

Photoproduction of doubly charmed tetraquark T_{cc} via photon-gluon fusion at ILC and CLIC

Juan-Juan Niu^{*} and Hong-Hao Ma[†]

Department of Physics, Guangxi Normal University, Guilin 541004, People's Republic of China



(Received 29 June 2025; accepted 11 August 2025; published 2 September 2025)

The photoproduction of doubly charmed tetraquark T_{cc} is predicted through the resolved channel $\gamma + g \rightarrow \langle cc \rangle [n] + \bar{c} + \bar{c} \rightarrow T_{cc} + \bar{c} + \bar{c}$ at ILC and CLIC. At e^+e^- colliders, the initial photons γ can be produced from two primary sources, well-delineated within the Weizsäcker Williams approximation (WWA) and the laser backscattering (LBS). And the initial gluon can be emitted from the photon. The spin and color quantum number $[n]$ of the intermediate diquark configuration can be $\langle cc \rangle [^3S_1]_3$. Then its nonperturbative hadronization to T_{cc} was discussed in the phenomenological potential models. Finally, the differential distributions and theoretical uncertainty of the doubly charmed tetraquark T_{cc} were analyzed. As the collision energy increases, the contribution of the resolved photon channel will become increasingly significant, and it may even dominate the production of T_{cc} with the laser backscattering spectrum. The conclusion is that it is promising to observe T_{cc} via the resolved channel of photoproduction both at the ILC and CLIC, and the results have a strong dependence on the mass of constituent charm quark m_c and the potential model.

DOI: [10.1103/7qf8-77kl](https://doi.org/10.1103/7qf8-77kl)

I. INTRODUCTION

The heavy exotic hadrons have attracted increasing attention due to their complex structures, which differ from the structure predicted by the conventional quark models [1–3]. The heavy exotic hadrons include tetraquarks, pentaquarks, quark-gluon hybrids, hadron molecular states, etc. Among them, the doubly charmed tetraquark $T_{cc}^+(3875)$ was discovered with two heavy charm quarks and two antiquarks ($cc\bar{u}\bar{d}$) and spin-parity quantum numbers $J^P = 1^+$ by the LHCb Collaboration in the $D^0 D^0 \pi^+$ invariant mass spectrum [4,5]. In-depth study of the doubly charmed tetraquark is conducive to revealing the internal structure of hadrons and understanding strong interactions. Theoretically, $T_{cc}^+(3875)$ has been investigated by multiple methods under molecular state assumptions, such as lattice quantum chromodynamics (QCD) [6–9], sum rules [10], constituent quark model [11–16], effective field theory [17–22] and so on [23–26]. However, as the candidate of compact tetraquark with the $\langle cc \rangle$ -diquark configuration [27–42], T_{cc} has also been phenomenologically studied through hadronic production [28,43,44], photon-photon

fusion [45], electron-positron production [46], and indirect production through Higgs and weak boson decay [47,48].

High-energy colliders provide convenient experimental conditions for studying the production and decay properties of the heavy doubly charmed tetraquark states. Among them, the electron-positron Colliders, such as the International Linear Collider (ILC) [49,50] and the Compact Linear Collider (CLIC) [51,52], have become good platforms for studying exotic states because of their clean background and high luminosity. Relying on the designed collision energy and experimental parameters, we can analyze the contribution of T_{cc} produced through the resolved photon channel, and make a comparative analysis with the results produced by the photon-photon fusion channel to provide certain guidance for the detection of future experiments. At e^+e^- colliders, there are two primary sources of the photon, bremsstrahlung [53] or the laser backscattering (LBS) [54]. Therefore, based on these two photon sources, we consider T_{cc} as a compact tetraquark and study its production rates via photon-gluon fusion at ILC with center-of-mass (CM) energy $\sqrt{s} = 250, 500, 1000$ GeV and CLIC with $\sqrt{s} = 380, 1500, 3000$ GeV, respectively.

Nonrelativistic QCD (NRQCD) [55,56] theory is applied to describe the production of compact tetraquark T_{cc} , which can be factorized into short-range coefficients and long-range matrix elements. Specifically, the short-range coefficients are perturbatively obtained by the production of heavy $\langle cc \rangle$ -diquark states through the resolved photon channel. The long-range matrix elements describe the

^{*}Contact author: niujj@gxnu.edu.cn

[†]Contact author: mahonghao@pku.edu.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

hadronization of the $\langle cc \rangle$ -diquark to T_{cc} . This process is nonperturbative and highly dependent on the potential model, capable of describing the key information of heavy exotics. The spin and color quantum number of the intermediate $\langle cc \rangle$ -diquark can be $[^3S_1]_{\bar{3}}$ and $[^1S_0]_6$ for the decomposition of the $SU(3)_C$ color group, $\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$. In this paper, only the $[^3S_1]_{\bar{3}}$ configuration is taken into account to form a compact diquark state.

The rest parts of this paper are arranged as follows. In Sec. II, the calculation technology is introduced based on NRQCD. Then we present the numerical results of the cross sections, the differential distributions for the production of T_{cc} , and the main sources of theoretical uncertainty in Sec. III. Finally, Sec. IV is reserved for a summary.

II. CALCULATION TECHNOLOGY

Within the framework of NRQCD, the differential cross section for the production of doubly charmed tetraquark T_{cc} via photon-gluon fusion in e^+e^- collision can be factored into

$$\begin{aligned} d\sigma(e^+e^- \rightarrow e^+e^- + T_{cc} + \bar{c} + \bar{c}) \\ = \int dx_1 f_{\gamma/e}(x_1) \int dx_2 f_{\gamma/e}(x_2) \\ \times \sum_{i,j} \int dx_i f_{i/\gamma}(x_i) \int dx_j f_{j/\gamma}(x_j) \\ \times \sum_n d\hat{\sigma}(ij \rightarrow \langle cc \rangle[n] + \bar{c} + \bar{c}) \langle \mathcal{O}_{[n]}^{T_{cc}} \rangle. \end{aligned} \quad (1)$$

Here $f_{\gamma/e}(x)$ represents the photon distribution function, where $x = E_\gamma/E_e$ is the energy fraction of the photon emitted from the initial electron or positron, $f_{i/\gamma}(i = \gamma, g, u, d, s)$ is the Glück-Reya-Schienbein (GRS) distribution function of parton i in photon [57] and $f_{\gamma/\gamma} = \delta(1-x)$ is for the direct photoproduction process, $d\hat{\sigma}$ is the differential partonic cross section for hard subprocess $\gamma + g \rightarrow \langle cc \rangle[^3S_1]_{\bar{3}} + \bar{c} + \bar{c}$, $\langle \mathcal{O}_{[n]}^{T_{cc}} \rangle$ is the hadronization from $\langle cc \rangle$ -diquark to T_{cc} , and its nonperturbative effect usually depends on the potential model.

