Unification of the Standard Model Via High-Energy Unitarity

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Abstract

High-energy unitarity is satisfied by adding a sextet quark doublet to QCD. The sextet sector produces electroweak symmetry breaking and is predicted to give large cross-section effects at the LHC. It embeds, uniquely, in a massless $SU(5)$ theory whose bound-state S-Matrix, potentially, reproduces the Standard Model. Infra-red chirality transitions of the massless Dirac sea play an essential dynamical role.

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1 Introduction

In this talk I will argue that the constraints of high-energy, multi-regge, unitarity are so strong that the Standard Model S-Matrix may be uniquely selected, together with an underlying, unifying, massless SU(5) gauge theory (QUĐ\(^1\)). The key points are -

1. The unitary Critical Pomeron uniquely selects QCD\(_S\) (a color sextet quark sector is added to the known triplet quarks) as the strong interaction.

2. Multi-regge scattering of electroweak bosons induces the QCD\(_S\) bound-state S-Matrix via anomalies. Sextet chiral symmetry breaking produces vector boson masses.

3. QCD\(_S\) and the electroweak sector embed, uniquely, in SU(5) gauge theory with massless, left-handed, fermions in the representation 5 + 15 + 40 + 45* ↔ QUD.

4. Remarkably, the QUD bound-state S-Matrix may have only the interactions of the Standard Model, with the known physical states as the low mass spectrum.

The picture we develop appears to be consistent with all existing experimental data. A crucial, and very unconventional, element is that the new physics producing electroweak symmetry breaking is due to a high mass sector of the (QCD) strong interaction that is predicted\(^1\), to produce dramatic, large cross-section, effects at the LHC. The new sextet sector also provides a natural explanation\(^1\) for the major mysteries of dark matter and the cosmic ray spectrum knee, as well as various other (currently mysterious) phenomena in both accelerator and cosmic ray physics.

We have arrived at QUD by singularly exploring research directions and problems considered “too difficult” and “far from the mainstream”, by the dictates of current fashion. As a result, our formalism appears obscure (for many physicists) and radical with respect to the current theoretical paradigm, making our arguments hard to present and their credibility easily questioned. Of course, it would be incredible if the Standard Model, with all of it’s complexity, has the underlying simplicity that we suggest. Nevertheless, all the needed ingredients are present and, despite the enormous amount still to be established, everything points to the correctness of our suggestion. If the predicted effects of the sextet sector are seen at the LHC, interest in QUD will surely rise rapidly.

Both QCD\(_S\) and QUD have special ultra-violet and infra-red properties that allow the construction of the high-energy, bound-state, S-Matrix using gauge theory reggeon diagrams and abstract multi-regge theory. Reggeons are gauge-invariant but carry the gauge group as a global symmetry that is confined by reggeization infra-red divergences. Physical amplitudes are selected by a further divergence due to chiral

\(^1\)QUĐ ↔ Quantum Unodynamics, or Quantum Unification Dynamics, or Quantum Unitary Dynamics
anomaly reggeon interactions[1]. With our regularization procedure, these interactions contain infra-red chirality transitions that, in effect, are the zero momentum contribution of a propagator to a condensate. However, the chirality transitions are present only in the S-Matrix and then only in special reggeon vertices obtained via the regge-limit reduction of large-order loop diagrams to effective triangle diagrams. The chirality transitions are crucial in the formation of physical states and in producing “wee gluon” interactions, but they do not break the short-distance gauge invariance. The resultant symmetry breaking and mass generation is a purely S-Matrix phenomenon - surely a radical element of our picture. There is no “Higgs field”, rather the masslessness of the field theory is essential.

