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The form factors existing in the $b \to sg^*$ decay and the possible CP violating effects in the noncommutative standard model

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Abstract: We study the form factors appearing in the inclusive decay $b \to sg^*$, in the framework of the noncommutative standard model. Here g^* denotes the virtual gluon. We get additional structures and the corresponding form factors in the noncommutative geometry. We analyse the dependencies of the form factors to the parameter $p\,\Theta\,k$ where p (k) are the four momenta of incoming (outgoing) b quark (virtual gluon g^*), Θ is a parameter which measures the noncommutativity of the geometry. We see that the form factors are weakly sensitive to this parameter.

Keywords: Non-Commutative Geometry, Standard Model, CP violation, QCD.

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Contents

1. Introduction

The quantum field theory over noncommutative spaces [1] has been reached a great interest in recent years . The string theory arguments are the reason for the re-motivation of the physics on the noncommutative spaces [2, 3]. Noncommutative field theories (NCFT's) are difficult to handle since they have non-local structure. Besides this, it has been argued that they were sensible field theories and they have been studied extensively in the literature. The renormalizability of NCFT's in general have been studied in [4]. The unitarity in noncommutative theories has been discussed in [5]. In [6], the unitarity properties of spontaneously broken noncommutative gauge theories have been examined. The noncommutative quantum electrodynamics (NCQED) and anomalous magnetic moments have been studied in [7] and a detailed calculation for the noncommutative electron-photon vertex has been presented. The noncommutative Yang-Mills theory has been studied in [8]. In [9] the noncommutative CP violating effects has been examined at low energies and it was ephasized that CP violation due to noncommutative geometry was comparable to the one due to the standard model (SM) only, for a noncommutative scale $\Lambda \leq 2\,\text{TeV}$. Noncommutative SM (NCSM) building has been studied in [10] and recently, the determination of triple neutral gauge boson couplings has been done in [11].

In noncommutative geometry the space-time coordinates x_μ are replaced by the Hermitian operators $\hat{x}_\mu$ where they do not commute

$$[\hat{x}_\mu, \hat{x}_\nu] = i\,\Theta_{\mu\nu}\,. \tag{1.1}$$

Here $\Theta_{\mu\nu}$ is real and antisymmetric tensor. On the other hand noncommutative field theory is equivalent to the ordinary one except that the usual product is replaced by the $*$ product

$$(f * g)(x) = e^{i\,\Theta_{\mu\nu}\,\partial^y_\mu\,\partial^z_\nu} f(y)\,g(z)|_{y=z=x}\,. \tag{1.2}$$

The commutation of the Hermitian operators $\hat{x}_\mu$ (see eq. (1.1)) holds with this new product, namely,

$$[\hat{x}_\mu, \hat{x}_\nu]_* = i\,\Theta_{\mu\nu}\,. \tag{1.3}$$

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For constructing the effective low energy theory it is convenient to choose the energy scale as $\Lambda = 1/\sqrt{\Theta}$ [9]. Here the parameter Θ is taken the average magnitude of the tensor $\Theta_{\mu\nu}$. NCSM can be constructed at least up to $O(\Theta)$ by replacing the ordinary products by $*$ product. This replacement modifies the Feynman rules considerably (see [9, appendix]).

In our work, we study the form factors appearing in the inclusive decay $b \to sg^*$, in the framework of the NCSM. When the noncommutative effects are switched on, the form factors due to the SM are modified and new structures with the corresponding form factors arise. The noncommutative effects are at least at the order of $p\,\Theta\,k$ where p (k) are the four momenta of incoming (outgoing) b quark (virtual gluon). Here, we take the noncommutative scale $\Lambda = 1/\sqrt{\Theta} \leq 1\,Tev$ and at these low energies, the problems of unitarity and causality are supressed. The combination $p\,\Theta\,k$, which appears in the expressions are at the order of the magnitude of $10^{-6} - 10^{-4}$ for our process. This is a small number which creates weak noncommutative effects in the calculation of form factors. However, these noncommutative effects may be stronger for the decays including heavy flavors. On the other hand, this parameter is a new source for the CP violation which exists with the help of the complex Cabibbo-Kobayashi-Maskawa (CKM) matrix elements in the ordinary SM.

