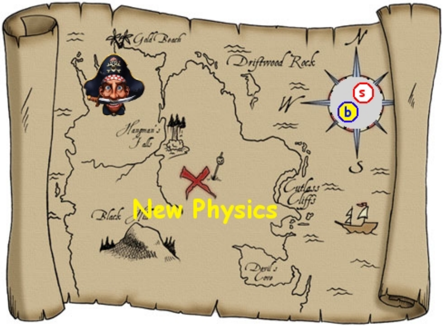
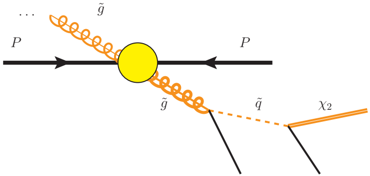
Lessons from B_s Lifetimes

Rob Knegjens



The **search** for **New Physics**

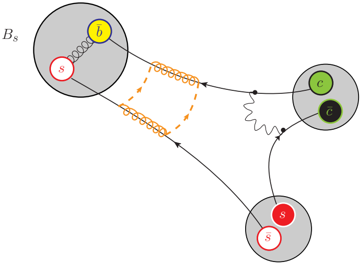


Direct searches

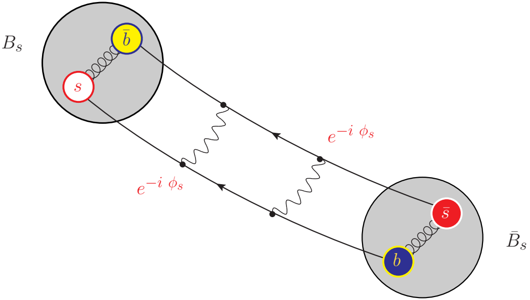
"The high energy frontier"

Indirect searches

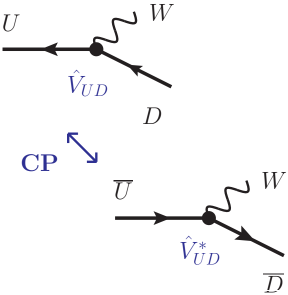
"The precision frontier"



A **sensitive probe** of **New CP Violating Physics**



Standard Model:



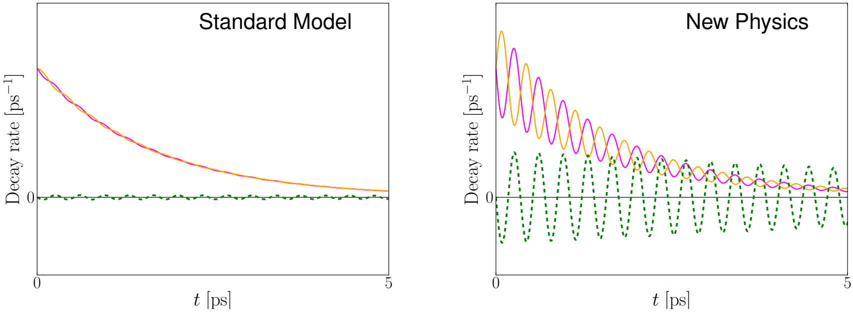
$$2\arg(V_{ts}\ V_{tb}{}^*) = -2.1^\circ$$

B_s–$\bar{B}_s$ **Mixing Phase:** $\phi_s \equiv -2.1^\circ +$ 

Time-dependent **tagged** CP measurement

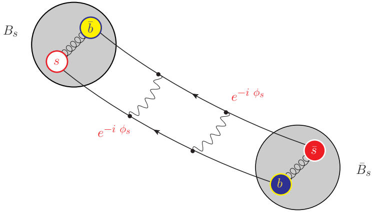
Tag $\equiv$ identify if B_s or $\bar{B}_s$

$$A_{\rm CP} = \frac{\Gamma\left(B_s(t) \to f\right) \; - \; \Gamma\left(\bar{B}_s(t) \to f\right)}{\Gamma\left(B_s(t) \to f\right) \; + \; \Gamma\left(\bar{B}_s(t) \to f\right)}$$



