Sextet Quark Physics at the Tevatron? *

Alan. R. White†

Argonne National Laboratory
9700 South Cass, Il 60439, USA.

Abstract

A sextet quark sector of QCD, together with the sextet higgs mechanism, would produce a major change in the strong interaction above the electroweak scale. This change may already be evident in Cosmic Ray physics and, if so, dramatic effects are to be expected at the LHC. In this paper we discuss whether evidence for the sextet sector could be seen at the Tevatron.

A major consequence of the connection between QCD and electroweak symmetry breaking is the strong coupling of the pomeron to the electroweak sector. At the Tevatron, the energy is too low to produce vector boson pairs directly via double pomeron exchange, but a number of small cross-section effects could be seen in diffractive, and diffractive related, processes involving $W^\pm$ and $Z^0$ vector bosons. Probably, the most important feature that could be decisively established is that the production cross-section for $W^+W^-$ and $Z^0Z^0$ pairs has an anomalous component with event characteristics different from the Standard Model. This would be the first indication of what should become a dominant, very large, cross-section at the LHC.

If the sextet quark dynamical mass scale is well above the top quark mass, then the production properties of $W$‘s and $Z$‘s could be the only new physics visible at the Tevatron scale. If this scale is lower the situation could be more subtle. The observed $t\bar{t}$ events could originate from the $\eta_6$ - the “sextet higgs”, even though they can be understood perturbatively. The interpretation of the top quark mass would, however, be different and non-perturbative decay modes should also be seen. A jet excess at large $E_T$ would provide supporting evidence for this picture, since $\alpha_s$ evolution should stop at $E_T \sim m_{\text{top}}$.

*Work supported by the U.S. Department of Energy under Contract W-31-109-ENG-38
†arw@hep.anl.gov
At first sight, the “sextet higgs mechanism”, in which the $W^\pm$ and $Z^0$ acquire their mass via the QCD chiral symmetry breaking of a color sextet quark sector, can be regarded\cite{1} as a very particular form of the general technicolor higgs mechanism\cite{2}, with QCD as the technicolor gauge group. Indeed, this is the framework in which it was originally proposed\cite{3}. If we consider the Standard Model without the usual higgs sector and add a doublet of sextet quarks ($U & D$), the breaking of the sextet chiral symmetry gives a triplet of “sextet pions” ($\Pi^\pm, \Pi^0$) and a “sextet higgs” particle - the $\eta_6$. The $W^\pm$ and $Z^0$ then acquire masses by “eating” the $\Pi$’s.

In fact, as we emphasized in \cite{4} and will emphasize further in a new paper that is in preparation\cite{5}, the sextet mechanism is radically different from the technicolor mechanism (and, in effect, all other proposed higgs mechanisms). Firstly, because the electroweak scale is, economically and very beautifully, a second (higher color) QCD scale, no new interaction is needed beyond the familiar SU(3)xSU(2)xU(1) gauge interactions of the Standard Model. (A short-distance SU(2)xU(1) anomaly can be avoided by adding heavy leptons, although an underlying grand unified theory could give a more elaborate high mass cancelation\cite{6}.) Secondly, electroweak symmetry breaking is intricately connected with QCD dynamics and, most importantly, produces a major change in the strong interaction above the electroweak scale. As we will briefly discuss, we believe this change is already evident in very high-energy Cosmic Ray physics. If this is the case, then large cross-section physics must necessarily be involved and it will be inescapably apparent at the LHC. At the Tevatron the situation could be more ambiguous. In this paper we will describe, in a general manner, some sextet quark physics that might be seen at the Tevatron.

We refer to QCD with six triplet flavors and two sextet flavors as $QCD_S$. (The suffix can be thought of as denoting either “sextet” or “special”, or even “saturated”, since the asymptotic freedom constraint on the quark content of QCD is saturated.) $QCD_S$ has several special features and, for a long time\cite{9}, we have argued that it has the particular attraction that it gives Critical Pomeron asymptotic high energy behavior\cite{10} (uniquely satisfying unitarity in all aspects). We have also argued that the pomeron and infinite momentum hadron states emerging from our work correspond to a special (S-Matrix) solution of QCD that is very close to perturbation theory and appears only in $QCD_S$.

