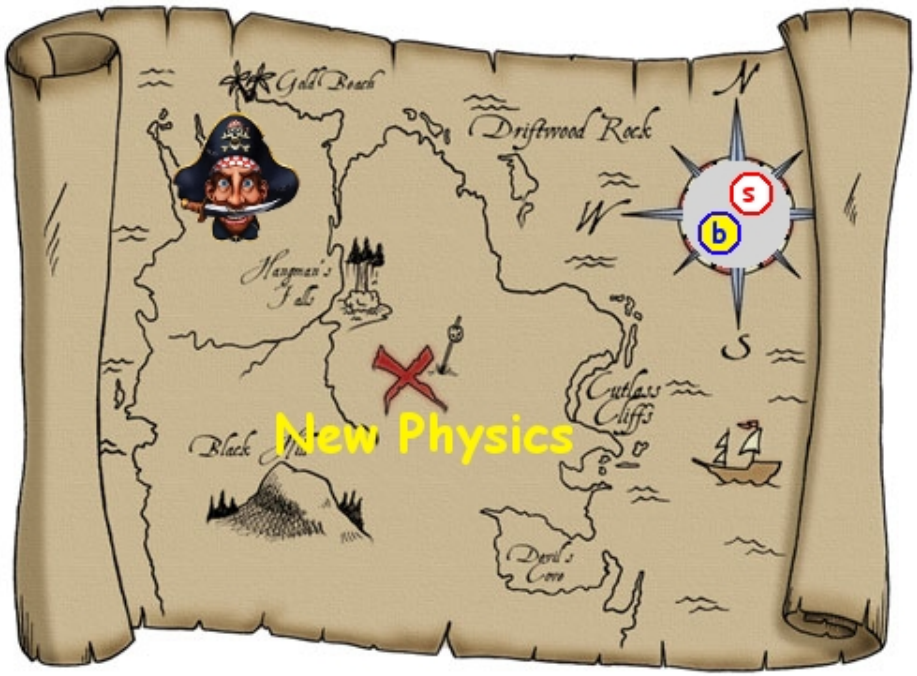
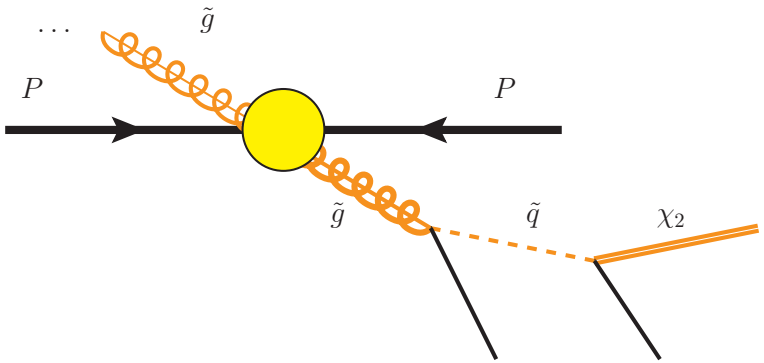
Lessons from B_s Lifetimes

Rob Knegjens (Nikhef)



The **search** for **New Physics** at the LHC

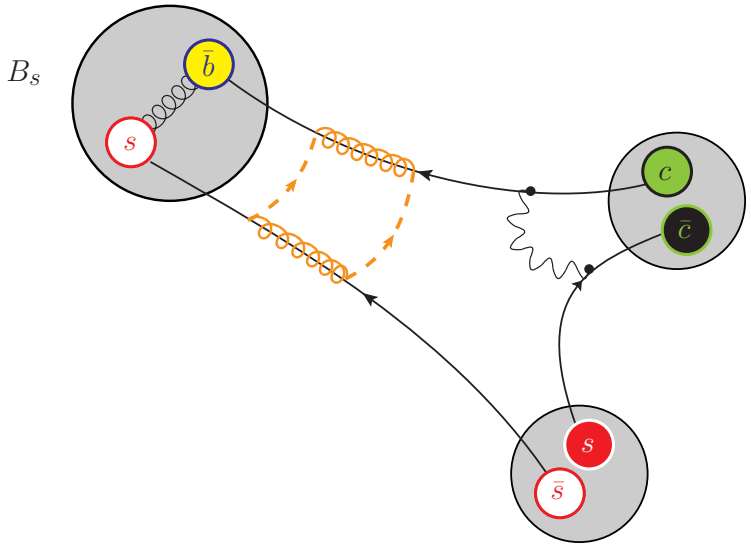


Direct searches

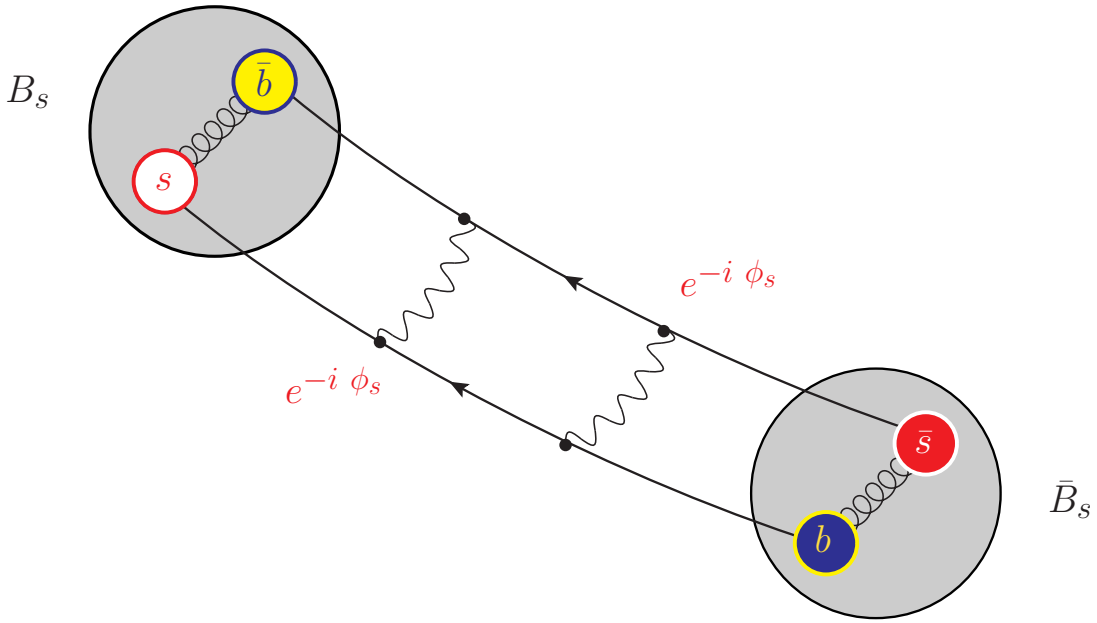
"The high energy frontier"

