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HADRONIC PRODUCTION OF J/ψ ASSOCIATED WITH A GLUON

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ABSTRACT

A mechanism for hadronic production of J/ψ associated with a gluon is discussed. This mechanism contributes a few percent to the measured production. In order to understand this mechanism we also calculate more examples, namely the hadronic production of η_c and $\chi(^3P_J)$ associated with a gluon.

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1. INTRODUCTION

Mechanisms for the hadronic production of J/ψ [1)-6)] have already been much discussed. Generally speaking, the mechanisms discussed can be classified as follows: one considers the annihilation of a pair of quark and antiquark ($u\bar{u}, d\bar{d}$ or $s\bar{s}$) or the direct combination of $c\bar{c}$ into J/ψ (Fig. 1); another considers a pair of gluons which transforms into a $\chi(^3P_J)$ state which eventually decays into J/ψ plus γ (Fig. 2). Both of them can be considered as generalized Drell-Yan mechanisms. A third mechanism considers a pair of $c,\bar{c}$ - quark produced in quark-antiquark or gluon-gluon collision and has the J/ψ produced by the fragmentation of one of them, c (or $\bar{c}$) (Fig. 3). It seems that all these mechanisms contribute, but that the situation is quite complex, none of them can dominate at all energies whatever choice of initial particles is made and none of them can be calculated in a parameter-free or parameter-insensitive way[1)]. Qualitatively speaking, due to the fact that the component of c and $\bar{c}$ in a proton or neutron is very small at $Q^2 \sim M^2_{J/\psi}$, the contribution, which comes from c and $\bar{c}$ combining into J/ψ (Fig. 1b), is negligible and the third mechanism (Fig. 3) has the specific property that some charmed meson, associated with J/ψ, should be seen. In addition to the previous mechanism, there are some other mechanisms which should be considered from the QCD point of view. In this paper we shall discuss one of them (Fig. 4), namely the hadronic production of J/ψ together with a gluon, we shall discuss the J/ψ production with a gluon in detail. It is calculable but we cannot estimate its importance at first sight. We can see at first sight that its order is lower than that of mechanism I [from now on we shall refer to process (Fig. 1) as mechanism I; (Fig. 2) as mechanism II; and so on], Mechanism I is a sixth order process, a OZI rule violation process, while mechanism IV (Fig. 4) is a third order one. If we compare it with mechanism II (Fig. 2), mechanism II can be considered as the contribution from two gluons each from one of the colliding hadron globally in a colour singlet, due to the enhancement provided by resonances and the branching ratios of $\chi(^3P_J)$ states decay into J/ψ plus γ which are quite big. While mechanism IV is in fact the contribution of two gluons also, but they are in a colour octet. Obviously mechanism II is a P wave annihilation while mechanism IV is an S wave annihilation where the J/ψ is produced directly. In general S wave annihilation is larger than P wave annihilation. So it is hard to know how important mechanism IV is unless we calculate it: it has no enhancement effect due to resonance but S wave annihilation larger than P wave annihilation when we compare with mechanism II, and while its order is lower than mechanism I, it has a two-body final state comparing with mechanism I. So it is the main purpose of this paper to see how big a contribution mechanism IV gives, namely investigating the two-gluon contribution when in a colour octet. The final result is that this mechanism gives a few percent contribution of the total production. It is neither very important nor negligible, especially when investigating high P_T events.

For a heavy quark-antiquark bound state, say charmonium, the quark mass M plays the role of "the large Q^2", we shall use perturbation theory[7)] even though the applicability still raises problems in this domain. We calculate the subprocess of mechanism IV (Fig. 4)

$$g + g \rightarrow J/\psi + g \tag{1}$$

which is similar to J/ψ decays into 3 gluons, but one gluon line is crossed.

We also calculate the following subprocesses:

$$q + \bar{q} \rightarrow \eta_c + g \tag{2}$$

$$q + \bar{q} \rightarrow \chi(^3P_J) + g \tag{3}$$

namely the subprocesses for hadronic production of η_c and $\chi(^3P_J)$ associated with a gluon (Fig. 5), giving more examples for hadronic production of a heavy quark-antiquark bound state in order to understand the mechanism associated with a gluon.

In this paper we first give a formula based on the Bethe-Salpeter wave function written in a Lorentz invariant form because in the case under study the charmonium states are moving. It is equivalent to that obtained calculating in the system where the bound state is at rest and finally boosting the system to be moving as the charmonium (bound) state because there is only one bound state in the processes. However, the former approach is more convenient and better suited when considering relativistic effects and calculating. Then we discuss how to choose the parameters which occur in the formula and to calculate $\sigma_{tot}(s)$, $d\sigma/dx_T$, $d\sigma/dx_T dx_L$ and so on. Finally some discussions and comments are given.

