B Meson Anomalies and Baryogenesis From a Two Higgs Doublet Model

Peter Winslow[1,2] and Sean Tulin[2]

[1] University of British Columbia, Vancouver, BC, Canada

[2] TRIUMF, Vancouver, BC, Canada

Motivation: B Meson Anomalies

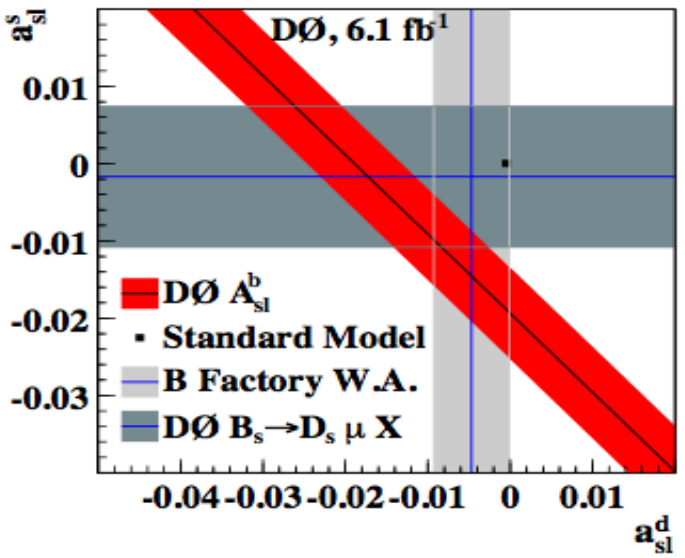
Within the SM CP violation is understood within the "CKM paradigm" to an accuracy of $\mathcal{O}(20\%)$

Y. Nir, Nucl. Phys. Proc. Suppl. **117**, 111 (2003)

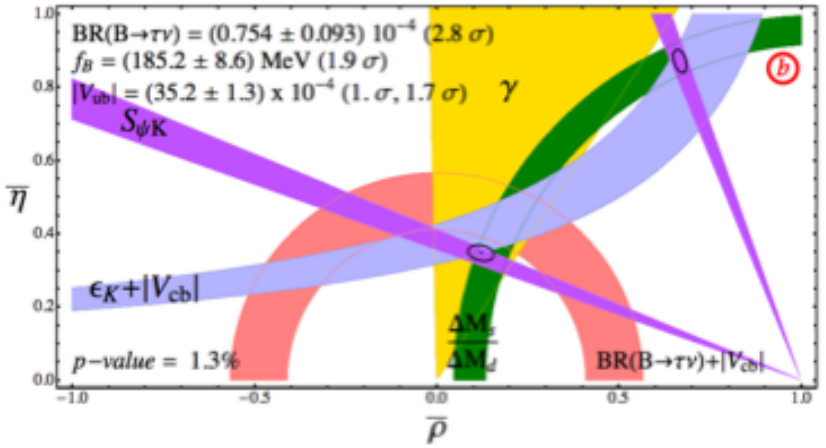
DØ measurement of the like-sign dimuon asymmetry

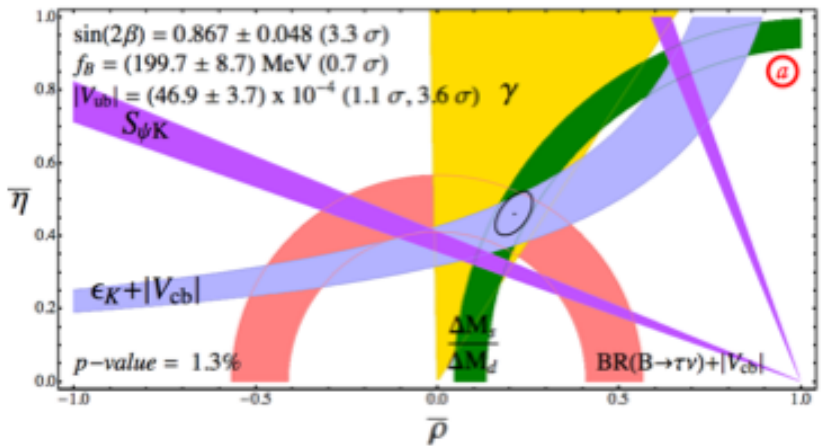
$$A_{sl}^{b} = -0.00957 \pm 0.00251\ (\text{stat.}) \pm 0.00146\ (\text{syst.})$$

