Strongly coupled fourth generation at the LHC

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We study extensions of the standard model with a strongly coupled fourth generation. This occurs in models where electroweak symmetry breaking is triggered by the condensation of at least some of the fourth-generation fermions. With focus on the phenomenology at the LHC, we study the pair production of fourth-generation down quarks, D_4 . We consider the typical masses that could be associated with a strongly coupled fermion sector, in the range (300–600) GeV. We show that the production and successive decay of these heavy quarks into final states with same-sign dileptons, trileptons, and four leptons can be easily seen above background with relatively low luminosity. On the other hand, in order to confirm the presence of a new strong interaction responsible for fourth-generation condensation, we study its contribution to D_4 pair production, and the potential to separate it from standard QCD-induced heavy quark production. We show that this separation might require large amounts of data. This is true even if it is assumed that the new interaction is mediated by a massive colored vector boson, since its strong coupling to the fourth generation renders its width of the order of its mass. We conclude that, although this class of models can be falsified at early stages of the LHC running, its confirmation would require high integrated luminosities.

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I. INTRODUCTION

The origin of electroweak symmetry breaking (EWSB) is one of the most important questions in particle physics today. A natural solution to the quantum instability of the Higgs potential suggests that there should be new physics at the TeV scale. The central task of the LHC is to illuminate this question. An appealing and economic mechanism to explain EWSB is the condensation of the top quark, leading to a unified description of the mechanism of symmetry breaking and the top mass [1]. However, if this scenario is to solve the hierarchy problem, the top quark should be considerably heavier, around $m_t \sim$ (600–700) GeV. Already in Ref. [1] it was suggested that the simplest model could be extended to the condensation of a heavy fourth generation. However, there are many problems with this proposal, the most important being the lack of a fundamental interaction leading to the condensation of just the fourth generation and a mechanism to generate the masses of the noncondensing fermions. In Ref. [2] this idea was pursued in the framework of a 5D model in a slice of anti-de Sitter (AdS) space [3]. There it was shown that it provides an UV completion of the original model up to a scale of order $M_{\rm Pl}$. The Kaluza-Klein (KK) partners of the gluon naturally induce the strong interactions responsible for the condensation of the zero modes of the fourth generation. The inevitable presence of bulk four-fermion operators also contributes to the strong interactions of the fourth generation and leads to fermion masses after the condensation. The model naturally explains the fermion mass hierarchy and can be extended, for instance, by allowing more than one fourthgeneration fermion to condense, or by modifying the fermion embedding into the larger 5D gauge symmetry. Regardless of the details of the particular realization chosen, there are some generic implications of this class of models that remain common to all of them. Among these features are a rather heavy fourth generation, with masses that can be in the range (300–700) GeV depending on which quarks condense, and a heavy Higgs which in the case that only one quark condenses has a mass of approximately $m_h \sim (700-900)$ GeV. In the specific realization of this class of models proposed in Ref. [2], only the up-type quark condenses leading to a one-Higgs-doublet model. We will take it as a benchmark of a large class of theories where EWSB is triggered in this way, in the hope that it can be used to study generic properties and signatures that rely only on the existence of a strongly coupled fourth generation.

The bounds from electroweak precision measurements on a fourth generation have been reanalyzed recently in Ref. [4], and are not as tight as they once were. More important, in the class of models we are interested in here the loop contribution from the fourth generation to the *S* parameter (from which the bounds mainly come) is neither the leading one nor well defined. This can be seen by the fact that AdS_5 models with Planck-brane localized light fermions, have a large *tree-level S* parameter [5]. Furthermore, it has been recently pointed out that in these models the one-loop contributions to *S* contain logarithmic divergences and therefore *S* must be renormalized [6]. This is also seen in deconstructed versions of Higgsless models [7]. The renormalization procedure would then affect all one-loop corrections in such a way that it is not correct to use them to put strict bounds on the contributing states. We then conclude that the presence of a fourth generation does not make the *S*-parameter problem of these models any worse than it is with only three generations.

In this paper we study experimental signatures at the LHC of the quark sector of a strongly coupled fourth generation. The defining aspect of these theories is the presence of a new interaction coupling strongly to the heavy fourth generation. In particular, the fourth-generation quarks couple strongly to a color-octet vector current, which is responsible for the condensation of at least one of them. In the bulk AdS_5 model of [2], this current corresponds to the KK excitations of the gluon, $G^{(n)}$. An unmistakable signal for the presence of this strong interaction would be to observe the production of fourth-generation quarks in channels involving the KK gluons such as¹

$$q\bar{q} \to G^{(1)} \to D_4 \bar{D}_4, U_4 \bar{U}_4. \tag{1}$$

In the specific scenario we study here, the U_4 is assumed to be the only condensing quark, making it somewhat heavier than D_4 . These processes will generate an excess in the production of the fourth generation when compared with the usual standard model (SM) QCD production that is characteristic of this class of models. This excess would provide evidence that the condensation mechanism is associated with EWSB. In particular, since D_4 does not condense, we expect it to be somewhat lighter than U_4 , and as a consequence it will be easier to produce D_4 pairs than U_4 pairs. Furthermore, when produced the U_4 would almost always decay to D_4 through the charged current. We will study the pair production of D_4 's both via QCD and the KK gluons in the model mentioned above.

In order to define the final state signal, we consider the fact that in these models the fourth generation has typically larger mixing with the third generation than with the lighter first two. This implies that D_4 will mostly decay to W^-t . Thus, the pair production of D_4 will lead to events with two W^+ 's, two W^- 's, and two b jets. Final states with only one charged lepton or with two opposite-sign leptons would be hard to observe at the LHC, above the large $t\bar{t}$ + jets background. Instead, we study the process with two same-sign leptons in the final state, which has a much smaller $t\bar{t}$ SM background [8]. We make a preliminary study for the observation of the down-type fourthgeneration quark in this channel and find that a 5σ significance requires an accumulated luminosity of about $L_{\min} \leq$ $\mathcal{O}(1)$ fb⁻¹ for $m_{D_4} = (300-600)$ GeV. We also study the possibility of measuring the excess in D_4 from the contribution of an *s*-channel KK gluon above the standard QCD production. This turns out to be quite difficult since the width of the KK gluon in fourth-generation models is of the order of its mass, making the KK-gluon excess over the QCD production featureless. As we will see below, a very large data sample, together with an excellent understanding of the QCD production process, will be necessary in order to observe this excess with significance.