CP violation in interference

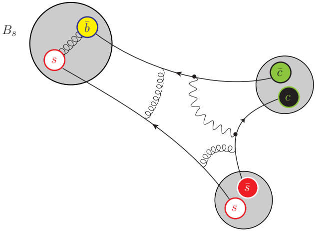
B_s^0–$\bar{B}_s^0$ Mixing



$\Delta M_s,\ \Delta\Gamma_s \equiv \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}$

$\left.\phi_s\ \right\}$

Decay Mode



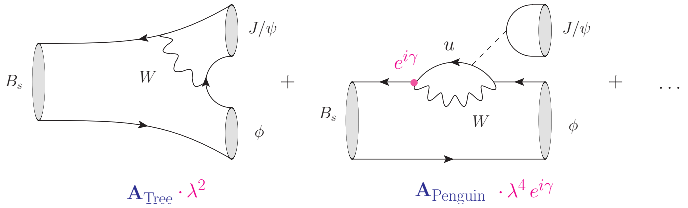
$\Delta\phi,\ C$ (direct CPV)

hadronic physics }

$$A_{\mathrm{CP}} = \text{function}\left(\Delta M_s, \Delta\Gamma_s,\ \boxed{\phi_s + \Delta\phi},\ C\right)$$

The **flagship Decay Mode**: $B_s/\bar{B}_s \to J/\psi\ \phi$

tagged analysis : $A_{\mathrm{CP}} = \text{function}\left(\Delta M_s, \Delta\Gamma_s, \boxed{\phi_s + \Delta\phi}, C\right)$



$$\boxed{\Delta\phi \sim \underbrace{\lambda^2}_{3^\circ} \sin\gamma \left(\frac{A_{\mathrm{Penguin}}}{A_{\mathrm{Tree}}}\right) + \mathcal{O}(\lambda^4)}$$

in SM : $\gamma \sim 70^\circ$

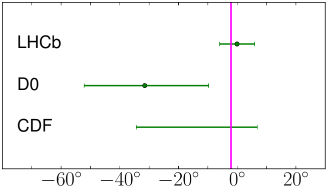
and similarly $C \propto \lambda^2$

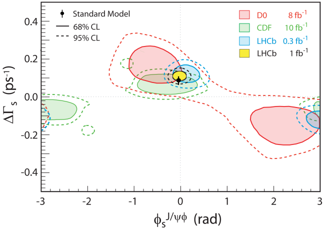
S. Faller, R. Fleischer and T. Mannel, Phys.Rev. D79 (2009) 014005

The **flagship** **Decay Mode**: $B_s / \bar{B}_s \to J/\psi\ \phi$

Latest results from Moriond 2012:

$\phi_s + \Delta\phi^{\lambda}_{J/\psi\phi}$





CP observables → SM predictions

- Possible to distinguish **smallish New Physics**?

$\Delta\phi \in [-3^\circ, 3^\circ]$

CP observables → SM predictions

Disentangle New Physics 

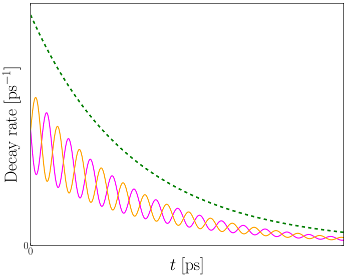
from **SM Hadronic Physics** 

and  Find **Complementary Analyses** for determining ϕ_s

- **In pursuit of new physics with $B_s \to K^+K^-$** R. Fleischer, RK (arXiv:1011.1096)
- **Anatomy of $B^0_{s,d} \to J/\psi\, f_0(980)$** R. Fleischer, RK, G. Ricciardi (arXiv:1109.1112)
- **Effective lifetimes of B_s decays and their constraints on the B^0_s–$\bar{B}^0_s$ mixing parameters** R. Fleischer, RK (arXiv:1109.5115)
- **Exploring CP Violation and η–η' Mixing with the $B^0_{s,d} \to J/\psi\eta^{(\prime)}$ Systems** R. Fleischer, RK, G. Ricciardi (arXiv:1110.5490)

