SEARCH FOR EXCITED QUARKS

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ABSTRACT

The Z boson has been found to decay surprisingly often into a hard photon and a lepton pair. Perhaps the only "conventional" explanation is the one that invokes the existence of excited leptons of mass 60 to 80 GeV. Perhaps excited quarks with masses of the same order of magnitude do also exist. In that case a hadron collider may produce them copiously in quark-gluon fusion and other processes. We investigate the production cross-sections and decay signatures of excited quarks.

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The UA1,2 collaborations at CERN's $\bar{p}p$ collider have made a serendipitous discovery: the Z boson decays into a lepton pair and a hard non-collinear photon with an unexpectedly large branching ratio: 3 "anomalous" versus 11 "conventional" lepton pair decays /1,2/. One of us (L.M.) is among those who can be blamed /3/ for the interpretation of the anomalous events as the decays of Z into a pair consisting of an excited and a normal lepton ($Z \rightarrow \ell^* \bar{\ell}$ or $\ell \bar{\ell}^*$, $\ell = e, \mu$), followed by electromagnetic de-excitation ($\ell^* \rightarrow \ell \gamma$). The greater of the two possible lepton-photon invariant masses is in all events in the 60-80 GeV range, within considerable errors (the smaller lepton-photon masses are too low to be interpretable as corresponding to excited leptons: they would be excluded by previous /4/ experiments).

Excited leptons and quarks are a naive prediction of "composite" models, and are expected to have large masses, of the order of their inverse radii, or the dimensionful parameter Λ characterizing the superstrong subconstituent binding forces. In these models, the lightness of the known quarks and leptons is attributed to a chiral global symmetry, broken only at the level of the standard $SU(2) \times U(1)$ interactions /5/.

The couplings of excited fermions to vector bosons and conventional fermions are of the transition-magnetic-moment type, with a form factor that would cure the apparent non-renormalizability of the effective theory.

In this framework, the main contribution to the masses of excited fermions is dynamical in origin: unrelated to the Higgs mechanism. Thus, the $SU(2) \times U(1)$ couplings of the excited fermions are expected to be vectorlike. Anomalies are nil and the level of flavour changing neutral currents is quite tolerable /3/.

Consider, for the sake of definiteness, the possibility that the "observed" heavy leptons be spin 1/2 weak isodoublets $L = (\nu^*, \ell^*)$. The coupling of vector bosons to a light-heavy pair of leptons is then of the form /3/:

$$\mathcal{L} = \frac{g f_2}{m} (\bar{\ell}^* \sigma_{\mu\nu} q^\nu \frac{\vec{\tau}}{2} \ell_L) \vec{W}^\mu + \frac{g' f_1}{m} (\gamma \bar{\ell}^* \sigma_{\mu\nu} q^\nu \ell_L) B^\mu \quad (1)$$

+ h.c.

where f_1 and f_2 are dimensionless transition magnetic moments, m is the excited lepton mass, $Y = -1/2$ for a lepton, and the rest of the notation is conventional in the standard model. To reproduce the observed $Z \rightarrow \ell^+ \ell^- \gamma$ branching ratio one needs to have $|f_2 \cos^2 \theta_W - f_1 \sin^2 \theta_W| \equiv \bar{F} \simeq 0.5$ /3/.

Should leptons have "sequential" partners, there is every reason (?) to expect quarks to have them as well. Let q^* denote an excited "starred quark", for brevity a "stark". For the sake of definiteness, assume starks to be spin 1/2, color triplet, weak isodoublets: $q^* = (u^*, d^*)$, etc..

The effective coupling of quarks (q) and gluons (g) to starks is then bound to be /6/:

$$\mathcal{L} = \frac{g_s f_s}{M} (\bar{q}^* \sigma_{\mu\nu} q^\nu \frac{\lambda^i}{2} q_L) g_\mu^i + h.c. \quad (2)$$

where g_s is the strong coupling constant, M is the stark mass, f_s is a strong transition magnetic moment and the rest of the notation follows standard QCD conventions. Notice that we have made Eq(2) SU(2) invariant by coupling q^* to q_L , also a weak doublet (f1).

