The large CP phase in $B_s - \bar{B}_s$ mixing from primary scalar unparticles

J. K. Parry
Kavli Institute for Theoretical Physics China, Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100190, China
and Center for High Energy Physics, Tsinghua University, Beijing 100084, China

In this letter we consider the case of primary scalar unparticle contributions to $B_d,s$ mixing. With particular emphasis on the impact of the recent hint of new physics in the measurement of the $B_s$ mixing phase, $\phi_s$, we determine the allowed parameter space and impose bounds on the unparticle couplings.

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I. INTRODUCTION

It has recently been suggested [1,2] that there may exist a non-trivial scale invariant sector at high energies, known as unparticle stuff. These new fields with an infrared fixed point are called Banks-Zaks fields [3], interacting with Standard model fields via heavy particle exchange,

$$ 1 \frac{M_U}{M_{U'}} \mathcal{O}_{SM} \mathcal{O}_{BZ}. $$

(1)

Here $\mathcal{O}_{SM}$ is a standard model(SM) operator of mass dimension $d_{SM}$, $\mathcal{O}_{BZ}$ is a Banks-Zaks(BZ) operator of mass dimension $d_{BZ}$, with $k = d_{SM} + d_{BZ} - 4$, and $M_U$ is the mass of the heavy particles mediating the interaction. At a scale denoted by $\Lambda_U$ the BZ operators match onto unparticle operators with a new set of interactions,

$$ C_U \frac{\Lambda_{d_{BZ} - d_U}^d}{M_U^d} \mathcal{O}_{SM} \mathcal{O}_{U}. $$

(2)

where $\mathcal{O}_{U}$ is an unparticle operator with scaling dimension $d_U$ and $C_U$ is the coefficient of the low energy theory. Unparticle stuff of scaling dimension $d_U$ looks like a non-integral number $d_U$ of invisible massless particles. It was recently suggested in [27] that conformal invariance implies constraints on the scaling dimension, $1 \leq d_U \leq 2$, and $3 \leq d_U \leq 4$, for scalar and vector unparticles respectively. This also implies the constraint $2 \leq d_U \leq 3$ for the non-primary operator $\partial^\mu \mathcal{O}_{U}$. We shall see later that assuming such constraints leads to the contributions from vector unparticles and from the non-primary operator $\partial^\mu \mathcal{O}_{U}$ being negligible, except in a small region of parameter space where the scaling dimension approaches integer values. As a result, in this work we shall follow the above suggestion and focus on the case of the primary scalar unparticle ($\mathcal{O}_{U}$) with couplings to the SM quarks as follows,

$$ \mathcal{L}_{S'} = \frac{c_{S'}^{L,bq}}{\Lambda_{d_{U}-1}} \bar{q}(1 - \gamma_5)q \mathcal{O}_{U} + \frac{c_{S'}^{R,bq}}{\Lambda_{d_{U}-1}} \bar{q}(1 + \gamma_5)q \mathcal{O}_{U}. $$

(3)

Here we assume that the left-handed and right-handed flavour-dependent dimensionless couplings $c_{S'}^{L,bq}$, $c_{S'}^{R,bq}$, are independent parameters. The above notation, $\mathcal{L}_{S',bq}$, has been used to distinguish the primary scalar operator studied here from $\mathcal{L}_{S}$ for the non-primary scalar case $\partial^\mu \mathcal{O}_{U}$ studied previously [13]. We analyze a number of scenarios, in each case determining the allowed parameter space and placing bounds on the unparticle couplings.

