

ON THE OBSERVABILITY OF PSEUDOSCALAR TOPONIUM AT FUTURE HADRON COLLIDERS

O. ÇAKIR^a, R. ÇİFTÇİ^b, E. RECEPOĞLU^a AND S. SULTANSOY^{b,c}

^aPhysics Department, Faculty of Sciences

Ankara University, 06100 Tandogan, Ankara, Turkey

^bPhysics Department, Faculty of Sciences and Arts, Gazi University

06500 Teknikokullar, Ankara, Turkey

^cInstitute of Physics, Azerbaijan Academy of Sciences

H. Cavid Avenue 33, Baku, Azerbaijan

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Possible existence of extra SM families and/or isosinglet E_6 quarks may sufficiently decrease $|V_{tb}|$ of CKM matrix so that toponia can be formed. Production of pseudoscalar toponium at the LHC and VLHC has been considered. The observability of $\eta_t \rightarrow \gamma\gamma$ signal is discussed.

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Large value of the top quark mass and estimation of $|V_{tb}|$, close to the one in the case of three SM families, have caused toponium to drop from agenda of particle physics. However, even though mass of the top quark is fixed, $|V_{tb}|$ may be relaxed in such a way that toponium can be formed. For example, this can be the case if extra SM families exist or E_6 model is preferred by nature. According to [1] in the case of three SM generations allowed region for V_{tb} is $0.9990 < |V_{tb}| < 0.9993$, whereas this range becomes $0.08 < |V_{tb}| < 0.9993$ if there are more than three generations.

It is well-known, that the fundamental fermions masses and mixings and even the number of fermion generations are not fixed by the Standard Model (SM). In this sense, SM may be deliberated as an effective theory of fundamental interactions rather than fundamental particles. The statement of the Flavor Democracy (or, in other words, the Democratic Mass Matrix approach), which is quite natural in the SM framework, may be considered as the interesting step in the true direction [2–5]. It is intriguing that, Flavor Democracy favors the existence of the fourth standard model family [6–9].

The experimental lower limits on masses of the fourth family fermions are [10]: $m_{\nu_4} > 45$ GeV from LEP 1, $m_{l_4} > 100$ GeV from LEP 2, $m_{d_4} > 199$ GeV (neutral current decays, $d_4 \rightarrow qZ$) and $m_{d_4} > 128$ GeV (charged current decays, $d_4 \rightarrow qW$) from FNAL (Tevatron Run I). Recently [11,12] it was shown that a single extra chiral family with a constrained spectrum is consistent with latest precision data without requiring any other new physics source. Moreover, two and three extra generations with relatively “light” neutrinos ($m_N \approx 50$ GeV) are also allowed [12].

Another way to relax the condition $|V_{tb}| \approx 1$ is the introduction of exotic fermions. We consider as an example the extension of the SM fermion sector which is inspired by E_6 GUT model initially suggested by Gursev and collaborators [13,14]. It is known that this model is strongly favored in the framework of SUGRA (see [15] and references therein).

In hadron collisions, gluon–gluon fusion is the main process for the production of heavy quarkonia [16]: the $J^{PC} = 0^{-+}$ pseudoscalar quarkonium state $\eta_t(^1S_0)$, which is produced in the subprocess $gg \rightarrow \eta$, has a production cross section two orders of magnitude larger than the $J^{PC} = 1^{--}$ vector state Ψ_t , since $gg \rightarrow g\Psi$ will be the mechanism for the vector quarkonium. For this reason, lepton colliders with $\sqrt{s} \simeq 350$ GeV will be more suitable for investigation of vector ψ_t quarkonium, whereas hadron machines are best for the investigation of pseudoscalar η_t quarkonium.

In this work, we consider the process $pp \rightarrow \eta_t X$ for the production of pseudoscalar ($t\bar{t}$) quarkonium with subsequent $\eta_t \rightarrow \gamma\gamma$ decay at the LHC and VLHC. Unfortunately, the observability of the η_t at the Tevatron is out of the question even for $L^{\text{int}} = 10 \text{ fb}^{-1}$.

The cross section for η_t production at hadron colliders can be expressed as

$$\sigma(pp \rightarrow \eta_t X) = K \frac{\pi^2}{8m_{\eta_t}^3} \Gamma(\eta_t \rightarrow gg) \tau \int_{\tau}^1 \frac{dx}{x} g(x, Q^2) g\left(\frac{\tau}{x}, Q^2\right), \quad (1)$$

where [17]

$$\Gamma(\eta_t \rightarrow gg) = \frac{8\alpha_s^2(Q^2)}{3m_{\eta_t}^2} |R_s(0)|^2 \left[1 + \frac{\alpha_s(Q^2)}{\pi} \left(\frac{\pi^2}{3} - \frac{20}{3} \right) \right], \quad (2)$$

$\alpha_s(Q^2)$ is the strong coupling constant and $\tau = m_{\eta_t}^2/s$ with \sqrt{s} being the center of mass energy of the collider. $R_s(0)$ is the radial wave function of the S -state evaluated at the origin [16]. $K \approx 1.4$ is the enhancement factor for the next-to-leading order QCD effects [18]. For gluon distribution function $g(x, Q^2)$ we have used CTEQ5L [19] with $Q^2 = m_t^2$.

