Enhanced $B_d^0 \to \mu^+\mu^-$ Decay : What if?

Masaya Kohda (National Taiwan Univ.)

Based on:

Wei-Shu Hou, M.K. and Fanrong Xu, Phys. Rev. D 87, 094005 (2013)

- Possibility of enhanced $B(B_d \to \mu^+\mu^-)$ by 4th Generation t'

  target: > (3-4) x B_{SM} $B_{SM} \sim 10^{-10}$

- 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

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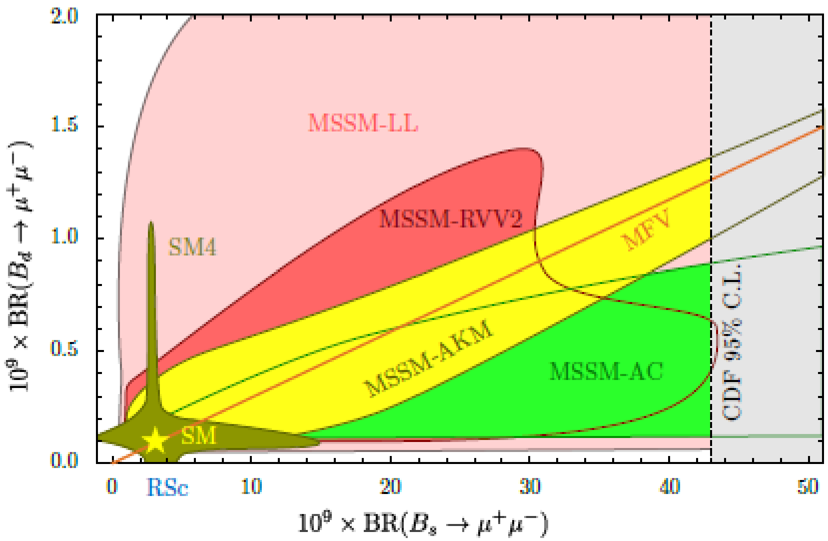
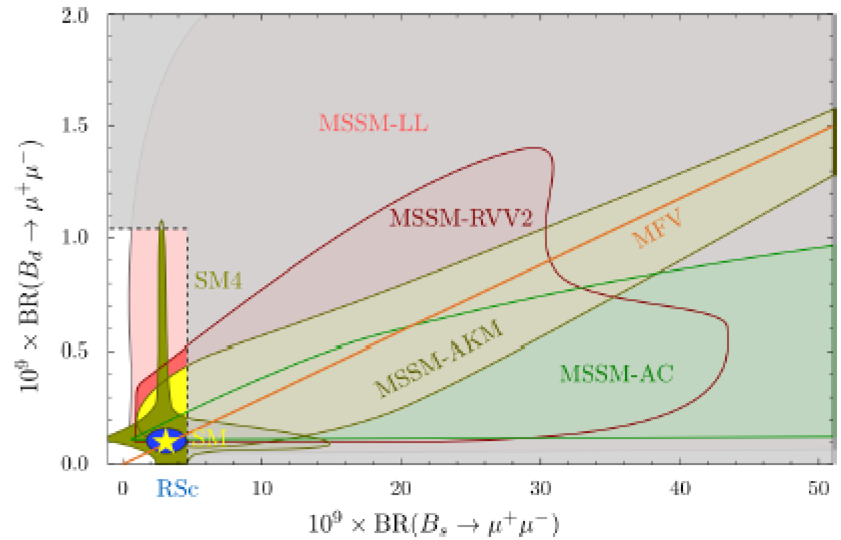


D. M. Straub, arXiv:1012.3893



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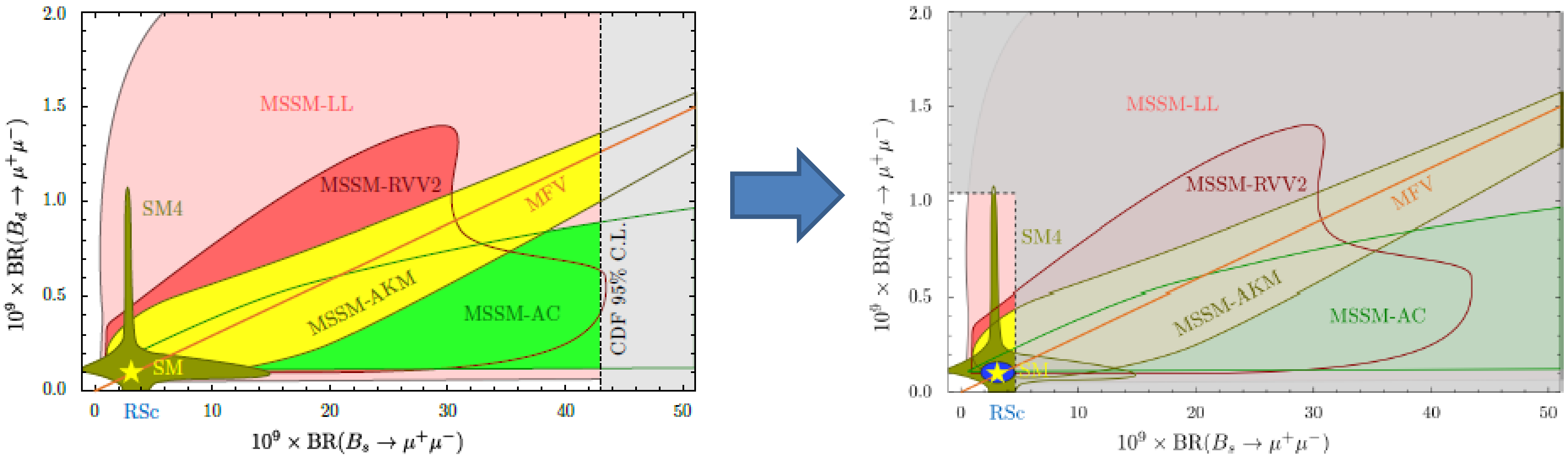

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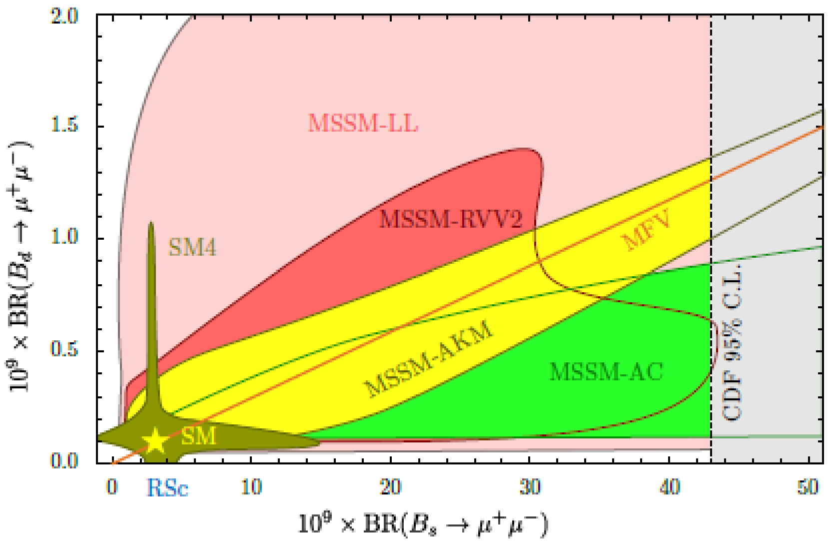

