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Recombination Mechanism for Baryon Production in Jets*

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ABSTRACT

We use the KUV jet calculus and a form of the recombination model to calculate the spectrum of single inclusive baryons in quark jets. The resulting spectra grow rapidly with Q^2 for experimentally accessible Q^2. At small x, most baryons come from recombination of three gluons; at large x, most come from recombination of the leading valence quark with two gluons.

In this letter we present a few highlights of our recent calculations of baryon production in quark jets, in order to stress particularly certain properties which have a chance of being tested with currently available and easily foreseen data. Further details, justifications, etc., are given in our longer paper [1].

The model is quite simple. We use the Konishi, Ukawa, Veneziano (KUV) jet calculus [2] to evolve an initial quark at Q^2 down to some Q_o^2. At this point, all the gluons in the jet are converted into quark - antiquark pairs by a technique which preserves momentum [3]. The quark triplets then present in the jet are converted into baryons by a recombination function. This sequence - the gluon conversion followed by quark recombination - produces three new "effective recombination functions": a three gluon recombination into (baryon + anything); and (two gluon + quark) and (gluon + two quark) recombination functions into the same final state, i.e. baryon + anything. One might think of these as a more general recombination followed by a fragmentation.

The two features of the results which we wish to emphasize in this letter are as follows:

(a) The recombination contribution rises from zero at some value of Q_o^2. For physically accessible values of Q^2, therefore, the contributions tend to rise; this is especially noticeable in the central x region. This is different from the behaviour given by simple application of the Owens - Uematsu equations, which tend to give a slow rise at small x and a slow drop at large x as the Q^2 evolution progresses [4].

The Owens type behaviour, predicted by the Altarelli - Parisi equations [5], will set in at very large Q^2 in the recombination contributions also (as it must if these are to be consistent with QCD); this is guaranteed by our use of the jet calculus for the jet evolution. However, it would be highly fortuitous if the Q^2 evolution expected at very large Q^2 persisted down to the physically measurable region.

As we show in our longer paper, in principle there are at least three contributions to baryon production in parton jets. One of these is the Owens - Uematsu type, and one is of the recombination model type. The third contribution is determined by the intrinsic diquark content of the partons at Q_o^2. The relative size of these three contributions may be determined by study of the Q^2 evolution. (b) The other feature we would like to emphasize in this letter is that, with the particular choice of recombination functions that we have - meaning here all the effective recombination functions discussed above - and with the use of jet calculus to count the number of partons expected in the spray at Q_o^2, our results have a very simple pattern. Namely, (i) at very large x most of the contribution to the production of baryons comes from terms where the original quark comes right through and recombines with two gluons from the spray and (ii) at small x, much of the contribution comes from terms where three gluons from the spray recombine.

These are both consistent with the previous discovery [6] that the multiplicity of partons in the jet at Q_o^2 is not very large, if the very soft ones are ignored. They are also consistent with and similar to our results for the meson case [7].

Our formula for the baryon spectrum is

$$D_{B,i}(x, Q^2) = \int D_{a_1a_2a_3,i}(x_1,x_2,x_3;Q^2)\, R^B_{a_1\,a_2\,a_3}(x_1,x_2,x_3,x)\, dx_1 \cdot dx_2\, dx_3 \qquad (1)$$

where $D_{a_1\,a_2\,a_3,\,i}(x_1,x_2,x_3;Q^2)$ is the probability for finding the three quarks a_1, a_2, a_3 with momentum fractions x_1, x_2 and x_3 when they originate from parton i.

