

THE SEXTET HIGGS MECHANISM AND THE POMERON*

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If electroweak symmetry breaking is a consequence of color sextet quark chiral symmetry breaking, dramatic, large cross-section, effects are to be expected at the LHC — with the pomeron playing a prominent role. The symmetry breaking is tied to a special solution of QCD which can be constructed, at high-energy, via the chiral anomaly and reggeon diagrams. There is confinement and chiral symmetry breaking, but physical states contain both quarks and a universal, anomalous, wee gluon component. A variety of Cosmic Ray effects could be supporting evidence, including the knee in the spectrum and the ultra-high energy events. The sextet neutron should be stable and is a natural dark matter candidate. A large E_T jet excess at Fermilab, and large x and Q^2 events at HERA, would be supporting accelerator evidence. Further evidence, including diffractive-related vector boson pair production and top quark related phenomena, could be seen at Fermilab as data is accumulated.

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1. Introduction

By pursuing a consistent description of high-energy QCD via the critical Pomeron we have been led [1] to the radical proposition that there should be a second (higher color) quark sector of the theory, with electroweak scale masses and even stronger interactions. In addition to providing a unitary high-energy solution of QCD, the existence of this sector would naturally link, and potentially solve, some of the most prominent problems of current-day astro-particle physics that, at first sight, are unrelated to QCD. Included are: the origin of electroweak symmetry breaking, the presence and dominance of dark matter, the knee in the cosmic ray spectrum and, perhaps, the origin and nature of ultra-high energy cosmic rays. In accelerator physics

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the first experimental evidence should be subtle, electroweak scale, deviations from standard QCD, that may have already been seen. At the LHC, there should be a multitude of large cross-section effects. Double pomeron exchange could produce the most immediately observable (definitive) effect and may be spectacular!

2. The sextet quark Higgs mechanism

A color sextet quark doublet (plus heavy leptons — to most easily avoid an $SU(2) \times U(1)$ anomaly) produces electroweak symmetry breaking in a manner that, at first sight, is simply a special version of technicolor, with QCD as the technicolor gauge group. Breaking of the sextet chiral symmetry gives a triplet Π^\pm , Π^0 of sextet pions and a “Higgs” (the η_6) and the W^\pm and Z^0 acquire masses by “eating” the Π ’s. But, economically and very beautifully, no new interaction is needed (beyond $SU(3) \times SU(2) \times U(1)$ gauge interactions). Instead, the electroweak scale is a second (higher color) QCD scale and electroweak symmetry breaking is intricately connected with QCD dynamics, with the direct QCD production of Π ’s giving a range of new phenomena.

3. QCD_S

QCD_S (with six color triplet and two color sextet quarks) has several special properties, compared to conventional QCD. An infra-red fixed point and the possibility to add an asymptotically-free scalar field allows a unitary high-energy S-Matrix to be constructed “diagrammatically” by starting with $SU(3)$ color broken to $SU(2)$ (CSQCD_S). As we describe below, there is confinement and chiral symmetry breaking but (infinite momentum) physical states contain both quarks and a crucial (universal) “anomalous wee gluon” component. The pomeron is (approximately) a regge pole and the “Critical Pomeron” describes asymptotic high-energy cross-sections.

A priori, the η_6 appears to be a light axion of the kind ruled out experimentally. Fortunately, in QCD_S the wee gluon content of the states breaks the associated $U(1)$ symmetry and there is no light axion in the “anomaly S-Matrix”. Instead, the η_6 should have an electroweak scale mass and could be responsible for top quark production. For related reasons, there should be no glueball asymptotic states, no BFKL pomeron, and no odderon. The only new baryons will be the “sextet proton” (P_6) and the “sextet neutron” (N_6). The N_6 should be stable and is a strong candidate for dark matter and also for the highest energy cosmic rays.

4. High-energy QCD_S via color superconductivity

That the regge behavior of QCD_S should be constructed via the (k_{\perp} cut-off) reggeon diagrams of CSQCD_S was first motivated by a match with supercritical pomeron diagrams. We now understand that this allows the chiral anomaly structure produced by longitudinal, massive, gluons to play a crucial role and resolves the (Gribov) ambiguity associated with infinite momentum longitudinal wee gluons in unbroken QCD.

