Penguin Uncertainties in ϕ_s and Effective B_s Lifetime Measurements

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Implications of LHCb Measurements and Future Prospects
CERN, 10–11 November 2011

- Prelude: penguin effects in $B_{d,s} \to J\psi K_{\rm S}$
- Effective B_s Decay Lifetimes: $\to$ general features
- Key Decays: $\to$ lifetimes & CP-violating asymmetries $\oplus$ hadronic uncertaintes

$$\boxed{B_s^0 \to K^+K^-,\ B_s^0 \to J/\psi f_0(980),\ B_s^0 \to J/\psi\phi} \quad \oplus \text{ "Control Channels"}$$

Setting the Stage

(New) Flavour Physics: Where Do We Stand?

Still no indirect/direct signal for New Physics at the LHC ...

- Implications for the structure of New Physics (NP):

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}(\varphi_{\rm NP}, g_{\rm NP}, m_{\rm NP}, ...)$$

  - Large characteristic NP scale $\Lambda_{\rm NP}$, i.e. not just $\sim$ TeV, which would be bad news for the direct searches at ATLAS and CMS, or (and?) ...
  - Symmetries prevent large NP effects in FCNCs and the flavour sector; most prominent example: *Minimal Flavour Violation (MFV):*

    $\rightarrow$ essentially the same CP & flavour violation as in the SM.

- Comments:
  - MFV has still not yet been experimentally established.
  - There are various non-MFV scenarios with room for sizeable effects: SUSY, WED, LHT, Z' models, 4th generation, ...

- LHC results: $\rightarrow$ prepare to deal with "smallish" NP effects ...

[see also Gino Isidori's talk]

Towards New Frontiers in Precision B-Physics

- We are still far from fully exploiting the power of LHCb...
- Crucial for resolving possible (smallish ...) effects of NP:
  - Have a critical look at theoretical analyses and their approximations:

    $\rightarrow$ key issue: $\boxed{\text{strong interactions: } \rightarrow \text{ “hadronic” effects}}$
  - Match the experimental and theoretical precisions.
- Prominent decays for studying CP violation: $B_s \to J/\psi\phi$, $B_s \to J/\psi f_0(980)$
  - Uncertainties from doubly Cabibbo-suppressed penguin contributions.
  - The effects are usually neglected; we cannot reliably calculate them...

    $\Rightarrow$ $\boxed{\text{how big are they \& how can they be controlled?}}$
- Probes of NP in B_s^0–$\bar{B}_s^0$ mixing complementary to CP asymmetries:
  - Effective B_s decay lifetimes $\rightarrow$ untagged data samples $\rightarrow$ new focus.
  - Cases that are very robust with respect to hadronic effects.

PhD Students:

Rob Knegjens
(Theory)

Kristof De Bruyn
(Theory $\oplus$ LHCb)

[Thanks to Rob for updating some plots]

Prelude:

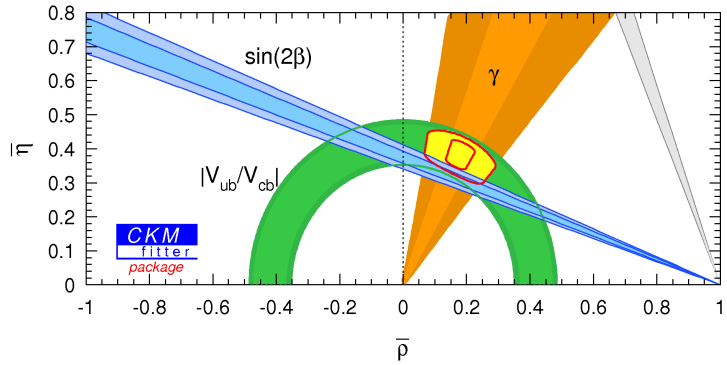
Penguin Effects in $B_{d,s} \to J\psi K_{\rm S}$

$\oplus$

Constraints from $B_d \to J/\psi\pi^0$

Penguin Effects in $B_d^0 \to J/\psi K_S$

- Tension in fit of UT: $(\phi_d)_{J/\psi K^0} - 2\beta_{\rm true} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ \to$ NP!?



- SM corrections: doubly Cabibbo-suppressed penguins $(\lambda \equiv |V_{us}| = 0.22) \to$

$$A(B_d^0 \to J/\psi\, K_S) \propto \left[1 + \epsilon a e^{i\theta} e^{i\gamma}\right] \quad (\epsilon \equiv \lambda^2/(1-\lambda^2) \sim 0.05)$$

- Generalized expression for mixing-induced CP violation: $[\phi_d = 2\beta + \phi_d^{\rm NP}]$

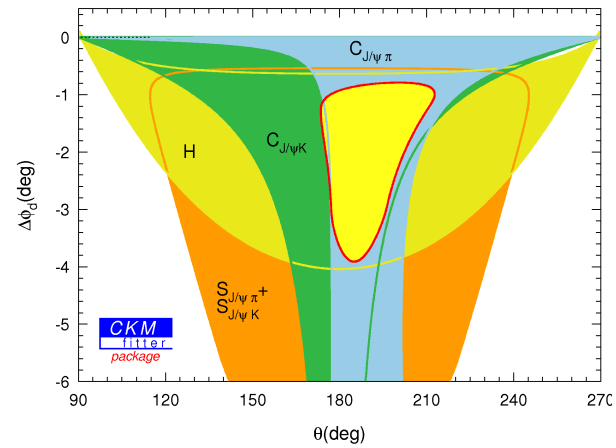
$$S(B_d \to J/\psi K_S) \propto \sin(\phi_d + \Delta\phi_d)$$

$$\begin{aligned} \sin\Delta\phi_d &\propto 2\epsilon a \cos\theta \sin\gamma + \epsilon^2 a^2 \sin 2\gamma \\ \cos\Delta\phi_d &\propto 1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2 \cos 2\gamma \end{aligned}$$

[S. Faller, R.F., M. Jung & T. Mannel (2008)]

- $\Delta\phi_d$ *cannot* be calculated: $\Rightarrow$ $\boxed{\text{use } B_d^0 \to J/\psi\pi^0 \text{ data \& } SU(3)}$

$$A(B_d^0 \to J/\psi\pi^0) \propto \left[1 - ae^{i\theta}e^{i\gamma}\right]$$



  - Fit to data, allowing also for $SU(3)$-breaking corrections:

    $\Rightarrow \Delta\phi_d \in [-6.7, 0.0]^\circ$, i.e. softens the tension in the fit of the UT.

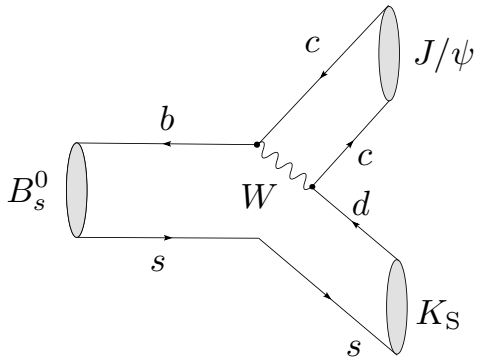
  - NP mixing phase: $\phi_d^{\rm NP} \in [-14.9, 4.0]^\circ$, i.e. no significant effect.

