Constraints on Unparticle Interaction from $b \to s\gamma$

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(Dated: June 5, 2008)

Abstract

We study unparticle effects on $b \to s\gamma$. The unparticle contributions can contribute significantly to both left- and right-handed chirality amplitudes. Using available experimental data and SM calculation for $B \to X_{s}\gamma$, we obtain constraints on various vector and scalar unparticle couplings. We find that the constraints sensitively depend on the unparticle dimension $d_{U}$. For $d_{U}$ close to one, the constraints can be very stringent. The constraints become weak when $d_{U}$ is increased. In general the constraints on scalar unparticle couplings are weaker than those for vector unparticle couplings. Sizeable coupling strength for unparticles with quarks is still allowed. We also show that polarization measurement in $\Lambda_{b} \to \Lambda \gamma$ can further constrain the couplings.

PACS numbers: 12.60.-i, 12.90.+b, 13.00.00, 13.20.He
I. INTRODUCTION

Recently Georgi proposed an interesting idea to describe possible scale invariant effect at low energies by unparticles\cite{1}. It was argued that operators $O_{SI}$ made of fields in the scale invariant sector may interact with operators $O_{SM}$ of dimension $d_{SM}$ made of Standard Model (SM) fields at some high energy scale by exchanging particles with large masses, $M_{U}$, with the generic form $O_{SM}O_{SI}/M_{U}^k$. At another scale $\Lambda_{U}$ the scale invariant sector induce dimensional transmutation, below that scale the operator $O_{SI}$ matches onto an unparticle operator $O_{U}$ with dimension $d_{U}$ and the unparticle interaction with SM particles at low energy has the form

$$\lambda_{U}^{4-d_{SM}-d_{U}} O_{SM}O_{U}. \quad (1)$$

Study of unparticle effects has drawn a lot of attentions from more theoretically related work to more phenomenologically studies. There are many possible ways unparticles may interact with the SM particles\cite{2}. Most of the phenomenological work concentrate on possible effects of unparticle interactions with SM particles and constraints on the interaction strength $\lambda_{U}^{4-d_{SM}-d_{U}}$. One of the subjects where a lot of activities have been devoted to is the study of low energy rare flavor changing processes involving quarks\cite{3} and charged leptons\cite{4,5}. In this work we study unparticle effects on $b \to s\gamma$ and constrain unparticle interactions using known SM values and current experimental data for $B \to X_{s}\gamma$.

The rare $b \to s\gamma$ decay process has been shown to provide interesting constraints on possible new physics beyond the SM\cite{6}. Experimentally the leading contribution to $B \to X_{s}\gamma$ with large $\gamma$ energy $E_{\gamma}$ is dominated by $b \to s\gamma$. Experimental measurement on this decay has achieved very high precision with $B(B \to X_{s}\gamma)$ given by\cite{7} $(3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$, with $E_{\gamma} > 1.6$GeV. On the theoretical side, the SM calculation for $B(B \to X_{s}\gamma)$ has been evaluated at the NNLO order\cite{8} with $(3.15 \pm 0.23) \times 10^{-4}$ for $E_{\gamma} > 1.6$GeV. It is clear that experimental data and SM prediction agree with each other very well leaving small room for new physics beyond the SM. Taking this on the positive side, the process $B \to X_{s}\gamma$ can provide stringent constraints on possible new physics beyond the SM. Several flavor changing processes have been studied\cite{3,4,5}, but unparticle contribution to $b \to s\gamma$ has not been studied. We therefore concentrate on this subject.

Although at present the detailed dynamics for interaction between unparticles and SM particles are not known, unparticle effects on various physical processes can be studied from
effective theory point of view using eq. (1). The main task is then, as many phenomenological
studies of unparticle physics, to use available data to constrain the allowed parameter space
and to see how large the unparticle effects can be and to test possible effects experimentally.

In principle, when the unparticle sector is coupled to the SM sector the scale invariance is
broken due to finite mass of the SM fields [9] and also due to spontaneous symmetry breaking
of Higgs vacuum expectation value if coupled [10]. The unparticle behavior may only exist
in a window below the scale \( \Lambda_U \) and above a scale \( \mu \) where the scale invariance is broken
again by SM particle effects. If this is the case, the contributions of the unparticles should
only be within this window and below \( \mu \) the effects should be replace by that resulted from
the residual degrees of freedom. However, at this stage there is no specific way, as far as we
know, to describe such effects. In our study of unparticle effects on \( b \to s\gamma \), we will follow
most of the phenomenological studies in the literature assuming that the unparticle effects
from the scale \( \Lambda_U \) down to zero.