As a guideline we shall scale our predictions to a "reference" expectation: that f_s is of the same magnitude as its leptonic analog $\bar{F} \simeq 0.5$, "measured" in Z decays.

This has an immediate consequence: since a hadron collider is, among other things, a quark-gluon collider, and since starks can be effectively produced by quark-gluon "fusion" (Fig.1a), a hadron collider is a "stark factory", able to copiously produce /6/ excited quarks with masses up to a good fraction of $\sqrt{s}$.

The width of the stark resonance can be computed from Eq(2) to be:

$$\begin{aligned} \Gamma &\cong \Gamma(q^* \rightarrow q \bar{q}) = \frac{1}{3} \alpha_s (f_s)^2 M = \\ &\simeq 0.5 \text{ GeV} (2 f_s)^2 \left(\frac{M}{60 \text{ GeV}} \right) \end{aligned} \quad (3)$$

where we have taken $\alpha_s \simeq 0.1$. Eq.(3) indicates that starks, for our guideline choice $2 f_s \simeq 1$, may be narrower than the experimental resolution of the decay channels in which we shall propose to search for them. A stark can also decay electromagnetically: $q^* \rightarrow q \gamma$, or, if it is heavy enough, into a quark and an intermediate vector boson.

Let $V = \gamma, W, Z$, and let μ be the mass of V . The $(q^* q V)$ couplings are as in Eq.(1), with the substitutions $(f_1, f_2, m, \ell^*, \ell) \rightarrow (f_1^*, f_2^*, M, q^*, q)$ and $Y = 1/6$.

The branching ratios for stark decay into vector bosons are:

$$\frac{\Gamma(q^* \rightarrow q V)}{\Gamma(q^* \rightarrow \text{all})} = \frac{3 \alpha}{4 \alpha_s} \left(\frac{f_V}{f_s} \right)^2 \left(1 - \frac{\mu^2}{M^2} \right)^2 \left(1 + \frac{\mu^2}{2 M^2} \right) \quad (4a)$$

$$f_\gamma = \frac{\tau_3}{2} f_2^* + \frac{1}{6} f_1^* \quad (4b)$$

$$f_z = \frac{c}{s} \frac{\tau_3}{2} f_2^* - \frac{1}{6} \frac{s}{c} f_1^* \quad (4c)$$

$$f_w = \frac{1}{\sqrt{2} s} f_2^* \quad (4d)$$

where $c = \cos \theta_w$, $s = \sin \theta_w$.

Should starks be lighter than intermediate vector bosons, the branching ratios for the decays $W, Z \rightarrow q^* \bar{q}$ are also of interest. Normalized to conventional leptonic decays, they are

$$\frac{\Gamma(W^+ \rightarrow u^* d)}{\Gamma(W^+ \rightarrow e^+ \nu)} = 3 (f_2^*)^2 \left(1 + \frac{\mu^2}{2M^2}\right) \left(1 - \frac{M^2}{\mu^2}\right)^2 \quad (5a)$$

$$\frac{\Gamma(Z \rightarrow u^* \bar{u} + u \bar{u}^*)}{\Gamma(Z \rightarrow e^+ e^-)} = \frac{6 (f_2^* c^2 - f_1^* s^2/3)^2}{1 - 4s^2 + 8s^4} \left(1 + \frac{\mu^2}{2M^2}\right) \left(1 - \frac{M^2}{\mu^2}\right)^2 \quad (5b)$$

$$\frac{\Gamma(Z \rightarrow d^* \bar{d} + d \bar{d}^*)}{\Gamma(Z \rightarrow e^+ e^-)} = \frac{6 (f_2^* c^2 + f_1^* s^2/3)^2}{1 - 4s^2 + 8s^4} \left(1 + \frac{\mu^2}{2M^2}\right) \left(1 - \frac{M^2}{\mu^2}\right)^2 \quad (5c)$$

The expression for the $W^+ \rightarrow u \bar{d}^*$ branching ratio coincides with Eq.(5a). We now proceed to discuss stark signatures.

