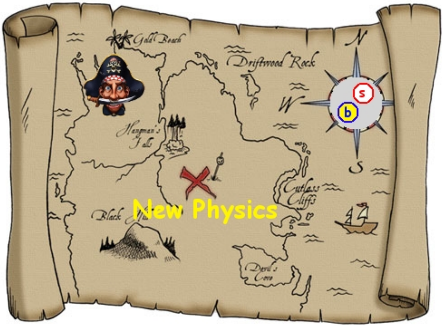
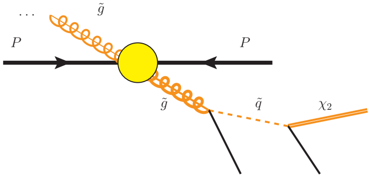
Lessons from B_s Lifetimes

Rob Knegjens



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

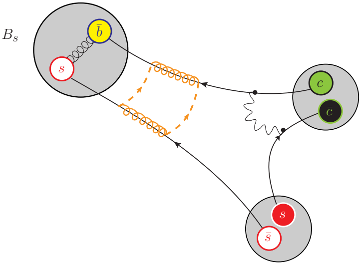


Direct searches

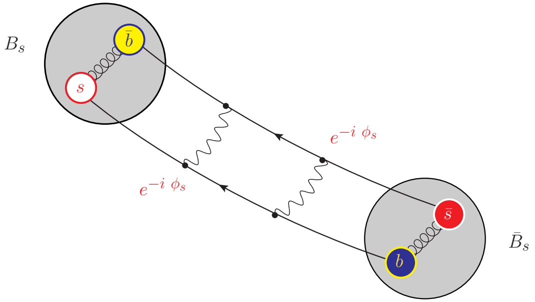
"The high energy frontier"

Indirect searches

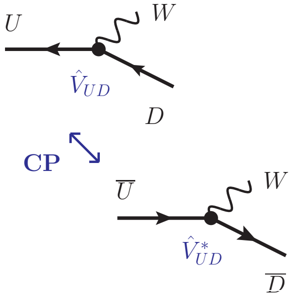
"The precision frontier"



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



Standard Model:



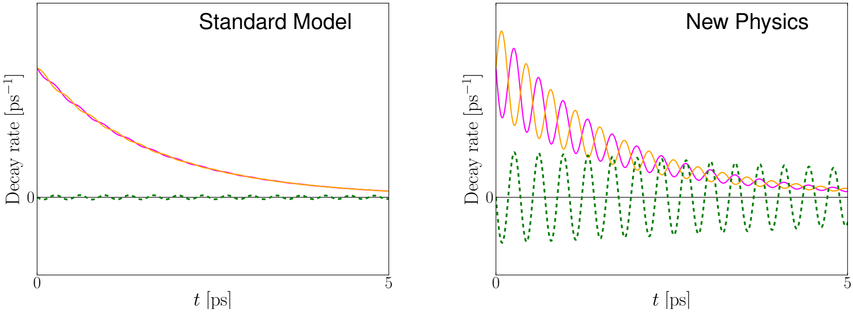
$$2\arg(V_{ts}\,V_{tb}{}^*) = -2.1^\circ$$

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

Time-dependent **tagged** CP measurement

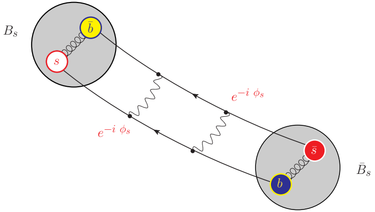
Tag $\equiv$ identify if B_s or $\bar{B}_s$

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



CP violation in interference

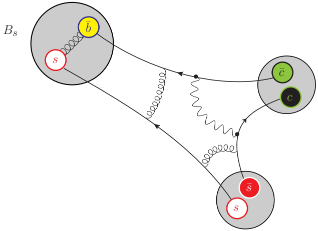
B_s^0–$\bar{B}_s^0$ Mixing



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

ϕ_s }

Decay Mode



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

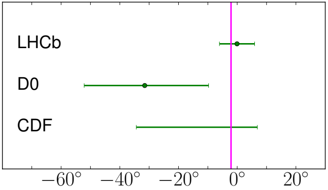
hadronic physics }

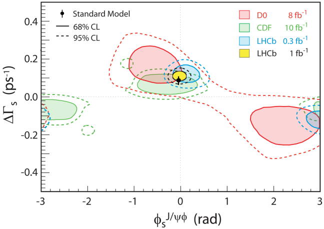
$$A_{\rm CP} = \text{function}\left(\Delta M_s, \Delta\Gamma_s, \boxed{\phi_s + \Delta\phi},\ C\right)$$

