trimuon data. These cross sections were calculated from the measured muon cross sections $\frac{d^2\sigma(\mu N \rightarrow \mu c\bar{c}X)}{dQ^2 dv}$ using the Hand convention for the virtual photon flux [23]. As can be seen the dimuon and trimuon data are mutually consistent.

The dimuon and trimuon data samples were compared in the region of overlap. The common branching ratio for the mean semileptonic decay of the D meson which gives the best relative normalisation between the two data samples was found to be $7 \pm 3\%$. The quoted error is mainly systematic (as discussed below) but also includes the statistical error. This mean branching ratio is consistent with the published value of $8.2 \pm 1.2\%$ [16].

The total cross section for the muoproduction of open charm in the current fragmentation region was derived as follows. The muon differential cross sections $\frac{d^2\sigma(\mu N \rightarrow \mu c\bar{c}X)}{dQ^2 dv}$ from the dimuon data, were integrated over Q^2 and v . A correction was then applied for the fraction of the cross section in the unseen range $Q_{\min}^2 < Q^2 < 1 \text{ GeV}^2$ which was estimated from the photon-gluon fusion model. This gave a value of 9.8 ± 3.3 nanobarns (nb) for the total open charm muoproduction cross section in the current fragmentation region. The error includes both the statistical and systematic uncertainties.

The systematic errors of the absolute cross sections arise mainly from the calculated acceptance. This is especially sensitive to the assumed fragmentation function of the charmed quarks which affects the loss of events with secondary muons below the minimum detectable momentum. To investigate

this uncertainty the acceptances were recalculated with the two extremes of the fitted fragmentation function, i.e. rising as $\exp(3.2Z_D)$ and flat in Z_D . The values of the acceptances changed in normalisation by $\pm 25\%$. There was little systematic variation in Q^2 but systematic variations in ν of $\pm 10\%$ in the range $60 < \nu < 220$ GeV occurred with $\pm 5\%$ systematic variations over the x range $0 < x < 0.6$. The variations in the acceptance give the systematic uncertainties in $\sigma(\gamma^*N \rightarrow c\bar{c}X)$ and the contribution of charm to the nucleon structure function F_2 (discussed below). Similar systematic errors apply to all experiments which have incomplete coverage of the decay muon energy range.

e) Cross sections for photoproduction of open charm by real ($Q^2 = 0$) photons

The total cross sections for real photoproduction of open charm were obtained by extrapolating the data in Table IV (a) to $Q^2 = 0$. At each value of ν a fit was performed to the Q^2 dependence of the form

$$\sigma_Y(Q^2) = \frac{\sigma_Y(Q^2 = 0)}{(1 + \frac{Q^2}{M^2})^2}, \quad (3)$$

where $\sigma_Y(Q^2 = 0)$ and M were free parameters in the fit. The mean value of M (see Table IV(c)) obtained from the fits was (3.9 ± 0.1) GeV. Fig. 11 and Table IV(c) show the values of $\sigma_Y(Q^2 = 0)$ as a function of ν . The error bars show the statistical uncertainties and the shaded band shows the systematic uncertainty which encompasses the data points as a whole. Fig. 11 also shows the published data from other experiments on open charm production [24, 25, 26, 36]. They are in reasonable agreement with the data presented here.

For comparison the cross sections for J/ψ photoproduction [10] and the other known vector meson photoproduction cross sections in the same energy region [27] are shown in fig. 11. It can be seen that the cross sections for charm production rise more rapidly with energy than those for light vector meson photoproduction. This increase is readily understandable for charm production in terms of the photon-gluon fusion model since, as the photon energy increases, charmed quarks can be produced from softer gluons. The increase in cross section then occurs because the gluon density increases rapidly for lower gluon momenta.

f) Determination of the gluon distribution in the nucleon

A fit of the photon-gluon fusion model was made to the dimuon data in Table IV(a). The quark mass, M_c , and the running coupling constant, α_s , were free parameters in the fit. Various forms of the gluon momentum distributions were tried and the results of the fits are given in Table V from which it can be seen that the gluon distributions proposed by Owens and Reya [28] and Hwa and Zahir [29] give meaningless values for α_s and poor fits to the data (large χ^2). The gluon distribution given by Buras and Gaemers [3] gave more realistic values of α_s but still a poor χ^2 . These gluon distributions all evolve too rapidly with Q^2 to give an adequate representation of the data and changing the gluon evolution energy scale to $Q^2 + s$ made no significant difference. The simple counting rule gluon distribution given in equation (2) gave an acceptable fit to the data with a reasonable value of α_s . A somewhat better fit was obtained with the gluon distribution proposed by Glück, Hoffman and Reya [30] which has a much slower evolution than the other Q^2 dependent distributions discussed above.

