

# The single production of the lightest $E_6$ isosinglet quark at the LHC

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## Abstract

We study the jet associated production of the new quarks predicted by the  $E_6$  GUT model at the LHC. Generator level considerations are made for different mass values of the lightest of the new quarks to investigate its discovery potential and the prospects for obtaining its mixing angle to the Standard Model quarks. We find that after  $100 \text{ fb}^{-1}$  of data taking, it is possible to discover the new quark with a significance more than  $5\sigma$  up to a mass of 1500 GeV. If no discovery is made, it is possible to constrain the mass vs quark mixing angle plane.

## 1 Introduction

One possible way to unify the electroweak and the strong forces is embedding the Standard Model (SM) into a larger symmetry group as the Grand Unified Theories (GUTs) suggest. One possible candidate, which is also favored as the low energy effective theory of super-strings, is the  $E_6$  model [1, 2]. The  $E_6$  model predicts a number of new particles, among which there is an isosinglet quark per SM family. The forthcoming LHC accelerator will be the place to search for the new colored objects in general and in particular for isosinglet quarks, if their masses are within the LHC kinematical range. The current experimental limit on the mass of an isosinglet quark with a  $-1/3$  electric charge is  $m > 199 \text{ GeV}$  [3]. The distinguishable feature of the isosinglet quarks is the existence of FCNCs at tree level as opposed to fourth SM family quarks. If a new quark is observed, this feature can be used to distinguish between different models. The pair production of the isosinglet quarks was previously studied for the Tevatron [4] and for the LHC [5]. The pair production cross section is practically independent of the mixing between the SM and the isosinglet quarks. This note addresses the discovery of the isosinglet quarks via their single production at the LHC and the measurements of the mixing angle between the new and the SM quarks.

## 2 The Model

We will denote the isosinglet quarks for the first, second, and the third SM families by letters  $D, S, B$ , respectively. In accordance with the SM fermion mass hierarchy, we assume that  $m_D < m_S < m_B$  and also that the intra-family mixing dominates the inter-family mixing. Further details of the model can be found in [5]. The mixing angle between the  $d$  and  $D$  quarks will be represented by the Greek letter  $\phi$ . Although the current limit on  $\phi$  is  $|\sin \phi| < 0.07$  [5], in this note we consider a more conservative value,  $\sin \phi = 0.045$ , for the calculation of the cross sections and decay widths. For other values, both of these two quantities can be scaled with a  $\sin^2 \phi$  dependence. The branching ratios are about 67 % for  $D \rightarrow W u$  and about 33 % for  $D \rightarrow Z d$ . If the masses of the SM quarks are generated by the Higgs mechanism, the branching ratios will be modified to incorporate also the  $D \rightarrow H d$  channel. For  $m_H \ll m_D$ , the branching ratios become 50 % for CC, 25 % for NC and 25% for the Higgs channel. Further study of the Higgs boson in the context of  $D$  quark decays is in preparation [6].

## 3 The Production at the LHC

We implemented the Lagrangian for the signal into a tree level Monte Carlo generator, CompHep v4.4.3 [7]. For both the signal and the background studies, the contributions from sea quarks were also considered. The parton distribution function utilized was CTEQ6L1 and the QCD scale was set to be the mass of the  $D$  quark for both signal and background processes.

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Figure 1: Cross section in single D production as a function of D quark mass for different  $\sin \phi$  values.

