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COLORONS: THEORY AND PHENOMENOLOGY[a]

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We briefly describe the structure and phenomenology of a flavor-universal extension of the strong interactions, focusing on the color-octet of massive gauge bosons ('colorons') present in the low-energy spectrum. We discuss current limits on the colorons and what future measurements may reveal.

1 Introduction

Data from the LEP and SLD experiments[1] is in such good agreement with the standard model that it tightly constrains non-standard electroweak physics. Yet the existence of significant non-standard strong interactions remains possible. Indeed an apparent excess of high-E_T jets has been found in the inclusive jet spectrum measured by CDF[2]. Finding a model that is consistent with both the LEP and Tevatron findings is an interesting challenge.

In this context, a flavor-universal coloron model[3] has been proposed. This model is a flavor-universal variant of the coloron model of Hill and Parke[4] which accommodates 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[5].

We will briefly describe the structure and phenomenology of the Higgs phase of the model (for a fuller discussion see ref. [6]). We discuss current limits on the colorons and what future measurements may reveal.

2 The model

In the flavor-universal coloron model[3], 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 $(3, \bar{3})$. In the model's Higgs phase, the scalar develops a non-zero vacuum expectation

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value $\langle\Phi\rangle$ at a scale where neither gauge coupling is strong. This vev breaks the two strong groups to their diagonal subgroup, which is identified 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 ($C^{\mu a}$) have a vectorial interaction with quarks

$$\mathcal{L} = -g_3 \cot\theta J^a_\mu C^{\mu a} \quad , \tag{1}$$

where $J^a_\mu \equiv \sum_f \bar{q}_f \gamma_\mu \frac{\lambda^a}{2} q_f$ 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 vev, the mass of the colorons is

$$M_c = \left(\frac{g_3}{\sin\theta\cos\theta}\right)\langle\Phi\rangle \quad . \tag{2}$$

The colorons decay to all sufficiently light quarks; assuming there are 6 flavors lighter than $M_c/2$ and writing $\alpha_s \equiv g_3^2/4\pi$, the decay width is

$$\Gamma_c \approx \alpha_s \cot^2\theta\, M_c \quad . \tag{3}$$

This model has several appealing features. The extended strong interactions can be grafted onto the standard one-Higgs-doublet model of electroweak physics, yielding a simple, complete, and renormalizable theory. The flavor-universality of the new strong interactions prevents the introduction of new flavor-changing neutral currents. Corrections to the ρ parameter are small (see section 3). Finally, the model fulfills its original purpose of accommodating the jet excess. Writing the low-energy interaction among quarks that results from heavy coloron exchange as a four-fermion interaction

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

and including its the contributions to the inclusive jet cross-section (setting $M_c/\cot\theta = 700$ GeV) yields the curve in figure 1, which compares quite nicely with the data.

3 Existing limits on colorons

A sufficiently light coloron would be visible in direct production at the Tevatron. The CDF Collaboration has searched for new particles decaying to dijets[b] and reported[7] a 95% c.l. upper limit on the incoherent production of such

[b]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. [6], however, the limit on colorons from b-tagged dijets will probably be weaker than that from the full dijet sample.

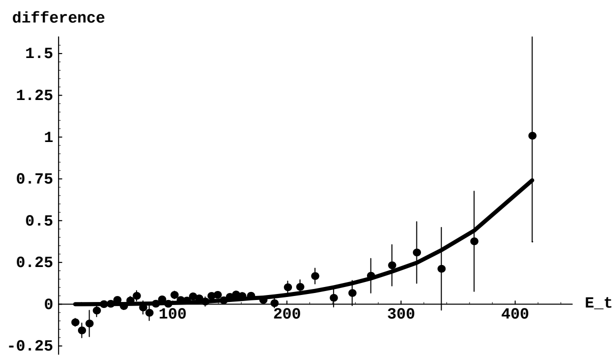

Figure 1: Difference plot ((data - theory)/theory) for the inclusive jet cross-section $\frac{1}{\Delta\eta}\int(d^2\sigma/d\eta\, dE_T)d\eta$ as a function of transverse jet energy E_t, where the pseudorapidity η of the jet falls in the range $0.1 \leq |\eta| \leq 0.7$. Dots with (statistical) error 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 (4) with $M_C/\cot\theta = 700$ GeV. Following CDF, we employed the MRSD0' structure functions [11] 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).

states. As discussed in [6], we calculated $\sigma \cdot B$ for colorons, and found find that for $\cot\theta = 1$, the range 200 GeV $< M_c <$ 870 GeV is excluded; at $\cot\theta = 1.5$, the upper limit of the excluded region rises to roughly 950 GeV; at $\cot\theta \gtrsim 2$, it rises to roughly 1 TeV. Realizing that $\sigma \cdot B$ is the same for a coloron with $\cot\theta = 1$ as for an axigluon [8] of identical mass [6] extends the excluded range of coloron masses. Axigluons with masses between 150 and 310 GeV are excluded by UA1's analysis [9] 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

$$\begin{array}{cccc} 150\mathrm{GeV} < & M_c & < 870\mathrm{GeV} & \cot\theta = 1 \\ 150\mathrm{GeV} < & M_c & < 950\mathrm{GeV} & \cot\theta = 1.5 \\ 150\mathrm{GeV} < & M_c & < 1000\mathrm{GeV} & \cot\theta \gtrsim 2 \quad , \end{array} \tag{5}$$

as summarized by the shaded region of figure 2.

