The $Z \to l^+ l^-$ and $W \to \nu_l l^+$ decays in the noncommutative standard model

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Abstract

We study $Z \to l^+ l^-$ and $W \to \nu_l l^+$ decays in the standard model including the noncommutative effects. We observe that these effects appear in the flavor dependent part of the decay widths of the processes under consideration and therefore, they are more effective for the heavy lepton decays.

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1 Introduction

Leptonic Z-decays are among the most interesting lepton flavor conserving (LFC) and lepton flavor violating (LFV) interactions. The improved experimental measurements at present stimulates the studies of these interactions. With the Giga-Z option of the Tesla project, there is a possibility to increase Z bosons at resonance [1]. The processes $Z \to l^- l^+$ with $l = e, \mu, \tau$ are among the LFC decays and they exist in the SM, even in the tree level. The experimental predictions for the branching ratios (BRs) of these decays are [2]

$$\begin{aligned} BR(Z \to e^+ e^-) &= 3.366 \pm 0.0081\,\% \,, \\ BR(Z \to \mu^+ \mu^-) &= 3.367 \pm 0.013\,\% \,, \\ BR(Z \to \tau^+ \tau^-) &= 3.360 \pm 0.015\,\% \,, \end{aligned} \tag{1}$$

and the tree level SM predictions are

$$\begin{aligned} BR(Z \to e^+ e^-) &= 3.331\,\% \,, \\ BR(Z \to \mu^+ \mu^-) &= 3.331\,\% \,, \\ BR(Z \to \tau^+ \tau^-) &= 3.328\,\% \,. \end{aligned} \tag{2}$$

This shows that the tree level contribution of the SM plays the main role within the experimental uncertainities. In the literature, there are various experimental and theoretical studies [3]-[12]. In [5] a method to determine the weak electric dipole moment was developed. The vector and axial coupling constants, v_f and a_f, in Z-decays have been measured at LEP [7]. In [9], various additional types of interactions have been performed and a way to measure these contributions in the process $Z \to \tau^- \tau^+$ was described. [12] is devoted to the possible new physics effects to the process $Z \to l^+ l^-$, in the general two Higgs doublet model.

$W \to \nu_l l^+$ ($l = e, \mu, \tau$) decays exist also in the tree level, in the SM and the experimental predictions for the branching ratios are [2]

$$\begin{aligned} BR(W \to \nu_e e^+) &= 10.9 \pm 0.4\,\% \,, \\ BR(W \to \nu_\mu \mu^+) &= 10.2 \pm 0.5\,\% \,, \\ BR(W \to \nu_\tau \tau^+) &= 11.3 \pm 0.8\,\% \,, \end{aligned} \tag{3}$$

The main contribution to this decay comes from the SM in the tree level, similar to the process $Z \to l^+ l^-$. There are large number of studies in the literature on this charged process [13].

In the present work, we study $Z \to l^+ l^-$ and $W \to \nu_l l^+$ decays, with $l = e, \mu, \tau$, in the SM, including the noncommutative (NC) effects. The noncommutativity in the space-time is a possible candidate to describe the physics at very short distances of the order of the Planck length, since the nature of the space-time changes at these distances. In the noncommutative geometry the space-time coordinates are replaced by Hermitian operators $\hat{x}_\mu$ which satisfy the equation [14]

$$[\hat{x}_\mu, \hat{x}_\nu] = i\,\theta_{\mu\nu}\,, \tag{4}$$

where $\theta_{\mu\nu}$ is a real and antisymmetric tensor with the dimensions of length-squared. Here $\theta_{\mu\nu}$ can be treated as a background field and its components are assumed as constants over cosmological scales.

