New Physics in B_s Mixing & Decay

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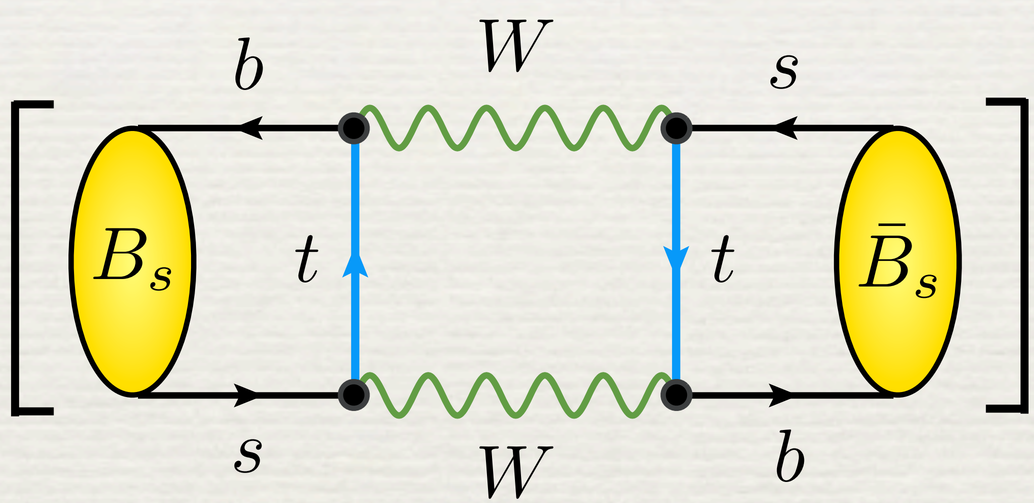
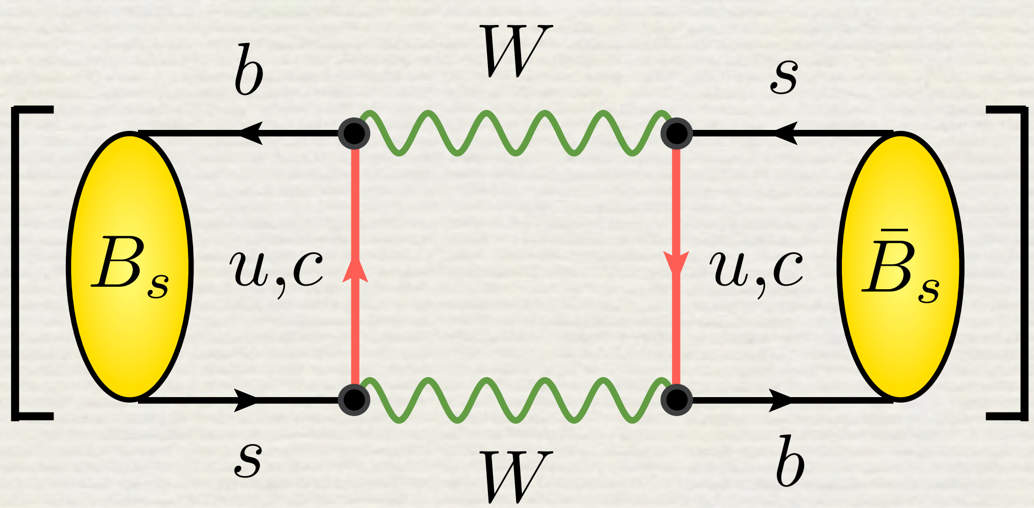
Standard Model & Beyond

- B_s–$\bar{B}_s$ oscillations encoded in elements M_{12} & Γ_{12} of hermitian mass & decay rate matrices (CPT $\Rightarrow$ $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$). In Standard Model (SM) leading effects due to electroweak box diagrams:

$(M_{12})_{\rm SM} \propto \mathrm{Re}$


dispersive part arising from “off-shell” top quark

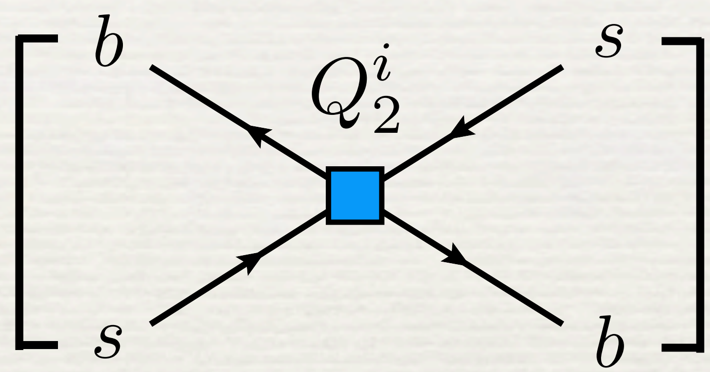
$(\Gamma_{12})_{\rm SM} \propto \mathrm{Im}$


absorptive part related to “on-shell” light up-type quarks

Standard Model & Beyond

- Generic, sufficiently heavy new physics (NP) in M_{12} (Γ_{12}) can be described via effective $\Delta B = 2$ ($\Delta B = 1$) interactions:

$$(M_{12})_{\mathrm{NP}} \propto C_2^i$$

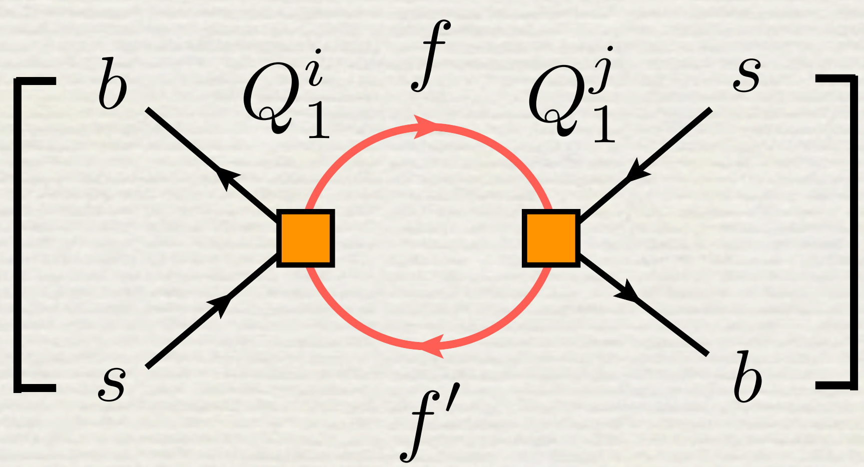


$$\sim \frac{1}{\Lambda^2_{\mathrm{NP}}}$$

NP scale

very sensitive to new particles:
SUSY, extra dimensions, ...

$$(\Gamma_{12})_{\mathrm{NP}} \propto C_1^i C_1^j \; \mathrm{Im}$$



$$\sim \frac{1}{(4\pi)^2} \frac{1}{\Lambda^4_{\mathrm{NP}}}$$

free of NP (?), since coefficients would also
give B decays into light final states X ($M_X < m_b$)

loop factor

Parameters & Observables

- Model-independent parametrization of NP effects in B_s system:

$$M_{12} = (M_{12})_{\rm SM} + (M_{12})_{\rm NP} = (M_{12})_{\rm SM}\, R_M\, e^{i\phi_M} ,$$

$$\Gamma_{12} = (\Gamma_{12})_{\rm SM} + (\Gamma_{12})_{\rm NP} = (\Gamma_{12})_{\rm SM}\, R_\Gamma\, e^{i\phi_\Gamma}$$

Expressed through $R_{M,\Gamma}$, $\phi_{M,\Gamma}$ & $(\phi_s)_{\rm SM} = \arg(-(M_{12})_{\rm SM}/(\Gamma_{12})_{\rm SM})$, mass ΔM & width difference $\Delta\Gamma$, flavor-specific (e.g. semileptonic) CP asymmetry a^s_{fs} & CP-violating (CPV) phase $\phi_{\psi\phi}$ take form

$$\boxed{\Delta M = (\Delta M)_{\rm SM}\, R_M\, ,} \qquad \boxed{\Delta\Gamma \approx (\Delta\Gamma)_{\rm SM}\, R_\Gamma \cos(\phi_M - \phi_\Gamma)\, ,}$$

$$\boxed{a^s_{fs} \approx (a^s_{fs})_{\rm SM}\, \frac{R_\Gamma}{R_M}\, \frac{\sin(\phi_M - \phi_\Gamma)}{(\phi_s)_{\rm SM}}\, ,} \qquad \boxed{\phi_{\psi\phi} = (\phi_{\psi\phi})_{\rm SM} + \phi_M}$$

Parameters & Observables

- Besides $\phi_{\psi\phi}$ (from mixed-induced, time-dependent CP asymmetry in $B_s \to \psi\phi$) & a^s_{fs} (from tree-level $B_s \to \mu^+ D_s^- X$ decay), there is a 3rd relevant CPV quantity in B sector, i.e., like-sign dimuon charge asymmetry A^b_{SL}:

