# A STUDY OF THE FORWARD PRODUCTION OF CHARM PARTICLE PAIRS IN p–Fe AND $\pi^-$–Fe INTERACTIONS

A. BODEK [1], R. BREEDON [2], R.N. COLEMAN [3], W. MARSH [3], S. OLSEN, J.L. RITCHIE
*University of Rochester, Rochester, NY 14627, USA*

B.C. BARISH, R.L. MESSNER [4], M.H. SHAEVITZ [5], E.J. SISKIND [6]
*California Institute of Technology, Pasadena, CA 91125, USA*

F.S. MERRITT
*University of Chicago, Chicago, IL 60637, USA*

H.E. FISK, Y. FUKUSHIMA [7], P.A. RAPIDIS
*Fermilab, Batavia, IL 60510, USA*

and

G. DONALDSON and S.G. WOJCICKI
*Stanford University, Stanford, CA 94305, USA*

Received 21 January 1982

The hadronic production of charm particle pairs produced in the forward direction has been investigated in study of $\mu^+\mu^-$ pairs with large missing energy (indicative of final-state neutrinos). These events result primarily from two semileptonic decays of charm–anticharm states. A comparison of the data with the prediction of the intrinsic charm diffractive model indicates that diffractive production cross sections are small (of the order of a few $\mu$b) in both 350 GeV proton and 278 GeV pion interactions.

The hadronic production of dimuon events with missing energy has been used to investigate the production of charm particle pairs in the forward direction for 350 GeV p–Fe and 278 GeV $\pi^-$–Fe interactions [‡1]. Studies of the production of charm at large Feynman $x$ are of present interest because of recent indications of large forward cross sections in p–p [‡2] and $\pi^-$–p [3] collisions. Large diffractive charm production cross sections are predicted in models with a 1% charm quark content (intrinsic charm [4]) in the hadron wave function.

The experimental setup is shown in fig. 1. A hadron beam was directed into a large (0.75 m × 0.75 m × 2.4 m) iron-scintillator calorimeter that served as a target and measured the total hadronic and electromagnetic energy of each interaction. The beam intensities were 1 to 2 × $10^5$ hadrons per one second spill. Data were taken for a total incident flux of 1.72 × $10^9$ and 1.63 × $10^9$ proton and pion interactions, respec-

---

[1] Alfred P. Sloan Foundation Fellow.

[2] Present address: CERN, Geneva, Switzerland.

[3] Present address: Fermilab, Batavia, IL 60510, USA.

[4] Present address: SLAC, Stanford, CA 94305, USA.

[5] Present address: Columbia University, New York, NY 10027, USA.

[6] Present address: Brookhaven National Laboratory, Upton, NY 11973, USA.

[7] Present address: Laboratory for High Energy Physics, Tsukuba-gun Ibaraki-Ken 305, Japan.

[‡1] Studies of such events at lower value of Feynman $x$ and intermediate $p_t$ have been reported in ref. [1].

[‡2] For a review of hadronic charm production see ref. [2].

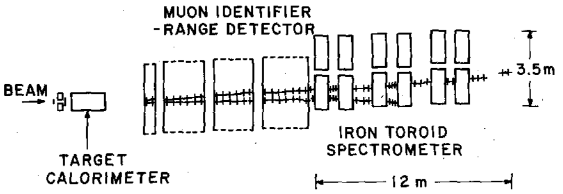

Fig. 1. Plan view of the apparatus.

tively. The scintillation counter gains were continuously monitored as a function of time and instantaneous rate using a fiber optics flasher system and electronic hardware that monitored the history of interactions in the calorimeter before each event. The calorimeter gave a linear response as a function of energy. For unbiased hadron interactions, the resolution was gaussian ($\sigma/E = [R(\mathrm{GeV})/E]^{1/2}$ with $R = 0.47$ for protons and $R = 0.44$ for pions) and independent of time or instantaneous rate (after small corrections using the gain monitoring hardware).