It is possible to pass to the noncommutative field theory by introducing $*$ product of functions, instead of the ordinary one,

$$(f * g)(x) = e^{\frac{i}{2}\,\theta_{\mu\nu}\,\partial^y_\mu\,\partial^z_\nu} f(y)\,g(z)|_{y=z=x}\,. \tag{5}$$

The commutation of the Hermitian operators $\hat{x}_\mu$ (see eq. (4)) holds with this new product, namely,

$$[\hat{x}_\mu, \hat{x}_\nu]_* = i\,\theta_{\mu\nu}\ . \tag{6}$$

With the re-motivation due to the string theory arguments [15, 16], various studies on the noncommutative field theory (NCFT) have been done in the literature. However, NCFT have a non-local structure and the Lorentz symmetry is explicitly violated. The violation of the Lorentz symmetry has been handled in [17, 18] and bounding noncommutative QCD due to the Lorentz violation has been studied in [18]. In this work, it was emphasised that the collider limits were not competitive with low energy tests of Lorentz violation for bounding the scale of space-time noncommutativity. Furthermore, the renormalizability and the unitarity of NC theories have been studied in the series of works [19], [20], [21] and [22]. The noncommutative quantum electrodynamics (NCQED) has been examined in [23, 24] and the noncommutativity among extra dimensions for QED has been studied in [25]. Furthermore, the noncommutativity in non-abelian case has been formulated in [26] and this formulation has been applied to the SM in [27]. Recently, a unique model for strong and electroweak interactions with their unification has been constructed in [28]. In the work [29], the SM forbidden processes $Z \to \gamma\gamma$ and $Z \to gg$ has been studied by including the NC effects. In [30], the form factors, appearing in the inclusive $b \to sg$ decay, has been calculated in the NCSM, using the approximate phenomenology and the new operators existing in $b \to sg$ decay due to the NC effects has been obtained in [31].

In the recent work, the possible effects of NC geometry on weak CP violation and the untarity triangles has been examined [32].

The paper is organized as follows: In Section 2, we present the explicit expressions for the branching ratios of $Z \to l^+ l^-$ and $W \to \nu_l l^+$ in the framework of the NCSM. Section 3 is devoted to discussion and our conclusions.

2 The noncommutative effects on the $Z \to l^+ l^-$ and $W \to \nu_l l^+$ decays in the SM

The flavor conserving $Z \to l^+ l^-$, $l = e, \mu, \tau$, decays appear in the tree level in the SM. When the non-commutative effects are switched on there exists a new contribution which is proportional to the a function of the noncommutative parameter θ. Our starting point is the effective action [27]

$$\begin{aligned} S_{Matter,leptons} &= \int d^4x \Bigg(\sum_i (\bar{L}_L^{(i)} + \bar{L}_L^{(i)1} + \bar{L}_L^{(i)2}) * i\,(\not{D}^{SM} + \not{\Gamma}) * (L_L^{(i)} + L_L^{(i)1} + L_L^{(i)2}) \\ &+ \sum_i (\bar{e}_R^{(i)} + \bar{e}_R^{(i)1} + \bar{e}_R^{(i)2}) * i\,(\not{D}^{SM} + \not{\Gamma}) * (e_R^{(i)} + e_R^{(i)1} + e_R^{(i)2}) \Bigg) + O(\theta^3)\,, \end{aligned} \quad (7)$$

with

$$\begin{aligned} D_\mu^{SM} L_L &= (\partial_\mu - i g' Y_L A_\mu - i g B_{\mu a} T_L^a) L_L\,, \\ D_\mu^{SM} e_R &= (\partial_\mu - i g' Y_R A_\mu) e_R\,, \end{aligned} \quad (8)$$

and

$$\begin{aligned} L_L^{(i)1} &= -\frac{1}{2}\theta_{\mu\nu}(g' Y_L A^\mu + g B_a^\mu T_L^a)\,\partial^\nu L_L^{(i)} + O(A^2, B^2, A\,B)\,, \\ L_L^{(i)2} &= -\frac{i}{8}\theta_{\mu\nu}\,\theta_{\alpha\beta}\,(g' Y_L\,\partial^\mu A^\alpha + g\,\partial^\mu B_a^\alpha T_L^a)\,\partial^\nu\,\partial^\beta L_L^{(i)} + O(A^2, B^2, A\,B)\,, \\ e_R^{(i)1} &= -\frac{1}{2}\theta_{\mu\nu}\,(g' Y_R A^\mu)\,\partial^\nu e_R^{(i)} + O(A^2)\,, \\ e_R^{(i)2} &= -\frac{i}{8}\theta_{\mu\nu}\,\theta_{\alpha\beta}\,(g' Y_R \partial^\mu A^\alpha)\,\partial^\nu\,\partial^\beta e_R^{(i)} + O(A^2)\,, \end{aligned} \quad (9)$$