The paper is organized as follows: in section 2, we present the structures and the form factors appearing in the $b \to sg^*$ decay in the SM, including the non-commutative effects. Section 3 is devoted to the analysis of these form factors and our discussions.

2. The form factors existing in the $b \to sg^*$ decay, in the SM including the non-commutative effects

In this section, we calculate the form factors of the decay $b \to sg^*$ in the framework of the SM, including the noncommutative effects. As it is well known, $b \to sg^*$ decay is created by flavor changing neutral currents at loop level in the SM. The possible interactions at one loop level are self energy and vertex type (see figure 1). At this stage, we use the on-shell renormalization scheme to get rid of the divergences appearing in the ordinary SM and obtain a gauge invariant vertex function. Notice that, in this scheme, the self energy diagrams do not contribute and only the vertex part survives. When the non-commutative effects are switched on, there appears new structures and the corresponding form factors, that contain new UV and IR divergences. Use of on-shell renormalization scheme helps one to get a gauge invariant vertex function however, the form factors appearing due to the noncommutative effects still need renormalization. Now, we will present the calculations [7] to get the form factors for the decay underconsideration.

The starting point of the calculation is to use the exponential representation for the propagators, i.e. the Schwinger parametrization

$$\frac{i}{p^2 - m^2 + i\epsilon} = \int_0^\infty dx_1 e^{i\,x_1\,(p^2 - m^2 + i\epsilon)} \tag{2.1}$$

and to obtain the denominator of the momentum integral for the vertex function, which

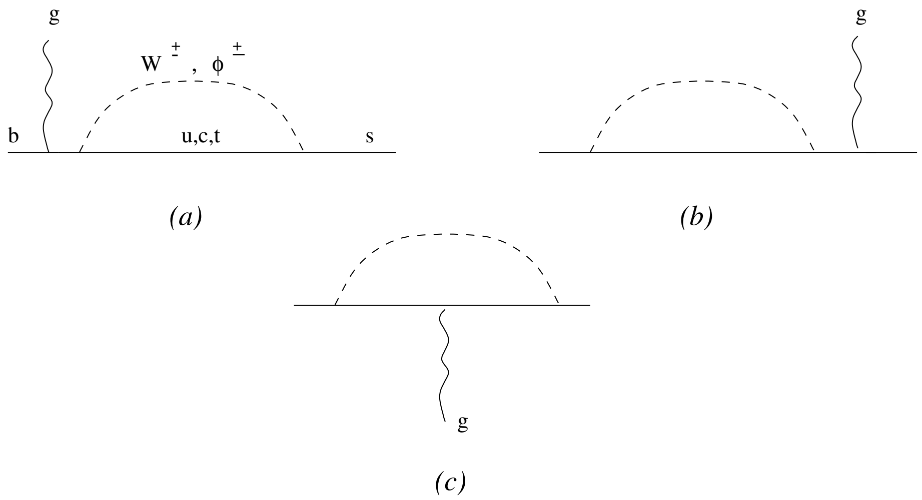

Figure 1: One loop diagrams contribute to $b \to s g^*$ in the NCSM. Wavy lines represent the chromomagnetic field and dashed lines the $W^\pm$ and $\phi^\pm$ fields.

