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Excited Quark Production at Hadron Colliders

U. Baur, I. Hinchliffe, and D. Zeppenfeld

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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 leptons¹⁾ 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

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

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

$$\Gamma(Q^* \rightarrow \gamma q) = \frac{1}{4} \alpha f_7^2 M^*, \quad (3)$$

$$\Gamma(Q^* \rightarrow Vq) = \frac{1}{8} \frac{g_V^2}{4\pi} f_V^2 M^* \left(1 - \frac{m_V^2}{M^{*2}}\right)^2 \left(2 + \frac{m_V^2}{M^{*2}}\right). \quad (4)$$

Here

$$f_7 = f_{T_3} + f' \frac{Y}{2}, \quad (5)$$

$$f_Z = f_{T_3} \cos^2 \theta_W - f' \frac{Y}{2} \sin^2 \theta_W, \quad (6)$$

$$f_W = \frac{f}{\sqrt{2}}, \quad (7)$$

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 $M^* = 1 \text{ TeV}$ and $f_s = f = f'$.

* If M^* would be smaller than $m_{W,Z}$, excited quarks should have been seen at the CERN $p\bar{p}$ -collider⁸⁾ 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 $p\bar{p}/pp \rightarrow Q^* \rightarrow q'V$, $V = g, \gamma, W, Z$ where both outgoing particles have a rapidity $|y_{q',V}| \leq y_c$ is given by

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

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

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

with

$$\hat{\Gamma}(Q^* \rightarrow q'V) = \frac{f_V^2(m^2)}{f_V^2} \left[\frac{m}{M^*} \right]^3 \Gamma(Q^* \rightarrow q'V) \quad (11)$$

and

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

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

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

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 pp -

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.

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

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 $|y| \leq 1.5$.

$\sqrt{s} \text{ [TeV]}$	$\mathcal{F}$	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 $\sim 7 \text{ TeV}$. 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

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. Peakin, 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).

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