QCD exotics versus a Standard Model Higgs

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The present collider data put severe constraints on any type of new strongly-interacting particle coupling to the Higgs boson. We analyze the phenomenological limits on exotic quarks belonging to non-triplet $SU(3)_C$ representations and their implications on Higgs searches. The discovery of the Standard Model Higgs, in the experimentally allowed mass range, would exclude the presence of exotic quarks coupling to it. Thus, such QCD particles could only exist provided that their masses do not originate in the SM Higgs mechanism.

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I. EXOTIC COLOURED FERMIONS

Exotic matter in higher representations of the $SU(3)_C$ colour group is an appealing possibility which was already considered in the early times of QCD [1–5]. In particular, the sextet representation has been extensively analyzed as a possible source of dynamical electroweak symmetry breaking [6–13]. It is well known that such exotic quarks modify very sizeably the running of the strong coupling and, therefore, their hypothetical existence is strongly constrained by the very successful experimental tests of asymptotic freedom [14].

Since not a single exotic QCD particle has been observed so far, their masses should be heavy enough to avoid the present experimental constraints from direct searches. However, even with very large masses, if those exotic quarks get their masses through the Standard Model Higgs mechanism, they would strongly enhance the production of Higgs bosons at LHC. The non-decoupling character of the Higgs couplings, being proportional to the coupled-object mass, implies sizeable effects from any strongly-interacting heavy mass scale generated by the Higgs mechanism. Therefore, the present collider limits on the production cross section $\sigma(gg \to H)$ put a very severe constraint on the possible existence of such objects.

Let us consider an exotic spin-$\frac{1}{2}$ fermion X_R, with mass M_X, belonging to the irreducible representation $\underline{R} \equiv (\lambda_1, \lambda_2)$ of $SU(3)_C$. The dimension of the representation is given by $d_R = \frac{1}{2}\,(\lambda_1+1)(\lambda_2+1)(\lambda_1+\lambda_2+2)$; the fundamental $\underline{3} = (1,0)$ [$\underline{3}^* = (0,1)$] and adjoint $\underline{8} = (1,1)$ representations have dimensions $d_F = 3$ and $d_A = 8$, respectively. The gluonic couplings of X_R are fixed by the generators t^a_R ($a = 1, \cdots, d_A$), satisfying $[t^a_R, t^b_R] = i f^{abc}\, t^c_R$. The quadratic Casimir operator,

$$\sum_{a=1}^{d_A} t^a_R\, t^a_R \;=\; C_R\, \mathbb{1}_{d_R}\,,$$
$$C_R \;=\; \frac{1}{3}\,\left(\lambda_1^2+\lambda_2^2+\lambda_1\lambda_2+3\lambda_1+3\lambda_2\right)\,, \qquad (1)$$

determines the trace normalization factor for the representation $\underline{R}$:

$$\mathrm{Tr}\left(t^a_R\, t^b_R\right) \;=\; T_R\,\delta^{ab}\,, \qquad\qquad T_R \;=\; \frac{C_R\, d_R}{d_A}\,. \qquad (2)$$

This trace factor grows rapidly with increasing dimensions d_R, implying larger contributions of the exotic object X_R to the relevant QCD cross sections: $T_F = \frac{1}{2}$, $T_6 = \frac{5}{2}$, $T_A = 3$, $T_{10} = \frac{15}{2}$, $T_{15} = 10\ldots$, where $\underline{6} = (2,0)$, $\underline{10} = (3,0)$, $\underline{15} = (2,1)\ldots$

If kinematically allowed, charged exotic quarks would be copiously produced in e^+e^- annihilation. For a charged X_R the ratio $R_{e^+e^-} \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^\cdot)$ would rise dramatically at the production threshold $s = 4M_X^2$ with an additive contribution $\Delta R_{e^+e^-} = d_R Q_X^2 \delta_{\mathrm{QCD}}$. A neutral exotic X_R^0 would be pair-produced at $\mathcal{O}(\alpha_s^2)$ through gluon emission, i.e. $e^+e^- \to q\bar{q}g \to q\bar{q}X_R^0\bar{X}_R^0$. Independently of their electric charge, exotic quarks would imply large modifications of the hadronic cross sections at pp and $p\bar{p}$ colliders and a proliferation of new hadrons containing X_R constituents (unless the X_R lifetime is too small to hadronize). The absence of any exotic signal in the present data puts the lower limit on the mass M_X well above 100 or 200 GeV.

