International Journal of Modern Physics A, Vol. 2, No. 4 (1987) 1285 – 1297
© World Scientific Publishing Company

EXCITED QUARK PRODUCTION AT HADRON COLLIDERS

U. BAUR*
Fermi National Accelerator Lab.
P.O. Box 500, Batavia, IL 60510 (USA)

I. HINCHLIFFE
Lawrence Berkeley Laboratory, University of California,
Berkeley, CA 94720 (USA)

D. ZEPPENFELD
Physics Dept., University of Wisconsin, Madison, WI 53706 (USA)

ABSTRACT

Composite models generally predict the existence of excited quark and lepton states. We consider the production and experimental signatures of excited quarks Q^* of spin and isospin 1/2 at hadron colliders and estimate the background for those channels which are most promising for Q^* identification. Multi-*TeV* *pp*-colliders will give access to such particles with masses up to several *TeV*.

Composite models of quarks and leptons$^{1)}$ with their potential of explaining the quark-lepton generation structure and the observed pattern of fermion masses and mixing angles have been quite popular in the last few years. The most convincing evidence for a substructure of quarks and leptons would be the discovery of excited quarks and leptons which are a common prediction of all composite models. The masses of excited fermions are generally expected to be at least of the order of a few hundred *GeV* since, according to present experimental constraints, the substructure scale Λ cannot be much smaller than 1 $TeV^{2)}$ and excited states should not be much lighter than Λ. It is, therefore, not very surprising that searches for excited fermions have been unsuccessful so far. With

---

* Max-Kade-Fellow

the availability of higher center of mass energies in $p\bar{p}$ collisions at the Tevatron and the realistic possibility of a multi-TeV pp-collider going into operation in the 1990's, the prospects for finding the lowest excited states of the spectrum become much better, if such particles exist at all. This has motivated us to reexamine excited quark production at hadron colliders (see also ref. [3]) and to try to estimate realistic discovery limits for them at the SSC, the LHC and the Tevatron collider. For simplicity we shall restrict ourselves to spin and isospin 1/2 objects, although it is by no means excluded that the lowest lying excited quark has spin 3/2 and/or has an isospin assignment different from 1/2.

Since the mass of excited quarks arises prior to $SU(2)\mathrm{x}U(1)$ breaking members of an excited weak doublet should be almost degenerate in mass. Furthermore, they should couple vectorlike to W- and Z-bosons. The coupling between excited spin 1/2 fermions, ordinary quarks and leptons and gauge bosons is uniquely fixed to be of magnetic moment type by gauge invariance. Requiring weak isospin gauge symmetry, the effective Lagrangian is given by[4,5,6)]

$$\mathcal{L}_{eff} = \frac{1}{2M^*}\,\overline{Q^*}\sigma^{\mu\nu}\,\left[g_s f_s \frac{\lambda^a}{2}F^a_{\mu\nu} + g f \frac{\vec{\tau}}{2}\vec{W}_{\mu\nu} + g' f' \frac{Y}{2}B_{\mu\nu}\right] q_L \; + \; h.c.\,. \qquad (1)$$

Here Q^* and q_L denote the isospin doublets of excited and lefthanded ground state quarks, $V_{\mu\nu}$, $V = F^a, \vec{W}, B$, is the field strength tensor for the gluon, the $SU(2)$ and the $U(1)$ gauge fields, and $Y = 1/3$ is the weak hypercharge. Finally, g_s, g and g' are the gauge coupling constants and f_s, f and f' are free parameters determined by the composite dynamics. Naively one would expect that they are all of order one. Higher dimensional operators in the full effective Lagrangian can be incorporated by changing the f's to form factors $f_s(q^2)$, $f(q^2)$ and $f'(q^2)$. These will be discussed in more detail below. To set the scale in $\mathcal{L}_{eff}$ we choose the Q^*-mass M^*.