The **flagship** **Decay Mode**: $B_s \to J/\psi\ \phi$

Latest results from Moriond 2012:

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



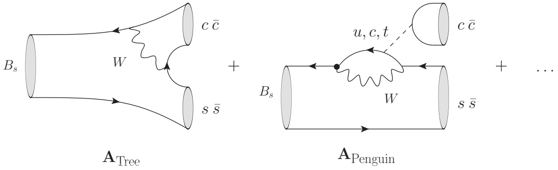


CP observables → SM predictions

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

$\Delta\phi = ??$

Optimal **Decay Mode** structure: $B_s \to \underbrace{J/\psi}_{\bar{c}c}\ \underbrace{\phi}_{\bar{s}s}$



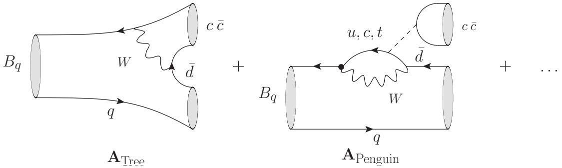
$$A(B_s \to \bar{c}c\bar{s}\,s) = A_{\rm T}\, V_{cb}^* V_{cs} + A_{\rm P}^u\, V_{ub}^* V_{us} + A_{\rm P}^c\, V_{cb}^* V_{cs} + A_{\rm P}^u\, V_{tb}^* V_{ts} + \ldots$$

$$= \mathcal{A}\left[1 + \underbrace{\lambda^2}_{0.05}\, e^{i\gamma}\, b\, e^{i\theta}\right], \qquad \text{in SM} : \gamma \sim 70^\circ$$

$$b\, e^{i\theta} = \underbrace{\left(\tfrac{1}{\lambda} - \tfrac{\lambda}{2}\right)\left|\tfrac{V_{ub}}{V_{cb}}\right|}_{\sim\frac{1}{2}} \left(\frac{A_{\rm P}^{(ut)}}{A_{\rm T} + A_{\rm P}^{(ct)}}\right)$$

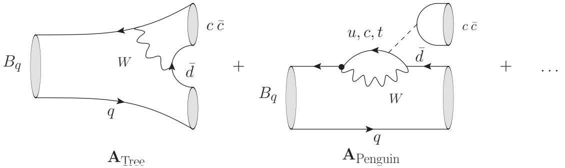
$$\begin{cases} C = -\overbrace{\lambda^2}^{5\%} \sin\gamma\ 2b\ \sin\theta + \mathcal{O}(\epsilon^2) \\ \Delta\phi = \underbrace{\lambda^2}_{3^\circ} \sin\gamma\ 2b\ \cos\theta + \mathcal{O}(\epsilon^2) \end{cases}$$

Penguin control via **flavour symmetry**



$$A(B_q \to \bar{c}c\bar{d}\,q) \overset{SU(3)_F}{=} -\lambda\,\mathcal{A}\left[1 - \underbrace{\not{\lambda}^2}_{1} e^{i\gamma}\, b\, e^{i\theta}\right]$$

Penguin control via **flavour symmetry**



$$A(B_q \to \bar{c}c\bar{d}\,q) \overset{SU(3)_F}{=} -\lambda\,\mathcal{A}\left[1 - \underbrace{\lambda^2}_{1} e^{i\gamma}\, b\, e^{i\theta}\right]$$

- Example: $B_d \to J/\psi\, K^0$ to $B_d \to J/\psi\, \pi^0$:

  $b \in [0.15, 0.67], \quad \theta \in [174^\circ, 212^\circ] \quad \Longrightarrow \quad \Delta\phi^d_{J/\psi\,K^0} = [-3.9^\circ, -0.8^\circ]$

