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UPPER LIMITS ON D^0 - $\bar{D}^0$ MIXING AND $B\bar{B}$ PRODUCTION FROM
MUON-NUCLEON SCATTERING

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ABSTRACT

In deep inelastic interactions of 200 GeV muons with a carbon target, we have found 17 events of the type $\mu^+N \rightarrow \mu^+\mu^+\mu^-X$ ("wrong-sign" dimuons). We derive upper limits of 1.2% (90% c.l.) on $D^0-\bar{D}^0$ transitions (mixing) or, alternatively, of 9 pb (90% c.l.) cross section for $B\bar{B}$ pair production as possible sources of such events.

1. INTRODUCTION

In deep inelastic scattering of muons on nucleons, so-called wrong-sign dimuon events of the type $\mu^+N \rightarrow \mu^+\mu^-\mu^-X$ resp. $\mu^-N \rightarrow \mu^-\mu^+\mu^+X$ can be produced via two non-trivial processes. The first is the production of a pair of charmed mesons including a D^0 , followed by a transition of the neutral particle to its antiparticle (mixing) and the semileptonic decay of both, e.g.

$$\begin{array}{lcl}
 \mu^+N \rightarrow \mu^+ (D^-, \bar{D}^0) D^0 X & & \\
 \downarrow & \searrow & \\
 & \bar{D}^0 & \\
 & \downarrow & \\
 & \mu^- \bar{\nu}_\mu X & \\
 \downarrow & & \\
 \mu^- \bar{\nu}_\mu X & &
 \end{array} \quad (1)$$

An alternative possibility is the production of bottom pairs ($B\bar{B}$) where the semileptonic decay of one B is associated to the semileptonic decay of a charmed particle in the decay chain of the other B, e.g.

$$\begin{array}{lcl}
 \mu^+N \rightarrow \mu^+ B \bar{B} X & & \\
 \downarrow & \searrow & \\
 & \bar{D} X & \\
 & \downarrow & \\
 & \mu^- \bar{\nu}_\mu X & \\
 \downarrow & & \\
 \mu^- \bar{\nu}_\mu X & &
 \end{array} \quad (2)$$

The rate of $D^0\text{-}\bar{D}^0$ transitions is expected to be very small (10^{-4} to 10^{-7}) in the Kobayashi-Maskawa scheme [1]. Until now, the effect has not been observed experimentally; limits ranging from 4.4% to 20% (at 90% c.l.) have been obtained in other experiments [2-7].

Cross sections for $B\bar{B}$ production with muon and photon beams have been predicted by several authors, mostly in the framework of the Vector Meson Dominance (VMD) or the Photon-Gluon Fusion (γ GF) model [9-15]. Experimental limits were obtained by the EMC [6] and BFP [8] experiments.

In this letter, we report on a high luminosity measurement of wrong-sign dimuon production yielding improved experimental limits for both processes [16].

2. APPARATUS AND DATA TAKING

The experiment was performed at the CERN SPS muon beam. The apparatus is a 50 m long toroidal iron magnet, centered on the beam axis and instrumented with scintillation counters and multiwire proportional chambers (MWPCs) to detect the scattered muons. The central bore of the magnet contained a 40 m long carbon target. A detailed description of the apparatus can be found in ref. [17].

The data presented here were obtained with μ^+ and μ^- beams of 200 GeV energy, and were selected from a data sample that was used to study electro-weak effects in deep inelastic muon-nucleon scattering [18]. The total number of incoming muons was $1.75 \cdot 10^{12}$, corresponding to an integrated luminosity of $9.16 \cdot 10^{39} \text{ cm}^{-2}$. The spectrometer magnetic field was reversed with each change of the beam polarity in order to always focus muons of the same sign as the incoming beam muon towards the spectrometer axis. Thus, data from μ^+ and μ^- beams were combined in the analysis. 165 candidate events with two wrong-sign (defocused) muon tracks were found in the raw data sample; the interacting beam muon escapes, in general, through the central hole of the spectrometer without being detected. Of these candidates, 114 were retained as good events after visual scanning by physicists. To ensure a good momentum determination, each track was required to have at least 4 points in each of the two projections recorded by the MWPCs and to have a momentum of at least 10 GeV. To suppress spurious triggers from hadronic punch-through and to select events for which the acceptance can be reliably calculated, the reconstructed muon tracks were required to fulfill the trigger of the apparatus. Since the spectrometer is designed to measure focused tracks but has a poor acceptance for defocused muons which rapidly escape the magnet volume, these cuts reduce the final data sample to only 17 events.

3. BACKGROUND FROM π/K DECAYS

The principal background in the selected data sample is due to ordinary π and K decays. It was computed with a Monte Carlo program which simulated the multiplicities of final state charged π 's and K's and their distributions in transverse momentum p_T and fractional energy z , including the correlation between these variables [19]. Primary hadrons were allowed to decay in the target region before entering the spectrometer iron; the development of hadronic showers due to secondary interactions inside the carbon target was neglected. We also neglected the effect of K^0 , vector meson (ρ , ω , ϕ), and strange baryon (Λ , Σ) production.

Decay muons were tracked through the detector, simulating multiple scattering and energy loss; they were reconstructed and the events selected in exactly the same way as the experimental data. The background from double hadron decay was found to be 15.5 ± 2.8 events which is consistent with the 17 events observed. Fig. 1 indicates a good agreement of the kinematic distributions of experimental data and simulated background, justifying a posteriori the above simplifications. We gain additional confidence in this simulation program from the good background description which is observed for other multimMuon topologies [16].