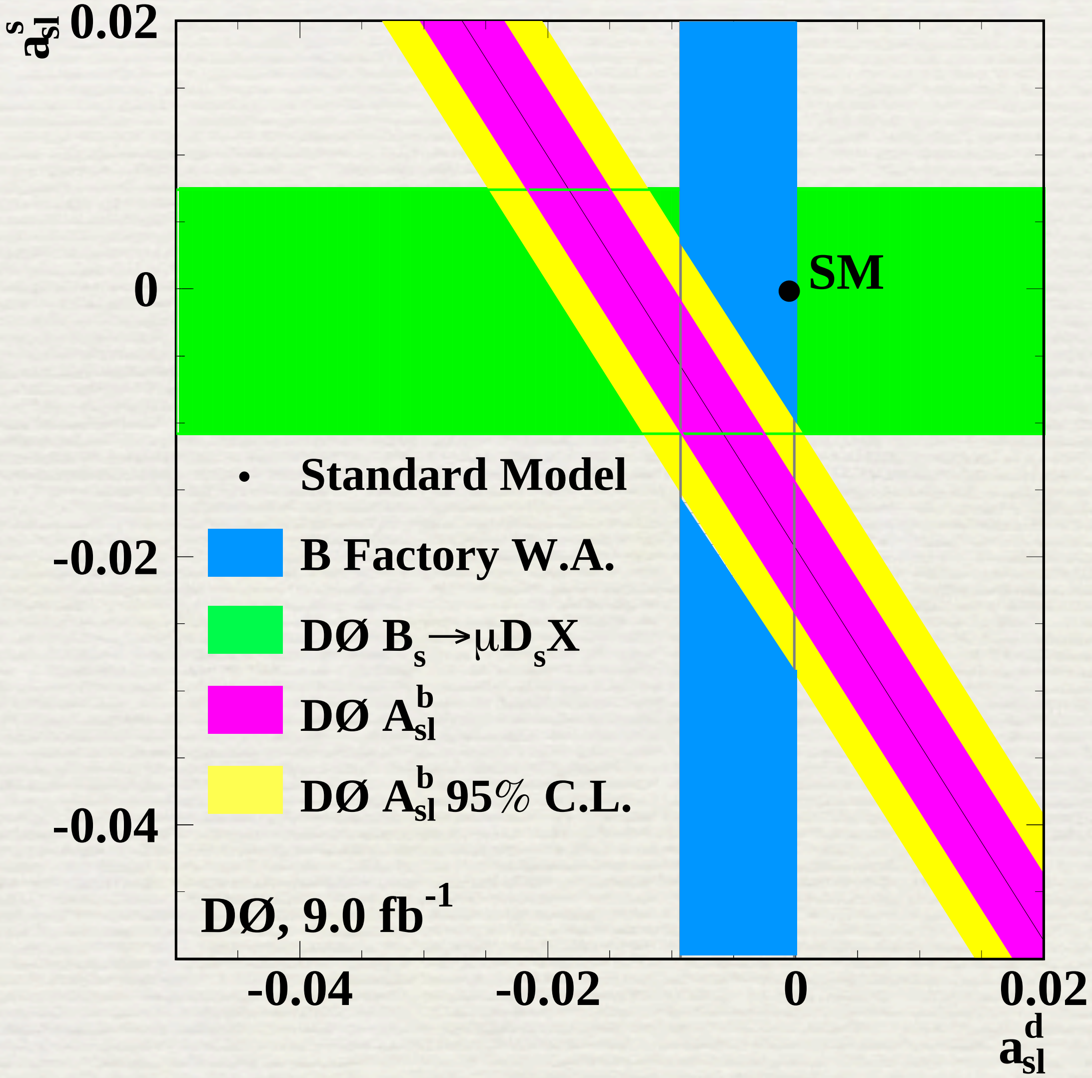
$$\boxed{A^b_{\rm SL}} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$= C_d \boxed{a^d_{fs}} + (1 - C_d) \boxed{a^s_{fs}},$$

$N_b^{\pm\pm} = \#$ of events with $\mu^\pm\mu^\pm$,

$C_d \approx [0.5, 0.6] \;\propto\;$ production B_d/B_s

[DØ 1106.6308]



SM Predictions vs. Data

	SM predictions [Lenz & Nierste, 1106.6308]	data before 2011
ΔM [ps^{-1}]	17.3 ± 2.6	17.70 ± 0.08 [CDF]
$\Delta\Gamma$ [ps^{-1}]	0.087 ± 0.021	$0.154^{+0.054}_{-0.070}$ (0.9σ) [CDF & DØ]
$\phi_{\psi\phi}$ [°]	-2.1 ± 0.1	-44^{+17}_{-21} (2.3σ) [CDF & DØ]
A^b_{SL} [10^{-4}]	-2.1 ± 0.4	-85 ± 28 (3.0σ) [DØ]
a^s_{fs} [10^{-5}]†	1.9 ± 0.3	-1200 ± 700 (1.7σ)

†calculated from measured A^b_{SL} & $a^s_{fs} = (-4.7 \pm 4.6) \times 10^{-3}$ from BaBar & Belle

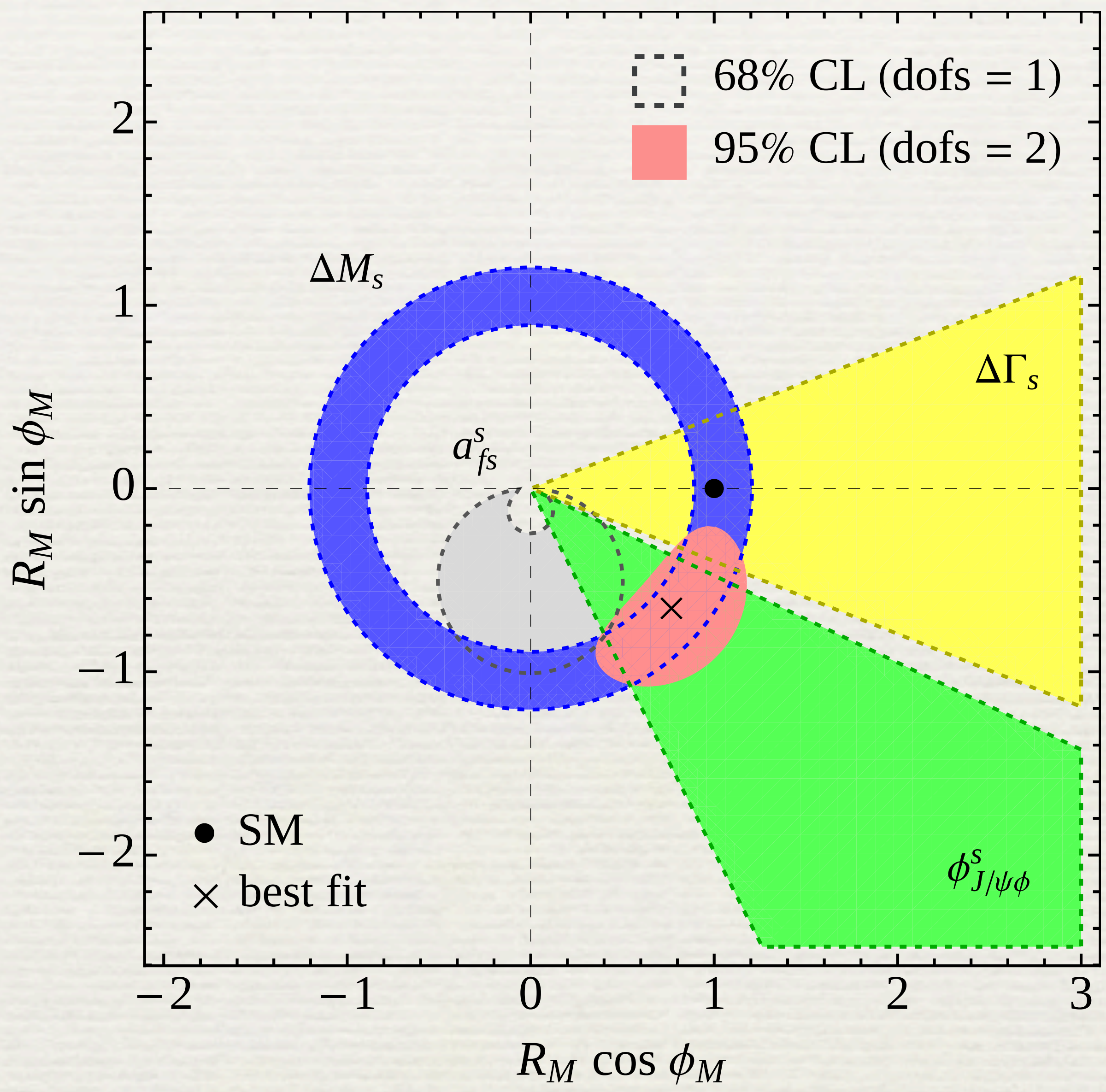
[HFAG, 1010.1589]

Implications of Before 2011 Data

- Assuming NP in M_{12} only, SM & models without a new phase (e.g. mSUGRA) are disfavored by more than 3σ

**[see e.g. UTfit, 0803.0659;
Lenz, Nierste & CKMfitter, 1008.1593; ...]**

[Bobeth & UH, 1109.1826]



