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Measurement of the Charm Structure Function and Its Role in Scale Noninvariance

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From a sample of 20 072 dimuon final states, a first determination of the structure function $F_2(c\bar{c})$ for diffractive charmed-quark pair production by 209-GeV muons is obtained. $F_2(c\bar{c})$ has a ν dependence similar to that of the photon-gluon fusion model, but its Q^2 dependence peaks at lower Q^2. Diffractive charm production accounts for $\sim\frac{1}{3}$ of the scale noninvariance observed in muon-nucleon scattering at low values of the Bjorken x variable, x_B.

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The original signature[1] for scale noninvariance in muon-nucleon scattering was the "shrinkage" of the structure function $F_2(x_B)$ towards low Bjorken x_B with rising Q^2, as confirmed by subsequent muon[2] and neutrino[3] experiments. Although this shrinkage may be viewed as a general increase with Q^2 in the number of resolved constituents, these data have been widely interpreted as confirming specific predictions of quantum chromodynamics (QCD).

Ambiguities in the interpretation of scale noninvariance are different at high and low x_B. Corrections for finite target mass[4] and for processes which are coherent over two or more constituents[5] are critical at high x_B, suggesting that the stronger QCD tests may be found at *low* x_B.[6] However, for $x_B \lesssim 0.1$, available beam energies prohibit reaching $Q^2 \gg m_{c\bar{c}}^2$, where $m_{c\bar{c}}$ is a typical charmed-quark–pair mass. The proximity of this charm mass scale complicates any low-x_B study of asymptotic scale noninvariance.

One previous estimate of the charm contribution to F_2 has been made.[7] We have presented[8] a high-statistics measurement of the cross section for charm muoproduction. Constrained by the differential spectra of these data, we choose one model for this process, and quantify its contribution to scale noninvariance over a range of Q^2 and x_B.

Three charm-muoproduction models are available. In the simplest vector-meson-dominance (VMD) picture[9] the photon cross section $\sigma_{\rm eff}$ has the Q^2 dependence $(1+Q^2/m_\psi^2)^{-2}$. Bletzacker and Nieh (BN) describe[10] a phenomenological "photon dissociation" mechanism. The photon-gluon-fusion (γGF) model[11] uses a Bethe-Heitler graph for $c\bar{c}$ production, and replaces the nuclear photon with a gluon carrying a fraction x of the target momentum. Typically, one assumes a $3(1-x)^5/x$ distribution for x and a quark mass $m_c = 1.5$ GeV/c^2. In all three models, the exchanged energy is shared by the charmed pair. In contrast, the simplest model for charm production by W^- exchange allows only one "strange-sea" quark to inherit that energy. Using a "charmed sea" to replace the gluon x distribution in a model for $c\bar{c}$ muoproduction would require redefining x and introducing some *a priori* correlation between the c and $\bar{c}$ momentum fractions.