4. PRODUCTION OF HEAVY QUARK PAIRS

To compute the acceptance of the apparatus for muon pairs from heavy quark decays, the kinematics of $c\bar{c}$ and $b\bar{b}$ pairs were calculated in the framework of the γ GF [20] and the quark-parton model in a similar way as in our study of muon pairs at 280 GeV energy [21,22]. The gluon distribution $G(\eta)$ and the QCD parameters relevant to the γ GF model are the same as in ref. [23] and are summarized in table 1.

5. $D^0-\bar{D}^0$ MIXING

We use the total diffractive charm production cross section of $\sigma(c\bar{c}) = 6.9^{+1.9}_{-1.4}$ nb measured by the BFP collaboration at 209 GeV beam energy [25], which is in good agreement with the EMC result $\sigma(c\bar{c}) = 9.8 \pm 3.3$ nb at 250 GeV [23] when the difference in beam energy is taken into account. We then assume the c quark to fragment with equal probability in charged and neutral D's [26], i.e. a cross-section of $\sigma(D^0\bar{c}) = 3.4$ nb for the production of $D^0\bar{D}^0$ and D^0D^- pairs. With the known semileptonic branching ratios of the D^0 (7.5%) and the $D^\pm$ (17%) [27], this corresponds to an effective cross section for μ pair production of $\sigma(D^0\bar{c}) \cdot B_{sl}^2 = 31.2$ pb. To this we assign a global systematic error of 50% which accounts for the quoted error of the total charm cross section, the uncertainty of the charged to neutral D production ratio, and a possible contribution of F and Λ_c production to the measured charm cross sections.

Assuming a fragmentation function for c quarks into charmed mesons $D(z) = [z(1 - 1/z - 0.25/(1 - z))^2]^{-1}$ in the $c\bar{c}$ c.m. system [24], we find an acceptance $A = 4.0 \cdot 10^{-3}$ for wrong sign dimuon final states. Flat fragmentation as advocated by the EMC [23] lowers this value to $A = 2.9 \cdot 10^{-3}$. We retain this more conservative figure to calculate the limit on the mixing rate.

The signal which we would expect for an (unphysical) mixing probability $P(D^0 \leftrightarrow \bar{D}^0) = 1$ is $L \cdot \sigma(D^0\bar{c}) \cdot B_{sl}^2 \cdot A = 830 \pm 425$ events, where the error includes a 10% statistical uncertainty of the Monte Carlo acceptance calculation and a 5% systematic uncertainty of the luminosity calibration.

Fig. 2 shows the simulated distribution of the sum of transverse momenta of muons from double charm decays. Since the shape is very similar to the corresponding spectrum of hadronic background, we calculate the upper limit on the mixing probability directly from the total data sample of 17 events. Combining all errors quadratically, we find $P(D^0 \leftrightarrow \bar{D}^0) < 1.2\%$ at 90% confidence level.

6. $B\bar{B}$ PRODUCTION

We assume that the semileptonic decay of B mesons proceeds predominantly via $b \rightarrow c\mu\nu$, with a branching ratio of 11.8% and a hadron recoil mass $M(X_c) = 2.0$ GeV [28]. The other B meson is assumed to decay into a charmed particle with 80% branching ratio [29] and a fragmentation function $D(z) \sim z^9(1-z)$ [30] in the $b\bar{b}$ pair c.m. system. The charmed particle, in turn, decays semileptonically via $c \rightarrow s\mu\nu$ with an average branching ratio of 10%. In this model, our acceptance for wrong-sign dimuons is $5.8 \cdot 10^{-3}$.

The muon p_T distribution from such decays is substantially harder than is observed in the data (fig. 2). We obtain the best upper limit on the $B\bar{B}$ cross section by selecting the single event with $\Sigma p_T > 4$ GeV/c which gives $\sigma(\mu N \rightarrow \mu B\bar{B}X) < 9$ pb (90% c.l.) at 200 GeV muon energy. Using the equivalent photon approximation [31] for photon energies $\nu > 50$ GeV, this corresponds to a limit of $\sigma(\gamma N \rightarrow B\bar{B}X) < 3.5$ nb (90% c.l.) at an average ν of 160 GeV.

7. CONCLUSIONS

From a study of wrong-sign dimuon final states in deep inelastic scattering, we have derived an upper limit on $D^0-\bar{D}^0$ mixing of 1.2% (90% c.l.) or, alternatively, a limit of 9 pb (90% c.l.) on bottom pair production in 200 GeV muon-nucleon interactions. The best earlier measurements gave limits on the mixing probability of 4.4% [2], albeit for somewhat different assumptions on charm cross sections, and of 12 pb for the $B\bar{B}$ cross section [5]. The limit on $D^0-\bar{D}^0$ mixing is still far above the prediction of the standard 6-quark model but rules out alternative models in which the mixing is predicted to be larger [32-35]. The limit on $B\bar{B}$ production rules out predictions based on vector dominance [10,11] which are consistently higher than those from the photon-gluon fusion model.

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TABLE 1

Parameters of the photon-gluon-fusion model
used in the Monte Carlo simulation

	$c\bar{c}$ production	$b\bar{b}$ production
Quark mass	$m_c = 1.5 \text{ GeV}$	$m_b = 4.6 \text{ GeV}$
Λ_{QCD}	500 MeV	
Gluon distribution	$\eta G(\eta) = 3(1-\eta)^5$	
Strong coupling constant	$\alpha_s(Q^2=4m_c^2)$	$\alpha_s(Q^2=4m_b^2)$

FIGURE CAPTIONS

Fig. 1 Wrong-sign dimuon data compared to the Monte Carlo simulation of background from π and K decays;

1(a) Sum of energies of the two μ 's;

1(b) Sum of transverse momenta.

Fig. 2 Sum of transverse momenta of the experimental data compared to expectations from charm production with subsequent $D^0-\bar{D}^0$ mixing and from $B\bar{B}$ production.

FIG. 1

FIG. 2