A time-dependent **untagged** analysis?

$$\langle\Gamma\rangle \equiv \Gamma(B_s(t) \to f) \; + \; \Gamma(\bar{B}_s(t) \to f)$$



Fitting $\frac{1}{\tau} e^{-t/\tau}$ - **effective lifetime**:

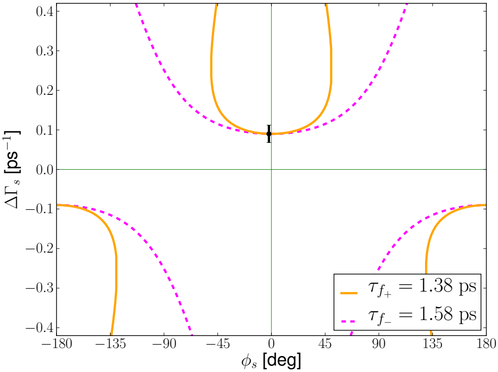
$$\tau_f \equiv \frac{\int_0^\infty \; t \; \langle\Gamma\rangle \; dt}{\int_0^\infty \; \langle\Gamma\rangle \; dt}$$

$$= \text{function}\left(\Delta\Gamma_s, \; \boxed{\phi_s + \Delta\phi_f}, \; C_f\right)$$

Contours in the ϕ_s–$\Delta\Gamma_s$ plane

Assume : $\Delta\phi_f = 0,\ C_f = 0 \quad \Longrightarrow \quad \boxed{\tau_f = \text{function}\,(\Delta\Gamma_s,\ \phi_s)}$

Different contours: $\quad CP\,|f_+\rangle = +\,|f_+\rangle, \quad CP\,|f_-\rangle = -\,|f_-\rangle$



Measured Effective Lifetimes

Final state:

- CP Even $B_s \to K^+K^-$: *LHCB-CONF-2012-001*

$$\tau_{K^+K^-} = [1.468 \pm 0.046]\ \mathrm{ps}$$

- CP Odd $B_s \to J/\psi f_0(980)$: *LHCb, 1204.5675*

$$\tau_{J/\psi f_0} = [1.71 \pm 0.03]\ \mathrm{ps}$$

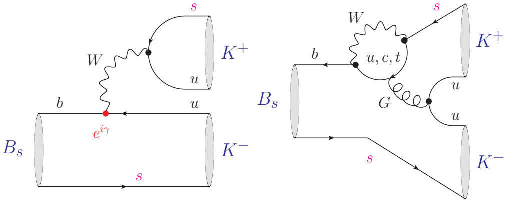
But...

$$\boxed{\Delta\phi \neq 0,\ \ C \neq 0}$$

...CP violation in **Decay Modes**

Controlling the **CP Even** Decay Mode

$$B_s \to K^+ K^-$$



$$\boxed{\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ}$$

$$C_{K^+K^-} = 0.09 \pm 0.05$$

- Use ***U*-spin** flavour symmetry (subgroup $SU(3)_F$):

$\boxed{\text{interchange } s \leftrightarrow d \text{ quarks}}$ Related to $B_d \to \pi^+\pi^-$

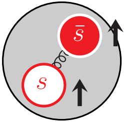
Extract **CP violating phase**: $\gamma = (68 \pm 7)^\circ$

R. Fleischer and RK, Eur.Phys.J. C71 (2011) 1532

Controlling the **CP Odd** Decay Mode

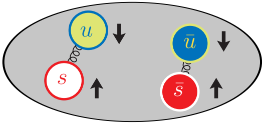
$$B_s \to J/\psi\, f_0(980)$$

Quark-antiquark



What is $f_0(980)$?

