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RESOLUTION OF TWO CHARM PUZZLES

HADROPRODUCTION AND NEUTRINO-INDUCED SAME-SIGN DILEPTONS

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ABSTRACT

We study the ambiguities in leading order QCD calculations of charm hadroproduction and neutrino-induced same-sign dimuons and question the popular belief that these processes constitute a challenge to the standard model.

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1. Introduction

Except for occasional warnings[1] we have routinely ignored the fact that the standard model, despite all its successes, fails to accomodate the experimental data[2,3] on the production of same-sign dimuons in the interaction of neutrinos with hadrons. We reconsider this problem in view of the confirmation of the earlier results by an experiment[4] with five times the sensitivity of earlier measurements.

The leading diagrams for the production of same-sign dimuons in the standard model are shown in Fig. 1. The second muon is of charm pair origin, *i.e.* $O(\alpha_s^2)$ in QCD, as the leading $O(1)$ diagrams such as $\nu s \to \mu^- c(\to \mu^+)$ only result in opposite sign leptons. It is a long-standing puzzle[1] that a routine calculation of the diagrams in Fig. 1 falls short of the measurements by $1 \sim 2$ orders of magnitude.

As the experimental signal is now well established one might be inclined to question the theoretical interpretation and blame the signal on soft, non-perturbative effects. This road has been traveled[5] and such an apology for the discrepancy between theory and experiment can actually be dismissed.[1] We briefly review the arguments. Large same-sign dimuon cross sections are supposed to be associated with a large non-perturbative probability for a quark jet, produced in a charged current interaction, to fragment in a $c\bar{c}$ pair, see Fig. 2a. The fragmentation function $D_{u\to c\bar{c}}$ can be adjusted[5] to describe the data. But as a result, a large non-perturbative charm production component is now predicted by factorization in hadron collisions, see Fig. 2b. This component would be diffractive in nature and a recent Fermilab beam dump experiment[6] limits the cross section of such a charm source to $30\,\mu$b if it is present in the data at all. Therefore,

$$D_{u\to c\bar{c}} \simeq \frac{\sigma_c}{\sigma_\pi} = \frac{\sigma(NN \to cX)}{n_\pi^{-1}\,\sigma(NN \to \pi X)} \lesssim 10^{-3}\,. \tag{1}$$

This puts a bound on the dimuon signal by factorization of the diagrams in Fig. 2

$$\frac{\sigma(\mu^-\mu^-)}{\sigma(\mu^-)} \simeq \mathrm{B}(c \to \mu)\; D_{u\to c\bar{c}} \lesssim 10^{-4}\,. \tag{2}$$

Hadron data at $\sqrt{s} \simeq 30\,\mathrm{GeV}$ put a bound on dimuons from a neutrino beam with $E_\nu > 150\,\mathrm{GeV}$ and therefore (2) falls short of the data.[‡1] Conversely, any explanation of the same-sign dimuon puzzle along these lines implies the existence of truly diffractive charm production in hadron collisions with observable cross section in the Fermilab/SPS energy range. Data do not seem to support this. On the theoretical side, the existence of such a large soft (intrinsic) charm component of the proton has been shown to be inconsistent with QCD.[8]

Same-sign dimuons can also result from D^0-$\bar{D}^0$ mixing and b-quark production followed by the cascade decay $b \to c \to \mu$. The cross sections are, however, very small.[9]

We therefore question whether the same-sign dimuon puzzle can be dismissed as a soft physics problem.

[‡1] Neutrino and hadron interactions in Fig. 2 should be compared at the same invariant energy of the u-quark, i.e.

$$s_{NN} = \langle x\rangle^{-1}\, s_{PN} = \langle x\rangle^{-1}\, s_{WN}$$

with $s_{WN} = 2M\nu - Q^2$. Here $\langle x\rangle \simeq 0.2$ corrects for the leading particle effect.[7] For $Q^2 \simeq 70\,\mathrm{GeV}^2$ we see indeed that $E_\nu \simeq 150\,\mathrm{GeV}$ corresponds to $\sqrt{s_{NN}} \simeq 30\,\mathrm{GeV}$. We also used $n_c = 1$ rather than 2 in (1) as only the forward (large x) charmed particle is subject to the $30\,\mu$b limit.