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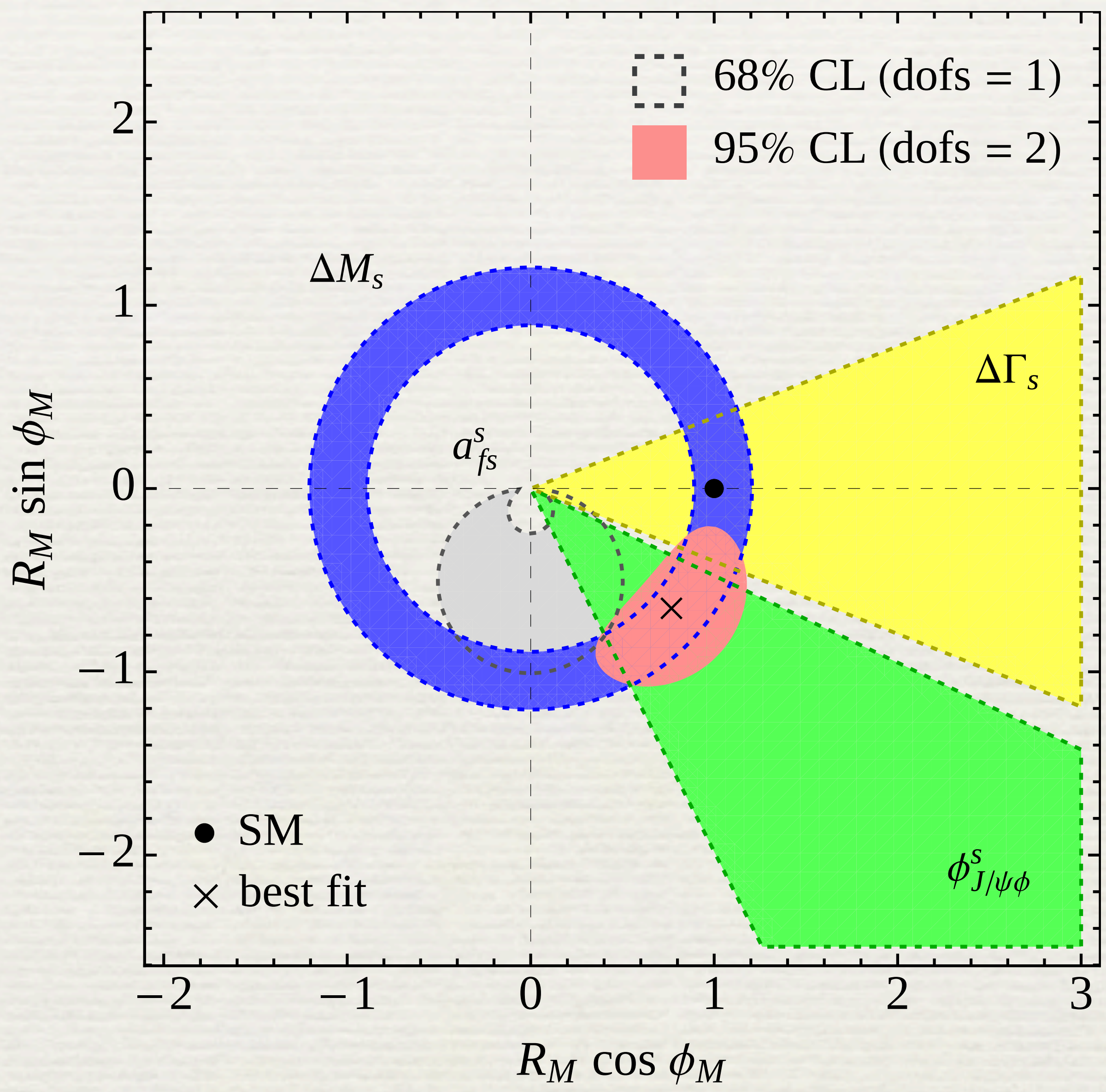
- But χ^2 of data not great. In fact, for NP in M_{12} only & $a^d_{fs} = (a^d_{fs})_{SM}$, A^b_{SL} measurement implies:

$$S_{\psi\phi} = \sin\phi_{\psi\phi} = -2.5 \pm 1.3$$

[see e.g. Dobrescu, Fox & Martin, 1005.4238; Ligeti et al., 1006.0432; ...]

[Bobeth & UH, 1109.1826]



If NP in M_{12}, Which Kind?

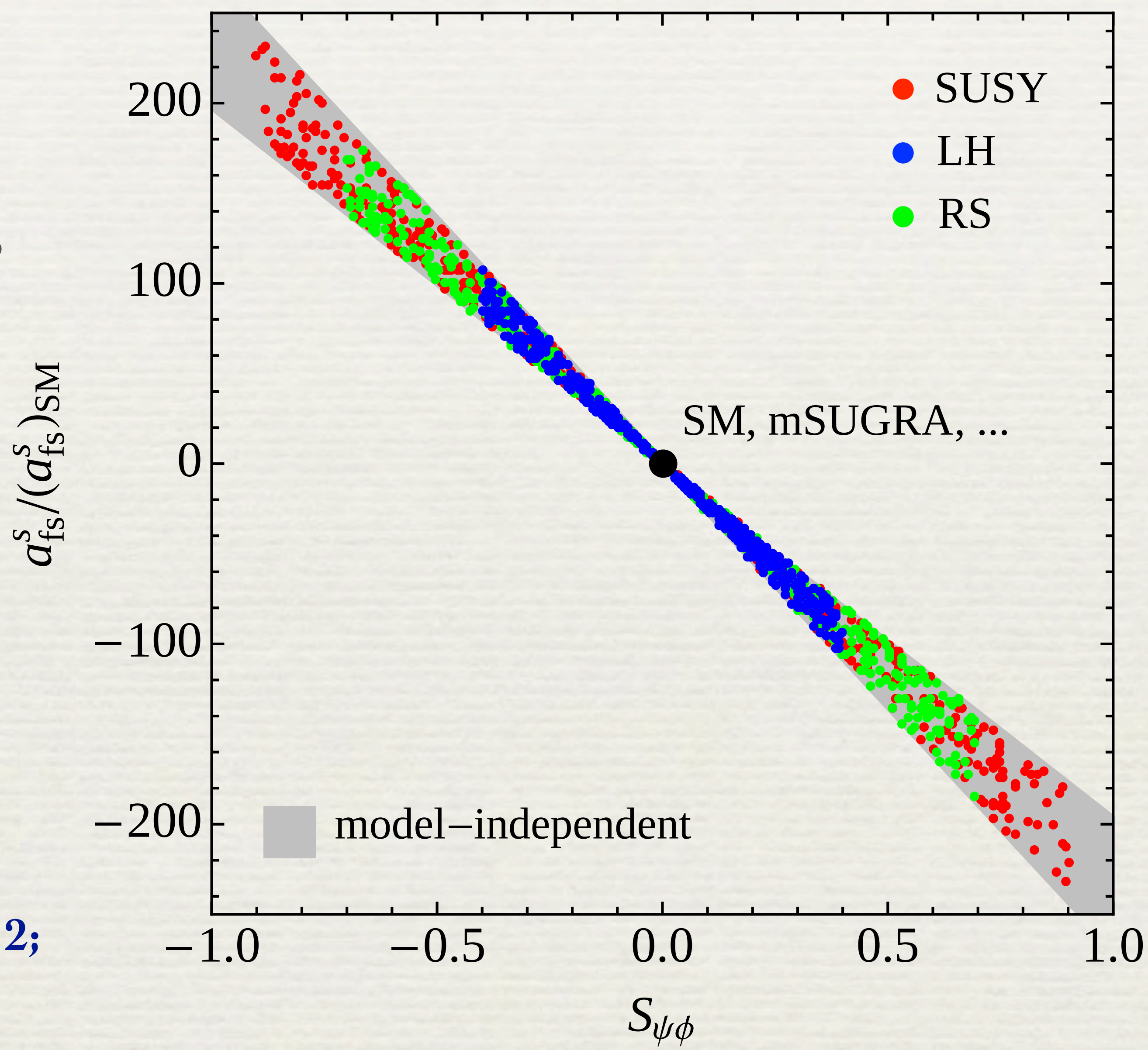
- In all NP models without direct CPV in decay (like SUSY, little Higgs (LH), Randall-Sundrum (RS) scenarios, ...), observables a_{fs}^s & $S_{\psi\phi}$ strongly correlated:

$$\frac{a_{fs}^s}{(a_{fs}^s)_{\rm SM}} \approx -240\,\frac{S_{\psi\phi}}{R_M}\,,$$

$$R_M = 1.05 \pm 0.16$$

[see e.g. Ligeti, Papucci & Perez, hep-ph/0604112; Blanke et al., 0805.4393, 0809.1073; Altmannshofer et al., 0909.1333; Casagrande et al., 0912.1625; ...]

[schematic plot]