From Table V it is clear that, without an exact knowledge of the gluon momentum distribution, α_s and consequently the QCD scale parameter Λ cannot be determined from these data. The main effects of changing Λ and M_c in the model are on the normalisation, both parameters having only minor effects on the shapes of the calculated distributions. The assumed gluon distribution alone strongly influences the shapes of the calculated distributions and can therefore be obtained most reliably from the fit. This was done by remaking the fits with Λ and M_c fixed.

As a more direct test of the Q^2 evolution of the gluon distribution the data in Table IV (a) were fitted to the photon-gluon fusion model in each bin of Q^2 with Λ and M_c fixed at 0.5 GeV and 1.5 GeV respectively. The gluon distribution was assumed to be of the form

$$G(\eta) = A \frac{(1-\eta)^m}{\eta} \quad (4)$$

where A and m were free parameters in each fit. Fig. 12(a) shows the fitted value of the power, m , as a function of Q^2 . Within the rather large errors, the fits indicate that the gluon distribution does not undergo strong Q^2 evolution. The average value of m is 5.1 ± 0.6 . The fitted values of the power m are insensitive to the value of Λ but they change by ± 0.5 standard deviation as the charmed quark mass changes by ∓ 0.25 GeV.

The smooth curves in fig. 12(a) show the evolution of the power, m , expected from the models of references [3, 30] and the parameterisation of the neutrino data obtained by the CDHS group [31] reduced to a simple power law distribution (at each Q^2) over the range of x covered by these data. There is some disagreement between the data and the curves. However, the energy-scale at the gluon-quark vertex (fig. 1a) is unknown. Thus it is not clear that the gluon distribution should evolve as Q^2 in the photon-gluon fusion model. Fig. 12(b) shows the same data plotted against $Q^2 + \langle s \rangle$ where $\langle s \rangle$ was taken to be 20 GeV^2 , the mean value of the energy squared in the photon-gluon rest frame estimated from the model. The data in fig. 12(b) are then consistent with both the CDHS parameterisation and the model of Glück, Hoffman and Reya [30], but there is still a marked disagreement with the model of Buras and Gaemers [3] consistent with that shown in Table V. This indicates that the parameterisations of [30,31] of the gluon distribution agree with these data if the energy scale for the evolution of the gluon distribution in this process is taken to be $Q^2 + \hat{s}$.

g) Fits of the photon-gluon fusion model to all the charm data

An overall fit was made to the dimuon, trimuon and J/ψ production [10] data including the J/ψ data from SLAC-CORNELL [38] at low v . As its evolution has been shown to be quite weak, a Q^2 independent gluon distribution of the form given in equation (4) was assumed taking the integral to be 0.5. The mean semileptonic branching ratio of the D meson and the fraction, F , of the $c\bar{c}$ pairs which form bound charm (for $s < 4M^2$) were free parameters as well as M_c and Λ . The best fit gave $M_c = 1.51 \pm 0.06 \text{ GeV}$, $\Lambda = 0.67 \pm 0.20 \text{ GeV}$, $F = 0.20^{+0.10}_{-0.05}$, mean semileptonic branching ratios of the D mesons $= 8.2^{+3.0}_{-1.2} \%$ and a gluon distribution $\eta G(\eta) \propto (1-\eta)^{5.2 \pm 0.5}$. There was no artificial renormalisation between the different data sets and the fit χ^2 was 203 for 134 degrees of freedom.

These parameters give a good phenomenological description of open charm and charmonium production in the framework of the photon-gluon fusion model rather than a direct measurement. However, the fact that the open charm and charmonium (J/ψ) data both yield consistent powers of the gluon distribution is a strong constraint on it. The overall χ^2 of the fit shows that the photon-gluon fusion model gives an acceptable description for both open charm and charmonium production.

h) The contribution, $F_2^{c\bar{c}}$, of open charm production to the nucleon structure function F_2

The muon differential cross section $\frac{d^2\sigma}{dQ^2 dv}$ was used to obtain the contribution of open charm, $F_2^{c\bar{c}}$ to the nucleon structure function F_2 assuming that $R(=\frac{\sigma_L}{\sigma_T})$ is zero. Fig. 13 shows $F_2^{c\bar{c}}$ versus Q^2 in 3 fixed v bins for the dimuon data. Fig. 14 shows $F_2^{c\bar{c}}$ as a function of Q^2 in fixed x bins and also the values of F_2 measured in single μ scattering on hydrogen and iron with the same apparatus [12,32]. Fig. 15 shows the variation of the slope $(\frac{dF_2^{c\bar{c}}}{d\ln Q^2})$ of straight lines fitted to the data in each x bin. Fig. 15 also shows the values of this slope obtained from measurements of the total F_2 [33].