New fermions in higher QCD representations would contribute to the QCD β function

$$\mu\,\frac{d\alpha_s}{d\mu} \;=\; \alpha_s\,\beta(\alpha_s)\,, \qquad\qquad \beta(\alpha_s) \;=\; \sum_{n=1}\beta_n\,\left(\frac{\alpha_s}{\pi}\right)^n\,. \qquad (3)$$

At the two loop level [15, 16],

$$\beta_1 = -\frac{11}{6}\,C_A \,+\, \frac{2}{3}\,\sum_R n_{_R}\, T_R\,,$$
$$\beta_2 = -\frac{17}{12}\,C_A^2 \,+\, \frac{1}{6}\,\sum_R n_{_R}\, T_R\,(5\,C_A + 3\,C_R)\,, \qquad (4)$$

where $n_{_R}$ is the number of fermion flavours in the representation $\underline{R}$. In the three-generation Standard Model ($n_F = 6$) both β_1 and β_2 are negative. In order to flip the sign of β_1 (β_2), $n_F > 16$ (8) triplet quarks would be needed. However, the larger algebraic contribution of a higher colour representation implies a much faster lost of asymptotic freedom. Keeping $n_F = 6$, the only possible additions preserving $\beta_1 < 0$ are at most two sextet or one octet fermion representations; but even a single sextet flips already the sign of β_2. Since the running of α_s has been successfully tested with high precision (at the four loop level) from the τ mass scale [17, 18] up to energies above 200 GeV [14], exotic quarks in higher QCD representations are clearly excluded in this energy domain [19–23].

Higher energy scales are presently being explored at the LHC, where the main production mechanism of exotic QCD fermions is $gg \to X_R \bar{X}_R$, with a subdominant contribution from $q\bar{q} \to X_R \bar{X}_R$. The calculation of the corresponding partonic cross sections is straightforward at tree level; we obtain

$$\sigma(gg \to X_R \bar{X}_R) = \frac{\pi \alpha_s^2}{16\, s}\, C_R\, d_R\; \mathcal{G}\left(\frac{4M_X^2}{s}\right), \qquad (5)$$

$$\sigma(q\bar{q} \to X_R \bar{X}_R) = \frac{2\pi \alpha_s^2}{27\, s}\, C_R d_R \left(1 + \frac{2M_X^2}{s}\right) \sqrt{1 - \frac{4M_X^2}{s}}\,,$$

where

$$\mathcal{G}(x) = \left[\left(1 + x - \frac{x^2}{2}\right) C_R + \frac{3}{4}\, x^2\right] \ln\left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}\right) - \left[(1+x)\, C_R + 1 + \frac{5}{4}\, x\right] \sqrt{1-x}\,, \qquad (6)$$

in agreement with Ref. [24]. Particularizing to the fundamental representation, one gets the well-known results for quark-antiquark production [25]. The production of exotic fermions in higher representations is enhanced by the global algebraic factor $\xi_R = C_R d_R/(C_F d_F)$ [$\xi_6 = 5$, $\xi_8 = 6$, $\xi_{10} = 15$, $\xi_{15} = 20$, $\ldots$], which is further reinforced by another factor C_R/C_F in the leading parts of the 2-gluon contribution. Figure 1 shows the ratio $\sigma(pp \to X_R \bar{X}_R)/\sigma(pp \to q\bar{q})$ at $\sqrt{s} = 7$ TeV, as a function of M_X, for the representations with lower dimensions. We have convoluted the partonic cross sections with standard parton distribution functions and have assumed a common K factor for all representations; i.e., we have taken the same QCD corrections as for triplet quark production. This is a very conservative assumption because, given the larger algebraic factors, gluonic corrections should be larger for higher colour representations. Thus, the curves in Fig. 1 are actually lower bounds on the expected production ratios. The enhancement factors are predicted to be larger than 10 for sextet and octet fields and much higher values are obtained for higher-dimensional representations.

