LIGHT LEPTOQUARKS

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The case is made for light spinless leptoquarks of the Goldstone boson type ($m \ll G_F^{-1/2}$) in the framework of nearby compositeness and special technicolor schemes. Their expected experimental signatures are worked out in the light of recently observed anomalous events of the type μ^+-jet–μ^--jet, monojet and monophoton.

Leptoquarks are rather exotic bosons which couple to a lepton–quark pair, i.e. they are color triplets, have fractional charge and both nonvanishing baryon and lepton number. They may appear in grand unified theories [1] [$m \gtrsim O(10^{14}$ GeV)], in "petite" unified gauge theories [2] like $SU(2)_L \times SU(2)_R \times SU(4)_{Pati-Salam}$, in technicolor schemes [3] and in composite models [4–8] (conservatively: $m \sim$ few 100 GeV–few TeV), i.e. in a variety of popular schemes leading beyond the standard model.

In this paper we first single out schemes which (i) allow leptoquarks to be *naturally light*, even considerably lighter than the Fermi scale $\Lambda_F = (\sqrt{2}G_F)^{-1/2} \sim 250$ GeV, and (ii) at the same time avoid (more or less) *naturally* conflict with proton lifetime and rare processes like those involving flavor changing neutral currents. Then we work out the expected experimental signatures of light leptoquarks in the light of anomalous events observed both with the CELLO detector [9] at PETRA and with the UA1/UA2 detectors [10–12] at the CERN p̄p collider. Events of the type "μ^+jet μ^-jet" as well as "monojets" and "monophotons" are of particular interest. Some of the results in the second part, though obtained independently, come later than those of ref. [13]. In order to minimize overlap with ref. [13], we shall concentrate on complementary information and on deviations due to the difference in theoretical input.

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We start by arguing that a possible natural source of light leptoquarks is nearby compositeness. In this scenario [14,4–8] quarks and leptons as well as $W^\pm$, Z are considered to be composites of a common set of preons which are subject to hypercolor confinement at the Fermi scale $\Lambda_F \sim 250$ GeV. Since quarks carry color, there will have to be colored preons. Hence, quite generally, colored composite bosons, i.e. colored spin 0 and spin 1 partners of the weak $W^\pm$, Z bosons, are expected. (With color acting like a flavor at distances Λ_F^{-1} [$\alpha_c(\Lambda_F) \sim 0.1$], this expectation is on similar footing as predicting strange baryons from the existence of strange K mesons in strong interactions).

A prominent possible source of colored bosons of the leptoquark type is the class of Abbott- and Farhi-initiated composite models [4–8] which (in the limit $\alpha, \alpha_c \to 0$) are distinguished by the *global* symmetry

$$SU(2)_{WI} \times \underbrace{SU(4)_L^{PS}}_{} \supset [SU(3)_c \times U(1)_{B-L}]_L \quad (1)$$

of weak interactons. Here $SU(2)_{WI}$ is the global weak isospin and $SU(4)^{PS}$ the Pati–Salam SU(4), unifying $SU(3)_c \times U(1)_{B-L}$ for $\alpha, \alpha_c \to 0$. The index L indicates restriction to that part of the group which acts on left-handed fermions only [remember $Y_L = (B-L)_L/2$].

As has been pointed out recently [7,8], in this class of models one is led to expect besides the standard $SU(2)_{WI}$ triplet of (composite) $W^{\pm,0}$ bosons an $SU(4)^{PS}$ 15-plet of new (composite) vector bosons. Among them are also spin 1 leptoquarks V_3, transforming like color triplets with electromagnetic charge 2/3. We shall briefly return to these at the end.

