The LHC Pomeron and Unification of the Standard Model
- a Bound-State S-Matrix Within a Fixed-Point Field Theory?

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Abstract

The Critical Pomeron solution of high-energy unitarity leads to a unique underlying massless field theory that might be the origin of the Standard Model. A color sextet quark sector - producing both electroweak symmetry breaking and dark matter - is added to QCD to saturate asymptotic freedom. The sextet sector is then embedded uniquely in “QUD” - an anomaly free, just asymptotically free, massless SU(5) theory with elementary lepton and triplet quark sectors very close to the Standard Model. A multi-regge bound-state S-Matrix is constructed using infra-red divergent scaling reggeon interactions that couple via massless fermion chiral anomalies. Within the QCD sub-sector there is an “anomalous wee gluon” critical phenomenon that produces a spectrum with confinement and chiral symmetry breaking. The exponentiation of left-handed gauge boson divergences implies that the full set of composite interactions and the low-mass spectrum of QUD could be just those of the Standard Model. All particles, including neutrinos, appear as massive, Goldstone boson related, bound-states and there is no Higgs field. The different coupling strengths, multiple mass scales, and multigenerational structure should also appear. The Critical Pomeron may be the S-Matrix manifestation of the underlying fixed-point field theory.

If QUD underlies the Standard Model as described, the sextet sector should produce new, unmistakeable, large cross-sections at the LHC, for which the pomeron could be the main diagnostic!
1. INTRODUCTION.

To suggest there may be a unique, unitary, particle S-Matrix is very heretical in the current theoretical climate - given the wide variety of field theories and string theories studied. Even so, I will argue that unitarity may be the key to the origin of the Standard Model as a bound-state S-Matrix embedded (without off-shell amplitudes) in an almost conformal massless field theory. This is a radical proposition which the LHC will determine to be either crazy heresy or singularly original insight.

To produce a unitary S-Matrix in an asymptotically free gauge theory, large momentum perturbation theory has to match with a high-energy, low transverse momentum, “non-perturbative” solution of both s and t-channel multiparticle unitarity that produces asymptotically rising cross-sections. This is an extremely strong constraint, the significance of which may not be fully appreciated. As far as is known, the only non-trivial solution of all high-energy unitarity constraints is the Reggeon Field Theory Critical Pomeron[1]. After a long quest to understand how this solution can be produced by gauge theory reggeon interactions, I have concluded that a unique underlying massless gauge theory is required. Furthermore, special small $\beta$-function properties of this theory allow a high-energy bound-state S-Matrix, dominated by fermion anomalies, to be constructed diagrammatically via multi-regge theory. Remarkably, it seems that the S-Matrix of the full Standard Model could emerge as a generalization of the emergence of the hadron S-Matrix from QCD. The asymptotic scaling of the Critical Pomeron is a reflection of a fixed-point in the underlying field theory. Here are some quotes from the opening paragraphs of a forthcoming paper[2].

“In this paper we will discuss a theory, which we refer to as QU D#, that it appears might provide a complete and self-contained origin for the Standard Model. We will present arguments that SU(5) gauge theory with the left-handed, massless, fermion representation[3]

$$5 \oplus 15 \oplus 40 \oplus 45^*$$

has a bound-state high-energy S-Matrix which contains only the interactions of the Standard Model and also has, qualitatively at least, the correct low mass spectrum. If the states and high-energy amplitudes are produced by chiral anomaly coupled multi-regge infra-red divergences, as we outline, then all elements of the Standard Model will be present in an extraordinarily economic manner ...

Although much remains to be done to complete the picture we develop and many of our arguments are speculative it is clear that an essential, but very unconventional, element that is required for the emergence of the Standard Model S-Matrix from QU D is that electroweak symmetry breaking is associated with a new, high mass, sector of the (QCD) strong interaction[4, 5, 6]. This new strong sector is predicted[4] to produce large cross-section effects at the LHC - in addition to providing a natural explanation for the existence and predominance of dark matter, the cosmic ray spectrum knee, and other cosmic ray phenomena.”

#Quantum Uno/Unification/Unitary/Underlying Dynamics
The discovery of QUD at the LHC would have a revolutionary effect on the field!!

**Experimentally**, the new physics involves large cross-section phenomena very different from common expectations for physics “beyond the Standard Model”.

- The new phenomena include the strong interaction production of both electroweak vector bosons and dark matter candidate “neutrons” composed of color sextet quarks. These cross-sections will be enhanced by large (sextet quark) color factors. Sextet neutrons will be stable and their (QCD) self-interaction will also be very strong, but with the short-range of the electroweak interaction - consistent with properties, currently, anticipated for dark matter.

- The ILC would be completely wrong - as the next machine. A higher-energy SSC would be the obvious choice, preferably with help from an e-p machine.

**Theoretically**, QUD also has very unexpected and unconventional properties.

- As a field theory, it is massless and almost conformally invariant. An infra-red fixed-point keeps the gauge coupling very small ($\alpha_u << 1/50$) - providing a potential explanation for small neutrino masses.

At first sight QUD is an “unparticle”[7] theory that, it would be expected[8], can not have a non-perturbative particle spectrum because of the infra-red scale invariance of off-shell Green’s functions. Our expectation is, however, that the full field theory is defined only perturbatively (as a large momentum expansion), with no well-defined non-perturbative Green’s functions, and in a major break with the current theoretical paradigm, we expect the physical states and interactions to appear only in the S-Matrix. Infra-red scale invariance is then manifest in the chiral anomaly coupled wee gluon reggeon interactions that dominate the dynamics producing a multi-regge bound-state S-Matrix. Amongst the significant properties that emerge are

1. Anomaly domination of wee gluon reggeon interactions implies that only a very small subset of the field theory degrees of freedom contribute to the S-Matrix.

2. An “anomalous wee gluon” critical phenomenon occurs in which, because of the conjugacy properties of the fermions, only Standard Model interactions survive.

3. All particles are, Goldstone boson related, bound-states with masses generated by reggeization, mixing, and anomaly interactions - there is no Higgs field.

It is well-known that, at infinite momentum, “universal wee partons” could, potentially, play the role of a vacuum and that this is probably a necessity for a full parton model to be valid in QCD. In fact, we are able to access “non-perturbative”
physics in the multi-regge region just because, in effect, infinite momentum frame
kinematics are introduced for all states and interactions. (As a result, our description
of the properties of states can be quite different from, although it must be consistent
with, descriptions at finite momentum.) By using the power of the multi-regge theory
that we have developed, we are then able to construct bound-state amplitudes in
terms of reggeon diagrams. Previously we have shown[4] that in massless QCD$_S$, a
QCD sub-sector of QUD, the chiral anomaly dynamics produces an anomalous wee
gluon “vacuum” component of both the pomeron (which is critical) and all bound-
states. Although there are important distinctive properties relative to conventional
QCD, as far as we know, our results are consistent with all the (experimentally
established) properties of QCD below the electroweak scale. A crucial distinction
is, however, the limitation on the spectrum of states compared to what would be
anticipated from just color confinement and chiral symmetry breaking. The spectrum
we obtain, particularly the absence of glueballs, is more consistent with experiment
than conventional QCD expectations, as is the absence of the BFKL pomeron.

In the following, we will outline arguments that the chiral anomaly dynamics
responsible for our solution of QCD$_S$, produces in QUD just the interactions and
bound-states of the Standard Model. As will become apparent, unfortunately, al-
though we are able to describe qualitatively how the dynamics operates and how
states and amplitudes are obtained, there is still much that needs to be done to
identify physical scales and even to determine how many parameters are actually
involved in the constructions we describe.

We build up the high-energy behavior of both QCD$_S$ and QUD by starting in
a supercritical pomeron (color superconducting) phase in which the gauge symmetry
is partially broken. A resulting anomalous gluon infra-red divergence produces a wee
gluon condensate and directly determines the physical amplitudes, with the physical
states being anomaly-pole chiral Goldstone bosons. Higher-order contributions of
chirality transition vertices can then be built up perturbatively. Restoration of the
full color symmetry produces critical behavior in which the production and absorption
of anomalous wee gluons becomes a dynamical collective phenomenon.

