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Limits on Flavor-Universal Colorons*

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Abstract

A flavor-universal extension of the strong interactions was recently proposed in response to the apparent excess of high- E_T jets in the inclusive jet spectrum measured at the Tevatron. The color octet of massive gauge bosons ('colorons') that is present in the low-energy spectrum of the model's Higgs phase is studied here. Experimental constraints already imply that the coloron mass must exceed 870-1000 GeV. The import of recent Tevatron data and the prospective input from future experiments are also mentioned.

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1 Introduction

A flavor-universal coloron model [1] was recently proposed to explain the apparent excess of high- E_T jets in the inclusive jet spectrum measured by CDF [2]. This model is a flavor-universal variant of the coloron model of Hill and Parke [3] which can accommodate the jet excess without contradicting other experimental data. It involves a minimal extension of the standard description of the strong interactions, including the addition of one gauge interaction and a scalar multiplet, but no new fermions. As such, it serves as a useful baseline with which to compare both the data and other candidate explanations of the jet excess [4]. Furthermore, the extended strong interactions can be grafted onto the standard one-Higgs-doublet model of electroweak physics, yielding a simple, complete, and renormalizable theory.

Here, we briefly describe the phenomenology of the Higgs phase of the model (for a fuller discussion see ref. [5]). We discuss the limits which current data places on the colorons and then indicate how future measurements may be of use.

2 The model

In the flavor-universal coloron model [1], the strong gauge group is extended to $SU(3)_1 \times SU(3)_2$. The gauge couplings are, respectively, ξ_1 and ξ_2 with $\xi_1 \ll \xi_2$. Each quark transforms as a $(1,3)$ under this extended strong gauge group.

The model also includes a scalar boson Φ transforming as a $(3, \bar{3})$ under the two $SU(3)$ groups. The most general¹ potential for Φ is

$$U(\Phi) = \lambda_1 \text{Tr} \left(\Phi \Phi^\dagger - f^2 \mathbf{I} \right)^2 + \lambda_2 \text{Tr} \left(\Phi \Phi^\dagger - \frac{1}{3} \mathbf{I} (\text{Tr} \Phi \Phi^\dagger) \right)^2 \quad (2.1)$$

where the overall constant has been adjusted so that the minimum of U is zero. For $\lambda_1, \lambda_2, f^2 > 0$ the scalar develops a vacuum expectation value $\langle \Phi \rangle = \text{diag}(f, f, f)$ which breaks the two strong groups to their diagonal subgroup. We identify this unbroken subgroup with QCD.

The original gauge bosons mix to form an octet of massless gluons and an octet of massive colorons. The gluons interact with quarks through a conventional QCD coupling with strength g_3 . The colorons ($C^{\mu a}$) interact with quarks through a new QCD-like coupling

$$\mathcal{L} = -g_3 \cot \theta J_\mu^a C^{\mu a} \quad , \quad (2.2)$$

¹As noted in [1] this model can be grafted onto the standard one-doublet Higgs model. In this case, the most general renormalizable potential for Φ and the Higgs doublet ϕ also includes the term $\lambda_3 \phi^\dagger \phi \text{Tr}(\Phi^\dagger \Phi)$. For a range of λ 's and parameters in the Higgs potential, the vacuum will break the two $SU(3)$ groups to QCD and also break the electroweak symmetry as required.

where J_μ^a is the color current

$$\sum_f \bar{q}_f \gamma_\mu \frac{\lambda^a}{2} q_f \quad . \quad (2.3)$$

and $\cot \theta = \xi_2/\xi_1$. Note that we expect $\cot \theta > 1$. In terms of the QCD coupling, the gauge boson mixing angle and the scalar vacuum expectation value, the mass of the colorons is

$$M_c = \left(\frac{g_3}{\sin \theta \cos \theta} \right) f \quad . \quad (2.4)$$

The colorons decay to all sufficiently light quarks; assuming there are n flavors lighter than $M_c/2$, the decay width is

$$\Gamma_c \approx \frac{n}{6} \alpha_s \cot^2 \theta M_c \quad (2.5)$$

where $\alpha_s \equiv g_3^2/4\pi$. We take the top quark mass to be 175 GeV so that $n = 5$ for $M_c \lesssim 350$ GeV and $n = 6$ otherwise.