2. Charm Hadroproduction Revisited

In this letter we speculate that the discrepancy between the perturbative calculation and the data might be illusionary and associated with large ambiguities in the calculation, especially the treatment of the $c\bar{c}$ threshold in diagrams such as those in Fig. 1. The crucial hint comes again from hadroproduction where heavy quarks are produced to leading order via the fusion diagrams $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$. The heavy quark threshold is implemented in the calculation by requiring that $s_{q\bar{q}}, s_{gg} \geq 4m_c^2$. Here m_c is a threshold parameter which is related, but not necessarily identical, to the quark mass obtained from considering nonrelativistic charmonium model. It is well-known[10] that the cross section for charm production is very sensitive to the value of m_c. This is illustrated in Fig. 3a for $\sqrt{s} = 27.4\,\mathrm{GeV}$ for various choices of structure functions.[11] The origin of the strong dependence of the predicted cross section on m_c is the very rapid dependence of the structure functions on s_{gg} (or $s_{q\bar{q}}$) which are integrated above threshold $x = 2\,m_c/\sqrt{s_{gg}}$.

We next draw attention to a recent measurement by the LEBC bubble chamber that the D cross section in pp interaction is $22\,\mu$b with a small error.[12,13] This experiment has large acceptance and is done on hydrogen target. No large phase space corrections are involved in obtaining the result, the error is essentially statistical. By using data from a hydrogen target we finesse problems related to nuclear corrections which are not understood.[14,6,13] In order to reconcile this result with leading order QCD we require that $m_c \lesssim 1.25\,\mathrm{GeV}$. The value could be smaller because Λ_c, F, … productions are not included, see Fig. 3. A value of $m_c \simeq 1.25\,\mathrm{GeV}$ has also been suggested by QCD sum rules from the charmonium spectrum.[15] A critical test of the suggestion that the normalization of the gluon fusion diagrams be increased by choosing $m_c < \frac{1}{2}m_\psi$ is that all other predictions of the model, which are not noticeably affected by the shift in mass, be correct. In other words, the Feynman x and transverse momentum dependence of the cross section as well as the correlation between the charm particles produced have to be consistent with the predictions of the leading order fusion calculation. Recent experiments show that this is indeed the case.[13] The observation of charm particles with large longitudinal momentum is now believed to be the consequence of a boost in momentum of the charm quark (produced with low x by the fusion mechanism) resulting from pickup of spectator valence quarks to form a charmed particle D, Λ_c. It is now questioned on both experimental[16] and theoretical[17] grounds whether "diffractive" charm production exists.

Both high energy $\bar{p}p$ collider and fixed target experiments seem to be consistent[16] with leading order QCD, although there might be some corrections. The evidence for unconventional sources of heavy quarks now rests mainly on ISR experiments. Given their complicated triggers and small phase space coverage they might have been misinterpreted as to the precise values of the cross section and the momentum distribution of the quarks.

This resolution of the charm hadroproduction puzzle can be tested in two obvious ways. One is the cross section in πp interactions. The results are shown in Fig. 3b. Our calculation with smaller m_c again agrees with data,[18] although the gluon distribution in pion is not known well. The second test directly involves measurement of the energy dependence of the charm cross section. In Fig. 3c we calculate the ratio of the pp cross section at 800 and 400 GeV. For the low values of the threshold parameter m_c the energy dependence of charm production is less strong than for previous calculations using $\frac{1}{2}m_\psi$ or m_D. A measurement of

this ratio is under way using Fermilab's doubler. We predict an increase in the cross section of less than a factor 2 from 400 GeV to 800 GeV where previously an increase of a factor 3 or more might have been expected.

3. Same-Sign Dileptons

Our suggestion to resolve the same-sign dimuon puzzle is now obvious. Other characteristics of the events are indeed compatible[4] with the predictions of the leading order gluon bremsstrahlung diagrams of Fig. 2. As for hadronic charm production only the normalization is a problem. We start by performing a straightforward calculation of the leading order QCD diagrams. The result is shown in Fig. 4 for EHLQ structure functions[11] which have been used because they have been fitted to neutrino data in a similar kinematic range. We show two illustrative calculations. Both use a coupling constant running in the invariant mass of the gluon in Fig. 1. The upper curve also assumes a running mass of the charm quark given by