It is now a straightforward exercise to calculate the rates for the Q^* decay modes from Eq. (1). Assuming $M^* > m_{W,Z}$[*] and neglecting ordinary quark masses one obtains[5,6] $(V = W, Z)$

$$\Gamma(Q^* \to gq) = \frac{1}{3}\alpha_s f_s^2 M^* \ , \tag{2}$$

$$\Gamma(Q^* \to \gamma q) = \frac{1}{4}\alpha f_\gamma^2 M^* \ , \tag{3}$$

$$\Gamma(Q^* \to Vq) = \frac{1}{8}\,\frac{g_V^2}{4\pi}\, f_V^2 M^* \Big(1 - \frac{m_V^2}{M^{*2}}\Big)^2 \Big(2 + \frac{m_V^2}{M^{*2}}\Big) \ . \tag{4}$$

Here

$$f_\gamma = fT_3 + f'\frac{Y}{2} \ , \tag{5}$$

$$f_Z = fT_3 \cos^2\theta_W - f'\frac{Y}{2}\sin^2\theta_W \ , \tag{6}$$

$$f_W = \frac{f}{\sqrt{2}} \ , \tag{7}$$

and $g_W = e/\sin\theta_W$ $(e = \sqrt{4\pi\alpha})$ and $g_Z = g_W/\cos\theta_W$ are the standard model W- and Z-coupling constants. T_3 in Eqs. (5) and (6) denotes the third component of the weak isospin.

According to Eq. (2) excited quarks will decay predominantly via strong interactions into ordinary quarks and a gluon. Radiative transitions and decays into quarks and a weak boson will typically appear at $O(\alpha/\alpha_s)$, i.e. at the few % level. As long as the Q^* mass is sufficiently large compared to m_W and m_Z the branching ratios will be very insensitive to M^*. They are summarized in Table 1 for excited up- (U^*) and down-quarks (D^*) with a mass $M^* = 1\ TeV$ and $f_s = f = f'$.

---

[*] If M^* would be smaller than $m_{W,Z}$, excited quarks should have been seen at the CERN $p\bar{p}$-collider[5] or will be discovered at SLC/LEP.

TABLE 1

Branching ratios of excited up- and down-quarks for $f_s = f = f'$ *and* $\alpha_s = 0.1$.

decay mode	br. ratio [%]	decay mode	br. ratio [%]
$U^* \to ug$	83.4	$D^* \to dg$	83.4
$U^* \to dW$	10.9	$D^* \to uW$	10.9
$U^* \to u\gamma$	2.2	$D^* \to d\gamma$	0.5
$U^* \to uZ$	3.5	$D^* \to dZ$	5.1

The total Q^* width for $f_s = f = f'$ is approximately given by

$$\Gamma(Q^*) \approx 0.04\, f^2 M^*. \tag{8}$$

The excited quarks will be rather narrow resonances unless the f's are much larger than one[7)].

In hadronic collisions excited quarks can be produced either pairwise or singly. Pair production, which mainly leads to four jets or jets plus one or two weak bosons in the final state, occurs, like for any heavy quark, through $q\bar{q}$ and gluon-gluon fusion via normal gauge couplings. Hence the corresponding cross-section can be reliably predicted provided form factor or anomalous "magnetic" moment effects are not large[8)] . The rates for $\overline{Q^*}Q^*$ production are quite small, however, ($\sigma \approx 2.4\ pb$ ($0.08\ pb$) for $M^* = 1\ TeV$ ($2\ TeV$) in pp-collisions at $\sqrt{s} = 40\ TeV$) so that the detection of excited quark pairs via their decays into hadronic jets will be severely limited by the background from ordinary QCD four-jet production. The decays into which will produce final states of a W (Z) pair and jets may be observable given that the background must now arise from the production of a pair of W's (Z's) and jets.