Other studies of the production and decay of fourthgeneration quarks at the LHC exist in the literature. For instance, in Ref. [9] a new technique for the heavy quark mass reconstruction is discussed, whereas in Ref. [10] flavor-violating decays involving the fourth generation are considered. In some of the previous papers [11] it is assumed that D_4 mixes primarily with the first two generations, instead of with the third as we consider here. The consequences of the existence of a fourth generation in flavor physics have also received considerable attention [12].

In the next section we present an effective model describing the interactions between fermions and vector currents at low energies. In Sec. III we describe our strategy to isolate the signal from the SM backgrounds. We then show our results regarding the observation of a heavy fourth generation at the LHC in Sec. IV. In Sec. V we discuss the potential for the separation of the KK-gluon signal from the standard QCD fourth-generation production, and finally conclude in Sec. VI.

II. EFFECTIVE MODEL

We consider a four-dimensional (4D) theory containing two sectors: a strongly coupled field theory (SCFT) sector and a sector of elementary fields corresponding to the SM gauge bosons and fermions, including the fourth generation.² The SCFT sector has a large number of colors N and is conformal at high energies. At the low energy $M_{\rm IR} \sim$ $\mathcal{O}(1)$ TeV, conformal invariance is spontaneously broken generating a mass gap, leading to a discrete spectrum of particles with the lightest masses being of order of 1 TeV. We assume that the SCFT has a global symmetry $SU(3)_c \times$ $SU(2)_L \times SU(2)_R \times U(1)_X$ that contains the SM gauge symmetry plus an extra SU(2), introduced to preserve a custodial symmetry. Hence the operators and states of this sector furnish complete multiplets of the large global group. This implies that the SCFT sector has several conserved currents transforming as color octets or isospin triplets. The SM vectors gauge the $SU(3)_c \times SU(2)_L \times$ $U(1)_Y$ subgroup, with $Y = T^{3R} + X$, and couple to the SCFT through its conserved currents. We will assume that the SM fermions couple linearly to the SCFT through fermionic operators \mathcal{O}_{ψ}

¹There will also be pair production via the interactions with color-singlet weak -currents corresponding to the KK excitations of the electroweak gauge bosons, but these will be suppressed compared with the strong production. Thus we will leave this channel for a future study and ignore it in the present work. In any case this is a conservative assumption.

²Although, as we will see below, heavier fermions will be mostly composite.

$$\mathcal{L} = \lambda \bar{\psi} \mathcal{O}_{\psi} + \text{H.c.}, \qquad (2)$$

which are in complete representations of the global symmetry. The SM fields can be embedded into the corresponding representation of the larger global symmetry by considering additional nondynamical components. The low energy behavior of the running coupling λ in Eq. (2) is determined by the anomalous dimension of the operator \mathcal{O}_{ψ} , $\gamma = \dim[\mathcal{O}_{\psi}] - 5/2$, with $\dim[\mathcal{O}_{\psi}]$ the conformal dimension of \mathcal{O}_{ψ} [13,14]. For $\gamma > 0$ the coupling between the elementary fermion and the SCFT is irrelevant, thus at energies below M_{IR} we have $\lambda \sim (M_{\text{IR}}/\Lambda)^{\gamma}$, resulting in a small mixing. For $\gamma < 0$ the coupling is relevant and flows to a fixed point, resulting in a large mixing of the elementary fermion with the SCFT.

The general setup described above provides the tools for a scenario where the electroweak symmetry is broken by the condensation of the fourth generation [2]. There are at least two sources that can induce the four fermion interaction needed for the condensation. First we consider composite operators in the SCFT coupling four fermionic resonances (for example, $\mathcal{O}_L \mathcal{O}_R \mathcal{O}_R \mathcal{O}_L$). These operators induce, through the interactions of Eq. (2), four fermion operators for the SM fermions. Second, there are operators in the SCFT that couple the fermionic resonances to the vector resonances created by the conserved global currents. Through Eq. (2), these operators generate interactions between four elementary fermions by the exchange of vector resonances. The strength of these interactions is governed by the anomalous dimensions γ that can correctly select the fermions with large interactions. Some of these fermions may condense breaking the electroweak symmetry and generating a dynamical Higgs at low energies. For simplicity, we will consider a scenario where just the up quark of the fourth generation, U_4 , condenses. Fermion masses result from the four fermion interactions by considering two operators corresponding to the condensing fermions. Therefore, heavy fermions, such as the top quark and the fourth generation, have large mixings with the SCFT states and thus they will be mostly composite, whereas the light fermions will be mostly elementary.

Inspired by the AdS/CFT correspondence, Ref. [2] proposed a weakly coupled 5D realization of the 4D theory described above. It makes use of a Randall-Sundrum spacetime [3] consisting of a slice of AdS₅ with a curvature $k \sim M_{\rm Pl}$. The extra dimension z is compact with boundaries in conformal coordinates given by $z_0 = 1/k$ (called UV boundary) and $z_1 = 1/M_{\rm IR}$ (called IR boundary). The theory is defined on the segment $z_0 \le z \le z_1$. There is a 5D gauge symmetry SU(3)_c × SU(2)_L × SU(2)_R × U(1)_X that is broken down to the SM group by boundary conditions on the UV boundary. There are four generations of 5D fermions that fulfill complete representations of the bulk gauge symmetry. Boundary conditions are imposed

