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Hadronic Production of Prompt Muons*†

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In an experiment performed at Fermilab (E-595) we have measured the production of prompt single muons and dimuons in hadronic interactions. Data were taken with both 350 GeV protons and 280 GeV π^- 's incident on an iron "beam dump" instrumented with scintillation counters. Density extrapolations were used to separate prompt muons from muons originating from the decays of long lived particles such as π 's, K's and hyperons. Prompt dimuons were identified in a very large acceptance muon identifier (see Figure 1). The target calorimeter identified interactions and measured the total electromagnetic and hadronic energy produced in the event ($\Delta E/E \sim 4\%$). The muon identifier identified all muons produced with a laboratory momentum greater than 5 GeV/c. Muon energies below 15 GeV were determined from their range in the muon identifier. Muon energies above 15 GeV were determined by use of toroidal magnets placed at the downstream end of the detector. Data were taken with two different triggers. One required a muon with $p_\mu > 8$ GeV/c (as determined from range in the apparatus) while the other required a muon which traversed the entire muon identifier ($p_\mu > 20$ GeV/c). The $p_\mu > 8$ GeV/c trigger was used with beam intensities which were typically $10^4/\text{sec}$ while the $p_\mu > 20$ GeV/c trigger was run at intensities of $\sim 10^5/\text{sec}$. Note that only those muons with $p_\mu > 15$ GeV/c penetrated enough of the toroids to enable a sign determination.

Here, we report results from the $p_\mu > 20$ GeV/c trigger only:

- (1) Prompt single μ (p-Fe, $\sim 1/2$ data sample)
- (2) Prompt 2μ + missing energy (p-Fe and π -Fe)

The prompt single muon results were reported earlier;¹ in this report we emphasize the recent 2μ + missing energy results.^{2,3} An analysis of the complete data sample, $p_\mu > 8$ GeV/c and $p_\mu > 20$ GeV/c triggers including both proton and pion induced data is in progress. In an early test run of this experiment we found $\sigma(c\bar{c}) = 22 \pm 9 \mu\text{b/nucleon}$

Fig. 1. Plan View of the Apparatus.

for 350 GeV p-Fe collisions using the $p_{\mu} > 8$ GeV/c trigger.⁴ These results are insensitive to the details of the production mechanism (charm acceptance $\approx 40\%$). Our new data will provide a substantial improvement in the low momentum region and also allow a comparison of proton and pion induced prompt muon production.

Prompt Single Muon Results (350 GeV p-Fe)

In the $p_{\mu} > 20$ GeV/c data the μ 's have traversed the toroid system and the sign of their charge is measured. In diffractive production from incident protons we expect μ^+ 's from Λ_c^+ while μ^- 's come from $\bar{D}$'s. Since in this picture we expect forward $\bar{D}$'s but not forward D's, differences between μ^+ production and μ^- production might be expected. Figure 2 shows the density extrapolation for the μ^+ and μ^- sample. The steeper slope for the μ^+ 's reflects the excess of π^+ 's over π^- 's in the forward direction. Note that both curves give the same intercept at $1/\rho = 0$, corresponding to equal amounts of prompt μ^+ and μ^- production.

There was a contamination in the single muon sample from asymmetric dimuon events because muons of momentum less than 5 GeV/c were not identified. This background was subtracted with the aid of a Monte Carlo calculation which was normalized to the observed number of identified dimuon events. The resulting prompt single muon distributions versus momentum are shown in Figure 3. The curves in each figure correspond to fits to the data using a central production model and a diffractive model using the x distributions suggested in Ref. 5. The

Fig. 2. Event rates vs. density for the μ^+ and μ^- data with $p_{\mu} > 20$ GeV/c. The symbol $(\mu^- \mu^+)$ refers to dimuon events with a triggering μ^+ .

Fig. 3. Prompt single muon rates vs. momentum for μ^+ (a) and μ^- (b). The rates are not corrected for trigger efficiency. The dashed line is the efficiency. It can be greater than 1.0 because it includes resolution smearing effects. The solid line is from the central $D\bar{D}$ production model.

diffractive curves are fit only to those points with $p_\mu > 50$ GeV/c. From the central model, using

$$E \frac{d^3\sigma}{dp^3} \propto (1-x_D)^\alpha e^{-\beta p_T}$$

with $\alpha = 4.7 \pm 1.0$, $\beta = 2.5$ (fixed), $B_\mu = .08$ and $A^{1.0}$ behavior we get

$$\sigma_{D\bar{D}} = 16 \pm 4 \text{ } \mu\text{b/nucleon.}$$

For diffractive production we use the intrinsic charm model of Brodsky, Hoyer, Peterson and Sakai.⁵ Using this model with an $A^{2/3}$ dependence we get

$$\sigma \cdot \text{BR}(\Lambda_c \rightarrow \mu^+ + \dots) = .27 \pm .08 \text{ } \mu\text{b/nucleon,}$$

$$\sigma \cdot \text{BR}(\bar{D} \rightarrow \mu^- + \dots) = .23 \pm .08 \text{ } \mu\text{b/nucleon.}$$