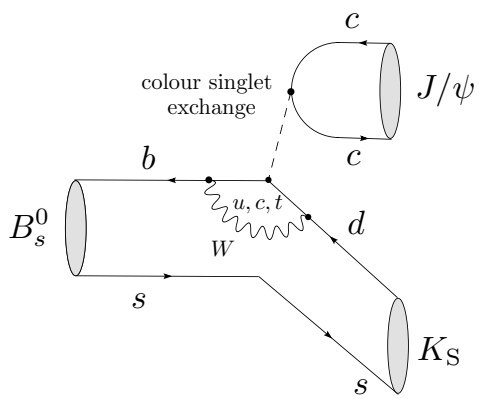
- Observation:

  - The quality of the B-factory data has essentially reached a level of precision where subleading SM effects have to be included!
  - This will be even much more relevant in the LHC era, but $B_d^0 \to J/\psi\pi^0$ is very challenging for this experiment (super-B factory could do) $\Rightarrow$

[Faller, R.F., Jung & Mannel (2008); also Ciuchini, Pierini & Silvestrini (2005 & 2011)]

(A New) Channel for LHCb: $B_s^0 \to J/\psi K_S$





$$A(B_s^0 \to J/\psi K_S) \propto \mathcal{A}\left[1 - a e^{i\theta} e^{i\gamma}\right]$$

- U-spin symmetry:[1] $\boxed{B_s^0 \to J/\psi K_S \;\Leftrightarrow\; B_d^0 \to J/\psi K_S}$ [R.F. (1999)]

  $\Rightarrow$ determination of the UT angle $\gamma \oplus$ penguin parameters

- Experimental status of the $B_s^0 \to J/\psi K_S$ decay:
  - Recent news from LHCb [P. Koppenburg @ Physics in Collision 2011]:

$$\frac{\mathrm{BR}(B_s \to J/\psi K_S)}{\mathrm{BR}(B_d \to J/\psi K_S)} = 0.0378 \pm 0.0058(\mathrm{stat}) \pm 0.0020(\mathrm{syst}) \pm 0.0030(\mathrm{frag})$$

  - First observation by CDF @ ICHEP2010: $0.041 \pm 0.007 \pm 0.004 \pm 0.005$

[1] U spin is an $SU(2)$ subgroup of strong $SU(3)_F$ relating down and strange quarks to each other.

through

$$\begin{aligned}&\Gamma(B(t) \to f) + \Gamma(\overline{B}(t) \to f)\\ &\quad = \mathrm{PhSp} \times |\mathcal{N}|^2 \times \left[R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}\right], \end{aligned} \tag{28}$$

where PhSp denotes an appropriate, straightforwardly calculable phase-space factor. Consequently, the overall normalization $|\mathcal{N}|^2$ is required in order to determine R. In the case of the decay $B_s \to J/\psi K_S$, this normalization can be fixed through the CP-averaged $B_d \to J/\psi K_S$ rate with the help of the U-spin symmetry.

In the case of $B_d \to J/\psi K_S$, we have

$$\begin{aligned}&\mathcal{N} = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}', \quad b = \epsilon a',\\ &\rho = \theta' + 180^\circ, \quad \text{with} \quad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2},\end{aligned} \tag{29}$$

whereas we have in the $B_s \to J/\psi K_S$ case

$$\mathcal{N} = -\lambda\mathcal{A}, \quad b = a, \quad \rho = \theta. \tag{30}$$

Consequently, we obtain

$$\begin{aligned}H &\equiv \frac{1}{\epsilon}\left(\frac{|\mathcal{A}'|}{|\mathcal{A}|}\right)^2 \left[\frac{M_{B_d}\Phi(M_{J/\psi}/M_{B_d}, M_K/M_{B_d})}{M_{B_s}\Phi(M_{J/\psi}/M_{B_s}, M_K/M_{B_s})}\right]^3 \frac{\langle\Gamma\rangle}{\langle\Gamma'\rangle}\\ &= \frac{1 - 2a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2},\end{aligned} \tag{31}$$

where

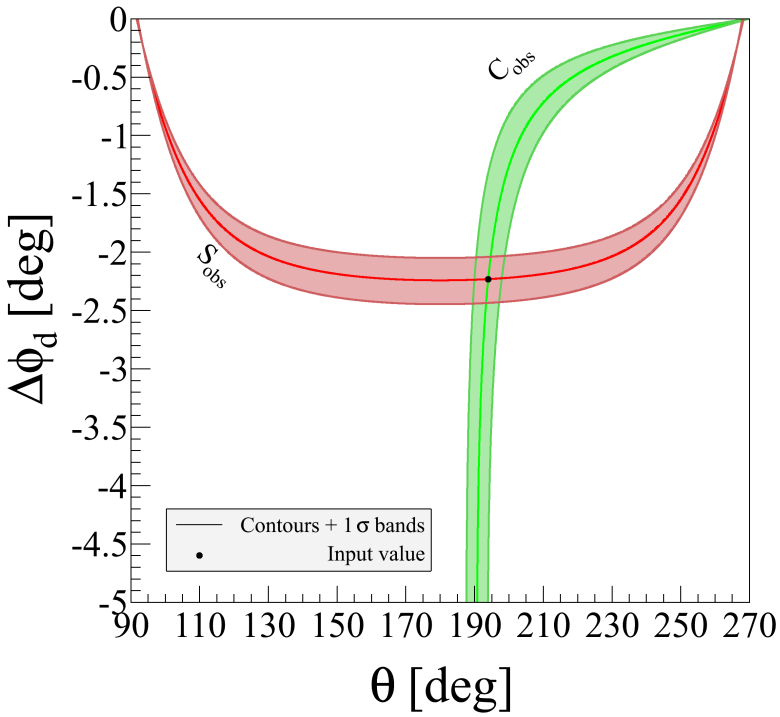
in the case of $B_d \to J/\psi K_S$. Since the value of the CP-violating parameter ε_K of the neutral kaon system is small, ϕ_K can only be affected by very contrived models of new physics [14].

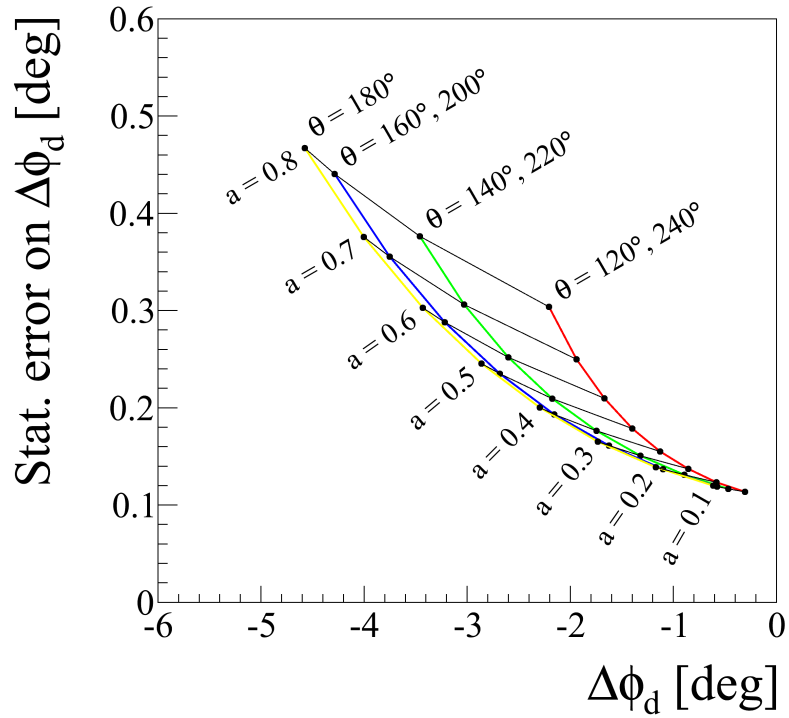
An important by-product of the strategy described above is that the quantities a' and θ' allow us to take into account the penguin contributions in the determination of β from $B_d \to J/\psi K_S$, which are presumably very small because of the Cabibbo suppression of $\lambda^2/(1-\lambda^2)$ in (3). Moreover, using (34), we obtain an interesting relation between the direct CP asymmetries arising in the modes $B_d \to J/\psi K_S$ and $B_s \to J/\psi K_S$ and their CP-averaged rates:

$$\begin{aligned}&\frac{\mathcal{A}_{CP}^{dir}(B_d \to J/\psi K_S)}{\mathcal{A}_{CP}^{dir}(B_s \to J/\psi K_S)} = -\epsilon H\\ &\quad = -\left(\frac{|\mathcal{A}'|}{|\mathcal{A}|}\right)^2 \left[\frac{M_{B_d}\Phi(M_{J/\psi}/M_{B_d}, M_K/M_{B_d})}{M_{B_s}\Phi(M_{J/\psi}/M_{B_s}, M_K/M_{B_s})}\right]^3 \frac{\langle\Gamma\rangle}{\langle\Gamma'\rangle}.\end{aligned} \tag{35}$$

An analogous relation holds also between the $B^\pm \to \pi^\pm K$ and $B^\pm \to K^\pm K$ CP-violating asymmetries [11,12]. At "second-generation" B-physics experiments at hadron machines, for instance at LHCb, the sensitivity may be good enough to resolve a direct CP asymmetry in $B_d \to J/\psi K_S$. In view of the impressive accuracy that can be achieved in the era of such experiments, it is also an important issue to think about the theoretical accuracy of the determination of β from $B_d \to J/\psi K_S$. The approach discussed above allows us to control these – presumably very small – hadronic uncertainties with the help of $B_s \to J/\psi K_S$.