Single production of Q^* via quark-gluon fusion, on the other hand, can be abundant at high energies provided that f_s is not too small. The subsequent decay of the excited quark into a gluon or a photon plus a quark leads to a peak in the jet-jet or photon-jet invariant mass at $m = M^*$. Provided that the background is not overwhelming, this is a particularly clean and simple signal for Q^*'s. In the following we concentrate on this production mechanism. The invariant mass distribution for $p\bar{p}/pp \to Q^* \to q'V$, $V = g, \gamma, W, Z$ where both outgoing particles have a rapidity $| y_{q',V} | \le y_c$ is given by

$$\frac{d\sigma}{dm}(p\bar{p}/pp \to Q^* \to q'V) = \frac{2}{m} \int\limits_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy \; \tau \mathcal{L}(x_1, x_2) \; \hat{\sigma}(m^2) \; P(\tau, y, y_c) \; . \tag{9}$$

Here m is the $q'V$ invariant mass, $\tau = x_1 x_2 = m^2/s$, $y = (1/2)\ln(x_1/x_2)$, s is the $p\bar{p}$ (pp) center of mass energy squared and the partonic cross section is given by,

$$\hat{\sigma}(m^2) = \pi \frac{\hat{\Gamma}(Q^* \to q'V) \; \hat{\Gamma}(Q^* \to qg)}{(m^2 - M^{*2})^2 + \hat{\Gamma}^2(Q^*) M^{*2}} \tag{10}$$

with

$$\hat{\Gamma}(Q^* \to q'V) = \frac{f_V^2(m^2)}{f_V^2} \; [\frac{m}{M^*}]^3 \; \Gamma(Q^* \to q'V) \tag{11}$$

and

$$\hat{\Gamma}(Q^*) = \sum_V \Gamma(Q^* \to q'V) \tag{12}$$

which yields a correct description off the resonance peak. $P(\tau, y, y_c)$ is the probability that both final state particles have rapidities $| y_{q',V} | \le y_c$ and

$$\mathcal{L}(x_1, x_2) = q(x_1, m^2) g(x_2, m^2) + q(x_2, m^2) g(x_1, m^2) \tag{13}$$

is the luminosity function for Q^* production.

The form factors $f_s(q^2)$, $f(q^2)$ and $f'(q^2)$ will be assumed to have the form

$$F(q^2) = F\left(\frac{2}{1+\frac{q^2}{M^{*2}}}\right)^n , \tag{14}$$

where F represents either f_s, f or f'. They normalized such that $F(M^{*2}) = F$. $f_V(q^2)$, $V = \gamma$, Z, W in Eq. (11) is related to $f(q^2)$ and $f'(q^2)$ via Eqs. (5) to (7). We have chosen $n = 3/4$ in order to get a total partonic cross-section $\sigma(m^2) \sim 1/m^4$: a $1/m^2$ falloff, as required by partial wave unitarity, would not allow enough phase space for multiparton final states when the compositeness threshold $\Lambda = M^*$ is crossed. Choosing n larger than 3/4 changes only slightly the results to be presented below.

While $Q^* \to gq$ and $Q^* \to \gamma q$ have simple signatures, decays into a quark and a weak boson will result in a more complicated event structure. A large fraction of them gives three-jet events through the subsequent decay of W/Z into a quark pair. Limited jet-jet invariant mass resolution and a significant QCD background will considerably complicate the reconstruction of such decay chains. If $Z \to \bar{\nu}\nu$ or $W \to \ell\nu$, $\ell = e$, μ, τ, the invariant mass can, due to the escaping neutrino(s), not be determined. Thus in addition to the gq and γq decays only $Q^* \to qZ$ with $Z \to \ell^+\ell^-$ offers good prospects for identifying excited quarks.

We therefore focus on Q^* production in the jet-jet, photon-jet and Z-jet channel. Since excited up- and down-quarks should, to a good approximation, be degenerate in mass and the Q^* charge cannot be determined experimentally, we sum up U^*, D^*, $\overline{U^*}$ and $\overline{D^*}$ rates. The production cross-sections for excited quarks are then equal in pp- and $p\bar{p}$-collisions. In Fig. 1 we show the total cross-sections

$$\sigma(p\bar{p}/pp \to Q^* \to q'V) = \int dm\, \frac{d\sigma}{dm}(p\bar{p}/pp \to Q^* \to q'V) \tag{15}$$

versus M^* for $|\, y_{q',V} \,| \leq 1.5$, $f_s = f = f' = 1$ at $\sqrt{s} = 1.8$ *TeV* (Tevatron), 17 *TeV* (LHC) and 40 *TeV* (SSC) using set 1 of the structure functions of ref.