We take all quarks massless¹, so that the pinching of quark and antiquark propagator poles produces zero momentum chirality transitions, via the anomaly, in the regge limit “effective vertex” triangle diagrams that appear in CSQCD_S. With a k_{\perp} cut-off, the chirality transitions produce wee gluon divergences at $k_{\perp} = 0$. Because of the infra-red fixed-point and regge exponentiation, these divergences remove all colored wee gluon states. An overall divergence that does not exponentiate, produced by color zero anomalous (charge parity \neq signature) wee gluons, selects the physical amplitudes. The divergence is factored out as a $k_{\perp} = 0$ “condensate” and the resulting physical states are “anomaly pole” Goldstone bosons (“pions”).

The simplest π - π scattering diagrams have the form shown in Fig. 1, where the dynamical contribution of the chirality transitions is also illustrated. In effect, an anomaly pole “pion” is created by the product of a physical quark field and a zero momentum “unphysical” antiquark field in which the Dirac sea is shifted. Via a chirality transition, the antiquark becomes physical in the presence of a compensating (condensate) wee gluon field. (There is no pure $q\bar{q}$ component in the infinite momentum pion “wave function” — the $q\bar{q}$ pair has vector-like spin!) In the scattering a further chirality transition re-aligns the initial state wee gluon field for absorption by the final state pion. The condensate can be viewed as a shift of the Dirac sea that produces an S-Matrix in which confinement of SU(2) color and chiral symmetry breaking completely determine the spectrum of states. The pomeron, in CSQCD_S, is a reggeized gluon plus the condensate, with supercritical pomeron interactions. The asymptotic states are

1. “pions” $\leftrightarrow \{q\bar{q} + \text{wee gluons}\} \rightarrow \text{normal meson spectrum in QCD}_S$,
2. “Pions” $\leftrightarrow \{Q\bar{Q} + \text{wee gluons}\} \rightarrow \Pi^{\pm}, \Pi^0 \text{ in QCD}_S$,
3. “nucleons” $\leftrightarrow \{qq/\bar{q}\bar{q} + \text{wee gluons}\} + \{q/\bar{q}\}, \rightarrow \text{SU}(3) \text{ color singlet}$
 $\rightarrow \text{normal nucleon spectrum in QCD}_S$,
4. “Nucleons” $\leftrightarrow \{QQ/\bar{Q}\bar{Q} + \text{wee gluons}\} + \{Q/\bar{Q}\}, \rightarrow N_6, P_6^{\pm} \text{ in QCD}_S$.

¹ We will not discuss whether effective quark masses can be generated by the sextet Higgs mechanism. Significant shifting of the Dirac sea, perhaps as envisaged by Gribov, has to be involved.