The vertices that couple anomalous wee gluons contain both a chirality tran-
sition and an on-shell longitudinal gluon interaction. This interaction is present in
the color superconducting phase and can be present in the unbroken theory via the
Gribov (light-cone) quantization ambiguity. Physically, the anomaly vertices describe
the production of a fermion pair, one of which is a zero momentum hole state which
becomes physical via compensating wee gluon emission. Viewing the wee gluon emis-
sion as resulting from an initial displacement of the Dirac sea, we can identify this
“Fermi surface fluctuation” as the order parameter of the pomeron phase-transition.
In the supercritical phase it is a correlated “reggeon condensate” that, in our con-
struction, is introduced by the color symmetry breaking. At the critical point the
Fermi surface fluctuations are dynamical and uncorrelated (locally random within
the color group), but produce long-range correlations as a collective phenomenon. In
QUD, the Fermi surface anomalous wee gluon emission (and Critical Pomeron be-

We will see that QUD is an extraordinarily minimal extension of the Standard
Model in that almost all of the elements that are clearly “Beyond the Standard Model”
have an essential dynamical role. There is a sextet quark sector that, as we have
emphasized, produces both electroweak symmetry breaking and dark matter. There
is also an octet quark sector that has lepton electroweak quantum numbers. As a real
SU(3) representation, the octet quarks play a crucial role in allowing leptons to be
SU(5) invariant, while having no strong interaction. The octet sector also appears to
be responsible for the emergence of the Standard Model generation structure.

2. COSMIC RAY AND TEVATRON EVIDENCE

There is already substantial evidence in cosmic ray physics that there could
be a major strong interaction change in the energy range between the Tevatron and
the LHC. In Fig. 1 we show the well-known knee in the cosmic ray spectrum. It
is a remarkable, very well-established, phenomenon that occurs between Tevatron
and LHC energies. The associated break in the slope stands out, distinctively, as
the energy increases over some ten orders of magnitude and the flux decreases by
thirty orders of magnitude. Although it is generally believed to be due to a (so
far not understood) conspiracy of external phenomena, a change in the atmospheric
interaction seems far more plausible. From it’s earliest discovery, it was suggested[9]
that the knee could be a threshold for production of neutral particles not observed
in the ground level detectors. The resulting underestimation of the shower energy
would lead to a pile-up of events that would be observed as a “knee”. However, a
major part of the cross-section has to be involved and there was no credible proposal
as to what the neutral particles could be.

The energy scale for the sextet sector is the electroweak scale and sextet cross-
sections should be larger than triplet cross-sections because of color factors. However,
the effective energy threshold for production of the sextet sector is determined by in-
clusive pomeron exchange, since this is the only large cross-section mechanism for
sextet states to be produced by triplet states. According to current diffractive phe-
nomenology, the onset of inclusive pomeron production of electroweak scale states
should be around the energy of the knee. Three effects that will contribute to the
formation of a knee are
Figure 1. The knee (a) all data (b) less data (c) with the slope extracted.

1. Prolific production of vector bosons will increase the average transverse momentum enormously and will also increase the relative neutrino production. Energies will be seriously underestimated by the unexpected shower spread and increased neutral component.

2. Dark matter (sextet neutron) production, and the resultant energy underestimation, will increase rapidly with energy. This is close to the original explanation of the knee as due to the production of neutrals. Of course, dark matter was unknown and the link with the knee, that I am proposing, could not have been imagined.

3. Sextet neutron dark matter should be a major component of incoming cosmic rays. Since the pomeron again has to be involved, the atmospheric interaction will have a threshold energy that is not far below the normal matter sextet threshold energy and, once underway, will share properties 1. and 2.

Probably, the observed knee can only be reproduced if this last effect (which will produce a direct “bump” in the spectrum) is a significant part of it’s formation.
Unfortunately, we have ignored this effect in our previous discussions. Consequently, using the knee events as a basis, our estimates of the needed magnitudes for the first two effects, and the corresponding LHC cross-sections, were dramatically large and, perhaps, impossible to reproduce theoretically. With the third effect included, the knee seems relatively straightforward to reproduce. The expected new LHC cross-sections must still be large, strong interaction, effects. However, they may not be quite as “dramatic” as we have previously emphasized.

There are a large number of other new phenomena seen in cosmic ray showers with energies above the knee. In Fig. 2 we show one of the most interesting[10], involving the production (essentially) of high $E_T$ jet pairs. A QCD Monte Carlo tuned to jet data at collider energies fails to reproduce the data above the knee, by orders of magnitude, as would be expected if the sextet sector is produced.

![Figure 2 Dijet production](image)

There are also indications from the Tevatron that there will be a strong interaction change at higher energies. We discuss two phenomena, illustrated in Fig. 3,

![Figure 3(a) The Inclusive Jet Cross-Section (b) Evolution of $\alpha_s$](image)
which both suggest that new QCD physics enters above the top mass scale. In Fig. 3(a) we show the Run 2 inclusive jet cross-section[11] obtained using a cone algorithm. Naively, the data pull away from the theory from $E_T \sim m_t$ upwards, indicating that QCD jet physics above the electroweak scale may be breaking down in just the manner that we would expect, as the sextet sector enters the theory.

In Fig. 3(b) we show the measured evolution[12] of $\alpha_s$. The inclusion of a sextet quark doublet in the QCD $\beta$-function would halt the evolution of $\alpha_s$, just as appears to be happening at $E_T \sim m_t$. That this is the right sextet scale can be argued by noting that $E_T \sim m_t$ is also $E_T \sim 2M_W$. Alternatively, as discussed at more length in [4], it could well be that top production is due to a resonance (the $\eta_6$) that is the sextet sector analog of the Higgs particle. This would imply that the top quark mass is actually the sextet constituent mass scale, and it would be expected that deviations from conventional QCD would start above this scale.

3. THE PATH TO CONFINING QUD

The logical steps that lead, uniquely, to QUD can be summarized as follows. They will be discussed in much more detail in [2].

1. The Critical Pomeron, obtained[1] as a renormalization group solution of Reggeon Field Theory (RFT), is the only known solution[13] of full multiparticle unitarity - in both the $t$ and $s$ channels - that gives asymptotically rising cross-sections.

2. Supercritical RFT matches[4] with color superconducting QCD. That hadrons must also have supercritical properties[4] is achieved, as we will see, by “anomalous wee gluons” appearing in both hadrons and the pomeron. The matching with supercritical RFT, shows that the Critical Pomeron occurs in QCD when asymptotic freedom is “saturated”. The only realistic quark content is six color triplets plus two color sextets, giving[14] what we refer to as \textquotedblleft QCD$_S$\textquotedblright.

3. If the sextet quarks have the right electroweak quantum numbers, the “sextet pion” sector will produce electroweak symmetry breaking - without any new interaction. The electroweak scale will be the QCD sextet chiral scale, which Casimir scaling implies[4, 5] is the right order of magnitude.

4. To cancel the electroweak anomaly and to generate particle masses, the sextet sector should be embedded in a left-handed unified theory.

5. Asking for the sextet sector, plus asymptotic freedom, plus anomaly cancellation, uniquely[3] selects QUD, i.e. SU(5) gauge theory with the left-handed fermion representation

\[5 \oplus 15 \oplus 40 \oplus 45^*\]
Amazingly, the triplet quark and lepton sectors of QUD, although they were not asked for, are very close to the Standard Model!! There are three “generations” of quarks and antiquarks with charges $\pm \frac{2}{3}$, $\pm \frac{1}{3}$, (implying that QUD contains QCD$_S$) and there are also three “generations” of leptons. The $SU(3) \otimes SU(2) \otimes U(1)$ decomposition of QUD is

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

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

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

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

The “Standard Model” quark and lepton generations, denoted by superscripts $\{1\}$, $\{2\}$, and $\{3\}$, are scattered amongst the separate SU(5) representations. Clearly, the SU(2)xU(1) quantum numbers are not quite right when compared directly with the Standard Model. For a long time this seemed to be an insuperable problem for relating QUD to the Standard Model via any standard (or non-standard) Higgs’ mechanism. Note that QUD is real, i.e. is a vector theory, with respect to SU(3)xU(1)$_{em}$.