$$m_c(q^2) = m_0 \times \left(\frac{\log(4m_0^2/\Lambda^2)}{\log(q^2/\Lambda^2)} \right)^{\frac{12}{25}} \tag{3}$$

with $m_0 = 1.0\,\mathrm{GeV}$, $\Lambda = 0.5\,\mathrm{GeV}$. The lower one assumes a fixed value $m_c = 1.25\,\mathrm{GeV}$. In both calculations we "borrowed" the $c \to D$ fragmentation function $\delta(1-z)$ which is known to adequately describe[19] hadronization of charm quarks in a description of hadroproduction in terms of gluon fusion. The fact that this is not the fragmentation function measured in $e^+e^- \to c\bar{c}$ is not directly relevant because of the quite different environment.

Before drawing conclusions, we proceed to estimate an "error" on these calculations. We do this by performing all possible calculations given that the following aspects are ambiguous: (*i*) the value of m_c, (*ii*) the choice of structure functions, (*iii*) the choice of scale ($\hat{s}$, Q^2 or $4m_c^2$) in coupling constant and structure functions. Furthermore, the momentum cut on the muons has an experimental error and the average momentum $\langle z \rangle$ in $c \to D$ fragmentation is ambiguous. In Table I we tabulate the conclusion in terms of the factor increase in the quantity $\sigma(\mu^-\mu^-)/\sigma(\mu^-)$ resulting from exploiting each of these ambiguities. The largest calculation in this set is shown as the solid line in Fig. 4. It is obtained for Owens-Reya structure functions (set 1)[11], m_c given by Eq. (3) with $m_0 = 1.0\,\mathrm{GeV}$ and all the parameters of Table I adjusted to maximize the result.

We conclude that theory and experiment are not inconsistent. Although our estimates of the ambiguities are on the cautious or even pessimistic side, there is little doubt that the results span an order of magnitude, see Table I. Pinning down a more stable prediction will require higher order calculations. These are difficult. One should also keep in mind that a non-perturbative contribution of the type discussed in the beginning could be present at some level. On the experimental side, one should also bear in mind that the data in Fig. 4 are obtained after subtraction of a large calculated background of muons from π, K-decay. In view of all this it could be argued that even a value of $m_c = 1.25$ GeV reconciles leading order QCD with experiment as was already the case for hadroproduction. In fact, the disagreement between the calculation with $m_c = 1.25\,\mathrm{GeV}$ and the data is less than two standard deviations.

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Helpful discussions with V. Barger, W. Y. Keung and D. Reeder are acknowledged. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U. S. Department of Energy under contract DE-AC02-76ER00881.

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Table I. Uncertainties in the calculation for the neutrino-induced same-sign dimuon cross section.

Ambiguity in calculation at $E_\nu = 100$ GeV	Factor in $\sigma(\mu^-\mu^-)/\sigma(\mu^-)$
threshold parameter m_c (1.0 ~ 1.65 GeV)	10.5 ± 0.4
choice of structure function parametrization	1.26 ± 0.05
scale of running coupling	1.47 ± 0.06
scale of structure functions	1.19 ± 0.05
measurement error on cut p_μ	1.25 ± 0.05
$\langle z \rangle$ of fragmentation $c \to D$	2.10 ± 0.08
details of charm decay, higher order corrections,...	?
cumulative factor	61 ± 15