Tetraquark



- With SM CP violation and **unknown decay amplitudes**:

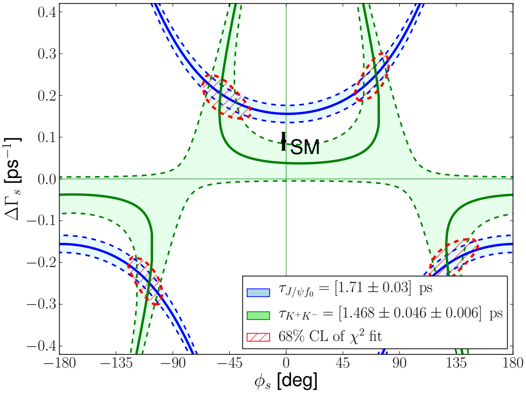
$$\boxed{\Delta\phi_{J/\psi f_0} \in [-3^\circ, 3^\circ]}, \quad C_{J/\psi f_0} \lesssim 0.05$$

R. Fleischer, RK, G. Ricciardi, Eur.Phys.J. C71 (2011) 1832

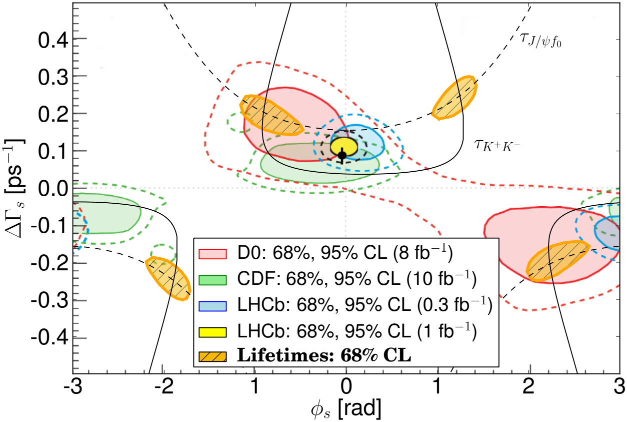
Lifetime contours

$$\tau_f = \text{function}\left(\Delta\Gamma_s,\ \boxed{\phi_s + \Delta\phi},\ C\right)$$

- **CP Even**: $B_s \to K^+K^- \ni \tau_{K^+K^-},\ \Delta\phi_{K^+K^-},\ C_{K^+K^-}$
- **CP Odd**: $B_s \to J/\psi\, f_0(980) \ni \tau_{J/\psi\, f_0},\ \Delta\phi_{J/\psi\, f_0},\ C_{J/\psi\, f_0}$



Untagged determination of B_s mixing parameters



Note : $\phi_s + \Delta\phi^{\lambda}_{J/\psi\phi} \neq \phi_s + \Delta\phi_{J/\psi f_0(980)}$

Summary

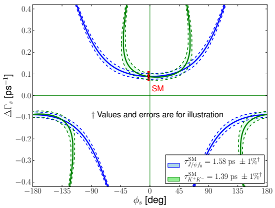
- CP observables → SM predictions

Disentangle New Physics

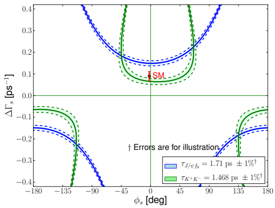
from **SM Hadronic Physics**

- **Probe** B_s mixing phase with **untagged** analysis:

