Can we have NP contributions to Γ_{12}?

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The theory behind Bs mixing

D0 measures the like-sign di-muon charge asymmetry

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

This result is interpreted as coming solely from mixing of neutral B mesons

$$A_{\rm sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

The theory behind Bs mixing

Di-muon asymmetry from mixing is related to the semileptonic charge asymmetry

$$a_{\rm sl}^q = \frac{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) - \Gamma(B_q^0(t) \to \mu^- X)}{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) + \Gamma(B_q^0(t) \to \mu^- X)}$$

One can calculate

$$A_{\rm sl}^b = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s$$

Semileptonic charge asymmetry given by

$$a_{\rm sl}^q = \frac{\left|\Gamma_q^{12}\right|}{\left|M_q^{12}\right|} \sin \phi_q$$

The measurements

What do direct measurements of semileptonic charge asymmetries tell us?

SM values predictions are

$$a_{\rm sl}^d({\rm SM}) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a_{\rm sl}^s({\rm SM}) = (2.1 \pm 0.6) \times 10^{-5}$$

Measurements not precise enough to test the SM

$$a_{\rm sl}^d = (-4.7 \pm 4.6) \times 10^{-3}$$
$$a_{\rm sl}^s = (-1.7 \pm 9.1) \times 10^{-3}$$

The measurements

Combining the semileptonic asymmetries, SM prediction is

$$A_{\rm sl}^{b}(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

Combining D0 measurement with CDF measurement

$$A_{\rm sl}^{b} = -(8.5 \pm 2.8) \times 10^{-3}$$

This is about 3σ from SM prediction

The measurements

Can convert this measurement into measurement of semileptonic asymmetry of B_s meson

Assuming no CP violation in B_d system:

$$(a^s_{\rm sl})_{{\rm SM}\ a^d_{\rm sl}} = -(12.2 \pm 4.9) \times 10^{-3}$$

Using experimental constraint on B_d system:

$$(a^s_{\rm sl})_{a^d_{\rm sl}\ {\rm meas}} = -(9.2 \pm 4.9) \times 10^{-3}$$

Compare this with SM prediction

$$a^s_{\rm sl}({\rm SM}) \ = \ (2.1 \pm 0.6) \times 10^{-5}$$

The problem with the data

As discussed before, theoretical relation is

$$a_{\rm sl}^q = \frac{\left|\Gamma_q^{12}\right|}{\left|M_q^{12}\right|}\sin\phi_q$$

The same parameters also affect other measurements

$$\begin{aligned}\Delta M_s &= 2|M_{12}^s| \\ \Delta\Gamma_s &= 2|\Gamma_{12}^s|\cos\phi^s \\ S_{\psi\phi} &= -\sin\phi^s\,,\end{aligned}$$

The measured values for these three observables are

$$\begin{aligned}\Delta M_s &= (17.78 \pm 0.12)\text{ps}^{-1} \\ \Delta\Gamma_s &= \left(0.154^{+0.054}_{-0.070}\right)\text{ps}^{-1} \\ S_{\psi\phi} &= 0.69^{+0.16}_{-0.23}\,.\end{aligned}$$

The problem with the data

Global fit to theoretical parameters

$$|M_{12}^s| = (8.889 \pm 0.060)\mathrm{ps}^{-1}$$
$$|\Gamma_{12}^s| = (0.112 \pm 0.040)\mathrm{ps}^{-1}$$
$$\phi^s = -0.79 \pm 0.24\,.$$

Fit assuming no new physics in B_d system

$$|M_{12}^s| = (8.889 \pm 0.060)\mathrm{ps}^{-1}$$
$$|\Gamma_{12}^s| = (0.131 \pm 0.041)\mathrm{ps}^{-1}$$
$$\phi^s = -0.88 \pm 0.24\,.$$

SM predictions are

$$|M_{12}^s|^{\mathrm{SM}} = (9.8 \pm 1.1)\mathrm{ps}^{-1}$$
$$|\Gamma_{12}^s|^{\mathrm{SM}} = (0.049 \pm 0.012)\mathrm{ps}^{-1}$$
$$\phi^s = (0.04 \pm 0.01)\,.$$