PHYSICAL REVIEW D 79, 075026 (2009)

such that in the UV boundary just the SM fermions and a standard fourth generation are dynamical. The IR boundary conditions lead to a set of massless zero modes corresponding to four generations of SM fermions. The 5D fundamental parameter that determines the degree of compositeness of the zero modes is the 5D fermion mass $m_{\psi} =$ $c_{th}k$. Following the holographic procedure of Ref. [13], the anomalous dimension associated to a left-handed fermion is $\gamma = |c + 1/2| - 1$, resulting in q_L being mostly fundamental for $c_q \ge 1/2$ and mostly composite for $c_q \le 1/2$ (and similarly for the right-handed fields, by making the replacement $c_q \rightarrow -c_{u,d}$.³ Therefore, c_{ψ} is the fundamental parameter that sets the strength of the couplings between the fermion ψ and the heavy states. The holographic prescription allows us to identify the elementary fields with the fields supported in the UV boundary, and the SCFT dynamics with the bulk and IR degrees of freedom. In this way, the KK modes are the resonances of the SCFT.

In Ref. [2] a bulk four-fermion interaction was considered, and its coefficient estimated by naive dimensional analysis (NDA). This operator leads to the four-fermion interaction in the SCFT sector mentioned above. On the other hand, the bulk gauge symmetry gives rise to 4D conserved currents, associated with the KK modes of the 5D gauge fields that couple to the fermionic modes. Relying on the results of Ref. [2], we estimate that the four-fermion interaction induced by the color-octet current mediation is of the same order (although numerically somewhat larger) as the one induced by the 5D fourfermion operator [see Eq. (4)]. The zero modes of the fourth generation condense if they are strongly localized toward the IR boundary, meaning that they are mostly composite states of the SCFT.

In what follows we consider the effective Lagrangian describing the relevant interactions for the processes we want to study. In the language of the weakly coupled 5D theory the relevant degrees of freedom correspond to the fermionic zero modes, the SM gauge fields, and the first KK-vector resonances. At low energies the four-fermion interactions and the interactions with the KK vectors are described by

$$\mathcal{L} = M_1^2 \operatorname{Tr}[G_{\mu}^{(1)}G^{(1)\mu}] + \sum_{\psi=q_l, u_R, d_R} g_{s\psi^a} \bar{\psi}^a \mathcal{G}^{(1)} \psi^a + \sum_{\psi\psi'=u, d} C_{abcd} (\bar{q}_L^a \psi_R^b) (\bar{\psi}_R^{\prime c} q_L^d) + \text{H.c.}, \qquad (3)$$

where $G_{\mu}^{(1)}$ is the first KK gluon, a = 1, ..., 4 numbers fermion generations, and we have neglected the momentum of the KK vectors compared with their mass. The coupling $g_{s\psi}$ corresponds to the one between the first

³In the 5D picture, a composite fermion is localized in the IR boundary at the TeV, whereas a fundamental fermion is localized in the UV boundary at the scale $M_{\rm Pl}$.

KK excitation of the gluon and the zero mode of the fermion ψ , and it depends on the degree of compositeness of the fermion, or its localization in the extra dimension in the 5D picture. For a 5D model $g_{s\psi}$ varies between $\simeq 8.4g_s$, corresponding to a composite (or TeV-localized) fermion, and $\simeq -0.2g_s$, corresponding to a fundamental (or Planck localized) fermion [15]. The mass of the first KK gluon M_1 depends on the size of the extra dimension $1/M_{\rm IR}$, and is approximately given by $M_1 \simeq 2.4 M_{\rm IR}$. The Higgs mass and the mass of the condensing quark U_4 depend on $M_{\rm IR}$. For instance, for $M_{\rm IR} \simeq 1$ TeV one has [2] $m_h \simeq 900 \text{ GeV}$ and $m_{U_4} \simeq 700 \text{ GeV}$. There are also similar interactions involving the KK modes of the electroweak gauge bosons that we have not written explicitly. Their structure is the same as the one for the KK gluon, with the couplings normalized with respect to the electroweak couplings g and g', instead of the QCD coupling g_s .

The last term of Eq. (3) contains the four-fermion interaction that generates the mass terms of the noncondensing fermions after the condensation of U_4 . The coefficient C_{abcd} is a dimensionful parameter that depends on all the 5D masses c_{ψ} of the fermions involved in the interaction. This coupling is exponentially suppressed if at least one of the fermions is Plank brane localized. This mechanism allows us to obtain the top-bottom hierarchy with fundamental parameters of the same order. The exact value of C_{abcd} depends on the embedding of the SM fermions into the larger bulk gauge group, but up to numbers of $\mathcal{O}(1)$, we expect it to be independent of the details of the model. In any case and to fix things, we assume that the 5D fermions transform as $q \in (2, 2)_{2/3} + (2, 2)_{-1/3}$, $u \in (1, 1)_{2/3}$, and $d \in (\mathbf{1}, \mathbf{1})_{-1/3}$ of $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$, as dictated by the constraints on the $Zb_L \bar{b}_L$ couplings [16] [the case with $u, d \in (3, 1)_{2/3} + (1, 3)_{2/3}$ is very similar and we do not expect large corrections in the process we are working on]. The four-fermion coupling is then given by [2]

$$C_{abcd} = C_{abcd}^{5D} \frac{k^3}{M_{\rm Pl}^3 M_{\rm IR}^2} \frac{1 - x^{4-c_L^a + c_R^b + c_R^c - c_L^d}}{4 - c_L^a + c_R^b + c_R^c - c_L^d} \left[\frac{(1 - 2c_L^a)(1 + 2c_R^b)(1 + 2c_R^c)(1 - 2c_L^d)}{(1 - x^{1-2c_L^a})(1 - x^{1+2c_R^b})(1 - x^{1-2c_L^d})} \right]^{1/2}, \tag{4}$$

where $x = M_{\rm IR}/k$ and $C_{abcd}^{\rm 5D}$ is a dimensionless coefficient measuring the strength of the four-fermion interaction in the 5D theory. We can estimate its size within NDA, as being

$$C_{abcd}^{5\mathrm{D}} \simeq O(1) \frac{36\pi^3}{N_f},\tag{5}$$

where N_f is the number of fermions running inside a 5D loop diagram contributing to the four-fermion interaction. For our specific choice for the embedding of the quarks into the larger 5D gauge symmetry, $N_f = 400$.

