第 58 卷 第 12 期 2009 年 12 月
1000-3290/2009/58(12)/8166-08
物 理 学 报
ACTA PHYSICA SINICA
Vol.58, No.12, December, 2009

关于光子对撞机上底夸克对产生的研究*

黄金书[1)2)†] 罗鹏晖[1)3)] 鲁公儒[1)]

1)(河南师范大学物理与信息工程学院,新乡 453007)

2)(南阳师范学院物理与电子工程学院,南阳 473061)

3)(南阳理工学院电子与电气工程系,南阳 473005)

(2009 年 1 月 28 日收到;2009 年 3 月 3 日收到修改稿)

计算了顶色辅助人工色模型对光子对撞机上底夸克对产生过程的 Yukawa 修正.发现在合理的参数范围内,赝标量 Goldstone 玻色子引起的相对修正与树图水平相比有 3.17% 到 5.90% 的压低.该结果明显地大于标准模型、双 Higgs 二重态模型和最小超对称模型中的相应贡献.这样的修正对于正在设计中的国际直线对撞机上检验标准模型和探索新物理是很有意义的.

关键词:顶色辅助人工色模型,光子对撞机,散射截面

PACC: 1380,1210D,1480D,1130Q

1. 引 言

正负电子对撞机产生的高能光子的碰撞为尝试标准模型(SM)和探索新物理提供了良机[1].利用对撞机中电子和正电子碰撞所产生的 Compton 激光背散射,可以获取高能量和高强度的光子束,在这种机制下可产生大量重的夸克对[2].光子的能谱分析表明,由于对撞过程中产生了大量的软光子,重的顶夸克产生受到很强的抑制,但并不抑制相对较轻的底夸克.因此研究光子光子对撞产生底夸克对的过程是很有意义的[3].

有人已经研究过这个过程在标准模型中的电弱修正,其相对修正很小,大约在 10^{-5} 的量级[4].文献[5]计算了双 Higgs 二重态模型和最小超对称模型对这个过程的 Yukawa 修正.结果表明,在一定的参数内,对 $e^+e^-\to\gamma\gamma\to b\bar{b}$ 总散射截面的相对修正小于 0.1%.本文重点考察顶色辅助人工色模型中荷电的赝标 Goldstone 玻色子对这个过程的效果.

2. 顶色辅助人工色模型的一般特性

人工色理论(TC),作为 $\Lambda\approx 1$ TeV标度上的一种费米子和规范玻色子的强相互作用,是电弱对称性破缺到电磁对称性的一种可能方案[6,7].考虑到使夸克、轻子和这个方案中的 TC 介子获得质量,人工色对称性被嵌入到一个更大的规范群当中,称为扩展的人工色理论(ETC)[8,9].由于味改变中性流和 ETC 产生夸克、轻子、TC 介子质量等级之间有矛盾,可以通过一个走动人工色和多标度人工色来压制传统的人工色[10—16].为了合理地解释顶夸克较大的质量与 ρ 参数,ETC 诱导 $Z\to b\bar{b}$ 分支比之间的冲突[17,18],进一步提出了原始的顶色辅助人工色理论(TOPCTC)[19,20]和顶色辅助多标度人工色理论(TOPCMTC)[21,22].

原始的 TOPCTC 模型假定[19—20,23—27]:(1)电弱对称性破缺主要是 ETC 造成的;(2)顶夸克质量的主要部分 $(1-\varepsilon)m_t$,由一个新的强动力学来产生,而顶夸克质量的一小部分 εm_t $(\varepsilon\approx 0.03—0.1)$,由 ETC 产生;(3)这个新的强动力学是一个在1 TeV标度的强手征相互作用,它主要和第三代费米子耦合,称为顶色相互作用(TOPC).顶色相互作用的规范结构为

$$SU(3)_1\times SU(3)_2\times U(1)_{Y_1}\times U(1)_{Y_2}\to SU(3)_{QCD}\times U(1)_{EM}. \quad (1)$$

这里 $SU(3)_1\times U(1)_{Y_1}$ $[SU(3)_2\times U(1)_{Y_2}]$ 和第三代

* 国家自然科学基金(批准号:10575029,10595047)、河南省自然科学基金(批准号:092300410205)和河南省教育厅自然科学基金(批准号:2007140013)资助的课题.

† E-mail:jshuang@vip.sina.com

(第一代、二代)相耦合. 该耦合相当强是指通过 $U(1)_{Y_1}$ 耦合与 $\langle \bar{t}t \rangle$ 凝聚而非与 $\langle \bar{b}b \rangle$ 凝聚. 剩余的整体对称性 $SU(3)' \times U(1)'$ 暗示存在一个有质量色单态的 Z' 粒子和一个色八重态的 B^{μ} 粒子. 对称性破缺将产生三个大致在顶夸克质量标度的顶色介子，即中性的 π_t^0 和荷电的 $\pi_t^{\pm}$.

这个模型有 60 个衰变常数为 $f_{\pi} = 123$ GeV 的 TC 介子和 3 个衰变常数为 $f_{\pi_t} = 50$ GeV 的 TOPC 介子，其 ETC 部分是一代人工色模型(OGTC)[7,8]. 与本研究过程相关的 TC 介子只有色单态的 π 和色八重态的 π_8，它们与顶夸克和底夸克的相互作用为

$$\frac{1}{f_{\pi}} c_t \varepsilon m_t \Big[\frac{i}{\sqrt{2}} \bar{t} \gamma_5 t \pi^0 + \frac{i}{\sqrt{2}} \bar{t} \gamma_5 t \pi^3 + \bar{t} L b \pi^+ + \bar{b} R t \pi^- \Big], \tag{2}$$

$$\frac{1}{f_{\pi}} \lambda^a \varepsilon m_t \Big[\frac{i}{\sqrt{2}} \bar{t} \gamma_5 t \pi_8^0 + \frac{i}{\sqrt{2}} \bar{t} \gamma_5 t \pi_8^3 + \bar{t} L b \pi_8^+ + \bar{b} R t \pi_8^- \Big]. \tag{3}$$

这里 $L, R = (1 \mp \gamma_5)/2$ 为左、右手征算符，$c_t = 1/\sqrt{6}$，λ^a 是表示普通色指标的 Gell-Mann 矩阵.