The KUV jet calculus formula for this distribution is

$$D_{a_1a_2a_3,i}(x_1,x_2,x_3;Q^2) = \sum_{jb_1b_2\,b_2'\,c_1c_2} \int_{Y_o}^{Y} dy \int_{Y_o}^{y} dy' \int dx\,dx'\,dx''$$

$$dz\, dz'\, dw_1\, dw_2\, dw_3\, D_{a_1b_1}(w_1, y-Y_o)\, D_{a_2c_1}(w_2,y' - Y_o)\, D_{a_3c_2}(w_3,y' - Y_o)$$

$$\hat{P}_{b_2' \to c_1c_2}(z')D_{b_2'b_2}(x'', y-y')\, \hat{P}_{j \to b_1b_2}(z)\, D_{ji}(x, Y-y)$$

$$\delta(x_1 - w_1\, zx)\, \delta[x' - x''(1-z)x]\, \delta(x_2 - w_2\, z'\, x')$$

$$\delta[x_3 - w_3(1-z')x']. \qquad (2)$$

The variable Y is related to Q^2 by $Y = (2\pi b)^{-1}\, \ell n[1+\alpha_o b\, \ell n(Q^2/\Lambda^2)]$ where $12\pi b = 11\, N_c - 2N_f$, with $N_c = 3$ colours and $N_f = 3$ flavours. The partons j, b_1, b_2, b_2', c_1 and c_2 have momentum fractions x,z,(1-z), x'',z',(1-z') respectively, with intermediate momenta integrated.

The KUV propagator $D_{\ell k}(v,y(Q^2))$ gives the probability for finding parton ℓ with momentum fraction v in the QCD generated cloud of parton k characterized by four-momentum squared Q^2. The P's are the A - P [5] branching functions for virtual partons. We use the notation given by Willen [8] for QCD strength and scale parameters $\Lambda'^2 = \Lambda^2 \exp[-1/b\alpha_o]$ and $\alpha_s = 1/b \, \ell n(Q^2/\Lambda'^2)$. The original jet has "off-shellness" Q^2 and the three partons are measured at off-shellness Q_o^2.

At Q_o^2 the jet consists of the original parton plus many radiated partons. Due to the rather primitive state of the recombination phenomenology, we wish to create baryons by combining only three quarks rather than by looking at sets of (three quarks plus multiple gluons). This forces us to do something with the gluons in the jet. The recipe used by Chang and Hwa [3], conversion of the gluons by fiat into quark - antiquark pairs in such a way that their momentum is conserved, was rather successful in the corresponding calculation of pion content for $e^+ e^- \to (\pi^+ + \pi^-) X$ [7,3], so we shall use that here†. Specifically, the probability that a gluon turns into a quark (antiquark) of momentum fraction z (1-z) is taken to be [5]

$$\overline{P}_{g \to q\bar{q}}(z) = \frac{3}{2N_f} \; [z^2 + (1-z)^2] \qquad (3)$$

Note that no additional powers of the strong coupling are included.

Finally we recombine all the quark triplets thus created with the simple recombination function [9]

$$R(x_1,x_2,x_3,x) = 27 \; \frac{x_1 x_2 x_3}{x^3} \; \delta \; (x_1+x_2+x_3-x) \qquad (4)$$

This is normalized by the requirement [10] that no set of three quarks can make more than one baryon $27xy(1-x-y) \leq 1$. In our longer paper we discuss this function and give some justification for its particular form. The properties which we emphasize in this letter are not strongly dependent on the functional form although, of course, the relation of the theoretical predictions to the data is strongly correlated with the normalization of the recombination function.

In Fig. 1 we show the predicted Q^2 dependence of the inclusive spectrum for $e^+e^- \to (p + \bar{p})X$. Note the rise with increasing Q^2 through the region of current physical interest. This behaviour will occur for almost all physically reasonable values of Q_o^2 if Λ=100 Mev; the asymptotic Owens-Uematsu like Q^2 dependence does not set in until $Y-Y_o \gtrsim 0.4$.

In Fig. 2 we show the breakdown of the proton spectrum at $Q^2 = 1089$ Gev^2 into the contributions from various parton configurations. The "leading quark" effect [11] - that at large x most of the result come from quark-gluon-gluon recombination - is emphasized by the results in Fig. 3. Here we present separately the production of protons and antiprotons in an up quark jet. Note that at small x the rates are almost identical due to the dominance of the three gluon recombination; at large x however, the antiproton rate is much smaller than the proton rate, since antiprotons cannot be produced from the leading quark. This is in qualitative agreement with the result of the EMC[12].