The most recent calculations[12,13] using the γGF

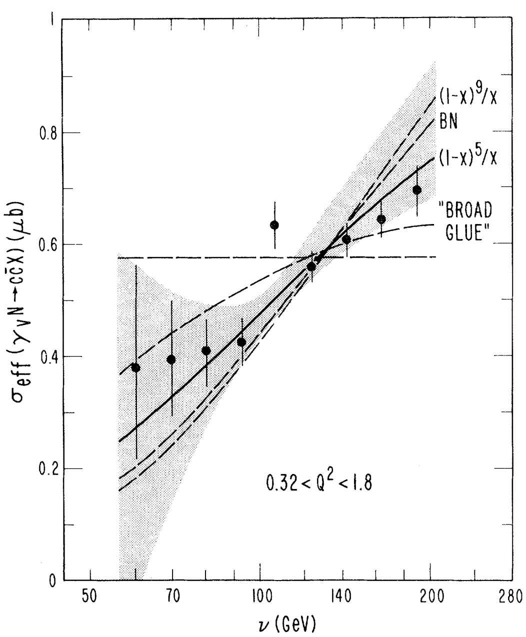

FIG. 1. Energy dependence of the effective cross section $\sigma_{\rm eff}$ for diffractive charm photoproduction. For $0.32 < Q^2 < 1.8$ (GeV/c)^2, $\sigma_{\rm eff}$ varies with Q^2 by $\lesssim 20\%$. Errors are statistical. The solid curve exhibits the ν dependence of the photon-gluon fusion model with the "counting-rule" gluon x distribution $3(1-x)^5/x$, and represents the data with 13% confidence. Other gluon-distribution choices $(1-x)^9/x$, and "broad glue" $(1-x)^5(13.5+1.07/x)$ (Ref. 11) are indicated by dashed curves. The dashed curve labeled BN is the phenomenological parametrization of Ref. 10, and the horizontal line represents the energy independence assumed by recent photoproduction analyses (Ref. 15). Curves are normalized to the data. The shaded band exhibits the range of changes in shape allowed by systematic error. For clarity it is drawn relative to the solid curve. Data below $\nu = 75$ GeV are excluded from further analysis.

model have successfully fit our experiment's data[14] on ψ muoproduction along with lower-energy ψ photoproduction data, despite the model's possible inapplicability at $Q^2 = 0$.[12] In the γGF model,[11] charmonium production is dual to $c\bar{c}$ production with $2m_c < m_{c\bar{c}} < 2m_D$, making the ψ fits sensitive both to m_c and to the fraction of charmonia realized as the ψ. These problems are reduced in muoproduction of open charm. We have displayed[8] the substantial level of agreement between γGF predictions and the data in six kinematic distributions. Without extra assumptions concerning quark fragmentation and charm decay, the γGF model predicts only the dependence on Q^2, ν, and $m_{c\bar{c}}$. Since the last quantity is not reconstructed, we focus on the virtual-photon variables.

The data were produced by interactions of 209-GeV muons in the multimuon spectrometer at Fermilab. Analysis methods and experimental details are described in Ref. 8. A calculated $(19 \pm 10)\%$ background from π, K decay is subtracted from the sample of 20 072 dimuon final states. Estimates of systematic error include uncertainties in acceptance modeling and background subtraction. Figure 1 displays the dependence of $\sigma_{\rm eff}$ on ν in a range of Q^2 centered at 0.75 (GeV/c)^2. The insensitivity of $\sigma_{\rm eff}$ to Q^2 in this range decouples its Q^2 and ν dependence. The γGF model with gluon distribution $3(1-x)^5/x$ successfully describes the ν dependence of these data. However, systematic uncertainties prevent the analysis from ruling out the BN model, or two alternative choices for the gluon x distribution. The data do reject the flat ν dependence assumed in recent photoproduction analyses.[15]

We define the charm structure function $F_2(c\bar{c})$ through the relation

$$Q^4 \nu\, d^2\sigma(c\bar{c})/dQ^2 d\nu = 4\pi\alpha^2(1 - y + y^2/2)F_2(c\bar{c}).$$

Here y is $\nu/\nu_{\rm max}$ and $\sigma(c\bar{c})$ is the cross section for diffractive charm muoproduction. We label $\sigma(c\bar{c})$, $F_2(c\bar{c})$, and $\sigma_{\rm eff}$ as "diffractive" because our analysis[8] is sensitive mainly to $c\bar{c}$ pairs which carry off most of ν. $F_2(c\bar{c})$ plays the same role in charm production as would F_2 in inclusive scattering if absorption of longitudinally polarized photons were negligible.