At e^+e^- colliders, there are two main sources that describe the distribution function of initial photon $f_{\gamma/e}(x)$. One of them is emanated through the photon bremsstrahlung of the initial electrons or positrons, which can be well described by the Weizsäcker-Williams approximation (WWA) [53],

$$\begin{aligned} f_{\gamma/e}^{\text{WWA}}(x) \\ = \frac{\alpha}{2\pi} \left(\frac{1+(1-x)^2}{x} \log \left(\frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} \right) + 2m_e^2 x \left(\frac{1}{Q_{\text{max}}^2} - \frac{1}{Q_{\text{min}}^2} \right) \right), \end{aligned} \quad (2)$$

where α denotes the electromagnetic fine structure constant, $Q_{\text{min}}^2 = m_e^2 x^2 / (1-x)$, $Q_{\text{max}}^2 = (\theta_c \sqrt{s}/2)^2 (1-x) + Q_{\text{min}}^2$, $\sqrt{s}$ is the CM energy, and $\theta_c = 32$ mrad is the maximum scattering angle of the electron or positron to ensure the real photon [58]. Another source of photon is the laser backscattering (LBS) and its photon energy spectrum is [54],

$$f_{\gamma/e}^{\text{LBS}}(x) = \frac{1}{N} \left(1 - x + \frac{1}{1-x} - \frac{4x}{x_m(1-x)} + \frac{4x^2}{x_m^2(1-x)^2} \right), \quad (3)$$

where the normalization factor N is

$$N = \left(1 - \frac{4}{x_m} - \frac{8}{x_m^2} \right) \log(1+x_m) + \frac{1}{2} + \frac{8}{x_m} - \frac{1}{2(1+x_m)^2}, \quad (4)$$

$x_m = 4E_e E_l \cos^2 \frac{\theta}{2}$ with the energy of incident electron and laser beams E_e and E_l , θ is the angle between them, and the energy fraction x of LBS is restricted by [59]

$$0 \leq x \leq \frac{x_m}{1+x_m} (x_m \approx 4.83). \quad (5)$$

We adopted both the WWA and LBS photon distribution functions for the photon at ILC with $\sqrt{s} = 250, 500, 1000$ GeV and CLIC with $\sqrt{s} = 380, 1500, 3000$ GeV, respectively.

A. Short-distance coefficient

Typical Feynman diagrams for the hard partonic process, $\gamma(p_1) + g(p_2) \rightarrow \langle cc \rangle[n](q_1) + \bar{c}(q_2) + \bar{c}(q_3)$ at leading order in $\mathcal{O}(\alpha_s^3)$ are shown in Fig. 1, and another twelve can be obtained by interchanging the initial photon and gluon lines. Here only $[n] = [^3S_1]_{\bar{3}}$ configuration is taken into account to obtain the compact $\langle cc \rangle$ -diquark state.

The differential cross section $d\hat{\sigma}$ can be rewritten as

$$\begin{aligned} d\hat{\sigma}(\gamma + g \rightarrow \langle cc \rangle[n] + \bar{c} + \bar{c}) \\ = \frac{1}{4\sqrt{(p_1 \cdot p_2)^2 - m_e^4}} \bar{\sum} |\mathcal{M}[n]|^2 d\Phi_3, \end{aligned} \quad (6)$$

where $\bar{\sum}$ stands for the average over the spins of the initial states and the sum over colors and spins of the final states, $d\Phi_3$ is the three-body phase space.

Note that, an additional factor $2^2/(2!2!)$ shall be multiplied by the squared amplitudes, where 2^2 contributes to the additional 24 Feynman diagrams resulting from the exchange of identical particles in the $\langle cc \rangle$ -diquark state, $1/(2!2!)$ due to the symmetry of identical particles of two heavy quarks inside the diquark and two final-state antiquarks. The momenta of the constituent quark in

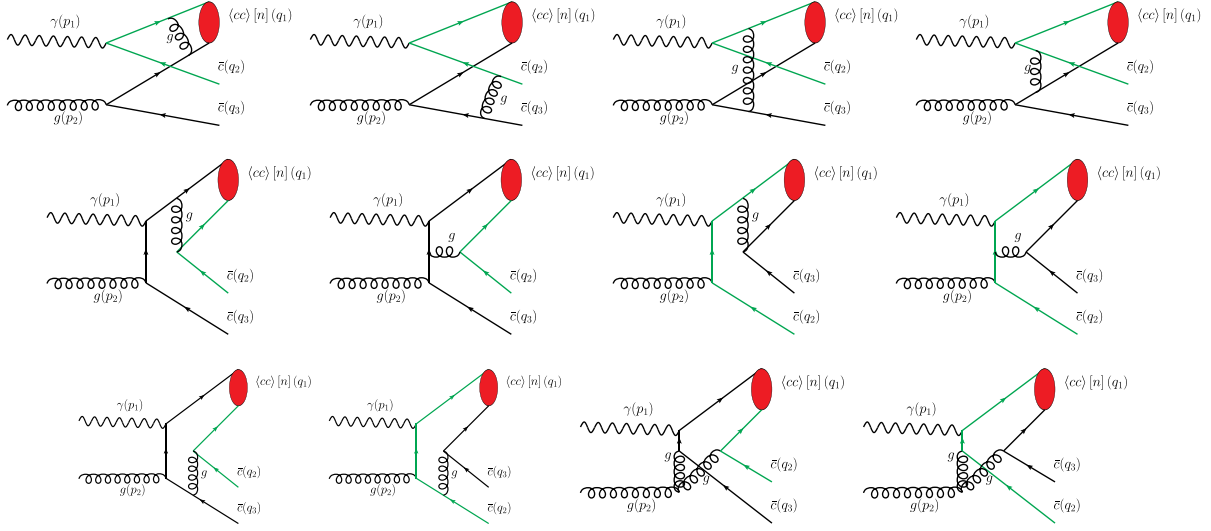


FIG. 1. Twelve typical Feynman diagrams for $\gamma + g \rightarrow \langle cc \rangle [n] + \bar{c} + \bar{c}$ subprocess, and another twelve can be obtained by interchanging the initial photon and gluon lines.

$\langle cc \rangle$ -diquark can be $q_{11} = q_1/2 + q$ and $q_{12} = q_1/2 - q$ with the small relative momentum q between two constituent quarks and $q = 0$ at the leading velocity expanding in NRQCD.

The amplitude $\mathcal{M}$ for the production of heavy $\langle cc \rangle$ -diquark can be obtained by applying the charge conjugate matrix $C = -i\gamma^2\gamma^0$ to reverse one of the fermion lines in the Feynman diagrams (green in Fig. 1). After the action of C parity, the amplitude for the production of $\langle cc \rangle$ -diquark can be related to the amplitudes of charmonium with an additional factor $(-1)^{\zeta+1}$, where ζ is the number of vector vertices in the reversed $c\bar{c}$ fermion chain [45,60].