The momentum of each incoming hadron was measured to ±0.5% with an upstream tagging spectrometer. The target calorimeter was followed by a muon identifier consisting of 42 3 m × 3 m scintillation counters and 21 3 m × 3 m wire spark chambers sandwiched periodically through the 4.5 m of steel. The toroidal muon spectrometer consisted of 24 magnetized iron disks each 20 cm thick and 1.8 m in radius (with a 12 cm radius hole) with scintillation counters every 20 cm of steel and spark chambers every 80 cm of steel. The toroids were displaced off axis by 0.9 m to avoid a hole in the acceptance for forward going muons. The muon energy resolution was measured to be ±11% (RMS) using beams of momentum tagged muons (the muom momenta were varied from 25 to 200 GeV/$c$). The measured muon resolution was gaussian in $1/P$ and agreed with Monte Carlo calculation, which included multiple scattering and $\mathrm{d}E/\mathrm{d}x$ effects. The scintillation counters in the muon identifier and in the toroids monitored the energy deposition of muons in the magnetized steel and allowed rejection of the small fraction of muons which lost energy via rare processes that resulted in large energy loss (e.g. high-energy knock-on electrons, muon bremsstrahlung and pair production, etc.).

The trigger required a hadron interaction in the first 40 cm of steel of the calorimeter together with at least one muon that reached the back of the toroid system (see fig. 1). This corresponded to a minimum muon energy of about 20 GeV. In addition, unbiased hadron interactions were recorded throughout the run using a prescaled trigger. Preliminary results of the single-muon analysis have been reported elsewhere [5]. Here we report on the analysis of the dimuon sample, in which the second (i.e. lower-energy) muon was required to traverse at least one third of the toroid system (corresponding to a minimum energy of 12 GeV). The following cuts were imposed on the data in order to ensure that large missing energy did not result from instrumental effects:

(a) A clean beam cut required a *single* hadron with the required beam momentum (as determined by the upstream tagging spectrometer) to interact in the calorimeter. The same requirements were applied to a random sample of unbiased proton interactions. In the calculation of the cross sections the fraction of hadron interactions that satisfied these requirements (93%) was used to rescale the incident flux.

(b) Poorly reconstructed muon tracks were eliminated, and the calorimetry counters in the muon identifier and in the toroid spectrometer were checked to ascertain that there was no hadronic energy deposited downstream of the fine grain calorimeter and that muons did not undergo any interaction with a large energy loss (>3 GeV) in the steel. The effects of all these cuts on dimuon events with *no* missing energy (i.e. total energy within ±10 GeV of the beam energy) introduced an inefficiency of 34%. An additional reconstruction inefficiency for dimuon events was determined by scanning to be 3%. These two inefficiencies were corrected for.

(c) Events with muons of energy >100 GeV were eliminated because the muon energy resolution was 11% (as compared to the hadron energy resolution of 4%). This removed events with a poor determination of the total energy. Calculations folding the measured muon and hadron energy resolution show that with this cut the total energy resolution for events with muons is gaussian and is similar to the resolution for unbiased hadron interactions.

The total observed energy distributions ($E = E_{\mathrm{muons}} + E_{\mathrm{calorimeter}}$) for $\mu^+\mu^-$ events and for same-sign events ($\mu^-\mu^- + \mu^+\mu^+$) are shown in figs. 2a and 2b for the proton and pion data, respectively. The solid points show the total energy distribution *measured* for unbiased hadron interactions in the cal-

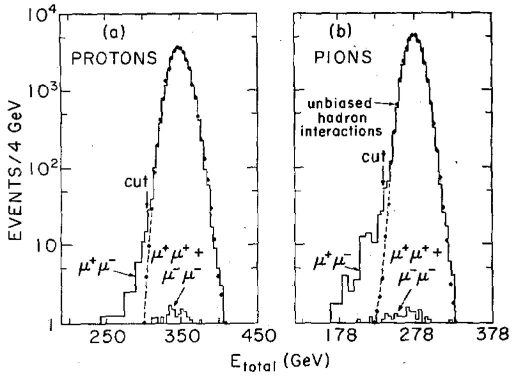

Fig. 2. Total energy distributions for accepted opposite-sign and same-sign dimuon events. The solid circles correspond to the observed energy distributions for unbiased sample of hadron interactions taken simultaneously with the dimuon data, (a) proton data and (b) pion data.

orimeter normalized to the total number of $\mu^+\mu^-$ events. There are 59 $\mu^+\mu^-$ events with missing energy $E_{\text{miss}} > 45$ GeV in the proton data sample. For the pion data the number of $\mu^+\mu^-$ events with $E_{\text{miss}} > 40$ GeV is 154. The number of events with such large missing energy due to resolution effects, as determined from the energy distribution of unbiased hadron interactions, is 5 and 10 events for protons and pions, respectively. We conclude that 54 ± 8 and 144 ± 12 $\mu^+\mu^-$ events with energetic neutrinos in the final state are observed in the proton and pion data, respectively.