Once produced, the exotic X_R particles should decay strongly generating an excess of (multi) jet events. Fermionic objects in the triplet, sextet and $\underline{15}$ representations could couple to a qq ($\bar{q}g$) operator and are thus expected to produce 2-jet events, while fermionic octets and decuplets have qqq ($\bar{q}\bar{q}\bar{q}$) quantum numbers and should be looked for in 3-jet events [24]. The generic 2-jet searches performed at the LHC [26, 27] have not found any evidence for new particle production, severely constraining

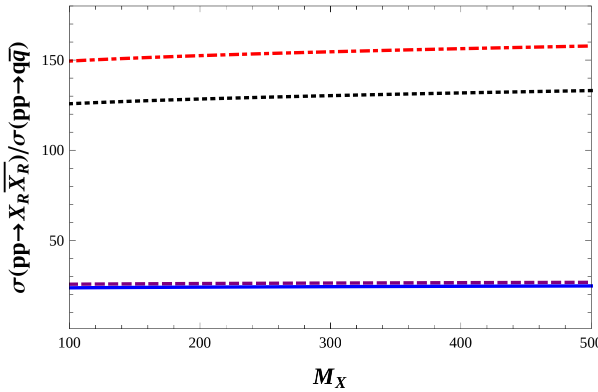

FIG. 1. Ratio $\sigma(pp \to X_R \bar{X}_R)/\sigma(pp \to q\bar{q})$ at $\sqrt{s} = 7\,$TeV, as a function of M_X. The different curves correspond to the exotic fermion X_R in the sextet (continuous, blue), octet (dashed, violet), decuplet (dotted, black) and $\underline{15}$ (dash-dotted, red) representations.

narrow resonances decaying into qq, qg or gg final states. The lower limits on different types of strongly-interacting particles have been pushed up beyond the 1 TeV scale; for instance the data excludes at 95% CL excited quarks with mass below 2.64 TeV or coloured octet scalars with mass below 1.92 TeV. Searches with 3 jets have been already performed by CMS [28] and CDF [29]; no significant excess has been found, excluding gluino masses up to 280 GeV [**?**].

A dedicated search for stable quarks in higher colour representations was performed a long time ago by CDF [34]. No such particles were found in 26.2 nb^{-1} of data; at 95% CL, the resulting lower limits for M_X were 98 (84) GeV for color sextets, 99 (86) GeV for octets, and 137 (121) GeV for decuplets, assuming that X_R carries charge one (either one or zero). A recent CMS search for heavy stable charged particles produced at LHC has put a lower limit of 808 GeV (95% CL) on a stable gluino, under the conservative hypothesis that any hadron containing this particle becomes neutral before reaching the muon detectors (relaxing this hypothesis, the limit improves to 899 GeV) [35]. Slightly weaker bounds have been set by ATLAS through a search for slow-moving gluino-based R-hadrons [36].

The present 95% CL limits on fourth-generation quarks, $m_{Q'} > 350$ GeV [37], $m_{b'} > 372$ GeV [38] and $m_{t'} > 404$ GeV [39–41] assume the decays (with 100% branching fraction) $Q' \to Wq$, $b' \to Wt$ and $t' \to Wb$, respectively. While these direct limits are set on new triplet quarks, the (absence of) experimental signature, W + Jets, is also sensitive to other strongly-interacting exotic particles in weak $SU(2)_L$ representations, as we are going to consider next, provided they decay within the detector through $X_R \to W X_R' \to W$ + Jets.

II. HIGGS PRODUCTION AT LHC

In the Standard Model, the Higgs mechanism is responsible for all particle masses. If the mass of the exotic colour object X_R is also generated through its coupling to the Higgs boson, the Higgs properties are modified through quantum loops involving the fermion X_R. Let us consider the consequences of a generic Higgs coupling

$$\mathcal{L}_H \;=\; -\frac{M_X}{v}\, H(x)\; \left[\bar{X}_R(x)\, X_R(x)\right] , \qquad (7)$$

with $v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV the Higgs vacuum expectation value. The usual Standard Model mechanism for fermion masses requires X_R to be an electroweak doublet. More specifically, X_R contains two fermion fields, differing by one unit of electric charge, with their left-handed chiralities forming a $SU(2)_L$ doublet while their right-handed chiralities are singlets. We neglect their mass difference since the two fields should be degenerated enough to satisfy the electroweak precision tests. One should also implement the cancelation of the electroweak anomalies generated by the new $SU(2)_L$ doublet; we will assume for the moment that this is achieved through the addition of new exotic leptons. We will comment later on the implications of arranging instead the anomaly cancelation with additional coloured objects. The anomaly constraints are discussed in the appendix for completeness.

