



# The $E_6$ inspired isosinglet quark and the Higgs boson

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## ABSTRACT

We consider the experimental implications of the down type isosinglet quark,  $D$ , predicted by the  $E_6$  group to Higgs boson searches at the LHC. The pair production of  $D$  quarks at the LHC and their subsequent decays  $D \rightarrow hd$  and  $D \rightarrow Wu$  has been analyzed. For a light Higgs boson of mass  $O(120 \text{ GeV})$ , an analysis based on fast simulation of the ATLAS detector response shows that the  $b\bar{b}$  channel becomes as efficient as the  $\gamma\gamma$  channel for discovering the Higgs particle if  $m_D < 630 \text{ GeV}$ .

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## 1. Introduction

Although the Standard Model (SM) explains the results of the particle physics experiments performed up to now with an accuracy high enough to withstand even the challenges set by the precision measurements, it still leaves some of the basic questions open. The number of elementary particles, the reason for their mass hierarchy, and the unification of gravity with the other known forces are some examples of these open issues. The grand unified theories (GUTs) aim to answer at least some of these questions by imposing a fundamental symmetry between all known fermions of the same family. This symmetry, manifesting itself at high energies, is expected to reduce the number of free parameters in the SM. The experimental implication of extending the existing  $SU_C(3) \times SU_W(2) \times U_Y(1)$  group structure of the SM to a single gauge group with a large fundamental representation is the prediction of new particles. The exceptional Lie group  $E_6$  has been long considered as one of the favorite candidates for such a GUT gauge symmetry group [1,2]. The new colored particles predicted by  $E_6$  are isosinglet quarks, leptoquarks and diquarks depending on model variations. Some of these particles may soon be accessible by the LHC experiments [3,4]. The current limit on the mass of the down type isosinglet quark is  $m_D > 199 \text{ GeV}$  [5]. The upgraded Tevatron could reach  $m_D \sim 300 \text{ GeV}$  [6], whereas the LHC will cover the region up to  $m_D \sim 1 \text{ TeV}$  for the pair production channel [7] independent of the mixing between  $d$  and  $D$  quarks. For the single production channel, if the sine of the mixing angle exceeds 0.025, the discovery reach would be  $m_D \sim 1.5 \text{ TeV}$  [8]. In this note, we consider the possible impact of the mixing

between the  $E_6$  isosinglet quark and the SM down type quarks on the light Higgs boson  $h$  (e.g.  $m_h < 135 \text{ GeV}$ ) searches with the ATLAS detector [3]. According to the ATLAS technical design report [3], for such a light Higgs boson, the  $h \rightarrow \gamma\gamma$  channel is the only one that would give a possible discovery with more than  $5\sigma$  significance with  $100 \text{ fb}^{-1}$  of integrated luminosity. However, if the  $E_6$  model is true and the mass of the lightest additional quark is suitable, its decays involving the Higgs boson enhance the Higgs discovery potential. In particular the channel studied in this note,  $pp \rightarrow D\bar{D} \rightarrow hjWj \rightarrow bbj\ell\nu j$ , becomes as efficient as the  $\gamma\gamma$  channel for discovering the Higgs particle if  $m_D < 630 \text{ GeV}$ .

This Letter is organized as follows: Section 2 contains the description of the model and the new interactions involving the Higgs particle. Section 3 briefly discusses the outcomes of the new interaction: (A) the possibility of differentiation between the quarks of this model and any other model with an additional down type quark and (B) an increase in the Higgs production rate at the LHC. Section 4 elaborates on the second outcome by describing the performed Monte Carlo (MC) studies based on a fast simulation of the ATLAS detector response. Section 5 summarizes the statistical analysis that estimates the experimental reach to discover a light Higgs for the early days of the LHC.

## 2. The Higgs interaction

If the SM  $SU_C(3) \times SU_W(2) \times U_Y(1)$  group structure originates from the breaking of the  $E_6$  GUT scale down to the electroweak scale, then the extended quark sector should be written as:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, D_L, D_R, \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}, c_R, s_R, S_L, S_R, \\ \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R, B_L, B_R. \quad (1)$$

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As shown, each SM family is extended by the addition of an isosinglet quark, respectively denoted by the letters  $D$ ,  $S$ , and  $B$ . The mixing between the new and the SM down type quarks is responsible for the decays of the former. In this study, the intra-family mixing of the new quarks is assumed to be dominant compared to their inter-family mixing. Considering a similar mass hierarchy between the SM and the new quarks, the  $D$  ( $B$ ) quark is assumed to be the lightest (heaviest) one. The Lagrangian relevant for the  $D$  quark weak interactions is:

$$L_D = \frac{\sqrt{4\pi\alpha_{em}}}{2\sqrt{2}\sin\theta_W} [\bar{u}^\theta \gamma_\alpha (1 - \gamma_5) d \cos\phi + \bar{u}^\theta \gamma_\alpha (1 - \gamma_5) D \sin\phi] W^\alpha - \frac{\sqrt{4\pi\alpha_{em}}}{4\sin\theta_W} \left[ \frac{\sin\phi \cos\phi}{\cos\theta_W} \bar{d} \gamma_\alpha (1 - \gamma_5) D \right] Z^\alpha - \frac{\sqrt{4\pi\alpha_{em}}}{12\cos\theta_W \sin\theta_W} [\bar{D} \gamma_\alpha (4\sin^2\theta_W - 3\sin^2\phi(1 - \gamma_5)) D + \bar{d} \gamma_\alpha (4\sin^2\theta_W - 3\cos^2\phi(1 - \gamma_5)) d] Z^\alpha + \text{h.c.} \quad (2)$$