3 Existing limits on colorons

A sufficiently light coloron would be visible in direct production at the Tevatron. Indeed, the CDF Collaboration has searched for new particles decaying to dijets and reported [6] an upper limit on the incoherent production of such states. Accordingly, as discussed in [5], we calculated $\sigma \cdot B$ for colorons with various values of M_c and $\cot \theta$. We followed the example of CDF in using CTEQ structure functions and in requiring $|\eta| < 2$ and $|\cos \theta^*| < 2/3$. For $\cot^2 \theta < 2$, the coloron's half-width falls within the dijet mass resolution of 10%; for larger $\cot \theta$ we counted only the portion of the signal that falls within a bin centered on the coloron mass and with a width equal to the resolution. Values of M_c and $\cot \theta$ which yield a theoretical prediction that exceeds the CDF upper limit are deemed to be excluded at 95% c.l. [6]. We find that for $\cot \theta = 1$, the range $200 \text{ GeV} < M_c < 870 \text{ GeV}$ is excluded; at $\cot \theta = 1.5$, the upper limit of the excluded region rises to roughly 950 GeV; at $\cot \theta = 2$, it rises to roughly 1 TeV. As the coloron width grows like $\cot^2 \theta$, going to higher values of $\cot \theta$ does not appreciably increase the upper limit of the excluded range of masses beyond 1 TeV.

To extend the excluded range of coloron masses to values below those probed by CDF, we note two things. First, σ increases as $\cot \theta$ does, so that exclusion of $\cot \theta = 1$ for a given M_c implies exclusion of all higher values of $\cot \theta$ at that M_c . Second, $\sigma \cdot B$ is the same for a coloron with $\cot \theta = 1$ as for an axigluon [7] of identical mass [5]. Axigluons with masses between 150 and 310 GeV have already been excluded by UA1's analysis [8] of incoherent axigluon production; by extension,

colorons in this mass range with $\cot \theta \geq 1$ are also excluded. The combined excluded ranges of M_c are

$$\begin{aligned}
150\text{GeV} < M_c < 870\text{GeV} & \quad \cot \theta = 1 \\
150\text{GeV} < M_c < 950\text{GeV} & \quad \cot \theta = 1.5 \\
150\text{GeV} < M_c < 1000\text{GeV} & \quad \cot \theta \gtrsim 2 \ .
\end{aligned}
\tag{3.1}$$

They are summarized by the shaded region of figure 1

Because the colorons couple to all flavors of quarks, they should also affect the sample of b-tagged dijets observed at Tevatron experiments. As discussed in ref. [5], however, the limit on colorons from b-tagged dijets will probably be weaker than that from the full dijet sample. This contrasts with the case of topgluons, which can be more strongly constrained by the b-tagged dijet sample because they decay almost exclusively to third-generation quarks.

An additional limit on the coloron mixing angle may be derived from constraints on the size of the weak-interaction ρ -parameter. Coloron exchange across virtual quark loops contributes to $\Delta\rho$ through the isospin-splitting provided by the difference between the masses of the top and bottom quarks. Limits on this type of correction [9] imply that [1]

$$\frac{M_c}{\cot \theta} \gtrsim 450\text{GeV} \ .
\tag{3.2}$$

This excludes the hatched region of the $\cot^2 \theta - M_c$ plane shown in figure 1. Note that this excludes an area of small M_c that the dijet limits did not probe, as well as an area at larger M_c and large $\cot \theta$.

Finally, we mention a theoretical limit on the coloron parameter space. While the model assumes $\cot \theta > 1$, the value of $\cot \theta$ cannot be arbitrarily large if the model is to be in the Higgs phase at low energies. Writing the low-energy interaction among quarks that results from coloron exchange as a four-fermion interaction

$$\mathcal{L}_{4f} = -\frac{g_3^2 \cot^2 \theta}{M_c^2} J_\mu^a J^{a\mu}
\tag{3.3}$$

we use the NJL approximation to estimate the critical value of $\cot^2 \theta$ as²

$$(\cot^2 \theta)_{crit} = \frac{2\pi}{3\alpha_s} \approx 17.5
\tag{3.4}$$

This puts an upper limit on the $\cot^2 \theta$ axis of the coloron's parameter space, as indicated in figure 1.

²In more conventional notation (see e.g. [3]), one would write the coefficient of the four-fermion operator as $-(4\pi\kappa/M^2)$ and find $\kappa_{crit} = 2\pi/3$.