We will study \( b \to s\gamma \) using the lowest possible dimension operators due to scalar and
vector unparticle and SM fields interactions. The unparticle contributions can contribute
significantly to both left- and right-handed chirality amplitudes. Using available experimental
data and SM calculation mentioned above, we obtain constraints on various vector and
scalar unparticle couplings. We find that the constraints sensitively depend on the unparticle
dimension \( d_U \). For \( d_U \) close to one, the constraints can be very stringent. The constraints
become weak when \( d_U \) is increased. In general the constraints on scalar unparticle couplings
are weaker than those for vector unparticle couplings. Sizeable coupling strength for unpar-
ticles with quarks is still allowed. We also find that polarization measurement in \( \Lambda_b \to \Lambda\gamma \)
can further constraint the couplings.

II. UNPARTICLE CONTRIBUTION TO \( b \to s\gamma \)

The lowest dimension operators, which can generate contributions to \( b \to s\gamma \) at one loop
level, come from interaction of vector unparticle with quarks and are given by [2]

\[
\lambda'_{QQ} \Lambda_U^{1-d_{u}} \bar{Q}_L \gamma_\mu Q_L O_U^{\mu}, \quad \lambda'_{DD} \Lambda_U^{1-d_{u}} \bar{D}_R \gamma_\mu D_R O_U^{\mu}.
\]

Here \( Q_L = (U_L, D_L)^T \), \( D_R \) are the SM left-handed quark doublet, and right-handed down-
quark, respectively.
FIG. 1: One loop Feynmann diagram for $b \to s\gamma$ by exchanging an unparticle. The $q_k$ can be $d$, $s$, and $b$ quark.

Scalar unparticle interaction with quarks can also induce $b \to s\gamma$. The lowest dimension operators which can contribute to $b \to s\gamma$ is at order $\Lambda^{-d_U}$. The following operator will generate finite contributions to $b \to s\gamma$ at one loop level:

$$\lambda^{YD} \Lambda^{-d_U} \bar{q}_L \bar{H} D_R O_{U}, \quad (2)$$

where $H$ is the SM Higgs doublet transforming under the SM gauge group $SU(2)_L \times U(1)_Y$ as $(2,1)$.

After the Higgs develops a non-zero vacuum expectation value $\langle H \rangle = v$, the above interaction between quarks and an unparticle becomes

$$\lambda^{YD}_{sb} \Lambda^{-d_U} \bar{s}_L b_R O_{U}. \quad (3)$$

At the same order in $\Lambda_U$, there are several other operators involving quarks and a scalar unparticle, such as

$$\bar{Q}_L \gamma_\mu \partial^\mu Q_L O_{U}, \quad \bar{D}_R \gamma_\mu \partial^\mu D_R O_{U}, \quad \bar{Q}_L \gamma_\mu Q_L \partial^\mu O_{U}, \quad \text{and} \quad \bar{D}_R \gamma_\mu D_R \partial^\mu O_{U}. \quad (4)$$

However, their one loop contributions to $b \to s\gamma$ diverge due to derivative couplings. Additional parameters or operators are need to render these divergences making the effects not calculable. We will not consider their effects here.

The one loop Feynmann diagram giving contribution to $b \to s\gamma$ is shown in Fig. 1. We will indicate the incoming $b$ quark by $q_i$ and the outgoing $s$ quark by $q_j$. The formula obtained can be easily adapted for other incoming and outgoing fermions. We obtain the vector unparticle contribution to $q_i \to q_j \gamma$ amplitude as

$$\mathcal{M}_v(q_i \to q_j \gamma) = \frac{Q_e}{2m_i} N_v(d_U) \bar{q}_j i\sigma_{\mu\nu} \epsilon^{*\mu} q^\nu (A^L_v \gamma_\nu + A^R_v \gamma_\nu) q_i, \quad (4)$$
where $q$ and $e^\mu$ are the photon momentum and polarization, respectively. $N_v(d_{ut}) = (A_{dt}/16\pi^2 \sin(\pi d_{ut})) (m_i/\Lambda_u)^{2d_{ut}-2}$ with $A_{dt} = (16\pi^{5/2}/(2\pi)^{2d_{ut}}) \Gamma(d_{ut}+1/2)/\Gamma(d_{ut}-1)\Gamma(2d_{ut})$, and

$$A^R_v = [-2f_1 + 2f_2 - f_{2x} + \frac{1}{2 - d_{ut}}(f_1 - 3f_{2x}) + z_{ki}^2 f_3(3f_{2x})] \lambda_j^L \lambda_k^L$$

$$+ z_{ji}[4f_1 - 2f_2 + \frac{1}{2 - d_{ut}}(3f_2 - 2f_1)] + z_{ki}^2 f_3 \lambda_j^R \lambda_k^R$$

$$+ z_{ki}^2 f_3 \lambda_j^L \lambda_k^L - f_3 z_{ji} z_{ki} \lambda_j^R \lambda_k^L$$