2. CROSS-SECTIONS

In terms of the Bethe-Salpeter (B-S) wave function, we write the S matrix element for subprocess (1) corresponding to (Fig. 4):

$$S_{if} = \frac{g^3 \delta(P+k-k_1-k_2)}{\sqrt{48 E \omega \omega_1 \omega_2}} \, Sp(T^a T^b T^c) \, Sp \int d^4p \left\{ \hat{e} \frac{(\hat{p}_1+\hat{k})-im}{(p_1+k)^2+m^2} \hat{e}_1 \frac{(\hat{k}_2-\hat{p}_2)-im}{(k_2-p_2)^2+m^2} \hat{e}_2 \right. \tag{4}$$

$$\left. + \text{Permutation terms} \right\} B^\lambda(P, p)$$

where $p_1 = P/2 + p$, $p_2 = P/2 - p$, namely P is the momentum of the J/ψ, p is relative momentum of the c, $\bar{c}$ quark inside the J/ψ, and $B^{\lambda}(P,p)$ is the B-S wave function. We have

$$B^{\lambda}(P,p)=\left[\hat{f}^{\lambda}+\frac{i\hat{P}}{M}\hat{f}^{\lambda}-\frac{2i(pf^{\lambda})}{M}-\frac{2}{M^2}\varepsilon_{\mu\nu\rho\sigma}f^{\lambda}_{\mu}p_{\nu}P_{\rho}\gamma_{\sigma}\gamma_5\right]\varphi_s(p) \tag{5}$$

for J/ψ,

$$B(P,p)=\left[1+\frac{i\hat{P}}{M}-\frac{1}{M^2}(\hat{P}\hat{q}-\hat{q}\hat{P})\right]\gamma_5\varphi_s(p) \tag{6}$$

for η_c and

$$B^{JM}(P,p)=\sum_{\lambda}C^{JM}_{1\lambda 1\lambda'}(f^{\lambda'}p)\left[\hat{f}^{\lambda}+\frac{i\hat{P}}{M}\hat{f}^{\lambda}-\frac{2i(Pf^{\lambda})}{M}-\frac{2}{M^2}\varepsilon_{\mu\nu\rho\sigma}f^{\lambda}_{\mu}p_{\nu}P_{\rho}\gamma_{\sigma}\gamma_5\right]\varphi_P(p) \tag{7}$$

for $\chi(^3P_J)$, where f^{λ}_{μ} is the polarization vector,

$$\sum_{\lambda}(-1)^{\lambda}f^{\lambda}_{\mu}f^{-\lambda}_{\nu}=\delta_{\mu\nu}-\frac{P_{\mu}P_{\nu}}{P^2} \tag{8}$$

In fact :

$$\sum_{s,t}C^{1\sigma}_{\frac{1}{2}s,\frac{1}{2}t}v_s(p_2)\bar{u}_t(p_1)\propto\left[\hat{f}^{\sigma}+\frac{i\hat{P}}{M}\hat{f}^{\sigma}-\frac{2i(pf^{\sigma})}{M}-\frac{2}{M^2}\varepsilon_{\mu\nu\rho\sigma}f^{\sigma}_{\mu}p_{\nu}P_{\rho}\gamma_{\sigma}\gamma_5\right] \tag{9}$$

$$\sum_{s,t}C^{00}_{\frac{1}{2}s\frac{1}{2}t}v_s(p_2)\bar{u}_t(p_1)\propto\left[1+\frac{i\hat{P}}{M}-\frac{1}{M^2}(\hat{P}\hat{q}-\hat{q}\hat{P})\right]\gamma_5 \tag{10}$$

When we only keep linear terms in p, and $M \equiv 2m$. In the non-relativistic case we can also drop the linear terms in (9) and (10) if we consider an S wave state, but for a P wave state we must keep it, because when multiplied by terms of $O(p^0)$ in the transition matrix element they will give a contribution of the same order as the terms of $O(p^0)$ in (9) or (10) times the terms of $O(p)$ in the transition matrix element while the contribution from the terms of $O(p^0)$ in (9) or (10) multiplied by the terms of $O(p^0)$ in the transition matrix element is zero, which is easy to understand from the symmetry property. We drop the linear terms for J/ψ (and η_c) in final calculation. And using the property of C parity the six terms in (4), as given by permutation, can be combined into three terms. Finally it is not difficult to obtain the cross-section:

$$\frac{d\sigma}{dt} = \frac{5\pi^2\alpha_s^3}{36 s^2}|\psi(0)|^2\left\{\frac{s^2}{(u+s)^2(t+s)^2} + \frac{t^2}{(t+s)^2(u+t)^2} + \frac{u^2}{(u+t)^2(u+s)^2}\right\} \tag{11}$$

for the subprocess (1), where

$$\psi(0) = \frac{1}{(2\pi)^4}\int d^4p\, \varphi_s(p) \tag{12}$$

and $s = -(k_1+k_2)^2, \quad t = -(k_1-P)^2, \quad u = -(k_1-k)^2.$

It is well known that Γ_e (or Γ_μ), the partial width for J/ψ decay into a lepton pair is also dependent on $|\psi(0)|^2$. So we express $|\psi(0)|^2$ in terms of Γ_e

$$|\psi(0)|^2 = \frac{27 M^3 \Gamma_e}{2^5 \pi\, \alpha^3} \tag{13}$$

and use the experimental Γ_e as input to determine $|\psi(0)|^2$ in our final numerical calculation.

Now we define,

$$X_L \equiv \frac{2P_L}{\sqrt{S_0}}, \quad X_j \equiv \frac{2k_L}{\sqrt{S_0}}, \quad X_T \equiv \frac{2P_T}{\sqrt{S_0}}$$

where P_L, k_L are the longitudinal components of $\vec{P}$ and $\vec{k}$ respectively in the C.M. system; $S_0 = -(P_1 + P_2)^2$; and P_T is the transverse component of $\vec{P}$. Then we have

$$\frac{d\sigma}{dx_L dx_T} = \int dx_j \frac{x y x_T S_0}{4A_j A_L} F_g^A(Q^2,x)\, F_g^B(Q^2,y)\frac{d\sigma}{dt} \tag{14}$$

where

$$A_j = \sqrt{x_j^2 + x_T^2}$$

$$A_L = \sqrt{x_L^2 + x_T^2 + \frac{4M^2}{S_0}}$$

$$x = \frac{1}{2}(x_j + A_j + x_L + A_L)$$

$$y = \frac{1}{2}(-x_j + A_j - x_L + A_L)$$

and $S = xyS_0$, $t = -\frac{1}{2} S_0 y(x_j + A_j)$, $u = M^2 - S - t$. $F_g^{A(B)}(Q^2,x)$ is the gluon distribution function in a colliding hadron $A(B)$. From (14) it easy to obtain $d\sigma/dx_T$ and $\sigma(S)$ by integration.