Eventually, I realized that QUD should be considered directly as a confining theory, without any additional symmetry breaking mechanism, and that this is how it can compare with the Standard Model. In the QUD S-Matrix SU(5) color is confined, not just SU(3) color, and so all elementary gauge bosons and fermions are confined and massless. For the Standard Model to emerge, it must have the same relationship to QUD that the hadronic sector has to QCD !!! All hadrons and leptons have to be QUD bound-states and, also, all Standard Model interactions have to be composite.

That confining QUD might give the Standard Model S-Matrix became apparent to me only after I understood[4] the dynamics of high-energy massless QCD$_S$ in which, as we have described in the Introduction, the S-Matrix is dominated by anomaly vertices containing zero momentum fermion chirality transitions. The chirality transitions play a similar role to condensates - but only in the S-Matrix !! In our multi-regge construction of amplitudes they appear as relic effects in anomalous reggeon vertices when initial mass generating scalar fields are decoupled. (The description of the dynamics that we give will make it clear why the chirality transitions contribute only in scattering processes involving asymptotic states.) In massless QCD$_S$, because it is a vector theory that conserves parity, the chirality transitions lead only to chiral symmetry breaking and color parity breaking by the pomeron. Correspondingly, it is because QUD is vector-like only with respect to an SU(3)xU(1)$_{em}$ subgroup that the chirality transition anomaly vertices naturally select the interactions of the Standard Model.
The only elements of the QUD fermion representation that are clearly “Beyond the Standard Model” are the following.

1. The sextet quark sector, as we have already talked about, produces both electroweak symmetry breaking and dark matter.

2. The octet quark sector has lepton electroweak quantum numbers. Because they carry a real SU(3) representation, the octets can not form physical states as chiral Goldston bosons. As a result, they play a very different dynamical role to the triplet and sextet quarks. As we will see, they are nevertheless crucial in allowing leptons to be SU(5) invariant and in producing the correct generation structure of the Standard Model.

3. We will not find a role for a pair of exotically charged triplet quarks.

4. MULTI-REGGE REGGEON AMPLITUDES

The analytic multi-regge theory that we have developed over the years[15] provides a very powerful tool for the construction of bound-state scattering amplitudes. For example, the amplitude for bound-state regge pole pions to scatter via pomeron exchange should be contained in a di-triple-regge amplitude, as illustrated in Fig. 4.

![Figure 4. A di-triple-regge amplitude.](image)

(It will be clear later why we have chosen the external scattering states to be vector bosons.) Kinematic descriptions of multi-regge limits can be found in various references[15] and we will not give them here. Suffice it to say that each circle vertex in Fig. 4 is separated from adjacent vertices by a large longitudinal momentum, in various space directions, in such a way that a regge exchange contributes to each leg of the diagram. (As we noted in the Introduction, this implies that both bound states and interactions can be viewed as infinite momentum states that, as we will see, have a “wee parton” component that has a vacuum-like role.) Here we will concentrate on
the procedure for obtaining an amplitude of the form of Fig. 4 from QCD$_S$ and QUD reggeon diagrams. What we describe will be just an outline. More details will be given in [2]. We anticipate that, if QUD is discovered, the use of reggeon diagrams to calculate bound-state amplitudes will become a major technology and what we describe would be just the beginning of what would become the central calculational procedure.

The multi-regge region is where the abstract properties of the S-Matrix are the most powerful[15, 16]. In this kinematic regime, S-Matrix amplitudes have a simple analytic structure and the physical region discontinuity formulae needed to write multiple dispersion relations have been established. As a consequence, multiparticle complex angular momentum theory has been put on a firm foundation and, most importantly, the multi-regge S-Matrix has been shown[15] to be controlled by “reggeon unitarity” equations formulated directly in the angular momentum plane. These equations are discontinuity formulae for all the singularities that control multi-regge asymptotic behavior. Before QCD, these equations were used to formulate Reggeon Field Theory as an effective lagrangian formalism which perturbatively solves the unitarity equations. A renormalization group formalism was then introduced and the Critical Pomeron obtained[1] as a fixed-point solution. That the reggeon unitarity equations are satisfied by the abstract, but calculable, RFT Critical Pomeron can be regarded as the pinnacle achievement, so far at least, of abstract S-Matrix Theory.

Reggeon unitarity is also satisfied, perturbatively, by all existing calculations of gauge theory regge behavior. The leading multi-regge behavior of a feynman diagram is typically obtained by routing the large external light-cone momenta through the diagram so that the maximal number of particles are close to mass-shell and have large, relative, longitudinal momentum separations. After longitudinal integrations are carried out, the result is a transverse momentum diagram (integral) multiplied by logarithms of invariant energies. In a non-abelian gauge theory, all the transverse momentum diagrams generated perturbatively can be organized[17] into gluon and quark reggeon diagrams. Reggeon diagrams are transverse momentum diagrams with additional reggeon propagators (in either complex angular momentum or rapidity space) that reproduce the energy logarithms while simultaneously satisfying reggeon unitarity.

As far as is known, when all the reggeons are massive, reggeon diagrams provide a complete, perturbative, description of a spontaneously broken gauge theory in all multi-regge limits. In particular, this is the case when the gauge symmetry is completely broken by the Higgs mechanism. The reggeon diagrams are gauge invariant but both the reggeized gauge bosons and the reggeized fermions carry their original gauge theory representations as global representations of the gauge group. In general, Higgs scalars do not reggeize and so (before the Higgs scalars are decoupled) multi-regge theory is applicable only to the leading high-energy behavior which originates
from the vector bosons and fermions.

To obtain the bound-state amplitude of Fig. 4 it is necessary, a priori, to consider all multi-regge reggeon diagrams of the general form illustrated in Fig. 5, and a lot more as well. At first sight, this an impossibly difficult task.

![Figure 5. A di-triple-regge reggeon diagram amplitude.](image)

Fortunately, the problem can be brought under control as follows. Reggeon unitarity determines[15] that the kinematic structure and interactions in each t-channel are the same as in well-known elastic scattering diagrams. Only the interactions coupling the separate t-channels (the largest circles in Fig. 5) are more complicated. As a result, we can discuss the infra-red divergences that occur when the reggeons are massless in general terms before considering the specific, very complicated, diagrams. We can then show that the divergences leave only a much smaller set of diagrams, with very special properties. Most importantly, in all the surviving diagrams, the largest circle amplitudes in Fig. 5 contain the anomaly vertices that we alluded to in the Introduction and describe further in the next Section.

To obtain our starting point of massive gauge boson and fermion reggeons we use fundamental representation scalar fields. According to complimentarity[18], this ensures a smooth restoration of the underlying gauge symmetry when there is a $k_\perp$ cut-off in place. (Note that it is the properties of reggeon diagrams in the $k_\perp$ infra-red region that are important for our purposes, in contrast to the large $k_\perp$ significance[19] of such diagrams in BFKL physics.) The problem then is to understand how, and in what circumstances, can the massive reggeon diagram solution of reggeon unitarity, that perturbatively describes a spontaneously broken gauge theory, convert to a bound-state and pomeron diagram description containing amplitudes of the form of Fig. 4, as the gauge symmetry is restored. Most importantly, of course, we want to
understand the circumstances that will give the Critical Pomeron. We expect that the emergence of Critical Behavior will be very important in allowing the decoupling mass and cut-off scales, that we start with, to be replaced by the scales of the massless theory.

5. INFRA-RED DIVERGENCES AND ANOMALIES

To give a general idea of what all the contributing factors are, we will keep the following description of our infra-red divergence analysis very qualitative. The technical details will be described in much more detail in [2].

