Searching for the toponium η_t with the $\eta_t \to W^+W^-$ decay*

Yueling Yang (杨悦玲) Bingbing Yang (杨冰冰) Jiazhi Li (李佳芝) Zhaojie Lü (吕兆杰) Junfeng Sun (孙俊峰)†

School of Physics, Henan Normal University, Xinxiang 453007, China

Abstract: Inspired by the observation of the η_t meson at the LHC and the promising prospect of the η_t meson available at the approaching HL-LHC, branching ratios for the $\eta_t \to f\bar{f}$, gg, $\gamma\gamma$, W^+W^-, Z^0Z^0, $Z^0\gamma$, and Z^0H decays are roughly estimated. It is found that tens of opposite-charge dilepton events from the $\eta_t \to W^+W^-$ decay and hundreds of events from the $\eta_t \to Z^0H \to \ell^+\ell^-H$ decay using the single Z^0 boson tagging method are expected to be accessible. This estimation provides a reference for future experimental study on the η_t meson.

Keywords: toponium, branching ratio, weak decay, η_t

DOI: 10.1088/1674-1137/ae18aa **CSTR:** 32044.14.ChinesePhysicsC.50033101

The top quark, denoted as t, is an extraordinary elementary particle in the Standard Model (SM) of particle physics. On one hand, the t quark has the most privileged Yukawa coupling to the Higgs boson and is the most massive elementary particle identified to date, m_t = 172.57±0.29 GeV [1], with a measuring accuracy better than 0.2%. The top quark mass is almost exactly equal to one unit of $v/\sqrt{2}$, where $v = (\sqrt{2}G_F)^{-1/2} = 246.22$ GeV [1] represents the vacuum expectation value of the scalar Higgs field. On the other hand, the considerable mass of the top quark facilitates an enormous phase space, which in turn results in a broad decay width proportional to the cube of the top quark mass[1)]. $\Gamma_t \approx 1.42^{+0.19}_{-0.15}$ GeV [1] with a measurement accuracy of less than 10%, and correspondingly an instantaneous lifetime, $\tau_t = 1/\Gamma_t \approx 0.5\times10^{-24}$ s, which is usually assumed to be shorter than the hadronization time. It was generally believed that a $t\bar{t}$ bound state could never be formed and observed. However, this conventional and prevalent view is greatly challenged by the recent intriguing measurements at the Large Hadron Collider (LHC). A significant excess of events close to the kinematic $t\bar{t}$ threshold is observed independently by two LHC experiments, with a statistical significance of over 5σ discovered by the CMS experiment [3, 4] and 7.7σ confirmed by the ATLAS experiment [5]. This new, fascinating, and mysterious resonance corresponding to the observed enhancement is preferably and consistently explained by both experiments with a composite color-singlet CP-odd pseudoscalar toponium, referred to as $\eta_t(1S)$ and abbreviated as η_t, the ground S-wave spin-singlet (1^1S_0) bound state consisting of a top and an antitop quark $t\bar{t}$.

Of particular interest are the properties of the toponium η_t. There are some similarities and differences between the toponium η_t, charmonium η_c, consisting of the $c\bar{c}$ quark, and bottomonium η_b, consisting of the $b\bar{b}$ quark. Based on the traditional quark model, the similarities are as follows: (a) They are all the ground S-wave spin-singlet pseudoscalar heavy quarkonium with the spectroscopic notation of 1^1S_0 and share the same spin, parity, and charge-parity quantum numbers $J^{PC} = 0^{-+}$. (b) They are all unflavored mesons. Their additive intrinsic quantum numbers, including the baryon number, electric charge, isospin, strangeness, charm, bottomness, and topness, are all zero. (c) Their masses are approximately the sum of their constituent quark masses, but just below the

Received 11 March 2025; Accepted 27 October 2025; Accepted manuscript online 28 October 2025