The projector for two constituent charm quarks $v(q_{12})\bar{u}(q_{11})$ into $\langle cc \rangle [^3S_1]_3$ take the following replacement [56],

$$\frac{1}{2\sqrt{2}m_c} \not{\epsilon}(q_1)(\not{q}_1 + 2m_c) \otimes \mathcal{G}, \quad (7)$$

$\epsilon(q_1)$ is the polarization vector of spin-triplet state, and $\mathcal{G}$ is the color factor of the diquark. Note that the mass of diquark $2m_c$ can be different from the mass $m_{T_{cc}}$ because the subsequent hadronization of diquark can further generate mass.

The color factor $C_{ij,k}$ for the production of $\langle cc \rangle [^3S_1]_3$ has been extracted from the amplitudes and it satisfies the following form

$$C_{ij,k} = N \times \sum_{a=1}^8 \sum_{m,n=1}^3 (T^a)_{im} (T^a)_{jn} \times \mathcal{G}_{mnk}, \quad (8)$$

where $N = \sqrt{1/2}$ is the normalization constant, i, j, m, n are the color indices of two outgoing antiquarks and two constituent charm quarks of the diquark, respectively, k

stands for the color index of the diquark, $\mathcal{G}_{mnk}$ is the color factor for diquark in Eq. (7) and it can be adopted the antisymmetric function ϵ_{mnk} for $\langle cc \rangle_3$, which satisfies,

$$\epsilon_{mnk}\epsilon_{m'n'k} = \delta_{mm'}\delta_{nn'} - \delta_{mn'}\delta_{nm'}. \quad (9)$$

Finally, the amplitudes of all 24 Feynman diagrams need to be summed, $\mathcal{M}[n] = \sum_{i=1}^{24} \mathcal{M}_i[n]$.

B. Long-distance matrix element

The long-distance matrix element $\mathcal{O}_{\langle cc \rangle [n]}^{T_{cc}}$ in Eq. (1) describes the hadronization from intermediate $\langle cc \rangle$ -diquark in spin and color state $[n]$ to T_{cc} , which is accompanied by a large nonperturbative effect and has a high dependence on the potential model. In this paper, we will theoretically predict its value in three different hadronization schemes. First of all, we will simply adopt the nonrelativistic quark model to correlate the long-range matrix element with the Schrödinger wave function at the origin $\Psi_{T_{cc}[n]}(r=0)$, and then they can be naturally associated with the radiation wave function at origin for S-wave [46],

$$\mathcal{O}_{\langle cc \rangle [n]}^{T_{cc}} \rightarrow |\Psi_{\langle cc \rangle [n]}^{T_{cc}}(r=0)|^2 = \frac{|R_{\langle cc \rangle [n]}^{T_{cc}}(r=0)|^2}{4\pi}. \quad (10)$$

Under the harmonic oscillator potential (HOP) [46], the solved value of $\mathcal{O}_{\langle cc \rangle [n]}^{T_{cc}}$ is 0.089 GeV^3 .

After that, the diquark-antiquark symmetry (DAS) [61–67] is utilized to analyze the long-distance matrix element. According to the color interaction, the $\langle cc \rangle$ -diquark in color antitriplet can act as an antiquark $\bar{c}$, which has the same color. Therefore, the hadronization of $\langle cc \rangle_3$ into the tetraquark state T_{cc} with quark constituents $cc\bar{u}\bar{d}$

can be related to the transition of an anticharm quark $\bar{c}$ to heavy anticharm baryon $\bar{\Lambda}_c^-$ with quark constituents $\bar{c}\bar{u}\bar{d}$, i.e., $\langle cc \rangle_3 \rightarrow T_{cc}(cc\bar{u}\bar{d}) \Leftrightarrow \bar{c} \rightarrow \bar{\Lambda}_c^-(\bar{c}\bar{u}\bar{d})$. And the transition probability of $\bar{c} \rightarrow \bar{\Lambda}_c^-(\bar{c}\bar{u}\bar{d})$ can be estimated by the fragmentation fraction of $c \rightarrow \Lambda_c^+(cud)$, whose value can be obtained by fitting the experimental data $f(c \rightarrow \Lambda_c^+) = 0.06$ [68]. For the transition of a heavy cc pair into $\langle cc \rangle$ -diquark, the Schrödinger wave function at the origin $\Psi_{cc}(0)$ is available, its value is slightly different and is estimated in different potential models. Under the power-law potential [69], $|\Psi_{cc}(0)|^2 = 0.039 \text{ GeV}^3$ is estimated in Ref. [70], and directly used in the numerical calculation. Therefore the hadronization $\mathcal{O}_{\langle cc \rangle[n]}^{T_{cc}}$ can be rewritten as,

$$\mathcal{O}_{\langle cc \rangle[n]}^{T_{cc}} \rightarrow |\Psi_{cc}(0)|^2 \times f(c \rightarrow \Lambda_c^+) = 0.00234 \text{ GeV}^3. \quad (11)$$

Similarly, DAS symmetry can be used to describe the light antidiquark $\langle \bar{u}\bar{d} \rangle$, the light antiquarks of T_{cc} , and its color interaction can be regarded as a light quark [71]. When the heavy cc pair transitions to the $\langle cc \rangle$ -diquark by $\Psi_{cc}(0)$, and then a light quark can be captured 100% from the vacuum to form the tetraquark state. This process is the same as the hadronization of doubly charmed baryons. By this way, the hadronization $\mathcal{O}_{\langle cc \rangle[n]}^{T_{cc}}$ can be

$$\mathcal{O}_{\langle cc \rangle[n]}^{T_{cc}} \rightarrow |\Psi_{cc}(0)|^2 = 0.039 \text{ GeV}^3. \quad (12)$$

These three hadronization schemes for the production of tetraquarks are accompanied by great uncertainties, and we will also conduct in-depth analysis in the numerical part.

III. NUMERICAL RESULTS

The input parameters in the numerical calculation are listed below

$$\begin{aligned} m_c &= 1.8 \text{ GeV}, & |\Psi_{cc}(0)|^2 &= 0.039 \text{ GeV}^3, \\ \alpha &= 1/132.23, & \mu &= \sqrt{4m_c^2 + p_T^2}, \end{aligned} \quad (13)$$

μ is the renormalization scale, which is typically taken as the transverse mass of the final-state doubly charmed tetraquark with its transverse momentum p_T . The strong running coupling can be obtained from the solution of the one-loop renormalization group equation with the reference point $\alpha_s(m_Z) = 0.1180$ [72]. The long-distance matrix element $\mathcal{O}_{\langle cc \rangle[n]}^{T_{cc}}$ obtained by HDAS hadronization scheme in Sec. II B is used as a representative for numerical calculation, and the theoretical uncertainty caused by the long-distance matrix element obtained in three different hadronization schemes are analyzed subsequently.