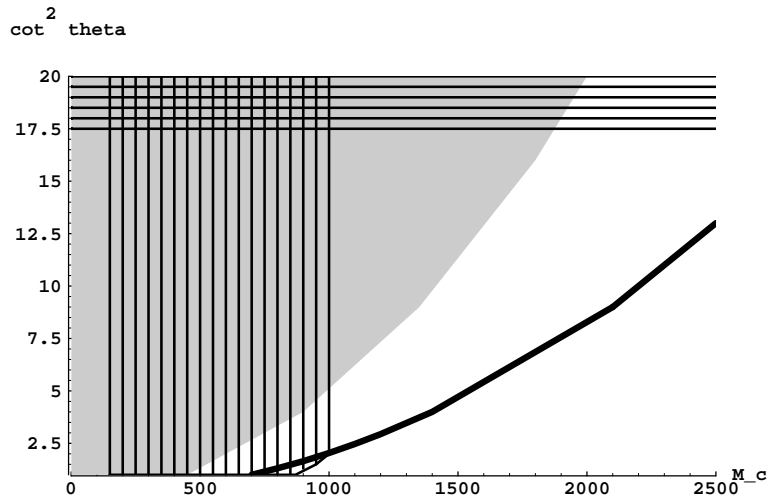


Figure 1: Current limits on the coloron parameter space: mass (M_c) vs. mixing parameter ($\cot^2 \theta$). The shaded region is excluded by the weak-interaction ρ parameter [1] as in equation 3.2. The vertically-hatched polygon is excluded by searches for new particles decaying to dijets [6, 8]. The horizontally-hatched region at large $\cot^2 \theta$ lies outside the Higgs phase of the model. The dark line is the curve $M_c / \cot \theta = 700$ GeV for reference.

4 Upcoming limits from Tevatron data

Both the inclusive jet spectrum ($d\sigma/dE_T$) and the dijet invariant mass spectrum ($d\sigma/dM_{jj}$) measured in CDF's run IA and IB data [2] appear to show excesses at high energy end of the spectrum. The dijet limits we derived earlier imply that the coloron is heavy enough that it would not be directly produced in the existing Tevatron data. Therefore, it is useful to start studying the data in terms of the four-fermion approximation (3.3) to coloron exchange. Comparison with the run IA CDF inclusive jet spectrum already [1] indicates that $M_c / \cot \theta = 700$ GeV is not obviously ruled out, as figure 2 illustrates. Figure 1 indicates where the curve $M_c / \cot \theta = 700$ GeV falls relative to the limits on the parameter space discussed earlier. Detailed analysis including both systematic and statistical errors should be able to determine a lower bound on $M_c / \cot \theta$.

For colorons weighing a little more than a TeV – those that are just above the current dijet mass bound – it is more appropriate to use the cross-sections for full coloron exchange [5] when making comparisons with the data. Such colorons are light enough that their inclusion yields a cross-section of noticeably different shape than the four-fermion approximation would give (see figure 3). Once the full coloron-

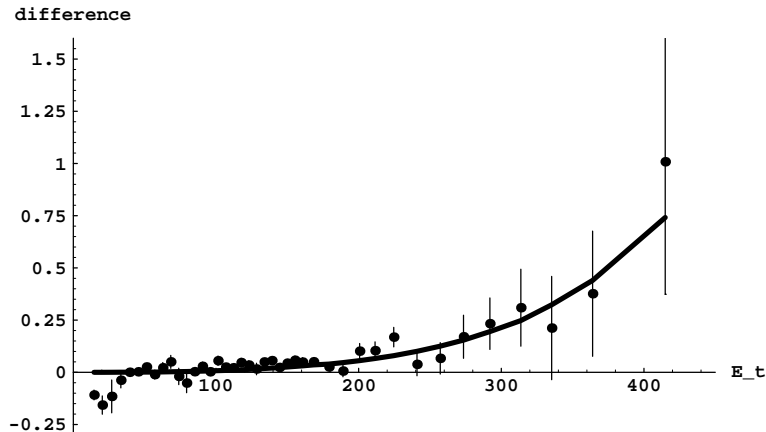


Figure 2: Difference plot $((\text{data} - \text{theory})/\text{theory})$ for the inclusive jet cross-section $\frac{1}{\Delta\eta} \int (d^2\sigma/d\eta dE_T) d\eta$ as a function of transverse jet energy E_t , where the pseudorapidity η of the jet falls in the range $0.1 \leq |\eta| \leq 0.7$. Dots with (statistical) error bars are the recently published CDF data [2]. The solid curve shows the LO prediction of QCD plus the contact interaction approximation to coloron exchange of equation (3.3) with $M_C/\cot\theta = 700$ GeV. Following CDF, we employed the MRSD0' structure functions [10] and 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).

exchange cross-sections are employed, the mass and mixing angle of the coloron may be varied independently. In particular, one may study the effects of light colorons with small values of $\cot^2\theta$. This can expand the range of accessible parameter space beyond what one would have reached by using the four-fermion approximation.