From Fig. 14 it can be seen that charm gives a small overall contribution to the value of the total F_2 . Fig. 15 shows, however, that as $F_2^{c\bar{c}}$ rises rapidly with Q^2 a substantial part of the rise in F_2 at $x < 0.25$ is attributable to charm. Thus fits (to obtain Λ) of the Altarelli-Parisi equations [34] to the Q^2 evolution of F_2 , at small x , require corrections for the production of charm [33].

Figure 16 shows the measured charm structure function $x C(x)$ as a function of x . Here

$$x C(x) = \frac{9 F_2^{c\bar{c}}}{8}$$

where it is assumed that $C(x) = \bar{C}(x)$. This assumption is experimentally justified by the approximate equality of the $++$ and $+-$ dimuon cross sections. The curves shown are the values of $xC(x)$ calculated from the photon-gluon fusion model and from the intrinsic charm model [4].

The distribution of the cross section $d\sigma/dx$ in the kinematic region of high acceptance was used in [6] to set limits of $\lambda < 0.28\%$ (90% confidence level, C.L.) for the form of $C(\xi)$ proposed in [4]. If this form of $C(\xi)$ was assumed to undergo the maximum possible evolution with Q^2 according to the Altarelli-Parisi equations [34] (by neglecting M_c and fixing α_s), a limit of $\lambda < 0.59\%$ (90% CL) was obtained. It can be seen from fig. 16 that the data appear to deviate from the PCF model at the highest values of Q^2 . This may indicate the onset of an intrinsic charm component with a strong threshold

suppression [39]. This suppression is required to be at least of the form $(1 - \frac{W_{th}^2}{W^2})^7$, where W_{th} is the threshold centre of mass energy, to be compatible with the data.

i) The decay muon distributions (for $Q^2 > 1 \text{ GeV}^2$)

Table VI and Fig. 17 show the distribution of $\frac{d^2\sigma(\mu N + \mu e \bar{c} X)}{dZ_\mu dp_T^2}$ for the dimuon data, in the range $Q^2 > 1 \text{ GeV}^2$, as a function of Z_μ and p_T^2 . The data show that the p_T^2 distribution broadens as Z_μ increases and this behaviour is well reproduced by the photon-gluon fusion model (the smooth curves in fig. 17). A similar effect has been observed in the inclusive lepto-production of hadrons [22] where in the latter case the effect is mainly produced by the internal momentum of the struck quark in the nucleon. In charm production, however, the effect is a result of the short distance scale of the photon-gluon interaction.

Fig. 18(a) shows the ϕ distribution of the dimuon cross sections (for $Q^2 > 1 \text{ GeV}^2$) at different values of p_T^2 ; where ϕ is the angle between the lepton scattering plane and the plane containing the decay muon and the virtual photon. The distributions are folded about $\phi = \pi$. Fits were performed to the data in Fig. 18(a) of the form

$$\frac{\pi}{\sigma} \frac{d\sigma}{d\phi} = 1 + a_1 \cos\phi + a_2 \cos 2\phi \quad (5)$$

where σ is the cross section integrated over ϕ . Fig. 18(b) shows the fitted values of a_1 and a_2 as a function of p_T^2 . The smooth curves are the predictions of Leveille and Weiler [35] for $Q^2 = 5 \text{ GeV}^2$ and $\nu = 150 \text{ GeV}$ for the coefficients applied to the distribution of the $c\bar{c}$ plane. Monte Carlo studies show that, notwithstanding fragmentation and decay, the decay muon is a good indicator for the $c\bar{c}$ plane for $p_T^2 > 0.6 \text{ GeV}^2$ with little reduction of the values a_1 and a_2 . Thus it is meaningful to compare the predictions and the data in this range. The variation of the coefficient a_2 with p_T^2 is consistent with a 1^- spin assignment for the gluon. However, the data cannot exclude the other possible spin-parity assignments. The measured coefficients a_1 are somewhat larger than the calculated values. No differences in the ϕ distributions for the $++$ and $+-$ dimuon samples could be detected within the statistical errors.