We can also, of course, predict the lambda content of jets. In Fig. 4a we present the lambda to proton ratio predicted by the model. Since at small x most ot the contribution comes from the three gluon terms and since there are six ways to pick up the u, d and s quarks for the lambda out of three gluons, but only three ways to pick out two u's and one d for the proton, we expect twice as many lambdas as protons at very large Q^2. At large x however, where most of the contribution comes from the leading quark + two gluons, the Λ to p ratio should just be determined by the ratio of these graphs (which by similar, but more complicated, combinatoric arguments, is exactly 4/3). Both these expectations are confirmed by the curves[‡]. In Fig. 4b we show calculations of the inclusive Λ spectrum in e^+e^- annihilation for comparison with currently available experiments [14,15]. In this regard, we should note that our current calculational technique allows us to look only at x greater than 0.3 for the produced baryons, so we cannot compare directly with the presently available high energy data for protons in e^+e^- jets.

To summarize, we have calculated the single inclusive baryon spectrum in e^+e^- annihilation using the KUV jet calculus and recombination. At large x, much of the result comes from the (2 gluon + quark) configuration, thus providing a quantitative basis for the leading quark effect seen in recent experiments, whereas at smaller x the three gluon terms dominate. The recombination mechanism produces a baryon spectrum which rises with Q^2 throughout the physically accessible region. We can thus hope that it will soon be subjected to a definite experimental test.

In another recent paper on the recombination model, Eilam and Zahir [13] approximately evaluate an expression like eqn. (2) with the y integral cut off at $Q^2 = 30\ \mathrm{Gev}^2$. Their results differ from ours both quantitatively and qualitatively; we analyze these differences in our longer paper [1].

FOOTNOTES

\+ We should note that this recipe is not the only possible thing one could do with the gluons, and that it clearly must be some sort of approximation. In principle we should leave some gluons unconverted in order to have some available for creation of glueballs by genuine gluon-gluon recombination [16], and the gluons in the jet need to be somehow partitioned into those saved for glueball creation and those used for conversion into quarks.

‡ The recombination functions used here are SU(3) symmetric, and all quarks are treated in the jet evolution as though they have zero mass. SU(3) breaking corrections would, of course, reduce the Λ/p ratio.

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FIGURE CAPTION

Fig. 1. Proton spectrum showing Q^2 dependence ($Q_o^2 = 2$ Gev^2, $\Lambda = 200$ Mev).

Fig. 2. Decomposition of the proton spectrum into contributions from the various recombination terms ($Q^2 = 1089$ Gev^2, $Q_o^2 = 2$ Gev^2, $\Lambda = 200$ Mev).

Fig. 3. The dominance of the quark + two gluon term in the fragmentation function at large x is shown by the small number of antibaryons produced in the u quark jet. At small x, on the other hand, the three gluon recombination dominates and produces equal number of baryons and antibaryons ($Q^2 = 25$ Gev^2, $Q_o^2 = 2$ Gev^2, $\Lambda = 200$ Mev).

Fig. 4a. Predictions for the relative size of $(\Lambda+\bar{\Lambda})$ and $(p+\bar{p})$ cross sections. At x = .31 the ratio $R = (\Lambda+\bar{\Lambda})/(p+\bar{p})$ is 1.87 (the dominant 3g terms have a ratio of 2);at x = .92 R = 1.33 (the dominant 2g terms have a ratio of 1.34); $Q^2 = 1089$ Gev^2, $Q_o^2 = 2$ Gev^2, $\Lambda = 200$ Mev.

Fig. 4b. Sample comparison with data from the Tasso Collaboration [14] for $e^+e^- \to (\Lambda+\bar{\Lambda})$ X. The theory was evaluated for $Q^2 = 1089$ Gev^2, $Q_o^2 = 5$ Gev^2 and $\Lambda = 200$ Mev; smaller values of Q_o^2 or larger values of Λ would produce larger values of s $d\sigma/dx$.

