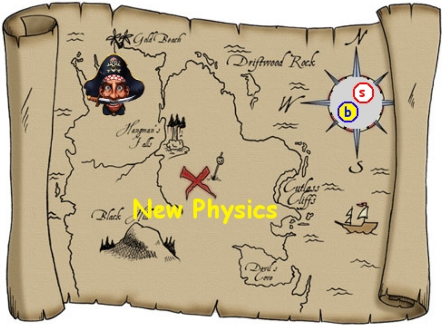
Recent Theoretical Studies of B_s Physics

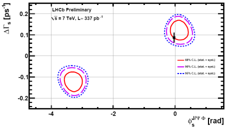
Rob Knegjens (Nikhef)

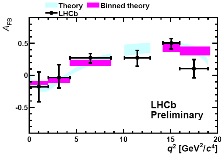


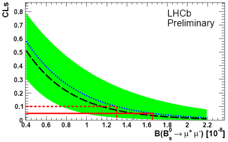
NIKHEF

FOM

Results from the LHC!







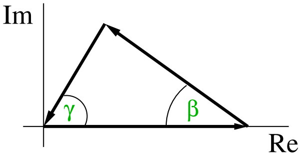
CP observables $\rightarrow$ SM predictions

Disentangle New Physics ☺

from **SM Hadronic Physics** ☹

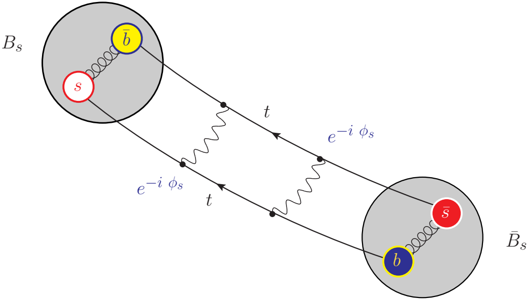
- **In pursuit of new physics with $B_s \rightarrow K^+K^-$** R. Fleischer, RK (arXiv:1011.1096)
- **Anatomy of $B^0_{s,d} \rightarrow J/\psi\, f_0(980)$** R. Fleischer, RK, G. Ricciardi (arXiv:1109.1112)
- **Effective lifetimes of B_s decays and their constraints on the B^0_s–$\bar{B}^0_s$ mixing parameters**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

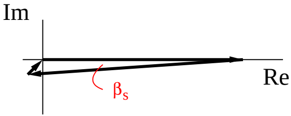
A **sensitive probe**: the B_s mixing phase



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3\, e^{-i\gamma} \\ -\lambda & 1 & \lambda^2 \\ \lambda^3\, e^{-i\beta} & -\lambda^2\, e^{i\beta_s} & 1 \end{pmatrix}$$

$$\lambda \approx 0.23$$



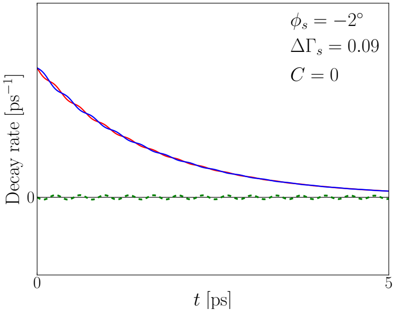


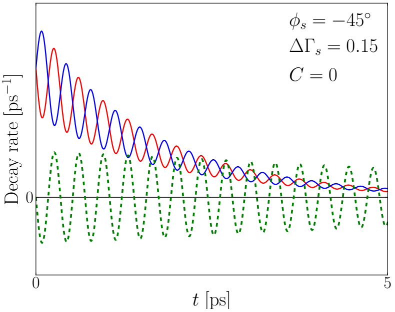
$$\phi_s \equiv -2\,\beta_s + \phi_s^{\rm NP}$$

Time-dependent **tagged** CP violation

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

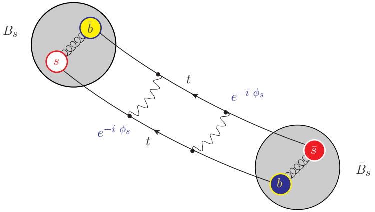
$$A_{\mathrm{CP}} = \frac{\Gamma\left(B_s(t) \to f\right) \; - \; \Gamma\left(\bar{B}_s(t) \to f\right)}{\Gamma\left(B_s(t) \to f\right) \; + \; \Gamma\left(\bar{B}_s(t) \to f\right)}$$