This indicates that the proportion of charmed quarks fragmenting to charmed baryons is probably small [21].

(j) Upper limit for the leptonic branching ratio $D^{\pm} \rightarrow \mu^{\pm} \nu$

Events in which either or both of the produced D mesons decayed in the mode $D^{\pm} \rightarrow \mu^{\pm} \nu$ would be characterised by on average a larger neutrino energy and a smaller hadronic energy than for the semileptonic mode. The region $E_{\text{MISS}} > 50 \text{ GeV}$, $E_{\text{STAC}} < 70 \text{ GeV}$ was chosen to optimise the search for such decays. Within this region 5 events were found. These are entirely consistent with the predicted background of 1.0 events from τ lepton pair production [14] and 4.2 events calculated from the standard photon-gluon fusion model discussed above, with the 3 body semileptonic decay mode.

The acceptance for events is much higher when one or both D's decay via the 2-body mode because fewer muons are lost by the momentum cut, and a greater fraction of the events populate the selected region. Hence a reasonable limit can be set for the leptonic branching ratio. If the final state contains an equal mixture of the four charge combinations D^+D^- , $D^+\bar{D}^0$, $D^-\bar{D}^0$, and $D^0\bar{D}^0$, and F and Λ_c production are ignored then a limit of 1.4% is obtained at 90% confidence. Reasonable changes in these assumptions do not move this limit above 2%.

Recently Barger et al. [40] have proposed a model for D decay in which both $W^{\pm}$ and charged Higgs ($H^{\pm}$) mediate the process. One consequence of this is a prediction that the branching ratio for $F^{\pm} \rightarrow \mu^{\pm} \nu$ should be $\sim 25\%$. If the upper limit on the observed events is attributed entirely to this decay then the F pair production cross section would have to be $\lesssim 3 \times 10^{-3}$ of the D -pair cross-section, so small a number as to make this model implausible. For an assumed production rate of $F^{\pm}$ of 20% of the charm production an upper limit for $F \rightarrow \mu \nu$ would be 3%.

VI. Discussion of the Results and Conclusions

The cross sections for charm production, studied through muoproduction of 2μ and 3μ events, have been presented. The total cross section for muoproduction of open charm at 250 GeV in the current fragmentation region is

9.8 ± 3.3 nb. Extrapolation to $Q^2 = 0$ shows that open charm production represents $\sim 0.6\%$ of the total, real, hadronic photoproduction cross section for $100 < \nu < 200$ GeV.

Open charm production is well described in first order QCD by the photon-gluon fusion model. Struck quark models based on the hypothesis of the existence of a charmed sea give a poor description of the data. Thus the charmed contribution to the nucleon sea is consistent with $c\bar{c}$ pairs generated by the dissociation of virtual gluons.

The rise in the total cross sections with photon energy at $Q^2 = 0$ is stronger for charm production than for light vector meson photoproduction. This rise for charm production is readily understood in the photon-gluon fusion model.

The fragmentation process for charmed quarks has been studied and is best understood in terms of the charmed quark fragmenting by sharing light quark-antiquark pairs with the residual nucleon with a fragmentation function well represented by $\exp(1.6 \pm 1.6)Z$. Thus the hadronization of charmed quarks is harder than that observed for light quarks.

The gluon distribution inside the nucleon has been studied and good fits to the data can be obtained with a simple unevolved counting rule glue. A study of the Q^2 dependence of the gluon distribution shows that any evolution must be quite weak. If Q^2 is used as the evolution energy scale the data disagree with the parameterisation of Glück, Hoffmann and Reya and the CDHS group. Consistency with these parameterisations can be obtained by using $Q^2 + \hat{s}$ as the evolution energy scale. More strongly evolving gluon distributions are inconsistent with the data. Averaging over the range $20 < Q^2 + \hat{s} < 100$ GeV² gives $\eta \cdot G(\eta) \propto (1-\eta)^{5.1 \pm 0.6}$.

The data show that charm production accounts for a substantial part of the observed rise of F_2 at small x . Thus corrections must be made to the F_2 data in this region before meaningful fits of the Q^2 evolution using the Altarelli-Parisi equations can be made. The effects of an intrinsic charm component of the nucleon are small [6] which implies that either intrinsic charm does not exist at the predicted level or there is strong threshold

suppression in the energy range of this experiment. In either case, corrections for a threshold rise of intrinsic charm to the values of F_2 at large values of x before fitting the Altarelli-Parisi equations should be small at these energies.

