PHYSICAL REVIEW D **77,** 116011 (2008)

Noncommutative standard model in the top quark sector

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(Received 19 March 2008; revised manuscript received 14 April 2008; published 26 June 2008)

In this article we aim to estimate the bounds on the noncommutative scale $\Lambda_{\rm NC}$ and to extract the 95% exclusion contours for some $\theta_{\mu\nu}$ components using the recent measurements of the top quark width and the W boson polarization in top pair events from CDF experiments at Tevatron.

DOI: 10.1103/PhysRevD.77.116011 PACS numbers: 11.10.Nx, 12.90.+b, 14.65.Ha

I. INTRODUCTION

The standard model (SM) of the particles has been found to be in good agreement with the present experimental data in many of its aspects. However, in the framework of the SM, the top quark is the only quark which has a mass in the same order as the electroweak symmetry breaking scale, $v \sim 246$ GeV, whereas all other observed fermions have masses which are a tiny fraction of this scale. This huge mass might be a hint that the top quark plays an essential role in the electroweak symmetry breaking. On the other hand, the reported experimental data from Tevatron on the top quark properties are still limited and no significant deviations from the standard model predictions has been seen. Several properties of the top quark have been already examined. They consist of studies of the $t\bar{t}$ production cross section, the top quark mass measurement, the measurement of W helicity in the top decay, the search for flavor changing neutral current, and many other studies [1]. However, it is expected that top quark properties can be examined with high precision at the Large Hadron Collider due to very large statistics [2]. Since the dominant top quark decay mode is into a W boson and a bottom quark, the tWb coupling can be investigated accurately. Within the SM, the top quarks decay via electroweak interaction before hadronization. This important property is one of the consequences of its large mass. Hence, the spin information of the top quark is transferred to its decay daughters and can be used as a powerful mean for investigation of possible new physics.

There are many studies for testing the top quark decay properties at hadron colliders. For instance, the nonstandard effects on the full top width have been investigated in the minimal supersymmetric standard model and in the technicolor model [3–7]. Some studies have been performed on the effects of anomalous tWb couplings on the top width and some constraints have been applied on the anomalous couplings [8–13].

The noncommutativity in space-time is a possible generalization of the usual quantum mechanics and quantum field theory to describe the physics at very short distances of the order of the Planck length, since the nature of the space-time changes at these distances (motivations to construct models on noncommutative space-time are coming from string theory, quantum gravity, Lorentz breaking [14–17]). In the simplest case, the noncommutativity in space-time is described by a set of constant c-number parameters $\theta^{\mu\nu}$ or equivalently by an energy scale $\Lambda_{\rm NC}$ and dimensionless parameters $C^{\mu\nu}$:

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} = \frac{i}{\Lambda_{\rm NC}^2} C_{\mu\nu} = \frac{i}{\Lambda_{\rm NC}^2}\begin{pmatrix} 0 & -E_1 & -E_2 & -E_3 \\ E_1 & 0 & -B_3 & B_2 \\ E_2 & B_3 & 0 & -B_1 \\ E_3 & -B_2 & B_1 & 0 \end{pmatrix}, \qquad (1)$$

where $\theta_{\mu\nu}$ is a real antisymmetric tensor with the dimension of $[L]^2$. Here we have defined dimensionless electric and magnetic parameters $(\vec{E}, \vec{B})$ for convenience. We note that a space-time noncommutativity, $\theta_{0i} \neq 0$, might lead to some problems with unitarity and causality [18,19]. It has been shown that the unitarity can be satisfied for the case of $\theta_{0i} \neq 0$ provided that $\theta^{\mu\nu}\theta_{\mu\nu} > 0$ [20]. However, for simplicity, in this article we take $\theta_{0i} = 0$ or equivalently $\vec{E} = 0$.