Indirect searches

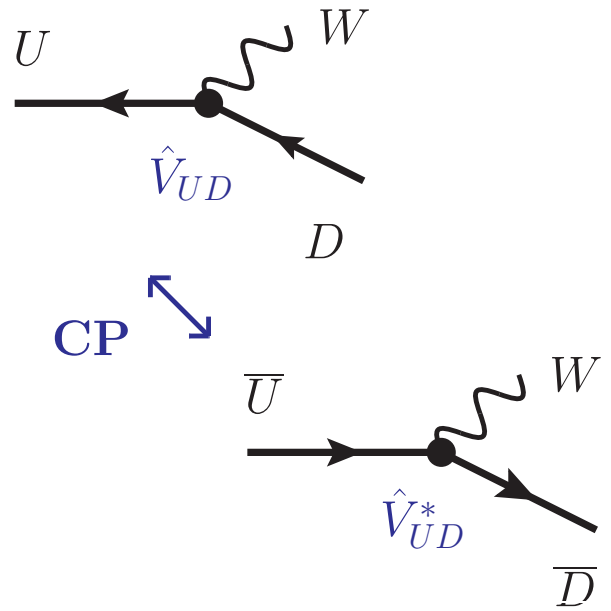
"The precision frontier"



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



Standard Model:



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

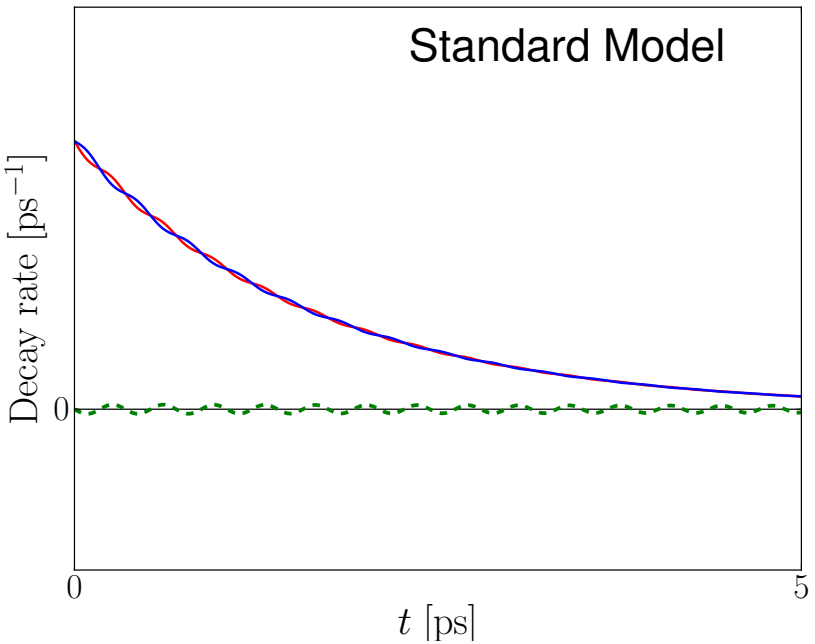
B_s–$\bar{B}_s$ **Mixing Phase:**

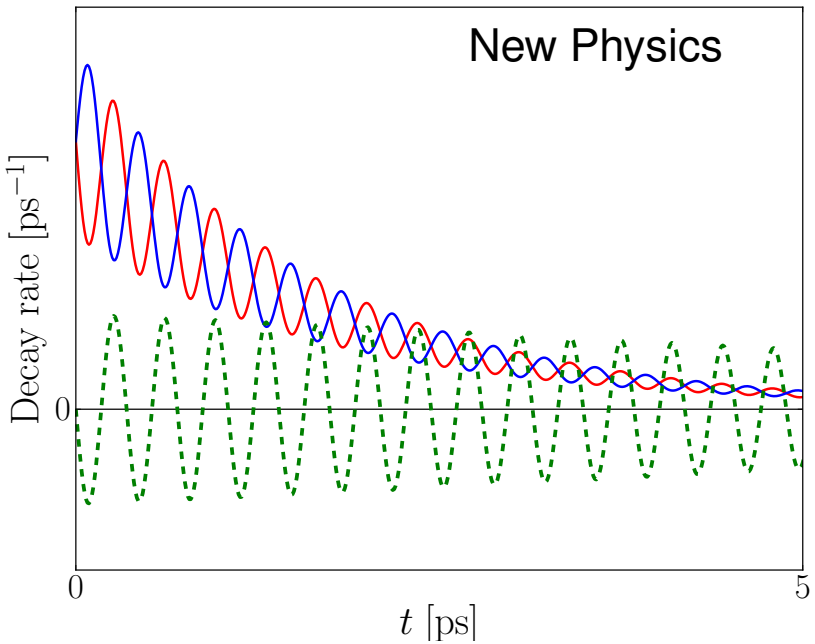
$$\phi_s \equiv -2.1^\circ + \text{  }$$

Time-dependent **tagged** CP measurement

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

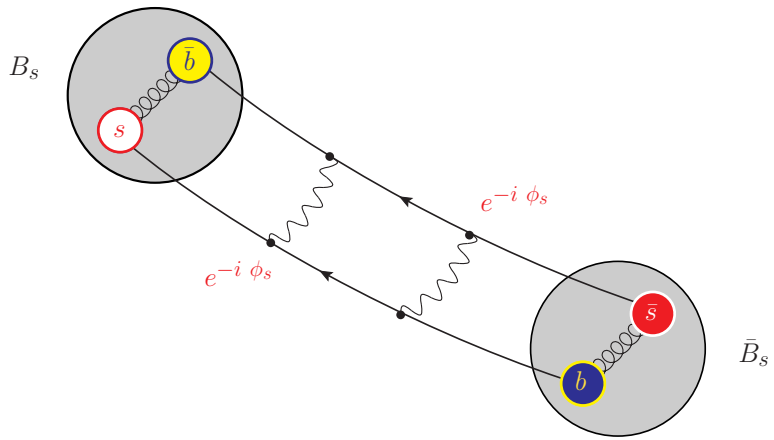
$$A_{\mathrm{CP}} = \frac{\Gamma\left(B_s(t) \to f\right) - \Gamma\left(\bar{B}_s(t) \to f\right)}{\Gamma\left(B_s(t) \to f\right) + \Gamma\left(\bar{B}_s(t) \to f\right)}$$