An upper limit on the branching ratio for the leptonic decay of the D meson ($D \rightarrow \mu\nu$) of $< 1.4\%$ (90% confidence level) has been derived. A more model dependent upper limit on the branching ratio of the decay $F \rightarrow \mu\nu$ of 3% has also been set.

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Cut	Number of Events		
	μ^{++}	μ^{+-}	$\mu^{+\pm}$
0 Initial Sample	9971	49791	59762
1 H5-Veto	8605	18669	27274
2 P0-Veto	6921	9821	16742
3 $E_{\text{STAC}} > 30 \text{ GeV}$	6139	5685	11824
4 $E_{\text{MISS}} > -90 \text{ GeV}$	5746	5636	11382
5 $E_{\text{MISS}} < 90 \text{ GeV}$	5632	4403	10035
6 Vertex in fiducial volume	4812	3879	8691
7 Trigger consistency	3556	2319	5875
8 $P_{\mu}^{\text{SCATT}} > 20 \text{ GeV}$	3470	2296	5766
9 $P_{\mu}^{\text{DECAY}} > 16 \text{ GeV}$	2323	2130	4453
10 $Q^2 > 1 \text{ GeV}^2$	1602	1442	3044
11 $60 \text{ GeV} < \nu < 220 \text{ GeV}$	1493	1374	2867

Table I

Number of events surviving the cuts in the dimuon sample.

Cut	Number of Events $\mu^+ \mu^+ \mu^-$
Initial sample	41571
1) $p_\mu > 10$ GeV	39948
2) Trigger Consistency	20548
3) Vertex in fiducial volume and good beam track	15511
4) Fully reconstructed events (all muons momentum analysed)	1187
5) $20 < E_{\text{STAC}} < 180$ GeV	
$Z_{\mu\mu} < 0.5$	
a) $M_{\mu\mu} < 1$ GeV	201 (149 weighted)
b) $1 < M_{\mu\mu} < 2.5$ GeV	83 (63 weighted)

Table II

Number of events surviving each cut in the trimuon sample.

TABLE III

Dimuon Cross Sections in the Range $Q^2 > 1 \text{ GeV}^2$, $60 < \nu < 220 \text{ GeV}$, $p_{\mu}^{\text{DECAY}} > 16 \text{ GeV}$

(i) $\frac{d\sigma}{d\nu}$ [nb/GeV]

ν Range GeV	60-80	80-100	100-120	120-140	140-160	160-180	180-200	200-220
$\frac{d\sigma}{d\nu} \text{ nb}$ $\times 10^{-3}$	$.124 \pm .024$ $\times 10^{-3}$	$.199 \pm .021$ $\times 10^{-3}$	$.264 \pm .022$ $\times 10^{-3}$	$.369 \pm .022$ $\times 10^{-3}$	$.406 \pm .021$ $\times 10^{-3}$	$.374 \pm .018$ $\times 10^{-3}$	$.415 \pm .017$ $\times 10^{-3}$	$.402 \pm .019$ $\times 10^{-3}$

(ii) $\frac{d\sigma}{dQ^2}$ [nb/GeV²]

Q^2 Range GeV ²	1-1.78	1.78-3.16	3.16-5.62	5.62-10.0	10.0-17.8	17.8-31.6	31.6-56.2	56.2-100	100-316
$\frac{d\sigma}{dQ^2}$	$.160 \pm .009$ $\times 10^{-1}$	$.993 \pm .047$ $\times 10^{-2}$	$.382 \pm .017$ $\times 10^{-2}$	$.166 \pm .007$ $\times 10^{-2}$	$.574 \pm .030$ $\times 10^{-3}$	$.160 \pm .012$ $\times 10^{-3}$	$.303 \pm .040$ $\times 10^{-4}$	$.650 \pm .142$ $\times 10^{-5}$	$.100 \pm .130$ $\times 10^{-6}$

(iii) $\frac{d\sigma}{dx_{Bj}}$ [nb]

x Range	.00178 -.00316	.00316 -.00562	.00562 -.01	.01 -.0178	.0178 -.0316	.0316 -.0562	.0562 -.1	.1 -.178	.178 -.316	.316 -.562
$\frac{d\sigma}{dx_{Bj}}$	$0.54 \pm .07$	$3.70 \pm .21$	$3.00 \pm .15$	$1.35 \pm .62$	$.58 \pm .03$	$.22 \pm .01$	$.065 \pm .005$	$.012 \pm .002$	$.21 \pm .04$ $\times 10^{-2}$	$.23 \pm .12$ $\times 10^{-3}$

TABLE III (contin.)