* Supported by the National Natural Science Foundation of China (12275068, 12275067), the National Key R&D Program of China (2023YFA1606000), the Natural Science Foundation of Henan Province (252300421491, 242300420250), and the Science and Technology R&D Program Joint Fund Project of Henan Province (225200810030), as well as the Science and Technology Innovation Leading Talent Support Program of Henan Province (254200510039)

† E-mail: sunjunfeng@htu.edu.cn

1) Neglecting the bottom quark mass and terms of α_s, the partial width predicted in the SM at the leading order approximation is [2],

$$\Gamma(t\to Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2\left(1-\frac{m_W^2}{m_t^2}\right)^2\left(1+2\frac{m_W^2}{m_t^2}\right), \quad (1)$$

with the weak interaction coupling Fermi constant $G_F \approx 1.166\times10^{-5}\,\text{GeV}^{-2}$, the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{tb}\approx 1$, and the W boson mass $m_W \approx 80.4$ GeV, it is observed from Eq. (1) that the heavier the top quark mass is, the more rapidly the top quark width increases.

open-flavor threshold. Thus, explicit-flavored hadronic decays, e.g., $\eta_c \to D\overline{D}$, $\eta_b \to B\overline{B}$, and $\eta_t \to T\overline{T}$, are absolutely prohibited by the law of conservation of energy, where the symbols D, B, and T denote the ground charmed, bottomed, and topped pseudoscalar mesons, respectively. The differences in the properties of η_t, η_c, and η_b include: (a) The η_t meson consists of the heaviest top quark and anti-top quark, and its mass is about $m_{\eta_t} \approx 2m_t \approx 343$ GeV [3−8], which is two orders of magnitude greater than $m_{\eta_c} = 2.9839(4)$ GeV [1] and exceeds 35 times that of $m_{\eta_b} = 9.3987(20)$ GeV [1]. (b) The toponium η_t is supercompact[1)], and its Bohr radius size is of order $r \sim 1/m_t\alpha_s(m_t) \sim 0.01$ fm, compared with the bottomonium size $r \sim 1/m_b\alpha_s(m_b) \sim 0.19$ fm and the charmonium size $r \sim 1/m_c\alpha_s(m_c) \sim 0.35$ fm. The small Bohr radius of the toponium allows probing the deep region of the QCD potential near the threshold where the strong coupling constant α_s is small. (c) Both components of the η_t meson, the t and $\bar{t}$ quarks, can decay individually. The toponium η_t decay width may be significantly large, of order $\Gamma_{\eta_t} \approx 2\Gamma_t \approx 3$ GeV [4−6], which is two orders of magnitude larger than $\Gamma_{\eta_{b,c}}$. The extremely large width makes the distinct η_t meson smear together into a broad threshold enhancement and very hard to identify in experiments, which is in striking contrast to the $\eta_{b,c}$ mesons. In addition, the mass difference between successive toponium states is smaller than the toponium width, so two successive toponium states overlap and become indistinguishable [8−15]. (d) The decay configurations differ greatly between the η_t and $\eta_{b,c}$ mesons. Based on the calculations of Refs. [16−25], the partial di-gluonic and diphotonic decay widths are inversely proportional to the square of the quarkonium mass[2)], $\Gamma(\eta_i \to gg) \propto \Gamma(\eta_i \to \gamma\gamma) \propto 1/m_{\eta_i}^2$ with i = c, b, and t. The $\eta_{b,c}$ mesons decay predominantly through the chromatic and electromagnetic interactions [1], while the shares of the weak interactions are negligible [26−29]. However, the chromatic and electromagnetic decay width of the η_t meson is terribly suppressed due to the huge mass m_{η_t}. The relationship $\Gamma_{\eta_t} \approx 2\Gamma_t$ is almost equivalent to a formal announcement that the η_t meson will decay overwhelmingly through the weak interactions. Therefore, the toponium decay process can be calculated reliably.

