SLAC-PUB-2520
May 1980
(T/E)

SECOND ORDER QCD EFFECT IN J/ψ-PHOTOPRODUCTION*

T. Tajima† and T. Watanabe§

Stanford Linear Accelerator Center

Stanford University, Stanford, California 94305

ABSTRACT

Second order QCD contributions are calculated for the J/ψ-photoproduction. We show that the measurement of the non-forward structure of the cross section $d\sigma/dt$ at large $-t(\geq 1\ GeV^2)$ could be an excellent test for QCD.

Submitted to Physical Review Letters

*Work supported by Department of Energy, Contract DE-AC03-76SF00515.

†Permanent address; Toyama Technical College, 13 Hongo-machi, Toyama 930-11, Japan

§Permanent address; Asia University, 5-24-10 Sakai Musashino, Tokyo 180, Japan

The cross section of J/ψ-photoproduction has been calculated to order α_s in QCD by the photon-gluon fusion mechanism.[1,2] The numerical result reproduces roughly the energy dependence of the cross section measured in the experiments.[3] This mechanism has been supported also from the experimental data of J/ψ-photoproduction in hadron-hadron collisions for which the corresponding gluon-fusion mechanism was shown to give very consistent explanations.[4]

As far as the lowest order graphs are concerned, the cross section for J/ψ-photoproduction is forward, in that $-t \simeq 0$, because by definition gluons must be near on-shell. This means that the higher order QCD contributions give the cross section in the non-forward region.[5] Thus in this paper we calculate the non-forward structure of the cross section through order α_s^2 and show that the measurement of the slope of the cross section $d\sigma/dt$ at large $-t(\gtrsim 1\ \mathrm{GeV}^2)$ could be an excellent test for QCD.

All of the order α_s^2 graphs are given in Fig. 1, where (A) $\sim$ (D) and (a) $\sim$ (h) give the contributions from light quark and gluon components in a target nucleon, respectively. The gauge invariance is easily proved for each of the sets of graphs (A) and (B), (C) and (D), and (a) $\sim$ (h). Fig. 2 gives the notation for momenta of particles.

The on-shell condition of the initial and final light quark or gluon determines the momentum fraction x, which is defined as $p = xP$, to be $x = q^2/2P\cdot q$ where $q(= p_- + p_+ - k)$ is the momentum transfer in the t channel. In the laboratory frame the cross section for the photoproduction of $c\bar{c}$ pair is

$$\frac{d^2\sigma}{dt\,dW_c^2}(\gamma N \to c\bar{c}X)$$

$$= \frac{\alpha\,\alpha_s^2}{4\pi M^2E^2|t|} \int_{M^2} dM_X^2\, \Sigma_0^2 \sqrt{W_c^2 - 4m_c^2} \int d\Omega_{\vec{\Delta}} \frac{1}{\left(\Sigma_0^2 \sin^2\varphi + W_c^2 \cos^2\varphi\right)^{3/2}}$$

$$\times \Bigg\{ 2e_c^2 \sum_{i=u}^{s} f_{i/N}(x) \left|\mathcal{M}_A + \mathcal{M}_B\right|^2 + 2 \sum_{i=u}^{s} e_i^2\, f_{i/N}(x) \left|\mathcal{M}_C + \mathcal{M}_D\right|^2$$

$$+ \frac{2}{3} e_c^2\, G_N(x) \Bigg[\sum_{j=a}^{f} \left|\mathcal{M}_j\right|^2 + 2\left(\mathcal{M}_a\mathcal{M}_f^* + \mathcal{M}_d\mathcal{M}_a^* + \mathcal{M}_f\mathcal{M}_d^*\right)$$

$$+ 2\left(\mathcal{M}_b\mathcal{M}_c^* + \mathcal{M}_c\mathcal{M}_e^* + \mathcal{M}_e\mathcal{M}_b^*\right)\Bigg]$$

$$- \frac{1}{12} e_c^2\, G_N(x) \cdot 2\left(\mathcal{M}_a + \mathcal{M}_d + \mathcal{M}_f\right)\left(\mathcal{M}_b^* + \mathcal{M}_c^* + \mathcal{M}_e^*\right)$$

$$+ \frac{3}{2} e_c^2\, G_N(x) \left|\mathcal{M}_g + \mathcal{M}_h\right|^2 \Bigg\} \qquad (1)$$