The most obvious and copious signature for stark production is a peak in the two-jet invariant mass M_{jj} , corresponding to the subprocess $qg \rightarrow q^* \rightarrow qg$, see Fig.1b. Realistically assume that

in the search for a peak, experimental cuts are made in the transverse momentum and pseudorapidity of both jets ($p_t^j > p_t$, $\eta^j < \eta$). To leading order in α_s , the cross section for the signal is:

$$\frac{d\sigma(q^*)}{dM_{jj}^2} = \mathcal{N} \int_0^{z_M} \frac{dz}{\sqrt{z^2 + 4\tau}} \left\{ q(x_1, M^2) g(x_2, M^2) + x_1 \leftrightarrow x_2 \right\} \times \quad (6a)$$

$$\times \sum (C_M)$$

$$\mathcal{N} = \frac{2\pi d_s f_s^2}{3s} \frac{M \Gamma}{(M_{ij}^2 - M^2)^2 + M^2 \Gamma^2} \simeq \frac{2\pi^2 d_s}{3s} \int_s^2 \delta(M_{ij}^2 - M^2) \quad (6b)$$

$$\sum (C_M) = \frac{1}{4} C_M (3 + C_M^2) \quad (6c)$$

$$x_{1,2} = \frac{1}{2} \left(\sqrt{z^2 + 4\tau} \pm z \right) \quad (6d)$$

$$C_M = \min \left\{ \sqrt{1 - \frac{4p_T^2}{M^2}} ; \frac{x_2 e^{2\eta} - x_1}{x_2 e^{2\eta} + x_1} \right\} \quad (6e)$$

$$z_M = \min \left\{ 1 - \tau ; 2\sqrt{\tau} \sinh \eta \right\} ; \quad \tau = \frac{M^2}{s} \quad (6f, g)$$

In the above expressions $g(x, M^2)$ and $q(x, M^2)$ are renormalization group improved structure functions for gluons and for the

quark whose stark is q^* . The $p\bar{p}(pp)$ center of mass energy is $\sqrt{s}$. $\sum(c_M)$ is the probability that q^* decays within the range $|\cos\theta| < c_M$ in its own rest frame ($d\sum/d\cos\theta = 3(1+\cos^2\theta)/8$). In Fig.2a we plot $d\sigma/dM_{jj}$ in nanobarns/(10 GeV), as a function of M_{jj} . A potential stark signal would be a narrow peak of width Γ , centered at $M_{jj}=M$. In the figure we have spread the expected signal over an assumed experimental width $\Delta M_{jj}=10 \text{ GeV} > \Gamma$, for various choices of M , $M=50, 70 \dots 150 \text{ GeV}$. The signal is computed from Eqs(6) with $f_g=1/2$, $\gamma=0.8$, $p_t=15 \text{ GeV}$. The $(u^* + \bar{u}^*)$ signal is about twice as large as the $(d^* + \bar{d}^*)$ signal at the same value of M , since the up constituency in a proton is roughly twice the down constituency. The continuous curve is the QCD background (f2) for two-jet production, computed with the same "experimental" cuts and structure functions /8/. The vertical scale to the right of Fig.2a is the number of events corresponding to the present UA1 integrated luminosity of 137 nb^{-1} . The figure shows that the background is severe, but not forbidding. For example, an $M=70$ (110)GeV u^* -signal would correspond to 500 (50) events on a background of 5000 (300) events: an effect of 7(3) standard deviations.

The second stark signal we consider is a peak in the photon-jet invariant mass $M_{\gamma j}$, corresponding to the subprocess $qg \rightarrow q^* \rightarrow q \gamma$, see Fig.(1c).