A noncommutative version of an ordinary field theory can be obtained by replacing all ordinary products with Moyal $\star$ product defined as [21]

$$(f \star g)(x) = \exp\left(\frac{i}{2}\theta^{\mu\nu}\partial_\mu^y \partial_\nu^z\right) f(y)g(z)\Big|_{y=z=x} = f(x)g(x) + \frac{i}{2}\theta^{\mu\nu}(\partial_\mu f(x))(\partial_\nu g(x)) + O(\theta^2). \qquad (2)$$

The approach to the noncommutative field theory based on the Moyal product and Seiberg-Witten maps allows the generalization of the standard model to the case of noncommutative space-time, keeping the original gauge group and particle content [22–27]. Seiberg-Witten maps relate the noncommutative gauge fields and ordinary fields in commutative theory via a power series expansion in θ. Indeed the noncommutative version of the standard model is a Lorentz violating theory, but the Seiberg-Witten map shows that the zeroth order of the theory is the Lorentz

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invariant standard model. The effects of noncommutative space-time on some rare decay, collider processes, leptonic decay of the W and Z bosons, and additional phenomenological results have been presented in [28–38] and some limits have been set on noncommutative scale.

The aim of this article is to estimate the bounds on the noncommutative scale $\Lambda_{\rm NC}$ and to estimate the 95% exclusion contours for $\vec{B}$ using the current measurements of the top quark width and the W boson polarization in the $t\bar{t}$ events from CDF experiments at Tevatron. In Sec. II, a short introduction for the noncommutative standard model (NCSM) is given. Section III is dedicated to review the W boson polarization in the top quark events. Section IV presents the noncommutative effects on the top quark width and limit on $\Lambda_{\rm NC}$ from current measured top width. Section V gives the limits on $\Lambda_{\rm NC}$ and $\vec{B}$ using W boson polarization. Finally, Sec. VI concludes the paper.

II. THE NONCOMMUTATIVE STANDARD MODEL

The action of the NCSM can be obtained by replacing the ordinary products in the action of the classical SM by the Moyal products and then matter and gauge fields are replaced by the appropriate Seiberg-Witten expansions. The action of NCSM can be written as

$$S_{\rm NCSM} = S_{\rm fermions} + S_{\rm gauge} + S_{\rm Higgs} + S_{\rm Yukawa}. \tag{3}$$

This action has the same structure group $SU(3)_C \times SU(2)_L \times U(1)_Y$ and the same field number of coupling parameters as the ordinary SM. The approach which has been used in [23–26] to build the NCSM is the only known approach that allows one to build models of an electroweak sector directly based on the structure group $SU(2)_L \times U(1)_Y$ in a noncommutative background. The NCSM is an effective, anomaly free, noncommutative field theory [39,40].

We just consider the fermions (quarks and leptons). The fermionic matter part in a very compact way is

$$\begin{aligned} S_{\rm fermions} = &\int d^4x \sum_{i=1}^{3} (\bar{\hat{\Psi}}_L^{(i)} \star (i\hat{\not{D}}\hat{\Psi}_L^{(i)})) \\ &+ \int d^4x \sum_{i=1}^{3} (\bar{\hat{\Psi}}_R^{(i)} \star (i\hat{\not{D}}\hat{\Psi}_R^{(i)})), \end{aligned} \tag{4}$$

where i is the generation index and $\Psi^i_{L,R}$ are

$$\Psi_L^{(i)} = \begin{pmatrix} L_L^i \\ Q_L^i \end{pmatrix}, \qquad \Psi_R^{(i)} = \begin{pmatrix} e_R^i \\ u_R^i \\ d_R^i \end{pmatrix}, \tag{5}$$

where L^i_L and Q^i_L are the well-known lepton and quark doublets, respectively. The Seiberg-Witten maps for the noncommutative fermion and vector fields yield:

$$\begin{aligned} \hat{\psi} &= \hat{\psi}[V] \\ &= \psi - \frac{1}{2}\theta^{\mu\nu}V_\mu\partial_\nu\psi + \frac{i}{8}\theta^{\mu\nu}[V_\mu, V_\nu]\psi + O(\theta^2), \\ \hat{V}_\alpha &= \hat{V}_\alpha[V] = V_\alpha + \frac{1}{4}\theta^{\mu\nu}\{\partial_\mu V_\alpha + F_{\mu\alpha}, V_\nu\} + O(\theta^2), \end{aligned} \tag{6}$$

where ψ and V_μ are ordinary fermion and gauge fields, respectively. Noncommutative fields are denoted by a hat. For a full description and review of the NCSM, see [23–26]. The $t(p_1) \to W(q) + b(p_2)$ vertex in the NCSM up to the order of θ^2 can be written as [32,36]