Using only the μ^- result, coupled with the $\text{BR}(D \rightarrow X\mu\nu) = 8\%$ gives

$$\sigma_{\Lambda\bar{D}\text{diffractive}} = 3 \pm 1 \text{ } \mu\text{b/nucleon.}$$

Comments:

- i) Using an $A^{1.0}$ dependence here would reduce the quoted cross section by a factor of 3.8.
- ii) This rate for diffractive production translates into a probability for intrinsic charm in the proton of about 0.02%. This should be contrasted to the 1% predicted by the proponents of this model, and suggested by recent ISR results.⁶

Prompt 2μ + Missing Energy (p-Fe and π -Fe)

In the $p_{\mu} > 20$ GeV/c sample we find a number of dimuon events. Of these some have a substantial amount of missing energy characteristic of parallel semileptonic charm decays with neutrinos carrying away a significant amount of energy. These data are used both to obtain limits on diffractive charm² and bottom production as well as for D^0 - $\bar{D}^0$ mixing.³

In Figure 4, we show the total measured energy for those events in the $p_{\mu} > 20$ GeV/c trigger which contained a second muon with $p_{\mu} > 15$ GeV/c. These results are shown both for 350 GeV protons and 278 GeV pions. The total measured energy corresponds to the energies of the two muons $E_{\mu+}$ and $E_{\mu-}$, inferred from the magnetic measurements, plus the total hadronic energy E_{had} , as determined by the target calorimeter. The solid points correspond to E_{TOT} measurements made using randomly triggered interactions. Note an excess of events in each sample for dimuon events on the low side of the curve. These events are interpreted as coming from charm-anticharm production where both the charm and anticharmed particle subsequently undergo semileptonic decays. The energy deficiency corresponds to energy of the neutrinos. The gaussian shape (no significant non-gaussian tails) of the curve corresponding to unbiased triggers and the lack of an excess of events with $E_{TOT} > E_{beam}$ provides confidence to this interpretation.

Dimuon events with $E_{missing} > 45$ GeV for the proton sample and >40 GeV for the π^- sample were selected as candidates for double charm decay. This corresponded to 59 $\mu^+\mu^-$ events for the proton sample and 154 events for the π^- sample. These numbers were corrected for possible backgrounds from π and K decay, Drell-Yan production of $\tau^+\tau^-$ pairs followed by two leptonic decays and leakage from ordinary dimuon events. These corrections corresponded to a total of about 10% in each data sample. (The number of same sign dimuons satisfying the same cuts were 0 ± 1 for the protons sample and 3 ± 1.7 for the π^- sample.)

The acceptance for central $D\bar{D}$ production is small (~1%). On the other hand, for charm production via diffractive processes a la the intrinsic charm model of Brodsky et al.⁵ it is quite good. In this model the x distributions of the Λ_c and $\bar{D}$ (with incident protons) and

Fig. 4. Total energy distributions for accepted opposite sign and same sign dimuon events. The solid circles correspond to the observed energy distributions for unbiased hadron interactions taken simultaneously with the dimuon data; a) proton data, b) pion data.

D and $\bar{D}$ (with incident π^- 's) peak near $x = 1/2$. Here we find the acceptance of our cuts to be about 16%. Thus those data are quite sensitive to diffractive like production but are poorer than the single muon data for determining $\sigma(c\bar{c})$ in the case of central production.

Figure 5a (b) shows the distribution of events for the proton (π^-) sample vs $E_{lep}(= E_{\mu^+} + E_{\mu^-} + E_{miss} = E_{beam} - E_{had})$. The dashed curve shows the results of normalizing the Brodsky model to all of the data and the solid curve shows the results of normalizing only to 3 points with $E_{lep} > 160$ GeV. Normalizing to the data with $E_{lep} > 160$ and assuming no central production contribution in this region, we can estimate diffraction cross sections to be $2.5 \mu\text{b}$ for pN and $1.9 \mu\text{b}$ for πN using an $A^{2/3}$ dependence. This corresponds to an intrinsic charm content of the proton or pion of $\sim 0.02\%$. Note that an $A^{1.0}$

Fig. 5. The $E_{\text{lep}} = E_{\mu^+} + E_{\mu^-} + E_{\text{miss}} = E_{\text{beam}} - E_{\text{had}}$ distribution for a) proton, b) pion events with missing energy. The lines are predictions of the intrinsic charm model. The dashed line is normalized to the data, the solid curve is normalized to the data with $E_{\text{lep}} > 160$ GeV.

behavior would result in diffractive cross sections which are a factor of 3.8 smaller.

In the dimuon + missing energy sample we see 59 $\mu^+\mu^-$ and no $\mu^+\mu^+$ or $\mu^-\mu^-$ events for 350 GeV/c incident protons, and 154 $\mu^+\mu^-$ with one $\mu^+\mu^+$ and two $\mu^-\mu^-$ events for 278 GeV/c incident pions.