Our main concern in this paper is to point out that the global $SU(4)^{PS}$ symmetry, in addition to being broken explicitly through color and electromagnetic gauge interactions, could also be broken *spontaneously* at the scale of hypercolor confinement, $\Lambda_F \sim 250$ GeV,

$$SU(4)^{PS} \xrightarrow{SSB} SU(3)_c \times U(1)_{B-L} . \qquad (2)$$

This would lead to a (complex) *Goldstone boson* multiplet χ, an $SU(2)_{WI}$ singlet spinless *leptoquark* with the same color and electromagnetic assignments as its vector partner V_3,

$$\chi = 3_{2/3} . \qquad (3)$$

These Goldstone bosons are of course pseudo-Goldstone bosons; they typically will acquire a color-radiative mass of order [15]

$$m_\chi \sim O(\sqrt{\alpha_c/\pi}\,\Lambda_F) \sim O(40 \text{ GeV}) \qquad (4)$$

(give or take a factor of two).

An important ingredient of composite models is that hypercolor confinement does not give rise to a *total* spontaneous breakdown of the chiral symmetry present on the fermionic preon level, in order to retain a chiral protection mechanism against large quark and lepton masses [16]. Partial breaking, however, may well occur and actually is often *enforced* by the non-existence of solutions to 't Hooft's anomaly matching equations [16] with respect to the full chiral symmetry group. In the original Abbott and Farhi model [4] there is no need for a spontaneous breakdown of the $SU(4)^{PS}$ symmetry from the point of view of anomaly matching. There are, however, extensions [5] of this model, designed to cure its two main unsatisfactory features, the naturality problem with elementary scalar preons and the fact that only the left-handed quarks and leptons are composite; in these extended models 't Hooft's anomaly matching conditions indeed enforce exactly the spontaneous breakdown (2).

In conclusion, in nearby compositeness the appearance of a spontaneously broken global $SU(4)^{PS}$ is not unlikely; this in turn would naturally entail spinless leptoquarks much lighter than the Fermi scale. There is no problem with baryon number violation, since in fact the $SU(4)^{PS}_L$ symmetry arises from an $U(4)^{PS}_L$ symmetry. The additional $U(1)_F$ symmetry of left-handed fermion number, giving rise to separate baryon and lepton number conservation ($B_L = \frac{1}{4}F + \frac{1}{2}Y_L$, $L_L = \frac{1}{4}F - \frac{3}{2}Y_L$), is broken only by hypercolor instantons. As worked out in ref. [4], these violations are far from being in conflict with present limits on the proton lifetime.

Another well-known source of pseudo-Goldstone bosons of the leptoquark type resides in technicolor schemes where some of the techniquarks carry color [3]. The standard estimate for their masses is $O(\sqrt{\alpha_c/\pi} \times \Lambda_{TC}) \sim O(200 \text{ GeV})$ for $\Lambda_{TC} \sim 1$ TeV. However, let us recall the interesting class of technicolor schemes involving a *gauged chiral color* symmetry [15] (i.e. the usual vectorlike color group is embedded in a gauged $SU(3)^c_L \times SU(3)^c_R$ group). In this case the color-radiative mass of the colored Goldstone bosons vanishes to leading order in α_c, leading again to exceptionally light spin 0 leptoquarks with mass of O(45 GeV).

In the schemes considered (nearly compositeness or technicolor with chiral color) light leptoquarks may generally appear as $SU(2)_{WI}$ singlets, doublets or triplets, with a corresponding variety of electromagnetic charges. To be specific, let us concentrate in the following on the minimal Goldstone boson multiplet (3), due to the spontaneous breakdown of $SU(4)^{PS}$ only, which is likely to appear in any scheme producing Goldstone boson leptoquarks at the Fermi scale. An extension of the following discussion to any further Goldstone boson leptoquark is straightforward.

Leptoquarks of the Goldstone boson type as discussed here have several favorable properties as compared to those of the Higgs type put forward in ref. [13]: (i) they have naturally small masses, (ii) the limits on the proton lifetime are automatically respected and (iii) their weak interaction coupling to a quark–lepton pair is small without fine tuning, as we shall see below.

Leptoquarks experience three types of interactions, just like quarks. They couple *weakly* to a quark–lepton pair and they experience ordinary *color* and *electromagnetic* gauge interactions.