Similarly, for the hadronic production of η_c and $\chi(^3P_J)$ associated with a gluon (Fig. 5) the corresponding S matrix element is

$$S_{if} = g^3 \delta(k_1+k_2-P-k)\bar{v}(k_1)T^b\gamma_\mu u(k_2)\frac{1}{(k_1+k_2)^2}\cdot\frac{1}{\sqrt{4E\omega}}\cdot\frac{1}{\sqrt{3}}Sp(T^aT^b)$$
$$\cdot\int d^4p\, Sp\left\{\gamma_\mu\frac{-(\hat{p}_2+\hat{k})-im}{(p_2+k)^2+m^2}\hat{e}+\hat{e}\frac{(\hat{p}_1+\hat{k})-im}{(p_1+k)^2+m^2}\gamma_\mu\right\}B(P,p) \tag{15}$$

It is very easy to obtain the differential cross-section for η_c:

$$\frac{d\sigma}{dt} = \frac{32(4\pi)^2\alpha_s^3}{27M^2S^2}|\psi(0)|^2\left[\frac{1}{2S}-\frac{ut}{S(S-M^2)^2}\right] \tag{16}$$

but for $\chi(^3P_J)$, due to the fact that it is a P wave annihilation, as mentioned above, it is more complicated than for S wave annihilation. We must keep linear terms in p. And under the approximation which we take, the obtained S matrix element is not gauge invariance. To guarantee gauge invariance is a very complicated problem for processes including bound states. Generally speaking one needs to consider a series of diagrams (Fig. 6)[8]. In all calculations about charmonium annihilation, it is assumed that short-distance effects play a dominant role, and the positronium-like calculation can be used and, as in the positronium case, diagrams, besides those which have been calculated and which are needed in order to guarantee gauge invariance, contribute $O(\langle p\rangle/M)$ [9] ($\langle p\rangle$ - mean value of p). This is true and consistent in the S wave case under our approximation (as it is enough to consider $O(p^0)$ only). But in the P wave case the leading contribution begins with $O(p)$ as mentioned above and some problems about gauge invariance occur. It implies that more diagrams have to be considered. However, now we are only interested in estimating the order of magnitude of the mechanism V (Fig. 5) corresponding to subprocess (3) and comparing it with the contribution for mechanism II (Fig. 2). So it is enough that we do not consider any more diagrams and only keep the gauge invariant terms which we have obtained and calculate both, the subprocess (3) related to mechanism V and the one related to mechanism II, in order to see their relative magnitude. Therefore, the final results given in this paper for hadronic production of $\chi(^3P_J)$ are reliable only to an order of magnitude. In this way we have

$$\frac{d\sigma}{dt} \simeq (4\pi)^2\alpha_s^3\frac{64}{81}\left\{\frac{1}{M^4}-\frac{2ut}{M^4(s-M^2)^2}\right\} \tag{17}$$

for $\chi(^3P_{J=0})$,

$$\frac{d\sigma}{dt} \simeq (4\pi)^2 \alpha_s^3 \frac{128}{9} \frac{|A'|^2}{s^3} \left\{ \frac{1}{M^4} + \frac{ut}{M^2 s(s-M^2)^2} + \frac{ut}{3M^6 s} - \frac{4ut}{3sM^4(s-M^2)} \right\} \quad (18)$$

for $\chi(^3P_{J=1})$ and

$$\frac{d\sigma}{dt} \simeq (4\pi)^2 \alpha_s^3 \frac{256}{81} \frac{|A'|^2}{s^3} \left\{ \frac{1}{M^4} - \frac{ut}{s(s-M^2)M^2} \left(\frac{1}{M^2} - \frac{1}{s-M^2} \right) \right\} \quad (19)$$

for $\chi(^3P_{J=2})$, where the definition of A' is as follows

$$A' = \frac{1}{3}(2\pi)^{-4} \int d^4p \sum_\lambda (-1)^\lambda (f^\lambda p)(f^{-\lambda} p)\, \varphi_P(p) \quad (20)$$

Consequently we have

$$\frac{d\sigma}{dx_L dx_T} = \int dx_j \frac{x y x_T S_0}{4A_j A_L} \left[F_q^A(Q^2,x) F_{\bar{q}}^B(Q^2,y) + F_{\bar{q}}^A(Q^2,x) F_q^B(Q^2,y) \right] \frac{d\sigma}{dt} \quad (21)$$

for mechanism V (η_c and $\chi(^3P_J)$ both) instead of (14). As these processes (Fig. 5) are that of a pair of q-$\bar{q}$ annihilation instead of that of a pair of gluons (Fig. 4), so the quark (antiquark) distribution function $F^{A(B)}_{q(\bar{q})}(Q^2,x)$ in a colliding hadron A (or B) appears instead of the gluon distribution function $F^{A(B)}_g(Q^2,x)$ in (21). Again we can obtain $d\sigma/dx_T$ and $\sigma(S)$ by integration.