The cross sections σ for the production of $T_{cc}[\bar{3}S_1]_3$ at ILC and CLIC are calculated through the resolved photon-gluon fusion using both WWA and LBS photon spectrum,

TABLE I. The cross sections (in unit: fb) for $T_{cc}[\bar{3}S_1]_3$ production at ILC and CLIC via photon-photon and photon-gluon fusion using the WWA and LBS spectrum.

$\sqrt{s}$ (GeV)		ILC			CLIC		
		250	500	1000	380	1500	3000
WWA	$\gamma + \gamma$	4.53	7.37	9.36	6.27	9.81	9.28
	$\gamma + g$	0.16	0.47	1.18	0.31	1.88	3.86
	Total	4.68	7.84	10.53	6.58	11.70	13.13
LBS	$\gamma + \gamma$	51.04	22.11	8.52	31.27	4.67	1.58
	$\gamma + g$	45.31	78.11	124.43	63.72	151.68	30.08
	Total	96.35	100.22	132.95	94.99	156.35	31.66

respectively. For comprehension, the cross sections via photon-photon fusion based on the same parameters are also listed in Table I. The designed CM collision energy is selected to be $\sqrt{s} = 250, 500, \text{ and } 1000 \text{ GeV}$ at ILC, and $\sqrt{s} = 380, 1500, \text{ and } 3000 \text{ GeV}$ at CLIC.

From Table I, we can see that the contribution from LBS photon spectrum is dominant than WWA. With the increase of CM energy, the trend of the cross section is to rise first and then decrease for LBS photon spectrum. However for the WWA photon spectrum, it is not until the CM energy reaches 3000 GeV that its downward trend was shown. For resolved photon-gluon fusion, the cross section keeps showing an increasing trend when the collision energy increases to 3000 GeV. In the WWA photon spectrum, as the CM energy increases, the contribution of the resolved photon-gluon channel continues to rise, being 3.53%, 6.38%, 12.61% of that of the photon-photon channel. The same conclusion can also be obtained at CLIC. While in the LBS photon spectrum, the contribution of the resolved photon-gluon channel increased significantly with the increase of CM energy at ILC, up to 88.77%, 3.53, 14.60 times of that of the photon-photon channel. At CLIC, the contribution of the resolved photon-gluon channel can be 2.04, 32.48, and 19.04 times of that of the photon-photon channel at $\sqrt{s} = 380, 1500, \text{ and } 3000 \text{ GeV}$. Therefore, the study of the production of tetraquark states through resolved photon-gluon channel cannot be ignored at e^+e^- collider.

With the designed luminosity $L = 2, 4, 8 \text{ ab}^{-1}$ corresponding to ILC at $\sqrt{s} = 250, 500, \text{ and } 1000 \text{ GeV}$ and $L = 1, 2.5, 5 \text{ ab}^{-1}$ for CLIC at $\sqrt{s} = 380, 1500, \text{ and } 3000 \text{ GeV}$, respectively, the total produced events of T_{cc} via photoproduction can be estimated by $\sigma \times L$, approximately 9.37×10^3 (1.92×10^5), 3.13×10^4 (4.01×10^5), and 8.43×10^4 (1.06×10^6) each year at ILC with $\sqrt{s} = 250, 500, \text{ and } 1000 \text{ GeV}$ using the WWA (LBS) photon spectrum. At CLIC with $\sqrt{s} = 380, 1500, \text{ and } 3000 \text{ GeV}$, the total produced events of T_{cc} via photoproduction can be 6.58×10^3 (9.50×10^4), 2.92×10^4 (3.91×10^5), and 6.57×10^4 (1.58×10^5) each year using

TABLE II. Theoretical uncertainty of the cross sections (in unit: fb) by varying $m_c = 1.5, 1.65, 1.8, 1.95$, and 2.1 GeV for the photoproduction of $T_{cc}[^3S_1]_3$ at $\sqrt{s} = 500$ GeV using the WWA and LBS spectrum.

m_c (GeV)		1.5	1.65	1.8	1.95	2.1
WWA	$\gamma + \gamma$	21.93	12.41	7.37	4.55	2.91
	$\gamma + g$	1.54	0.83	0.47	0.28	0.17
	Total	23.47	13.24	7.84	4.83	3.08
LBS	$\gamma + \gamma$	48.60	32.20	22.11	15.64	11.36
	$\gamma + g$	227.79	130.27	78.11	48.72	31.30
	Total	276.39	162.47	100.22	64.36	42.66

the WWA (LBS) photon spectrum. Based on such a base number and considering the subsequent decay of the doubly charmed tetraquark, it is still possible for T_{cc} to be experimentally discovered at linear electron-positron colliders through photoproduction.

Then three main sources of theoretical uncertainty are emphatically analyzed, the mass of charm quark, the renormalization scale, and the long-distance element matrix. First is the mass of the constituent charm quark. In Table II, the mass of the constituent charm quark is set to be $m_c = 1.8 \pm 0.3$ GeV to analyze the theoretical uncertainty of cross section at $\sqrt{s} = 500$ GeV, and m_c takes five options, $m_c = 1.5, 1.65, 1.8, 1.95$, and 2.1 GeV. Note that when analyzing the theoretical uncertainty arising from one source, the other parameters from different sources remain at their central values. Table II shows that with the increase of m_c , the cross section decreases significantly for the suppression of the phase space. Second, by typically changing the renormalization energy scale μ to be $\mu_0/2$, μ_0 , and $2\mu_0$ with $\mu_0 = \sqrt{4m_c^2 + p_T^2}$, the dependence of the cross section on the energy scale can be seen from Table III. Due to the asymptotic freedom characteristic of QCD, as the energy scale increases (decrease), the strong running coupling constant α_s decreases logarithmically, resulting in a decrease (increase) in the cross section. Finally, three hadronization schemes are applied to compare the non-perturbative effect of the long-distance matrix element $\mathcal{O}_{(cc)[n]}^{T_{cc}}$, which is presented in Table IV. As can be seen

TABLE III. Theoretical uncertainty of the cross sections (in unit: fb) by varying $\mu = \mu_0/2, \mu_0$ and $2\mu_0$ with $\mu_0 = \sqrt{4m_c^2 + p_T^2}$ for the photoproduction of $T_{cc}[^3S_1]_3$ at $\sqrt{s} = 500$ GeV using the WWA and LBS spectrum.

Scale	WWA			LBS		
	$\mu_0/2$	μ_0	$2\mu_0$	$\mu_0/2$	μ_0	$2\mu_0$
$\gamma + \gamma$	12.53	7.37	5.02	36.58	22.11	15.31
$\gamma + g$	0.58	0.47	0.40	87.16	78.11	70.37
Total	13.11	7.84	5.42	123.73	100.22	85.68

TABLE IV. Theoretical uncertainty of the cross sections (in unit: fb) by applying three hadronization schemes, HOP, HDAS, and DAS, to obtain the long-distance matrix element $\mathcal{O}_{(cc)[n]}^{T_{cc}}$ for the photoproduction of $T_{cc}[^3S_1]_3$ at $\sqrt{s} = 500$ GeV using the WWA and LBS spectrum.