The leading $\chi\bar{q}\ell$ interaction term in the effective weak interaction lagrangian which realizes the $SU(4)_L^{PS}$ symmetry non-linearly [and respects $SU(2)_{WI}$ symmetry] involves the familiar dimension-5 operator

$$\mathcal{L}_{\chi\bar{q}\ell} \sim [O(1)/F_\chi]\,\{\bar{q}_L \gamma^\mu \ell_L \partial_\mu \chi + \text{h.c.}\} + O(1/F_\chi^2). \tag{5}$$

Summation over color and $SU(2)_{WI}$ indices is implied. F_χ is the χ decay constant

$$F_\chi \sim O(\Lambda_F) \sim O(250\ \text{GeV}). \tag{6}$$

On the tree level this induces the familiar Goldberger–Treiman type [17] couplings of χ to a fermion pair,

$$\mathcal{L}_{\chi\bar{q}\ell} \sim O(1)\bar{q}\,\{(m_q - m_\ell)/F_\chi + [(m_q + m_\ell)/F_\chi]\gamma_5\}\,\ell\chi + \text{h.c.}, \tag{7}$$

giving rise to a decay width

$$\Gamma(\chi \to q\bar{\ell}) \sim [O(1)/4\pi]\, m_\chi (m_q^2 + m_\ell^2)/F_\chi^2 \quad (\text{for } m_\chi \gg m_{q,\ell}). \tag{8}$$

In the chiral limit, $m_{q,\ell}/F_\chi \to 0$, the fermions decouple. For finite, but small (current) quark and lepton masses, a *natural strong suppression of the weak interactions* of Goldstone boson leptoquarks results. This is of course what is needed to accommodate the conspicuous absence of contributions from light spin 0 leptoquark exchanges in low-energy weak interactions, in particular in potentially dangerous rare processes like μe conversion, $K_L^0 \to e^+\mu^-$ and $K_L^0 \to \mu^+\mu^-$. A quantitative evaluation, basing on the formulae of ref. [18], shows that the small mass ratios $m_{q,\ell}/F_\chi$ in the $\chi\bar{q}\ell$ couplings are almost sufficient. The O(1) coefficient in the estimates (5)–(8) has to be replaced by O(0.1), more precisely by 0.16 for $m_\chi \sim 40$ GeV and by 0.08 for $m_\chi \sim 20$ GeV. This is marginal, but still far from the stigma of fine tuning. For these estimates we used current quark masses [‡1], since weak interactions take place at short distances, $O(G_F^{1/2})$.

Next let us discuss the issue of generations. Typical for technicolor is a single χ-type leptoquark, coupling to all $q\bar{\ell}$ pairs with charge 2/3. Following the rule (7), χ will predominantly decay into $t\bar{\nu}_\tau$ (or into $b\tau^+$ if $m_\chi < m_t + m_{\nu_\tau}$). This may be and presumably will be different in nearby compositeness. There all three, the leptoquarks, the quarks and the leptons share the same level of compositeness (in contradistinction to technicolor. Generational selection rules for leptons, like $\mu \not\to e\gamma$, may have their origin on the level of preons which are common to leptons and leptoquarks. This in turn would translate into a generational selection rule for leptoquarks. (For a discussion of generational selection rules in composite models in the context of rare decays we refer to ref. [20].) A realistic possibility in the nearby-compositeness framework then is the existence of three leptoquarks $\chi^{(1)}$, $\chi^{(2)}$ and $\chi^{(3)}$, one per generation, each one decaying into the two lepton–quark pairs of its own generation with $Q = 2/3$,

$$\chi^{(1)} \to u\bar{\nu}_e,\ de^+, \tag{9a}$$

$$\chi^{(2)} \to c\bar{\nu}_\mu,\ s\mu^+, \tag{9b}$$

$$\chi^{(3)} \to t\bar{\nu}_\tau,\ b\tau^+. \tag{9c}$$

In this case there is no leptoquark exchange in μe conversion and $K_L^0 \to e^+\mu^-$. The only limits come, via Cabibbo mixing, from $K_L^0 \to \mu^+\mu^-$, requiring a replacement of the O(1) coefficient in eqs. (5)–(8) by

$$O(1) \to \sim 0.4 \quad \text{for } m_\chi \sim 40\ \text{GeV}, \qquad \sim 0.2 \quad \text{for } m_\chi \sim 20\ \text{GeV}. \tag{10}$$

This is of the order of $1/\pi$ and even less dramatic than the replacement by O(0.1) required above.