In the QCD\(_S\) S-Matrix, there is confinement and chiral symmetry breaking but, in agreement with experiment, there is a much more limited spectrum[1] than is conventionally expected in QCD. (There are no glueballs, no BFKL pomeron, and no odderon.) When we first discovered[2] QUD, we were amazed and puzzled by the closeness of the triplet quark and lepton sectors to the Standard Model. (We asked only for the sextet sector.) With the emergence, in the QUD multi-regge S-Matrix, of the SU(3)\(\otimes\)SU(2)\(\otimes\)U(1) interaction structure, the deeper significance of this feature becomes clear. The dynamics is analogous to that of QCD\(_S\), but the gauge group appears broken at low transverse momentum because the anomaly divergences pick out (as the strong interaction) vector-like gauge boson exchanges invariant under an SU(3) subgroup. SU(3) octet quarks with lepton-like quantum numbers also play a vital role. They do not couple to the strong interaction (pomeron), but their short-distance presence produces the generation structure of the physical states and also reconciles leptons with the underlying SU(5) symmetry.

In this talk, we will outline only how the basic structure of the Standard Model S-Matrix emerges from QUD. We will not discuss how the physical scales, and associated phenomena, appear. A paper, explaining the arguments in detail, and also elaborating the physics, is in preparation[3]. We begin, very briefly, with the abstract formalism and unitarity constraints that provide the technical framework for our discussion.

## 2 Reggeon Unitarity and the Critical Pomeron

Multi-regge behavior is controlled by partial-wave amplitudes in which the (J-plane) singularity structure is determined by reggeon unitarity[4] equations (obtained from multiparticle unitarity in the corresponding t-channel). When first derived[5] these equations were a spectacular generalization from low-order field theory calculations. They were generally accepted only after the development of multiparticle asymptotic dispersion relations provided a fundamental basis for the complex angular-momentum
theory involved[4]. Reggeon unitarity is satisfied by all existing gauge theory calculations (including NLO BFKL) and plays a crucial role in our generalization of (still relatively low-order) known results to the multi-regge region of both QCD$_S$ and QUD.

Reggeon Field Theory[6] (RFT) provides an “effective field theory” solution of reggeon unitarity. For a pomeron with intercept one, multi-pomeron singularities accumulate at $J = 1$ (when $t = 0$) but, beautifully, an RFT renormalization group (fixed-point) formalism can be applied to obtain an interacting pomeron theory with the “universality” property of a critical phenomenon[7]. Scaling laws can be derived for many cross-sections and $s$-channel unitarity shown to be satisfied[8]. The “Critical Pomeron” provides a complete, unique, solution of high-energy unitarity - with asymptotically rising cross-sections. Since no competitive solution exists (field-theoretic or otherwise) the question is clearly whether there is a field theory which gives the Critical Pomeron.

3 The Critical Pomeron and QCD$_S$

The supercritical phase, in which the pomeron intercept is initially above one, provides a direct link between the Critical Pomeron and QCD$_S$. A pomeron condensate pushes the physical intercept back below one while also giving[9] new classes of RFT diagrams in which a reggeized vector particle appears that couples pairwise to the pomeron. When SU(3) color is broken to SU(2) (giving “color superconducting QCD” - CSQCD) a single massive, reggeized, vector particle is deconfined - exactly as in the supercritical pomeron phase. A necessary condition for critical behavior is that the scalar field involved be asymptotically free, so that SU(3) symmetry restores smoothly at large and small momentum. This requires[10] saturation of the QCD asymptotic freedom constraint[1]. Also, we will see that a regge pole pomeron appears from divergent reggeon diagrams only when there are scaling interactions due to the infrared fixed-point produced by the same saturation. The unique (physically realistic) possibility[11] to achieve saturation is to add two color sextet quarks to the known six triplets - giving QCD$_S$. The “sextet pions” can then become the longitudinal components of massive electroweak vector bosons.