$\mathcal{O}_{(cc)[n]}^{T_{cc}}$		HOP	HDAS	DAS
WWA	$\gamma + \gamma$	280.17	7.37	122.77
	$\gamma + g$	17.89	0.47	7.84
	Total	298.06	7.84	130.61
LBS	$\gamma + \gamma$	840.93	22.11	368.50
	$\gamma + g$	2970.92	78.11	1301.86
	Total	3811.86	100.22	1670.36

from Table IV, the contributions for the photoproduction of $T_{cc}[^3S_1]_3$ in the HOP hadronization scheme are much greater than those in the DAS and HDAS hadronization scheme, being 2.28 times and 36.63 times, respectively, because the long-distance element matrix obtained in HOP hadronization scheme are much larger, while the matrix elements obtained by HDAS are the smallest. This is also the reason why we select the matrix element obtained by HDAS as the center value for numerical calculation in Tables I–III. This phenomenon shows a very large non-perturbation effect.

In order to show the kinematic properties and provide some guidance for future experimental detection, the differential distributions for the photoproduction of doubly charmed tetraquark T_{cc} at $\sqrt{s} = 500$ GeV are presented in Fig. 2, including the transverse momentum p_T distribution, the invariant mass s_{12} , the angular $\cos \theta$ and $\cos \theta_{12}$, where the definition of squared invariant mass $s_{12} = (q_1 + q_2)^2$, θ (θ_{12}) is the angle between the momenta $\vec{q}_1$ of T_{cc} and the initial photon $\vec{p}_1$ (outgoing anticharmed quark $\vec{q}_2$). From Fig. 2, the contributions from LBS spectrum are much larger than that of using WWA. And in the WWA spectrum, the contribution of photon-photon fusion (blue line) is larger than that of photon-gluon fusion (red line) in the whole region. From the transverse momentum p_T distribution and invariant mass s_{12} distribution, the differential cross section shows a major downward trend for photoproduction of T_{cc} . And in the LBS spectrum, the results from the resolved photon channel become dominant only in the small transverse momentum p_T region, $p_T \leq 30$ GeV. From the angular distributions $\cos \theta$ and $\cos \theta_{12}$, it is shown that the curves present a valley shape. And the greatest contribution can be obtained when $\theta = 0(\pi)$, that is to say T_{cc} is most likely to move back-to-back with the anticharm quark $\bar{c}$ in the beam direction.

Combined with the experimental parameters, different transverse momentum cuts, $p_T \geq 1, 5, 10$ GeV, are adopted to evaluate the cross sections for the photoproduction of T_{cc} at ILC and CLIC. The results are listed in Table V. From

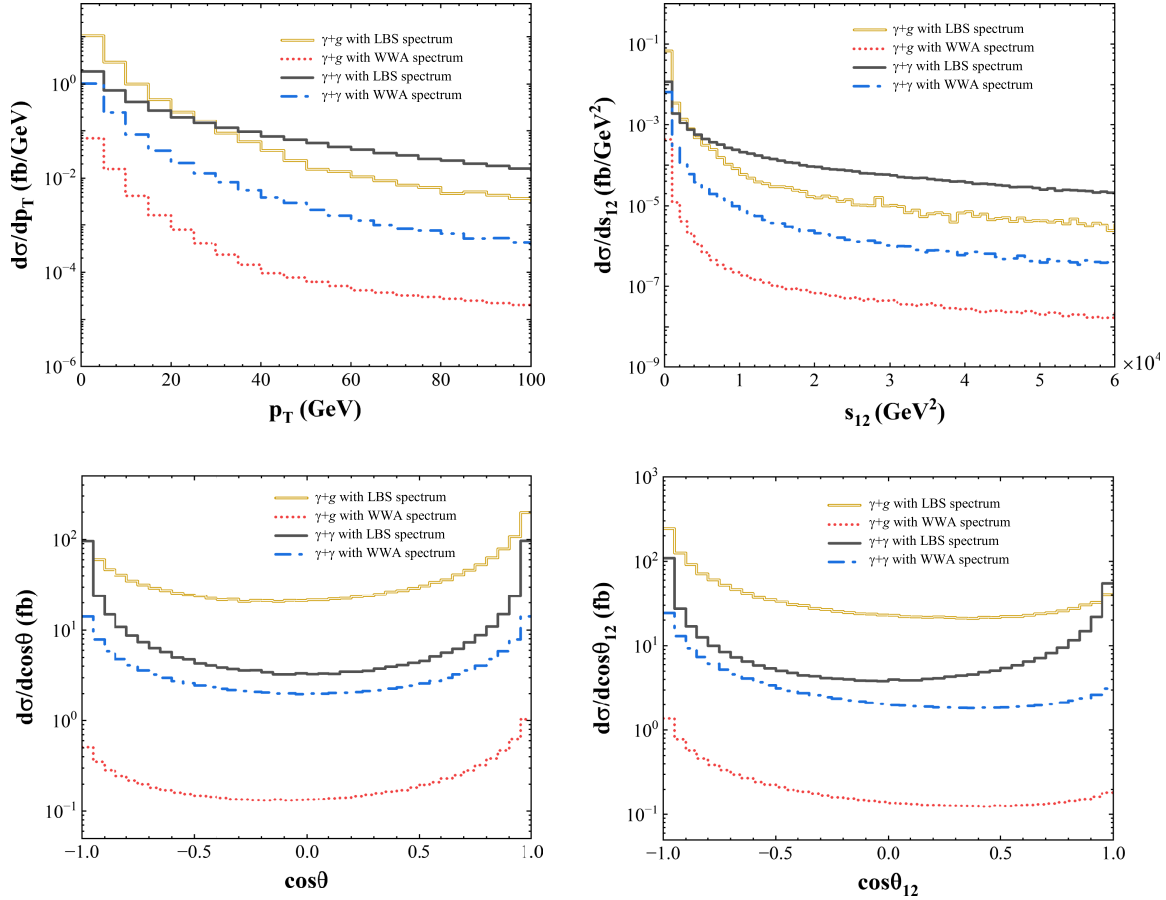
FIG. 2. Differential distributions for the photoproduction of T_{cc} at $\sqrt{s} = 500$ GeV.

Table V, we see that the cross sections for the photoproduction of T_{cc} through WWA (LBS) with $p_T \geq 1, 5, 10$ GeV cut are 84.2% (85.2%), 29.8% (38.4%), 12.7% (20.3%) of that without the transverse momentum cut correspondingly at $\sqrt{s} = 500$ GeV. Therefore, the contributions in small p_T region are crucial for experimental detection.

