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BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 3, no. 2, 2009

Physics

ATLAS Sensitivity to the Flavour Changing Neutral Currents Decay $t \to Hq$ ($H \to b\bar{b}$)

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(Presented by Academy Member A. Khelashvili)

ABSTRACT. The sensitivity of the ATLAS detector to flavour changing neutral current (FCNC) rare decays of the top quark $t \to Hu(c) \to b\bar{b}j$ has been estimated at $\sqrt{s}$ =14 TeV, in $t\bar{t} \to HqWb \to bbj, l^{\pm}\nu b, (l=e, \mu)$ events. The Standard Model backgrounds $t\bar{t}$, $\overline{ttH}$, $W + jets$, WZ, WH and $W\, b\bar{b}$ have been considered. The FCNC branching ratio sensitivities (assuming a 5σ signal significance) with LHC integrated luminosity of 10 fb^{-1} (100 fb^{-1}) have been obtained.

Key words: *ATLAS, LHC, Higgs, top quark.*

I. Introduction

This paper is devoted to the study of the ATLAS experiment [1] sensitivity to top quark flavour changing neutral currents (FCNC) rare decay mode $t \to Hq$ (where q represents c and u quarks), and H is the Standard Model (SM) Higgs boson (m_t = 175 GeV/c^2, m_H = 120 GeV/c^2).

In the framework of the Standard Model, the loop suppression and heaviness of gauge bosons make this process extremely rare. The SM prediction for the branching ratio is of order Br ($t \to H_{SM}q$) ~ $0.9 \cdot 10^{-13}$ (4.10^{-15}) for m_H = 100(160) GeV/c^2 [2]. Thus, an observation of this decay mode at the Large Hadron Collider (LHC), would provide a clear signal of new physics beyond the SM, such as new dynamical interactions of top quark, multi-Higgs doublets, exotic fermions or other possibilities [3-10].

The LHC will operate with a center-of-mass energy of 14 TeV, and in the low luminosity phase ($L = 10^{33}$ cm^{-2} s^{-1}) several millions of top quarks will be produced per year due to the dominant mechanism for $t\bar{t}$ pair production at the LHC via gg, $q\bar{q}$ strong interactions. If the SM Higgs boson exists with a mass in the vicinity of its experimental upper limit of 114.4 GeV/c^2 [11], as indicated by the electroweak precision fits, its decay products consist of a $b\bar{b}$ pair about 70% of the time.

For the different decay channels of Higgs : $H \to \gamma\gamma$, $H \to$, $H \to ZZ^*$, $H \to WW^*$ the sensitivity of ATLAS experiment has been estimated, requiring at least five signal events and assuming no backgrounds at high luminosity L= 100 fb^{-1}, 100 % signal efficiency and lepton identification efficiency ε^l = 0.9.

It has been shown that even if there are no backgrounds, the processes with $H \to \gamma\gamma$ and $H \to ZZ^*$ decays will be less promising than with $H \to b\bar{b}$ and $H \to cWW^*$ [12]. Unfortunately the extraction of a signal $t \to H \to b\bar{b}$ decays will be very difficult at LHC due to large backgrounds [13], nevertheless, it has been supposed that the backgrounds, in the case of additional cuts such as the requirement of three *b*-tagged jets and reconstruction of $b\bar{b}j$ invariant mass for $t \to Hq \to b\bar{b}j$ decays, can be reduced. The analysis presented here focuses on the following final state topology of $t\bar{t} \to HqWb \to b\bar{b}j, l^{\pm}\nu b$, ($l=e, \mu$) events.

II. Monte Carlo Event Generation

In the framework of ATLAS experiment software Athena release 12.0.6 [14], the generator Pythia (6.401) [15] was set up to produce $t\bar{t}$ events at $\sqrt{s}$ = 14 TeV, m_t = 175 GeV/c^2 and m_H = 120 GeV/c^2, with proton structure function CTEQ6L. Initial and final state QED and QCD (ISR, FSR) radiation, multiple interactions, fragmentations and decays of unstable particles were enabled.

The decay of the $t \to Hq$ is not implemented in the standard release of Pythia. To include this process in Pythia, all individual decay channels of the top quark were first switched off, except for $t \to Wb$ and $t \to Ws$. Replacing *W* by *H* and *s* by *c*(*u*) the channel $t \to Ws$ was completely replaced by the decay of the $t \to Hq$. The total NLO cross-section σ for production was assumed to be σ = 833pb [16,17].