3. RESULTS AND DISCUSSIONS

We follow S. Ellis et al.[3] and take

$$F_g^{A(B)}(Q^2,x) = c\,(1-x)^5$$

for a proton (or neutron). Now we have $Q^2 = M^2$. c is a constant[*)], and we take $\alpha_S = 0.2$, then we obtain the $\sigma(S)$ as given by the curve in Fig. 7. We can see that σ is of the order of a few nb at $\sqrt{S} \simeq 50$ GeV while $\sigma \simeq 200$-300nb according to experiments[7]. As it is expected that mechanism IV (Fig. 4) will give a larger P_T than that of mechanism I and mechanism II, (it is obvious that mechanism I (Fig. 1) cannot give a large P_T for J/ψ production unless one more "hard" gluon bremmstrahlung considered, and since the mass difference between J/ψ and χ is small, mechanism II (Fig. 2) cannot either), so we also give curves for $d\sigma/dx_T$ at different energies (Fig. 8) and curves for $d\sigma/dx_L dx_T$ (Figs 9.10) at $\sqrt{S} = 40$ GeV. We can see that at $x_T = 0$, $d\sigma/dx_T$ and $d\sigma/dx_T dx_L$ are zero and that they increase very quickly and then fall slowly as x_T increases.

*) In our case c = 3, different from (3), because the colour factor has been considered in (11).

For the hadronic production of η_c [or $\chi(^3P_J)$] associated with a gluon, we use the structure function $F^{A(B)}_{q(\bar{q})}(x,Q^2)$ given by A.J. Buras et al.[11]. From the charmonium point of view J/ψ and η_c have a spin-spin structure separation, so the wave function at the origin of the η_c should be equal to that of J/ψ. Thus we do so, namely, we take $\psi(0)$ of the η_c as being the same as that of the J/ψ. There are two condidates for η_c, one is $M_{\eta c} = 2.8$ discovered at DESY, another is $M_{\eta c} = 2.97$ GeV discovered by the crystal ball experiment group at SLAC[12]. As our calculation is not very exact so we take $M_{\eta c} = 3.0$ GeV to calculate $\sigma(S)$ considering these candidates. The result is given in Fig. 7. In order to see the different roles of valence and sea quark in a proton producing η_c associated with a gluon we give two curves, one is for pp collision and the other is for $p\bar{p}$ collision. We can see that $\sigma^{pp}(S)/\sigma^{p\bar{p}}(S) \simeq 0.5$ at $\sqrt{S} \simeq 50$ GeV. We compare them with the Drell-Yan mechanism[3] and find they are 10^{-3} of Drell-Yan mechanism at $\sqrt{S} \simeq 50$ GeV.

As pointed above, for our calculation of the $\chi(^3P_J)$, only in magnitude order, it is reliable. So only the ratio of $\sigma(S)$ for the hadronic production of $\chi(^3P_J)$ associated with one gluon to that without gluon is worth giving. This ratio is about $10^{-2}-10^{-3}$ at $\sqrt{S} \simeq 50$ GeV. One point which has to be noted is that mechanism II (Fig. 2) cannot produce any $\chi(^3P_{J=1})$ due to Yang's theory, namely two gluons cannot be in a $J = 1$ and colour singlet state, but mechanism IV (Fig. 4) as well as mechanism I (but annihilate into $\chi(^3P_{J=1})$ instead of J/ψ Fig. 1) can.

In summary, mechanism IV (Fig. 4) can give a few percent contribution to the total hadronic production of J/ψ and is expected that it will give somewhat larger P_T events J/ψ than mechanism I and II (but less than mechanism III).

There is still another subprocess associated with two gluons (Fig. 11). But now from the experience of hadronic production η_c and $\chi(^3P_J)$. We are sure that it is smaller than with one gluon. Because it has one more vertex and one more gluon propagator which gives a suppression by $10^{-2} - 10^{-3}$ at $\sqrt{S} \sim 50$ GeV.

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FIGURES CAPTIONS

Fig. 1 : (a) Hadronic production of J/ψ by annihilation of quark-antiquark pair.
(b) Hadronic production of J/ψ by direct combination of $c,\bar{c}$.

Fig. 2 : Hadronic production of J/ψ by two steps: two gluons produce a $\chi(^3P_J)$; the $\chi(^3P_J)$ decays into J/ψ.

Fig. 3 : Hadronic production fo J/ψ by fragmentation of c (or $\bar{c}$).

Fig. 4 : Hadronic production of J/ψ associated with one gluon by collision of two gluons.

Fig. 5 : Hadronic production of $\eta_c,\chi(^3P_J)$ associated with one gluon by annihilation of $q,\bar{q}$.

Fig. 6 : The diagram which should be added in order to guarantee gauge invariance (in fact, it represents a series of diagrams),

Fig. 7 : The total cross-sections for hadronic production of J/ψ, η_c associated with one gluon.

Fig. 8 : The differential cross-sections $d\sigma/dx_T$.

Fig. 9 : The differential cross-sections $d\sigma/dx_T dx_L$ as a function of x_L with different x_T fixed.

Fig. 10 : The differential cross-sections $d\sigma/dx_T dx_L$ as a function of x_T with different x_L fixed.

Fig. 11 : Hadronic production of J/ψ associated with two gluons.