$$A^L_v = [-2f_1 + 2f_2 - f_{2x} + \frac{1}{2 - d_{ut}}(f_1 - 3f_{2x}) + z_{ki}^2 f_3(3f_{2x})] \lambda_j^R \lambda_k^R$$

$$+ z_{ji}[4f_1 - 2f_2 + \frac{1}{2 - d_{ut}}(3f_2 - 2f_1)] + z_{ki}^2 f_3 \lambda_j^L \lambda_k^L - f_3 z_{ji} z_{ki} \lambda_j^R \lambda_k^L,$$ (5)

where $z_{ji} = m_j/m_i$. $\lambda^L = \lambda^L_{QQ}$, and $\lambda^R = \lambda^R_{DD}$. The functions $f_i(d_{ut})$ are defined as

$$f_0(d_{ut}) = \int_0^1 dx \int_0^1 dy \frac{y^{d_{ut}} - (1 - y)^2 - d_{ut}}{u^{2 - d_{ut}}},$$

$$f_1(d_{ut}) = \int_0^1 dx \int_0^1 dy \frac{y^{d_{ut} - 1} - (1 - y)^2 - d_{ut}}{u^{2 - d_{ut}}},$$

$$f_2(d_{ut}) = \int_0^1 dx \int_0^1 dy \frac{y^{d_{ut}} - (1 - y)^2 - d_{ut}}{u^{3 - d_{ut}}},$$

$$f_3(d_{ut}) = \int_0^1 dx \int_0^1 dy \frac{y^{d_{ut}} - (1 - y)^2 - d_{ut}}{u^{3 - d_{ut}}},$$ (6)

with $u = z_{ki}^2 - (1 - x)(1 - y) - x(1 - y)^2$. For scalar contribution, we obtain

$$\mathcal{M}_s(q_i \rightarrow q_j \gamma) = \frac{Q_e}{2m_i} N_s(d_{ut}) q_j i \sigma_{\mu \nu} \epsilon^{*\mu} q^\nu (A^L_s + A^R_s) q_i,$$ (7)

where $N_s(d_{ut}) = (A_{dt}/16\pi^2 \sin(\pi d_{ut}))(v^2/m_i^2)(m_i/\Lambda_u)^{2d_{ut}}$, and

$$A^R_s = [f_2(d_{ut}) - f_{2x}(d_{ut})] \lambda_{jk}^D \lambda_{ki}^{D*} + f_{2x}(d_{ut}) z_{ji} \lambda_{jk}^D \lambda_{ki}^{D*} + f_0(d_{ut}) z_{ki} \lambda_{jk}^D \lambda_{ki}^{D*}$$

$$A^L_s = [f_2(d_{ut}) - f_{2x}(d_{ut})] \lambda_{jk}^{D*} \lambda_{ki}^D + f_{2x}(d_{ut}) z_{ji} \lambda_{jk}^{D*} \lambda_{ki}^D + f_0(d_{ut}) z_{ki} \lambda_{jk}^{D*} \lambda_{ki}^D.$$ (8)

In our calculations, we will use the central quark masses given in PDG [11]: $m_b = 4.70$ GeV, $m_s = 95$ MeV and $m_{s}/m_d = 19$.

The above amplitudes are evaluated at the unparticle scale $\mu = \Lambda_{ut}$. When running down to the relevant scale $\mu = m_b$ for $b \rightarrow s \gamma$, there are corrections. The gluonic penguin with
the photon $\gamma$ replaced by a gluon $g$, $b \to sg$, generated at $\Lambda_U$ will also contribute to $b \to s\gamma$ at a lower scale $m_b$. The amplitude for $M_{U=v,s}(q_i \to q_j g)$ is given by

$$M_{U}(q_i \to q_j g) = \frac{g_s}{2m_i} N_{U(d_{U})} \bar{q}_j i\sigma_{\mu\nu}\epsilon^\mu_a q^\nu (A^L_{U} L + A^R_{U} R) T^a q_i, \quad (10)$$

where $g_s$ is the strong interaction coupling, $\epsilon^\mu_a$ is the gluon polarization vector and $T^a$ is the generator of the color gauge group $SU(3)_C$ normalized to $Tr(T^a T^b) = \delta^{ab}/2$.

One can easily translate the above amplitudes into the usual amplitudes defined by

$$M(b \to s\gamma) = -V_{tb} V_{ts}^* G_F \frac{e}{\sqrt{2} \pi^2} C_7(\mu) \bar{s} \sigma_{\mu\nu} F^\mu\nu (m_s L + m_b R)b,$n

$$M(b \to sg) = -V_{tb} V_{ts}^* G_F \frac{g_s}{\sqrt{2} \pi^2} C_8(\mu) \bar{s} \sigma_{\mu\nu} G^\mu\nu (m_s L + m_b R) T^a b, \quad (11)$$

where $F^\mu\nu$ and $G^\mu\nu_a$ are the field strength of photon and gluon fields.

