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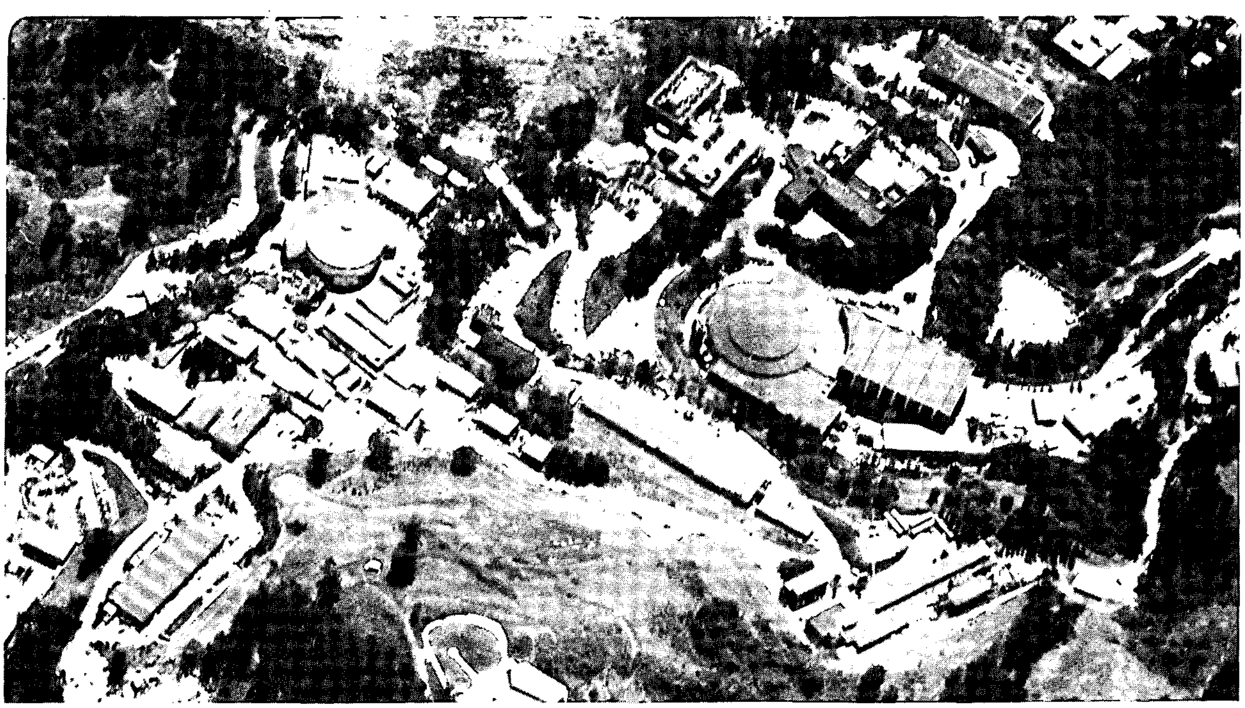

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DISCLAIMER

EXCITED QUARK PRODUCTION AT HADRON COLLIDERS

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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

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modes from Eq. (1). Assuming $M^*_- > m_{W,Z}$* and neglecting ordinary quark masses one obtains[5,6] $(V = W, Z)$

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

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

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

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 $f_s = f = f'$.

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* If M^* would be smaller than $m_{W,Z}$, excited quarks should have been seen at the CERN $p\bar{p}$-collider[8] or will be discovered at SLC/LEP.

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 $\mid y_{q',V} \mid \leq y_c$ is given by

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

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 $\mid y_{q',V} \mid \leq y_c$ 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.