Phase different at $\sim 3\sigma$

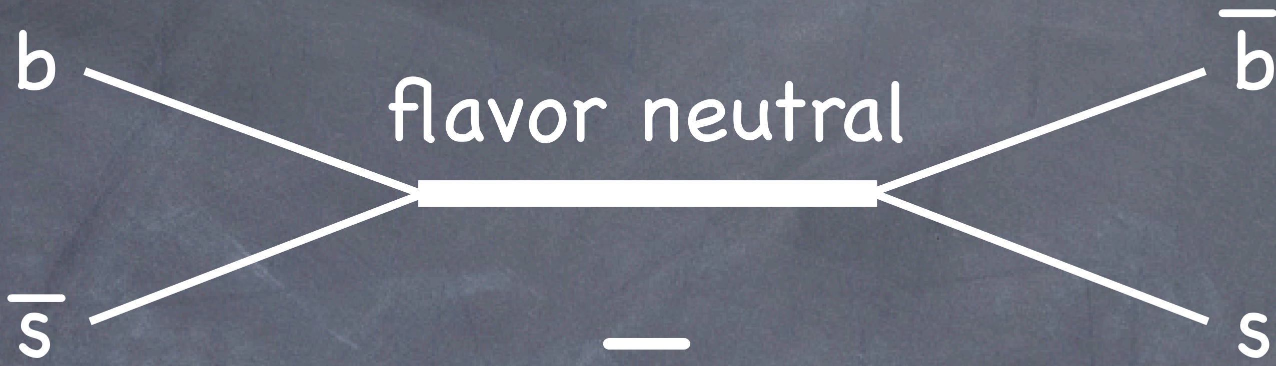
But Γ_{12} also different at 1.5σ-2σ

What are the constraints on NP to Γ_{12}?

Outline

- List of operators contributing to Γ_{12}
- The physics behind constraining the operators
- Discussion of the resulting constraints
- Worrying about the B_d lifetime
- Discussion of the resulting constraints
- Conclusions

Possible operators for Bs decays



$$O = \bar{b}\, s\, R$$

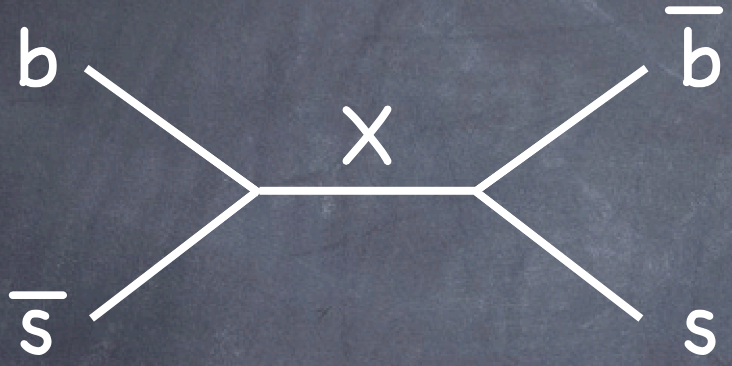
R has to be flavor neutral with mass below m_{Bs}

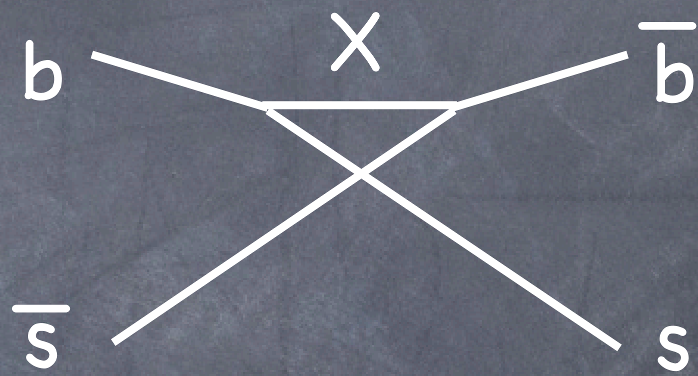
Operators of lowest dimension are

$O_1 = b\ s\ X$	$O_1 = b\ s\ \psi\psi$
X = SM field	ψ = SM field
X = BSM field	ψ = BSM field

