PROCEEDINGS OF SCIENCE

Effect of High Mass t' on $\sin 2\Phi_{B_s}$

George Wei-Shu Hou
National Taiwan University
E-mail: wshou@phys.ntu.edu.tw

Chien-Yi Ma*
National Taiwan University
E-mail: machienyi@hep1.phys.ntu.edu.tw

The Standard Model predicts the CP violation phase $2\Phi_{B_s}^{\rm SM} = \arg M_{12} \simeq \arg(V_{ts}^* V_{tb})^2 \simeq -0.04$ in B_s–$\bar{B}_s$ mixing is very small, of $O(\lambda^2\eta)$. Any finite value of Φ_{B_s} measured at the Tevatron would mean New Physics. Recent hints for finite $\sin 2\Phi_{B_s}$ have appeared from CDF and DØ experiments at the Tevatron Run II. We consider the possibility to account for it with the 4th generation t' quark. Considering recent direct search bounds, we set the mass to be near the unitarity bound of 500 GeV. Combining the measurement values of Δm_{B_s} with $\mathscr{B}(B_d \to X_s \ell^+\ell^-)$, together with typical f_{B_s} values, we find a sizable $\sin 2\Phi_{B_s}^{\rm SM4} \sim -0.35$. Using a typical value of $m_{b'} = 480$ GeV, we get a range of values, $0.06 < |V_{t'b}| < 0.13$, from the constraints of $\Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$, $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and Δm_{D^0}. A future measurement of $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$, when combined with ε_K, will determine $V_{t'd}$.

European Physical Society Europhysics Conference on High Energy Physics, EPS-HEP 2009,
July 16 - 22 2009
Krakow, Poland

*Speaker.

PoS(EPS-HEP 2009)175

1. Large $\sin 2\Phi_{B_s}$?

The measured CPV phase $\sin 2\Phi_{B_d}$ ($\equiv \sin 2\phi_1 \equiv \sin 2\beta$) via $B_d \to J/\psi K^0$ modes is consistent [1] with SM. However, recent measurements by the CDF and DØ experiments of the analogous $\sin 2\Phi_{B_s}$ (also called $-\sin 2\beta_s$ or $\sin\phi_s$) in tagged $B_s^0 \to J/\psi\phi$ decay seems to give a large and negative value, which is 2.1σ (see plenary talk by G. Punzi) away from the SM expectation of -0.04. Though not yet significant, the central value is tantalizingly close to a prediction [2] based on the 4th generation interpretation of the observed B^+ vs $B^0 \to K\pi$ direct CPV difference. The t' quark interferes with the top in the B_s–$\bar{B}_S$ mixing box diagram.

With four generations, the extra $V_{t's}^* V_{t'b}$ turns the familiar unitarity triangle into a quadrangle

$$\Sigma_{q=u}^{t'} \lambda_q = V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} + V_{t's}^* V_{t'b} = 0. \tag{1.1}$$

We will follow Ref. [3] and use Δm_{B_s}, together with the Z-penguin dominant $\mathscr{B}(b \to s\ell\ell)$ to constrain the range of $\lambda_{t'} \equiv V_{t's}^* V_{t'b} \equiv r_{sb} e^{i\phi_{sb}}$. The present study explores variations in f_{B_s} and $m_{t'}$.

Since the main source of information is from B physics, we use the parametrization of Ref. [4] for the 4×4 CKM matrix, where the 4th row and 3rd column are particularly simple. We list the following elements for the convenience of our later discussions:

$$V_{t'd} = -c_{24}c_{34}s_{14}\, e^{-i\phi_{db}}, \;\; V_{t's} = -c_{34}s_{24}\, e^{-i\phi_{sb}}, \;\; V_{t'b} = -s_{34}, \;\; V_{t'b'} = c_{14}c_{24}c_{34}, \tag{1.2}$$

$$V_{ub'} = \; c_{12}c_{13}s_{14}\, e^{i\phi_{db}} + c_{13}c_{14}s_{12}s_{24}\, e^{i\phi_{sb}} + c_{14}c_{24}s_{13}s_{34}\, e^{-i\phi_{ub}}, \tag{1.3}$$