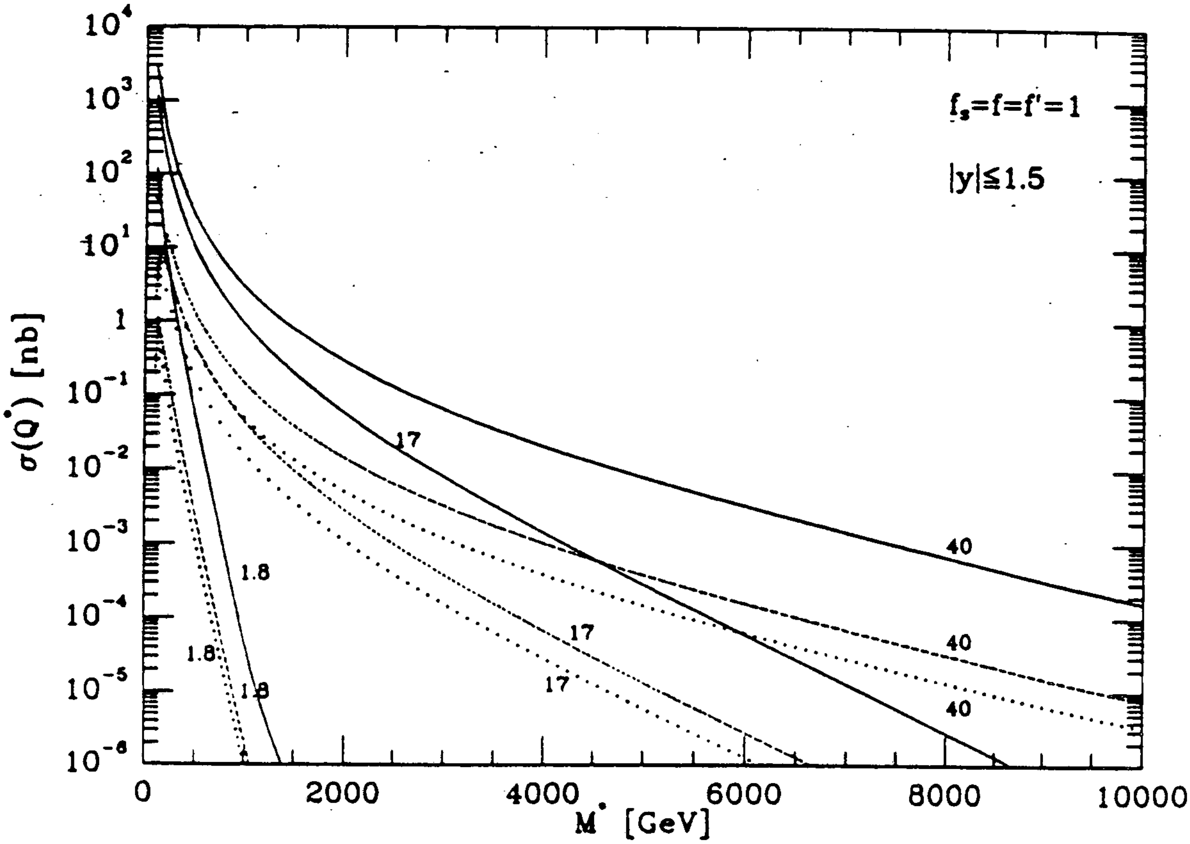

Fig. 1: *Single excited quark production cross-section in the jet-jet (solid lines), Z-jet (dashed lines) and photon-jet (dotted lines) channel. The numbers attached to the curves denote the $\sqrt{s}$ value in TeV.*