The observation of toponium will initiate another new way to study the strong interaction, because the heaviest top quark mass makes nonrelativistic approximations more reliable and perturbative QCD (pQCD) predictions more trustworthy. In fact, the quest for toponium at colliders has been discussed based on pQCD and potential models in many papers, such as Refs. [31−45]. The spin-triplet n^3S_1 vector toponium states, $\Theta(nS)$ mesons, can be directly produced at hadron colliders through the $q\bar{q}$ annihilation processes and future e^+e^- colliders [34−38], such as the CEPC [46] and FCC-ee [47]. The spin-singlet n^1S_0 pseudoscalar toponium states, $\eta_t(nS)$ mesons, are promisingly accessible at hadron colliders through the gluon-gluon color-singlet fusion processes [39−43]. The pQCD theoretical estimation on the η_t production cross section with the gluon fusion mechanism, including state-of-the-art higher-order QCD corrections, is $\sigma(\eta_t) = 6.43$ (or 7.54) pb [7] at the centre-of-mass energy $\sqrt{s} = 13$ (or 14) TeV at the LHC, which is marginally in agreement with the measured cross section at $\sqrt{s} = 13$ TeV with an integrated luminosity of ~140 fb^{-1}, *e.g.*, $8.8^{+1.2}_{-1.4}$ pb with the CMS detector [4] and 9.0±1.3 pb with the ATLAS detector [5]. With an integrated luminosity of about 3 ab^{-1} at 14 TeV over 10 years of operation of the HL-LHC [48], more than 2×10^7 η_t mesons are expected to be available in the future, offering valuable opportunities and promising prospects to discover and study the η_t meson at high-energy and high-luminosity experiments.

The low near-threshold production ratio relative to the non-resonant $t\bar{t}$ production cross section[3)] and the large decay width make the identification of the paratoponium η_t extremely difficult against the complicated $t\bar{t}$ muddy entanglement background. It is indisputable that the dominant η_t decay mode is the intrinsic decays of the constituent top and anti-top quarks. With the obvious hierarchy relations among the CKM matrix elements, $|V_{tb}| \gg |V_{ts}| \gg |V_{td}|$, the top quark decay, almost exclusively into a real W boson and a bottom quark, $t \to W^+b$, is the dominant channel, where the b-jets can be distinguished experimentally from other jets due to the long lifetime of the bottom quarks and relativistic time dilation. The decay rate is $\Gamma(t{\to}Wb)/\Gamma(t{\to}Wq) = (95.7\pm3.4)\%$ [1], where q denotes all the weak-isospin down-type quarks $q = d$, s, and b. The η_t meson decay is predominantly induced by the $t \to W^+b$ decay, *i.e.*, $\eta_t \to \overline{T} + W^+ + b$ (or $T + W^- + \bar{b}$) [30], if the topped T hadrons could instantaneously exist [49, 50], followed immediately by a complex cascade decay series of the T hadrons and W bosons. In principle, the η_t meson and the non-resonant $t\bar{t}$ pair will have the same final states $W^+bW^-\bar{b}$. Experimentally, based on whether the final states of the $W^\pm$ boson decays are the leptons or quarks, the η_t and non-resonant $t\bar{t}$ event reconstruction can be divided into three classes

1) For comparison, common hadrons have a Bohr radius of order $r_h \sim 1/\Lambda_{\rm QCD} \sim 1/200\,{\rm MeV} \sim 1$ fm. The revolution time of toponium, estimated as $t \sim r/c$ [2], is of the same order of magnitude as the toponium lifetime.

2) See Eq.(2) and Eq.(3)

3) It is theoretically estimated that the η_t meson production contributes to 0.79 of the total non-resonant $t\bar{t}$ production cross section at 13 TeV at the LHC [7]. The ratio of the production cross section $\sigma(\eta_t)/\sigma(t\bar{t})$ is measured to be $8.8^{+1.2}_{-1.4}$ pb $/833.9^{+20.5}_{-30.0}$ pb ~ 1.06(17) by the CMS group [4] and 9.0±1.3 pb $/833.9^{+37.4}_{-43.0}$ pb ~ 1.08(17) by the ATLAS group [5].