- Fresh look: [R.F., K. De Bruyn & P. Koppenburg, arXiv:1010.0089 [hep-ph]]
  - First LHCb (toy) feasibility study: $\rightarrow \gamma$ extraction is feasible, but cannot compete with other methods in terms of precision.
  - *Main application:* control of the penguin effects in $(\phi_d)_{J/\psi K_S}$:





$\Rightarrow$ interesting study for the LHCb upgrade

Effective B_s Decay Lifetimes:

$\rightarrow$ promising probes of B_s^0–$\bar{B}_s^0$ mixing

[R.F. & Rob Knegjens, arXiv:1109.5115 [hep-ph]]

General Formalism

- $B_s \to f$ with a final state f into which both a B_s^0 and a $\bar{B}_s^0$ can decay:

$$\langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B_s^0(t) \to f) + \Gamma(\bar{B}_s^0(t) \to f)$$

$$= R_{\rm H}^f \, e^{-\Gamma_{\rm H}^{(s)} t} + R_{\rm L}^f \, e^{-\Gamma_{\rm L}^{(s)} t} \propto \; e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \mathcal{A}_{\Delta\Gamma}^f \, \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right]$$

$$\left[2\Gamma_s \equiv \Gamma_{\rm L}^{(s)} + \Gamma_{\rm H}^{(s)}, \quad \Delta\Gamma_s \equiv \Gamma_{\rm L}^{(s)} - \Gamma_{\rm H}^{(s)} \right]$$

- Effective lifetime of the $B_s \to f$ decay: $[y_s \equiv \Delta\Gamma_s/(2\Gamma_s), \; \tau_{B_s} = 1/\Gamma_s]$

$$\tau_f \equiv \frac{\int_0^\infty t \, \langle \Gamma(B_s(t) \to f) \rangle \, dt}{\int_0^\infty \langle \Gamma(B_s(t) \to f) \rangle \, dt} = \frac{R_{\rm L}^f/\Gamma_{\rm L}^{(s)2} + R_{\rm H}^f/\Gamma_{\rm H}^{(s)2}}{R_{\rm L}^f/\Gamma_{\rm L}^{(s)} + R_{\rm H}^f/\Gamma_{\rm H}^{(s)}}$$

$$\frac{\tau_f}{\tau_{B_s}} = \frac{1}{1 - y_s^2} \left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma}^f \, y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^f \, y_s} \right) = 1 + \mathcal{A}_{\Delta\Gamma}^f \, y_s + \left[2 - (\mathcal{A}_{\Delta\Gamma}^f)^2 \right] y_s^2 + \mathcal{O}(y_s^3)$$

- Decay dynamics: $\to$ encoded in the observable $\mathcal{A}_{\Delta\Gamma}^f$ $\to$ $\boxed{?}$

- Consider the case where f is a CP eigenstate with eigenvalue η_f:

$$A(B_s^0 \to f) = A_1^f e^{i\delta_1^f} e^{i\varphi_1^f} + A_2^f e^{i\delta_2^f} e^{i\varphi_2^f}$$

  - $A_{1,2}^f$: real parameters (chosen to be ≥ 0)
  - $\delta_{1,2}^f$: CP-conserving strong phases
  - $\varphi_{1,2}^f$: CP-violating weak phases (enter through CKM matrix elements)

  $\to$ general SM expression, using the unitarity of the CKM matrix

- B_s^0–$\bar{B}_s^0$ mixing formalism:

$$\mathcal{A}_{\Delta\Gamma}^f = \frac{2\,\mathrm{Re}\,\xi_f^{(s)}}{1 + \left|\xi_f^{(s)}\right|^2}$$

$$\xi_f^{(s)} = -\eta_f e^{-i\phi_s} \left[\frac{e^{-i\varphi_1^f} + h_f e^{i\delta_f} e^{-i\varphi_2^f}}{e^{i\varphi_1^f} + h_f e^{i\delta_f} e^{i\varphi_2^f}} \right], \qquad h_f e^{i\delta_f} \equiv \frac{A_2^f}{A_1^f} e^{i(\delta_2^f - \delta_1^f)}$$

$\to$ can derive compact expressions: $\Rightarrow$

$$[\phi_s \equiv \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}} \quad \text{with} \quad \phi_s^{\mathrm{SM}} \equiv -2\beta_s = -(2.08 \pm 0.09)^\circ]$$

- Relevant combination for the calculation of the observable(s):

$$\frac{2\,\xi_f^{(s)}}{1+\left|\xi_f^{(s)}\right|^2} = -\eta_f\sqrt{1-C_f^2}\,e^{-i(\phi_s+\Delta\phi_f)}$$

  - Direct CP asymmetry C_f of the $B_s \to f$ decay:

$$C_f \equiv \frac{1-|\xi_f|^2}{1+|\xi_f|^2} = \frac{2\,h_f \sin\delta_f \sin(\varphi_1^f-\varphi_2^f)}{N_f}$$

$$N_f \equiv 1 + 2h_f\cos\delta_f\cos(\varphi_1^f-\varphi_2^f) + h_f^2$$

  - Hadronic phase shift [also expressions for $\sin\Delta\phi_f$ and $\cos\Delta\phi_f$]:

$$\tan\Delta\phi_f = \frac{\sin 2\varphi_1^f + 2h_f\cos\delta_f\sin(\varphi_1^f+\varphi_2^f) + h_f^2\sin 2\varphi_2^f}{\cos 2\varphi_1^f + 2h_f\cos\delta_f\cos(\varphi_1^f+\varphi_2^f) + h_f^2\cos 2\varphi_2^f}.$$

- Final expression for $\mathcal{A}_{\Delta\Gamma}^f$:

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

Lifetime Contours in the ϕ_s–$\Delta\Gamma_s$ Plane

$$\frac{\tau_f}{\tau_{B_s}} = \frac{1}{1-y_s^2}\left(\frac{1+2\mathcal{A}^f_{\Delta\Gamma}\,y_s+y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}\,y_s}\right) \Rightarrow \text{ cubic equation for } y_s\text{:}$$

$$\boxed{y_s^3 + a_2 y_s^2 + a_1 y_s + a_0 = 0}$$

$$a_0 \equiv \frac{\tau_{B_s}-\tau_f}{\tau_f\mathcal{A}^f_{\Delta\Gamma}}, \quad a_1 \equiv \frac{2\,\tau_{B_s}-\tau_f}{\tau_f}, \quad a_2 \equiv \frac{\tau_{B_s}+\tau_f}{\tau_f\mathcal{A}^f_{\Delta\Gamma}}.$$

- Analytic solution: formula by Girolamo Cardano [1501–1576]