where  $\phi$  is the mixing angle between the  $d$  and  $D$  quarks, and  $\theta$  represents the usual CKM quark mixings, taken to be in the up sector for simplicity of calculation. Assuming that the squared sum of the row elements of the new  $3 \times 4$  CKM matrix gives unity, the measured values of  $V_{ud}$ ,  $V_{us}$ , and  $V_{ub}$  [5] constrain  $\sin\phi \leq 0.07$  [7]. The total decay width and the contribution from neutral and charged currents were already estimated in [9]. As reported in that work, the  $D$  quark decays through a  $W$  boson with a branching ratio of 67% and through a  $Z$  boson with a branching ratio of 33%.

The origin of the masses of SM particles is explained by using the Higgs mechanism. The Higgs mechanism can also be preserved in  $E_6$  group structure as an effective theory, although other alternatives such as dynamical symmetry breaking are also proposed [10]. On the other hand, the origin of the mass of the new quarks ( $D$ ,  $S$ ,  $B$ ) should be due to another mechanism since these are isosinglets. Therefore, the mass terms in the Lagrangian, written in the mass basis, are simply:

$$L_{dD}^M = m_d \bar{d}_L^M d_R^M + m_D \bar{D}_L^M D_R^M + \text{h.c.} \quad (3)$$

where  $m_d$  and  $m_D$  are the masses of the  $d$  and  $D$  quarks, respectively. Based on this initial consideration, the studies in [7,9] did not consider the channels involving the Higgs boson  $h$  for the  $D$  quark decays. However, the mixing between  $d$  and  $D$  quarks will lead to decays of the latter involving  $h$  after spontaneous symmetry breaking (SSB). To find these decay channels, the interaction between the Higgs field and both down type quarks of the first family should be considered before SSB. In this study, the Lagrangian in SM basis, containing also the cross terms between  $d$  and  $D$  with mass-like coefficients ( $a_{dD}$ ,  $m_{Dd}$ ), is written as:

$$L_{dD}^0 = a_{dd} \bar{d}_L^0 d_R^0 H + a_{dD} \bar{d}_L^0 D_R^0 H + m_{Dd} \bar{D}_L^0 d_R^0 + m_{DD} \bar{D}_L^0 D_R^0 + \text{h.c.} \quad (4)$$

The four interaction coefficients ( $a_{dd}$ ,  $a_{dD}$ ,  $m_{Dd}$ ,  $m_{DD}$ ) in Eq. (4) can be obtained in terms of the two quark masses and the two mixing angles between the left and right components of the two down type quarks. In order to use the new variable set, the first step is to write the mixing between the SM and the mass states as follows:

$$D_{L/R}^0 = D_{L/R}^M \cos\phi_{L/R} - d_{L/R}^M \sin\phi_{L/R}, \quad d_{L/R}^0 = D_{L/R}^M \sin\phi_{L/R} + d_{L/R}^M \cos\phi_{L/R} \quad (5)$$

where  $\phi_{L/R}$  is the  $d$ - $D$  quark mixing angle with the subscript  $L$  ( $R$ ) standing for the left (right) components of the quark fields and the superscript 0 ( $M$ ) standing for the SM (mass) basis. After the SSB, the Higgs field is expanded around the new minimum,  $v$ ,

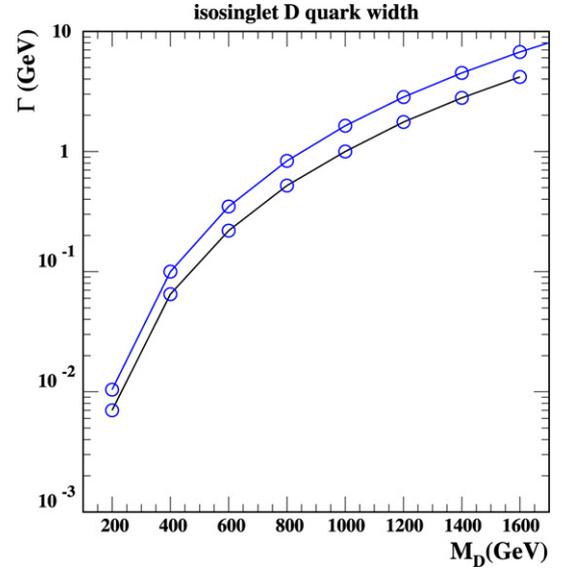


Fig. 1. The decay width of the  $D$  quark for  $\sin\phi = 0.045$ : The lower curve corresponds to the case without Higgs interaction, whereas the upper curve has been calculated by taking into account the Higgs channels for  $m_H = 120$  GeV.