$$V_{cb'} = \; c_{12}c_{14}c_{23}s_{24}\, e^{i\phi_{sb}} - c_{23}s_{12}s_{14}\, e^{i\phi_{db}} + c_{13}c_{14}c_{24}s_{23}s_{34} - c_{14}s_{12}s_{13}s_{23}s_{24}\, e^{i(\phi_{sb}+\phi_{ub})} - c_{12}s_{13}s_{14}s_{23}\, e^{i(\phi_{db}+\phi_{ub})}. \tag{1.4}$$

with $V_{tb'}$ also complicated, while $V_{ub} = c_{34}s_{13}\, e^{-i\phi_{ub}}$, $V_{cb} = c_{13}c_{34}s_{23}$, $V_{tb} = c_{13}c_{23}c_{34}$ are simple and close to the usual SM3 parametrization. In the small angle limit, this allows us to take the PDG values for $s_{12},\ s_{23},\ s_{13}$ and $\phi_{ub} = \phi_3 \simeq 60^\circ$ as input [1], so $V_{ij} \simeq V_{ij}^{\rm SM}$ for $i = u, c$ and $j = d, s, b$. From (1.1), one can also express $\lambda_t \equiv V_{ts}^* V_{tb} \simeq -r_{sb} e^{i\phi_{sb}} - \lambda_u^{\rm SM} - \lambda_c^{\rm SM}$ in terms of r_{sb} and ϕ_{sb}.

The box diagram formula for Δm_{B_s} is well known [5],

$$M_{12} = \frac{G_F^2 M_W^2}{12\pi^2} m_{B_s} \hat{B}_{B_s} f_{B_s}^2 (\lambda_t^2\, \eta\, S_0(x_t) + \eta'\, \lambda_{t'}^2\, S_0(x_{t'}) + 2\,\tilde{\eta}\,\lambda_t\,\lambda_{t'}\,\tilde{S}_0(x_t, x_{t'})), \tag{1.5}$$

where η, η' and $\tilde{\eta} = \sqrt{\eta\eta'}$ are QCD factors. In a previous study [3], $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.295$ GeV was used, together with $m_{t'} = 300$ GeV. Since the lattice errors are still quite large, here we take the latest result $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.266$ GeV [6] for comparison. In light of rising lower bounds at the Tevatron, we also consider the heavy t' case.

Because $\Delta m_{B_s}^{\rm exp} = (17.77 \pm 0.12)\ {\rm ps}^{-1}$ is precisely measured, we get a unique value of ϕ_{sb} for each r_{sb} (and $m_{t'}$), and a corresponding value of $\mathscr{B}(b \to s\ell\ell)$. However, $\mathscr{B}^{\rm exp}(b \to s\ell\ell) = (4.5 \pm 1.0) \times 10^{-6}$ [1] has a sizable error, so a range of (r_{sb}, ϕ_{sb}) allowed, as shown in Fig. 1 for $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.266$ GeV and $m_{t'} = 300$ GeV. Note that the SM prediction for Δm_{B_s} (dashed line) is much closer to experiment (solid line) than $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.295$ GeV case, allowing a much lower bound of $r_{sb} = 0.003$, compared with $r_{sb} = 0.020$ for the latter [3]; a larger $f_{B_s}\hat{B}_{B_s}^{1/2}$ would imply a larger $\sin 2\Phi_{B_s}$. Taking the central value of $\mathscr{B}(b \to s\ell\ell)$, we have $\sin 2\Phi_{B_s},\ r_{sb},\ \phi_{sb} = -0.37$,

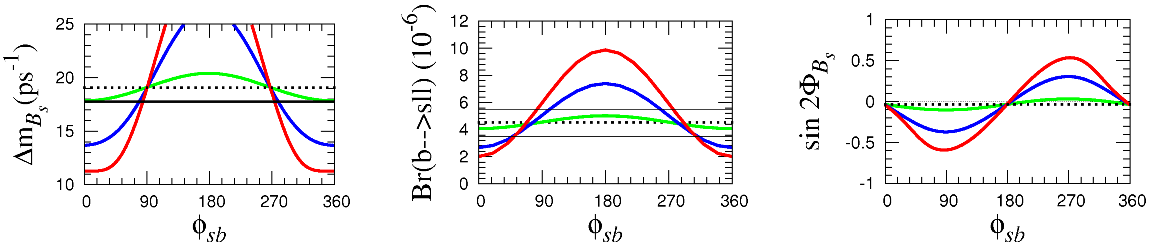

Fig. 1: (L) Δm_{B_s}, (M) $\mathscr{B}(b \to s\ell\ell)$, (R) $\sin 2\Phi_{B_s}$ vs. ϕ_{sb}, for $r_{sb} = 0$ (dashed), 0.003, 0.015, 0.025 (strongest variation), $m_{t'} = 300$ GeV, and $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.266$ GeV. The solid straight line in L is the CDF measurement.