we call the core integral,

$$I = -i \int \frac{d^d q}{(2\pi)^d}\, e^{i\,(q\,z - (1/2)(p-q)\,\widetilde{(p'-q)})}\, \frac{1}{(q^2 - m_W^2)\,\left((p-q)^2 - m_i^2\right)\left((p'-q)^2 - m_i^2\right)}, \tag{2.2}$$

where $\tilde{v}_\mu = \Theta_{\mu\nu}\, v^\nu$, p (p') is four momentum of b (s) quark, $p = p' - k$ and k is virtual gluon four momentum. Here, the new factor $e^{-i\,1/2(p-q)\,\widetilde{p'-q}}$ is due to the non-commutative geometry and it can be rewritten as $e^{-i/2\,p\,\tilde{p}'}\, e^{-i/2\,q\,\tilde{k}}$. The factor $e^{i\,q\,z}$ is introduced to obtain the expressions appearing in the numerator of the momentum integral, by differentiation [12]. Using the parametrization in eq. (2.1) and making the momentum integration, the integral I in eq. (2.2) can be written as

$$I = \int_0^\infty dx_1\, dx_2\, dx_3\, \frac{e^{\frac{-i\,(\tilde{k}+4\,x_2\,p'+4\,x_3\,p-2\,z)^2+16\,(x_1+x_2+x_3)\,m_W^2\,(x_1+x_i\,(x_2+x_3)-x_b\,x_3)}{16\,(x_1+x_2+x_3)}}}{(4\pi)^2\,(x_1+x_2+x_3)^2}\,, \tag{2.3}$$

where $x_i = m_i^2/m_W^2$, $x_b = m_b^2/m_W^2$. Notice that we take $m_s = 0$ in the expressions.

Here we will summarize the procedure used in the following:

- calculating the the numerator of the integral by differentiating the momentum integrated core integral with respect to the auxilary variable z and set z to zero at the end;
- applying the Wick rotation $x_i \to x_i/i$ and using the identity $\int_0^\infty d\rho\, \delta(\rho - (x_1 + x_2 + x_3)) = 1$;
- making the rescaling $x_i \to \rho\, x_i$;
- redefining the core integral by introducing the UV regulator $e^{i/((x_1+x_2+x_3)\,\Lambda^2)}$ as

$$I = -\frac{1}{16\,\pi^2}\, e^{-(i/2)p\tilde{p}'} \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy\, \exp\left[\frac{e_1}{\rho} + e_2\rho - \frac{i}{2}\tilde{k}.p\,(1-x)\right], \tag{2.4}$$

with the functions e_1 and e_2

$$
\begin{aligned}
e_1 &= -\frac{1}{\Lambda_{\rm eff}^2}\,, \\
e_2 &= -m_W^2\,\left(x + x_i\,(1-x) - x_b\,(1-x-y)\,(x+s\,y)\right),
\end{aligned} \tag{2.5}
$$

and $\Lambda_{\rm eff}$

$$
\Lambda_{\rm eff}^2 = \frac{1}{1/\Lambda^2 - \widetilde{k}^2/16}\,, \tag{2.6}
$$

where $s = k^2/m_b^2$. With this procedure one obtains all the structures and the corresponding raw coefficients due to the decay under consideration. Now, we use the on-shell renormalization scheme and extract the nonvanishing structures to get a gauge invariant result. In this scheme, only the vertex diagram (figure 1) contributes and the self energy diagrams vanish. Using the raw bare vertex function, $\Gamma_\mu^{0\,a}$, introducing the counterms $\Gamma_\mu^{C\,a}$ to satisfy the expression

$$
k^\mu \Gamma_\mu^{({\rm Raw})\,{\rm Ren},\,a} = 0\;, \tag{2.7}
$$

where $\Gamma_\mu^{({\rm Raw})\,{\rm Ren},\,a}$ is $\Gamma_\mu^{({\rm Raw})\,{\rm Ren},\,a} = \Gamma_\mu^{0\,a} + \Gamma_\mu^{C\,a}$ and neglecting the s-quark mass we get