as  $H = v + h$  to separate the terms that contribute to interaction and mass coefficients:

$$a_{dd} = \frac{m_d \cos\phi_L \cos\phi_R + m_D \sin\phi_L \sin\phi_R}{v}, \quad a_{dD} = \frac{m_d \cos\phi_L \sin\phi_R - m_D \sin\phi_L \cos\phi_R}{v}, \quad m_{Dd} = m_d \sin\phi_L \cos\phi_R - m_D \cos\phi_L \sin\phi_R, \quad m_{DD} = m_d \sin\phi_L \sin\phi_R + m_D \cos\phi_L \cos\phi_R \quad (6)$$

where  $v = \eta/\sqrt{2}$  and  $\eta = 247$  GeV is the vacuum expectation value of the Higgs field. After simple calculations, the Lagrangian for the interaction between  $d$ ,  $D$  quarks, and the Higgs boson becomes:

$$L_h^M = \frac{m_D}{v} \sin^2\phi_L \bar{D}^M D^M h - \frac{\sin\phi_L \cos\phi_L}{2v} \bar{D}^M [(1 - \gamma^5)m_D + (1 + \gamma^5)m_d] d^M h - \frac{\sin\phi_L \cos\phi_L}{2v} \bar{d}^M [(1 + \gamma^5)m_D + (1 - \gamma^5)m_d] D^M h + \frac{m_d}{v} \cos^2\phi_L \bar{d}^M d^M h. \quad (7)$$

Note that the right mixing angle has completely disappeared from the final formula (7) making  $\phi$  of Eq. (2) a short hand notation for  $\phi_L$ . The total width of the  $D$  quark as a function of its mass is shown in Fig. 1 for the illustrative value of  $\sin\phi = 0.045$  that will be used for the remainder of this study. It is seen that the  $D$  quark has a narrow width and becomes even narrower with decreasing values of  $\phi$  since it scales through a  $\sin^2\phi$  dependence. The relative branching ratios for the decay of the  $D$  quark depend on both the  $D$  quark and the Higgs mass values. For example, at the values of  $D$  quark mass around 200 GeV and the Higgs mass around 120 GeV:  $\text{Br}(D \rightarrow Wu) \sim 60\%$ ,  $\text{Br}(D \rightarrow hd) \sim 12\%$ ,  $\text{Br}(D \rightarrow Zd) \sim 28\%$ , whereas as the  $D$  quark mass increases the same ratios asymptotically reach 50%, 25% and 25%, respectively. As the Higgs mass increases from 120 GeV, these limit values are reached at higher  $D$  quark masses. The branching ratios as a function of the  $D$  quark mass are given in Fig. 2 for two values of the Higgs mass: 120 GeV (solid lines), which is just above the limit imposed by LEP II results, and 135 GeV (dashed lines), where the

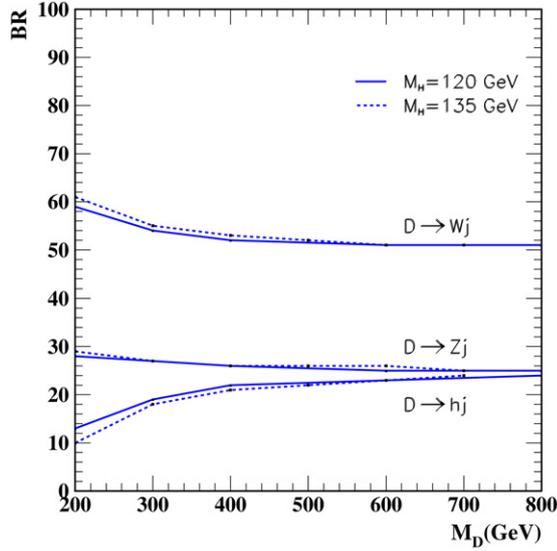


Fig. 2. The  $D$  quark branching ratios as a function of the  $D$  quark mass for two Higgs mass values: 120 GeV and 135 GeV.

$b\bar{b}$  decay mode is taken over by the  $W^+W^-$  mode. One should also mention that contribution of the  $D$  quark to the loop induced Higgs production is suppressed by a factor  $\sin^2\phi$  as implied by the first term of Eq. (7).

The model built in this section is a rather simplistic one. It is assumed that only one light SM-like Higgs boson exists in relevant mass range and the other new gauge bosons and new leptons are neglected. The possible impact from these other fields of the  $E_6$  GUT model will be discussed in the last section of this note.

### 3. The experimental implications

Studies about the  $D$  quark pair production without the Higgs particle have been previously reported elsewhere [7]. This section concentrates on the possible impact of the interactions involving the Higgs particle. For example, Eq. (7) shows that, the Higgs boson could be used in the  $s$  channel for the creation of  $D$ - $d$  quark pairs:  $h \rightarrow \bar{D}d$  or  $dD$ . However, as the Higgs couplings depend on the quark masses, the right handed  $D$  quarks ( $D_R$ ) would be produced  $(\frac{m_D}{m_d})^2$  times more often than the left-handed ones ( $D_L$ ). Due to the left handedness of the charged weak interactions, the produced  $D$  quarks would subsequently decay mostly via the neutral current channel. The precise measurement of such a process could help in differentiating the  $E_6$  model from other models that also involve additional down type quarks.