0.015, 81° for the 0.266 GeV case, versus −0.60, 0.025, 70° for the 0.295 GeV case [3]. Thus, if $-\sin 2\Phi_{B_s}$ is found larger than 0.6, higher $f_{B_s}\hat{B}_{B_s}^{1/2}$ is preferred.

Following similar procedure for $m_{t'} = 500$ GeV, we get the central values of $\sin 2\Phi_{B_s}$, r_{sb}, $\phi_{sb} =$ −0.33, 0.006, 75° for the $f_{B_s}\hat{B}_{B_s}^{1/2} = 0.266$ GeV case, and −0.38, 0.010, $\phi_{sb} = 61°$ respectively for the 0.295 GeV case. A larger $m_{t'}$ diminishes the need for large r_{sb}, hence $\sin 2\Phi_{B_s}$ is smaller and less sensitive to $f_{B_s}\hat{B}_{B_s}^{1/2}$.

2. Bounding $|V_{t'b}|$, and Future Utility of $K_L \to \pi^0 \bar{\nu}\nu$ Measurement

An upper bound on $V_{t'b}$ comes from $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ due to the loop diagram with t'. Following Ref. [7] and using the good approximation $|V_{tb}|^2 \simeq 1 - |V_{t'b}|^2$, we find

$$|V_{t'b}| \leq 0.24\ (0.13) \quad \text{for } m_{t'} = 300\ (500)\ \text{GeV}. \tag{2.1}$$

A lower bound on $V_{t'b}$ comes from $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and $D - \bar{D}$ mixing, where we use [8, 9],

$$\kappa_+ |V_{us}|^{-5} \left|\lambda_c^{ds} |V_{us}|^4 P_c + \lambda_t^{ds} \eta_t X_0(x_t) + \lambda_{t'}^{ds} \eta_{t'} X_0(x_{t'})\right|^2 < 3.6 \times 10^{-10}\ (90\%\ \text{CL}), \tag{2.2}$$

$$|V_{ub'}^* V_{cb'}| < 0.0033\ (0.0021), \quad \text{for } m_{b'} = 280\ (480)\ \text{GeV}, \tag{2.3}$$

with $\lambda_q^{ds} \equiv V_{qd} V_{qs}^*$. We have used the latest experimental values, $\mathscr{B}^{\text{exp}}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ and $x_D^{\text{exp}} = (9.1^{+2.5}_{-2.6}) \times 10^{-3}$. When calculating Δm_D, we follow Ref. [9], *i.e.* keep only the term $|V_{ub'}^* V_{cb'}|^2 S_0(x_{b'})$ and equate it with x_D^{exp}, but enlarge by a factor of 3 (to allow for long distance effects). From Eqs. (1.2)-(1.4), $V_{t'b}$, $V_{t's}$, $V_{t'd}$ are proportional to s_{34}, s_{24}, s_{14}, respectively, and $|V_{cb'}| \simeq |V_{t's}|$ if s_{24} dominates. But, $V_{ub'} \propto s_{14}$ is less likely. So, for *fixed* $V_{t's}^* V_{t'b}$, as $|V_{t'b}| \simeq s_{34}$ is lowered, $|V_{t's}| \simeq s_{24}$ would grow. To satisfy the constraint of Eq. (2.2), one would have to reduce $|V_{t'd}| \simeq s_{14}$. But then, from Eq. (1.3), $|V_{ub'}|$ would likely rise and cause tension with Eq. (2.3). We see that when $|V_{t'b}|$ is lowered to 0.12 (0.06) for $m_{t'} = 300$ (500) GeV, the allowed regions from $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and Δm_D do not intersect anymore, as shown in Fig. 2(L). We conclude

$$|V_{t'b}| \geq 0.12\ (0.06), \quad m_{t'},\ m_{b'},\ V_{t's}^* V_{t'b} = 300,\ 280\ (500,\ 480),\ 0.015\, e^{i81°}\ (0.006\, e^{i75°}), \tag{2.4}$$

where masses are in GeV. In the above analysis, we have used $-V_{t'b} = 0.18$ (0.10) and $-V_{t's} = 0.083\, e^{-i81°}$ $(0.060\, e^{-i75°})$ for $m_{t'} = 300$ (500) GeV for illustration. Electroweak precision tests disfavor $V_{t'b}$ values near the upper bound.