[1]: (a) the dilepton channels, where both W bosons decay into leptons[1)], with a ratio of 10.5%, (b) the hadronic channels, where both W bosons decay into quarks, with a ratio of 45.7%, and (c) the lepton+jets channels, where one W boson decays into quarks, and the other W boson decays into leptons, with a ratio of 43.8%. Anyhow, the decay products of the η_t meson and the $t\bar{t}$ pair are miscellaneous, resulting in the horrible complexity of kinematics and dynamics.

The toponium decays have a variety of interesting final state topologies compared with the $\eta_{b,c}$ meson decays. Besides the dominant decay $\eta_t \to W^+bW^-\bar{b}$, there are also conventional signals from the $\eta_t \to gg$, $\gamma\gamma$, $f\bar{f}$ decays. Moreover, the potentially interesting signals are the η_t meson decay into the electroweak gauge boson pairs W^+W^-, Z^0Z^0, $Z^0\gamma$ and also into Z^0H, where the $W^\pm$ and Z^0 gauge bosons devour three degrees of the freedom of the Higgs field and acquire masses. These final states containing the on-shell $W^\pm$ or Z^0 or Higgs particles are kinematically inaccessible for the $\eta_{b,c}$ meson decays due to the energy conservation. The $\eta_t \to \gamma H$ decay is not allowed by the C-parity conservation law. Due to the Majorana character of the color-singlet Higgs scalar particle with $J^{PC} = 0^{++}$, the η_t meson decay into two identical Higgs particles, $\eta_t \to HH$, is forbidden by the Bose-Einstein statistics and the CP conservation law [21]. The lowest-order expressions of these partial widths are listed as follows [15–25, 33].

$$\Gamma(\eta_t \to gg) = \frac{8}{3}\,\alpha_s^2\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{2}$$

$$\Gamma(\eta_t \to \gamma\gamma) = \frac{64}{27}\,\alpha_{\rm em}^2\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{3}$$

$$\Gamma(\eta_t \to f\bar{f}) = N_f\,\frac{3\alpha_Z^2}{32}\,\frac{x_f}{x_Z^2}\,\lambda^{1/2}(1,x_f,x_f)\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{4}$$

$$\Gamma(\eta_t \to W^+W^-) = \frac{3\alpha_W^2}{2}\,\lambda^{-1/2}(1,x_W,x_W)\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{5}$$

$$\Gamma(\eta_t \to Z^0Z^0) = \frac{\alpha_Z^2}{432}\,\frac{(9-24\sin^2\theta_W+32\sin^4\theta_W)^2}{(1-2x_Z)^2\,\lambda^{-3/2}(1,x_Z,x_Z)} \times \frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{6}$$

$$\Gamma(\eta_t \to Z^0\gamma) = \frac{2\alpha_{\rm em}\alpha_Z}{27}\,\frac{(3-8\sin^2\theta_W)^2}{\lambda^{-1/2}(1,x_Z,0)}\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{7}$$

$$\Gamma(\eta_t \to Z^0H) = \frac{3\alpha_Z^2}{64}\,\frac{\lambda^{3/2}(1,x_Z,x_H)}{x_Z^2}\,\frac{|R_S(0)|^2}{m_{\eta_t}^2}, \tag{8}$$

where the strong coupling constant α_s, the electromagnetic fine-structure constant $\alpha_{\rm em}$, the electroweak coupling factors $\alpha_Z = \alpha_{\rm em}/(\sin^2\theta_W\cos^2\theta_W)$ and $\alpha_W = \alpha_{\rm em}/\sin^2\theta_W$, the ratio of the mass square $x_i = m_i^2/m_{\eta_t}^2$, and the color number N_f in Eq. (4) is equal to 1 for the leptons and 3 for the quarks. $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$ is the Källén function. $R_S(0)$ is the radial wave function of the S wave state evaluated at the origin $r = 0$, and can approximately be obtained with the solution of the Schrödinger equation with a phenomenological potential. The above partial decay widths are proportional to $|R_S(0)|^2/m_{\eta_t}^2$. The effects arising from the higher-order QCD corrections seem to be limited due to the small coupling $\alpha_s(m_t)$. The total decay width Γ_{η_t} should be dominated by the single-top-quark electroweak decay, which is independent of the value of the wave function at the origin.