V. M. Abazov *et al.*, Phys. Rev. D **82**, 032001 (2010)



Tension at ~3σ between $B \to \tau\nu$ and $S_{\psi K}$



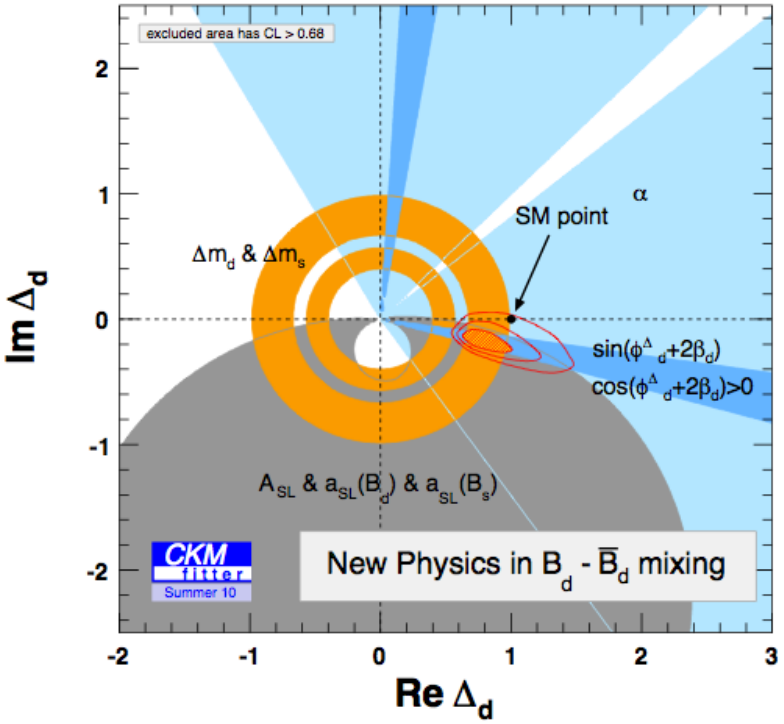


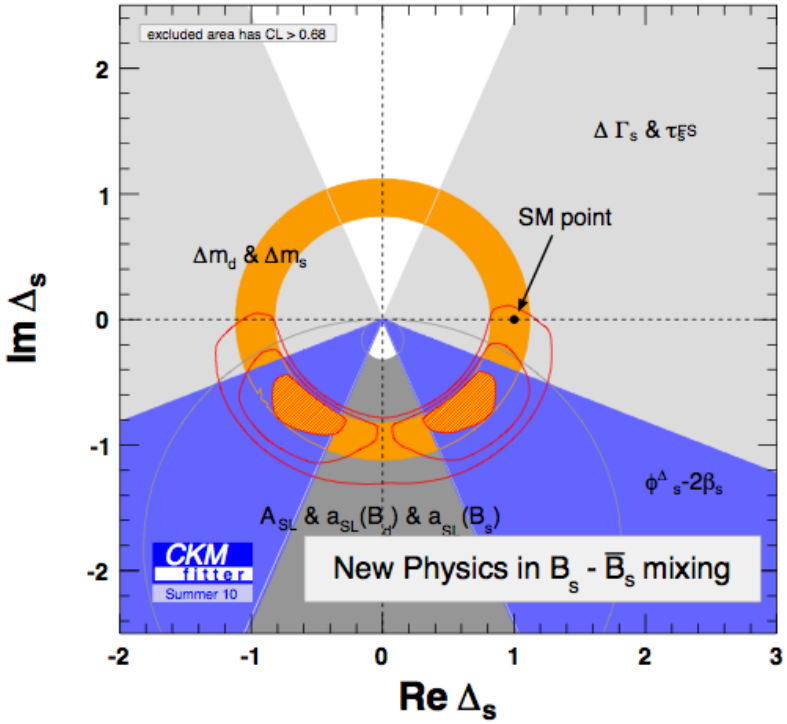
E. Lunghi and A. Soni, Phys. Lett. B **697**, 323 (2011)

Motivation: B Meson Anomalies

CKMFitter Group has performed a global fit to all flavor observables allowing for arbitrary new physics in both $B_{d,s}$ mixing amplitudes (scenario 1)

$$M_{12}^q = (M_{12}^q)_{SM} + (M_{12}^q)_{NP} \equiv (M_{12}^q)_{SM} \Delta_q$$





A. Lenz *et al.*, Phys. Rev. D **83**, 036004 (2011)

Results imply new bosonic degrees of freedom with new large CP violating phases

$$\mathcal{L}_{NP} = \frac{c_d}{\Lambda^2}(\bar{b}d)^2_{V-A} + \frac{c_s}{\Lambda^2}(\bar{b}s)^2_{V-A} + h.c.$$

Motivation: Baryogenesis

Sakharov's conditions for baryogenesis within the SM

- Baryon number violation	electroweak sphalerons	☑
- C and CP violation	KM phase	☒
- departure from equilibrium	EWPT	☒

For a successful description of electroweak baryogenesis one needs new CP violation and new bosonic degrees of freedom at $\Lambda \sim \Lambda_{EW}$ for a strong enough first order phase transition

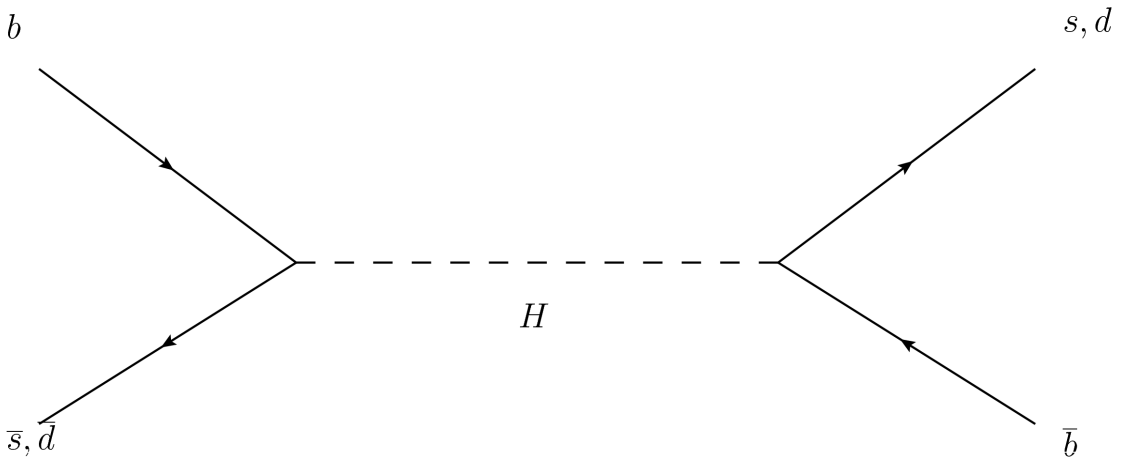
A singular source for both B meson anomalies and baryogenesis?