Possible operators for Bs decays

$$O = \bar{b}\, s\, X$$



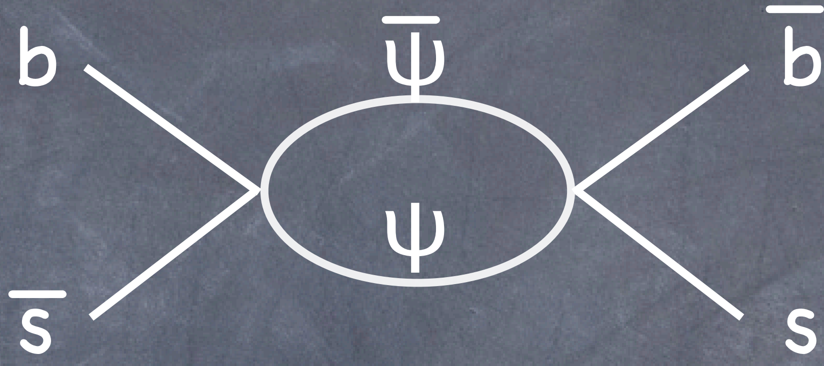


The s coming out of operator is highly energetic. In order to be part of B_s system, strong suppression needed.

Will not consider this possibility further

Possible operators for Bs decays

$$O = \bar{b}\, s\, \bar{\psi}\psi$$



For ψ = Fermion, dim(O) = 6 $\Rightarrow$ C ~ $1/\Lambda^2$

For ψ = Boson, dim(O) = 7 $\Rightarrow$ C ~ $1/\Lambda^3$

Will focus on ψ = Fermion, but other possibilities can be treated using similar methods

Possible operators for Bs decays

bs uu
bs dd
bs cc
bs ss
bs ee
bs μμ
bs ττ
bs νν
bs sd
bs ds
bs cu
bs uc

Contributions of the operators to the EW Hamiltonican

$$H \sim 4\frac{G_F}{\sqrt{2}}\sum_i C_i O_i$$

Size of Wilson coefficient of operators

$$C^s_{\rm NP} \sim g^2_{\rm NP} m^2_W / \Lambda^2_{\rm NP}$$

Possible operators for B decays

How does contribution to Γ_{12} compare to SM?

SM contribution from operator bs cc with $C \sim |V_{cb}|^2$

Rough relation is

$$\frac{|\Gamma_{12}^{\rm NP}|}{|\Gamma_{12}^{\rm SM}|} \sim \left(\frac{C_{\rm NP}^{s}}{|V_{\rm cb}|}\right)^2$$

This gives

$$C_{\rm NP}^{s} \sim \lambda^2$$

or equivalently

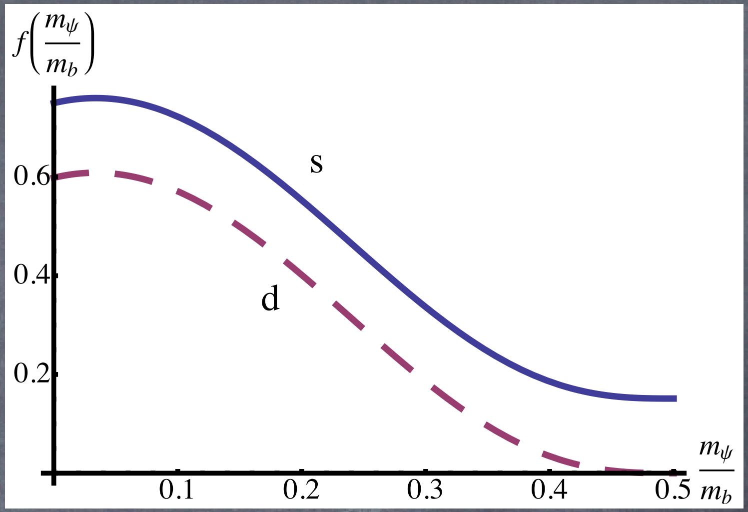
$$\Lambda_{\rm NP} \lesssim g_{\rm NP}\, m_W / \lambda$$

The physics behind constraints

1. Contribution to total lifetime

Can work out:

$$\frac{\Gamma^{d,s}_{\rm NP}}{\Gamma^{d,s}_{\rm tot}} \sim \frac{\Delta\Gamma^{s}_{\rm NP}}{\Delta\Gamma^{s}_{\rm tot}} \times f_{d,s}(m_\psi/m_b)$$