TOPC 介子与顶夸克和底夸克的耦合为

$$\frac{1}{f_{\pi_t}} (1 - \varepsilon) m_t \Big[\frac{i}{\sqrt{2}} \bar{t} \gamma_5 t \pi_t^0 + \bar{t} L b \pi_t^+ + \bar{b} R t \pi_t^- \Big]. \tag{4}$$

光子和 TOPC 介子 $\pi_t^{\pm}$ 的耦合为

$$i e (p' - p)^{\mu}, \tag{5}$$

其中 p', p 分别表示 π_t^+ 和 π_t^- 的动量. 计算中用到的其他 Feynman 规则见文献[28—32]中给出.

对于 TOPCMTC 模型，它与原始 TOPCTC 模型的差别仅仅在于 ETC 部分，原始 TOPCTC 模型的 ETC 部分是 OGTC，相应的模型参数为 $f_{\pi} = 123$ GeV 和 $c_t = 1/\sqrt{6}$. 而 TOPCMTC 的 ETC 部分是多标度人工色模型，相应的模型参数为 $f_{\pi} = 40$ GeV 和 $c_t = 2/\sqrt{6}$[21,22,33].

3. 光子和光子对撞中底夸克对产生 Yukawa 修正的计算

与 $\gamma\gamma \to b\bar{b}$ 过程相关的 Feynman 图如图 1 所示. 计算中采用 Feynman 规范，维数正规化和质壳重正化方案[34—36]. $\gamma\gamma \to b\bar{b}$ 过程重正化的不变振幅为

$$M_{\rm ren} = M_0 + \delta M = M_0 + \delta M^{\rm self} + \delta M^{\rm vertex} + \delta M^{\rm box} + \delta M^{\rm tr}. \tag{6}$$

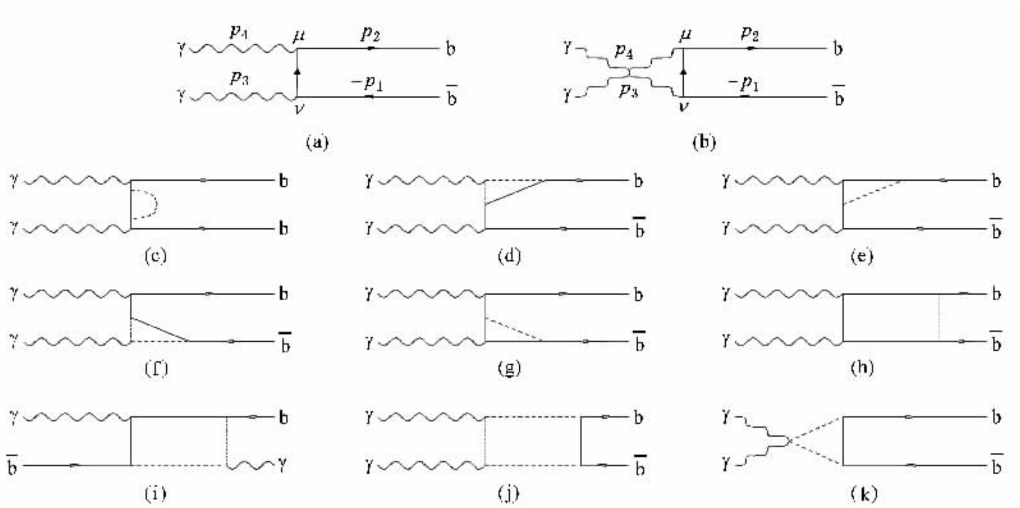

图 1　TOPCTC 模型中赝标 Goldstone 玻色子对 $\gamma\gamma \to b\bar{b}$ 过程贡献的 Feynman 图　其中 (a)—(b)为树图，(c)为自能图，(d)—(g)为顶角图，(h)—(j)为箱图，(k)为三角图. 仅画出与树图(a)相应的单圈图. (c)—(k)中的虚线表示荷电的 TC 介子 $\pi^{\pm}$，$\pi_8^{\pm}$ 和 TOPC 介子 $\pi_t^{\pm}$

这里 M_0 是树图水平的不变振幅，$\delta M^{\rm self}$，$\delta M^{\rm vertex}$，$\delta M^{\rm box}$ 和 $\delta M^{\rm tr}$ 分别表示自能图、顶角图、箱图和三角图的 Yukawa 修正. 它们的简洁形式如下：

$$M_0 = M_0^{\hat{t}} + M_0^{\hat{u}}, \tag{7}$$

$$\delta M^{\rm self} = \delta M^{s(\hat{t})} + \delta M^{s(\hat{u})}, \tag{8}$$

$$\delta M^{\rm vertex} = \delta M^{v(\hat{t})} + \delta M^{v(\hat{u})}, \tag{9}$$

$$\delta M^{\rm box} = \delta M^{b(\hat{t})} + \delta M^{b(\hat{u})}, \tag{10}$$

其中

$$M_0^{\hat{t}} = -i \frac{e^2 Q_b^2}{\hat{t} - m_b^2} \varepsilon_{\mu}(p_4) \varepsilon_{\nu}(p_3) \bar{u}(p_2) \gamma^{\mu} \times (\not{p}_2 - \not{p}_4 + m_b) \gamma^{\nu} \nu(p_1), \tag{11}$$

$$M_0^{\hat{u}} = M_0^{\hat{t}} (p_3 \leftrightarrow p_4, \hat{t} \leftrightarrow \hat{u}), \tag{12}$$

$$\delta M^{s(\hat{t})} = \mathrm{i}\,\frac{e^2 Q_\mathrm{b}^2}{(\hat{t}-m_\mathrm{b}^2)^2}\varepsilon_\mu(p_4)\varepsilon_\nu(p_3)\bar{u}(p_2)\times[f_1^{s(\hat{t})}\gamma^\mu\gamma^\nu + f_2^{s(\hat{t})}p_2^\mu\gamma^\nu + f_3^{s(\hat{t})}\not{p}_4\gamma^\mu\gamma^\nu]v(p_1), \tag{13}$$

$$\delta M^{s(\hat{u})} = \delta M^{s(\hat{t})}(p_3\leftrightarrow p_4,\hat{t}\leftrightarrow\hat{u}), \tag{14}$$