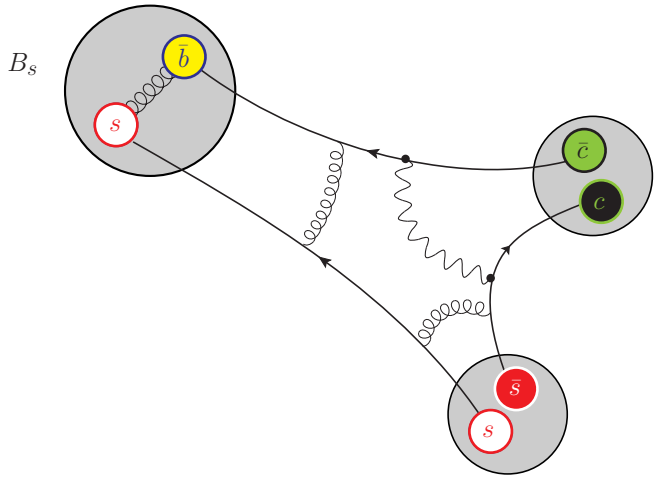


CP violation in interference

B_s^0–$\bar{B}_s^0$ Mixing



Decay Mode



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

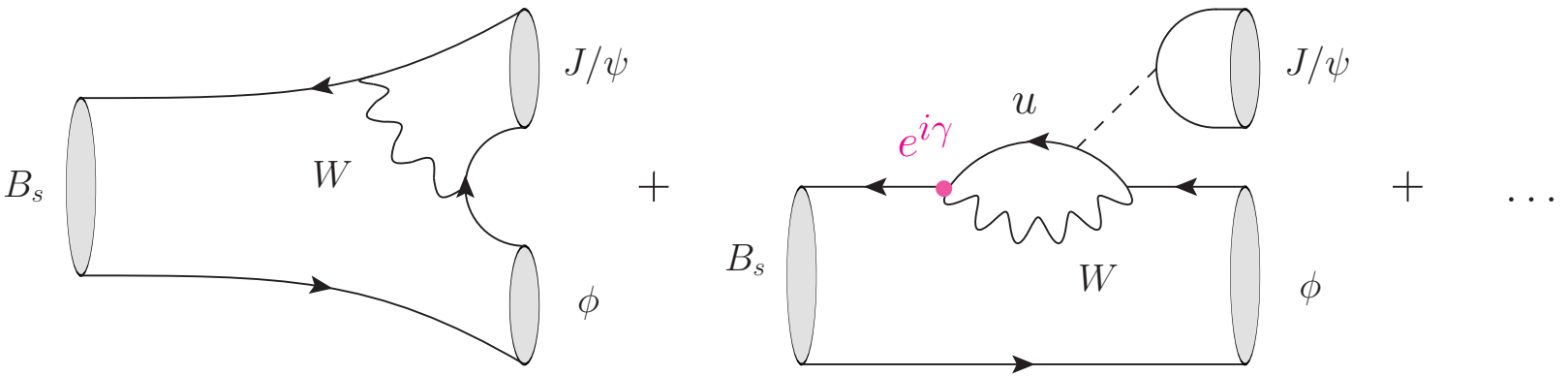
$\Delta\phi,\ C$ (direct CPV)

hadronic physics

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

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

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



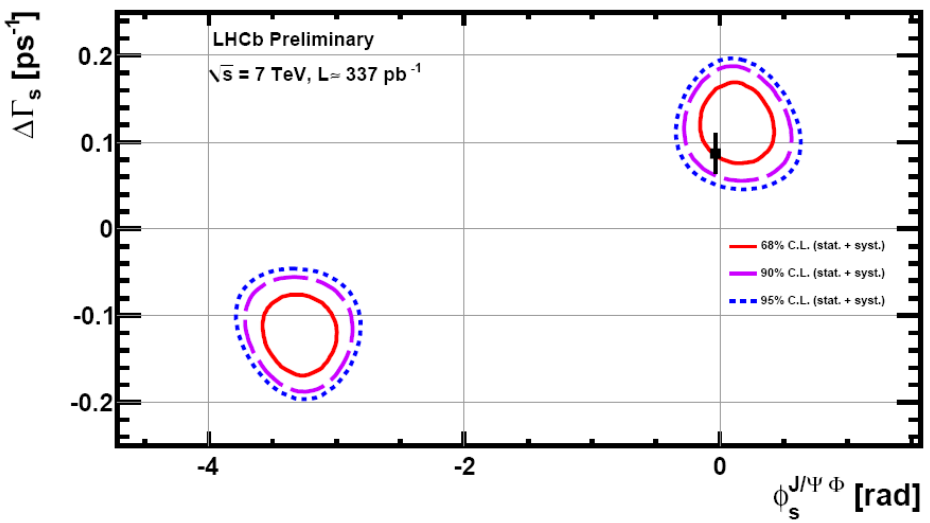
$\mathbf{A}_{\text{Tree}} \cdot \lambda^2$ $\mathbf{A}_{\text{Penguin}} \cdot \lambda^4 e^{i\gamma}$

$$\boxed{\Delta\phi \sim \arctan\left(\lambda^2 \sin\gamma \left[\frac{A_{\text{Penguin}}}{A_{\text{Tree}}}\right]\right) \in [-3°, 0°]} \qquad \lambda^2 \sim 0.05$$

S. Faller, R. Fleischer and T. Mannel (arXiv:0810.4248)

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

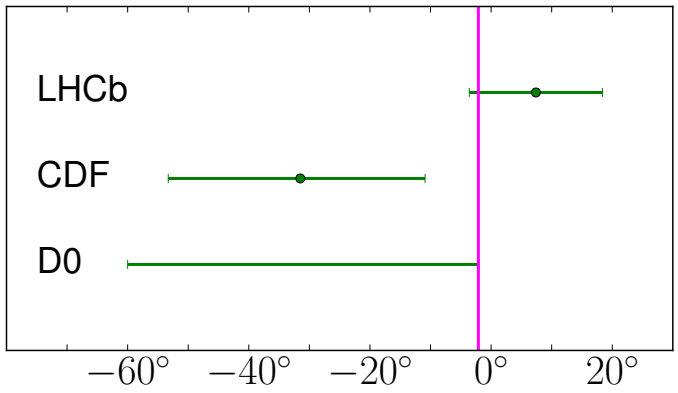
Results from LHCb!
(Lepton-Photon 2011)