It is well-known that the massless limit produces exponentiating infra-red divergences, associated with reggeization, that “confine” the global color in the sense that only reggeon diagrams containing color zero combinations of reggeons survive. However, this is not real confinement in that color zero multi-gluon singularities remain. In our procedure we carry out the “confinement” of (global) color in stages. We impose a $k_\perp$ cut-off until the last stage when, as we discuss in the following Section, an asymptotically-free scalar field can be used. A major consequence of the cut-off is that fermion loop reggeon interactions do not have Ward identity zeroes at $k_\perp = 0$ and, as a result, additional infra-red divergences appear. Almost all of the additional divergences exponentiate and so, because of the cut-off, a much larger part of the theory, beyond just the color non-zero sectors, is removed. As we will see, there is a dominant surviving divergence, due to the fermion anomaly vertices that we discuss next, that does not exponentiate. Because this divergence does produce genuine confinement we will be able to simply refer to a massless limit that restores a global color symmetry as confining that symmetry.

Reggeon interaction vertices that contain anomalies couple “anomalous gluons”. As we will define explicitly in Section 7, “anomalous gluons’ are combinations of gluon reggeons that are reggeon generalizations of the well-known anomaly current. The anomalies appear in effective triangle diagrams that are produced when fermions in large loops are placed on-shell by a multi-regge limit. Because multi-regge limits are defined for on mass-shell amplitudes, the anomalies that are generated are a strictly S-Matrix phenomenon. Examples of anomaly vertices (derived in my papers) are shown in Fig. 6.

The first vertex shown appears in the coupling of a scattering vector boson to the combination of fermions and anomalous gluons that becomes a regge pole pion as we describe below. As is also illustrated, in this vertex an (on-shell) longitudinal vector interaction plays an essential role in producing the effective triangle diagram. This is one major reason why starting with massive reggeons is a necessary part of producing the anomaly vertices. Because anomalies require three-dimensional kinematics they can only occur in vertices coupling external states or in vertices coupling
distinct reggeon t-channels. Therefore, they can appear in the vertices represented by circles in Fig. 4 and by the largest circles in Fig. 5, but they can not occur within the self-interactions of a multi-reggeon configuration forming a single t-channel reggeon state (i.e. the pion and pomeron in Figs. 4 and 5).

A further property of an anomaly vertex, that has a deep significance for our construction of bound-state amplitudes, is also illustrated in the first vertex of Fig. 6. An “anomaly pole” is generated\cite{20} when the anomalous gluons involved carry $k_\perp = 0$. As illustrated, production of the pole involves a zero momentum chirality transition, that would be the zero-momentum contribution of a propagator to a condensate. The presence of such chirality transitions is another consequence of starting with masses for all fermions and gauge bosons that is also crucial for the generation of anomalies. The chirality transitions are effects of the initial masses which remain in the anomaly vertices after the masses are sent to zero. We emphasize that the masses decouple straightforwardly in all non-anomaly reggeon interactions and therefore the associated large $k_\perp$ perturbation theory is given by the massless theory.

Figure 6. Anomaly Vertices
In a flavor channel, the presence of the chirality transition breaks a chiral symmetry that would otherwise be present in the massless theory and, in so doing, produces an anomaly pole that is a Goldstone Boson particle pole. As we will see below, this is how multi-regge bound-states are produced. We can regard an anomaly pole Goldstone boson as the quark/antiquark state that is initially produced within the corresponding triangle diagram. In this case, either the quark or the antiquark has to be in a zero momentum “negative energy” state. Alternatively, we can regard the Goldstone boson as the produced combination of a “normal” quark/antiquark state together with \( k_\perp = 0 \) anomalous gluons. The “semi-classical” gluon field can be viewed as compensating for the chirality transition of the zero momentum quark or anti-quark. Equivalently, we can say that, in the process of creating the particle state, there is a shift of the Dirac sea Fermi surface in that a negative energy hole state becomes physical via the introduction of a compensating “wee gluon” state.

In the pion/pion/pomeron and triple pomeron vertices appearing in Fig. 5, the anomaly pole appears in a U(1) channel involving only gluons. In this case, the anomaly pole acts as a \( k_\perp \) conserving \( \delta \)-function that crucially connects scaling divergences in separate channels. Again we can say that the anomaly pole is created by a shift of the Fermi surface in which a negative energy hole state becomes physical via the introduction of a compensating “wee gluon” state.

6. THE SMALL \( \beta \)-FUNCTION AND COLOR SUPERCONDUCTIVITY

QUD and massless QCD\( S \) share three, closely related, small \( \beta \)-function properties that are very important for the construction of multi-regge amplitudes.

1. The asymptotic freedom constraint is saturated[3].

2. An infra-red fixed-point keeps the \( \beta \)-function small[21] and also produces reggeon kernels that scale canonically in the \( k_\perp \) infra-red region.

3. An asymptotically free fundamental representation scalar field can be used[22, 23] in both QCD\( S \) - to break SU(3) color to SU(2) to give CSQCD\( S \) (“color superconducting QCD\( S \”) ), and in QUD - to break SU(5) color to SU(4) to give CSQUD (“color superconducting QUD”).

Because of these three properties, the multi-regge reggeon diagrams of CSQCD\( S \) and CSQUD can be used to obtain the corresponding QCD\( S \) and QUD amplitudes, respectively. (As we will discuss a little more later, a major virtue of this construction procedure is that the anomaly interactions that are introduced, effectively, provide a resolution of the Gribov ambiguity in light-cone quantization of the unbroken theory.)
The scaling reggeon kernels play an essential role in the occurrence of anomaly-coupled infra-red divergences that produce physical amplitudes, while the absence of a cut-off as the full color group is confined is essential for the development of the Critical Pomeron reggeon critical phenomenon.

We will first discuss SU(2) confinement, which is essentially the same in both QCD$_S$ and QUD. We will then specifically discuss massless QCD$_S$ and afterwards turn to QUD. However, we will see that massless QCD$_S$ contains a large array of massless Goldstone boson states that probably jeopardize the actual existence of the S-Matrix. The only possibility (that we know of) to add masses to the massless states of QCD$_S$, while preserving the dynamics, is to embed the theory in QUD. According to our arguments, QUD has no massless particles and so there should be no threat to the (perhaps unique) existence of the S-Matrix.

7. SU(2) CONFINEMENT

In the limit giving SU(2) color confinement, a central role is played by color zero ($I = 0$) combinations of gluon reggeons that we call “anomalous gluons”. These are sets of gluon reggeons that carry color charge parity $C$ not equal to their signature $\tau$. The “analytic” definition of signature for a reggeon state is (for vector reggeons) simply the odd/even number of reggeons. For SU(2), if $I = 0$, only $\tau = -1$ anomalous combinations are possible. There is also a “group-theoretic” signature[24] which has to coincide with the analytic definition. When parity ($P$) is conserved, the combination of incoming and outgoing particle states to which a reggeon combination couples (via a vertex of the form of Fig. 6(a)) can be assigned a parity which is also carried by the reggeon state. The signature is the sign given by a TCP transformation of the complete coupling. Since T simply interchanges the ingoing and outgoing particles, it must be that $\tau = CP$. As a result, anomalous gluon couplings must have $P = -1$.

If we consider forward scattering then $P = -1$ for the coupling implies that there must be a parity change between the initial and the final scattering state. In a parity-conserving vector theory, such a change can only come from an anomaly vertex that contains a zero momentum chirality transition. Hence anomalous gluons can only couple via anomaly vertices. They can couple to external states via anomaly vertices of the form of Fig. 7(a).
There will, however, be no anomalous gluon interactions of the form of Fig. 7(b), because of the absence of anomaly vertices for single channel interactions.

As SU(2) color is confined (with a $k_{\perp}$ cut-off) all divergences exponentiate, except for the infra-red divergence which occurs\cite{20} within a set of $I = 0$ anomalous gluons when the transverse momenta of all the gluons is scaled uniformly to zero.