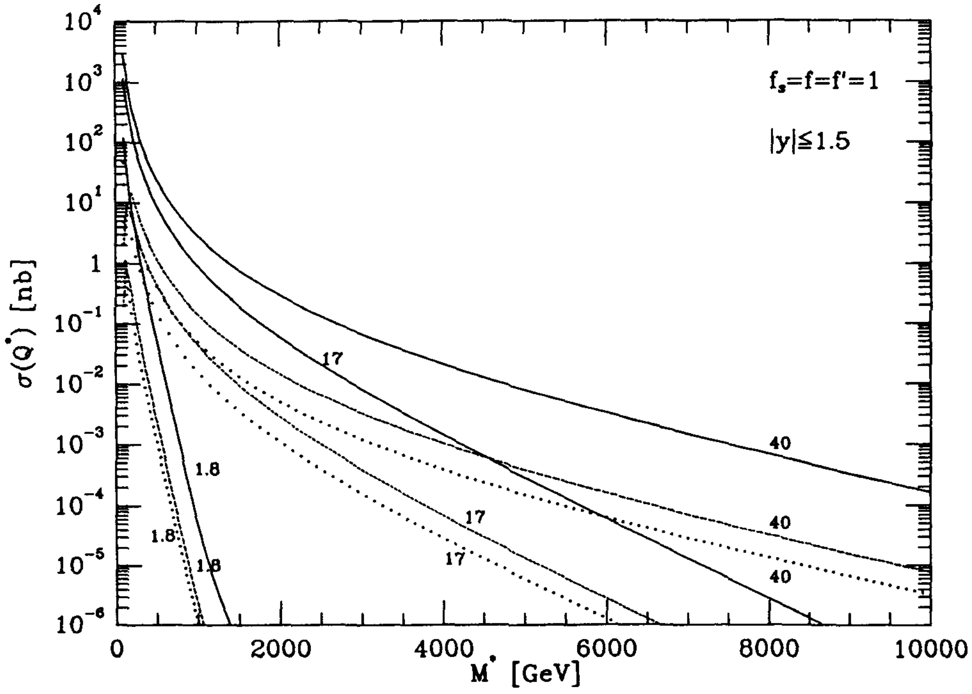

Fig. 1: *Single excited quark production cross-section in the jet-jet (solid lines), Z-jet (dashed lines) and photon-jet (dotted lines) channel. The numbers attached to the curves denote the $\sqrt{s}$ value in TeV.*

[9]. The numbers attached to the curves denote the value of $\sqrt{s}$ in TeV. Solid, dashed and dotted lines give the cross-sections in the jet-jet, Z-jet and photon-jet channel, respectively. If $f_s = f = f' \neq 1$, the results displayed in Fig. 1 have to be multiplied by a factor f^2.

It is obvious that the cross-sections in all three channels are quite large over a wide range of M^*, provided that the f's are not much smaller than one. This bodes well for a discovery of excited quarks with masses up to a few hundred GeV at the Tevatron and up to several TeV at the LHC and SSC, and only the question about background remains. In Figs. 2 to 4 we compare $d\sigma/dm$ for pp-