The best way to detect low mass spin 0 leptoquarks, *unhampered* by their small weak interaction couplings, is via *pair production*, either in $e^+e^- \to \chi\bar{\chi}$ through electromagnetic gauge interactions or in $\bar{p}p \to \chi\bar{\chi}$ through color gauge interactions (see fig. 1a,b). Depending on whether the subsequent $\chi, \bar{\chi}$ decays go via the charged lepton mode, $\chi \to q_{-1/3}\ell^+$, or via the neutrino mode, $\chi \to q_{2/3}\bar{\nu}$, one expects three possible final state signatures

$$\text{jet} + \ell^+ + \text{jet} + \ell^-, \tag{11a}$$

$$\text{jet} + \ell^\pm + \text{jet} + p_T^{\text{miss}}, \tag{11b}$$

$$\text{jet} + \text{jet} + p_T^{\text{miss}}. \tag{11c}$$

‡1 This is perfectly consistent in nearby compositeness. Internal consistency problems in technicolor schemes lead to choices like e.g. m_{fermion} as large as 1 GeV in ref. [18]. Following ref. [19], we advocate a dismissal of the problematic fermion-mass generating mechanism through extended technicolor gauge bosons as rescue for the original nice technicolor idea.

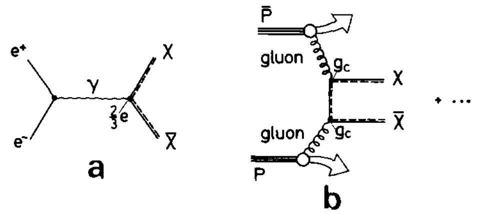

Fig. 1. Leptoquark pair production (a) in e^+e^- through electromagnetic gauge interactions, (b) in $\bar{p}p$ in the dominant gluon–gluon subprocess through color gauge interactions.

The only unknowns in the cross sections are the χ mass and its branching ratios.

The cleanest signals for leptoquarks are anomalous events of the type "jet ℓ^+jet ℓ^-". One such event with $\ell^\pm = \mu^\pm$ has been seen by CELLO at PETRA [9] and recently two strikingly similar ones by UA1 at the CERN $\bar{p}p$ collider [10]. It is of course tempting to interprete these three events as signatures of spinless leptoquarks of the Goldstone boson type (see also ref. [13]),

$$\left.\begin{matrix} e^+e^- \\ \bar{p}p \end{matrix}\right\} \to \underset{\hookrightarrow q\mu^+}{\chi} + \underset{\hookrightarrow \bar{q}\mu^-}{\bar{\chi}} \to \text{jet}\,\mu^+\text{jet}\,\mu^- . \qquad (12)$$

Let us follow up this intriguing but speculative possibility. A first consistency check is contained in fig. 2.

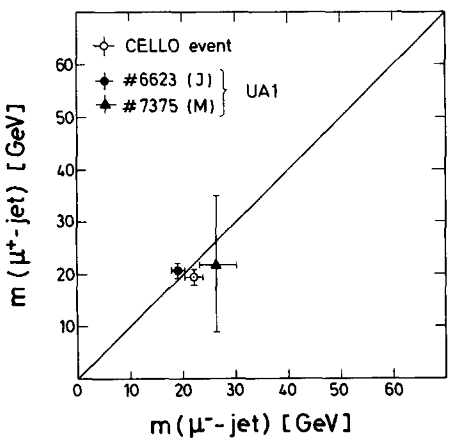

Fig. 2. $m(\mu^+\text{jet})$ versus $m(\mu^-\text{jet})$ for the anomalous $\mu^+\text{jet}\,\mu^-\text{jet}$ events, (o) from CELLO [9], (•,▲) from UA1 [10]. The $\mu^\pm$–jet pairings are chosen such as to maximize the angle between the μ and jet momenta within each pair.

