POLARIZATION PROPERTIES OF γ-QUANTA IN $H \Rightarrow f + \bar{f} + \gamma$ DECAYİNG

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We have analyzed the Higgs-boson decaying process of $H \Rightarrow f + \bar{f} + \gamma$ based on the Feynman diagram. While considering the helicity of fermion-antifermion and the linear (circular) polarization , the cross-section of the $H \Rightarrow f + \bar{f} + \gamma$ in the framework of the standard model (SM) has been calculated. The linear or the circular polarization of the $\gamma -$ quanta has been evaluated and the dependency of the fermion-antifermion pair over the x i.e. the invariant mass and the exiting θ angle has been investigated.

The value for the linear and circular polarization of the γ-quanta during the $H \Rightarrow \tau^- + \tau^+ + \gamma$ has been shown.

Keywords: Higgs Boson, Standard Model, γ-quanta polarization, Scattering matrix, Electroweak interaction, tau leptons.
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1. INTRODUCTION

Based on $SU_c(3) \times SU_l(2) \times U_y(1)$ symmetry, the standard model (SM) predicts and describe all the phenomena of strong, weak and electromagnetic forces.

The main part of this model is the spontaneous symmetry breaking via higgs mechanism. In this process, the non-zero scalar field is being introduced. Because of interaction with this field and based on the computations of quantum electrodynamics, the higgs particles are being created. Thanks to ATLAS and CMS collaboration the higgs boson was finally discovered in 2012(see reference [5-7]).

Higgs boson is an unstable particle and will be decayed through different channels [2,8-10].

In Large Hadron Collider (LHC), it is through the following channels $H \Rightarrow \gamma + \bar{\gamma}$ two photon decaying, 2 electron-positron pair and 2 muon-antimuon channels. The mentioned channels are as follow $H \Rightarrow e^- + e^+ + e^- + e^+$, $H \Rightarrow e^- + e^+ + \mu^- + \mu^+$, $H \Rightarrow \mu^- + \mu^+ + \mu^- + \mu^+$.

These decaying are being shown as follow:

$$H \Rightarrow zz^* \Rightarrow 4l$$

Here, z is the real and $z^*$the virtual boson while l signifies one of the $e^\pm$ or $\mu^\pm$.

In ATLAS and CMS the decaying of $H \Rightarrow WW^* \Rightarrow l_\nu l_\nu$ is also being discovered where the W is the real and W^* is virtual boson while υ is the electron neutrino (or even muon neutrino).

Higs boson in most cases is being decayed into $H \Rightarrow b + \bar{b}$ where the $b\bar{b}$ pair is one of the most observed phenomena in proton-proton and proton-anti proton collision. This state occurs even at the absence of Higgs boson. Because of this selecting information regarding higgs boson is very difficult. So, as a result of processes like this, during the collision of proton-proton, the higgs boson are produced with the W boson at the same time and the w boson is decayed to υ_e pair. Here e is either $e^\pm$ or $\mu^\pm H \Rightarrow b + \bar{b}$, $Z \Rightarrow 2e$ or $Z \Rightarrow 2\upsilon$ decayings are also a result of $p + p \Rightarrow z + H$. Unfortunately in LHC selection of these reactions from the background has not been possible.

One of the main channels for the decaying of higgs boson are the following channels of $H \Rightarrow \gamma + e, H \Rightarrow \gamma + Z$. Besides these channels, it creates the radiative reactions of higgs boson of $H \Rightarrow f + \bar{f} + \gamma$ that are very interesting. Here $f\bar{f}$ signifies fermion-antifermion pairs [11-15].

In this work, the cross section for the process is carried out and the distribution over the angles and energies has being researched and the assymetry for longitudinal and transverse polarization problems has been investigated. The features of Gamma quantas though has been ignored. For now, the main goals for the current work is to study the cross section of the decay, while considering the linear and circular polarization of $H \Rightarrow \tau^- + \tau^+ + \gamma$ while obtaining numerical results.