Using the leading QCD corrected effective Wilson coefficient at the scale $m_b$ for $b \to s\gamma$ is given by [12], $\mathcal{C}^{eff}_7(m_b) = 0.689C_7(m_W) + 0.087C_8(m_W)$, we obtain an approximate expression for the QCD corrected unparticle contribution, at the scale $\mu = m_b$,

$$\tilde{M}_{U}(q_i \to q_j \gamma) = \bar{q}_j i\sigma_{\mu\nu}\epsilon^\mu_a q^\nu (\tilde{A}^L_{U} L + \tilde{A}^R_{U} R) q_i,$n

$$\tilde{A}^L,R_{U=v,s} = \frac{Q e}{2m_i} N_{U=v,s}(d_{U})(0.689 + 0.087/Q) A^L,R_{U=v,s}. \quad (12)$$

Using the above expression one can put constraints on unparticle couplings.

## III. NUMERICAL ANALYSIS AND CONCLUSIONS

To see how unparticle interactions affect $B \to X_s\gamma$, we use the following to measure possible unparticle contribution,

$$R_{exp-SM} = \frac{\Gamma_{exp} - \Gamma_{SM}}{\Gamma_{SM}} = \frac{B_{exp}}{B_{SM}} - 1. \quad (13)$$

Using the available experimental and SM values, we find $R_{exp-SM} = 0.117 \pm 0.113$ with $E_\gamma > 1.6$ GeV. It is clear that at this stage there is no evidence of new physics beyond SM. However, we can turn the argument around and use allowed value of $R$ to constrain new interactions.

To compare with data and aim at the leading correction from unparticle to the SM prediction, we first define an effective SM for $b \to s\gamma$ amplitude $\tilde{A}^L,R_{SM}$ with $\tilde{A}^L_{SM}/\tilde{A}^R_{SM} \approx$
$m_s/m_b$, as should be in the SM, such that the corresponding Wilson coefficient at the leading order amplitude reproduces the SM prediction for the branching ratio with relevant in put parameters from Ref.\[11\]. We then add to it the leading QCD corrected unparticle contribution $\tilde{A}^{L,R}_{u}$ to obtain the total amplitude. Replacing $\Gamma_{exp}$ by $\Gamma_{un-SM}$ determined by the total SM and unparticle leading contributions, we obtain a quantity similar to $R_{exp-SM}$

$$R_{un-SM} = \frac{\left|\tilde{A}^L_{SM} + \tilde{A}^R_{u}\right|^2 + \left|\tilde{A}^R_{SM} + \tilde{A}^L_{u}\right|^2}{\left|\tilde{A}^L_{SM}\right|^2 + \left|\tilde{A}^R_{SM}\right|^2} - 1. \quad (14)$$

We finally approximate $R_{un-SM}$ to $R_{exp-SM}$ and obtain constraints on unparticle couplings. There are higher order SM corrections to the above formula, but for our purpose of obtaining leading constraints on unparticle effects, this should be sufficient.

In the SM $\tilde{A}^L_{SM}/\tilde{A}^R_{SM} = m_s/m_b$. It is obvious that the main contribution of SM is the right hand couplings. For unparticle contributions, $\tilde{A}^L_{u}$ can be comparable or even larger than $\tilde{A}^R_{u}$. We will obtain bounds on the unparticle couplings from data and known SM numbers allow the theoretical value $R_{un-SM}$ to be in the $1\sigma$ range. Depending on the intermediate quarks exchanged in the loop, different quark-unparticle couplings can appear. We will constrain the coupling for each of the combinations with non-zero contribution and set other equal to zero first assuming the couplings are all real.

There are three possibilities involving a quark in the loop. We discuss them in the following.

a) For $d$ quark and vector unparticle in the loop, it is possible to constrain $\lambda_{sd}^R\lambda_{db}^R$, $\lambda_{sd}^L\lambda_{db}^L$, $\lambda_{sd}^R\lambda_{db}^L$, $\lambda_{sd}^L\lambda_{db}^R$. For scalar unparticle in the loop, it is possible to constrain $\lambda_{sd}^Y\lambda_{bd}^{Y*}$, $\lambda_{ds}^{Y*}\lambda_{db}^Y$, $\lambda_{sd}^Y\lambda_{db}^Y$, and $\lambda_{ds}^{Y*}\lambda_{bd}^{Y*}$.

b) For $s$ quark and vector unparticle in the loop, it is possible to constrain $\lambda_{ss}^R\lambda_{sb}^R$, $\lambda_{ss}^L\lambda_{sb}^L$, $\lambda_{ss}^R\lambda_{sb}^L$, and $\lambda_{ss}^L\lambda_{sb}^R$. For scalar unparticle in the loop, it is possible to constrain $\lambda_{ss}^Y\lambda_{bs}^{Y*}$, $\lambda_{ss}^{Y*}\lambda_{sb}^Y$, and $\lambda_{ss}^Y\lambda_{bs}^Y$. For real couplings, there are only two needed to be considered, with sub-indices $(ss, sb)$ and $(ss, bs)$.

