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The latest electroweak precision data allow the existence of additional chiral generations in the standard model. We study prospects of search for the fourth standard model family fermions and quarkonia at e^+e^- and $\gamma\gamma$ options of CLIC. It is shown that CLIC will be powerfull machine for discovery and investigation of both fourth family leptons and quarkonia. Moreover, the formation of the fourth family quarkonia will give a new opportunity to investigate Higgs boson properties.

I. INTRODUCTION

Today, the mass and mixing patterns of the fundamental fermions are the most mysterious aspects of particle physics. Even the number of fermion generations is not fixed by the Standard Model (SM). In this sense, SM may be treated 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 [1–4]. It is intriguing, that Flavor Democracy favors the existence of the fourth standard model family [5–8].

Two years ago, the fourth SM family seemed to be "excluded" by precision electroweak data [9]. However, the situation has been changed and as quoted from a recent paper [10]: "It is shown that additional chiral generations are not excluded by the latest electroweak precision data if one assumes that there is no mixings with the known three generations. In the case of "heavy extra generations", when all four new particles are heavier than Z boson, quality of the fit for the one new generation is as good as for zero new generations (Standard Model)".

The fourth family quarks will be copiously produced at the LHC [11,12]. In addition, the Higgs boson "golden mode" will be observable at the upgraded Tevatron for $125 < m_H < 165$ GeV and $175 < m_H < 300$ GeV with more than 3 σ significance [13], if the fourth SM family exists. For same reasons, the SM Higgs boson could be seen at the LHC via the "golden mode" even with an integral luminosity of only a few fb^{-1} [14]. In our opinion, lepton colliders will be advantageous for investigation of the fourth SM family leptons and quarkonia. The potential of muon colliders in this context was analyzed in [15]. With this paper we complete general overlook of the subject considering the potential of CLIC [16].

II. PAIR PRODUCTION

Predicted masses of the fourth SM family fermions, lie between 300 GeV and 700 GeV [6,8]. Therefore, CLIC will give opportunity to search the fourth SM family fermions and quarkonia in details.

A. e^+e^- option

Annihilation of e^+e^- is the classic channel to produce and study new heavy fermions, because the cross sections are relatively large compared to backgrounds [17]. The cross section for the process $e^+e^- \to f\,\bar{f}$ has the well-known form

$$\sigma = \frac{2\pi\alpha^2}{3s}\xi\beta\left\{Q_f\left(Q_f - 2\chi_1 v v_f\right)\left(3-\beta^2\right) + \chi_2\left(1+v^2\right)\left[v_f^2\left(3-\beta^2\right)+2\beta^2 a_f^2\right]\right\} \tag{1}$$

where

$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\frac{s\left(s-M_Z^2\right)}{\left(s-M_Z^2\right)^2+\Gamma_Z^2 M_Z^2}$

$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{\left(s-M_Z^2\right)^2+\Gamma_Z^2 M_Z^2}$

$v = -1 + 4\sin^2\theta_W$

$a_f = 2T_{3f}$

$v_f = 2T_{3f} - 4Q_f\sin^2\theta_W$

$\beta = \sqrt{1-4m_Q^2/s}.$

$T_3 = \frac{1}{2}$ for ν_4 and u_4, $T_3 = -\frac{1}{2}$ for l_4 and d_4

$\xi = 1$ for leptons, $\xi = 3$ for quarks.

Obtained cross-section values for pair production of the fourth SM family fermions with $m_4 = 320$ and 640 GeV and corresponding number of events per working year (10^7 s) are given in Tables I and II, respectively. Event signatures are defined by the mass pattern of the fourth family and 4×4 Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. According to scenario given in [7], dominant decay modes are following: $u_4 \to b\ W^-$, $d_4 \to t\ W^+$, $l_4 \to \nu_\tau W^-$ and $\nu_4 \to \tau^- W^+$.