As we discuss again below, because of the scaling property of the reggeon kernels, this divergence is preserved as the anomalous gluons self-interact. Also, there are no interactions of the form of Fig. 7(b) that would exponentiate the divergence. Divergences in separate channels can be coupled\cite{20} via anomaly vertices and as a result the simplest divergent di-triple-regge amplitudes have the form shown in Fig. 8.

When external left-handed massive vector mesons are utilised, as in Fig. 4, they provide initial anomalous couplings, that contain Goldstone boson anomaly poles, as illustrated. If any of the anomalous gluon configurations in Fig. 8 is replaced by non-anomalous $I = 0$ gluon reggeons then fermion loop interactions, of the form of Fig. 9, exist that will (because of the absence of Ward identity zeroes - due to the $k_{\perp}$ cut-off) exponentiate the amplitude to zero. Consequently, the divergence necessarily involves anomalous gluons in every channel.

After the divergence is factored off, the remaining bound-state “physical amplitudes” contain a $k_{\perp} = 0$ “wee gluon condensate” as a relic of the divergence. In
the first approximation, provided by Fig. 8,

- The bound-states are anomaly poles that appear as \( I = 0 \) combinations of fermions in the anomalous wee gluon background.

- Interactions are due to a finite transverse momentum gauge boson, that carries \( I = 0 \), in the same wee gluon background.

Because the bound-states are anomaly poles, they must be Goldstone bosons and so there must be a corresponding chiral symmetry - when the confined color is SU(2). As we noted above, we can regard the Goldstone bosons as initially created by a product of quark/antiquark operators provided we remember that removal of the wee gluon component corresponds to a chirality transition. As we also observed, we can regard the chirality transition as equivalent to the zero-momentum shift of the Dirac sea Fermi surface during the interaction. Using this language, the lowest-order scattering process of Fig. 8 can be described as follows.

An anomaly pole Goldstone Boson “pion” is created by the product of a physical quark field and a zero momentum “unphysical” antiquark field in which the Fermi surface is shifted. The antiquark becomes physical, via a chirality transition, that introduces an accompanying “semiclassical” anomalous wee gluon field (condensate) that effectively moves the Fermi surface back to it’s perturbative location. In the scattering process, there is a large rapidity perturbative exchange interaction in which the wee gluon fields of the incoming pions are transformed into those of the outgoing pions by anomaly couplings that involve further shifts of the Fermi surface. The final state pions are created via further shifts of the Dirac sea that reabsorb the anomalous wee gluon fields.

Higher-order effects will add interactions amongst the gluons in an anomalous gluon state. Divergent fermion loop contributions are exponentiated out and the remaining gluon interactions can be described by kernels \( K \) that, because of the infra-red fixed-point, scale in the infra-red region. As the kernel interactions are iterated the degree of divergence does not increase. Instead, in an integral involving a product of many kernels, there is a distinct contribution from each intermediate state. This divergence can be isolated and the remaining integrations factorized as illustrated in Fig. 10.

![Figure 10. Factorization of a Wee Gluon Divergence.](image)

The factorising residues imply that the condensate component of the bound-states becomes a “wee gluon distribution” in which the gluons have zero transverse momen-
tum but carry non-zero “wee” longitudinal momenta. The wee gluon distribution will have a dynamical scale, in addition to the cut-off and reggeon masses that we have introduced as scales. The condensate scale, associated with the divergence, at this point, is a parameter that has to be determined by matching with supercritical pomeron theory, as we discuss briefly below.

As illustrated in Fig. 11, in higher orders there will also be interactions, containing anomalies, between the anomalous gluon components of the scattering states and the exchanged “interaction” state. These interactions are the source of the triple pomeron interaction, including supercritical pomeron interactions, and the mass generation for vector bosons.

![Figure 11. Interactions Involving Anomalous Gluons in the Scattering States.](image)

8. STATES AND AMPLITUDES IN MASSLESS QCD$_S$

In CSQCD$_S$, the first approximation to the interaction is the even signature combination of a massive SU(2) singlet gluon reggeon in the odd signature anomalous wee gluon condensate. As a result, there is the pomeron/reggeon exchange degeneracy that defines the supercritical RFT phase. The wee gluon condensate also produces interactions, of the form of Fig. 11, that include those of the RFT supercritical pomeron. The restoration of SU(3) color should then produce the Critical Pomeron as the QCD$_S$ high-energy interaction. As part of the approach to the phase transition, the SU(2) singlet gluon will become massless and decouple. Simultaneously, the wee gluon condensate will disappear and a corresponding dynamical degree of freedom will appear. That is, the shifting of the Dirac sea (the chirality transitions within the anomaly vertices - the triple pomeron vertex in particular) will become dynamical. As we already discussed in the Introduction, the shifting of the Dirac sea is the “order parameter” of the transition. In the supercritical phase this degree of freedom is ordered into a single, semi-classical, wee gluon gauge field contribution, while in the sub-critical phase it is random. For this to happen, longitudinal vector meson interactions, which at first sight should decouple as the color symmetry breaking is removed, must still be present - at zero light-cone momentum. In fact, the role of zero light-cone momentum, longitudinal, gluons is a major ambiguity of light-cone
quantization[14]. By constructing the high-energy behavior of $QCD_S$ via $CSQCD_S$ we resolve this ambiguity.

Much remains to be done to map the reggeon diagrams of $CSQCD_S$ onto the pomeron diagrams of supercritical RFT. In particular, the parameters of $CSQCD_S$, including the reggeon condensate value, have to be matched with the RFT parameters. Because the $k_{\perp}$ cut-off is a relevant parameter for the RFT critical point, it is very important that this can be removed before the color symmetry restoration. In [25] we describe arguments, that we first developed a lot earlier, why the number of quark flavors should be reflected in the pomeron intercept as a parameter and gave general arguments why the asymptotic freedom constraint should be saturated, as it is in $QCD_S$. We also discussed, how the Critical Pomeron scaling functions contain a variety of critical indices that have to be closely related to properties of the underlying field theory. In particular, in the zero mass limit, the elastic scaling function collapses to a single critical index function in a way that suggests this index should be a direct property of an infra-red fixed-point in an underlying vector theory. Very likely, the well-defined critical indices of the $QCD_S$ fixed-point are, in fact, the critical indices of the Critical Pomeron scaling functions. In this sense, this would make the Critical Pomeron the S-Matrix manifestation of the underlying fixed-point field theory.

The physical states of $QCD_S$ correspond to the Goldstone bosons of $CSQCD_S$. Included are all flavor non-neutral pseudoscalar mesons containing only triplet quarks, which there will be many of. A potential flavor neutral meson mixes with pure gluon states and, hence, does not appear as a Goldstone boson. Since quark and antiquark representations are equivalent when the gauge symmetry is SU(2), there are also “nucleon” Goldstone boson states, reflecting real chiral symmetries[26] of $CSQCD_S$. These states will become baryons by acquiring an additional quark (or antiquark). To discuss this we need to study more the role of the SU(2) singlet quarks in $CSQCD_S$. Since these quarks are not Goldstone bosons, they can not be physical states. They can, nevertheless, appear in regge exchanges. In particular, there will be a regge exchange involving the combination of a Goldstone boson “nucleon” and an SU(2) reggeized quark that can become a normal, reggeized, nucleon as SU(3) color is restored. Understanding this better is important because the corresponding formation of QUD states is considerably more complicated.

