

Hadronic Production of the New Resonances:  
Are Gluons Important?M. B. EINHORN and S. D. ELLIS  
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In analogy with the Drell-Yan model for quark-antiquark annihilation into massive virtual photons, we study the possibility that the (presently) hypothetical pseudoscalar partner ( $\eta_c$ ) of the new vector resonance ( $\phi_c$ ), observed at 3095 MeV, is produced via gluon-gluon annihilation. This framework allows us to estimate cross sections for  $\eta_c$  production in hadronic reactions and also suggests the interesting possibility of employing  $\eta_c$  production as a probe of the distributions of gluons in hadrons. In addition estimates are made for the production of pairs of charmed hadrons.

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One of the most interesting proposals concerning the identity of the newly discovered resonances<sup>1</sup> is that, within the framework of the quark model, these particles are bound states of a new, heavy quark ( $c$ ) and its antiquark ( $\bar{c}$ ).<sup>2</sup> The most popular speculation is that these heavy quarks carry the heretofore unobserved quality of charm.<sup>3</sup> However the specific quantum number content of the new quarks is not really germane to the present discussion. We shall utilize the term charm only as a general label for some new quantum number. The features which are relevant are the conjectures that the quarks are massive and that the new particles, being composed of quarks, are hadrons. Consequently, it is interesting to consider by what mechanisms these particles and their charmed brothers



can be produced in purely hadronic reactions. Such studies are useful to determine both how the particles can be efficiently produced and how their properties can be probed in production processes.

In this letter we discuss a novel extension of the Drell-Yan mechanism.<sup>4</sup> In particular we wish to focus attention on the possibility that the states containing a  $c\bar{c}$  pair are produced dominantly, not via quark-antiquark interactions as in the usual Drell-Yan picture, but rather through the interaction of gluons. (By the term gluon we are referring to the presumed vector constituent of hadrons which mediates the interaction between the quarks but which is inaccessible to the usual weak and electromagnetic probes.) The motivation for this suggestion follows from: 1) the "experimental" result that only about half of the proton's momentum seems to reside in the charged constituents<sup>5</sup> (the remainder is presumably carried by the gluons) and 2) within the framework of the asymptotically free picture of  $c\bar{c}$  bound states, the dominant hadronic decays are calculated as if  $c\bar{c}$  annihilated into a small number of gluons. In particular, the  $\phi_c$  (3095) decays via 3 gluons whereas its pseudoscalar ( $\eta_c$ ) partner (which is nearly degenerate in mass), decays into 2 gluons. From this picture, the width of the  $\eta_c$  into 2 gluons is estimated to be  $\approx 75$  times that of the  $\phi_c$  into 3 gluons, i.e.,  $\Gamma_{\eta_c} \approx 5 \text{ MeV}$ .<sup>6</sup> This is all made plausible by arguing that, in a region well above the masses of the ordinary quarks and not too near the threshold for the production of charmed particles, one can use perturbation theory in the (small) effective strong coupling  $\alpha_s$  which turns out to be  $\approx .25$  here.<sup>2</sup> All this suggests that there may be a fairly sizeable  $\eta_c$  production in hadronic reactions via the direct coupling

of 2 gluons. Hence, we imagine the reaction  $A + B \rightarrow \eta_c + X$  to proceed as shown in Fig. 1 which is described by the formula:

$$E_{\eta_c} \frac{d\sigma}{dp_{L\eta_c}} = (x_+ + x_-) \frac{d\sigma}{dx_L} = \frac{8\pi^2 \Gamma_{\eta_c}}{M_{\eta_c}^3} \left( x_+ F_g^A(x_+) \right) \left( x_- F_g^B(x_-) \right) \quad (1)$$

where  $x_{\pm} = \sqrt{\tau + x_L^2/4} \pm x_L/2 = \left( E_{\eta_c} \pm p_{L\eta_c} \right) / \sqrt{s}$ ,  $\tau = M_{\eta_c}^2/s$ ,  $x_L = 2p_{L\eta_c} / \sqrt{s}$  ( $p_A$  is in the +L direction) and  $s = (p_A + p_B)^2$ . The function  $F_g^A(x)$  describes the probability of finding a gluon of momentum fraction  $x$  in hadron  $A$ , summed over the polarizations and averaged over the  $SU_3$  octet of gluons. With this definition of  $F_g^N(x)$  for nucleons, where the gluons carry half the momentum, the appropriate normalization is

$$\int dx x F_g^N(x) \approx 1/16 \quad . \quad (2)$$

The total production cross section is given by

$$\sigma_{\eta_c} = \frac{8\pi^2 \Gamma_{\eta_c}}{M_{\eta_c}^3} \tau \int_{\tau}^1 \frac{dx}{x} F_g^A(x) \cdot F_g^B(\tau/x) \quad . \quad (3)$$