Motivation: Baryogenesis

Constraints on $\Delta M_{d,s}$ in $B^0_{s,d}$ systems from tree level Higgs exchange require that

$$\Lambda^2/|c_d| \gtrsim (500\mathrm{TeV})^2$$

$$\Lambda^2/|c_s| \gtrsim (100\mathrm{TeV})^2$$



G. Isidori, Y. Nir and G. Perez, [arXiv:1002.0900 [hep-ph]]

Sufficient baryon number generation requires $|c_{d,s}| \gtrsim \mathcal{O}(10^{-2})$
while a viable first order phase transition requires $\Lambda \lesssim 1\mathrm{TeV}$

$$\Rightarrow \Lambda^2/|c_{d,s}| \lesssim (10\mathrm{TeV})^2$$

If NP operators are generated at 1-loop level there is extra loop suppression

$$c_{d,s} \to c_{d,s}/(4\pi)^2$$

Our Model

A simple (type III) 2HDM with top-charm flavor violation

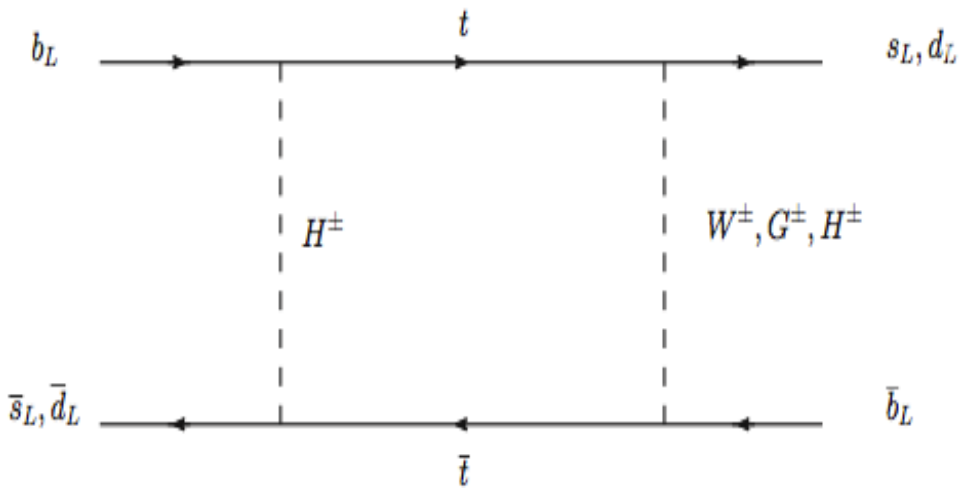
$$H_1 = \begin{pmatrix} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_{Yukawa} \supset -\frac{1}{\sqrt{2}} \tilde{y}_{it} \overline{u}_{i_L} t_R (H^0 - iA^0) - \left(V_{CKM}^{\dagger} \tilde{y} \right)_{it} \overline{d}_{i_L} t_R H^- + h.c.$$

$$\tilde{y}_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_{ct} \\ 0 & 0 & \tilde{y}_{tt} \end{pmatrix} \qquad |\tilde{y}_{tt}| >> |\tilde{y}_{ct}|$$

Strongest constraints come from flavor observables

Contribution to B mixing enters through box diagrams



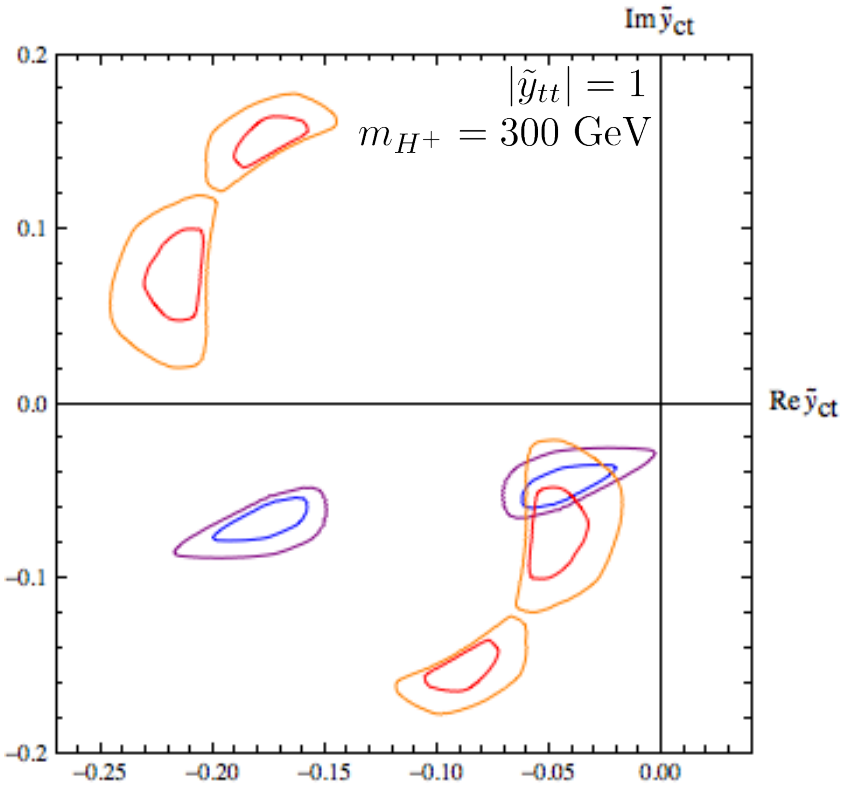
Flavor Constraints: Neutral B Mixing

General Method:

Fix $|\tilde{y}_{tt}|, m_{H^+}$ and explore preferred regions for $|\tilde{y}_{ct}|$ and θ_{ct} consistent with flavor observables

Same new physics phase is constrained by all flavor observables

$$\theta_{ct} = \arg\left(\frac{V_{cs}^* \tilde{y}_{ct}}{V_{ts}^* \tilde{y}_{tt}}\right)$$