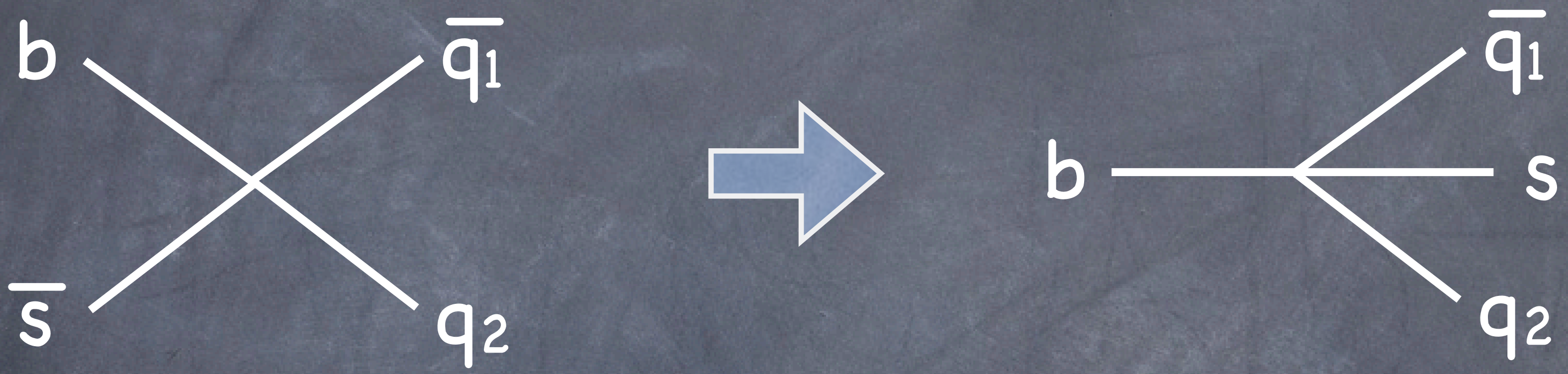
O(1) NP contrib to $\Delta\Gamma$ ⇒ O(50%) NP contrib to τ_B

Very constraining, but τ_B difficult to calculate

Look for additional constraints

The physics behind constraints

2. Contribution to non-leptonic B decays



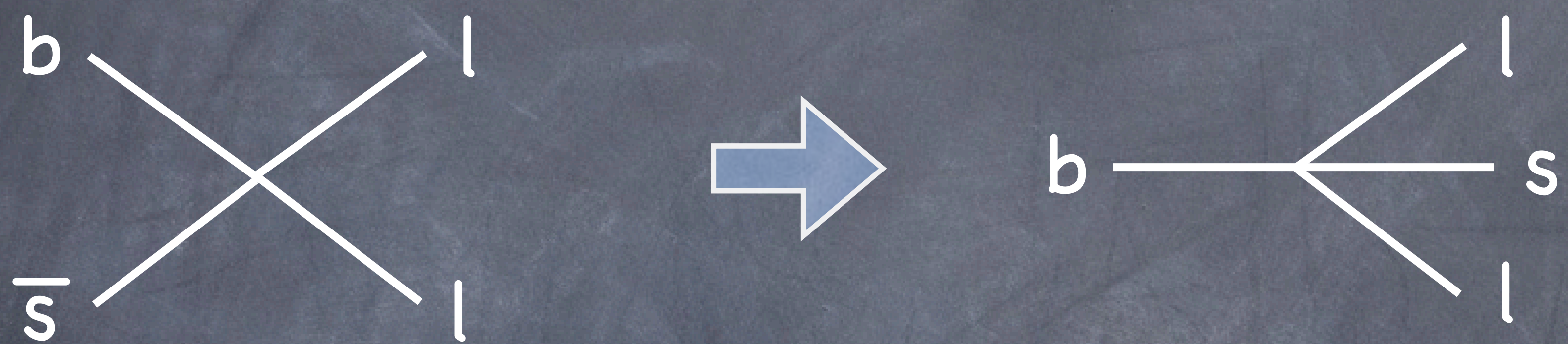
Using simple factorization theorem, and $C \sim \lambda^2$

$$\mathrm{Br}(B \to M_1 M_2) \;\sim\; \tau_B G_F^2 |C|^2 \frac{f_M^2 m_b^3 F_{B\to M}}{32\pi} \;\sim\; 10^{-3}$$

Should understand as order of magnitude result

The physics behind constraints

3. Contribution to B→Kll decays



Using simple factorization theorem, and $C \sim \lambda^2$

$$\mathrm{Br}(B \to M_1 \ell^+ \ell^-) \sim \tau_B G_F^2 |C|^2 \frac{F_{B\to M} m_b^5}{192\pi^3} \mathrm{PS}(m_\ell/m_b) \sim 0.02\, \mathrm{PS}(m_\ell/m_b)$$