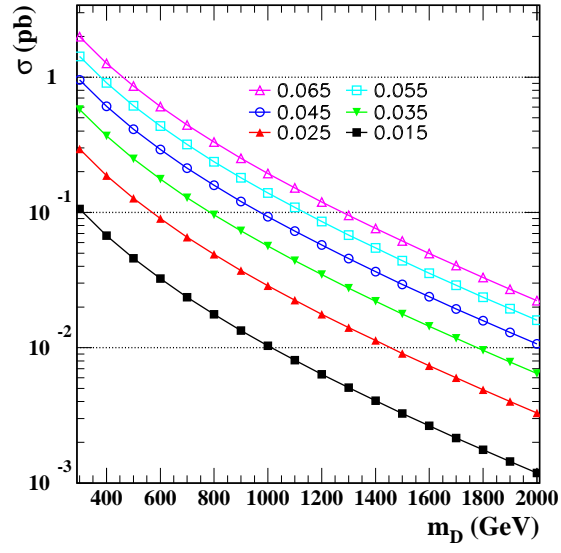


Figure 2: The main tree level signal processes

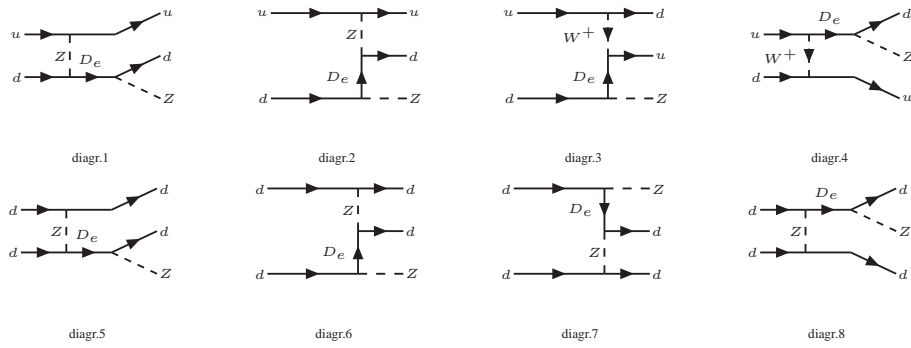
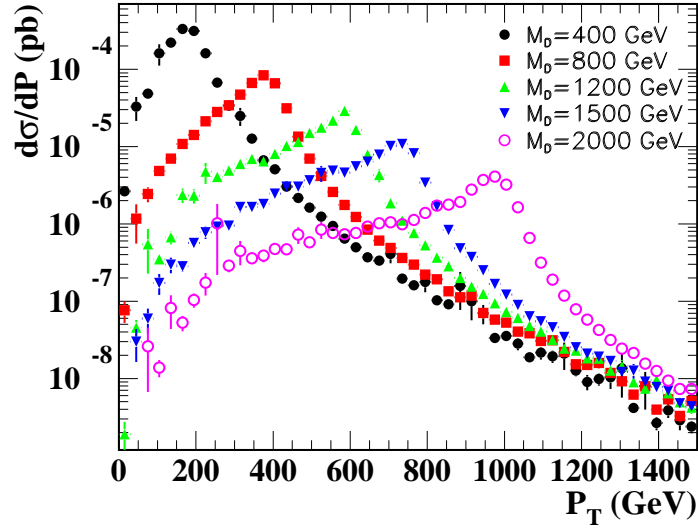


Figure 3: The transverse momentum distribution of the parton with the highest energy for the signal case.



The cross section for single production of the  $D$  quark for its mass up to 2 TeV and for various mixing angles is given in figure 1. The main tree level signal processes with their neutral current decays are given in figure 2. The remaining processes originating from the sea quarks contribute about 20 percent to the total signal cross section.

Although this note considered a generator level study, various parameters of the ATLAS detector [9] such as the barrel calorimeter geometrical acceptance, minimum angular distance for jet separation and minimum transverse momentum for jets[10] were taken into account. Four mass values (400, 800, 1200, 1500 and 2000 GeV) were studied to investigate the mass dependence of the discovery potential for this channel. The cuts common to all considered mass values are:

$$\begin{aligned}
 P_{T_p} &> 15 \text{ GeV} \\
 |\eta_p| &< 3.2 \\
 |\eta_Z| &< 3.2 \\
 R_p &> 0.4 \\
 M_{Zp} &= M_D \pm 20 \text{ GeV}
 \end{aligned}$$

where  $p$  stands for any parton;  $R$  is the cone separation angle between two partons;  $\eta_p$  and  $\eta_Z$  are pseudorapidities of a parton and  $Z$  boson respectively; and  $P_{T_p}$  is the parton transverse momentum. The main property that allows discriminating between the signal and the background is the transverse momentum distribution of the parton with the highest energy. In figure 3, the transverse momentum distributions of the partons that survive the common cuts are shown for the signal case. One can observe that the distribution peaks at about one half of the  $D$  quark mass value. The same distribution for the background is given in figure 4, which shows rapidly decreasing differential cross section as a function of parton  $P_T$  since the final state partons are originating directly from the initial partons.