In these models, described in detail in Ref. [2], the interactions of KK gluons with fourth-generation quarks induced by the second term in Eq. (3), together with the four-fermion interactions of the third term, result in strong interactions among the four-generation quarks. Because of the $k/M_{\rm Pl}$ suppression appearing in Eq. (4), the latter contribution is subleading. The strength of the resulting effective interaction quark in the extra dimension. In particular, we consider the case with the zero mode of the up-type quark U_4 sufficiently localized toward the IR so as to make its four-fermion interaction supercritical, leading to electroweak symmetry breaking. Ignoring the contribution from the last term in Eq. (3), the criticality condition can be approximately written as [2]

$$(g_{sU_4}^L)(g_{sU_4}^R) > \frac{8\pi^2}{N_c},$$
 (6)

where N_c is the number of colors. This condition is easily

satisfied by localizing the U_4 zero mode toward the IR brane. In Ref. [2] we model this strong coupling behavior with a Nambu–Jona-Lasinio interaction, improved with renormalization group evolution. However, the rest of the KK theory is not strongly coupled to this degree and the KK description remains an appropriate one.

Since the Higgs comes from the condensation of the mostly composite U_4 , the size of the Yukawa couplings of the noncondensing fermions would also depend on their degree of compositeness or localization in the 5D. This means that the Yukawas are also controlled by c_{ψ} . To obtain a heavy but noncondensing D_4 , this fermion must have a rather large degree of compositeness, but with an upper bound so as to forbid its condensation. This roughly means $|c_{D_4}| < 1/2$. The mass of D_4 depends on the value of c_{D_4} , but we estimate it to be in the range (200–600) GeV. In order to avoid direct bounds [17,18] we conservatively consider here $m_{D_4} \ge 300$ GeV.

Another necessary consideration is the mixing of the fourth generation with the other three. The analysis of Ref. [4] shows that there are strong constraints in the mixings between the light fermions and a fourth generation. On the other hand, the 95% C.L. lower bound $V_{tb} > 0.68$, obtained from the observation of single top production [19], still allows for a large mixing between the third-and the fourth-generation quarks. For the purpose of our work, we need only assume that this mixing is much larger than the ones with the two lighter generations, resulting in the dominant decay mode of D_4 being $D_4 \rightarrow W^- t$.

The interactions of Eq. (3) lead to the decay of the KK gauge bosons and determine their widths and branching

STRONGLY COUPLED FOURTH GENERATION AT THE LHC

ratios. The width of the first KK gluon is mostly determined by its couplings to the fourth-generation quarks, and to a lesser extent to the top quark, since its couplings to light quarks are much smaller. We have scanned over the parameter space of the 5D model, with the following constraints: U_4 has a supercritical four-fermion effective interaction and condenses, D_4 is heavier than 300 GeV but does not condense, and the top and bottom have their physical masses. We have considered 5D parameters C_{abcd}^{5D} not larger than 3 times the NDA estimate of Eq. (5) in order to avoid unnaturally large numbers in the fundamental theory. The width of the first KK gluon, Γ_1 , is larger the more composite (or TeV localized) are U_4 and D_4 . On the other hand, Γ_1 is smaller the closer is the U_4 coupling from being critical, and the lighter is D_4 . However, in most cases the width is typically $\Gamma_1 \sim M_1 \simeq$ (2.4–3) TeV. We can consider the lower limit to be $\Gamma_1 \simeq$ 0.37 M_1 , obtained for C_{4444}^{5D} 3 times its NDA estimate, tuning the effective 4D four-fermion interaction to be in the critical limit and taking D_{4R} to be almost fundamental. However, we stress that this is only a very small region of the parameter space, and the natural size of the KK-gluon width is $\Gamma_1 \sim M_1$. This is due to its large couplings to the fourth generation, as well as to the top. This result has important consequences for the phenomenology, since it precludes the existence of a resonant peak associated with the color-octet current responsible for U_4 condensation, and ultimately for electroweak symmetry breaking.

The pair production of the fourth-generation quarks proceeds mostly through QCD and KK-gluon mediation.⁴ In what follows, we discuss the strategy to observe the signal, as well as the possibility of separating the KK-gluon contribution from the standard QCD production mechanism.

III. SIGNAL AND BACKGROUNDS

The pair production of D_4 can proceed through the standard QCD contributions to heavy quark productions, as well as through the *s*-channel contribution of the first KK excitation of the gluon. With the assumption of the mode $D_4 \rightarrow tW^-$ dominating the decay, the final state contains multiple W's

$$pp \rightarrow D_4 \bar{D}_4 \rightarrow W^- t W^+ \bar{t} \rightarrow W^+ W^- b W^+ W^- \bar{b}$$
 (7)

rendering the full reconstruction of the final state difficult. We then choose to focus on inclusive states exhibiting charged leptons (e^{\pm} and μ^{\pm}) from *W* decays and jets; see Fig. 1. More specifically we study the production of two, three, and four leptons accompanied by at least two hard jets. In the case of dilepton production the standard model $t\bar{t}$ production is a formidable background. As a consequence, we restrict our analysis to same-sign dilep-



FIG. 1. Feynman diagram corresponding to the pair production of D_4 and decay to a final state with two same-sign leptons.

tons allowing them to be of different flavor. The same-sign dilepton inclusive channel turns out to be one of the best modes to study the D_4 pair production, being a powerful tool to falsify our model in case that no events are observed. However, an observation of this particular signal should be supplemented by others so as to confirm the D_4 hypothesis. The processes with three and four leptons should also be observed if there is a heavy fourth generation. As we will see below, for the four-lepton processes, the smaller signal is compensated by a negligible background. In conclusion, this set of signals offers a very good test for the model which should be eventually completed with the full reconstruction of the D_4 mass peak in its decay into jets.

