Brief Reports

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Searching for scalar-quarkonium at proton-antiproton colliders

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(Received 17 December 1984; revised manuscript received 14 March 1985)

We calculate the cross section for producing the $^1S_0$ bound state of the scalar quarks of supersymmetry $(\tilde{q}\,\tilde{q}^*)$ in $p\bar{p}$ collisions via two-gluon fusion for various scalar-quark masses.

Supersymmetry[1] predicts the existence of spin-zero partners for every quark, the scalar quarks $\tilde{q}$. In many models based on supergravity the natural scale for the masses of the scalar quarks is[2] ~ 100 GeV and they are expected to decay via $\tilde{q}\rightarrow q\tilde{\gamma}$, $q\tilde{g}$ very rapidly. The general form of the scalar-quark mass matrix[3] suggests that for very heavy quarks, e.g., the t quark, one component $(\tilde{q}_L,\tilde{q}_R)$ of the scalar quark might be lighter than the corresponding quark. (The stringent bounds on the mass difference between $\tilde{q}_L$ and $\tilde{q}_R$ from parity violation and flavor-changing neutral currents[4] are only applicable to the first two generations.) Thus, one could imagine a top quark decaying via $t\rightarrow\tilde{t}\,\tilde{\gamma}$, $\tilde{t}\,\tilde{g}$ at electromagnetic or strong rates, and a relatively long-lived $\tilde{t}$ with a decay pattern similar to that of the scalar neutrino[5] (two-body $\tilde{t}$ decays to $c\tilde{\gamma}$ via one-loop graphs or four-body decays such as $b\tilde{\gamma}\nu_e e^+$).

In this scenario the narrow resonances of the t-quarkonium system would be washed out by the large t decay width and the scalar-quarkonium $\tilde{t}\,\tilde{t}^*$ might be the next narrow bound state. Such scalar-quark bound states have been discussed by Nappi[6] and others.[7] Their detection in e^+e^- annihilations is difficult because they must be produced in a P wave and therefore have small leptonic widths. Narrow resonance searches provide lower bonds of only 3 GeV for $Q=+\frac{2}{3}$ scalar-quark masses.[6] Other searches at e^+e^- machines, assuming the decay $\tilde{q}\rightarrow q\tilde{\gamma}$, have looked for acoplanar jets and missing energy, and have set bounds[8] of $m_{\tilde{Q}}\gtrsim 18$ GeV. Collider data (i.e., the monojet sample), have been taken to imply[9] lower bounds of ~ 40 GeV for scalar-quark masses but these analyses also assume that the dominant decay mode is $\tilde{q}\rightarrow q\tilde{\gamma}$. If the decay $\tilde{q}\rightarrow q\tilde{g}$ is possible, such bounds are weakened. Moreover, in our case, the four-body decays can become comparable to the two-body photino modes (depending on the details of the supersymmetric-particle mass spectrum), which can also weaken the bounds.

The $^1S_0$ $\tilde{t}\,\tilde{t}^*$ scalar-quarkonium state (hereafter $\tilde{\eta}_t$) can couple to two gluons and so can be produced in $p\bar{p}$ collisions and detected by its subsequent decays to two photons in the same way as proposed[10–12] for the η_c, η_b, and η_t. In this Brief Report we discuss the production and detection of the $\tilde{\eta}_t$ in this manner and briefly discuss backgrounds.

We begin by calculating the cross section for two-photon production in hadron-hadron collisions via $gg\rightarrow\tilde{\eta}_t\rightarrow\gamma\gamma$ and find[13]

$$\frac{d\sigma}{dy}=\frac{K\pi^2}{8M_{\tilde{\eta}}^{\,3}}\Gamma(\tilde{\eta}_t\rightarrow gg)B(\tilde{\eta}_t\rightarrow\gamma\gamma)\tau f_g^A(x_A)f_g^B(x_B) \quad , \tag{1}$$

where x_A (x_B) and $f_g^A(x_A)$ $(f_g^B(x_B))$ are the gluon momentum fraction and gluon distribution function in hadron A (B) and x_A, x_B are related to the rapidity y by

$$x_A=\sqrt{\tau}e^{y},\quad x_B=\sqrt{\tau}e^{-y} \quad , \tag{2}$$

where $\sqrt{\tau}=M_{\tilde{\eta}}/\sqrt{s}$. K is a QCD enhancement factor due to higher-order corrections which we take equal to 2. The hadronic decay width of the $\tilde{\eta}_t$, $\Gamma(\tilde{\eta}_t\rightarrow gg)$, is half[6,7] that of the corresponding $q\bar{q}$ state (for the same mass $M_\eta=M_{\tilde{\eta}}$), i.e.,

$$\Gamma(\eta_t\rightarrow gg)=\frac{4}{3}\frac{\alpha_s^{\,2}}{M_{\tilde{\eta}}^{\,2}}4\pi|\psi(0)|^2=\tfrac{1}{2}\Gamma(\eta_t\rightarrow gg) \quad . \tag{3}$$