where $*$ in eq. (7) denotes the Moyal-Weyl star product (see eq. (5)), $L_L^{(i)}$ ($e_R^{(i)}$) is the left (right) handed lepton doublet of i^{th} family, $Y_L = -\frac{1}{2}$, $Y_R = -1$ and $O(A^2, B^2, A\,B)\,(O(A^2))$ is the part of $L_L^{(i)1,2}$ ($e_R^{(i)1,2}$) which includes the interactions of more than one gauge fields. Here the function Γ has no interest since it contains two gauge field interactions, which do not give any contribution to our processes $Z(W) \to l^+ l^- (\nu_l l^+)$. Furthermore, we do not present the parts of $L_L^{(i)1,2}$ and $e_R^{(i)1,2}$, $O(A^2, B^2, A\,B)$ and $O(A^2)$, which include the interactions of more than one gauge fields (see [26] and [27] for details).

Finally, the additional vertex to the $Z \to l^+ l^-$ decay to the second order in θ can be obtained as

$$\begin{aligned} V^Z_{\mu,NC} &= \Big((\theta_{\mu\nu}\gamma_\alpha + \theta_{\nu\alpha}\gamma_\mu + \theta_{\alpha\mu}\gamma_\nu)\, p_Z^\nu p_1^\alpha - \frac{i}{4}\,(\theta_{\mu\nu}\gamma_\alpha + \theta_{\nu\alpha}\gamma_\mu + \theta_{\alpha\mu}\gamma_\nu)\,\theta_{\gamma\sigma}\, p_Z^\gamma\, p_Z^\alpha\, p_1^\sigma\, p_1^\nu \Big) \times \\ & \quad (c_1\, L + c_2\, R)\,, \end{aligned} \tag{10}$$

where $c_1 = -e\frac{2sin^2\theta_W - 1}{4\, sin\theta_W cos\theta_W}$, $c_2 = -e\frac{tan\theta_W}{2}$, $L(R) = \frac{1-\gamma_5}{2}\,(\frac{1+\gamma_5}{2})$ and p_Z $(-p_1)$ incoming (ougoing) four momentum of Z boson with polarization vector ϵ^μ (anti-lepton). Notice that the part of the vertex proportional with $\theta_{\nu\alpha}$ would be the whole contribution in the case that the NC effects enter into the expressions as an exponential factor $e^{\frac{i}{2}\,\theta_{\mu\nu} p_Z^\mu p_1^\nu}$, which is consistent in approximate phenomenology (see [33] and references therein).

Now we present the BR of the process $Z \to l^+ l^-$ including the non commutative effects at the least order in θ, in the Z boson rest frame:

$$BR = \frac{\alpha_{em}\, m_Z}{6\,\Gamma_Z\, sin^2\, 2\theta_W} \Big((1 - 4\, sin^2\theta_W + \sin^4\theta_W) - \frac{m_l^2}{m_Z^2} (1 + 8\, sin^2\,\theta_W - 16\, sin^4\,\theta_W + \frac{m_Z^4}{16}\, f(\theta)) \Big)\,, \tag{11}$$

where Γ_Z is the total decay width of Z boson, $\Gamma_Z = 2.490\, GeV$, and $\alpha_{em} = \frac{e^2}{4\,\pi}$. As shown in this equation, the NC effects appear as the function of θ,

$$f(\theta) = (\vec{\theta}_T.\hat{p}_1)^2 + (\vec{\theta}_S.\hat{p}_1)^2 - (|\vec{\theta}_T|^2 + |\vec{\theta}_S|^2) + 2\,\hat{p}_1.(\vec{\theta}_T \times \vec{\theta}_S)\,. \tag{12}$$