Now focus on the rather striking properties of Eq. 1 (which is just the invariant cross section integrated over  $p_{\perp}$ , which we have ignored here). The first important feature is the factorization in the variables  $x_+$ ,  $x_-$ .<sup>7</sup> The ratio of the cross section at two different values of  $x_+$  but at the same  $x_-$  must be independent of  $x_-$ . An experimental test of this property should be very useful in establishing the validity of the picture discussed here. The most exciting prospect suggested by Eq. 1 is that, if this mechanism is dominant, data over a range in  $s$  and  $x_L$  (i.e., over a range in  $x_{\pm}$ ) will enable one to determine the gluon distribution (including the normalization, if  $M_{\eta_c}$  and  $\Gamma_{\eta_c}$  are known). Thus one can actually hope to test the momentum sum rule, Eq. 2, and check the entire underlying quark-gluon

picture. Finally, having determined the gluon distributions in nucleons, one may obtain the gluon distributions for mesons by observing  $\eta_c$  production with meson beams.

In the following, we will estimate the magnitude of the cross section for nucleon-nucleon collisions due to this gluon mechanism. To do this, a form must be assumed for the gluon distribution  $F(x)$ . In the absence of any complete theory, the simple form  $F(x) = C_n (1-x)^n / x$  was used, with  $C_n = (n+1)/16$  chosen to ensure the normalization of Eq. 2. Four cases of possible interest are  $n = 7, 5, 3,$  and  $0$ , which integers are motivated elsewhere.<sup>8</sup> Lacking any experimental information, we have used values typical of the simple charmonium picture,<sup>2,6</sup>  $M_{\eta_c} = 3.05 \text{ GeV}$  and  $\Gamma_{\eta_c} = 5 \text{ MeV}$ . In Fig. 2a, we display the results of calculations for total  $\eta_c$  production in nucleon-nucleon collisions (Eq. 3) as a function of energy, using the parameters given above. Note that over the Fermilab energy range, cross sections between  $100 \text{ nb}$  and  $1 \mu\text{b}$  are anticipated and that this value is essentially independent of the value of  $n$ . Even larger cross sections are expected at the ISR. Depending on the value of  $n$ , a dramatic increase with energy, by as much as three orders of magnitude, may be observed from  $s = 60 \text{ GeV}^2$  through  $s = 3000 \text{ GeV}^2$ . The behavior of the differential cross section (Eq. 1) is illustrated in Fig. 2b for an energy of  $s = 600 \text{ GeV}^2$ . Note that for  $pp$  collisions the differential cross section is symmetric about  $x_L = 0$ . Although the detailed forms of the curves depend on the particular gluon distributions, there is a general peaking at  $x_L = 0$  (except for  $n = 0$ ) which becomes more pronounced as  $s$  increases.

A slightly more speculative exercise concerns estimating the production of hadrons of nonzero charm. In the present context we shall assume that

such hadrons appear when we produce a  $c\bar{c}$  pair, not in a bound state. We may estimate this production via the process  $2 \text{ gluons} \rightarrow c\bar{c}$ , where the  $c\bar{c}$  pair is treated as free. In the spirit of asymptotic freedom, one assumes that, at least well above threshold, the cross section predicted for this simple process (with no final state interactions) is a good description of the actual production rate for final states containing two charmed hadrons.

