

DESY 97-43
BI-TP 97/09
March 1997

FORMATION AND DECAY OF SCALAR LEPTOQUARKS/SQUARKS IN ep COLLISIONS

T. PLEHN¹, H. SPIESBERGER^{2,*}, M. SPIRA³, AND P. M. ZERWAS¹

¹ Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg

² Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld

³ CERN, Theory Division, CH-1211 Geneva 23

Abstract

The cross sections for the formation of scalar resonances, leptoquarks or squarks, in electron/positron-proton collisions at HERA are presented including next-to-leading order QCD corrections. Depending mildly on the mass of the resonances, the K -factors increase the production cross sections by up to 30% if the target quarks are valence quarks. The QCD corrections to the partial decay widths of leptoquarks/squarks to leptons and quarks are small. The electron spectrum in the decays is softened nevertheless by perturbative gluon radiation at a level of 3.4 GeV for a leptoquark/squark mass of 200 GeV.

* Supported by Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Bonn, Germany, Contract 05 7BI92P (9).

1 Introduction

An excess of events has recently been observed in deep-inelastic e^+p scattering at HERA for high x and high Q^2 [1, 2]. If these events are attributed to the formation of a resonance in e^+q collisions, decaying subsequently into lepton–quark final states, the events should cluster at the invariant mass $M = \sqrt{xs}$. Moreover, if scalar resonances are formed, the distribution in the scaling variable y should be flat, corresponding to isotropic angular decay distributions in the rest frame of the resonance. Indeed, a clustering around $M = 200$ GeV is indicated in the H1 data and the events are distributed up to large y values [1]. These observations have initiated theoretical analyses of possible resonance formation at HERA, and cross checks with experimental results from LEP [3], the Tevatron [4] and from rare decays have been performed. The analyses have been carried out for leptoquarks in general and squarks in supersymmetric theories with R -parity breaking in particular [5–10].

In the present report we present the cross sections for the formation of scalar resonances, leptoquarks or squarks, including next-to-leading order QCD corrections in $e^\pm p$ collisions. The step beyond the leading order analysis [11] is motivated by two points. First, the theoretical predictions for the cross sections are stabilized with regard to variations of the renormalization and factorization scales. The choice of the leptoquark/squark mass M , which can *a priori* be considered as a natural choice for these spurious parameters, can thus be investigated in detail. Second, to derive the theoretical predictions for the formation cross sections to an accuracy of $\mathcal{O}(\alpha_S) \sim 10\%$ is a reasonable goal for the time being. The results are presented for a single scalar resonance

$$e + q \rightarrow LQ/\tilde{q} \tag{1}$$

where e generically denotes electrons and positrons, q quarks and antiquarks, and LQ/\tilde{q} leptoquarks and squarks (Fig. 1a). The coupling λ is defined by

$$\mathcal{L}_{int} = \lambda(\bar{e} q)S + h.c. \tag{2}$$

with the (opposite) helicities of the lepton and the quark fixed for the specific leptoquark/squark state S (see e.g. Table 1 of Ref. [6]).

By the same token, we have determined the partial width of leptoquark/squark decays

$$LQ/\tilde{q} \rightarrow e + q(g) \tag{3}$$

to order α_s in QCD. For massless quarks in the final state, the (scaled) lepton energy $x_e = 2E_e/M$ is fixed to be 1 in lowest order. The lepton energy is softened by gluon radiation and the spectrum becomes continuous, peaking however strongly for x_e just below 1.

2 Production of Scalar Particles in ep Collisions

The *cross section* in leading order QCD can be cast into the form

$$\begin{aligned}\sigma_{LO} &= \sigma_0 x q(x, M^2) \\ \sigma_0 &= \frac{\pi\lambda^2}{4M^2}\end{aligned}\tag{4}$$

with

$$x = M^2/s\tag{5}$$

The density of the target quarks at the scale $\mu_F = M$ is denoted by $q(x, M^2)$.