Here we use the definitions $(\theta_T)_i = \theta_{0i}$ and $(\theta_S)_i = \frac{1}{2}\epsilon_{ijk}\theta^{jk}$, $i, j, k = 1, 2, 3$ and $\vec{p}_1 = \frac{m_Z}{2}\hat{p}_1$. $(\theta_T)_i$ and $(\theta_S)_i$ are responsible for time-space and space-space noncommutativity, respectively. The noncommutative effects enter into expression with lepton mass and their effects are much more suppressed in the case of light leptons. Notice that, the terms of the vertex eq. (10) which is second order in θ do not give any contribution to the BR of the decay $Z \to l^+ l^-$, in the Z boson rest frame.

The charged $W \to \nu_l l^+$ decays exist with the charged current and they also appear at the tree level in the SM. Similar to the $Z \to l^+ l^-$ decay, the noncommutative effects are controlled by the additional vertex

$$\begin{aligned} V^W_{\mu,NC} &= -\frac{e}{2\,\sqrt{2}\, sin\theta_W} \times \\ & \Big((\theta_{\mu\nu}\gamma_\alpha + \theta_{\nu\alpha}\gamma_\mu + \theta_{\alpha\mu}\gamma_\nu)\, p_W^\nu p_1^\alpha - \frac{i}{4}\,(\theta_{\mu\nu}\gamma_\alpha + \theta_{\nu\alpha}\gamma_\mu + \theta_{\alpha\mu}\gamma_\nu)\,\theta_{\gamma\sigma}\, p_W^\gamma\, p_W^\alpha\, p_1^\sigma\, p_1^\nu \Big)\, L\,, \end{aligned} \tag{13}$$

where p_W $(-p_1)$ incoming (ougoing) four momentum of W boson with polarization vector ϵ^μ (anti-lepton). The BR of the process $W \to \nu_l l^-$ including the non commutative effects, at the least order in θ, in the W boson rest frame reads as:

$$BR = \frac{\alpha_{em}\, m_W}{384\,\Gamma_W\, sin^2\,\theta_W}\left((32 + \frac{m_l^2}{m_W^2}(16 - m_W^4\, f(\theta))\right)\,, \tag{14}$$

where Γ_W is the total decay width of W boson, $\Gamma_W = 2.060\,GeV$. Here the function $f(\theta)$ (see eq. (12)) represents the noncommutative effects. The terms of the vertex eq. (13) which is second order in θ give a non-zero contribution to the BR of the decay $W \to \nu_l l^+$, in the W boson rest frame. This contribution is proportional to $m_l^2\, m_W^2\, (\vec{\theta}_T.\hat{p}_1)^2$. However, it is cancelled by the part, coming from the vertex linear in θ.

At this stage we try to parametrize the vectors $(\theta_T)_i$ and $(\theta_S)_i$ which are responsible for time-space and space-space noncommutativity, respectively. With the assumption that the matrix $\theta_{\mu\nu}$ is real and constant, we take

$$\begin{aligned} \vec{\theta}_T &= A_1\hat{p}_1 + A_2\hat{p}^T_{1\perp}\,, \\ \vec{\theta}_S &= B_1\hat{p}_1 + B_2\hat{p}^S_{1\perp}\,, \end{aligned} \tag{15}$$

where $\hat{p}_1$ $(\hat{p}^T_{1\perp},\, \hat{p}^S_{1\perp})$ is the unit vector in the direction of (the perpendicular direction to) the incoming lepton three momentum $\vec{p}_1$ (for $\vec{\theta}_T$, $\vec{\theta}_S$), A_i, B_i are the corresponding real coefficients. Using this parametrization, $f(\theta)$ can written as

