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Measuring 4th Generation CKM Parameters at the LHC

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With search for 4th generation t' and b' quarks continuing at the LHC, we note that the measurements of CPV phase in $B_s \to J/\psi\phi$ and the $B_s \to \mu^+\mu^-$ rate would provide a measurement of $V_{t's}^* V_{t'b}$. The third measurement of $A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$ would provide further information. Summer 2011 data reveal that t' and b' quark mass bounds are already rather close to the unitarity bound, while all B physics results (except A_{SL} of D0) are now consistent with the 3 generation Standard Model. The implications of these results are presented, in particular giving an illustrative $b \to s$ quadrangle that may be relevant for the Baryon Asymmetry of the Universe. With $|V_{t's}^* V_{t'b}|$ likely smaller than indicated by past data, we point out that a measurement of $\mathscr{B}(t' \to b'W^*)$ (or $\mathscr{B}(b' \to t'W^*)$) could be an excellent probe of rather small $V_{t'b}$ (or $V_{tb'}$).

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1. Introduction

CMS has put forth stringent mass bounds of $m_{t'} > 450$ GeV [1] and $m_{b'} > 495$ GeV at 90% C.L. [2]. We show that, concurrent with direct t' and b' search, measurement of CPV phase $\sin 2\Phi_{B_s} \equiv \sin\phi_s$ in $B_s \to J/\psi\phi$, as well as the $B_s \to \mu^+\mu^-$ rate, could give us $V^*_{t's}V_{t'b}$ that could touch [3] upon the baryon asymmetry of the Universe (BAU).

2. Measuring $V^*_{t's}V_{t'b}$ via $\sin 2\Phi_{B_s}$ and $\mathscr{B}(B_s \to \mu^+\mu^-)$

The B_s mixing amplitude $M^s_{12} = \frac{G_F^2 M_W^2}{12\pi^2} m_{B_s} f^2_{B_s} \hat{B}_{B_s} \eta_B\, \Delta^s_{12}$ is modified by the presence of t', i.e.

$$\Delta^s_{12} = \left(\lambda_t^{\rm SM}\right)^2 S_0(t,t) + 2\lambda_t^{\rm SM}\lambda_{t'}\Delta S_0^{(1)} + \lambda_{t'}^2 \Delta S_0^{(2)}, \tag{2.1}$$

where $\lambda_q \equiv V^*_{qs}V_{qb}$, and $\Delta S_0^{(i)}$ [4] are GIM-subtracted t' effects. Unlike $\Delta m_{B_s} \equiv 2|M^s_{12}|$, the CPV phase $2\Phi_{B_s} = \arg \Delta^s_{12}$ is purely short distance. Normalizing [5] the $B_s \to \mu^+\mu^-$ rate by Δm_{B_s},

$$\mathscr{B}(B_s \to \bar{\mu}\mu) = \frac{3g_W^4 m_\mu^2}{2^7\pi^3 M_W^2}\,\frac{\tau_{B_s}\eta_Y^2}{\hat{B}_{B_s}\eta_B}\,\frac{|\lambda_t^{\rm SM} Y_0(x_t) + \lambda_{t'}\Delta Y_0|^2}{|\Delta^s_{12}|/\Delta m_{B_s}|^{\rm exp}}, \tag{2.2}$$

where ΔY_0 is similar to ΔS_0, the f_{B_s} dependence is removed, making it another useful measurable.

The summer 2011 result for $\sin\phi_s$ by LHCb did not support the indication, since 2008, of a large and negative value. But -0.3 is still allowed at $\sim 2\sigma$. Thus, we take two possible values

$$\sin 2\Phi_{B_s} = -0.3 \pm 0.1;\ -0.04 \pm 0.1 \quad ({\rm LHCb} > 1\ {\rm fb}^{-1}). \tag{2.3}$$

The combined $B_s \to \mu^+\mu^-$ rate of LHCb and CMS is now only 3.4 times SM value, hence we take

$$10^9\,\mathscr{B}(B_s \to \mu^+\mu^-) = 5.0 \pm 1.5;\ 2.0 \pm 1.5 \quad (2012), \tag{2.4}$$

which are adjacent regions that intersect at the SM rate. The numbers and errors in Eqs. (2.3) and (2.4) anticipate possible developments in 2012. Together we have 4 cases: Case A when both high; Case B (C) for Eq. (2.3) SM-like, but Eq. (2.4) higher (lower) than SM; and Case D. In Fig. 1 we illustrate Case A in the $\phi_{sb} \equiv \arg V^*_{t's}V_{t'b}$, $r_{sb} \equiv |V^*_{t's}V_{t'b}|$ plane for $m_{t'} = 550$ GeV, with the overlap of contours marked as A, and likewise for Cases B and C. We see that these cases cover a good part of the region for $|V^*_{t's}V_{t'b}| \lesssim 0.01$, with Case D in fact a sliver that is complement to Case A.