Figure 2 exhibits the dependence of $F_2(c\bar{c})$ on Q^2 at two values of fixed average ν. At its peak $F_2(c\bar{c})$ is ~4% of F_2. None of the models adequately represents the data. The γGF shapes for $m_c = 1.5$ and 1.2 GeV/c^2 are nearly degenerate, since they depend on $m_{c\bar{c}}$, which cannot be less

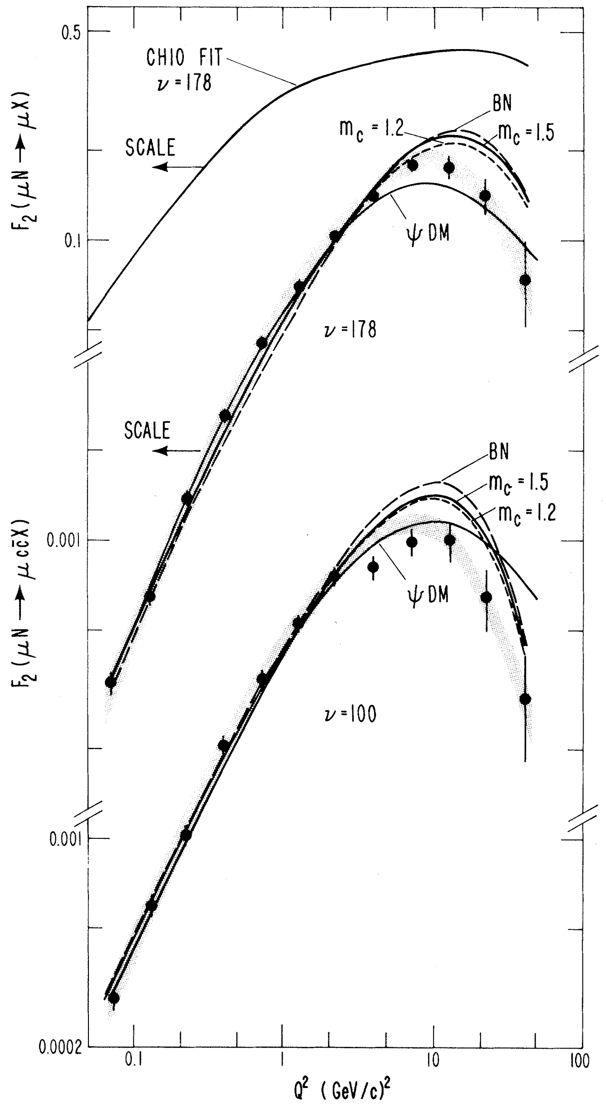

FIG. 2. Q^2 dependence of the structure function $F_2(c\bar{c})$ for diffractive charm muoproduction. At each of the two average photon energies, each curve is normalized to the data. Errors are statistical. The solid (short-dashed) curves labeled $m_c = 1.5$ (1.2) exhibit the photon-gluon–fusion prediction with a charmed-quark mass of 1.5 (1.2) GeV/c^2. Solid curves labeled ψDM correspond to a ψ-dominance propagator, and long-dashed curves labeled BN are the model of Ref. 10. Shown at the top is a fit adapted from Ref. 2 to the inclusive structure function F_2 for isospin-0 μN scattering. The shape variations allowed by systematic errors are represented by the shaded bands.

than $2m_{D^0}$.[11] The maxima predicted by both the γGF and BN models resemble the data in shape and in ν dependence, but occur at higher values of Q^2. The ψ-dominance functions drop too slowly at high Q^2. Systematic errors are only weakly correlated with Q^2 and do not obscure the disagreement.

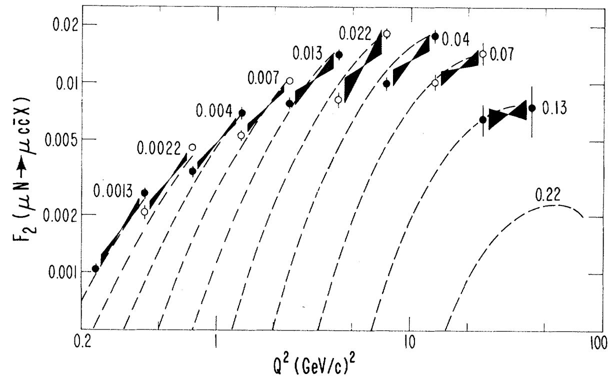

FIG. 3. Scale noninvariance of $F_2(c\bar{c})$. Data points are arranged in pairs, alternately closed and open. The points in each pair are connected by a solid band and labeled by their common average value of $x_B = Q^2/2m_p\nu$. Errors are statistical. The dashed lines are the prediction of the photon-gluon fusion model with $m_c = 1.5$ GeV/c^2 except that the model is renormalized and damped at high Q^2 as described in the text. The solid bands represent the slope variations allowed by systematic errors.