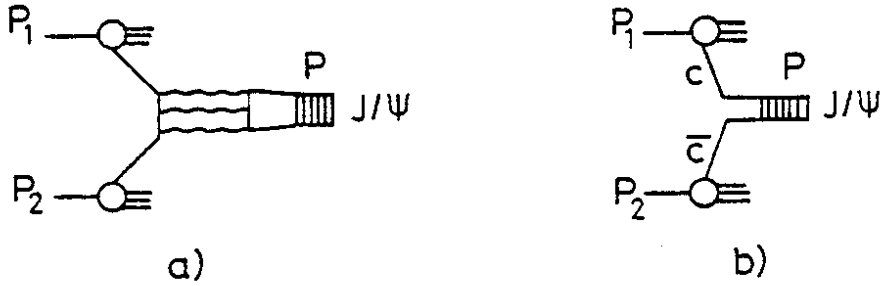


FIG.1

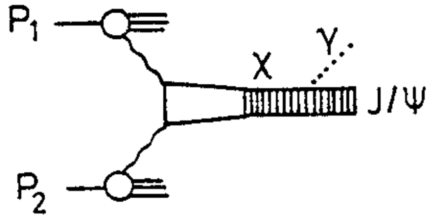


FIG. 2

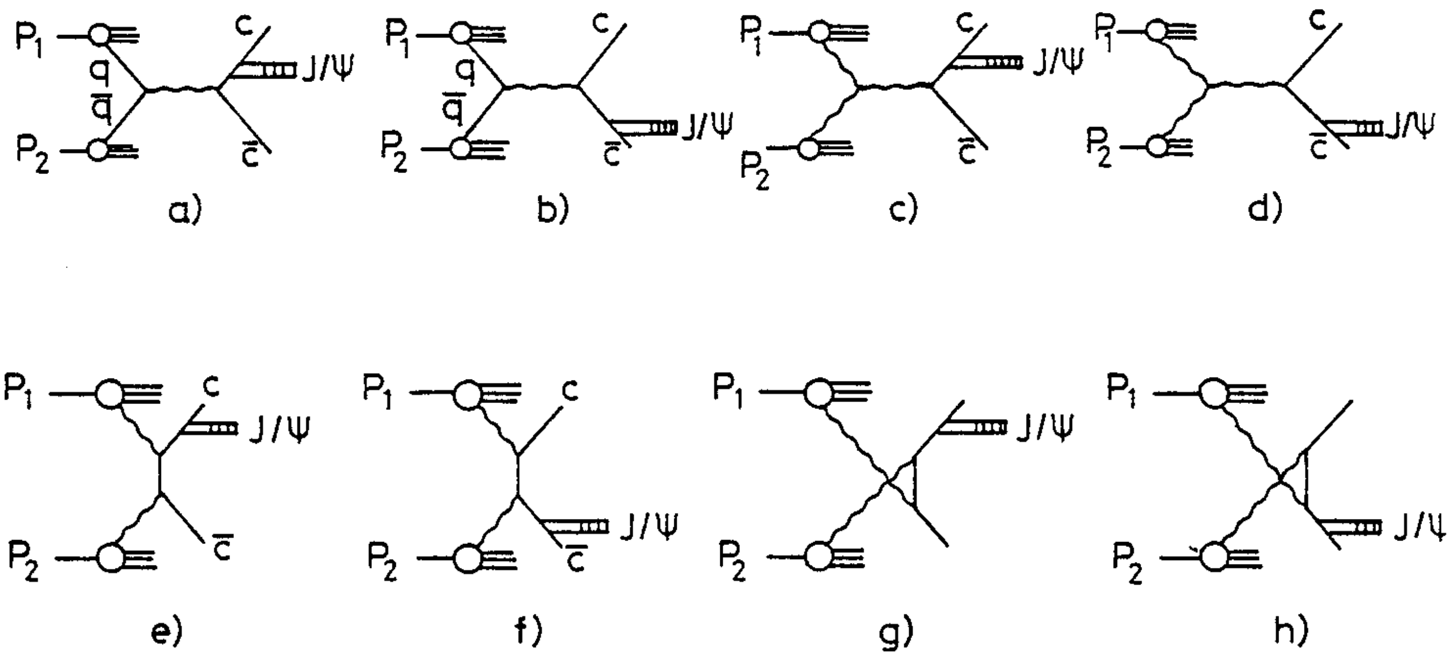


FIG.3

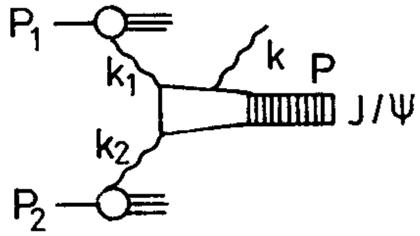