c) For $b$ quark and vector unparticle in the loop, it is possible to constrain $\lambda_{sb}^R\lambda_{bb}^R$, $\lambda_{sb}^L\lambda_{bb}^L$, $\lambda_{sb}^R\lambda_{bb}^L$, and $\lambda_{sb}^L\lambda_{bb}^R$. For scalar unparticle in the loop, it is possible to constrain $\lambda_{sb}^Y\lambda_{bb}^{Y*}$, $\lambda_{sb}^{Y*}\lambda_{bb}^Y$, and $\lambda_{bs}^{Y*}\lambda_{bb}^{Y*}$. For real couplings, there are only two needed to be considered, with sub-indices $(sb, bb)$ and $(bs, bb)$.

The various constraints are shown in Tables I, II and III for different values of unparticle dimension $d_u$ with $\Lambda_u$ set to be 1 TeV. The central values for the unparticle couplings
are obtained by taking the SM leading values and require the unparticle contributions to produce the central value of $R_{\text{exp-SM}}$. In general there are two solutions. One comes from constructive interference contribution relative to the SM dominant contribution, and another from destructive interference. In the case that the unparticle contribution is dominated by the same chirality, $R = (1 + \gamma_5)/2$, amplitude as that of the dominate one in SM, the allowed unparticle amplitude from destructive case will be larger than the SM one. These are the cases with one of the central values (absolute values) much larger than the other in the tables. We hold the view that SM should dominate the contribution to $b \to s\gamma$, therefore we consider these cases not good ones for constraints.

For bounds on the couplings, we list the bounds corresponding to positive and negative solutions separately in the same way as their central values. Positive numbers indicate that the couplings should be smaller than the numbers listed, and negative numbers indicate that the couplings should be larger than the numbers listed.

It can be seen that the constraints sensitively depend on the unparticle dimension parameter $d_U$. For $d_U$ not too far away from 1, the constraints are stringent, but become weaker as $d_U$ increases. It is also clear that the constraints on the vector unparticle couplings are stronger than those for scalar unparticle couplings. This can be easily understood by noticing that the scalar unparticle couplings is suppressed by a factor of $v/\Lambda_U$ compared with vector unparticle couplings. Sizeable coupling strength for unparticles with quarks is still allowed.

Note that using $B \to X_s\gamma$ branching ratio alone, it is not possible to distinguish the above solutions since it is proportional to $|\tilde{A}_R^{\text{total}}|^2 + |\tilde{A}_L^{\text{total}}|^2$ which is how the constraints are obtained. We comment that measurement of polarization $\alpha_\Lambda$ in $\Lambda_b \to \Lambda\gamma$ can provide more information to distinguish some of the solutions. The polarization parameter $\alpha_\Lambda$ is defined by [13]

$$\frac{d\Gamma}{\Gamma d\cos\theta} = \frac{1}{2}(1 + \alpha_\Lambda \cos\theta), \quad \alpha_\Lambda = \frac{|\tilde{A}_R^{\text{total}}|^2 - |\tilde{A}_L^{\text{total}}|^2}{|\tilde{A}_R^{\text{total}}|^2 + |\tilde{A}_L^{\text{total}}|^2},$$

where $\Gamma$ is the decay rate for $\Lambda_b \to \Lambda\gamma$, and $\theta$ is the angle between the $\Lambda$ polarization and the photon momentum directions.

In the SM, since $\tilde{A}_S^{L}/\tilde{A}_S^{R} = m_s/m_b$, one would have $\alpha_\Lambda \approx 1$. In the Tables, we list $\alpha_\Lambda$ for the corresponding constraints on the couplings. We see that unparticle contributions can change the value for $\alpha_\Lambda$ significantly. Future measurement for $\alpha_\Lambda$ can provide more
information about unparticle interactions.

There are several studies of unparticle flavor changing effects in $B$ decays. The couplings are constrained from several processes\cite{3}, such as stringent constraints on the couplings $(\lambda'_{(d,s)b})^2$ and $(\lambda^{Y_D}_{(d,s)b} - \lambda^{Y_D*}_{b(d,s)})^2$ from $B_{d,s} - \bar{B}_{d,s}$ mixing\cite{3}. If all $\lambda_{ij}$ (or $\lambda^{Y_D}_{ij}$) are similar in size, the constraints from these considerations are stronger than the ones obtained on Tables I, II and III. However, one cannot exclude that the couplings are different for different generations, therefore the constraints obtained here are on different combinations and are new. There are also several studies of radiative decays involving leptons\cite{5}. The couplings obtained here are in general less stringent compared with the ones involving leptons. The bounds obtained here involve quarks and are, again, new ones.