Pair of CP odd and even **effective lifetimes**

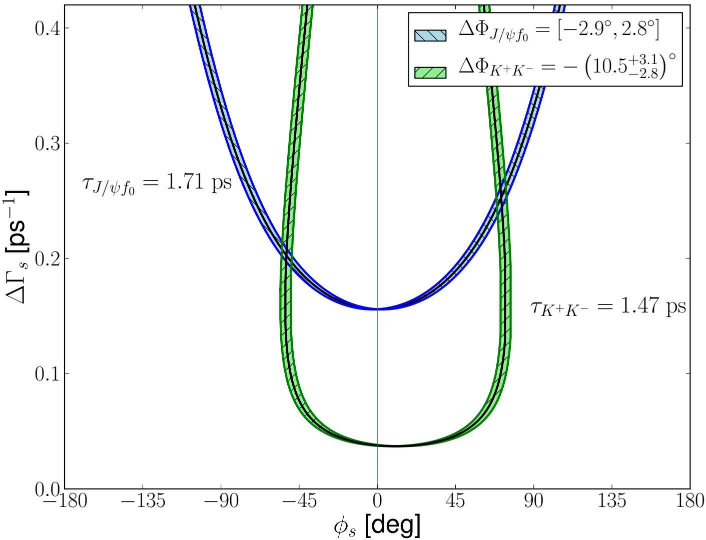


End of 2012 ??



Backup

Hadronic uncertainties



Effective Lifetime

$$\tau = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\,\mathcal{A}_{\Delta\Gamma}\, y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}\, y_s} \right)$$

$$\boxed{\mathcal{A}_{\Delta\Gamma} = -\eta \sqrt{1 - C^2} \cos(\phi_s + \Delta\phi)}$$

$$y_s^3 + \left(\frac{\tau_{B_s} - \tau}{\tau\, \mathcal{A}_{\Delta\Gamma}} \right) y_s^2 + \left(\frac{2\,\tau_{B_s} - \tau}{\tau} \right) y_s + \left(\frac{\tau_{B_s} + \tau}{\tau\, \mathcal{A}_{\Delta\Gamma}} \right) = 0$$

Fitting an effective lifetime

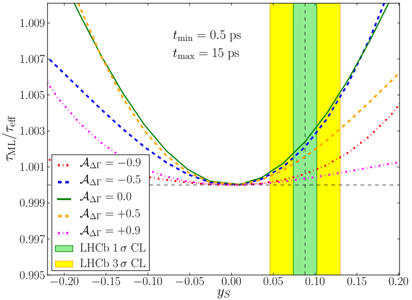
$$f_{\rm true}(t) \equiv \frac{A(t)\,\langle\Gamma(t)\rangle}{\int_0^\infty A(t)\,\langle\Gamma(t)\rangle\,dt}, \qquad f_{\rm fit}(t;\tau) \equiv \frac{A(t)\,e^{-t/\tau}}{\int_0^\infty A(t)\,e^{-t/\tau}\,dt}$$

$$\textbf{Minimise}: \quad -\log L(\tau) = -n\int_0^\infty dt\; f_{\rm true}(t)\log\left[f_{\rm fit}(t;\tau)\right]$$

$$\frac{\int_0^\infty t\,A(t)e^{-t/\tau}\,dt}{\int_0^\infty A(t)e^{-t/\tau}\,dt} = \frac{\int_0^\infty t\,A(t)\langle\Gamma(t)\rangle dt}{\int_0^\infty A(t)\langle\Gamma(t)\rangle dt}$$

Limit that $A(t) = 1$:

$$\tau = \frac{\int_0^\infty t\,\langle\Gamma(t)\rangle dt}{\int_0^\infty \langle\Gamma(t)\rangle dt} \equiv \tau_{\rm eff},$$



Notation

The CP asymmetry:

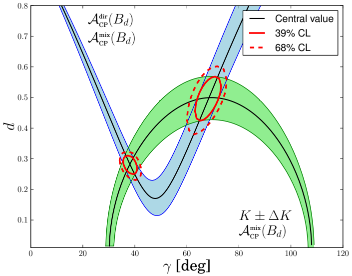
$$\frac{\Gamma\,(B_s(t)\to f)-\Gamma(\bar{B}_s(t)\to f)}{\Gamma(B_s(t)\to f)+\Gamma(\bar{B}_s(t)\to f)}=\frac{C\cos(\Delta M_s\,t)-S\,\sin(\Delta M_s\,t)}{\cosh(\Delta\Gamma_s\,t)+\mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s\,t)}$$