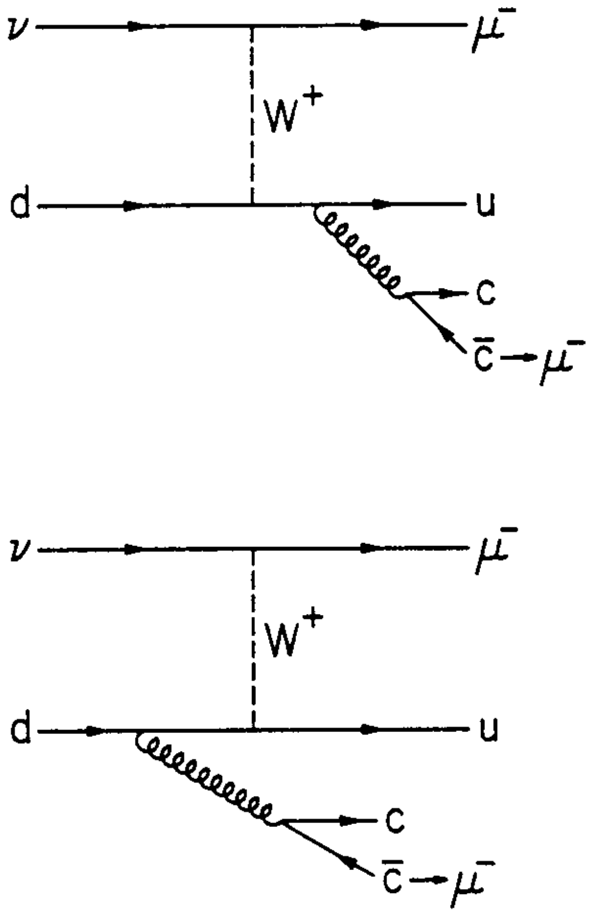
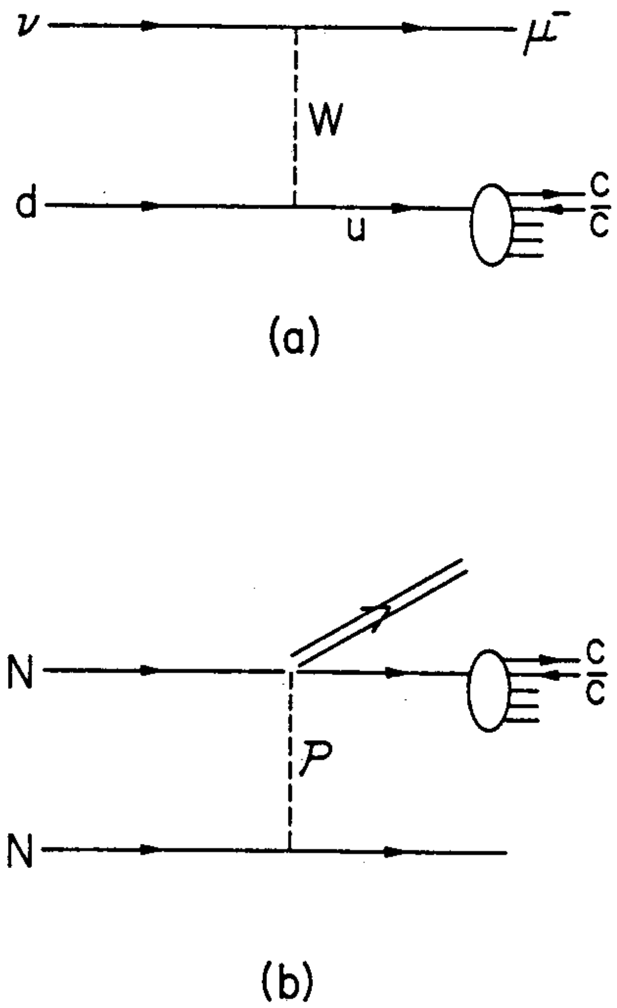


Fig. 1



(a)

(b)

Fig. 2

FIGURE CAPTIONS

Fig. 1. Leading order QCD diagrams for the production of same sign dimuons in ν-nucleon interactions.

Fig. 2a. Soft, non-perturbative $c\bar{c}$ pair in the final state quark jet in a regular charged current ν-nucleon interaction.

Fig. 2b. $c\bar{c}$ pair in final state quark jet in a soft (Pomeron $\mathcal{P}$-exchange) nucleon-nucleon interactions.

Fig. 3a. Cross section for charm production in proton-proton interactions with $\sqrt{s} = 27.4\,\mathrm{GeV}$ as a function of the threshold parameter m_c appearing in the calculation of the leading order $q\bar{q} \to c\bar{c}$, $gg \to c\bar{c}$ diagrams. The band represents different choices of structure functions.[11] We use a running coupling constant with Λ appropriate for the corresponding structure function. The running scales are fixed at $4m_c^2$. The data[12] on D production is shown as a lower limit on the charm cross section.

Fig. 3b. Same as 3a for πN interactions.

Fig. 3c. Ratio of charm production cross sections at 800 GeV and 400 GeV for the calculations shown in 3a.