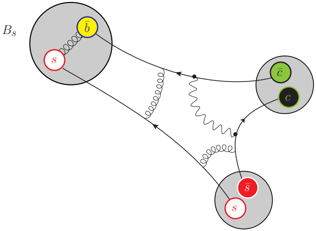
CP violation in interference

B_s^0–$\bar{B}_s^0$ Mixing



ϕ_s, $\Delta\Gamma_s \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$

Decay Mode



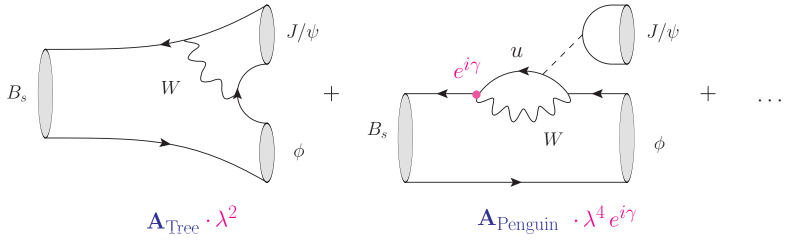
$\Delta\phi$, C

hadronic physics } ?

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

The **Superstar** Decay Mode

$B_s / \bar{B}_s \to J/\psi\ \phi$



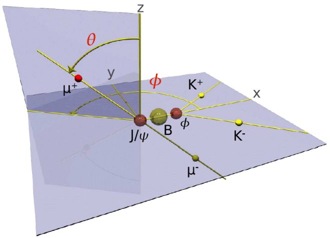
- Branching ratio ☺
- Theory ☺ **?**

$$\Delta\phi \sim \arctan\left(\lambda^2 \sin\gamma \left[\frac{A_{\rm Penguin}}{A_{\rm Tree}}\right]\right)$$

$$\lambda^2 \sim 0.05$$

The **Superstar** **Decay Mode**

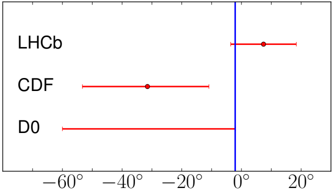
$B_s / \bar{B}_s \rightarrow J/\psi\ \phi$



$\left.\begin{matrix} J/\psi \\ \phi \end{matrix}\right\}$ spin 1 mesons

Need **angular analysis**

ϕ_s



- Branching ratio ☺
- Theory ☺ **?**
- **Experimentally challenging** ☹

An **alternative tagged** analysis?

S. Stone and L. Zhang, Phys. Rev. D 79 (2009)

$$B_s \;/\; \bar{B}_s \;\to\; J/\psi \;\not{\phi}\; f_0(980)$$

No **angular analysis** needed!

$f_0(980)$ [a] $I^G(J^{PC}) = 0^+(0^{++})$ **$f_0(980)$ Section References**

See also the minireview on scalar mesons .

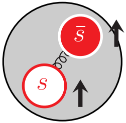
Mass m = (980 ± 10) MeV
Full width Γ = 40 to 100 MeV

$f_0(980)$ DECAY MODES

Γ_i	Mode	Fraction (Γ_i / Γ)	p (MeV/c)
Γ_1	$\pi\,\pi$	dominant	471
Γ_2	$K\,\bar{K}$	seen	-1
Γ_3	$\gamma\,\gamma$	seen	490
Γ_4	$e^+\,e^-$		490

What is the $f_0(980)$?

Quark-antiquark picture

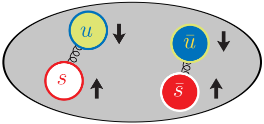


$$S = 1, \quad \mathbf{L = 1} \quad \rightarrow \quad J = 0$$

$$f_0(980) = \cos\varphi_M \; s\,\bar{s} \; + \; \frac{\sin\varphi_M}{\sqrt{2}} \left(u\,\bar{u} \; + \; d\,\bar{d} \right)$$