$$\delta M^{v(\hat{t})} = -\mathrm{i}\,\frac{e^2 Q_\mathrm{b}}{\hat{t}-m_\mathrm{b}^2}\varepsilon_\mu(p_4)\varepsilon_\nu(p_3)\bar{u}(p_2)\times[f_1^{v(\hat{t})}\gamma^\mu\gamma^\nu + f_2^{v(\hat{t})}\gamma^\mu p_1^\nu + f_3^{v(\hat{t})}p_2^\mu\gamma^\nu + f_4^{v(\hat{t})}p_2^\mu p_1^\nu + f_5^{v(\hat{t})}\not{p}_4\gamma^\mu\gamma^\nu + f_6^{v(\hat{t})}\not{p}_4\gamma^\mu p_1^\nu + f_7^{v(\hat{t})}\not{p}_4 p_2^\mu\gamma^\nu]v(p_1), \tag{15}$$

$$\delta M^{v(\hat{u})} = \delta M^{v(\hat{t})}(p_3\leftrightarrow p_4,\hat{t}\leftrightarrow\hat{u}), \tag{16}$$

$$\delta M^{b(\hat{t})} = -\mathrm{i}\,\frac{e^2}{16\pi^2}\varepsilon_\mu(p_4)\varepsilon_\nu(p_3)\bar{u}(p_2)\times[f_1^{b(\hat{t})}\gamma^\mu\gamma^\nu + f_2^{b(\hat{t})}\gamma^\nu\gamma^\mu + f_3^{b(\hat{t})}\gamma^\mu p_1^\nu + f_4^{b(\hat{t})}p_1^\mu\gamma^\nu + f_5^{b(\hat{t})}\gamma^\mu p_2^\nu + f_6^{b(\hat{t})}p_2^\mu\gamma^\nu + f_7^{b(\hat{t})}p_1^\mu p_1^\nu + f_8^{b(\hat{t})}p_1^\mu p_2^\nu + f_9^{b(\hat{t})}p_2^\mu p_1^\nu + f_{10}^{b(\hat{t})}p_2^\mu p_2^\nu + f_{11}^{b(\hat{t})}\not{p}_4\gamma^\mu\gamma^\nu + f_{12}^{b(\hat{t})}\not{p}_4\gamma^\nu\gamma^\mu + f_{13}^{b(\hat{t})}\not{p}_4\gamma^\mu p_1^\nu + f_{14}^{b(\hat{t})}\not{p}_4 p_1^\mu\gamma^\nu + f_{15}^{b(\hat{t})}\not{p}_4\gamma^\mu p_2^\nu + f_{16}^{b(\hat{t})}\not{p}_4 p_2^\mu\gamma^\nu + f_{17}^{b(\hat{t})}\not{p}_4 p_1^\mu p_1^\nu + f_{18}^{b(\hat{t})}\not{p}_4 p_1^\mu p_2^\nu + f_{19}^{b(\hat{t})}\not{p}_4 p_2^\mu p_1^\nu + f_{20}^{b(\hat{t})}\not{p}_4 p_2^\mu p_2^\nu]v(p_1), \tag{17}$$

$$\delta M^{b(\hat{u})} = \delta M^{b(\hat{t})}(p_3\leftrightarrow p_4,\hat{t}\leftrightarrow\hat{u}), \tag{18}$$

$$\delta M^{\mathrm{tr}} = \mathrm{i}\,\frac{e^2}{8\pi^2}f_1^{\mathrm{tr}}g^{\mu\nu}\varepsilon_\mu(p_4)\varepsilon_\nu(p_3)\times\bar{u}(p_2)v(p_1), \tag{19}$$

这里 $\hat{t}=(p_4-p_2)^2$，$\hat{u}=(p_4-p_1)^2$，p_3 和 p_4 分别表示两个入射光子的四动量，p_2 和 p_1 分别表示出射的底夸克及其反夸克的四动量.

(13)—(19)式中的形式因子 $f_i^{s(\hat{t})}$，$f_i^{v(\hat{t})}$，$f_i^{b(\hat{t})}$，f_i^{tr}用两点、三点和四点标量积分函数来表示[37—39]. 自能图形式因子 $f_i^{s(\hat{t})}$ 的具体结果为

$$f_1^{s(\hat{t})} = -2m_\mathrm{b}(p_2\cdot p_4)\left[\Sigma_S^b(\hat{t})+\Sigma_V^b(\hat{t})-\frac{\delta m_\mathrm{b}}{m_\mathrm{b}}\right],$$
$$f_2^{s(\hat{t})} = 4m_\mathrm{b}^2\left[\Sigma_S^b(\hat{t})-\frac{\delta m_\mathrm{b}}{m_\mathrm{b}}-\delta Z_V^b\right] + 4(m_\mathrm{b}^2-p_2\cdot p_4)[\Sigma_V^b(\hat{t})+\delta Z_V^b],$$
$$f_3^{s(\hat{t})} = \frac{1}{2}f_2^{s(\hat{t})}, \tag{20}$$

其中

$$\Sigma^b(p^2) = \not{p}[\Sigma_V^b(p^2)+\gamma_5\Sigma_A^b(p^2)] + m_\mathrm{b}\Sigma_S^b(p^2),$$
$$\Sigma_V^b(p^2) = -\frac{\lambda_i^2}{32\pi^2}B_1(p^2,m_\mathrm{t},m_\mathrm{i}),$$
$$\Sigma_A^b(p^2) = \frac{\lambda_i^2}{32\pi^2}B_1(p^2,m_\mathrm{t},m_\mathrm{i}),$$
$$\Sigma_S^b(p^2) = 0,$$
$$\delta m_\mathrm{b} = m_\mathrm{b}[\Sigma_V^b(m_\mathrm{b}^2)+\Sigma_S^b(m_\mathrm{b}^2)],$$
$$\delta Z_V^b = -\Sigma_V^b(m_\mathrm{b}^2) - 2m_\mathrm{b}^2\frac{\partial}{\partial p^2}[\Sigma_V^b(p^2)+\Sigma_S^b(p^2)]\big|_{p^2=m_\mathrm{b}^2}. \tag{21}$$

这里 Σ^b，δm_b 和 δZ_V^b 分别表示未重正化自能函数，底夸克质量和波函数重正化常数的 Yukawa 贡献，由于 $\Sigma_A^b(p^2)$包含 γ_5，实际上它对形状因子 $f_i^{s(\hat{t})}$ 没有贡献.