We have mentioned that the fourth family quarks with $m_4 < 1$ TeV will be discovered at LHC. However due to sufficiently large event numbers and clean environment, CLIC will give opportunity to investigate their properties in details. Prospects for observation of the fourth family leptons at hadron colliders are not so good because of low statistics and large background. The charged l_4 lepton will have clear signature at CLIC. For example, if produced $W^\pm$ bosons decay leptonically, one deals with two acoplanary opposite charge leptons and large missing energy. Pair production of the neutral ν_4 leptons will lead to more complicated event topology. In this case, τ tagging will be helpfull in identification of events. Indeed, produced τ leptons will decay at the distance 1-2 cm from interaction point, which can be easily measured by vertex detector.

B. $\gamma\gamma$ option

It is well known that linear e^+e^- colliders will allow to construct TeV energy $\gamma\gamma$ colliders on their basis [18–20]. The fourth SM family quarks and charged leptons will be copiously produced at $\gamma\gamma$ machines. The cross-section for $\gamma\gamma \to f\overline{f}$ at fixed $\widehat{s}$ has the form

$$\widehat{\sigma} = \frac{2\xi\pi\alpha_{em}^2 Q_f^4}{\widehat{s}(1+\beta^2)}\left[2\beta(\beta^4-\beta^2-2)+(\beta^6+\beta^4-3\beta^2-3)\ln\left(\frac{1-\beta}{1+\beta}\right)\right] \tag{2}$$

where $\beta = \sqrt{1-4m^2/\widehat{s}}$. Further integration over the photon spectrum should be performed to obtain the resulting cross section

$$\sigma = \int\limits_{\tau_{\min}}^{(0.83)^2} d\tau \int\limits_{\tau/0.83}^{0.83} \frac{dx}{x} f_\gamma\left(\frac{\tau}{x}\right) f_\gamma(x)\,\widehat{\sigma}(\tau s) \tag{3}$$

where $\tau_{\min} = 4m^2/s$ and $\widehat{s} = \tau s$. The energy spectrum of the high energy photons obtained through Compton backscattering of laser photons on the high energy electron beam has the form

$$f_\gamma(y) = \frac{1}{1.84}\left[1-y+\frac{1}{1-y}-\frac{4y}{\zeta(1-y)}+\frac{4y^2}{\zeta^2(1-y)^2}\right] \tag{4}$$

with $\zeta = 4.8$. Using $\sqrt{s_{ee}} = 1$ TeV, which corresponds to $\sqrt{s_{\gamma\gamma}}^{\max} = 0.83\sqrt{s_{ee}} = 0.83$ TeV and $\sqrt{s_{ee}} = 3$ TeV, which corresponds to $\sqrt{s_{\gamma\gamma}}^{\max} = 0.83\sqrt{s_{ee}} = 2.5$ TeV, the obtained values of cross-section and event number per year are presented in Tables I and II, respectively.

III. QUARKONIUM PRODUCTION

The condition for forming $(Q\overline{Q})$ quarkonia states with new heavy quarks is [21]

$$m_Q \leq (125\ GeV)\ \left|V_{Qq}\right|^{-2/3} \tag{5}$$

where $Q = u_4$ or d_4; q denotes known quarks ($q = d, s, b$ for $Q = u_4$ and $q = u, c, t$ for $Q = d_4$). Differing from t quark, fourth family quarks will form quarkonia because u_4 and d_4 are almost degenerate and their decays are suppressed by small CKM mixings [6–8]. Below, we consider resonance productions of ψ_4 quarkonia at e^+e^- and η_4 quarkonia at $\gamma\gamma$ options of CLIC.

A. e^+e^- option

The cross section for the formation of the fourth family quarkonium is given with the well-known relativistic Breit-Wigner equation

$$\sigma\left(e^+e^- \to \left(Q\,\bar{Q}\right)\right) = \frac{12\pi\left(s/M^2\right)\Gamma_{ee}\Gamma}{\left(s-M^2\right)^2 + M^2\Gamma^2}, \tag{6}$$

where M is the mass, Γ_{ee} is the partial decay width to e^+e^- and Γ is the total decay width of the fourth family quarkonium. Using corresponding formulas from [22] in the frame of Coulomb potential model, we obtain decay widths for the main decay modes of $\psi_4(u_4\overline{u_4})$ and $\psi_4(d_4\overline{d_4})$, which are given in Table III. One can see that dominant decay mode for both $\psi_4(u_4\overline{u_4})$ and $\psi_4(d_4\overline{d_4})$ quarkonia is $\psi_4 \to W^+W^-$. Next important decay modes are $\psi_4 \to \gamma Z$ and $\psi_4 \to \gamma H$.