2. THE AMPLİTUDE OF $H \Rightarrow f\bar{f}\gamma$ DECAYİNG

The radiative higgs boson decay $H \Rightarrow f + \bar{f} + \gamma$ takes place through the feynman diagrams depicted in fig.1. Based on these diagrams the higgs boson is first decayed to fermion-antifermion and then emits γ-quanta.

The amplitude for this procss is given by:

$$M_{i\to f} = iA_0 Q_f \left[\bar{u}_f(p_1, \lambda_1) R \vartheta_f(p_2, \lambda_2)\right] \quad (2)$$

Where

$$A_0 = -\frac{2\pi\alpha_{KED} m_f}{M_w \sin\theta_w} \quad (3)$$

$$R = \hat{e}^* \frac{\widehat{p_1} + \hat{k} + m_f}{(p_1+k)^2 - m^2 f} - \frac{\widehat{p_2} + \hat{k} + m_f}{(p_2+k)^2 - m^2 f} \hat{e}^* \quad (4)$$

Here θ_w is the weinberg angle , M_w stands for the mass of the boson, $P, P_1, P_2 and\ K$ are the 4-momentum of higgs boson,fermion-antifermion and γ-quanta. $\lambda_1 and \lambda_2$ shpw the chirality of fermion-antifermion and e^* is the four-vector for the polarization of γ-quanta.

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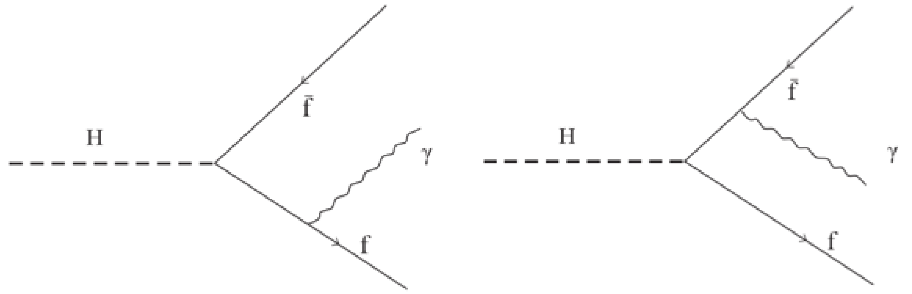

Fig.1.

Using Dirac equation,

$$\bar{u}_f(p_1, \lambda_1)(\widehat{p_1} - m_f) = 0,$$
$$(\widehat{p_2} + m_f)\vartheta_f(p_2, \lambda_2) = 0 \qquad (5)$$

We will get the following for the R:

$$\hat{R} = \frac{2(e^*, p_1) + \hat{e}^*\hat{k}}{2(p_1 \cdot k)} - \frac{2(e^*, p_2) + \hat{e}^*\hat{k}}{2(p_2 \cdot k)} \qquad (6)$$

The amplitude of the relation (2) in the system of equation ($\overrightarrow{p_1} + \overrightarrow{p_2} = 0, \vec{p} = \vec{k}$) will give the relation as follow:

$$\left|M_{i\to f}\right|^2 = \frac{A_0^2}{2}\left(\frac{1}{(p_1 \cdot k)} + \frac{1}{(p_2 \cdot k)}\right)^2 \{(1 + \lambda_1\lambda_2)[M_H^2(ep_1)(ep_1{}^*) + (p_1 \cdot k)(p_2 \cdot k)] - i(\lambda_1 + \lambda_2)[(ep_1)(p_1p_2ke^*)_\varepsilon - (e^* \cdot p_1)(p_1p_2ke)_\varepsilon + (k \cdot p_2)(p_1ke^+e)_\varepsilon]\} \qquad (7)$$

where the $(abcd)_\varepsilon$ is being considered.
The cross section for the decaying of higgs-boson is proportional to the square of $\left|M_{i\to f}\right|(i.e. \left|M_{i\to f}\right|^2)$.

