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EVIDENCE FOR LEADING PARTICLE EFFECTS IN CHARM FRAGMENTATION
FROM NEUTRINO DATA

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A B S T R A C T

Recent data on the CERN-Dortmund-Heidelberg-Saclay collaboration on opposite sign dimuon events produced in neutrino interactions are shown to require a fragmentation function $D(z)$ for charmed quarks non-negligible near $z=1$, in contrast with the general current belief. Although the published data already suggest that the gross features of $D(z)$ are to be described by a constant or slowly rising (near $z=1$) behaviour, we find that a much more decisive test would be provided by the $E_+/(E_H + E_+)$ distribution, where E_+ and E_H are the energies of the positive muon and of the hadron shower, respectively.

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The CERN-Dortmund-Heidelberg-Saclay (CDHS) collaboration has recently presented¹⁾ data on opposite sign dimuon events produced in neutrino and antineutrino interactions, which considerably improve our experimental knowledge of this process. This is because of both the size of the sample (257 neutrino events and about one fifth as much for antineutrinos) and the completeness of the information (for each event the charges and momenta of the two muons, the energy of the hadron shower and the type of incident particle are known).

Although the gross features of the data can be almost immediately understood in terms of a generic quark parton model (QPMC) for the production of charmed mesons, which subsequently decay semileptonically, the quality of the data allows to extract more specific information. As already remarked in Ref. 1) a QPMC with a conventional choice for the fragmentation function^{*)} $D(z)$, i.e., small or vanishing near $z = 1$ [e.g., $\exp(-3z)$ as phenomenologically argued in Ref. 3), or $(1-z)^2$ which is favoured theoretically^{4),5)}], is not able to reproduce the observed tail of neutrino induced events at large E_+ , the positive muon energy. (No similar statement can be made for the antineutrino events because of insufficient statistics.) The existence of a similar effect in the HPWF neutrino data⁶⁾ has been recently emphasized by Barger et al.⁷⁾, who propose a heavy lepton (produced at the upper vertex) origin for it. This interpretation, however, cannot be accepted in face of the evidence presented in Ref. 1). Specifically, for these high E_+ events the value of p_{TS} (the transverse momentum of μ^+ relative to the hadron shower) remains small, and the distribution of ϕ (the angle between the projection of the two muon momenta on a plane perpendicular to the neutrino direction) becomes even more peaked at 180° . Applying the cut $E_+ > 0.35 (E_\nu - E_-)$ (E_ν and E_- being the energies of the incident neutrino and of μ^- , respectively), proposed in Ref. 7) and meant to exclude events of charm origin, also the x distribution remains essentially unchanged⁸⁾. The latter fact also excludes the possible relevance of a conventional diffractive contribution for these events (which should be confined to small Q^2 , and thus essentially small x).

It looks, therefore, as if a QPMC is quite all right for explaining these high E_+ events, and that one has just to change $D(z)$. On the other hand one can regard this as a welcome opportunity to extract information about the z distribution of charmed mesons. In neutrino interactions, in fact, charmed mesons have been "detected" so far only through their semileptonic decay mode. In spite

*) When not otherwise specified standard notations are used, see, e.g., Sehgal and Zerwas²⁾.

of the unpleasant smearing introduced by the (variable) decay momentum of the μ^+ , there is no other way at the moment of getting at their z distribution (unlike other hadrons such as $\pi^\pm$, K_S^0 and Λ^0 , for which the z distributions have been directly measured)⁹⁾⁻¹¹⁾. Knowledge of the fragmentation function for charmed quarks is required, for instance, in any practical calculation directed to contrast, for the sake of discrimination, lepton spectra expected from charm and from the decay of heavy leptons⁴⁾.

In this paper we consider a standard QPMC model with various types of $D(z)$ functions. We find that the published CDHS data on $\mu^+\mu^-$ events¹⁾ clearly require a $D(z)$ which is not negligible near $z = 1$, and exhibit a marked preference for a constant or slowly rising $D(z)$. We also show that a much more sensitive discriminator among the possible behaviour of $D(z)$, and which should be used to reach a more firm conclusion, is provided by the experimental distribution of $E_+/(E_H+E_+)$ (where E_H is the energy of the hadron shower). We finally make a few comments on this result, in the context of other data and from the point of view of the theoretical interpretation.