This process is described by

$$\frac{d\sigma_{c\bar{c}}}{dM^2} = \frac{\tilde{\sigma}(M^2)}{s} \int_{\tau}^1 \frac{dx}{x} F(x) F(\tau/x) \quad (4)$$

where  $M$  is the mass of the  $c\bar{c}$  pair and as before  $\tau = M^2/s$ . The quantity  $\tilde{\sigma}(M^2)$  is the cross section for 2 gluons to produce a  $c\bar{c}$  pair of mass  $M$ . This is proportional to the corresponding two photon cross section.<sup>9</sup>

$$\tilde{\sigma}(M^2) = C_{\text{color}} \frac{2\pi\alpha_s^2}{M_c^2} \left\{ \frac{(\gamma^2 + 4\gamma + 1) \ln(\gamma + \beta\gamma) - \beta(\gamma + 3)}{(\gamma + 1)^3} \right\} \quad (5)$$

Here we have defined  $y = M^2/4M_c^2$ ,  $\gamma = 2y - 1$  and  $\beta = \frac{2}{\gamma} \sqrt{y(y-1)}$  where  $M_c$  is the  $c$  quark mass and  $\alpha_s$  is the effective coupling. The coefficient

$C_{\text{color}}$  assumes the value  $16/3$  if we sum over all possible color states of the  $c\bar{c}$  pair or  $2/3$  if we require the pair to be a color singlet. Since it remains unclear how the quarks evolve into hadrons, e.g., whether the process conserves color locally in momentum, the former (more optimistic) example was actually used for numerical studies.

The quantity most likely to be of general experimental interest is the total cross section  $\sigma(s, M_{\text{th}}^2)$  obtained from Eq. 4 by integrating from some threshold mass  $M_{\text{th}}^2$  up to  $s$ . The threshold mass  $M_{\text{th}}$  is given by twice the

mass of the lightest charmed hadron which we take from theoretical estimates<sup>3</sup> to be about 2.25 GeV giving  $M_{th}^2 \cong 20 \text{ GeV}^2$ . Motivated by the charmonium picture<sup>2</sup> we take  $M_c = 1.5 \text{ GeV}$  and  $\alpha_s = 1/4$ . As would be expected, the differential cross section (Eq. 4) falls rapidly with increasing  $M^2$ , so that the total cross section  $\sigma(s, M_{th}^2)$  is dominated by the threshold region. We find a total cross section of the order of  $1 \mu\text{b}$  at Fermilab energies ( $s \approx 600 \text{ GeV}^2$ ) independent of the value of  $n$  (within a factor of 2). As with  $\eta_c$  production, the energy dependence from  $s = 60$  to  $s = 600 \text{ GeV}^2$  is quite sensitive to the value chosen for  $n$ . In any case, our results suggest rates for charmed hadron production which should be detectable experimentally.<sup>10</sup> More detailed numerical results are presented in Ref. 8.

Let us turn now to the question of  $\phi_c$  production. By charge conjugation invariance and color conservation, the  $\phi_c$  couples to a minimum of three gluons.<sup>2</sup> In the spirit of the preceding discussion, the dominant mechanism of  $\phi_c$  production might be the annihilation of two gluons from one hadron with one gluon from another. The calculation of this cross section requires knowledge of the probability distribution to find 2 gluons in a hadron. We have even less reliable intuition about this quantity than about the single gluon distribution and we will not present any calculation. However, barring some unforeseen enhancement,<sup>11</sup> this  $\phi_c$  cross section should be smaller than the  $\eta_c$  cross section by at least a factor  $\alpha_s$  ( $\alpha_s/\pi?$ ). Hence we regard

the curves in Fig. 2 for  $\eta_c$  production as likely upper limits for  $\phi_c$  production via similar processes.

It is difficult to compare our estimates with the presently available, somewhat limited, data. Assuming an  $x_L$  independent cross section, Aubert, et al.<sup>1</sup> estimate a cross section for  $pN \rightarrow \phi_c X$  at  $s = 60 \text{ GeV}^2$  of order  $2 \times 10^{-33} \text{ cm}^2$  (assuming a 5% branching ratio to leptons). However, if the cross section is peaked at  $x_L = 0$ , as suggested in Fig. 2b, this is an overestimate by a factor 1.5-4. Preliminary results<sup>12</sup> on  $\phi_c$  production with a neutron beam at Fermilab suggest a cross section per nucleon of about  $10^{-31} \text{ cm}^2$  ( $x_L > .24$ ). The neutron beam flux peaks around 250 GeV/c so this preliminary result suggests a  $\phi_c$  cross section comparable to the  $\eta_c$  production estimates in Fig. 2. As discussed above this is somewhat larger than one might expect from the mechanisms discussed here. While there are undoubtedly other dynamical sources of production for these particles, as yet we know of none which competes quantitatively with the one discussed here. Elsewhere,<sup>8</sup> we elaborate further the model discussed above and review several more conventional possibilities for  $\phi_c$  production.