$$f(\theta) = 2\,A_2\,B_2\,\hat{p}_1.(\hat{p}^T_{1\perp} \times \hat{p}^S_{1\perp}) - (A_2^2 + B_2^2)\,. \tag{16}$$

and this shows that the transverse components of the vectors $\hat{p}^T_{1\perp}$ and $\hat{p}^S_{1\perp}$ to the incoming lepton three momentum $\vec{p}_1$ play the main role for the NC effects. In the case of $\hat{p}^T_{1\perp}\perp\hat{p}^S_{1\perp}\perp\hat{p}_1$ with $A_2 = B_2$, the noncommutative effects are switched off. Furthermore, for $\vec{\theta}_T \parallel \hat{p}_1$ $(\vec{\theta}_S \parallel \hat{p}_1)$, the coefficient $A_2 = 0$ $(B_2 = 0)$ and therefore, only the space-space (space-time) noncommutativity is responsible for the noncommutative effects. This is interesting in the determination of the noncommutative directions with the help of the future sensitive experimental results.

3 Discussion

In this section, we analyse the NC effects on the BR of the flavor conserving $Z \to l^+ l^-$ and charged $W \to \nu l^+$ decays, in the framework of the SM. The processes underconsideration exist in the tree level in the SM and the theoretical calculation of the BRs obey the experimental results within the measurement errors.

The flavor $l = e, \mu, \tau$ dependence of the part of the $BR(Z \to l^+ l^-)$ is extremely weak

$$\begin{aligned} R_{\mu e} &= \frac{BR(Z \to \mu^+ \mu^-)}{BR(Z \to e^+ e^-)} = 1.0008 \pm 0.005 \,, \\ R_{\tau e} &= \frac{BR(Z \to \tau^+ \tau^-)}{BR(Z \to e^+ e^-)} = 0.998 \pm 0.005 \,. \end{aligned} \tag{17}$$

This part, which controls the flavor effects, is proportional to the factor $\frac{m_l^2}{m_Z^2}$ and it includes the noncommutative effects. Therefore, it is more informative to study the heavy lepton decays to determine the noncommutativity of the geometry. Notice that we choose the non-commutative parameter $\theta = |\theta_{\mu\nu}|$ as at the order of the magnitude of $\sim 10^{-6} - 10^{-5}\, GeV^{-2}$.

In Fig. 1, we present the noncommutative parameter $f(\theta)$ dependence of ratio $r_1^Z = \frac{BR_{flavor}}{BR_{tot}}$ where BR_{flavor} is the flavor dependent part of the BR and BR_{tot} is the total BR, for the process $Z \to \tau^+ \tau^-$. This figure shows that the noncommutative effects are at most at the order of the magnitude of 0.001%, even for the heavy lepton τ decay. This dependence becomes extremely small, $10^{-6}\,\%$, for $Z \to \mu^+ \mu^-$ decay (see Fig. 2), since the mass of the lepton μ is small and there is a strong suppression factor $\frac{m_\mu^2}{m_Z^2}$ for BR_{flavor}.

Fig. 3 is devoted to the $f(\theta)$ dependence of ratio $r_3^Z = \frac{BR_{flavor_\theta}}{BR_{flavor}}$ where BR_{flavor_θ} is the noncommutative-flavor dependent part of the BR, for the process $Z \to \tau^+ \tau^-$. It is observed that the noncommutative effects on the flavor dependent part can reach to 0.1%.

Now we would like to study the charged $W \to \nu_l l^+$ decay and the noncommutative effects on this process. The BR for this process is

$$BR(W \to \nu_l l^+) = 10.74 \pm 0.33\,\% \tag{18}$$

and the flavor $l = e, \mu, \tau$ dependence of this value is weak. Similar to the $Z \to l^+ l^-$ decay, the part of the BR($W \to \nu l^+$) which controls the flavor effects is proportional to the factor $\frac{m_l^2}{m_W^2}$ and the noncommutative effects appear in this part.