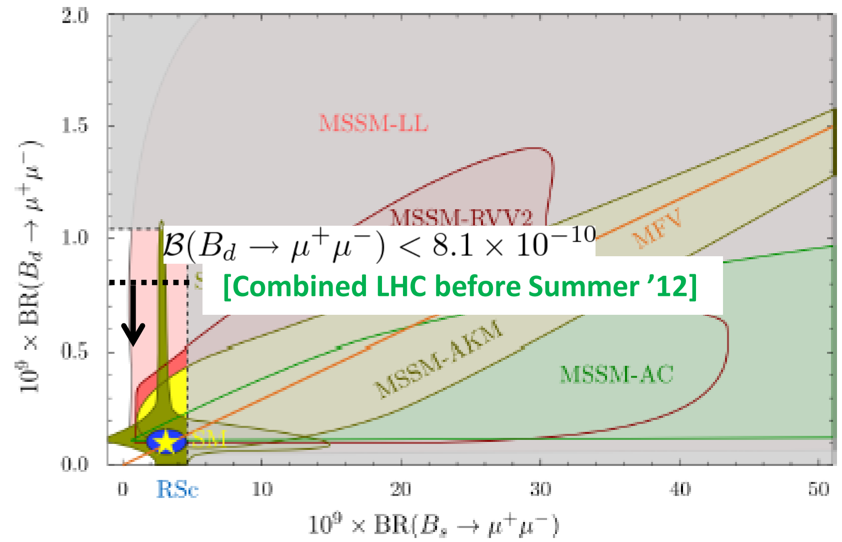

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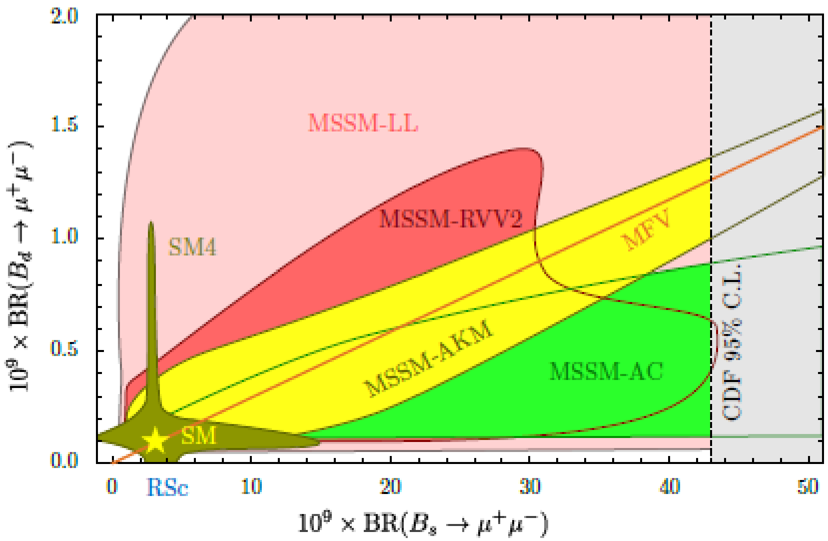

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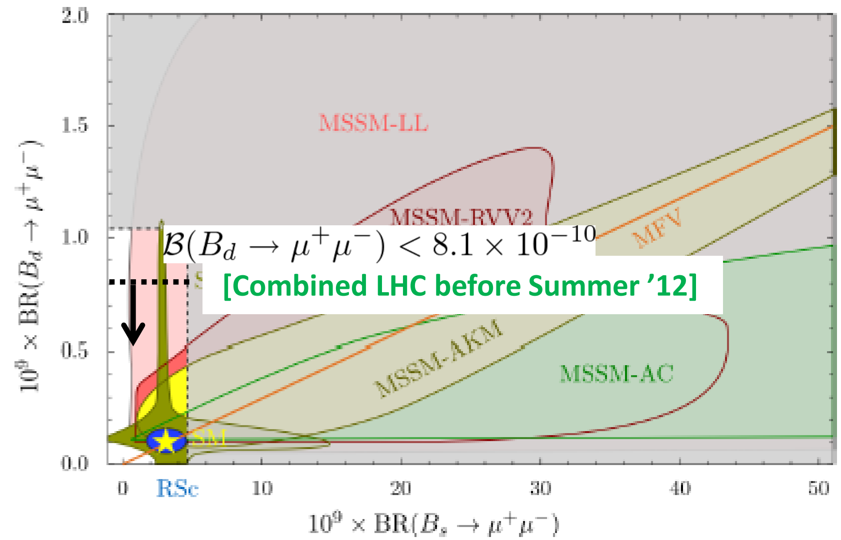

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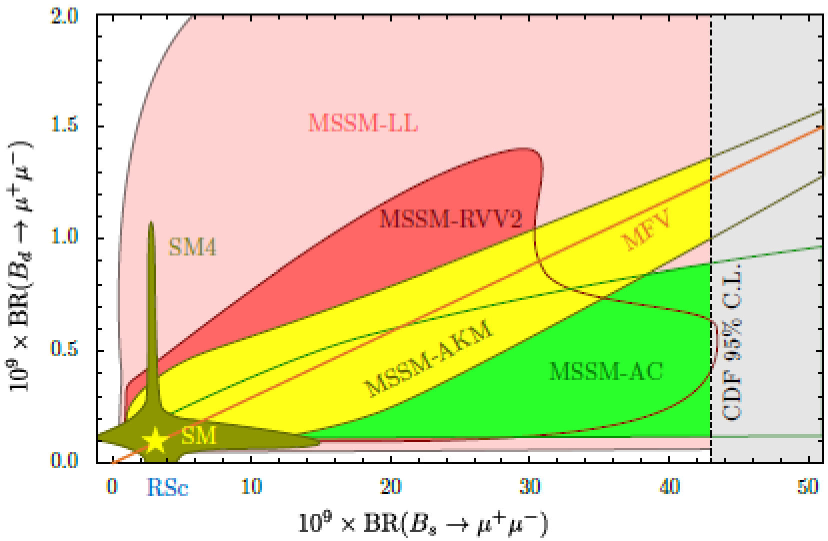

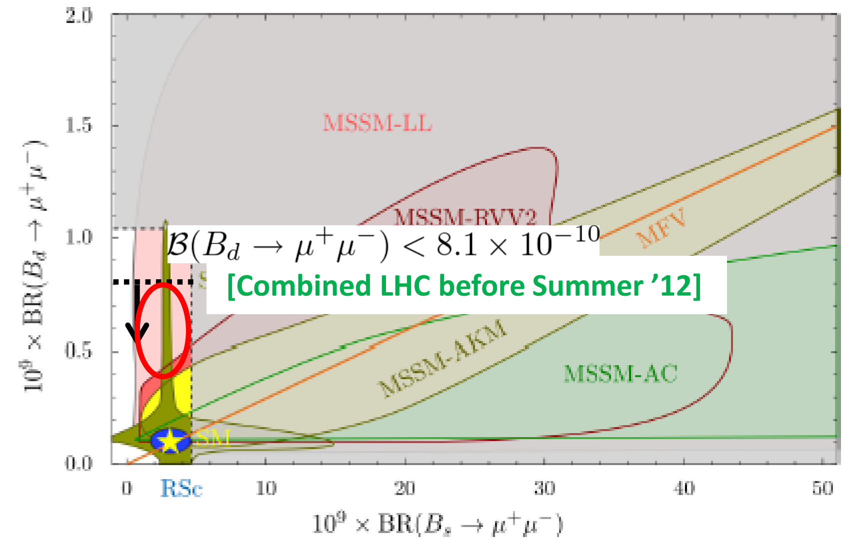

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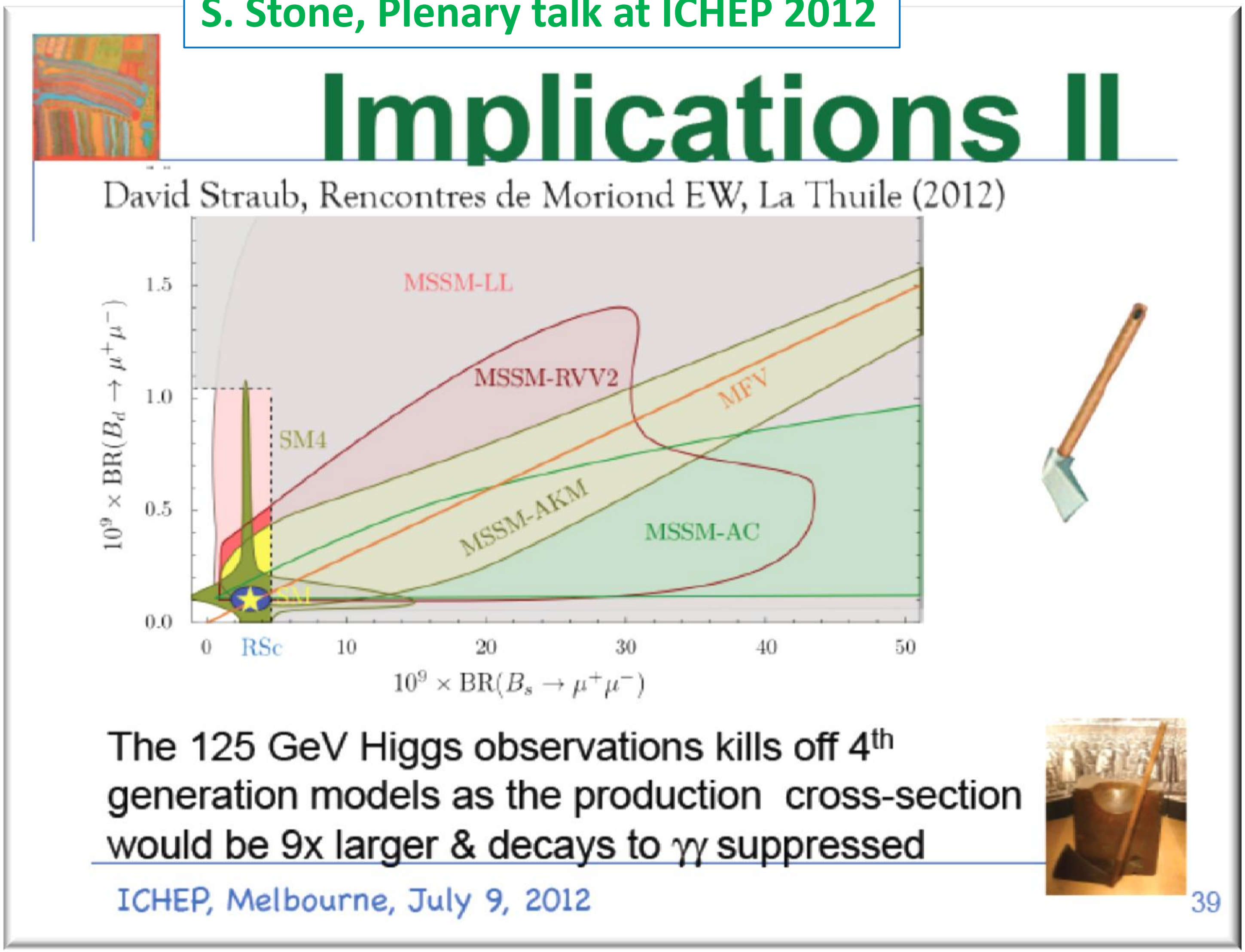
- $B_d \to \mu^+\mu^-$: Still much room for enhancement and may be the last chance for New Physics at the LHC in flavor sector before 13 TeV run
  - If observed beyond (3-4) x $B(B_d \to \mu^+\mu^-)_{SM}$, 4G is a likely explanation