Since X_R couples strongly to gluons, the vertex in Eq. (7) generates a very sizeable contribution to the main Higgs production channel at LHC, through an intermediate $X_R\bar{X}_R$ virtual pair: $gg \to X_R\bar{X}_R \to H$. The resulting amplitude can be easily obtained from the standard quark-loop result, accounting for the different colour factors:

$$\sigma(gg\to H) \;=\; \frac{M_H^2\alpha_s^2}{256\pi\, v^2}\, \Bigg| \sum_q T_F\, \mathcal{F}\!\left(\frac{4m_q^2}{M_H^2}\right) + 2\, T_R\, \mathcal{F}\!\left(\frac{4M_X^2}{M_H^2}\right) \Bigg|^2 \;\delta(s - M_H^2)\, , \qquad (8)$$

where

$$\mathcal{F}(x) \;=\; \frac{x}{2}\, \left[4 + (x-1) f(x)\right] ,$$
$$f(x) \;=\; \begin{cases} -4\, \arcsin^2 (1/\sqrt{x})\, , & x \ge 1 \\ \left[\ln\left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}\right) - i\pi\right]^2 , & x < 1 \end{cases} . \qquad (9)$$

The first term in (8) is the usual triplet-quark contribution; it is completely dominated by the top loop because the function $\mathcal{F}(x)$ vanishes in the massless limit $(x \to 0)$. The second term stands for the additional contribution from the exotic coloured fermion multiplet X_R. Given the experimental constraints on M_X discussed before, $M_H^2 < 4M_X^2$ in the interesting kinematical regime and the corresponding loop function does not have any absorptive part. Moreover, the numerical result is not sensitive to the exact value of M_X because $\mathcal{F}(x)$ is a very smooth function for $x \ge 1$, decreasing gently from $\mathcal{F}(1) = 2$ to $\mathcal{F}(\infty) = 4/3$.

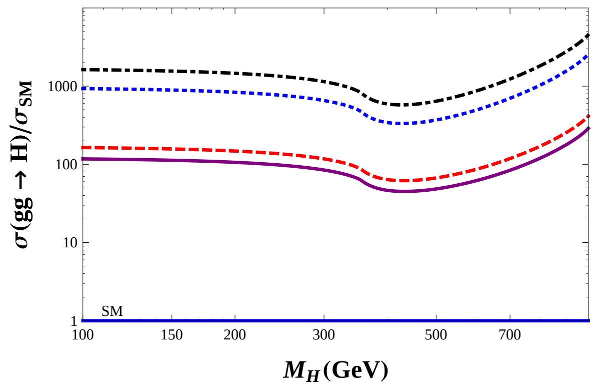

FIG. 2. Ratio $\sigma(gg \to H)/\sigma_{\rm SM}$ at $\sqrt{s} = 7\,$TeV and $M_X = 500$ GeV, as a function of M_X. The different curves correspond to an exotic fermion multiplet X_R in the sextet (continuous), octet (dashed), decuplet (dotted) and $\underline{15}$ (dash-dotted) representations.

Owing to the relative colour enhancement factor T_R/T_F, the X_R contribution generates a large increase of the Higgs production cross section. The ratio $\sigma(gg \to H)/\sigma_{\rm SM}$ for different colour representations is shown in Fig. 2, as a function of M_H, taking $\sqrt{s} = 7$ TeV and $M_X = 500$ GeV. The normalization $\sigma_{\rm SM} \equiv \sigma(gg \to H)_{\rm SM}$ is the Standard Model cross section with three quark families. Again, we have assumed the same QCD corrections as for triplet quarks, which underestimates the actual cross section. Very large enhancement factors are obtained for all non-triplet representations. In the sextet and octet cases, the Higgs production cross section is larger than the SM one by a factor between 40 or 300, depending on M_H. The enhancement surpasses the three orders of magnitude for the $\underline{15}$ and higher colour representations.

III. HIGGS SEARCH

Since the decay $H \to X_R\bar{X}_R$ is not kinematically allowed for $M_H < 2M_X$, a heavy Higgs would decay into WW, ZZ and $t\bar{t}$ with approximately the same branching fractions as in the absence of the fermion X_R. The Standard Model Higgs has already been experimentally excluded for Higgs masses between $2M_W$ and 600 (525) GeV, at 95% CL (99% CL) [42, 43]. The existence of an additional coloured fermion would only make the exclusion much stronger. More care has to be taken below the WW threshold, because the same enhancement present in the Higgs production cross section also appears in the $H \to gg$ decay width, modifying all branching ratios. Figure 3 shows the total Higgs decay width Γ_H, as a function of M_H, for the Standard Model with three fam-

