Enhanced $B^0_d \rightarrow \mu^+ \mu^-$ Decay: What if?

Masaya Kohda (National Taiwan Univ.)

Based on:

- Possibility of enhanced $B(B_d \rightarrow \mu^+ \mu^-)$ by 4th Generation $t'$
  
  target: $> (3-4) \times B_{SM}$ \hspace{1cm} $B_{SM} \sim 10^{-10}$

- If observed with current (2011-2012) LHC data, uplift 4G

  may cast doubt on the SM Higgs interpretation of the 126 GeV boson

EPS HEP 2013 @ Stockholm, July 19, 2013
Introduction

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PRL 110, 021801 (2013)
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  \[
  B(B_d \rightarrow \mu^+ \mu^-) < 8.1 \times 10^{-10}
  \]
  
  [Combined LHC before Summer ’12]

  \[\text{PRL 110, 021801 (2013)}\]

- $B_d \rightarrow \mu^+ \mu^-$: Still much room for enhancement and may be the last chance for New Physics at the LHC in flavor sector before 13 TeV run

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- If observed beyond $(3-4) \times B(B_d \rightarrow \mu^+ \mu^-)_{SM}$, 4G is a likely explanation
Conventional wisdom against 4G

David Straub, Rencontres de Moriond EW, La Thuile (2012)

The 125 GeV Higgs observations kills off 4th generation models as the production cross-section would be 9x larger & decays to $\gamma\gamma$ suppressed

ICHEP, Melbourne, July 9, 2012
Remarks:

- The 125 GeV boson may not be the Higgs boson, e.g., a dilaton
  - heavy 4G may accommodate scale invariance, which is broken by condensations of 4G fermions
    - P.Q. Hung and C. Xiong, ’10
    - Y. Mimura, W.-S. Hou, and H. Kohyama, ’12
- The SM Higgs does not mainly enter $B_d \rightarrow \mu^+ \mu^-$
- Given these situations, it is important to keep an open mind
Other motivation: tension for $\sin(2\beta/\phi_1)$

Lunghi and Soni, PLB666(2008), Buras and Guadagnoli, PRD78(2008)

- Tension for $\sin(2\beta/\phi_1)$: direct measurement vs. indirect determination

**Direct** \( \sin(2\beta/\phi_1) = 0.679 \pm 0.020 \) [world ave. by HFAG, winter 2012]

**Indirect**

\[
\frac{\beta}{\phi_1} = \arg[V_{td}^* V_{tb}]^{\text{SM}} = \arg \lambda_t^{\text{SM}}
\]

\[
\lambda_t^{\text{SM}} = -\lambda_u - \lambda_c \simeq -|V_{ud}| |V_{ub}| e^{-i\phi_3} + |V_{cd}| |V_{cb}|
\]

\[ \lambda_i \equiv V_{id}^* V_{ib} \]

all measurable via tree-processes

(Here we do not use global fit)
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$\phi_3 = \gamma = (68^{+10}_{-11})^\circ$ [PDG ’12] being measured at LHC
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$$\phi_3 = \gamma = (68^{+10}_{-11})^\circ \quad [\text{PDG '12}]$$

being measured at LHC

$$|V_{ub}|^{\text{incl.}} = 4.41 \times 10^{-3}$$

$$|V_{ub}|^{\text{excl.}} = 3.23 \times 10^{-3}$$

$$|V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3} \quad [\text{PDG '12}]$$
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\[ \phi_3 = \gamma = (68^{+10}_{-11})^\circ \] \textbf{[PDG '12]}

all measurable via tree-processes
(here we do not use global fit)

\[ \sin 2\beta/\phi_1 = \begin{cases} 
0.81 & |V_{ub}|^{\text{incl.}} = 4.41 \times 10^{-3} \\
0.63 & |V_{ub}|^{\text{excl.}} = 3.23 \times 10^{-3} \\
0.76 & |V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3} \end{cases} \] \textbf{[PDG ’12]}

all three deviates more than 2\sigma from direct measurement
Flavor observables and constraints