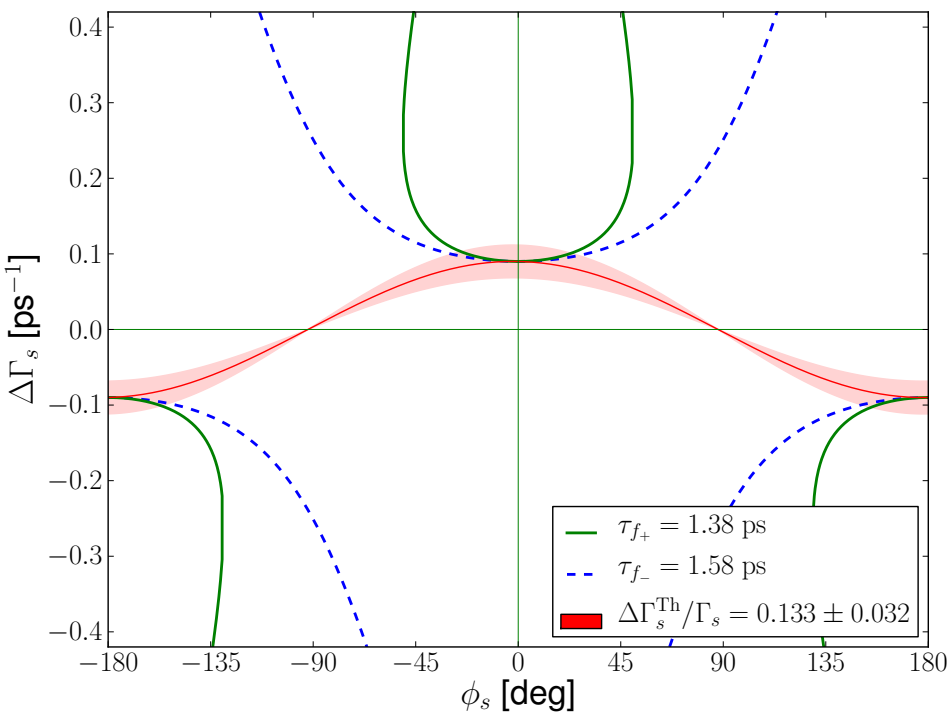
  $\rightarrow$ details in our paper [arXiv:1109.5115 [hep-ph]]

- Approximate solution: $\rightarrow$ excellent agreement with the exact solution:

$$y_s \approx -\frac{1}{2}\left[\frac{\mathcal{A}^f_{\Delta\Gamma}}{2-(\mathcal{A}^f_{\Delta\Gamma})^2}\right] \pm \frac{1}{2}\sqrt{\left[\frac{\mathcal{A}^f_{\Delta\Gamma}}{2-(\mathcal{A}^f_{\Delta\Gamma})^2}\right]^2 + \frac{4}{\tau_{B_s}}\left[\frac{\tau_f-\tau_{B_s}}{2-(\mathcal{A}^f_{\Delta\Gamma})^2}\right]}$$

- Illustration:
  - Consider two B_s decays to CP eigenstates, $B_s \to f_+$ and $B_s \to f_-$, with positive and negative CP eigenvalues, respectively.
  - Moreover: $h_{f_\pm} = 0$, $\varphi_1^{f_\pm} = 0 \Rightarrow C_{f_\pm} = 0$ and $\Delta\phi_{f_\pm} = 0$.
  - Use $\Delta\Gamma_s^{\rm Th}/\Gamma_s = 2\,y_s^{\rm Th} = 0.133 \pm 0.032$ [Lenz & Nierste (2011)], and assume that NP enters $\Delta\Gamma_s$ only through B_s mixing [Grossman (1996)]:

$$y_s = \frac{\Delta\Gamma_s^{\rm Th}\cos\tilde{\phi}_s}{2\Gamma_s} = y_s^{\rm Th}\cos(\tilde{\phi}_s^{\rm SM} + \phi_s^{\rm NP}), \quad \tilde{\phi}_s^{\rm SM} = (0.22 \pm 0.06)^\circ$$



◇ Practical Implementation:

→ key channels (data already available):

- $B_s^0 \to K^+K^-$

- $B_s^0 \to J/\psi f_0(980)$

→ hadronic effects?

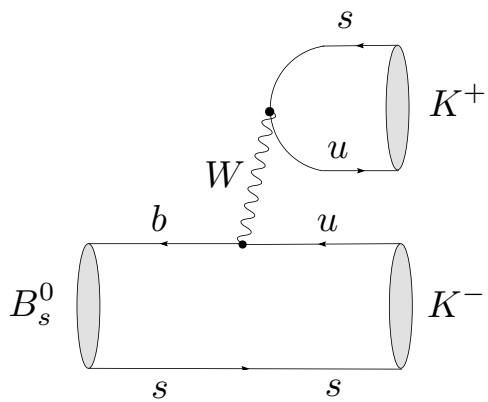
$$\boxed{B_s \to K^+K^-}$$

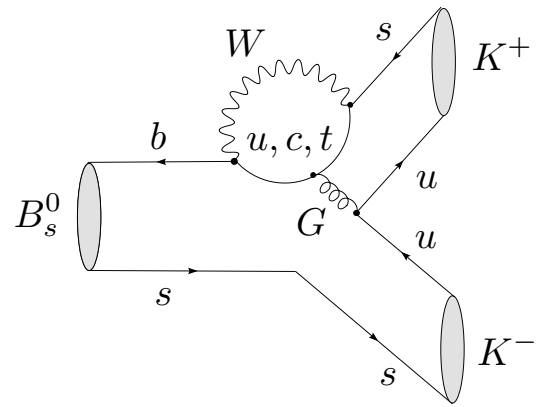
$\oplus$ U-Spin Partner

$$\boxed{B_d \to \pi^+\pi^-}$$

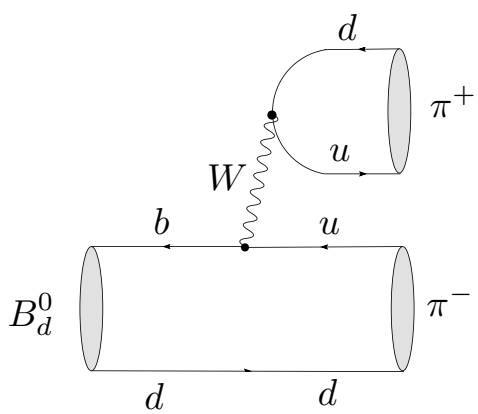
Decay Topologies & Amplitudes

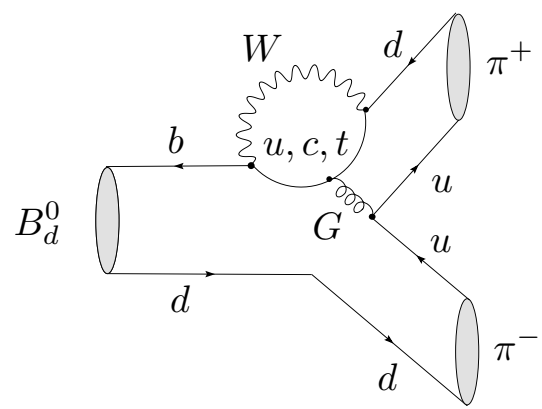
- $B_s^0 \to K^+K^-$: $$A(B_s^0 \to K^+K^-) \propto \mathcal{C}\left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d e^{i\theta}\right]$$





- $B_d^0 \to \pi^+\pi^-$: $$A(B_d^0 \to \pi^+\pi^-) \propto \mathcal{C}'\left[e^{i\gamma} - d'\, e^{i\theta'}\right]$$





$$\Rightarrow \quad \boxed{s \leftrightarrow d}$$

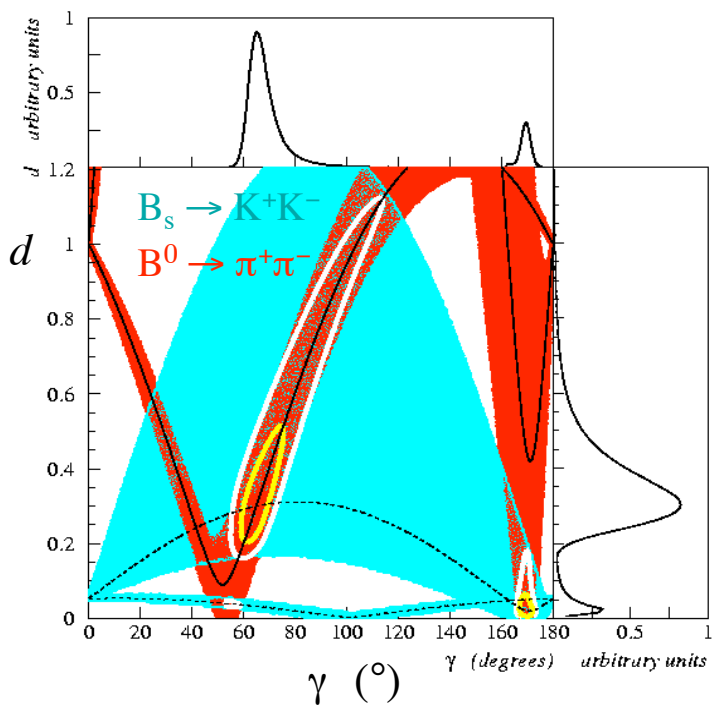
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

$$\boxed{U\text{-spin symmetry}} \quad \Rightarrow \quad d' = d,\ \theta' = \theta$$