$$
\begin{aligned}
\Gamma_\mu^{{\rm Ren}\,a} &= \frac{-ig^2 g_s}{32 m_W^2 \pi^2}\lambda^a \Big(F_1^{\rm Raw}(k^2)\,(k_\mu \not{k} - k^2 \gamma_\mu) L + i\,F_2^{\rm Raw}(k^2)\,m_b\,\sigma_{\mu\nu}\,k^\nu R + \\
&\quad + i\,F_3^{\rm Raw}(k^2) m_b\,\widetilde{k}_\mu R + i\,F_4^{\rm Raw}(k^2)(\gamma_\mu \not{k}\widetilde{\not{k}} - k_\mu \widetilde{\not{k}}) L + F_5^{\rm Raw}(k^2)\widetilde{k}_\mu \widetilde{\not{k}} L\Big)
\end{aligned} \tag{2.8}
$$

where k_μ is the gluon momentum 4-vector and k^2 dependent functions $F_1^{\rm Raw}(k^2)$ and $F_2^{\rm Raw}(k^2)$ are proportional to the charge radius and dipole form factors. $F_3^{\rm Raw}(k^2)$, $F_4^{\rm Raw}(k^2)$ and $F_5^{\rm Raw}(k^2)$ are the new form factors appearing when the noncommutative effects are switched on and they read as

$$
\begin{aligned}
F_1^{\rm raw}(k^2) &= \frac{m_W^2}{2} \sum_{i=u,c,t} V_{ib} V_{is}^* \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy e^{-(i/2)p\widetilde{p'}}\; e^{e_1/\rho + e_2\rho - (i/2)\widetilde{k}.p(x-1)} \times \\
&\quad \times \left(x_i\,(x^2 - (2-3\,y)\,x + 1 + 2\,y^2 - 4\,y) + 2\,(x^2 + 2\,y\,(y-1) x\,(3\,y-2)\right), \\
F_2^{\rm raw}(k^2) &= \frac{m_W^2}{2} \sum_{i=u,c,t} V_{ib} V_{is}^* \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy e^{-i/2p\widetilde{p'}}\; e^{(e_1/\rho) + e_2\rho - (i/2)\widetilde{k}.p(x-1)} \times \\
&\quad \times \left(x_i + x^2\,(2+x_i) + x\,(x_i\,(y-2) + 2\,y)\right), \\
F_3^{\rm raw}(k^2) &= \frac{m_W^2}{4} \sum_{i=u,c,t} V_{ib} V_{is}^* \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy\, e^{-i/2p\widetilde{p'}}\; \frac{e^{e_1/\rho + e_2\rho - i/2\widetilde{k}.p(x-1)}}{\rho} \times \\
&\qquad \times (2+x_i)\,(1-x-y)\,, \\
F_4^{\rm raw}(k^2) &= \frac{m_W^2}{8} \sum_{i=u,c,t} V_{ib} V_{is}^* \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy\, \frac{e^{-i/2p\widetilde{p'}}\; e^{e_1/\rho + e_2\rho - i/2\widetilde{k}.p(x-1)}}{\rho} \times \\
&\quad \times (2 - \; x_i + x\,(2+x_i))\,, \\
F_5^{\rm raw}(k^2) &= -\frac{m_W^2}{16} \sum_{i=u,c,t} V_{ib} V_{is}^* \int_0^\infty d\rho \int_0^1 dx \int_0^{1-x} dy\, e^{-i/2p\widetilde{p'}}\; \frac{e^{e_1/\rho + e_2\rho - i/2\widetilde{k}.p(x-1)}}{\rho^2}\,(2+x_i)\,.
\end{aligned} \tag{2.9}
$$