In Fig. 4, we present the noncommutative parameter $f(\theta)$ dependence of ratio $r_1^W = \frac{BR_{flavor}}{BR_{tot}}$ where BR_{flavor} is the flavor dependent part of the BR and BR_{tot} is the total BR for the process $W \to \nu_\tau \tau^+$. It is observed that the noncommutative effects are at most at the order of the magnitude of 0.001%, for the heavy lepton τ decay.

Fig.5 represents the $f(\theta)$ dependence of ratio $r_3^W = \frac{BR_{flavor_\theta}}{BR_{flavor}}$ where BR_{flavor_θ} is the noncommutative-flavor dependent part of the BR for the process $W \to \nu_\tau \tau^+$. Here, the noncommutative effects on the flavor dependent part can reach to 0.1%, similar to the process $Z \to \tau^- \tau^+$.

In conclusion, the NC effects in the decays under consideration are effective in the flavor dependent part of their BRs. With the possible future experiments, which are sensitive to the flavor dependent part of these processes, those effects can be extracted and the noncommutative direction can be determined.

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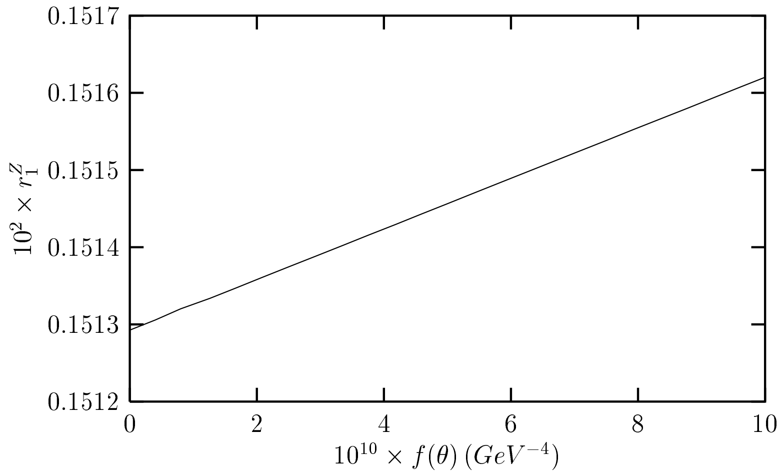

Figure 1: $f(\theta)$ dependence of ratio $r_1^Z = \frac{BR_{flavor}}{BR_{tot}}$ where BR_{flavor} is the flavor dependent part of the BR and BR_{tot} is the total BR, for the process $Z \to \tau^+\tau^-$.

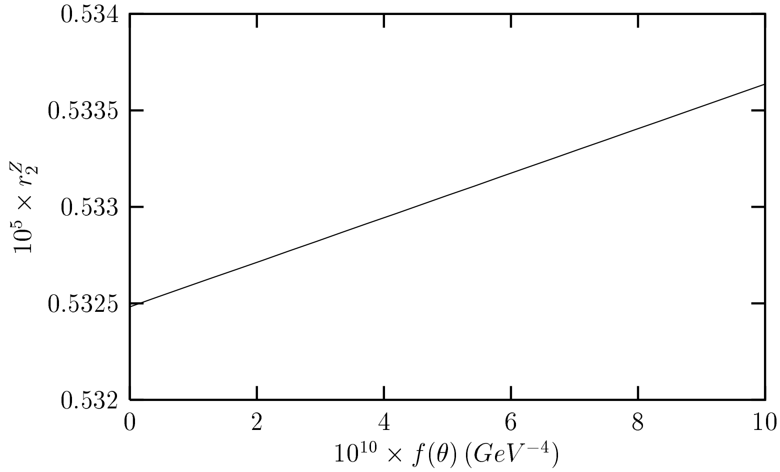

Figure 2: The same as Fig. 1 but for $Z \to \mu^+\mu^-$ decay.