In any case it seems likely that further surprises are in store for us. In the meantime, the estimates discussed in this paper might serve as a guide for experimentalists.<sup>13</sup> We emphasize again the intriguing possibility that if the gluon annihilation mechanism does indeed dominate the production process, the production of the new heavy particles may serve to probe the gluons in a manner quite analogous to the role played by massive photons for the charged constituents of matter.

We are pleased to acknowledge many stimulating discussions with our colleagues both at the Fermilab and elsewhere. In particular, we thank W. Bardeen, J. Carazzone, B.W. Lee, and C. Quigg for several helpful discussions.

#### REFERENCES

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- <sup>2</sup>T.W. Appelquist and H.D. Politzer, Phys. Rev. Letters 34, 43 (1975); A. De Rujula and S.L. Glashow, ibid., p. 46.
- <sup>3</sup>For a recent review see M.K. Gaillard, B.W. Lee, and J.L. Rosner, Fermilab-Pub-74/86-THY (1974).
- <sup>4</sup>S.D. Drell and T.-M Yan, Phys. Rev. Letters 25, 316 (1970).
- <sup>5</sup>See, for example, D.H. Perkins, "Experimental Aspects of Neutrino Interactions", lectures given at the Fifth Hawaii Topical Conference in Particle Physics, August, 1973 (Oxford University, Nuclear Physics Laboratory, Ref. 67-73).
- <sup>6</sup>These results appeared originally in the first paper of Ref. 2. See also B.W. Lee and C. Quigg, Fermilab-74/110-THY (1974).
- <sup>7</sup>A similar factorization does not occur in the ordinary Drell-Yan model because quarks and antiquarks are distinguishable particles with different distributions.
- <sup>8</sup>M.B. Einhorn and S.D. Ellis, Fermilab-75/17-THY (1975).
- <sup>9</sup>J.M. Jauch and F. Rohrlich, The Theory of Photons and Electrons, Reading, 1955; Addison-Wesley, p. 269.

- <sup>10</sup>R. D. Field and C. Quigg (Fermilab-75/15-THY(1975) ) have shown that charmed particle production based on the exchange of charmed Reggeons is also expected to be quite small ( $\lesssim$  nb).
- <sup>11</sup>Some effect is not impossible if, for example, the presumably large multiplicity of wee gluons plays some role.
- <sup>12</sup>W. Y. Lee, et al., Fermilab seminar, January 17, 1975, to be published.
- <sup>13</sup>We have not discussed how the  $\eta_c$  is actually to be detected. Two reasonable candidates are  $p\bar{p}$  and  $\gamma\gamma$  final states but it is difficult to ascertain what the branching ratio should be (see, e.g., Ref. 2, 6). If we take the  $\phi_c$  as an example, the  $p\bar{p}$  branching ratio is  $\sim .1\%$  whereas if we replace  $\alpha_s$  by  $\alpha$  in our calculation of  $\Gamma_{\eta_c}$  to get the  $\gamma\gamma$  yield we again find a branching ratio (to  $\gamma\gamma$ ) less than 1%. Thus the situation for two-body modes is not overly encouraging, but we would prefer to wait for the experimental dust to settle before drawing any conclusions.

#### FIGURE CAPTIONS

Fig. 1            Production of  $\eta_c$  by two gluon annihilation. The notation is solid lines for quarks and dashed lines for gluons. The incoming hadrons are labeled A and B.