$$m_{f_0} < m_{\eta^{(\prime)}} \;\; ?$$

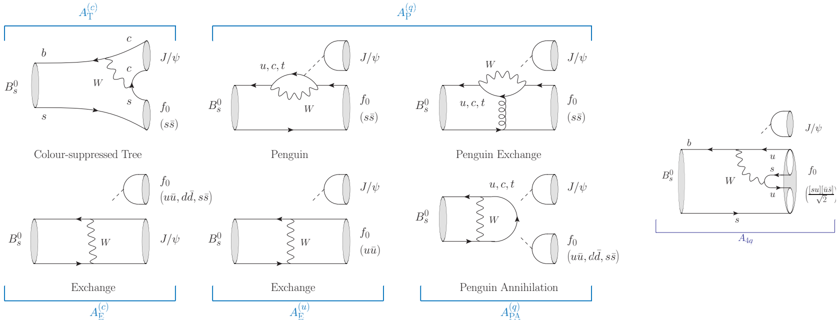
Tetraquark picture



$$\mathbf{L = 0}$$

$$f_0(980) = \frac{[s\,u][\bar{s}\,\bar{u}] \; + \; [s\,d][\bar{s}\,\bar{d}]}{\sqrt{2}}$$

Hadronic uncertainty of the **Decay Mode**



$$\Delta\phi_{J/\psi f_0} = \arctan\left(\lambda^2 \;\; \sin\gamma \; \mathrm{Re}\left[\frac{??}{A_{\mathrm{T}} + ??}\right] + \mathcal{O}(\lambda^4)\right)$$

Controlling the hadronic uncertainty

$$\Delta\phi_{J/\psi f_0} = \text{arctan}\left(\boxed{\lambda^2} \; \sin\gamma \; \text{Re}\left[\frac{??}{A_{\rm T} + ??}\right] + \mathcal{O}(\lambda^4)\right)$$

- **Control channel**: $B_d \to J/\psi\, f_0(980)$ (unobserved)

$$\boxed{\text{No } \lambda^2 \sim 0.05 \text{ suppression}}$$

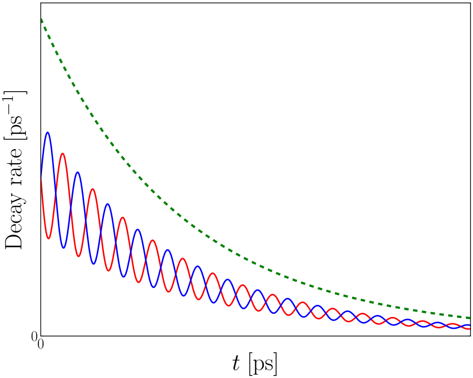
Prediction (tetraquark picture)

$$\text{BR}(B_d^0 \to J/\psi\, f_0;\, f_0 \to \pi^+\pi^-) \sim (1\text{–}3) \times 10^{-6}$$

R. Fleischer, RK, G. Ricciardi (arXiv:1109.1112)

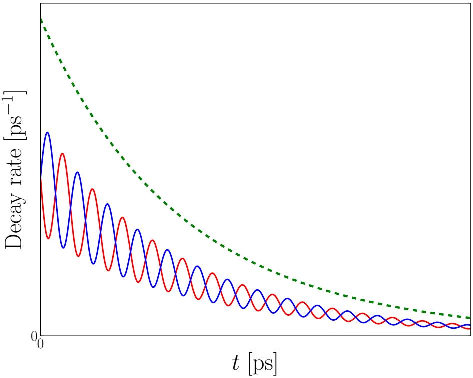
An **untagged** analysis?

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



An **untagged** analysis?

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



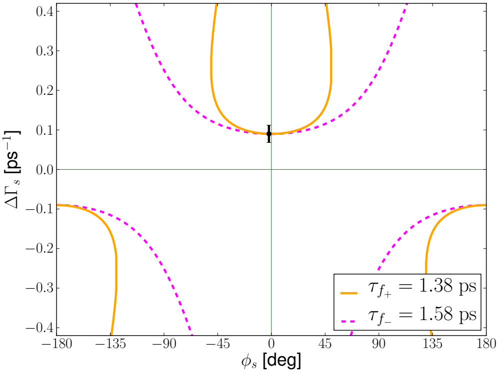
Effective Lifetime

$$\tau \equiv \frac{\int_0^\infty t\,\langle\Gamma\rangle\,dt}{\int_0^\infty \langle\Gamma\rangle\,dt} = \mathrm{fn}\left(\Delta\Gamma_s,\ \boxed{\phi_s + \Delta\phi},\ C\right)$$

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



Measured Effective Lifetimes

- $B_s \to K^+K^-$ (LHCb): CP Even

$$\tau_{K^+K^-} = [1.44 \pm 0.096 \pm 0.010]\ \mathrm{ps}$$

- $B_s \to J/\psi f_0(980)$ (CDF): CP Odd

$$\tau_{J/\psi f_0} = \left[1.70^{+0.12}_{-0.11} \pm 0.03\right]\ \mathrm{ps}$$

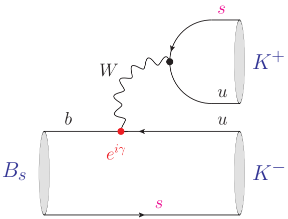
But...