FIG.4

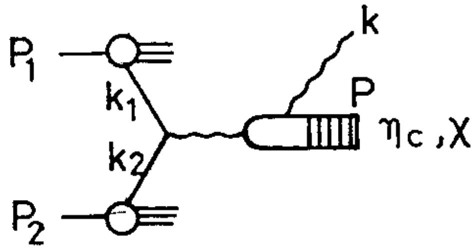


FIG.5

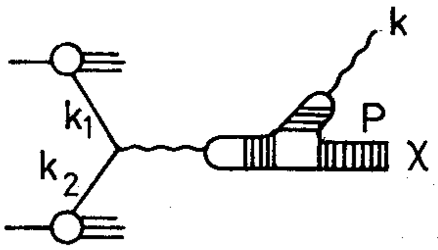
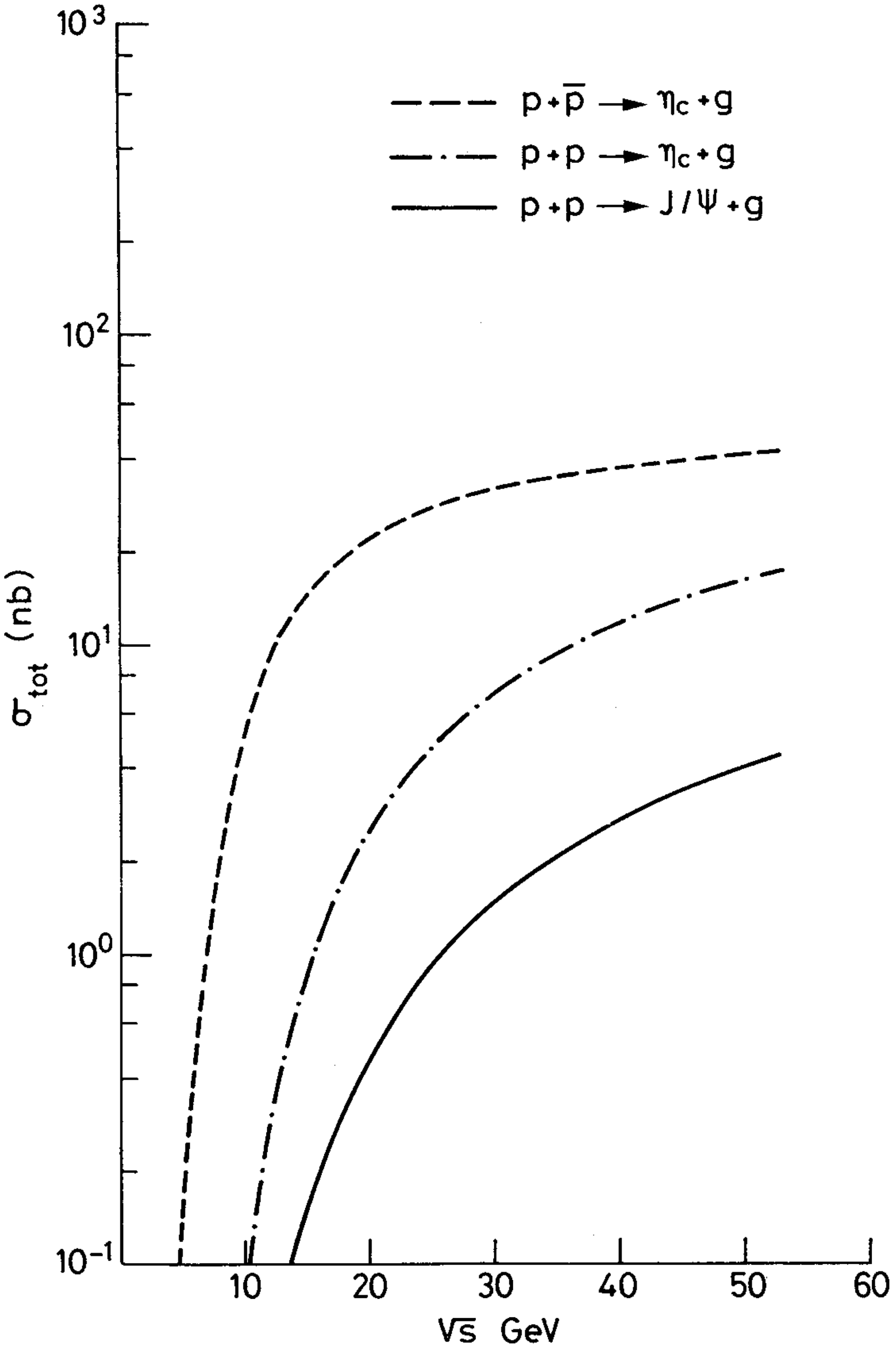
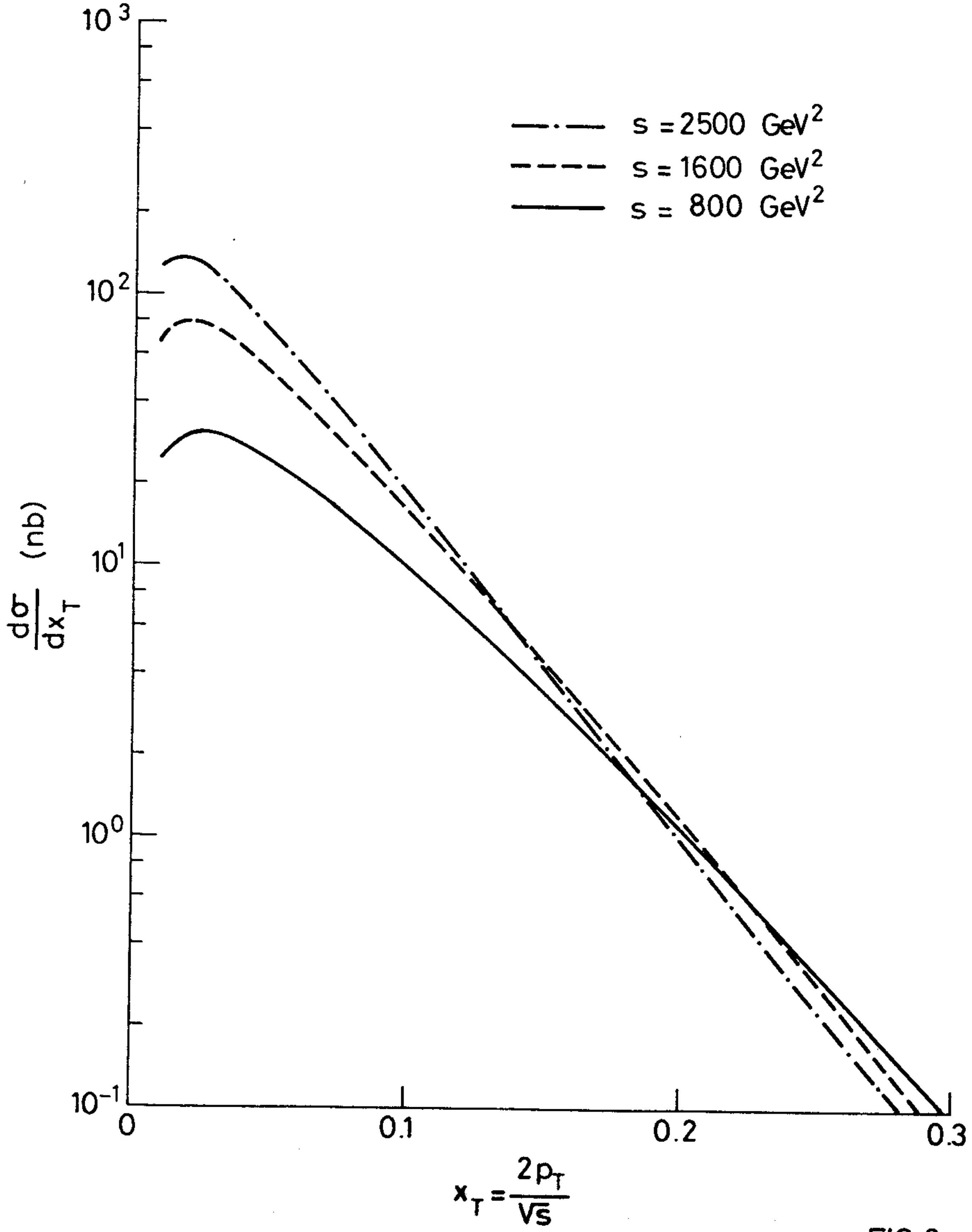