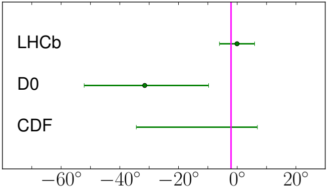
  S. Faller, R. Fleischer, M. Jung, T. Mannel, PRD 79 014030 (2009) M. Ciuchini, M. Pierini, L. Silvestrini, PRL 95 221804 (2005)/arXiv:1102.0392

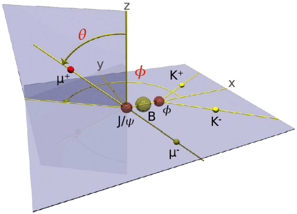
- Soon also $B_s \to J/\psi\, K^0$

  K. De Bruyn, R. Fleischer, P. Koppenburg, Eur.Phys.J. C70 (2010) 1025-1035

The **flagship Decay Mode**: $B_s \to J/\psi\ \phi$

$$\phi_s + \overbrace{\Delta\phi^{\lambda}_{J/\psi\phi}}^{[-3^\circ,3^\circ]}$$





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

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

CP observables → SM predictions

Disentangle New Physics 

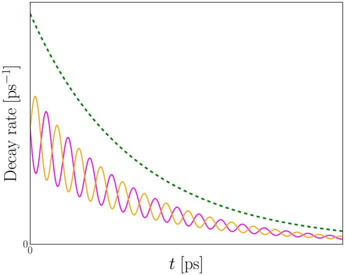
from **SM Hadronic Physics** 

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?

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

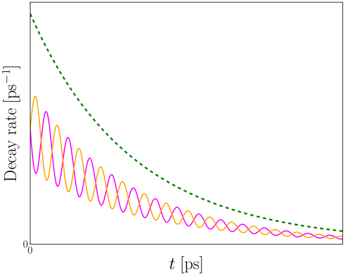


A time-dependent **untagged** analysis?

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

$$\propto e^{-\Gamma_s t}\Big[\cosh(\Delta\Gamma_s\, t) \quad + \underbrace{\mathcal{A}^f_{\Delta\Gamma} \quad \times}_{\text{function}(\phi_s + \Delta\phi_f, C_f)} \quad \sinh(\Delta\Gamma_s\, t)\Big]$$

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



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

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

$$= \text{function}\Big(\Delta\Gamma_s, \; \underbrace{\phi_s} + \Delta\phi_f, \; C_f\Big)$$

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

$$\boxed{\tau_f = \frac{\tau_{B_s}}{1 - {y_s}^2}\left(\frac{1 + 2\,\mathcal{A}^f_{\Delta\Gamma}\,y_s + {y_s}^2}{1 + \mathcal{A}^f_{\Delta\Gamma}\,y_s}\right)}, \qquad y_s \equiv \Delta\Gamma_s/2\Gamma_s$$

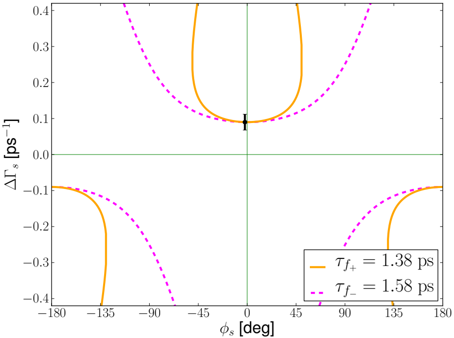
$$\mathcal{A}^f_{\Delta\Gamma} = -\eta_f\,\sqrt{1 - C_f^2}\,\cos(\phi_s + \Delta\phi_f)$$

$$\mathcal{CP}|f\rangle = \eta_f|f\rangle$$

Assuming:

$$\Delta\phi_f = 0,\;\; C_f = 0$$

$$\mathcal{A}^f_{\Delta\Gamma} = \begin{cases} -\cos\phi_s & : \quad f_{\text{even}} \\ +\cos\phi_s & : \quad f_{\text{odd}} \end{cases}$$



Measured Effective Lifetimes

Final state:

- CP Even $B_s \to K^+K^-$: *LHCB, arXiv:1207.5993*

$$\tau_{K^+K^-} = [1.455 \pm 0.046 \pm 0.006]\ \mathrm{ps}$$

- CP Odd $B_s \to J/\psi f_0(980)$: *LHCb, arXiv:1207.0878*

$$\tau_{J/\psi f_0} = [1.700 \pm 0.040 \pm 0.026]\ \mathrm{ps}$$

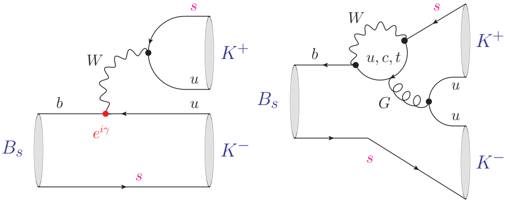
But...