$$\begin{aligned} \Gamma_{\mu,\rm NC} = \frac{gV_{tb}}{\sqrt{2}}\Big[&\gamma_\mu + \frac{1}{2}(\theta_{\mu\nu}\gamma_\alpha + \theta_{\alpha\mu}\gamma_\nu + \theta_{\nu\alpha}\gamma_\mu)q^\nu p_1^\alpha \\ &- \frac{i}{8}(\theta_{\mu\nu}\gamma_\alpha + \theta_{\alpha\mu}\gamma_\nu + \theta_{\nu\alpha}\gamma_\mu)(q\theta p_1)q^\alpha p_1^\nu\Big]P_L, \end{aligned} \tag{7}$$

where $P_L = \frac{1-\gamma_5}{2}$ and $q\theta p_1 \equiv q^\mu\theta_{\mu\nu}p_1^\nu$. This vertex is similar to the vertex of W decays into a lepton and antineutrino [37]. However, one should note that due to the ambiguities in the Seiberg-Witten maps there are additional terms in the above vertex. Since they will not affect the results, we have ignored them [41].

III. W BOSON POLARIZATION IN TOP EVENTS

This section presents the observables used to measure the polarization of the W boson. The real W in the $t \to W + b$ decay can be produced with a longitudinal, left-handed or right-handed helicity. The corresponding probabilities are F_0, F_L, and F_R, respectively, whose SM expectations at tree level in the zero b-mass approximation are

$$\begin{aligned} F_0 &= \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to Wb)} = \frac{m_t^2}{m_t^2 + 2m_W^2} = 0.703, \\ F_L &= \frac{\Gamma(t \to W_L b)}{\Gamma(t \to Wb)} = \frac{2m_W^2}{m_t^2 + 2m_W^2} = 0.297, \\ F_R &= \frac{\Gamma(t \to W_R b)}{\Gamma(t \to Wb)} = 0.000, \end{aligned} \tag{8}$$

where m_t and m_W are the top and W masses in GeV. $\Gamma(t \to Wb)$ is the top quark width. We have the restriction $F_0 + F_L + F_R = 1$. Since massless particles must be left-handed in the SM, right-handed W bosons do not exist in the zero b-mass approximation, due to angular momentum conservation. Including QCD and electroweak radiative corrections, finite width corrections and nonzero b-quark mass induces small variations: $F_0 = 0.695$, $F_L = 0.304$, and $F_R = 0.001$ for $m_t = 175$ GeV/c^2 [42]. Because the top quark is very heavy, F_0 is large and the top decay is the only significant source of longitudinal W bosons. Deviations of F_0 from its SM value would bring into question the validity of the Higgs mechanism of the spontaneous symmetry breaking, responsible for the longitudinal degree of freedom of the massive gauge bosons. Any deviation of F_R from zero could point to non-standard model couplings such as Wtb anomalous couplings or new couplings coming from space-time noncommutativity introduced in the last section. The best way to access particle spin information is to measure the angular distribution of its decay products, thereby called spin analyzers. As an example, the charged lepton from the decay of longitudinally polarized W boson tends to be emitted transversally to the W boson direction, due to angular momentum conservation. Similarly, the charged lepton from a left-handed (right-handed) W boson is preferentially emitted in the opposite (same) W boson direction. By definition of θ_l^* to be the angle between the charged lepton direction in the W boson rest frame and the W direction in the top quark rest frame, the normalized differential decay rate can be expressed as the following [43]:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}(1+\cos\theta_l^*)^2 F_R + \frac{3}{8}(1-\cos\theta_l^*)^2 F_L + \frac{3}{4}(\sin\theta_l^*)^2 F_0. \tag{9}$$

The measured values of the fractions F_0 and F_R of longitudinally polarized and right-handed W bosons in top quark decays using data collected with the CDF II detector (the data set used in the analysis corresponds to an integrated luminosity of approximately 955 pb^{-1}) are as the following [44]:

$$\begin{aligned} F_0 &= 0.59 \pm 0.12(\text{stat})^{+0.07}_{-0.06}(\text{syst}),\\ F_R &= -0.03 \pm 0.06(\text{stat})^{+0.04}_{-0.03}(\text{syst}),\\ F_R &\leq 0.1 \quad \text{at } 95\% \text{ C.L.} \end{aligned} \tag{10}$$

