საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 5, №1, 2011
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 5, no. 1, 2011

Physics

ATLAS Experiment Sensitivity to FCNC Top Quark Rare Decay $t \rightarrow Zq$ at $\sqrt{s} = 10$ TeV

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ABSTRACT. The sensitivity of the ATLAS detector to flavour changing neutral current (FCNC) rare decays of the top quark $t \rightarrow Zu(c) \rightarrow l^+l^- j$ in $t\bar{t}$ pair production events at a center-of-mass collision energy of $\sqrt{s} = 10$ TeV was studied within the framework of ATLAS software Athena. The full simulation Monte Carlo samples of the signal and backgrounds have been used for the analysis. The Standard Model backgrounds $t\bar{t}$, W+*jets, Z+jets, WZ, WW, ZZ,* $Wb\bar{b}$ and single top have been considered. The results obtained by the cut-based analysis are presented within two different approaches: the FCNC branching ratio sensitivities (assuming a 5σ signal significance for discovery) and 95% confidence level upper limits (in the hypothesis of signal absence) for the integrated luminosities L=1 and 10 fb^{-1}.

The results demonstrate that in ATLAS experiment a branching ratio Br (t→ Zq→llq) as low as 1.1 x 10^{-2}, 3.6 x 10^{-3} could be discovered at energy of $\sqrt{s} = 10$ TeV at the 5σ level for the LHC integrated luminosities of L=1fb^{-1} and 10 fb^{-1}, respectively. If no signal evidence is found, the following 95% confidence level upper limits on the branching ratio are expected: 3.11 x 10^{-3}, 2.57 x 10^{-4} for the integrated luminosities of L=1 and 10 fb^{-1}, respectively. *© 2011 Bull. Georg. Natl. Acad. Sci.*

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

The paper reviews the study of the ATLAS experiment [1] sensitivity to the flavor changing neutral current (FCNC) top quark rare decays, t → qZ (where q represents c and u quarks), in tt events produced at the LHC at CERN.

The LHC will be a top quark factory, producing millions of $t\bar{t}$ pairs in a sample of 10 fb^{-1}, which is expected to be collected during the first years of LHC operation, making the LHC an ideal place to explore rare decays of top quark. The reason for the interest in top quark rare decays via FCNC is at least twofold. First, these decays are strongly suppressed in the Standard Model (SM) at tree level due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [2]. Although absent at tree level, small FCNC contributions are expected at one-loop level, determined by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [3-6] and the typical branching ratios for the rare top quark FCNC decays predicted within the SM are so small (Br(t → Zc) ~1.3×10^{-17}), Br(t→Zu) ~1.3×10^{-14}) [7,8], that the observation of several events of this decay would provide a clear signal of new physics beyond the SM, like supersymmetry (SUSY) [9], multi-Higgs doublets [10] and models with exotic (vector-like) quarks [11-13], which have predicted the presence of FCNC contributions already at tree level and significantly enhanced the FCNC decay branching ratios (up ~10^{-5}, 10^{-4}) compared to the SM predictions. Second, due to its large mass (m_t = 175 GeV) top quark could play a momentous role in the search for Higgs physics beyond the SM.

FCNC t → Zq decays have been studied at colliders and the followng experimentally observed upper limits on the branching ratios at 95% confidence level (C.L.) from the direct searches have been derived: 7.8%, 49% and 3.7% for LEP [14-17], HERA[18] and Tevatron [19] experiments, respectively.

The analysis presented here focuses on the following final state topology of $t\bar{t} \to ZqWb \to l^- l^+ j, l^\pm \nu b$, $(l = e, \mu; q = c, u)$ events.

Event samples

The signal event samples $t\bar{t} \to ZqWb \to l^- l^+ q, l^\pm \nu b$, (where q = c, u and l = e, μ.) and backgrounds events ($t\bar{t}$, *W+jets*, $Wb\bar{b}$, *Z+jets*, diboson (*WW, WZ, ZZ*), single top quark production) have been produced within the framework of the different versions of ATLAS software Athena 14, 15 at energy of $\sqrt{s} = 10$ and obtained by full simulation steps (generation, simulation, digitalization, reconstruction, Analysis Object Data (AOD) creation).