FIG.6



p + p̄ → ηc + g
p + p → ηc + g
p + p → J/Ψ + g
σtot (nb)
10³
10²
10¹
10⁰
10⁻¹
10
20
30
40
50
60
√s GeV

FIG. 7



10^3
10^2
10^1
10^0
10^{-1}
s = 2500 GeV^2
s = 1600 GeV^2
s = 800 GeV^2
$\frac{d\sigma}{dx_T}$ (nb)
0
0.1
0.2
0.3
$x_T = \frac{2p_T}{\sqrt{s}}$

FIG. 8

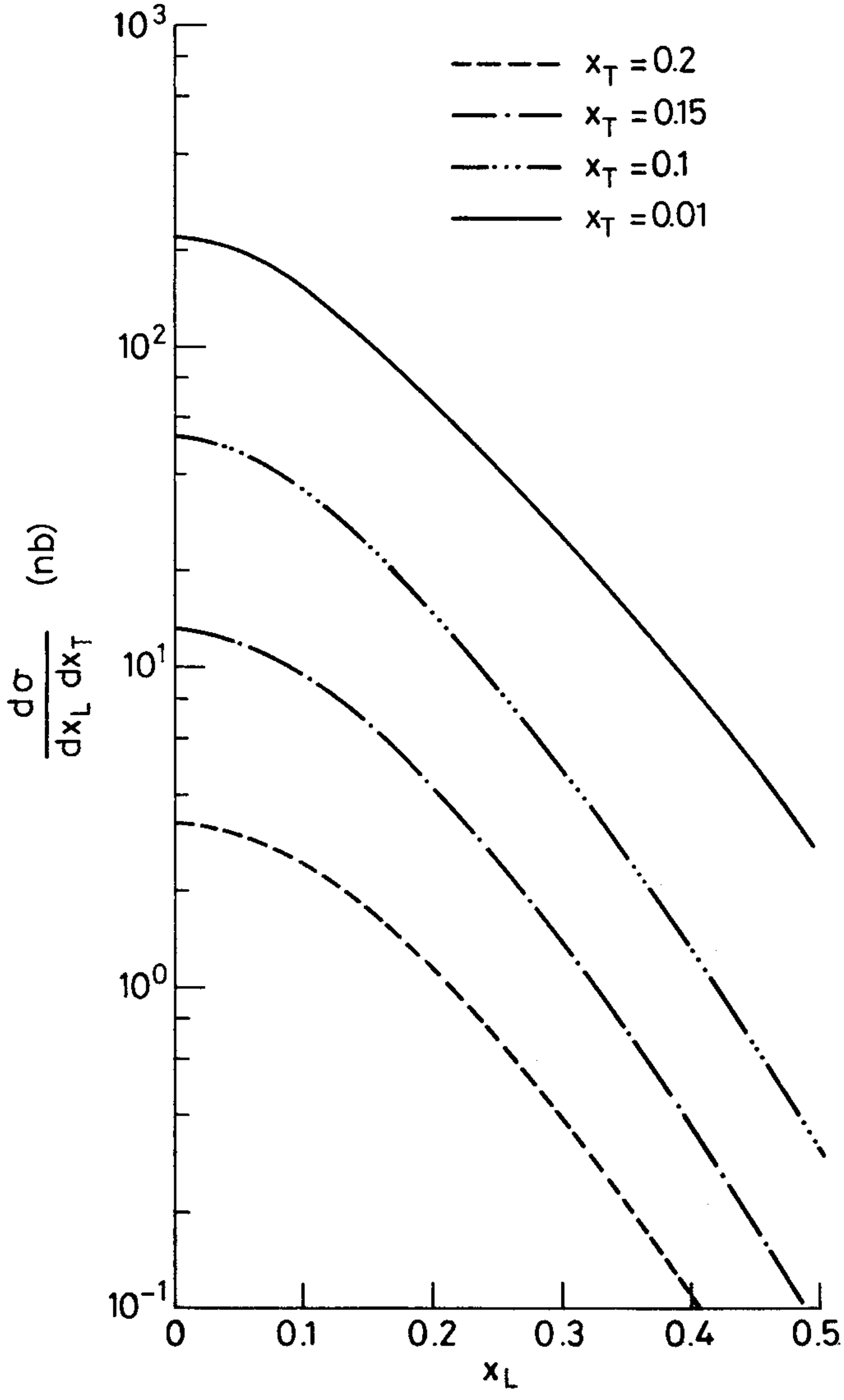