The production of D_4 pairs at the LHC takes place in $q\bar{q}$ fusion, via g and $G^{(1)}$ exchange, as well as QCD gluongluon fusion.

$$q\bar{q} \rightarrow (G^{(1)}, g) \rightarrow D_4 \bar{D}_4,$$
 (8)

$$gg \to D_4 \bar{D}_4.$$
 (9)

In order to obtain the final states that can be reached from the above processes, e.g., Eq. (7), we work in the narrow width approximation for the D_4 's, as well as for the top quarks and W's coming from its decay. Notwithstanding, we preserve the spin correlations in the production and decay chains of the new fourth-generation quarks.

Same-sign dileptons are produced when two samecharge *W*'s decay leptonically while the two other *W*'s decay hadronically. In general these events present a large number of jets and significant missing transverse momentum due to escaping neutrinos. In the dilepton search we require at least two hard jets; however, we did not impose any cut on the observed transverse momentum or try to explore the jet multiplicity of the events since the samesign dilepton signal is extremely clean. The main SM backgrounds are as follows:

(i) QCD production of $t\bar{t}$ and its decay into $W^+W^-b\bar{b}$: In this channel one of the same-sign leptons originates from a *W* while the other lepton comes from the semileptonic decay of the *b*. Although there is a small probability to obtain an isolated lepton from

⁴There is also a contribution mediated by the four-fermion interaction. However it is exponentially suppressed; see Eq. (4).

the b decay, this is compensated by the large production cross section.

- (ii) $W^{\pm}W^{\pm}jj$ production followed by the leptonic decay of the same-charge W's: Here *j* denotes a jet.
- (iii) $W^{\pm}W^{\pm}jjj$: Although this process is higher order in QCD with respect to the previous one, this can be compensated if the extra jet is not very hard.⁵
- (iv) $W^{\pm}Zjj$: Where the weak gauge bosons decay leptonically and the differently charged lepton escapes undetected.
- (v) $W^{\pm}t\bar{t}$: Where one of the top quarks decays semileptonically while the other decays into jets.
- (vi) We also considered the following possible sources of same-sign dileptons: $W^{\pm}W^{\pm}W^{\mp}$ with and without an extra jet and $W^+W^-t\bar{t}$ production.

We used MADEVENT [20] with the CTEQ6L parton distribution function, to generate the signal and above backgrounds at the parton level, except for the $t\bar{t}$ production that was studied using PYTHIA version 6.409 [21,22], with default settings, in order to better take into account the semileptonic decay of the *b* quark.

In the trilepton signal only one W in Eq. (7) decays hadronically while the others decay leptonically. These events present a smaller jet activity than the dilepton signal, although we still require the presence of two hard jets. The main SM backgrounds for the trilepton channel are as follows:

- (i) diboson electroweak gauge boson production, i.e.,
 ZZjj and W[±]Zjj, where the W's and Z's decay leptonically;
- (ii) $W^{\pm}W^{\pm}W^{\mp}jj$ that receives a contribution from the intermediate state $t\bar{t}W^{\pm}$ when the jets are *b* jets.

Finally, the cleanest state that can be obtained from Eq. (7) is when all *W*'s decay into leptons. Although only a small fraction of the signal ends up in this state, this is compensated by an extremely low background. We looked for this topology requiring four leptons and two jets in the central region of the detector. In our study we took into account the main SM backgrounds: ZZjj, W^+W^-Zjj , and $W^+W^+W^-W^-jj$ productions.

We present our results for three representative points of the parameter space given by three D_4 masses: 300, 450, and 600 GeV. Nevertheless, a choice for the D_4 mass does not completely fix the parameter space because there is still some freedom in obtaining the couplings and width of the first Kaluza-Klein excitation of the gluon [2]. We further assume a heavy Higgs with $m_h \sim 900$ GeV, which is consistent with the existence of a condensing heavy fourth generation. In Table I we show the first KK-gluon width and couplings used in our simulations which were computed using the 5D condensation model [2]. The large

TABLE I. Benchmark points in the parameter space of the effective theory. $g_{s\psi}$ is the coupling between the first KK gluon and the fermion ψ , and depends on the degree of compositeness of the fermion.

m_{D_4} (GeV)	$g_{sQ_L^4}$	$g_{sU_{4R}}$	$g_{sD_{4R}}$	$g_{sq_L^3}$	g_{st_R}	Γ_1/M_1
300	$4.4g_{s}$	$4.4g_{s}$	$1.1g_{s}$	$0.5g_{s}$	$3.3g_s$	0.68
450	$3.7g_s$	$4.4g_{s}$	$2.8g_{s}$	$0.6g_s$	$3.9g_s$	0.68
600	$5.4g_{s}$	$5.4g_{s}$	$3.1g_s$	$1.0g_{s}$	$1.7g_{s}$	0.98

values of the couplings seen in this table correspond to the fourth generation being almost completely composite. Although we quote here the results for only three benchmark points in the parameter space of the model, we scanned over a large region of the parameter space and we checked that our results are general enough not depending on our specific choices.

IV. ANALYSIS

In this section we study the two, three, and four lepton signals from D_4 pair production and their respective SM backgrounds, in order to assess the LHC potential for the discovery of this new heavy quark. We quantify the LHC reach by quoting the minimum required luminosity for a given signal to be observed.

A. Signal with two same-sign leptons

The D_4 pair production leads to same-sign dileptons when two equally charged W's decay leptonically. Although it does not allow one to reconstruct the D_4 mass peak, this topology presents only a modest SM background. Therefore, this final state should provide a first hint of the existence of the fourth generation. We start by applying the following acceptance and isolation cuts:

$$p_T^{\ell} > 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \quad p_T^{J} > 20 \text{ GeV},$$

 $|\eta_j| < 3, \quad \Delta R_{\ell\ell} \ge 0.7, \quad (10)$
 $\Delta R_{\ell j} \ge 0.7, \quad \Delta R_{j j} \ge 0.7,$

where $\ell(j)$ are the two hardest charged leptons (jets). In Table II we present the cross sections after the above cuts for the signal and SM backgrounds. For the signal we quote the results with and without the inclusion of the KK-gluon contribution in order to estimate its impact on D_4 pair production.

