Sextet Quarks and the Pomeron at the LHC^{*}

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Abstract

Adding two color sextet quarks to QCD gives many special features. The high-energy S-Matrix, constructed via reggeon diagrams and chiral anomalies, contains the Critical Pomeron and electroweak symmetry breaking is produced, by sextet pions. Cosmic ray phenomena suggest large cross-section effects will be seen at the LHC, in particular, involving the pomeron. The sextet sector embeds, uniquely, in a massless, confining, left-handed SU(5) theory. The anomaly based high-energy S-Matrix could be that of the full Standard Model.

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1 High Energy QCD_S

When two, massless, color sextet quarks are added to QCD (with six, massless, triplet quarks already present) we obtain [1] a special version of QCD that we call QCD_S . Particular infra-red and ultra-violet properties of QCD_S allow the high-energy behavior to be constructed via the reggeon diagrams of " $CSQCD_S$ ", in which SU(3) color is broken to SU(2). "Non-perturbative" amplitudes appear via chiral anomalies occuring in reggeon effective vertices that contain triangle diagrams, generated as illustrated



Figure 1: A reggeon vertex triangle diagram.

in Figure 1. With a k_{\perp} cut-off, vector Ward identities are violated for the anomaly vertices and "wee gluon" infra-red divergences occur coupled to anomaly poles. The divergence of color zero, anomalous color parity ($C \neq \tau$) gluons is preserved to all orders. Factorizing off the divergence as a "wee gluon condensate" Goldstone boson anomaly pole "pions" are selected as physical states and the simplest $\pi - \pi$ scattering diagrams have the form shown in Figure 2. Within each anomaly vertex there is a zero momentum chirality transition or, equivalently, a Dirac sea shift. The exchanged pomeron is a massive (reggeized) gluon in a wee gluon condensate (with, in higher-orders, supercritical RFT interactions.)

SU(3) color is restored via the Critical Pomeron phase transition (asymptotic freedom properties of $CSQCD_S$ are crucial). The wee gluon condensate disappears and the Dirac sea shifting becomes dynamical. The physical states all originate as Goldstone bosons in $CSQCD_S$. There are triplet mesons and nucleons, sextet "pions" (Π 's) and "nucleons" (P_6 and N_6). There are no hybrid sextet/triplet states and no glueballs. There is also no BFKL pomeron and no odderon.

2 The Sextet QCD Scale, Electroweak Masses, and Existing Evidence

We gluons in the scattering states produce interactions that mix anomaly poles with exchanged electroweak vector bosons and generate a mass. This mass appears only in



Figure 2: Pion Scattering

the S-Matrix and only for vectors with a left-handed coupling. No photon (or gluon) mass is generated. For a sextet quark loop $M_W^2 \sim g_W^2 \int dk \ k \equiv g_W^2 \ F_{\Pi}^2$ where k is a wee gluon momentum. Sextet quarks dominate because of larger color factors and the Casimir Scaling rule $(C_6 \ \alpha_s(F_{\Pi}^2) \ \sim \ C_3 \ \alpha_s(F_{\pi}^2)$ with $C_6/C_3 \approx 3)$ implies that F_{Π} can consistently be the electroweak scale. The large wee gluon coupling implies the pomeron couples very strongly ($\sim F_{\Pi}$) to sextet quarks.

Evidence for the sextet sector may, perhaps, have already been seen at HERA and Fermilab. An anomaly pole Π can be produced via a large k_{\perp} "hard interaction" of the pomeron with a color neutral γ , Z^0 , or W^{\pm} . The diffractive DIS amplitude is strongly enhanced by the anomaly when k_{\perp} is electroweak scale, and so, the largest Q^2 (> 40,000 GeV²) event seen by ZEUS (before 97) could be diffractive production of a Z^0 . Different methods for reconstruction of the event give significantly different results (outside the errors) and the disagreement could result from a large jet mass. Consistency is achieved if the jet has a mass squared of 8,077 GeV² = (89.9 GeV)² suggesting that a massive Z^0 jet was indeed produced.

Diffractive (sextet pion) hard vertices will also appear when a Z^0 , W^{\pm} , or γ , is emitted from a quark in a hadron, but cross-sections will be relatively small and not easy to detect. Diffractive production of a W or Z pair via a double anomaly pole vertex may give a detectable cross-section. An excess W^+W^- cross-section (2 events) was apparently observed at the $S\bar{p}pS$ by UA1 and should, presumably, be also seen at the Tevatron. Double pomeron production of W^+W^- is probably not observable below LHC energies, but γZ^0 might be seen.

The η_6 mixes with a pure glue state and could be responsible for $t\bar{t}$ production. If so, m_t is a sextet scale and α_s evolution should stop at $E_T \sim m_t$, giving a jet excess just as in Figure 3.



Figure 3: CDF measurements of a) α_s in Run I and b) the jet cross-section in Run II

3 Dark Matter and Cosmic Ray Physics

Because of the Casimir effect, the sextet sector will constitute a stronger coupling sector of QCD_S . Inclusive pomeron amplitudes will give the largest effect and, above an effective threshold, sextet states will start to dominate the inelastic x-section. In particular multiple W^{\pm} and Z^0 production will cover most of the rapidity axis - in analogy with low-energy pion production. Because of the absence of hybrid triplet/sextet states, the sextet neutron (the N_6) will be stable and, at high energy, will be the dominant stable state produced. (If $M_6 \sim m_t$ then, we expect, $m_{N_6} \approx$ 500 GeV.) $N_6 \bar{N}_6$ production will dominate the formation of matter in the early universe and form cold dark matter, as (sextet) nuclei, clumps, etc.