In addition to the standard mass corrections for colored quarks and bosons which are defined on the mass shells, the QCD corrections involve the renormalization of the $e - q - LQ/\tilde{q}$ vertex displayed in Fig. 1b. The $e - q - LQ/\tilde{q}$ coupling λ has been defined at the point $\mu_R = M$ in the \overline{MS} renormalization scheme. The QCD vertex corrections make the coupling run according to the formula

$$\lambda^2(\mu_R) = \frac{\lambda^2(M)}{1 + \frac{\alpha_s}{\pi} \log \frac{\mu_R^2}{M^2}}\tag{6}$$

The second class of diagrams, Fig. 1c/d, describe the radiation of gluons off the initial quark and final leptoquark/squark state: $e + q \rightarrow g + LQ/\tilde{q}$. The sum of the virtual and bremsstrahlung corrections is ultraviolet and infrared finite. Finally, the formation process initiated by lepton-gluon collisions must be added: $e + g \rightarrow \bar{q} + LQ/\tilde{q}$, as shown in Fig. 1e. The collinear divergences due to gluon emission off the initial state quark line and due to gluon splitting to quark-antiquark pairs will be absorbed in the renormalization of the quark and gluon parton densities [12].

The final result of this simple analysis can be summarized in the standard form

$$\sigma(ep \rightarrow LQ/\tilde{q} + X) = \sigma_0 \left[1 - \frac{2\pi^2 \alpha_s}{9 \pi} \right] xq(x, M^2) + \Delta\sigma_q + \Delta\sigma_g\tag{7}$$

with

$$\begin{aligned}\Delta\sigma_q &= \int_x^1 dx' q(x', M^2) \times \frac{\alpha_s}{\pi} \sigma_0 \left\{ -\frac{z}{2} P_{qq}(z) \log z + \frac{4}{3} [1 + z] \right. \\ &\quad \left. + \frac{4}{3} \left[2 \left(\frac{\log(1-z)}{1-z} \right)_+ - \left(\frac{1}{1-z} \right)_+ - (2 + z + z^2) \log(1-z) \right] \right\} \\ \Delta\sigma_g &= \int_x^1 dx' g(x', M^2) \times \frac{\alpha_s}{\pi} \sigma_0 \frac{z}{2} \left\{ -P_{qg}(z) \left[\log \frac{z}{(1-z)^2} + 1 \right] + z(1-z) \log z + 1 \right\}\end{aligned}$$

The auxiliary variable z is defined as usual by $z = x/x'$. P_{qq} and P_{qg} are the standard $q \rightarrow q(g)$ and $g \rightarrow q(\bar{q})$ splitting functions

$$P_{qq}(z) = \frac{4}{3} \left\{ 2 \left(\frac{1}{1-z} \right)_+ - 1 - z + \frac{3}{2} \delta(1-z) \right\} \quad (8)$$

$$P_{qg}(z) = \frac{1}{2} \left\{ z^2 + (1-z)^2 \right\} \quad (9)$$

The distribution F_+ is defined by $F_+(z) = F(z) - \delta(1-z) \int_0^1 dz' F(z')$, regularizing the singularities at $z = 1$. The renormalization point μ_R and the factorization point μ_F have been identified with the mass M of the resonance. They may be re-introduced as free parameters in Eq. (4) by substituting $\lambda(M) \rightarrow \lambda(\mu_R)$ and adding the term $+\log \mu_R^2/M^2$ to the coefficient of α_S/π in the virtual correction; in addition, the mass scale M in the parton densities must be replaced by μ_F and $\log \mu_F/M^2$ must be added to the logarithms attached to the parton splitting functions.

The results are exemplified in Fig. 2 for the K -factors properly defined by

$$K = \sigma_{NLO}/\sigma_{LO} \quad (10)$$

where all quantities (couplings, parton densities) in the numerator and denominator are to be evaluated consistently in next-to-leading and leading order, respectively. This definition guarantees the correct theoretical interpretation of the size of the QCD corrections. The K -factors are presented for e^\pm projectiles on valence (u, d) targets in Fig. 2. The K -factors are larger than unity in the range of leptoquark masses we are interested in. The NLO cross sections are larger than the leading order cross sections by about 20 to 30%. The vertex corrections reduce the cross section, as apparent from Eq. (7). This effect is over-compensated however by the quark contribution $\Delta\sigma_q$, while gluon splitting, $\Delta\sigma_g$, plays a minor rôle. For sea quark targets, the K -factor is close to 1.15 for $M = 150$ GeV and falls to values below 1 for masses above 195 GeV. The different behavior of K -factors for valence and sea quarks is a straight consequence of the different shapes of the parton densities.

The improvement of the theoretical prediction is clearly visible in Fig. 3. The cross sections in next-to-leading order are compared with the leading order for the process $e+d \rightarrow LQ/\bar{q}$ as a function of the renormalization scale μ_R and the factorization scale μ_F . μ_R and μ_F are identified for the sake of simplicity. While the LO cross section changes by nearly a factor of 2 if μ/M is varied from 3 to 1/3, the change of the NLO cross section is damped to 1.2 in this range. Thus, if the next-to-leading order corrections are taken into account, the theoretical prediction of the cross section for scalar resonance formation is stabilized considerably.