Axes are defined as

$$Re\tilde{y}_{ct} = |\tilde{y}_{ct}| \cos\theta_{ct}$$
$$Im\tilde{y}_{ct} = |\tilde{y}_{ct}| \sin\theta_{ct}$$

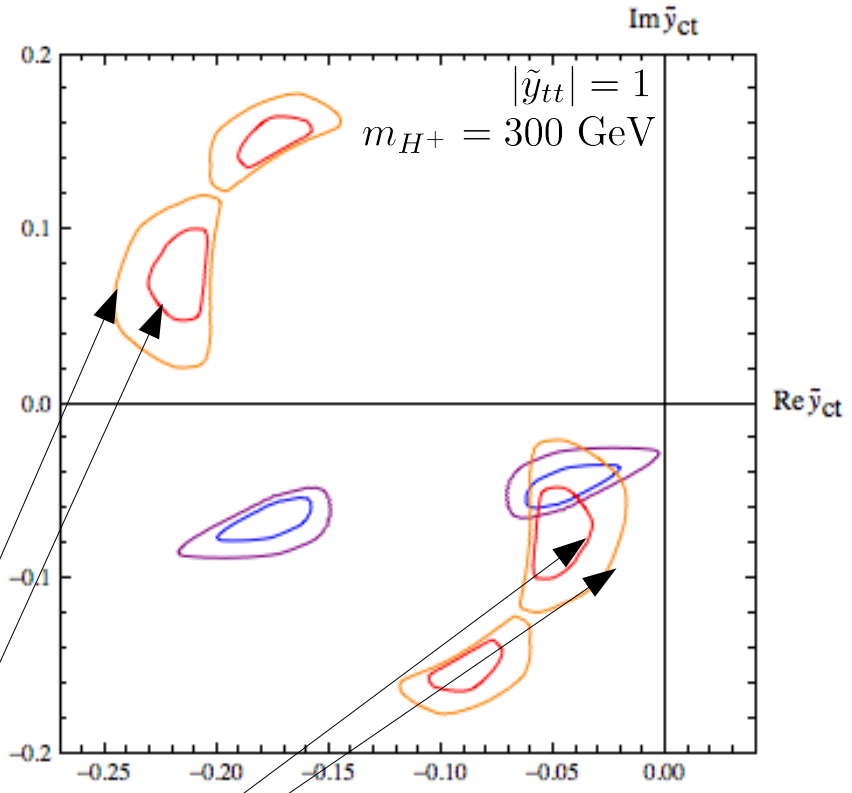
Flavor Constraints: Neutral B Mixing

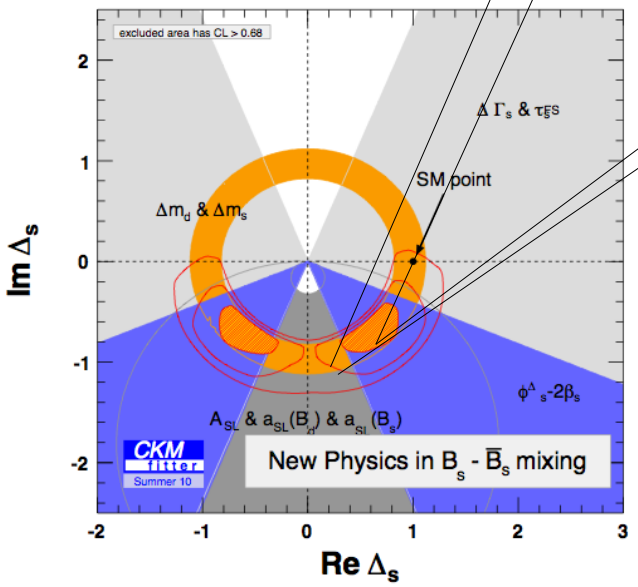
General Method:

Fix $|\tilde{y}_{tt}|, m_{H^+}$ and explore preferred regions for $|\tilde{y}_{ct}|$ and θ_{ct} consistent with flavor observables

Same new physics phase is constrained by all flavor observables

$$\theta_{ct} = \arg\left(\frac{V_{cs}^* \tilde{y}_{ct}}{V_{ts}^* \tilde{y}_{tt}}\right)$$





Axes are defined as

$$Re\tilde{y}_{ct} = |\tilde{y}_{ct}| \cos\theta_{ct}$$
$$Im\tilde{y}_{ct} = |\tilde{y}_{ct}| \sin\theta_{ct}$$

- Constraint enters as a quadratic

B_s mixing:

Map 1 and 2 σ best fit regions for Δ_s onto the model parameter space

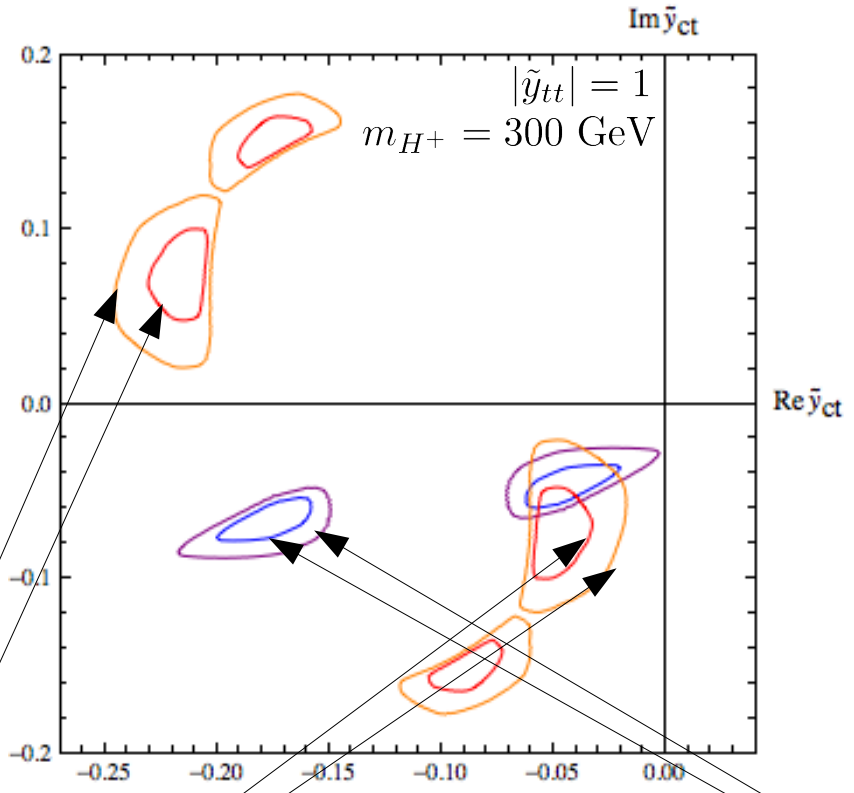
Flavor Constraints: Neutral B Mixing

General Method:

Fix $|\tilde{y}_{tt}|, m_{H^+}$ and explore preferred regions for $|\tilde{y}_{ct}|$ and θ_{ct} consistent with all flavor observables

Same new physics phase is constrained by all flavor observables

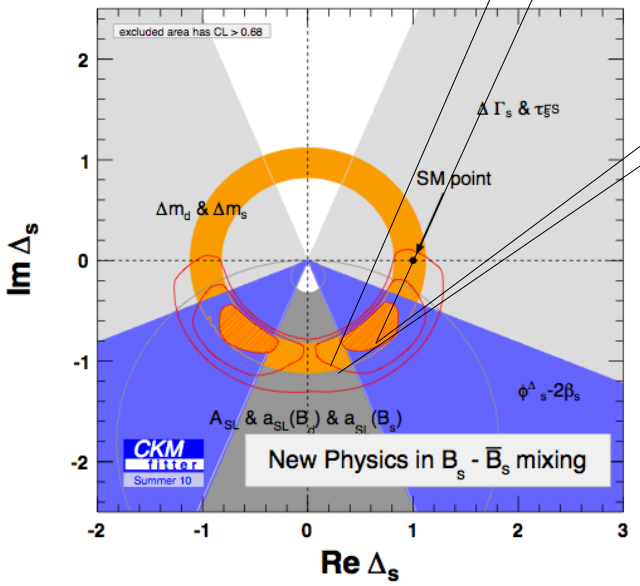
$$\theta_{ct} = \arg\left(\frac{V_{cs}^* \tilde{y}_{ct}}{V_{ts}^* \tilde{y}_{tt}}\right)$$



Axes are defined as

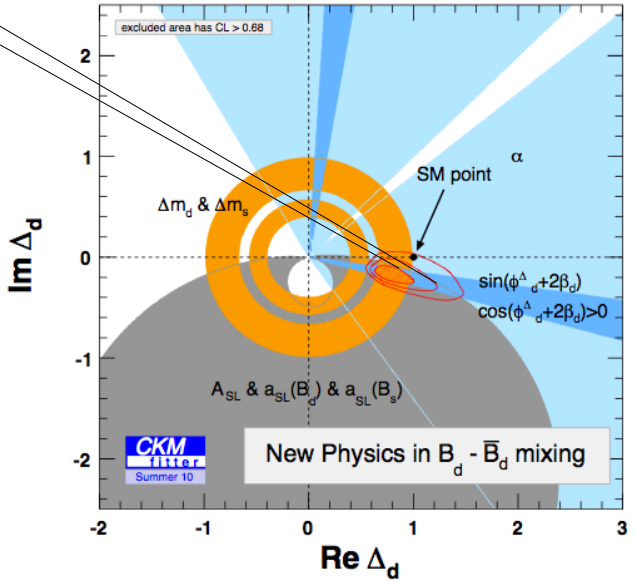
$$Re\tilde{y}_{ct} = |\tilde{y}_{ct}| \cos\theta_{ct}$$
$$Im\tilde{y}_{ct} = |\tilde{y}_{ct}| \sin\theta_{ct}$$

- Constraint enters as a quadratic



$B_{d,s}$ mixing:

Map 1 and 2 σ best fit regions for $\Delta_{d,s}$ onto the model parameter space



Flavor Constraints: Rare B Decays

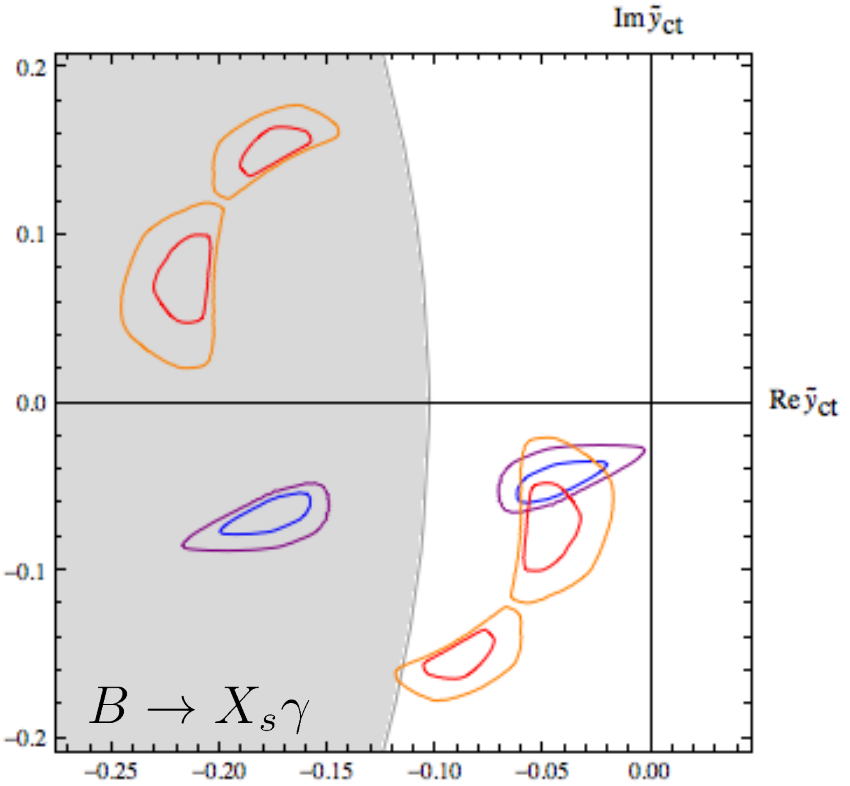
Constraint from rare B decays defines an annulus in the model parameter space