IV. THE NONCOMMUTATIVE EFFECTS ON THE TOP QUARK WIDTH

Using the introduced Feynman rule for the Wtb vertex in the NCSM in Eq. (7), the decay rate is easily evaluated. The decay rate in the top quark rest frame, which contains the noncommutative effects can be expressed as the following [36]:

$$\Gamma(t \to Wb) = \frac{|V_{tb}|^2}{16\pi m_t}\left(\frac{g}{2\sqrt{2}m_W}\right)^2 \lambda^{1/2}\left(1, \frac{m_W^2}{m_t^2}, \frac{m_b^2}{m_t^2}\right) \times [A_{\rm SM} + A_{\rm NC}], \tag{11}$$

where,

$$\begin{aligned} A_{\rm SM} &= 2[m_W^2(m_t^2 + m_b^2 - m_W^2) + ((m_t^2 - m_b^2)^2 - m_W^4)],\\ A_{\rm NC} &= \frac{m_W^2}{12\Lambda_{\rm NC}^4}|\vec{B}|^2(5m_b^2 + m_t^2 - m_W^2)[m_b^4 + (m_t^2 - m_W^2)^2 - 2m_b^2(m_t^2 + m_W^2)]. \end{aligned} \tag{12}$$

One should note that in the above relation we have set $\theta_{i0} = 0$ and the terms with θ_{ij} or equivalently $\vec{B}$ are kept.

The SM prediction for the top quark lifetime is around 4×10^{-25} s which corresponds to the top quark width of 1.5 GeV. It is notable that because of the limited resolutions of the experiments, it is very difficult to measure this very short lifetime or the corresponding width. However, we are able to set an upper limit on the top quark width from the available data from Tevatron. In [45] an upper limit has been set on the top quark width using a likelihood fit to the reconstructed top mass distribution. In the analysis the lepton + jets channel of $t\bar{t}$ candidates, in which one of two W bosons decays to $l\nu_l$ while the other decays to $q\bar{q}$, is used to reconstruct the top quark mass. Finally, the estimated upper bound on the top quark width is 12.7 GeV with 95% C.L. This is corresponding to the lower limit of 5.2×10^{-26} s for the top quark lifetime.

The measured upper limit on the top quark width and Eq. (11) lead to the following bound on $\Lambda_{\rm NC}$:

$$\Lambda_{\rm NC} \geq 624 \text{ GeV} \quad \text{for } |\vec{B}|^2 = 1 \quad \text{with } 95\% \text{ C.L.} \tag{13}$$

V. THE EFFECTS OF NONCOMMUTATIVITY ON W BOSON POLARIZATION

The noncommutative corrections to F_0 and F_R can be calculated using the general Wtb vertex given by Eq. (7). The noncommutative corrections to F_0 are proportional to $|\theta_{i0}|^2$ and there is no contribution from $|\theta_{ij}|$. Therefore, F_0 cannot provide any information about $|\theta_{ij}|$. The noncommutative corrections to the matrix element of the decay of $t(p) \to W(q) + b(k)$ in the top quark rest frame assuming $\theta_{i0} = 0$ has the following form:

$$\mathcal{M}_{\rm NC}(t \to W + b) = \left(\frac{igV_{tb}m_t}{2\sqrt{2}}\right)\epsilon_\alpha^*(q)\bar{u}(k)P_R u(p)\theta^{\alpha\beta}q_\beta, \tag{14}$$

where $\epsilon_\alpha(q)$ denotes the polarization of the W boson. The noncommutative corrections to F_R can be evaluated by calculating the corrections to $\Gamma(t \to W_R b)$. $\mathcal{M}_{\rm NC}(t \to W_R + b)$ is obtained by replacing $\epsilon(q) = \frac{1}{\sqrt{2}}(0, 1, i, 0)$ in the above relation and after some algebra it leads to the following:

$$\begin{aligned} \Gamma_{\rm NC}(t \to W_R b) &= \frac{|V_{tb}|^2}{16\pi m_t}\left(\frac{g}{2\sqrt{2}}\right)^2 \lambda^{1/2}\left(1, \frac{m_W^2}{m_t^2}, \frac{m_b^2}{m_t^2}\right)\Delta_R,\\ \Delta_R &= \frac{m_t^4}{48}(m_t^2 + m_b^2 - m_W^2)\sum_{i=1}^{2}\theta^{i\mu}\theta_\mu^i, \end{aligned} \tag{15}$$