(iv) $\frac{d\sigma}{dp_T^2}$ [nb/GeV²]

p^2 Range GeV ²	001- .10	.10- .178	.178- .316	.316- .562	.562- 1.0	1.0- 1.78	1.78- 3.16	3.16- 5.62	5.62- 10.0	10.0- 17.8
$\frac{d\sigma}{dp_T^2}$ nb/GeV ²	.112 $\pm$.006	.086 $\pm$.006	.067 $\pm$.004	.041 $\pm$.002	.175 $\pm$.008 $\times 10^{-1}$	.565 $\pm$.031 $\times 10^{-2}$	.131 $\pm$.010 $\times 10^{-2}$	.204 $\pm$.024 $\times 10^{-3}$	.173 $\pm$.042 $\times 10^{-4}$	.132 $\pm$.073 $\times 10^{-5}$

(v) $\frac{d\sigma}{dz_\mu}$ [nb]

z_μ Range	.05- .1	.1- .15	.15- .2	.20- .25	.25- .3	.3- .35	.35- .4	.4- .5	.5- .6	.6- .7	.7- .8
$\frac{d\sigma}{dz_\mu}$ nb	.083 $\pm$.006	.267 $\pm$.010	.238 $\pm$.010	.175 $\pm$.009	.103 $\pm$.007	.058 $\pm$.005	.037 $\pm$.004	.021 $\pm$.003	.012 $\pm$.003	.022 $\pm$.012	.07 $\pm$.07

TABLE IV

$\sigma(\gamma^*N \rightarrow c\bar{c}X) (Q^2, \nu)$ [nb]

a) Dimuon Data

Q^2 (GeV ²)	1. -1.78	1.78 -3.16	3.16 -5.62	5.62 -10.0	10.0 -17.8	17.8 -31.6	31.6 -56.2	56.2 -100
ν (GeV)								
60-80	500 ± 318	31 ± 55	162 ± 94	97 ± 32	75 ± 29	24 ± 15	16 ± 14	-
80-100	398 ± 135	243 ± 77	209 ± 48	121 ± 27	124 ± 26	40 ± 14	0 ± 6	13 ± 17
100-120	336 ± 101	392 ± 88	220 ± 41	191 ± 30	139 ± 23	44 ± 13	11 ± 6	3 ± 4
120-140	399 ± 87	374 ± 62	395 ± 49	241 ± 28	152 ± 20	78 ± 16	26 ± 9	16 ± 7
140-160	430 ± 71	651 ± 79	458 ± 49	275 ± 30	146 ± 20	84 ± 16	42 ± 11	17 ± 8
160-180	461 ± 62	493 ± 56	314 ± 33	282 ± 27	227 ± 26	113 ± 18	38 ± 11	14 ± 7
180-200	520 ± 52	670 ± 58	399 ± 35	364 ± 33	197 ± 24	134 ± 21	23 ± 10	13 ± 8
200-220	590 ± 58	563 ± 54	407 ± 41	385 ± 42	194 ± 29	113 ± 25	89 ± 25	36 ± 21

b) Trimuon Data

Q^2 GeV ²	$Q^2_{\min}$ - .178	.178-.562	.562-1.78	1.78-5.62	5.62-17.8	17.8-56.2
160 < ν < 240 GeV	1041 $\pm$ 387	981 $\pm$ 268	476 $\pm$ 148	354 $\pm$ 111	148 $\pm$ 67	65 $\pm$ 41

c) Extrapolation of dimuon data to $Q^2 = 0$ (systematic error in brackets).