### 3.1 The discovery potential

The results from the scanning of the signal significance for the hard jet  $P_T$  are given in figure 5 for  $D$  quark mass values under study. For each case, the optimal value is found by maximizing the significance ( $S/\sqrt{B}$ ) and it is used for calculating the effective cross sections presented in table 1. To obtain the actual number of events for each mass value, the  $e\bar{e}$  and  $\mu\bar{\mu}$  decays of the  $Z$  boson were considered for simplicity of reconstruction. Table 2 contains the expected number of reconstructed events for both signal and background for 100 fb<sup>-1</sup> of data taking. Although the lepton identification and reconstruction efficiencies are not considered, one can note that the statistical significance at  $m_D = 1500$  GeV, is above  $5\sigma$  after one year of nominal luminosity run.

Figure 4: The transverse momentum distribution of the parton with the highest energy for the background case.

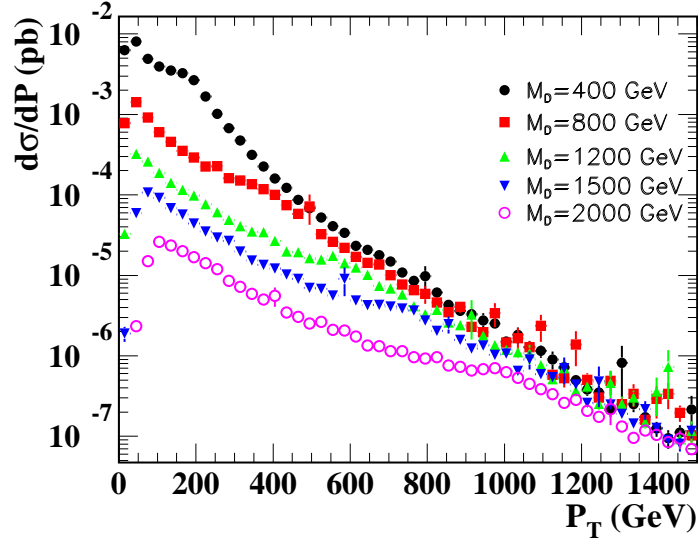


Figure 5: Dependence of the signal significance on hard jet  $P_T$  for different  $D$  quark mass values

