Lower Bound on Axigluon Mass from Electron-Positron Annihilation

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We compute the cross-section ratio R in e^+e^- scattering in chiral color theory and provide a new lower limit on the axigluon mass of 65 GeV if $\Lambda_{\rm QCD}=100$ MeV, or 100 GeV if $\Lambda_{\rm QCD}=200$ MeV.

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Gauge theories have been successful in describing a diversity of phenomena ranging from strong and electroweak forces to condensed-matter phenomena. It is generally believed in the nuclear- and particle-physics communities that the quantum chromodynamics (QCD) theory of quarks and gluons is acceptable as a basic theory underlying the nuclear force. It is still important, however, to investigate whether there are further elementary particles, beyond quarks and gluons, in the atomic nucleus, playing a key role in the strong interaction.

A recent alternative to QCD, chiral color theory,[1] predicts the existence of a color octet of massive axigluons, corresponding to the broken generators of the $SU(3)_L \times SU(3)_R$ chiral color gauge group. At the Fermi mass this symmetry spontaneously breaks down to the familiar $SU(3)_{\rm QCD}$. Several mass bounds have been set on the axigluon,[2,3] and two possible windows are left: from 25 to 125 GeV and above 275 GeV.

This Letter investigates the possibility of discovering the axigluon, or setting a better lower bound for its mass, by studying its influence on radiative corrections to the hadronic normalized cross section in e^+e^- scattering:

$$R=\frac{\sigma(e^+e^-\to\gamma^*,Z^{0*}\to\text{hadrons})}{e^4/12\pi s}, \qquad (1)$$

where e is the charge of the electron and s is the e^+e^- beam energy squared. We shall set all quark masses equal to zero in our calculations, which is a good approximations below the top-quark threshold.

The first-order axigluon Feynman diagrams contributing to the hadron production in e^+e^- collisions are shown in Fig. 1. Diagrams (a) and (b) produce two-jet events and their interference gives rise to the cross section

$$\sigma_2=|(\mathrm{a})+(\mathrm{b})|^2=\frac{e^4}{12\pi s}\left(3\sum_{\text{flavors}}\Gamma_f\right)\left(1+\frac{\alpha}{\pi}L+O(\alpha^2)\right), \qquad (2)$$

where α is the strong coupling and L is a function of $\sqrt{s}/M$, M being the mass of the axigluon. Obviously $L=0$ when $\sqrt{s}/M=0$. The argument in the sum over quark flavors, Γ_f, represents the photon channel, the Z^0 channel, and their interference. It is given by

$$\Gamma_f=Q_f^2+\frac{(v_e+a_e)^2(v_f+a_f)^2s^2-2v_ev_fQ_fs(s-m_Z^2)}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}, \qquad (3)$$

where Q_f is the quark electric charge, m_Z and Γ_Z are the mass and decay width of the Z^0, and v and a are the vector and axial-vector couplings of the Z^0 to the electron or quark. It is essential to realize that, as for QCD, in the limit where the quark masses are set to zero, the photon and Z^0 contributions enter, at this order, as completely separate terms.

Diagrams (c) and (d) originate the three-jet events, and their interference yields the cross section

$$\sigma_3=|(\mathrm{c})+(\mathrm{d})|^2=\frac{e^4}{12\pi s}\left(3\sum_{\text{flavors}}\Gamma_f\right)\left(\frac{\alpha}{\pi}T\right), \qquad (4)$$

where T is also a function of $\sqrt{s}/M$. Obviously $T\geq 0$ when $\sqrt{s}\geq M$.

In order to describe the total cross section for hadron production, we must also consider QCD diagrams similar

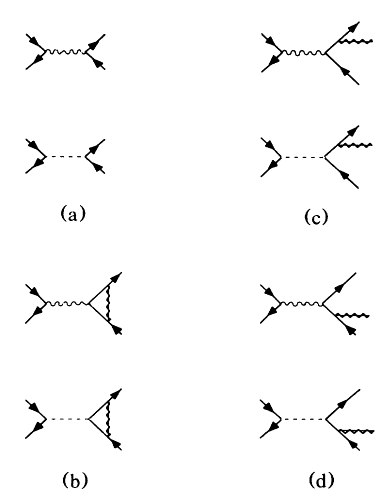

FIG. 1. Feynman diagrams. Straight lines are fermions, dashed lines are Z^0's, curved lines are photons, and jagged lines are axigluons.

to graphs (b), (c), and (d), with axigluons replaced by gluons. To first order in α, these diagrams remain uncoupled from the previous ones. The gluonic contribution is given by[4]

$$\sigma_{\text{gluon}} = \frac{e^4}{12\pi s}\left[3\sum_{\text{flavors}}\Gamma_f\right]\left[\frac{\alpha}{\pi}\right], \tag{5}$$

so that the total-cross-section ratio R is given by

$$R = \left[3\sum_{\text{flavors}}\Gamma_f\right]\left[1+\frac{\alpha}{\pi}(1+f)+O(\alpha^2)\right], \tag{6}$$

where

$$f(\sqrt{s}/M) = L+T\,. \tag{7}$$

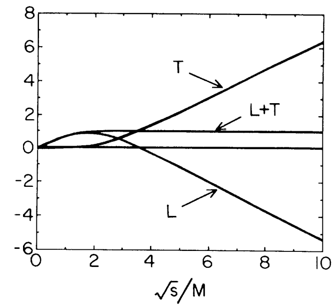

FIG. 2. Plot of L and T from Eqs. (8) and (10).