In the energy range of the data in Fig. 3, $F_2(c\bar{c})$ is clearly scale-noninvariant for $Q^2 < 10$ (GeV/c)^2, or $x_B \lesssim 0.07$. To model the charm contribution to F_2 for smaller photon energies, we normalize the γGF model to the data and damp it at high Q^2 by the factor $[1 + Q^2/(10\ \text{GeV}/c)^2]^{-2}$. The resulting family of dashed curves in Fig. 3 adequately matches the data.

To describe the full effect of charm production on F_2 we must include the charmonium contribution. The ψ-muoproduction rate[14] agrees with the unmodified γGF prediction if elastic ψ production accounts for $\frac{1}{6}$ of all charmonium production.[13] Adopting this model, we augment the measured[8] $6.9^{+1.9}_{-1.4}$ nb open charm cross section by 2.8 nb of bound charm production. This increases the maximum charm contribution to inclusive scale noninvariance only by ~15%. Fitted values[2] of ∂F_2(inclusive)$/\partial \ln Q^2$ at fixed x_B are compared in Table I to $\partial F_2(c\bar{c})/\partial \ln Q^2$. The latter is augmented for charmonium production and is calculated with the (γGF) model that has been matched to the muoproduction data. Where charm scale noninvariance is most important, the calculation is reliable to ≈±40%.

We conclude that diffractive charm production is responsible for ~$\frac{1}{3}$ of the total inclusive scale noninvariance in a region bounded by $2 < Q^2 < 13$ (GeV/c)^2 and $50 < \nu < 200$ GeV, and centered at x_B

TABLE I. Calculated $10^4\partial F_2/\partial \ln Q^2$ at fixed x_B vs ν (top), Q^2 (left margin), and x_B (diagonals, right margin). For each Q^2-ν combination, two values are shown. The bottom value is fit to the structure function F_2 for μN scattering (Ref. 2). The top value is the contribution $F_2(c\bar{c})$ to F_2 from diffractive muoproduction of bound and unbound charmed quarks.

ν (GeV)	27	42	67	106	168	
Q^2 $(\text{GeV}/c)^2$		$10^4\partial F_2(c\bar{c})/\partial \ln Q^2$ / $10^4\partial F_2(\mu N)/\partial \ln Q^2$				x_B
0.63	17 / 1070	30 / 1090	43 / 1110	54 / 1120	58 / 1130	
1.0	23 / 980	43 / 1010	63 / 1040	77 / 1050	84 / 1060	0.002
1.6	30 / 650	59 / 680	87 / 700	107 / 720	116 / 730	0.003
2.5	36 / 310	73 / 340	110 / 350	139 / 360	146 / 360	0.005
4.0	36 / 320	80 / 390	128 / 430	162 / 460	163 / 480	0.008
6.3	29 / 210	75 / 330	128 / 410	165 / 460	154 / 490	0.013
10	15 / 50	54 / 220	104 / 340	138 / 430	112 / 480	0.020
16	4 / -130	27 / 50	64 / 230	90 / 360	52 / 440	0.032
25	-2 / -189	7 / -126	26 / 50	40 / 230	0 / 370	0.050
40	0 / -31	-1 / -171	6 / -122	10 / 50	-22 / 240	0.080
63		0 / -23	1 / -154	1 / -119	-16 / 50	0.130

≈ 0.025. This region provided most of the original evidence[1] for scale noninvariance in muon scattering. VMD arguments[8] raise the possibility that nondiffractive charm muoproduction might add substantially to the diffractive scale noninvariance we have discussed. We emphasize that deeper implications of scale noninvariance in muon scattering can be understood only by first correcting for such kinematic effects.

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