In the calculation of the coefficients, at first, the ρ integrations are taken. These integrations bring the modified Bessel functions of first and second type. For the high energy limit, namely $\Lambda^2 \to \infty$, or the low energy limit $k \to 0$ simultaneously, the integration of $F_1^{\rm raw}$ and $F_2^{\rm raw}$ over ρ does not bring any divergence. However, the ρ integrations of $F_3^{\rm raw}$ and $F_4^{\rm raw}$ result in the modified Bessel functions of first type, where the logarithmic divercences appear. Here we assume that these divercences can be overcome by adding the necessary counter terms, i.e. the NCSM model is renormalizable at least at one loop level, similar to NCQED [13]. The result of the integration of the form factor $F_5^{\rm raw}$ over ρ is proportional to the cut-off factor $\Lambda_{\rm eff}^2$. Fortunately, this term is irrelevant because of the following reason (see [7]). If we consider the UV limit, namely, $1/\Lambda^2 \ll \widetilde{k}^2$ or $\Lambda_{\rm eff}^2 \sim 1/\widetilde{k}^2$, this term is finite. However as Λ^2 tends to zero, we have $1/\Lambda^2 \gg \widetilde{k}^2$ and therefore $\Lambda^2\widetilde{k}^2 \ll 1$. Since the structure due to $F_5^{\rm raw}$ contains the term proportional to $\widetilde{k}^2$, this term is irrelevant in the IR limit. Finally, we end up with the form factors $F_1(s)$, $F_2(s)$, $F_3(s)$ and $F_4(s)$:

$$
\begin{aligned}
F_1(s) &= e^{-i/2p.\widetilde{p'}} \sum_{i=,u,c,t} V_{ib}V_{is}^* \int_0^1 dx \int_0^{1-x} dy e^{-i/2p.\widetilde{k}(1-x)} \times \\
&\quad \times \frac{x_i\,(x^2-(2-3y)x+1+2y^2-4\,y)+2(x^2+2\,y\,(y-1)+x(3y-2)}{2(x_i+x_b y(y-1)s - x(-1+x_i+x_b\,y\,(1-s))}\,, \\
F_2(s) &= e^{-i/2p.\widetilde{p'}} \sum_{i=,u,c,t} V_{ib}V_{is}^* \int_0^1 dx \int_0^{1-x} dy e^{-i/2p.\widetilde{k}(1-x)} - \\
&\quad - \frac{x_i + x^2\,(2+x_i) + x\,(x_i\,(y-2)+2\,y)}{2\,(x_i + x_b\,y\,(y-1)\,(s-1) - x\,(-1+x_i+x_b\,y\,(1-s))}\,, \\
F_3(s) &= e^{-i/2p.\widetilde{p'}} \frac{\mathrm{EulerGamma}\, m_b\, m_W^2}{2} \sum_{i=,u,c,t} V_{ib}V_{is}^* \int_0^1 dx \int_0^{1-x} dy \times \\
&\quad \times e^{-i/2p.\widetilde{k}(1-x)}\,(2+x_i)\,(1-x-y)\,, \\
F_4(s) &= -e^{-i/2p.\widetilde{p'}} \frac{\mathrm{EulerGamma}\, m_W^2}{4} \sum_{i=,u,c,t} V_{ib}V_{is}^* \int_0^1 dx \int_0^{1-x} dy \times \\
&\quad \times e^{-i/2p.\widetilde{k}(1-x)}\,(2-\;x_i + x\,(2+x_i))\,. \qquad (2.10)
\end{aligned}
$$

$F_3(s)$ and $F_4(s)$, the integration over the parameters x and y can be performed easily and we get

$$
\begin{aligned}
F_3(s) &= \sum_{i=,u,c,t} V_{ib}V_{is}^* \mathrm{EulerGamma} m_W^2 \times \\
&\quad \times \frac{e^{-i\,p.\widetilde{p'}}\left(4\,p.\widetilde{p'} + i\left((p.\widetilde{p'})^2 + 8\,(e^{(i\,p.\widetilde{p'})/2}-1)\right)\,(2+x_i)\right)}{2(p.\widetilde{p'})^3}\,, \\
F_4(s) &= \sum_{i=,u,c,t} V_{ib}V_{is}^*\ \mathrm{EulerGamma}\ m_W^2 \times \qquad (2.11) \\
&\times \frac{e^{-i\,p.\widetilde{p'}}\left(4\,p.\widetilde{p'}(2e^{(i\,p.\widetilde{p'})/2} + x_i) + i\left((p.\widetilde{p'})^2\,(x_i-2) + 8\,(e^{(ip.\widetilde{p'})/2}-1)(2+x_i)\right)\right)}{2\,(p.\widetilde{p'})^3}\,.
\end{aligned}
$$