The propagators for scalar unparticle are as follows [2,4],

$$ \int d^4x e^{iP\cdot x}(0|\mathcal{O}_{U}(x)\mathcal{O}_{U}(0)|0) = \frac{A_{d_{U}}}{2 \sin d_{U} \pi} \frac{1}{(P^2 + i\epsilon)^{2 - d_{U}}} e^{-i\phi_{U}}. $$

(4)

where

$$ A_{d_{U}} = \frac{16\pi^{5/2}}{(2\pi)^{2d_{U}}} \frac{\Gamma(d_{U} + 1/2)}{\Gamma(d_{U} - 1)\Gamma(2d_{U})}, \quad \phi_{U} = (d_{U} - 2)\pi $$

(5)

(6)
The effects of unparticles, both scalar and vector, on meson-anti-meson mixing has been studied in the literature [5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. In this work we shall study the constraints on primary scalar unparticles coming from the measurements of $B_{s,d}$ meson mass differences $\Delta M_{s,d}$ and also their CP violating phases $\phi_{s,d}$. In the $B_d$ system these quantities have been well measured for some time and show no sizeable deviations from the SM expectations. In the $B_s$ system recent measurements have also found small discrepancies between the SM expectation for $\Delta M_s$ [15], but now the CP violating phase $\phi_s$, measured by the D0 [16] and CDF [17] collaborations reveals a deviation of $3\sigma$ [18, 19, 20]. This is the first evidence for new physics in $b \to s$ transitions. Studying primary scalar unparticles, we derive the constraints imposed by these latest measurements on the coupling between SM fields and unparticles, with particular interest on the impact of $\phi_s$.

II. MESON-ANTIMESON MIXING FROM UNPARTICLES

Using the interactions listed in eq. (3) to evaluate the s- and t-channel contributions to meson mixing we obtain the effective Hamiltonian,

$$\mathcal{H}_{\text{eff}}^{S',q'q} = \frac{A_{d_{bt}}}{2\sin d_{bt} \pi} \frac{e^{-i\phi_{bt}}}{\Lambda_{t}^{2d_{bt}-2}} \left[ Q_2 \left( c_{L}^{S',q'q} \right)^2 + Q_2 \left( c_{R}^{S',q'q} \right)^2 + 2 Q_4 \left( c_{L}^{S',q'q} c_{R}^{S',q'q} \right) \right]$$

(7)

Here we have defined the quark operators $Q_1 - Q_5$ and their hadronic matrix elements as in [13]. Writing the $\Delta F = 2$ effective Hamiltonian in terms of these operators we have,

$$\mathcal{H}_{\text{eff}}^{S',q'q} = \sum_{i=1}^{5} C_{i}^{S',q'q} Q_i + \sum_{j=1}^{3} \tilde{C}_{j}^{S',q'q} \tilde{Q}_j$$

(8)

Here the operators $\tilde{Q}_{1,2,3}$ are obtained from $Q_{1,2,3}$ by the exchange $L \leftrightarrow R$. From eq. (7), it is straightforward to calculate the Wilson coefficients for primary scalar unparticles which are as follows,

$$C_{2}^{S'} = \frac{A_{d_{bt}}}{\sin d_{bt} \pi} \frac{e^{-i\phi_{bt}}}{M_{M}^2 \Lambda_{t}^2} \left( M_{M}^2 \Lambda_{t}^2 \right)^{d_{bt}-1} \left( c_{L}^{S',q'q} \right)^2$$

(9)

$$C_{4}^{S'} = 2 \frac{A_{d_{bt}}}{\sin d_{bt} \pi} \frac{e^{-i\phi_{bt}}}{M_{M}^2 \Lambda_{t}^2} \left( M_{M}^2 \Lambda_{t}^2 \right)^{d_{bt}-1} \left( c_{L}^{S',q'q} c_{R}^{S',q'q} \right)$$

(10)

$$\tilde{C}_{2}^{S'} = \frac{A_{d_{bt}}}{\sin d_{bt} \pi} \frac{e^{-i\phi_{bt}}}{M_{M}^2 \Lambda_{t}^2} \left( M_{M}^2 \Lambda_{t}^2 \right)^{d_{bt}-1} \left( c_{R}^{S',q'q} \right)^2$$