It turns out that L and T are separately infrared divergent in the limit where $\sqrt{s}/M=\infty$.[5] This is due to the fact that in this limit the axigluon can be soft, and the quark propagator can go on mass shell. Nevertheless, the sum $f=L+T$ always remains finite[6] and goes to 1 when $\sqrt{s}/M=\infty$, because in this limit there is no difference between gluons and axigluons. This behavior of L and T is shown in Fig. 2.

The two-jet events contribution is given by the integral over Feynman parameters

$$L = \frac{8}{3}\int_0^1 dx\int_0^{1-x} dy\left[\ln\left(1+\frac{s}{M^2}\frac{xy}{x+y-1}\right)+\frac{s(1-x)(1-y)}{sxy+M^2(x+y-1)}\right]. \tag{8}$$

This integral has a closed form, provided we make use of the Spence function[7]

$$\int dt\,\frac{\ln(t-1)}{t} = \tfrac{1}{2}\ln^2(t)+\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\left(\frac{-1}{t}\right)^n. \tag{9}$$

The three-jet events contribution is given by the phase-space integral

$$T = \frac{2}{s^2}\int_M^{(s+M^2)/2s} dx\int_M^{E_G} dy\,\frac{X}{2(s-M^2)^{1/2}}(\text{leptonic current})_{\mu\nu}(\text{hadronic current})^{\mu\nu}, \tag{10}$$

where

$$E_G = \text{axigluon energy},$$

$$X = [(\sqrt{s}-2E_1)(\sqrt{s}-2E_2)]^{1/2}, \tag{11}$$

$$E_1(E_2) = \text{quark (antiquark) energies}.$$

This integral can be computed in closed form if we use[7]

$$\int dt\,\frac{\ln[t+(t^2-1)^{1/2}]}{t} = \tfrac{1}{2}\ln^2(2t)+\sum_{n=1}^{\infty}\frac{(2n-1)!!}{(2n-2)!!(2n)^3}\left(\frac{1}{t}\right)^{2n}. \tag{12}$$

The detailed behavior of $f(\sqrt{s}/M)$ is shown in Fig. 3. As the axigluon behaves like a massive gluon (for massless quarks), f goes to 1 when $\sqrt{s}/M\to\infty$.

To compare our result with experiment, we use the following value of $\alpha_s(\sqrt{s})$, which has been obtained from a wide range of R measurements:[8]

$$\alpha_s(34\text{ GeV}) = 0.165\pm 0.030\,. \tag{13}$$

In chiral color, as shown in Eq. (6), this result has to be reinterpreted as

$$(1+f)\alpha_s(34\text{ GeV}) = 0.165\pm 0.030\,, \tag{14}$$

and, using the second-order result of the renormalization-group equations, we find

$$f\left(\frac{34\text{ GeV}}{M}\right) = (0.165\pm 0.030)\frac{23\ln(34\text{ GeV}/\Lambda_{\text{QCD}})}{6\pi[1-\frac{174}{529}\ln 2\ln(34\text{ GeV}/\Lambda_{\text{QCD}})/\ln(34\text{ GeV}/\Lambda_{\text{QCD}})]}-1\,. \tag{15}$$

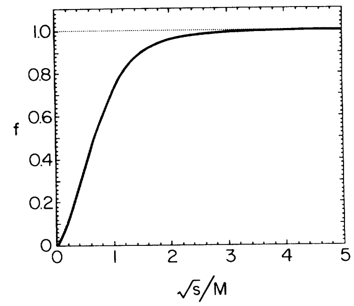

FIG. 3. Detailed behavior of $f = L + T$ (see also Fig. 2).

If one takes $\Lambda_{\mathrm{QCD}} = 200$ MeV, according to (15), f should be below 0.21, which, by examining Fig. 3, yields a minimum admissible value for M of ~ 100 GeV. In the case where $\Lambda_{\mathrm{QCD}} = 100$ GeV, the value of f has to be below 0.35, and accordingly the lower bound for M is ~ 65 GeV.

We should note that our analysis is somewhat crude since it is based on the estimate (13) from Ref. 8. This estimate is the result of a fitting to the data on R over a range of energies and from different experiments. A more accurate analysis would require a full refitting of all the experimental data using chiral color from the outset. Our results indicate, however, that e^+e^- annihilation provides a better lower bound on the axigluon mass than any obtained previously, for example, from upsilon decay. We expect that a complete analysis of the e^+e^- data will yield results qualitatively similar to those we have obtained.

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[1]P. H. Frampton and S. L. Glashow, Phys. Lett. B **190**, 157 (1987); Phys. Rev. Lett. **58**, 2168 (1987).

[2]M. A. Doncheski, H. Grotch, and R. W. Robinett, Phys. Rev. D **38**, 412 (1988).

[3]J. Bagger, C. Schmidt, and S. King, Phys. Rev. D **37**, 1188 (1988).

[4]T. Appelquist and H. Georgi, Phys. Rev. D **8**, 4000 (1973); A. Zee, Phys. Rev. D **8**, 4038 (1973).

[5]G. Sterman and S. Weinberg, Phys. Rev. Lett. **29**, 1436 (1977).

[6]T. Kinoshita, J. Math. Phys. **3**, 650 (1962); T. D. Lee and M. Nauenberg, Phys. Rev. **133**, B1549 (1964).

[7]A. P. Pridnikov, Yu. A. Brychkov, and O. I. Marichev, *Integrals and Series* (Gordon and Breach, New York, 1987).

[8]W. de Boer, SLAC Report No. SLAC-PUB-4428, 1987 (to be published); Proceedings of the Tenth Warsaw Symposium on Elementary Particle Physics, Kazimierz, Poland, 25–29 May 1987 (to be published).