These events could come from three possible sources:

(a) Two decays of $\pi$'s or K's produced in the interaction.

(b) Drell–Yan production of $\tau^+\tau^-$ pairs followed by two leptonic decays.

(c) Production of heavy quark states such as charm (e.g. $D\bar{D}$) or bottom (e.g. $B\bar{B}$) followed by two semileptonic decays.

The double $\pi$ and K decay backgrounds were determined in two ways. One estimate was obtained from the *same-sign* events with missing energy ($\{\mu^-\mu^- + \mu^+\mu^+\}$), and yields 0 ± 1 and 3 ± 1.7 events for protons and pions, respectively. This estimate does not include contributions from $K^+K^-$ pairs. Another estimate which includes all contributions was calculated by multiplying the number of *single-muon* events with missing energy [‡3] times the probability that the remaining hadrons in the shower produce a decay muon of the opposite sign. This probability was measured in separate runs using a lower momentum muon trigger with incident beams of various energies. The calculation yields 1.4 and 2.4 background events for protons and pions, respectively.

The contribution from Drell–Yan production of $\tau^+\tau^-$ pairs is less than 1 event. This was determined by assuming that the number of $\tau^+\tau^-$ pairs is equal to the number of $\mu^+\mu^-$ events with $M_{\mu\mu} > 2M_\tau$, and including the $\tau$ leptonic braching ratios. The number of $\mu^+\mu^-$ events from $B\bar{B}$ production should be about the same as the number of *prompt* same-sign events from the same source. For this data sample [6] [‡4] we measured −1.1 ± 1.0 and 1.1 ± 1.7 *prompt* same-sign events for protons and pions, respectively, indicating

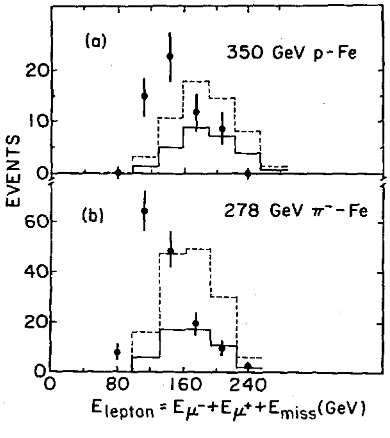

Fig. 3. The $E_{\text{leptons}} \equiv E_{\mu^+} + E_{\mu^-} + E_{\text{miss}} = E_{\text{beam}} - E_{\text{calorimeter}}$ distributions for events with missing energy; (a) protons and (b) pions. The lines are the predictions of the diffractive intrinsic charm model. The dashed line is normalized to the data. The solid line is normalized to the data with $E_{\text{leptons}} > 160$ GeV. Note that the absolute prediction of the model has to be normalized downward by about two orders of magnitude.

---

[‡3] We have used the single muon events with more than 37 GeV (protons) and 32 GeV (pions) of missing energy. We have determined from our measurements that on the average an additional 8 GeV in missing energy is due to the neutrino from the decay of the second pion.

[‡4] Same-sign events could originate from $B\bar{B}$ decays in the following manner: $B \to \mu^- x$ and $\bar{B} \to \bar{D}x$ with $\bar{D} \to \mu^- x$.

a negligible contribution from $B\bar{B}$ production.

We conclude that the observed events originate primarily from the production and decay of charm particle pairs. The distributions of the total lepton energy ($E_{\mathrm{leptons}} = E_{\mu^+} + E_{\mu^-} + E_{\mathrm{miss}}$) for these events are shown in fig. 3. These distributions were compared to the predictions of charm production models in the following manner. Dimuon events resulting from semileptonic decays of both the charm and anticharm states were generated according to the model predictions and were propagated through the apparatus using a Monte Carlo program which included effects of multiple scattering, $\mathrm{d}E/\mathrm{d}x$ and resolution. The resulting Monte Carlo data tapes were then analyzed in an identical fashion to the regular data.