(11)

$$C_{1}^{S'} = \tilde{C}_{1}^{S'} = C_{5}^{S'} = \tilde{C}_{5}^{S'} = \tilde{C}_{3}^{S'} = 0$$

(12)

where we have approximated $t = s \sim M_{M}^2$. This set of Wilson coefficients is rather similar to that for the non-primary operator $\partial^\mu C_{bt}$, with the main differences being the sign of $C_{2}$ and the power to which the unparticle scale $\Lambda_t$ is raised. These Wilson coefficients will mix with each other as a result of renormalisation group(RG) running down to the scale of $M_{M}$. For the $B$ system, with a scale of new physics $\Lambda_t = 1 \text{ TeV}$, these Wilson coefficients at the scale $\mu_b = m_b$ are approximated as in [13]. The $\Delta F = 2$ transitions are defined as,

$$\langle M^0 | \mathcal{H}_{\text{eff}}^{F=2} | M^0 \rangle = M_{12}$$

(13)

with the meson mass eigenstate difference defined as, $\Delta M \equiv M_H - M_L = 2|M_{12}|$. We can define in a model independent way the contribution to meson mixings in the presence of New Physics(NP) as,

$$M_{12} = M_{12}^{\text{SM}}(1 + R)$$

(14)

where $M_{12}^{\text{SM}}$ denotes the SM contribution and $R = re^{i\sigma}$ is $M_{12}^{\text{NP}}/M_{12}^{\text{SM}}$ parameterizes the NP contribution. The associated CP phase may then be defined as,

$$\phi = arg(M_{12}) = \phi^{\text{SM}} + \phi^{\text{NP}}$$

(15)

where $\phi^{\text{SM}} = arg(M_{12}^{\text{SM}})$ and $\phi^{\text{NP}} = arg(1 + re^{i\sigma})$. 

A. $B_{s,d}$ mixing and unparticle physics

In this work we shall focus on the constraints imposed on unparticle physics couplings from $B_{s,d}$ mixing. Therefore we set $q^t = b$, $q = s$, $d$ and $M^0 = B^0_s$, $B^0_d$. In the B system, the Standard Model contribution to $M^q_{12}$ is given by,

$$M^q_{12} = \frac{G_F M_W^2}{12\pi^2} M_{B_q} \hat{g}^B \hat{f}_{B_q} \hat{B}_{B_q}(V^*_{tq} V_{tb})^2 S_0(x_t)$$

where $G_F$ is Fermi’s constant, $M_W$ the mass of the W boson, $\hat{g}^B = 0.551$ is a short-distance QCD correction identical for both the $B_s$ and $B_d$ systems. The bag parameter $\hat{B}_{B_q}$ and decay constant $f_{B_q}$ are non-perturbative quantities and contain the majority of the theoretical uncertainty. $V^*_{tq}$ and $V_{tb}$ are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix $[23, 24]$, and $S_0(x_t) = m_t^2/M_W^2 = 2.34 \pm 0.03$, with $m_t(m_t) = 164.5 \pm 1.1$ GeV $[25]$, is one of the Inami-Lim functions $[26]$.

We can now constrain both the magnitude and phase of the NP contribution, $r_q$ and $\sigma_q$, through the comparison of the experimental measurements with SM expectations. From the definition of eq. $[14]$, we have the constraint,

$$\rho_q = \frac{\Delta M_q}{\Delta M^q_{SM}} = \sqrt{1 + 2r_q \cos \sigma_q + r_q^2}$$

The values for $\rho_q$ given by the UTfit analysis $[18, 20]$ at the 95% C.L. are,

$$\rho_s = [0.53, 2.05], \quad \rho_d = [0.62, 1.93]$$

These constraints on $\rho_q$ encode the CP conserving measurements of $\Delta M_{d,s}$. The phase associated with NP can also be written in terms of $r_q$ and $\sigma_q$,

$$\sin \phi_q^{NP} = \frac{r_q \sin \sigma_q}{\sqrt{1 + 2r_q \cos \sigma_q + r_q^2}}$$