Conventional wisdom against 4G

S. Stone, Plenary talk at ICHEP 2012



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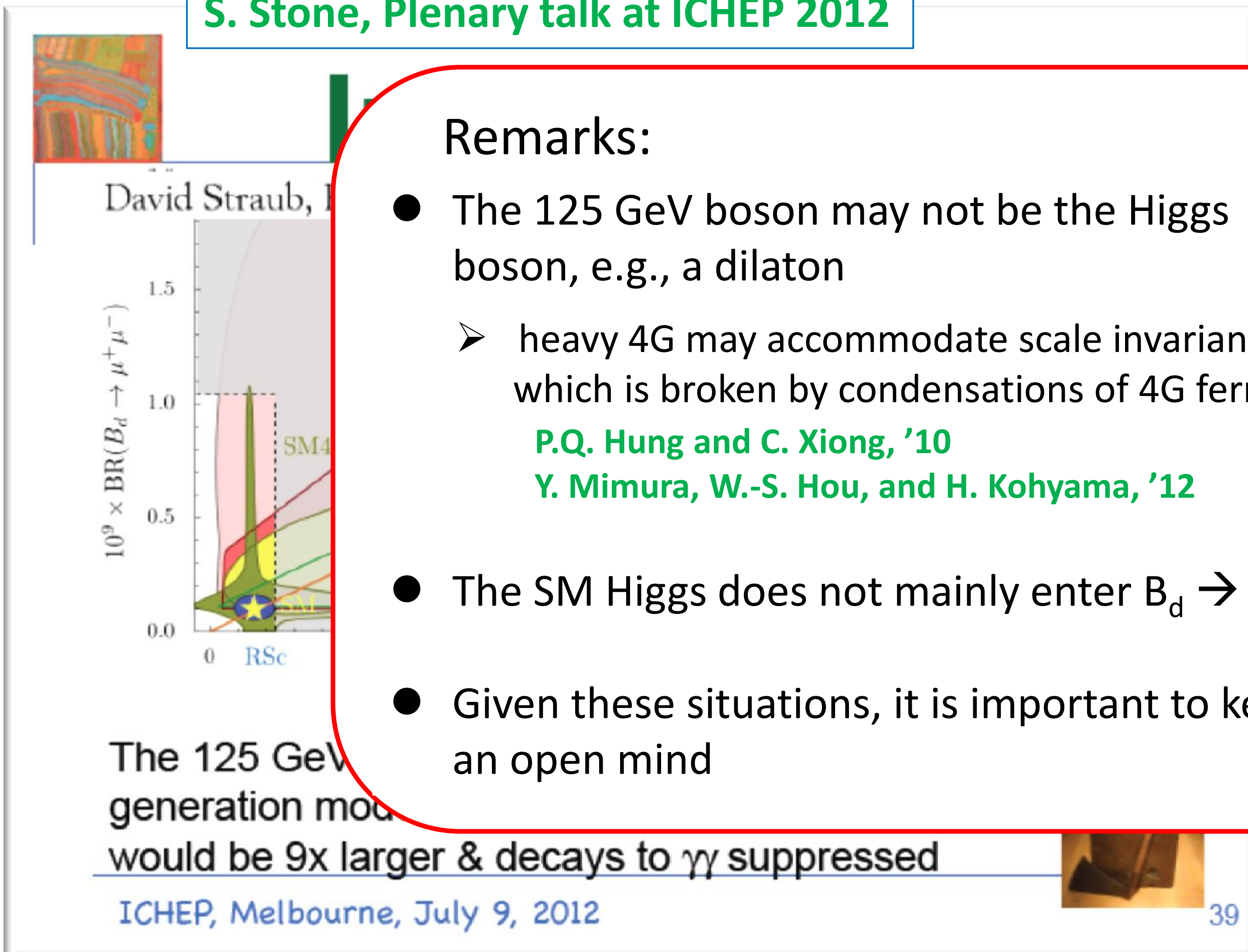

Remarks:

- 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 $B_d \to \mu^+\mu^-$
- 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 $\beta/\phi_1 = \arg[V_{td}^* V_{tb}]^{\rm SM} \equiv \arg \lambda_t^{\rm SM}$

$$\lambda_t^{\rm SM} = -\lambda_u - \lambda_c \simeq \underbrace{-|V_{ud}||V_{ub}|e^{-i\phi_3} + |V_{cd}||V_{cb}|}_{\text{all measurable via tree-processes}} \qquad \lambda_i \equiv V_{id}^* V_{ib}$$

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

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

$$|V_{ub}|^{\rm ave.} = 4.15 \times 10^{-3}$$ [PDG '12]

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$\phi_3 = \gamma = (68^{+10}_{-11})^\circ$ [PDG '12]
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$$\sin 2\beta/\phi_1 = \begin{cases} 0.81 \leftarrow |V_{ub}|^{\rm incl.} = 4.41 \times 10^{-3} \\ 0.63 \leftarrow |V_{ub}|^{\rm excl.} = 3.23 \times 10^{-3} \\ 0.76 \leftarrow |V_{ub}|^{\rm ave.} = 4.15 \times 10^{-3} \end{cases}$$

[PDG '12]

all three deviates more than 2σ from direct measurement

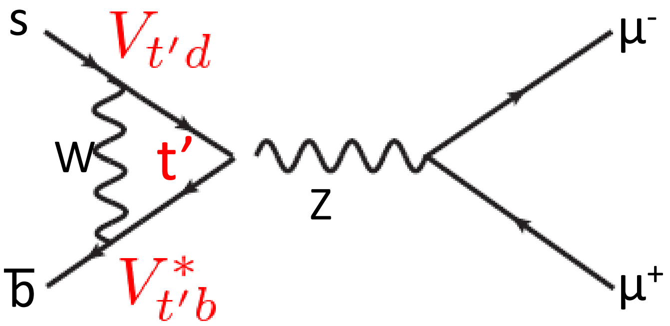
Flavor observables and constraints

- $B(B_d \to \mu^+ \mu^-)$
- $\sin(2\beta/\phi_1)$
- Δm_{B_d}
- $B(B^+ \to \pi^+ \mu^+ \mu^-)$
- $b \to d \gamma$ ← C_7 is not sensitive to t', so do not consider

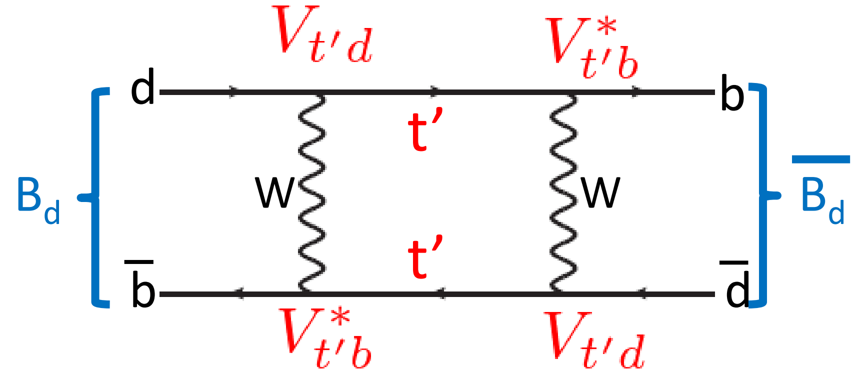
three parameters

$$\lambda_{t'} \equiv V^*_{t'd} V_{t'b} = r_{db}\, e^{i\phi_{db}}$$

$$m_{t'}$$



B_d-mixing



$$\Delta m_{B_d} \simeq \frac{G_F^2 M_W^2}{6\pi^2} m_{B_d} f_{B_d}^2 \hat{B}_{B_d} \eta_B |\Delta_{12}^d|$$