where $e_i = (2/3, -1/3, -1/3)$, $e_c = 2/3$, M is the nucleon mass, E is the photon energy, $t = q^2$, $\Sigma = p_+ + p_-$, $\Delta = p_- - p_+$, φ is the angle between $\vec{\Sigma}$ and $\vec{\Delta}$, $f_{i/N}(x)$ $(i = u,d,s)$ and $G_N(x)$ are the distribution functions of quarks and gluons, respectively and $\mathcal{M}_i$ $(i = A, \ldots, h)$ are invariant amplitudes of the graphs given in Fig. 1. Here the numbers 2, 2, 2/3, −1/12 and 3/2 are the QCD color factors stemming from the color summation of the final partons and the color average of the initial partons. Σ_0 is given by the relation $\Sigma_0 = (s + t - M_x^2)/2M$. The upper bound of M_x^2

is determined by the condition $\cos\theta \leq 1$, where θ is the angle between $\vec{\Sigma}$ and $\vec{k}$, as $M_x^2 = s + t + M[(W_c^2 + |t|)^2 + 4\, E^2 W_c^2]/2E\ (W_c^2 + |t|)$.

Before proceeding further, we should remark here that the graph (D) in Fig. 1 does not cause a divergence in the integral (1) although it seems to do so at the configuration $\vec{p}\ //\ \vec{k}$. The proof is following. The denominator of the quark propagator can be expressed as $W_c^2 - 2xM\Sigma_0$ in terms of Σ and x. So the divergence comes from the point of $x = W_c^2/2M\Sigma_0$. As shown before, x has been already determined by the on-shell condition of the initial and final quarks as $x = -q^2/2M(E - \Sigma_0)$. Therefore if the equation $W_c^2/\Sigma_0 = -q^2/(E - \Sigma_0)$ has a solution for Σ_0, the integral (1) diverges. Fortunately it can be easily shown that this equation has no solution because of $W_c^2 \geq 4m_c^2$.

In the following step to connect Eq. (1) to J/ψ-photoproduction, we use the same technique as in the photon-gluon fusion model.[1,2] The $c\bar{c}$ pair produced in the reaction given in Fig. 1 will undergo some final state interaction (which must include a color rearrangement process if the $c\bar{c}$ pair is a color octet state) and will turn into some charmonium state such as J/ψ, χ etc. or into a pair of charmed particles. Then the J/ψ-production, in general, comes from two components; the direct J/ψ-production from the $c\bar{c}$ pair and the decays of the higher-mass states into J/ψ state.[1] Thus we find that the cross section of the J/ψ-production is associated with the direct production of all charmonium states from the $c\bar{c}$ pair. Because the contributions from the decays are due to charmonium states with masses less than $2m_D$ (m_D is the mass of D(1.86)), the cross section for J/ψ-production is supposed to be given approximately by some fraction of the value obtained by integrating Eq. (1) over W_c^2 from $4m_c^2$ (m_c is the mass of the charmed quark) to $4m_D^2$.

We introduce the number N_D to express the cross section for J/ψ-production as the above integral divided by N_D. As discussed above this number will be determined roughly by the probabilities of the direct productions of charmonium states and the branching ratio for the decays of the higher-mass states into J/ψ. Although we do not have enough knowledge about these, we can fortunately use the approximate value of N_D obtained from comparing the cross section calculated to order α_s with the experimental data of the total cross section. N_D has been known to be around 8 if we use m_c = 1.5 GeV and the power n = 5 in the following form for the gluon distribution function which we shall use:
$G_N(x) = 0.5\ (n + 1)(1 - x)^n/x$.[7] As Jones and Wyld pointed out,[1] N_D depends strongly on m_c and n. Therefore we will mention later the dependences on m_c and n for our predictions calculated from Eq. (1).

Before proceeding to numerical calculations, we must specify the distribution functions $f_{i/N}(x)$ for the light quarks in the target nucleon. As will be found soon, our main prediction does not almost depend on these functions. So we use here only the Field-Feynman parametrization.[6]

We first temporarily choose the values m_c = 1.5 GeV and n = 5.[8] Figure 3 shows the numerical result of $d\sigma/dt$ for J/ψ-photoproduction at the photon laboratory energy E = 20 GeV where we take N_D = 8 and $\alpha_s = 12\pi/25 \ln M_{J/\psi}^2/\Lambda^2 (= 0.41)$ with Λ = 0.5 GeV.[9] The main pattern of the contributions from quarks and gluons is that the contribution from gluons dominates the cross section in the lower $-t$ region ($-t < 15$ GeV^2) and the one from quarks emerges prominently at higher $-t$. In this figure we describe the typical diffractive curve 20 $e^{2.9t}$(nb/GeV^2) which was suggested by the SLAC experiments.[3] Comparing the numerical result to this diffractive curve, we can predict that the slope of $d\sigma/dt$ should turn out to change very much apart from the diffractive curve around $-t = 1$ GeV^2.