Depending on the masses of the  $D$  quark and the Higgs boson itself, the  $E_6$  model could also boost the overall Higgs production at the LHC. This boost is particularly interesting for the Higgs hunt, one of the main goals of the ATLAS experiment. For example, if the  $D$  quark mass is as low as 250 GeV, its pair production cross section at the LHC becomes as high as  $10^5$  fb as can be seen in Fig. 3. Convolution of the cross section with the  $D$  quark decay branching ratios from previous section (17% for  $D \rightarrow hj$  at  $m_D = 250$  GeV) yields the number of expected Higgs events. In the low mass range considered in this note (from 115 up to 135 GeV), the branching ratio  $h \rightarrow b\bar{b}$  is about 70% [3]. The signatures of the expected final states involving at least one Higgs boson are listed in Table 1 together with the yearly expected number of events for two example  $D$  quark masses: 250 and 500 GeV. For the remaining of this note, although the case involving the  $Z$  is more suitable from the event reconstruction point of view, we will concentrate on the last row, which has the highest number of expected Higgs events per year.

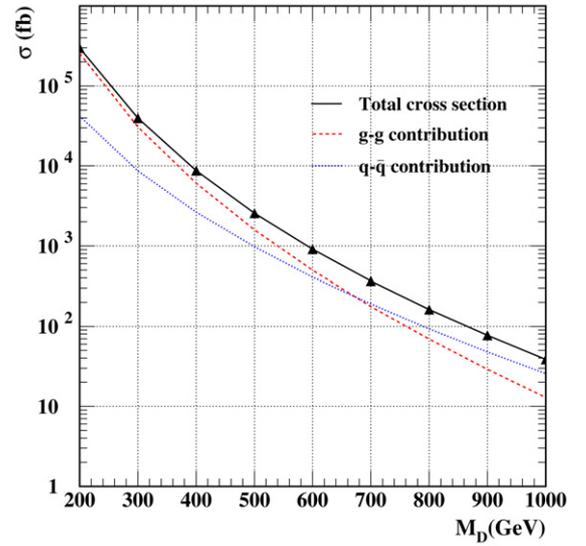


Fig. 3. Tree level pair production of  $D$  quarks at LHC as a function of the new quark's mass.

Table 1

For pair production of  $D$  quarks, the decay channels involving at least one Higgs boson. The branching ratios and the number of expected Higgs particles are calculated assuming  $m_H = 120$  GeV and  $m_D = 250(500)$  GeV

$D_1$	$D_2$	BR	#expected Higgs/100 fb $^{-1}$	Expected final state
$D \rightarrow hj$	$D \rightarrow hj$	0.029 (0.053)	$0.58 \times 10^6$ ( $2.65 \times 10^4$ )	$2j4j_b$
$D \rightarrow hj$	$D \rightarrow Zj$	0.092 (0.120)	$0.92 \times 10^6$ ( $3.01 \times 10^4$ )	$2j2j_b2\ell$
$D \rightarrow hj$	$D \rightarrow Wj$	0.190 (0.235)	$1.9 \times 10^6$ ( $6.04 \times 10^4$ )	$2j2j_b\ell E_{T,miss}$

### 4. Monte Carlo study

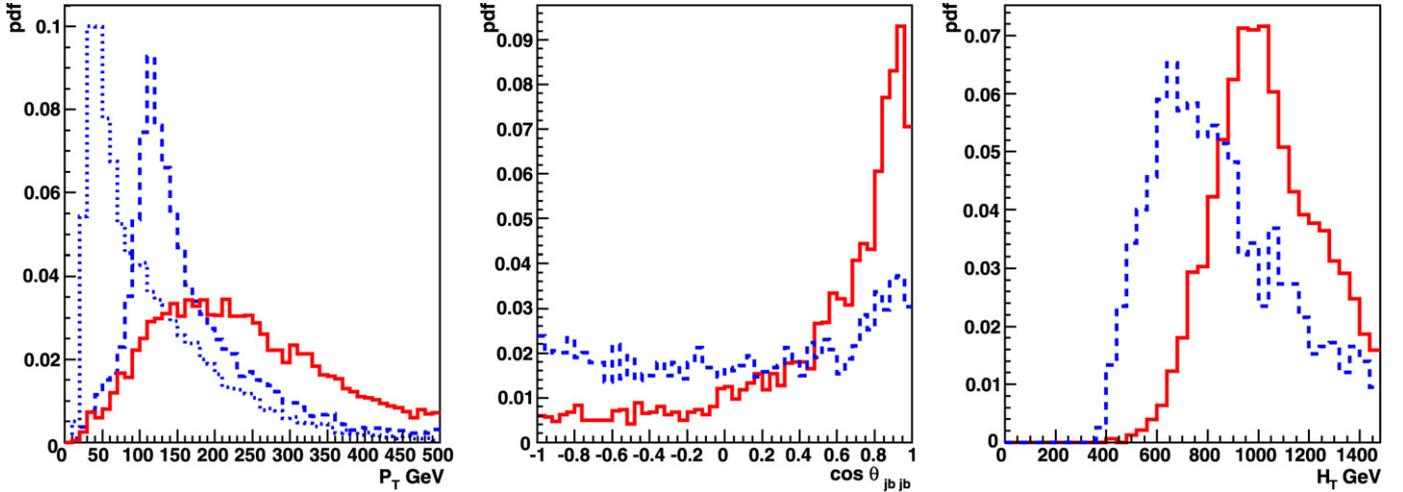
The Lagrangian presented in Section 2 has been implemented in a tree level event generator, Comphep v4.4.3. [11], to investigate the possibility of detecting the Higgs particle and reconstructing it from  $b$ -jets using the ATLAS detector. Assuming a light Higgs boson of mass 120 GeV, four mass values for the  $D$  quark have been taken as examples: 250 GeV, 500 GeV, 750 GeV, and 1000 GeV. 10000 signal events were produced for each mass value under study with the  $Whjj$  ( $h \rightarrow b\bar{b}$  and  $W \rightarrow \ell\nu$ ) final states using the CTEQ6L1 PDF set [12]. Other parameterizations, such as CTEQ5M and CTEQ5L1 were also tested to investigate the systematic effect of the PDF selection on the  $D\bar{D}$  pair production total cross section. It was found that the difference was less than 10% over the range of 200 to 1600 GeV, CTEQ6L1 giving the lowest results up to a  $D$  quark mass of 1 TeV. The generator level cuts on the partons, guided by the performance of the ATLAS detector, are listed as:

$$|\eta_p| \leq 3.2,$$

$$p_{T_p} \geq 15 \text{ GeV},$$

$$R_p > 0.4$$

where  $\eta_p$  is the pseudo-rapidity for the partons giving rise to jets;  $p_{T_p}$  is the transverse momentum of the partons; and  $R_p$  is the angular separation between the partons. The imposed maximum value of  $\eta_p$  requires the jets seeded by the partons to be in the extended barrel region of the calorimeter where the jet energy resolution is optimal. The imposed lower value of  $p_{T_p}$  ensures that no jets that would eventually go undetected along the beam pipe are generated at all. The imposed lower value of  $R_p$  provides good separation between the two jets in the final state. Using the interface provided by CPYTH v2.3 [13], the generated particles are processed within the ATLAS software framework version 11.0.41.



**Fig. 4.** The distributions of kinematic parameters for SM background and signal for an example  $D$  quark mass of value of 500 GeV. The solid histograms are for signal and the dashed ones for the background events. The leftmost plot contains the  $p_T$  distribution for the light jets which show clear distinction between signal and background cases. It also contains the  $p_T$  distribution for the  $b$ -jets (dotted histogram) which has the same shape for both signal and background. However, the middle plot shows that the  $b$ -jets originating from the signal events can be discriminated from the background ones by considering the angle between the two jets. Finally the rightmost plot contains the scalar sum of all transverse momenta providing another criterion for separating the signal from the background.

The decay and hadronization processes were handled in PYTHIA [14] and detector response simulation was performed with fast Monte Carlo program ATLFast [15] which uses a general parameterization of the detector, ignoring the individual event topology. The default properties of the parameterized fast simulation are discussed elsewhere [7,15]. One should also note that in this work, the reconstructed  $b$ -jet energy and momenta were re-calibrated like in [3] to have a good match between the mean value of the reconstructed Higgs mass and its parton level value.

As for the background study, all the SM interactions giving the  $W^\pm j_b j_b jj$  final state have been computed in another tree level generator, MadGraph v2.1. [16], using the same parton level cuts and PDF. The SM background cross section is calculated to be  $520 \pm 11$  pb. The reasons for using two separate event generators, their compatibility, and their relative merits have been discussed elsewhere [7]. The generated 40 000 background events were also processed in the same way using the ATLAS software framework for hadronization and calculation of detector effects.

#### 4.1. Analysis details for $m_D = 500$ GeV

The  $W$  boson will be reconstructed using an electron or a muon and the missing energy associated with the undetected neutrino, whereas the  $b$ -jets will be combined to reconstitute the  $h$  boson. These two bosons can be merged together with the remaining two jets to obtain the invariant masses of the two  $D$  quarks. Therefore, the final state particles of interest are  $j_b j_b jj \ell E_{T,\text{miss}}$  for which the distributions of the kinematic values are shown in Fig. 4. On the leftmost plot, one can observe that the  $p_T$  distribution of the light quark jets coming from  $D$  quark decays peaks around 200 GeV (solid line), whereas the same distribution for the background jets is much less energetic: the peak is around 120 GeV (dashed line). This difference can be used to reject the background events most of which (about 80%) are originating from the  $t\bar{t}$  production. In these events, one  $W$  decaying leptonically and the other hadronically give rise to the same final state particles as the signal. The  $p_T$  distribution of the  $b$ -jets, however, peaks around 40 GeV (dotted line) for both signal and background cases. Another property that can be used to discriminate the background events is the fact that two  $b$ -jets in the signal originate from the same particle, whereas for most of the background cases, they originate from two different particles. The cosine of the angle between these jets, shown