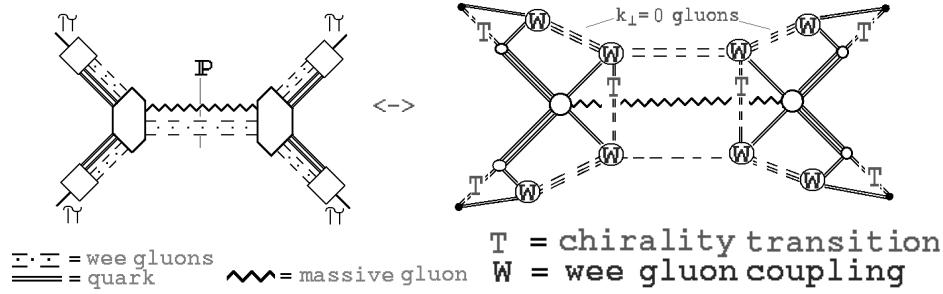


Fig. 1. The pion scattering amplitude

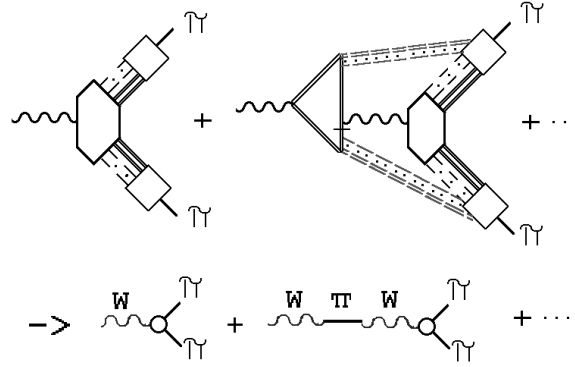
The states and amplitudes of QCD_S are obtained by removing the k_{\perp} cut-off and restoring SU(3) gauge symmetry via the critical pomeron phase transition. As part of the transition, the condensate disappears and the shifting of the Dirac sea becomes dynamical! Simultaneously, the SU(2) singlet gluon becomes massless and decouples. The only remnant of the symmetry breaking is anomaly couplings involving (longitudinal) wee gluons. The pomeron is (approximately) a short-distance, gauge-invariant, reggeized gluon combined with a color compensating, dynamical, anomalous, wee gluon contribution. “pions” and “Pions” have the same wee gluon component, but with a short-distance quark–antiquark pair. It is very important that, because of the color antisymmetry of qq nucleons, there are no $qq\bar{Q}$ hybrids. Consequently, either the N_6 or the P_6 has to be stable.

Shortly, we will discuss hard diffractive interactions of the pomeron. Because wee gluon interactions are not involved, we can still represent the wee gluons as a zero transverse momentum “condensate”. (In reality the wee gluons give a much more complicated dynamical contribution over a range of infra-red transverse momenta.)

5. The sextet QCD scale and electroweak masses

The wee gluons of an infinite momentum pion reproduce vacuum effects. Via the anomaly, wee gluon interactions of the form shown in Fig. 2 produce a W mass $M^2 \sim g_W^2 \int k dk$ where k is a wee gluon momentum. (The left-handed W coupling is crucial.) From Feynman graph color factors, we expect triplet and sextet quark momentum scales to be related (approximately) by “Casimir Scaling” so that, if the wee gluon coupling ($\int k dk$) to triplet and sextet quarks is F_H^2 and F_{π}^2 , respectively,

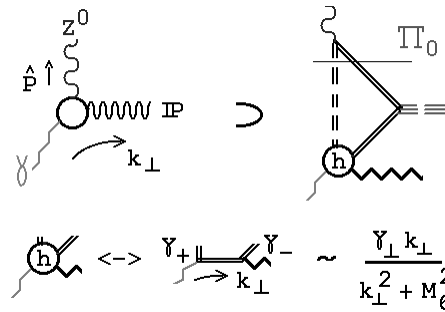
$$C_6 \alpha_s(F_H^2) \sim C_3 \alpha_s(F_{\pi}^2), \quad \frac{C_6}{C_3} \approx 3.$$

Fig. 2. W mass generation.

Consequently, M will be dominated by sextet quark anomaly contributions in Fig. 2 and the mass generation can be interpreted as due to the W - Π coupling, as illustrated. If F_π is the usual triplet chiral scale and α_s evolves sufficiently slowly (*e.g.* $\alpha_s(F_\pi^2) \sim 0.4$) F_Π can indeed be the electroweak scale ! Note that this implies the wee gluon component of the pomeron couples very strongly ($\sim F_\Pi$) to sextet quarks.

6. Large x and Q^2 at HERA

An anomaly pole Pion can be produced via a large k_\perp “hard interaction” of the pomeron with a γ , Z^0 , or W^\pm , as illustrated in Fig. 3 for a γ . M_6 is a dynamical sextet quark mass that, in the following, we will simply identify with F_Π . The pomeron provides, directly, the wee gluon component that is needed for a massless Pion to appear via the anomaly pole. Could the $\gamma Z^0 \Pi$ vertex be seen at HERA ?

Fig. 3. The $\gamma Z^0 \Pi$ vertex.

Using the anomaly amplitude $(\hat{P}_+ \hat{P}_- \hat{P}_+)/(\hat{P}_- \hat{P}_+) = \hat{P}_+$ to extrapolate from $\hat{P}^2 \neq 0$ and combining it with the wee gluon coupling F_Π , the Z^0 propagator, and vertices g_w , gives (using $M = g_w F_\Pi$)

$$F_\Pi \hat{P}_+ g_w^2 \frac{(g_{-\nu} - \frac{\hat{P}_- \hat{P}_\nu}{M^2})}{(\hat{P}^2 - M^2)} = -\frac{\hat{P}_-}{F_\Pi} \frac{\hat{P}^2 \delta_{-, \nu}}{\hat{P}^2 - M^2} - \frac{\hat{P}_+ \delta_{+, \nu}}{F_\Pi}.$$

The first term (which is present as soon as $\hat{P}^2 \neq 0$) produces physical, longitudinal, W 's and Z 's. The second term has no pole, but provides the background cross-section σ_Π , on top of which the Z peak appears. Combined with the hard interaction h it gives a factor $(\hat{P}_+/F_\Pi)(\gamma_\perp \cdot k_\perp k_\perp^2 + M_6^2) \sim \hat{P}_+ k_\perp / F_\Pi^3$. (Note that when $\hat{P}_+ \sim F_\Pi$, and $\hat{P}_- \ll \hat{P}_+$, this term gives a direct coupling to fermion final states proportional to fermion masses.)