Evidence for the energy scale at which the dominance of sextet states appears, may be provided by cosmic ray data. The "knee" in the cosmic ray spectrum is an extraordinary phenomenon and suggests a major strong interaction change between Tevatron and LHC energies. A production threshold for particles not observed at ground level would lead to an underestimation of energies above the threshold, and produce a knee via the pile-up of events below the threshold energy and a depletion of the spectrum above the threshold. However, a major part of the x-section must be involved, as would be the case for the sextet threshold. Multiple W^{\pm} and Z^{0} production will give a huge increase of the large E_T jet cross-section implying that an unexpectedly large fraction of shower particles will be undetected. There will also be a much larger fraction of (undetected) neutrinos and, at high enough energy, dark matter (N_6) production will take away a major part of the energy. In detail, the knee suggests that, at the LHC, the new physics should contribute $\sim 10-20\%$ of the hadronic cross-section. Many other effects seen in cosmic ray showers, with energies above the knee, also suggest new physics appears. In particular, the production of dijets (core pairs) is orders of magnitude above the QCD prediction. Also ultra highenergy events with $E_0 > 10^{20} eV$ (exceeding the GZK cut-off) are not understood. Since N_6 's avoid the GZK cut-off (because they are both neutral and massive), and have large high-energy hadronic cross-sections, they could be reponsible. If this is the

case, the mysteries of dark matter, the knee, and the ultra high-energy events would all have a common origin.

4 LHC Physics

Via anomaly pole amplitudes, the hard double pomeron production of electroweak vector bosons gives jet cross-sections comparable with normal QCD jet (non-diffractive) cross-sections, with the boson pair cross-section estimated to be, roughly, twelve orders of magnitude larger than in the Standard model. Combining this estimate with pomeron regge theory, gives a small transverse momentum cross-section that is correspondingly large. During the initial "soft physics" running period of the LHC, it should be straightforward to look for vector boson pairs in the CMS central detector, produced in combination with scattered protons in the TOTEM Roman Pots.

As discussed above, there will be very large inclusive cross-sections for sextet states, across most of the rapidity axis. Multiple vector boson production will give jet cross-sections, at very large transverse momentum, that will be orders of magnitude larger than expected. The production cross-section for sextet nucleon pairs should also be hadronic in size, although stable sextet neutrons (dark matter!) may be difficult to detect. If the sextet nucleon double pomeron cross-section is extraordinarily large, it might be detectable in the low luminosity run. If not, it might be seen by the high luminosity detectors that will look for double pomeron production of the Standard Model Higgs particle.

5 \mathbf{GUT}_S

The QCD_S fixed point implies that, well above the electroweak scale, $\alpha_s \sim \alpha_{ew}$ and so supersymmetry is not required for unification ! A priori, unification could also determine how the (short-distance) $SU(2) \otimes U(1)$ sextet sector anomaly is canceled, as well as providing an origin for masses. Many years ago (with Kyungsik Kang) we found a remarkable, but puzzling, result. We looked at asymptotically free, anomaly-free. left-handed unified theories that contain the sextet sector, We discovered that a unique theory is selected, i.e. SU(5) gauge theory with the fermion representation $5 + 15 + 40 + 45^*$ ($\equiv \text{GUT}_S$). Amazingly, the triplet quark and lepton sectors, which were not asked for, are remarkably close to the Standard Model. There are three "generations" of quarks/anti-quarks, with quark charges $\frac{2}{3}$ and $-\frac{1}{3}$, and three "generations" of SU(2) doublet (SU(3) singlet) leptons. The puzzle is that the $SU(2) \otimes U(1)$ quantum numbers are almost, but not quite, right and there are also (apparently unwanted) color octet quarks with lepton-like electroweak quantum numbers. At the time, we considered various "anomalous fermion phenomena", but found no convincing dynamical route to the Standard Model.

6 A Massless Theory of Matter ?

In fact, GUT_S has, essentially, the same infra-red and ultra-violet properties as massless QCD_S . As a result the high-energy S-Matrix can also be constructed via reggeon diagram anomaly interactions. Although an infra-red fixed-point keeps the SU(5)coupling very small, reggeon infra-red divergences will confine SU(5) color in the S-Matrix. Hence, all elementary fermions will be massless and confined and the Dirac sea will control the dynamics, but with a crucial difference from QCD_S . In GUT_S , left-handed fermion interactions will exponentiate the initial anomalous color parity divergences that lead to the states and amplitudes of QCD_S . Therefore, these divergences will only be produced by the $SU(3) \otimes U(1)$ vector part of the theory and will lead to the dominance of this sector in the S-Matrix. The left-handed vector bosons, with no SU(3) color, will aquire a mass, as described in Section 3 and there will be a related bound-state mass spectrum in which, because of the fermion representation structure, there will be no (unwanted) symmetries. As yet, very little is certain, but an initial study suggests that the states and interactions of the Standard Model could be generated within the GUT_S S-Matrix (with the octet quarks essential for generating bound-state leptons). If the Standard Model does, indeed, emerge in this manner it will be crucial that (as we have seen in QCD_S) the infra-red chiral anomaly effects of a massless Dirac sea can produce a bound-state S-Matrix with dramatically different properties from those implied, at first sight, by the underlying field theory.

References

 For further elaboration, and references, see A.R. White, *Phys. Rev.* D72, 036007 (2005).