We plotted $m(\text{jet}\,\mu^+)$ versus $m(\text{jet}\,\mu^-)$ for the CELLO and the two UA1 events. The μjet combinations were chosen such as to maximize the angles between the jet and μ momenta within each pair (for reasons given below). The data cluster on the diagonal, around $m(\text{jet}\,\mu)$ $\sim$ 20–22 GeV. Let us tentatively assume [9]

$$m_\chi \sim 20.5 \text{ GeV}, \qquad (13)$$

with substantial error of course. In view of the theoretical estimate (4) this mass is marginally small, but certainly not ruled out.

Let us first discuss the CELLO event. The CMS energy, $\sqrt{s}$ = 43.45 GeV, is a few GeV larger than $2m_\chi$, allowing the interpretation of a point-like production of a pair of *spin 0* objects, $\chi\bar{\chi}$ (as in fig. 1a), with a cross section

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to \chi\bar{\chi} \to \text{jet}\,\mu^+\text{jet}\,\mu^-)$$

$$= \tfrac{1}{3}\pi(\alpha^2/s)\,(1-4m_\chi^2/s)^{3/2}\sin^2\theta\, Br^2(\chi \to q\mu). \qquad (14)$$

This cross section is maximal at 90°, consistent with the CELLO event angle of $\theta \sim 73°$. On the other hand, as concerns the leptoquark decay, $\sqrt{s}$ is still quite close to the $\chi\bar{\chi}$ production threshold. If produced at rest, χ and $\bar{\chi}$ decay into a back-to-back jet–muon pair each, leading to a *coplanar event signature* (two intersecting lines form a plane!). This is consistent with the near-coplanarity of the CELLO event. Due to the suppression factor p^3 in eq. (14), one does not expect a step in $R_{e^+e^-}$ at $2m_\chi$, but a smooth increase $\propto p^3$, reaching the asymptotic value of 1/3 well above the PETRA range. Given the integrated PETRA luminosity of $\sim$70 pb^{-1} at $\sqrt{s} \gtrsim 43.45$ GeV, available so far in all four PETRA experiments, from eq. (14) one expects

$$\#\text{evts}(e^+e^- \to \chi\bar{\chi} \to \text{jet}\,\mu^+\text{jet}\,\mu^-)^{\text{PETRA}}_{|\cos\theta| \lesssim 0.7}$$

$$\sim 70 \times \tfrac{1}{2} Br^2(\chi \to q\mu). \qquad (15)$$

In $\bar{p}p$ collisions the leptoquark pair is mainly produced in the subprocess gluon + gluon $\to \chi\bar{\chi}$. Since the gluon distribution in the proton is peaked at small x, one expects the $\chi\bar{\chi}$ production to peak at $\chi\bar{\chi}$ energies not far above $2m_\chi$. This is indeed the case for the two UA1 events which have (jet μ^+jet μ^-)-energies of 45 ± 1.8 and 59 ± 12 GeV, respectively [10]. These energies are sufficiently large to lead away from coplanarity and sufficiently small to justify the criterion going into fig. 2 that the het and μ decay products of a leptoquark should have a large relative angle. Folding in the UA1 cuts, the expected number of events has been calculated [21] to be

$$\#\text{evts}(\bar{p}p \to \chi\bar{\chi} \to \text{jet}\,\mu^+\,\text{jet}\,\mu^-)^{\text{UA1}} \sim 80\,Br^2(\chi \to q\mu). \tag{16}$$

From eqs. (15) and (16) the ratio

$$\#\text{evts}(e^+e^-) : \#\text{evts}(\bar{p}p) \sim 35 : 80 \sim 1 : 2.3 \tag{17}$$

is *predicted, independently of the unknown* $Br(\chi \to q\mu)$. This is in agreement with the experimental ratio, 1 : 2, of one CELLO e^+e^- event to two UA1 $\bar{p}p$ events. Consistency with the absolute number of observed jet μ^+jet μ^- events requires $Br(\chi \to \text{jet}\,\mu)_{\text{exp}} \sim 0.2$ from eq. (15).