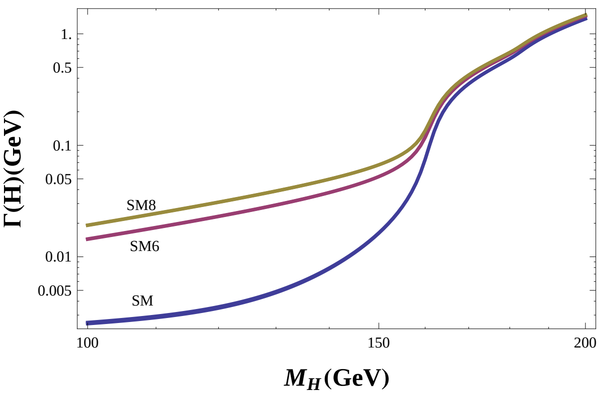

FIG. 3. Higgs total decay width in the 3-generation Standard Model (SM), and with the addition of colour sextet (SM6) or octet (SM8) multiplets.

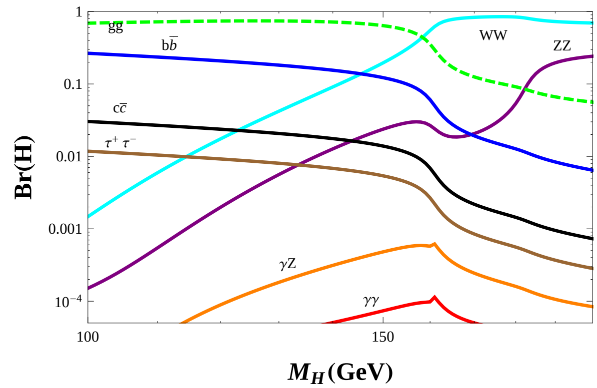

FIG. 5. Higgs branching ratios with the addition of a colour sextet multiplet.

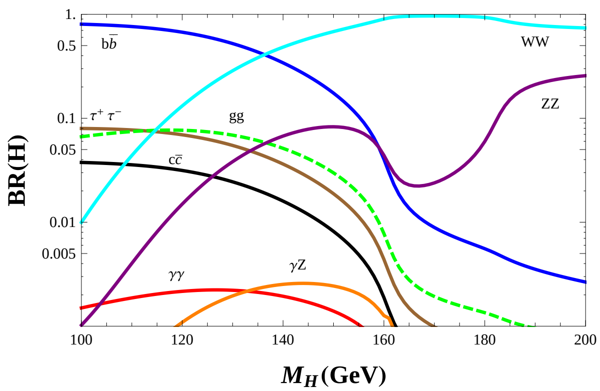

FIG. 4. Higgs decay branching ratios in the 3-generation Standard Model.

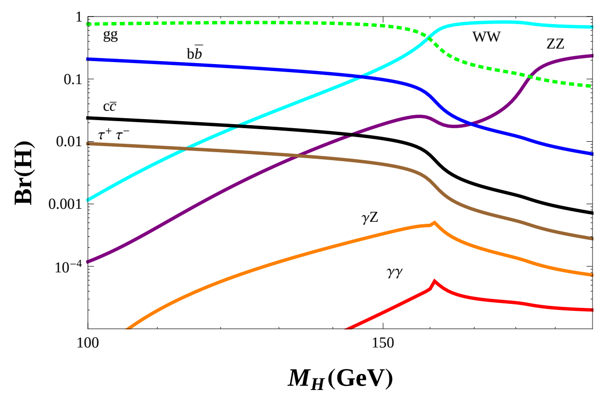

FIG. 6. Higgs branching ratios with the addition of a colour octet multiplet.

ilies of triplet quarks, and with the addition of one (electroweak doublet) colour sextet or octet multiplet. The exotic contributions are small for $M_H > 2M_W$, but at lower Higgs masses they generate a big enhancement of Γ_H. Figures 4, 5 and 6 plot the corresponding branching ratios in the different channels.

The strong enhancement of the two-gluon decay channel at low Higgs masses, affects in a very sizeable way the suppressed (one loop) 2γ and γZ decay modes, making them insignificant. However, in the WW and ZZ modes the branching fraction suppression cannot compensate the large enhancement of the production rate. In order to compare with the LHC experimental data, the relevant ratio is

$$R_{VV} \;=\; \frac{\sigma(pp\to H)\,\mathrm{Br}(H\to VV)}{\sigma(pp\to H)_{\mathrm{SM}}\,\mathrm{Br}(H\to VV)_{\mathrm{SM}}}\,, \qquad (10)$$

where SM refers again to the Standard Model with three quark families and $V = W, Z$. This is plotted in Fig. 7, for sextet and octet colour representations, showing that, at $\sqrt{s} = 7$ TeV, $R_{VV} > 15$ in the relevant range of Higgs masses. Much larger values of R_{VV} would be obtained with higher-dimensional representations or additional coloured fermion multiplets. Therefore, the present ATLAS [42] and CMS [43] searches in the WW and ZZ channels, already exclude a Standard Model Higgs boson coupled to exotic colour multiplets, in the whole range between 110 and 600 GeV.