For $s > 4\,m_i^2/m_b^2$, $i = u, c$, the internal u and c quarks are on mass-shell and an absorptive part appears in the coefficients related with the light quark part. Notice that when the non-commutative effects are switched off the form factors $F_3(s)$ and $F_4(s)$ disappears and we obtain the form factors in the ordinary SM.

3. Discussion

This section is devoted to the analysis of the form factors appearing in the $b \to s g^*$ process in the framework of the SM including noncommutative effects. The new parameter existing in this geometry is $p\widetilde{k}$ and it is at the order of the magnitude of $10^{-6} - 10^{-4}$ for the process underconsideration. This factor is also a new source for the CP violating effects in addition to the complex CKM matrix elements in the SM, V_{ub} in our case. It enters into expressions as an exponential and its odd powers in the expansion of the exponential factor bring new CP violating effects, even for real CKM matrix elements. In our work, we study $p\widetilde{k}$ and the $\sin\delta$ dependence of the real and imaginary parts of the form factors. Here, we use the parametrization $V_{ub} = e^{i\delta}\,|V_{ub}|$ and $\sin\delta$ is proportional to the imaginary part of V_{ub}, which is the only source of the CP violating effects in the commutative SM. Note that we take the numerical value $|V_{ub}\,V_{us}| = 6 \times 10^{-3}$.

In figure 2 we present the $\sin\delta$ dependences of the real parts of the form factors F_3 and F_4, for different values of the parameter $p\widetilde{k}$, namely 10^{-6}, 10^{-5} and 10^{-4}. It is seen that $\mathrm{Re}[F_3]$ and $\mathrm{Re}[F_4]$ are not sensitive to $p\widetilde{k}$. However, there is a weak sensitivity to $\sin\delta$. $\mathrm{Re}[F_3]$ ($\mathrm{Re}[F_4]$) decreases (increases) with the increasing values of $\sin\delta$. Both form factors are almost at the order of the magnitude of $58.5 \pm 0.05\,\mathrm{GeV}^2$.

Figure 3 and 4 is devoted to the $\sin\delta$ dependence of the imaginary part of the form factor F_3 (F_4), for three different values of the parameter $p\widetilde{k}$, 10^{-6}, 10^{-5} and 10^{-4}. It is seen that $\mathrm{Im}[F_3]$ ($\mathrm{Im}[F_4]$) is sensitive to $p\widetilde{k}$ and it increases (decreases) as a magnitude when $p\widetilde{k}$ decreases. $\mathrm{Im}[F_3]$ can have both signs for large values of $p\widetilde{k}$, depending on the parameter $\sin\delta$. The sensitivity of $\mathrm{Im}[F_3]$ ($\mathrm{Im}[F_4]$) to the parameter $\sin\delta$ is strong. $\mathrm{Im}[F_3]$ ($\mathrm{Im}[F_4]$) can reach to the values $1.7\,\mathrm{GeV}^2$ ($-0.9\,\mathrm{GeV}^2$)

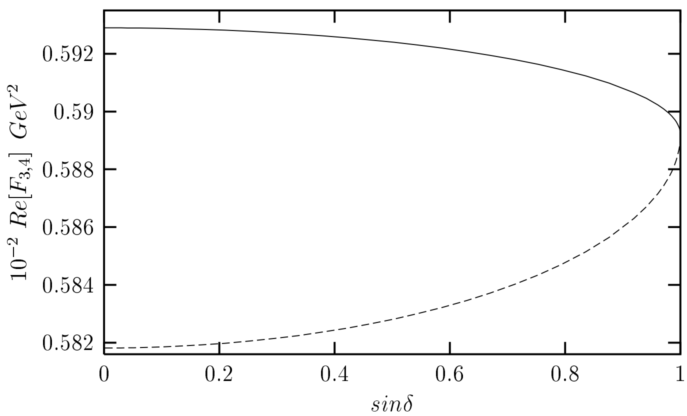

Figure 2: $\mathrm{Re}[F_3]$ and $\mathrm{Re}[F_4]$ as a function of $\sin\delta$. The solid (dashed) line represents $\mathrm{Re}[F_3]$ ($\mathrm{Re}[F_4]$).