The signal cross section is:

$$\frac{d\sigma}{dM_{\gamma j}} = BR(q^* \rightarrow q \gamma) \frac{d\sigma(q^*)}{dM_{jj}} \quad (7)$$

with the branching ratio given by Eqs(4a, b). To be specific we compute the signal for "non anomalous" transition magnetic moments ($f_1^* = f_2^*$, $f_\gamma = Qf^*$) assumed to be of the same magnitude as their leptonic counterparts ($f^* \simeq 1/2$). In Fig.2b we show the $u^* + \bar{u}^*$ and $d^* + \bar{d}^*$ signals in $d\sigma/dM_{\gamma j}$ with "experimental" cuts on a photon and a jet that are identical to the ones we applied to the two-jet signal. We have spread the narrow signals over an assumed resolution $\Delta M_{\gamma j}=5 \text{ GeV}$. We have also computed and plotted

the QCD background /9/, shown in Fig.(2b) as a continuous line in units of nb/5 GeV. Though both signal and background in $d\sigma/dM_{\gamma j}$ are down by $O(\alpha/\alpha_s)$ relative to their values in $d\sigma/dM_{jj}$, the signal/noise ratio is better in the photon-jet channel. The main reason is that there are fewer QCD-background subprocesses in the (γj) than in the (jj) channel. The signal for d^* production and electromagnetic de-excitation is roughly a factor 8 smaller than for u^* , a factor 2 for quark constituency times 4 for the ratio of squared charges. The figure shows that the signal/noise level is extremely favourable: unlike in the jet-jet channel setting limits on stark production and electromagnetic decay is more a question of luminosity than resolution.

Next, we study stark signals in events with three jets or two jets and a photon in the final state. Consider first the possibility that starks may be lighter than the Z, or both the Z and the W. Starks are then efficiently made in the decays of these particles, with the branching ratios of Eqs(5). Once made, they may decay strongly or electromagnetically, as in Figs (1e-f). This leads to the signatures we are discussing: a localized enhancement in a plot of $M(j_1 j_2 j_3)$ versus $M(j_\alpha j_\beta)$ in the case of a strong stark decay, a similar enhancement in $M(j_1 j_2 \gamma)$ versus $M(j_\alpha \gamma)$ in the electromagnetic case. The enhancement is in both cases at the point $\{M_W \text{ (or } M_Z), M(q^*)\}$. It is likely that the masses of u^*, c^*, d^* and s^* starks are degenerate within the accuracy of the invariant mass plots we are discussing. In that case the branching ratio for $W \rightarrow q^* \bar{q} + q \bar{q}^*$ normalized to $W^+ \rightarrow e^+ \nu$ is four times that of Eq.(5a). This branching ratio is shown in Fig.2a for $f_2^* = 1/2$: it directly allows one to estimate the number of expected 3 jet events given the experimental number of $W \rightarrow e \nu$ events (a grand total of four score plus events at the time of writing). For $M \lesssim 70$ GeV the expected events are many: 100(30) for $M=60(70)$ GeV.

Similarly, we expect the branching ratio for $Z \rightarrow q^* \bar{q}$ or $q \bar{q}^*$ versus $Z \rightarrow e^+ e^-$ to be twice the sum of Eqs (5b) and (5c). This branching ratio, for $f_1^* = f_2^* = 1/2$ is also shown in Fig.3a and,

for $M \lesssim 80$ GeV, it corresponds to a considerable number of expected 3-jet events: 10 $Z \rightarrow e^+e^-$ events have been collected so far, corresponding to 54 (26) expected $Z \rightarrow q^*q \rightarrow jjj$ events, for $M = 60(70)$ GeV.

We have not computed the QCD 3-jet background in an $M(j_1j_2j_3)$ versus $M(j_\alpha j_\beta)$ plot. For the large masses we are considering, and barring accidental degeneracy between starks and intermediate bosons, we expect the QCD background to be negligible. The reason is that the signal is of order α and concentrated in a single two-dimensional bin, while the background is of order α_s^3 and is spread and peaked at low masses. The number of $(jj\gamma)$ events, mediated by either W or Z is (for $f_1^* = f_2^*$), approximately $5\alpha/24\alpha_s \approx 1.5\%$ of the number of (jjj) events.

To give a couple of examples, for $M = 60(70)$ GeV we expect a total of 1.5(0.5) $W \rightarrow q^*q \rightarrow jj\gamma$ events, and a total of 0.8 (0.4) $Z \rightarrow q^*q \rightarrow jj\gamma$ events in past UA1+UA2 running. Not many, but fairly striking, and again expected to stand against no background.