形式因子 $f_i^{v(\hat{t})}$，$f_i^{b(\hat{t})}$，f_i^{tr} 分别为

$$f_1^{v(\hat{t})} = -\frac{\lambda_i^2 Q_\mathrm{t}}{16\pi^2}m_\mathrm{b}p_2\cdot p_4(C_0^2+C_{11}^2+C_0^4+C_{11}^4),$$
$$f_2^{v(\hat{t})} = \frac{\lambda_i^2}{8\pi^2}p_2\cdot p_4[(C_{12}^3+C_{23}^3)+Q_t(C_{12}^4+C_{23}^4)],$$
$$f_3^{v(\hat{t})} = \frac{\lambda_i^2}{8\pi^2}[-m_\mathrm{b}^2(C_{11}^1+C_{21}^1)+p_2\cdot p_4(C_{12}^1+C_{23}^1)+(-C_{24}^1+C_{24}^3)] + \frac{\lambda_i^2 Q_\mathrm{t}}{16\pi^2}[(m_\mathrm{t}^2+m_\mathrm{b}^2)(C_0^2+C_0^4) + 2m_\mathrm{b}^2C_{11}^2 + 2p_2\cdot p_4(C_{12}^4+C_{23}^4) + m_\mathrm{b}^2(C_{21}^2-C_{21}^4) - 2(C_{24}^2+C_{24}^4)] - 4Q_\mathrm{t}\delta Z_V^b,$$
$$f_4^{v(\hat{t})} = -\frac{\lambda_i^2}{8\pi^2}m_\mathrm{b}[(C_{11}^3+C_{21}^3)+Q_t(C_{11}^4+C_{21}^4)],$$

$$f_5^{v(\hat{t})} = \frac{\lambda_i^2}{16\pi^2}[-C_{24}^1 + C_{24}^3] + \frac{\lambda_i^2 Q_t}{32\pi^2}[(m_t^2 + m_b^2)(C_0^2 + C_0^4) + 2p_2 \cdot p_4(C_{12}^2 + C_{23}^2 + C_{12}^4 + C_{23}^4)$$
$$- m_b^2(C_{21}^2 + C_{21}^4) - 2(C_{24}^2 + C_{24}^4)] - 2Q_t \delta Z_V^b,$$

$$f_6^{v(\hat{t})} = \frac{1}{2} f_4^{v(\hat{t})},$$

$$f_7^{v(\hat{t})} = \frac{\lambda_i^2}{16\pi^2} m_b[(C_{11}^1 + C_{21}^1) - Q_t(C_{11}^2 + C_{21}^2)]. \quad (22)$$

$$f_1^{b(\hat{t})} = \frac{1}{2}\lambda_i^2 Q_t^2 m_b[m_t^2(D_0^1 + D_{11}^1) + m_b^2(-D_0^1 - 2D_{11}^1 + D_{12}^1 - D_{13}^1 - 2D_{21}^1 - D_{23}^1$$
$$+ 2D_{24}^1 - 2D_{25}^1 - D_{31}^1 + D_{34}^1 - D_{35}^1) + \hat{s}(D_{25}^1 - D_{26}^1 + D_{35}^1 - D_{310}^1)$$
$$+ \hat{t}(-D_{11}^1 - D_{12}^1 + D_{13}^1 - D_{21}^1 - 2D_{24}^1 + 2D_{25}^1 - D_{34}^1 - D_{35}^1) - 4(D_{27}^1 + D_{311}^1)]$$
$$+ \lambda_i^2 Q_t m_b(D_{27}^2 + D_{311}^2 - D_{312}^2 + D_{313}^2) - \lambda_i^2 m_b D_{311}^3,$$

$$f_2^{b(\hat{t})} = \lambda_i^2 Q_t^2 m_b(D_{27}^1 + D_{311}^1) + \lambda_i^2 Q_t m_b(D_{27}^2 + D_{311}^2 - D_{312}^2 + D_{313}^2) - \lambda_i^2 m_b D_{311}^3,$$

$$f_3^{b(\hat{t})} = \lambda_i^2 Q_t^2[m_t^2(-D_{12}^1 + D_{13}^1) + m_b^2(D_{12}^1 - D_{13}^1 - D_{22}^1 + 3D_{23}^1 + 2D_{24}^1 - D_{25}^1 - D_{26}^1$$
$$+ D_{34}^1 - D_{35}^1 - D_{36}^1 - D_{38}^1) + \hat{s}(D_{37}^1 + D_{38}^1 - D_{39}^1 - D_{310}^1)$$
$$+ \hat{t}(D_{22}^1 - 3D_{23}^1 - D_{25}^1 + D_{26}^1 + D_{36}^1 + D_{38}^1) + 2(D_{27}^1 + 2D_{312}^1 - 3D_{313}^1)]$$
$$+ \lambda_i^2 Q_t[m_t^2(-D_{11}^2 + D_{12}^2) + m_b^2(D_{11}^2 - D_{12}^2 + D_{21}^2 - 3D_{22}^2 - D_{24}^2 + 2D_{25}^2$$
$$- 2D_{26}^2 - D_{32}^2 - D_{34}^2 + 2D_{35}^2 + 4D_{36}^2 + 3D_{37}^2 + 2D_{28}^2 - 5D_{310}^2)$$
$$+ \hat{s}(2D_{22}^2 - D_{36}^2 - D_{37}^2 - D_{38}^2 - D_{39}^2 + D_{310}^2) + \hat{t}(D_{21}^2 + D_{22}^2 - 2D_{24}^2 + D_{31}^2$$
$$- 2D_{34}^2 - D_{36}^2 - D_{37}^2 - D_{38}^2 - D_{39}^2 + D_{310}^2) + 2(D_{27}^2 + 2D_{311}^2 - 2D_{312}^2)]$$
$$- 2\lambda_i^2(D_{27}^3 - D_{312}^3),$$

$$f_4^{b(\hat{t})} = \lambda_i^2 Q_t^2[-m_t^2 D_{13}^1 + m_b^2(-D_{13}^1 + D_{23}^1 - D_{25}^1 + D_{35}^1 + D_{38}^1 - D_{310}^1) + \hat{s}(-D_{38}^1 + D_{39}^1)$$
$$+ \hat{t}(-D_{23}^1 + D_{25}^1 - D_{38}^1 + D_{310}^1) + 4D_{311}^1] + 2\lambda_i^2 Q_t(D_{312}^2 - D_{313}^2) + 2\lambda_i^2 D_{313}^3,$$