Because of the particular quark content of $QCD_S$, the high-energy behavior can be constructed from the reggeon diagrams of the color superconducting version of the theory (in which the gauge symmetry is broken from SU(3) to SU(2) ). The key feature of the superconducting theory is that a “wee gluon anomaly condensate” is produced by the interplay between the chiral anomaly properties of Goldstone bosons.

\footnote{We also discussed expected sextet sector effects, at accelerators\cite{7}, and in Cosmic Ray physics\cite{8}, previously. Since then, however, an improved understanding of $QCD_S$ has led us to different expectations, particularly concerning the irrelevance of instanton interactions.}
and reggeon vertex anomalies[4, 9]. In $QCD_S$ the wee gluon condensate becomes a “dynamical wee gluon component” of infinite momentum physical states that, in effect, is responsible for the non-perturbative properties of confinement and chiral symmetry breaking§.

The origin of the wee gluon component, in the superconducting theory, implies that it carries both (global) color and spin. Also, since all “hadrons” originate as Goldstone boson states in the superconducting theory, they necessarily have a short-distance (large momentum) component that is gauge invariant (via reggeization) but retains global color and spin properties that are canceled by the wee gluon component. A “pion” is, in first approximation, a color octet quark/antiquark pair (either color triplet or color sextet) in a vector-like spin state combined with a wee gluon component. Similarly, the pomeron (in first approximation) is a color octet (reggeized) vector gluon combined with a wee gluon component. Because of the anomaly origin of the wee gluon component it can not be generated (radiatively) by the short distance component. As a result, there is a well-defined separation between the short-distance and wee gluon components which implies that a parton model is valid. However, the special features of the short-distance component are different to those usually anticipated in the QCD parton model. Most importantly, there is no short-distance contribution that carries directly all the quantum numbers of the hadron. This is crucial for the status of the $\eta_6$ in $QCD_S$, as we will discuss later.

Because the (high-energy) solution of $QCD_S$ is so close to perturbation theory, dynamical triplet and sextet quark momentum scales will be related (approximately) by the “Casimir Scaling” rule that is, roughly, satisfied by Feynman diagrams. For example, if $F_\pi$ and $F_\Pi$ are, respectively, triplet and sextet chiral scales, we expect

$$C_6 \alpha_s(F^2_\Pi) \sim C_3 \alpha_s(F^2_\pi) \quad \quad C_6/C_3 \approx 3$$

(0.1)

where $C_3$ and $C_6$ are triplet and sextet Casimirs. If $\alpha_s$ evolves sufficiently slowly (e.g. $\alpha_s(F^2_\pi) \sim 0.4$ ) then $F_\Pi$, which gives the mass scale for $W^\pm$ and $Z^0$ vector bosons, can indeed be the electroweak scale.

As we discussed in [4], and will discuss at length in [5], $F_\Pi$ also provides the scale for the coupling of the wee gluon component of the pomeron to sextet pions. Combining this with the formation of Goldstone boson “pions” via triangle diagram anomaly poles, we have developed[4, 5] a semi-perturbative method for estimating the magnitude of hard diffractive production of $W$'s and $Z$'s when the sextet higgs mechanism is operative. The essential feature is that the diffractive interactions shown in Fig. 1 can be shown to be large, via anomaly pole production, when $k_\perp \gtrsim M_W$.

§We will discuss in [5] how construction of $QCD_S$ via the superconducting theory resolves the infinite momentum quantization ambiguity of the contribution of “unphysical” longitudinal wee gluons, an ambiguity that is well-known to be related to the finite momentum choice of vacuum.
Fig. 1 Diffractive Interactions Produced by Sextet Quark Loop Anomalies

The first two interactions, in Fig. 1, contain a hard vertex which combines with a sextet quark loop anomaly pole, involving the wee gluons in the pomeron, to produce the sextet pion that becomes a final state vector boson. In the second two interactions, two sextet pions are produced and so there are two sextet quark loop anomalies within each interaction. The hard diffractive estimates can also be combined with pomeron regge theory to obtain predictions for soft diffraction. The anomaly pole method allows us to estimate the interactions at large $k_{\perp}$ and, when continued to smaller momentum transfers, the rapid increase of the pomeron coupling to a scattering hadron state strongly enhances the cross-section.