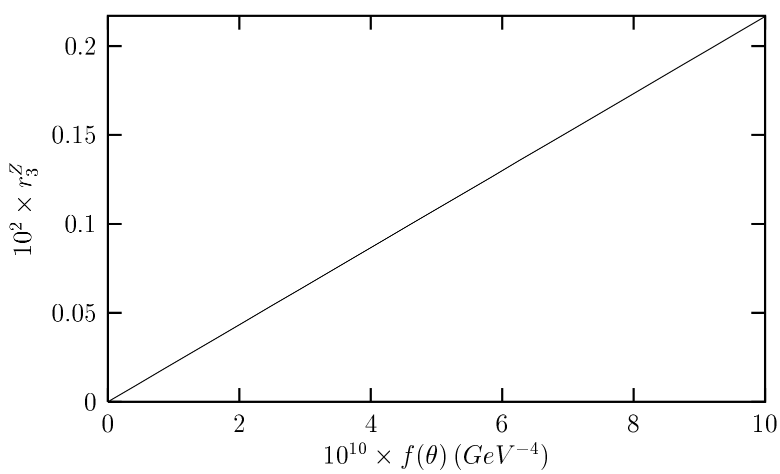

Figure 3: $f(\theta)$ dependence of ratio $r_3^Z = \frac{BR_{flavor_\theta}}{BR_{flavor}}$ where BR_{flavor_θ} is the noncummutative-flavor dependent part of the BR, for the process $Z \to \tau^+\tau^-$.

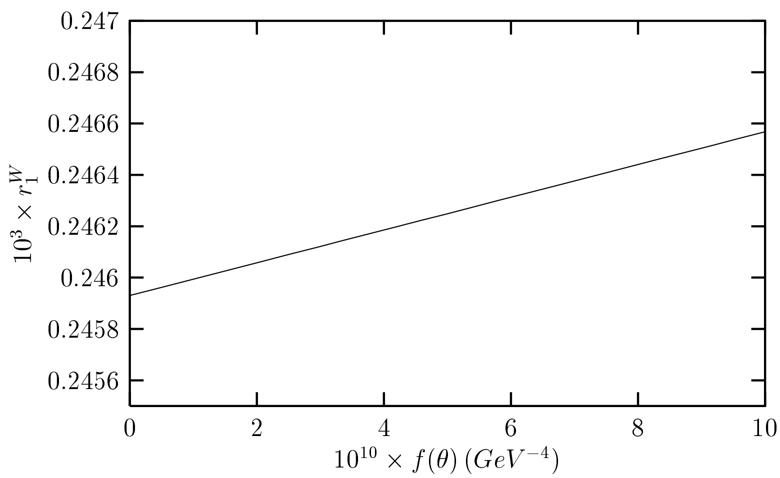

Figure 4: The same as Fig. 1 but for $W \to \nu_\tau \tau^+$ decay.

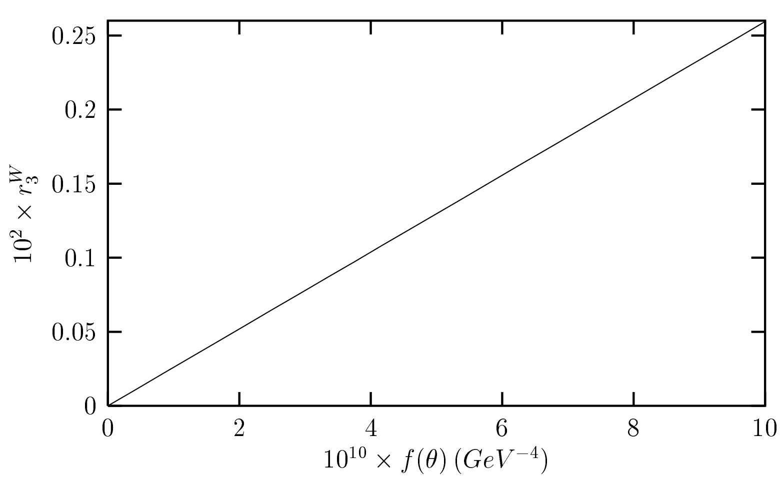

Figure 5: The same as Fig. 3 but for $W \to \nu_\tau \tau^+$ decay.