$$f_5^{b(\hat{t})} = \lambda_i^2 Q_t^2[m_t^2(D_{11}^1 - D_{12}^1) + m_b^2(-D_{11}^1 + D_{12}^1 - 2D_{21}^1 - D_{22}^1 + 3D_{24}^1 - 2D_{26}^1$$
$$- D_{31}^1 + 2D_{34}^1 - D_{35}^1 - D_{36}^1 - 2D_{38}^1 - D_{310}^1) + \hat{s}(D_{35}^1 + D_{37}^1 - 2D_{310}^1)$$
$$+ \hat{t}(D_{22}^1 - D_{24}^1 + 2D_{26}^1 - D_{34}^1 + D_{35}^1 + D_{36}^1 + D_{310}^1) - 4(D_{311}^1 + 2D_{312}^1)]$$
$$+ \lambda_i^2 Q_t[m_t^2 D_{13}^2 + m_b^2(-2D_{23}^2 - D_{25}^2 + D_{26}^2 - 2D_{33}^2 - D_{37}^2 - 2D_{38}^2 + 3D_{39}^2 + D_{310}^2)$$
$$+ \hat{s}(D_{33}^2 - D_{39}^2) + \hat{t}(-D_{25}^2 + D_{26}^2 + D_{33}^2 - D_{35}^2 - D_{39}^2 + D_{310}^2) - 4D_{313}^2]$$
$$- 2\lambda_i^2(2D_{27}^3 + D_{311}^3 - D_{312}^3),$$

$$f_6^{b(\hat{t})} = \lambda_i^2 Q_t^2[m_t^2 D_0^1 + m_b^2(D_0^1 + 2D_{11}^1 - 2D_{13}^1 + D_{21}^1 - 3D_{25}^1 + D_{26}^1 + 2D_{38}^1) + \hat{s}(D_{25}^1 - D_{26}^1)$$
$$+ \hat{t}(D_{25}^1 - D_{26}^1) + 2(D_{311}^1 - D_{313}^1)] + 2\lambda_i^2 Q_t(D_{27}^2 + D_{311}^2) - 2\lambda_i^2(D_{27}^3 + D_{311}^3 - D_{313}^3),$$

$$f_7^{b(\hat{t})} = 2\lambda_i^2 Q_t^2 m_b(D_{26}^1 + D_{310}^1) + 2\lambda_i^2 Q_t m_b(D_{22}^2 - D_{24}^2 + D_{25}^2 - D_{26}^2 - D_{32}^2 - D_{34}^2$$
$$+ D_{35}^2 + 2D_{36}^2 + 2D_{37}^2 + D_{38}^2 - D_{39}^2 - 3D_{310}^2) + 2\lambda_i^2 m_b(D_{25}^3 - D_{310}^3),$$

$$f_8^{b(\hat{t})} = 2\lambda_i^2 Q_t^2 m_b(-D_{25}^1 + D_{26}^1 - D_{35}^1 + D_{310}^1) + 2\lambda_i^2 Q_t m_b(-D_{23}^2 + D_{26}^2 - D_{33}^2 - D_{37}^2$$
$$- D_{38}^2 + 2D_{39}^2 + D_{310}^2) + 2\lambda_i^2 m_b(2D_{25}^3 + D_{35}^3 - D_{310}^3),$$

$$f_9^{b(\hat{t})} = 2\lambda_i^2 Q_t^2 m_b(-D_{12}^1 - 2D_{24}^1 + D_{26}^1 - D_{34}^1 + D_{310}^1) + 2\lambda_i^2 Q_t m_b(-D_{11}^2 + D_{12}^2 - 2D_{21}^2$$
$$- D_{22}^2 + 3D_{24}^2 - D_{25}^2 + D_{26}^2 - D_{31}^2 + 2D_{34}^2 - D_{35}^2 - D_{36}^2 + 3D_{310}^2)$$

$$+2\lambda_i^2 m_b(-D_{11}^3-D_{21}^3+D_{24}^3+D_{25}^3+D_{34}^3-D_{310}^3),$$

$$f_{10}^{b(\hat{t})}=2\lambda_i^2 Q_t^2 m_b(D_{11}^1-D_{12}^1+2D_{21}^1-2D_{24}^1-D_{25}^1+D_{26}^1+D_{31}^1-D_{34}^1-D_{35}^1+D_{310}^1)$$
$$+2\lambda_i^2 Q_t m_b(D_{23}^2+2D_{25}^2-D_{26}^2+D_{35}^2+D_{38}^2-D_{310}^2)$$
$$+2\lambda_i^2 m_b(-2D_{11}^3-3D_{21}^3+D_{24}^3+2D_{25}^3-D_{31}^3+D_{34}^3+D_{35}^3-D_{310}^3),$$

$$f_{11}^{b(\hat{t})}=\frac{1}{2}\lambda_i^2 Q_t^2[m_t^2(D_0^1-D_{12}^1+2D_{13}^1)+m_b^2(D_0^1+D_{12}^1-D_{13}^1-D_{21}^1-D_{22}^1-D_{23}^1+4D_{24}^1$$
$$-2D_{25}^1+D_{31}^1-D_{35}^1-D_{36}^1-D_{38}^1-D_{310}^1)+\hat{s}(D_{25}^1-D_{26}^1+D_{37}^1+D_{38}^1+D_{39}^1-D_{310}^1)$$
$$+\hat{t}(D_{22}^1+D_{23}^1+D_{36}^1+D_{38}^1-D_{310}^1)+2(2D_{312}^1-D_{313}^1)]-\lambda_i^2 Q_t(D_{311}^2-D_{313}^2)+\lambda_i^2(D_{312}^3-D_{313}^3),$$

$$f_{12}^{b(\hat{t})}=-\lambda_i^2 Q_t^2(D_{27}^1+D_{313}^1)-\lambda_i^2 Q_t(D_{27}^2+D_{311}^2-D_{313}^2)+\lambda_i^2(D_{312}^3-D_{313}^3),$$

$$f_{13}^{b(\hat{t})}=\lambda_i^2 Q_t^2 m_b(-D_{12}^1+D_{22}^1-D_{24}^1-2D_{25}^1+2D_{26}^1+2D_{310}^1)$$
$$+\lambda_i^2 Q_t m_b(-D_{11}^2+D_{12}^2-D_{21}^2-D_{22}^2+2D_{24}^2-D_{25}^2+D_{26}^2),$$

$$f_{14}^{b(\hat{t})}=\lambda_i^2 Q_t^2 m_b(D_{23}^1+D_{25}^1),$$

$$f_{15}^{b(\hat{t})}=\lambda_i^2 Q_t^2 m_b(D_{11}^1-D_{12}^1+D_{21}^1+D_{22}^1-D_{24}^1+2D_{26}^1+2D_{310}^1)+\lambda_i^2 Q_t m_b(D_{13}^2+D_{25}^2-D_{26}^2),$$