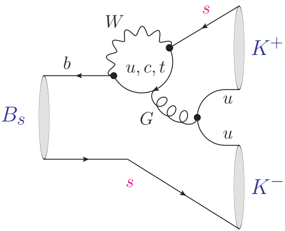
$$\boxed{\Delta\phi \neq 0,\ \ C \neq 0}$$

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

Controlling the **CP Even** Decay Mode

$B_s \to K^+K^-$

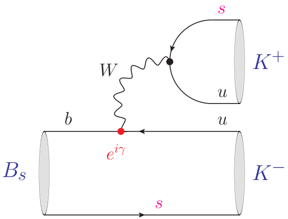


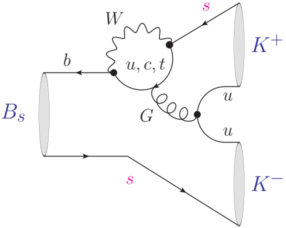


$\Delta\phi_{K^+K^-} = ??$

Controlling the **CP Even** Decay Mode

$B_s \to K^+ K^-$





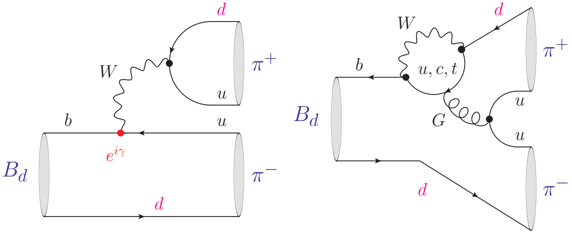
$\Delta\phi_{K^+K^-} = ??$

- Use *U*-**spin** flavour symmetry:

$$\text{interchange } s \leftrightarrow d \text{ quarks}$$

Controlling the **CP Even** Decay Mode

$B_s \to K^+K^-$



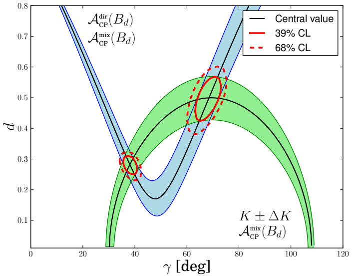
$\Delta\phi_{K^+K^-} = ??$

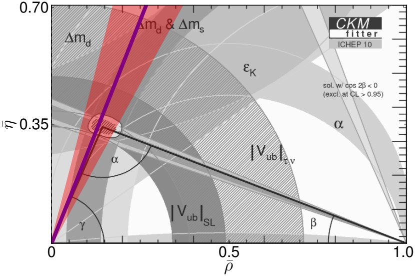
- Use *U*-**spin** flavour symmetry:

interchange $s \leftrightarrow d$ quarks

Related to $B_d \to \pi^+\pi^-$

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)

Controlling the **CP Odd** Decay Mode

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

$$\boxed{\Delta\phi_{J/\psi f_0} = ??}$$

- No **control channels** available
- Assume $\gamma = (68 \pm 7)^\circ$ and $A_{\rm T} > A_{\rm others}$:

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

We are set!

For $B_s \to f$:

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

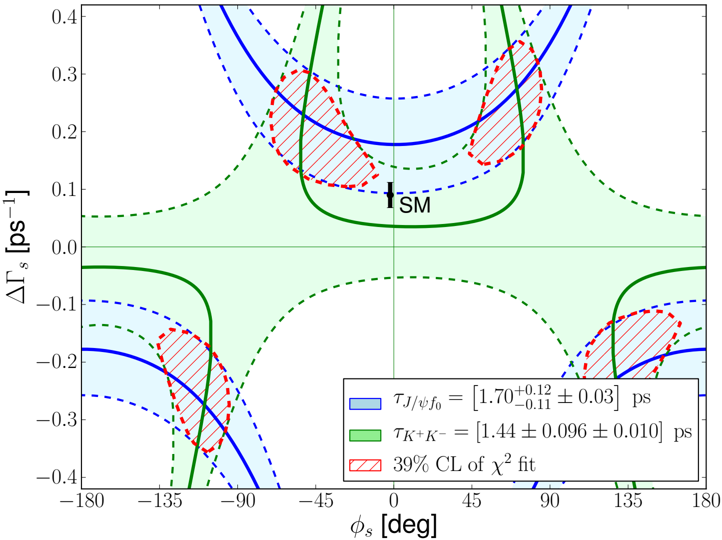
- CP Even final state:

$$\tau_{K^+K^-} = [1.44 \pm 0.096 \pm 0.010]\ \text{ps},$$
$$\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ$$
$$C_{K^+K^-} = 0.09$$

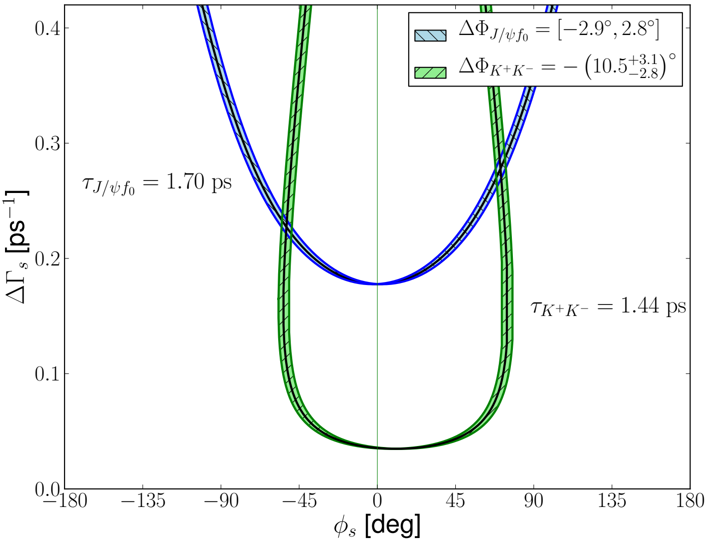
- CP Odd final state:

$$\tau_{J/\psi f_0} = \left[1.70^{+0.12}_{-0.11} \pm 0.03\right]\ \text{ps},$$
$$\Delta\phi_{J/\psi f_0} \in [-3^\circ, 3^\circ]$$
$$C_{J/\psi f_0} \lesssim 0.05$$