In conclusion, we have studied unparticle effects on $b \to s\gamma$. The unparticle contributions can contribute significantly to both left- and right-handed chirality amplitudes. Using available experimental data on $b \to s\gamma$ and SM calculation, we have obtained new constraints on various vector and scalar unparticle couplings. The constraints sensitively depend on the unparticle dimension $d_U$. For $d_U$ close to one, the constraints can be very stringent. The constraints become weaker when $d_U$ is increased. In general the constraints on scalar unparticle couplings are weaker than those for vector unparticles. Sizeable coupling strength for scalar unparticles are still allowed leaving rooms for direct search for unparticle effects at colliders, such as LHC. Polarization measurement in $\Lambda_b \to \Lambda\gamma$ can further constraint the couplings.

**Acknowledgments** We thank Shao-Long Chen for early participation in this work and for many discussions. This work was supported in part by the NSC and NCTS.
TABLE I: Central values (c-value) and bounds for unparticle couplings with $d$ quark in the loop for $\Lambda_{d} = 1$ TeV. In the table “∼” indicates that the central values are larger than 10 implying weak constraints which we do not list. The corresponding values for $\alpha_{\Lambda}$ are listed below the constraints on couplings. In the table “∼ 1.” indicates a value very close to one.

| $d_{u}$ | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|---------|-----|-----|-----|-----|-----|
| $\lambda_{sd}^{R} \lambda_{db}^{R}$ c-value | $-2.1 \times 10^{-5} (2.4 \times 10^{-5})$ | $-0.00073 (0.00079)$ | $-0.019 (0.019)$ | $-0.30 (0.28)$ | $-1.3 (1.2)$ |
| $\alpha_{\Lambda}$ | 0.79 (0.79) | 0.79 (0.79) | 0.79 (0.79) | 0.79 (0.79) | 0.79 (0.79) |
| $\lambda_{sd}^{R} \lambda_{db}^{R}$ bound | $3.0 \times 10^{-5} (3.2 \times 10^{-5})$ | $-0.0010 (0.0011)$ | $-0.026 (0.026)$ | $-0.41 (0.39)$ | $-1.8 (1.6)$ |
| $\alpha_{\Lambda}$ | 0.63 (0.62) | 0.63 (0.62) | 0.63 (0.63) | 0.62 (0.63) | 0.62 (0.63) |
| $\lambda_{sd}^{L} \lambda_{db}^{L}$ c-value | $-3.9 \times 10^{-6} (0.00013)$ | $-0.00021 (0.00028)$ | $-0.019 (0.019)$ | $-1.1 (0.77)$ | $-7.0 (2.11)$ |
| $\alpha_{\Lambda}$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ |
| $\lambda_{sd}^{L} \lambda_{db}^{L}$ bound | $7.4 \times 10^{-6} (0.00013)$ | $-0.00036 (0.00030)$ | $-0.026 (0.026)$ | $-1.1 (0.14)$ | $-2.7 (0.41)$ |
| $\alpha_{\Lambda}$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ |
| $\lambda_{sd}^{R} \lambda_{db}^{L}$ c-value | $-0.0056 (0.00035)$ | $-0.12 (0.068)$ | $-1.6 (1.4)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.98 (1.) | 0.99 (0.99) | 1.0 (1.4) | $\sim$ | $\sim$ |
| $\lambda_{sd}^{R} \lambda_{db}^{L}$ bound | $-0.0024 (0.00016)$ | $-0.15 (0.10)$ | $-6.6 (6.8)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.45 (0.75) | 0.46 (0.75) | 0.66 (0.66) | $\sim$ | $\sim$ |
| $\lambda_{sd}^{YD} \lambda_{db}^{YD}$ c-value | $-0.048 (0.0015)$ | $-0.74 (0.054)$ | $-4.2 (4.2)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.94 (1.) | 0.99 (1.) | $\sim 1. (1.)$ | $\sim$ | $\sim$ |
| $\lambda_{sd}^{YD} \lambda_{db}^{YD}$ bound | $-0.049 (0.0028)$ | $-0.78 (0.099)$ | $-5.9 (5.9)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.95 (1.) | 0.99 (1.) | $\sim 1. (1.)$ | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ c-value | $-0.012 (0.0061)$ | $-0.23 (0.17)$ | $-4.2 (4.2)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.63 (0.87) | 0.74 (0.83) | 0.79 (0.79) | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ bound | $-0.015 (0.0093)$ | $-0.31 (0.25)$ | $-5.9 (5.9)$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.44 (0.75) | 0.57 (0.68) | 0.63 (0.63) | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ c-value | $-0.31 (0.013)$ | $-4.4 (0.79)$ | $\sim$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim$ | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ bound | $-0.32 (0.025)$ | $-5.0 (1.4)$ | $\sim$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | $\sim 1. (1.)$ | $\sim 1. (1.)$ | $\sim$ | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ c-value | $-0.067 (0.061)$ | $-1.9 (1.8)$ | $\sim$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.79 (0.79) | 0.79 (0.79) | $\sim$ | $\sim$ | $\sim$ |
| $\lambda_{ds}^{YD} \lambda_{db}^{YD}$ bound | $-0.093 (0.087)$ | $-2.7 (2.6)$ | $\sim$ | $\sim$ | $\sim$ |
| $\alpha_{\Lambda}$ | 0.63 (0.63) | 0.63 (0.63) | $\sim$ | $\sim$ | $\sim$ |
TABLE II: Central values (c-value) and bounds for unparticle couplings with $s$ quark in the loop for $\Lambda_d = 1$ TeV. In the table “$\sim$” indicates that the central values are larger than 10 implying weak constraints which we do not list. The corresponding values for $\alpha_\Lambda$ are listed below the constraints on couplings. In the table “$\sim 1$” indicates a value very close to one.