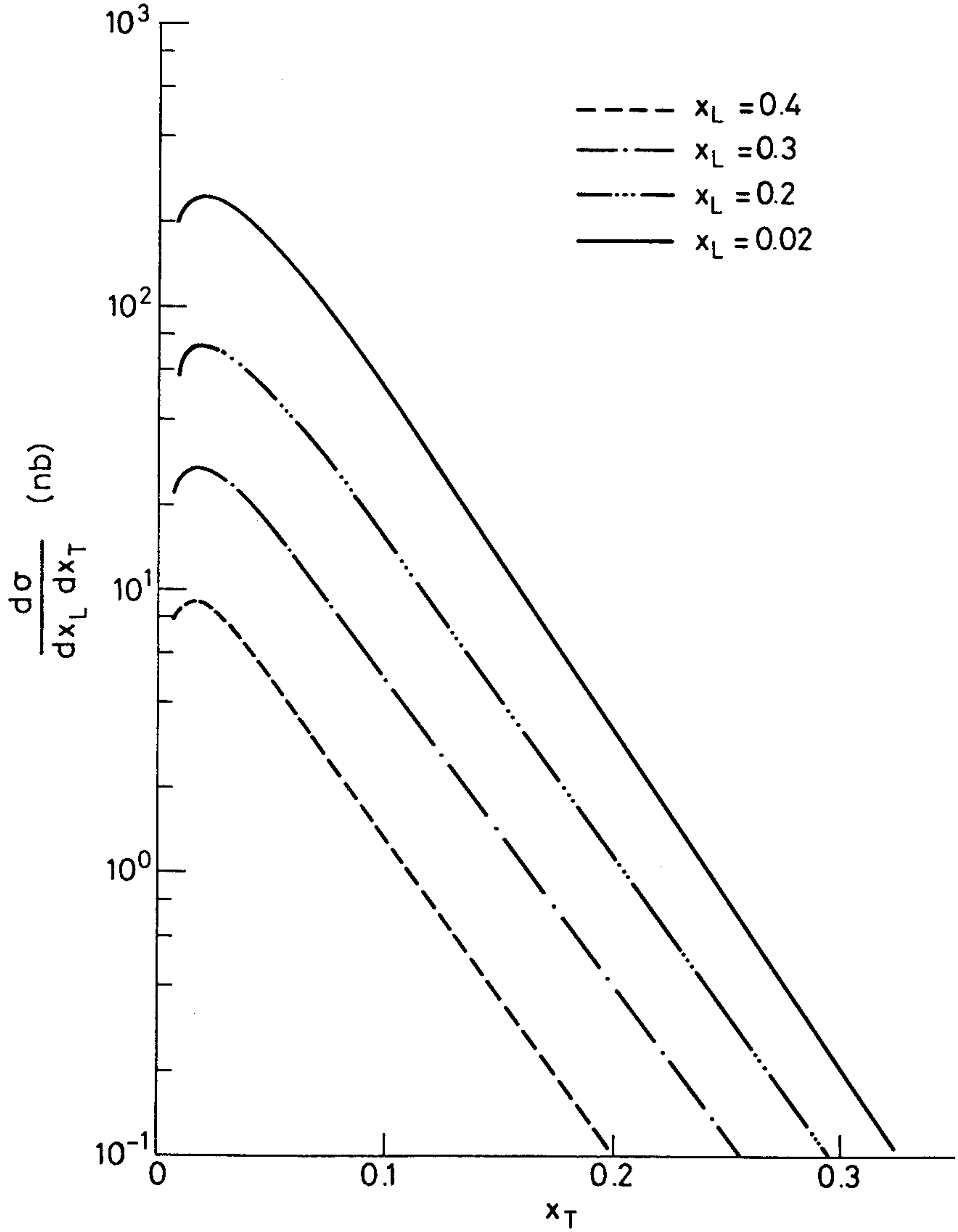

$x_T = 0.2$
$x_T = 0.15$
$x_T = 0.1$
$x_T = 0.01$
$\frac{d\sigma}{dx_L\,dx_T}$ (nb)
10^3
10^2
10^1
10^0
10^{-1}
0
0.1
0.2
0.3
0.4
0.5
x_L

FIG. 9



x_L = 0.4
x_L = 0.3
x_L = 0.2
x_L = 0.02
dσ / dx_L dx_T (nb)
10^3
10^2
10^1
10^0
10^-1
0
0.1
0.2
0.3
x_T

FIG. 10

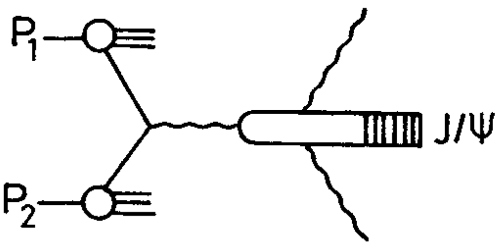


FIG.11