We can see from Table II that the SM background is still quite large after these minimum cuts, totaling 2.1 pb. Its main contribution comes from $t\bar{t}$ production, despite the small probability of obtaining an isolated lepton from the semileptonic decay of a *b* quark. The strong interaction production of $t\bar{t}$ pairs account for 98% of the total SM background. On the other hand, the signal cross section is appreciable, varying from 50 to 1300 fb depending on the D_4 mass.

 $^{^{5}}$ We require that the additional jet in the event passes the acceptance and isolation cuts given in Eq. (10).

TABLE II. Same-sign dilepton signal and SM background cross sections in femtobarn for several choices of cuts. We present the signal cross section with the inclusion of the KK-gluon contribution, denoted by signal, and with just the QCD contribution, marked as QCD. The empty entries correspond to cross sections $\sigma \leq O(10^{-2})$ fb.

Process/cuts	Eq. (10)	Eqs. (10) and (11)	Eqs. (10)–(12)
Signal: $m_{D_4} = 300 \text{ GeV}$	1388	412	87.0
QCD: $m_{D_4} = 300 \text{ GeV}$	1360	402	83.4
Signal: $m_{D_4} = 450 \text{ GeV}$	222	164	54.2
QCD: $m_{D_4} = 450 \text{ GeV}$	204	150	48.8
Signal: $m_{D_4} = 600 \text{ GeV}$	48	44	17.8
QCD: $m_{D_4} = 600 \text{ GeV}$	42	38	15.5
tī	2060	452	1.2
W^+W^+jj	8.2	4.0	1.0
W^-W^-jj	3.8	1.8	0.6
W^+W^+jjj	8.1	5.0	1.3
W^-W^-jjj	3.4	2.1	0.8
W^+Zjj	9.4	1.2	0.3
W^-Zjj	4.3	0.6	0.2
$W^+ t \overline{t}$	8.6	2.3	0.6
$W^- t\bar{t}$	3.5	0.9	0.2
$W^+W^-t\bar{t}$	0.2	0.1	
$W^+W^+W^-$	0.7		
$W^+W^+W^-j$	1.2	0.3	

In order to suppress the SM backgrounds and enhance the signal we tightened the transverse momentum cuts. In Fig. 2 we present the normalized transverse distribution for the two hardest jets in the event. As can be seen from this figure, the signal has a tendency of producing harder jets, especially for larger masses. Therefore, we further require that the hardest jets $(j_{1,2})$ satisfy

$$p_T^{J_{1,2}} > 100 \text{ GeV.}$$
 (11)

In principle, this cut could be harder for heavier D_4 's. However, here we keep it constant for the sake of simplicity. The effects of the cuts (10) and (11) in the signal and SM backgrounds are presented in Table II.

Further reduction of the SM backgrounds can be achieved by demanding harder leptons, since leptons originating from the *b* semileptonic decay in $t\bar{t}$ production are rather soft. This can be seen in Fig. 3, displaying the lepton transverse momentum spectrum of the signal and backgrounds. In particular, the second hardest lepton has a very steep spectrum compared to the background, since the latter is dominated by $t\bar{t}$. We then require that the two same-sign leptons satisfy



FIG. 2. Normalized transverse momentum distribution of the two hardest jets after applying the acceptance and isolation cuts given in Eq. (10). The left (right) panels depicts the p_T distribution of the hardest (second hardest) jet. The dashed, continuous, and dotdashed lines correspond, respectively, to the signal with $m_{D_4} = 300, 450$, and 600 GeV, while the dotted lines correspond to the sum of the backgrounds, dominated by $t\bar{t}$.



FIG. 3. Same as Fig. 2 but for leptons.

$$p_T^{\ell_{1,2}} > 50 \text{ GeV.}$$
 (12)

This cut has a large impact in the $t\bar{t}$ background, which is suppressed by a factor ≈ 370 as can be seen from Table II.

TABLE III. Same-sign dilepton signal and background total cross section, as well as, signal-to-background ratio after cuts (10)–(12). \mathcal{L}_{min} stands for the minimum integrated luminosity needed to discover the dilepton signal at the 5σ level.

m_{D_4}	$\sigma_{\mathcal{S}}$ (fb)	$\sigma_{\mathcal{B}}$ (fb)	\mathcal{S}/\mathcal{B}	$\mathcal{L}_{\min} \ (pb^{-1})$
300 GeV	87.0	6.2	14.	44
450 GeV	54.2	6.2	8.7	84
600 GeV	17.8	6.2	2.9	460



FIG. 4. Normalized differential cross section as a function of H_T for the signal with two same-sign leptons. We applied cuts (10)–(12) and we have summed the SM background to the signal. The total areas under the curves are normalized to one in all the cases.

On the other hand, this cut reduces the signal only by a factor of 3-5.

Table III summarizes the signal and SM background cross sections after cuts (10)–(12). We see that the dilepton channel has a large signal-to-background ratio even for heavier D_4 's. We also present in this table the required integrated luminosity for the signal to have a statistical significance of 5σ . We conclude that this signal can be established at the very early stages of the LHC run, even before collecting 1 fb⁻¹.

Finally, the total transverse energy H_T can be used since it follows m_{D_4} , even though it is not possible to reconstruct the D_4 mass. The H_T spectrum is peaked at a value of H_T of order of $H_t \sim 2m_{D_4}$, as seen in Fig. 4. In order to make a more quantitative statement, we can fit the mean value⁶ of H_T , $\langle H_t \rangle$, with m_{D_4} after cuts (10)–(12). We obtained that

$$\langle H_T \rangle = a + bm_{D_4},\tag{13}$$

with a = 426 GeV and b = 1.23. We stress that Eq. (13) gives just a rough estimate and should not replace a determination of m_{D_4} obtained from a full D_4 mass reconstruction.