Same sign dimuon events with missing energy can come from three sources:

- 1) An additional π or K decay in association with a single muon event (the single muon event can be from charm or pion decay).

- 2) D^0 - $\bar{D}^0$ mixing, i.e., charm production followed by two semi-leptonic decays where in one decay a D^0 decayed to the wrong sign muon.

3) Bottom particle production in which one B particle decayed semileptonically and the other B particle decayed to charm followed by a semileptonic decay of the charm particle.

Backgrounds from π and K decay were determined experimentally to be $1.1 \pm .1$ and $1.9 \pm .9$ ($\mu^+\mu^+ + \mu^-\mu^-$) for the proton and pion data samples, respectively.

In order to extract a limit on $D^0-\bar{D}^0$ mixing (i.e., the relative probability that a D^0 will decay to the wrong sign rather than the right sign muon, $P(D^0 \rightarrow \bar{D}^0)$) we need to make assumptions about (a) the probabilities that a charm quark fragments to D^0 's and other charm states, and (b) the semileptonic branching ratio of the D^0 relative to those of the other charm states. If we assume that the fragmentations of the charm quark and charm antiquark are independent then

$$P(D^0 \rightarrow \bar{D}^0) = \frac{1}{2} \left[\frac{N_{\mu^+\mu^+} + N_{\mu^-\mu^-}}{N_{\mu^+\mu^-}} \right] \left[\frac{\sum_0^3 f_i B_i}{f_0 B_0} \right]$$

where f_0, f_1, f_2, f_3 and B_0, B_1, B_2, B_3 are the fractions of D^0, D^+, F^+, Λ_c and their semileptonic branching ratios respectively. The available data on charm particle semileptonic decays are $B_0 < 4\%$ (90% CL) and $B_1 = 22.0^{+4.4}_{-2.2}\%$ from the DELCO group;⁷ and $B_0 = 5.5 \pm 3.7\%$ and $B_1 = 16.8 \pm 6.5\%$ from the Mark II group.⁸ Other information on semileptonic decays is available if we assume that the ratios of the semileptonic branching ratios are proportional to the lifetimes. An average of the available data on charm particle lifetimes⁹ (in units of 10^{-13} sec) is

$$\begin{aligned} \tau(D^0) &= 2.8 \pm 0.6, \quad \tau(D^+) = 8.1 \pm 1.4, \quad \tau(F^+) = 2.0^{+1.8}_{-0.8}, \\ \tau(\Lambda_c) &= 1.4^{+0.8}_{-0.4}. \end{aligned}$$

The ratios of the lifetimes are consistent with the data on semileptonic decays.

For the fractions f_i , $f_0(D^0) = 0.35$, $f_1(D^+) = 0.35$, $f_2(F^+) = 0.15$ and $f_3(\Lambda_c) = 0.15$ are assumed. Such production probably underestimates $f_0(D^0)$ since substantial D^* production would favor D^0 's over $D^{\pm}$'s. Assuming the above lifetimes are proportional to the semileptonic branching ratios we find an upper limit (90% CL) of $P(D^0 \rightarrow \bar{D}^0) < 0.044$.

In general, the fraction of wrong sign muons is related¹¹ to the difference in mass δm and the difference in inverse lifetimes $\delta \lambda$ for the CP eigenstates of the D^0

$$P(D^0-\bar{D}^0) = \frac{\delta m^2 + \frac{1}{4} \delta \lambda^2}{2\lambda^2 + \delta m^2 - \frac{1}{4} \delta \lambda^2} \leq 0.044$$

where λ is the average inverse lifetime of both D^0 states. Using $\lambda = 0.36 \times 10^{13} \text{ sec}$ we obtain the limit

$$\delta m \leq 1 \times 10^{12} \hbar \text{ sec}^{-1} (= 6.5 \times 10^{-4} \text{ ev})$$

This can be compared with the measured $K_L^0 - K_S^0$ mass difference of $0.5 \times 10^{10} \hbar \text{ sec}^{-1}$. Our data also imposes the limit $\delta\lambda/\lambda < 0.55$ on the difference in the inverse lifetimes of the CP eigenstates of the D^0 .

The same sign dimuons can also be used to investigate diffractive bottom particle production in hadronic collisions. Using muon and neutrino distributions from CESR data,¹¹ semileptonic branching ratios for $B \rightarrow \mu X$ and $\bar{B} \rightarrow (D \rightarrow \mu X) X$ of 10% and 8%, respectively, and production distributions analogous to those for intrinsic charm,⁵ we find upper limits (90% CL) for diffractive bottom production of 40 $\mu\text{b/nucleon}$ for 350 GeV protons and 140 $\mu\text{b/nucleon}$ for 278 GeV π^- 's. These upper limits assume an $A^{2/3}$ behavior. If $A^{1.0}$ is assumed, these limits should be reduced by a factor of 3.8.

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