The $\gamma\gamma/gg$ branching ratio is the same as for ordinary quarks as it involves only group-theoretic factors, so that

$$B(\tilde{\eta}_q\rightarrow\gamma\gamma)=\Gamma(\tilde{\eta}_q\rightarrow\gamma\gamma)/\Gamma(\tilde{\eta}_q\rightarrow gg)$$
$$=9\alpha^2e_q^{\,4}/2\alpha_s^{\,2} \quad . \tag{4}$$

The usual quarkonium potential-model calculations[14,15] can then be used to derive the bound-state properties of the $\tilde{\eta}_t$ as a function of the $\tilde{t}$ mass. The mass $M_{\tilde{\eta}}$ should be taken to be at the center of gravity of the $^1S_0$ and $^3S_1$ masses in the $t\bar{t}$-system calculations. Relativistic corrections are expected to be small[16] for $m_{\tilde{t}}\gtrsim 20$ GeV. The potentials we consider take into account the logarithmic variation of α_s. Since the cross-section calculations depend on the $\tilde{\eta}_t$ wave function at the origin, our estimates depend very sensitively on the short-distance part of the confining potential. More singular potentials, such as the Cornell potential,[17] will give cross sections that are an order of magnitude larger than our results for heavy scalar quarks.[18]

In Table I we evaluate the differential cross sections for $\tilde{\eta}_t$ production, $(d\sigma/dy)|_{y=0}$, for various top-scalar-quark masses at $\sqrt{s}=540$ (2000) GeV. We use the quarkonium wave functions and masses of Ref. 14 and two different Q^2-dependent gluon distributions.[19,20] The total cross sections $\sigma(p\bar{p}\to\tilde{\eta}_t\to\gamma\gamma)$ are approximately 2 (4) times these values. These estimates suggest that detection of the $\tilde{\eta}_t$ at either the CERN SPS or Fermilab Tevatron with a reasonable luminosity (say 10^3 nb^{-1}), will be very difficult. As mentioned previously, however, uncertainties in the singular part of the confining potential can increase these rates by an order of magnitude, in which case one could probe 25 (40) GeV scalar-quark masses at the SPS (Tevatron). The cross sections for producing and detecting the $^1S_0$ bound state of $Q=-\frac{1}{3}$ scalar quarks of the same masses (the supersymmetric partners of a heavy fourth generation perhaps) would be down by a factor of 16.

The $\tilde{\eta}$ will decay predominantly into two gluons and occasionally the resulting two jets will both consist of a single π^0 or η^0 decaying electromagnetically. The charge multiplicity in quark jets deduced in e^+e^- experiments is roughly six at the highest current energies. The charge multiplicity in gluon jets is not expected to be much different. Thus the probability that a jet will have no charged particle is much less than 1% and the probability that a two-jet event will simulate a 2γ decay will be much less than Eq. (4). As the charge multiplicity increases with energy, this background should not be a problem for heavy $\tilde{t}$ scalar quarks. Two-photon production from $qq\to\gamma\gamma$ and $gg\to\gamma\gamma$ will also be a background. Berger, Braaten, and Field[21] have made a detailed study of the production of high-p_T double photons in $p\bar{p}$ collisions. We can use their results to estimate the differential cross section $(d^2\sigma/dm\,dy)|_{y=0}$, where y is the rapidity and m is the mass of the two-photon system. At $m=40$ (80) GeV corresponding to $m_{\tilde{t}}=20$ (40) GeV, we estimate that $(d^2\sigma/dm\,dy)|_{y=0}\simeq 0.3$ (0.02) pb/GeV at $\sqrt{s}=540$ GeV. Multiplying these values by a typical energy resolution of 1 GeV allows us to compare this background with the $\tilde{\eta}_t$ signal in Table I. With the potential models we have used we see that these processes will pose a severe background problem. On the other hand, for more singular short-distance potentials with $\tilde{\eta}_t$ signals an order of magnitude bigger, these backgrounds should be manageable.