- t' enters in box diagram:

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

- Main uncertainty comes from hadronic parameter:

$$f_{B_d}\hat{B}_{B_d}^{1/2} = (227 \pm 19)\mathrm{MeV}$$

Laiho et al. (Lattice Averages), End of 2011

$$\sin 2\Phi_{B_d} \simeq \sin(\arg \Delta_{12}^d)$$

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

- Theoretically clean and well-measured: $\sin(2\beta/\phi_1) = 0.679 \pm 0.020$

$B^+ \rightarrow \pi^+ \mu^+ \mu^-$

For details in SM case, see poster by Fanrong Xu

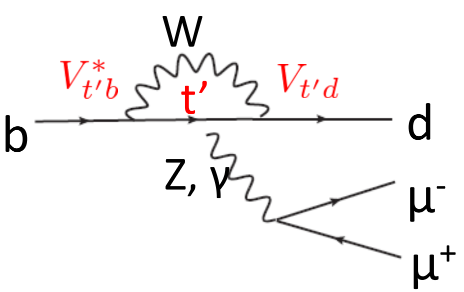
- Recently measured by LHCb (rarest B decay ever observed)

$$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$$

[LHCb, JHEP12(2012)]

  - ➢ compatible SM (Naïve factorization)

- Sensitive to t' loop



- We calculate BR based on QCD factorization
  [Beneke, Feldmann, Seidel, NPB612(2001); EPJC41(2005)]
  w/ NLO WC & LO decay amplitude
  - ➢ take ratio with SM to reduce form factor uncertainty

$$R_{\pi\mu\mu} \equiv \frac{\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)|_{4\mathrm{G}}}{\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)|_{\mathrm{SM}}}$$

* integrated over: $q^2 = [1, 6]\ \mathrm{GeV}^2$ ← different from LHCb
(to ensure large recoil of π, and to avoid resonances)

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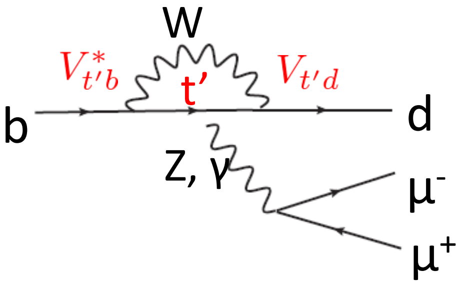

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Simply impose: < 2 or 3 (otherwise, LHCb would have found inconsistency with SM)

* integrated over: q^2 = [1, 6] GeV^2 ← different from LHCb

(to ensure large recoil of π, and to avoid resonances)

$B_d \rightarrow \mu^+ \mu^-$

- Current best 95% C.L. limit:

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

ATLAS + CMS + LHCb, LHCb-CONF-2012-017

- Take ratio with Δm_{B_d} to reduce hadronic uncertainty **Buras, PLB566(2003)**

$$\hat{\mathcal{B}}(B_d \to \mu^+\mu^-) = \frac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\Delta m_{B_d}}(\Delta m_{B_d})_{\rm exp}$$
$$= C\frac{\tau_{B_d}(\Delta m_{B_d})_{\rm exp}\eta_Y^2}{\hat{B}_{B_d}\eta_B}\frac{\left|\lambda_t^{\rm SM}Y_0(x_t) + \lambda_{t'}\Delta Y_0\right|^2}{|\Delta_{12}^d|}$$

$$C = 6\pi\left(\frac{\alpha}{4\pi\sin^2\theta_W}\right)^2\frac{m_\mu^2}{M_W^2}$$

  - remaining hadronic uncertainty:

    $\hat{B}_{B_d} = 1.26 \pm 0.11$ **Laiho et al. (Lattice Averages), End of 2011**

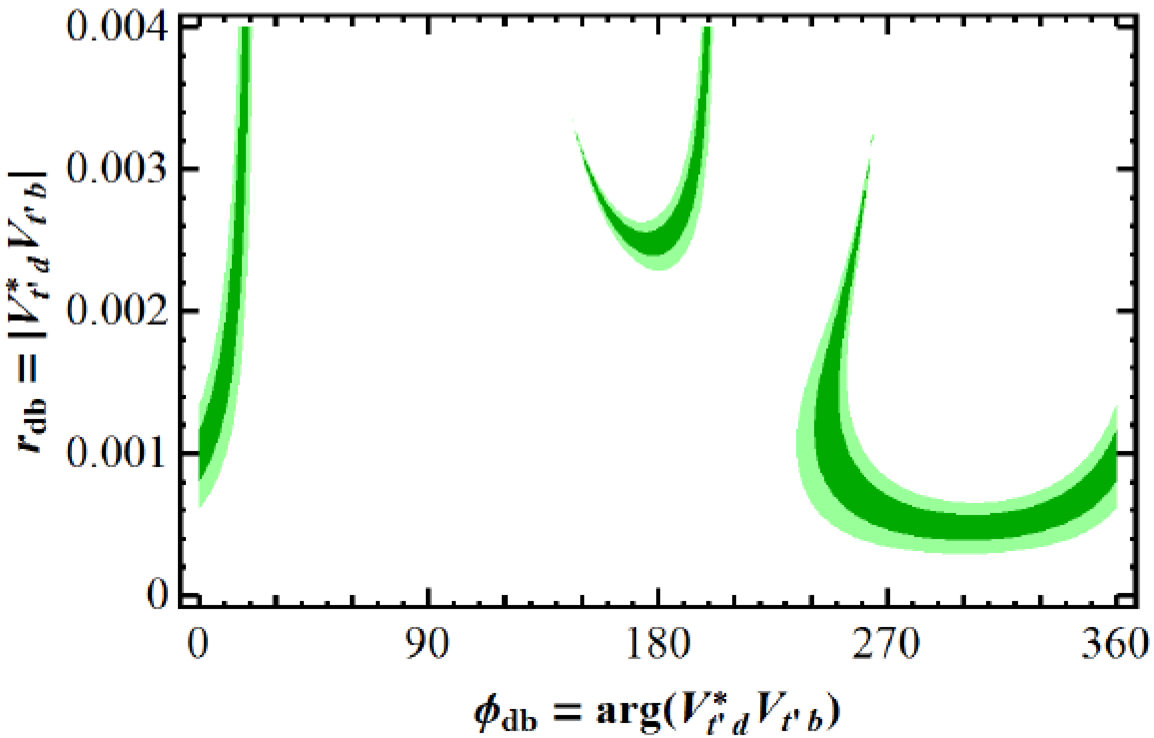
  - V_{ub} dependence also reduced:
  - Reproduce SM result:

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

Phenomenological study with heavy t’

Allowed region for $\lambda_{t'} = V_{t'd}^* V_{t'b}$

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



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

1(2)σ: darker(lighter) green

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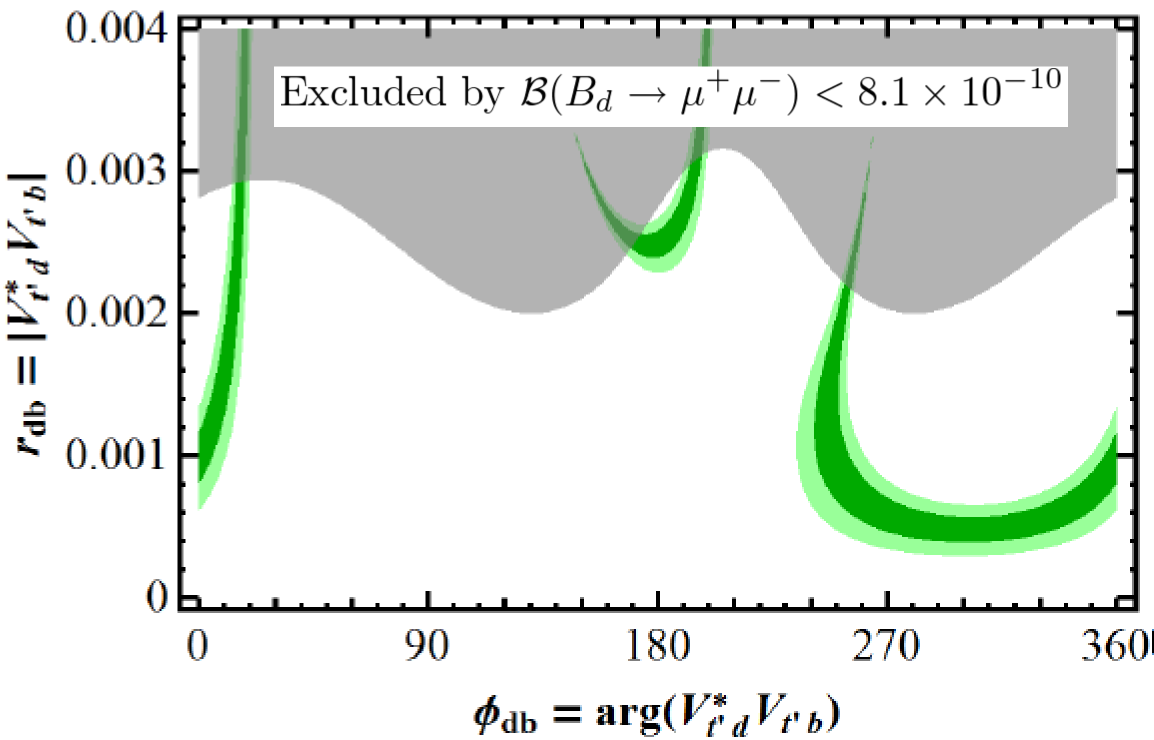