We have studied to what extent the above prediction depends on m_c and n, i.e., the form of $G_N(x)$ in the range 1.25 GeV $\leq m_c \leq$ 1.75 GeV and $3 \leq n \leq 7$. The numerical results show a striking feature that the slope of $d\sigma/dt$ does not almost depend on m_c in the region $-t \leq 15$ GeV^2 where the gluon contribution dominates. On the other hand, the slope has a slight n-dependence, but which is not sufficiently large to be discriminated in experiments. Therefore we can conclude that the slope of $d\sigma/dt$ will be expected to reflect the significant feature peculiar to the higher order interactions of QCD and irrelevant to the values of m_c and the form of $G_N(x)$ in the region $-t \leq 15$ GeV^2.

We finally discuss the energy dependence of the cross section $d\sigma/dt$ calculated to order α_s^2. Here we take the values $m_c = 1.5$ GeV and $n = 5$. In Fig. 4 we give the calculated curves of $d\sigma/dt$ versus $-t$ at E = 50 and 100 GeV. This figure shows that the curves become flatter as E increases but the change of the slope does not strongly depend on E. This is supported also from our numerical result that the energy dependence is almost due to the phase space included in Eq. (1) and has a tendency similar to the total cross section calculated to order α_s in the photon-gluon fusion model.

ACKNOWLEDGMENTS

We are pleased to acknowledge their kind hospitality at SLAC as well as useful conversations with the members of SLAC Theory Group. We would especially like to thank S. D. Drell and P. Tsai for their encouragement of this work and S. J. Brodsky for his careful reading of our paper and useful comments. Work supported by Department of Energy, Contract DE-AC03-76SF00515.

REFERENCES

1. L. M. Jones and H. W. Wyld, Phys. Rev. D17, 759, 2332 (1978); see also H. Fritzsch and K. H. Streng, Phys. Lett. 72B, 385 (1978).

2. M. Glück and E. Reya, Phys. Lett. 79B, 453 (1978).

3. T. Nash et al., Phys. Rev. Lett. 36, 1233 (1976); D. C. Hom et al., Phys. Rev. Lett. 36, 1236 (1976).

4. M. Glück, J. F. Owens, and E. Reya, Phys. Rev. D17, 2324 (1978).

5. As to J/ψ-leptoproduction, the attempt to calculate the non-forward pattern of the cross section in QCD has been tried in the paper; J. P. Leveille and T. Weiler, Phys. Lett. 86B, 377 (1979).

6. R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590 (1977).

7. M. B. Einhorn and S. D. Ellis, Phys. Rev. D12, 2007 (1975).

8. S. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973).

9. In all the calculations in this paper, we use the approximation $\cos\theta = 1$ in the integrand of Eq. (1). The condition $M_X^2 \geq M^2$ $(x \leq 1)$ leads the lower bound of $\cos\theta$,
$\cos\theta \geq [(E + M)\Sigma_0 - (ME + W_c^2/2)]/E \cdot |\vec{\Sigma}| \geq 0.9$. Taking into account that the contribution coming from the region of $x \sim 1$ is suppressed due to the distribution functions, we find that this approximation is quite good in the integral (1).

FIGURE CAPTIONS

1. Feynman graphs for $\gamma + N \to c\bar{c} + X$ up to order α_s^2. The notation in this and subsequent figures is solid lines for quarks, dashed lines for gluons, and wavy lines for photons.

2. The picture of the order α_s^2 graphs to show the notation for momenta of particles. The nucleon labeled by N has the momentum P. The dash-dot lines denote quarks (or gluons) which have the momentum p and p'. Symbols p_-, p_+ denote momenta of charm quarks c and $\bar{c}$ and k is the one of photon. W_c is the invariant mass of the channel $c\bar{c}$ and M_X is the one of hadrons included in the anything X.