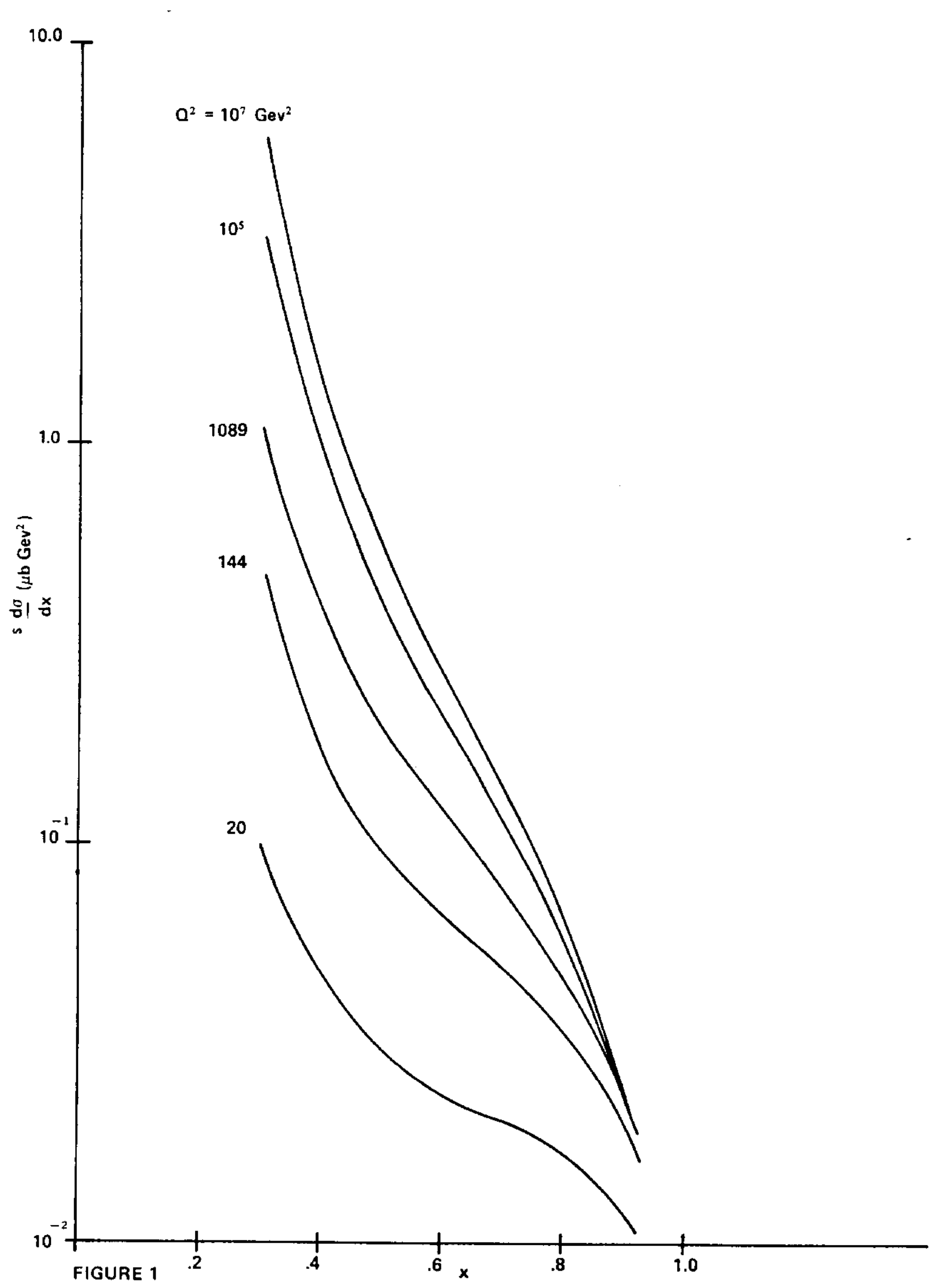