Because cross-sections fall in both the subcritical and supercritical phases, while perturbative gauge theory cross-sections rise, if the pomeron is not critical it is unlikely that asymptotically free perturbation theory can be matched with unitary forward amplitudes. Assuming the explicit connection between CSQCD$_S$ and the supercritical pomeron is as described in the next Section, then QCD$_S$ uniquely gives the Critical Pomeron and unitarity of the strong interaction is linked directly to electroweak symmetry breaking.
4 The States and Amplitudes of QCD$_S$

We consider multi-regge kinematic regions[12] where, a priori, we expect[1] to see the high-energy scattering of bound-state regge poles. We, initially, construct amplitudes with the reggeon diagrams of CSQCD$_S$ (as in the particular example shown in Figure 1). Reggeon unitarity determines that the reggeon diagrams involved are similar to elastic scattering diagrams, except for the crucial difference that vertices coupling distinct reggeon channels can contain triangle anomalies. In fact, an infra-red divergence selects, as bound-state physical amplitudes, those in which all reggeon channels are coupled via anomalies.

To describe the role of anomalies, we consider the multiple vector boson amplitude shown in Figure 1, in which there are color zero massless gluon components in each reggeon channel. The divergence of reggeization exponentiates to zero (in momentum space) all CSQCD$_S$ amplitudes with non-zero $SU(2)$ color in any channel. Figure 1 is the simplest amplitude in which anomalies appear in all vertices. They are generated[13, 14] as illustrated in Figure 2, which also shows how an “anomaly pole” appears, via a chirality transition, when the gluon reggeons carry zero transverse momentum. (We discuss the deeper implications of using vector boson external states in the next Section.)

![Figure 1: Reggeon diagrams giving pion scattering via pomeron exchange.](image1)

![Figure 2: Generation of a reggeon vertex triangle anomaly. The hatched lines are on-shell and the broken quark line indicates a zero momentum chirality transition.](image2)
The initial effect of the anomalies is a large transverse momentum (non-unitary) power enhancement [13] of the high energy behavior. A cut-off removes the problem, but gauge invariance violation then gives an infra-red divergence as all gluon transverse momenta scale to zero. If a massless gluon state has normal color parity (= signature), interactions with additional reggeons exponentiate this divergence. It is not exponentiated only if all massless gluon states have “anomalous” (≠ signature) color parity. In a vector theory, such states couple only to anomalies. Crucially, the fixed-point scaling of higher-order gluon interactions preserves the “anomalous wee gluon” divergence to all orders.

The residue of the wee gluon divergence gives a physical CSQCD$_S$ amplitude in which the cut-off can be removed and all the massless gluons in Figure 1 contribute only as an anomalous wee gluon condensate. $SU(2)$ anomalous gluons have odd signature and so the pomeron is an even signature regge pole which, because of the condensate, is exchange degenerate with a reggeized massive gluon, just as in supercritical RFT. The anomaly poles produce [1] Goldstone boson particles that, because of the equivalence of conjugate $SU(2)$ representations, include quark/quark and antiquark/anti-quark nucleons, in addition to quark/antiquark pions. The condensate is a crucial component in both the particles and the pomeron. It provides the (vacuum equivalent) “universal wee parton” component of infinite momentum physical states. Within the anomaly vertex, the condensate is absorbed by the chirality transition of a zero momentum anti-quark (or quark), implying that a pion can be viewed as a pure quark/antiquark state, but either the quark or antiquark has to be in an unphysical, “negative energy”, state.

By removing the cut-off after the extraction of anomaly infra-red divergences, we replace ultra-violet chirality violation (producing bad high-energy behavior) by infra-red chirality violation producing particle poles. This is how a confining, chiral symmetry breaking, bound-state spectrum is generated out of perturbative reggeon diagrams.