The combined CDF and D0 data [44] exclude Higgs masses between 100 and 108 GeV (95% CL), within the three-generation Standard Model. Although $gg\to H$ accounts for 76% of the Higgs production cross section in this mass region, the Tevatron constraints are mainly extracted from $q\bar{q}\to WH/ZH$, with a small contribution from $q\bar{q}\to q'\bar{q}'H$. These production mechanisms are not enhanced by the exotic colour-multiplet contributions. In this mass range the main Higgs signature is $H\to b\bar{b}$; therefore, the Tevatron information translates into 95% CL upper bounds for $\mathcal{R}_{b\bar{b}} \equiv \mathrm{Br}(H\to b\bar{b})/\mathrm{Br}(H\to b\bar{b})_{\mathrm{SM}}$ ranging from 0.45 at 100 GeV to 1.1 at 110 GeV [44]. The addition of a sextet (octet) multiplet implies $\mathcal{R}_{b\bar{b}}$ values ranging from 0.33 (0.26) at 100 GeV to 0.31 (0.24) at 110 GeV, which are slightly below the present Tevatron bounds. A mild improvement of the Tevatron constraints could exclude sextet ot octet contributions for M_H between 100 and 110 GeV.

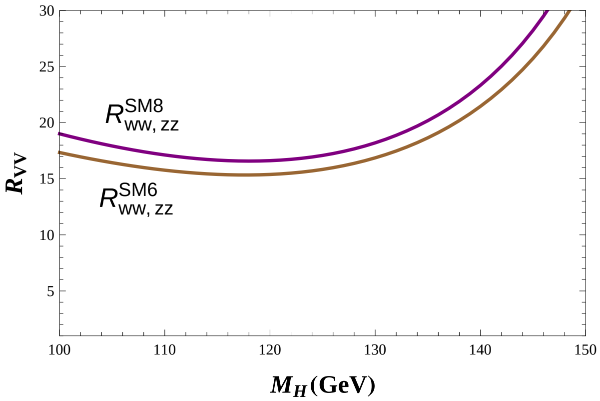

FIG. 7. $R_{WW,ZZ}$ at $\sqrt{s} = 7$ TeV, as a function of M_H, with the addition of colour sextet (SM6) or octet (SM8) multiplets.

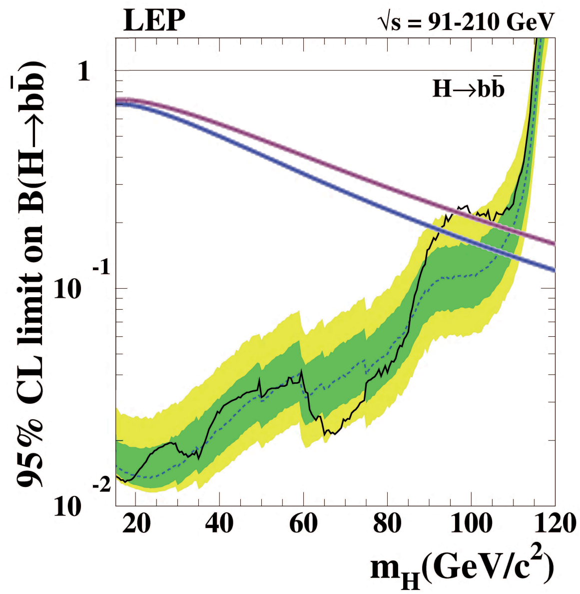

FIG. 8. The LEP exclusion limits on $\text{Br}(H \to b\bar{b})$ [45], as a function of M_H, are compared with the expected signals in the presence of one exotic (electroweak doublet) sextet (top red curve) or octet (bottom blue curve) multiplets.