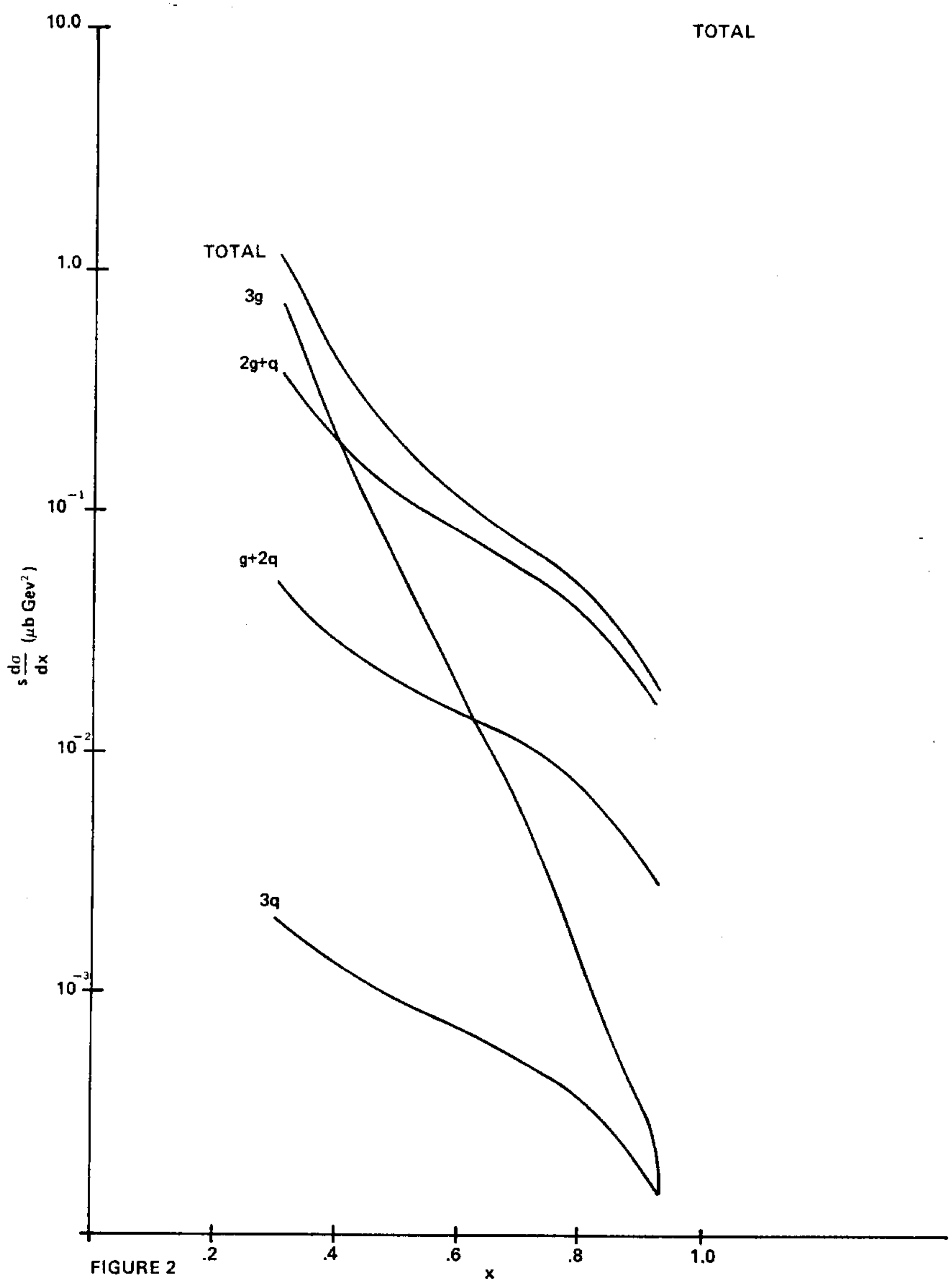