3. Utility of $A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$; and Measuring $|V_{t'b}|$ by Threshold Effect

Contrary to earlier indications, LHCb again found $A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$ consistent with SM. In left plot of Fig. 2, Cases A–C are compared with contours of zero crossing point $s_0 \equiv q^2|_{A_{\rm FB}=0}$ (insensitive to form factors), where $s_0^{\rm SM} \simeq 4.4$ GeV^2. For the four sample points, marked as small ellipses from high to low r_{sb}, the differential $A_{\rm FB}$ curves are given in center plot of Fig. 2 from top to bottom. The black solid curve is for SM. We see that the upper two curves or sample points are ruled out by LHCb data, implying that $|V^*_{t's}V_{t'b}| \lesssim 0.008$ for $m_{t'} = 550$ GeV. Note that for higher $m_{t'}$ values, the formulas we use may no longer apply, as t', b' Yukawa couplings turn nonperturbative.

Since $V_{t'b}$ could now be rather small, we mention that a measurement of $\mathscr{B}(b' \to t'W^*)$ could probe very tiny $V_{tb'}$ values. This is because $b' \to t'W^*$ is phase space suppressed (as electroweak precision tests imply proximity of $|m_{t'} - m_{b'}| \lesssim M_W$), while $b' \to tW$ is suppressed by $|V_{tb'}|^2$. This effect is illustrated in the right plot of Fig. 2, where the threshold is when the W^* turns on-shell.

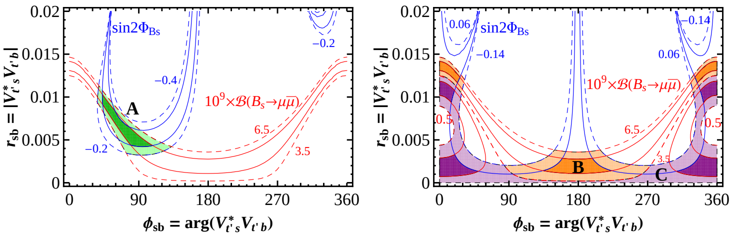

Figure 1: Overlap region for Cases A–C corresponding to Eqs. (2.3) and (2.4) as described in text.

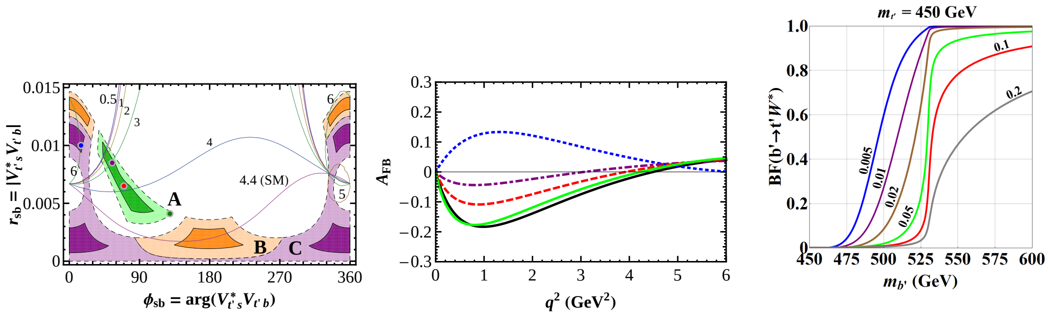

Figure 2: Left: $s_0 \equiv q^2|_{A_{\rm FB}=0}$ contours overlayed with Cases A–C; Center: $dA_{\rm FB}/dq^2$ vs q^2, where curves in descending order are for sample points (small ellipses) from high to low r_{sb} in left plot, plus SM (black solid curve); Right: Probing very small $|V_{tb'}|$ via $\mathcal{B}(b' \to t'W^*)$, i.e. transition between 4th generation quarks.

4. Conclusion: Towards $b \to s$ Quadrangle

To illustrate the implications of our proposed program, we plot $V^*_{t's}V_{t'b} \simeq 0.0065\, e^{i70^\circ}$ in Fig. 3. This corresponds to both $\sin 2\Phi_{B_s}$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ on the large side allowed by current data. Note that $V^*_{us}V_{ub}$ and $V^*_{cs}V_{cb}$ are measured by tree processes, and we assume CKM4 unitarity.

In conclusion, along with direct search of t' and b' quarks, the LHC could measure 4th generation CKM parameters in the near future, which could bear the matter asymmetry of the Universe.

References

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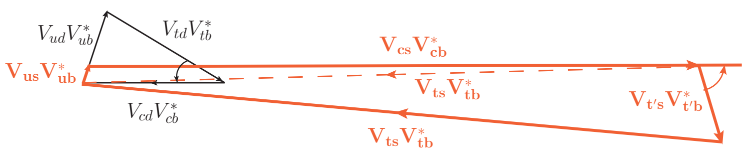

Figure 3: An illustrative $b \to s$ quadrangle of SM4, together with $b \to d$ and $b \to s$ triangles of SM3. .