The LEP exclusion limit below 114.5 GeV [45] needs also to be re-analyzed in view of the strong enhancement of $\text{Br}(H \to gg)$. While the production mechanism $e^+e^- \to Z^* \to ZH$ remains unchanged in the presence of exotic quarks, there is a large suppression of the Higgs branching fractions into $b\bar{b}$ and $\tau^+\tau^-$ and, therefore, of the sought experimental signal. OPAL performed a generic search for neutral scalars decaying into an arbitrary combination of hadrons, leptons, photons and invisible particles, covering as well the possibility of a stable scalar [46]. Thus, the OPAL bound, $M_H > 81$ GeV (95% CL) [46], remains valid in the presence of exotic colour multiplets. For larger masses, the combined LEP analysis relies in the $H \to b\bar{b}$ decay mode. Figure 8 compares the LEP bounds on $\text{Br}(H \to b\bar{b})$ [45], with the expected values with one (electroweak doublet) sextet (top red curve) or octet (bottom blue curve) multiplet. Higgs masses below 96 (92) GeV are then excluded in the sextet (octet) case.

The triplet case of a fourth quark generation has been already discussed before [47–59]. The enhancement of $\sigma(gg \to H)$ is milder, about a factor of 9, but enough to exclude Higgs masses above 110 GeV from the LHC constraints on R_{VV}. The corresponding weaker enhancement of $\text{Br}(H \to gg)$ implies a much smaller suppression of the remaining channels; in particular, for Higgs masses smaller than 110 GeV, the $b\bar{b}$ branching fraction is predicted to be above the LEP bound in Fig. 8. Therefore, in the presence of an additional (electroweak doublet) colour quark triplet, the Higgs boson is excluded in the whole mass range up to 600 GeV.

Note, however, that additional exotic multiplets or higher colour representations would imply a larger suppression of $\text{Br}(H \to b\bar{b})$, weakening the LEP and Tevatron constraints. That would be the case, for instance, if the anomaly matching condition is fulfilled with (at least two) coloured exotic multiplets, instead of leptons. Thus, in the region of Higgs masses between 81 and 110 GeV the constraints are sensitive to the assumed exotic spectrum. This is not the case for lower or higher values of M_H; Higgs masses between 110 and 600 GeV, or smaller than 81 GeV, are excluded in the presence of any exotic colour multiplets coupled to the Higgs boson.

IV. DISCUSSION

Present LHC data imply that a Standard Model Higgs cannot exist in the presence of new coloured fermions coupled to it, in exotic QCD representations, except for a small M_H region between 92 (81 with several exotic multiplets) and 110 GeV which could be soon excluded. Exotic quarks in higher-dimension colour representations generate a very large enhancement of $\sigma(gg \to H)$, in contradiction with the available experimental bounds. Strong limits have been already put before in the case of a fourth quark generation, where the enhancement of the Higgs production cross section is milder [49–51].

One could certainly try to evade the experimental constraints, enlarging the Standard Model in appropriate ways to compensate the enhancement from exotic quarks. For instance, introducing additional coloured scalars with couplings to the Higgs adjusted to suppress the $gg \to H$ amplitude [60–64]. Another possibility is "hiding" the Higgs; i.e., opening new decay channels into invisible modes without strong interactions [53, 54, 65–71], in order to suppress the visible branching fractions. While well-motivated arguments, such as dark matter, exist to do it, we feel that this hides the main reason behind such strong exclusion: the intrinsic non-decoupling of the Yukawa vertex (7) makes the Higgs boson sensitive to arbitrary high mass scales.

The Higgs vacuum expectation value is linked to the electroweak scale, i.e., to the gauge boson masses M_W and M_Z. In the Standard Model this scale is also used to generate all fermion masses through the Yukawa couplings. The known pattern of lepton and quark masses, with very different mass scales, implies a large variety of Yukawa couplings with magnitudes ranging from $m_\nu/v \sim 10^{-13}$ to $m_t/v \sim 0.7$. This wide range of couplings/scales is not yet understood. Introducing additional fermions with even higher masses, would bring much larger Yukawa couplings inducing a non-perturbative dynamical regime in the electroweak sector. In fact, the Higgs production and decay amplitudes used in our analysis are subject to potentially large electroweak corrections [59].