There will also be meson and nucleon states involving the two sextet quarks. If the sextet quarks have the right electroweak quantum numbers and the electroweak sector is added, the sextet mesons (“sextet pions”) will be eaten by the electroweak vector bosons and the only remaining sextet states will be the sextet nucleons (apart from the $n_6$, which will have an electroweak scale mass due to mixing with the pomeron sector). Because of the larger color factors that are involved, the sextet states will dominate production cross-sections once the energy is well above the effective threshold (involving pomeron exchange).
Because there are no corresponding Goldstone bosons in CSQCD, there will be no hybrid sextet/triplet quark states. Consequently, the lightest sextet nucleon will be stable. The (triplet quark) proton is lighter than the neutron only because the current mass of the $d$ quark is bigger than that of the $u$. We expect effective quark masses to be generated by the embedding of QCD in QUD. However, sextet quark current masses must remain zero for sextet pions to combine with the massless electroweak vector bosons to produce massive states. (More strictly, it is the combination of sextet and triplet quarks that couples to the vector bosons that must have zero current mass.) Therefore, the sextet nucleon mass difference has to be entirely electromagnetic in origin, and the $N_6$ will be stable. If the sextet quark dynamical mass is given by the top quark mass, as discussed earlier, the $N_6$ mass should be $\approx 500$ GeV and the $P_6$ mass should be just a little higher. Because the neutral $N_6$ will not only be stable but will also dominate ultra high-energy cross-sections it, potentially, provides a natural explanation for both the production and dominance of “dark matter”.

Since triplet and sextet quarks can not combine to form bound states, sextet nucleons should not form bound states with triplet nucleons. (If pion exchange provides the binding force for nucleons to form nuclei, there is no common “pion” to bind sextet and triplet nucleons as nuclei.) Therefore, we can expect the sextet nucleons to form separate “dark matter nuclei”.

The QCD pomeron produces rising cross-sections via a critical phenomenon but, nevertheless, is a regge pole with RFT interactions and has the factorizing couplings that are essential if its wee parton component is to be universal and reproduce “vacuum properties”. This is a, rarely emphasized, essential requirement for the validity of an infinite momentum parton model[14]. To the extent that the wee gluon component of infinite momentum states is the equivalent of a finite energy vacuum, we can say that the “QCD vacuum” is a critical phenomenon of dynamical, zero momentum, fermion chirality transisitions. The physical states that are stable in this “vacuum” are much fewer and the interaction much simpler than in conventional QCD. Moreover, we have a diagrammatic description of how the states are formed. The spectrum is consistent with, but much less than, just requiring confinement and chiral symmetry breaking. There is also no BFKL pomeron, no odderon, and no glueballs. In general, there is much better agreement[27] with experiment!

9. QUD STATES AND AMPLITUDES

To construct QUD states and amplitudes we again start with all reggeons carrying global color and with masses generated by fundamental representation scalars. For QUD, in contrast to QCD, it is essential that the initial fermion masses are generated by condensates. This has important consequences for the structure of the
anomaly interactions, containing zero momentum chirality transitions, that remain in the massless theory after the symmetry breaking is removed. It is, however, the effect of left-handed reggeon couplings that is the central element in the structure of QUD reggeon diagram divergences.

Since a left-handed interaction violates parity, fermion interactions of the form of Fig. 9 will exist for both normal and anomalous color parity combinations of massless gauge bosons in which one or more of the bosons has a left-handed coupling. As long as a $k_\perp$ cut-off is in place, therefore, the absence of Ward identity zeroes will then imply that these interactions exponentiate to zero any divergences involving massless left-handed reggeons. Consequently, in QUD the analog of “anomalous gluon divergences” in QCD can not involve left-handed gauge boson reggeons. Anomalous divergences coupled to chirality fluctuations, can involve only a maximal non-abelian vector subgroup. The resulting “strong interaction” pomeron is therefore a singlet under an SU(3) subgroup. Because the SU(5) color symmetry of reggeons is a global symmetry, an SU(5) singlet pomeron interaction (involving a minimum of four gauge boson reggeons - with three forming an anomalous configuration) can be obtained by, effectively, summing over all SU(3) subgroups. It is then an outcome of QUD that the strong interaction is produced by a, parity conserving, vector interaction that is invariant under an underlying SU(3) gauge group.

To construct QUD amplitudes, we use the $SU(3) \otimes SU(2) \otimes U(1)$ breakdown described earlier and denote the various subgroups of SU(5) as in Figure 12.

![Figure 12. SU(5) subgroups](image)

The $SU(3)_C$ subgroup will correspond to a vector interaction. We will first restore the $SU(2)_C$ symmetry, then go straight to the $SU(4)$ symmetry. Restoring the $SU(3)_C$ symmetry will coincide with the final restoration of the full SU(5) symmetry. The $x$, $x'$ and $x''$ vectors will, therefore, remain massive until the final symmetry restoration. We initially consider di-triple-regge amplitudes of the form of Fig. 8 with massive, left-handed, $x''$ vector bosons as the external states.

Since $SU(2)_C$ is a vector symmetry, after it is restored the states will be chiral Goldstone bosons ($\pi_C$’s). These will be $qq$, $\bar{q}\bar{q}$, and $q\bar{q}$ pairs in a condensate,
where the q’s are $3^\prime$s, $6^\prime$s, & $8^\prime$s under SU(3)$_C$. $8^\prime$s are real wrt SU(3)$_C$, but contain complex doublets with respect to SU(2)$_C$ that will have a chiral symmetry.

The interactions that are selected by the SU(2) condensate and that will also produce SU(3)$_C$ singlets (after the final symmetry restoration) are just

1. a massive x gluon in the condensate - corresponding to the supercritical pomeron.

2. SU(2)$_L \otimes U(1)$ bosons in the condensate, corresponding to $W^{\pm,0}$ and Y vector bosons.

At first sight, the left-handed bosons will have interactions with the condensate, of the form of Fig. 9, that will give exponentiating divergences. However, interactions of the form shown in Fig. 11, involving the (vacuum) wee gluons of the scattering states, give left-handed $W^{\pm}$ & $Z^0$ exchanges a mass, via the last anomaly vertex appearing in Fig. 6 - that corresponds to mixing with the sextet $\pi_C$’s. (The mixing with octet pions will disappear after the SU(3)$_C$ symmetry is restored.) Because of this mixing, the massive vector bosons will carry the sextet SU(2) flavor symmetry in a manner that will allow them to interact via anomalies only. This eliminates interactions of the form of Fig. 9.

Restoring SU(4) symmetry to obtain CSQUD involves only left-handed and abelian vector bosons and so all new divergences exponentiate, leaving only states and interactions that are SU(4) invariant. “Leptons” are present as reggeon bound states of “elementary leptons” and “octet pions”. The SU(2)$_L \times U(1)$ quantum numbers of octet $\pi$’s are $(2, \frac{1}{2})$, $(1, -1)$, and $(3, -1)$ and so the elementary lepton component has (modulo gauge boson contributions) the generation structure of the Standard Model.

The SU(3)$\times$SU(2)$_L \times U(1)$ content of the bound-state leptons is

1. $(e^-, \nu)$ candidate
   $\leftrightarrow (1, 2, -\frac{1}{2}) \times (8, 1, 1)(8, 2, -\frac{1}{2}) \leftrightarrow SU(5)$ singlet $- 45^* \times 40 \times 45^*$

2. $e^+$ candidate
   $\leftrightarrow (1, 3, 1) \times (8, 2, -\frac{1}{2})(8, 2, -\frac{1}{2}) \leftrightarrow SU(5)$ singlet $- 15 \times 45^* \times 45^*$

3. $(\mu^-, \nu)$ candidate
   $\leftrightarrow (1, 2, \frac{1}{2})(1, 2, -\frac{1}{2})(1, 2, -\frac{1}{2}) \times (8, 1, 1)(8, 2, -\frac{1}{2})$
   $\leftrightarrow SU(5)$ singlet $- 5 \times 45^* \times 45^* \times 40 \times 45^*$

4. $(\tau^-, \nu)$ candidate
   $\leftrightarrow (1, 2, \frac{3}{2})(1, 2, \frac{1}{2})(1, 2, \frac{1}{2}) \times (8, 1, 1)(8, 2, -\frac{1}{2})$
   $\leftrightarrow SU(5)$ singlet $- 40 \times 5 \times 5 \times 40 \times 45^*$

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Clearly “hadron” states will be present that contain a triplet “pion” and, or, a triplet “nucleon” combined with octet quark pions. Similarly there will be sextet “nucleons” combined with octet pions. (The sextet pions will have already been absorbed by the vector bosons.) When we have described the fate of octet pions after the full SU(5) restoration, it will be clear why leptons must involve octet pions. It will not be so clear why SU(5) invariant quark states should contain octet pions. It seems likely that this is an outcome of the SU(2)xU(1) anomaly cancellation in the infra-red, but we have yet to understand this. It may also be that anomaly cancellation effects of this kind are only evident after the full symmetry restoration.

