The phenomenology of scalar color octets

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We discuss the phenomenology of color scalar octet particles. Namely, we discuss the discovery potential of scalar octets at LEP, FNAL, and LHC. It appears that new hadrons composed from scalar color octets are rather long-lived ($\Gamma \leqslant O(10)$ keV). We point out that the current experimental data are consistent with the existence of light ($M \sim O(1)$ GeV) scalar octets. Light scalar color octets give an additional contribution to the QCD β-function and can improve the agreement between the deep inelastic and LEP data. © *1995 American Institute of Physics.*

In this note we discuss the phenomenology of scalar color octets. Relatively light [$M \leqslant O(1)$ TeV] scalar color octets are predicted in some nonsupersymmetric and supersymmetric GUTs.[1,2] Here we consider the potential for discovery of scalar octets at LEP, FNAL, and LHC. It appears that new hadrons composed of scalar octets are rather long-lived [$\Gamma \leqslant O(10)$ keV]. We point out that the current experimental data are consistent with the existence of light [$M \sim O(1)$GeV] scalar octets. Light scalar octets give an additional contribution to the QCD β-function and can improve the agreement between the deep inelastic and LEP data.

To be specific, in this paper we consider light scalar color octets neutral under the $SU(2) \otimes U(1)$ electroweak gauge group. Such particles are described by the self-conjugate scalar field $\Phi^\alpha_\beta(x)$ $[(\Phi^\alpha_\beta(x))^+ = \Phi^\beta_\alpha(x)$, $\Phi^\alpha_\alpha(x) = 0)$ interacting only with gluons. Here $\alpha = 1$, 2, 3; $\beta = 1, 2, 3$ are $SU(3)$ indices. The scalar potential for the scalar octet field $\Phi^\alpha_\beta(x)$ has the form

$$V(\Phi) = \frac{M^2}{2}\mathrm{Tr}(\Phi^2) + \frac{\lambda_1 M}{6}\mathrm{Tr}(\Phi^3) + \frac{\lambda_2}{12}\mathrm{Tr}(\Phi^4) + \frac{\lambda_3}{12}(\mathrm{Tr}\Phi^2)^2. \tag{1}$$

The term $(\lambda_1 M/6)\mathrm{Tr}(\Phi^3)$ in the scalar potential (1) breaks the discrete symmetry $\Phi \to -\Phi$. The existence of such term in the Lagrangian leads to the decay of the scalar octet mainly into two gluons through one-loop diagrams similar to the corresponding one-loop diagrams describing the Higgs boson decay into two photons. One can show that the decay width of the scalar octet is given by the formula

$$\Gamma(\Phi \to gg) = \frac{15}{4096\pi^3}\alpha_s^2 c^2 \lambda_1^2 M, \tag{2}$$

where

$$c=\int_0^1\int_0^{1-w}\frac{wu}{1-u-w}dudw=0.048 \tag{3}$$

and α_s is the effective strong coupling constant at some normalization point $\mu\sim M_z$. Numerically, for $\alpha_s=0.12$ we find that

$$\Gamma(\Phi\rightarrow gg)=0.39\times10^{-8}\lambda_1^2M. \tag{4}$$

From the requirements that color $SU(3)$ symmetry is unbroken (the minimum $\Phi_\beta^\alpha(x)=0$ is the deepest one) and the effective coupling constants $\bar{\lambda}_2$, $\bar{\lambda}_3$ do not have Landau pole singularities up to the energy $M_0=100M$ we find that $\lambda_1\leq O(1)$. Therefore the decay width of the scalar color octet is less than $O(10)$ eV, $O(100)$ eV, $O(1)$ keV, and $O(10)$ keV for the octet masses $M=1$, 10, 100, and 1000 GeV, respectively. It means that new hadrons composed of the scalar octet Φ, quarks, and gluons ($\bar{q}\Phi q$, Φg, $qqq\Phi$) are long-lived even for very high scalar octet mass).

Light scalar octets with masses M of the order of several GeV give an additional contribution to the QCD β-function that alters the evolution of the QCD effective strong coupling constant. For instance, in the one-loop approximation we have the following formula[3,4] for the effective strong coupling constant:

$$\alpha_s(Q)=\frac{4\pi}{b_0\ln(Q^2/\Lambda^2)}, \tag{5}$$

where $b_0=11-2/3N_f$ for the standard case and $b_0=11-2/3N_f+1/2$ for the case when we take into account a light scalar octet in the loop. In complete analogy with the case of the light gluino,[5,6] allowance for light scalar octets leads to modification of the strong coupling constant at the M_z scale extracted from low-energy deep inelastic data and data on the τ-lepton decay width. Namely, one can find that the "modified" strong coupling constant, including the QCD evolution due to a light scalar octet, is

$$\alpha_s^{\mathrm{mod}}(M_z)=\frac{1}{1/\alpha_s(M_z)-0.08\ln(M_z/M)}. \tag{6}$$