TABLE V. Cross sections (in unit: fb) by added different transverse momentum cuts, $p_T \geq 1, 5, 10$ GeV, for the photoproduction of $T_{cc}[^3S_1]_3$ at $\sqrt{s} = 500$ GeV using the WWA and LBS spectrum.

p_T cuts		$p_T \geq 1$ GeV	$p_T \geq 5$ GeV	$p_T \geq 10$ GeV
WWA	$\gamma + \gamma$	6.21	2.22	0.95
	$\gamma + g$	0.39	0.12	0.04
	Total	6.60	2.34	0.99
LBS	$\gamma + \gamma$	19.45	12.78	9.08
	$\gamma + g$	65.97	25.72	11.31
	Total	85.42	38.50	20.39

IV. SUMMARY

Within the framework of NRQCD, the photoproduction of doubly charmed tetraquark T_{cc} has been analyzed through the resolved photon channel, $\gamma + g \rightarrow \langle cc \rangle [n] + \bar{c} + \bar{c} \rightarrow T_{cc} + \bar{c} + \bar{c}$ at leading order in $\mathcal{O}(\alpha_s^3)$, where both the WWA and LBS photon spectrum are adopted for the initial photon at ILC and CLIC. Only the color and spin quantum number $^3S_1]_3$ of the intermediate $\langle cc \rangle$ -diquark is taken into consideration to form the compact T_{cc} .

The cross sections for the photoproduction of photon-gluon fusion and photon-photon fusion are numerically calculated at ILC with $\sqrt{s} = 250, 500, 1000$ GeV and CLIC with $\sqrt{s} = 380, 1500, 3000$ GeV. From Table I, it can be seen that the contribution from LBS photon spectrum is dominant than WWA. In WWA photon spectrum, as the CM energy increases, the contribution of the resolved photon-gluon channel continues to rise, being 3.53%, 6.38%, 12.61% of that of the photon-photon channel. The same trend can also be obtained at CLIC. While in LBS photon spectrum, the contribution of the resolved photon-gluon channel increased significantly with the increase of CM energy at ILC, up to 88.77%, 3.53, 14.60 times of that of the photon-photon channel. At CLIC,

the contribution of the resolved photon-gluon channel can be 2.04, 32.48, and 19.04 times of that of the photon-photon channel at $\sqrt{s} = 380, 1500$, and 3000 GeV. Therefore, the study of the production of tetraquark states through resolved photon-gluon channel cannot be ignored at e^+e^- collider.

With the designed luminosity $L = 2, 4, 8 \text{ ab}^{-1}$ corresponding to ILC at $\sqrt{s} = 250, 500$, and 1000 GeV and $L = 1, 2.5, 5 \text{ ab}^{-1}$ for CLIC at $\sqrt{s} = 380, 1500$, and 3000 GeV, respectively, the total produced events of T_{cc} via photoproduction can be approximately $9.37 \times 10^3 - 8.43 \times 10^4$ ($1.92 \times 10^5 - 1.06 \times 10^6$) each year at ILC with $\sqrt{s} = 250, 500$, and 1000 GeV using the WWA (LBS) photon spectrum. At CLIC with $\sqrt{s} = 380, 1500$, and 3000 GeV, the total produced events of T_{cc} via photoproduction can be $6.58 \times 10^3 - 6.57 \times 10^4$ ($9.50 \times 10^4 - 3.91 \times 10^5$) each year using WWA (LBS) photon spectrum. Based on such a base number and considering the subsequent decay of the doubly charmed tetraquark, it is still possible for T_{cc} to be experimentally discovered at linear electron-positron colliders through photoproduction.

Three main sources of theoretical uncertainty, the mass of charm quark, the renormalization scale, and the long-distance element matrix, are emphatically analyzed, which are shown in Tables II–IV. The constituent charm quark mass of $\langle cc \rangle$ -diquark is set to be $m_c = 1.8 \pm 0.3$ GeV and the renormalization energy scale μ is changed to be $\mu_0/2$, μ_0 , and $2\mu_0$ with $\mu_0 = \sqrt{4m_c^2 + p_T^2}$ to analyze the theoretical uncertainty. Three different hadronization schemes, HOP, HDAS, and DAS for the $\langle cc \rangle [^3S_1]_3$ into T_{cc} are also discussed. This phenomenon shows a very large non-perturbation effect.

Finally, the transverse momentum, the invariant mass, and the angular distributions of T_{cc} are presented in Fig. 2. As can be found in LBS spectrum, the results from the resolved photon channel become dominant only in the small transverse momentum p_T region, $p_T \leq 30$ GeV. From the angular distributions $\cos\theta$ and $\cos\theta_{12}$, it is shown that the greatest contribution can be obtained when $\theta = 0(\pi)$, that is to say T_{cc} is most likely to move back-to-back with the anticharm quark $\bar{c}$ in the beam direction. Therefore, compared to the traditional photon-photon fusion channel, the contribution of T_{cc} through the photon-gluon channel is also significant, and a sufficient number of events can be produced for experiments on future ILC and CLIC to be detected.

ACKNOWLEDGMENTS

Thanks for helpful discussion with Xi-Jie Zhan and Jun Jiang. This work was partially supported by the Natural Science Foundation of Guangxi (No. 2024GXNSFBA010368, No. 2025GXNSFAA069775). This work was also supported by Guangxi Young Elite Scientist Sponsorship Program (No. GXYESS2025005). This work was still funded by the National Natural Science Foundation of China (Grants No. 12505106).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] M. Gell-Mann, A schematic model of baryons and mesons, *Phys. Lett.* **8**, 214 (1964).
 - [2] G. Zweig, An SU(3) model for strong interaction symmetry and its breaking, Version 1, European Organization for Nuclear Research (CERN) Report No. CERN-TH-401, 10.17181/CERN-TH-401.
 - [3] G. Zweig, An SU(3) model for strong interaction symmetry and its breaking, Version 2, European Organization for Nuclear Research (CERN) Report No. CERN-TH-412, 10.17181/CERN-TH-412.
 - [4] R. Aaij *et al.* (LHCb Collaboration), Observation of an exotic narrow doubly charmed tetraquark, *Nat. Phys.* **18**, 751 (2022).
 - [5] R. Aaij *et al.* (LHCb Collaboration), Study of the doubly charmed tetraquark T_{cc}^+ , *Nat. Commun.* **13**, 3351 (2022).
 - [6] Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, and J. Meng, Doubly charmed tetraquark T_{cc}^+ from lattice QCD near physical point, *Phys. Rev. Lett.* **131**, 161901 (2023).
 - [7] M. Padmanath and S. Prelovsek, Signature of a doubly charmed tetraquark pole in DD^* scattering on the lattice, *Phys. Rev. Lett.* **129**, 032002 (2022).
 - [8] S. Chen, C. Shi, Y. Chen, M. Gong, Z. Liu, W. Sun, and R. Zhang, $T_{cc}^+(3875)$ relevant DD^* scattering from $N_f = 2$ lattice QCD, *Phys. Lett. B* **833**, 137391 (2022).
 - [9] S. Collins, A. Nefediev, M. Padmanath, and S. Prelovsek, Toward the quark mass dependence of T_{cc}^+ from lattice QCD, *Phys. Rev. D* **109**, 094509 (2024).
 - [10] Q. Xin and Z. G. Wang, Analysis of the doubly-charmed tetraquark molecular states with the QCD sum rules, *Eur. Phys. J. A* **58**, 110 (2022).
 - [11] X. Chen and Y. Yang, Doubly-heavy tetraquark states $cc\bar{u}\bar{d}$ and $bb\bar{u}\bar{d}^*$, *Chin. Phys. C* **46**, 054103 (2022).
 - [12] C. Deng and S. L. Zhu, T_{cc}^+ and its partners, *Phys. Rev. D* **105**, 054015 (2022).
 - [13] C. R. Deng and S. L. Zhu, Decoding the double heavy tetraquark state T_{cc}^+ , *Sci. Bull.* **67**, 1522 (2022).