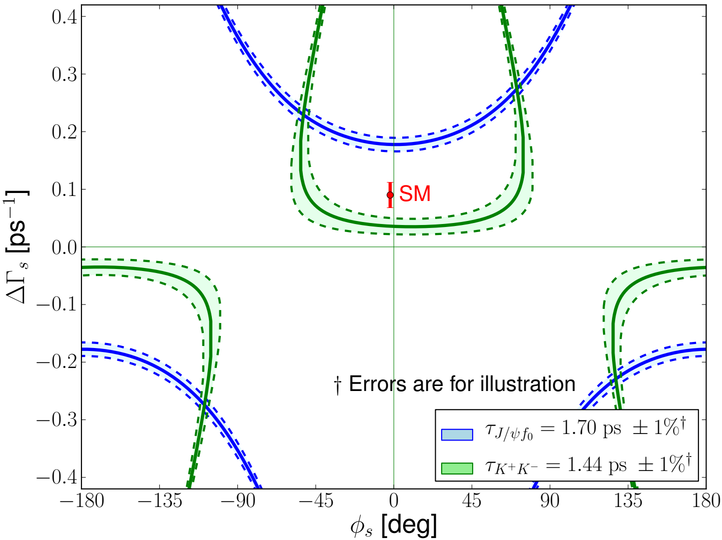
Lifetime contours



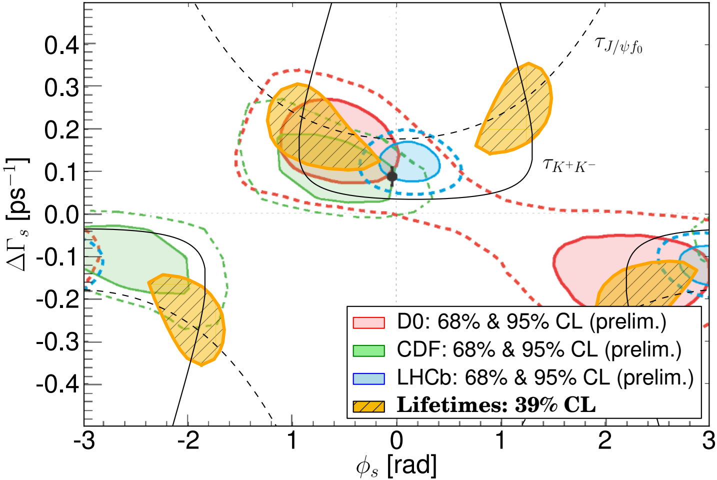
Hadronic uncertainties



Future precision



A complementary analysis



Summary

- CP observables → SM values

Disentangle New Physics
from Hadronic Physics

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

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

- We eagerly await new lifetime measurements!

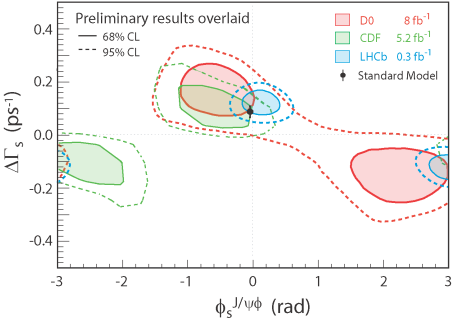
Backup

Combined Fits

- Assume $\gamma = (68 \pm 7)^\circ$ and $A_{\mathrm{T}} > A_{\mathrm{others}}$:

$$\Delta\phi^{f}_{J/\psi f_0} \in [-3^\circ, 3^\circ]$$

$$\phi_s + \Delta\phi_{J/\psi\phi} \quad \neq \quad \phi_s + \Delta\phi_{J/\psi f_0}$$



Effective Lifetime

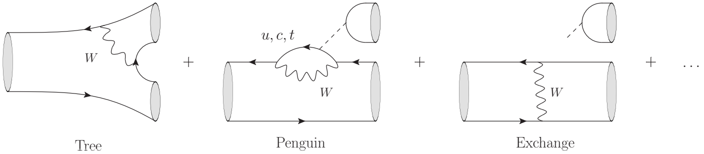
$$\tau = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\,\mathcal{A}_{\Delta\Gamma}\, y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}\, y_s} \right)$$

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

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

Decay Amplitudes: General Formalism

In reality:



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

$$h\, e^{i\delta} \equiv \frac{A_2}{A_1} e^{i(\delta_2-\delta_1)}, \qquad \boxed{\xi = -\eta\, e^{-i\phi_s}\left[\frac{e^{-i\varphi_1} + e^{-i\varphi_2}\, h\, e^{i\delta}}{e^{i\varphi_1} + e^{i\varphi_2}\, h\, e^{i\delta}}\right]}$$

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)*

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

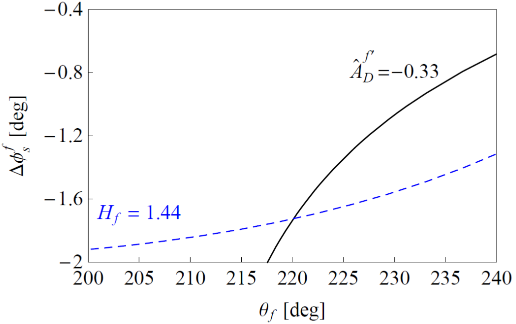
- Theoretical calculation: *Lenz & Nierste (1102.4274)*

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

$B_s \to J/\psi\phi$ 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 (arXiv:0810.4248)



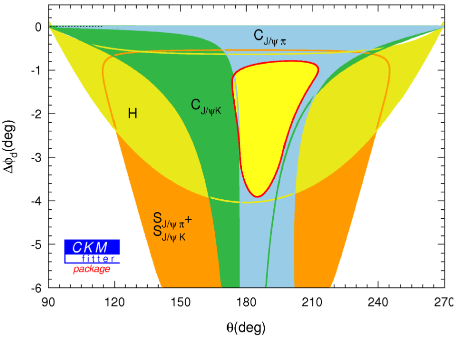
- Future control channels: $B_s \to J/\psi \bar{K}^{*0}$ and $B_d \to J/\psi \rho^0$

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)*