For the generation of signal events the TopReX [20] package has been used. The hadronisation was handled by PYTHIA [21]. Background events coming from *W+n* partons and $Wb\bar{b} + n$ partons were generated with AlpGen 2.06 [22] interfaced with HERWIG 6.510 [23].

Generation of SM $t\bar{t}$ events (fully hadronic and fully leptonic) was done using the NLO generator MC@NLO 3.1 [24]. Partons were fragmented and hadronized using HERWIG linked with the multiple parton scattering generator JIMMY [25,26]. The AcerMC generator [27] was also used to generate semi-leptonic $t\bar{t}$. The AcerMC was interfaced with Pythia. The *Z+jets* events were generated using the AlpGen library interfaced with HERWIG and JIMMY generators. Only the $Z \to l^+ + l^-$ (electrons and muons with $p_T > 10$ GeV and taus with $p_T > 5$ GeV) decays were considered.

The generator AlpGen interfaced with HERWIG was used to generate diboson (*WZ, ZZ, WW*) pairs events with at least one true electron or a muon with $p_T > 10$ GeV.

The three channels of the single top quark production were generated with AcerMC. The *t*-channel was generated by combining LO and NLO diagrams, while the *s* and the *Wt* channels were generated at LO. Only the leptonic decays of the W bosons ($W \to e\nu_e, \mu\nu_\mu, \tau\nu_\tau$) were allowed, except in the *Wt* channel, where one of the W bosons was forced to decay hadronically and the other one to decay leptonically. The hadronisation was done by PYTHIA. TAUOLA and PHOTOS [28] were used to process τ decays and radiative corrections. A top quark mass of 172.5 GeV was assumed for all processes.

The CTEQ 6L PDF [29] was used for all events, except those generated with MC@NLO, where CTEQ 6M was used. Initial and final state QED and QCD radiation, and multiple interactions were simulated in agreement with Tevatron data extrapolated to LHC. No pile-up events were added. Only the samples of $t\bar{t}$ (with at least one lepton) and single top events generated by AcerMC were produced with pile-up.

A detailed GEANT4 simulation of the detector was used.

Event Analysis

We have studied the rare top quark decays via FCNC t→Zq using simulated LHC data of 40 000 $t\bar{t}$ events, where one of the top quarks is assumed to decay through its dominant SM decay mode (t→Wb), while the other top quark decays via the FCNC mode t → Zq. Due to the large QCD background, it is very difficult to search for FCNC signal using a mode where W decays hadronically. Due to this reason, only leptonic decay of W was taken into account.

Thus the experimental signature of $t\bar{t} \to ZqWb \to l^+ l^- j, l^\pm \nu b$, $(l=e, \mu)$ events is three isolated leptons (electrons or muons) separated by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} > 0.4$ from other objects, missing transverse energy E_t (comes from the neutrino), one jet tagged as b-jet and one jet tagged as light jet.

The following final topologies of the SM background processes were considered: WZ → $l^\pm$ ν, l^+l^- +X, WW → $l^\pm$ ν, $l^\pm$ ν +X, ZZ → l^+l^-, l^+l^- +X, *W+jets*→$l^\pm\nu$+jets, W$b\bar{b}$ → $l^\pm$ ν, $b\bar{b}$ +X, *Z+jets* l^+l^- + jets, $t\bar{t} \to WbWb \to$ $l^\pm \nu b$, $l^\pm$ νb+ 2 $l^\pm$ νb,jjb, $(l=e, \mu)$.

The cut-based analysis has been carried out in order to estimate the branching ratio (BR) sensitivity for *t*→Zq decay. A set of the following selection cuts have been applied in sequence for the signal and backgrounds:

- The preselection cut required the presence of 3 isolated leptons (electrons or muons), one light jet (from u, or c quarks) and one b-tagged jet (from b quark). The requirement of three leptons reduces significantly the Z+jets, W+jets, $Wb\bar{b}$, $Wc\bar{c}$ and $t\bar{t}$ backgrounds, while the requirement of two jets reduces significantly diboson (WZ, ZZ, WW) backgrounds.