In [4] we briefly discussed how, at HERA, events[11] at large $x$ and $Q^2$ might be produced (essentially) by the first diffractive interaction in Fig. 1, in which a photon is excited to a $Z^0$. At the Tevatron, the second interaction shown in Fig. 1 would allow a perturbatively produced $W^\pm$ or $Z^0$ to scatter via pomeron exchange. This scattering could explain the push towards larger rapidities, that may have been observed[12], when a $W^\pm$ or $Z^0$ is produced in association with a large $E_T$ jet. The third interaction shown in Fig. 1 should produce a diffractive cross-section for the production of $W^\pm$ and $Z^0$ pairs that is large compared to the Standard Model diffractive cross-section. This process might be the most direct way to detect the presence of sextet quark physics at the Tevatron. Unfortunately, the size of the cross-section is limited by requiring the initial, perturbative, production of a $W$ or $Z$.

The last interaction shown in Fig. 1 is a double pomeron interaction that does not require any initial vector boson production. As a result we argued in [4] that, because of the enhancement by pomeron couplings at small momentum transfer, the LHC cross-section for double pomeron production of $W^\pm$ and $Z^0$ pairs should be very large. This would be clear, direct, evidence for the sextet higgs mechanism that could be produced very soon after the LHC turns on.

In fact, if the double pomeron interaction of Fig. 1 is large, then “cut pomeron” amplitudes involving $W^\pm$ or $Z^0$ pairs coupling as sextet pions should also be large. In particular, the amplitude shown in Fig. 2, which describes the central region inclusive production of a $W^\pm$ pair, should be large, as should be the corresponding $Z^0$ pair amplitude. As a result, $W^\pm$ and $Z^0$ pairs should be multiply produced (more and more abundantly as the energy increases) across most of the rapidity axis, in close
analogy with pion production at much lower energies.

Fig. 2 A Contribution to the $W^+W^-$ Inclusive Cross-Section.

We believe this is a major change in the strong interaction which is able to explain the observed “knee” in the Cosmic Ray spectrum (between Tevatron and LHC energies) that, while becoming more and more firmly established, has baffled Cosmic Ray physicists for more than forty years[13].

In the initial cosmic ray collision, because of the interaction change, the average transverse momentum of the produced particles will rise dramatically with energy and an increasingly larger fraction will be undetected at ground level. Also a significant fraction of the produced energy will go into neutrinos that are not detected. As a result of these effects, the energy of the incoming Cosmic Ray will be seriously underestimated. The result will be an, apparent, knee in the deduced incoming energy spectrum at (roughly) the effective threshold for significant production of $W^\pm$ and $Z^0$ pairs. To produce as large an effect as is seen, a significant part of the cross-section must be involved. In effect, at high enough energy, $W$ and $Z$ production must be competitive with pion production in the strong interaction, which is not unreasonable if two comparable quark sectors of QCD are involved. Note that there is specific evidence[14] from the Cosmic Ray experiments of very large transverse momenta, in “dijet” events, above the knee. The cross-sections involved are orders of magnitude larger than anticipated in conventional QCD. Most probably, the dijets are $W$ or $Z$ pairs.

Apparently[15], there is already an anomalously large $W$ pair cross-section at the energy of the $S\bar{p}pS$ collider and since we expect this cross-section to be really large at the LHC, it seems that an “anomalous” (although still relatively small) cross-section should surely be observed at the Tevatron. A complication is that detection of events in which one of the pair decays hadronically is much more difficult at the Tevatron than it was at the $S\bar{p}pS$ because of the large background from the QCD production of $W$ (or $Z$) plus two jets. Double pomeron production which, as we described above, we expect to be a very clean signal at the LHC, is (strictly) inaccessible kinematically at the Tevatron. However, the single diffractive interactions
discussed above, and other related events with unexpectedly low\(^\dagger\) (and high\(^\parallel\)) associated multiplicity, should still give an anomalous cross-section that develops into the anticipated very large cross-section at higher energies.

