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New Strong Interactions at the Tevatron?

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Abstract

Recent results from CDF indicate that the inclusive cross section for jets with $E_T > 200$ GeV is significantly higher than that predicted by QCD. We describe here a simple flavor-universal variant of the "coloron" model of Hill and Parke that can accommodate such a jet excess, and which is not in contradiction with other experimental data. As such, the model serves as a useful baseline with which to compare both the data and other models proposed to describe the jet excess. An interesting theoretical feature of the model is that if the global chiral symmetries of the quarks remain unbroken in the confining phase of the coloron interaction, it realizes the possibility that the ordinary quarks are composite particles.

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Recent results from CDF [1] indicate that the inclusive cross section for jets with $E_T > 200$ GeV is significantly higher than that predicted by QCD. This excess can be fit by a phenomenological model of quark substructure [1], or by a model containing a new strongly-coupled Z' gauge boson [2, 3]. Here we describe a simple flavor-universal variant of the "coloron" model of Hill and Parke [4] that can accommodate such an excess, and which is not in contradiction with other experimental data. The model is minimal in its structure, in that it involves the addition of one new interaction, one new scalar multiplet, and no new fermions. As such, the model serves as a useful baseline with which to compare both the data and other models proposed to describe the jet excess. In addition, if the global chiral symmetries of the quarks remain unbroken in the confining phase of the coloron interaction, it provides a simple realization of the possibility that the ordinary quarks are composite particles.

1   The Model: Higgs Phase Description

Following Hill and Parke [4] the QCD gauge group is extended to $SU(3)_1 \times SU(3)_2$, with gauge couplings ξ_1 and ξ_2 respectively, with $\xi_2 \gg \xi_1$. In contrast to Hill and Parke we assign *all* quarks to triplet representations of the strong $SU(3)_2$ group. As in [4], we break the symmetry to its diagonal subgroup at a scale f by introducing a scalar-boson Φ which transforms as a $(3, \bar{3})$ under the two $SU(3)$ groups. For such a field there are three independent non-derivative operators of dimension less than or equal to four, and we can write the potential as

$$U(\Phi) = \lambda_1 \mathrm{Tr} \left(\Phi\Phi^\dagger - f^2 I \right)^2 + \lambda_2 \mathrm{Tr} \left(\Phi\Phi^\dagger - \frac{I}{3}(\mathrm{Tr}\,\Phi\Phi^\dagger) \right)^2 \qquad (1.1)$$

where we have adjusted the overall constant such that the minimum of U is zero. For the range of parameters $\lambda_1, \lambda_2, f^2 > 0$ the scalar field Φ will develop a vacuum expectation value (VEV), $\langle \Phi \rangle = \mathrm{diag}(f, f, f)$, breaking the two strong groups down to a single $SU(3)$ which we identify with QCD.

Once this VEV has developed there remain massless gluons interacting with quarks through a conventional QCD coupling with strength g_3, as well as an octet of massive colorons ($C^{\mu a}$) interacting with quarks through a new QCD-like coupling

$$\mathcal{L} = -g_3 \cot \theta J_\mu^a C^{\mu a} \ , \qquad (1.2)$$

where J_μ^a is the color current

$$\sum_f \bar{q}_f \gamma_\mu \frac{\lambda^a}{2} q_f \ , \qquad (1.3)$$

and where

$$\tan \theta = \frac{\xi_1}{\xi_2} \ . \qquad (1.4)$$

Since g_3 is identified with the QCD coupling constant, it has a value of approximately 1.2 (corresponding to $\alpha_3(M_Z) \approx .12$). In terms of these parameters the mass of the colorons is

$$M_C = \left(\frac{g_3}{\sin\theta\cos\theta}\right) f \ .$$ (1.5)

Below the scale M_C, coloron-exchange may be approximated by the effective four-fermion interaction

$$\mathcal{L}_{eff} = -\frac{g_3^2\cot^2\theta}{2!M_C^2} J_\mu^a J^{\mu a} \ .$$ (1.6)

The effects of this and similar operators on jet production has been studied[1] in [5]. Fig. 1 plots the published CDF data [1], the pure leading-order QCD prediction (corresponding to the limit $M_C \to \infty$), and the prediction for[2] $M_C/\cot\theta = 700$ GeV. As in the case of a contact interaction between left-handed quarks studied in [1], the prediction in the presence of this new coloron interaction is a better fit to the data than the QCD prediction. While this is suggestive, a complete analysis of this phenomenology and the assignment of statistical significance requires analysis of the full data sample.