$\Delta\phi \in [-3^\circ, 0^\circ]$

CP observables $\to$ SM predictions

$\phi_s + \Delta\phi$



CP observables $\rightarrow$ SM predictions

Disentangle New Physics 

from **SM Hadronic Physics** 

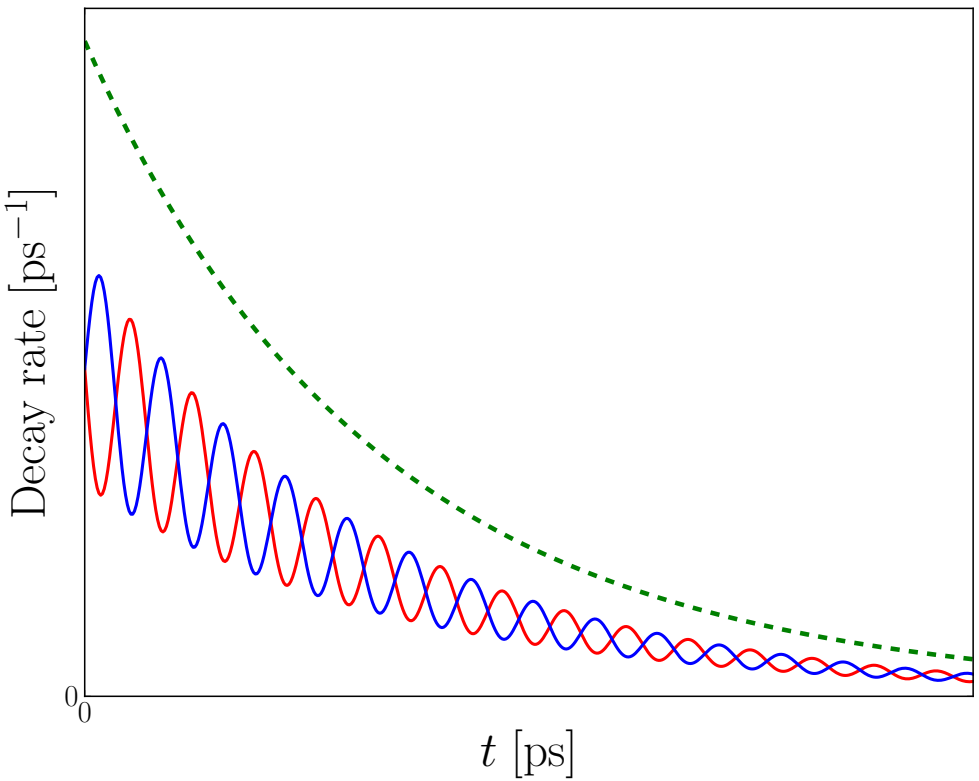
and 

Find **Complementary Analyses** for determining ϕ_s, $\Delta\Gamma_s$

- **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)

An **untagged** analysis?

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



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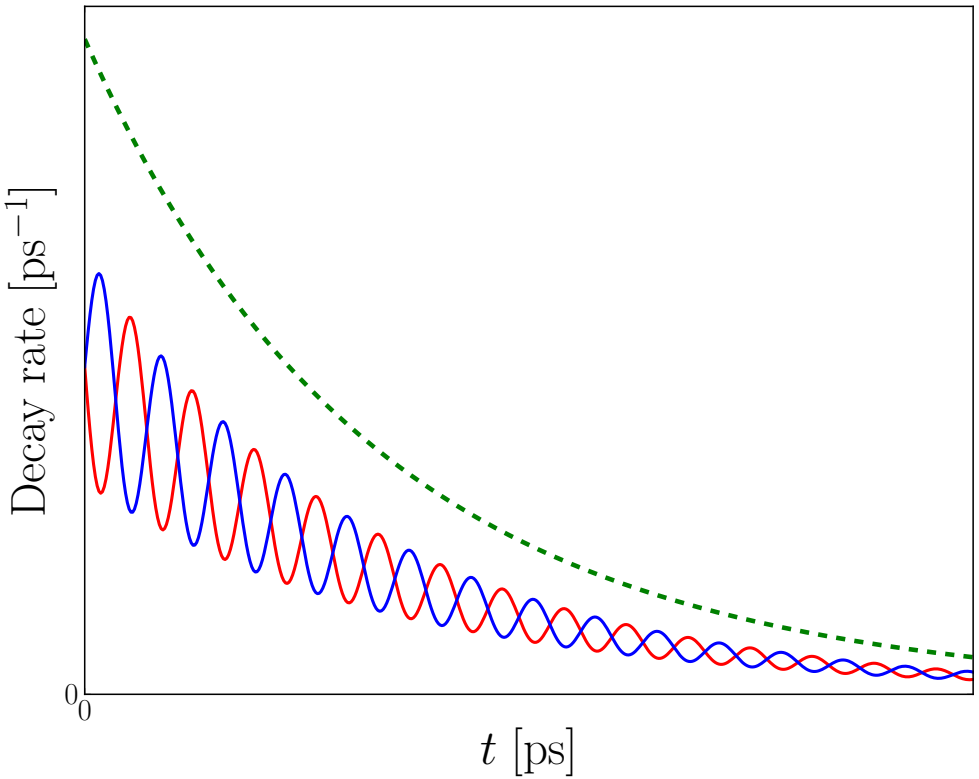


Effective Lifetime

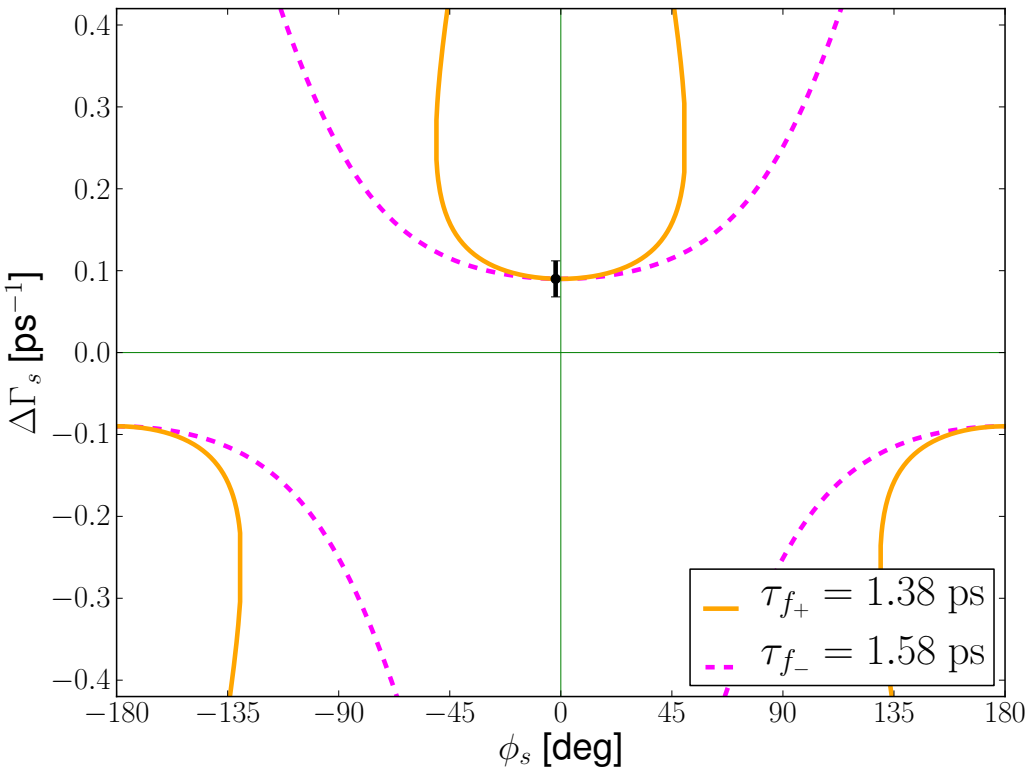
$$\tau \equiv \frac{\int_0^\infty t \, \langle \Gamma \rangle \, dt}{\int_0^\infty \langle \Gamma \rangle \, dt}$$

$$= \mathrm{fn}\left(\Delta\Gamma_s, \; \boxed{\phi_s + \Delta\phi}, \; C \right)$$