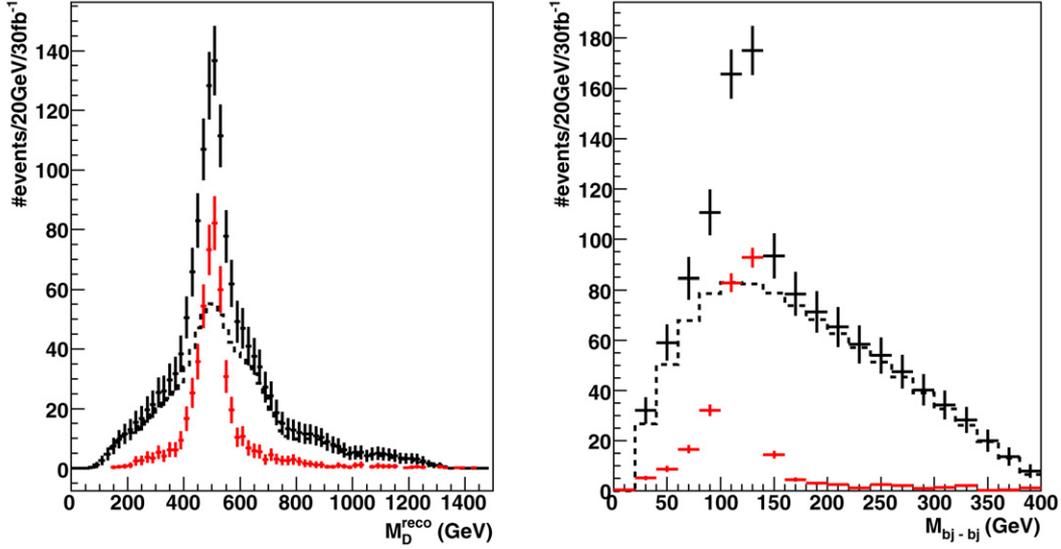
in Fig. 4 middle plot, is therefore peaked at one for the signal events, as opposed to the background case, where the distribution is more uniform. The scalar sum of all transverse momenta in an event ( $H_T$ ), is given in the same figure, rightmost plot, with again a solid line for the signal events and with a dashed line for the background events. This variable will be of great benefit for distinguishing the signal events from the background, especially for the high  $D$  quark mass values.

The reconstruction starts with the requirement of 1 electron or 1 muon and at least 4 jets, two of them identified as  $b$ -jets. For the leptons, the transverse momentum minimum value ( $p_{T,\ell} > 15$  GeV) is selected. The transverse momentum requirement on the two most energetic jets and the cosine of the angle between the two  $b$ -jet are optimized to get the best signal to background ratio for the final  $D$  quark invariant mass distribution. The  $h$  boson invariant mass is formed using the two  $b$  tagged jets remaining after the angular cut. To further reduce the background, the invariant mass of the two non- $b$  tagged jets is also calculated, and the events yielding a value smaller than  $M_Z$  are rejected. As there are no  $Z$  bosons in this search channel, this cut ensures the purity of the selected events by removing the background events originating from the hadronic decays of the SM  $Z$  boson. Another rejection criteria applied at this stage is related to  $H_T$ , where only events with  $H_T > 800$  GeV are selected. The association between the two most energetic jets and the reconstructed bosons is not unique. Both possibilities are calculated and the case with the smallest difference between the two reconstructed  $D$  quark invariant masses is selected. As the last consistency check, the difference between the two reconstructed  $D$  quark masses is required to be smaller than 100 GeV, a value compatible with the resolution of the reconstructed mass. The event selection cuts imposed on both signal and background are given in Table 2 in the order they were applied in the analysis. The same table also contains the individual efficiency values of each cut for both signal and background cases with an error of a few percent. As can be calculated from the table, the final efficiency for the signal is about 11% and for the background is about 2%.

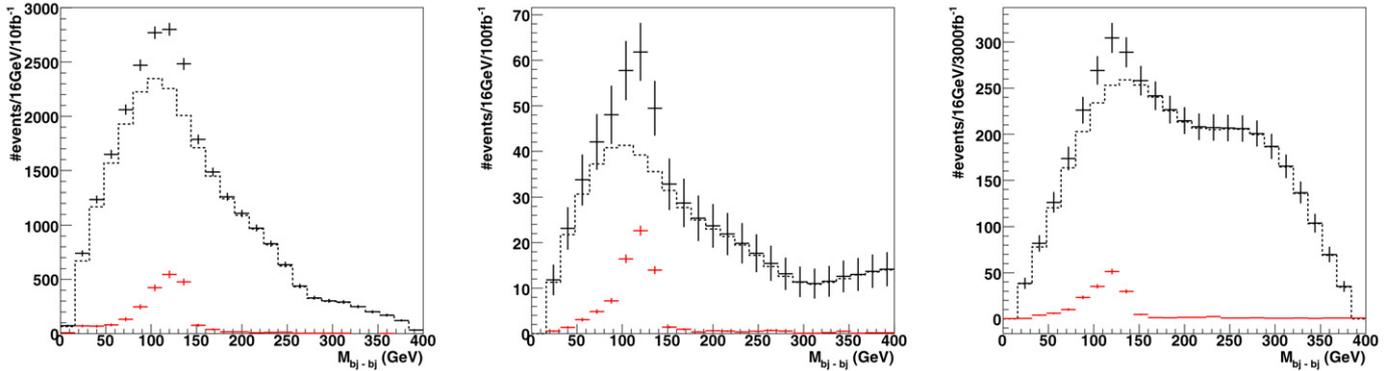
The invariant mass distributions after all cuts for the  $D$  quark and the Higgs boson are presented in Fig. 5 for  $30 \text{ fb}^{-1}$  integrated luminosity. After defining the signal region for  $D$  as  $M_D \pm 50$  GeV and for  $h$  as  $M_h \pm 30$  GeV, the number of events for the signal ( $S$ ) and the background ( $B$ ) can be integrated for both to obtain the