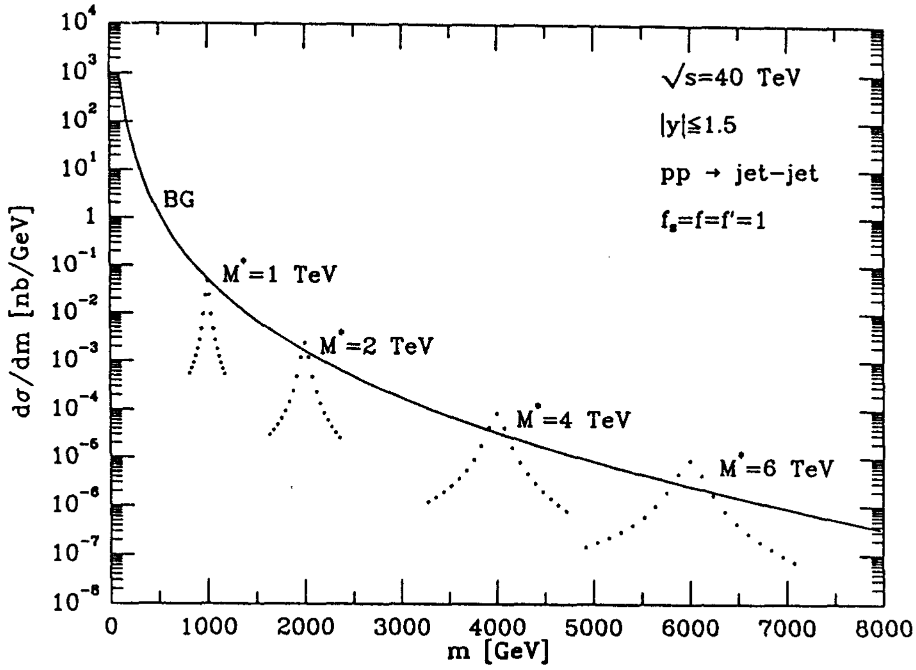

Fig. 2: *Invariant mass distribution $d\sigma/dm$ of excited quarks in $pp \to jet - jet$ versus the invariant jet-jet mass m for various values of M^* (dotted lines). The solid curve represents the standard model jet-jet background.*

collisions at $\sqrt{s} = 40\ TeV$, $f_s = f = f' = 1$ and various values of M^* with the standard model background (labeled by "BG"). Both outgoing particles are required to have a rapidity $| y | \leq 1.5$. One observes that the signal to background ratio improves with growing M^*. Even in the jet-jet case, where the most dangerous background is expected, the signal stands out clearly for larger values of M^*. In the photon-jet and Z-jet channel the background is always seen to be significantly smaller than the Q^* signal. A value different from one for $f_s = f = f'$ changes the width of the Q^* resonance, but not its peak value. For pp-collisions at $\sqrt{s} = 17\ TeV$ the situation is very similar to the one shown in