  - Determination of γ and hadronic parameters $d(= d')$, θ and θ'.
  - Internal consistency check of the U-spin symmetry: $\theta \stackrel{?}{=} \theta'$.

[R.F. (1999)]

- Detailed studies show that this strategy is very promising for LHCb:



$\to$ experimental accuracy for γ of a few degrees!

[LHCb Collaboration (B. Adeva *et al.*)
LHCb-PUB-2009-029, arXiv:0912.4179v2]

Getting ready for LHCb data:

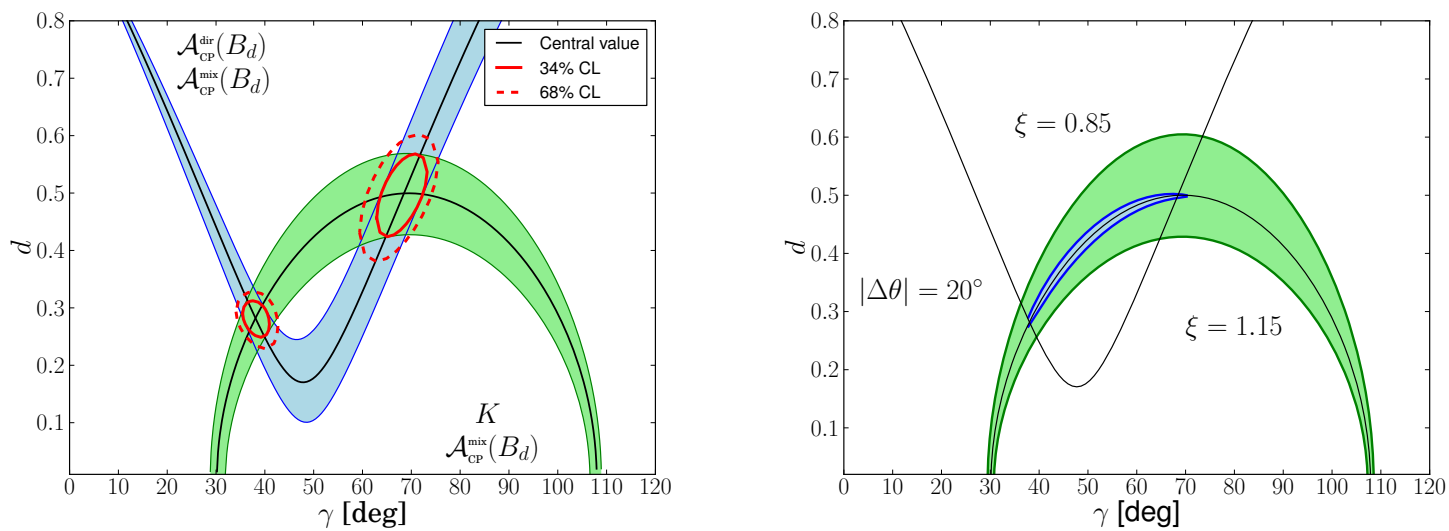
- Use B-factory data as input, as well as ...
- BR($B_s \to K^+K^-$) [CDF and Belle @ $\Upsilon(5S)$]
- Updated information of U-spin-breaking form-factor ratios.

Measurements of CPV in $B_s \to K^+K^-$ *are not yet available*

[R.F. & R. Knegjens, arXiv:1011.1096 [hep-ph]]

Current Picture for γ

- Input data:
  - Information on $K \propto \mathrm{BR}(B_s \to K^+K^-)/\mathrm{BR}(B_d \to \pi^+\pi^-)$;
  - CP violation in $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^\mp K^\pm$;
  - U-spin-breaking corrections: $\xi \equiv d'/d = 1 \pm 0.15$, $\Delta\theta \equiv \theta' - \theta = \pm 20^\circ$:



$$\Rightarrow \boxed{\gamma = (68.3^{+4.9}_{-5.7}|_{\rm input}{}^{+5.0}_{-3.7}|_{\xi}{}^{+0.1}_{-0.2}|_{\Delta\theta})^\circ}$$

(2-fold ambiguity can be resolved [R.F. ('07)])

- Fits of the UT: $\gamma = (67.2^{+3.9}_{-3.9})^\circ$ (CKMfitter), $(69.6 \pm 3.1)^\circ$ (UTfit).

Current Picture for the Hadronic Parameters

- Parameters of the general lifetime discussion: $[\epsilon \equiv \lambda^2/(1-\lambda^2)]$

$$A(B_s^0 \to K^+K^-) = \lambda\,\mathcal{C}\left[e^{i\gamma} + \frac{1}{\epsilon} d e^{i\theta}\right] \quad \Rightarrow$$

$$h_{K^+K^-} = d/\epsilon, \quad \delta_{K^+K^-} = \theta, \quad \varphi_1^{K^+K^-} = \gamma, \quad \varphi_2^{K^+K^-} = 0 \quad \Rightarrow$$

$$\tan\Delta\phi_{K^+K^-} = 2\epsilon\left[\frac{d\cos\theta + \epsilon\cos\gamma}{d^2 + 2\epsilon\, d\cos\theta\cos\gamma + \epsilon^2\cos 2\gamma}\right]\sin\gamma$$

- K, $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)$ and $\gamma = (68 \pm 7)^\circ$ [$\oplus$ U-spin-breaking]: $\Rightarrow$

$$d = 0.50^{+0.12}_{-0.11}, \quad \theta = (154^{+11}_{-14})^\circ \quad \Rightarrow$$

  - Hadronic phase shift:

$$\Delta\phi_{K^+K^-} = -\left(10.5^{+0.3}_{-0.5}\Big|_\gamma{}^{+2.9}_{-2.1}\Big|_d{}^{+0.9}_{-1.7}\Big|_\theta\right)^\circ = -\left(10.5^{+3.1}_{-2.8}\right)^\circ$$

  - Direct CP asymmetry: $C_{K^+K^-} = 0.09^{+0.05}_{-0.04}$

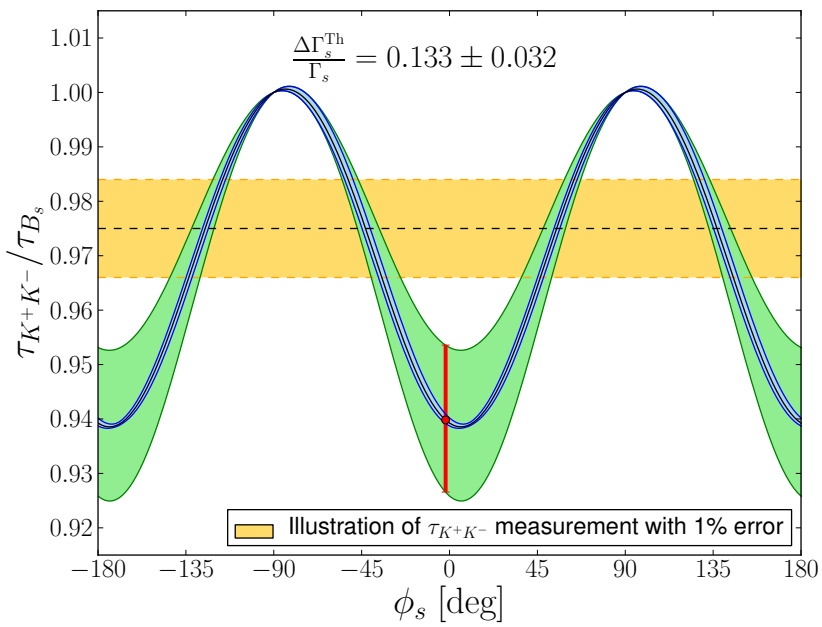
The Effective $B_s^0 \to K^+K^-$ Lifetime