Assuming high-energy CSQCD$_S$ maps completely on to the supercritical pomeron (as all evidence suggests), then the transition to QCD$_S$ does indeed give the Critical Pomeron. Because the triple pomeron vertex involves [1] a chirality transition, and the Critical Pomeron is an all-orders phenomenon, there will be arbitrarily large numbers of transitions in any scattering process. The wee gluon condensate, carrying fixed SU(3) color, will disappear and instead there will be dynamical (effectively random) multi-reggeon gauge field fluctuations within the color group (that are specifically allowed by the Gribov ambiguity in the light-cone quantization of QCD.) The transition from a fixed “magnetization” for the Dirac sea shifting gauge field, to a random, fluctuating, field is the “critical phenomenon” underlying the Critical Pomeron. It provides a complex, but beautiful, wee parton (vacuum-like) phenomenon which makes a dramatic selection of the field theory degrees of freedom contributing to
the S-Matrix. The gauge symmetry is not broken but color charge parity and chiral symmetry are both broken spontaneously.

QCD$_{S}$ baryons are bound states of CSQCD$_{S}$ nucleons and $SU(2)$ singlet quarks. (Most likely, the additional quark also contributes, initially, via a zero momentum chirality transition.) Because there are no chiral symmetries mixing the two sectors, there will be no “hybrids” consisting of sextet quarks (antiquarks) and triplet antiquarks (quarks). This has the very important implication that the only new baryons will be the sextet proton and the sextet neutron. The neutron is expected to be stable and so provides a naturally dominant (and very attractive) source of dark matter[1].

For the physics of QCD$_S$ to be as we have described it, the quarks have to be massless (implying many massless Goldstone bosons). This is a non-trivial problem, and it may very well be that the only possibility to introduce effective quark masses is via the bound-state masses resulting from the embedding of QCD$_S$ in QUD discussed below.

5 QCD$_S$ and the Electroweak Sector

The use of left-handed vector bosons as external states ensures that our pions are Goldstone bosons of the weak interaction. Indeed, it could be that the pion states and amplitudes we have described are not present in QCD$_S$ in isolation and that the presence of the electroweak interaction is essential. In fact, the nature of the physical states in QCD$_S$ is, in turn, essential for the generation of a mass for an exchanged vector boson.

Sextet quarks (antiquarks) have the same $SU(3)$ triality as triplet antiquarks (quarks) and so we anticipate that their electroweak couplings will be the same. At infinite momentum, the “anomalous wee gluons” (wee partons!) should reproduce finite momentum “vacuum properties”. A wee gluon anomaly interaction generates[1] a vector boson mass, via mixing with a pion anomaly pole, as illustrated in Figure 3. Adding the diagram with $1 \leftrightarrow 2$ gives the mass as an integral over wee gluon

![Figure 3: Interactions Producing the Vector Boson Mass.](image)
longitudinal momenta ($ \mathcal{M}_V^2 \sim \int kdk$). This mass appears only in the S-Matrix, and occurs only for vectors with a left-handed coupling. Both sextet and triplet pions contribute but the sextet pions dominate because of larger color factors. Assuming the Casimir Scaling rule holds ($C_6 \alpha_s(F_\Pi^2) \sim C_3 \alpha_s(F_\pi^2)$ with $C_6/C_3 \approx 3$), the sextet chiral scale gives an electroweak scale of the right magnitude! (The large wee gluon coupling to sextet quarks is central in our understanding of high-energy cross-sections.)

6 Embedding $QCD_S$ in QUD

If sextet pions are to produce electroweak symmetry breaking, the sextet electroweak anomaly must be canceled. Above the electroweak scale, the $QCD_S$ infra-red fixed point implies that $\alpha_s \leq 1/34 \sim \alpha_{ew}$ and so the sextet sector can produce the decrease in $\alpha_s$ needed for unification. Supersymmetry is not required!! Looking for a unified theory, we found[2] (a long time ago) a remarkable result. Requiring that the sextet sector be contained in an asymptotically free, anomaly free, theory uniquely selects QUD.