3 Decay Width and Lepton Spectrum

The *partial width* for the decays

$$LQ/\tilde{q} \rightarrow e + q(g) \quad (11)$$

can easily be calculated in a similar way [13], including the one-loop QCD corrections:

$$\Gamma[LQ/\tilde{q} \rightarrow eq(g)] = \frac{\lambda^2 M}{16\pi} \left[1 + \left(\frac{9}{2} - \frac{4\pi^2}{9} \right) \frac{\alpha_s}{\pi} \right] \quad (12)$$

The coefficient in front of α_s/π is tiny, ~ 0.11 , so that QCD corrections to the width are small. For small Yukawa couplings $\lambda \sim e/10$ the partial width is therefore very narrow, i.e. $\Gamma \sim 3$ MeV for $M \sim 200$ GeV. If for leptoquarks/squarks no other channels are open, apart from $LQ \rightarrow eq$ or νq , and $\tilde{q} \rightarrow eq$, the lifetime is very long, and the leptoquark/squark will be bound into a fermionic ($LQ\bar{q}$) or ($\tilde{q}\bar{q}$) state. This is different for squarks if the branching ratio for R -parity violating decays is small compared to R -parity conserving (neutralino/gaugino) decays.

To lowest order, the scaled lepton energy of the decay process (3) in the rest-frame¹ of the isolated leptoquark or squark,

$$x_e = 2E_e/M \quad \text{with} \quad 0 \leq x_e \leq 1 \quad (13)$$

is fixed to 1 if the final-state quark is treated as a massless parton. However, perturbative gluon radiation (and the non-perturbative hadronization of quark jets) reduces the lepton energy and gives rise to a continuous energy spectrum. This effect is analogous to the radiation of gluons in $q\bar{q}$ pair production of e^+e^- annihilation; LEP measurements can therefore serve as a solid basis for estimating non-perturbative parameters which are not accessible to theoretical QCD analyses.

The energy spectrum of the lepton, after real gluon emission is switched on, is given by the expression

$$x_e < 1 : \quad \frac{1}{\Gamma} \frac{d\Gamma}{dx_e} \Big|_{\mathcal{O}(\alpha_s)}^{pQCD} = \frac{4}{3} \frac{\alpha_s}{\pi} \left[\frac{1}{x_1} \left(\log \frac{1}{x_1} - \frac{7}{4} \right) + \log \frac{1}{x_1} + \frac{7}{4} - \frac{x_e}{4} \right] \quad (14)$$

with the abbreviation $x_1 = 1 - x_e$. This form of the spectrum is normalized to the partial eq decay width. (If other decay channels are open, Eq. (14) must be supplemented by the branching ratio B_{eq} for absolute normalization). In the limit $x_e \rightarrow 1$, the leading singularities may be resummed to give

$$x_e \rightarrow 1 : \quad \frac{1}{\Gamma} \frac{d\Gamma}{dx_e} \Big|_{resum}^{pQCD} = \frac{1}{\Gamma} \frac{d\Gamma}{dx_e} \Big|_{\mathcal{O}(\alpha_s)}^{pQCD} \times \exp \left(\frac{4}{3} \frac{\alpha_s}{\pi} \left[-\frac{1}{2} \log^2 \frac{1}{x_1} - \frac{7}{4} \log \frac{1}{x_1} \right] \right) \quad (15)$$

¹The scaled lepton energy can be defined in a Lorentz-invariant way as $x_e = 2(p_e p_{LQ/\tilde{q}})/M^2$.

The singularity of Eq. (14) for $x_e \rightarrow 1$ is removed by resummation [14]. In fact, the spectrum (15) approaches zero for $x_e \rightarrow 1$ and a sharp maximum develops just below 1. The final lepton-energy spectrum as predicted in pQCD is shown by the full line in Fig. 4. The spectrum in the approximation of one-gluon radiation without resummation (singular near $x_e \rightarrow 1$) is indicated by the broken line.