ν range	$\sigma (Q^2=0)[\text{nb}]$	$M[\text{GeV}](\text{see text})$	χ^2/DOF
60-100	$364 \pm 100 (\pm 120)$	3.41 ± 0.53	7.3/6
100-140	$535 \pm 62 (\pm 144)$	3.60 ± 0.26	4.5/6
140-180	$664 \pm 47 (\pm 152)$	3.80 ± 0.18	8.5/6
180-220	$715 \pm 40 (\pm 150)$	4.07 ± 0.20	12.1/6

TABLE V

Fits of the photon-gluon fusion model to the data with different gluon distributions

<u>Assumed Gluon Distribution</u>	<u>Fitted Parameters</u>		
	α_s (at $Q^2 + \hat{s} = 20 \text{ GeV}^2$)	M_C GeV	$\chi^2/\text{Degree of freedom}$
Buras and Gaemers [3] $(1-\eta)^5$ at Q_0^2	0.48	1.67	127/50
Buras and Gaemers [3] $(1-\eta)^{1.0}$ at Q_0^2	0.69	1.72	268/50
Owens and Reya [28]	2.38	1.81	167/50
Hwa and Zahir [29]	1.92	2.21	179/50
Glück, Hoffmann and Reya [30] evolving from $Q_0^2 = 4$ as Q^2	0.44	1.66	38/29
Glück, Hoffmann and Reya [30] evolving from $Q_0^2 = 4$ as $Q^2 + \hat{s}$	0.46	1.66	29/29
Counting rule (equation 2) The fitted gluon distribution was $nG(\eta) = 2.81 (1-\eta)^{4.61}$ assuming that $\int_{\eta_{\min}}^1 nG(\eta) d\eta = 0.50$	0.56	1.83	62/49

TABLE VI
 $d^2\sigma/dZ dp_T^2$ ($Q^2 > 1 \text{ GeV}^2$) [nb/GeV 2]

p_T^2 [GeV 2]	≤ 0.1	.100 - .178	.178 - .316	.316 - .562	.562 - 1.00	1.00 - 1.78	1.78 - 3.16	3.16 - 5.62	5.62 - 10.0	10.0 - 17.8
Z_μ										
0.05-0.1	44.5 ± 6.0	26.8 ± 5.4	15.7 ± 2.6	9.10 ± 1.56	1.92 ± 0.40	.267 $\pm .099$	0.	0.	0.	0.
0.1-0.2	10.1 ± 0.8	8.66 ± 0.71	6.17 ± 0.43	3.25 ± 0.20	1.30 ± 0.09	.282 $\pm .024$	.047 $\pm .006$	.0036 $\pm .0010$	.00044 $\pm .00032$	0.
0.2-0.3	2.43 ± 0.33	1.91 ± 0.29	1.71 ± 0.19	1.15 ± 0.12	.538 $\pm .046$	.163 $\pm .031$	.030 $\pm .004$	.0092 $\pm .0016$	.00026 $\pm .00014$	0.
0.3-0.4	.983 $\pm .226$	.390 $\pm .118$	.386 $\pm .096$	.427 $\pm .089$	.142 $\pm .024$	.074 $\pm .010$	.018 $\pm .003$	.0025 $\pm .0007$	.00037 $\pm .00016$	.00002 $\pm .00002$
0.4-0.5	.036 $\pm .050$	.158 $\pm .094$	.218 $\pm .100$	.111 $\pm .038$	.061 $\pm .019$	.052 $\pm .012$	.019 $\pm .006$	.0009 $\pm .0005$	.00020 $\pm .00015$	.00020 $\pm .00020$
0.5-0.6	0.	.056 $\pm .049$	.127 $\pm .074$	.125 $\pm .188$	.016 $\pm .013$	.007 $\pm .004$	.039 $\pm .016$	.0010 $\pm .0006$	.00130 $\pm .00160$	0.
0.6-0.7	0.	0.	0.	0.	.049 $\pm .052$	.004 $\pm .004$	0.	.0003 $\pm .0004$	0.	0.

FIGURE CAPTIONS

Fig. 1 Models for muoproduction of charm.

- a) Photon-gluon fusion model
- b) Struck quark model.

Fig. 2 Missing energy distributions for the dimuon events. Histograms labelled cut 0 are the raw data. The shaded histograms labelled cut 3 show the remaining events after excluding those with small angle muons (Table I).

Fig. 3 $M_{\mu\mu}$ distribution for all trimuon events. The dashed curve shows the QED trident calculation. The agreement of this curve with the data shows that the majority of the original trimuons originate from tridents.

Fig. 4 $Z_{\mu\mu}$ distributions for trimuon events in the ranges $M_{\mu\mu} < 1$ GeV, and $1 < M_{\mu\mu} < 2.5$ GeV. The dashed curve shows the calculated QED trident background. a) Shows the distribution of all event. b) Shows the weighted distribution for events with $E_{STAC} > 20$ GeV.