Because of the requirements of large missing energy and the cuts on the minimum muon momenta the total non-hadronic energy ($E_{\mathrm{leptons}}$) of the $\mu^+\mu^-$ events with large missing energy is high. Consequently these events come primarily from charm particle pairs with large values of $x$ ($x_{D\bar{D}} \geqslant 0.4$). Therefore, only a small fraction ($\simeq$1%) of centrally produced charm states contribute to this data sample [‡5], and the extraction of *central* cross sections from these data is very model dependent. Better results on central cross section will be available following completion of our analysis of the prompt single-muon data at small values of $x$. In contrast, the acceptance for diffractive production of charm is very high. For example, the acceptance is 16% for charm production via the diffractive intrinsic charm model of Brodsky et al. [4]. In this model, the $x$ distributions of the produced $\Lambda_c$ and $\bar{D}$ (with incident protons) and D and $\bar{D}$ (with incident pions) are peaked near Feynman $x = 1/2$ because the heavy charm quarks carry most of the momentum, and the sum of the $x$ values of the charm and anticharm states are constrained to be 1.0.

We have compared the data to the predictions of the intrinsic charm model. The predicted distributions of $\mu^+\mu^- \nu\bar{\nu}$ events were obtained by assuming a 3% branching ratio for the decay mode [‡6] $\Lambda_c \to \Lambda^0 \mu\nu$ and a 8% branching ratio for the decay mode $D \to (0.6\ K + 0.4\ K^*)\mu\nu$. If *all* the events are assumed to be produced via intrinsic charm, and the predicted distributions are normalized to the data, then the fits to the lepton energy distributions are *very poor* (see dashed line in fig. 3). The $\chi^2$ values are 40 and 136 (for 5 degrees of freedom) for the proton and pion data, respectively. These poor fits yield cross sections of 5.3 μb and 5.4 μb for protons and pions, respectively.

The poor $\chi^2$ of the fits is probably due to some additional charm production mechanism besides diffraction. The main contribution to the large $\chi^2$ comes from the excess of events with low $E_{\mathrm{leptons}}$ which may be due to a high-$x$ tail of central charm production. Accordingly, a better way to obtain the estimate of the intrinsic charm model cross section is to normalize its prediction to higher-energy events, $E_{\mathrm{leptons}} > 160$ GeV (see solid line in fig. 3), where the contribution of central production would be significantly lower. This procedure yields diffractive cross sections of 2.5 μb and 1.9 μb for protons and pions, respectively. These intrinsic charm cross sections (obtained assuming an $A^{2/3}$ dependence) are much smaller than the predictions [4] [‡7] of 210 μb and 90 μb for 350 GeV protons and 278 GeV pions, respectively, assuming a 1% intrinsic charm component in the hadronic wave function. The data imply an intrinsic charm component [‡8] of less than 0.012% and 0.021% for protons and pions respectively. A limit of 0.28% on the intrinsic charm component of the proton has been reported by the European Muon Collaboration [9].

If a linear $A$ dependence is assumed (as suggested by some authors [‡9]) then the cross sections should

---

[‡5] A central model which fits our preliminary single muon data (ref. [5]) yields an acceptance of 1% for this data sample.

[‡6] If we assume $\Lambda_c \to \Lambda(1520)\mu\nu$ then our acceptance is reduced by 26%.

[‡7] Brodsky's model (ref. [4]) with 1% intrinsic charm predicts

$$\sigma_{c\bar{c}} = 0.01 \times \sigma_T \{\ln(0.2s/M_{c\bar{c}}^2)/\ln[0.2(53)^2/M_{c\bar{c}}^2]\}\,.$$

We have used $\sigma_T = 40$ mb and $\sigma_T = 20$ mb for p–p and π–p total cross sections and $M_{c\bar{c}} = 5$ GeV. $s$ is the square of the center-of-mass energy [$s = (53)^2$ at the ISR].

[‡8] The relation between the intrinsic charm fraction $P_c$, and diffractive charm production at asymptotic energy depends on whether we take $P_c = \sigma_{c\bar{c}}/\sigma_{\mathrm{Total}}$ as originally defined by Brodsky (ref. [4]), $P_c = \sigma_{c\bar{c}}/\sigma_{\mathrm{elastic}}$ as proposed by Bertsch et al. [7], or $P_c = \sigma_{c\bar{c}}/\sigma_{\mathrm{Total}}$ (diffractive part only), as proposed by Roy [8]. The above definitions differ by a factor of six.