The softening of the lepton spectrum due to the perturbative gluon radiation can be characterized by the average lepton energy $\langle x_e \rangle$ defined for $LQ \rightarrow e + q(g)$ decays. It is easy to derive from the spectrum:

$$\langle x_e \rangle^{pQCD} = 1 - \frac{4}{9} \frac{\alpha_s}{\pi} \quad (16)$$

This corresponds to a loss of ~ 3.4 GeV in the lepton energy due to perturbative gluon radiation for a leptoquark mass of 200 GeV.

In addition to the perturbative energy loss, residual non-perturbative hadronization effects reduce the lepton energy, affecting the shape as well as the average energy. Such effects can be parametrized in a power series $\delta x_e^{NP} = -\mathcal{C}_1/M + \dots$. Estimates of the size of the non-perturbative coefficient \mathcal{C}_1 may be derived from the shape variable thrust [15]. A closer analogon is the direct-photon spectrum in e^+e^- annihilation to hadrons [16] at LEP. With $\mathcal{C}_1 \sim 0.7$ GeV for thrust, the non-perturbative contribution $\delta x_e^{NP} \sim (-$ a few $10^{-3})$ is expected well below the perturbative attenuation effect. In Monte Carlo calculations, which are beyond the scope of the present analysis, this qualitative estimate can be turned into a quantitative prediction. The overall picture drawn from the pQCD calculation presented above coincides well with the result of shower Monte Carlo programs employed in the H1 analysis [17]. This is expected from the QCD analyses at LEP. Scenarios in which squarks decay so fast that the color flux lines of the quarks in the decay final state are connected directly to the proton remnant, require more elaborate Monte Carlo programs.

Acknowledgements

We are very grateful to P. Mättig and P. Schleper for discussions on experimental aspects.

References

- [1] C. Adloff et al., H1 Collab., DESY-97-024, *Z. Phys. C* in press.
- [2] J. Breitweg et al., Zeus Collab., DESY-97-025, *Z. Phys. C* in press.
- [3] S. Komamiya, for the OPAL collaboration, CERN Seminar, Feb. 25th, 1997; P. Mättig, Proceedings, *International Conference on High Energy Physics* (Warsaw 1996); OPAL Physics Note PN 280, and P. Mättig, private communication.
- [4] D0 collaboration, <http://d0wop.fnal.gov/public/new/lq/lq-blurb.html>.

- [5] G. Altarelli, J. Ellis, G.F. Giudice, S. Lola, and M.L. Mangano, CERN-TH-97-040 (hep-ph/9703276).
- [6] J. Kalinowski, R. Rückl, H. Spiesberger, and P.M. Zerwas, DESY 97-38 (hep-ph/9703288).
- [7] J. Blümlein, DESY-97-32 (hep-ph/9703287).
- [8] K.S. Babu, C. Kolda, J. March-Russell, and F. Wilczek, IASSNS-HEP-97-04 (hep-ph/9703299).
- [9] D. Choudhury and S. Raychaudhuri, CERN-TH/97-26 (hep-ph/9702392); D. Choudhury and S. Raychaudhuri, CERN-TH/97-51 (hep-ph/9703369);
- [10] H. Dreiner and P. Morawitz, RAL report (hep-ph/9703287).
- [11] J. Wudka, *Phys. Lett.* **167B** (1986) 337; W. Buchmüller, R. Rückl, and D. Wyler, *Phys. Lett.* **B191** (1987) 442.
- [12] G. Altarelli, R.K. Ellis, and G. Martinelli, *Nucl. Phys.* **B157** (1979) 461; W. Furmanski and R. Petronzio, *Z. Phys.* **C11** (1982) 293.
- [13] W. Beenakker, R. Höpker, and P.M. Zerwas, *Phys. Lett.* **B378** (1996) 159.
- [14] G. Schierholz, SLAC Summer Inst. 1979, p. 476; P. Binétruy, *Phys. Lett.* **91B** (1980) 245.
- [15] P. Abreu et al., Delphi Collab., *Z. Phys.* **C73** (1997) 229.
- [16] R. Akers et al., Opal Collab., *Z. Phys.* **C67** (1995) 15.
- [17] P. Schleper, private communication.