In the light of eq. (8) this relatively large value seems to support the hypothesis (9) of leptoquarks conserving generation number. Let us follow up further consequences of this hypothesis. The jet μ^+jet μ^- events then arise from $\chi^{(2)}\bar{\chi}^{(2)}$ pair production with subsequent $\chi^{(2)} \to s\mu^+$ decay. In this case *strange* leading particles are predicted in both jets of the CELLO and the UA1 events. In fact, in the UA1 event #6623 (J) both, a K^0 and a Λ, have been identified [10]. Next let us quote the expected number of events for other interesting $\chi^{(2)}$ decay channels [for an acceptance $\epsilon = 1$ relative to jet μ^+jet μ^- and $Br(\chi^{(2)} \to c\bar{\nu}_\mu) \sim 0.8$]:

s-jet $\mu^\pm$ c-jet $p_T^{\text{miss}}(\nu_\mu)$:

2.8 evts. per PETRA group, $\sqrt{s} \gtrsim 43.5$ GeV,

25.6 evts. for UA1. (18)

c-jet $\bar{c}$-jet $p_T^{\text{miss}}(\nu_\mu\bar{\nu}_\mu)$:

5.6 evts. per PETRA group, $\sqrt{s} \gtrsim 43.5$ GeV,

51.2 evts. for UA1. (19)

The event rate (19) is not in conflict with existing PETRA limits [22] for acoplanar two-jet events. Improvements on limits for such events are of course desirable.

It is also worthwhile to look for signals of possible first and third generation leptoquarks $\chi^{(1)}$ and $\chi^{(3)}$, coupling to the $q\bar{\ell}$ pairs of the first and third generation, respectively. At PETRA, jet e^+jet e^- signals due to $\chi^{(1)}\bar{\chi}^{(1)}$ production are probably hard to disentangle from the (two-photon) background. $\chi^{(3)}$ is presumably heavier than $\chi^{(2)}$, however the off-chance that it is pair produced still within the PETRA reach should not be discarded right away. If $m_{\chi(3)} < m_t$ then $\chi^{(3)}$ decay proceeds exclusively via b-jet + τ^+. Depending on the τ decay modes, unusual events of the type 4 jets + p_T^{miss}, $\mu^\pm$ + 3 jets + p_T^{miss} or $\mu^+\mu^-$ + 2 jets + p_T^{miss} are expected above $2m_{\chi(3)}$ in e^+e^- and $\bar{p}p$ collisions.

Next we turn to "monojet" events of the type jet + p_T^{miss} (+$\ell^\pm$) as observed at UA1 [11] (UA2 [12]). From the point of view of leptoquarks there are two possible explanations. Let us start with the less clean one. As has been pointed out [23,24] recently, the UA1 jet trigger and jet algorithm may lead to a merged monojet signal of two jets. Thus the dominant channel (11c) through which a leptoquark pair manifests itself, may appear in the UA1 detector in form of a monojet signal. Now, leptoquarks χ have the same color and spin as squarks ($\tilde{q}$) and thus identical pair production rate in the dominant gluon–gluon subprocess; their decay mode $\chi \to q_{2/3}\bar{\nu}$ is epxerimentally indistinguishable from the $\tilde{q} \to g\tilde{\gamma}$ decay. So, the interpretation of UA1 monojets as evidence for supersymmetry in form of $\tilde{q}\bar{\tilde{q}}$ pair production [24] translates into a comparably good interpretation in terms of leptoquark pair production. The distinction from the supersymmetry signal lies in the *charged* lepton decay mode, $\chi \to q_{-1/3}\,\ell^+$. This leads to signatures of the type (11a,b) – with the two jets again possible merged into a single one – probably with a smaller rate though [see eq. (8)]. UA2 events [12] of the type jet + ℓ + p_T^{miss} are possible candidates for (11b). Whether a single leptoquark of mass ~20 GeV can be made responsible simultaneously for the monojets and the anomalous jet μ^+jet μ^- events has still to be clarified.