The toponium strongly resembles a non-relativistic positronium. The interactions between the t and $\bar{t}$ quarks at the short distances should be governed by electroweak and perturbative QCD effects [34]. For the superheavy quarkonia with a sub-femtometer Bohr radius, a non-relativistic treatment of the interquark potential becomes possible due to the asymptotic freedom of QCD. The potential is usually written as a short-distance part V_S plus a long-distance part V_L, where the V_S part arises from the gluon-exchange interaction between quarks, and the V_L part is motivated by confinement [51]. It is recognized phenomenologically that the Bohr radius of the toponium is sufficiently deep in V_S and thus sufficiently far away from the confinement part of the potential. The radial wave functions at the origin should be predominantly determined by the short-distance potential V_S with the spherically symmetric and static Coulomb-like form [34–37, 51].

$$V(r) = -C_{\rm F}\,\frac{\alpha_s}{r}, \tag{9}$$

where $C_{\rm F} = 4/3$. The general expression for the radial wave functions at the origin of the S states is given by [51],

$$|R_{nS}(0)|^2 = \frac{4}{n^3}\left(C_{\rm F}\,\alpha_s\,\mu_Q\right)^3, \tag{10}$$

where the reduced mass $\mu_Q = m_t/2$ for the $\eta_t(nS)$ mesons.

With the above formula for the partial widths in Eq.

1) The dilepton channels where both W bosons decay into $e\nu_e$ or $\mu\nu_\mu$ have a share of ~5%, but with relatively little background. The τ channels where one or both W bosons decay into $\tau\nu_\tau$ are very difficult to identify with present detectors due to the additional neutrinos from the τ decays.