An additional limit on $\cot\theta$ comes from constraints on 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

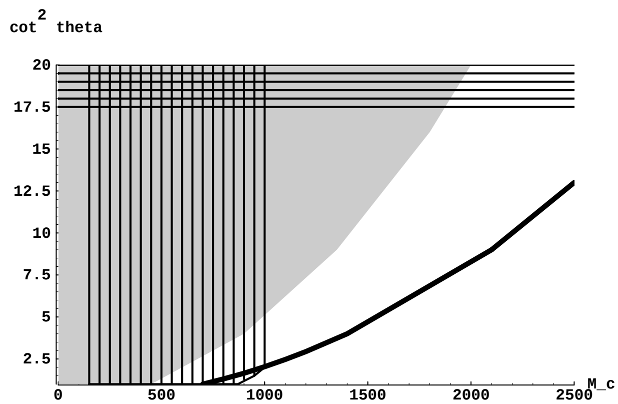

Figure 2: Current limits on the coloron parameter space: mass (M_c) vs. mixing parameter ($\cot^2\theta$). The shaded region is excluded by the weak-interaction ρ parameter [3] as in equation 6. The vertically-hatched polygon is excluded by searches for new particles decaying to dijets [7,9]. The horizontally-hatched 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.

the t and b quarks. Limits on this type of correction [10] imply that [3]

$$\frac{M_c}{\cot\theta} \gtrsim 450\text{GeV} \quad . \tag{6}$$

This excludes the hatched region of the $\cot^2\theta - M_c$ plane shown in figure 2.

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 in the Higgs phase at low energies. Starting from the low-energy four-fermion interaction (4) resulting from heavy coloron exchange, we use the NJL approximation to estimate the critical value of $\cot^2\theta$ as

$$(\cot^2\theta)_{crit} = \frac{2\pi}{3\alpha_s} \approx 17.5 \tag{7}$$

This puts an upper limit on $\cot^2\theta$ as indicated in figure 2.

4 Upcoming limits from Tevatron data

For colorons weighing a little more than a TeV – those that are just above the current dijet mass bound of figure 2 – it is appropriate to use the cross-sections for full coloron exchange [6] when making comparisons with the data. Such colorons are light enough that their inclusion yields differential cross-sections of noticeably different shape than the four-fermion approximation would give (see figure 3). Once the full coloron-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 $\cot^2\theta$, extending the range of accessible parameter space.

In principle, a detailed analysis (including propagating colorons) of the inclusive jet spectra measured by CDF and D0 should provide a lower bound on the coloron mass and coupling. In practice, however, the limit obtained from the inclusive jet spectrum will depend strongly on which structure functions are used to calculate the theoretical cross-sections. For instance, the new CTEQ structure functions[5], which reduce the apparent jet excess, would give stronger limits on colorons than the MRSD0' structure functions we have employed.

An analysis that is more independent of structure functions could be based, instead, on the dijet angular distribution. Some non-standard strong interactions would produce dijet angular distributions like that of QCD; others predict distributions of different shape. In terms of the angular variable χ

$$\chi = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|} \tag{8}$$

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

$$R_\chi \equiv \frac{N_{events}, 1.0 < \chi < 2.5}{N_{events}, 2.5 < \chi < 5.0} \tag{9}$$

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 [12]. The preliminary data appears to be consistent either with QCD or with QCD plus a color-octet four-fermion interaction like (4) 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 currently allows the presence of a coloron and will eventually help put bounds on M_c and $\cot\theta$.

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

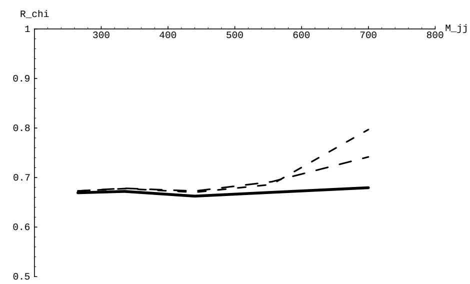

Figure 3: Plot of R_χ as a function of dijet invariant mass showing the effects of propagating colorons of different masses when the ratio $M_c/\cot\theta$ is fixed at 700 GeV. The solid curve is the prediction of QCD. The short-dashed curve (upper) is for a light coloron: $M_c = 1050$ GeV, $\cot\theta = 1.5$. The long-dashed curve corresponds to much heavier colorons ($M_c > 1400$ GeV) with correspondingly larger values of $\cot\theta$. Only the cross-section for the heavier colorons is well-approximated by the contact interaction (4) at Tevatron energies.

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 theory would be even more interesting if it could also shed light on the origins of electroweak and flavor symmetry breaking. While the minimal model described here has little connection to these issues, it appears possible to include the extended strong interactions within a framework that addresses them[6]. Work on these questions is in progress.

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