$$d\Gamma(H \Rightarrow f\bar{f}\gamma) = \frac{1}{2E_H}\left|M_{i\to f}\right|^2 d\Phi \qquad (8)$$

where the $d\phi$ is the invariant volume of the phases.

$$d\Phi = (2\pi)^4 \frac{d\overrightarrow{p_1}}{(2\pi)^3 \cdot 2E_1} \cdot \frac{d\overrightarrow{p_2}}{(2\pi)^3 \cdot 2E_2} \cdot \frac{d\vec{k}}{(2\pi)^3 \cdot 2E_\gamma} \; \delta(p - p_1 - p_2 - k) \qquad (9)$$

The heavier the mass of the fermion, the stronger the interaction of the fermion-antifermion pair will be causing the constant of interaction to be larger. we get from here that the higgs boson mass equal to $M_H = 125Gev$ will decay to $\tau\tau^+$, $c\bar{c}$ and $b\bar{b}$ fermion pairs.
Because of the low value for its mass the followig decaying channels of $H \Rightarrow e^- + e^+ + \gamma$, $H \Rightarrow \mu^- + \mu^+ + \gamma$, $H \Rightarrow u + \bar{u} + \gamma$, $H \Rightarrow d + \bar{d} + \gamma$ and $H \Rightarrow s + \bar{s} + \gamma$ are not possible.

The $H \Rightarrow \tau^- + \tau^+ + \gamma$ radiation decaying is also very attractive meaning $\tau^- \Rightarrow \pi^- + \upsilon_\tau$, $\tau^- \Rightarrow K^- + \upsilon_\tau$, $\tau^- \Rightarrow \rho^- + \upsilon_\tau$ decaying channels allow us to measure the polarization. Additionally during $H \Rightarrow \tau^- + \tau^+ + \gamma$, the γ-quanta can obtain the linear or circular polarization and its measurement will make possible to investigate some feature of the higgs boson. The squared fraction for radiative reactions $H \Rightarrow q^- + q^+ + \gamma$, $H \Rightarrow c + \bar{c} + \gamma$ and $H \Rightarrow b + \bar{b} + \gamma$ are $(\frac{m_\tau}{M_H})^2 = 0.0002 \ll 1$ and $(\frac{m_b}{M_H})^2 = 0.0015 \ll 1$.
Because of this, in the cross section calculation, we can ignore the related $\varepsilon\frac{m_f^2}{M_H^2}$.

3. THE LİNEAR POLARİZATİON OF γ - QUANTA

At the center of the fermion-antifermion pairs, the angle θ is the polar angle and φ the azimuthal angle.
At the center of the fermion-antifermion pair, the cross section of $H \Rightarrow f + \bar{f} + \gamma$ for the linearly polarized γ quanta is given by:

$$\frac{d\Gamma(\vec{e})}{dx\, d\Omega} = \frac{A_0^2\, M_H\vartheta}{2^{12}\pi^4(1-x)} \cdot \frac{N_C(1+\lambda_1\lambda_2)}{(1-\vartheta^2\cos^2\theta)^2}\left[4x\vartheta^2(\vec{e}\vec{n})^2 + (1-x)^2(1-\vartheta^2\cos^2\theta)\right] \quad (10)$$

Here $d\Omega = d(\cos\theta)d\varphi$ is the angle of the emission for the fermion f and the x is the invariant mass for the fermion-anti fermions in M_H^2 units.

$$x = \frac{s}{M_H^2} = \frac{(p_1 + p_2)^2}{M_H^2}$$

Where $v = \sqrt{1 - 4m_f^2/s}$ is the velocity of fermion and the N_c is the constant of quark (lepton) pair production$N_c = 3(1)$.

From the equation (10) for the cross section of the decay we get that the helicity for fermion-anti fermion must be equal (λ1= λ2=±1). So fermion-anti fermion will either have right polarization fr,fr or left polarization fl,fl. This is the result of conservation of energy in $H \Rightarrow f + \bar{f}$ decaying.