It is also, of course, very interesting to consider whether we can find evidence of sextet quarks in jet physics, possibly in events where no electroweak bosons are present. The contribution of one sextet quark to the $\beta$-function of QCD is the same as five triplet quarks. As a consequence, the inclusion of a sextet quark doublet halts the evolution of $\alpha_s$ almost entirely. (Asymptotic freedom still holds, but it would be manifest only as a very slow decrease of $\alpha_s$ at energies well above the sextet scale.) Therefore, if the jet inclusive cross-section is calculated using standard perturbative QCD, $\alpha_s$ should not evolve beyond the $E_T$ scale at which the sextet quarks enter the theory. If we consider just the sextet pions, i.e. the $W^\pm$ and $Z^0$, then $E_T \sim 2M_W$ would appear to be the scale at which sextet quarks enter the (sextert) flavor neutral part of the theory. This is, indeed, roughly the scale above which the non-evolution of $\alpha_s$ can be viewed, experimentally, as responsible\(^[17]\) for a large $E_T$ jet excess. However, $M_W$ is the chiral scale of the sextet sector and, a priori, we would expect that the non-chiral dynamical mass scale would determine the scale at which the evolution of $\alpha_s$ is affected. As we now discuss, we expect this scale to be associated with the mass of the $\eta_6$.

Usually, it is assumed that the only explicit, non-perturbative, axial chiral symmetry breaking in QCD is that due to topological (instanton) contributions to the anomaly current. If this were the case in $QCDS$, there would be a $U(1)$ symmetry associated with the $\eta_6$ that would be unbroken. As a consequence, in addition to being the analog of the usual higgs scalar, the $\eta_6$ would also be\(^[16]\) a light axion of the kind that is ruled out experimentally.

At this point, the existence of the wee gluon component of the $\eta_6$ is essential. As we briefly noted in [4], and will discuss in more detail in [5], in QCDS the anomaly vertices that create the wee gluon component of a hadron break both the sextet and triplet $U(1)$ symmetries. As a consequence, there is no light axion in the spectrum. Because of the presence of the wee gluons, the short-distance component of the $\eta_6$ does not carry all of it’s quantum numbers. Rather this component is a flavor singlet sextet quark/antiquark pair that carries octet color and so can couple directly to an, unphysical, component of the gluon. As a result, a multigluon regge exchange (initially a daughter of the pomeron) mixes with the $\eta_6$. We anticipate that this mixing generates an electroweak scale dynamical mass for the $\eta_6$. (As we discuss below, the multigluon exchange also mixes with the corresponding flavor singlet composed of

---

\(^\dagger\)Low multiplicity events can anticipate higher energy rapidity gap cross-sections.
\(^\parallel\)A connection between diffractive cross-sections and events with twice the average multiplicity density (in rapidity) is required by the AGK cutting rules. In addition, the Wilson lines attached to sextet quarks should generate higher associated multiplicities than triplet quark lines.
color triplet quarks).

Our construction of high-energy $QCD_S$ is crucially dependent on effects of the chiral anomaly when the quarks are massless and so we necessarily construct the massless version of the theory first. In fact, in [4] and [5] we discuss how vector boson masses are generated by the sextet higgs mechanism, but do not consider whether the generation of effective (current) triplet quark masses could involve the same mechanism. To be physically applicable, therefore, effects of triplet quark current masses, including that of the top, must be added to the S-Matrix of $QCD_S$. For the sextet higgs mechanism to be operative, sextet quarks cannot have a current quark mass. How dynamically generated sextet mass scales compare with the top quark mass is, therefore, crucial.

It is possible that the $\eta_6$ mass could be too large for it to be seen at the Tevatron (say 1 TeV). In this case we could, perhaps, assume that all effects of the sextet sector, apart from those in which sextet pions are involved, can be integrated out at the top quark mass scale. This would imply that standard perturbative QCD could be applied to top quark production and the only evidence of the sextet quark sector would be in the vector boson production cross-sections that we have already discussed. For consistency $\alpha_s$ should, presumably, evolve as usual up to and beyond the top mass. Therefore, a jet excess would have to be entirely due to the multiple production of $W$’s and $Z$’s that would be outside of the standard perturbative calculation.