- $\text{B}(B_d \rightarrow \mu^+ \mu^-)$
- $\sin(2\beta/\phi_1)$
- $\Delta m_{B_d}$
- $\text{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)$
- $B(B^+ \rightarrow \mu^+ \mu^-)$
- $\text{b} \rightarrow \text{d} \gamma$  
  \[ \lambda_{t'} \equiv V_{t'd}^* V_{t'b} = r_{db} e^{i\phi_{db}} \]

Three parameters

$\text{C}_7$ is not sensitive to $t'$, so do not consider
\[ \Delta m_{B_d} \simeq \frac{G_F M_W^2}{6\pi^2} m_{B_d} f_{B_d}^2 \hat{B}_{B_d} \eta_B |\Delta_{12}^d| \]

- \( t' \) enters in box diagram:
  \[ \Delta_{12}^d = (\lambda_t^{SM})^2 S_0(x_t) + 2\lambda_t^{SM} \lambda_{t'} \Delta S_0^{(1)} + \lambda_{t'}^2 \Delta S_0^{(2)} \]

- Main uncertainty comes from hadronic parameter:
  \[ f_{B_d} \hat{B}_{B_d}^{1/2} = (227 \pm 19)\text{MeV} \quad \text{Laiho et al. (Lattice Averages), End of 2011} \]

\[ \sin 2\Phi_{B_d} \simeq \sin(\text{arg } \Delta_{12}^d) \]

\[ M_{12}^d \equiv |M_{12}|e^{2i\Phi_{B_d}} \]

- Theoretically clean and well-measured: \( \sin(2\beta/\phi_1) = 0.679 \pm 0.020 \)
\[ \mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8} \quad [\text{LHCb, JHEP12(2012)}] \]

- Recently measured by LHCb (rarest B decay ever observed)

- Sensitive to t’ loop

- We calculate BR based on QCD factorization


\[ w/ \text{ NLO WC & LO decay amplitude} \]

\[ \text{take ratio with SM to reduce form factor uncertainty} \]

\[ R_{\pi \mu \mu} \equiv \frac{\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)|_{4G}}{\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)|_{\text{SM}}} \]

\* integrated over: \( q^2 = [1, 6] \text{ GeV}^2 \) \( \leftrightarrow \) different from LHCb

(to ensure large recoil of \( \pi \), and to avoid resonances)
\[ B^+ \rightarrow \pi^+ \mu^+ \mu^- \]

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  \[ \mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8} \]  
  [LHCb, JHEP12(2012)]

  - compatible SM (Naïve factorization)

- Sensitive to t’ loop

- We calculate BR based on QCD factorization
  

  w/ NLO WC & LO decay amplitude

  - take ratio with SM to reduce form factor uncertainty

  \[ R_{\pi\mu\mu} \equiv \frac{\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)|_{4G}}{\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)|_{SM}} < 2 \text{ or } 3 \]  

  (otherwise, LHCb would have found inconsistency with SM)

  * integrated over: \( q^2 = [1, 6] \text{ GeV}^2 \)  

  \( \leftarrow \) different from LHCb

  (to ensure large recoil of \( \pi \), and to avoid resonances)
$B_d \rightarrow \mu^+ \mu^-$

- Current best 95\% C.L. limit:

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 8.1 \times 10^{-10}$$

- Take ratio with $\Delta m_{B_d}$ to reduce hadronic uncertainty

$$\hat{\mathcal{B}}(B_d \rightarrow \mu^+ \mu^-) = \frac{\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)}{\Delta m_{B_d}} (\Delta m_{B_d})_{\text{exp}}$$

$$= C \frac{\tau_{B_d} (\Delta m_{B_d})_{\exp} \eta_Y^2}{\hat{B}_{B_d} \eta_B} \left| \lambda_t^{\text{SM}} Y_0(x_t) + \lambda_{t'} \Delta Y_0 \right|^2$$

- remaining hadronic uncertainty:

$$\hat{B}_{B_d} = 1.26 \pm 0.11$$

- $V_{ub}$ dependence also reduced:

- Reproduce SM result:

$$\hat{\mathcal{B}}(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = 1.1 \times 10^{-10}$$

$\alpha$, $\theta_W$, $m_\mu$, $M_W$
Phenomenological study with heavy $t'$
Allowed region for $\lambda_{t'} = V_{t'd}^* V_{t'b}$