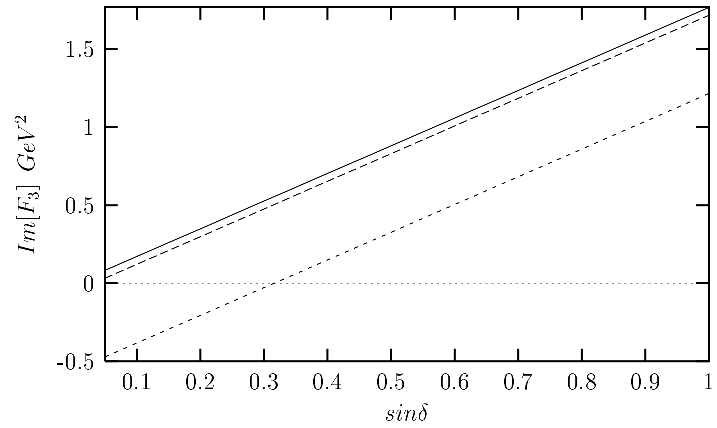

Figure 3: $\mathrm{Im}[F_3]$ as a function of $\sin\delta$. The solid (dashed, small dashed) line represents $\mathrm{Im}[F_3]$ for $\widetilde{pk} = 10^{-6}$ (10^{-5}, 10^{-4}).

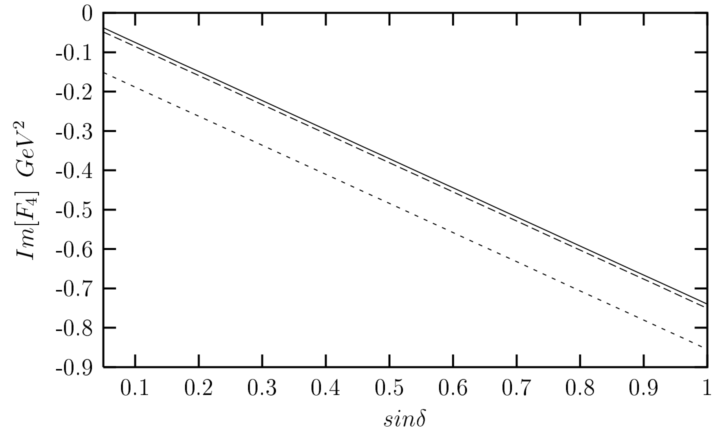

Figure 4: The same as figure 3 but for $\mathrm{Im}[F_4]$.

Figure 5 and 6 shows the $\sin\delta$ dependence of the real part of the form factor F_1 (F_2), for three different values of the parameter $\widetilde{pk}$, 10^{-6}, 10^{-5} and 10^{-4}. F_1 (F_2) is not sensitive to $\widetilde{pk}$ and weakly sensitive to $\sin\delta$. It is predicted that its magnitude is 0.0845 ± 0.0005 (0.0038 ± 0.0001).

Finally figure 7 is devoted to the $\sin\delta$ dependence of the imaginary part of the form factor F_1 and F_2. $\mathrm{Im}[F_1]$ and $\mathrm{Im}[F_2]$ are not sensitive to $\widetilde{pk}$, however the sensitivity to $\sin\delta$ not small. Their magnitudes are at the order of 0.001 ± 0.001.