The model. We adopt a standard quark parton model for the production of charm [see, e.g., Refs. 2), 12) and 13)]. Because of the experimental lower cut on the muon energies and of the average over the incident neutrino spectrum, the results are completely insensitive to the way one handles the threshold region. The numerical results we present are obtained assuming fast rescaling¹²⁾ and an effective threshold $W > W_{th} = 4 \text{ GeV}$ for the invariant hadron mass (raising W_{th} to 5-6 GeV makes practically no difference). The quantities we are interested in (Table and Figs. 1 and 2) are only very marginally dependent on the x distribution, $Q(x)$, (except for ϕ) through the kinematical and threshold limits¹²⁾. We have taken $Q(x)$ equal to the measured x distribution (in principle it should be corrected, before being used as input, for $x \geq 0.8$, but it is anyway small in this region). An ambiguity in our results might in principle originate from the choice of the decay mechanism [$D \rightarrow \mu\nu K(495)$, $D \rightarrow \mu\nu K^*(890)$, etc.]. The decay mechanism is relevant not only to fix the energy of the μ^+ , but also, because of the missing neutrino energy, to give E_H and the direction of the hadron shower, necessary to calculate p_{TS} . In our calculation these are obtained, in fact, by subtracting the energies and momenta, respectively, of μ^+ , μ^- and the final neutrino from those of the incident neutrino. In practice, however, the Q value of the decay is essentially determined by the p_{TS} and $p_\perp$ distributions ($p_\perp$ is the momentum component of μ^+ perpendicular to the plane defined by the momenta of the incident neutrino and of μ^- -- $\langle p_{TS} \rangle = 2 \langle p_\perp \rangle$ if the missing neutrino energy were identically zero).

Such components of the μ^+ momentum (if one neglects for P_{TS} the extra broadening induced by the missing neutrino energy) are built up exclusively by the decay momentum of μ^+ and by the transverse momentum p_{DT} of the produced D meson. The data are well fitted by a p_{DT} distribution

$$f(p_{DT}) = \exp(-b p_{DT}^2)$$

with

$$1/b = \langle p_{DT}^2 \rangle = 0.5 \text{ GeV}^2$$

(resulting from an interpolation between the experimentally observed $\langle p_T^2 \rangle$ of J/ψ and of lighter mesons produced in hadronic interactions, see, e.g., Ref. 14) and a decay $D(1.87) \rightarrow \mu\nu K(498)$. The role of p_{DT} is limited -- taking $\langle p_{DT}^2 \rangle = 0$, $\langle p_{TS} \rangle$ and $\langle p_L \rangle$ decrease by $\approx 20\%$ only. Assuming $D(1.87) \rightarrow \mu\nu K^*(890)$, and the same $\langle p_{DT}^2 \rangle$, the resulting $\langle p_{TS} \rangle$ and $\langle p_L \rangle$ are about 25% lower and too short of the experimental values. It is worth while mentioning that the most recent DASP data on the momentum spectrum of electrons in e^+e^- anomalous electron + hadron events are unable to decide between a dominant $D \rightarrow \mu\nu K$ or $D \rightarrow \mu\nu K^*$ decay¹⁵⁾. As far as the need for a substantial $D(z)$ near $z = 1$ is concerned, it is clear that in order to reproduce the data such a need becomes increasingly stronger as the Q value of the assumed decay decreases. The assumption of $D \rightarrow \mu\nu K$, therefore, represents in any case the most conservative choice that one can make from this point of view. In the actual calculations we have used $D(1.87) \rightarrow \mu\nu K(495)$ described by a matrix element with constant form factors (assuming pure phase space makes little difference, though). The complete expression for the differential cross-section we use can be written compactly as

$$\begin{aligned} d\sigma = & \frac{G^2 M E_\nu}{\pi} Q(x) F(y) D(z) f(p_{DT}) \\ & * \theta(W - W_{th}) H[p_\mu(\mu^+), p_\mu(\nu)] \\ & * dx dy dz \frac{d^3 p(\mu^+)}{E_+} \frac{d^3 p(\nu)}{p_0(\nu)} \end{aligned}$$

where $F(y) = 1$ for incident neutrinos, and H represents the Lorentz invariant decay distribution for the charmed meson.