(2)−(8), the radial wave function in Eq. (10), and the inputs in Table 1, the estimated partial widths and branching ratios of the $\eta_t(1S)$ meson decay into different final states are listed in Table 2, which is consistent with those obtained in Ref. [15] if using a relatively large coupling constant α_s = 0.189 and small total width Γ_{η_t} = 2.84 GeV. Here it should be pointed out that the numbers in Table 2 are only a rough estimate. For example, it has been shown [21−25] that the QCD corrections to the partial width for the $\eta_t \to gg$, $\gamma\gamma$ decays could reach up to ~ 10%. In addition, the mass m_{η_t} and the decay width Γ_{η_t} have not been determined experimentally. Furthermore, the theoretical uncertainties from the top quark mass, the higher order electroweak correction effects, the different forms of the radial wave functions, the threshold effects, the interquark potential model dependence, and so on, which will have much influence on the results, are not considered carefully here. Notwithstanding, the estimated numbers in Table 2 have a certain reference significance in investigating the η_t decays. It is seen from Table 2 that (1) among the traditional decay modes, the $\eta_t \to gg$ decay is the dominant one. The chromo gluons will convert into quark and antiquark pairs and finally fragment into various hadrons after a complicated hadronization process. So, the $\eta_t \to gg$ decay would be obscured by the strong interaction backgrounds. (2) For the $\eta_t \to \gamma\gamma$ decays, the high energy photons should be efficiently reconstructed from their energy deposits in the calorimeter at the LHC. The photon identification efficiency exceeds 95% with the ATLAS experiment for the transverse energy 100 GeV < E_T < 200 GeV in the pseudorapidity range of $|\eta|$ < 2.37 [52]. (3) The branching ratios for the $\eta_t \to f\bar{f}$ decays, being directly proportional to the square of the fermion mass as in Eq. (4), are very small, and might be beyond the detectability limits when considering the complex backgrounds at hadron collisions. (4) The $\eta_t \to Z^0Z^0$, $Z^0\gamma$, Z^0H channels may signal the η_t existence. The Z^0 boson is usually and effectively reconstructed through its decays into the e^+e^- or $\mu^+\mu^-$ pairs at the ATLAS and CMS experiments, where the leptons provide a clean signature and ensure high trigger efficiency and good invariant mass resolution [53]. However, the event reconstruction from all the final leptons seems to be exceedingly difficult or inaccessible because the branching ratios for the $\eta_t \to Z^0Z^0$ ($Z^0\gamma$) $\to \ell^+\ell^-\ell'^+\ell'^-$ ($\ell^+\ell^-\gamma$) decays and the $\eta_t \to Z^0(\to\ell^+\ell^-)H(\to\mu^+\mu^-)$ decay are about 10^{-9}, using $\mathcal{B}r(Z^0\to\ell^+\ell^-)$ ~ 3.4% and $\mathcal{B}r(H\to\mu^+\mu^-)$ ~ 2.6×10^{-4} [1]. The experimental research on the $\eta_t \to Z^0(\to\ell^+\ell^-)H(\to\tau^+\tau^-)$ decay is strongly influenced by the additional invisible neutrinos from the τ decays. Perhaps the single Z^0 boson tagging method could be used to search for and explore the $\eta_t \to Z^0H$ decay, then more than 200 events of the $\eta_t \to Z^0H \to \ell^+\ell^-H$ decay (with ℓ = e and μ) are expected to be observable. (5) For the $\eta_t \to W^+W^-$ decay, at least two b-jets are less than the decay products $W^+bW^-\bar{b}$ of the $t\bar{t}$ pair and the η_t meson. In addition, the charged $W^\pm$ bosons are back-to-back in the rest frame of the η_t meson, and have definite energy and momenta, which will help to recognize unambiguous signals and minimize chaotic backgrounds. The identification technology of the W bosons is very sophisticated at experiments. Under certain circumstances, the single W boson tagging analysis methods can be used to improve the reconstruction efficiency. Considering the branching ratio for the leptonic decays of the W bosons $\mathcal{B}r(W^+\to\ell^+\nu_\ell)$ ~ 11% [1], it is expected to observe some 30 opposite-charge dilepton events where both W bosons decay into $e\nu_e$ or $\mu\nu_\mu$, and some 100 lepton+jets events where one W boson decays into $e\nu_e$ or $\mu\nu_\mu$ and the other W boson decays into quarks. Of course, if using the branching ratio $\mathcal{B}r(\eta_t\to W^+W^-)$ = 2.42×10^{-4} estimated by Ref. [15], the events of the $\eta_t \to W^+W^-$ decay will increase sevenfold. The $\eta_t \to W^+W^-$ decay provides a specific and feasible process to identify the η_t meson.

In summary, the intriguing paratoponium η_t, as one of

Table 2. The possible partial widths (Γ_i), branching ratios ($\mathcal{B}r_i = \Gamma_i/\Gamma_{\eta_t}$), and event numbers ($N_i = \mathcal{B}r_i \times N_{\eta_t}$) of the η_t decay, with the full width Γ_{η_t} = 3 GeV and $N_{\eta_t} = 2\times10^7$.

decay mode	Γ_i	$\mathcal{B}r_i$	N_i
$\mu^+\mu^-$	0.22 eV	7.39×10^{-11}	0
$\tau^+\tau^-$	62.68 eV	2.09×10^{-8}	0.4
$c\bar{c}$	166.09 eV	5.54×10^{-8}	1
$b\bar{b}$	1.36 keV	4.53×10^{-7}	9
gg	1989.08 keV	6.63×10^{-4}	13261
$\gamma\gamma$	9.32 keV	3.11×10^{-6}	62
W^+W^-	97.45 keV	3.25×10^{-5}	650
Z^0Z^0	6.32 keV	3.11×10^{-6}	42
$Z^0\gamma$	2.01 keV	6.71×10^{-7}	13
Z^0H	537.43 keV	1.79×10^{-4}	3583

Table 1. The mass of particles and physical constants are taken from [1], where their central values are regarded as the default inputs unless otherwise specified.