Another means of determining what kind of new strong interaction is being detected is measurement of the dijet angular distribution. Some new interactions would produce dijet angular distributions like that of QCD; others predict distributions of different shape. In terms of the angular variable χ

$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|} \quad (4.1)$$

QCD-like jet distributions appear rather flat while those which are more isotropic in $\cos\theta^*$ peak at low χ (recall that θ^* is the angle between the proton and jet directions). The ratio R_χ

$$R_\chi \equiv \frac{N_{\text{events}, 1.0 < \chi < 2.5}}{N_{\text{events}, 2.5 < \chi < 5.0}} \quad (4.2)$$

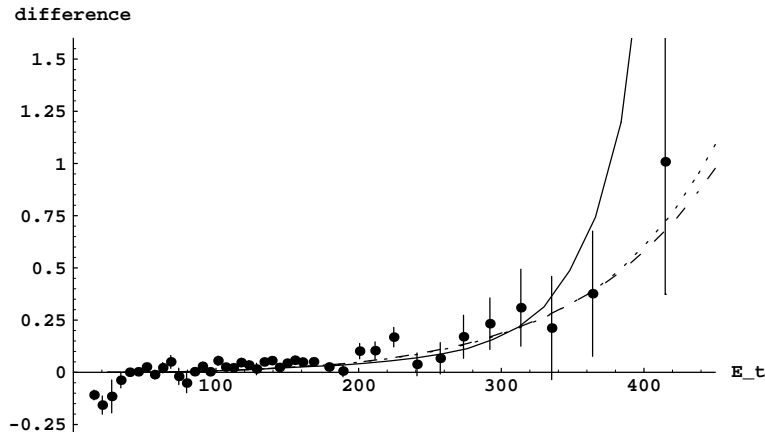


Figure 3: Difference plot for $d\sigma/dE_T$ (see figure 3) showing the effects of colorons of different masses when the ratio $M_c/\cot\theta$ is fixed at 700 GeV. Here full one-coloron exchange is included, rather than the contact interaction approximation. The solid curve is for a light coloron: $M_c = 1050$ GeV, $\cot\theta = 1.5$. The dotted and dashed curves correspond to much heavier colorons ($M_c = 1750$ GeV and 2000 GeV) with correspondingly larger values of $\cot\theta$ (2.5 and 3.0). The cross-section for the heavier colorons is well-approximated by the contact interaction approximation at Tevatron energies; the cross-section for the lighter coloron is not.

then captures the shape of the distribution for a given sample of events, e.g. at a particular dijet invariant mass.

The CDF Collaboration has made a preliminary analysis of the dijet angular information in terms of R_χ at several values of dijet invariant mass [11]. The preliminary data appears to be consistent either with QCD or with QCD plus a color-octet four-fermion interaction like (3.3) for $M_c/\cot\theta = 700$ GeV. Our calculation of R_χ including a propagating coloron gives results consistent with these. It appears that the measured angular distribution can allow the presence of a coloron and can help put a lower bound on $M_c/\cot\theta$.

5 Conclusions and Prospects

The flavor-universal coloron model can accommodate an excess at the high- E_t end of the inclusive jet spectrum at Tevatron energies without contradicting other data. Previous measurements of the weak-interaction ρ parameter and searches for new

particles decaying to dijets imply that the coloron must have a mass of at least 870 GeV. Measurements of jet spectra and angular distributions from runs IA and IB at the Tevatron, from future Tevatron runs, and eventually from the LHC will shed further light on the model.

This model would be even more interesting if it could also shed light on the origins of electroweak and flavor symmetry breaking. The minimal form described here has little connection to electroweak physics and none to flavor physics. However, it appears possible to include the extended strong interactions within a framework that addresses both issues. The simplest possibility³ is to build a variant of topcolor-assisted technicolor [12] in which electroweak symmetry breaking arises largely from technicolor, the strong interactions are as in the flavor-universal coloron model, and a pair of flavor-discriminating $U(1)$ interactions cause formation of a top condensate (and therefore a large top quark mass). Such a model would have low-energy jet phenomenology resembling that of the flavor-universal coloron model and potentially smaller FCNC effects involving bottom quarks, but would also have a large number of relatively light scalar bound states made of the light quarks.

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