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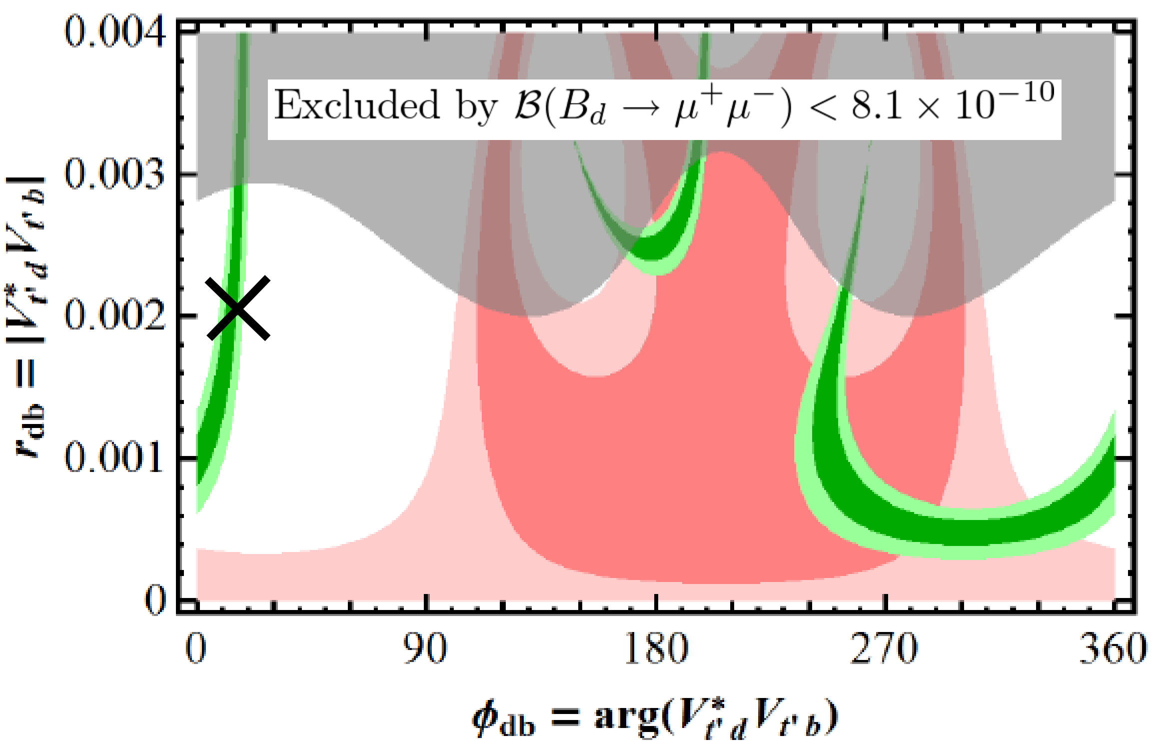

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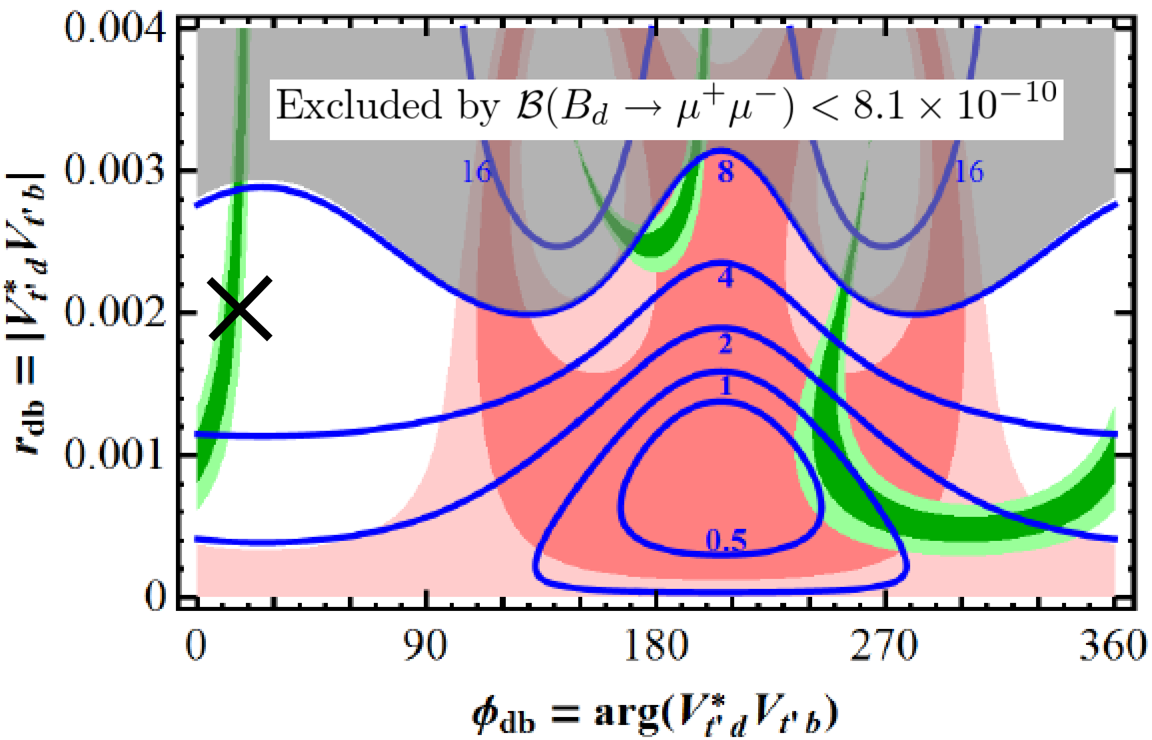

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$10^{10} \times \hat{\mathcal{B}}(B_d \to \mu^+\mu^-)$

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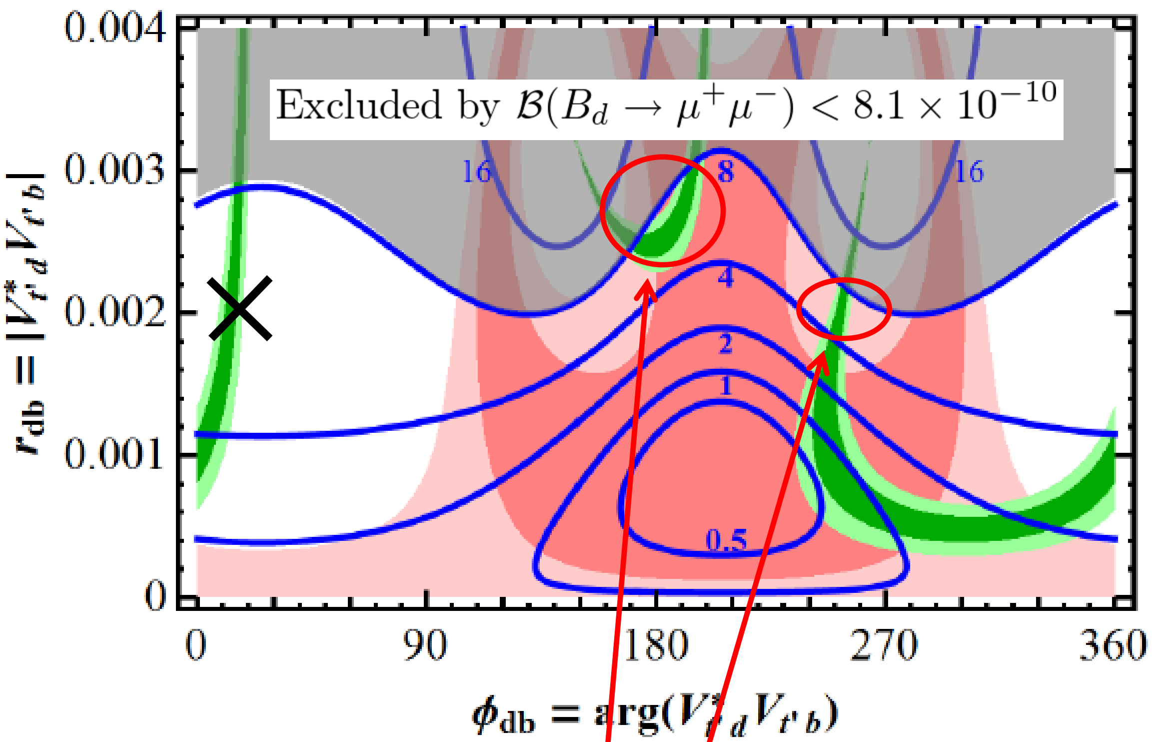