Here $[18, 20]$ gives the 95% C.L. constraints,

$$\phi_d^{NP} = [-16.6, 3.2]^\circ$$

$$\phi_s^{NP} = [-156.90, -106.40]^\circ \cup [-60.9, -18.58]^\circ$$

these constraint represent those of the CP phase measurements of $\phi_{d,s}$. As in $[13]$, in order to consistently apply the above constraints all input parameters are chosen to match those used in the analysis of the UTfit group $[18, 20]$.

III. NUMERICAL ANALYSIS

First let us re-examine the contributions to $B_{d,s}$ mixing from primary vector unparticles $O^{\mu}_d$ and the non-primary $\partial^\mu O_d$. The Wilson coefficients for these cases can be found for example in $[13]$. Following the arguments of $[27]$ we have the bounds $2 \leq d_{\mu} \leq 3$ for $\partial^\mu O_d$ and $3 \leq d_{\mu} \leq 4$ for $O^{\mu}_d$. These bounds produce a very large suppression of the contributions to $B_{d,s}$ mixing, unless we are sufficiently close to the pole in the unparticle propagator. These poles occur as $d_{\mu}$ approaches integer values, due the 1/sin nature of the propagator. Therefore the only significant contributions may occur for values of the scaling dimension, $d_{\mu} = A + \epsilon$ and $d_{\mu} = B - \delta$, where $A = 2(3)$ and $B = 3(4)$ for $\partial^\mu O_d$ ($O^{\mu}_d$), with $\epsilon, \delta \ll 1$. Fig. 1 and 2 show the size of $\rho_s$ which results from varying $\epsilon$ and $\delta$ for couplings between SM operator and unparticle operator in the range $( -1, 1 )$. From these plots we can see that for the unparticle operator $\partial^\mu O_d$, we require $\epsilon \lesssim 0.1$ or $\delta \lesssim 10^{-7}$ to get significant contributions to $B_s$ mixing. For the vector unparticle operator $O^{\mu}_d$, the requirement is $\epsilon \lesssim 0.005$ or $\delta \lesssim 10^{-10}$. The range of values of $d_{\mu}$ for which the present allowed region for $\rho_s$ may provide a constraint on the couplings is even smaller than those stated above. For example for the non-primary operator $\partial^\mu O_d$ we require $\epsilon \lesssim 0.025$ before the $\rho_s$ constraints begin to have any effect on the size of the couplings. The requirements for non-negligible contributions to $B_d$ mixing will be less strict. It seems that, barring a small region of parameter space, the contributions from primary vector and non-primary scalar unparticles are negligible. As a result we here consider only the primary scalar unparticle contribution to $B_{s,d}$ mixing.

For our analysis of the primary scalar contribution to $B_{s,d}$ mixing we shall take the unparticle scale $\Lambda_U = 1$ TeV and generally fix $d_{\mu} = \frac{3}{2}$. In the following we shall consider possible coupling patterns as follows,
One real coupling; \(c_S^{bq}_L \neq 0, c_S^{bq}_R = 0\), with \(c_S^{bq}_L \in \mathbb{R}\)

Two real couplings; \(c_S^{bq}_L \neq 0, c_S^{bq}_R \neq 0\), with \(\{c_S^{bq}_L, c_S^{bq}_R\} \in \mathbb{R}\)

One complex coupling; \(c_S^{bq}_L \neq 0, c_S^{bq}_R = 0\), with \(c_S^{bq}_L \in \mathbb{C}\)

Two complex couplings; \(c_S^{bq}_L \neq 0, c_S^{bq}_R \neq 0\), with \(\{c_S^{bq}_L, c_S^{bq}_R\} \in \mathbb{C}\)