$\mathrm{PS}(0) = 1 \quad \mathrm{PS}(m_\tau/m_b) = 0.05$

The physics behind constraints

4. Contribution to $B_s \to ll$ decays

Clearly, any leptonic operator will contribute to the annihilation decay $B_s \to ll$

$$\mathrm{Br}(B \to \ell^+\ell^-) \sim \tau_B G_F^2 |C|^2 \frac{f_B^2 m_b^3}{32\pi} H(m_\ell/m_b) \sim 0.3\, H(m_\ell/m_b)$$

Depending on the Dirac structure of the operator, there can be a helicity suppression factor

If helicity suppressed:

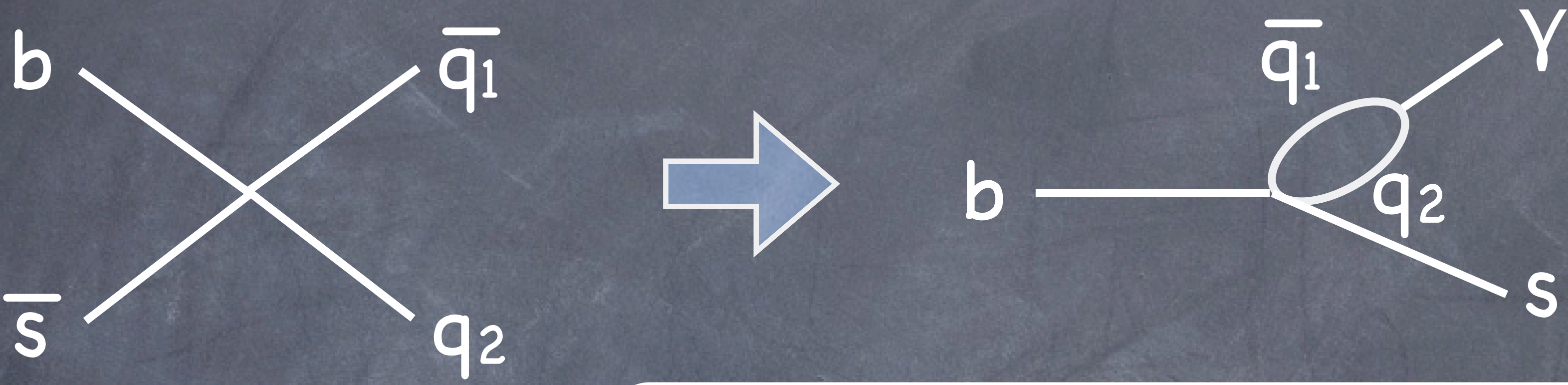
$H(m_l/m_b) = m_l^2/m_b^2$

If not:

$H(m_l/m_b) = 1$

The physics behind constraints

5. Contribution to $B_s \to X_s \gamma$ decays



Mixing depends on form of operator

$$\frac{\mathrm{Br}(B \to M\gamma)^{\mathrm{NP}}}{\mathrm{Br}(B \to M\gamma)^{\mathrm{SM}}} \sim 2\,r\,\frac{C^s_{\mathrm{NP}}}{V_{cb}} + r^2 \left(\frac{\tilde{C}^s_{\mathrm{NP}}}{V_{cb}}\right)^2$$

$r = 1$: non-leptonic vector ops

$r = \alpha/\alpha_s$: leptonic vector ops

$r = 4\pi/\alpha_s$: scalar and tensor ops

Very strong constraint for non-leptonic scalar ops

The data we use

The B factories Babar and Belle have measured an incredible amount of exclusive decay channels, many very precisely

Here is a somewhat random list with order of magnitude numbers

$B \to \pi\pi$	10^{-5}
$B \to K\pi$	10^{-5}
$B \to KK$	10^{-6}
$B \to \Phi K$	10^{-5}
$B \to Kll$	10^{-7}
$B \to X_s\gamma$	10%
$B \to K\nu\nu$	$< 10^{-5}$
$B \to DK$	10^{-4}
$B \to D_s\pi$	10^{-5}