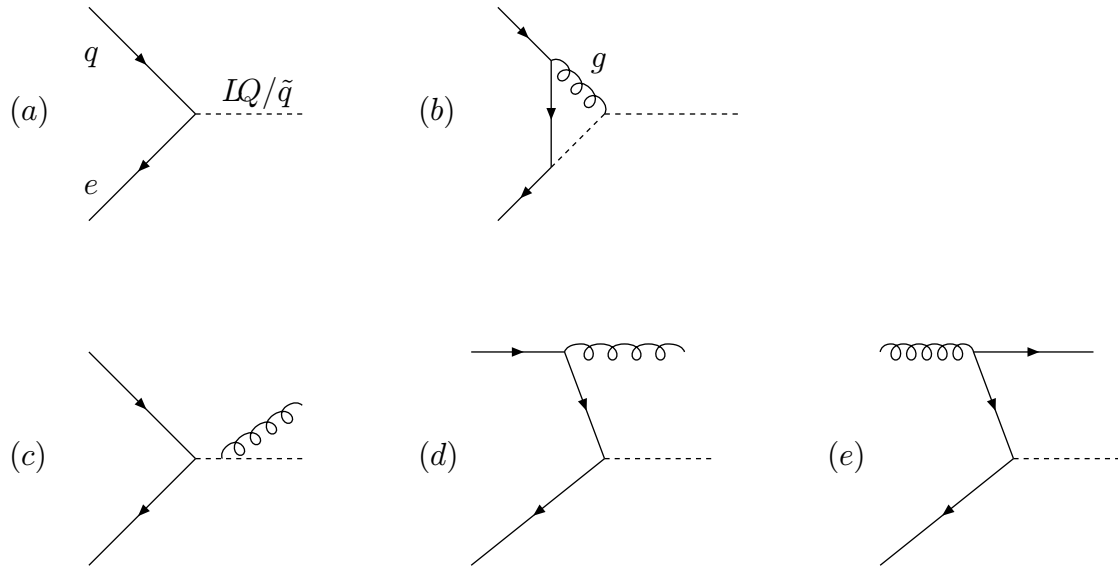


Figure 1: *The basic diagrams contributing in QCD to the formation of leptoquarks/squarks in ep collisions. (a) Born term; (b) vertex loop; (c) gluon radiation off the leptoquark/squark; (d) gluon radiation off the quark; (e) gluon splitting to quarks and antiquarks. The same diagrams (a) to (d), interpreted backwards, describe the decay of leptoquarks/squarks to order α_s .*

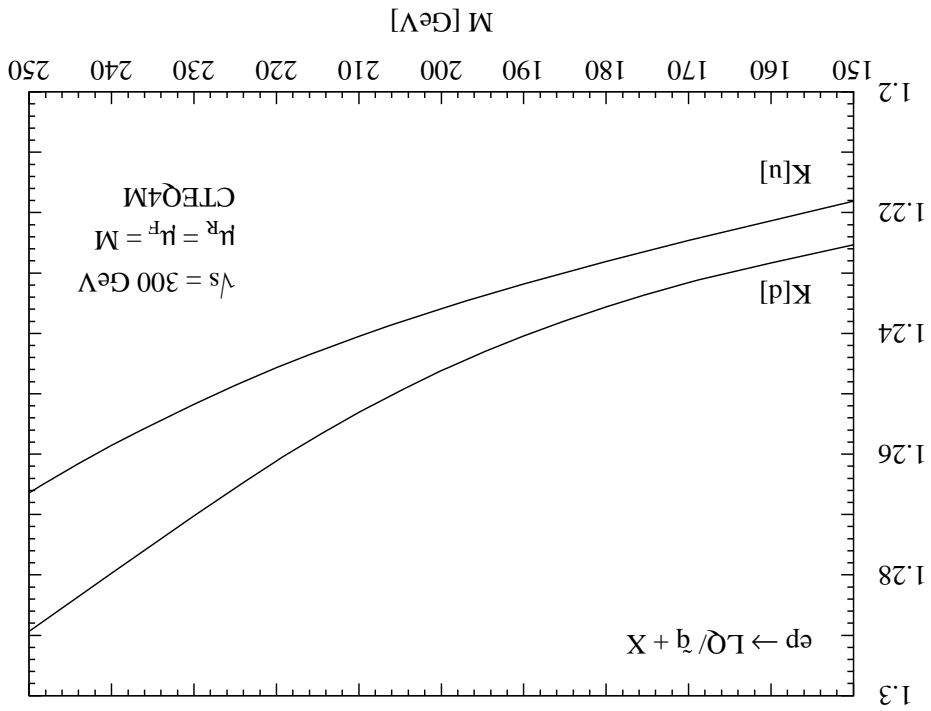


Figure 2: K -factors for $ed, eu \rightarrow LQ/\tilde{q}$ as a function of the leptoquark/squark mass.