and F_R is

$$F_R = \frac{\Gamma_{NC}(t \to W_R b)}{\Gamma(t \to Wb)}. \quad (16)$$

In obtaining the above relation we have neglected the contributions from θ_{i0}. The sum over i is from one to two which is due the fact that the top quark is only restricted to decay into right-handed W bosons. Obviously, even in the limit of vanishing b-quark mass and neglecting the QCD and electroweak corrections, there are nonzero contributions to the F_R from noncommutativity. F_R is very sensitive to Λ_{NC} for low values. The maximum value of F_R which is equal to one, corresponds to $\Lambda_{NC} \sim 870$ GeV. With the increase in Λ_{NC}, F_R approaches the SM value which is zero. The combination of the upper limit on F_R measured by CDF, mentioned in Sec. III, and the above relation leads to

$$\Lambda_{NC} \geq 1550 \text{ GeV} \quad \text{for } |\vec{B}|^2 = 1 \quad \text{with 95\% C.L.} \quad (17)$$

This bound is higher than the one obtained in [28] (from $Z\gamma$ production at the Tevatron and the LHC) and the bound obtained in [34] from SM forbidden decays which is $\Lambda_{NC} > 1$ TeV. It is noticeable that any better measurement on the upper bound of F_R causes a higher limit on Λ_{NC}.

The noncommutative corrections to F_R and the CDF upper limit provides the 95% C.L. exclusion contours on B_1, B_2, B_3 for different values of Λ_{NC} (200, 500, 800 GeV). These contours are presented in Fig. 1. According to the form of variation of $\vec{B}$ with changing the frame (such as the Lorentz transformation of a magnetic field in electrodynamics), the change of frame leads to slightly lower limits on Λ_{NC} and tighter bounds on B_1, B_2, B_3 (the exclusion contours get smaller), providing that the boost direction is not parallel to the direction of $\vec{B}$.

The estimated bounds are comparable with the bounds estimated in [28] and lead to $|\theta_{ij}| \leq 10^{-7}$ GeV^{-2}.

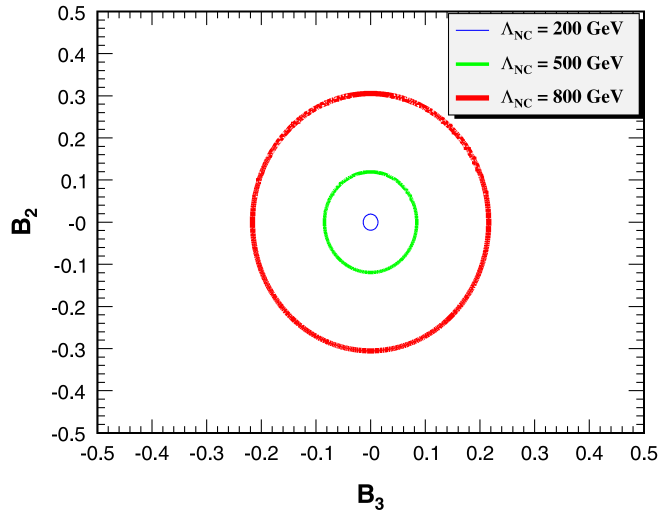

FIG. 1 (color online). The 95% C.L. exclusion contours on B_2, B_3 for different values of Λ_{NC}.

VI. CONCLUSION

The recent measurements of the top quark width and W boson polarization have been used to estimate the noncommutative scale Λ_{NC} and to estimate the 95% exclusion contours on $B_{1,2,3}$. The extracted limits confirms the limits obtained by other studies. The 95% bound on Λ_{NC} from the measured top quark width and W polarization are $\Lambda_{NC} \geq 625$ GeV, $\Lambda_{NC} \geq 1550$ GeV (assuming $|\vec{B}|^2 = 1$), respectively. The obtained limit on Λ_{NC} from W boson polarization is higher than the one obtained from the top width and also is higher than the limits obtained in [28] from $Z\gamma$ production and the limits estimated in [34] from SM forbidden decays. The 95% exclusion contours on $B_{1,2,3}$ lead to $|\theta_{ij}| \leq 10^{-7}$ GeV^{-2}.

ACKNOWLEDGMENTS

The author would like to thank Professor H. Arfaei for fruitful discussions.

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