[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 $p\bar{p}$-

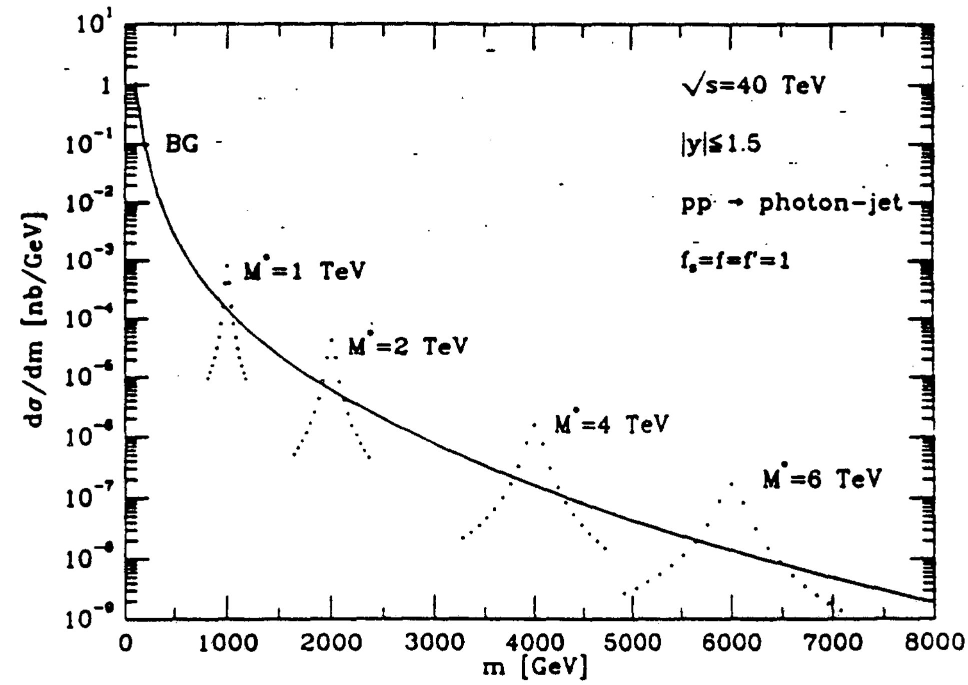

Fig. 3: *The same as in Fig. 2 for the photon-jet channel.*

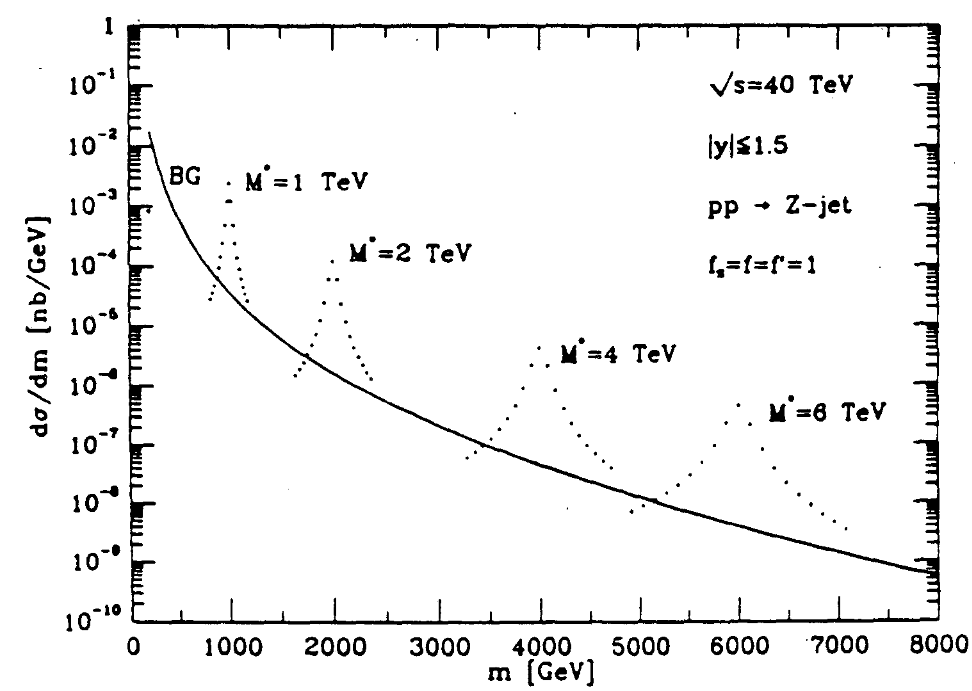

Fig. 4: *The same as in Fig. 2 for the Z-jet channel.*

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

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

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