The cross section for the γ-quanta decaying along x ($\vec{e} = \overrightarrow{e_x}$) and y (($\vec{e} = \overrightarrow{e_y}$)) is given by the relation (11) and (12).

$$\frac{d\Gamma(\overrightarrow{e_x})}{dx\, d\Omega} = \frac{A_0^2\, M_H \vartheta}{2^{10}\pi^4(1-x)} \cdot \frac{N_C}{(1-\vartheta^2\cos^2\theta)^2}\left[4x\vartheta^2\sin^2\theta\cos^2\varphi + (1-x)^2(1-\vartheta^2\cos^2\theta)\right] \quad (11)$$

$$\frac{d\Gamma(\overrightarrow{e_y})}{dx\, d\Omega} = \frac{A_0^2\, M_H \vartheta}{2^{10}\pi^4(1-x)} \cdot \frac{N_C}{1-\vartheta^2\cos^2\theta}\left[4x\vartheta^2\sin^2\theta\sin^2\varphi + (1-x)^2(1-\vartheta^2\cos^2\theta)\right] \quad (12)$$

According to equation 13(mentioned below) we are now going to evaluate the order(magnitude) of linear polarization for the γ-quanta.

$$P_\gamma(\vec{e}) = \frac{d\Gamma(\overrightarrow{e_x})/dx\, d\Omega - d\Gamma(\overrightarrow{e_y})/dx\, d\Omega}{d\Gamma(\overrightarrow{e_x})/dx\, d\Omega + d\Gamma(\overrightarrow{e_y})/dx\, d\Omega} = \frac{2x\vartheta^2\sin^2\theta\cos 2\varphi}{2x\vartheta^2\sin^2\theta + (1-x)^2(1-\vartheta^2\cos^2\theta)} \quad (13)$$

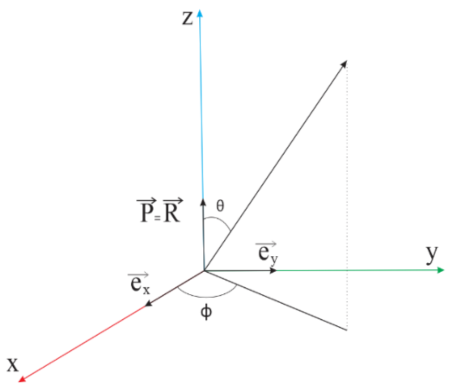

Fig .2. The Polarization of fermion-antifermion pair for polar θ-angle and φ-azimuthal angle.

The maximum value for linear polarization for the γ quanta appears to be at azimuthal angle of φ=0.in figure 3 the linear polarization is being depicted for the γ-quanta at the θ=90 and mH=125 Gev and m_τ=1.778 Gev over the x variable for the $H \Rightarrow \tau^- + \tau^+ + \gamma$ decaying. It is seen from the diagram that as x increases the linear polarization of the γ-quanta will increase monotonically and at the end of the spectrum at x=1 obtains its highest value of p(γ=100%). At the maximum value of invariant mass(x=1) the photon will have the lowest possible energy.

Correspondingly, the higgs bosons during $H \Rightarrow f + \bar{f} + \gamma$ decaying will give rise to the light photons of linear polarization.

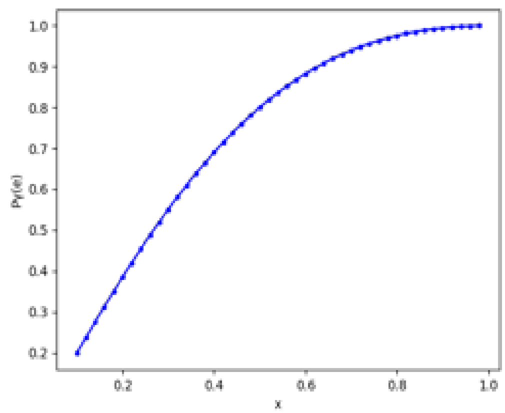

Fig.3. The x-dependency of magnitude of linear polarization of γ-quanta at θ=90°.