A much cleaner source of true monojets in form of final states

$$\text{jet} + p_T^{\text{miss}}, \quad \text{jet} + \ell^\pm + p_T^{\text{miss}}, \quad \text{jet} + \ell_1^+ + \ell_2^- \tag{20}$$

is expected from *single production of leptoquarks* in $\bar{p}p$, see fig. 3a. Unfortunately, single production of spinless Goldstone boson leptoquarks is disfavored, since it involves the small $\chi\bar{q}\ell$ coupling at the lower vertex. There is, however, no such suppression for sin-

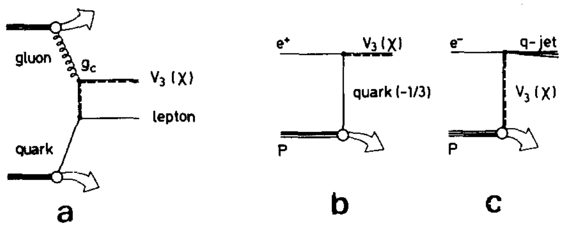

Fig. 3. (a,b) Production of a single leptoquark (V_3: of spin 1, χ: of spin 0) in (a) $\bar{p}p$ collisions, (b) e^+p collisions. (c) Quark jet in electron-beam direction as a result of leptoquark exchange in e^-p collisions.

gle production of spin 1 leptoquarks. A similar situation, suppression of spin 0 and no suppression for spin 1 leptoquarks, arises in single leptoquark production in e^+p collisions, see fig. 3b. The e^+ instead of the e^- beam is needed, if a charge 2/3 leptoquark is to be produced from a valence quark in the proton. For the CERN $\bar{p}p$ collider and an e^+p option at HERA this is only of interest, if the mass of the vector boson leptoquark is $\lesssim O(\Lambda_F)$. Whether such a low mass is compatible with the constraints from rare processes requires careful investigation, in particular into the issue of generational symmetry, e.g. along the lines of refs. [20,7,8]. This analysis is still in progress.

Finally let us briefly touch upon an exciting subject which deserves further investigation. Leptoquarks (like any new colored particles) could give rise to a completely new hadron spectroscopy. This is in particular expected for the *long-lived* Goldstone boson type leptoquark. Possible hadrons are e.g. $\bar{u}\chi$, $\bar{d}\chi$, ... bound state fermions with non-vanishing lepton number (see also ref. [13]). Also $\chi\bar{\chi}$-onia, preferably with spin 0, could be formed. If an $\chi\bar{\chi}$-onium mass is smaller than $2m_\chi$, it will be a narrow state. Even though a spin 0, 40 GeV $\chi\bar{\chi}$-onium light lie within the PETRA energy range, it could easily have escaped detection; the production rate for spin 1-onia is suppressed, since the constituents have spin 0. A spin 0 $\chi\bar{\chi}$-onium could, however, easily be produced at the CERN $\bar{p}p$ collider via two-gluon fusion. Its main decay channels presumably will be into ordinary hadrons via two gluons and into two quark–lepton pairs with signatures (11a–c). But also more exotic decay modes are possible like

$$\chi\bar{\chi}\text{-onium} \to \nu\bar{\nu}\gamma$$
$$\to \ell^+\ell^-\gamma. \qquad (21)$$

The first decay mode has a "monophoton" signature, not unlike the monophoton events reported by UA1 [11]. The latter decay mode, for $m_{\chi\bar{\chi}\text{-onium}} \sim 90$ GeV, might even be associated with the UA1/UA2 events [25] which so far have been interpreted as $Z \to \ell^+\ell^-\gamma$ decays.

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