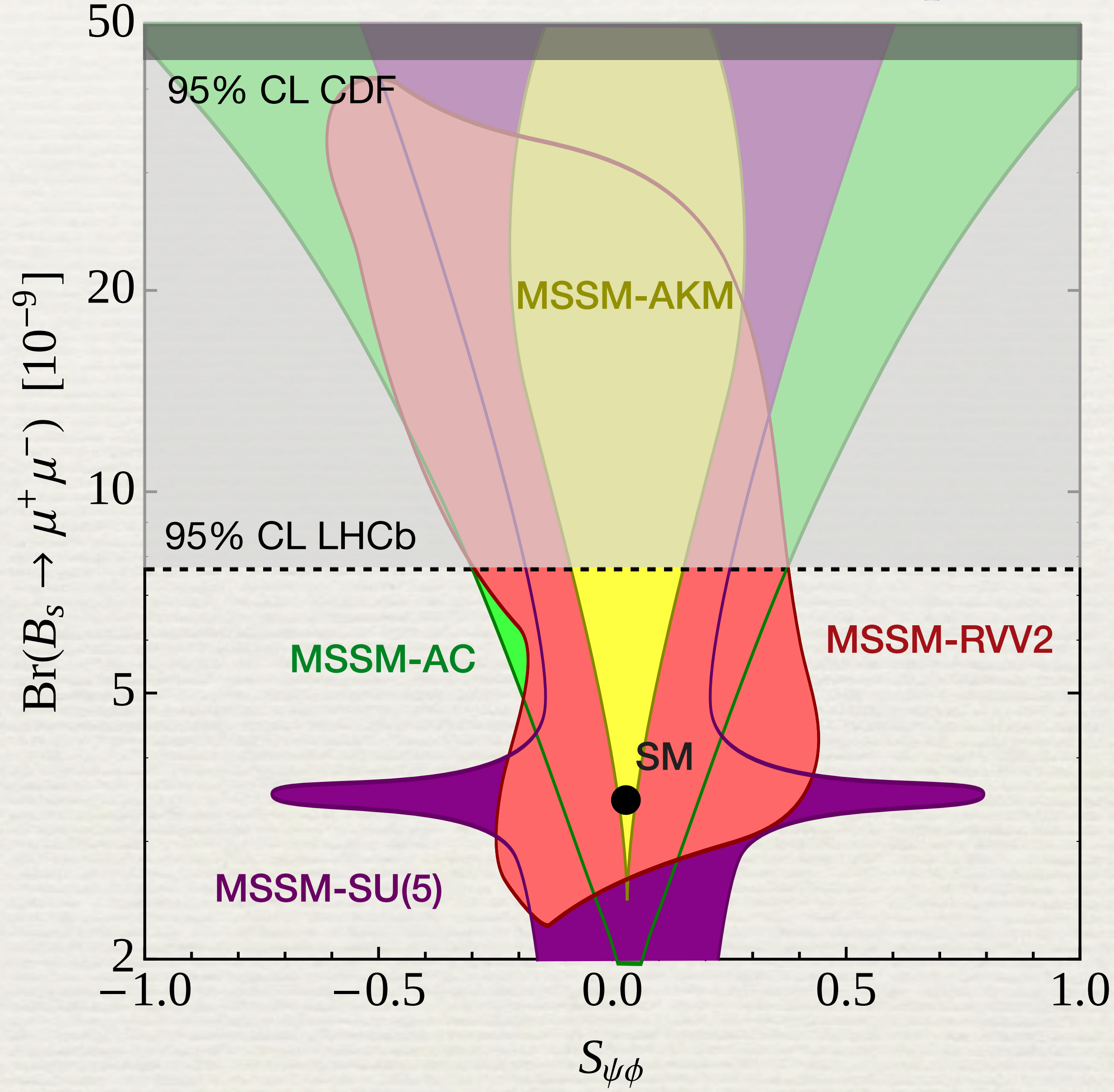


If NP in M_{12}, Which Kind?

- Even a clear signal of NP in B_s mixing will not allow to pinpoint nature of beyond-SM dynamics. One needs to study correlations with other channels such as $B_s \to \mu^+\mu^-$

  Unfortunately, given great performance of LHC, one starts walking on thin ice ...

[Straub, 1107.0266 (update)]



[see e.g. talk by Langenegger for CMS, http://indico.cern.ch/conferenceDisplay.py?confId=178806]

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†calculated from measured A^b_{SL} & $a^s_{fs} = (-4.7 \pm 4.6) \times 10^{-3}$ from BaBar & Belle

[HFAG, 1010.1589]

Implications of After 2011 Data

- For $(M_{12})_{NP} \neq 0$, $(\Gamma_{12})_{NP} = 0$, fit to new data only slightly better than SM hypothesis (χ^2/dofs = 3.3/2 vs. χ^2/dofs = 3.4/2)

[Bobeth & UH, 1109.1826;
also Lenz, Nierste & CKMfitter, 1203.0238]

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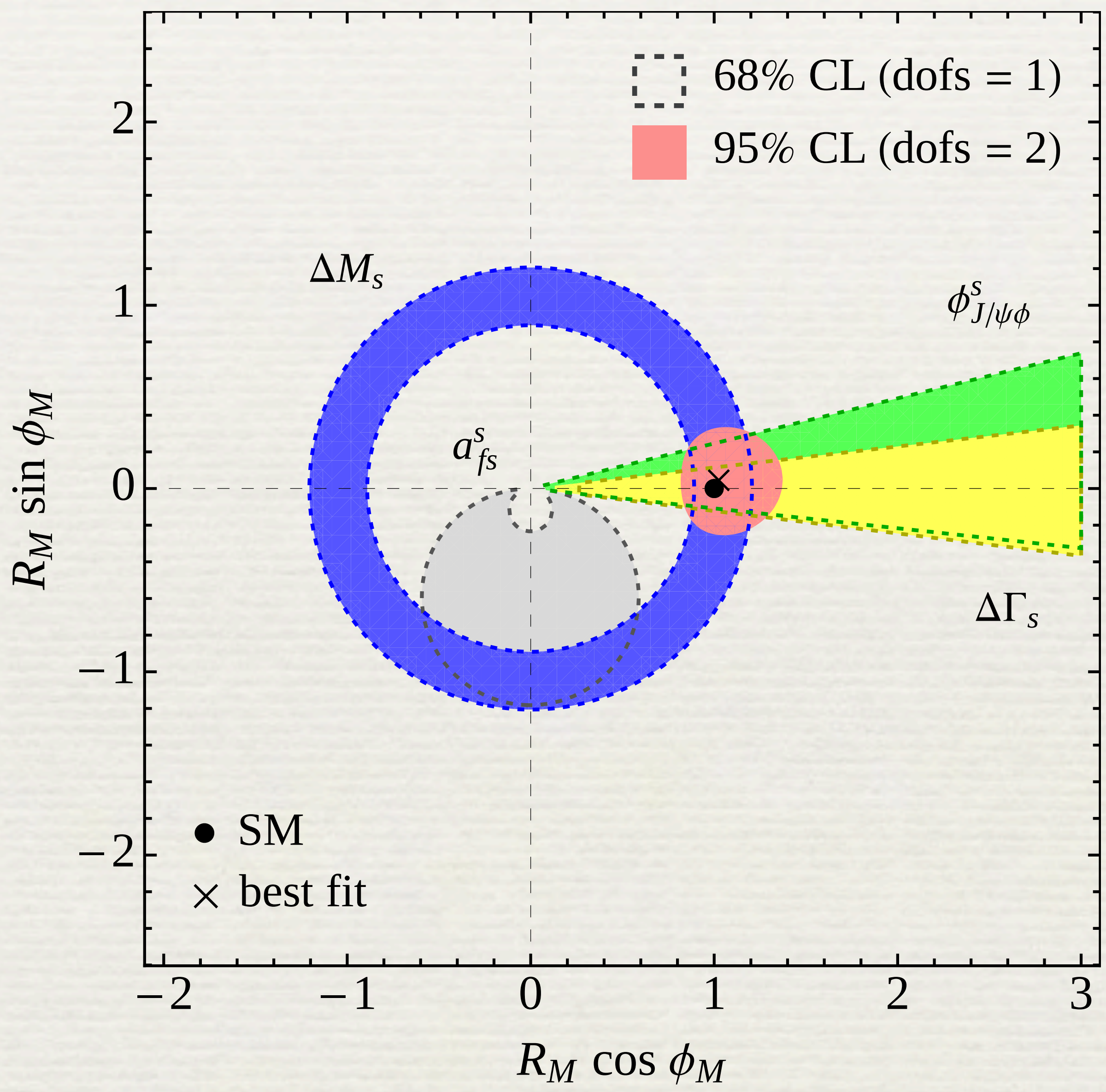

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- In fact, scenario with NP in Γ_{12} only, allows for a significantly better fit (χ^2/dofs = 0.2/2) than M_{12}-only assumption

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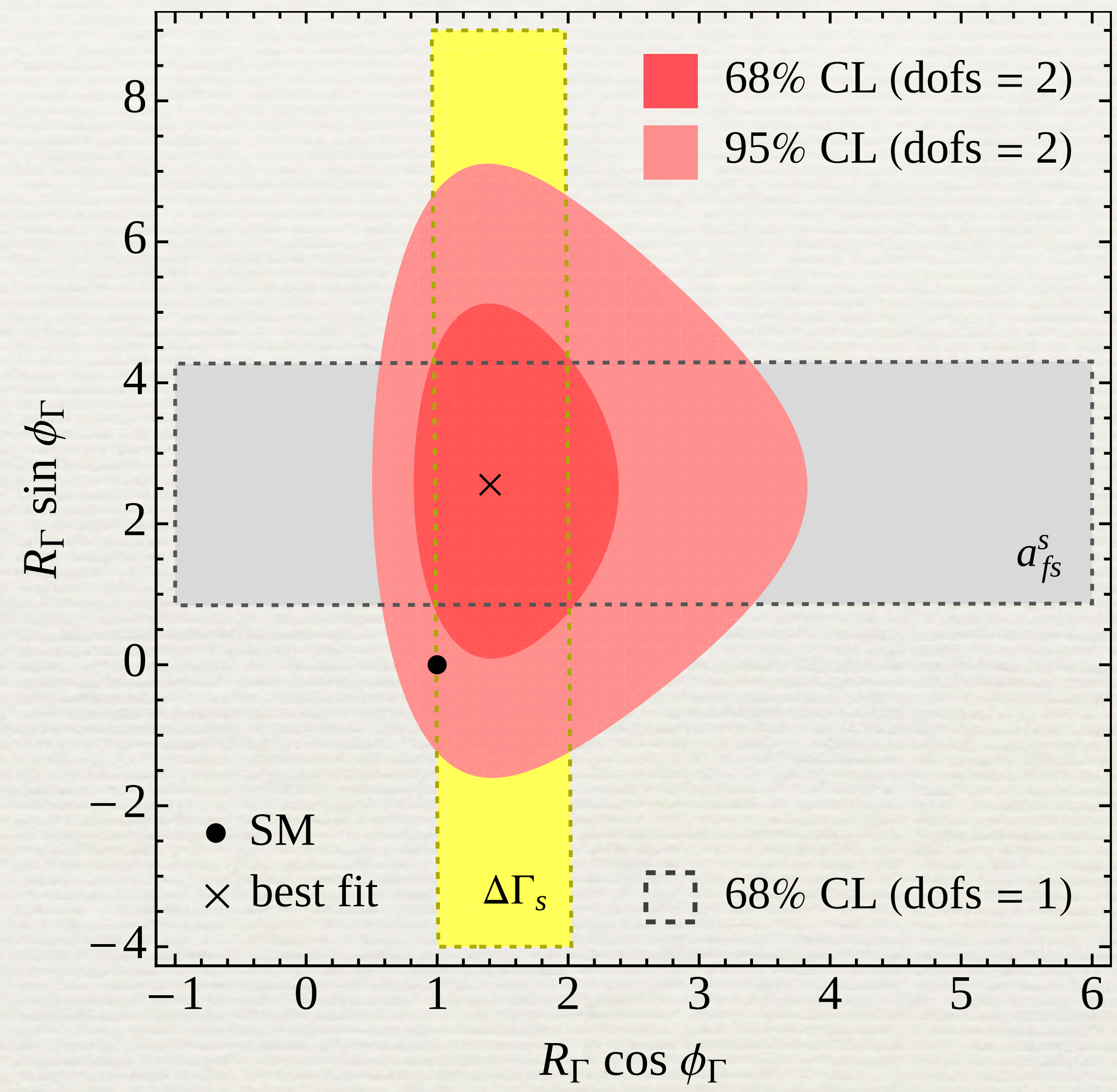