The restoration of SU(5) symmetry is an elaborate phenomenon that certainly needs much more study and that, as yet I only partially understand. My current understanding includes the following.

- The pomeron interaction becomes critical - as an SU(3) subgroup interaction that is summed over subgroups.
- The $\gamma, W^\pm$ and $Z^0$ wee gluon component becomes even signature.

The octet quarks, which at first sight might have seemed unwanted, are fundamental for the SU(5) invariance and the generation structure of the states.

- After SU(3)$_C$ is restored, the octet $\pi$’s are no longer Goldstone bosons. Instead, they contribute to bound-states as (what would normally be unphysical) anomaly poles generated by large $k_\perp$ quark and antiquark pairs which carry opposite sign energies. This is a subtle, and very crucial, phenomenon that will be elaborated on in much more detail in [2].
- SU(3)$_C$ reality implies that the octet $\pi$’s have no anomaly coupling to the pomeron and so leptons have no strong interaction and no infra-red SU(3)$_C$ mass generation.
- With the octet $\pi$’s contributing to states only at large $k_\perp$, the SU(2)$_L$\(\otimes\)U(1) symmetry appears in low $k_\perp$ interactions via the SU(2) flavor symmetry of the sextet sector. This is another phenomenon that will be discussed in more detail in [2].
- The SU(2)$\otimes$U(1) quantum numbers of the octet $\pi$’s implies that low $k_\perp$ states will have the singlet/doublet structure of the Standard model.
- Since the octet pions are embedded in leptons at large $k_\perp$, we expect (although we have yet to develop a proper argument) that the bound-state lepton contribution to the infra-red SU(2)$_L$\(\otimes\)U(1) anomaly is equal to the perturbative contribution. This would imply the existence of three generations of leptons.
The SU(2)$_L \otimes$U(1) anomaly cancellation then requires the formation of three generations of quark hadrons that similarly contain the octet pions.

Although we will not attempt to discuss it in any detail here, the mass spectrum will be generated by a combination of factors. Firstly, there will be straightforward perturbative reggeization effects that carry, initially, the momentum scale corresponding to the evolution scale of the underlying gauge theory. Large color factors and the, related, high mass sector will emphasize the SU(3) strong interaction. In addition, anomaly interactions, analagous to that generating the $W$ and $Z$ masses, will mix all the reggeon states. There seems every reason to believe that the large disparity in (generalised) color factors can produce a wide range of scales within the S-Matrix. The most obvious example being the disparity in scales for the strong and electroweak interaction produced by Casimir scaling of SU(3) color factors. Without a better understanding of the anomaly interactions and the related wee gluon distributions it is unclear how many parameters could be involved, in general. In particular, although CP violation could easily be a consequence of chiral anomaly dominance of interactions, at this point it is obviously not clear whether it is actually necessary. Nevertheless, to suggest that the physical mass spectrum could emerge from QUD is clearly not unreasonable.

10. GENERAL PROPERTIES

Apart from explaining why the strong interaction is an SU(3) vector theory and why it is that the left-handed interaction aquires a mass, there are many other general features of QUD that are encouraging.

1. The experimentally attractive SU(5) value of the Weinberg angle should hold - even though there is no proton decay!
2. Small $\alpha_u$ should be the explanation of small neutrino masses.
3. The QCD sector agrees better[27] with experiment (than conventional QCD) - no glueballs, no BFKL pomeron and no odderon.
4. The existence and dominance of Dark Matter is naturally explained.
5. The electroweak symmetry breaking shares key features with successful[28] “Walking Technicolor” theories that are consistent with precision constraints.
6. The high mass QCD sector produces unification without supersymmetry.
7. There are no unwanted symmetries constraining the mass spectrum.
8. QUD is contained in a single SO(10) representation - the 144. Although there is no S-Matrix for the enlarged representation (according to our arguments) this could be relevant for {string?} unification with gravity.

11. WHAT SHOULD BE SEEN AT THE LHC?

In this Section I will briefly review what should be seen at the LHC and how, in particular, double pomeron processes can provide the definitive proof that a sextet sector has appeared. A more extended discussion can be found in [4].

Because large cross-sections are involved, the emergence of the sextet sector should be obvious. The immediate evidence will be that multiple vector boson and jet x-sections are much, much, larger than expected. \( < p_\perp > \) should undergo a major increase from the low energy hadron scale and move significantly towards the electroweak scale. There will, however, be competing explanations for these effects, such as black holes, sphalerons, etc..

A priori, \( N_6 \overline{N}_6 \) pair production (dark matter) should be seen - with the \( N_6 \) mass, perhaps, \( \sim 500 \text{ GeV} \). Unfortunately, this will be difficult to detect, since missing energies of several hundred GeV will be common. Also the low energy \( N_6 \) hadronic cross-section, for collisions in a calorimeter, is probably small. \( P_6 \overline{P_6} \) pair production should be seen - assuming the \( P_6 \) is not too unstable. Again, however, a massive charged particle with a large production x-section will not be immediately identified with the sextet sector!

Surprisingly, perhaps, the double pomeron cross-section could actually provide the most definitive evidence for the existence of the sextet sector. With the pomerons detected via Roman pots, the environment is clean and well controlled. \( W \) and \( Z \) pairs will be produced in the double pomeron cross-section via sextet pion anomaly poles. As (triplet quark) pion pairs dominate the double pomeron cross-section at low mass, so \( W \) and \( Z \) pair production will dominate the cross-section at the electroweak mass scale. Naively, a factor of \( [F_{\pi_6}/F_{\pi_3}]^4 \gtrsim O(10^{12}) \) is involved in relating sextet and triplet sector “pion” anomaly-pole cross-sections. However, this is not very useful since normal double-pomeron production of pions does not involve vector states and so does not proceed via anomaly poles.

When \( |k_\perp| \) is electroweak scale, the double-pomeron \( W \) and \( Z \) pair amplitude for producing jets is comparable with a standard jet amplitude that has, apart from anomaly loops that are \( O(1) \), the same propagators and couplings. This suggests that the jet cross-section from double-pomeron \( W \) and \( Z \) pairs will be comparable with the non-diffractive jet cross-sections predicted by standard QCD. While the \( \#PW^+W^- \#P \) and \( \#PZ^0Z^0\#P \) vertices should vary only slowly with \( k_\perp \), the \( pp\#P \) vertices have strong
$k_{\perp}$-dependence. This implies there should be an extremely large x-section at small $t$.

In the initial low luminosity running, an “extremely large x-section” could be detected by TOTEM in combination with the CMS central detector (assuming it is operational) - where it should be straightforward to look for the leptonic decays of $W$ and $Z$ pairs. Apart from factors of sextet isospin, the $Z$ pair cross-section will have the same order of magnitude as the $W$ pair cross-section. Consequently, some spectacular events should be expected, in which protons are tagged and only (a multitude of) large $E_T$ charged leptons are seen in the central detector.

FP420 (with Roman pots designed to look for a Standard Model Higgs’ boson) will take over during the high luminosity running and should surely see an enhanced cross-section, even if it is too small to have been seen by CMS/TOTEM. With the planned parameters for FP420, the $W$ and $Z$ pair cross-section should overwhelm all other physics.

The observation of a very large double-pomeron cross-section for $W$ and $Z$ pairs would imply that the longitudinal components of the $W$ and the $Z$ have direct strong interactions. The only known possibility for this is the existence of the sextet sector and, as we have discussed, to give a well-defined theory this sector has to be embedded in QUD!