B. Trilepton signal

Given that the D_4 production cross section is large enough, confirmation of the fourth-generation origin of the previous signal could be obtained by the observation of the less-frequent trilepton events. In this case, three of the W's present in (7) decay leptonically. This final state is clean and presents very small SM backgrounds.

We require the presence of three, and only three, charged leptons and at least two jets satisfying the following acceptance and isolation cuts:

⁶We have considered the mean value of H_T instead of the maximum because the former is much more stable under statistical fluctuations.

TABLE IV. Trilepton signal and SM background cross sections in femtobarn after cuts. We present the signal cross section with the inclusion of the KK-gluon contribution, denoted by signal, and with just the QCD contribution, marked as QCD. The empty entries correspond to cross sections $\leq O(10^{-2})$ fb.

Process/ cuts	Eq. (14)	Eqs. (14)–(16)
Signal: $m_{D_4} = 300 \text{ GeV}$	612	210
QCD: $m_{D_4} = 300 \text{ GeV}$	604	200
Signal: $m_{D_4} = 450 \text{ GeV}$	100	61
QCD: $m_{D_4} = 450 \text{ GeV}$	93.7	56.9
Signal: $m_{D_4} = 600 \text{ GeV}$	21.3	15.4
QCD: $m_{D_4} = 600 \text{ GeV}$	18.5	13.3
$W^{\pm}Zjj$	79.4	
$W^{\pm}W^{\pm}W^{\mp}jj$	3.9	1.0
ZZjj	1.3	

$$p_T^{\ell} > 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \qquad p_T^{j} > 20 \text{ GeV}, \\ |\eta_j| < 3, \qquad \Delta R_{\ell\ell} \ge 0.7, \qquad (14) \\ \Delta R_{\ell j} \ge 0.7, \qquad \Delta R_{jj} \ge 0.7.$$

In Table IV we collect the total cross sections for the signal and SM backgrounds after these cuts. We verified that these cuts are enough to suppress the background coming from top pair production followed by the leptonic decay of the W's, with one of the b's decaying semileptonically. The signal-to-background ratio is already large after the acceptance cuts. However, we make further requirements in order to enhance the signal for large m_{D_4} , by demanding that the two hardest jets satisfy

$$p_T^{j_1} > 80 \text{ GeV}$$
 and $p_T^{j_2} > 50 \text{ GeV}$. (15)

After the initial cuts, the dominant SM background comes from $W^{\pm}Zjj$ production. This can be efficiently suppressed by imposing a cut on the invariant mass of the lepton pair of the same flavors and opposite charges

$$m_{\ell^+\ell^-} > 100 \text{ GeV.}$$
 (16)

The effect of these two additional cuts is presented in Table IV. As we can see, the SM background becomes negligible after these cuts while a large fraction of the signal is kept at large m_{D_4} . For small m_{D_4} the signal is suppressed by a factor of ≈ 3 . However, the signal cross section is still large enough even after this reduction.

Since the trilepton signal is essentially background free after cuts, we required 5 events to determine the integrated luminosity needed to establish the signal at the LHC. As shown in Table V, the discovery of the trilepton signal requires approximately the same integrated luminosity as the one needed to establish the same-sign dilepton signal. This fact can be used for further tests of the model.

PHYSICAL REVIEW D 79, 075026 (2009)

TABLE V. Trilepton signal and background total cross sections after cuts (14)–(16). \mathcal{L}_{min} stands for the minimum integrated luminosity needed to discover the trilepton signal with the production of 5 events in the absence of SM backgrounds.

m_{D_4}	$\sigma_{\mathcal{S}}$ (fb)	$\sigma_{\mathcal{B}}$ (fb)	$\mathcal{L}_{\min} \ (pb^{-1})$
300 GeV	210	1	24
450 GeV	61.0	1	82
600 GeV	15.4	1	325

TABLE VI. Same as Table IV but for the production of four charged leptons.

Process/cuts	Eq. (17)	Eqs. (17) and (18)
Signal: $m_{D_4} = 300 \text{ GeV}$	59.6	7.87
QCD: $m_{D_4} = 300 \text{ GeV}$	58.6	7.52
Signal: $m_{D_4} = 450 \text{ GeV}$	10.0	2.92
QCD: $m_{D_4} = 450 \text{ GeV}$	9.2	2.63
Signal: $\vec{m}_{D_4} = 600 \text{ GeV}$	2.4	1.02
QCD: $m_{D_4} = 600 \text{ GeV}$	2.1	0.88
ZZjj	5.0	
W^+W^-Zjj	0.2	

C. Signal with four leptons

Finally, D_4 pair production also leads to final states with four isolated leptons and two jets. Although D_4 production leads to this final state only in 0.2% of the events, the final state is extremely clean and with a low background. We select these events by applying the acceptance and isolation cuts

$$p_T^{\ell} > 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \quad p_T^{J} > 20 \text{ GeV},$$

 $|\eta_j| < 3, \quad \Delta R_{\ell\ell} \ge 0.4, \quad (17)$
 $\Delta R_{\ell j} \ge 0.4, \quad \Delta R_{j j} \ge 0.4.$

As we can see from Table VI, the SM background is dominated by the production of Z pairs, with W^+W^-Zjj production⁷ a distant second. These backgrounds can be easily removed by requiring that

$$p_T^{J_{1,2}} > 50 \text{ GeV}$$
 and $m_{\ell^+\ell^-} > 100 \text{ GeV}$, (18)

where $m_{\ell^+\ell^-}$ stands for the invariant mass of any oppositecharge and same-flavor dileptons. As expected, the SM background is essentially eliminated by the invariant mass requirement. However, the signal is also considerably reduced. Requiring five events to establish the four-lepton signal demands an integrated luminosity of 0.6 (1.7 or 4.9) fb⁻¹ for a D_4 mass of 300 (450 or 600) GeV. Thus, although this final state will obviously not be used for an

⁷We verified that the SM production of $W^+W^-W^+W^-jj$ has a negligible cross section.

early discovery, its presence constitutes further evidence of the production of a fourth-generation heavy quark.