$$f_{16}^{b(\hat{t})}=-\lambda_i^2 Q_t^2 m_b(D_{11}^1-D_{13}^1+D_{21}^1-D_{25}^1),$$

$$f_{17}^{b(\hat{t})}=2\lambda_i^2 Q_t^2(D_{23}^1-D_{26}^1-D_{37}^1+D_{39}^1)+2\lambda_i^2 Q_t(-D_{22}^2+D_{24}^2-D_{25}^2+D_{26}^2+D_{34}^2-D_{35}^2$$
$$-D_{36}^2+D_{37}^2+D_{38}^2-D_{39}^2)+2\lambda_i^2(D_{23}^3-D_{26}^3+D_{37}^3-D_{39}^3),$$

$$f_{18}^{b(\hat{t})}=2\lambda_i^2 Q_t^2(D_{25}^1-D_{26}^1-D_{37}^1-D_{38}^1+D_{39}^1+D_{310}^1)+2\lambda_i^2 Q_t(D_{23}^2-D_{26}^2-D_{33}^2+D_{38}^2+D_{39}^2-D_{310}^2)$$
$$+2\lambda_i^2(2D_{23}^3-2D_{26}^3+D_{37}^3+D_{38}^3-D_{39}^3-D_{310}^3),$$

$$f_{19}^{b(\hat{t})}=2\lambda_i^2 Q_t^2(D_{22}^1+D_{23}^1-D_{25}^1+D_{26}^1+D_{36}^1-D_{37}^1+D_{39}^1+D_{310}^1)+2\lambda_i^2 Q_t(D_{21}^2-D_{25}^2+D_{26}^2+D_{31}^2$$
$$-D_{34}^2-D_{35}^2+D_{310}^2)+2\lambda_i^2(D_{12}^3-D_{13}^3-D_{22}^3+D_{23}^3+D_{24}^3-D_{25}^3-D_{36}^3+D_{37}^3-D_{39}^3+D_{310}^3),$$

$$f_{20}^{b(\hat{t})}=2\lambda_i^2 Q_t^2(D_{22}^1-D_{24}^1+D_{25}^1+D_{26}^1-D_{34}^1+D_{35}^1+D_{36}^1-D_{37}^1-D_{38}^1+D_{39}^1+2D_{310}^1)$$
$$+2\lambda_i^2 Q_t(D_{23}^2-D_{24}^2-D_{25}^2+D_{35}^2+D_{38}^2)+2\lambda_i^2(2D_{12}^3-2D_{13}^3-D_{22}^3+2D_{23}^3+3D_{24}^3-3D_{25}^3$$
$$-D_{26}^3+D_{34}^3-D_{35}^3-D_{36}^3+D_{37}^3+D_{38}^3-D_{39}^3). \tag{23}$$

$$f_1^{\mathrm{tr}}=-\frac{1}{2}\lambda_i^2 m_b C_{11}^5. \tag{24}$$

(22)—(24)式中

$$C^1=C(-p_2,p_4,m_t,m_i,m_i),$$
$$C^2=C(p_2,-p_4,m_i,m_t,m_t),$$
$$C^3=C(p_1,-p_3,m_t,m_i,m_i),$$
$$C^4=C(-p_1,p_3,m_i,m_t,m_t),$$
$$C^5=C(-p_2,p_1+p_2,m_t,m_i,m_i),$$
$$D^1=D(p_2,-p_4,-p_3,m_i,m_t,m_t,m_t),$$
$$D^2=D(-p_1+p_3,p_1,-p_1+p_4,m_i,m_t,m_i,m_t),$$
$$D^3=D(-p_2,p_4,p_3,m_t,m_i,m_t,m_i). \tag{25}$$

这里 $\hat{s}=(p_1+p_2)^2$. 对于 $i=\pi,\pi_8,\pi_t$，分别有

$$\lambda_\pi=\frac{c_t\varepsilon m_t}{f_\pi},$$
$$\lambda_{\pi_8}=\frac{\varepsilon m_t\lambda^a}{f_\pi},$$
$$\lambda_{\pi_t}=\frac{(1-\varepsilon)m_t}{f_{\pi_t}}. \tag{26}$$

容易发现，有效顶角中所有的紫外发散都可以抵消.

对于未极化的光子，$\gamma\gamma\to b\bar{b}$ 过程的散射截面为

$$\hat{\sigma}(\hat{s})=\frac{N_c}{16\pi\hat{s}^2}\int_{\hat{t}^-}^{\hat{t}^+}\mathrm{d}\hat{t}\overline{\sum_{\mathrm{spins}}}|M_{\mathrm{ren}}(\hat{s},\hat{t})|^2, \tag{27}$$

这里 N_c 表示色的数目，积分上下限 $\hat{t}^\pm$ 为

$$\hat{t}^\pm=\left(m_b^2-\frac{1}{2}\hat{s}\right)\pm\frac{1}{2}\hat{s}\sqrt{1-4m_b^2/\hat{s}};$$

$\overline{\sum_{\mathrm{spins}}}$ 表示对初态自旋求平均

$$\overline{\sum_{\text{spins}}}|M_{\text{ren}}(\hat{s},\hat{t})|^2 = \overline{\sum_{\text{spins}}}|M_0|^2 + 2\text{Re}\overline{\sum_{\text{spins}}}M_0^+\delta M. \tag{28}$$

过程 $e^+e^-\to\gamma\gamma\to b\bar{b}$ 的总散射截面 $\sigma(s)$ 可由子过程 $\gamma\gamma\to b\bar{b}$ 的散射截面 $\hat{\sigma}(\hat{s})$ 求出[4,5]，

$$\sigma(s) = \int_{2m_b/\sqrt{s}}^{x_{\max}} \mathrm{d}z\,\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z}\hat{\sigma}(\hat{s})(\gamma\gamma\to b\bar{b},\hat{s}=z^2 s). \tag{29}$$

这里 $\sqrt{s}$ 和 $\sqrt{\hat{s}}$ 分别表示 e^+e^- 和 $\gamma\gamma$ 的质心能量，$\mathrm{d}L_{\gamma\gamma}/\mathrm{d}z$ 是光子亮度，

$$\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = 2z\int_{z^2/x_{\max}}^{x_{\max}}\frac{\mathrm{d}x}{x}F_{\gamma/e}(x)F_{\gamma/e}(z^2/x), \tag{30}$$

其中 $F_{\gamma/e}$ 是光子结构函数[4,40—42]，

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)}\left[1-x+\frac{1}{1-x}-\frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x^2)}\right], \tag{31}$$

而

$$D(\xi) = \left(1-\frac{4}{\xi}-\frac{8}{\xi^2}\right)\ln(1+\xi)+\frac{1}{2} + \frac{8}{\xi}-\frac{1}{2(1+\xi)^2}. \tag{32}$$

这里 $\xi=4E_eE_0/m_e^2$，m_e 和 E_e 表示初态电子的质量和能量，E_0 表示初态光子的能量，$x_{\max}=\xi/(1+\xi)$. 对于 $\xi=4.8$，有[40—42] $x_{\max}\approx0.83$，$D(\xi)\approx1.8$.

