The Production of $\Xi_{bb}$ at Photon Collider

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The inclusive production of the doubly heavy baryon $\Xi_{bb}$ is investigated at polarized and unpolarized photon collider. bb pair in both color triplet and sextet have been considered to transform into $\Xi_{bb}$. The results indicate that the contribution from color sextet is about 8% for $\Xi_{bb}$ production. For the ILC collision energy ranging from $91\text{GeV}$ to $1000\text{GeV}$, the total cross section of $\Xi_{bb}$ shows a downtrend, i.e., the production of $\Xi_{bb}$ has the maximal rate at $\sqrt{s} = 91\text{GeV}$. Our results indicate that the initial beam polarization may be an important asset for the production of $\Xi_{bb}$. At some collision point, the production rate of $\Xi_{bb}$ can be increased about 17% with an appropriate choice of the initial beam polarization.

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The 125GeV Higgs-like boson are discovered at ATLAS and CMS, which may be a big breakthrough in precise testing of the Standard Model (SM). So the main goal of all kinds of colliders is not only hunting the new physics but also testing the SM precisely. In SM, baryon with two heavy quarks called doubly heavy baryon, is conformed to exist. At present, only the doubly heavy baryon $\Xi_{cc}$ has been observed by SELEX collaboration [1,2]. However, the decay width and production rate measured at SELEX are not consistent with most of the theoretical predictions. There is no any evidence for the doubly heavy baryon $\Xi_{bb}$ or $\Xi_{bc}$ in experiments. These doubly heavy baryons offer good opportunities to study various perturbative or non-perturbative QCD theories, especially they can shine on the color connections of internal QQ pair and the transformation into the color singlet[4, 5]. So it is necessary to study the production mechanism more precisely. The theoretical studies concerning $\Xi_{bb}$ production can be found in all kinds of colliders, such as $pp$, $ep, e^+e^-$ [6–15], etc.. These studies show that the production rate of $\Xi_{bb}$ is much less than that of $\Xi_{cc}$. Thus a more cleaning environment is needed for investigating the production of $\Xi_{bb}$. The International Linear Collider (ILC) may be a good platform for studying the production of $\Xi_{bb}$.

The International Linear Collider (ILC) can play a key role in the precise measurements of future elementary particle physics. The collider has many advantages. First, it is possible to run at arbitrary center of mass (CM) energies between $91\text{GeV}$ to $1000\text{GeV}$ with high luminosity[16]. Second, the ILC can provide an environment in which high energy collisions can be measured with high precision and one can perform physics analyses on all final states of the decay particles. The last, at the ILC, spin effects can provide us crucial new handles on investigation of all kinds of physics, which can be realized by easily controlling the polarization of the initial beams. The photon photon collider can be realized at ILC by Compton backscattering laser light [17], which may produce very high energy photons, and photon photon collider has all of the above advantages at ILC. Thus many physics programs can be employed at the photon collider, during which the production of doubly heavy baryon $\Xi_{bb}$ is a potential one. The advantages of ILC may be helpful for looking for the doubly heavy baryon $\Xi_{bb}$.

The factorization can be used to handle the production of $\Xi_{bb}$ [18, 19]. The first is the production of heavy quark pair bb, which can be calculated using perturbative QCD. The second is the non-perturbative transformation of bb into $\Xi_{bb}$, which can be handled with non-relativistic QCD (NRQCD) because of the small velocity of b quark in the rest frame of $\Xi_{bb}$ [18, 19]. In this letter, we systematically investigate the inclusive production of $\Xi_{bb}$ at photon photon collider. It is found that proper choice of the initial beam polarization may increase the production rate of $\Xi_{bb}$ up to 17%. We hope this can further improve the theoretical predictions and be helpful for the research of $\Xi_{bb}$ at ILC.