In order to reproduce the CDHS data¹⁾ we have folded in the CERN narrow band neutrino spectrum¹⁶⁾, and imposed the experimental lower cut on the muon energies $E_{\pm} > E_{\min} = 4.5 \text{ GeV}$ ¹⁾. Angular acceptance effects are negligible, because of the large acceptance of the apparatus¹⁾. To take into account the broadening effects on the experimental distributions [especially of E_+ and $E_+/(E_H+E_+)$] due to the uncertainty in the measurement of the hadron shower and muon energies, we have simulated such effects in the Monte Carlo program taking

$$\Delta E_H / E_H = 1.3 \sqrt{E_H (\text{GeV})}$$

and

$$\Delta E_{\pm} / E_{\pm} = 0.15$$

The resulting spill-over onto regions where the distributions are originally small is not dramatic, although worth taking into consideration.

Results. Among the published CDHS data¹⁾ the distribution most sensitive to $D(z)$ is that of E_+ . Also the azimuthal angle ϕ provides an indicator in this respect (as already noted in Ref. 3)). The p_{TS} distribution, once the decay mechanism is fixed so as to reproduce the [essentially $D(z)$ independent] $p_{\perp}$ distribution, has some feeling of the high z tail of $D(z)$ because of the broadening effects induced by the missing neutrino energy (the published¹⁾ scatter plot of p_{TS} versus E_+ shows these effects quite visibly). In the Table, besides the average values of these quantities, also that of y is included, for a more complete check with the data. A relevant entry is that of the expected number of events with $E_+ > 30 \text{ GeV}$ (normalized to the experimentally observed 168 events with $E_+ > 5 \text{ GeV}$)¹⁾. The calculated E_+ distributions are compared with the data in Fig. 1. We have made a choice of $D(z)$ functions mainly in view of the different weights they apply to the large z region. Some of these have also been proposed in the literature with various justifications [see Ref. 4) for $(1-z)^2$, Ref. 3) for $\exp(-3z)$, Refs. 3) and 17) for $\delta(z-0.84)$ -- see also Ref. 2) for $(1-z)/z$, and Ref. 18) for $1/z$].

It should be taken into account that because of the $E_{\min}$ cut the low z region is suppressed, and therefore the behaviour of $D(z)$ therein does not matter

much. Moreover, because of the smearing due to the μ^+ decay momentum the results are sensitive only to the gross features of $D(z)$. The published data appear to be well described by a constant or slightly rising (near $z = 1$) $D(z)$. But, although they seem to rule out extreme forms like $(1-z)^2$ and $\delta(z-0.84)$, one would clearly like to have a more sensitive test before arriving to a firm conclusion. We call attention for this sake to the much stronger discriminating power of the $E_+/(E_H+E_+)$ distribution (Fig. 2). In the hypothetical case of a semileptonic decay of $D(1.87)$ with (almost) zero Q value, such distribution would coincide with that of z . The actually finite decay momentum of μ^+ (and in part that of the neutrino) produces a smearing, but the gross features of the z distribution still surface in that of $E_+/(E_H+E_+)$. According to preliminary indications, the experimental distribution actually lies in between those for $D(z) = \text{constant}$ and $D(z) = \exp(+3z)$ as plotted in Fig. 2⁸⁾. It is worth while to stress again that, because of the smearing due to the μ^+ decay momentum, the calculated distributions are not sensitive to the detailed shape of $D(z)$. For instance the effects of a constant $D(z)$ can be also simulated by a parametrization of the type

$$D(z) = (1-z)^2/z + K \delta(z - 0.84)$$

(similar to that used in Ref. 19)) with $K \approx 0.4$. The only firm point is that $D(z)$ must be substantial near $z = 1$.