In order to estimate the number of produced quarkonium states, one should take into account the luminosity distrubition at CLIC which is influenced from energy spread of electron and positron beams and beamstrahlung. In our calculations we use GUINEA-PIG simulation code [24]. For illustration we suppose that $m_{\psi_4} \simeq 1$ TeV. The estimated event numbers per year for ψ_4 production, as well as, $\psi_4 \to \gamma H$ and $\psi_4 \to ZH$ decay channels are presented in Table IV. In our opinion, γH decay mode of $\psi_4(u_4\overline{u_4})$ quarkonium is promising for investigation of Higgs boson properties, especially if energy spread of electron and positron beams about 10^{-3} could be managed succesfully.

B. $\gamma\gamma$ option

Pseudoscalar η_4 quarkonia formed by the fourth SM family quarks will be copiously produced at LHC [12,23]. Decay widths for main decay modes of $\eta_4(u_4\overline{u_4})$ and $\eta_4(d_4\overline{d_4})$ are given in Table V. As seen from the table, the dominant decay mode is $\eta_4 \to ZH$. One can estimate $\gamma\gamma \to \eta_4$ production cross-section approximately by using following relation [25]:

$$\sigma \approx 50\text{fb}(1+\lambda_1\lambda_2)\left(\frac{\text{Br}_{\gamma\gamma}}{4\times10^{-3}}\right)\left(\frac{\Gamma_{tot}}{1\ \text{MeV}}\right)\left(\frac{200\ \text{GeV}}{M_\eta}\right)^3 \tag{7}$$

where $\text{Br}_{\gamma\gamma}$ is the branching ratio of $\eta_4 \to \gamma\gamma$ decay mode, Γ_{tot} is the quarkonium total decay width and $\lambda_{1,2}$ are helicities of initial photons. Assuming $\lambda_1\lambda_2 = 1$, we obtain total event numbers of η_4 production, as well as numbers of $\eta_4 \to ZH$ events, which are given in Table VI. The advantage of $\eta_4(u_4\overline{u_4})$ with respect to $\eta_4(d_4\overline{d_4})$ is obvious.

IV. CONCLUSION

We have shown that both fourth family fermions and quarkonia will be copiously produced at CLIC. If the fourth SM family exists, CLIC will be excellent place for investigation of fourth family quarkonia and leptons. Formation of the fourth SM family quarkonia will give a new opportunity to investigate Higgs bosons properties especially due to $e^+e^- \to \psi_4 \to \gamma H$ channel.

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TABLE I. Cross sections and event numbers per year for pair production of the fourth standard model family fermions with mass 320 GeV at CLIC ($\sqrt{s_{ee}} = 1$ TeV, $L_{ee} = 2.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and $L_{\gamma\gamma} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$)

		$u_4\overline{u_4}$	$d_4\overline{d_4}$	$l_4\overline{l_4}$	$\nu_4\overline{\nu_4}$
e^+e^- option	σ (fb)	130	60	86	15
	N_{ev}/year	35000	16000	23000	4100
$\gamma\gamma$ option	σ (fb)	34	2	58	-
	N_{ev}/year	3400	200	5700	-

TABLE II. Cross sections and event numbers per year for pair production of the fourth standard model family fermions with mass 640 GeV at CLIC ($\sqrt{s_{ee}} = 3$ TeV, $L_{ee} = 1 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $L_{\gamma\gamma} = 3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

		$u_4\overline{u_4}$	$d_4\overline{d_4}$	$l_4\overline{l_4}$	$\nu_4\overline{\nu_4}$
e^+e^- option	σ (fb)	16	8	10	2
	N_{ev}/year	16000	8000	10000	2000
$\gamma\gamma$ option	σ (fb)	27	2	46	-
	N_{ev}/year	8100	600	14000	-

TABLE III. Decay widths for main decay modes of ψ_4 for $m_H = 150$ (300) GeV with $m_{\psi_4} \simeq 1$ TeV