For the leading order contribution at photon collider, the production of doubly heavy baryon $\Xi_{bb}$ can be described via the following inclusive process

$$\gamma(p_1, \lambda_1) + \gamma(p_2, \lambda_2) \rightarrow \Xi_{bb}(k) + \bar{b}(p_3) + \bar{b}(p_4) + X_N, \quad (1)$$

where $\lambda_1$ and $\lambda_2$ are the polarizations of the photons, the momenta of the corresponding particles are respectively denoted as $p_i (i = 1, 2, 3, 4)$ and $k$. $X_N$ is the non-perturbative unobserved state. Here, the high energy photons can

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be provided by Compton backscattered laser beam \[17\] and the corresponding process is shown in Figure 1. The total effective cross section for \( \Xi_{bb} \) production can be written as

\[
\frac{d\sigma(S)}{d\hat{s}d\lambda_1d\lambda_2} = \frac{1}{4} \frac{1}{2\pi^2} \sum \frac{d^3k_1d^3k_3}{(2\pi)^4} A_{ij}(k_1,k_2,p_3,p_4,\lambda_1,\lambda_2) \frac{1}{2} \left( \gamma^0 A^1(k_3,k_4,p_3,p_4,\lambda_1,\lambda_2) \gamma^0 \right)_{kl} \int d^4x_1d^4x_3 e^{-ik_1\cdot x_1+ik_3\cdot x_3} \langle 0|b_4(0)b_1(x_3)|\Xi_{bb}+X_N\rangle \langle \Xi_{bb}+X_N|\bar{b}_i(x_1)\bar{b}^i_1(0)|0\rangle,
\]

with the photons' polarization

\[
\lambda_i = \frac{1}{f^2_{\gamma} (y_i,P_{\gamma}\gamma)} \left( \frac{1}{1-y} \right) \left[ 1 + (1-y)(2r-1)^2 - (2r-1)P_{\gamma}\gamma \left( \frac{1}{1-y} + 1+y \right) \right], i = 1, 2.
\]

Here we imply the average over the photons' polarization and the summation over the spin and color of all final state particles. \( A_{ij}(k_1,k_2,p_3,p_4,\lambda_1,\lambda_2) \) is the scattering amplitude for the production of heavy quark pair \( bb \) in photon photon collision, which can be calculated using perturbative QCD. \( k_1, k_2 \) denote the four-momentum of the internal \( bb \) quarks and \( k_1 = k_2 = k/2 \). \( b(x) \) is the Dirac field for \( b \) quark. Fig. 2 shows the contributions in Eq. (4). Employing
the non-relativistic normalization for $\Xi_{bb}$ and the translation invariance to handle the sum over $X_N$, one can obtain

$$d\sigma(s, \lambda_1, \lambda_2) = \frac{1}{4(2\pi)^3} d^3k \int \frac{d^3p_3}{(2\pi)^32E_3} \frac{d^3p_4}{(2\pi)^32E_4} \int \frac{d^3k_1}{(2\pi)^4} \frac{d^3k_3}{(2\pi)^4} \frac{1}{2} A_{ij}(k_1, k_2, p_3, p_4, \lambda_1, \lambda_2) \cdot \frac{1}{2} \gamma^0 A^j(k_3, k_4, p_3, p_4, \lambda_1, \lambda_2)^0_{kl} \cdot \frac{1}{2} (2\pi)^4 \delta^4(k_1 - m_b v) (2\pi)^4 \delta^4(k_2 - m_b v) (2\pi)^4 \delta^4(k_3 - m_b v) \cdot \left[-(\delta_{a_1a_4} - \delta_{a_2a_5} + \delta_{a_1a_5} - \delta_{a_4a_5})(P_v^T C \gamma_5 P_v)_{ji}(P_v \gamma_5 C P_v^T)_{lk} \cdot h_1 \right. $$

$$\left. + (\delta_{a_1a_2} - \delta_{a_3a_4} - \delta_{a_4a_2} - \delta_{a_3a_4})(P_v^T C \gamma_5 P_v)_{ji}(P_v \gamma_5 C P_v^T)_{lk}(v_{\mu} v_{\nu} - g_{\mu\nu}) \cdot h_3 \right],$$

(6)

where $P_v = 1 + \gamma \cdot v/2$, $C = i \gamma^2 \gamma^0$, and $v^\mu = k^\mu/M_{\Xi_{bb}}$. The color and Dirac indices are respectively denoted as $a_i(i = 1, 2, 3, 4)$ and $i, j, k, l$. For bb quark system, there are two states contributing to the production of $\Xi_{bb}$, one is bb in $^3S_1$ and color triplet, the other is in $^1S_0$ and color sextet. The corresponding probability to transform into the baryon can be respectively represented by $h_1$ and $h_3$, which should be determined by non-perturbative QCD. Under NRQCD, as noted in $^4\overleftrightarrow{\Xi}$, one can have $h_1 \approx h_3 = |\Psi_{bb}(0)|^2$.