The complete list of constraints

bs uu	$K^+\pi^-$, $K^+\pi^0$
bs dd	$K^0\pi^+$, $K^+\pi^0$
bs cc	$(X_s\gamma)$
bs ss	ΦK^0
bs ee	Kee
bs μμ	$K\mu\mu$
bs ττ	$(X_s\gamma)$
bs νν	$K\nu\nu$
bs sd	K^0K^0, K^+K^0
bs ds	K^+K^0
bs cu	K^0D^0
bs uc	D^-K^+

Almost all operators ruled out by current measurements

bs ττ and bs cc can be ruled out as scalar operators, since it would give too large mixing into O_7

The complete list of constraints

bs uu	$K^+\pi^-$, $K^+\pi^0$
bs dd	$K^0\pi^+$, $K^+\pi^0$
bs cc	$(X_s\gamma)$
bs ss	ΦK^0
bs ee	Kee
bs μμ	Kμμ
bs ττ	$(X_s\gamma)$
bs νν	Kνν
bs sd	K^0K^0, K^+K^0
bs ds	K^+K^0
bs cu	K^0D^0
bs uc	D^-K^+

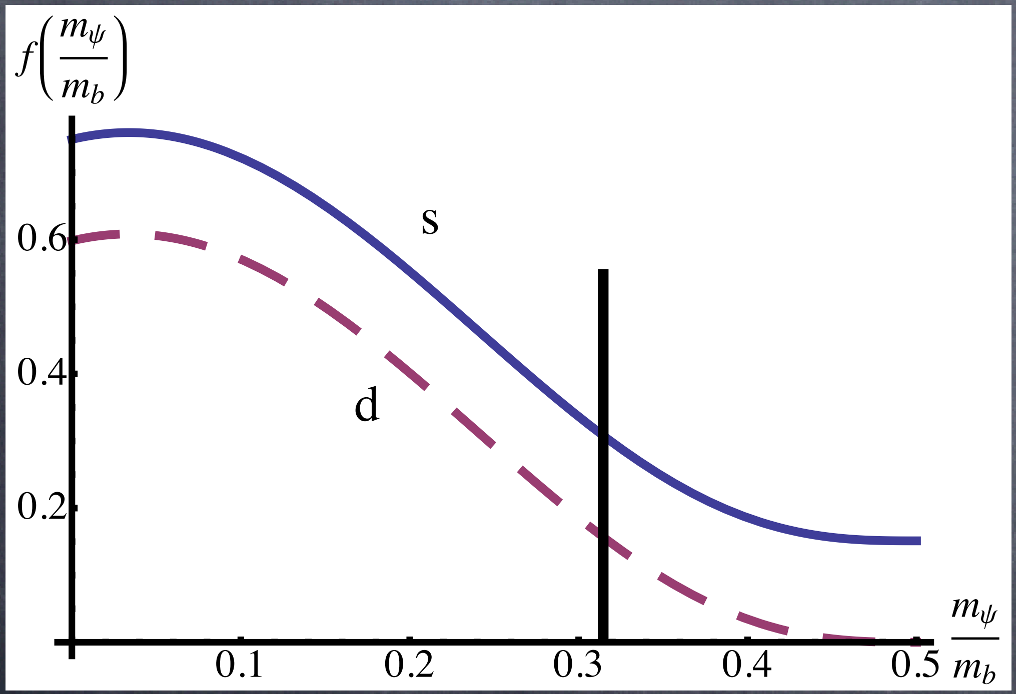
Almost all operators ruled out by current measurements

bs ττ and bs cc can be ruled out as scalar operators, since it would give too large mixing into O_7

But current arguments allow them as vector operators

The lifetime revisited

NP contributions to either one these operators would change both the B_s and B_d lifetime



Change would be at 10% - 20% level, but given potentially large non-perturbative corrections, this might be difficult to detect

Can we say anything more?

What about the ratio B_d/B_s ?

Can be calculated to high precision (non-perturbative physics identical in SU(3) limit

$$\frac{\tau(B_s)}{\tau(B_d)} = 1 \pm O(1\%)$$

3-body decays from both operators affect the B_d and B_s lifetime in the same way

But both operators give rise to annihilation contributions to B_s decays which are absent for B_d decays

What about the ratio B_d/B_s ?

This annihilation is exactly what gives rise to Γ_{12}

$$\frac{\tau(B_s)}{\tau(B_d)} \sim 1 - \frac{\Delta\Gamma_{12}^{(s),NP}}{\Gamma^{(s)}} + \frac{\Delta\Gamma_{12}^{(d),NP}}{\Gamma^{(d)}}$$

Thus, to keep ratio of lifetimes unchanged, need to add lifetime difference to B_d system as well

Repeat same analysis as before...