4 > x B_{SM}

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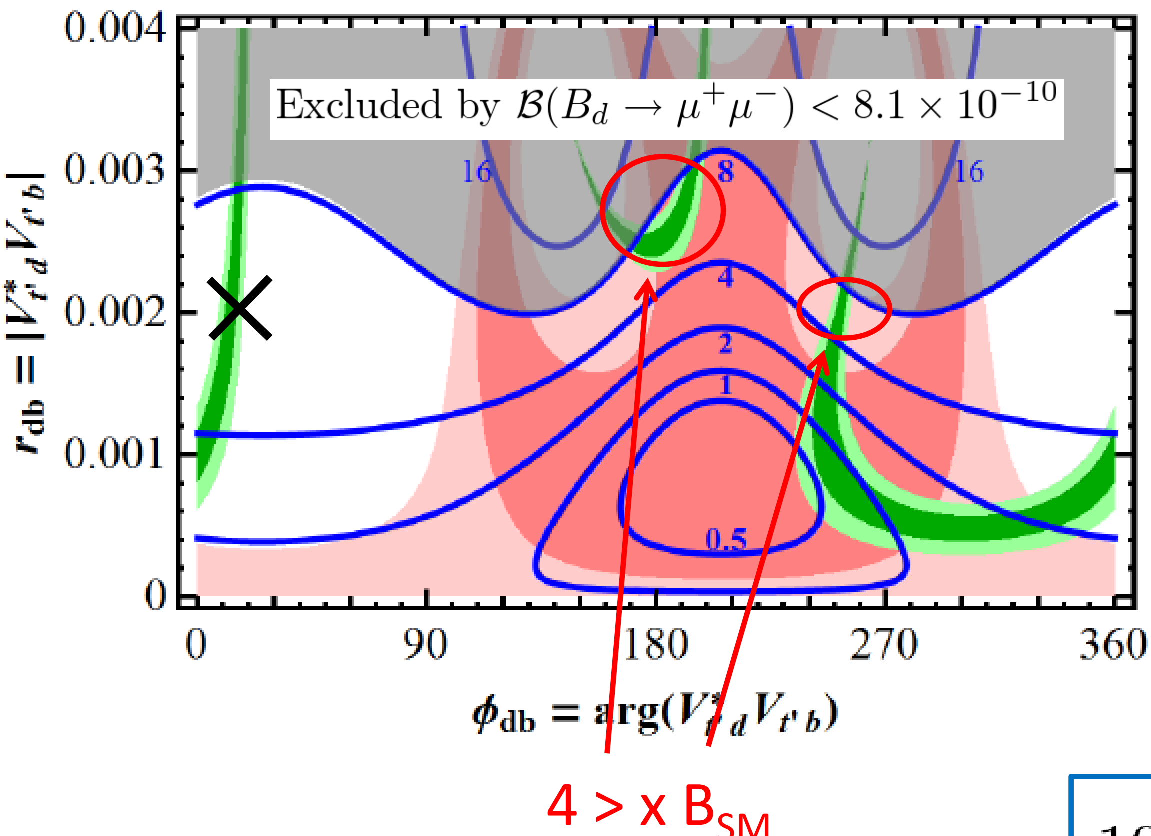

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in most part, within 2 x BSM

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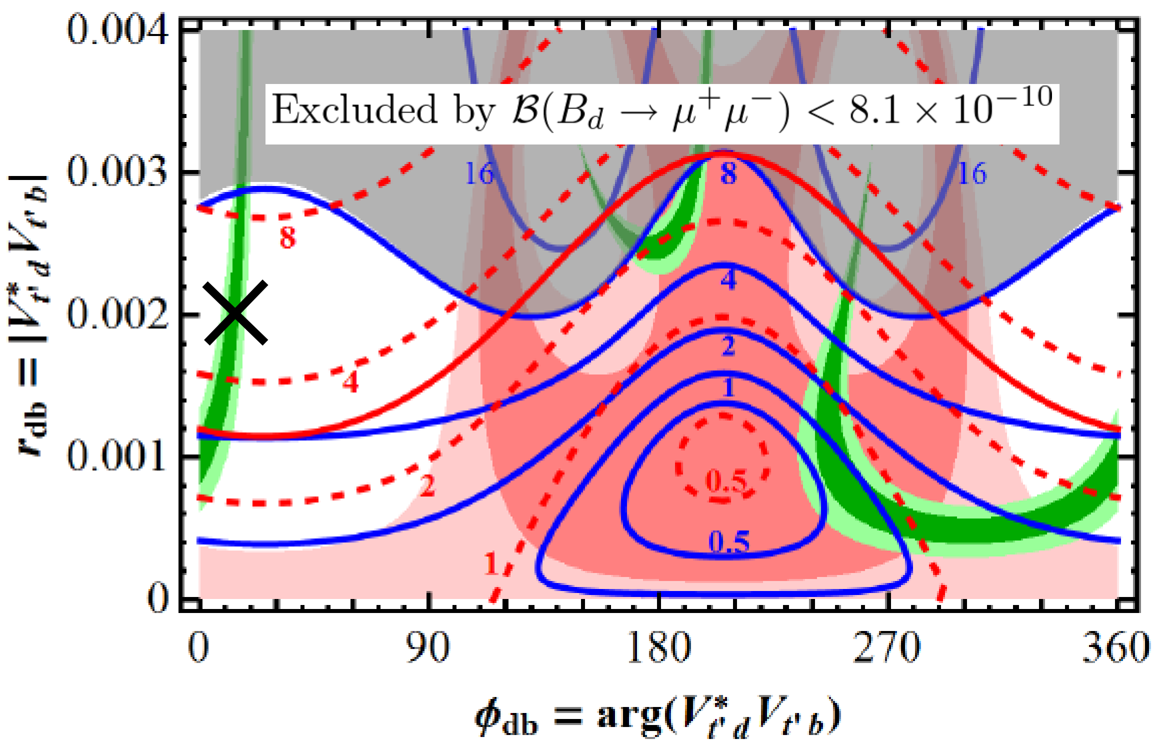

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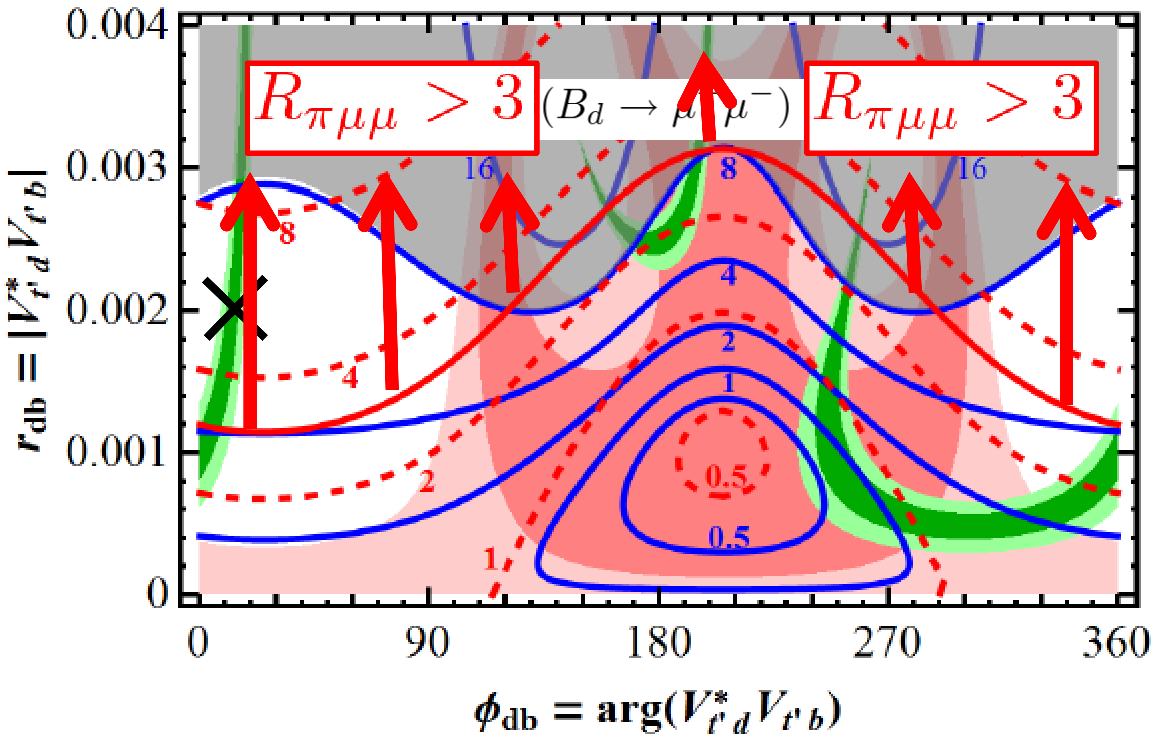