The original coloron model was proposed in the context of "top-color" [9] models of electroweak symmetry breaking. The introduction of the new strong $SU(3)$ gauge-group was motivated by an attempt to dynamically explain the heavy top quark mass, and consequently in topcolor models the coloron coupled more strongly to third generation quarks. The only motivation for the introduction of the new $SU(3)$ interaction in our model is the potential discrepancy in the jet data, and the couplings of the coloron in this model are flavor-universal. As a result, the model can simply be grafted on to the standard one-doublet Higgs model yielding a simple, complete, and renormalizable theory[3].

Since the couplings considered here are flavor universal, the theory is not subject to the customary stringent constraints from flavor physics [10, 11] in topcolor models. Coloron interactions do contribute to corrections to the weak-interaction ρ parameter (where the isospin splitting is provided through the $t-b$ mass splitting). Limits on such corrections [12] imply that

$$\frac{M_C}{\cot\theta} \gtrsim 450\,\text{GeV}.$$ (1.7)

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[1]Following [6], in the study of compositeness it is conventional to define the coefficient of a product of currents as $4\pi/\Lambda^2$. Using eqn. (1.6), the relationship between M_C and this conventionally defined Λ is $M_C = \sqrt{\alpha_3}\cot\theta\,\Lambda$.

[2]The analysis of *earlier* (1988-89) CDF jet data [7], which did not have a pronounced jet excess at high-E_T, in [5] implies that $M_C/\cot\theta$ cannot be much less than 700 GeV.

[3]The most general renormalizable potential for Φ and the Higgs-doublet φ also includes the term $\lambda_3\varphi^\dagger\varphi\text{Tr}(\Phi^\dagger\Phi)$. For a range of λ's and parameters in the Higgs potential the vacuum will break the two $SU(3)$ groups to QCD and break the electroweak symmetry as required.
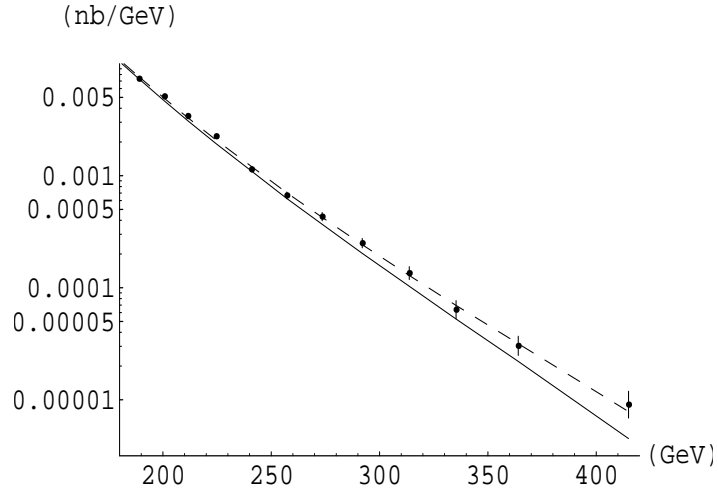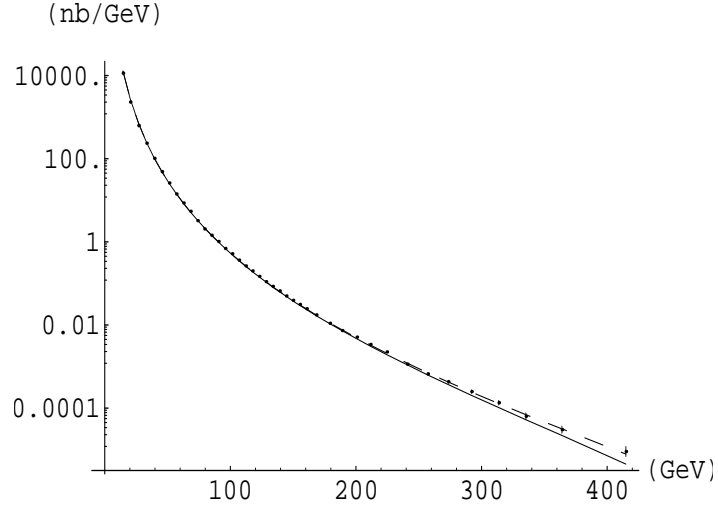
(nb/GeV)