- Current experimental situation:
  - LHCb (2011): $\tau_{K^+K^-} = [1.44 \pm 0.096(\text{stat}) \pm 0.010(\text{syst})]\,\text{ps}$
  - CDF (2006): $\tau_{K^+K^-} = [1.53 \pm 0.18 \pm 0.02]\text{ps}^{-1}$

$\gamma = (68 \pm 7)^\circ \oplus$ hadronic parameters allow theoretical analyses:

- Theoretical analysis (I):

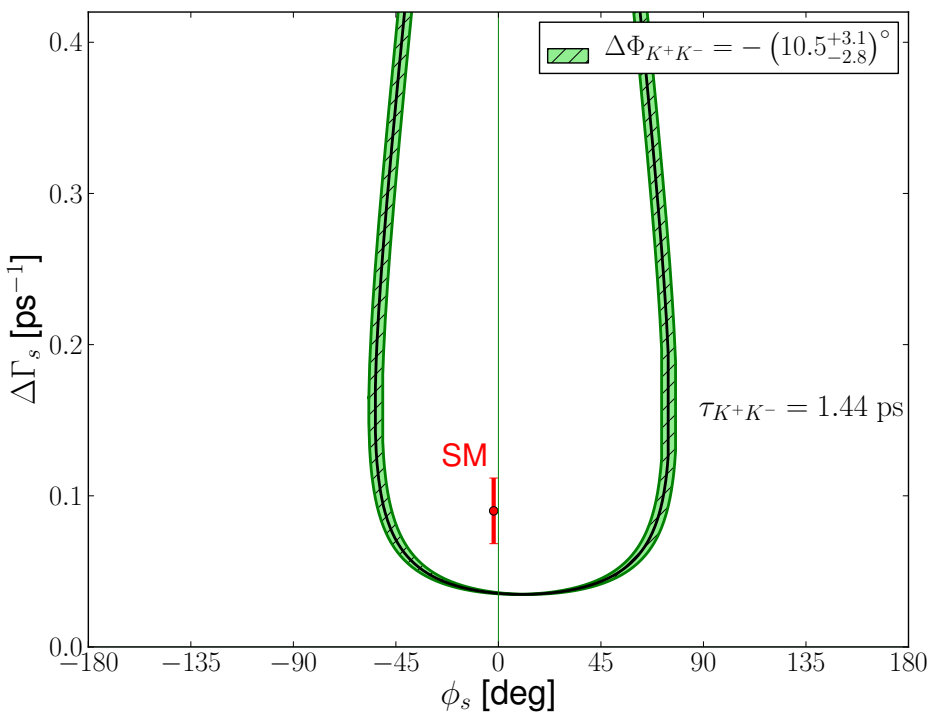
$\to$ use theoretical value of $\Delta\Gamma_s^{\text{Th}}$ [Lenz & Nierste]: $\to$ dominates the error:



- Theoretical analysis (II): $\rightarrow$ contours in the ϕ_s–$\Delta\Gamma_s$ plane:

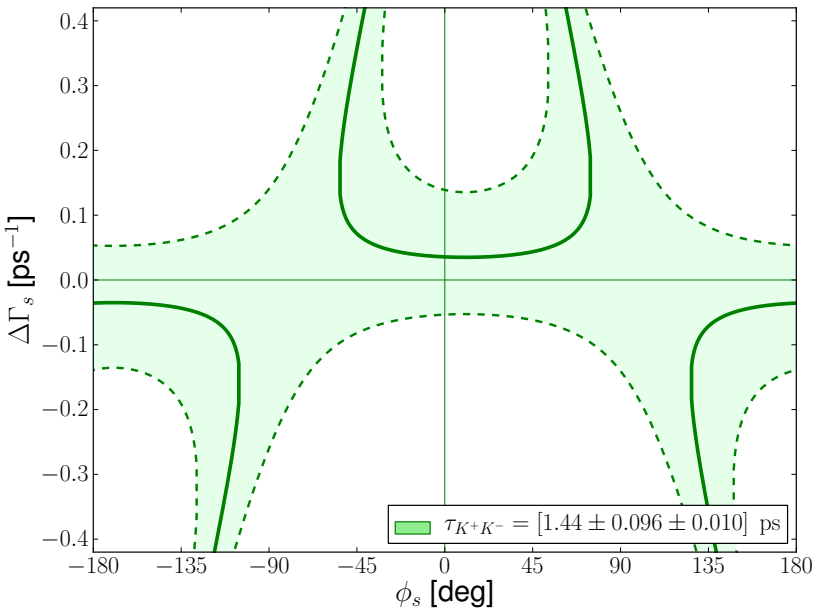
$\Rightarrow$ *advantage:* does not depend on $\Delta\Gamma_s^{\rm Th}$ $\rightarrow$ very clean:

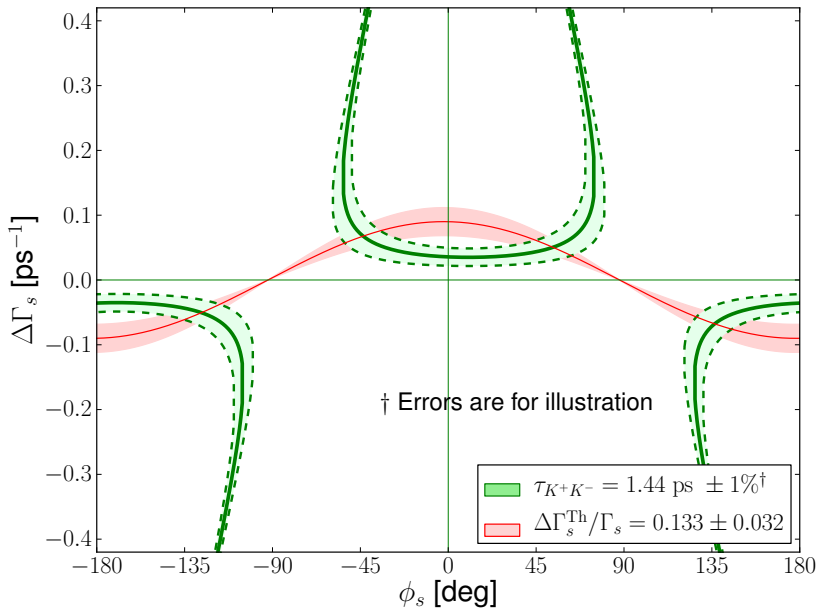
$\diamond$ LHCb current central value of $\tau_{K^+K^-}$ for illustration $\Rightarrow$



[R.F. & Rob Knegjens, arXiv:1109.5115 [hep-ph]]

- Current experimental error and extrapolation to the future:





  - Error will hopefully be reduced to the 1% level soon.
  - Shall return to this topic in the $B_s^0 \to J/\psi f_0(980)$ discussion.