In principle, ILC can run on any energy stage from 91GeV to 1000GeV with high luminosity. So we choose different CM energies for the numerical calculation of $\Xi_{bb}$. Here we take $\alpha_s(m_Z) = 0.1185$ and let the leading order $\alpha_s$ run. With the renormalization scale being chosen to be $2m_b$, one can have $\alpha_s(2m_b) = 0.178$ for $m_b = 5.1$GeV.

The total effective cross sections for $\Xi_{bb}$ at $\sqrt{S} = 500$GeV are given in Table 1. In Ref. $^4\overleftrightarrow{\Xi}$, $|\Psi_{bb}(0)|^2 = 0.152$GeV$^3$. Here, the values of $|\Psi_{bb}(0)|^2$ change from 0.136GeV$^3$ to 0.168GeV$^3$. One can find that, when the parameter $h_1(h_3)$ is raised(reduced) 10%, the total cross section correspondingly increase (drop down) about 10%. The exact values of $h_1$ and $h_3$ have impacts on the production rate of $\Xi_{bb}$. For the production of $\Xi_{bb}$, the contribution from bb pair in the color sextet is approximately 10% of that from the color triplet one. The total cross section promptly drops down when b quark mass changes from $m_b = 4.1$GeV to $m_b = 5.35$GeV, i.e., the production rate of $\Xi_{bb}$ reduces by a factor of 67% corresponding to the 30% of b quark mass.

Employing the polarizations of the electron (laser) beams, we calculate the total effective cross section of $\Xi_{bb}$ for $\sqrt{S} = 250$GeV at photon collider. The results are shown in Table 2. One can notice that the choice of $(P_{e1}, P_{e2}; P_{l1}, P_{l2}) = (0.85, -0.85; +1, -1)$ can increase the production rate of $\Xi_{bb}$ by approximately 17%, which means that the polarization of initial beams is an important asset for $\Xi_{bb}$ production. Compared with the results in Table 1, one can find that the cross section of $\Xi_{bb}$ at $\sqrt{S} = 250$GeV is twice larger than that at 500GeV CM energy.

Table 1. Total cross section (in unit: fb) of $\Xi_{bb}$ production at $\sqrt{S} = 500$GeV.

FIG. 2: The contributions in eq.(4)
Table 2. Results for the effective cross section (in unit: fb) of $\Xi_{bb}$ (for $m_b = 5.1 GeV$) at $\sqrt{s} = 250 GeV$.

| $h_1$(GeV$^3$) | $h_2$(GeV$^3$) | spin averaged | 0 | 0.152 | 0 | 0.152 |
|----------------|----------------|--------------|----|-------|----|-------|
| (0.136,0)      | 7.13 x 10^{-3} | 5.45 x 10^{-3} | 4.26 x 10^{-3} | 3.37 x 10^{-3} | 2.66 x 10^{-3} | 2.16 x 10^{-3} |
| (0.136,0.136)  | 8.08 x 10^{-2} | 6.28 x 10^{-2} | 4.99 x 10^{-2} | 4.01 x 10^{-2} | 3.20 x 10^{-2} | 2.65 x 10^{-2} |
| (0.144,0.144)  | 9.32 x 10^{-2} | 7.22 x 10^{-2} | 5.73 x 10^{-2} | 4.61 x 10^{-2} | 3.67 x 10^{-2} | 3.04 x 10^{-2} |

In the following numerical calculation, we take the parameters as that in Ref.[7]

$$|\Psi_{bb}(0)|^2 = 0.152 GeV^3, \quad m_b = 5.1 GeV.$$ (7)