(nb/GeV)

Figure 1: Single jet inclusive cross-section $\frac{1}{\Delta\eta}\int(d^2\sigma/d\eta\,dE_T)d\eta$ as a function of transverse jet energy E_t, where the pseudorapidity η of the jet falls in the range $0.1 \leq |\eta| \leq 0.7$. Dots with (statistical) error bars are the recently published CDF data [1]. The solid curve shows the LO prediction of pure QCD. The dashed curve shows the LO prediction of QCD plus the color-octet contact interactions of equation (1.6) with $M_C/\cot\theta = 700$ GeV. Following CDF, we employed the MRSD0' structure functions [8] and we normalized the curves to the data in the region where the effect of the contact interactions is small (here this region is $45 < E_T < 95$ GeV). The upper plot shows the full transverse-energy range; the lower plot shows more detail of the high-energy range $E_T > 200$ GeV.

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2 Complementarity: The Confining Picture

The model proposed contains scalars in the antifundamental representation of the strong $SU(3)_2$ gauge group. In the absence of fermions, such a model exhibits "complementarity" [13] with an exact equivalence between the Higgs- and the confining-phases. In the presence of quarks however, there are two possibilities for the physics of the $SU(3)_2$ confining-phase. The global $SU(6)_L \times SU(6)_R$ chiral symmetries of the quarks may spontaneously break to $SU(6)_V$ (this is implicitly assumed to happen in topcolor models). Alternatively, the global chiral symmetries may remain unbroken with the ordinary quarks being massless $SU(3)_2$-singlet composites of the fundamental fermions and the strongly interacting scalars (much like the strongly-coupled standard model [14]).

If the global chiral symmetries of the quarks remain unbroken in the $SU(3)_2$ confining phase, this model realizes the possibility that the ordinary quarks are composite particles. In this case *all* four-fermion contact interactions consistent with parity and the global chiral symmetries are allowed. If, in addition to the color current J_μ^a defined above, we also define

$$J_{5\mu}^a = \sum_f \bar{q}_f \gamma_\mu \gamma_5 \frac{\lambda^a}{2} q_f \ , \tag{2.1}$$

$$J_\mu = \sum_f \bar{q}_f \gamma_\mu q_f \ , \tag{2.2}$$

and

$$J_{5\mu} = \sum_f \bar{q}_f \gamma_\mu q_f \ , \tag{2.3}$$

the most general such interaction may be written

$$\mathcal{L} = \frac{4\pi}{2!\Lambda^2} \left(c_1 J_\mu^a J^{\mu a} + c_2 J_{5\mu}^a J_5^{\mu a} + c_3 J_\mu J^\mu + c_4 J_{5\mu} J_5^\mu \right) \ . \tag{2.4}$$

These terms can be thought of as arising from the exchange of color-octet and color-singlet, vector and axial resonances. If Λ is chosen to be of order the masses of these resonances, the c_i are expected to be of order one [6, 15].

3 Phenomenology

The phenomenology of the model depends on whether it is realized in the Higgs or confining phase. In the Higgs phase, the leading contribution to new jet physics is due to the exchange of the heavy coloron, resulting in the "VV" interaction in eqn. (1.6). Away from the QCD $\hat{t}$-channel pole, this results in an angular distribution *identical* to that of QCD. On the other hand, in the confining phase one obtains the low-energy interactions eqn. (2.4), with potentially comparable amounts of both

"VV" and "AA" contributions resulting in an angular distribution which differs from that of QCD.