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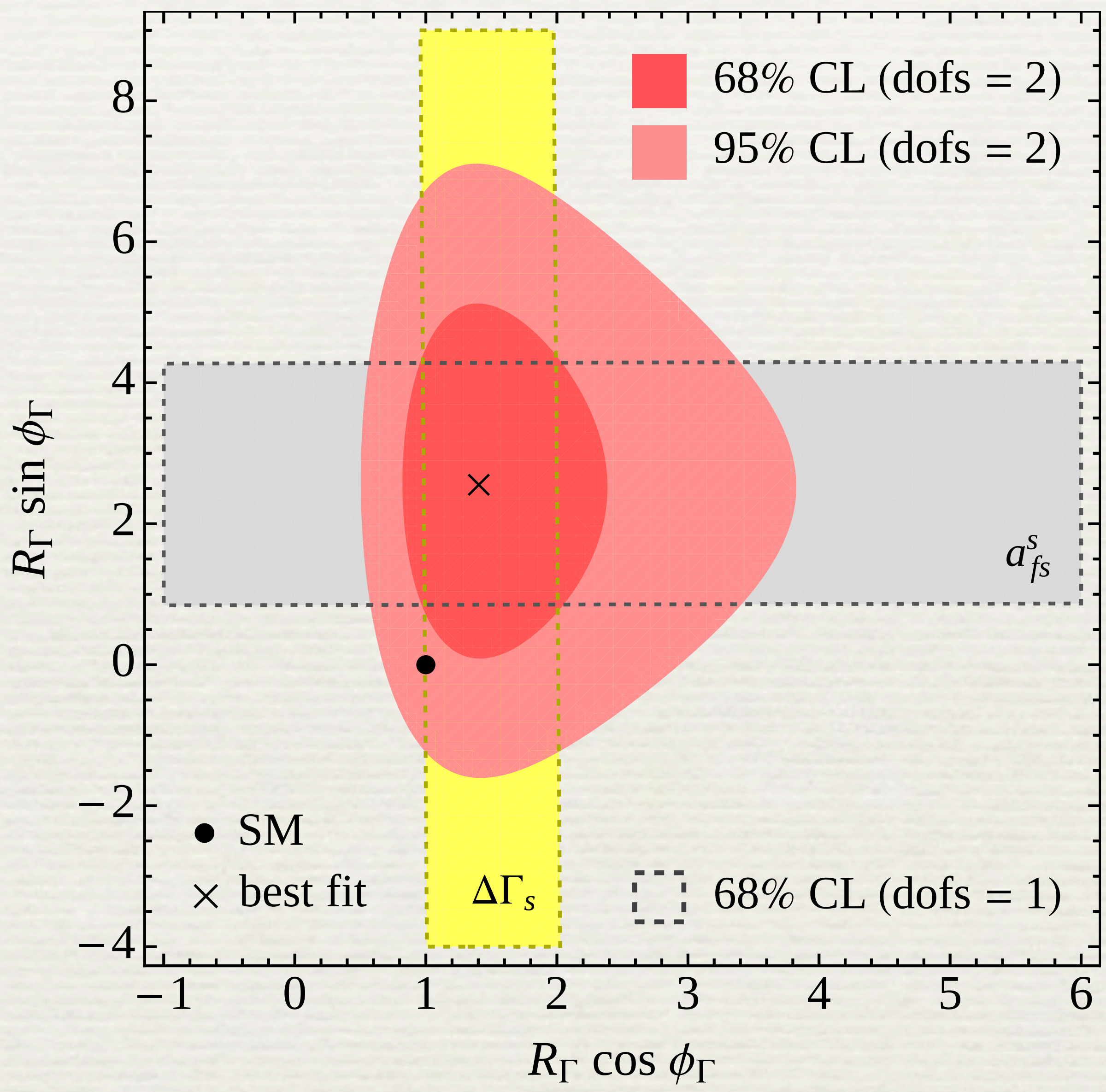

Given latter result, worthwhile to ask: how big can NP in Γ_{12} be?

NP in Γ_{12}: $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- While any operator $(\bar{s}b)f$ with f leading to a flavor-neutral final state of 2 or more fields & mass less than m_b can alter Γ_{12}, possible f's in practice limited, because $B_s \to f$ & $B_d \to X_s f$ channels with f involving light states strongly constrained. One exception are B decays to tau pairs

[see e.g. Dighe, Kundu & Nandi, 0705.4547, 1005.1629;
Bauer & Dunn, 1006.1629;
Alok, Baek & London, 1010.1333;
Kim, Seo & Shin, 1010.5123;
Bobeth & UH, 1109.1826; ...]

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- Can study size of NP in Γ_{12} using an effective theory containing a complete set of $(\bar{s}b)(\tau\bar{\tau})$ operators (A, B = L, R):

$$\mathcal{L}_{\rm eff}^{\rm NP} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i Q_i \,,$$

$$\boxed{Q_{S,AB} = (\bar{s} P_A b)(\bar{\tau} P_B \tau)\,,}$$

$$\boxed{Q_{V,AB} = (\bar{s} \gamma_\mu P_A b)(\bar{\tau} \gamma^\mu P_B \tau)\,,}$$

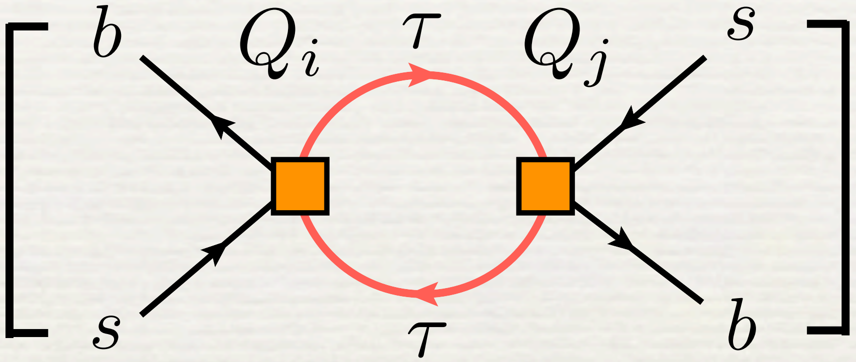
$$P_{L,R} = (1 \mp \gamma_5)/2\,,$$

$$\boxed{Q_{T,A} = (\bar{s} \sigma_{\mu\nu} P_A b)(\bar{\tau} \sigma^{\mu\nu} P_A \tau)}$$

NP in Γ_{12}: $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- Assuming single operator dominance, calculation of

$$(\Gamma_{12})_{\text{NP}} \propto C_i C_j \ \text{Im}$$



translates into

$$\boxed{(R_\Gamma)_{S,AB} < 1 + (0.4 \pm 0.1)\, |C_{S,AB}|^2 \ ,}$$

$$\boxed{(R_\Gamma)_{V,AB} < 1 + (0.4 \pm 0.1)\, |C_{V,AB}|^2 \ ,}$$

$$\boxed{(R_\Gamma)_{T,A} < 1 + (0.9 \pm 0.2)\, |C_{T,A}|^2}$$

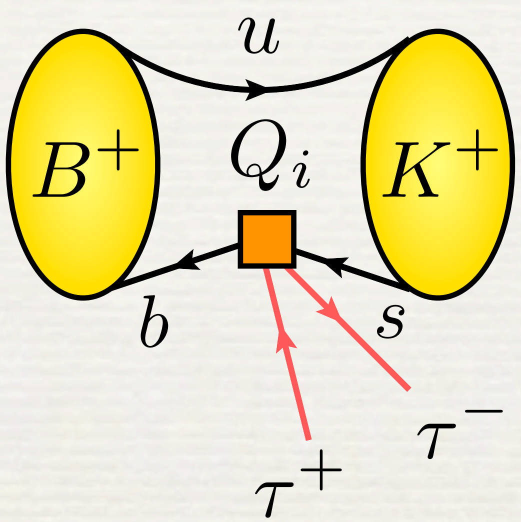
which implies that C_i's have to be around 1 (i.e. size of leading SM current-current coefficient) or larger to describe data well

Bounds on $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- Direct constraints arise from