4. 数值结果与讨论

数值计算中用到的输入参数取为[43] $m_t=171.2$ GeV，$m_b=4.2$ GeV，$G_F=1.166392\times10^{-5}$ GeV^{-2}，$\sin^2\theta_W=0.2315$，$\alpha=1/137.036$. 对于模型依赖的参数，我们取 $m_\pi=150$ GeV，$m_{\pi_8}=246$ GeV 以及 150 GeV $<m_{\pi_t}<$ 450 GeV 来考察散射截面对 TOPCTC 模型参数模型的依赖性，最后的数值结果在图 2—图 4 中给出.

图 2 中，我们给出了当 $\sqrt{s}=500$ GeV，$m_{\pi_t}=225$ GeV 时相对修正 $\delta\sigma(e^+e^-\to\gamma\gamma\to b\bar{b})$ 随参数 ε 的变化曲线. 从图 2 可以发现：相对修正是负的，大致在 -4.48% 和 -5.17% 之间变化；相对修正随着 ε 的增大而缓慢地减小；当 $\varepsilon=0.03$ 和 $\sqrt{s}=500$ GeV 时，相对修正的最大值为 -5.17%.

图 3 给出的是 $\sqrt{s}=500$ GeV，$\varepsilon=0.06$ 情形相对修正 $\delta\sigma(e^+e^-\to\gamma\gamma\to b\bar{b})$ 随参数 m_{π_t} 的变化曲线. 从

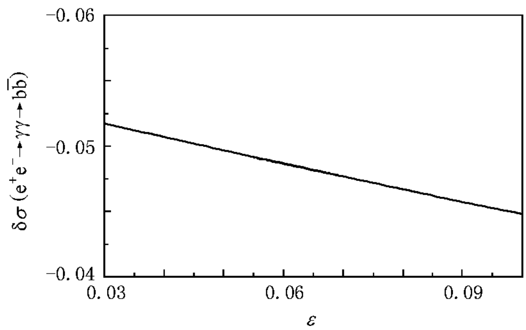

图 2　当 $\sqrt{s}=500$ GeV，$m_{\pi_t}=225$ GeV 时截面相对修正 $\delta\sigma(e^+e^-\to\gamma\gamma\to b\bar{b})$ 随参数 ε 的变化曲线

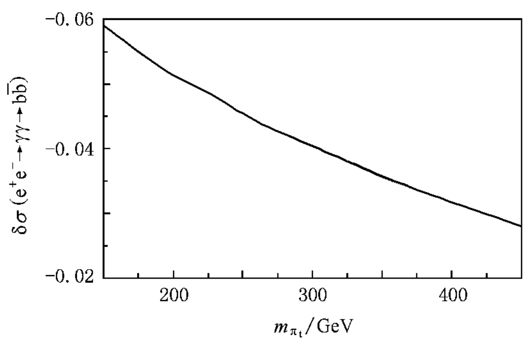

图 3　当 $\sqrt{s}=500$ GeV，$\varepsilon=0.06$ 时截面相对修正 $\delta\sigma(e^+e^-\to\gamma\gamma\to b\bar{b})$ 随参数 m_{π_t} 的变化曲线

图 3 可以发现：相对修正随着 m_{π_t} 的增加迅速地减小；当 $m_{\pi_t}=150$ GeV 时，相对修正的最大值为 -5.90%，而当 $m_{\pi_t}=450$ GeV 时，相对修正的最大值只有 -3.17%.

为考察 $e^+e^-\to\gamma\gamma\to b\bar{b}$ 的总散射截面 σ 随质心能量 $\sqrt{s}$ 的变化规律，我们取 $m_\pi=150$ GeV，$m_{\pi_8}=246$

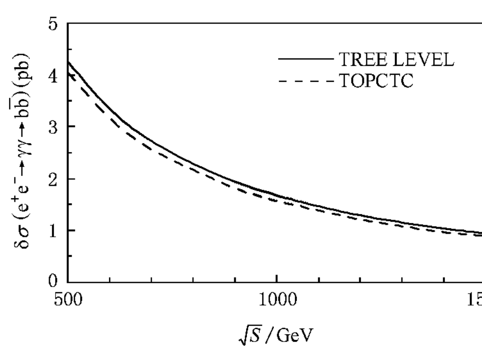

图 4　当 $m_{\pi_t}=225$ GeV 和 $\varepsilon=0.06$ 时 $e^+e^-\to\gamma\gamma\to b\bar{b}$ 的总散射截面随质心能量的变化曲线

GeV，$m_{\pi_t} = 225$ GeV 以及 $\varepsilon = 0.06$ 的情形作为一个例子，如图 4 所示. 从图 4 可以发现：与 $\gamma\gamma \rightarrow t\bar{t}$ 散射不同[3,40—42]，在 500—1500 GeV 的范围内，$\gamma\gamma \rightarrow b\bar{b}$ 的散射截面随着质心能量的增加而减小；含有圈图修正的散射截面与树图水平情形的偏差很平滑，没有明显的起伏.

我们的计算表明，TOPCMTC 模型的总散射截面仅比 TOPCTC 模型的情形稍微大一些，两者之间没有明显的差别.

我们知道，国际直线对撞机（ILC）是未来重要的下一代线性对撞机. 根据其设计报告，将于 2010 年开始建造，其前四年运行的质心能量为 $\sqrt{s} = 500$ GeV，总积分亮度可达 $L = 500\ \mathrm{fb}^{-1}$，并逐步提高到 $L = 1000\ \mathrm{fb}^{-1}$. 这意味着届时 ILC 上每年将有数百万个底夸克对的产生，在 500 GeV 情形赝标 Goldstone 玻色子贡献引起的 -3.17% 到 -5.90% 的偏差将会给出一个明显的改变. 相对而言，标准模型中 Higgs 玻色子引起的相对修正大约只有 10^{-5} 的量级，而双 Higgs 二重态模型和最小超对称模型中的相应贡献均小于 0.1%，因此，在 ILC 上对于 $\gamma\gamma \rightarrow b\bar{b}$ 散射过程的探测，将为尝试标准模型和探索新物理提供了一种可能.