The angular behavior is implicit in the two-body parton scattering cross sections

$$\frac{d\sigma}{d\hat{t}}(ab \to cd) = \frac{\pi\alpha_s^2}{\hat{s}^2}\Sigma(ab \to cd). \tag{3.5}$$

The leading QCD contributions to $\Sigma(ab \to cd)$ may be found in [16, 17] and we have adapted the $O(1/\alpha_s\Lambda^2)$ contributions due to the quark contact operators from the results of ref. [5]. The $\Sigma(ab \to cd)$ conventionally include initial state color averaging factors and are written in terms of the partonic invariants $\hat{s}$, $\hat{t}$ and $\hat{u}$. For scattering of light quarks, whose masses may be neglected, we have:

$$\Sigma(qq' \to qq') = \frac{4}{9}\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{8}{9}\frac{(c_1 + c_2)\hat{s}^2 + (c_1 - c_2)\hat{u}^2}{\alpha_s\Lambda^2\,\hat{t}} \tag{3.6}$$

$$+\frac{4}{9}\left[\frac{(2(c_1 + c_2)^2 + 9(c_3 + c_4)^2)\hat{s}^2 + (2(c_1 - c_2)^2 + 9(c_3 - c_4)^2)\hat{u}^2}{2\alpha_s^2\Lambda^4}\right]$$

$$+O\left(\frac{1}{\alpha_s\Lambda^4}\right)$$

$$\Sigma(q\bar{q} \to q'\bar{q}') = \frac{4}{9}\frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} + \frac{8}{9}\frac{(c_1 + c_2)\hat{u}^2 + (c_1 - c_2)\hat{t}^2}{\alpha_s\Lambda^2\,\hat{s}} \tag{3.7}$$

$$+\frac{4}{9}\left[\frac{(2(c_1 + c_2)^2 + 9(c_3 + c_4)^2)\hat{u}^2 + (2(c_1 - c_2)^2 + 9(c_3 - c_4)^2)\hat{t}^2}{2\alpha_s^2\Lambda^4}\right]$$

$$+O\left(\frac{1}{\alpha_s\Lambda^4}\right)$$

$$\Sigma(qq \to qq) = \frac{4}{9}\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2}\right) - \frac{8}{27}\frac{\hat{s}^2}{\hat{t}\hat{u}} \tag{3.8}$$

$$+\frac{8c_1}{9\alpha_s\Lambda^2}\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}}\right) + \frac{8c_2}{9\alpha_s\Lambda^2}\left(\frac{\hat{s}^2 - \hat{u}^2}{\hat{t}} + \frac{\hat{s}^2 - \hat{t}^2}{\hat{u}}\right)$$

$$+\left(\frac{8(c_1 + c_2)}{27\alpha_s\Lambda^2} - \frac{16(c_3 + c_4)}{9\alpha_s\Lambda^2}\right)\frac{\hat{s}^3}{\hat{t}\hat{u}}$$

$$+\frac{4}{9}\left[\frac{(2(c_1 + c_2)^2 + 9(c_3 + c_4)^2)2\hat{s}^2 + (2(c_1 - c_2)^2 + 9(c_3 - c_4)^2)(\hat{u}^2 + \hat{t}^2)}{2\alpha_s^2\Lambda^4}\right]$$

$$-\frac{8\hat{s}^2}{27\alpha_s^2\Lambda^4}\left[(c_1 + c_2 - 6c_3 - 6c_4)^2 - \frac{81}{2}(c_3 + c_4)^2\right]$$

$$+O\left(\frac{1}{\alpha_s\Lambda^4}\right)$$

$$\Sigma(q\bar{q} \to q\bar{q}) = \frac{4}{9}\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}\right) - \frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}} \tag{3.9}$$

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$$+\frac{8c_1}{9\alpha_s\Lambda^2}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}}\right)-\frac{8c_2}{9\alpha_s\Lambda^2}\left(\frac{\hat{s}^2-\hat{u}^2}{\hat{t}}+\frac{\hat{t}^2-\hat{u}^2}{\hat{s}}\right)$$

$$+\left(\frac{8(c_1+c_2)}{27\alpha_s\Lambda^2}-\frac{16(c_3+c_4)}{9\alpha_s\Lambda^2}\right)\frac{\hat{u}^3}{\hat{s}\hat{t}}$$

$$+\frac{4}{9}\left[\frac{(2(c_1+c_2)^2+9(c_3+c_4)^2)2\hat{u}^2+(2(c_1-c_2)^2+9(c_3-c_4)^2)(\hat{s}^2+\hat{t}^2)}{2\alpha_s^2\Lambda^4}\right]$$