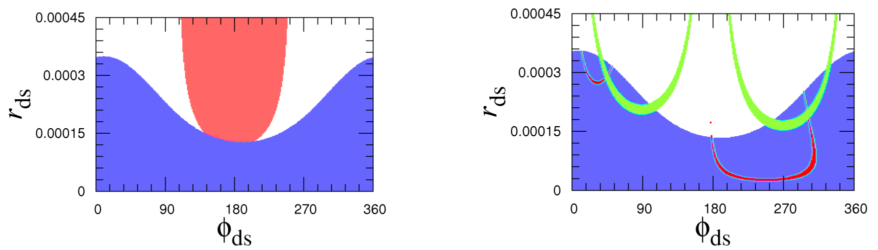

Fig. 2: (L) $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ (blue), D–$\bar{D}$ mixing (red) vs. ϕ_{ds}, for $V_{t's} = -0.10\,e^{-i75^\circ}$ at $m_{t'} = 500$, $m_{b'} = 480$ GeV, $V_{t'b} = -0.06$, where the two regions barely touch; and (R) all $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ (blue) is allowed by Δm_D for $V_{t's} = -0.060\,e^{-i75^\circ}$, $V_{t'b} = -0.10$, with ε_K (red), $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ (green) overlayed.

In the previous work, we have tried to utilize ε'/ε as a constraint. But as we allow $m_{t'}$ to vary, it becomes clear that huge hadronic uncertainties preclude the utility of ε'/ε in providing a constraint. Instead, let us illustrate the potential impact of a future measurement of $K_L \to \pi^0 \nu\bar{\nu}$. The SM predicts $\mathscr{B}^{\rm SM}(K_L \to \pi^0 \nu\bar{\nu}) = (2.8 \pm 0.4) \times 10^{-11}$. The latest limit of $\mathscr{B}^{\rm exp}(K_L \to \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8}$ is from E391a. The E14 experiment proposes to conduct a three-year physics run beginning in 2011, to reach of order 10 events if SM holds. Suppose 100-250 events are observed, it would imply $\mathscr{B}^{\rm exp}(K_L \to \pi^0 \nu\bar{\nu}) = (1.00 \pm 0.14) \times 10^{-9}$. If one combines this with $\varepsilon_K^{\rm exp} = (2.229 \pm 0.012) \times 10^{-3}$, one could then find two possible solutions of $V_{t'd}$, as illustrated in Fig. 2(R).

3. Conclusion

For $f_{B_s} \hat{B}_{B_s}^{1/2} = 266$ MeV case, the central value of $\sin 2\Phi_{B_s} \sim -0.35$ is less sensitive to $m_{t'}$ than the 295 MeV case. However, for the 295 MeV case, $\sin 2\Phi_{B_s} \simeq -0.60$ is rather large for $m_{t'} = 300$ GeV. An upper bound of $|V_{t'b}|$ arises from R_b, while a lower bound comes from combining $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and $D - \bar{D}$ mixing. $V_{t'd}$ can be determined cleanly from the future measurement of $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ by combining with ε_K, and can be further crosschecked with a precise measurement of $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$.

Acknowledgement. This work is supported in part by grants from the NSC.

References

[1] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

[2] W.S. Hou, M. Nagashima, A. Soddu, Phys. Rev. Lett. **95**, 141601 (2005); Phys. Rev. D **72**, 115007 (2005).

[3] W.S. Hou, M. Nagashima, A. Soddu, Phys. Rev. D **76**, 016004 (2007).

[4] W.S. Hou, A. Soni and H. Steger, Phys. Lett. B **192**, 441 (1987).

[5] A. Arhrib and W.S. Hou, Eur. Phys. J. C **27**, 555 (2003).

[6] E. Gamiz *et al.* [HPQCD Collaboration], Phys. Rev. D **80**, 014503 (2009).

[7] T. Yanir, JHEP06 (2002) 044.

[8] A.J. Buras, F. Schwab and S. Uhlig, Rev. Mod. Phys. **80** 965 (2008).

[9] M. Bobrowski, A. Lenz, J. Riedl and J. Rohrwild, Phys. Rev. D **79**, 113006 (2009).