By summation for the polarization of γ-quanta in eq-10:

$$\sum_e (\vec{e}\vec{n})^2 = (\overrightarrow{e_x}\vec{n})^2 + (\overrightarrow{e_y}\vec{n})^2 = sin^2\theta(cos^2\varphi + sin^2\varphi) = sin^2\theta$$

We will get the following cross section for $H \Rightarrow f + \bar{f} + \gamma$:

$$\frac{d\Gamma}{dx\, d(\cos\theta)} = \frac{A_0^2 M_H N_C \vartheta}{128\,\pi^3} \cdot \frac{1+x^2}{(1-x)(1-\vartheta^2\cos^2\theta)} \quad (14)$$

Fig 4 shows the width of $H \Rightarrow \tau^- + \tau^+ + \gamma$ decaying for$M_H = 125Gev$, $M_w = 80.385\ Gev$, $sin^2\theta_w = 0.2315$ for differnet invariant mass of $x = 0.2; x = 0.5; x = 0.8;$ over the emitted θ angle.

As θ increases the width of the decaying $H \Rightarrow \tau^- + \tau^+ + \gamma$ increase and at $\theta = 90$ obtains its maximumvalue. The further increse of θ will decrease the width. The further increase of θ will decrease the width. The increase in fermion-antifermion invariant mass (by decreasing the width of γ-quanta) will increase the width of the decaying.

By integrating the relation 14 for the decay over emitting angle we will obtain the relation of tau-lepton decaying over the invariant mass:

$$\frac{d\Gamma}{dx} = \frac{A_0^2 M_H}{128\,\pi^3} \cdot \frac{1+x^2}{(1-x)} \cdot \ln\frac{1+\vartheta}{1-\vartheta} \qquad (15)$$

Figure 5 depicts the width of decaying of $H \Rightarrow \tau^- + \tau^+ + \gamma$ over the invariant mass. According to the diagram, increasing the energy obtained from fermion-antifermion pair will result in the increase of the width of $d\Gamma(H \Rightarrow \tau^- + \tau^+ + \gamma)/dx$.

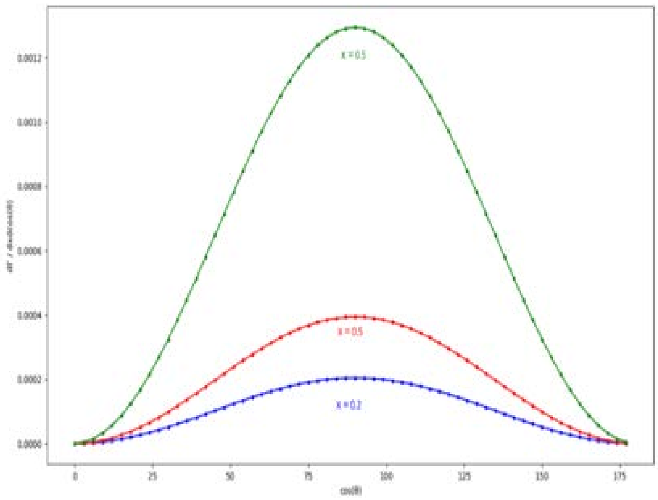

Fıg.4 . The $H \Rightarrow \tau^- + \tau^+ + \gamma$ decaying for different x over emitting angle.