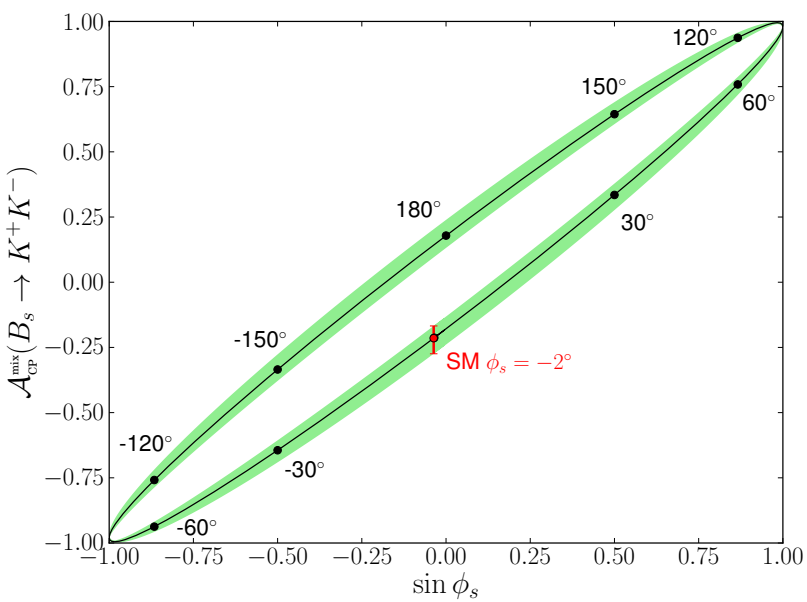
Mixing-Induced $B_s^0 \to K^+K^-$ CP Asymmetry

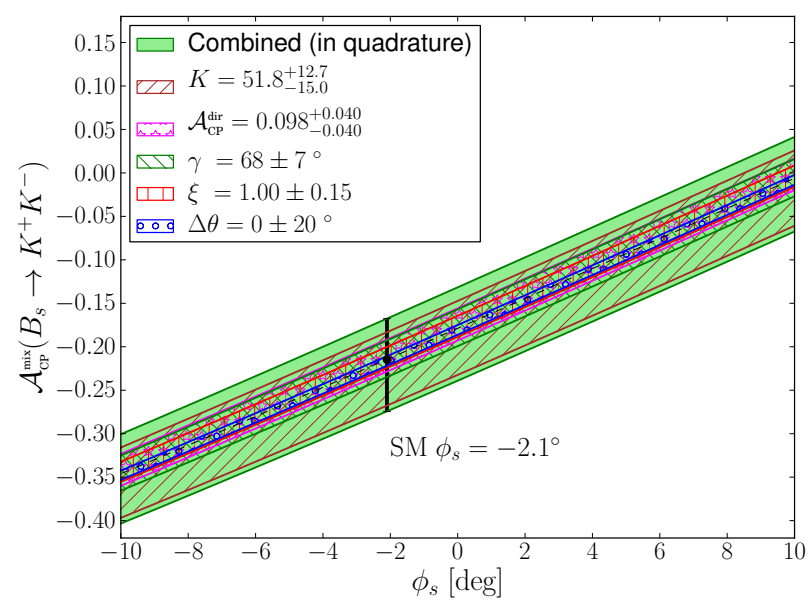
$$a_{\rm CP}(t) = \frac{C\cos(\Delta M_s t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

- Compact expression:

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = \sqrt{1 - C^2_{K^+K^-}}\,\sin(\phi_s + \Delta\phi_{K^+K^-})$$

- K, $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)$, $\gamma \oplus U$-spin-breaking effects: $\Rightarrow$



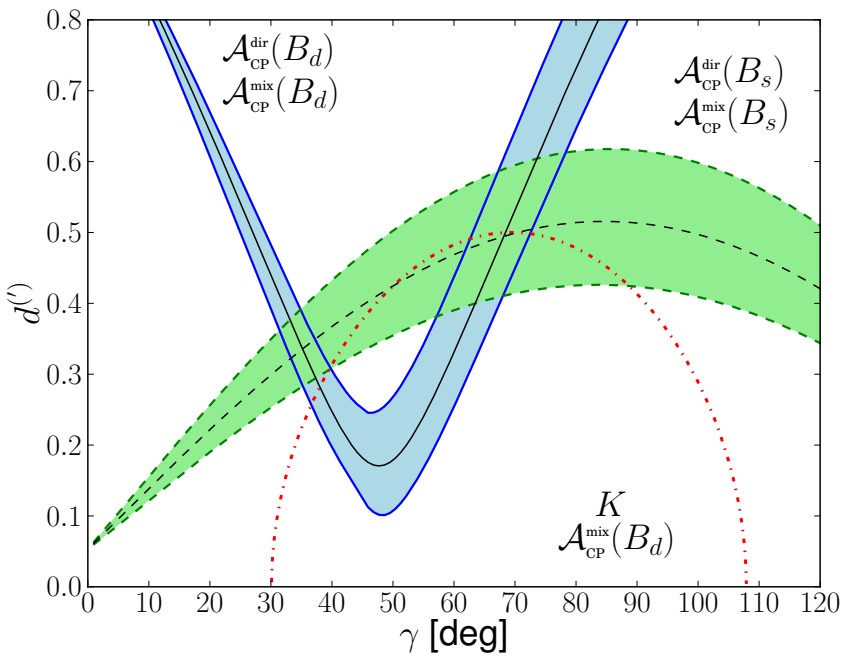


- SM prediction: $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)|_{\rm SM} = -0.215^{+0.047}_{-0.060}$

Final Goal: Optimal Determination of γ

- Measurement of the CP asymmetries of $B_s^0 \to K^+K^-$:

$\Rightarrow$ theoretically clean contour in the γ–d plane:



[Green band represents the 1σ errors of the current SM projection.]

- Intersection with the γ–d contour fixed through the CP asymmetries of $B_s^0 \to \pi^+\pi^-$ allows us to determine γ, $d = d'$ and θ, θ' [$\to U$-spin test].

- Expect a stable situation with respect to U-spin-breaking corrections.

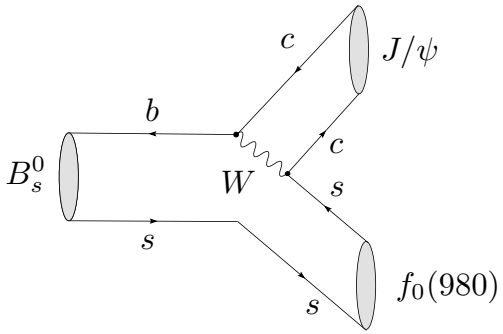
$$\boxed{B_s \to J/\psi f_0(980):}$$

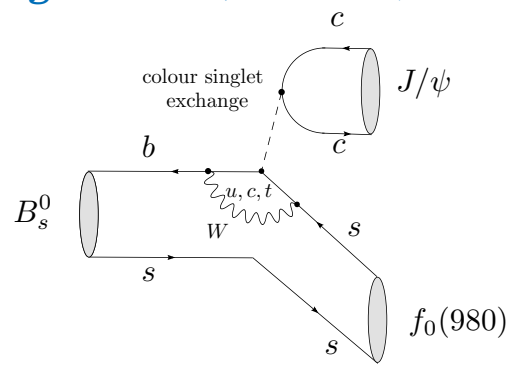
$\to$ emerging interesting new decay

[Detailed analysis: R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph];

see also arXiv:1110.5490 [hep-ph], giving a discussion of $B_{s,d} \to J/\psi \eta^{(\prime)}$]

General Features of $B_s^0 \to J/\psi f_0(980)$





- $f_0(980)$ is a scalar $J^{PC} = 0^{++}$ state: $\Rightarrow$ no angular analysis is required!
- Dominant mode: $B_s^0 \to J/\psi f_0$ with $f_0 \to \pi^+\pi^-$.
- Recent observation of $B_s^0 \to J/\psi f_0$ at LHCb, Belle, DØ and CDF:

$$R_{f_0/\phi} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi f_0; f_0 \to \pi^+\pi^-)}{\mathrm{BR}(B_s^0 \to J/\psi \phi; \phi \to K^+K^-)} \sim 0.25$$

... but as no angular analysis is required:

$\Rightarrow$ $B_s^0 \to J/\psi f_0$ offers an interesting alternative to $B_s^0 \to J/\psi \phi$