Even if the mass scale is very high, the existence of a non-perturbative QCD sector above the mass of the top quark makes it worrisome that the concept of a perturbative, electroweak scale, current quark mass can be well-defined enough to be directly measured. (There would surely be a large dynamical mass generated above, if not at, the electroweak scale.) This worry becomes ever stronger as we decrease, as an assumption, the mass of the $\eta_6$. To discuss what we might expect, it is instructive to consider the effect of smoothly adding a top quark mass to massless $QCD_S$.

In the massless theory the $\eta_6$ will mix, as we noted above, with both a multigluon state and the flavor neutral triplet quark meson (composed of all six triplet quarks) that we will refer to as the $\eta_3$. Initially, because of their different dynamical mass scales, one state will remain primarily triplet quark, which we can continue to identify as the $\eta_3$, while the other will remain primarily a sextet state, and can be identified as the $\eta_6$. Consider, first, the effect on the $\eta_3$ of increasing the top mass, ignoring the mixing with the $\eta_6$. As the top mass is increased the mass of the $\eta_3$ will increase, it’s triplet quark content will become primarily $\bar{t}t$, and it will also become increasingly unstable - that is it’s width will increase. When the current quark top mass is such that the mass of the $\eta_3$ is well past the threshold for $W^+W^-b\bar{b}$ production so that, effectively, the top quark has become significantly unstable, we anticipate that the $\eta_3$ will have such a large width that it will be physically unobservable. At this stage we would also anticipate that the sextet sector is already
contributing, dynamically, to the effective top quark mass.

If we now consider the fate of the $\eta_6$, we will find that the mixing with the $\eta_8$ increases as the top mass is increased. However, the essential sextet quark composition of the $\eta_6$ will make it’s mass higher. It’s width, which will come amost entirely from the mixing with the triplet sector, will be narrower (although still large). As a consequence the $\eta_6$ could be observable at a relatively low electroweak scale mass and have $t\bar{t}$ as a primary decay mode, in addition to other triplet quark decay modes and non-perturbative $W$ and $Z$ decay modes that we discuss next. At the parton model level, the $\eta_6$ would be produced primarily via gluon production, just as is the top. It is natural, therefore, to raise the possibility that the observation of a $t\bar{t}$ “threshold” at the Tevatron might actually be the observation of the $\eta_6$. Since many experimental features would be similar to the perturbative picture, a key signal of this could be the observation of, one or more, non-perturbative decay modes.

To discuss non-perturbative decay modes of the $\eta_6$, the best we can do is to exploit the parallel between the $\{\Pi^\pm, \Pi^0, \eta_6\}$ sextet states, corresponding to $\{W^\pm, Z^0, \eta_6\}$, and the familiar $\{\pi^\pm, \pi^0, \eta\}$ triplet quark states. Although the width would be large, we should, presumably, take the mass of the $\eta_6$ to be $\sim \ 2m_{ttop} \sim 350$ GeV. In this case, the relative couplings and masses of the vector mesons, and the photon, imply that the primary non-perturbative decay mode should be (in parallel with $\eta \to \pi^+ \pi^- \pi^0$)

$$\eta_6 \to W^+ W^- Z^0$$

which, when $Z^0 \to b\bar{b}$, would give the same final state as $t\bar{t}$. The next most significant mode

$$\eta_6 \to Z^0 Z^0 Z^0$$

(in parallel with $\eta \to \pi^0 \pi^0 \pi^0$) should have a smaller branching ratio, because of the larger $Z^0$ mass. In addition, (0.3) would be indistinguishable from (0.2) when the $Z^0$’s decay hadronically, as they do most of the time. Because the $\eta_6$ mass is so large, decay modes involving an electromagnetic coupling, such as

$$\eta_6 \to W^+ W^- \gamma, \ Z^0 Z^0 \gamma, \ Z^0 \gamma \gamma, \ \gamma \gamma \gamma$$

would be expected to have smaller branching ratios but should be present at some level.