Mass of leptons	m_τ = 1776.93(9) MeV,	m_μ = 105.658 MeV,	
Mass of quarks	m_t = 172.57(29) GeV,	m_b = 4.78(6) GeV,	m_c = 1.67(7) GeV,
Mass of bosons	m_H = 125.20(11) GeV,	m_Z = 91.1880(20) GeV,	m_W = 80.3692(133) GeV,
Physical constant	$\alpha_{\rm em}(m_W)$ = 1/128,	$\alpha_s(m_Z)$ = 0.1180(9),	$\sin^2\theta_W$ = 0.23129(4).

the most compact bound states consisting of the $t\bar{t}$ pair and beyond conventional imagination, has been observed by both the CMS and ATLAS groups with a statistical significance of over 5σ now. The properties of the η_t meson, including its mass, decay width and modes, production cross section, and so forth, will become a focus of attention for many particle physicists. Due to the large mass of the η_t meson, some unusual and characteristic final states, such as W^+W^-, Z^0Z^0, and Z^0H, can be accessible with the η_t decays. Encouraged by a promising prospect of more than $2{\times}10^7$ η_t mesons available at the forthcoming HL-LHC, a rough magnitude order estimation on the branching ratios for the two-body $\eta_t \to f\bar{f}$, gg, $\gamma\gamma$, W^+W^-, Z^0Z^0, $Z^0\gamma$, and Z^0H decays is calculated. If considering the Z^0 and $W^{\pm}$ boson reconstruction via the pure lepton flavors, tens of opposite-charge dilepton events from the $\eta_t \to W^+W^-$ decay and hundreds of events from the $\eta_t \to Z^0H \to \ell^+\ell^-H$ decay using the single Z^0 boson tagging method, are expected to be exploited. We wish that our estimation of the η_t decays can provide a ready reference for the future experimental probe and study of the η_t meson.