| $d_d$ | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|-------|-----|-----|-----|-----|-----|
| $\lambda^R_{s,s} \lambda^R_{s,b}$ c-value | $-2.0 \times 10^{-5}$ | $2.2 \times 10^{-5}$ | $0.00071(0.00076)$ | $-0.018(0.018)$ | $-0.29(0.27)$ | $-1.3(1.2)$ |
| $\alpha_\Lambda$ | 0.79(0.79) | 0.79(0.79) | 0.79(0.79) | 0.79(0.79) | 0.79(0.79) | 0.79(0.79) |
| $\lambda^R_{s,s} \lambda^R_{s,b}$ bound | $-2.8 \times 10^{-5}$ | $3.1 \times 10^{-5}$ | $0.010(0.011)$ | $-0.026(0.026)$ | $-0.41(0.39)$ | $-1.8(1.6)$ |
| $\alpha_\Lambda$ | 0.63(0.62) | 0.63(0.62) | 0.63(0.63) | 0.62(0.63) | 0.62(0.63) | 0.62(0.63) |
| $\lambda^L_{s,s} \lambda^L_{s,b}$ c-value | $-4.2 \times 10^{-6}$ | $0.00011$ | $0.0023(0.0024)$ | $-0.021(0.016)$ | $-1.1(0.075)$ | $-7.0(0.21)$ |
| $\alpha_\Lambda$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda^L_{s,s} \lambda^L_{s,b}$ bound | $-7.9 \times 10^{-6}$ | $0.00011$ | $0.0042(0.0025)$ | $-0.028(0.024)$ | $-1.1(0.14)$ | $-7.2(0.41)$ |
| $\alpha_\Lambda$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda^R_{s,s} \lambda^R_{s,b}$ c-value | $-7.7 \times 10^{-5}$ | $0.0019$ | $0.0048(0.085)$ | $-0.21(2.5)$ | $-6.2(48)$ | $-68$ |
| $\alpha_\Lambda$ | $\sim 1.(-0.65)$ | $\sim 1.(-1.1)$ | $0.99(-0.74)$ | $0.97(-0.3)$ | $- -$ | $- -$ |
| $\lambda^R_{s,s} \lambda^R_{s,b}$ bound | $-0.0015(0.0020)$ | $0.009(0.089)$ | $0.38(2.6)$ | $- -$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $\sim 1.(-0.6)$ | $0.98(-0.99)$ | $0.96(-0.81)$ | $- -$ | $- -$ | $- -$ |
| $\lambda^L_{s,s} \lambda^L_{s,b}$ c-value | $-0.011(0.0013)$ | $0.049(0.083)$ | $-0.63(0.81)$ | $-4.9(60)$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $-0.32(0.99)$ | $0.37(0.99)$ | $0.94(0.94)$ | $0.99(0.56)$ | $- -$ | $- -$ |
| $\lambda^L_{s,s} \lambda^L_{s,b}$ bound | $-0.0012(0.0024)$ | $0.055(0.014)$ | $-0.92(1.1)$ | $-9.1(64)$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $-0.43(0.96)$ | $0.28(0.96)$ | $0.89(0.89)$ | $0.98(0.54)$ | $- -$ | $- -$ |
| $\lambda^{YD}_{s,s} \lambda^{YD}_{b,s}$ c-value | $-0.021(0.0014)$ | $-0.37(0.050)$ | $-2.8(3.0)$ | $- -$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $0.92(\sim 1)$ | $\sim 1.1$ | $\sim 1.1$ | $- -$ | $- -$ | $- -$ |
| $\lambda^{YD}_{s,s} \lambda^{YD}_{b,s}$ bound | $-0.022(0.0026)$ | $-0.41(0.089)$ | $-4.0(4.2)$ | $- -$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $0.9(\sim 1)$ | $\sim 1.1$ | $\sim 1.1$ | $- -$ | $- -$ | $- -$ |
| $\lambda^{YD}_{s,s} \lambda^{YD}_{b,s}$ c-value | $-0.015(0.0019)$ | $-0.16(0.11)$ | $-1.3(6.7)$ | $- -$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $0.42(0.98)$ | $0.86(0.92)$ | $0.98(0.54)$ | $- -$ | $- -$ | $- -$ |
| $\lambda^{YD}_{s,s} \lambda^{YD}_{b,s}$ bound | $-0.017(0.0033)$ | $-0.22(0.17)$ | $-2.2(7.7)$ | $- -$ | $- -$ | $- -$ |
| $\alpha_\Lambda$ | $0.33(0.95)$ | $0.76(0.84)$ | $0.94(0.44)$ | $- -$ | $- -$ | $- -$ |
TABLE III: Central values (c-value) and bounds for unparticle couplings with $b$ quark in the loop for $\Lambda_4 = 1$ TeV. In the table “$-$” indicates that the central values are larger than 10 implying weak constraints which we do not list. The corresponding values for $\alpha_4$ are listed below the constraints on couplings. In the table “$\sim 1$” indicates a value very close to one.