For the generation of Standard Model backgrounds $t\bar{t}$, $t\bar{t}H$, *W+jets, WZ, WH* and $Wb\bar{b}$ Pythia 6.401, HERWIG 6.5 [18], TopReX 4.11 [19] generators in the Athena (12.0.6) environment have been used.

The performance of the ATLAS detector was simulated using the fast simulation package ATLFAST [20] in the Athena environment, which uses parametrizations of the detector resolution functions.

III. Event Analysis

We have studied the rare top quark decays via FCNC $t \to Hq$ using simulated LHC data of 80 000 $t\bar{t}$ events, where one of the top quarks is assumed to decay through its dominant decay mode ($t \to Wb$), while the other top quark decays via the FCNC mode $t \to Hq$. Due to the large QCD backgrounds, it is very difficult to search for FCNC signal using mode where *W* decays hadronically. Due to this reason, only leptonic decay of *W* was taken into account.

Thus the experimental signature of $t\bar{t} \to HqWb \to b\bar{b}j$, $l^{\pm}\nu b$, ($l=e, \mu$) events includes one isolated charged lepton (electron or muon), three *b*-jets, missing transverse momentum due to the neutrino and additional one light jet.

Table 1.

The number of events and efficiencies (%) of kinematic cuts applied in sequence for the signal and backgrounds for high luminosity L=100 fb$^{-1.}$ The number of events after cuts for the backgrounds is presented according to the expected events.

Description of Cuts	$t \to Hq$ Signal		Background Processes			
			$t\bar{t}$		$t\bar{t}H$	
	Number of events	Eff (%)	Number of events	Eff (%)	Number of events	Eff (%)
Number of generated events	80 000		300 000		100 000	
Number of expected events			$24.3 \cdot 10^6$		12314	
Three b-tag jets $p_{T\text{b-jet}} > 40$GeV/c $\lvert\eta_{\text{jet}}\rvert < 2.5$	2581	3.23	128790	0.53	279	2.27
One light jet with $p_{T\text{jet}} > 40$ GeV/c $\lvert\eta_{\text{jet}}\rvert < 2.5$ One lepton with $p_{Tl} > 20$ GeV/c $\lvert\eta_{\text{lept}}\rvert < 2.5$	1292	161	60750	0.25	162	1.31
$p_T^{\text{miss}} > 30$ GeV/c $m_{H(bb)} \pm 40$ GeV/c^2 $m_{t(bb\bar{j})} \pm 32$ GeV/c^2 $m_{t(l\nu b)} \pm 24$ GeV/c^2	472	0.59	19440	0.08	36	0.29

Table 2.

The number of events and efficiencies (%) of kinematic cuts applied in sequence for the signal and backgrounds for high luminosity L=100 fb^{-1}. The number of events after cuts for the backgrounds is presented according to the expected events.

Description of Cuts	$t \to Hq$ Signal		Background Processes			
			WH		*WZ*	
	Number of events	Eff (%)	Number of events	Eff (%)	Number of events	Eff (%)
Number of generated events	80 000		60 000		100 000	
Number of expected events			19 000		88 282	
Three b-tag jets $p_{T\,b\text{-jet}}$ > 40 GeV/c $\lvert\eta_{\text{jet}}\rvert$ < 2.5	2581	3.226	10	0.053	15	0.017
One light jet $p_{T\,\text{jet}}$ > 40 GeV/c $\lvert\eta_{\text{jet}}\rvert$ <2.5 One lepton p_{Tl} > 20 GeV/c $\lvert\eta_{\text{lept}}\rvert$ <2.5	1292	1.615	3	0.016	6	0.007
p_T^{miss} > 30 GeV/c $m_{H(bb)} \pm 40$ GeV/c^2 $m_{t(bbj)} \pm 32$ GeV/c^2 $m_{t(l\nu b)} \pm 24$ GeV/c^2	472	0.590	0	0.002	0	0

The following final topologies of the SM background processes: $WZ \to l^{\pm}\nu\ b\bar{b} + X$, W+$jets \to l^{\pm}\nu$+jets, $t\bar{t} \to WbWb \to l^{\pm}\nu b\, l^{\pm}\nu b + 2\, l^{\pm}\nu b\, jjb$, $WH \to l^{\pm}\nu\ b\bar{b} + X$, $t\bar{t}H \to WbWbH \to l^{+}\nu b l^{\pm}\nu b\ b\bar{b} + 2\, l^{\pm}\nu b\, jjb$ (l=e,μ) were considered.