References

[1] S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)
[2] I. Bigi, Y. Dokshitzer, V. Khoze *et al.*, Phys. Lett. B **181**, 157 (1986)
[3] The CMS Collaboration, CMS PAS HIG-22-013, arXiv: 2507.05119[hep-ex]
[4] A. Hayrapetyan *et al.* (The CMS Collaboration), Rept. Prog. Phys. **88**, 087801 (2025)
[5] The ATLAS Collaboration, ATLAS-CONF-2025-008
[6] J. Aguilar-Saavedra, Phys. Rev. D **110**, 054032 (2024)
[7] B. Fuks, K. Hagiwara, K. Ma *et al.*, Phys. Rev. D **104**, 034023 (2021)
[8] G. Wang, T. Feng, and Y. Wang, Phys. Rev. D **111**, 096016 (2025)
[9] P. Artymowicz, Acta Phys. Polon. B **15**, 505 (1984)
[10] J. Feigenbaum, Phys. Rev. D **43**, 264 (1991)
[11] W. Kwong, Phys. Rev. D **43**, 1488 (1991)
[12] Y. Sumino, Acta Phys. Polon. B **25**, 1837 (1994)
[13] Y. Sumino, Acta Phys. Polon. B **28**, 2461 (1997)
[14] S. Jiang, B. Li, G. Xu *et al.*, arXiv: 2412.18527[hep-ph]
[15] Y. Bai, T. Chen, and Y. Yang, arXiv: 2506.14552[hep-ph]
[16] R. Barbieri, R. Gatto, and R. Kögerler, Phys. Lett. B **60**, 183 (1976)
[17] V. Novikov, L. Okun, M. Shifman *et al.*, Phys. Rept. **41**, 1 (1977)
[18] V. Barger and A. Martin, Phys. Rev. D **31**, 1051 (1985)
[19] V. Barger, E. Glover, K. Hikasa *et al.*, Phys. Rev. D **35**, 3366 (1987)
[20] O. Éboli, A. Natale, and F. Simão, Phys. Rev. D **39**, 2668 (1989)
[21] W. Kwong, P. Mackenzie, R. Rosenfeld *et al.*, Phys. Rev. D **37**, 3210 (1988)
[22] J. Kühn and E. Mirkes, Phys. Rev. D **48**, 179 (1993)
[23] N. Fabiano, A. Grau, and G. Pancheri, Phys. Rev. D **50**, 3173 (1994)
[24] N. Fabiano, A. Grau, and G. Pancheri, Nuovo Cim. A **107**, 2789 (1994)
[25] O. Çakir, R. Çiftçi, E. Recepoğlu *et al.*, Acta. Phys. Polo. B **35**, 2103 (2004)
[26] J. Sun, Y. Yang, J. Huang *et al.*, Adv. in High Energy Phys. **2016**, 5071671 (2016)
[27] Y. Yang, J. Sun, Y. Guo *et al.*, Phys. Lett. B **751**, 171 (2015)
[28] J. Sun, Y. Yang, J. Gao *et al.*, Phys. Rev. D **94**, 034029 (2016)
[29] Y. Yang, X. Zhao, S. Fang *et al.*, Int. J. Theor. Phys. **60**, 3041 (2021)
[30] J. Kühn and K. Streng, Nucl. Phys. B **198**, 71 (1982)
[31] L. Sehgal and P. Zerwas, Nucl. Phys. B **183**, 417 (1981)
[32] V. Fadin and V. Khoze, JETP Lett. **46**, 525 (1987)
[33] J. Kühn and P. Zerwas, Phys. Rept. **167**, 321 (1988)
[34] V. Fadin, V. Khoze, and T. Sjöstrand, Z. Phys. C **48**, 613 (1990)
[35] M. Strassler and M. Peskin, Phys. Rev. D **43**, 1500 (1991)
[36] Y. Sumino, K. Fujii, K. Hagiwara *et al.*, Phys. Rev. D **47**, 56 (1993)
[37] K. Fujii and T. Matsui, Phys. Rev. D **50**, 4341 (1994)
[38] M. Beneke, A. Signer, and V. Smirnov, Phys. Lett. B **454**, 137 (1999)
[39] K. Hagiwara, Y. Sumino, adn H. Yokoya, Phys. Lett. B **666**, 71 (2008)
[40] Y. Kiyo, J. Kühn, S. Moch *et al.*, Eur. Phys. J. C **60**, 375 (2009)
[41] Y. Sumino and H. Yokoya, JHEP **09**, 034 (2010) [Erratum: JHEP **06**, 037 (2016)]
[42] F. Llanes-Estrada, Phys. Lett. B **866**, 139510 (2025)
[43] M. Garzelli, G. Limatola, S. Moch *et al.*, Phys. Lett. B **866**, 139532 (2025)
[44] B. Fuks, K. Hagiwara, K. Ma *et al.*, Eur. Phys. J. C **85**, 157 (2025)
[45] J. Fu, Y. Li, H. Yang *et al.*, Phys. Rev. D **111**, 114020 (2025)
[46] W. Abdallah *et al.* (CEPC Study Group), Radiat. Detect. Technol. Methods **8**, 1 (2024)
[47] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. ST. **228**, 261 (2019)
[48] A. Abada *et al.*, Eur. Phys. J. Special Topics **228**, 1109 (2019)
[49] S. Zhang, X. Luo, H. Yang *et al.*, arXiv: 2508.03422[hep-ph]
[50] S. Luo, Q. Huang, and X. Liu, *The quest for topped hadrons*, arXiv: 2508.17646[hep-ph]
[51] K. Hagiwara, K. Kato, A. Martin *et al.*, Nucl. Phys. B **344**, 1 (1990)
[52] G. Aad *et al.* (the ATLAS Collaboration), JHEP **05**, 162 (2024)
[53] G. Aad *et al.* (the ATLAS and CMS Collaborations), Phys. Rev. Lett. **132**, 021803 (2024)