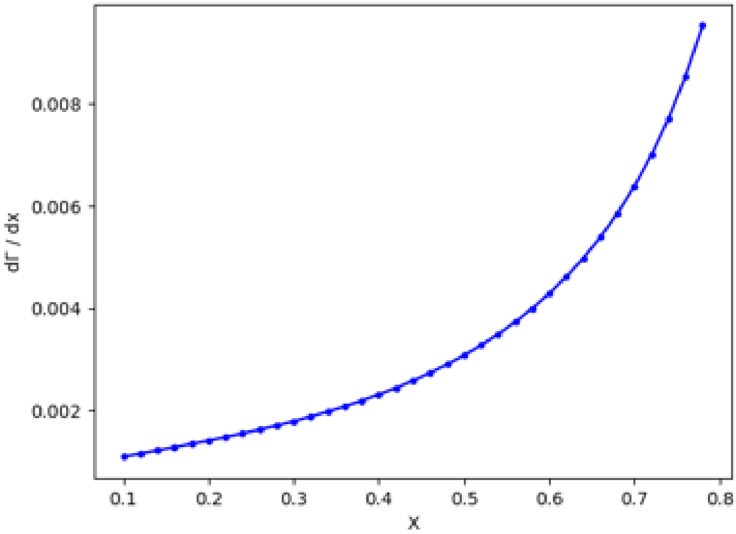

Fıg. 5. Width of the $H \Rightarrow \tau^- + \tau^+ + \gamma$ decaying and its dependency over the invariant mass x.

4. CİRCULAR POLARİZATİON OF γ-QUANTA

Let's observe the polarization of γ-quanta from fermion-antifermion during $H \Rightarrow f + \bar{f} + \gamma$ decaying. The circular polarization vectors for the γ-quanta are:

$$\vec{e} = \frac{1}{\sqrt{2}}\left(\vec{\beta} + i\, s_\gamma\, [\vec{n}_0\vec{\beta}]\right),\ \vec{e}^* = \frac{1}{\sqrt{2}}\left(\vec{\beta} i\, s_\gamma\, [\vec{n}_0\vec{\beta}]\right) \qquad (16)$$

Here, $\vec{n}_0$ and $\vec{\beta}$ quantities,respectively, stand for the orientation of unit vectors of themomentum vector and prependicular to them. The $s_\gamma = \pm 1$ though characteriz the right and left polarization of the γ-quanta.
The $\vec{e}$ and $\vec{e}^*$ polarization vectors have the following properties:

$$(\vec{e}\vec{e}^*) = 1, [\vec{e}\vec{e}^*] = -i\, s_\gamma \vec{n}_0, [\vec{e}\vec{n}_0] = i\, s_\gamma \vec{e}, [\vec{n}_0\vec{e}^*] = i\, s_\gamma \vec{e}^*$$

The width of the decaying $H \Rightarrow f + \bar{f} + \gamma$, while considering the circular polarization of γ-quanta is being given by:

$$\frac{d\Gamma(\lambda_1;S_\gamma)}{dxd(\cos\theta)} = \frac{A_0^2 M_H \vartheta}{2^{10}\,\pi^3(1-x)} \cdot \frac{N_C}{(1-\vartheta^2\cos^2\theta)^2} \cdot \{(1+\lambda_1\lambda_2)(1+x^2)(1-\vartheta^2\cos^2\theta) + S_\gamma(\lambda_1+\lambda_2)(1-x)[2x\vartheta^2\sin^2\theta + (1-x)(1-\vartheta^2\cos^2\theta)]\} \quad (17)$$

the order of the circular polarization of γ-quanta is obtained using eq.18:

$$P_\gamma(S_\gamma) = \frac{\frac{d\Gamma(\lambda_1;S_\gamma=1)}{dxd(\cos\theta)} - \frac{d\Gamma(\lambda_1;S_\gamma=-1)}{dxd(\cos\theta)}}{\frac{d\Gamma(\lambda_1;S_\gamma=1)}{dxd(\cos\theta)} + \frac{d\Gamma(\lambda_1;S_\gamma=-1)}{dxd(\cos\theta)}} = \lambda_1 \cdot \frac{(1-x)[2x\vartheta^2\sin^2\theta + (1-x)(1-\vartheta^2\cos^2\theta)]}{(1+x^2)(1-\vartheta^2\cos^2\theta)} \quad (18)$$

Figure 6 depicts the order of circular polarization for γ-quanta at $\lambda_1 = -1$ for the $H \Rightarrow \tau^- + \tau^+ + \gamma$ over the θ angle.