3. The numerical result of $d\sigma/dt$ versus $-t$ for $\gamma + N \to \psi + X$ at E = 20 GeV. Here we set m_c = 1.5 GeV and n = 5 in Eq. (2). A dashed line shows that contribution from gluons, a dash-dot line the one from quarks and a solid line is the total of them. At the same time we describe the curve of $20\ e^{2.9t}$(nb/GeV^2) and the typical diffractive curve suggested by the experiment.[3]

4. The calculated curves of $d\sigma/dt$ versus $-t$ for $\gamma + N \to \psi + X$ at E = 50 and 100 GeV.

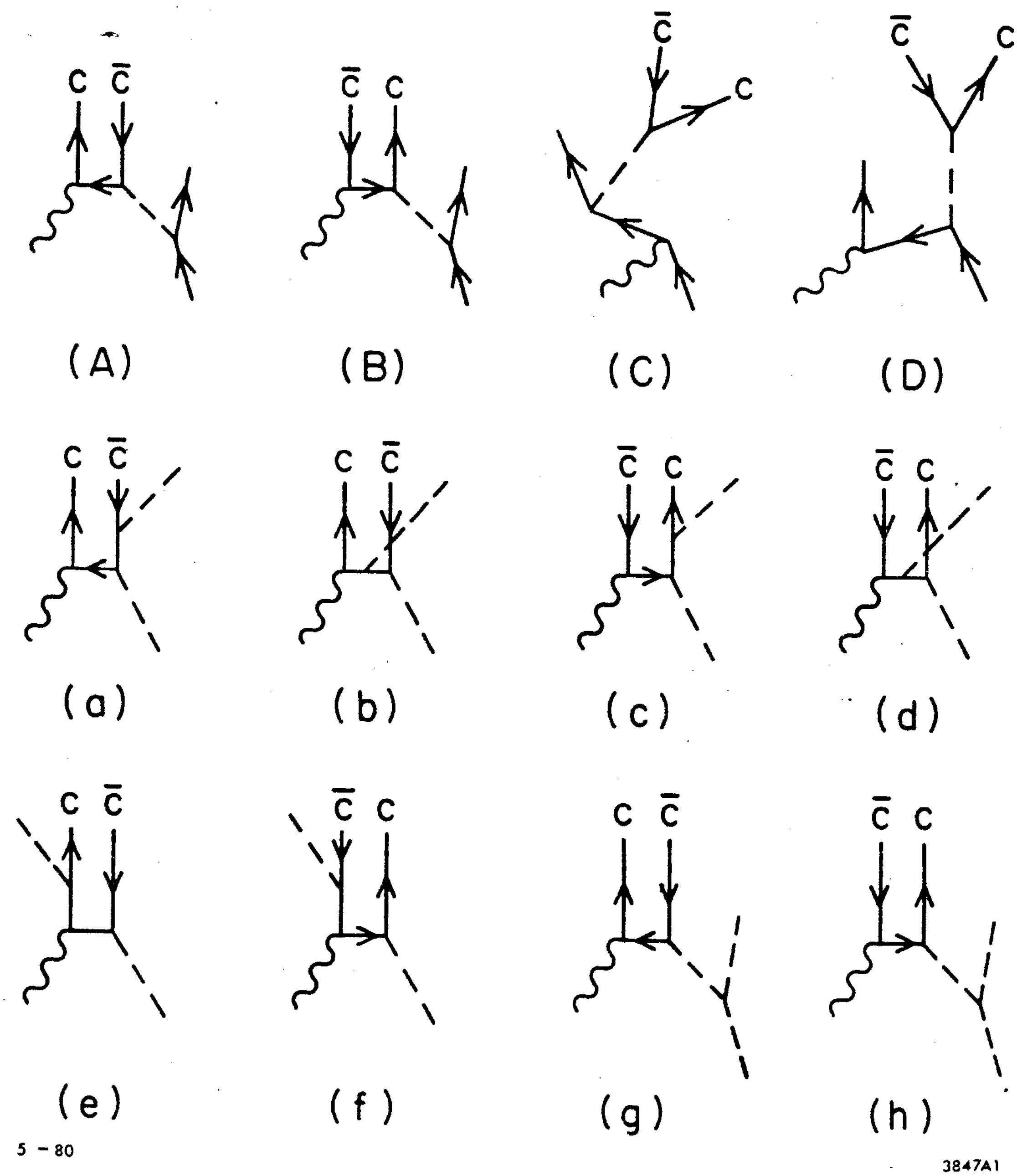


Fig. 1

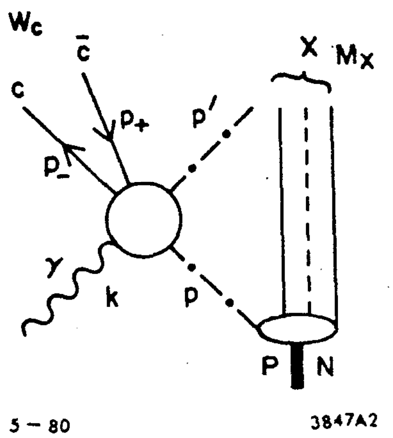
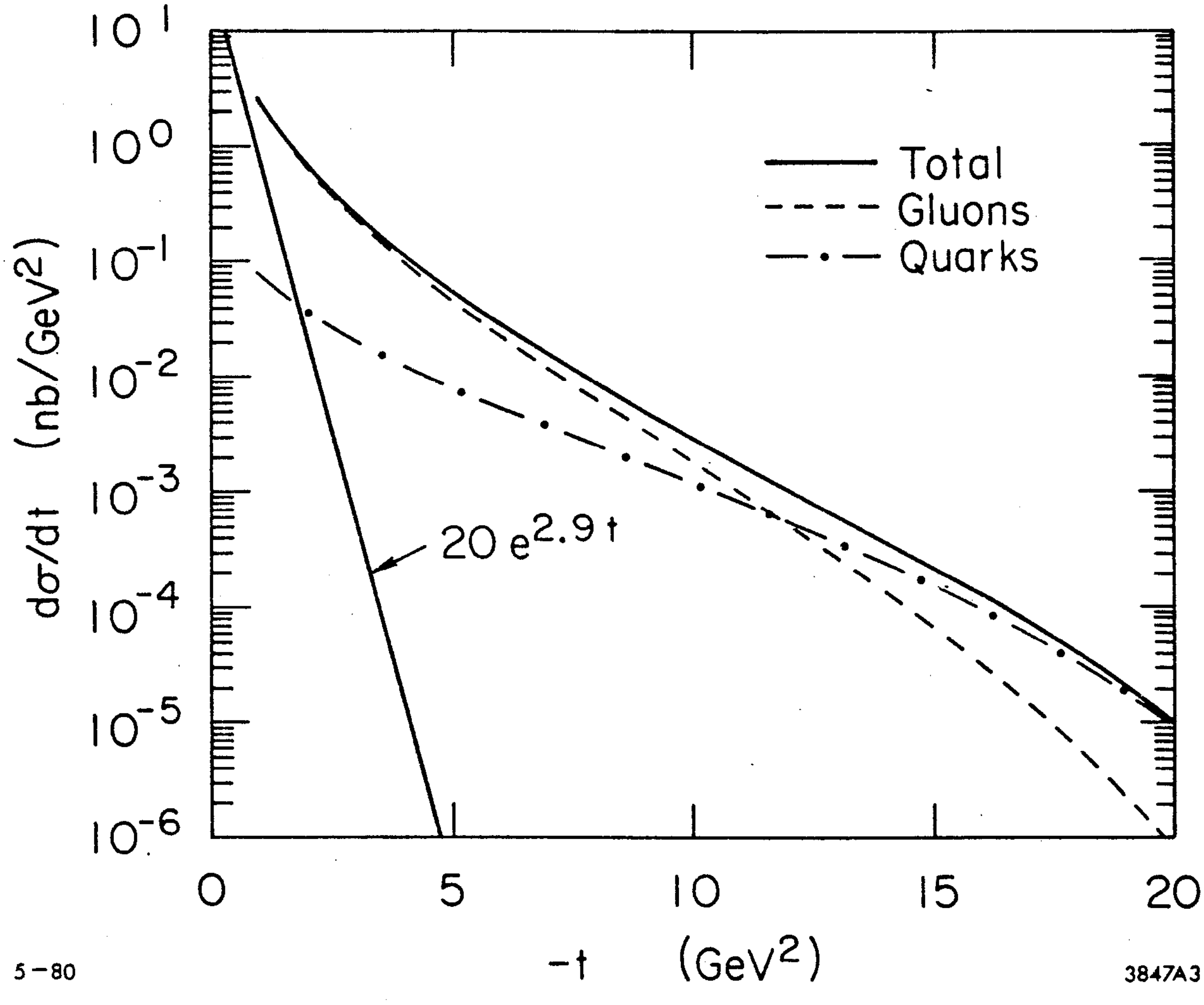