If we consider the full DIS amplitude shown in Fig. 4(a) and compare it with the standard two jet amplitude shown in Fig. 4(b), the only dif-

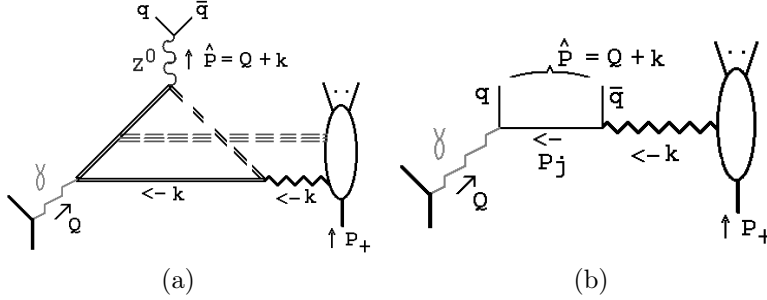


Fig. 4. Z^0 and jet amplitudes.

ference, apart from compensating gap and color factors, is that a (triplet) quark propagator carrying momentum $P_j \sim k_\perp$ replaces the sextet triangle diagram factor $\sim \hat{P}_+ k_\perp / F_\Pi^3$ (for the background amplitude). Therefore, $\hat{P}_+ \sim k_\perp \sim F_\Pi$, $\rightarrow \sigma_\Pi \sim \sigma_{2j}$.

At HERA, large Q_\perp requires large x and Q^2 . $Q_\perp \gtrsim 100$ GeV requires $Q^2 \gtrsim 30,000$ GeV², $x \gtrsim 0.5$. But $k_\perp \gtrsim 100$ GeV and $\hat{P}^2 \sim M_{Z^0}^2$, requires $|t| \gtrsim 2k_\perp^2 \sim 20,000$ GeV² and σ_{2j} will be much too small. However, the “non-perturbative” γZ^0 IP vertex should decrease only slowly (with a scale determined by M_6) as k_\perp (and $|t|$) decreases. Therefore, the increase of the proton/pomeron coupling as $|t|$ decreases, combined with the contribution of the Z^0 pole could give an observable jet cross-section.

7. The η_6 , $t\bar{t}$, and large E_T jets

In CSQCD_S, the η_6 has two anomaly couplings to wee gluons. As illustrated in Fig. 5, there is both a $Q\bar{Q}$ and an SU(2) singlet gluon coupling (where the gluon has a non-leading helicity).

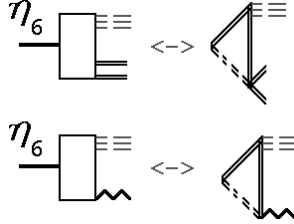


Fig. 5. η_6 couplings.

mixes with a pure glue state and so should have an electroweak scale mass determined, essentially, by M_6 . The η_6 also mixes, via the gluon state, with the triplet flavor singlet (η_3) that will be dominated by $t\bar{t}$ at the electroweak scale. Consequently, the electroweak scale short-distance component of the η_6 (which carries octet color that is compensated by wee gluons) can be produced via gluon production and, since sextet quarks are stable, it will decay,