Fig. 2            (a) Cross section,  $\sigma_{\eta_c}$ , for gluon annihilation into  $\eta_c$  as a function of  $s$ . (b) The invariant differential cross section

$$E_{\eta_c} \frac{d\sigma}{dp_{L\eta_c}} = (x_+ + x_-) \frac{d\sigma}{dx_L} \text{ at } s = 600 \text{ GeV}^2 .$$

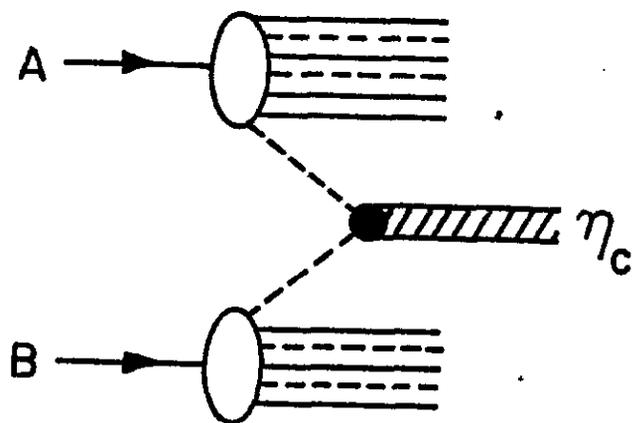


Fig. 1

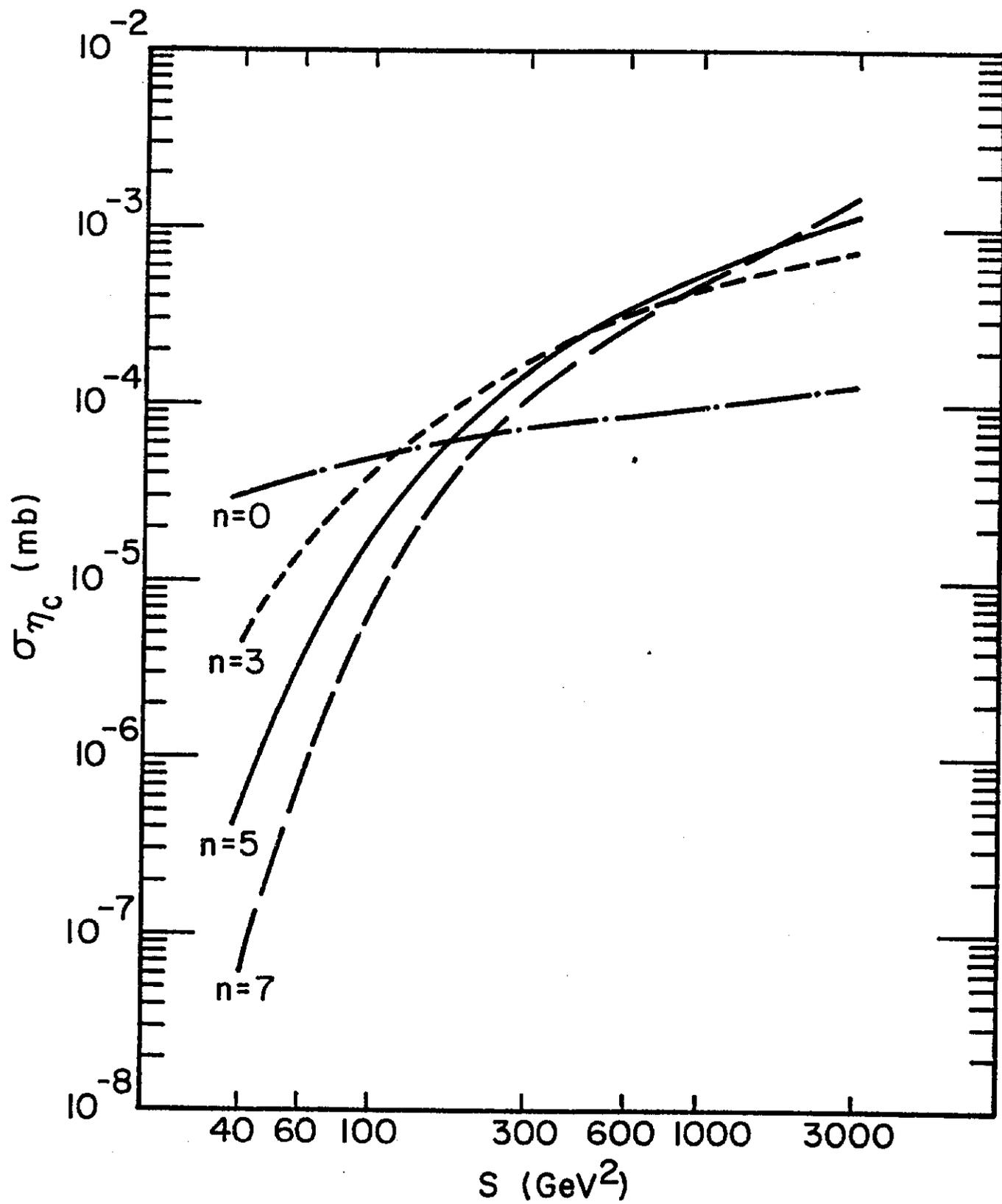


Fig. 2a