Branching Ratios of $H \to b\bar{b}$ decays have been calculated by the FORTRAN code HDECAY [21] Br($H \to b\bar{b}$) = 0.6773 for m_H=120 GeV/c^2.

The cut-based analyses have been carried out in order to estimate the branching ratio (BR) sensitivity for $t \to Hq$ decay. The set of selection cuts have been applied in sequence for the signal and backgrounds.

Tables 1 and 2 summarize the effects of the sequential application of the various analysis cuts on the background samples and on the sample of signal events.

The requirement of four jets reduces significantly *WZ*, *WH*, *Wbb* and *W* + jets backgrounds.The most effective cut to reduce all backgrounds is a requirement of the presence of exactly three b-jets within the acceptance region of transverse momentum $p_{T\,b\text{-jet}}$ > 40 GeV/c and pseudorapidity $|\eta_{\text{jet}}|$ < 2.5. This requirement reduces the signal and $t\bar{t}\,\boldsymbol{H}$ background up to 3.23% and 2.27% respectively. Next, it was demanded that there be at least one light jet with $p_{T\,\text{jet}}$ > 40 GeV/c, $|\eta_{\text{jet}}|$ < 2.5 and one isolated, charged lepton (electron or muon) with p_{Tl} > 20 GeV/c, $|\eta_{\text{lept}}|$ < 2.5. The last requirement gives variation of relative acceptance for the signal and backgrounds in the range 0.63-0.75.

Despite the presence of neutrinos in all processes the requirement of missing transverse momentum cut p_T > 30 GeV/c is effective at further reducing the backgrounds while having little impact on the signal.

The requirement of the presence of exactly three b-jets with $p_{T\,b\text{-jet}}$ > 40 GeV/c, two of which reconstruct

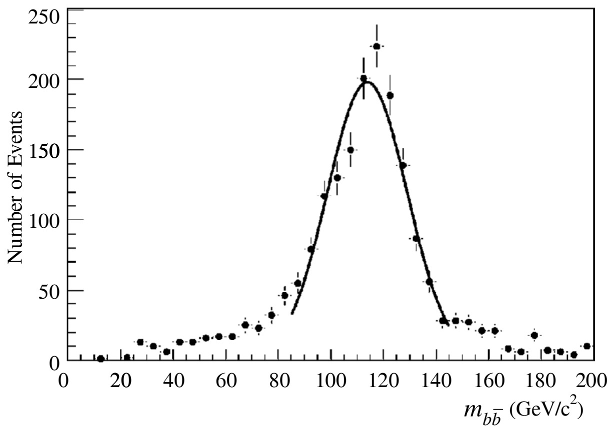

Fig. 1. Distribution of reconstructed invariant mass of the $b\bar{b}$ pairs, $m_{b\bar{b}}$, for all b-jets best combinations.

$b\bar{b}$ invariant mass within the $m_H \pm 40$ GeV/c^2 mass window (~ 2σ), is a powerful cut against all backgrounds.

The distribution of invariant mass $m_{b\bar{b}}$ for signal events is shown in Fig.1 for a Higgs boson mass of 120 GeV/c^2 at high luminosity. The Higgs-boson mass is reconstructed with a resolution of $\sigma(m_{b\bar{b}}) = 15.14$ GeV/c^2.

Finally, a peak at the top quark mass in the $b\bar{b}j$ invariant mass distribution was sought. In Fig. 2, the distribution of reconstructed invariant mass $m_{b\bar{b}j}$ for best combinations of $b\bar{b}j$ is presented for the signal events. The top quark mass resolution is $\sigma(m_{b\bar{b}j}) = 15.5$ GeV/c^2. Accepted combinations were required to lie within a window around the known top quark mass: $m_t \pm 32$ GeV/c^2 (~2σ).