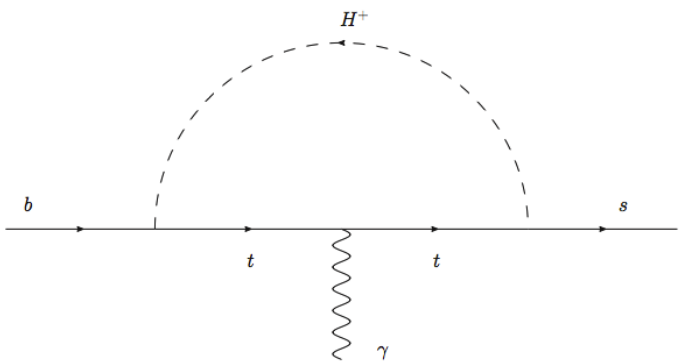
$$\frac{Br^{exp}(B \to X_s\gamma)}{Br^{SM}(B \to X_s\gamma)} = 1 + G_1(x_H, x_t) Re\tilde{y}_{ct} + G_2(x_H, x_t)|\tilde{y}_{ct}|^2$$

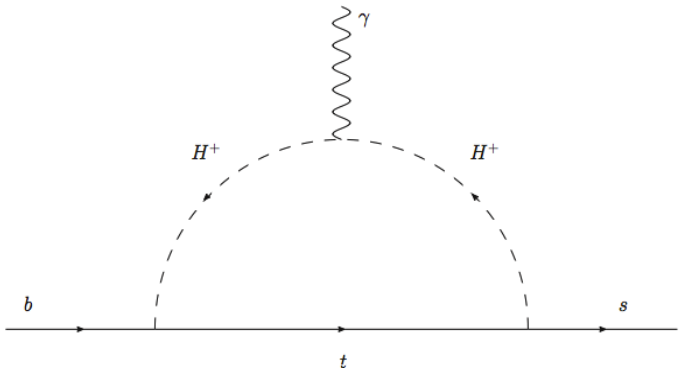
White region corresponds to region which is consistent with

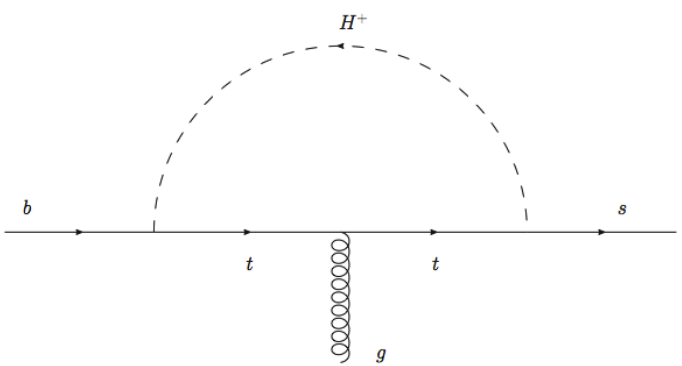
$$Br(B \to X_s\gamma)^{exp} = (3.55 \pm .39) \times 10^{-4}$$