- For leptons p_T^l>30 GeV/c has been required.
- The next requirement, namely that the missing transverse momentum in the event satisfies p_T^{miss}>30 GeV/c, is effective at further reducing the *Z+jets* background while having little impact on the signal and other background sources.
- Next, it was demanded that there must be at least two jets with p_T^{jet} > 40 GeV/c, $|\eta_{jet}| < 2.5$, and satisfying the following isolation conditions: ΔR_{jj} > 0.4 (jet-jet) isolation.
- The presence of a reconstructed $Z \to l^+l^-$ decay is a powerful cut against the $t\bar{t}$ background. An opposite sign and same-flavour pair of isolated leptons were required to reconstruct the Z mass within $m_Z \pm 6$ GeV/c^2.
- A peak at the top quark mass in the *Zj* invariant mass distribution was sought. In Fig the distribution of reconstructed invariant mass m_{llj} for the best combinations of *llj* is presented for full simulation samples. The top quark mass resolution is $\sigma(m_{llj}) = 11$ GeV/c^2 for full simulation samples. Accepted combinations were required to lie within ± 24 GeV/c^2 (~ 2σ) around the known top quark mass fast simulation samples.
- The leptonic top quark decay was reconstructed as part of the signal requirement. First the *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 (~ 1σ) around m_t. The top mass resolution is $\sigma(m_{l\nu b}) = 24$ GeV/c^2.

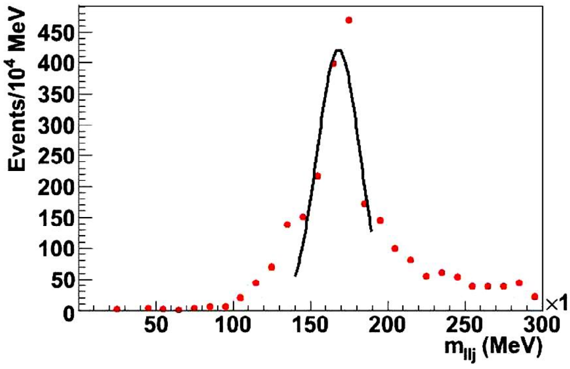

Fig. Reconstructed invariant mass of $t \to Zq \to llj$ for the best combinations of llj for m_{top} = 172.5 GeV/c^2.

The top quark with Standard Model semileptonic decay ($t \to l\nu b$) cannot be directly reconstructed due to the presence of an undetected neutrino in the final state. Nevertheless, the neutrino four-momentum can be estimated by assuming the missing transverse energy to be the neutrino transverse momentum. The longitudinal component (p_Z^ν) can be determined, with a quadratic ambiguity, by constraining the *W* mass (calculated as the invariant mass of the neutrino and the most energetic remaining lepton) to its known central value $m_W = 80.4$ GeV.

The following χ^2 expression has been estimated for each event with requirement of its minimization:

$$\chi^2 = \frac{(m_{llj} - m_t)^2}{\sigma_t^2} + \frac{(m_{l\nu b} - m_t)^2}{\sigma_t^2} + \frac{(m_{l\nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{ll} - m_Z)^2}{\sigma_Z^2}$$

where $m_{llj}, m_{l\nu b}, m_{l\nu}, m_{ll}$ are the reconstructed mass of the top quark decaying via FCNC, the top quark mass decaying through Standard Model, the *W* boson mass from the top quark Standard Model decay and the *Z* boson mass from the top quark FCNC decay, respectively. The following values are used for the constraints: m_W= 80.42 GeV, m_Z= 91.19 GeV, σ_t = 14 GeV, σ_W= 10 GeV, σ_Z= 3 GeV, m_t= 172.5 GeV.

The final signal efficiency is 6.73% after applying the above-mentioned cuts in sequence for the signal and backgrounds. The most dangerous background is $t\bar{t}$ process.

Assuming a signal discovery with a 5σ significance, the branching ratio (BR) sensitivities to FCNC decay of t→Zq for integrated luminosities L=1 and 10 fb^{-1}1 have been estimated. In this estimation the SM cross-section for $t\bar{t}$ production in *pp* collisions at $\sqrt{s}$ = 10 TeV for m_{top} = 172.5GeV/c^2, $\sigma(t\bar{t}_{SM}) = 401.60$ pb (the NLO+NLL calculation) and the charged lepton identification efficiency $\varepsilon_l = 0.9$ have been considered. The expected branching ratio sensitivities for a 5σ discovery for different luminosities are shown in Table.