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

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

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



Measured Effective Lifetimes

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

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

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

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

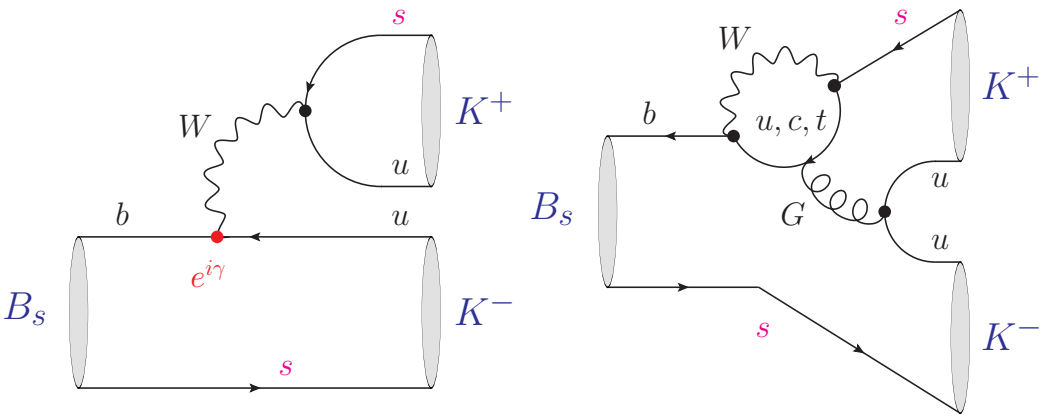
But...

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

...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 $SU(3)_F$):

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

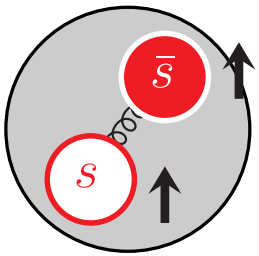
Related to $B_d \to \pi^+\pi^-$

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

Controlling the **CP Odd** Decay Mode

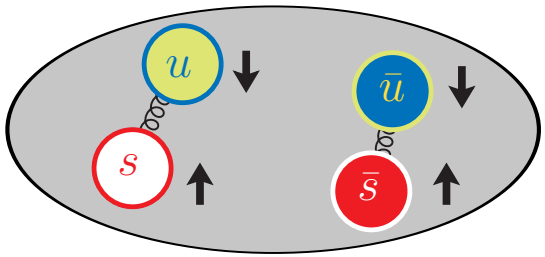
$$B_s \to J/\psi\, f_0(980)$$

Quark-antiquark



What is $f_0(980)$?

Tetraquark



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

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

- **Control channel**: $B_d \to J/\psi\, f_0(980)$ (search for at LHCb!)

Measured Effective Lifetimes

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

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

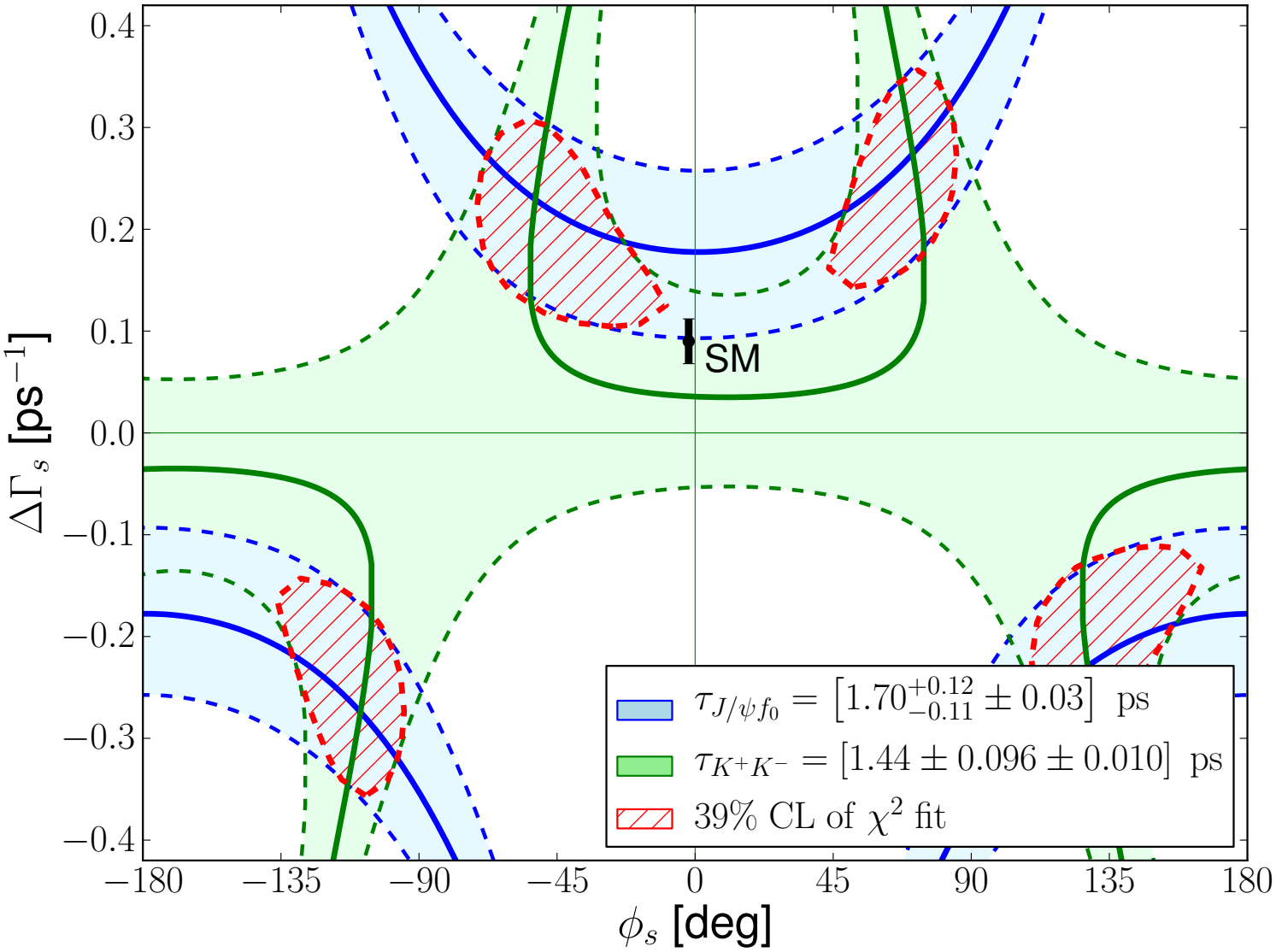
- $B_s \to J/\psi f_0(980)$ (CDF): CP Odd