Fig. 4 The relative rate of same-sign dileptons to charged current leptons are compared to the data of Ref. 3. It is calculated from the leading order QCD diagrams of Fig. 2 and integrated over the CDHS neutrino spectra for each bin (the curves are drawn to guide the eye). For the lower two curves, the strong coupling constant scale is taken to be the gluon mass squared, the running mass and the structure function scales are taken to be the momentum transfer squared. The lower curve corresponds to a fixed mass $m_c = 1.25\,\mathrm{GeV}$, and the higher to a running mass with $m_0 = 1.0\,\mathrm{GeV}$. The highest curve is explained in the text.

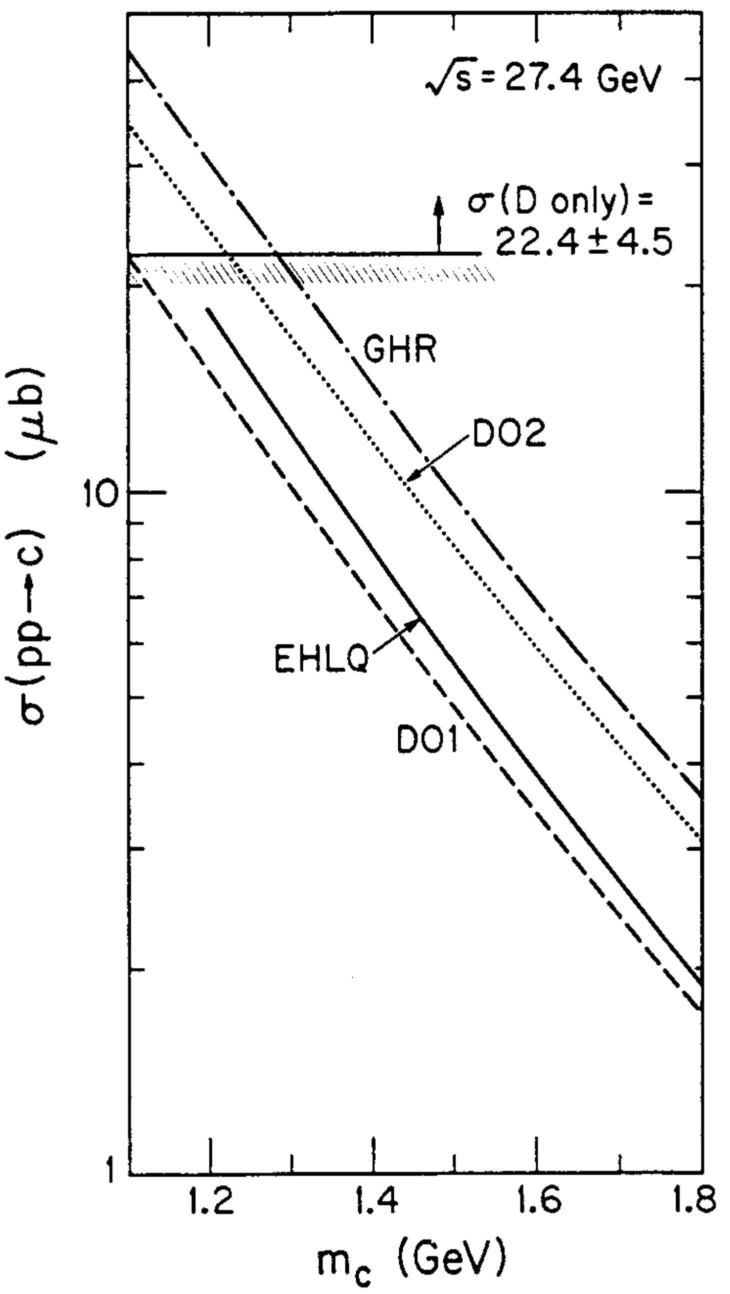

$\sqrt{s}$ = 27.4 GeV
σ(D only) =
22.4 ± 4.5
GHR
DO2
EHLQ
DO1
σ(pp→c) (μb)
10
1
1.2
1.4
1.6
1.8
m_c (GeV)