[1] Brodsky S J，Zerwas P M 1995 *Nucl. Instrum. Meth.* A **355** 19

[2] Ginzburg I F，Kotkin G L，Serbo V G，Telnov V I 1981 *Pisma Zh. Eksp. Teor. Fiz.* **34** 514

[3] Halzen F，Kim C S，Stong M L 1992 *Phys. Lett.* B **274** 489

[4] Eboli O J P，Goznalez-Garcia M C，Halzen F，Novaes S F 1993 *Phys. Rev.* D **47** 1889

[5] Han L，Hu C G，Li C S，Ma W G 1996 *Phys. Rev.* D **54** 2363

[6] Weinberg S 1979 *Phys. Rev.* D **19** 1277

[7] Susskind L 1979 *Phys. Rev.* D **20** 2619

[8] Dimopoulos S，Susskind L 1979 *Nucl. Phys.* B **155** 237

[9] Eichten E，Lane K 1980 *Phys. Lett.* B **90** 125

[10] Holdom B 1981 *Phys. Rev.* D **24** 1441

[11] Appelouquist T，Karabali D，Wijewardhana L C R 1986 *Phys. Rev. Lett.* **57** 957

[12] Appeloquist T，Wijewardhana L C R 1987 *Phys. Rev.* D **36** 568

[13] Yamawaki K，Bando M，Matumoyo K 1986 *Phys. Rev. Lett.* **56** 1335

[14] Akiba T，Yanagida T 1986 *Phys. Lett.* B **169** 432

[15] Lane K，Eichten E 1989 *Phys. Lett.* B **222** 274

[16] Lane K，Ramana M V 1991 *Phys. Rev.* D **44** 2678

[17] Chivukula R S，Selipsky S B，Simmons E H 1992 *Phys. Rev. Lett.* **69** 575

[18] Chivukula R S，Simmons E H，Terning J 1994 *Phys. Lett.* B **331** 383

[19] Hill C T 1995 *Phys. Lett.* B **345** 483

[20] Hill C T，Simmous E H 2003 *Phys. Rep.* **381** 235

[21] Lane K，Eichten E 1995 *Phys. Lett.* B **352** 382

[22] Lane K 1996 *Phys. Rev.* D **54** 2204

[23] Hill C T 1991 *Phys. Lett.* B **266** 419

[24] Martin S P 1992 *Phys. Rev.* D **45** 4283

[25] Lindner M，Ross D 1992 *Nucl. Phys.* B **370** 30

[26] Bönisch R 1991 *Phys. Lett.* B **268** 394

[27] Lu G R，Xiong Z H，Cao Y G 1997 *Nucl. Phys.* B **487** 43

[28] Ellis J，Gaillard M K，Nanopoulos D V，Sikivie P 1981 *Nucl. Phys.* B **182** 529

[29] Eichten E，Hinchliffe I，Lane K D，Quigg C 1984 *Rev. Mod. Phys.* **56** 579

[30] Miransky V A，Tanabashi M，Yamawaki K 1989 *Phys. Lett.* B **221** 177

[31] Bardeen W A，Hill C T，Lindner M 1990 *Phys. Rev.* D **41** 1647

[32] Hill C T，Kennedy D，Onogi T，Yu H L 1993 *Phys. Rev.* D **47** 2940

[33] Lü G，Huang J S，Lu G R 2006 *Phys. Rev.* D **73** 015008

[34] Bohm M，Spiesberger H，Hollik W 1986 *Fortschr Phys.* **34** 687

[35] Hollik W 1990 *Fortschr Phys.* **38** 165

[36] Grzadkowski B，Hollik W 1992 *Nucl. Phys.* B **384** 101

[37] Clements M，Footman C，Kronfeld A S，Narasimhan S，Photiadis D 1983 *Phys. Rev.* D **27** 570

[38] Axelrod A 1982 *Nucl. Phys.* B **209** 349

[39] Passarino G，Veltman M 1979 *Nucl. Phys.* B **160** 151

[40] Cheung K M 1993 *Phys. Rev.* D **47** 3750

[41] Zhou H Y，Kuang Y P，Yue C X，Wang H，Lu G R 1998 *Phys. Rev.* D **57** 4205

[42] Sahin I 2009 *Eur. Phys. J.* C **60** 431

[43] Amsler C 2008 *Phys. Lett.* B **667** 1

Bottom quark pair production in $\gamma\gamma$ collision*

Huang Jin-Shu[1)2)†] Luo Peng-Hui[1)3)] Lu Gong-Ru[1)]

1)(*College of Physics and Information Engineering*, *Henan Normal University*, *Xinxiang* 453007, *China*)

2)(*College of Physics and Electric Engineering*, *Nanyang Normal University*, *Nanyang* 473061, *China*)

3)(*Department of Electronics and Electric Engineering*, *Nanyang Institute of Technology*, *Nanyang* 473004, *China*)

(Received 28 January 2009; revised manuscript received 3 March 2009)

Abstract

We study the Yukawa corrections to the $\gamma\gamma \to b\bar{b}$ cross section in the topcolor assisted technicolor models at the photon-photon colliders. We find that, for the favorable parameters, the relative corrections from pseudo-Goldstone bosons give out a 3.17%—5.90% decrement of the cross section from the tree level when $\sqrt{s}$ = 500 GeV, the total relative corrections are significantly larger than the corresponding corrections in the standard model, the general two Higgs doublet model and the minimal supersymmetric standard model. So the observation of the correction to the $\gamma\gamma \to b\bar{b}$ process at the International Linear Colliders is certainly the clue to the standard model and new physics.

Keywords: topcolor assisted technicolor models, gamma collider, cross section

PACC: 1380, 1210D, 1480D, 1130Q

* Project supported by the National Natural Science Foundation of China (Grant Nos. 10575029, 10595047), the Natural Science Foundation of Henan Province, China (Grant No. 092300410205) and the Natural Science Foundation of Education Bureau of Henan Province, China (Grant No. 2007140013).

† E-mail: jshuang@vip.sina.com