In the first case, a single real coupling \((c_L^{S,bq} \neq 0, c_R^{S,bq} = 0)\) between primary scalar unparticle operator and our SM quark operator, we allow the scaling dimension to vary in the range indicated by the bounds discussed earlier. Fig. 3 and 4 show the experimentally allowed parameter space in this case in the plane of the scaling dimension, \(d_U\), and the coupling \(c_S^{S,bq}\). This plot shows a very similar behaviour to that found for non-primary scalar unparticles with real couplings \(c_L^{S,bq} = c_R^{S,bq}\) \([13]\), with the allowed parameter space generally increasing for increasing \(d_U\). This similarity between these two seemingly different cases is simply because they both give negative \(M_{12}^U\) due to the sign of the Wilson coefficient \(C_2\).

Fig. 3 shows the allowed \(d_U - c_L^{S,bq}\) parameter space, black points obey the constraint from \(\Delta M_d\) while grey points obey constraints from both \(\Delta M_d\) and \(\phi_d\). From the left panel of fig. 3 with \(d_U = \frac{3}{2}\), we can extract bounds,

\[
|c_L^{S,bq}| \leq 0.0002 \quad (\Delta M_d \text{ only}) \tag{22}
\]

\[
|c_L^{S,bq}| \leq 0.00005 \quad (\Delta M_d & \phi_d) \tag{23}
\]
FIG. 3: Constraints on the $d_U$ versus $c_{S', bq}^L$ parameter space from $B_d$ mixing (left) and $B_s$ mixing (right) for the case of a single real coupling $c_{S', bq}^L \neq 0$ and $c_{S', bq}^R = 0$. Black points indicate the $\Delta M_{d,s}$ allowed regions, while grey points indicate the regions are in agreement with both $\Delta M_q$ and the CP phase $\phi_q$.

From the right panel of fig. 3, with $d_U = \frac{3}{2}$, we can extract the bounds,

$$|c_{S', bq}^L| \leq 0.001 \quad (\Delta M_s \text{ only}) \quad (24)$$

$$|c_{S', bq}^L| \text{ excluded} \quad (\Delta M_s \& \phi_s) \quad (25)$$

where we see that the combined constraints of $\Delta M_s \& \phi_s$ exclude this possibility at the 3 $\sigma$ level, for all values of $d_U$.

FIG. 4: Plot of the allowed $c_{S', bq}^L, c_{S', bq}^R$ parameter space for $B_d$ mixing (left) and $B_s$ mixing (right) in the case of two real couplings and scaling dimension fixed as $d_U = 3/2$. Black points show regions which agree with the measurement of $\Delta M_{d,s}$ while grey points show additional agreement with the measurement of the CP phases $\phi_{d,s}$.

For the second case of two real couplings, $c_{S', bq}^L$ and $c_{S', bq}^R$, we take two sub-cases, $c_{S', bq}^L \neq c_{S', bq}^R$ and $c_{S', bq}^L = c_{S', bq}^R$, shown in fig. 4 and 5 respectively. For the first sub-case, $c_{S', bq}^L \neq c_{S', bq}^R$, shown in fig. 4 there are generally no bounds that can be set on the couplings with the allowed parameter space stretching along two lines, similar to the case of two real non-equal couplings to unparticle operator $\partial^\mu O_U$. Looking at the grey area of fig. 4 we can see that including the $\phi_s$ and $\phi_d$ constraints further restrict the allowed parameter space. For the second sub-case, $c_{S', bq}^L = c_{S', bq}^R$, shown in fig. 5 the allowed parameter space is rather similar to the case of unparticle operators $O_U^\mu$ and $\partial^\mu O_U$ with a single
real coupling, [13]. For this sub-case we can now set the bounds,

\[
|c_{L}^{S',bd}| = |c_{R}^{S',bd}| \leq 0.00034 \quad (\Delta M_d \text{ only}) \tag{26}
\]

\[
|c_{L}^{S',bd}| = |c_{R}^{S',bd}| \leq 0.00012 \quad (\Delta M_d & \phi_d) \tag{27}
\]

\[
|c_{L}^{S',bs}| = |c_{R}^{S',bs}| \leq 0.0013 \quad (\Delta M_s \text{ only}) \tag{28}
\]

\[
0.00058 \leq |c_{R}^{S',bs}| = |c_{L}^{S',bs}| \leq 0.0013 \quad (\Delta M_s & \phi_s) \tag{29}
\]

for \(d_U = \frac{3}{2}\).