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$|V_{ub}|$ dependence

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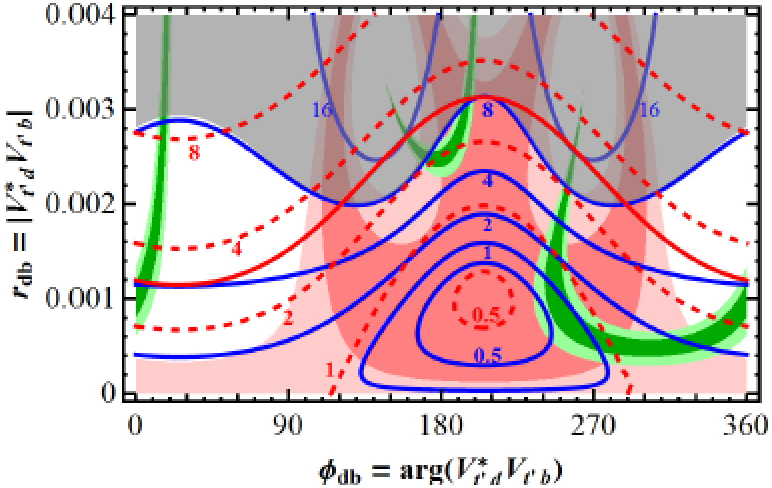

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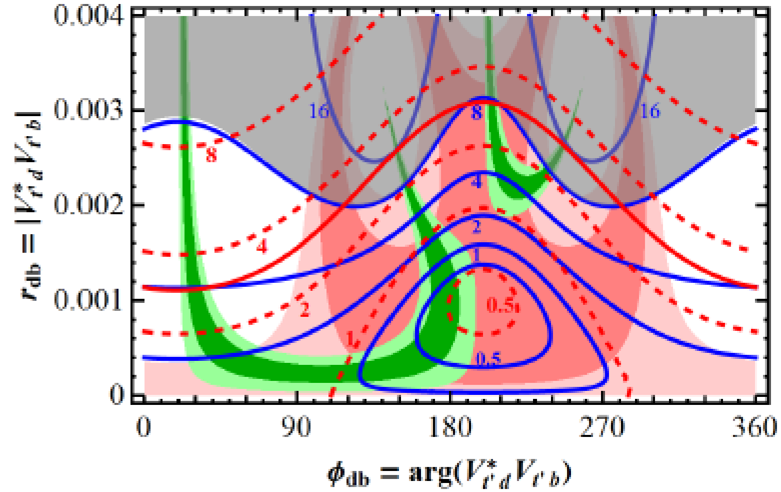

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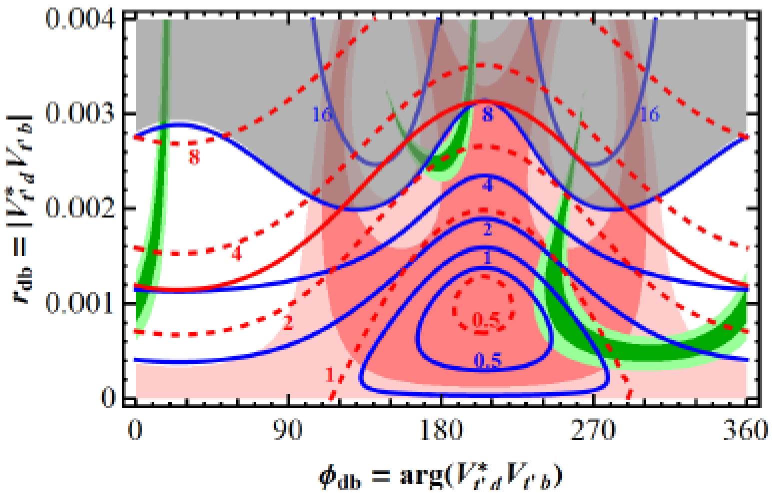

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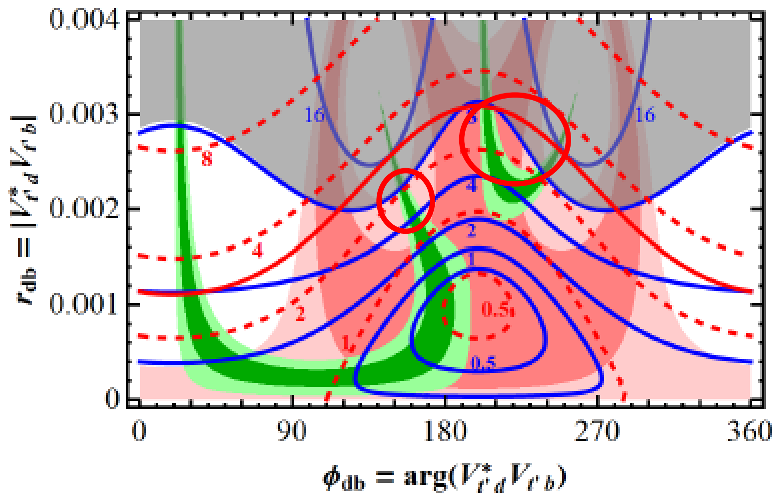

- 4 x SM rate still possible

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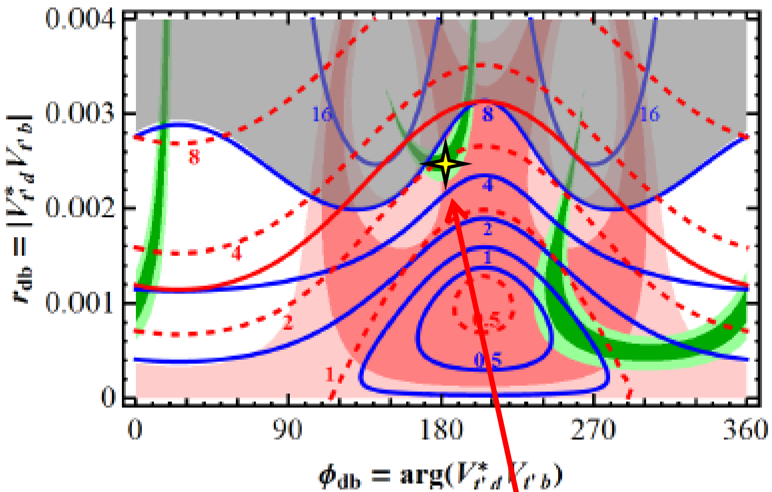