**Table 2**  
Optimized event selection cuts and their efficiencies for  $m_D = 500$  GeV

	N-leptons	N-jets	N-b-jets	$p_T$ -lepton	$p_T$ -jet	$\cos\theta_{j_b, l_b}$	$M_{jj}$	$H_T$	$ m_{D1} - m_{D2} $
Cut value	= 1	$\geq 4$	$\geq 2$	$\geq 15$ GeV	$\geq 100$ GeV	$\geq -0.8$	$\geq 90$ GeV	$\geq 800$ GeV	$\leq 100$ GeV
$\varepsilon_{\text{signal}}(\%)$	83	99	33	95	83	97	99	90	59
$\varepsilon_{\text{backgr}}(\%)$	79	99	36	94	69	89	65	55	37



**Fig. 5.** Reconstructed invariant masses of the  $D$  quark (left) and of the Higgs boson (right) together with the SM background (dotted lines) after  $30 \text{ fb}^{-1}$  integrated luminosity. The mass of the  $D$  quark is set to 500 GeV and Higgs boson to 120 GeV.



**Fig. 6.** The reconstructed masses for the Higgs particles for different  $D$  quark mass values. The dashed histogram represents the SM background, the red data points are for the signal case and the black data points are the sum of signal and the background. From left to right 250, 750 and 1000 GeV  $D$  quarks were considered using 10, 100 and  $3000 \text{ fb}^{-1}$  integrated luminosities, respectively.

statistical significance  $\sigma = S/\sqrt{S+B}$ . For this set of parameters, it is found that the  $D$  quark can be observed with a significance of  $13.2\sigma$  and at the same time the Higgs boson with a significance of about  $9.5\sigma$ . One should note that, in the SM Higgs searches, such a high statistical significance can only be reached with more than 3 times more data: with about  $100 \text{ fb}^{-1}$  integrated luminosity.

#### 4.2. Extension to other mass values

An analysis similar to the one presented in the previous section was performed for the other three  $D$  quark masses: 250, 750 and 1000 GeV. For each mass, the cut values were re-optimized to get the best statistical significance in the Higgs boson search. The method is to start from a low value of the  $H_T$  cut and scan the available sample by increasing the cut value, like a sliding threshold to look for a peak in the reconstructed mass histogram. The

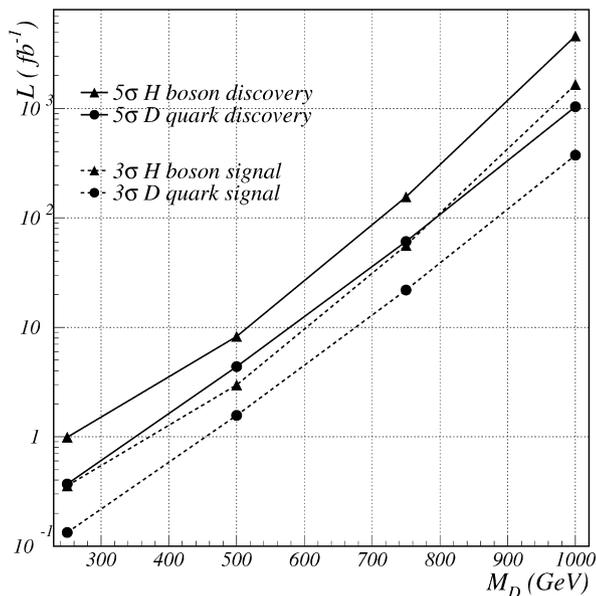
invariant mass distribution of the reconstructed Higgs boson for different  $D$  quark mass values is given in Fig. 6 where the dashed line shows the SM background, the red data points are for the signal events only and the black data points are the sum of the signal and the background events. For each increasing  $D$  quark mass value under consideration, the total integrated luminosity was also increased to be able to observe the Higgs boson signal.

Table 3 gives the number of events for signal and background processes after 3 years of low luminosity data taking time ( $30 \text{ fb}^{-1}$  integrated luminosity) for all considered  $D$  quark mass values. With such integrated luminosity, the  $3\sigma$  signal observation limit for the  $D$  quark is at 750 GeV. If  $m_D \geq 1000$  GeV, the required luminosities can be attained either by running the LHC for many years at the design parameters or by considering a possible upgrade, named as Super-LHC, which would yield  $1000 \text{ fb}^{-1}$  per year. On the other hand, the significance values presented in Table 3

**Table 3**

The expected number of signal ( $S$ ) and background ( $B$ ) events for  $D$  quark and Higgs boson searches after  $30 \text{ fb}^{-1}$  integrated luminosity. The counted events are in a range of  $\pm 50 \text{ GeV}$  ( $\pm 20 \text{ GeV}$ ) from the generator level value of the  $D$  quark (Higgs boson)

$M_D$ (GeV)	250		500		750		1000	
	$D$	$H$	$D$	$H$	$D$	$H$	$D$	$H$
$S$	8802	5303	336	222	27	19	1.9	1.4
$B$	29379	31717	313	321	32	56	3.1	10.6
$S/\sqrt{B+S}$	45.1	27.6	13.2	9.5	3.5	2.1	0.84	0.42



**Fig. 7.** The 3 and  $5\sigma$  reach of ATLAS in the Higgs and  $D$  quark search for increasing  $D$  quark mass values.

could be reduced by systematic errors which have not been evaluated here, and by the dilution of the statistical significance which occurs in searches for an excess in any bin of distribution.