For instance, for $\alpha_s(M_z)=0.113$, extracted from deep inelastic data for $Q_0=5$ GeV, we find that $\alpha_s^{\mathrm{mod}}(M_z)=0.1161$, 0.1153, 0.1146, and 0.1136 for the scalar octet masses $M=5$, 10, 20, and 30 GeV, respectively. Thus we find that the greatest effect is a decrease of the effective strong coupling constant by 0.003, which is a welcome effect since it improves the agreement between strong coupling constant extracted from data on the Z-boson total hadronic decay width and deep inelastic scattering. For the current situation as to the experimental determination of $\alpha_s(M_z)$ see Ref. 7.

Let us now consider the possibility of discovering scalar octets at LEP1. For scalar octets lighter than $M_z/2$ the differential decay width

$$Z(p)\rightarrow\bar{q}(p_1)q(p_2)\Phi(p_3)\Phi(p_4) \tag{7}$$

in the leading approximation in the strong coupling constant $\alpha_s(M_z)$ for massless quarks is determined by the formula

$$d\Gamma(Z\rightarrow\bar{q}q\Phi\Phi)[\Gamma(Z\rightarrow\mathrm{hadrons})]^{-1}=A\ dm_{12}^2dp^2, \tag{8}$$

$$A=\frac{4\alpha_s^2}{3\pi^2 p^2}\left(1-\frac{4M^2}{M_z^2}\right)^{3/2}\left[BC^{-1}\ln\left(\frac{C+D}{C-D}\right)-2D\right]. \tag{9}$$

Here α_s is the effective strong coupling constant at some normalization point $\mu\sim M_z$, $m_{12}^2=(p_1+p_2)^2$, $p^2=(p_3+p_4)^2$, $C=1/2(M_z^2+p^2-m_{12}^2$, $B=C^2+1/2m_{12}^2(M_z^2+p^2)$, $D^2=C^2-M_z^2p^2$. In our numerical estimates we shall take $\alpha_s=0.12$. For the branching ratio $B=10^3\Gamma(Z\rightarrow\bar{q}q\Phi\Phi)[\Gamma(Z\rightarrow\text{hadrons})]^{-1}$ our numerical results are:

M GeV:	2,	5,	10,	15,	20,	25,	30,	35
B:	7.25,	1.63,	0.22,	0.037,	0.0058,	0.00078,	7.0×10^{-5},	2.7×10^{-6}.

For light scalar octets (M of the order of several GeV) the process $Z\rightarrow\bar{q}q\Phi\Phi$ gives an additional contribution to the standard QCD four-jet production in Z-decay. We have found that the four-jet cross section of the process $Z\rightarrow\bar{q}q\Phi\Phi$ is approximately 15% of the standard QCD four-jet cross section $Z\rightarrow\bar{q}q\bar{q}'q'$, which in turn is around 5% of the total four-jet cross section.[8] Therefore, the discovery at LEP of light scalar octets by measurement of the four-jet cross section is rather problematical. For scalar masses $M\geqslant O(10)$ GeV a scalar octet decaying into two gluons produces two gluon jets, so we shall have 6-jet events with 4 gluon jets. Unfortunately, the 6-jet cross sections are not known very well. We can estimate that the 6-jet cross section is a factor of $\alpha_s^2\sim0.01$ smaller than the 4-jet cross section, so the standard 6-jet QCD cross section is comparable to the 6-jet cross section resulting from the scalar octet decays. By measurement of the differential 6-jet cross section

$$d\sigma/dm_{12}dm_{34} \tag{10}$$

(here $m_{12}^2=(p_{1,jet}+p_{2,jet})^2$ and $m_{34}^2=(p_{3,jet}+p_{4,jet})^2$ are the invariant two-jet square masses) it is possible to detect scalar octets with masses 10 GeV$\leqslant M\leqslant$20 GeV, provided that the accuracy in the determination of the two-jet invariant mass is better than 25%, since in this case we earn an additional factor $\geqslant O(16)$ for suppression of the background. It would therefore be very interesting to consider the distributions of 6-jet events at LEP1 over the two-jet invariant masses. As far as I know, there has been no such analysis of the LEP1 data.