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

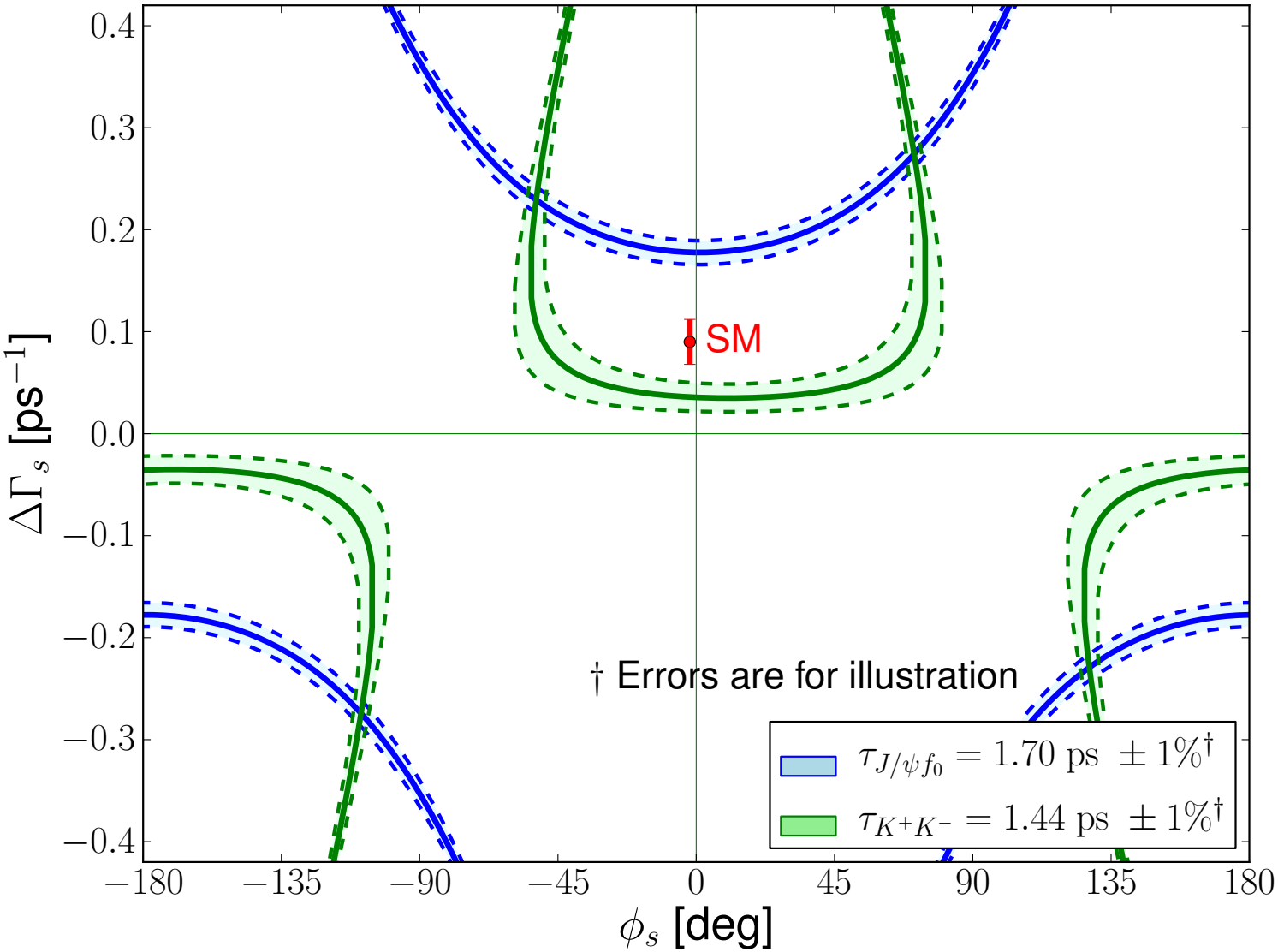
We are set!