- [14] P. G. Ortega, J. Segovia, D. R. Entem, and F. Fernandez, Nature of the doubly-charmed tetraquark T_{cc}^+ in a constituent quark model, *Phys. Lett. B* **841**, 137918 (2023); , **847**, 138308(E) (2023).
- [15] L. Meng, Y. K. Chen, Y. Ma, and S. L. Zhu, Tetraquark bound states in constituent quark models: Benchmark test calculations, *Phys. Rev. D* **108**, 114016 (2023).
- [16] Y. Ma, L. Meng, Y. K. Chen, and S. L. Zhu, Doubly heavy tetraquark states in the constituent quark model using diffusion Monte Carlo method, *Phys. Rev. D* **109**, 074001 (2024).
- [17] S. Fleming, R. Hodges, and T. Mehen, T_{cc}^+ decays: Differential spectra and two-body final states, *Phys. Rev. D* **104**, 116010 (2021).
- [18] L. Meng, G. J. Wang, B. Wang, and S. L. Zhu, Probing the long-range structure of the T_{cc}^+ with the strong and electromagnetic decays, *Phys. Rev. D* **104**, 051502 (2021).
- [19] K. Chen, R. Chen, L. Meng, B. Wang, and S. L. Zhu, Systematics of the heavy flavor hadronic molecules, *Eur. Phys. J. C* **82**, 581 (2022).
- [20] E. Braaten, L. P. He, K. Ingles, and J. Jiang, Triangle singularity in the production of $T_{cc}^+(3875)$ and a soft pion, *Phys. Rev. D* **106**, 034033 (2022).
- [21] B. Wang and L. Meng, Revisiting the DD^* chiral interactions with the local momentum-space regularization up to the third order and the nature of T_{cc}^+ , *Phys. Rev. D* **107**, 094002 (2023).
- [22] L. Dai, S. Fleming, R. Hodges, and T. Mehen, Strong decays of T_{cc}^+ at NLO in an effective field theory, *Phys. Rev. D* **107**, 076001 (2023).
- [23] M. L. Du, V. Baru, X. K. Dong, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, and Q. Wang, Coupled-channel approach to T_{cc}^+ including three-body effects, *Phys. Rev. D* **105**, 014024 (2022).
- [24] M. Albaladejo, T_{cc}^+ coupled channel analysis and predictions, *Phys. Lett. B* **829**, 137052 (2022).
- [25] V. Montesinos, M. Albaladejo, J. Nieves, and L. Tolos, Properties of the $T_{cc}(3875)^+$ and $T_{cc}(3875)^-$ and their heavy-quark spin partners in nuclear matter, *Phys. Rev. C* **108**, 035205 (2023).
- [26] G. J. Wang, Z. Yang, J. J. Wu, M. Oka, and S. L. Zhu, New insight into the exotic states strongly coupled with the DD^{*-} from the T_{cc}^+ , *Sci. Bull.* **69**, 3036 (2024).
- [27] W. X. Zhang, H. Xu, and D. Jia, Masses and magnetic moments of hadrons with one and two open heavy quarks: Heavy baryons and tetraquarks, *Phys. Rev. D* **104**, 114011 (2021).
- [28] Q. Qin, Y. F. Shen, and F. S. Yu, Discovery potentials of double-charm tetraquarks, *Chin. Phys. C* **45**, 103106 (2021).
- [29] Y. Jin, S. Y. Li, Y. R. Liu, Q. Qin, Z. G. Si, and F. S. Yu, Color and baryon number fluctuation of preconfinement system in production process and T_{cc} structure, *Phys. Rev. D* **104**, 114009 (2021).
- [30] X. Z. Weng, W. Z. Deng, and S. L. Zhu, Doubly heavy tetraquarks in an extended chromomagnetic model, *Chin. Phys. C* **46**, 013102 (2022).
- [31] T. Guo, J. Li, J. Zhao, and L. He, Mass spectra of doubly heavy tetraquarks in an improved chromomagnetic interaction model, *Phys. Rev. D* **105**, 014021 (2022).
- [32] S. S. Agaev, K. Azizi, and H. Sundu, Newly observed exotic doubly charmed meson T_{cc}^+ , *Nucl. Phys.* **B975**, 115650 (2022).
- [33] R. Albuquerque, S. Narison, and D. Rabetiarivony, Improved XTZ masses and mass ratios from Laplace sum rules at NLO, *Nucl. Phys.* **A1023**, 122451 (2022).
- [34] D. Gao, D. Jia, Y. J. Sun, Z. Zhang, W. N. Liu, and Q. Mei, Masses of doubly heavy tetraquarks $QQ\bar{q}\bar{n}$ with $J^P = 1^+$, *Mod. Phys. Lett. A* **37**, 2250223 (2022).
- [35] L. Maiani, A. Pilloni, A. D. Polosa, and V. Riquer, Doubly heavy tetraquarks in the Born-Oppenheimer approximation, *Phys. Lett. B* **836**, 137624 (2023).
- [36] X. Y. Liu, W. X. Zhang, and D. Jia, Doubly heavy tetraquarks: Heavy quark bindings and chromomagnetically mixings, *Phys. Rev. D* **108**, 054019 (2023).
- [37] Q. Meng, E. Hiyama, M. Oka, A. Hosaka, and C. Xu, Doubly heavy tetraquarks including one-pion exchange potential, *Phys. Lett. B* **846**, 138221 (2023).
- [38] S. Noh and W. Park, Nonrelativistic quark model analysis of T_{cc} , *Phys. Rev. D* **108**, 014004 (2023).
- [39] T. W. Wu and Y. L. Ma, Doubly heavy tetraquark multiplets as heavy antiquark-diquark symmetry partners of heavy baryons, *Phys. Rev. D* **107**, L071501 (2023).
- [40] H. Mutuk, Masses and magnetic moments of doubly heavy tetraquarks via diffusion Monte Carlo method, *Eur. Phys. J. C* **84**, 395 (2024).
- [41] D. Wang, K. R. Song, W. L. Wang, and F. Huang, Spectrum of S- and P-wave $cc\bar{q}\bar{q}'$ ($\bar{q}, \bar{q}' = \bar{u}, \bar{d}, \bar{s}$) systems in a chiral SU(3) quark model, *Phys. Rev. D* **109**, 074026 (2024).
- [42] S. Y. Li, Y. R. Liu, Z. L. Man, Z. G. Si, and J. Wu, Doubly heavy tetraquark states in a mass splitting model, *Phys. Rev. D* **110**, 094044 (2024).
- [43] Y. q. Chen and S. z. Wu, Production of four-quark states with double heavy quarks at LHC, *Phys. Lett. B* **705**, 93 (2011).
- [44] H. Yang, J. Jiang, and B. Long, Doubly heavy hadron production in ultraperipheral collision, *Phys. Rev. D* **109**, 114034 (2024).
- [45] J. Jiang, S. Y. Li, X. Liang, Y. R. Liu, Z. G. Si, and Z. J. Yang, Production of doubly charmed tetraquark T_{cc} via photon-photon fusion at electron-positron colliders, *Phys. Lett. B* **866**, 139543 (2025).
- [46] T. Hyodo, Y. R. Liu, M. Oka, K. Sudoh, and S. Yasui, Production of doubly charmed tetraquarks with exotic color configurations in electron-positron collisions, *Phys. Lett. B* **721**, 56 (2013).
- [47] J. J. Niu, B. B. Shi, Z. K. Tao, and H. H. Ma, Indirect production of doubly charmed tetraquark T_{cc} at high energy colliders, *Phys. Rev. D* **111**, 014019 (2025).
- [48] F. A. Martynenko, A. P. Martynenko, and A. V. Eskin, Production of heavy quark bound states in rare exclusive decays of Higgs boson, [arXiv:2505.04530](https://arxiv.org/abs/2505.04530).
- [49] J. Brau *et al.* (ILC Collaboration), ILC reference design report volume 1—executive summary, [arXiv:0712.1950](https://arxiv.org/abs/0712.1950).
- [50] A. Djouadi *et al.* (ILC Collaboration), International linear collider reference design report volume 2: Physics at the ILC, [arXiv:0709.1893](https://arxiv.org/abs/0709.1893).
- [51] L. Linssen, A. Miyamoto, M. Stanitzki, and H. Weerts, Physics and detectors at CLIC: CLIC conceptual design report, [arXiv:1202.5940](https://arxiv.org/abs/1202.5940).