We have also explored the possible relevance of other sources for the observed tail at large E_+ ²⁰⁾. Rare high Q value decays of D -- if $D \rightarrow \pi\mu\nu$ is assumed with a 100% μ -semileptonic branching ratio (which is much beyond the experimental bounds)¹⁵⁾, then [with $D(z) = \exp(-3z)$] the number of events with $E_+ > 30$ GeV increases by only three units. $F \rightarrow \mu\nu$ -- if the $\mu^+\mu^-$ events are entirely attributed to the production of the F meson (whose observation has been recently reported, with a quoted mass of 2.03 ± 0.06 GeV)²¹⁾ and its subsequent purely leptonic decay (a possibility discouraged by the DASP data)¹⁵⁾ retaining $D(z) = \exp(-3z)$ one is barely able to account for the observed 28 events with $E_+ > 30$ GeV. But, besides the fact that these are very extreme assumptions, there is complete disagreement with the transverse momentum distribution of μ^+ . In other words, an extremely high effective Q value for the decay, beyond acceptable limits, is to be used in order to compensate for a decreasing $D(z)$.

Concluding remarks. Data on the z distribution of $\pi^\pm$ and K_S^0 (and Λ^0 as well) in neutrino interactions at Fermilab energies are now available and allow for a meaningful comparison [Ref. 9) -- see also Refs. 10) and 11)]. In principle one could expect K_S^0 production by neutrinos to be directly comparable to that of charmed mesons, the charmed quark being simply replaced by the strange quark. But, because of the much lower mass of K_S^0 , production of $\bar{K}K$ pairs, proceeding through the Cabibbo favoured $\Delta S = 0$ component of the weak current, is expected to be substantial and thus the similarity is lost. The experimental z distribution of K_S^0 looks somewhat flatter than the one for $\pi^\pm$, which appears to be well described by an $\exp(-4.5 z)$ law⁹⁾. A still flatter z distribution for charmed mesons, then, would not look unnatural. This transition can be in part understood trivially, as a result of the much lower production multiplicity of charmed mesons, due to their larger mass. The strong rise near $z = 0$ of the π distribution appears in fact very likely due to the contribution of events with large π multiplicities. Such an argument, however, does not seem to us sufficient to account for the large contribution near $z = 1$ apparently required in the case of charmed mesons. Maybe some simple understanding may be found in the framework of the bremsstrahlung picture for the fragmentation of quarks^{20),22)}.

It is worth while to mention that a further check of the conclusions presented here may be provided by e^+e^- data on lepton spectra^{23),15)}. The energies for which such data are available at present are rather low, however, and thus charm threshold effects are still expected to be dominant.

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	E_+ ^{a)} (GeV)	No. evts. $E_+ > 30$ ^{b)}	ϕ	p_{TS} (GeV)	$p_{\perp}$ (GeV)	y
Experimental Data	17.5 ± 1.5	28	$128^\circ \pm 3^\circ$	0.76 ± 0.4		0.58 ± 0.02
$(1-z)^2$	12.7	8.5	124°	0.65	0.33	0.62
$\exp(-3z)$	13.9	12.5	126°	0.69	0.33	0.61
Const.	17.0	22	133°	0.77	0.32	0.57
$\exp(+3z)$	19.2	29	138°	0.88	0.32	0.54
$\delta(z - 0.84)$	20.7	34.5	141°	0.91	0.31	0.53
a) Average value for $E_+ > 5$ GeV with $\pi \rightarrow \mu$, $K \rightarrow \mu$ background subtracted. b) Normalized to 168 events observed above $E_+ = 5$ GeV after subtraction of $\pi \rightarrow \mu$ and $K \rightarrow \mu$ background.						

TABLE - Comparison with data ¹⁾ of calculated average quantities and number of events above 30 GeV for various $D(z)$ functions.

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FIGURE CAPTIONS

Figure 1 Comparison with data ¹⁾ of calculated E_+ distributions.

Figure 2 Calculated $E_+/(E_H + E_+)$ distributions. Curves are normalized
to 233 events.

fig 1

fig 2