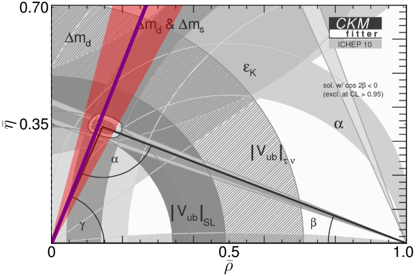
Observables for $\mathcal{CP}|f\rangle=\eta\,|f\rangle$:

$$\xi_f\equiv\frac{q}{p}\,\frac{A(\overline{B}{}_s^0\to f)}{A(B_s^0\to f)}=-\eta\,e^{-i\phi_s}\,\sqrt{\frac{1-C}{1+C}}\,e^{-i\Delta\phi}$$

$$\mathcal{A}_{\Delta\Gamma}-i\,S=\frac{2\,\xi_f}{1+|\xi_f|^2}=\boxed{-\eta\,\sqrt{1-C^2}\,e^{-i(\phi_s+\Delta\phi)}}$$

U-spin determination





Decay Mode CP violation: $\gamma = (68 \pm 7)^\circ$

$$\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ, \quad C_{K^+K^-} = 0.09 \pm 0.05$$

Robert Fleischer, RK (arXiv:1011.1096)

Tetraquarks

- diquark–antidiquark (colour) bound states

$$\sigma = [ud][\bar{u}\bar{d}]$$
$$\kappa = [su][\bar{u}\bar{d}]; [sd][\bar{u}\bar{d}] \quad (+\mathrm{c.d})$$
$$f_0 = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$
$$a_0 = [su][\bar{s}\bar{d}]; \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}}; [sd][\bar{s}\bar{u}]$$

diquark $\equiv [q_1\, q_2]$, colour $\overline{\mathbf{3}}$, flavour $\overline{\mathbf{3}}$, $S = 0$

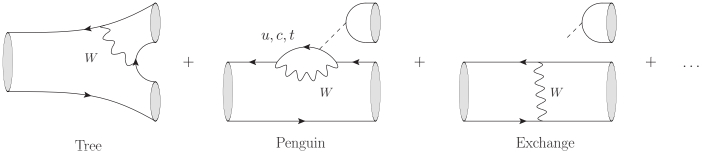
- Issues: $f_0 \to \pi\pi$ coupling too small, $a_0 \to \eta\pi$ too large.
- Solved by adding *instanton-induced effects*

A Theory of Scalar Mesons, G. 't Hooft, G. Isidori, A.D Polosa, V. Riquer,

(arXiv:0801.2288)

Decay Amplitudes: General Formalism

In reality:



$$\text{e.g.}\quad A(B \to f) = A_{\rm T} + A_{\rm P}^{u} + A_{\rm P}^{c} + A_{\rm P}^{t} + \ldots$$
$$= |A_{\rm T}|e^{i\delta_T}e^{i\varphi_T} + |A_{\rm P}^{u}|e^{i\delta_u}e^{i\varphi_u} + |A_{\rm P}^{c}|e^{i\delta_c}e^{i\varphi_c} + \ldots$$
$$= |A_1|e^{i\delta_1}\left(e^{i\varphi_1} + e^{i\varphi_2}\, h\, e^{i\delta}\right)$$

$$h\, e^{i\delta} \equiv \frac{A_2}{A_1} e^{i(\delta_2-\delta_1)},$$

$$\boxed{\xi = -\eta\, e^{-i\phi_s}\left[\frac{e^{-i\varphi_1} + e^{-i\varphi_2}\, h\, e^{i\delta}}{e^{i\varphi_1} + e^{i\varphi_2}\, h\, e^{i\delta}}\right]}$$