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

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

Controlling the **CP Even** Decay Mode

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



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

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

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

interchange $s \leftrightarrow d$ 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

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

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

$f_0(980)$ [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

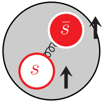
$f_0(980)$ DECAY MODES

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

Controlling the **CP Odd** Decay Mode

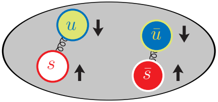
$$B_s \to J/\psi\, f_0(980)$$

Quark-antiquark



What is $f_0(980)$?

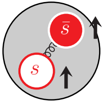
Tetraquark



Controlling the **CP Odd** Decay Mode

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

Quark-antiquark



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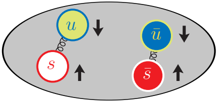
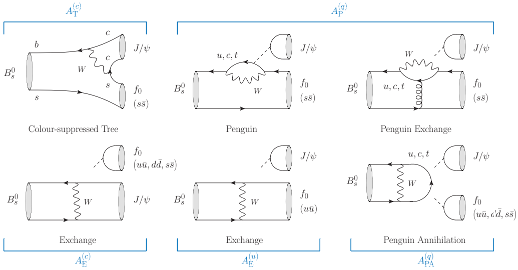
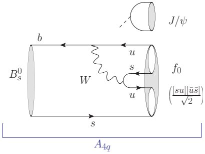


- Decay amplitudes may vary:





Controlling the **CP Odd** Decay Mode

- Propose **control channel**: $B_d \to J/\psi\, f_0(980)$
- **Useful** if :

$$\boxed{A_{\rm T}, A_{\rm P} \gg A_{\rm E}, A_{\rm PA}, A_{4q}}$$

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

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

- **Predict**:

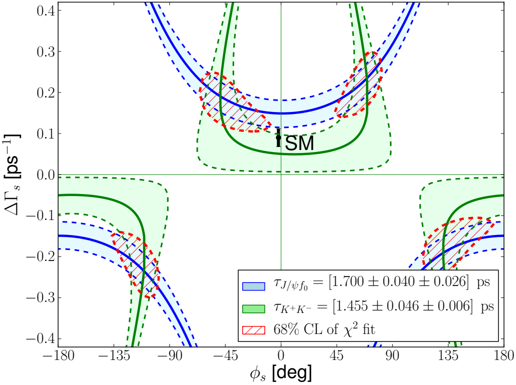
$$\mathrm{BR}(B_d \to J/\psi\, f_0; f_0 \to \pi^+\pi^-)$$
$$\sim (1-3) \times 10^{-6} \times \begin{cases} \left[\frac{\tan\varphi_M}{\tan 35^\circ}\right]^2 & : \quad q\bar{q} \\ 1 & : \quad \text{tetraquark} \end{cases}$$

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

Lifetime contours in the ϕ_s–$\Delta\Gamma_s$ plane

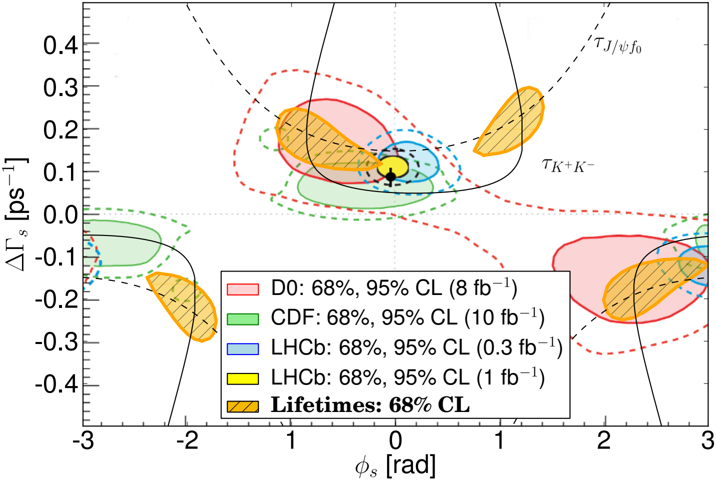
$$\tau_f = \text{function}\left(\Delta\Gamma_s,\ \boxed{\phi_s + \Delta\phi},\ C\right)$$

