A Model for Like Sign Dimuons—Detailed Analysis

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Abstract. A detailed account of a model for like sign dimuons, recently proposed by us, is presented and compared with all the like sign dimuon data available. It can naturally account for the rate and all the kinematic features of these events, as given by the CHARM, CFRR and CFNRR experiments. The predicted event distributions are shown for the CHARM experiment, since it has sufficient number of events for a meaningful comparison. The implication of the model for other processes like neutrino induced trimuons and charm hadroproduction are also discussed.

Introduction

Neutrino production of prompt like sign dimuons (LSD) is now well established experimentally [1–5]; but it has so far defied theoretical explanation [6–8]. Nonetheless there are strong indications in the data suggesting associated charm production as the most likely source, i.e.

\[ \nu N \rightarrow \mu^- CC X \]
\[ \rightarrow \mu^- X, \]  

(1)

\[ \bar{\nu} N \rightarrow \mu^+ CC X \]
\[ \rightarrow \mu^+ X \]  

(2)

where \( CC \) are a pair of charm particles. Moreover, as we shall see later, the measured rate and the measured values of the kinematic variables suggest that the asymptotic \( CC \) production has a rate of \( \approx 1\% \) and a diffractive configuration (i.e. forward production of the \( CC \) pair carrying the bulk of the hadron energy). Interestingly, the photoproduction [9, 10] and hadroproduction [11] processes also show diffractive \( CC \) production at the \( \approx 1\% \) level, at asymptotic energies. However, they have generally been ascribed to two distinct mechanisms, photon–gluon fusion for photoproduction and intrinsic charm for hadroproduction, neither of which contributes to \( CC \) production in the neutrino reactions of (1), (2)*. There is a perturbative QCD contribution to this process via gluon bremsstrahlung [6]; but it gives an extremely low rate and a nondiffractive configuration [8].

In a recent letter [15], we have proposed a phenomenological model for like sign dimuons in terms of diffractive \( CC \) production. The present paper contains a more detailed account of this model and its application to the LSD data. We also discuss its implications for processes other than LSD to allay the apprehensions, expressed in [16] and [17], that the model may have problem with neutrino induced trimuon and charm hadroproduction data.

The following section describes the model in detail. In the next section, the model predictions are compared with the LSD data. Besides comparing the predicted rate with that of a global data compilation, we compare the predicted average values of various kinematic variables with those of the CHARM [5], CFRR [2] and CFNRR [3] data. We see that the model can satisfactorily account for all the essential features of the available LSD data. We also show the predicted distributions in these kinematic variables for the CHARM experiment, since it has sufficient statistics for a meaningful comparison. In the last section, we discuss the model predictions for processes other than LSD—i.e. the neutrino induced trimuon and like sign \( \mu e \) events [18] and the hadroproduction of charm.

* They can contribute to LSD via bottom particle production [14]; but the rates are too low by over an order of magnitude [7, 8].
Model Formulation

We start with the standard quark parton model for the charged current interactions of (1) and (2). This corresponds to a $d\rightarrow u$ quark transition for the neutrino interaction (1) as illustrated in Fig. 1a. The $c\bar{c}$ pair is assumed to evolve in the hadronisation process of the $u$ quark jet. In the perturbative QCD model of [6], this occurs via gluon bremsstrahlung, as shown in Fig. 1b. This corresponds to a short time (and distance) scale evolution of $c\bar{c}$ which are then assumed to hadronise independently of the quark jet and its other bremsstrahlung products (indicated by dots in the figure). Thus the $C\bar{C}$ production rate and configuration are essentially given by the hard scattering diagrams of Figs 1a, b. One gets an extremely low rate since it is suppressed both by the QCD coupling $\alpha_s$ and the gluon propagator $g^{-4} < (2m_c)^{-4}$. Moreover one gets a nondiffractive configuration for the $C\bar{C}$ pair, as it carries the energy-momentum of only one of the bremsstrahlung gluons. Our model assumes that there is a nonperturbative $c\bar{c}$ component in the $u$ jet, at the $\sim 1\%$ level, which evolves over a long (typically hadronic) time scale, as illustrated in Fig. 1c. This means that the jet fragments are not independently emitted one after another (as in Fig. 1b); but they all undergo mutual interaction over a long time scale before emerging as a cluster of hadrons. Since the fragments have to travel with similar velocities in order to stay together over a long time scale, the heavier ones $(C\bar{C})$ carry the bulk of energy-momentum, as originally suggested by Bjorken [19] and Suzuki [20].

Our model is motivated by the work of Brodsky et al. [13, 14], mentioned above. They assume a nonperturbative charm quark–antiquark component in the proton wave function $(u_d d_c \bar{c} \bar{c})$ at the $\sim 1\%$ level, wherein the $c\bar{c}$ pair carry the bulk of the proton energy-momentum. This seems to be supported by the charm hadroproduction data [11] as well as the recent data on charm muoproduction [21, 22]. Of course, a $c\bar{c}$ component in the proton wave function will not contribute to charm pair production in the charged current reactions of interest here. In view of the phenomenologically observed symmetry between the quark structure functions and fragmentation functions [23], however, it seems plausible to assume that the $u$ quark fragmentation function has an analogous component of energetic $C\bar{C}$ at the $\sim 1\%$ level. Moreover, the original argument of [13] in support of a $\sim 1\%$ nonperturbative $c\bar{c}$ component in the proton wave function, seems to apply equally well to the $u$ quark fragmentation function. It assumes the Okubo–Zweig–Iizuka suppressed processes like charmonium decay to proceed via a two step transition $c\bar{c} \rightarrow c\bar{c} uu \rightarrow u\bar{u}$. And since the charm pair generation in the proton wave function or the $u$ quark fragmentation function involves only the second step, the probability is given by the square root of the OZI suppression factor $(\sim 10^{-2})$.

The above estimate of the magnitude of the nonperturbative $c\bar{c}$ component is admittedly model dependent and at best of qualitative significance. Alternatively, one may regard this magnitude as a model parameter, with a phenomenological value of $\sim 1\%$. Given such a nonperturbative (long time scale) $c\bar{c}$ component, however, the diffractive configuration follows naturally from the Bjorken–Suzuki argument [19, 20]. These authors have applied this to the charm quark fragmentation function, which corresponds to interchanging the $u$ and $c$ quarks in Fig. 1c. We shall closely follow the Suzuki model [20], in view of its quantitative success in explaining the experimental fragmentation function of charm quark into charm particle. In particular it predicts the fragmentation function to have a threshold at $z \approx (2/3)^2$ followed by a peak at $z \approx 2/3$, in contrast to a flat fragmentation function predicted by the independent gluon bremsstrahlung model [24]. Both the features are in remarkable agreement with the recent $e^+e^- \rightarrow C\bar{C}$ data [25] as well as $\nu N \rightarrow \mu C X$ data [26].

Following [20], we assume that the jet fragments undergo multiple collisions over a long hadronisation

* Of course, one needs colour compensation between the $c\bar{c}$ pair on one hand and the remaining jet fragments as well as the remainder of the hadron on the other. However, this is assumed to take place via soft gluon exchanges without affecting the $C\bar{C}$ production rate or configuration

Following [19, 20] we also assume that the colour compensation between the jet fragments and the remainder of the hadron can be taken care of by a chain of slow pions, carrying a negligible fraction of the jet energy-momentum

** Charm quark and hadron are denoted by small and capital letter respectively.