## 5. Conclusions

This work gives the Lagrangian for the  $D$  quark including its interaction with the known SM particles and Higgs boson. One of the two implications of the Higgs interaction is discussed in detail: the boost to the Higgs discovery potential at the LHC. It is shown that the ATLAS experiment can use the  $D$  quark decay channels to enhance the Higgs discovery potential. The prospects for the Higgs discovery are discussed using Monte Carlo and fast simulation techniques for a light Higgs particle (120 GeV) and some exemplary  $D$  quark mass values ranging from 250 to 1000 GeV. Fig. 7 contains the  $3\sigma$  (dashed lines) and the  $5\sigma$  (solid lines) reaches of Higgs boson (triangles) and  $D$  quark (circles) searches for the above mentioned values. Therefore, a light Higgs boson could be discovered with a  $5\sigma$  statistical significance using the  $D\bar{D} \rightarrow hWjj$  channel within the first year of low luminosity data taking (integrated luminosity of  $10 \text{ fb}^{-1}$ ) if  $m_D < 500 \text{ GeV}$ . Under the same conditions but with one year of design luminosity (integrated luminosity of  $100 \text{ fb}^{-1}$ ), the  $5\sigma$  Higgs discovery can be reached if  $m_D \leq 700 \text{ GeV}$ . This is to be compared with the studies from the ATLAS TDR, where the most efficient channel to discover such a light Higgs is the  $h \rightarrow \gamma\gamma$  decay. This search yields about  $8\sigma$  signal significance with  $100 \text{ fb}^{-1}$  integrated luminosity. The presently discussed model could give the same significance (or more) with the same integrated luminosity if  $m_D < 630 \text{ GeV}$ . Our results are essentially independent of  $\phi$ , the mixing angle between  $d$  and  $D$

quarks, since the pair production of the new quark is mainly from strong interactions and also since  $\sin\phi$  can be factored out of its decay branching fractions, leaving only  $\cos\phi$  dependency which is close to unity. Therefore, if the isosinglet quarks exist and their masses are suitable, they will provide a considerable improvement for the Higgs discovery potential. The same channel also provides the possibility to search for the lightest of the isosinglet quarks, providing a  $5\sigma$  discovery signal if  $m_D < 800 \text{ GeV}$ , within  $100 \text{ fb}^{-1}$  of integrated luminosity. However one should note that the version of the fast simulation software used in this note was not fully validated by the ATLAS Collaboration. The study of other channels involving leptonic decays of the  $Z$  boson with thoroughly validated versions of the simulation and reconstruction software is in progress.

Finally, it is worth mentioning that the presented results remain mainly unchanged with respect to the consideration of other new fields predicted by the  $E_6$  GUT model. The matter sector of  $E_6$  inspired models also includes new heavy leptons (for details see review article [2]). In order to influence the above results, these new leptons should be sufficiently light to contribute to  $W$ ,  $Z$  and  $H$  boson decays. This possibility is already excluded experimentally by lower limits on new charged and neutral lepton masses [5].  $E_6$  GUT model has also a rich bosonic sector. The lightest of the new neutral gauge bosons,  $Z'$ , predicted by the enlarged gauge group, is already expected to be heavier than 700 GeV from Tevatron results [5]. Taking this lower limit and a  $D$  quark of one TeV, one finds that the  $D \rightarrow Z'd$  branching ratio is 0.2%, which is practically negligible. The existence of a  $Z'$  with appropriate mass would slightly increase the production cross section, hence improving the above given results. For example, if  $m_{Z'} = 2000 \text{ GeV}$ , the increase to the  $D\bar{D}$  pair production cross section is  $\simeq 4 \text{ fb}$  (a 1% effect) for  $m_D = 700 \text{ GeV}$ . Similarly, the consideration of additional Higgs fields lighter than  $D$  quark changes the above results very little. For example, an additional neutral Higgs boson of mass 500 GeV with SM-like coupling vertex, acquires a branching fraction of about 6%, reducing the  $\text{BR}(D \rightarrow hd) \times \text{BR}(D \rightarrow Wu)$  by 0.01 for  $m_D = 700 \text{ GeV}$ . A charged Higgs boson of again 500 GeV, with 2HDM-like couplings, would have to have an unrealistically large  $\tan\beta$  of  $10^5$  to further reduce the same BR again by 0.01 since the charged Higgs couplings are proportional to the masses of up type quarks. On the other hand, if the additional neutral Higgs boson has a lower mass, it could mix with the SM-like one and change the results presented above. In the case of a mass-degenerate light (120 GeV) Higgs bosons with both SM-like couplings the  $\text{BR}(D \rightarrow hd) \times \text{BR}(D \rightarrow Wu)$  is reduced by 0.02, affecting the final results minimally. If the mixing is such that the resulting states do not have SM-like couplings this analysis would have to be changed to replace  $D \rightarrow hd$  decay by  $D \rightarrow Zd$  as previously studied in [17].

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