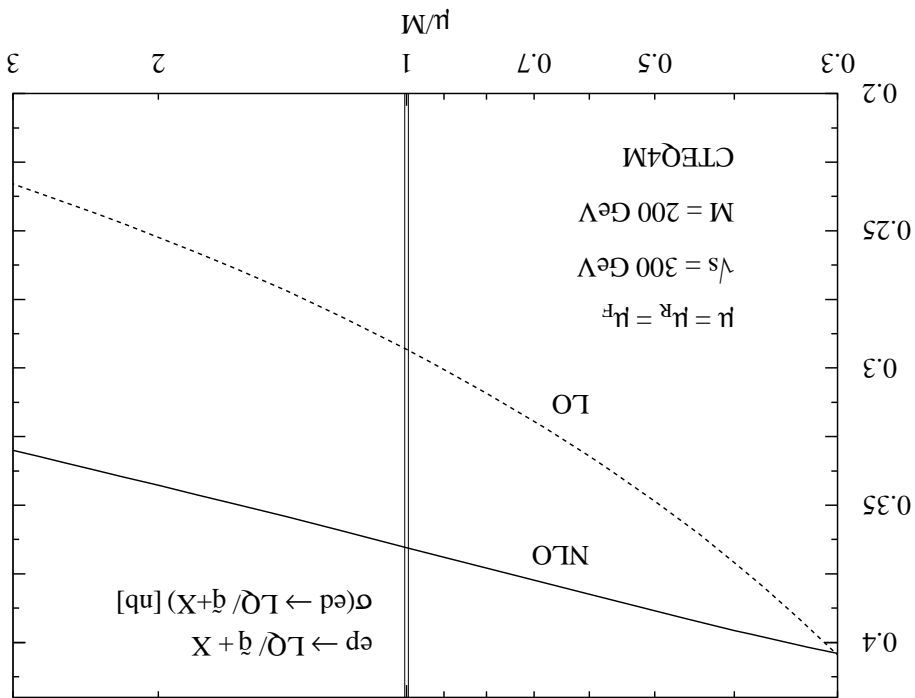


Figure 3: Comparison of the renormalization and factorization scale dependence in LO and NLO for the cross section for $\sigma(e + d \rightarrow LQ/\bar{q})$.

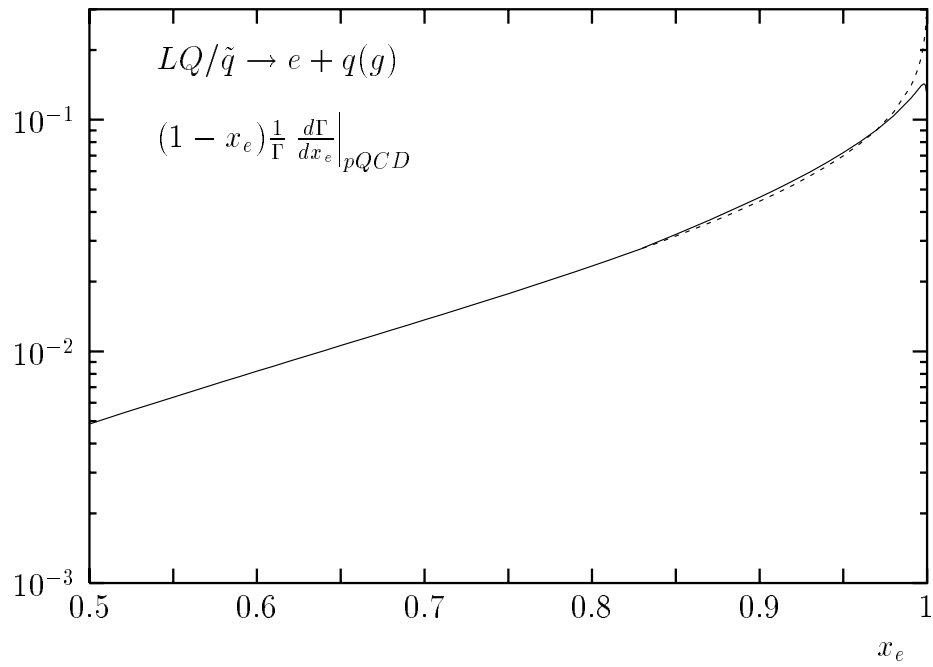


Figure 4: *The lepton-energy spectrum as predicted in perturbative QCD (full line). (The broken line corresponds to the $\mathcal{O}(\alpha_s)$ result without resummation near $x_e \rightarrow 1$).*