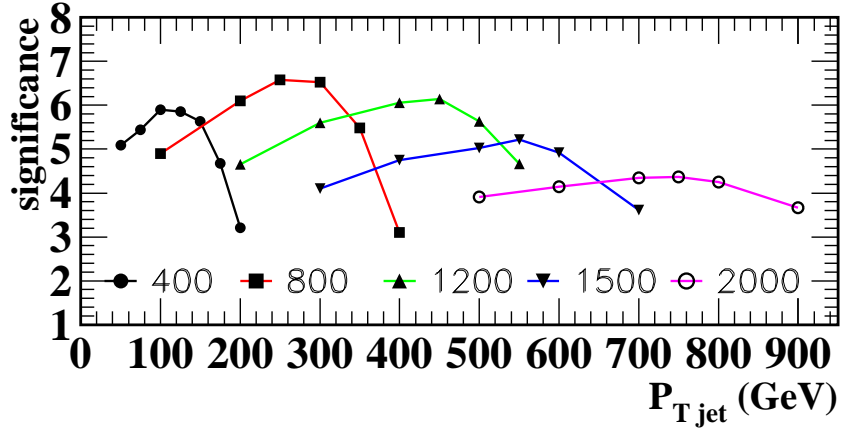


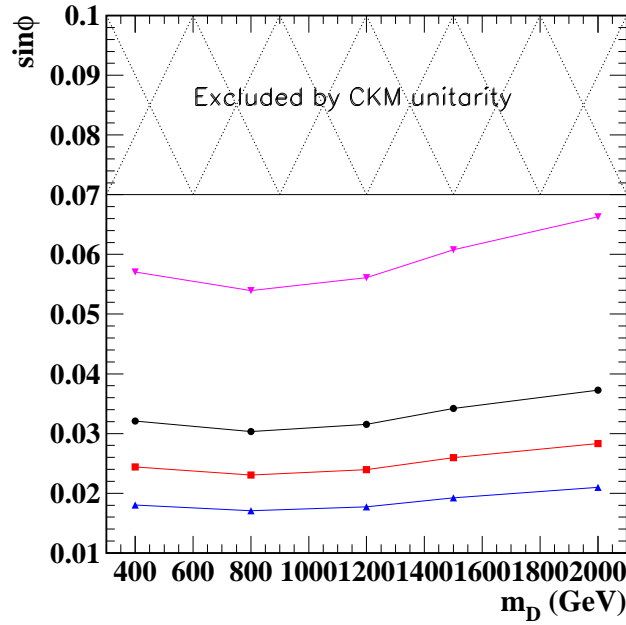
Table 1: The signal and background effective cross sections before the  $Z$  decay and after the optimal cuts, together with the  $D$  quark width in GeV for each considered mass.

$M_D(\text{GeV})$	400	800	1200	1500	2000
$\Gamma(\text{GeV})$	0.064	0.51	1.73	3.40	8.03
Signal (fb)	100.3	29.86	10.08	5.09	1.92
Background (fb)	2020	144	18.88	6.68	1.36
optimal $P_T$ cut	100	250	450	550	750

Table 2: Expected number of reconstructed events using electron and muon decays of the  $Z$  boson and signal significance for  $100 \text{ fb}^{-1}$  of data taking.

$M_D(\text{GeV})$	400	800	1200	1500	2000
Signal Events	702	209	71	36	13.5
Background Events	14000	1008	132	47	9.5
Signal significance	5.9	6.6	6.1	5.2	4.37

Figure 6:  $3\sigma$  exclusion curves for 10, 100, 300, 1000  $\text{fb}^{-1}$  integrated luminosities are shown from top to down.



### 3.2 Extracting the quark mixing angle

As mentioned before, the pair production cross section is almost independent of the  $D - d$  quarks mixing angle, therefore we will use the single production discovery results given in the previous section to investigate this angle. In the event of a discovery in the single production case, the mixing angle can be obtained directly. If no discoveries are made, then the limit on the cross section can be converted to a limit curve in the  $D$  quark mass vs mixing angle plane. Therefore we calculated the angular reach for a  $3\sigma$  signal by extrapolating to other  $\sin\phi$  values. Figure 6 gives the mixing angle versus  $D$ -quark mass plane and the  $3\sigma$  reach curves for different integrated luminosities ranging from  $10 \text{ fb}^{-1}$  to  $1000 \text{ fb}^{-1}$ , which correspond to one year of low luminosity LHC operation and one year of high luminosity super-LHC operation respectively. The hashed region in the same plot is excluded using the current values of the CKM matrix elements. One should note that, this channel allows reducing the current limit on  $\sin\phi$  by half in about  $100 \text{ fb}^{-1}$  run time.

## 4 The Results and Conclusions

The process of single production of the  $E_6$  isosinglet quarks could essentially enhance the discovery potential if  $\sin\phi$  exceeds 0.02. For example, with  $300 \text{ fb}^{-1}$  integrated luminosity, the  $3\sigma$  discovery limit is  $m_D = 2000 \text{ GeV}$ , if  $\sin\phi = 0.03$ . It should also be noted that for pair production the  $3\sigma$  discovery limit was found to be about 900 GeV, independent of  $\sin\phi$ . If ATLAS discovers an 800 GeV  $D$  quark via pair production, single production will give the opportunity to confirm the discovery and measure the mixing angle if  $\sin\phi > 0.03$ . The FCNC decay channel analyzed in this paper is specific for isosinglet down type quarks and gives the opportunity to distinguish it from other models also involving additional down type quarks, for example the fourth SM family. Therefore, the possible discovery of isosinglet quarks at the LHC would validate the  $E_6$  as a GUT group.

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