$$-\frac{8\hat{u}^2}{27\alpha_s^2\Lambda^4}\left[(c_1+c_2-6c_3-6c_4)^2-\frac{81}{2}(c_3+c_4)^2\right]$$

$$+O\left(\frac{1}{\alpha_s\Lambda^4}\right)$$

where q' denotes a quark of a flavor other than q. The top quark is heavy enough that it must be treated separately. Firstly the top quark content of the proton is negligible and we need not consider contributions from initial-state top quarks. Secondly top quarks are produced in quark-quark scattering with a mass dependent cross-section [18, 5]

$$\Sigma(q\bar{q}\to t\bar{t})=\frac{4}{9\hat{s}^2}\left[\hat{t}^2+\hat{u}^2+4m_t^2\hat{s}-2m_t^4\right]\tag{3.10}$$

$$+\frac{8}{9\hat{s}\alpha_s\Lambda^2}\left[c_1(\hat{t}^2+\hat{u}^2+4m_t^2\hat{s}-2m_t^4)+c_2\hat{s}(\hat{t}-\hat{u})\right]$$

$$+\frac{4}{9\alpha_s^2\Lambda^4}\Big[(c_1{}^2+\frac{9}{2}c_3{}^2)(\hat{t}^2+\hat{u}^2+4m_t^2\hat{s}-2m_t^4)$$

$$+(c_2{}^2+\frac{9}{2}c_4{}^2)(\hat{t}^2+\hat{u}^2-2m_t^4)$$

$$+(2c_1c_2+9c_3c_4)\hat{s}(\hat{t}-\hat{u})\Big].\tag{3.11}$$

Since we are including terms that are $O(1/\Lambda^4)$ in the scattering cross-sections, we need to comment on possible contributions from dimension-8 operators. The dimension-eight operators that contribute to the processes above include two more derivatives than the dimension-6 operators in (2.4); for instance, one of the operators is

$$\frac{4\pi}{2!\Lambda^4}D^\nu J_a^\mu D_\nu J_{\mu\,a}.\tag{3.12}$$

The contributions this operator makes to the scattering amplitude will clearly of the same form as those of the related dimension-6 operator – but will be suppressed by a factor of s/Λ^2, as one would expect from the rules of dimensional analysis [15]. The leading contributions of such dimension-8 operators to the cross-section (which arise from interference with QCD) are $O(1/\alpha_s\Lambda^4)$, *i.e.* down by $O(\alpha_s)$ relative to the contributions from the dimension-6 operators kept above.

It is important to note that the high-E_T jet excess predicted by this model will be *flavor universal*. Regardless of whether the model is in the Higgs or confining

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phase, the characteristics (rate and angular distribution) of jets at high-E_T should be the same for jets with tagged b- or c-quarks as for all quark-jets.

Finally, at higher energy hadron colliders such as the LHC one would see (potentially broad) resonances in the two-jet cross section at invariant masses of order one to several TeV. In the Higgs phase, the resonances would correspond to colorons, while in the confining phase one would expect color-octet and color-singlet, vector and axial bound state resonances.

4 Conclusions and Caveats

In this note we have described a simple flavor-universal variant of the coloron model of Hill and Parke that can accommodate the apparent excess of high-E_T jets at the Tevatron. The model is minimal in its structure, in that it involves the addition of one new interaction, one new scalar multiplet, and no new fermions. As such, the model serves as a useful baseline with which to compare both the data and other models proposed to describe the jet excess. Furthermore, if the global chiral symmetries of the quarks remain unbroken in the confining phase of this new interaction, it provides a simple realization of the possibility that the ordinary quarks are composite particles.

Theoretically, the biggest draw-back of this model is that it introduces new physics at an energy scale of order a TeV without contributing to an explanation of electroweak or flavor symmetry breaking. If features of this model are confirmed, it is to be hoped that the actual dynamics is based on an extension of the model that will bear on these questions. For example, some "Composite Technicolor Standard Models" [19] contain chiral coloron gauge groups (which are used to break the extended technicolor gauge symmetries) and produce flavor-universal, though not parity-invariant, interactions of a form similar to eqn. (2.4).

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