Fig. 3a

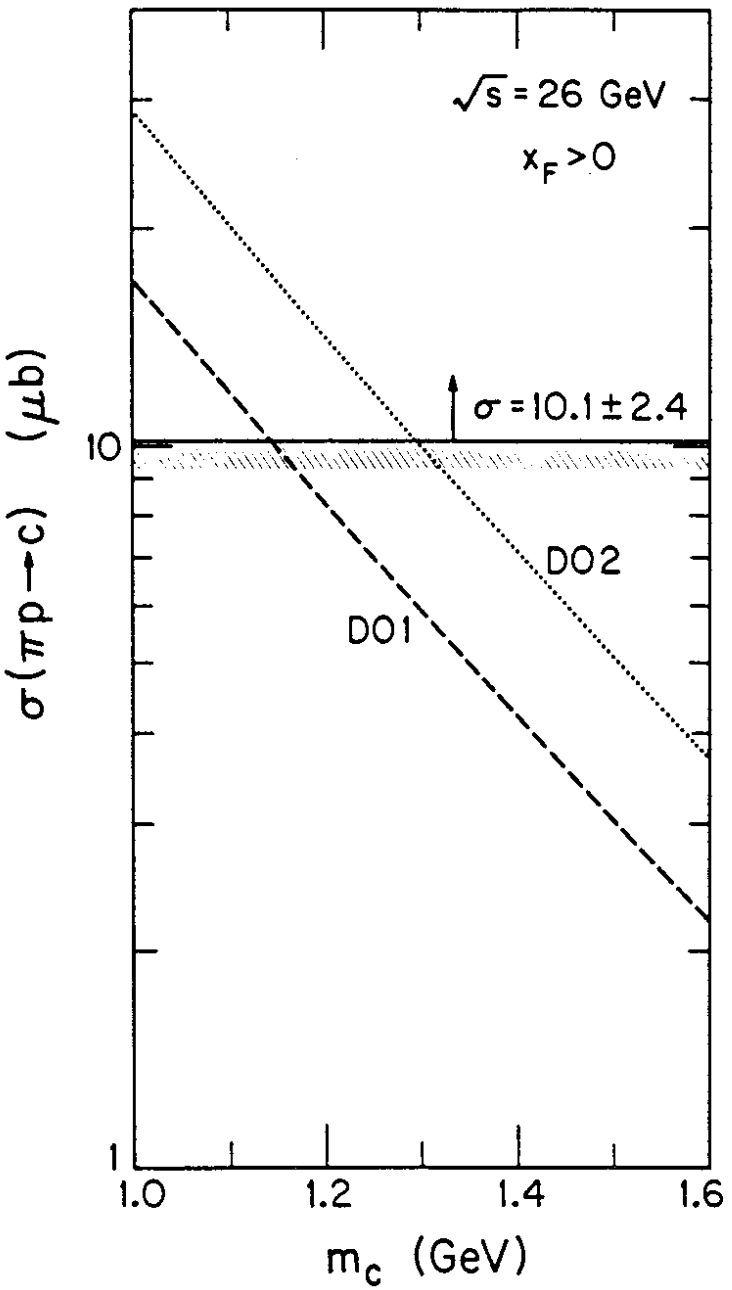

$\sqrt{s}$ = 26 GeV
x_F > 0
σ = 10.1 ± 2.4
DO2
DO1
σ(πp→c) (μb)
10
1
1.0
1.2
1.4
1.6
m_c (GeV)