10.0
1.0
10^{-1}
10^{-2}
$s\,\frac{d\sigma}{dx}$ (μb Gev^2)
$Q^2 = 10^7$ Gev^2
10^5
1089
144
20
.2
.4
.6
.8
1.0
x

FIGURE 1



TOTAL
10.0
1.0
10^{-1}
10^{-2}
10^{-3}
$s\frac{d\sigma}{dx}$ (μb Gev^2)
TOTAL
3g
2g+q
g+2q
3q
.2
.4
.6
.8
1.0
x

FIGURE 2

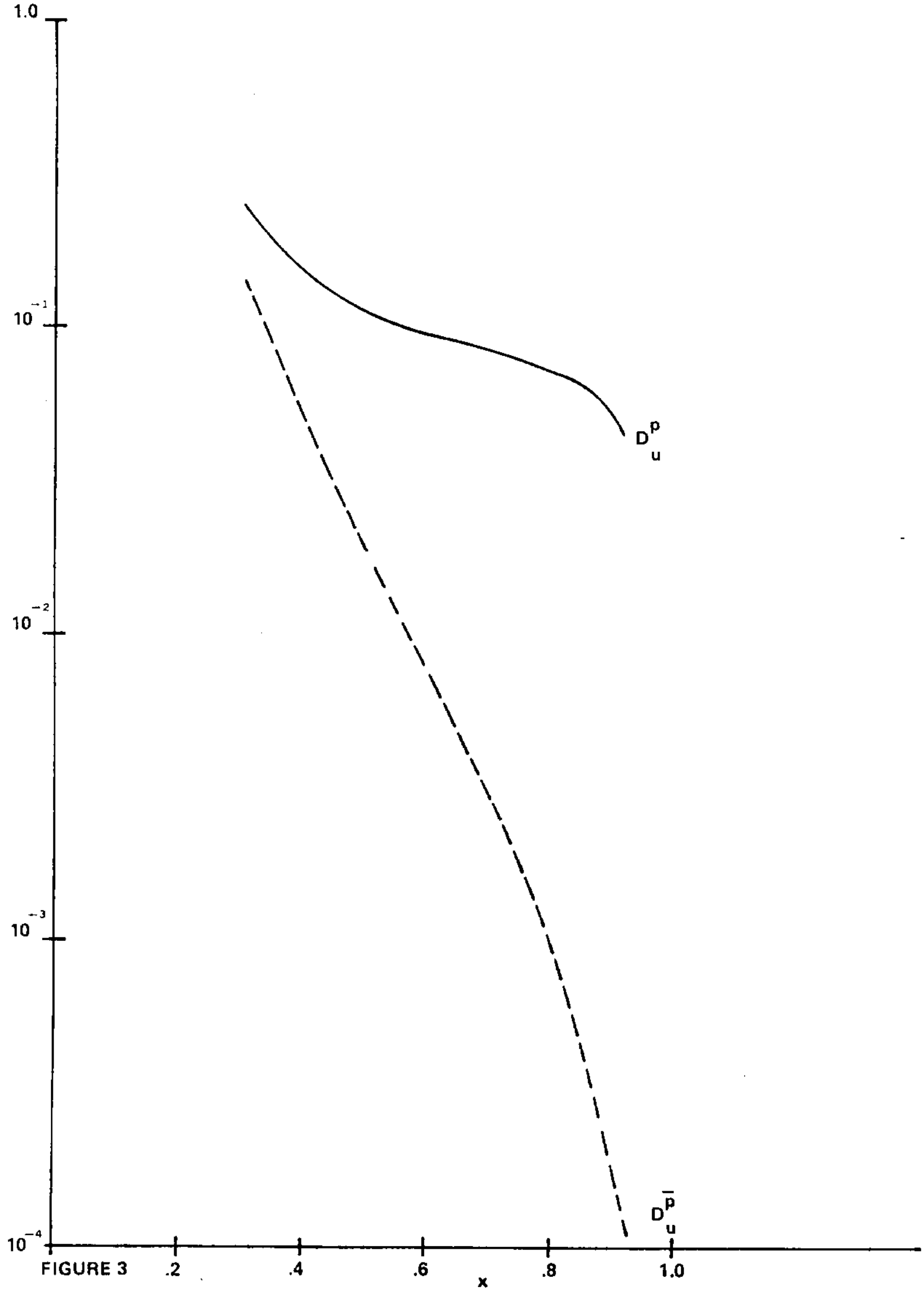