Finally we consider the possibility that starks be heavier than intermediate vector bosons. In that case the decays $q^* \rightarrow qW$ or qZ , followed by $W, Z \rightarrow q\bar{q}$, would also constitute spectacular 3-jet events with a peak at $\{M(jjj)=M, M(j_\alpha j_\beta)=M(W/Z)\}$. A small fraction of events with vector boson leptonic decay may be even more spectacular i.e. $q^* \rightarrow qW \rightarrow \text{jet } \ell\nu$, not to speak of $q^* \rightarrow qZ \rightarrow \text{jet } \ell^+ \ell^- \gamma$!

The rate of $q^* \rightarrow qW, qZ$ events may be estimated (without paying too much attention to experimental cuts) by multiplying the stark production cross sections of Eqs(6) and Fig.2 by the branching ratios of Eqs(4), that we have plotted in Fig.(3b) for our guideline choice $f_2^* = f_1^* = 0.5$. For $M=100$ (120 GeV) and with the present UA1 luminosity, we estimate 1.7 (1.5) events of the type $u^* \rightarrow dW$ and $6 \cdot 10^{-2}$ (0.3) events of either type $u^*, d^* \rightarrow qZ$. Again, barring accidental stark-vector boson degeneracy, these three-jet events would be few, but striking and background-free.

Suppose we believe that excited leptons with $M \simeq 70$ GeV have been found, and that excited quarks with similar masses will be found. In that case we are having a first glimpse into a new substructure, a situation similar to the discovery of non-trivial nucleon form factors. We may anticipate that somewhat above (twice ?) the mass scale of the excited fermions one may be sensitive to the presence of the "harder" subconstituents. Possible signatures above this new threshold (glints) have been discussed by one of us /10/. Pre-threshold signatures have been studied in Ref.(11,6,12).

To summarize, we have argued that stars of mass $M \lesssim \sqrt{s}/4$ may be copiously produced at a hadron collider. The star search in jet-jet invariant mass distributions is limited by resolution, but not by yield. In a jet-photon invariant mass plot, the contrary is the case. We expect very small background, and considerable signals, in star searches via three-jet versus two-jet invariant mass plots. In similar plots for events wherein a jet is substituted for a photon, stars would produce scarcer but even more striking signals.

It goes without saying that our "theory" of stars may be wrong. Their quantum numbers could differ from the ones we have assumed for the sake of definiteness. Star couplings could be bigger or smaller than the ones we have scaled to scarce and wildly interpreted "data on excited leptons". Modifications of our assumptions could affect our star expectations either way. All we are suggesting are a few ways that could be fruitful to analyze existing data. After all, in experimental physics, one of the ways to find something is to look for it.

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- Footnotes -

- (f1) We do realize that in writing Eq.(2) have introduced a new source of parity violation in nuclear physics. The new effect is of order $\alpha_s f_s^2 / M^2$, to be compared with the standard effects of order $\alpha / (M_W^2 \sin^2 \theta_W)$. For M comparable to M_W , we do not expect this new effect to be worrisome.
- (f2) We have only included in our calculation the QCD subprocesses leading to two gluon jets or a gluon and a quark jet. These are known to be the dominant QCD contributions at high p_t /7/. We have also checked that our quark distribution reproduces the observed W-production cross section.

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- Figure Captions -

- 1) A diversity of stark production and decay processes discussed in text.
- 2) Stark signals and QCD background in invariant mass plots of: (a) jet-jet events; (b) jet-photon events. Notice that $d\sigma/dM_{jj}$ is in units of nb/(10 GeV) and $d\sigma/dM_{\gamma j}$ in units of nb/(5 GeV).
- 3) (a) Normalized branching ratios for $Z \rightarrow q^* q \rightarrow 3$ jets and $W \rightarrow q^* q \rightarrow 3$ jets as a function of stark mass M ; (b) Branching ratios for stark decays into vector bosons as functions of M . The $d^* \rightarrow dW$ branching ratio coincides with the $u^* \rightarrow dW$ one, shown in the figure.

Fig. - 1 -

Fig.-2-

Fig.-3-