The total cross sections of $\Xi_{bb}$ versus the collision energy are shown in Fig.B. $\Xi_{bb}$ bb pair in different color states are calculated in Fig.B(a). The contribution from color triplet is much larger than color sextet. One can find that the largest production rate appears around $\sqrt{s} = 91 GeV$, which is the supposed energy at Giga-Z program. The cross sections of $\Xi_{bb}$ with all kinds of polarizations of the initial beams are considered. The choices of $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, 0.85; +1, +1)$ and $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, -0.85; +1, -1)$ have large impacts on the production rate, which are shown in Fig.B(b). For different CM energy, the choice of initial beam polarization shows different effect. When the CM energy is less than 400GeV, the choice of $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, -0.85; +1, -1)$ can increase the production rate of $\Xi_{bb}$, while $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, 0.85; 1, 1)$ has the same impact when $\sqrt{s} > 400 GeV$.

The cos$\theta$-distributions, $x_T$-distributions and $z$-distributions for $\Xi_{bb}$ are given in Fig.B(b) and (d) respectively. Here the collision energy is taken to be 250GeV. $\theta$ is the angle between the initial $e^+$ beam and the final $\Xi_{bb}$, moving direction, $x_T = 2p_T/\sqrt{s}$ and $z = 2E/\sqrt{s}$, with $p_T$ and $E$ the transverse momentum and energy of $\Xi_{bb}$. The contributions of bb pair in both color states have the same decency in each distribution for $\Xi_{bb}$ production at $\sqrt{s} = 250 GeV$. Different polarizations of the initial beams slightly change the distributions, which can be seen from Fig.B(b) and (d). For $\Xi_{bc}$ production, one have more hadronic matrix elements to describe the internal bc quark system, which is due to no restriction from Pauli principle for the heavy quark pair bc.

In summary, we investigate the production of the doubly heavy baryon $\Xi_{bb}$ at $\gamma \gamma$ collider. We find that for $\Xi_{bb}$ production, the contribution from the color sextet is about 8%. Therefore, the color triplet and sextet should both be included for the production of $\Xi_{bb}$. The value of $m_b$ has large impact on the $\Xi_{bb}$ production. For a fixed value of $m_b$ , the largest production rate appears around $\sqrt{s} = 91 GeV$, as the collision energy running up, the total cross section drops down. For different collision energy, there are different choices of the initial beam polarization which can increase the production rate of $\Xi_{bb}$. For example, The production rate of $\Xi_{bb}$ can be increased about 17% with the initial beam polarization $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, -0.85; +1, -1)$ at $\sqrt{s} = 250 GeV$. The enhancement is larger than the contribution from the color sextet. These results indicate that the initial beam polarization may be an important asset for the production of $\Xi_{bb}$. We hope these results can be helpful for the investigation of $\Xi_{bb}$ production at ILC.
FIG. 3: The total cross sections of $\Xi_{bb}$ versus the center of mass energy. (a) The solid line stands for $h_3 = h_1 = |\Psi_{bb}(0)|^2$, the dotted stands for $h_1 = |\Psi_{bb}(0)|^2$ and $h_3 = 0$, and the dashed stands for $h_3 = |\Psi_{bb}(0)|^2$ and $h_1 = 0$. (b) The solid line stands for $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, -0.85; +1, -1)$, the dotted stands for $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, 0.85; +1, +1)$, and the dashed line stands for spin averaged.

FIG. 4: The distributions of $\cos\theta$. (a) The solid line stands for $h_3 = h_1 = |\Psi_{bb}(0)|^2$, the dotted stands for $h_1 = |\Psi_{bb}(0)|^2$ and $h_3 = 0$, and the dashed stands for $h_3 = |\Psi_{bb}(0)|^2$ and $h_1 = 0$. (b) The solid line stands for $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, -0.85; +1, -1)$, the dotted stands for $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, 0.85; -1, -1)$, and the dashed line stands for spin averaged.

FIG. 5: Same as Fig.4 but for $x_T$-distributions.
FIG. 6: Same as Fig. 4 but for $x$-distributions.

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