Untagged observable: General Formalism

$$\xi = -\eta\, e^{-i\phi_s} \left[\frac{e^{-i\varphi_1} + e^{-i\varphi_2}\, h\, e^{i\delta}}{e^{i\varphi_1} + e^{i\varphi_2}\, h\, e^{i\delta}} \right]$$

$$\boxed{\frac{2\,\xi}{1+|\xi|^2} = -\eta\,\sqrt{1-C^2}\; e^{-i(\phi_s+\Delta\phi)}}$$

$$C = \frac{2\,h\,\sin\delta\,\sin(\varphi_1-\varphi_2)}{1+2\,h\,\cos\delta\cos(\varphi_1-\varphi_2)+h^2}$$

$$\Delta\Phi = \arctan\left(\frac{\sin 2\varphi_1 + 2\,h\,\cos\delta\,\sin(\varphi_1+\varphi_2) + h^2\,\sin 2\varphi_2}{\cos 2\varphi_1 + 2\,h\,\cos\delta\cos(\varphi_1+\varphi_2) + h^2\,\cos 2\varphi_2}\right)$$

$$\mathcal{A}_{\Delta\Gamma} = -\eta\cos\phi_s \quad \rightarrow \quad \boxed{\mathcal{A}_{\Delta\Gamma} = -\eta\,\sqrt{1-C^2}\,\cos(\phi_s+\Delta\phi)}$$

The Decay Width Difference

$$\Delta\Gamma_s \equiv \Gamma_{\rm L} - \Gamma_{\rm H} \simeq 2|\Gamma_{12}|\cos(\Theta_{\rm M} - \Theta_\Gamma)$$

- No absorptive New Physics: *Grossman (hep-ph:9603244)*

$$y_s = \frac{\Delta\Gamma_s^{\rm Th}}{2\,\Gamma_s}\cos\tilde{\phi}_s, \qquad \tilde{\phi}_s = 0.22^\circ + \phi_s^{\rm NP}$$

- Theoretical calculation: *Lenz & Nierste (1102.4274)*

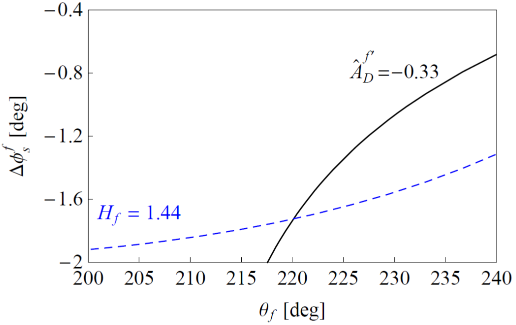
$$\frac{\Delta\Gamma_s^{Th}}{\Gamma_s} = 0.133 \pm 0.032$$

$B_s \to J/\psi\phi$ hadronic uncertainties

$$\text{Measure}: \quad \phi_s + \Delta\phi^f_{J/\psi\phi}$$

- **Numerical example** compatible with $\Delta\phi_d$ analysis

  S. Faller, R. Fleischer and T. Mannel, Phys.Rev. D79 (2009) 014005



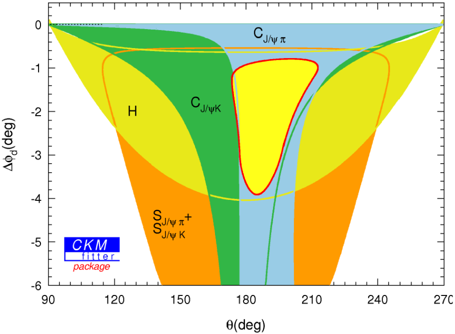
- Future control channels: $B_s \to J/\psi\bar{K}^{*0}$ and $B_d \to J/\psi\rho^0$

Hadronic uncertainty of B_d^0–$\bar{B}_d^0$ mixing

$$\text{Measure}: \quad 2\beta + \Delta\phi_d$$

Probe using $B_d \to J/\psi\, K_S$ and $B_d \to J/\psi\, \pi$

S. Faller, R. Fleischer, M. Jung, T. Mannel (arXiv:0809.0842)



See also: *Extracting gamma and Penguin Topologies through CP Violation in* $B_s^0 \to J/\psi K_S$, *K. De Bruyn, R. Fleischer and P. Koppenburg (arXiv:1010.0089)*