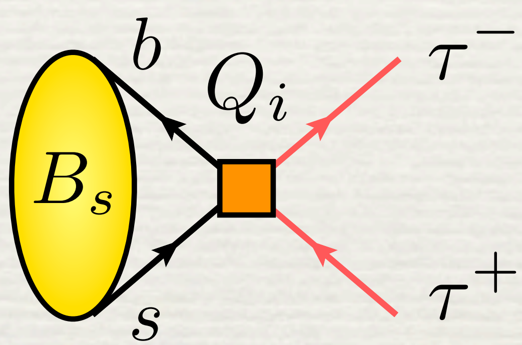
  - $\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$ (90% CL)

    [Flood for BaBar, PoS ICHEP2010, 234 (2010)]



  - $\mathrm{Br}(B_s \to \tau^+\tau^-)$, $\mathrm{Br}(B \to X_s\tau^+\tau^-) \lesssim 5\%$

    [see e.g. Grossman, Ligeti & Nardi, hep-ph/9607473; Dighe, Kundu & Nandi, 1005.4051]



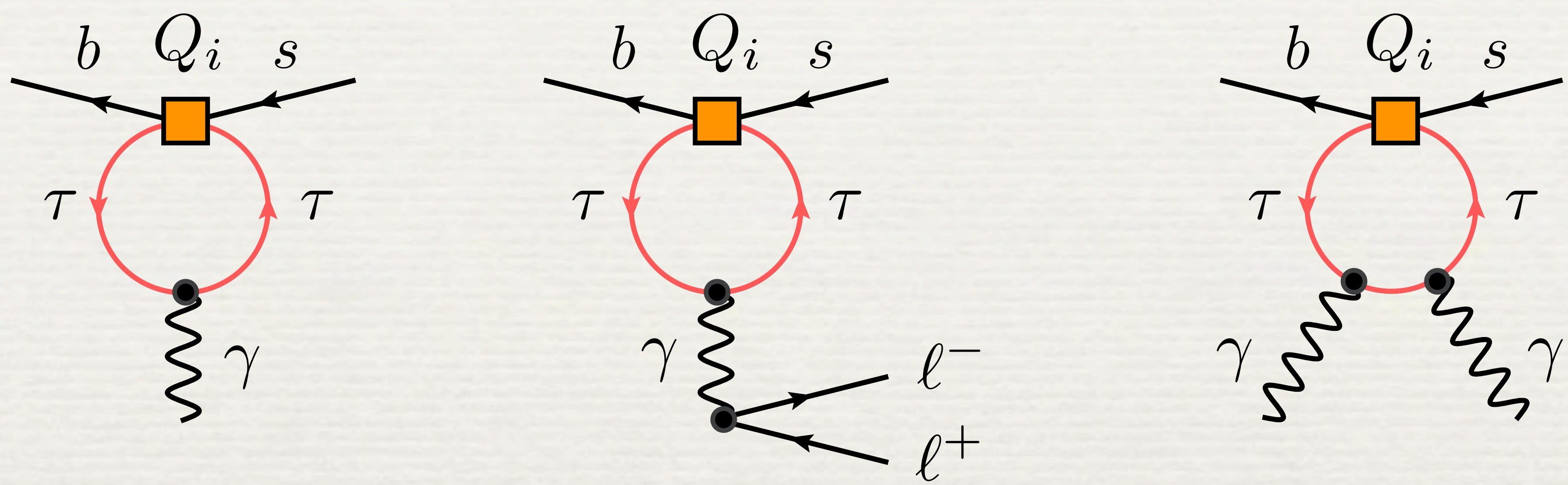
Bounds on purely leptonic & inclusive semileptonic Br's derived from ratio of $B_{d,s}$ lifetimes† & LEP searches of B decays with missing energy. Similar limits follow from charm counting

†bound improved to around 3.5% by LHCb measurement of $\Delta\Gamma$

[LHCb-CONF-2011-049]

Bounds on $(\bar{s}b)(\bar{\tau}\tau)$ Operators

- Indirect constraints due to operator mixing & matrix elements:†



$$Q_{T,R} \to Q_7\,, \qquad Q_{V,LA} \to Q_9\,, \qquad Q_{S,AB} \to \vec{\epsilon}_1 \cdot \vec{\epsilon}_2\,,$$

$$Q_{T,L} \to Q_7' \qquad Q_{V,RA} \to Q_9' \qquad Q_{S,AB}, Q_{V,AB} \to \vec{\epsilon}_1 \times \vec{\epsilon}_2$$

Bounds on C_i's derived by taking into account measurements of $B \to X_s\gamma$ (Br), $B \to K^*\gamma$ (Br, S, A_I), $B \to X_s l^+ l^-$ (Br), $B \to K l^+ l^-$ (Br), $B \to K^* l^+ l^-$ (Br, A_{FB}, F_L) & upper limit on $B_s \to \gamma\gamma$ (Br)

† $Q_{S,AB}$ does not mix into $b \to s\gamma$, l^+l^- but has non-zero $b \to s\gamma\gamma$ elements

Upper Bounds on Wilson Coefficients

	limit on $C_i(m_b)$	limit on Λ_{NP} for $C_i^{\Lambda} = 1$	process
S, AB	< 0.8	1.3 TeV	$B^+ \to K^+\tau^+\tau^-$
V, AB	< 0.8	1.0 TeV	$B^+ \to K^+\tau^+\tau^-$
T, L	< 0.06	3.2 TeV	$b \to s\gamma, l^+l^-$
T, R	< 0.09	2.7 TeV	$b \to s\gamma, l^+l^-$

- Assuming single operator dominance & complex C_i, one obtains quite loose bounds on scalar & vector operators, whereas tensor contributions are severely constrained, mostly due to $B \to X_s\gamma$

After 2011 Data: $(\Gamma_{12})_{NP}$ Due to $b \to s\tau^+\tau^-$

- Upper limit on C_i translate into:

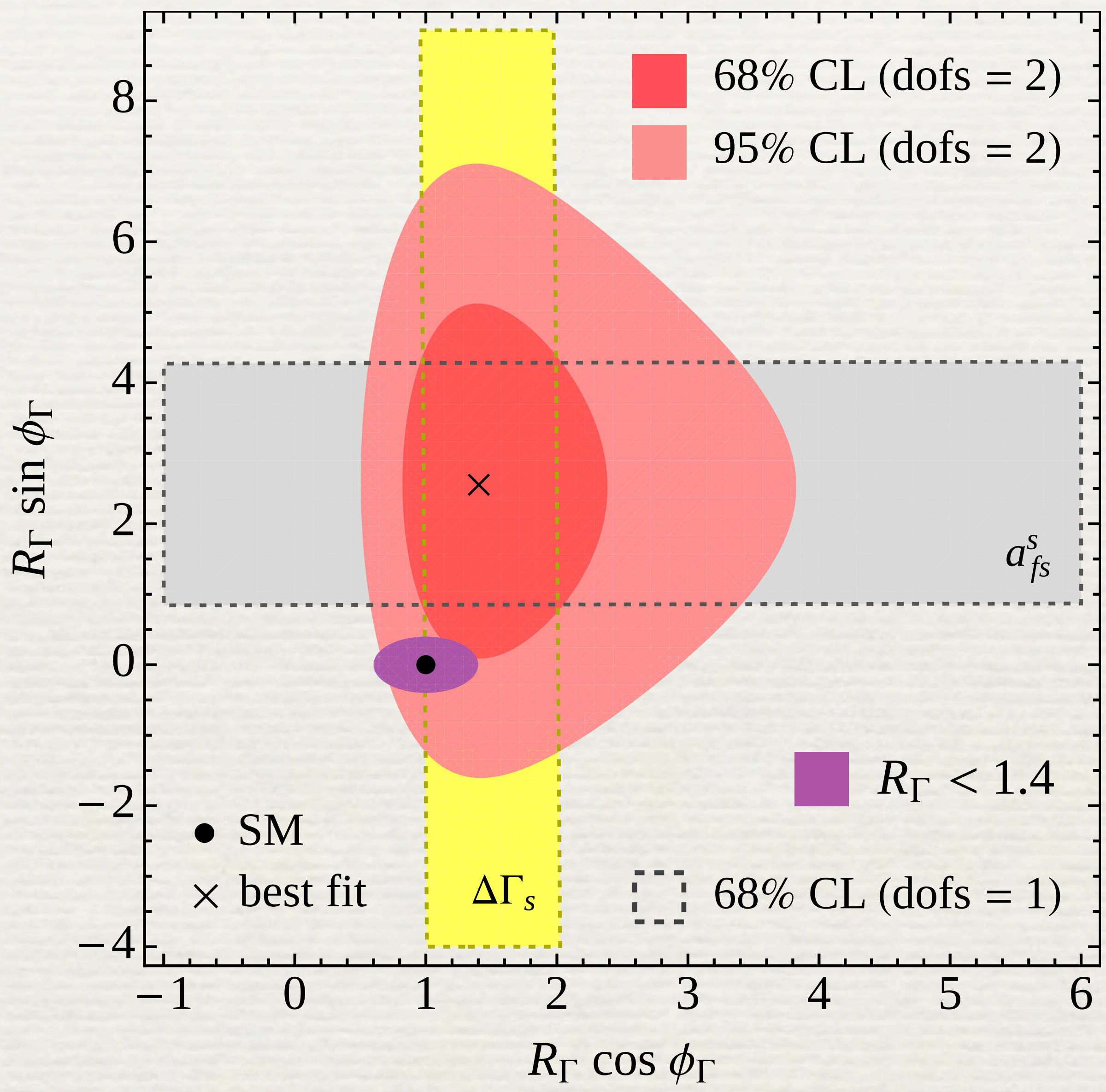
$$\boxed{(R_\Gamma)_{S,AB} < 1.4\,,}$$

$$\boxed{(R_\Gamma)_{V,AB} < 1.3\,,}$$

$$\boxed{\begin{aligned}(R_\Gamma)_{T,L} &< 1.004\,,\\ (R_\Gamma)_{T,R} &< 1.008\end{aligned}}$$