Another, potentially larger source of background will come from ordinary QCD two-jet events. Such events have been observed at collider energies[22] and seem to agree well with theoretical expectations.[23] Using these results, we can estimate the relevant differential cross section to be $(d^2\sigma/dm\,dy)|_{y=0}\simeq 100$ (2) nb/GeV at $\sqrt{s}=540$ GeV for invariant masses of 40 (80) GeV. The probability that one jet will be misidentified as a photon because it lacks charged particles will be approximately $\exp[-\langle n_{\rm ch}(E)\rangle]$, where $\langle n_{\rm ch}\rangle$ is the average charge multiplicity. Using $\langle n_{\rm ch}\rangle\simeq 5$ (7) (Ref. 24), we estimate that two-jet events will contribute to the $\gamma\gamma$ background at a rate $(d^2\sigma/dm\,dy)|y=0 \simeq 4.5$ (0.002) pb/GeV, which is well below the direct 2γ background for heavier scalar quarks. Direct γ-jet production, while smaller in cross section by $O(\alpha/\alpha_s)$, needs only one jet to fluctuate to zero-charge multiplicity to mimic a 2γ event. We estimate its contribution to be $(d^2\sigma/dm\,dy)|_{y=0}\simeq 1.2$ (0.006) pb/GeV, which is larger than the contamination from two-jet processes for heavier scalar quarks but still below the direct $\gamma\gamma$ background.

TABLE I. The differential cross sections for $\tilde{\eta}_t$ production at $\sqrt{s}=540$ (2000) GeV using the gluon distributions of (a) Ref. 19, and (b) Ref. 20. The quarkonium parameters of Ref. 11 are used.

$m_{\tilde{t}}$ (GeV)	$\left(\frac{d\sigma}{dy}\right)\Big\vert_{y=0}^{(a)}$ (pb)	$\left(\frac{d\sigma}{dy}\right)\Big\vert_{y=0}^{(b)}$ (pb)
15	0.9 (6)	0.8 (5.9)
20	0.17 (1.3)	0.17 (1.3)
25	0.05 (0.5)	0.06 (0.45)
30	0.02 (0.22)	0.02 (0.17)
35	0.008 (0.12)	0.009 (0.08)
40	0.004 (0.06)	0.004 (0.04)

If a two-photon signal is seen in $p\bar{p}$ collisions, how does one distinguish between an $\tilde{\eta}_t$ and η_t interpretation? Given sufficiently precise gluon distributions and quarkonium potential models, measurements of the mass of the state fixes all parameters. The fact that η is produced twice as often as the $\tilde{\eta}$ (for the same mass), would then, in principle, be sufficient to distinguish between the two possibilities. The uncertainties in these inputs, however, make such a distinction based on absolute rates very difficult. For the $t\bar{t}$ system, one can also produce the χ_t (within a fraction of a GeV in mass of the η_t) via two-gluon fusion and detect its subsequent decay via $\chi_t\to\gamma\psi_t\to\gamma l^+l^-$ [at a rate smaller than for the η_t (Refs. 11 and 12)], while for the $\tilde{\eta}$ no such additional leptonic decays would be seen.

If the t quark is found to decay with the expected decay products and rate we then must infer that $m_t\lesssim m_{\tilde{t}} + m_{\tilde{\gamma}}(m_{\tilde{g}})$. A narrow scalar-quarkonium might still exist, however, if the t and $\tilde{t}$ were approximately degenerate in mass or if the photino (gluino) were massive. Such a spectrum, with both scalar quarks and the t quark at approximately 40 GeV, has been considered by Ellis and Sher,[24] who find it to be consistent with collider data and several popular supersymmetry models.

Finally, if a narrow $\tilde{t}\,\tilde{t}^*$ scalar-quarkonium exists and is lighter than the $^3S_1(t\bar{t})$ quarkonium then the $\tilde{\eta}_t$ can also be produced in the radiative process $^3S_1(t\bar{t})\to\tilde{\eta}_t+\gamma$ via diagrams with intermediate gluons or via gluino-exchange diagrams. The branching ratio for this process has been estimated to be possibly as large as 0.1%.[25]

In conclusion, we have discussed the production of the $^1S_0$ bound states of scalar quarks (especially but not exclusively in the context of supersymmetry), at $p\bar{p}$ colliders. We have argued that any collider searches for the expected η_t (however difficult they may be) can also produce suspected scalar-quarkonia at essentially the same rate but that the production rate for either type of heavy quarkonia depends sensitively on the short-distance part of the confining potential.

We both gratefully acknowledge conversations with S. Rudaz and the hospitality of the Lewes Center for Physics where this work was begun. This research was supported in part by the Department of Energy (P.M.) and the National Science Foundation (R.R.).

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