[‡9] The model of Barger et al. [10], which is based on a QCD evolution of the sea, also predicts only a factor of 2 increase in the cross section from Fermilab to ISR energies.

be reduced by a factor of 3.8. The cross sections that are quoted are twice the cross sections for $x > 0$, to account for production in the backward hemisphere [10]. This assumption is probably valid for production by protons, but may not be entirely correct for incident pions.

The small diffractive cross section for 278 GeV pions does not confirm preliminary reports of diffractive cross sections of order 40 $\mu$b in 217 GeV $\pi^-$–p interactions [8]. Within the framework of the intrinsic charm model which predicts only a factor two increase in the cross section between Fermilab and ISR energies [7] [9]. The data are hard to reconcile with the large diffractive cross sections of several hundred $\mu$b reported by experiments at the CERN Intersecting Storage Ring (ISR) [2,10], since within the intrinsic charm model, such cross sections imply [4] a diffractive charm cross section of 150 $\mu$b in 350 GeV proton collisions.

Finally we have also fit our proton data to a model assuming *uncorrelated* production of D's and Λ's [e.g. $E\,\mathrm{d}\sigma(\bar{\mathrm{D}})/\mathrm{d}x \propto (1-x)^3$ and a flat $\mathrm{d}\sigma/\mathrm{d}x$ for the $\Lambda_c$], as used by other groups [11]. Using this model we obtain a cross section of 29 $\mu$b for 350 GeV protons (assuming $A^{2/3}$ dependence of the cross section). Note, however, that uncorrelated production is *not expected* in either intrinsic charm or in diquark models [12], and that preliminary data from CERN experiment NA16 using the high resolution bubble chamber, LEBC, indicate [13] a large rapidity correlation between the charm and anticharm states in 360 GeV $\pi^-$–p and p–p interactions.

In conclusion, we have observed production of dimuon events with missing energy in the forward direction. The data can accommodate diffractive charm production cross sections of a few $\mu$b but are inconsistent with the large diffractive cross sections predicted in models with a large intrinsic charm component in the hadron wave function.

We would like to thank Fermilab for its support. One of us (AB) would like to thank the Alfred P. Sloan Foundation for its support. This work was supported by the US Department of Energy and the National Science Foundation.

## *References*

[1] A. Diament-Berger et al., Phys. Rev. Lett. 43 (1979) 1774.

[2] S. Wojcicki, in: High energy physics – 1980, Proc. XXth Intern. Conf. (Wisconsin), eds. L. Durand and L.G. Pondrom, p. 1430;
see also: D. Treille, Lepton photon Conf. (Bonn, 1981), unpublished (CERN EP/81-133);
D. Drijard et al., Phys. Lett. 81B (1979) 250;
K.L. Gibboni et al., Phys. Lett. 85B (1978) 437;
W. Lockman et al., Phys. Lett. 85B (1979) 443.

[3] L.J. Koester, in: High energy physics – 1980, Proc. XXth Intern. Conf. (Wisconsin), eds. L. Durand and L.G. Pondrom;
see also: J. Cooper, Proc. XVIth Recontre de Moriond (1981), unpublished.

[4] S.J. Brodsky et al., Phys. Lett. 93B (1980) 451; Phys. Rev. D23 (1981) 2745.

[5] A. Bodek et al., Univ. of Rochester preprints UR-783, and UR-792, unpublished, to be published in: Proc. XVIth Rencontre de Moriond (1981), and in: Proc. Lisbon EPS Conf. (1981).

[6] A. Bodek et al., Phys. Lett. 113B (1982) 82.

[7] G.F. Bertsch et al., Phys. Rev. Lett 47 (1981) 297.

[8] D.P. Roy, Phys. Rev. Lett. 47 (1981) 213.

[9] J.J. Aubert et al., CERN-EP/81-161 (1981).

[10] V. Barger et al., Phys. Rev. D24 (1981) 1428; DOE-ER/00881-215 (1981), unpublished.

[11] M. Basile et al., Nuovo Cimento Lett. 63A (1981) 230; CERN-EP/81-73; Nuovo Cimento Lett. 30 (1981) 481, 487.

[12] R. Hogan and M. Jacob, Ref. TH 3164-CERN (1981), unpublished.

[13] M. Aguilar-Benitez, CERN/EP 81-131 (1981), to be published in: Proc. Lisbon EPS Conf.

---

[10] All the quoted cross sections have also been corrected for production by secondary interactions (12% for protons and 4% for pions).