	$(u_4\overline{u_4})$		$(d_4\overline{d_4})$	
	$m_H = 150$ GeV	$m_H = 300$ GeV	$m_H = 150$ GeV	$m_H = 300$ GeV
$\Gamma(\psi_4 \to \ell^+\ell^-)$, 10^{-3} MeV	18.9	18.9	7.3	7.3
$\Gamma(\psi_4 \to u\,\bar{u})$, 10^{-2} MeV	3.2	3.2	1.9	1.9
$\Gamma(\psi_4 \to d\,\bar{d})$, 10^{-2} MeV	1.4	1.4	1.7	1.7
$\Gamma(\psi_4 \to Z\gamma)$, 10^{-1} MeV	15	15	3.7	3.7
$\Gamma(\psi_4 \to ZZ)$, 10^{-1} MeV	1.7	1.7	5.4	5.4
$\Gamma(\psi_4 \to ZH)$, 10^{-1} MeV	1.7	1.6	5.5	5.2
$\Gamma(\psi_4 \to \gamma H)$, 10^{-1} MeV	14.4	13.4	3.6	3.4
$\Gamma(\psi_4 \to W^+W^-)$, MeV	70.8	70.8	71.2	71.2

TABLE IV. The production event numbers per year for the fourth SM family ψ_4 quarkonia at CLIC 1 TeV option with $m_{\psi_4} \simeq 1$ TeV

			Events per year	
		$\Delta E/E$	$m_H = 150$ GeV	$m_H = 300$ GeV
$e^+e^- \to \psi_4$	$(u_4\overline{u_4})$	10^{-2}	3500	3500
		10^{-3}	26600	26700
	$(d_4\overline{d_4})$	10^{-2}	1400	1400
		10^{-3}	10400	10400
$e^+e^- \to \psi_4 \to \gamma H$	$(u_4\overline{u_4})$	10^{-2}	70	60
		10^{-3}	510	480
	$(d_4\overline{d_4})$	10^{-2}	7	6
		10^{-3}	50	70
$e^+e^- \to \psi_4 \to ZH$	$(u_4\overline{u_4})$	10^{-2}	8	7
		10^{-3}	60	60
	$(d_4\overline{d_4})$	10^{-2}	10	10
		10^{-3}	80	70

TABLE V. Decay widths for main decay modes of η_4 for $m_H = 150$ (300) GeV with $m_{\eta_4} = 0.75$ TeV

	$(u_4\overline{u_4})$		$(d_4\overline{d_4})$	
	$m_H = 150$ GeV	$m_H = 300$ GeV	$m_H = 150$ GeV	$m_H = 300$ GeV
$\Gamma(\eta_4 \to \gamma\gamma)$, 10^{-3} MeV	19.5	19.5	1.06	1.06
$\Gamma(\eta_4 \to Z\gamma)$, 10^{-3} MeV	4.6	4.6	3.7	3.7
$\Gamma(\eta_4 \to ZZ)$, 10^{-1} MeV	2.2	2.2	2.8	2.8
$\Gamma(\eta_4 \to gg)$, MeV	5.1	5.1	5.1	5.1
$\Gamma(\eta_4 \to ZH)$, MeV	47.3	30.9	47.3	30.9
$\Gamma(\eta_4 \to W^+W^-)$, 10^{-2} MeV	5.7	5.7	5.7	5.7
$\Gamma(\eta_4 \to t\bar{t})$, MeV	16.4	16.4	16.4	16.4
$\Gamma(\eta_4 \to b\bar{b})$, 10^{-2} MeV	1.0	1.0	1.0	1.0

TABLE VI. The production event numbers per year for the fourth SM family η_4 quarkonia at $\gamma\gamma$ option with $m_{\eta_4} = 0.75$ TeV

		Events per year	
		$m_H = 150$ GeV	$m_H = 300$ GeV
$\gamma\gamma \rightarrow \eta_4$	$(u_4\overline{u_4})$	900	900
	$\left(d_4\overline{d_4}\right)$	56	56
$\gamma\gamma \rightarrow \eta_4 \rightarrow ZH$	$(u_4\overline{u_4})$	610	520
	$\left(d_4\overline{d_4}\right)$	38	33