$m_{t'} = 700$ GeV \hspace{1cm} |V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3}$

Allowed by $\sin(2\beta/\phi_1)$

$1(2)\sigma$: darker(lighter) green
Allowed region for $\lambda_{t'} = V_{t'd}^* V_{t'b}$

$m_{t'} = 700 \text{ GeV} \quad |V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3}$

Excluded by $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) < 8.1 \times 10^{-10}$

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Allowed by \( \Delta m_{B_d} \)

1(2)\(\sigma\): darker(lighter) pink
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$10^{10} \times \hat{\mathcal{B}}(B_d \to \mu^+ \mu^-)$
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$4 > x B_{\text{SM}}$

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$4 > x_{B_{\text{SM}}}$

in most part, within $2 \times \text{BSM}$

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$$m_{t'} = 700 \text{ GeV} \quad |V_{ub}|_{\text{ave.}} = 4.15 \times 10^{-3}$$

$$R_{\pi\mu\mu} > 3 \quad \text{ allowed by } \sin(2\beta/\phi_1)$$

1(2)$\sigma$: darker(lighter) green

Allowed by $\Delta m_{B_d}$

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$|V_{ub}|$ dependence

$m_{t'} = 700$ GeV

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● 4 x SM rate still possible
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- Representative points

$\lambda_{t'} = V_{t'd}^* V_{t'b} = 0.0025e^{i180^\circ}$

$\lambda_{t'} = V_{t'd}^* V_{t'b} = 0.0023e^{i230^\circ}$

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- Case with Vub(incl.) is similar to case of Vub(ave.)
**Larger $m_{t'}$ case**

\[ m_{t'} = 1000 \text{ GeV} \]

\[
|V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3}
\]

\[
|V_{ub}|^{\text{excl.}} = 3.23 \times 10^{-3}
\]

- Large $r_{db}$ region ($\phi_{db} \sim 180^\circ$) is not allowed for $V_{ub}(\text{ave.})$
- Preferred $r_{db}$ values drop
Discussion and Conclusion
Discussion

- $b \to d$ “quadrangle” for $m_{t'} = 700 \text{ GeV}$

$$
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$$

for $|V_{ub}|^{\text{ave.}} = 4.15 \times 10^{-3}$

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\lambda_{t'} = V_{t'd}^* V_{t'b} = 0.0023 e^{i 230^\circ}
$$

for $|V_{ub}|^{\text{excl.}} = 3.23 \times 10^{-3}$

- May link to the Baryon Asymmetry of the Universe (Hou, Chin. J. Phys. 47 (2009))

- Unusual CKM pattern

$$
|V_{t'd}^* V_{t'b}| \sim 0.002 - 0.003 \text{ with } |V_{t'b}| < 0.1
$$

(Hou, Ma PRD ’11)

- Heavier $t'$ is more natural in this sense
Conclusion

- $B(B_d \to \mu^+ \mu^-)$ may be the last chance to find New Physics in flavor sector at the LHC before 13-14 TeV run

- 4G t’ can enhance $B(B_d \to \mu^+ \mu^-)$ over $4 \times B_{SM}$, within parameter region suggested by $\sin(2\beta/\phi_1)$

- Chance of such enhancement is not large (since only corner of parameter space & unusual CKM hierarchy), but nonzero

- Within factor 2 of $B_{SM}$ is more likely to occur, but probably beyond current LHC data. In this case, continued experimental searches in 13-14 TeV run is quite important

- If observed by current data, impact is very huge: may cast doubt on the SM Higgs interpretation of the 126 GeV boson
Back Up Slides
Beyond Unitarity Bound

- We consider $m_{t'} = 700, 1000 \text{ GeV}$, which satisfy direct search limit
- Beyond perturbative unitarity limit $\sim 550 \text{ GeV}$
  
  Chanowitz, Furman and Hinchliffe (1978)

$$
\Delta_{12}^d = (\lambda_t^{\text{SM}})^2 S_0(x_t) + 2\lambda_t^{\text{SM}} \lambda_{t'} \Delta S_0^{(1)} + \lambda_{t'}^2 \Delta S_0^{(2)}
$$

- perturbation in $\lambda_{t'}$ still works and one expects structures do not change