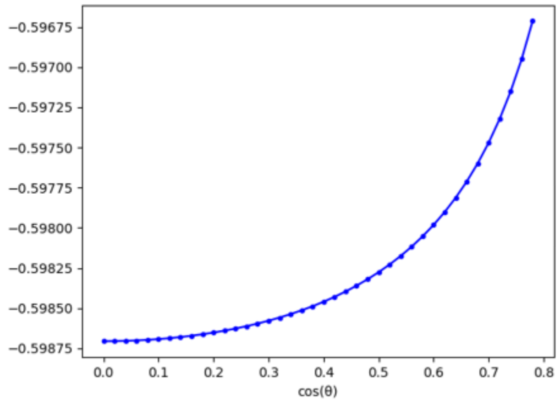

Fig. 6. $P_\gamma(S_\gamma)$ dependency over cos θ.

As it is seen the order of circular polarization for γ-quanta is negative and it can be said that it is independent of the θ angle. The energy obtained from fermion-antifermion pair cause the order of circular polarization to get reduced.

By integrating the equation 17 over the θ angle the spectrum of fermion-antifermion pair will get us the following relation:

$$\frac{d\Gamma(\lambda_1;S_\gamma)}{dx} = \frac{A_0^2 M_H \vartheta}{2^9\,\pi^3}\frac{N_C}{1-x}\{(1+x^2)L + S_\gamma\lambda_1(1-x)[-2x + (1+x\vartheta^2 L)]\} \quad (19)$$

where $L = \frac{1}{v} ln\frac{1+v}{1-v}$.

We can calculate the order of circular polarization of γ-quanta by the following relation:

$$P_\gamma(S_\gamma) = \frac{d\Gamma(\lambda_1;S_\gamma=1)/dx - d\Gamma(\lambda_1;S_\gamma=-1)}{d\Gamma(\lambda_1;S_\gamma=1)/dx + d\Gamma(\lambda_1;S_\gamma=-1)} \quad (20)$$

Using relation 19:

$$P_\gamma(S_\gamma) = \lambda_1 \cdot \frac{(1-x)[-2x + (1+x\vartheta^2 L)]}{(1+x^2)L} \quad (21)$$

Fig-7 draws the order of circular polarization of γ-quanta for the $H \Rightarrow \tau^- + \tau^+ + \gamma$ at $\lambda_1 = -1$ for τ-lepton pair over the invariant mass x. As it is seen the order of circular polarization for γ-quanta is negative and its magnitude decrease as the x-invariant mass increase.

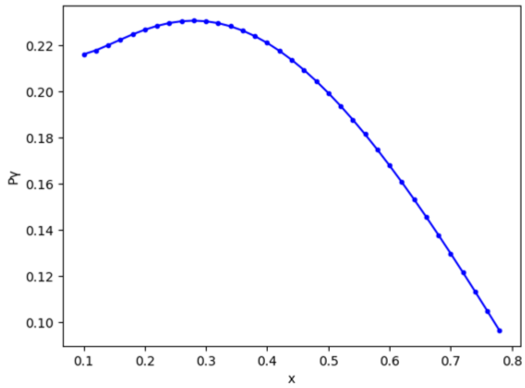

Fig. 7. The Circular Polarization for $H \Rightarrow \tau^- + \tau^+ + \gamma$ of the γ-quanta.

RESULT

We have analyzed the Higgs boson decaying by the γ-radiation from fermion-antifermion pair. Considering the helicity of fermion-antifermion pair and linear(circular) polarization, the cross section for $H \Rightarrow f + \bar{f} + \gamma$ in the framework of standard model has been calculated. The order of linear and circular polarization is being calculated and its dependency on the invariant mass od fermion-antifermion x and the angle of output θ is being carried out. The value of order of linear and circular polarization for γ-quanta in $H \Rightarrow \tau^- + \tau^+ + \gamma$ is being shown.

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