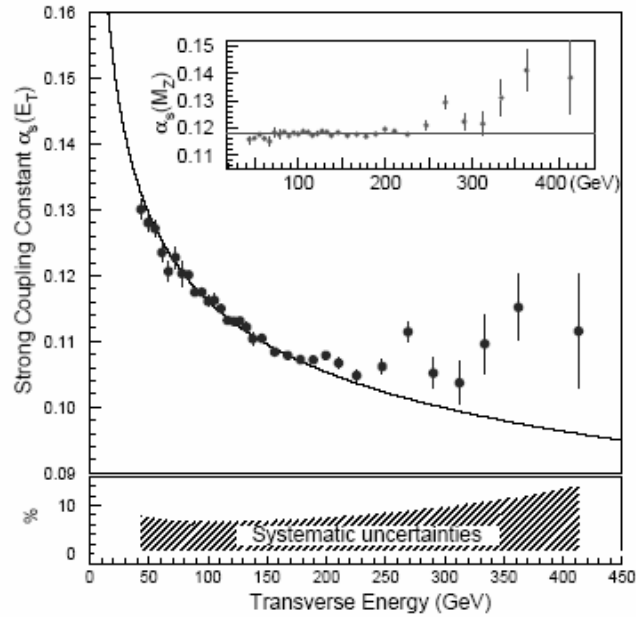


Fig. 6. α_s at large E_T .

primarily, through $t\bar{t}$. Therefore, “perturbative” $t\bar{t}$ production at Fermilab could be due to the η_6 , with $m_{\eta_6} \sim “2m_t”$. This would resolve the paradox of the apparent production of a confined, colored, quark. The sextet doublet ($\equiv 10$ triplets) would then halt the evolution of α_s at $E_T \sim m_t$, implying a jet excess above $E_T \sim m_t$ of the kind that, as shown in Fig. 6, is apparently seen in the data [2]. If the η_6 is indeed responsible for $t\bar{t}$ production, then we would also expect to see “non-perturbative” decay modes of the form

$$\begin{aligned} \eta_6 &\rightarrow W^+W^-Z^0 \rightarrow W^+W^-b\bar{b} \ / \ \rightarrow W^+W^-c\bar{c} \ / \ \cdots, \\ \eta_6 &\rightarrow Z^0Z^0Z^0, \ \eta_6 \rightarrow W^+W^-\gamma, \cdots. \end{aligned}$$

8. Diffractive-related physics at Fermilab

The Tevatron energy is probably too low for the pure pomeron production of W and Z pairs that, as we discuss below, we expect to see at the LHC. Single diffractive production of a W or Z can proceed via WW IP and ZZ IP vertices that are analogous to the γZ IP vertex but, because an initial (perturbative) W or Z is required, cross-sections will be relatively small. However, the t dependence of the pomeron/hadron vertex implies there should be “relatively large” forward cross-sections. Also, anomalous rapidity dependence in W/Z + jet cross-sections is expected. Diffractive production of a W or Z pair via a double anomaly pole vertex, as in Fig. 7, may give the most clearly anomalous cross-section (although still small). Related W or Z pair events with unexpectedly low associated multiplicity (anticipating the higher-energy double pomeron cross-section), or high multiplicity (via AGK), should contribute to an inclusive cross-section that, as we discuss next, becomes very large at higher energies.

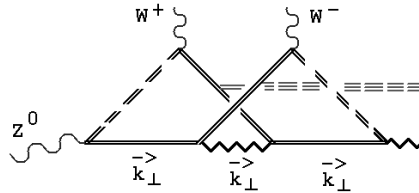


Fig. 7. Z^0 IP $\rightarrow W^+W^-$

9. Dramatic physics at the LHC

If the sextet sector exists, the LHC will most probably be the discovery machine. The first evidence is likely to be that, in general, diboson cross-sections are much larger than expected. However, the double pomeron cross-section may well be the most definitive early evidence.

Double Pomeron Exchange. Pions can be pair-produced directly in double pomeron exchange via the anomaly mechanism illustrated in Fig. 8. An order-of-magnitude argument, analogous to that discussed above, says that

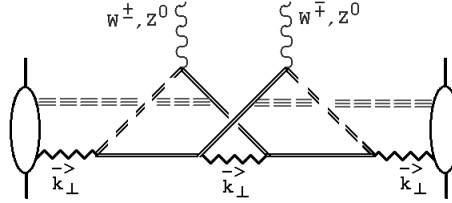


Fig. 8. $\text{IP IP} \rightarrow \pi \pi$

the production of (large k_{\perp}) W^+W^- and Z^0Z^0 pairs should give jet cross-sections that are as large as those predicted by standard QCD. There should also be top quark production via the “background” anomaly vertex and if new leptons exist, with electroweak scale masses, there will be similar vertices for their production. While the central double pomeron vertices should vary only slowly with k_{\perp} , the external hadron-IP vertices will have strong k_{\perp} — dependence and give large cross-sections at small t . With forward protons tagged, as planned, it should be immediately seen that the double pomeron cross-section for vector boson pairs is excessively large and, moreover, has the strong t dependence of a typical hadronic pomeron cross-section. Possibly, there could be spectacular events in which the forward protons are tagged and only large E_T leptons are seen in the central detector!!