| $d_L$ | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
|-------|-----|-----|-----|-----|-----|
| $\lambda_{sb}^R \lambda_{bb}^R$ c-value | $-0.0026(0.00020)$ | $-0.0053(0.0043)$ | $-0.079(0.067)$ | $-0.72(0.63)$ | $-1.8(1.6)$ |
| $\alpha_4$ | 0.76(0.81) | 0.77(0.81) | 0.78(0.8) | 0.78(0.8) | 0.79(0.79) |
| $\lambda_{sb}^R \lambda_{bb}^R$ bound | $-0.0035(0.00030)$ | $-0.0072(0.0063)$ | $-0.11(0.096)$ | $-0.99(0.90)$ | $-2.4(2.2)$ |
| $\alpha_4$ | 0.59(0.65) | 0.6(0.65) | 0.61(0.64) | 0.62(0.63) | 0.62(0.63) |
| $\lambda_{sb}^D \lambda_{bb}^D$ c-value | $-0.0014(3.8 \times 10^{-5})$ | $-0.029(0.00080)$ | $-0.44(0.012)$ | $-4.0(0.11)$ | $-10(0.28)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda_{sb}^D \lambda_{bb}^D$ bound | $-0.0014(7.3 \times 10^{-5})$ | $-0.030(0.0015)$ | $-0.45(0.023)$ | $-4.2(0.21)$ | $-10(0.53)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda_{bb}^{\Lambda \Lambda \Lambda \Lambda} c$-value | $-8.9 \times 10^{-3}(9.8 \times 10^{-5})$ | $-0.0023(0.0025)$ | $-0.046(0.05)$ | $-0.7(0.76)$ | $-5.2(5.7)$ |
| $\alpha_4$ | 0.79(0.79) | 0.79(0.79) | 0.78(0.8) | 0.78(0.8) | 0.78(0.8) |
| $\lambda_{bb}^{\Lambda \Lambda \Lambda \Lambda} bound$ | $-0.00013(0.00014)$ | $-0.0032(0.0034)$ | $-0.065(0.07)$ | $-0.99(1.1)$ | $-7.4(7.9)$ |
| $\alpha_4$ | 0.62(0.63) | 0.62(0.63) | 0.62(0.63) | 0.62(0.63) | 0.62(0.63) |
| $\lambda_{sb}^{Y \Lambda \Lambda \Lambda \Lambda} c$-value | $-1.6 \times 10^{-3}(0.00056)$ | $-0.00039(0.014)$ | $-0.008(0.29)$ | $-0.12(4.4)$ | $-0.91(33)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda_{sb}^{Y \Lambda \Lambda \Lambda \Lambda} bound$ | $-3.0 \times 10^{-5}(0.00058)$ | $-0.00075(0.015)$ | $-0.015(0.30)$ | $-0.23(4.5)$ | $-1.7(34)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda_{bb}^{Y \Lambda \Lambda \Lambda \Lambda} c$-value | $-0.00075(0.027)$ | $-0.011(0.42)$ | $-0.14(5.0)$ | $-1.1(39)$ | $-2.4(86)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
| $\lambda_{bb}^{Y \Lambda \Lambda \Lambda \Lambda} bound$ | $-0.0014(0.028)$ | $-0.022(0.43)$ | $-0.27(5.1)$ | $-2.1(40)$ | $-4.5(88)$ |
| $\alpha_4$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ | $\sim 1.1$ |
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