- [52] P. N. Burrows *et al.* (CLICdp and CLIC Collaborations), The compact linear collider (CLIC)—2018 summary report, [arXiv:1812.06018](#).
- [53] S. Frixione, M. L. Mangano, P. Nason, and G. Ridolfi, Improving the Weizsacker-Williams approximation in electron-proton collisions, *Phys. Lett. B* **319**, 339 (1993).
- [54] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, and V. I. Telnov, Colliding ge and gg beams based on the single-pass $e^\pm e^-$ colliders (VLEPP type), *Nucl. Instrum. Methods* **205**, 47 (1983).
- [55] G. T. Bodwin, E. Braaten, and G. P. Lepage, Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium, *Phys. Rev. D* **51**, 1125 (1995); **55**, 5853(E) (1997).
- [56] A. Petrelli, M. Cacciari, M. Greco, F. Maltoni, and M. L. Mangano, NLO production and decay of quarkonium, *Nucl. Phys. B* **514**, 245 (1998).
- [57] M. Gluck, E. Reya, and I. Schienbein, Radiatively generated parton distributions of real and virtual photons, *Phys. Rev. D* **60**, 054019 (1999); **62**, 019902(E) (2000).
- [58] M. Klasen, B. A. Kniehl, L. Mihaila, and M. Steinhauser, Evidence for color octet mechanism from CERN LEP-2 $\gamma\gamma \rightarrow J/\psi + X$ data, *Phys. Rev. Lett.* **89**, 032001 (2002).
- [59] V. I. Telnov, Problems of obtaining $\gamma\gamma$ and γe colliding beams at linear colliders, *Nucl. Instrum. Methods Phys. Res., Sect. A* **294**, 72 (1990).
- [60] H. H. Ma, J. J. Niu, and L. Guo, Further study on excited $\Xi_{QQ'}$ via photoproduction at CEPC and FCC-ee, *J. High Energy Phys.* **05** (2025) 197.
- [61] D. B. Lichtenberg, Symmetry and supersymmetry in hadrons containing both heavy and light quarks, *J. Phys. G* **16**, 1599 (1990).
- [62] M. Anselmino, E. Predazzi, S. Ekelin, S. Fredriksson, and D. B. Lichtenberg, Diquarks, *Rev. Mod. Phys.* **65**, 1199 (1993).
- [63] J. Carlson, L. Heller, and J. A. Tjon, Stability of dimesons, *Phys. Rev. D* **37**, 744 (1988).
- [64] M. J. Savage and M. B. Wise, Spectrum of baryons with two heavy quarks, *Phys. Lett. B* **248**, 177 (1990).
- [65] N. Brambilla, A. Vairo, and T. Rosch, Effective field theory Lagrangians for baryons with two and three heavy quarks, *Phys. Rev. D* **72**, 034021 (2005).
- [66] S. Fleming and T. Mehen, Doubly heavy baryons, heavy quark-diquark symmetry and NRQCD, *Phys. Rev. D* **73**, 034502 (2006).
- [67] T. D. Cohen and P. M. Hohler, Doubly heavy hadrons and the domain of validity of doubly heavy diquark-anti-quark symmetry, *Phys. Rev. D* **74**, 094003 (2006).
- [68] M. Lisovskyi, A. Verbitskyi, and O. Zenaiev, Combined analysis of charm-quark fragmentation-fraction measurements, *Eur. Phys. J. C* **76**, 397 (2016).
- [69] E. Bagan, H. G. Dosch, P. Gosdzinsky, S. Narison, and J. M. Richard, Hadrons with charm and beauty, *Z. Phys. C* **64**, 57 (1994).
- [70] S. P. Baranov, On the production of doubly flavored baryons in pp, ep and $\gamma\gamma$ collisions, *Phys. Rev. D* **54**, 3228 (1996).
- [71] J. B. Cheng, S. Y. Li, Y. R. Liu, Z. G. Si, and T. Yao, Double-heavy tetraquark states with heavy diquark-antiquark symmetry, *Chin. Phys. C* **45**, 043102 (2021).
- [72] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).