The SU(3)$\otimes$SU(2)$\otimes$U(1) decomposition of the individual fermion representations is[2]

$5 = (1, 3, -\frac{1}{3})^{(3)} + (2, 1, \frac{1}{3})^{(2)}$, $\quad 15 = (1, 3, 1) + (3, 2, \frac{1}{3})^{(1)} + \{6, 1, -\frac{2}{3}\}$

$40 = (1, 2, -\frac{3}{2})^{(3)} + (3, 2, \frac{1}{3})^{(2)} + (3^*, 1, -\frac{2}{3}) + (3^*, 3, -\frac{2}{3}) + \{6^*, 2, \frac{1}{3}\} + \{8, 1, 1\}$

$45 = (1, 2, -\frac{1}{2})^{(1)} + (3^*, 1, \frac{1}{3}) + (3^*, 3, \frac{1}{3}) + (3, 1, -\frac{4}{3}) + (3, 2, \frac{7}{6})^{(3)} + \{6, 1, \frac{1}{3}\} + \{8, 2, -\frac{1}{2}\}$

Very importantly, as we will see, the complete representation is real with respect to SU(3)$\otimes$U(1)$_{em}$. There are three “generations” of quarks/anti-quarks (labeled $\{1\}, \{2\}, \{3\}$) with quark charges $\frac{2}{3}$ and $-\frac{1}{3}$ and so QUD contains $QCD_S$. There are also three “generations” of leptons - SU(2) doublets that are SU(3) singlets. Given that there is no freedom to add more fermions, it is very fortunate that we already have the triplet quark and lepton sectors of the Standard Model, together with dark matter!! However, the SU(2) $\otimes$ U(1) quantum numbers are clearly not quite right. Also, at first sight, the color octet quark sector is completely unwanted, as are the exotic quarks.

It would be bizarre indeed if we had arrived at a unique theory that “almost” produces the Standard Model. Originally, although we saw that QUD has the same asymptotic freedom saturation properties as massless $QCD_S$, we did not understand the construction of high-energy $QCD_S$ well enough to appreciate that high-energy QUD could be constructed in a similar manner. Once this is understood, it is only a short step to the stunning realization that the Standard Model S-Matrix could
actually emerge.

7 Construction of QUD High-Energy States and Amplitudes

We refer to SU(5) gauge boson reggeons as unons. It will be essential that, because unons are gauge invariant, the symmetries we discuss are global and cancelations can involve unons carrying very different transverse momentum. We will identify three fundamental dynamical elements as crucial in producing the states and S-Matrix of the Standard Model from QUD. The first, and most important, is

[1] interactions of left-handed unons exponentiate “anomalous” divergences.

As a result, “wee unon anomaly divergences” and the corresponding dynamical chirality transitions, can only involve unon combinations within a maximal non-abelian vector subgroup. This selects the strong interaction as involving (a sum over) unon combinations that are each singlets under some SU(3) subgroup. To construct high-energy amplitudes explicitly, we go to the multi-regge kinematic region, as we did when discussing QCD$_S$.

We start within CSQUD (SU(5) color broken to SU(4)) and expect to find high-energy QUD as a critical phenomenon. Imposing a $k_L$ cut-off and choosing the vector SU(3) symmetry as illustrated in Figure 4(a) we also, initially, break SU(4) to SU(2)$_C$. The resulting massive unons are an SU(4) singlet vector $x$, two SU(2)$_C$ doublet vectors $x'$, and left-handed SU(2)$_C$ singlets $x''$. As illustrated in Figure 4(b), we consider the scattering of $x''$ unons in the multi-regge region. (The $x''$ unons will decouple as SU(5) symmetry is restored, leaving only bound-state amplitudes.)

\[ \text{SU(3) color} \]
\[ \begin{array}{c|c|c|c|c}
   x & x' & x'' & x'' & x'' \\
   \hline
   x' & \sigma & \sigma & \sigma & \sigma \\
   x'' & \sigma & \sigma & \sigma & \sigma \\
   \hline
   \text{SU(2)$_C$} & \text{SU(2)$_C$} & \text{SU(2)$_C$} & 0 & 0 \\
   \text{SU(2)$_L$} & \text{SU(2)$_L$} & \text{SU(2)$_L$} & 0 & 0 \\
\end{array} \]

\[ x,x',x'' = \text{massive unons} \]
\[ o = \text{SU(2)$_C$} \times \text{SU(2)$_L$} \text{unons} \]