$$Br(B \to X_s\gamma)^{SM} = (3.6 \pm 0.3) \times 10^{-4}$$



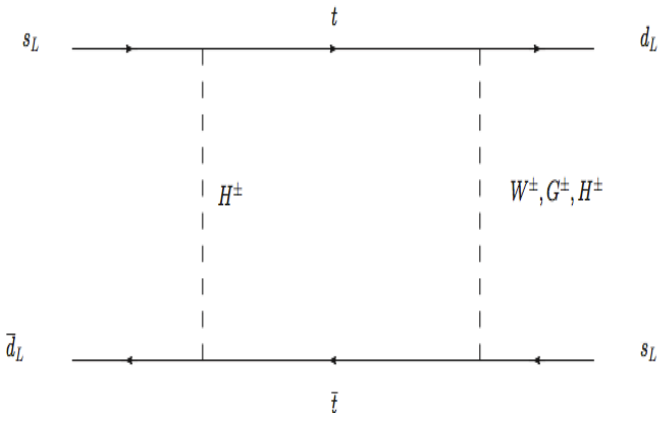


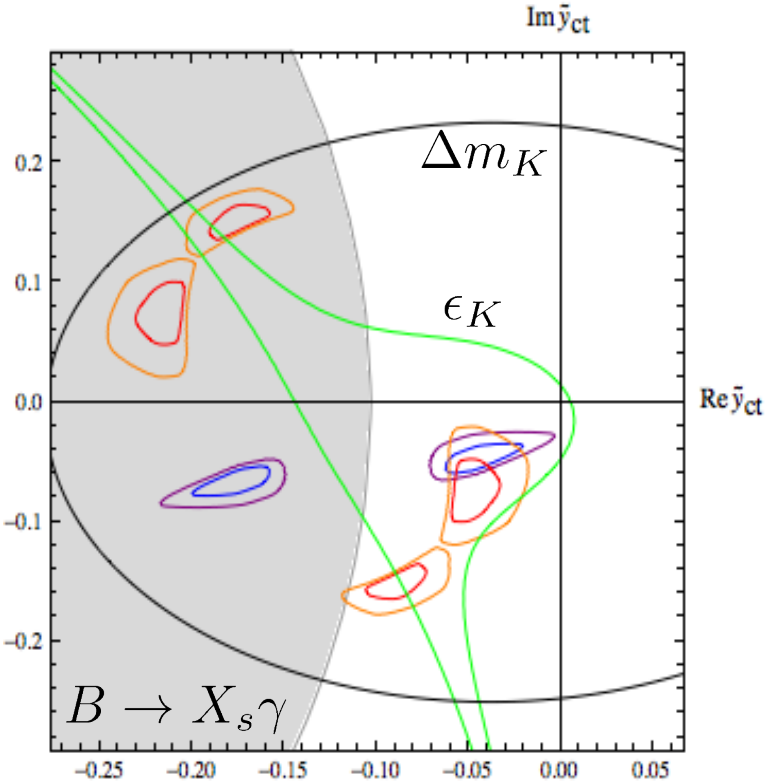




Flavor Constraints: Neutral Kaon Mixing

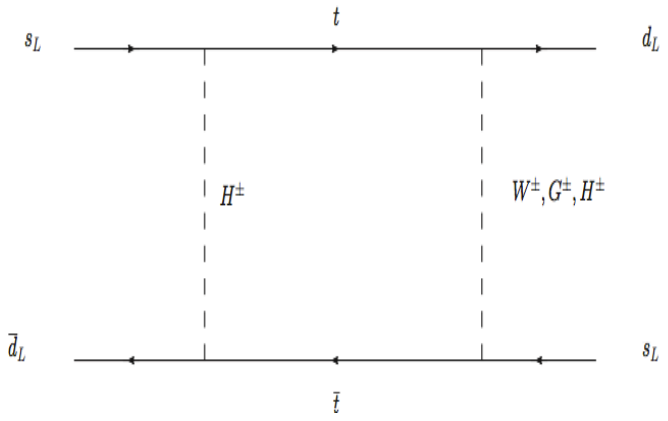
New physics contributions to $K^0 - \overline{K^0}$ arise from box diagrams similar to $B^0 - \overline{B^0}$ mixing

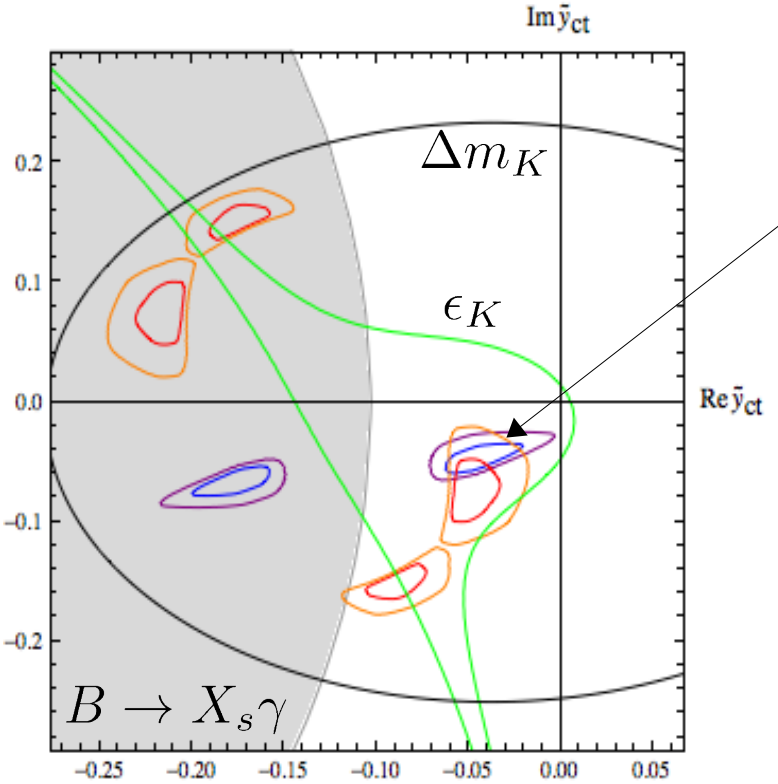




Flavor Constraints: Neutral Kaon Mixing

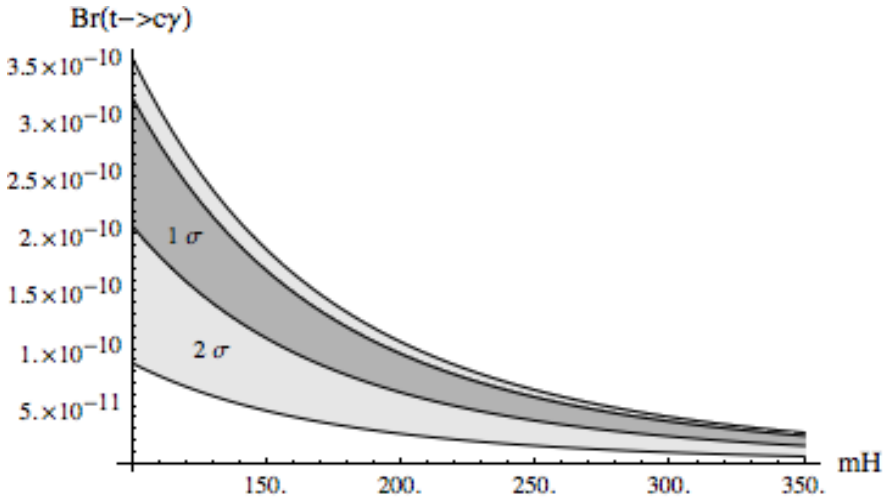
New physics contributions to $K^0 - \overline{K^0}$ arise from box diagrams similar to $B^0 - \overline{B^0}$ mixing