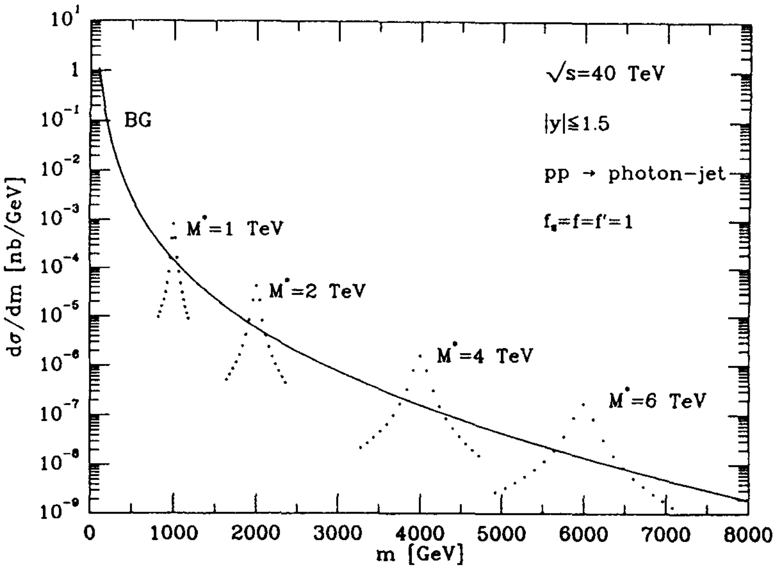

Fig. 3: *The same as in Fig. 2 for the photon-jet channel.*

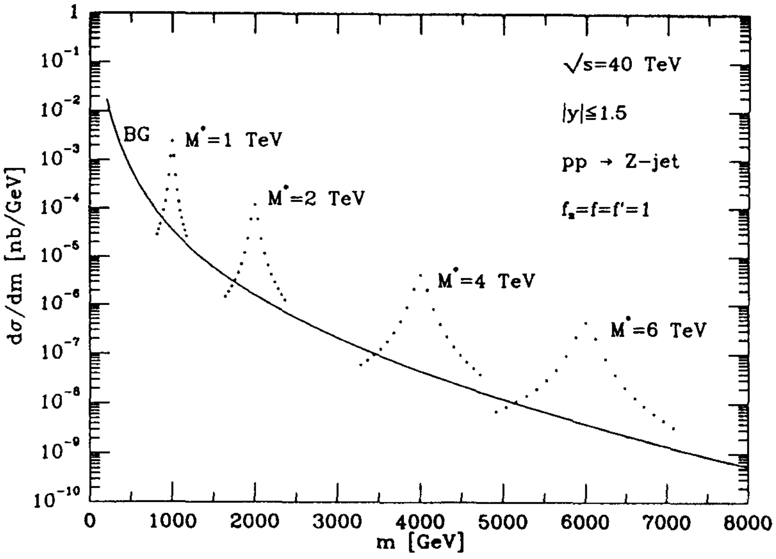

Fig. 4: *The same as in Fig. 2 for the Z-jet channel.*

the figures, whereas for $p\bar{p}$-collisions at $\sqrt{s} = 1.8\ TeV$ the signal to background ratio is generally somewhat worse than in the other two cases.

Finally, we would like to estimate the maximum excited quark mass accessible at hadron-colliders in a certain channel. As a discovery criterion we adopt the requirement that at least 100 signal events where the outgoing particles have a rapidity $\mid y \mid \leq 1.5$ are observed. Furthermore, we demand that the signal must constitute at least a 5σ effect. Since the rate for the channel $Q^* \to qZ \to q\ell^+\ell^-$ is, due to the small branching ratio for $Z \to \ell^+\ell^-$ (≈ 6 % for $\ell = e,\ \mu$), about one (two) order(s) of magnitude smaller and the signature is more complicated than that for the channel $Q^* \to \gamma q$ ($Q^* \to gq$), we shall restrict ourselves subsequently to the jet-jet and photon-jet case.

To arrive at realistic estimates we have to take into account the finite energy resolution $\delta E/E$ of the detector. In the following we shall assume that$^{10)}$

$$\frac{\delta E}{E} = \frac{0.1}{\sqrt{E}} + 0.01 \tag{16}$$

for photons and

$$\frac{\delta E}{E} = \frac{0.5}{\sqrt{E}} + 0.05 \tag{17}$$

for jets (E in GeV). Neglecting possible errors in the measurement of the jet-jet and photon-jet angle, the resolution $\delta m/m$ for the invariant mass of the jet-jet system is then between 14 % and 8 %, and between 10 % and 5 % in the photon-jet case if E is varied from 0.1 to 20 TeV. To estimate the background we integrate the invariant mass distribution of the background, $(d\sigma/dm)_{bg}$, over twice the Q^*-width or the invariant mass resolution, whatever is larger:

$$\sigma_{bg} \approx \int_{-M}^{M} dm\ (\frac{d\sigma}{dm})_{bg} \tag{18}$$

$$M = \max\{\Gamma(Q^*),\ \delta m\}\ . \tag{19}$$

Outgoing particles are again required to have a rapidity $|\ y\ | \leq 1.5$. Using the cross-sections of Fig. 1 and assuming an integrated luminosity of 10 pb^{-1} for the Tevatron and 10^4 pb^{-1} for the LHC and SSC, we present in Table 2 the maximum Q^*-mass accessible at the various colliders for $f_s = f = f' = \mathcal{F}$, $\mathcal{F} = 0.1$ and 1.

TABLE 2

Maximum excited quark mass M^* accessible at hadron colliders in the jet-jet and photon-jet channel for $f_s = f = f' = \mathcal{F}$. Final state particles are required to have a rapidity $|\ y\ | \leq 1.5$.