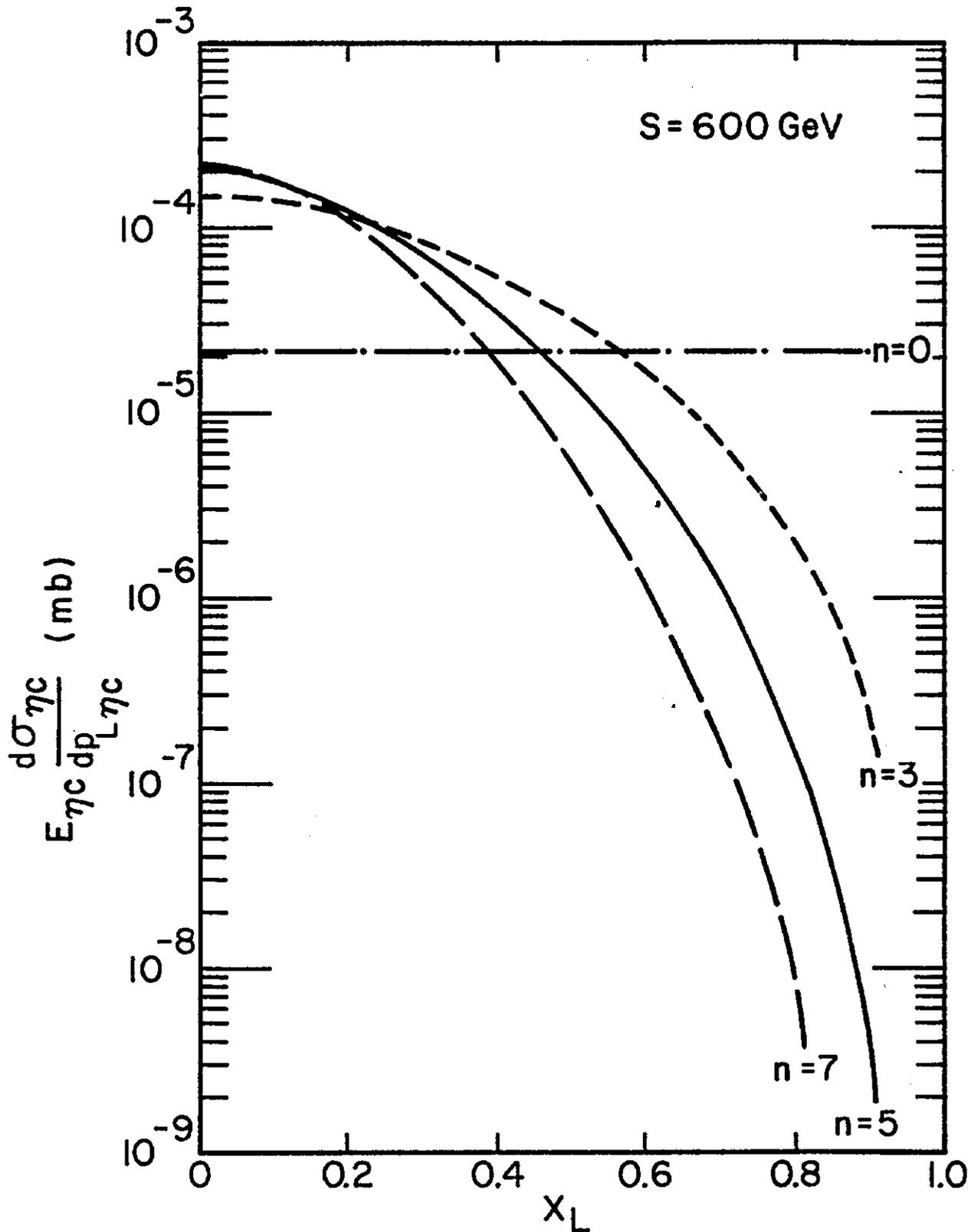


Fig. 2b

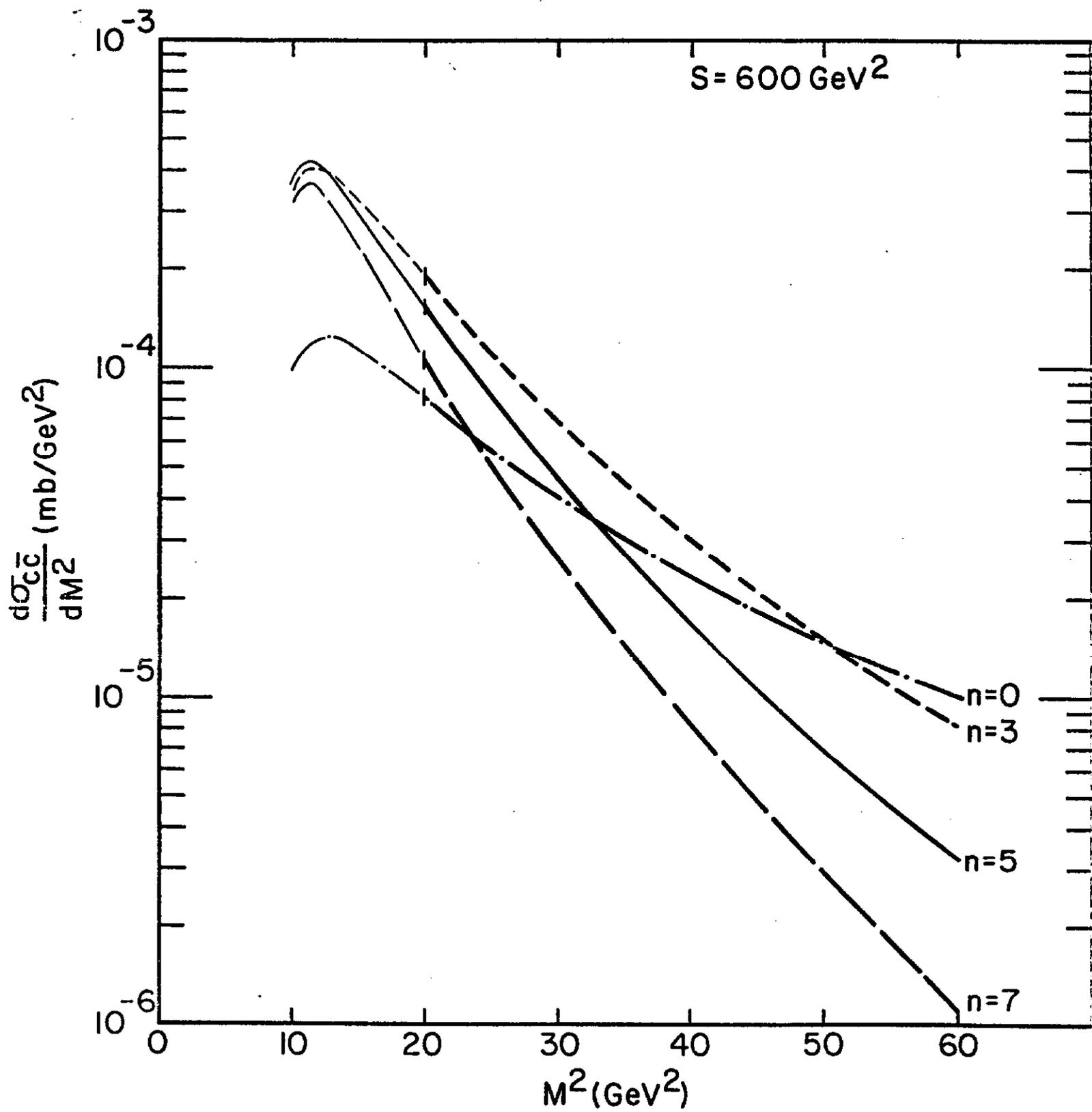


Fig. 3a

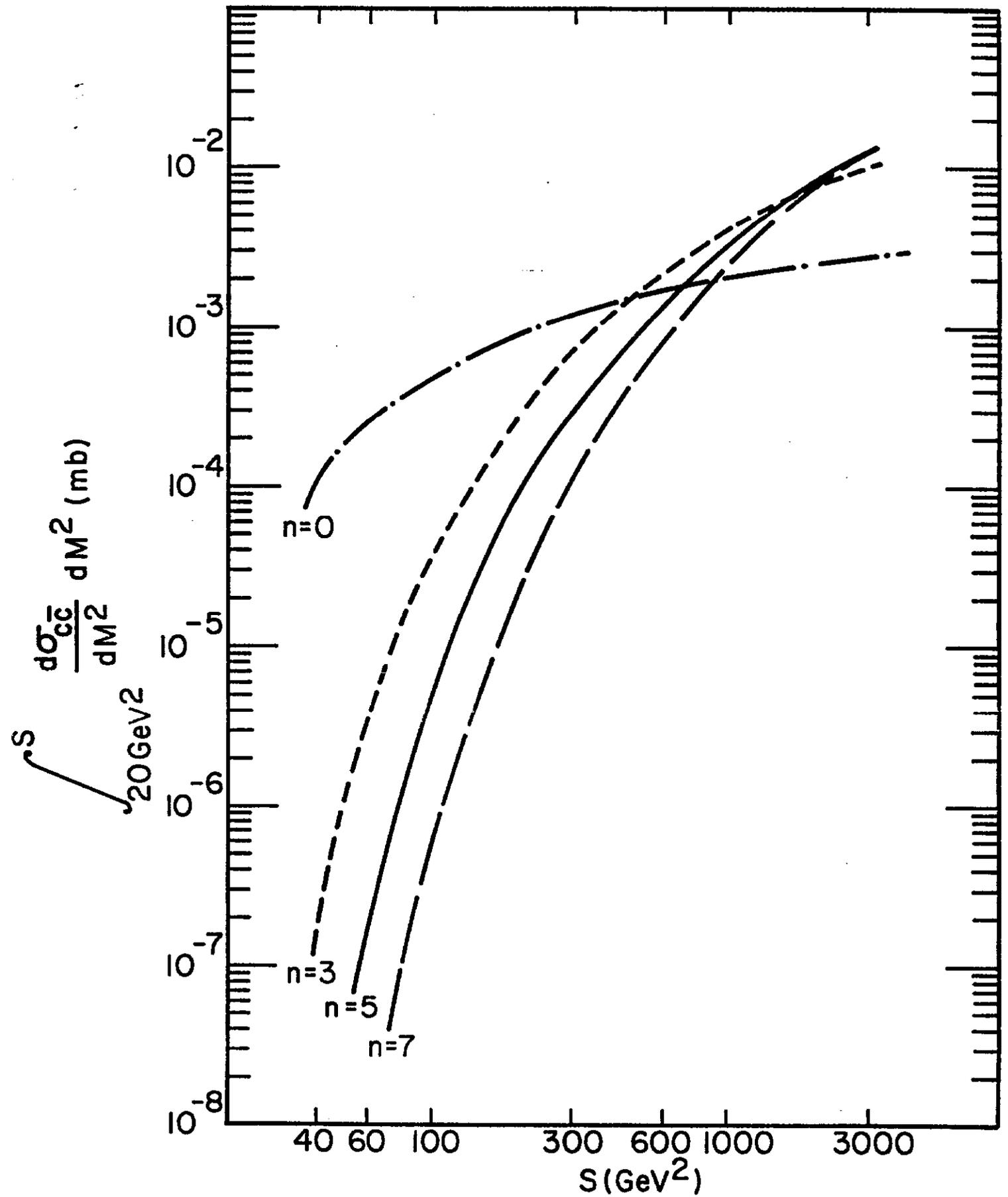


Fig. 3b