Largest correction due to scalar operator can change $|\Gamma_{12}|_{SM}$ by up to 40%. Easing tension in B-meson sector is hence possible (χ^2/dofs > 2.2/2), but not a full resolution of issue

[Bobeth & UH, 1109.1826]



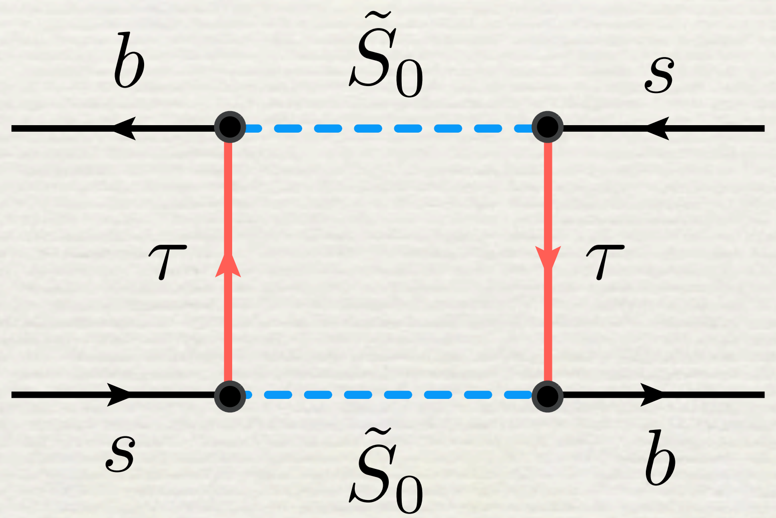
Lepto-Quark Contributions to Γ_{12}

- For SU(2) singlet scalar lepto-quarks (LQs) relevant coupling

$$\mathcal{L}_{\rm LQ} \ni (\lambda_{R\tilde{S}_0})_{ij}\left(\bar{d}^c_j P_R e_i\right)\tilde{S}_0 + \text{h.c.}$$

leads to $\Delta B = 1$ & $\Delta B = 2$ interactions

$$\mathcal{L}_{\rm eff} \ni -\frac{(\lambda_{R\tilde{S}_0})_{32}(\lambda_{R\tilde{S}_0})_{33}}{2M^2_{\tilde{S}_0}}\, Q_{V,RR}$$

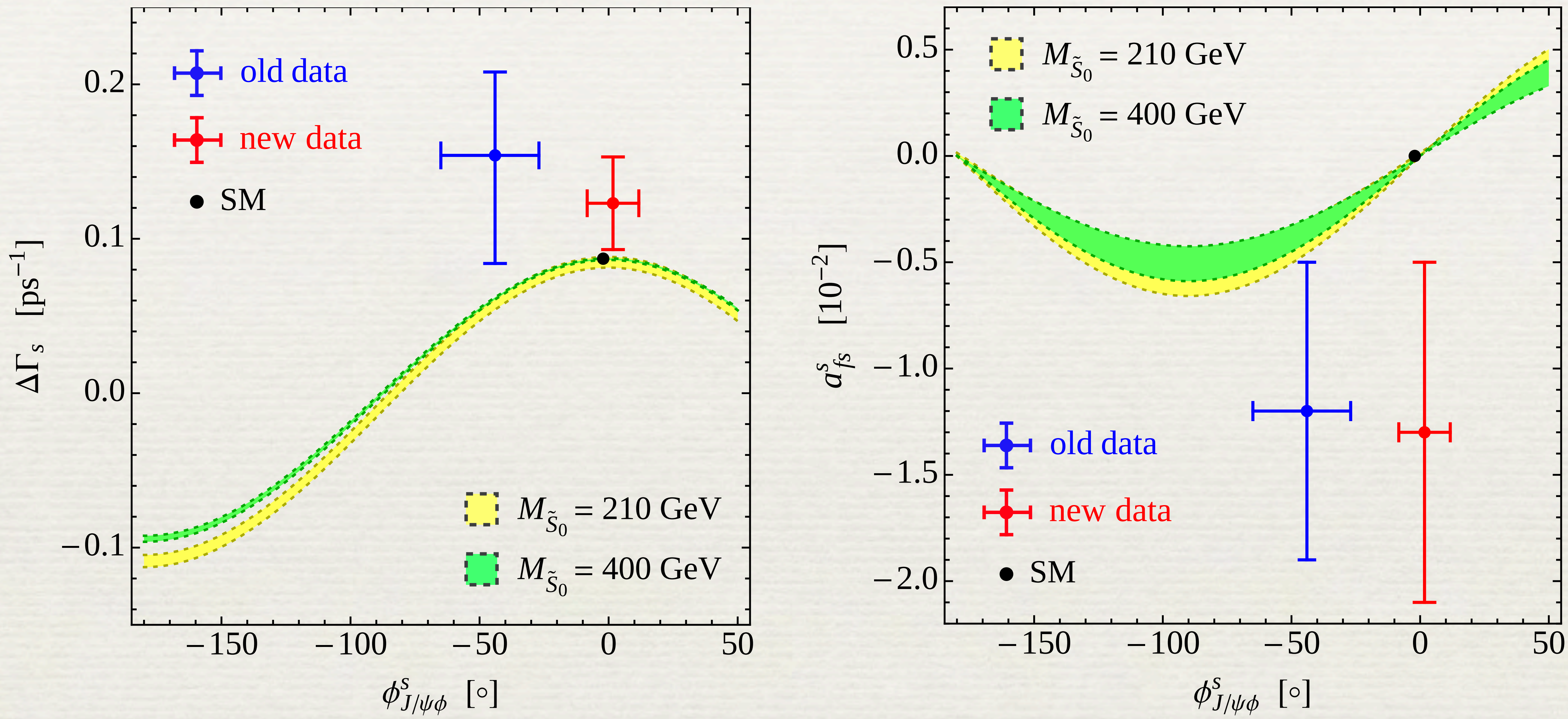


which give a real ratio (btw. $r_{\rm SM} \approx -200$)

$$\boxed{r_{\rm LQ} = \frac{(M_{12})_{\rm LQ}}{(\Gamma_{12})_{\rm LQ}} = 2084\left(\frac{M^2_{\tilde{S}_0}}{250\,\text{GeV}}\right)}$$

Predictions for SU(2) Singlet Scalar LQs

[Bobeth & UH, 1109.1826]



- Even a light LQ fails to describe data & parameter space shrinks further for heavier LQs. Visible cosine-, sine-like correlations & $\Delta\Gamma < (\Delta\Gamma)_{SM}$ model-independent feature

No New Physics in B_s Mixing & Decay

Ulrich Haisch
University of Oxford

Recontres de Moriond EW 2012,
La Thuile, Aosta Valley, Italy,
3-10 March 2012

Best-Fit Solutions to Data

	before 2011	after 2011
R_M	1.05 ± 0.16	1.05 ± 0.16
ϕ_M [°]	-46 ± 19	1.5 ± 10.0
R_Γ	3.3 ± 1.5	3.4 ± 1.7
ϕ_Γ [°]	7 ± 30	58 ± 23

- Even before measurements of B_s-mixing observables by LHCb, a perfect 4-parameter fit ($\chi^2 = 0$) to data required large corrections in Γ_{12}. New data set favors both enhanced magnitude R_Γ & phase ϕ_Γ

Details on Bounds on Wilson Coefficients

$C_i(m_b)$	$B^+ \to K^+\tau^+\tau^-$	$B_s \to \tau^+\tau^-$	$B \to X_s\tau^+\tau^-$	$b \to s\gamma, l^+l^-$	$B_s \to \gamma\gamma$
S, AB	< 0.8	$\lesssim 0.7$	$\lesssim 9.6$	—	$< 3.4, 2.3$
V, AB	< 0.8	$\lesssim 1.4$	$\lesssim 4.8$	$< 1.1, 1.0$	< 5.9
T, A	< 0.4	—	< 1.4	$< 0.06, 0.09$	—
7	—	—	—	< 0.29	< 2.2
$7'$	—	—	—	< 0.19	< 1.9
9	—	—	—	< 2.0	—
$9'$	—	—	—	< 1.0	—

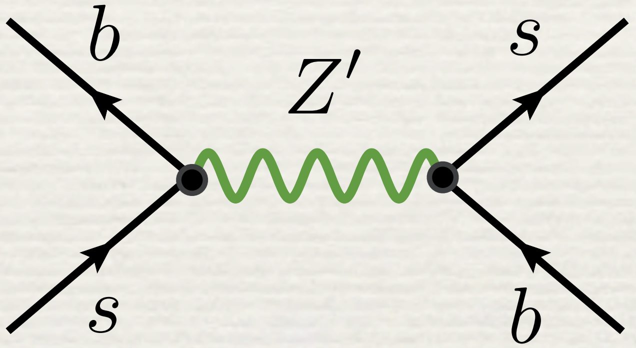
Z' Contributions to Γ_{12}

- For left-handed Z' boson relevant couplings

$$\mathcal{L}_{Z'} \ni \frac{g}{\cos\theta_W} \left[\left(\kappa_{sb}^L \, \bar{s}\gamma^\mu P_L b + \text{h.c.} \right) + \kappa_{\tau\tau}^L \, \bar{\tau}\gamma^\mu P_L \tau \right] Z'_\mu$$

give rise to $\Delta B = 1$ & $\Delta B = 2$ interactions

$$\mathcal{L}_{\text{eff}} \ni -\frac{8G_F}{\sqrt{2}} \frac{M_Z^2}{M_{Z'}^2} \kappa_{sb}^L \, \kappa_{\tau\tau}^L \, Q_{V,LL}$$