As a summary, there are additional structures and corresponding form factors in the non-commutative geometry. The factor $\widetilde{pk}$ is the new source for the CP violating effects and its magnitude depends on the process studied. In our case $\widetilde{pk}$ is small, namely $\widetilde{pk} \sim 10^{-5}$ and the form factors are not so much sensitive to this parameter. In the calculation of the CP violation of any decay which is based on the process $b \to sg^*$, the non-commutative effects probably weak. However, we belive that these effects would be stronger when the processes with heavy flavors have been considered, even in the framework of the SM.

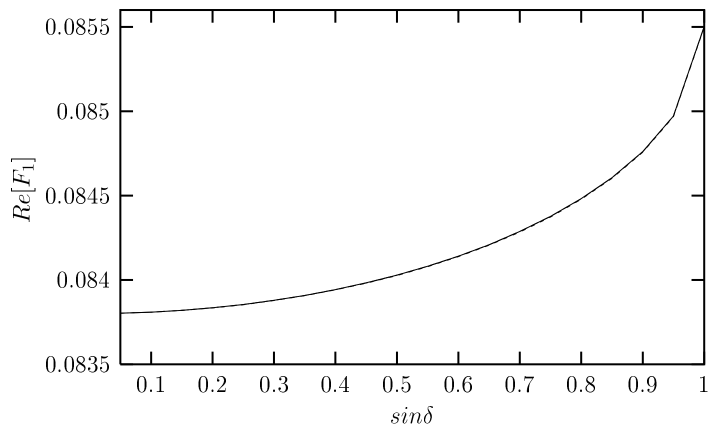

Figure 5: Re$[F_1]$ as a function of $\sin\delta$.

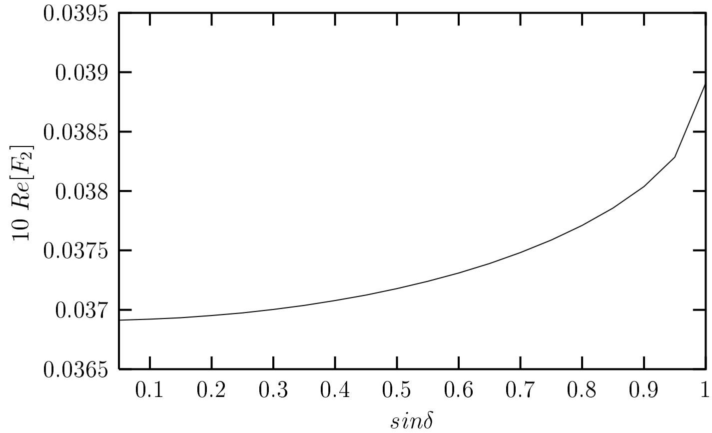

Figure 6: The same as figure 5 but for Re$[F_2]$.

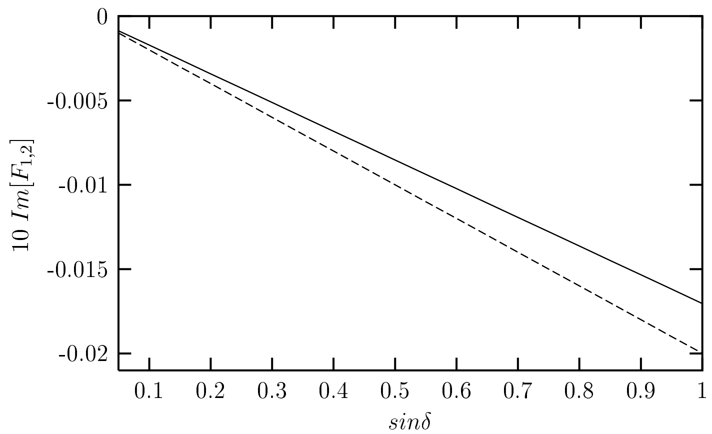

Figure 7: Im$[F_1]$ and Im$[F_2]$ as a function of $\sin\delta$. The solid (dashed) line represents Im$[F_1]$ (Im$[F_2]$).

Acknowledgments

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