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

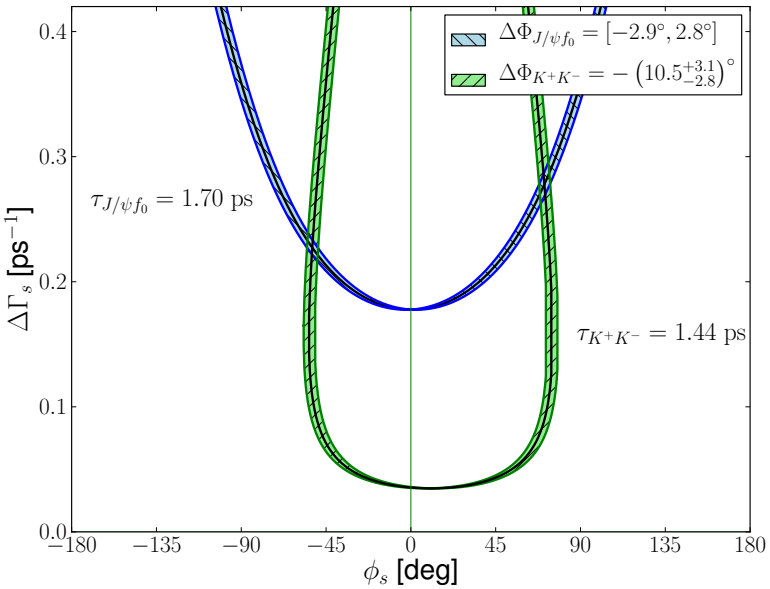
Lifetime contours

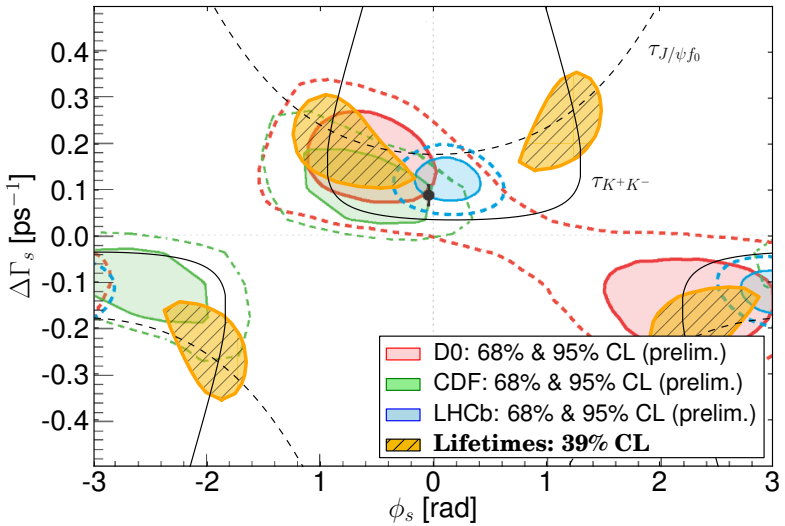


Future Precision



Robust hadronic uncertainties





Can compare with **tagged** analyses

Summary

- CP observables $\rightarrow$ SM values

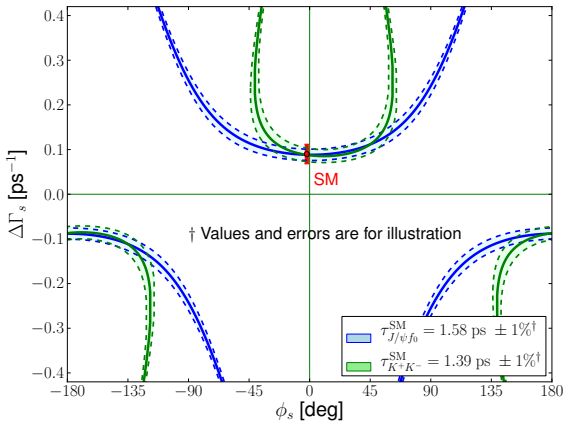
Disentangle New Physics

from **SM Hadronic Physics**

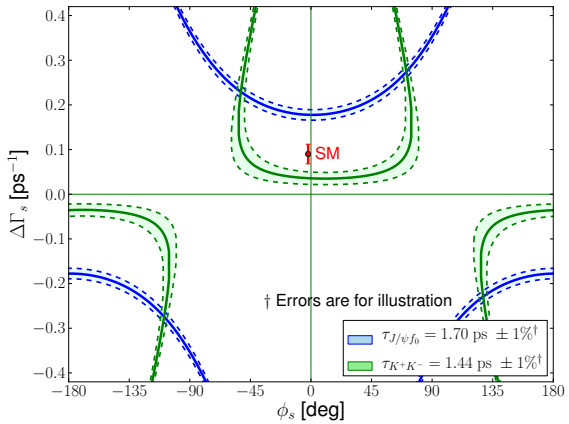
- **Probe** B_s mixing phase with **untagged** analysis:

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

- We eagerly await **lifetime** and **CP violation** measurements!

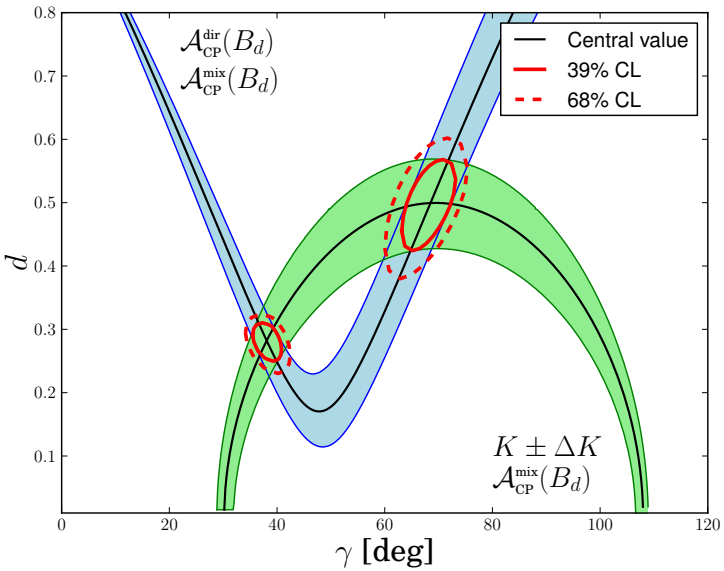


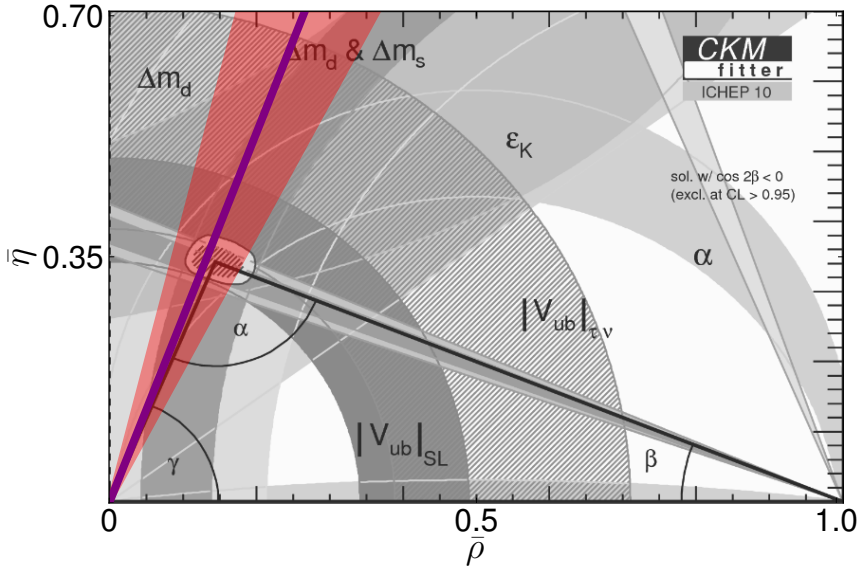
Jamboree
2012 ??



Backup

U-spin determination





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

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

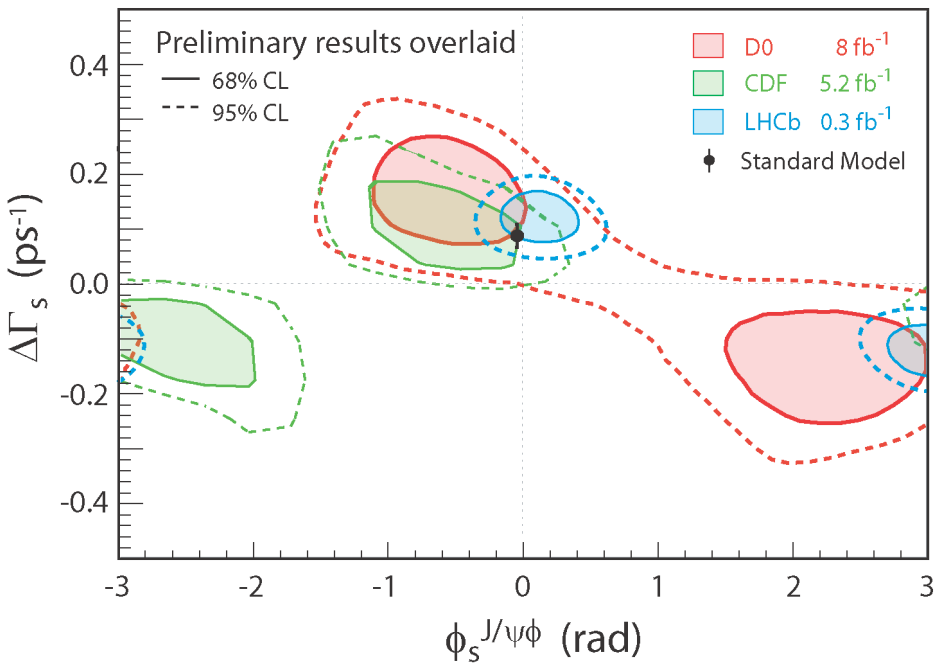
Robert Fleischer, RK (arXiv:1011.1096)