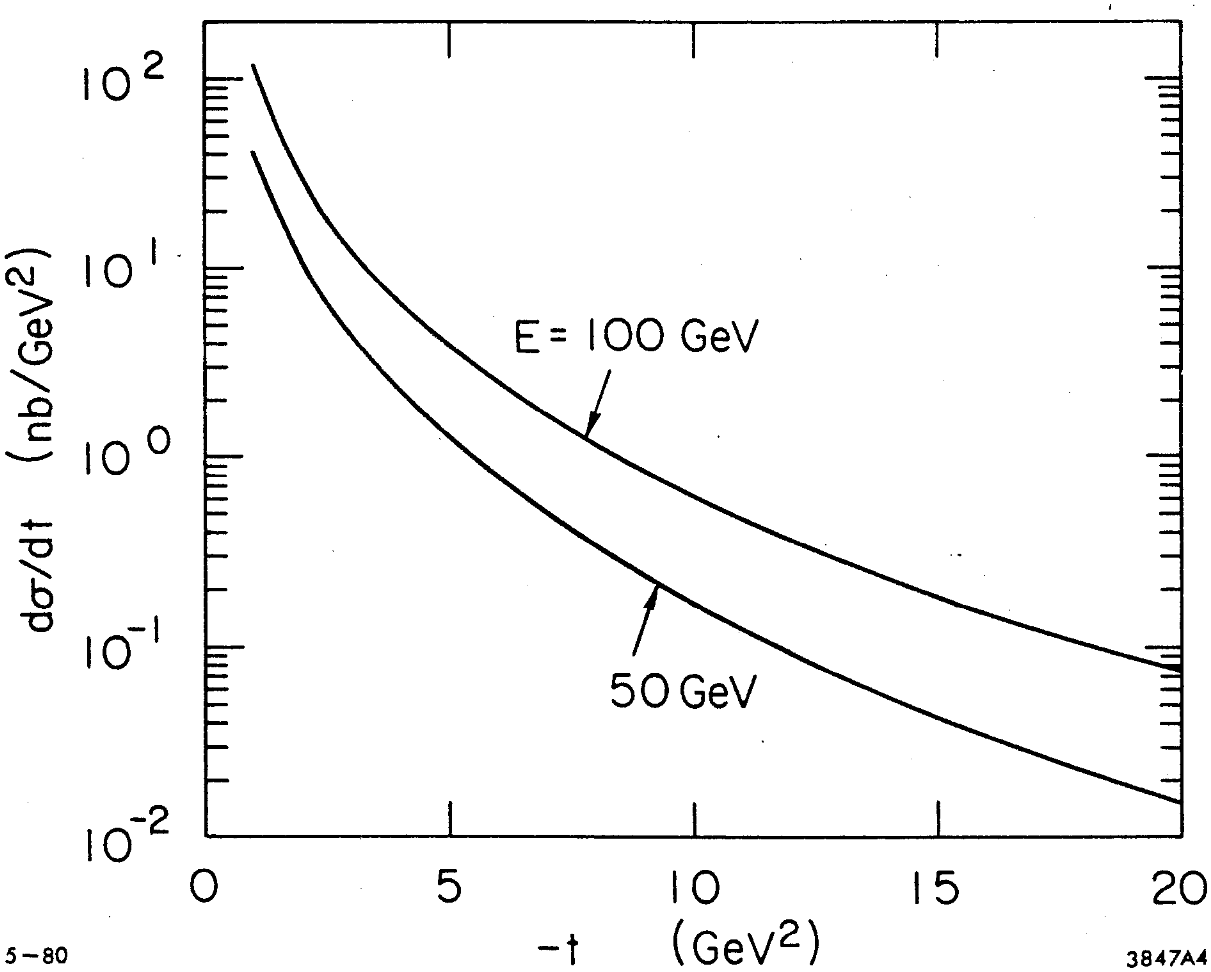


Fig. 2



10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
dσ/dt (nb/GeV^2)
Total
Gluons
Quarks
20 e^2.9 t
0
5
10
15
20
-t (GeV^2)
5-80
3847A3

Fig. 3



10^2
10^1
10^0
10^{-1}
10^{-2}
$d\sigma/dt$ (nb/GeV^2)
E = 100 GeV
50 GeV
0
5
10
15
20
$-t$ (GeV^2)
5–80
3847A4

Fig. 4