The allowed parameter space for the third case, a single complex coupling, \(c_{L}^{S',bd} \neq 0\) and \(c_{R}^{S',bd} = 0\), is...
shown in Fig. 6. In this case we have the bounds,

\[ |c_{L,bq}^{S',bd}| \leq 0.00029 \quad (\Delta M_d \text{ only}) \]  
\[ |c_{L,bq}^{S',bd}| \leq 0.00018 \quad (\Delta M_d & \phi_d) \]  
\[ |c_{L,bq}^{S',bs}| \leq 0.0014 \quad (\Delta M_\phi \text{ only}) \]  
\[ 0.00046 \leq |c_{L,bq}^{S',bs}| \leq 0.0014 \quad \text{and} \quad 48.2^\circ \leq \phi_L^{S',bs} \leq 115.6^\circ \quad (\Delta M_\phi & \phi_s) \]  

For the final case of two complex couplings, \( c_{L,bq}^{S',bd} \neq 0 \) and \( c_{R,bq}^{S',bd} \neq 0 \). Black plotted points agree with the CP conserving quantities \( \Delta M_{d,s} \), while grey points also agree with \( \phi_{d,s} \).

IV. CONCLUSION

It was recently suggested in [27] that conformal invariance implies constraints on the scaling dimension, \( 1 \leq d_U \leq 2 \), and \( 3 \leq d_U \leq 4 \), for scalar and vector unparticles respectively. These constraints imply a rather large suppression of the contribution of vector and non-primary scalar unparticles to \( B_{d,s} \) mixing, except for in a rather small range of scaling dimension close to integer values. The largest range where non-negligible contributions exist is for the non-primary operator \( \partial^5 C_U \) with \( 2 \leq d_U \leq 2.1 \). For primary scalar unparticles the suppression is far less and as such the range of scaling dimension for which sizable contributions to \( B_{d,s} \) mixing exists is far larger. As a result, we have here considered, for the first time, the contribution of a primary scalar unparticle operator \( C_U \) to \( B_{d,s} \) mixing. Considering a number of different coupling patterns, we have determined the allowed parameter space and set bounds on the unparticle couplings in each case. To illustrate the impact of the inclusion of the constraints from the CP
FIG. 8: Plot of the allowed $|c'_L,bq|\phi'_L,bq$ parameter space for $B_d$ mixing(left) and $B_s$ mixing(right) for the case of one complex coupling $c'_L,bq = c'_R,bq$ and scaling dimension fixed as $d_U = 3/2$. Black plotted points agree with the CP conserving mixing quantities $\Delta M_{d,s}$, while grey points also agree with $\phi_{d,s}$.

phases associated with $B_{d,s}$ mixing, in particular the recently measured hint of new physics in $\phi_s$, we have analyzed constraints with and without the inclusion of $\phi_{d,s}$. In each case we have found that these CP phases have an important role to play in constraining the parameter space, highlighted by the case of a single real unparticle coupling, $c'_{L,bq} \neq 0$ and $c'_{R,bq} = 0$, which was excluded for all values of the scaling dimension $d_U$.

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[29] It should be noted that the combination of D0 and CDF results for $\phi_s$ were made without full knowledge of the likelihoods, which could have an effect on the significance of this SM deviation. These are now being made available and a new experimental combination is due to be released soon. Until that time this present hint of new physics is the best available and remains a very exciting prospect.