The main decay modes of η_t are the single quark decay and $\eta_t \rightarrow gg$. The branching ratio for $\eta_t \rightarrow \gamma\gamma$ is given by

$$\text{BR}(\eta_t \rightarrow \gamma\gamma) \approx \frac{\Gamma(\eta_t \rightarrow \gamma\gamma)}{\Gamma(\eta_t \rightarrow gg) + 2\Gamma_t}, \quad (3)$$

where [20, 21]

$$\Gamma(\eta_t \rightarrow \gamma\gamma) = \frac{12Q_t^4 \alpha^2 (Q^2)}{m_{\eta_t}^2} |R_s(0)|^2 \left[1 + \frac{\alpha_s(Q^2)}{\pi} \left(\frac{\pi^2}{3} - \frac{20}{3} \right) \right], \quad (4)$$

$$\begin{aligned} \Gamma_t &= \frac{m_t^3}{16\pi v^2} |V_{tb}|^2 \left[1 - \left(\frac{m_W}{m_t} \right)^2 \right]^2 \left[1 + 2 \left(\frac{m_W}{m_t} \right)^2 \right] \\ &\times \left[1 - \frac{2}{3} \frac{\alpha_s(Q^2)}{\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2} \right) \right], \end{aligned} \quad (5)$$

where $\alpha(Q^2)$ is fine-structure constant, $v \approx 245$ GeV is the vacuum expectation value of the Higgs field.

For the background calculations we use COMPHEP 4.2 [22]. The dominant backgrounds are $f\bar{f} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ with cross sections 2×10^4 pb and 3×10^5 pb, respectively. In order to suppress the backgrounds we apply a cut $p_T > 0.4m_{\eta_t}$ on transverse momentum of both photons. This requirement reduces the signal by $\sim 40\%$, whereas the background drops drastically. Furthermore, we use 60% efficiency for two photon identification. Finally, we consider a mass window $m_{\gamma\gamma} \pm 2\sigma_m$ for two photons invariant mass using

$$\sigma_m = m_{\gamma\gamma} \left(\frac{0.07}{\sqrt{E_\gamma}} + 0.005 \right). \quad (6)$$

As a result we obtain the signal cross sections for $|V_{tb}| = 0.1, 0.2$ and 0.3 shown in the fifth column of Table I. The signal cross-sections for $\eta_t \rightarrow \gamma\gamma$ channel are practically insensitive to the Higgs mass in the range $120 < m_H < 250$ GeV. Using the criteria given above we calculate the background cross sections presented in the third column of the table.

We have evaluated the statistical significance for the signal using

$$\text{SS} = \frac{S}{\sqrt{B}}. \quad (7)$$

The statistical significance for $L^{\text{int}} = 1000 \text{ fb}^{-1}$ (characteristic value for superbunch options [23] of LHC and VLHC) and the integrated luminosities needed to achieve 3σ and 5σ discovery criteria are presented in the last three columns of Table I.

TABLE I

$\eta_t \rightarrow \gamma\gamma$ channel: The number of signal, background events and corresponding statistical significances for $L_{\text{int}} = 1000 \text{ fb}^{-1}$. The integrated luminosities needed to achieve 3σ and 5σ levels are also given.

	\sqrt{s} (TeV)	σ_B (fb)	V_{tb}	σ_S (fb)	S/\sqrt{B}	$L_{\text{int}}(\text{fb}^{-1})$ for 3σ	$L_{\text{int}}(\text{fb}^{-1})$ for 5σ
LHC	14	16.14	0.1	0.30	2.36	1600	4500
			0.2	0.08	0.63	22700	63000
			0.3	0.04	0.31	90800	252000
	28	21.90	0.1	1.29	8.72	120	330
			0.2	0.35	2.36	1600	4500
			0.3	0.16	1.08	7700	21400
VLHC	40	32.30	0.1	2.54	14.13	45	125
			0.2	0.70	3.89	600	1600
			0.3	0.31	1.72	3000	8400
	175	141.50	0.1	22.71	60.37	2.5	7
			0.2	6.28	16.69	32	90
			0.3	2.82	7.50	160	450

In conclusion, pseudoscalar toponium could manifest itself at the LHC with $\sqrt{s} = 14 \text{ TeV}$ if $|V_{tb}| \approx 0.1$. A possible upgrade of the LHC with $\sqrt{s} = 28 \text{ TeV}$ [24] will give opportunity to reach $|V_{tb}| \approx 0.2$. If $|V_{tb}| \lesssim 0.25$, η_t could be observed at VLHC with $\sqrt{s} = 40 \text{ TeV}$, whereas VLHC with $\sqrt{s} = 175 \text{ TeV}$ cover whole range up to $|V_{tb}| \approx 0.4$. Finally, let us mention, that measurement of V_{tb} via s -channel single top at ATLAS [25] will as well give an indirect information on the existence of the pseudoscalar toponium.

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