After the combination of IP, $W/Z$, and jet physics has established that sextet quark physics is definitively discovered, the search for “dark matter” will become all important. The cross-section for double-pomeron production of stable $N_6\bar{N}_6$ pairs (with a pair mass $\gtrsim 1\ TeV$) could be large enough that it will be definitively seen by the forward pot experiments. It will be a spectacular process to look for - via the following.

1. The tagged protons determine a very massive state is produced.
2. No charged particles are seen in any of the detectors.
3. Having low energy, the $N_6$ hadronic cross-section will, probably, be small but some hadronic activity may be seen in the central calorimeter.
4. Charged lepton comparison would allow a separation wrt the multiple $Z^0$ production of neutrinos.

Of course, if the $P_6$ is relatively stable, and not too different in mass from the $N_6$, it would be much simpler to first detect $P_6\bar{P}_6$ pairs.
12. COMMENTS AND PERSPECTIVE

Although there is not as much speculation in what I have described as probably appears to be the case to the non-specialist reader (almost everyone), there certainly is a considerable amount. Even with the publication of [2], much will remain that needs to be both better established and also better understood. Many questions will remain unanswered and many details will still be missing. As a result, it will surely be some time before serious calculational procedures can be developed. Nevertheless, I am hopeful that my discovery of QUD, and all of it’s remarkable properties, will eventually demonstrate that (contrary to popular belief) solving the infra-red problem of constructing physical states that produce a unitary S-Matrix may actually be more difficult, more special, and ultimately at least as fundamental as the solving of the ultra-violet problem of a field theory.

While it may appear that I have introduced way too much that is radical, and in conflict with the current theoretical paradigm, I would argue that this was not by choice. I have been led along the path I have followed by logical necessity. Most significantly, I have been led to, what seems to me at least to be, a very beautiful proposition, that the relevant entity for particle physics is the bound-state S-Matrix of a very special, small $\beta$-function, massless field theory that, at first sight, is an “unparticle theory” [7]. In fact, as I have described, the zero momentum “Fermi surface” of the massless Dirac sea offers crucial possibilities for wee gluon interactions via anomalies that prevent the scale invariance property of the unparticle theory from carrying over into the physical S-Matrix (although understanding and elaborating how all the S-Matrix scales originate is a significant part of the work that remains to be done). More importantly, perhaps, it seems that the massless gauge theory need only be evident in (and, therefore, need only exist as a quantum field theory in) short-distance perturbation theory. Mass generation becomes an S-Matrix property which is, effectively, separated from the problem of having a sufficiently well-defined short-distance field theory.

It is important to emphasize that, besides my construction via multi-regge theory, there is no other formalism capable of constructing bound-state scattering amplitudes. Without this ability it would not have been possible to envision the existence of an S-Matrix within a field theory with the properties of QUD. In effect, I diagrammatically construct the high-energy S-Matrix via infra-red and ultra-violet cut-off manipulations that determine the contribution of fermion anomalies in the (multi-regge region) perturbation expansion. Although I have very little idea as to how the finite energy S-Matrix might be analogously obtained, it seems unlikely that the states I find could appear as intermediate states in any off-shell Green’s functions. (As we noted in the Introduction, if there were a connection to field operator Green’s
functions, infra-red scale invariance would be in conflict with [8] the existence of a
particle spectrum.) The zero momentum chirality transitions and resulting anomalous
wee gluon interactions are introduced via the formation of asymptotic states and so
are clearly particular to the S-Matrix. As a result, I anticipate that the S-Matrix
is the only well-defined non-perturbative element of the theory. Although this is a
radical notion, according to current thinking, it is well-established historically that it
is fully viable from a practical (experimental) viewpoint[29]. It could also have the
great advantage that (as a matter of principle) there would be no need to confront the
overwhelmingly difficult, and so far elusively intractable, problem[30] of constructing
a full, non-perturbative, quantum field theory (with or without a mass gap) in four
dimensions.

We can ask, of course, why the massless field theory has to be QUD. My
answer has been that I demand the appearance of the Critical Pomeron. However, I
can also phrase this requirement in terms that would be, perhaps, more familiar to
the general reader via comments already made in previous Sections. The (infra-red
fixed-point) small $\beta$-function is required, firstly for the persistence of the scaling wee
gluon interactions that enhance infra-red fermion anomaly interactions, and secondly
to allow the color-superconductivity starting point that resolves the quantization
ambiguities associated with Gribov copies and Gauss's law. The vector interaction
non-abelian gauge group has to be as large as SU(3) to produce, via scaling wee gluon
interactions, a universal wee gluon distribution that can carry vacuum properties.
This property is surely essential[14] for the existence of an infinite momentum “parton
model” that allows asymptotically free perturbation theory to produce an ultra-violet
finite S-Matrix. If the vector gauge group is larger than SU(3), the anomalous wee
gluon scaling interactions are more complicated and the universal wee parton property
is lost. The SU(3) gauge group can, however, be extended by left-handed interactions,
that acquire a mass via the anomalies, since the only effect is to also generate bound
state masses. This is a beneficial effect in that it alleviates potential S-Matrix infra-
red problems. (Essentially, the infinite momentum, wee parton, properties are not
affected.) Asking that this extension generates masses for all bound-states while
introducing no short-distance anomaly then brings us close to, if not directly to,
QUD. Therefore, I believe that although I have funneled my discussion through the
Critical Pomeron, in fact all of the properties needed to obtain a well-defined particle
S-Matrix come together to uniquely select QUD.

It is currently accepted, almost without question, that “non-perturbative”
QCD and all similar unbroken non-abelian gauge theories should be well-defined by
the euclidean path integral. This is taken to imply that there must be a physical
S-Matrix and that, moreover, the physical states appear as intermediate states in off-shell Green’s functions (derived from the path integral) of appropriate operators. Although there is no evidence to support this hypothesis, the considerable
phenomenological success of various “non-perturbative QCD” formalisms, particularly lattice QCD, implies there must be some approximate truth in the assumptions. Nevertheless, at the level where we are asking to understand why a theory is uniquely chosen by nature it is important to emphasize that approximations are being made and that there are significant assumptions involved.

The existence of a short-distance field theory may be essential, not only for the large momentum finiteness of the S-Matrix, but also, as discussed in [16], for local analyticity properties. That the S-Matrix can be obtained from “non-perturbative” off-shell Green’s functions does not, however, appear to be essential for any of its basic properties. The global analyticity domains that are normally thought to be a consequence of an off-shell field theory probably follow from the construction of physical high-energy amplitudes via the perturbation expansion. In fact, when the fields are massless and bound states related to infra-red anomalies are involved there is probably no general reason to expect a connection between Green’s functions and the S-Matrix.

In general, there is not even a formal property of a non-abelian gauge theory path integral which implies that a unitary, bound-state, S-Matrix can be derived via Green’s functions. Even worse, because of infra-red problems, the path integral itself is, most likely, not well-defined - both because of the infinite volume convergence problem in four dimensions and, more seriously perhaps, because of the ambiguity of the function space implied by the Gribov copy problem. Since there are no “non-perturbative” methods for constructing gauge theory S-Matrix amplitudes that do not, effectively, appeal to the formal euclidean functional integral, to seriously discuss whether a unitary S-Matrix exists in a general gauge theory is a highly non-trivial problem.

Of course, it would be incredible if the Standard Model, with all of it’s complexity, has the underlying simplicity that I have suggested. Nevertheless, all the necessary ingredients are present and if the predicted effects of the sextet sector are seen at the LHC, I doubt that the radical/heretical nature of what I am proposing will impede the rapid rise of interest in QUD that will surely ensue. It is important to emphasize that, in principle, there is no freedom for variation in QUD. It is an “all or nothing” explanation of the origin of the Standard Model. Although my current understanding has not allowed any really quantitative predictions, an unavoidable central element and most striking prediction of QUD is that the new physics producing electroweak symmetry breaking is due to an additional strong interaction sector that will be abundantly evident at the LHC.
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massless reggeons
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