Combined Fits

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

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

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



Effective Lifetime

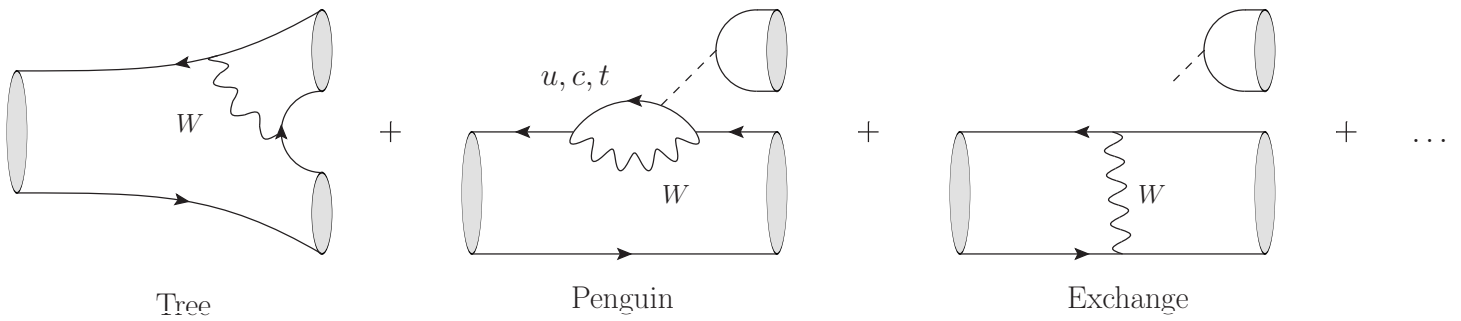
$$\tau = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2\,\mathcal{A}_{\Delta\Gamma}\, y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}\, y_s} \right)$$

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

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

Decay Amplitudes: General Formalism

In reality:



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

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

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

$$\begin{aligned}\Delta\Gamma_s &\equiv \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} \\ &\simeq 2|\Gamma_{12}|\cos(\Theta_{\mathrm{M}} - \Theta_{\Gamma})\end{aligned}$$

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

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

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

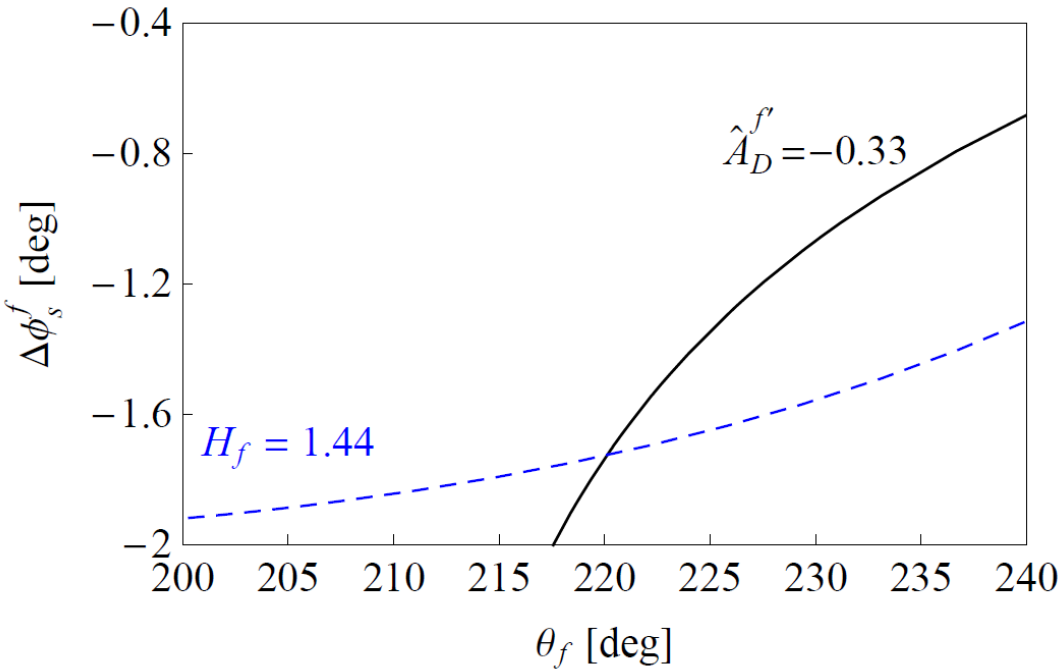
$$\frac{\Delta\Gamma_s^{Th}}{\Gamma_s} = 0.133 \pm 0.032$$

$B_s \to J/\psi\phi$ 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)



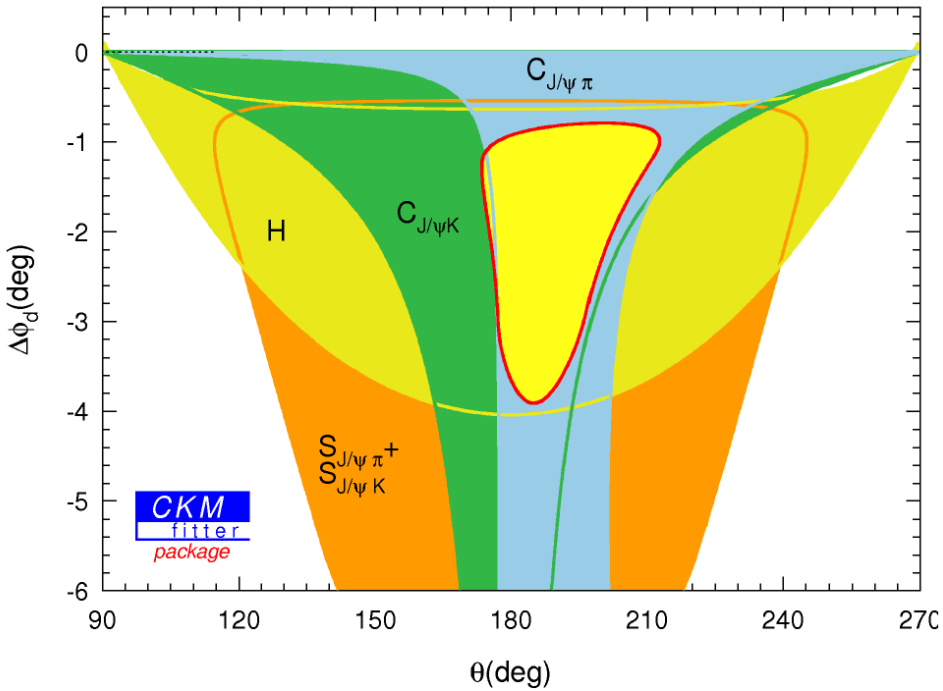
- Future control channels: $B_s \to J/\psi\bar{K}^{*0}$ and $B_d \to J/\psi\rho^0$

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)