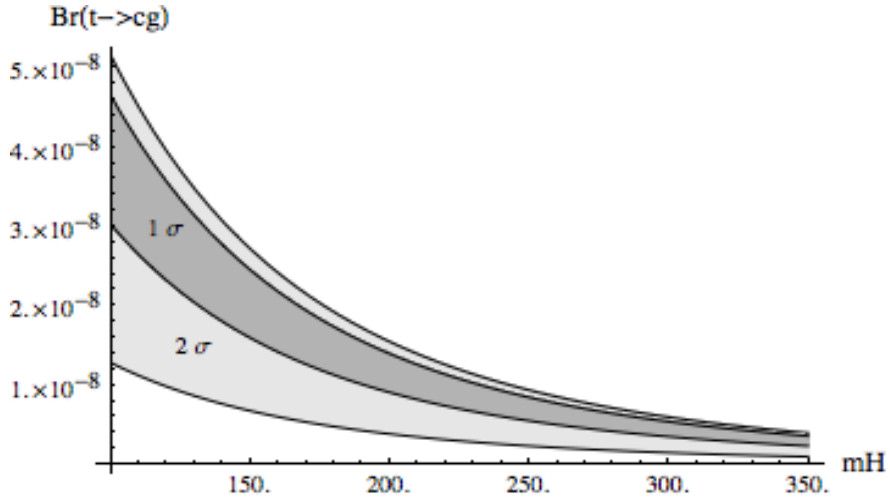




The tightly constrained parameter space allows for predictions of other processes

- $Br(t \to c\gamma)$
- $Br(t \to cg)$
- $Br(t \to cZ)$
- ?





Baryogenesis

Viable Baryogenesis?
- Strong enough 1st order phase transition?
- Sufficient CP violation?

For a general type II 2HDM a strong enough first order phase transition can occur for
$m_{h^0} \lesssim 200\ \mathrm{GeV}$ and $300\ \mathrm{GeV} \lesssim m_{H^0} \lesssim 500\ \mathrm{GeV}$

L. Fromme, S. J. Huber and M. Seniuch, JHEP **0611**, 038 (2006)

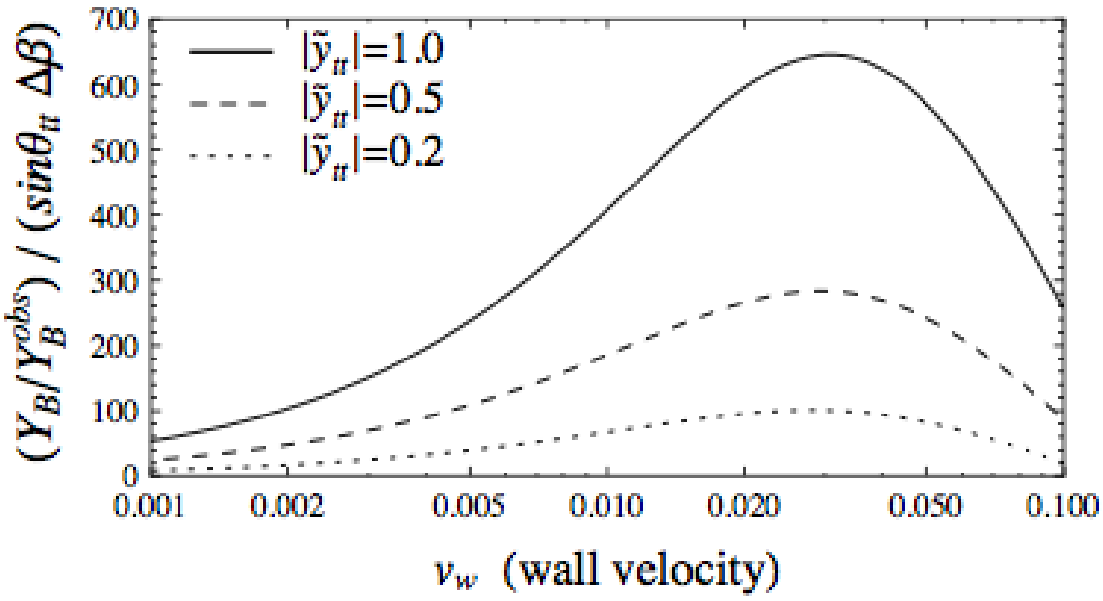
- Existence of strong enough first order phase transition is assumed for the moment

- Sole source of CP violation is the phase $\theta_{tt} = arg(\tilde{y}_{tt})$

Not same phase that enters flavor constraints!!

$\Delta\beta$ is related to the shift in the shift in the Higgs vevs across the bubble wall

The model can easily account for the BAU provided that $|\tilde{y}_{tt}| \gtrsim 0.2$ with $\mathcal{O}(1)$ phase!!!



Conclusions

- Recent anomalies in the B sector could imply new weak-scale bosonic d.o.f. and new large CP-violating phases
- These ingredients are exactly what is required for viable electroweak baryogenesis
- We propose a single 2HDM to account for both the B meson anomalies and the baryon asymmetry of the universe
- Viable electroweak baryogenesis requires $|\tilde{y}_{tt}| \sim 1$ and a light new Higgs scale $m_{H^+} \lesssim 500 \text{ GeV}$
- Flavor constraints are also consistent with $|\tilde{y}_{tt}| \sim 1$ and a light new Higgs scale $m_{H^+} \lesssim 500 \text{ GeV}$
- More investigation is needed to explore possible interesting collider signatures and to address the true strength of the phase transition