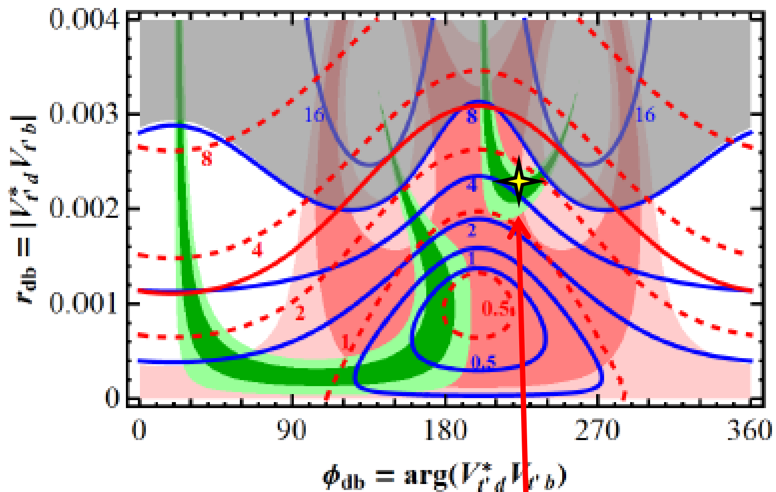

- Representative points

- 4 x SM rate still possible

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

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

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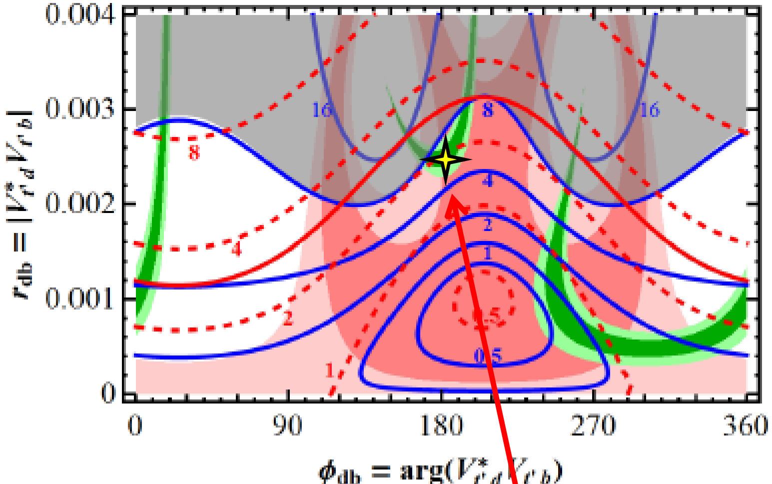
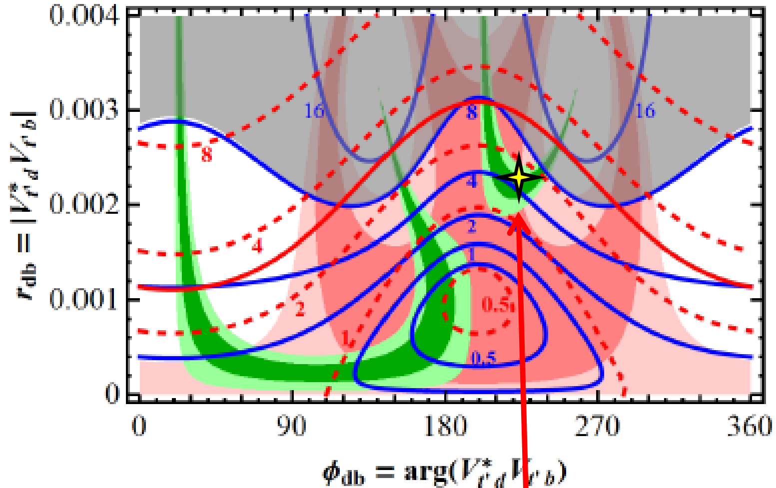
$$|V_{ub}|^{\mathrm{excl.}} = 3.23 \times 10^{-3}$$





- 4 x SM rate still possible

- Representative points

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

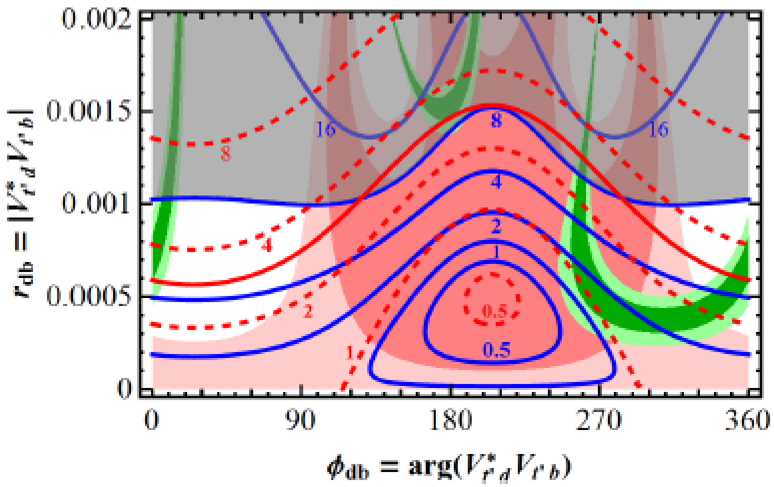
$$\lambda_{t'} = V^*_{t'd} V_{t'b} = 0.0023 e^{i230^\circ}$$

- Case with Vub(incl.) is similar to case of Vub(ave.)

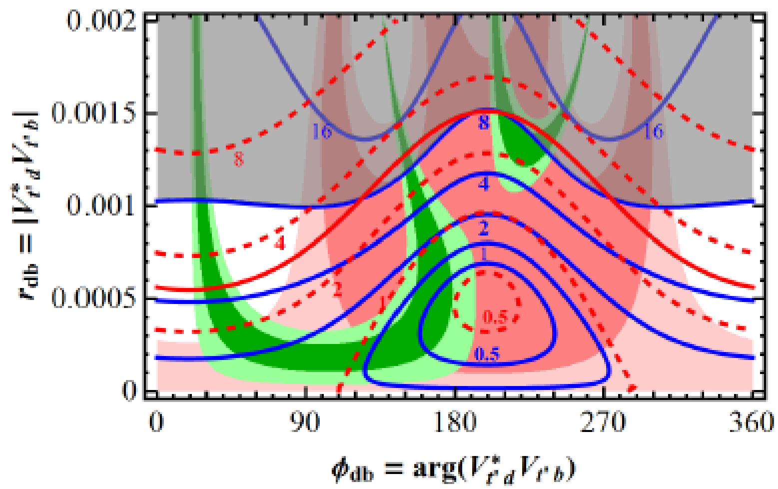
Larger $m_{t'}$ case

$$m_{t'} = 1000 \text{ GeV}$$

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



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

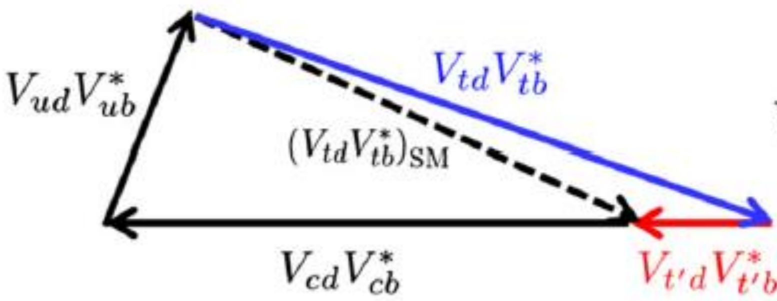


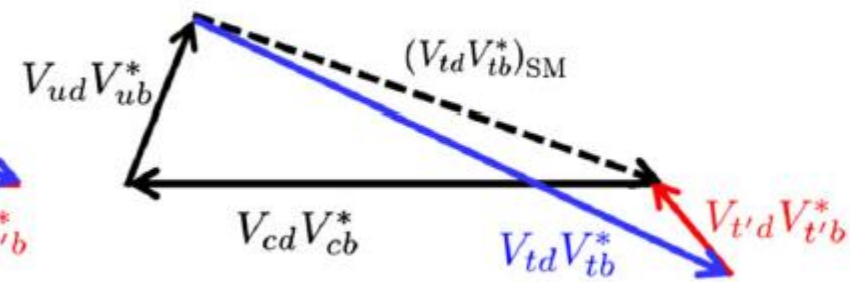
- Large r_{db} region (ϕ_{db} ~ 180°) is not allowed for V_{ub}(ave.)
- Preferred r_{db} values drop

Discussion and Conclusion

Discussion

- b → d "quadrangle" for $m_{t'} = 700\ \mathrm{GeV}$





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

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

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

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

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

- Unusual CKM pattern

  $|V_{t'd}^* V_{t'b}| \sim 0.002 - 0.003$ with $|V_{t'b}| < 0.1$ ⇒ $|V_{t'd}| > |V_{td}|^{\rm SM}$

  Hou, Ma PRD '11   > 0.02   ~ 0.01

  - ➢ Heavier t' is more natural in this sense

Conclusion

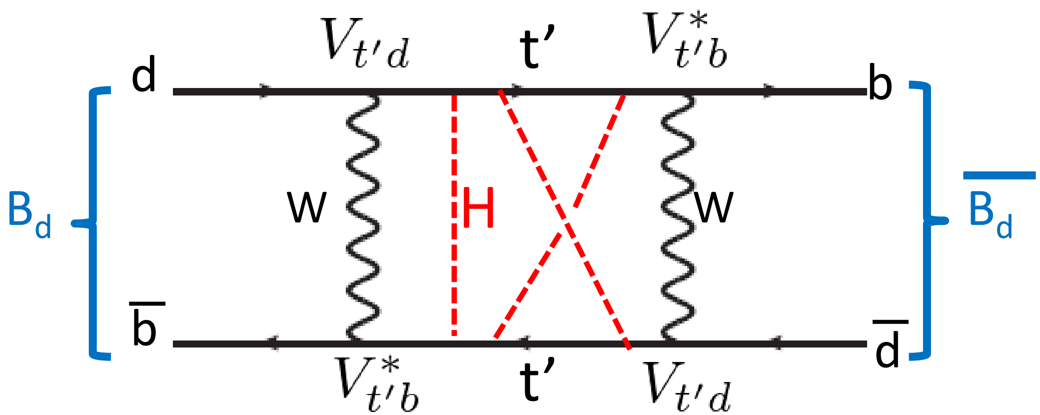
- $B(B_d \to \mu^+\mu^-)$ may be the last chance to find New Physics in flavor sector at the LHC before 13-14 TeV run
- 4G t' can enhance $B(B_d \to \mu^+\mu^-)$ over 4 x B_{SM} , within parameter region suggested by $\sin(2\beta/\phi_1)$
- Chance of such enhancement is not large (since only corner of 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 mt' = 700, 1000 GeV, which satisfy direct search limit
- Beyond perturbative unitarity limit ~ 550 GeV

  Chanowitz, Furman and Hinchliffe (1978)



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

modified

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