FIGURE 3

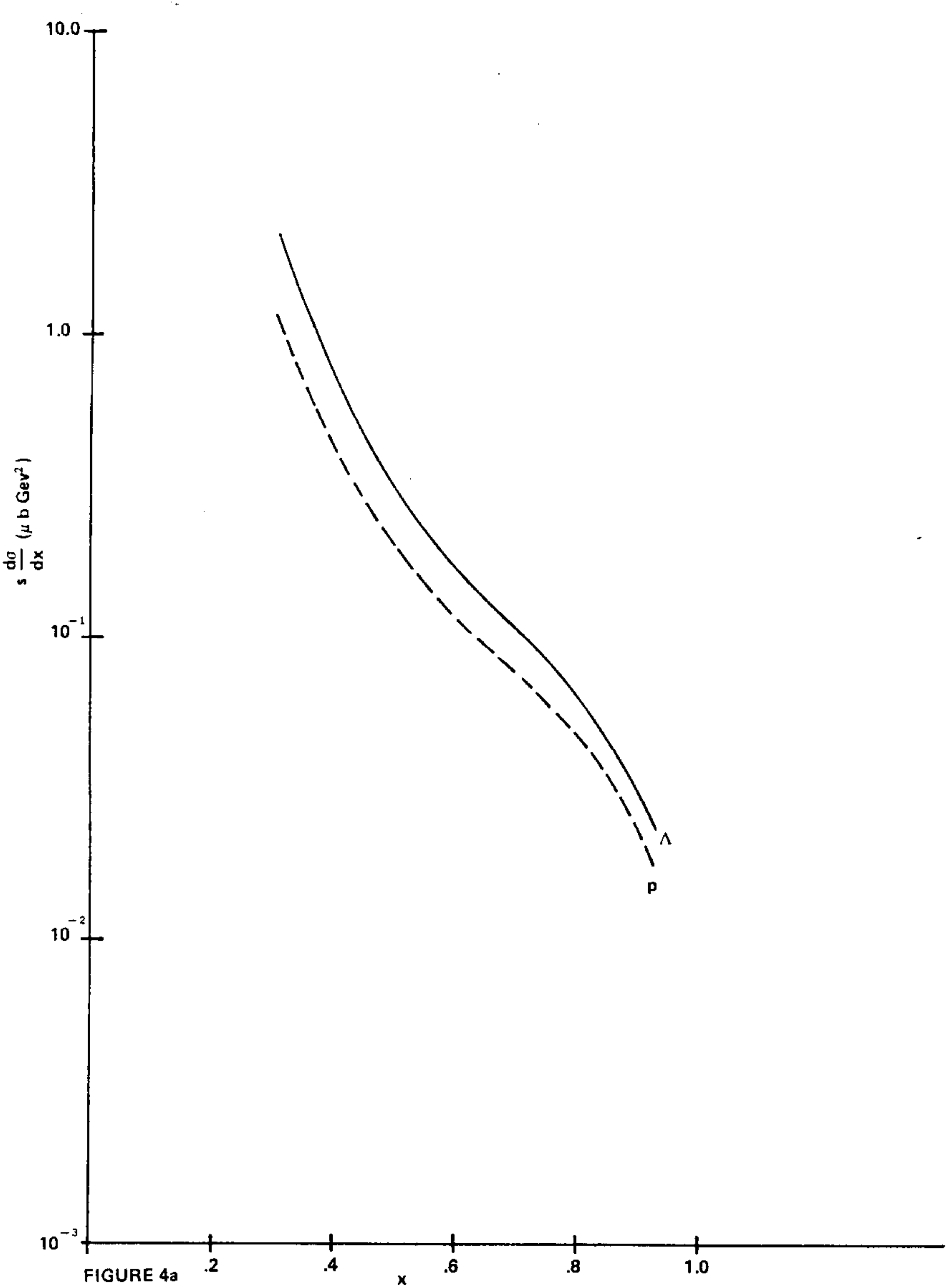


FIGURE 4a

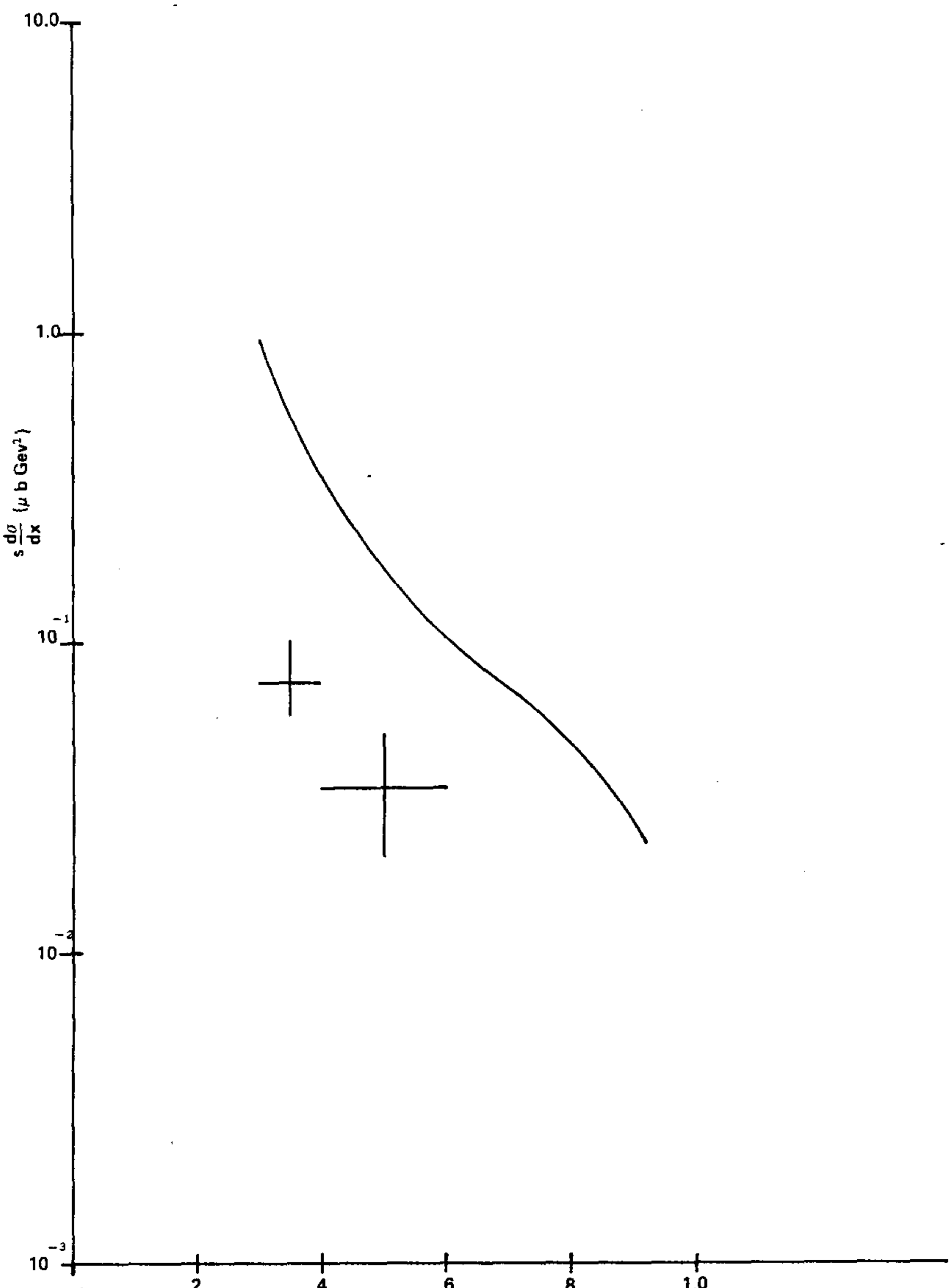


FIGURE 4b