The top quark with Standard Model semileptonic decay ($t \to bl\nu$) cannot be directly reconstructed due to the presence of an undetected neutrino in the final state. The neutrino four-momentum was estimated using the missing transverse energy and allowing the p_Z^{ν} value in the range (-500 ÷ +500) GeV/c.

To suppress the backgrounds, it was necessary to use the information that signal events contain, in addition to the decay $t \to Hq$, the semileptonic decay $t \to Wb \to l\nu b_{jet}$ of the other top quark. The semileptonic top quark decay was reconstructed as part of the signal requirement. First W invariant mass was reconstructed. Then the requirement was made to have one jet tagged as b-jet. Finally $l\nu b_{jet}$ invariant mass was required to lie within 24 GeV/c^2 (~ 2σ) around m_t. Figure 3 presents the distribution of the reconstructed invariant top mass ($m_{l\nu b}$) for the best combinations of $l\nu b_{jet}$ for the signal. The top mass resolution is $\sigma(m_{l\nu b})$=14.8 GeV/c^2.

The full event reconstruction was performed using a χ^2, defined by

$$\chi^2 = \frac{\left(m_{b\bar{b}j} - m_t\right)^2}{\sigma_t^{\,2}} + \frac{\left(m_{l\nu b} - m_t\right)^2}{\sigma_t^{\,2}} + \frac{\left(m_{l\nu} - m_W\right)^2}{\sigma_W^{\,2}},$$

where $m_{b\bar{b}j}$, $m_{l\nu b}$, $m_{l\nu}$ are, for each jet and lepton combination, the reconstructed mass of the top quark decaying via FCNC, the top quark decaying through Standard Model and the W boson from the top quark with Standard Model decay, respectively. The following values are used for the constraints: m_t = 175 GeV/c^2, m_W = 80.42GeV/c^2, m_H = 120 GeV/c^2, σ_t = 15 GeV/c^2, σ_W = 10 GeV/c^2. The b-tag information was used to reconstruct the event kinematics.

As summarized in Tables 1 and 2, the final signal efficiency is 0.59% for Pythia/Atlfast chain after applying the above mentioned cuts in sequence for the signal and backgrounds. The top mass windows remove almost completely the WH, WZ and W+jets backgrounds. The most dangerous background is $t\bar{t}$ process, as after applying all cuts and taking into account lepton identification efficiency about 17345 events remain. Table 3 summarizes the Branching ratios for the FCNC $t \to Hq$ decay. The sensitivities to BR($t \to Hq$) have been calculated similarly as in [12, 22, 23].

Assuming a signal discovery with a 5σ significance, the branching ratio (BR) sensitivity for the studied FCNC decay of $t \to Hq$ is estimated by:

$$BR = \frac{5\sqrt{B\varepsilon_l}}{2L\sigma(t\bar{t}_{sm})\,\varepsilon_t\varepsilon_l},$$

where $\sigma(t\bar{t}_{sm})$ is the NLO calculation of the SM cross-section for $t\bar{t}$ production in pp collisions at $\sqrt{s}$ =14 TeV. B is the total number of selected background events, ε_t is the signal efficiency convoluted with the appropriate branching ratios and ε_l =0.9 is the charged lepton

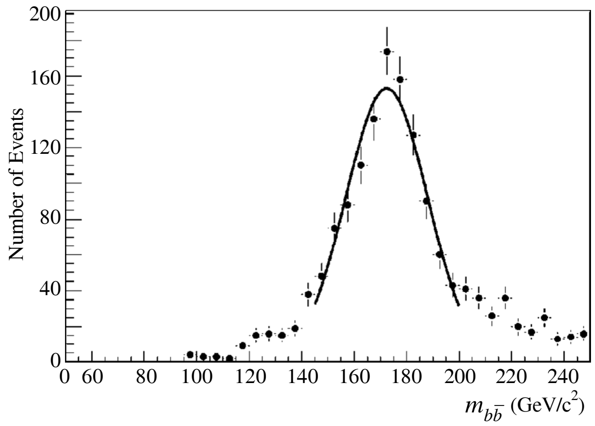

Fig. 2. Invariant $b\bar{b}j$ mass distribution for the FCNC decay of $t \to Hq \to b\bar{b}j$.