Inclusive Cross-Sections for Sextet States. If double pomeron couplings are large then “cut pomeron” amplitudes, of the kind illustrated in Fig. 9, that describe the central region inclusive production of a W^{\pm} or Z^0 pair will also be large. Therefore, the initial “major change” in the strong interaction that we expect above the electroweak scale is that W and Z

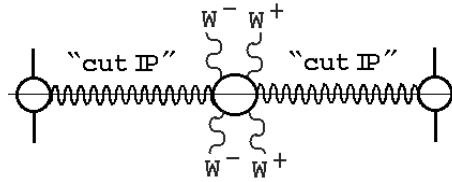


Fig. 9. Cut IP's.

(sextet pion) pairs will be multiply, and strongly, produced across most of the rapidity axis — in close analogy with pion production at much lower energies.

Although N_6 and P_6^\pm pairs (and η_6 pairs) may be too massive for double pomeron exchange, central region inclusive cross-sections should be large, implying that “dark matter” (see below), in the form of stable, massive, neutral, strongly interacting particles, should be copiously produced.

10. Dark matter and cosmic ray physics

Sextet quark current masses must be zero. If not, Pions would be massive and could not mix with massless W/Z states to give them masses. Therefore, the P_6-N_6 mass difference is entirely electromagnetic in origin and (without unification) the N_6 is neutral, stable, and presumably very massive (~ 500 GeV, 1 TeV?). It does not form bound states with normal quark states and would have been very strongly produced in the early universe. It is a natural candidate to form dark matter (nuclei, clumps?).

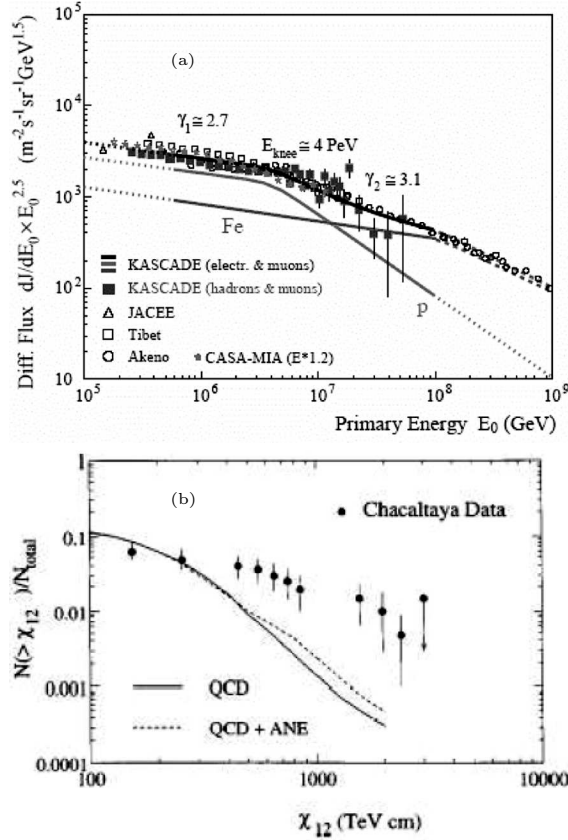


Fig. 10. a — the knee, b — “dijets”.

The well-known “knee” in the cosmic ray spectrum, shown [3] in Fig. 10(a), suggests a major interaction change, between Tevatron and LHC energies, that could be produced by the orders of magnitude rise in the W and Z pair production cross-section described above. Because the average k_{\perp} increases dramatically, an increasing fraction of produced particles will miss the detectors. Also an increasing amount of energy will go into undetected neutrinos (and, at higher energy, N_6 pairs). Serious underestimation of the total energy will then give an effective “knee” in the spectrum. As illustrated in Fig. 10(b), large k_{\perp} “dijets” have been seen [4] with a cross-section that is orders of magnitude larger than in conventional QCD.

Because neutral, massive, N_6 ’s will avoid the GZK cut-off they could also be ultra high-energy cosmic rays! Since they would simply be very high energy dark matter, their origin would, presumably, no longer be a mystery.

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