In the hypothesis of a FCNC top quark decay signal absence, the expected upper limits at 95% confidence level have been estimated. The results are presented in Table. One can see, that Br (t→Zq→llq) as low as 1.1 x 10^{-2}, 3.6 x 10^{-3} could be discovered at energy of $\sqrt{s}$ = 10 TeV in the center mass system at the 5σ level, assuming m_{top} = 172.5 GeV/c^2, for the integrated luminosities of L=1 and 10 fb^{-1}, respectively. If no signal evidence is found, the following 95% confidence level limits on the branching ratio are

Table

The expected branching ratio sensitivities to the FCNC top quark rare decay for a 5σ discovery and the expected 95% CL limits on the FCNC top quark decay branching ratio, in the hypothesis of signal absence.

Channel	Energy (cms)	BR(L=1 fb^{-1})	BR(L=10 fb^{-1})
$t \to Zq \to llq$ 95%C.L. limits for BR	$\sqrt{s}$ =10 (TeV) $\sqrt{s}$ =10 (TeV)	1.1×10^{-2} 3.11×10^{-3}	3.6×10^{-3} 2.57×10^{-4}

expected: 3.11×10^{-3}, 2.57×10^{-4} for the integrated luminosities of L=1 and 10 fb^{-1}, respectively.

Conclusion

The sensitivity of the ATLAS experiment to the FCNC rare decays of the top quark in the tt^{-} pair production events $t\bar{t} \to ZqWb \to l^-l^+j, l^{\pm}\nu b, (l = e, \mu; q = c, u)$ at a center-of-mass collision energy of $\sqrt{s} = 10$ TeV was estimated using the full simulation Monte Carlo samples of the signal and backgrounds. The cut-based analysis was used to obtain the FCNC branching ratio sensitivities (assuming a 5σ signal significance for discovery) for the integrated luminosities L=1 and 10 fb^{-1}. The results demonstrate that, a branching ratio Br ($t\to Zq\to llq$) as low as 1.1×10^{-2}, 3.6×10^{-3}, could be discovered at a center of mass system energy of $\sqrt{s} = 10$ TeV at the 5σ level, assuming $m_{top} = 172.5$ GeV/c^2, for the integrated luminosities of L=1, and 10 fb^{-1}, respectively. If no signal evidence is found, the following 95% confidence level upper limits on the branching are expected: 3.11×10^{-3}, 2.57×10^{-4} for the integrated luminosities of L=1 and 10 fb^{-1}, respectively.

Acknowledgements. We are thankful to Prof. A.Onofre, Dr. F.Veloso, Prof. J.Carvalho, Dr. N.Castro, Prof. V.Kartvelishvili, and Dr. G. Khoriauli for the very interesting and useful discussions. This work was supported partly by GNSF grant G-185 and ISTC grant G-1458.

ფიზიკა

“ATLAS” ექსპერიმენტის მგრძნობიარობა არომატის შემცვლელი ნეიტრალური დენებით მიმდინარე ტოპ კვარკის იშვიათი დაშლის $t\to Zq$ მიმართ ენერგიისათვის $\sqrt{s} = 10$ TeV

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(წარმოდგენილია აკადემიკოს ა. ხელაშვილის მიერ)

ნაშრომში განხილულია დიდი ადრონული კოლაიდერის “ATLAS” ექსპერიმენტის მგრძნობიარობა არომატის შემცვლელი ნეიტრალური დენებით მიმდინარე ტოპ კვარკის იშვიათი დაშლის მიმართ $t\to Zq\to l^+l^-j$, როცა ურთიერთქმედების ენერგია მასათა ცენტრის სისტემაში $\sqrt{s} = 10$ ტევია, ხოლო კოლაიდერის ინტეგრალური ნათება არის 1 ფბ$^{-1}$ და 10 ფბ$^{-1}$.

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Received September, 2010