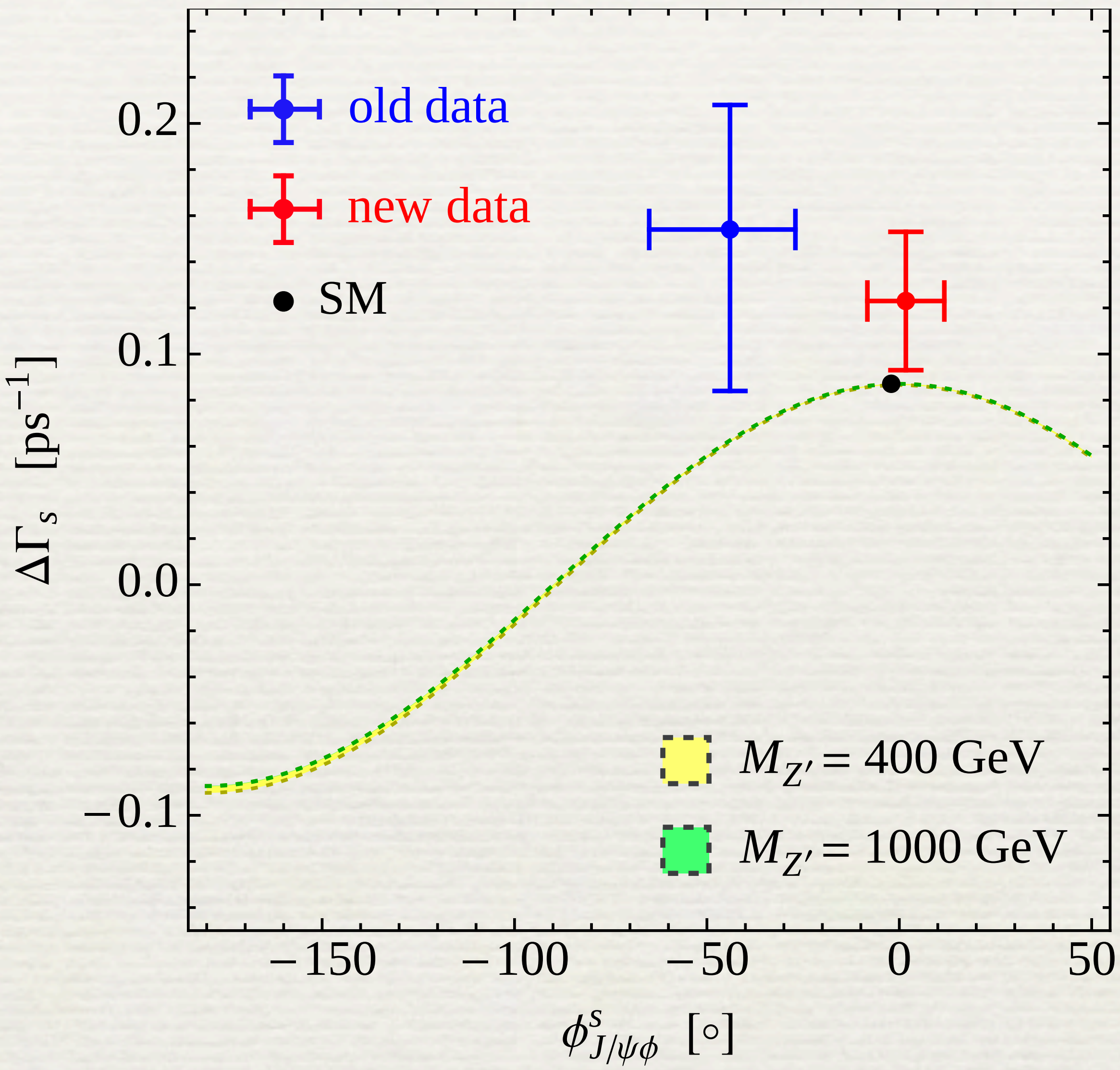


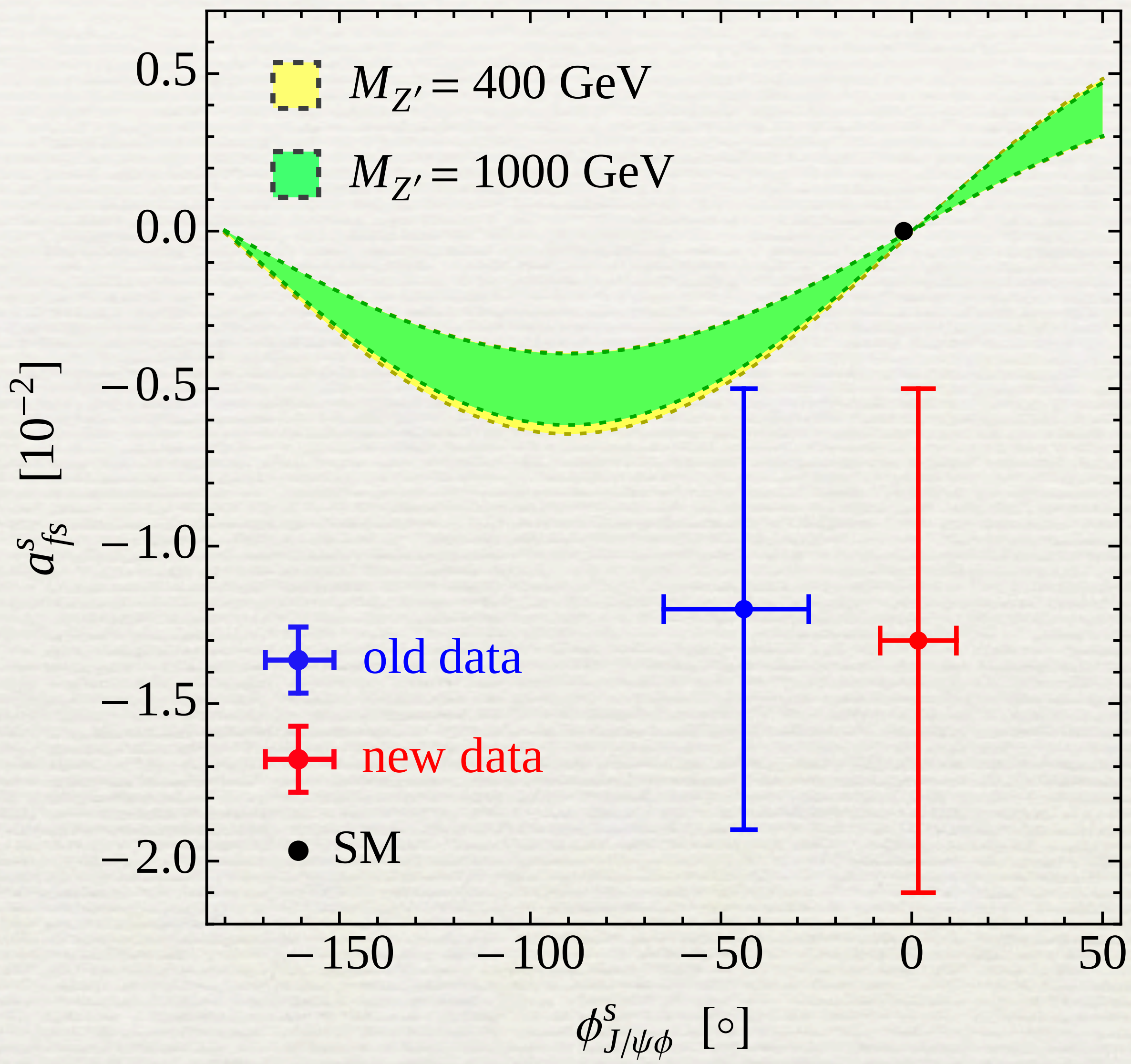
which again produce a real ratio

$$\boxed{r_{Z'} = \frac{(M_{12})_{Z'}}{(\Gamma_{12})_{Z'}} = 6.0 \cdot 10^5 \left(\frac{M_{Z'}}{250\,\text{GeV}} \frac{1}{\kappa_{\tau\tau}^L} \right)^2}$$

Predictions for Left-handed Z'

[Bobeth & UH, 1109.1826]





- Left-handed Z' provides an even worse description of data than LQs. Model-independent correlations & $\Delta\Gamma < (\Delta\Gamma)_{SM}$ also present in case of new neutral vector boson

Further Comments on NP in $\Gamma_{12}^{s,d}$

- Bounds on $(\bar{s}b)(\bar{\tau}\mu)$ are stronger by roughly a factor of 7 than those on $(\bar{s}b)(\bar{\tau}\tau)$ operators, since $\mathrm{Br}(B^+ \to K\tau^\pm\mu^\mp) < 7.7 \cdot 10^{-5}$ compared to $\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$. Hence, contributions from $(\bar{s}b)(\bar{\tau}\mu)$ operators cannot improve fit to B_s data notable

- An contribution from $(\bar{d}b)(\bar{\tau}\tau)$ operators to Γ_{12}^{d} large enough to explain data excluded by bound $\mathrm{Br}(B \to \tau^+\tau^-) < 4.1 \cdot 10^{-3}$. Case of $\tau^\pm\mu^\mp$ final state even less favorable

- My naive guess is that $(\bar{d}b)(\bar{c}c)$ operators are heavily constrained (should be numerically smaller than QCD/electroweak penguins in SM) by exclusive B decays & thus also cannot resolve tension in B-mixing sector. A dedicated analysis is however missing