What about the ratio B_d/B_s ?

Allowed operators			
B_s		B_d	
$O^s_{\rm NP}$	Constr Γ	$O^d_{\rm NP}$	Constr Γ
$\bar{b}s\bar{u}u$	$K^+\pi^-$, $K^+\pi^0$	$\bar{b}d\bar{u}u$	$\pi^+\pi^-$, $\pi^+\pi^0$
$\bar{b}s\bar{d}d$	$K^0\pi^+$, $K^+\pi^0$	$\bar{b}d\bar{d}d$	$\pi^+\pi^0$
$\bar{b}s\bar{c}c$		$\bar{b}d\bar{c}c$	$X_d\gamma$
$\bar{b}s\bar{s}s$	ϕK^0	$\bar{b}d\bar{s}s$	$\bar{K}^0K^+$, $K^0\bar{K}^0$
$\bar{b}s\bar{e}e$	$K^{(*)}e^+e^-$	$\bar{b}d\bar{e}e$	$(\pi,\rho)e^+e^-$
$\bar{b}s\bar{\mu}\mu$	$K^{(*)}\mu^+\mu^-$	$\bar{b}d\bar{\mu}\mu$	$(\pi,\rho)\mu^+\mu^-$
$\bar{b}s\bar{\tau}\tau$		$\bar{b}d\bar{\tau}\tau$	$\tau^+\tau^-$
$\bar{b}s\bar{\nu}\nu$	$K^{(*)}\bar{\nu}\nu$	$\bar{b}d\bar{\nu}\nu$	$(\pi,\rho)\bar{\nu}\nu$
$\bar{b}s\bar{s}d$	$\bar{K}^0K^0$, $K^+\bar{K}^0$	$\bar{b}d\bar{s}d$	$\bar{K}^0\pi^+$ (no bound)
$\bar{b}s\bar{d}s$	$\bar{K}^0\bar{K}^0$ (no bound), $K^+\bar{K}^0$	$\bar{b}d\bar{d}s$	$K^0\pi^+$
$\bar{b}s\bar{c}u$	$D_s^+\pi^-$, K^0D^0 (no bound)	$\bar{b}d\bar{c}u$	$D^+\pi^-$ (no bound)
$\bar{b}s\bar{u}c$	D^-K^+, $\bar{D}^0K^+$	$\bar{b}d\bar{u}c$	

What about the ratio B_d/B_s ?

But what IS the ratio B_d/B_s?

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$$\frac{\tau(B_s)}{\tau(B_d)} = 0.965 \pm 0.017$$

What about the ratio B_d/B_s ?

But what IS the ratio B_d/B_s?

$$\frac{\tau(B_s)}{\tau(B_d)} = 0.965 \pm 0.017$$

Interestingly enough, about 2σ away from unity

However, deviation not large enough to explain Γ_{12}

Need a more precise measurement of this ratio!

Conclusions about Γ_{12}

- Central values of data $\Rightarrow$ Γ_{12} different than current SM predictions
- Could be that errors in SM calculation underestimated
  - Remember that we energy release is $m_b - 2m_c = 2$ GeV
  - All theoretical calculations perform OPE with expansion in $\Lambda/(m_b - 2m_c)$
  - Not sure we can trust the small uncertainties in SM calculations

I have nothing concrete to say, so investigated possibility of NP contributions

Conclusions about Γ_{12}

- Central values of data $\Rightarrow$ Γ_{12} different than current SM predictions
- Could be NP contributions to Γ_{12}
  - NP strongly constrained using existing B decay data
  - If we don't want to screw up SM prediction of ratio of τ_{Bd}/τ_{Bs}, need to add new physics to B_d system as well
  - Need completely unrelated ops in B_s and B_d system to have coefficients that are strongly correlated

This seems very contrived and does not make for easy model building!

Final conclusions

- If the measurements of D0 are confirmed, and the central values stay as the errors shrink, NP would be required in the mixing of B mesons
- If SM calculations can be trusted, would need to affect both the magnitude of Γ_{12}, as well as the relative phase between Γ_{12} and M_{12}
- While it is not impossible to construct models giving rise to NP in Γ_{12}, it seems very contrived and most models are already ruled out

In my opinion, should spend our energy to validate the experimental measurement!