- **CP Even :** $\tau_{K^+K^-}$, $\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ$, $C_{K^+K^-} = 0.09$
- **CP Odd :** $\tau_{J/\psi f_0}$, $\Delta\phi_{J/\psi f_0} \in [-3^\circ, 3^\circ]$, $C_{J/\psi f_0} \leq 0.05$



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

Untagged determination of B_s mixing parameters



B_s Branching Ratios

K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, N. Tuning, Phys.Rev.D 86 (2012)

- Measured:

$$\mathrm{BR}(B_s \to f)_{\mathrm{exp}} \equiv \frac{1}{2}\int_0^\infty \langle \Gamma_f(t) \rangle \, dt$$
$$= \frac{1}{2}\left[\frac{\Gamma(B_{\mathrm{H}} \to f)}{\Gamma_{\mathrm{H}}} + \frac{\Gamma(B_{\mathrm{L}} \to f)}{\Gamma_{\mathrm{L}}}\right]$$

- Computed:

$$\mathrm{BR}(B_s \to f)_{\mathrm{theo}} \equiv \frac{1}{2}\left[\frac{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to f)}{\frac{1}{2}(\Gamma_{\mathrm{H}} + \Gamma_{\mathrm{L}})}\right]$$
$$= \frac{1}{2}\left[\frac{\Gamma(B_{\mathrm{H}} \to f) + \Gamma(B_{\mathrm{L}} \to f)}{\frac{1}{2}(\Gamma_{\mathrm{H}} + \Gamma_{\mathrm{L}})}\right]$$

- Dictionary for $\Delta\Gamma_s \equiv \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} \neq 0$ via effective lifetime τ_f:

$$\boxed{\mathrm{BR}(B_s \to f)_{\mathrm{theo}} = \left[2 - (1 - {y_s}^2)\frac{\tau_f}{\tau_{B_s}}\right] \mathrm{BR}(B_s \to f)_{\mathrm{exp}}}$$

Probing New Physics in $B_s \to \mu^+\mu^-$

K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, A. Pellegrino, N. Tuning, Phys.Rev.Lett 109 (2012)

- Rare decay in SM, **very sensitive** to scalar New Physics

A. Buras, Proc.Sci.BEAUTY (2011)

$$\mathrm{BR}\left(B_s \to \mu^-\mu^-\right)_{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

- Experimentally bounded

LHCb, Phys. Rev.Lett 108 (2012)

$$\mathrm{BR}\left(B_s \to \mu^-\mu^-\right)_{\mathrm{exp}} < 4.5 \times 10^{-9} \quad @\ 95\%\ \mathrm{C.L}$$

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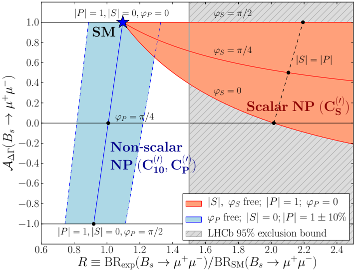
- Untagged observable:

$$\tau_{\mu^+\mu^-} / \mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}$$

experimentally feasable **probe** of NP



Summary

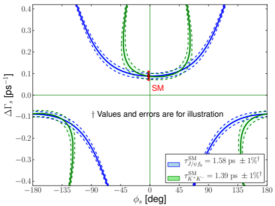
- CP observables → SM predictions

Disentangle **New Physics**

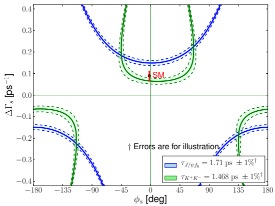
from **SM Hadronic Physics**

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

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

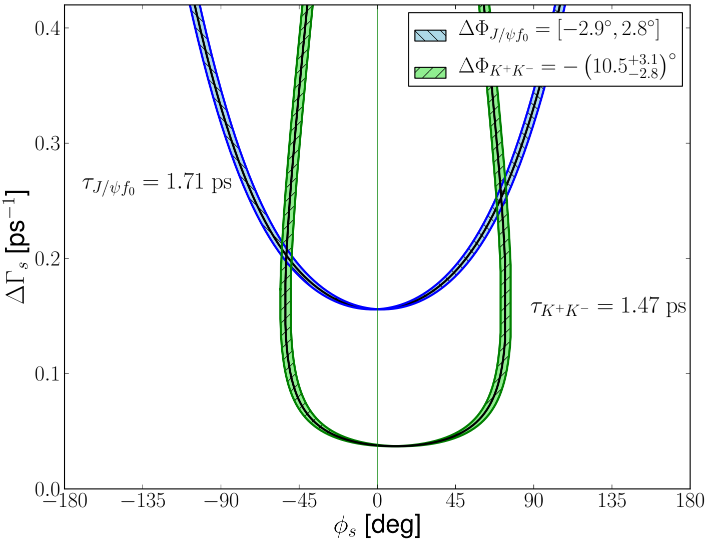


Summer 2013 ??



Backup

Hadronic uncertainties



Effective Lifetime

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

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

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

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

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

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

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 $\overline{\mathbf{3}}$, $S = 0$

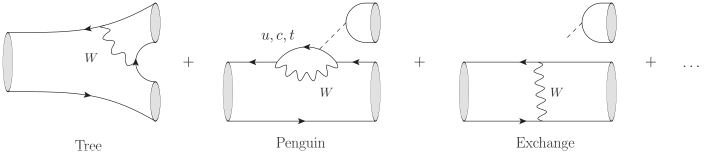
- Issues: $f_0 \to \pi\pi$ coupling too small, $a_0 \to \eta\pi$ too large.
- Solved by adding *instanton-induced effects*

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

(arXiv:0801.2288)

Decay Amplitudes: General Formalism

In reality:



$$\text{e.g.}\quad A(B \to f) = A_{\mathrm{T}} + A_{\mathrm{P}}^{u} + A_{\mathrm{P}}^{c} + A_{\mathrm{P}}^{t} + \ldots$$

$$= |A_{\mathrm{T}}|e^{i\delta_T} e^{i\varphi_T} + |A_{\mathrm{P}}^{u}|e^{i\delta_u} e^{i\varphi_u} + |A_{\mathrm{P}}^{c}|e^{i\delta_c} e^{i\varphi_c} + \ldots$$

$$= |A_1|e^{i\delta_1}\left(e^{i\varphi_1} + e^{i\varphi_2}\, h\, e^{i\delta}\right)$$

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

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

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)*

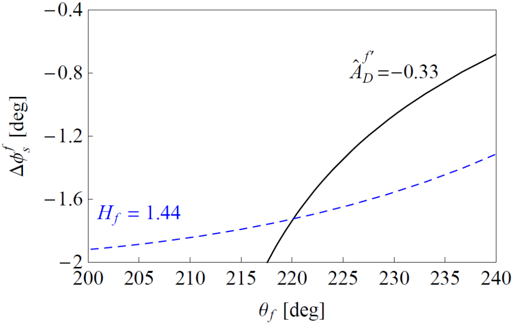
$$\frac{\Delta\Gamma_s^{Th}}{\Gamma_s} = 0.133 \pm 0.032$$

$B_s \to J/\psi\phi$ 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



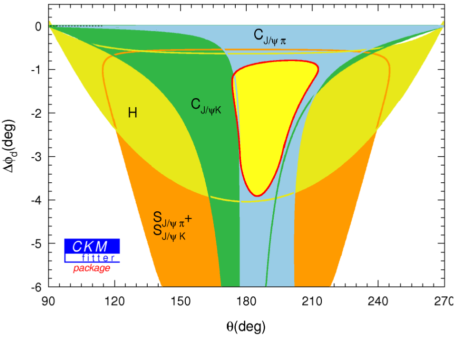
- Future control channels: $B_s \to J/\psi \bar{K}^{*0}$ and $B_d \to J/\psi\rho^0$

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)*