Figure 4: (a) Symmetry Breaking (b) Vector Boson Scattering

SU(2)$_C$ is a vector symmetry and so, as in CSQCD$_S$, there will be a “wee gluon condensate” that produces the physical amplitudes. All states are SU(2)$_C$ singlet chiral Goldstone bosons ($\pi_C$’s). They are quark, antiquark, and quark/antiquark pairs, with one of the pair unphysical (or, equivalently, both physical within the
condensate). Under SU(3) color, the quarks are 3’s, 6’s, and also 8’s. The 8’s appear because

[2] octets are real under SU(3), but contain complex conjugate doublets under SU(2)C.

This is the second fundamental dynamical element. The doublets have the necessary chiral symmetry to form Goldstone boson physical states via SU(2)C divergences.

The x’ and SU(2)C⊗SU(2)L unons will be confined via SU(2)C divergences. Interactions due to SU(2)C singlet unons in the wee gluon condensate will be

1. Exchange of a massive x gluon in the condensate ↔ pomeron.
2. Exchange of SU(2)L⊗ U(1) unons in the condensate ↔ W±, 0, Y.
3. Exchange of a massive x” unon in the condensate.

together with the exchange of any combination. The “vacuum properties” of the SU(2)C condensate are the third fundamental dynamical element. As described in Section 5,

[3] wee gluon interactions give left-handed SU(2)L× U(1) unons a mass.

Only left-handed unons (W± and Z0) acquire a mass this way. In even signature channels, a similar mixing should generate masses for all πC’s that do not couple to the W± and Z0. (There are no exact chiral symmetries, and hence, no massless particles in QUD.)

Because the unons involved are either left-handed or abelian, restoring SU(2)L⊗U(1) symmetry gives no new anomaly divergences, but reggeization divergences imply that only SU(4) invariant states and interactions survive. “Leptons” are present as bound states of elementary leptons and octet pions. For example, in SU(3)⊗SU(2)⊗U(1) notation, the electron/neutrino will be (1, 2, −⅓) × (8, 1, 1) × (8, 2, −⅓) ↔ SU(5) singlet 45∗×40×45∗. (The muon will contain three elementary leptons, as will the τ.)

Full SU(5) symmetry is achieved by removal of the cut-off, followed by SU(3) restoration. The pomeron becomes critical and the wee gluon component of the photon and the W±, Z0 becomes even signature (essentially the zero transverse momentum component of the pomeron). The octet pions are no longer Goldstone bosons and so they disappear from the low transverse momentum region. SU(3) reality also implies they have no anomaly coupling to the pomeron. As a result, leptons have no strong interaction and no infra-red SU(3) mass generation. Because the octet pions contribute only at large transverse momentum, the SU(2)L⊗U(1) symmetry will appear as physical in low transverse momentum interactions (with SU(2)L → sextet pion flavor symmetry). Assuming the SU(2)L⊗U(1) anomaly cancellation is maintained by bound-states, three generations of “hadrons” will form from triplet quarks and octet pions, as low mass bound-state partners of the leptons. The SU(2)L⊗U(1)
quantum numbers of the octet pions are \((2, \frac{1}{2})\), \((1, -1)\), and \((3, -1)\), with unons canceling the triplet. Therefore, at low transverse momentum, the states will have the \(SU(2) \otimes U(1)\) singlet/doublet generation structure of the Standard model. Clearly, the octet quarks, which at first sight seem unwanted, are fundamental for \(SU(5)\) invariance and the generation structure of states.

We are a long way from establishing much of what we have described and obvious questions have been left unanswered (partly because of lack of space). There is also much more that we have not discussed at all. Nevertheless, the possibility that QUD produces the Standard Model S-Matrix seems very real indeed.

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