V. THE MECHANISM OF ELECTROWEAK SYMMETRY BREAKING

The breaking of the electroweak symmetry by the condensation of the fourth generation relies in the strong coupling between the KK gluon and the quarks of the fourth generation [2]. Therefore, a conclusive test of the scenario described in Sec. II would be the detection of the KK gluon through its strong coupling to the fourthgeneration quarks. Here we briefly discuss the feasibility of such an important test.

As mentioned in Sec. II, the KK gluon is too broad for its resonant peak to be observed. Its only effect is to give an extra contribution to the production of the fourthgeneration quarks, particularly D_4 . However, since the cross section is very sensitive to the D_4 mass, pure QCD with a lighter D_4 quark can mimic the effect of the KK gluon. For concreteness, let us consider the signal with two same-sign leptons and $m_{D_4} = 450$ GeV; see Sec. IVA. The corresponding cross section after the cuts (10)-(12) is equal to the cross section with $m_{D_4} = 435$ GeV in pure QCD, i.e., a lighter D_4 quark and no KK gluon. Although the distributions are not identical, they are very similar. To distinguish them would require not only a very large luminosity, but also a determination of m_{D_4} with an uncertainty smaller than 15 GeV. As an example, in Fig. 5 we show the number of events as a function of H_T for both scenarios with an integrated luminosity of 100 fb $^{-1}$. Since



FIG. 5. Number of events as a function of H_T for the signal with two same-sign leptons. We applied cuts (10)–(12) and assumed an integrated luminosity of 100 fb⁻¹. The dashed line corresponds to pure QCD with $m_{D_4} = 435$ GeV and the continuous one to the 5D scenario with $m_{D_4} = 450$ GeV. The total number of events is the same in both cases.

the shapes are indistinguishable, we conclude that it would be very hard to detect the presence of the KK-gluon component in this way.

In principle, there are other tests of this scenario that could be performed, albeit indirect. One such example is the detection of the KK excitations of the electroweak gauge bosons, which would also have large couplings to the fourth generation. We estimate the width of these resonances to be in the range (10-20)% of their masses, making their detection somewhat easier than in the KKgluon case. Although the electroweak KK modes induce only a small contribution to the four-fermion interaction leading to the condensation, the reason behind the large couplings is the same, i.e., the heavy fourth generation and the massive vectors are composite states of a strongly interacting sector with couplings $g_{\text{SM}} \leq g \leq 4\pi$. Then, the existence of KK excitations of the electroweak gauge bosons with large couplings to the fourth generation would be a very important indication for the present scenario. We leave a careful study of these signals for future work.

VI. CONCLUSIONS

We have considered the first LHC signals of a heavy fourth-generation decaying preferentially to the third generation. These signals are present in a scenario where the electroweak symmetry is broken by the condensation of at least one of the fourth-generation quarks [2]. We focused on the production and decays of D_4 , the down quark of the fourth generation, which is assumed to be lighter than U_4 , the up-type fourth-generation quark.

The existence of D_4 necessarily leads to final states with same-sign dileptons, trileptons, and four charged leptons at the LHC. These signals can be used to falsify a model of EWSB by the condensation of the fourth generation such as the one presented in Ref. [2]. We showed that the samesign dilepton channel, as well as the trilepton one, should be observable at the LHC for integrated luminosities smaller than 1 fb^{-1} . The nonobservation of such signals would be a strong constraint on this class of models, leading to many such scenarios being ruled out. The presence of this signal, on the other hand, would not necessarily point to the existence of a fourth generation, which would require a lot more data than 1 fb^{-1} to be confirmed. For instance, in the scenario of Ref. [8] the KK excitations of down-type quarks may be of masses similar to the ones considered here for D_4 . Their QCD production cross sections are the same, and the final state branching ratios might be very similar. Thus the observation of other channels, such as the production of U_4 and even the fourthgeneration leptons, in addition to the full reconstruction of the D_4 invariant mass [9], would be needed to confirm the presence of a chiral fourth generation. This would take considerably larger data samples. In any event, the observation of these signals at such low accumulated luminosities would at least indicate that the new physics is produced through strong interactions and not by electroweak processes. This is the case in many extensions of the SM, such as in the present scenario, as well as in most supersymmetric models [23] among others. On the other hand, at least a few tens fb^{-1} are needed to establish the electroweak production of heavy Majorana neutrinos [24] or to test type II seesaw models [25].

Finally, to confirm the existence of a strong interaction involving the fourth-generation quarks and leading to EWSB it would be necessary, in addition to the QCDinduced production of D_4 , to directly observe this new strong interaction. We have shown that even when modeled as coming from integrating out a massive color-octet vector particle, or a KK excitation of the gluon in AdS₅ models [2], this results in a featureless enhancement of the D_4 production. In the language of having a vector particle mediating the condensing interaction, its width is large (of the order of its mass). We studied the effects of the presence of this KK gluon in the same-sign dilepton channel and we showed that a very large luminosity, beyond what is foreseeable in the near future, is needed to disentangle the QCD and KK-gluon contributions. In compari-

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son, in Randall-Sundrum models without a strongly coupled fourth generation, the KK-gluon width remains smaller than its mass, and it may be observed at the LHC [26], even in scenarios such as that of Ref. [13] with down-type KK quarks of only a few hundred GeV.

We conclude that in the type of models presented here other strategies must be pursued in order to observe the new strong interactions of the fourth generation. These might include the observation of the KK excitations of the weak gauge bosons decaying into the fourth-generation leptons, as well as the flavor-violating effects of the KK excitations that are only present in their amplitude and do not suffer contamination from the SM QCD or electroweak amplitudes. We leave their study for future work.

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