If the top quark events are produced by the $\eta_6$ then “$m_{ttop}$” would be the sextet dynamical mass scale above which $\alpha_s$ would not evolve. In this case there should surely be a jet excess at the Tevatron which, at least in part, can be interpreted[17] as non-evolution of $\alpha_s$ beyond $E_T \sim m_{ttop}^{-1}$. Although there is little difference between $E_T \sim 2M_W$, as discussed above, and $E_T \sim m_{ttop}^{-1}$, it is clear that if the top mass has the significance that we are now discussing then the sextet sector has fully
entered the theory at this scale. Note that the increasing entry of sextet sector states into the dynamics should imply that the “excess” continues to grow as $E_T$ increases. Indeed, we would expect that in the highest $E_T$ excess region there is an enrichment of jets with $M_{jet} \approx M_{W/Z}$.

Theoretically, and “philosophically”, it would surely be attractive if an electroweak scale mass, i.e. 350 GeV, is explained as the (dynamical) mass of a sextet quark/antiquark bound state, rather than as (twice the value of) a lagrangian parameter of the triplet quark sector. Whether a well-determined top quark “mass” should still be, experimentally, identifiable is not clear. Theoretically, it would also be appealing if the logical paradox, that the mass of a colored (confined) state is a well-defined physical observable, could be avoided altogether.

Since top quark physics at the Tevatron is very complex, with elaborate analyses needed to make a connection between theory and experiment, it is clear that it may not be an easy place to look for new physics of the kind we have discussed. Whether or not $W^+W^-$ and $Z^0Z^0$ production conform to Standard Model expectations may be a much more straightforward issue to determine. If, however, significant evidence for sextet quark physics begins to accumulate then, obviously, all possible discovery directions should be pursued intensely.

Acknowledgement

I am indebted to Mike Albrow for stimulating the serious consideration of the role of the $\eta_6$ that led me to realize what it’s true significance might be.
References

[1] E. Braaten, A. R. White and C. R. Willcox, *Int. J. Mod. Phys.*, **A1**, 693 (1986).

[2] T. Appelquist, in Proceedings of the International Workshop on Electroweak Symmetry Breaking, Hiroshima, Japan (1991).

[3] W. J. Marciano, *Phys. Rev.* **D21**, 2425 (1980).

[4] A. R. White, presentation at “Physics with Forward Proton Taggers at the Tevatron and at the LHC”, Manchester, UK, December 2003 - http://glodwick.hep.man.ac.uk/conference/talks/masthm.pdf (2003).

[5] A. R. White, “$W^\pm$ and $Z^0$ Production via Sextet Pions”, to appear.

[6] See, for example, K. Kang and A. R. White, *Int. J. Mod. Phys.* **A2** 409 (1987).

[7] A. R. White, hep-ph/9704248 (1997)

[8] A. R. White, Proceedings of the 8th International Symposium on Very High Energy Cosmic Ray Interactions, Tokyo (1994).

[9] See A. R. White, *Phys. Rev.* **D66**, 056007 (2002) and further references therein.

[10] A. A. Migdal, A. M. Polyakov and K. A. Ter-Martirosyan, *Zh. Eksp. Teor. Fiz.* **67**, 84 (1974); H. D. I. Abarbanel and J. B. Bronzan, *Phys. Rev.* **D9**, 2397 (1974).

[11] ZEUS Collaboration (M. Derrick et al.), *Z. Phys.* **C74** 207 (1997); H1 Collaboration (C. Adloff et al.), *Z. Phys.* **C74** 191 (1997).

[12] G. E. Forden, presentation at ISMD94. See also D0 Collaboration (S. Abachi et al.). FERMILAB-CONF-95-218-E (1995), presented at HEP 95.

[13] S. P. Swordy et al., *Astropart. Phys.* **18** 129 (2002) and further references therein.

[14] Z. Cao, L. K. Ding, Q. Q. Zhu, Y. D. He, *Phys. Rev.* **D56** 7361 (1997).

[15] UA1 Collaboration (C. Albajar et al.), *Phys. Lett.* **B193** 389 (1987).

[16] T. E. Clark, C. N. Leung, S. T. Love and J. L. Rosner, *Phys. Lett.* **B177**, 413 (1986).

[17] CDF Collaboration (T. Affolder et al.), *Phys. Rev. Lett.* **88** 042001 (2002).