If a light neutral scalar boson is finally discovered, one should study very carefully its properties in order to clarify the true pattern of electroweak symmetry breaking. The Standard Model is certainly a very plausible possibility, but heavier mass scales should not couple to the Higgs boson, i.e., they should have a different origin. Multi-Higgs models offer a much more flexible framework to accommodate future data, but soon or later they would also face the characteristic non-decoupling of the Higgs mechanism in (parts of) their extended Yukawa couplings. A perhaps more interesting possibility is that fermion masses could be generated through a mechanism different than the one responsible for the gauge boson masses. Another alternative, of course, is that the Higgs boson does not exist (dynamical symmetry breaking) or it is a composite object with rather different properties. The forthcoming LHC data should soon show us the option chosen by Nature to break the electroweak symmetry and hopefully provide some hints on the dynamics behind the observed pattern of fermion masses and mixings.

ACKNOWLEDGEMENTS

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APPENDIX

The cancelation of the triangular gauge anomalies requires [72]

$$\mathrm{Tr}\left(\left\{T^a, T^b\right\} T^c\right)_L - \mathrm{Tr}\left(\left\{T^a, T^b\right\} T^c\right)_R \;=\; 0\,, \qquad (11)$$

where T^a are the Standard Model group generators and the traces sum over all possible left- and right-handed fermions. Owing to the algebraic properties of the $SU(2)$ and $SU(3)$ generators, the only non-trivial anomalies involve one or three $U(1)_Y$ bosons, giving conditions on traces of Y and Y^3, respectively, where the hypercharge is related to the electric charge through $Y = Q - T^3$. These relations imply that the sum of all fermion electric charges should be zero:

$$\sum_f Q_f \;=\; \mathrm{Tr}\,(Y)_L \;=\; \mathrm{Tr}\,(Y)_R \;=\; 0\,. \qquad (12)$$

Let us consider N $SU(2)_L$ fermion doublets ψ_i with $Y(\psi_{i,L}) = y_i$, and their corresponding right-handed singlets with $Y(\psi_{i,R}) = Q_i = y_i + \frac{1}{2}$ and $Y(\psi'_{i,R}) = Q'_i = y_i - \frac{1}{2}$. In order to cancel the Standard Model gauge anomalies, one needs to satisfy

$$2\sum_i^N d_i\, y_i \;=\; \sum_i^N d_i\,(2Q_i - 1) \;=\; 0\,, \qquad (13)$$

where d_i denotes the multiplicity of the $SU(3)_C$ representation of ψ_i. The number of left-handed fermion doublets, $\sum_i^N d_i$, should be even in order to avoid a global (non-perturbative) $SU(2)$ chiral gauge anomaly [73]. The normal Standard Model generations fulfill these conditions with one quark ($d_q = 3$, $y_q = \frac{1}{6}$) and one lepton ($d_l = 1$, $y_l = -\frac{1}{2}$) multiplets.

Thus, there are many possible ways of adding exotic coloured fermions to the 3-generation Standard Model, while preserving the anomaly cancelation conditions. A single exotic representation with even dimension and $y = 0$ ($Q = \frac{1}{2}$, $Q' = -\frac{1}{2}$) would of course be anomaly free, but it would be stable (it cannot decay into ordinary quarks and gluons). The simplest solution to the anomaly constraint involves two exotic multiplets with the same $SU(3)_C$ multiplicity and opposite hypercharge.

The most general solution with two additional multiplets of different dimensionalities is $y_2 = -y_1 d_1/d_2$, with $d_1 + d_2$ even. For odd-dimensional exotic representations ($d_1 = 15, 27\ldots$), it is then possible to cancel the anomaly with a new lepton multiplet of hypercharge $y_2 = -y_1 d_1$. Two lepton multiplets with $y_2 + y_3 = -y_1 d_1$ would be needed to cancel the anomaly of an exotic representation with even multiplicity ($d_1 = 6, 8, 10\ldots$). For any exotic colour representation of dimension d and hypercharge y, the anomaly could of course be canceled with d lepton multiplets of hypercharge $y_l = -y$.

The figures shown in the paper refer to the simplest case of a single (electroweak doublet) exotic quark multiplet, with the anomaly canceled by exotic lepton multiplets. If one considers instead models where the anomaly is canceled through additional coloured fermions, the LHC constraints become much stronger in the whole mass range analyzed. For instance two exotic quark multiplets with the same $SU(3)_C$ multiplicity and opposite hypercharge, would increase the ratio R_{VV} (Fig. 7) by a factor close to two. Therefore the range of Higgs masses between 110 and 600 GeV is completely excluded in any exotic model. However, since additional coloured fermions imply a suppression of $\mathrm{Br}(H \to b\bar{b})$, weakening the LEP and Tevatron constraints, an open window of allowed Higgs masses between 81 and 110 GeV remains in this type of models.

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