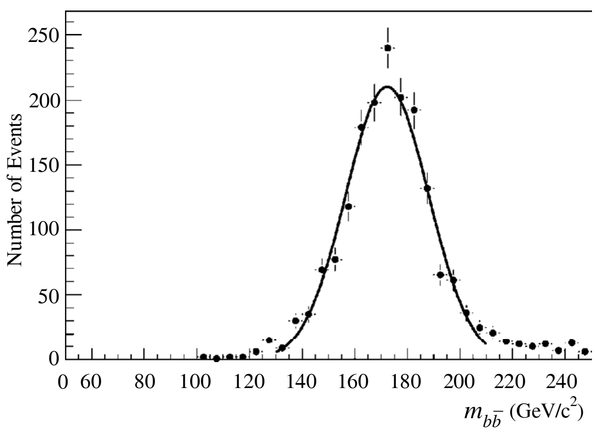

Fig. 3. Invariant $l\nu b_{jet}$ mass distribution for the decay of $t \to Wq \to l\nu b_{jet}$.

Table 3.

The branching ratio sensitivity in the 5σ discovery hypothesis.

Channel	Analysis type	Generation/Simulation	BR(L=10 fb^{-1})	BR(L=100 fb^{-1})
$t \rightarrow Hq$	cut-based	Pythia/Atlfast	1.45 x 10^{-2}	4.58 x 10^{-3}

identification efficiency. The factor 2 in the denominator takes into account the t and $\bar{t}$ contributions to the BR. To evaluate the expected branching ratio sensitivities for a 5σ signal significance of discovery in the cut-based analysis, the kinematic cuts were applied in sequence for the signal and backgrounds. The expected branching ratio sensitivities for a 5σ discovery are shown in Table 3.

One can see from Table 3 that Br ($t \rightarrow Hq \rightarrow b\bar{b}j$) as low as 1.45 x 10^{-2} could be discovered at the 5σ level with an integrated luminosity of L=10 fb^{-1} and as low as 4.58x10^{-3} with an integrated luminosity of L=100 fb^{-1}.

IV Conclusion

We have performed a study of Branching ratio sensitivity of ATLAS experiment to the rare top quark decays via FCNC $t \rightarrow Hq$ (m_H = 120 GeV/c^2, m_t = 175 GeV/c^2) at $\sqrt{s}$ = 14 TeV using simulated LHC data of $t\bar{t}$ events where one of the top quarks is assumed to decay through its dominant SM decay mode ($t \rightarrow Wb$), while the other top quark decays via the FCNC mode $t \rightarrow Hq$. Due to the large QCD backgrounds, only leptonic decay of W was taken into account $t\bar{t} \rightarrow HqWb \rightarrow b\bar{b}j, l^{\pm}\nu b$ ($l=e, \nu$).

The results demonstrate that a branching ratio as low as 1.45x10^{-2} (4.5x10^{-3}) could be discovered at the 5σ level with an integrated luminosity of 10 fb^{-1} (100 fb^{-1}).

Acknowledgements

We are thankful to J.Parsons, M.Cobal, E.Richter-Wass, V.Kartvelishvili, G.Khoriauli and S.Slabospitsky for the very interesting and important discussions. This work was supported partially by GNSF grant 185 and ISTC grant G-1458.

ფიზიკა

“ATLAS” ექსპერიმენტის მგრძნობიარობა არომატის შემცვლელი ნეიტრალური დენებით მიმდინარე იშვიათი დაშლის $t \rightarrow Hq$ $(H \rightarrow b\bar{b})$ მიმართ

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** ი. ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტის მაღალი ენერგიების ფიზიკის ინსტიტუტი

(წარმოდგენილია აკადემიის წევრის ა.ხელაშვილის მიერ)

ნაშრომში განხილულია დიდი ადრონული კოლაიდერის “ATLAS” ექსპერიმენტის მგრძნობიარობა არომატის შემცვლელი ნეიტრალური დენებით მიმდინარე ტოპ კვარკის იშვიათი დაშლის მიმართ $t \rightarrow Hq$

($H \to b\bar{b}$) სტანდარტული მოდელის ჰიგსის მასისათვის $m_H = 120$ გევ/c^2, როცა ურთიერთქმედების ენერგია მასათა ცენტრის სისტემაში $\sqrt{s} = 14$ ტევ და ინტეგრალური ნათება არის 10 ფბ$^{-1}$, 100 ფბ$^{-1}$.

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Received February, 2009