Fig. 3b

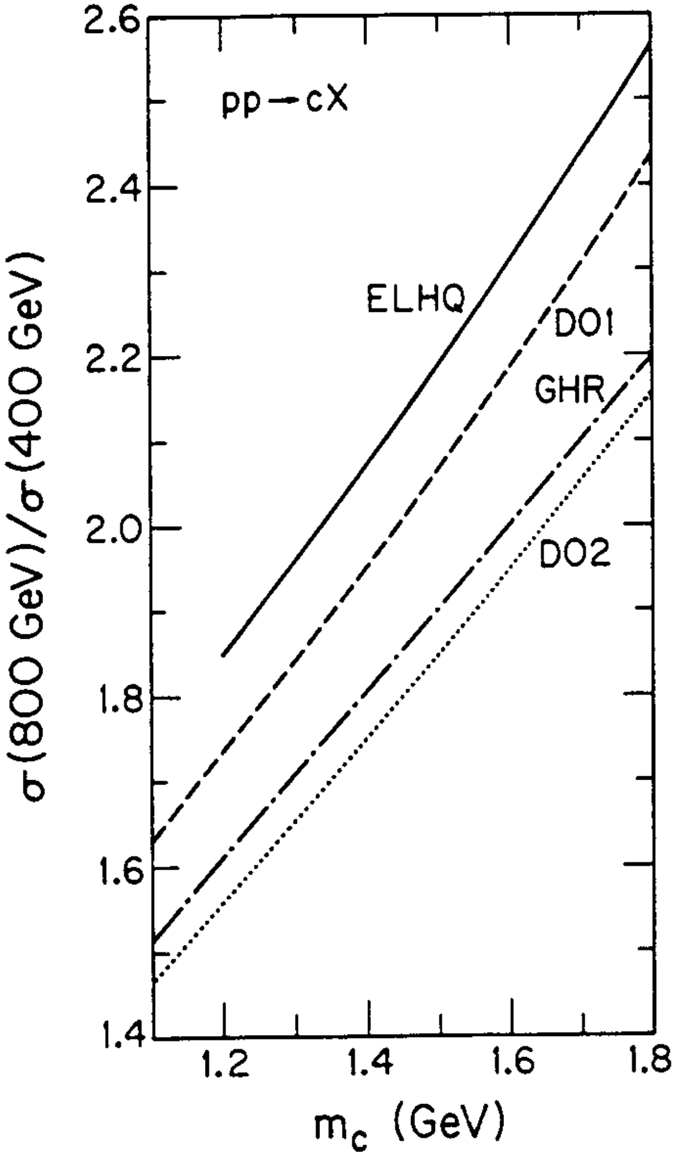
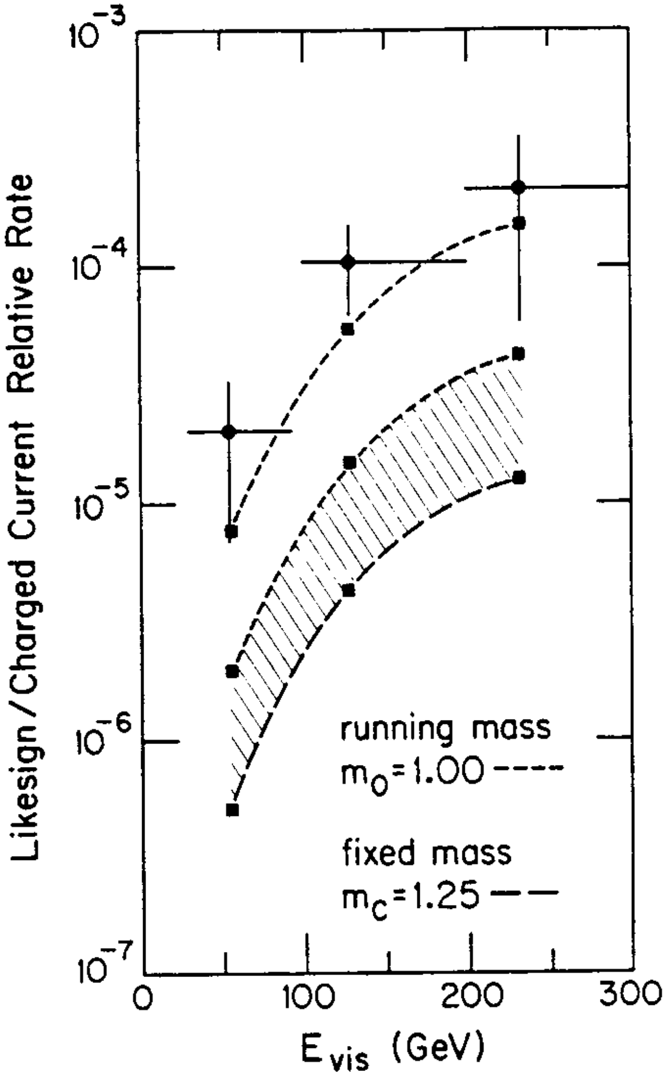

pp → cX
ELHQ
DO1
GHR
DO2
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.4
1.6
1.8
σ(800 GeV)/σ(400 GeV)
m_c (GeV)

Fig. 3c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10^-4
10^-5
10^-6
10^-7
0
100
200
300
Likesign/Charged Current Relative Rate
E_vis (GeV)
running mass
m_0=1.00 ----
fixed mass
m_c=1.25 — —

Fig. 4