

THE PHENOMENOLOGY OF SCALAR COLOUR OCTETS

*N. V. Krasnikov*¹⁾*Institute for Nuclear Research, RAS**117312 Moscow, Russia*

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We discuss the phenomenology of colour 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 colour octets are rather longlived ($\Gamma \leq O(10)\text{keV}$). We point out that the current experimental data don't contradict to the existence of light ($M \sim O(1)\text{GeV}$) scalar octets. Light scalar colour octets give additional contribution to the QCD β -function and allow to improve agreement between deep inelastic and LEP data.

The aim of this note is the discussion of the phenomenology of scalar colour octets. The relatively light ($M \leq O(1)\text{TeV}$) scalar colour octets are predicted in some nonsupersymmetric and supersymmetric GUTs [1, 2]. Here we consider the discovery potential of scalar octets at LEP, FNAL and LHC. It appears that new hadrons composed from scalar octets are rather longlived ($\Gamma \leq O(10)\text{KeV}$). We point out that the current experimental data don't contradict to the existence of light ($M \sim O(1)\text{GeV}$) scalar octets. Light scalar octets give additional contribution to the QCD β -function and allow to improve agreement between deep inelastic and LEP data.

To be precise in this paper we consider colour light scalar octets neutral under $SU(2) \otimes U(1)$ electroweak gauge group. Such particles are described by the selfconjugate scalar field $\Phi_\beta^\alpha(x)$ ($(\Phi_\beta^\alpha(x))^+ = \Phi_\alpha^\beta(x)$, $\Phi_\alpha^\alpha(x) = 0$) 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 $\Phi_\beta^\alpha(x)$ has the form

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

The term $\frac{\lambda_1 M}{6} \text{Tr}(\Phi^3)$ in the scalar potential (1) breaks the discrete symmetry $\Phi \rightarrow -\Phi$. 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 find that the decay width of the scalar octet is determined by the formula

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

where

$$c = \int_0^1 \int_0^{1-w} \frac{wu}{1-u-w} du dw = 0.048 \quad (3)$$

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

$$\Gamma(\Phi \rightarrow gg) = 0.39 \cdot 10^{-8} \lambda_1^2 M. \quad (4)$$

¹⁾e-mail: KRASNIKO@MS2.INR.AC.RU

From the requirements that colour $SU(3)$ symmetry is unbroken (the minimum $\Phi_\beta^\alpha(x) = 0$ is the deepest one) and the effective coupling constants $\bar{\lambda}_2, \bar{\lambda}_3$ don't 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 colour octet is less than $O(10)eV, O(100)eV, O(1)keV, O(10)keV$ for the octet masses $M = 1, 10, 100, 1000 GeV$ correspondingly. It means that new hadrons composed from scalar octet Φ , quarks and gluons ($\bar{q}\Phi q, \Phi g, q\bar{q}\Phi$) are longlived even for very high scalar octet mass).

Light scalar octets with the mass $M = O(several) GeV$ give additional contribution to the QCD β -function that changes evolution of the QCD effective strong coupling constant. For instance, in one-loop approximation we have the following formula [3, 4] for the effective strong coupling constant:

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

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 light scalar octet in the loop. In complete analogy with the case of light gluino [5, 6] an account of light scalar octets leads to the 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 taking into account the QCD evolution due to light scalar octet is

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

For instance, for $\alpha_s(M_z) = 0.113$ extracted from deep inelastic data for $Q_0 = 5 GeV$ we find that $\alpha_s^{mod}(M_z) = 0.1161; 0.1153; 0.1146; 0.1136$ for the scalar octet masses $M = 5; 10; 20; 30 GeV$ correspondingly. So we find that the maximal effect is the decrease of the effective strong coupling constant by 0.003 that is welcomed effect since it improves the agreement between strong coupling constant extracted from Z -boson total hadronic decay width and deep inelastic data. For the current situation with experimental determination of $\alpha_s(M_z)$ see ref.[7].

Consider now the possibility of the discovery of scalar octets at LEP1. For the scalar octets lighter than $M_z/2$ the differential decay width

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

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

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

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

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

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

For light scalar octets ($M \sim O(\text{several}) \text{ GeV}$) the process $Z \rightarrow \bar{q}q\Phi\Phi$ gives 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 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]. So the discovery at LEP of light scalar octets by the measurement of the four-jet cross section is rather problematic. For the scalar masses $M \geq O(10) \text{ GeV}$ the scalar octet decaying into two gluons produces two gluon jets, so we shall have 6-jet events with 4 gluon jets. Unfortunately we don't know rather well 6-jet cross sections. We can estimate that 6-jet cross section is $\alpha_s^2 \sim 0.01$ smaller than 4-jet cross section, so the standard 6-jet QCD cross section is comparable with the 6-jet cross section resulting from the scalar octet decays. By the measurement of the differential 6-jet cross section

$$d\sigma/dm_{12}dm_{34} \quad (10)$$

(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 discover the scalar octets with masses $10 \text{ GeV} \leq M \leq 20 \text{ GeV}$ provided the accuracy in the determination of the two-jet invariant mass is less than 25% since in this case we earn additional factor $\geq O(16)$ for the suppression of the background. So, it would be very interesting to consider the distributions of 6-jet events at LEP1 on the two-jet invariant masses. As I know there was not such analysis of 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

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

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

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

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

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 for the parton distributions of ref.[9], namely, in our calculations we have used set 1 of the parton distributions. We have found that at LHC the main contribution ($\geq 95\%$) comes from the gluon annihilation into two scalar octets $gg \rightarrow \Phi\Phi$, whereas at FNAL gluon-gluon and quark-antiquark annihilation cross sections are comparable. The results of our calculations are presented in tables 1 and 2. For the light scalar octets two gluon and quark-antiquark annihilations into two scalar octets give 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]

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

Even for the most favorable case $t = u = -s/2$ the cross section (12) is 20 times less than gluon-gluon cross section (15). So the perspective to detect light scalar octets by the measurement of the two-jet cross sections looks hopeless. For rather big values of the scalar octet mass ($M \geq O(100)$ GeV) the scalar octet decays into two gluons that leads to the four-jet events. The cross section for the 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. So by the measurement of the two-jet invariant masses like as in the case of LEP1 it is possible (if we know two-jet invariant masses with an accuracy better than 20%) to earn additional factor ~ 25 and to discover the scalar octets.

Table 1

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

$M(\text{TeV})$		2	1.5	1	0.75	0.5	0.3	0.2
σ	$Q = 0.375 \text{ TeV}$	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

Table 2

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

$M(\text{GeV})$		300	250	200	150	125	100	75	50
σ	$Q = 450 \text{ GeV}$	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

To conclude, in this note we have studied the perspectives of the discovery of scalar octets at LEP1, FNAL and LHC. New hadrons composed from scalar octets are rather longlived even for high scalar octet masses. We have found that the existence of light scalar octets with the masses $O(\text{several})$ GeV don't contradict to the existing experiments. Heavy scalar octets could be discovered at LHC, FNAL or LEP by the measurement of the distributions of the differential cross sections on the invariant two-jet masses provided the accuracy of the determination of the two-jet invariant mass is better than 20%. More detailed discussion of the perspective to detect scalar octets by the measurement of the invariant two-jet masses will be done elsewhere.

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