$\sqrt{s}$ $[TeV]$	$\mathcal{F}$	jet-jet	photon-jet
1.8, $p\bar{p}$	0.1	–	–
1.8, $p\bar{p}$	1	620 GeV	350 GeV
17, pp	0.1	2.3 TeV	1.2 TeV
17, pp	1	7.2 TeV	4.7 TeV
40, pp	0.1	3.7 TeV	1.7 TeV
40, pp	1	14.1 TeV	8.4 TeV

Hence the discovery limits for excited quarks are quite high if $\mathcal{F}$ is of order one. In this case, such particles could be observed at the SSC in the jet-jet channel with masses of up to 14 TeV, while the LHC would be only capable to see excited quarks with a mass less than ~ 7 TeV. The larger value of the center of mass energy of the SSC is thus directly reflected by the Q^* discovery limit. The Tevatron should be able to find excited quarks in the jet-jet channel for M^* values up to about 600 GeV if $\mathcal{F} = 1$. Of course, a peak in the invariant mass of jet pairs would not be specific for excited quarks but could as well signal e.g. the existence of a new heavy vector boson. A peak in the photon-jet invariant mass, on the other hand, would (almost) conclusively establish the existence of excited quarks. Although the signal to background ratio is more favorable in this case, the discovery limits are significantly weaker than for the jet-jet channel, due to the smaller rate.

As one can see from Table 2 the maximum mass accessible depends considerably on the value of $\mathcal{F}$. Varying $\mathcal{F}$ between 1 and 0.1 it drops by about a factor 3 to 4 for both the LHC and the SSC. To a large extend this is the consequence of the quadratic dependence of the cross-sections on the f's. Nevertheless, the discovery limits for $\mathcal{F} = 0.1$ are still significantly better than the ones expected for Q^* pair production (if both Q^*'s decay into jets: $\sim 2\ TeV$ ($1\ TeV$) at the SSC (LHC)[11] ; at least a factor two less if one the excited quarks decays into γq). At the Tevatron no useful limit on M^* can be established for $\mathcal{F} = 0.1$.

In summary, hadron colliders turn out to be very well suited for the search of excited quarks. Single Q^* production may be much larger than $\overline{Q^*}Q^*$ production and leads to clean and simple experimental signatures with a small background. This is fully reflected by the discovery limits for various hadron colliders summarized in Table 2.

ACKNOWLEDGEMENT

One of us (U.B.) would like to thank the Max-Kade-Foundation, New York, for financial support. This work was supported in part by the University of Wisconsin Research Committee with Funds granted by the Wisconsin Alumni Research Foundation, and in part by the Department of Energy under contracts DE-AC02-76ER00881 (D.Z.) and DE–AC03–76SF00098 (I.H.).

REFERENCES

1. For a review see e.g. Buchmüller, W., *Acta Physica Austriaca Suppl.* XXVII, 517 (1985);
   Peccei, R., DESY 86-010 (1986).
2. See e.g. Peskin, M.E., Proceedings of the 1981 Intern. Symp. on Lepton and Photon Interactions at High Energies, ed. W. Pfeil et al. pp. 880 (Bonn, 1981);
   Komamiya, S., Proceedings of the 1985 Intern. Symp. on Lepton and Photon Interactions at High Energies, Kyoto, August 1985, p. 612 (1985).
3. Kleiss, R. and Zerwas, P., to appear in the proceedings of the Workshop on "Physics at Future Accelerators", La Thuile (Val d'Aosta) and CERN, 7-13 January 1987.
4. Cabibbo, N., Maiani, L. and Srivastava, Y., *Phys. Lett.* 139B, 459 (1984).
5. DeRújula, A., Maiani, L. and Petronzio, R., *Phys. Lett.* 140B, 253 (1984).
6. Kühn, J. and Zerwas, P., *Phys. Lett.* 147B, 189 (1984).
7. Bars, I. and Hinchliffe, I., *Phys. Rev.* D33, 704 (1986).
8. Hagiwara, K., Komamiya, S. and Zeppenfeld, D., *Z. Phys.* C29, 115 (1985).
9. Duke, D.W. and Owens, J.F., *Phys. Rev.* D30, 49 (1984).
10. Angelopoulos, V. et al., CERN-TH 4682 (1987) and Proceedings of the Workshop on "Physics at Future Accelerators", La Thuile (Val d'Aosta) and CERN, 7-13 January 1987.
11. Eichten, E., Hinchliffe, I., Lane, K. and Quigg, C., *Rev. Mod. Phys.* 56, 579 (1984); Erratum 58, 1065 (1986).