Consider now the production of scalar octets at FNAL and LHC. The corresponding lowest-order predictions for the parton cross sections have the form

$$\frac{d\sigma}{dt}(\bar{q}q\rightarrow\Phi\Phi)=\frac{4\pi\alpha_s^2}{s^4}(tu-M^4), \tag{11}$$

$$\frac{d\sigma}{dt}(gg\rightarrow\Phi\Phi)=\frac{\pi\alpha_s^2}{s^2}\left(\frac{7}{96}+\frac{3(u-t)^2}{32s^2}\right)\left(1+\frac{2M^2}{u-M^2}+\frac{2M^2}{t-M^2}+\frac{2M^4}{(u-M^2)^2}\right.$$
$$\left.+\frac{2M^4}{(t-M^2)^2}+\frac{4M^4}{(t-M^2)(u-M^2)}\right), \tag{12}$$

$$\sigma(\bar{q}q\rightarrow\Phi\Phi)=\frac{2\pi\alpha_s^2}{9s}k^3, \tag{13}$$

TABLE I. The cross section $\sigma(pp\rightarrow\Phi\Phi+...)$ in pb for different values of the octet masses and momentum transfer Q at LHC.

M(TeV)		2	1.5	1	0.75	0.5	0.3	0.2
σ	$Q=0.375$ TeV	0.00024	0.004	0.093	0.60	6.0	76.3	786.4
σ	$Q=2M$	0.00026	0.0042	0.10	0.69	7.40	84.3	701.4
σ	$Q=4M$	0.00028	0.0043	0.092	0.619	6.6	91.0	832

$$\sigma(gg\rightarrow\Phi\Phi)=\frac{\pi\alpha_s^2}{s}\left[\frac{15k}{16}+\frac{51kM^2}{8s}+\frac{9M^2}{2s^2}(s-M^2)\ln\left(\frac{1-k}{1+k}\right)\right], \tag{14}$$

where $k=(1-4M^2/s)^{1/2}$. We have calculated the cross sections for the production of scalar octets at FNAL and LHC using the results of Ref. 9 for the parton distributions, namely, in our calculations we have used set 1 of the parton distributions. We have found that at LHC the main contribution ($\geqslant 95\%$) comes from gluon annihilation into two scalar octets $gg\rightarrow\Phi\Phi$, whereas at FNAL the gluon–gluon and quark–antiquark annihilation cross sections are comparable. The results of our calculations are presented in Tables I and II. For the light scalar octets, two-gluon and quark–antiquark annihilations into two scalar octets give an additional contribution to the two-jet cross section. However, this additional contribution is rather small. For instance, the cross section for gluon–gluon scattering is[10]

$$\frac{d\sigma}{dt}(gg\rightarrow gg)=\frac{9\pi\alpha_s^2}{2s^2}\left[3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right]. \tag{15}$$

Even for the most favorable case $t=u=-s/2$ the cross section (12) is 20 times less than the gluon–gluon cross section (15). Thus the prospects of detecting light scalar octets by measurement of the two-jet cross sections look hopeless. For large values of the scalar octet mass [$M\geqslant O(100)$ GeV] the scalar octet decays into two gluons, leading to four-jet events. The cross section for scalar octet production for $M\sim 100$ GeV is $O(10^{-2})$ of the standard QCD two-jet cross section and it has the same order of magnitude as the standard 4-jet QCD cross section. Therefore, by measurement of the two-jet invariant masses, as in the case of LEP1, it is possible (if we know the two-jet invariant masses to an accuracy better than 20%) to earn an additional factor ~ 25 and so to detect the scalar octets.

To conclude, in this note we have studied the prospects for discovering scalar octets at LEP1, FNAL, and LHC. New hadrons composed of scalar octets are rather long-lived even for high scalar octet masses. We have found that the existence of light scalar octets with masses of the order of several GeV are consistent with the existing experiments. Heavy scalar octets could be discovered by LHC, FNAL, or LEP by measurement of the

TABLE II. The cross section $\sigma(\bar{p}p\rightarrow\Phi\Phi+...)$ in pb for different values of the octet masses and momentum transfer Q at FNAL.

M(GeV)		300	250	200	150	125	100	75	50
σ	$Q=450$ GeV	0.014	0.07	0.40	3.0	9.9	38.8	198.4	1620
σ	$Q=2M$	0.013	0.074	0.42	3.56	10.8	52.4	267.4	2940
σ	$Q=4M$	0.014	0.058	0.33	2.8	9.6	40.3	208.3	1782

distributions of the differential cross sections over the invariant two-jet masses, provided that the accuracy of determination of the two-jet invariant mass is better than 20%. A more detailed discussion of the prospects of detecting scalar octets by measurement of the invariant two-jet masses will be given elsewhere.

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