Fig. 5 Missing energy distributions for the final samples of trimuon and dimuon events. The curve labelled single arm is the measured distribution from deep inelastic muon scattering events observed concurrently in this experiment [12]. The distributions labelled π/K are the calculated backgrounds from π/K decays in hadron showers from deep inelastic scattering.

Fig. 6 The dimuon distributions in Q^2 , ν and p_T^2 . The dashed curve is the absolute prediction of the photon-gluon fusion model (PGF) and the solid curve that for the π/K decay background.

Fig. 7 The trimuon distributions in Q^2 , ν , p_T^2 and $\Delta\phi$. The curves show the absolute predictions of the photon-gluon fusion model (PGF).

Fig. 8 a) Z_μ distribution for dimuons
b) $Z_{\mu\mu}$ distribution for trimuons.

The smooth curves show the predictions for the photon-gluon fusion model. The shaded band shows the variation in shapes between the extreme fragmentation functions, i.e. flat (solid curve) and $e^{3.2Z}$ (dashed curve). The dash-dotted curve is for flat fragmentation in the photon-gluon centre of mass frame.

Fig. 9 Dimuon differential cross-sections in the range $Q^2 > 1 \text{ GeV}^2$, $60 < \nu < 220 \text{ GeV}$ and $p_\mu^{\text{Decay}} > 16 \text{ GeV}$. Key to curves:
- • - struck quark model using $C(x)$ from Buras and Gaemers [3];
----- photon-gluon fusion model;
—— struck quark model assuming 1% intrinsic charm component of the nucleon [4].

Fig. 10 The virtual photon total cross-section for charm production plotted against Q^2 in fixed ν bins, derived from the dimuon and trimuon data. The smooth curves are fits of the form given in equation (3).

Fig. 11 Variation of the total open charm photoproduction ($Q^2 = 0$) cross-section with incident photon energy. The shaded band shows the systematic uncertainty. Vector meson photoproduction cross sections are also shown. The J/ψ data are from [10] and the ρ , ω , ϕ cross sections are from [27]. The open charm production data points come from; ■ this experiment, Δ SLAC [24], $\times$ WA4 [25], $\square$ BFP [26], ∇ CIF [36].

Fig. 12 Results of fitting a gluon distribution of the form $\eta G(\eta) \propto (1-\eta)^m$. The fitted value of m (solid circles) is plotted against a) Q^2 and b) $Q^2 + \langle s \rangle$ where $\langle s \rangle = 20 \text{ GeV}^2$. The curves labelled BG, GHR and CDHS show the parameterisations of references [3], [30] and [31] respectively. The J/ψ points (solid squares) are from [10].

Fig. 13 The contribution, $F_2^{c\bar{c}}$, of charm production to the nucleon structure function F_2 . The curves show the predictions from the photon-gluon fusion model and from a 1% expected intrinsic charm content of the nucleon. The data of [37] are also shown for comparison.

Fig. 14 The value of $F_2^{c\bar{c}}$ against Q^2 for fixed x . For comparison the measured values of the total nucleon structure function F_2 [12, 32] are shown.

Fig. 15 $\frac{dF_2^{c\bar{c}}}{d\ln Q^2}$ plotted against x obtained from a linear least squares fit in each x bin to the data in fig. 14. Also shown are the measured values of the slopes from F_2 [33]. The dashed error bar is the systematic error and the solid one the statistical error.

Fig. 16 The charmed quark momentum density distribution $x C(x)$ as a function of x and Q^2 . The smooth curves are the predictions of the photon-gluon fusion model and the struck quark model using the intrinsic charm distribution [4].

Fig. 17 Absolute differential cross-sections (for $Q^2 > 1$) $\frac{d^2\sigma(\mu p \rightarrow \mu c\bar{c}X)}{dZ_\mu dp_T^2}$ against p_T^2 in different Z_μ bins derived from the dimuon data. The curves are the predictions of the photon-gluon fusion model.

Fig. 18 The absolute differential cross-section $\frac{\pi}{\sigma} \frac{d\sigma}{d\phi}$ (for $Q^2 > 1 \text{ GeV}^2$) where σ is the integrated total cross-section. The curves in (a) show the best fit curves of the form in equation (5). (b) shows the values of a_1 and a_2 (equation (7)) against p_T^2 with the predictions of [35] (the smooth curves) for different gluon spin-parity assignments.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

$$\mu N \rightarrow \mu \mu^+ \mu^- X$$

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG.11

FIG. 12

FIG. 13

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18