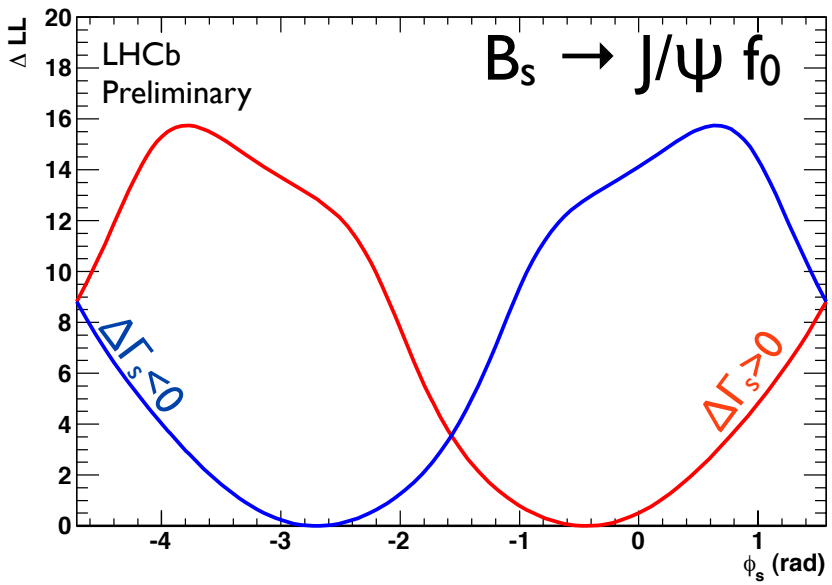
[S. Stone & L. Zhang (2009)]

New Results for $B_s^0 \to J/\psi f_0$

- First measurement of the effective lifetime: [CDF, arXiv:1106.3682 [hep-ex]]

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

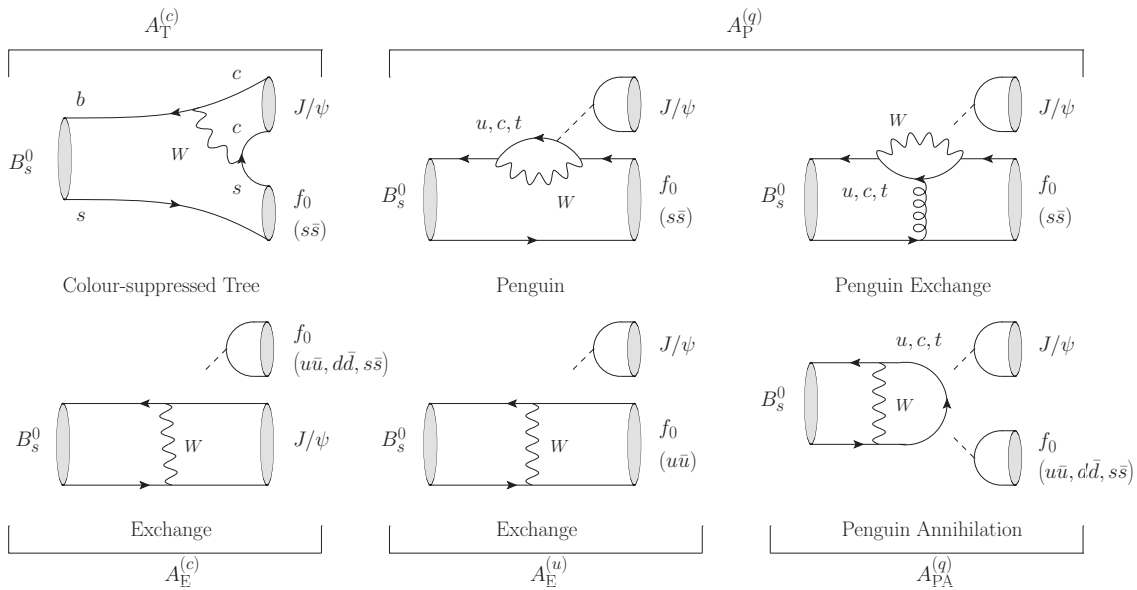
- First study of CP violation in $B_s^0 \to J/\psi f_0$: [LHCb, G. Raven @ LP 2011]



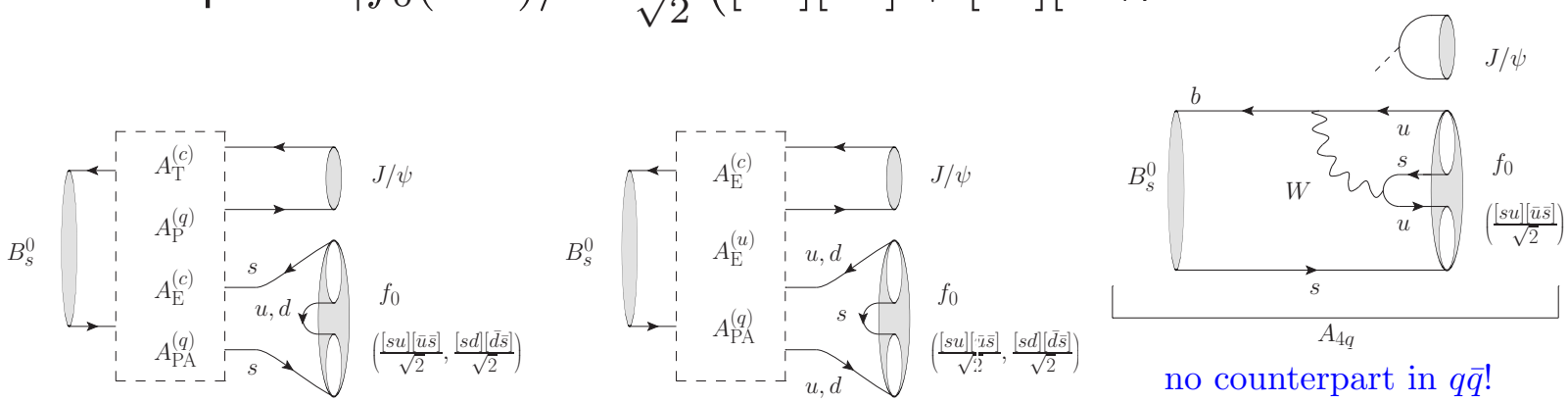
$\to \phi_s = -(25 \pm 25 \pm 1)^\circ \to$ look forward to future results ...

Theoretical Uncertainties?

- Decay topologies:



- The composition of the $f_0(980$ is still poorly known: $\rightarrow$ 2 benchmarks:
  - Quark–antiquark: $|f_0(980)\rangle = \cos\varphi_M |s\bar{s}\rangle + \sin\varphi_M \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$
  - Tetraquark: $|f_0(980)\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right) \rightarrow$



no counterpart in $q\bar{q}$!

[R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph]]

Amplitude Structure of $B_s^0 \to J/\psi f_0$

- General SM parametrization:

$$A(B_s^0 \to J/\psi f_0) \propto \left[1 + \epsilon\, b e^{i\vartheta} e^{i\gamma}\right] \quad \text{with} \quad \epsilon \equiv \lambda^2/(1-\lambda^2)$$

- Here we have introduced a CP-conserving hadronic parameter:

$$b e^{i\vartheta} \equiv R_b \left[\frac{A_{\rm P}^{(ut)} + A_{\rm E}^{(u)} + A_{\rm PA}^{(ut)}}{A_{\rm T}^{(c)} + A_{\rm P}^{(ct)} + A_{\rm E}^{(c)} + A_{\rm PA}^{(ct)}}\right]$$

$\to$ hadron dynamics (?), *but enters in a doubly Cabibbo-suppressed way*

- Characteristic hadronic phase shift: $\to$ enters lifetime and CP asymmetry

$$\tan \Delta\phi_{J/\psi f_0} = \frac{2\epsilon b \cos\vartheta \sin\gamma + \epsilon^2 b^2 \sin 2\gamma}{1 + 2\epsilon b \cos\vartheta \cos\gamma + \epsilon^2 b^2 \cos 2\gamma}$$

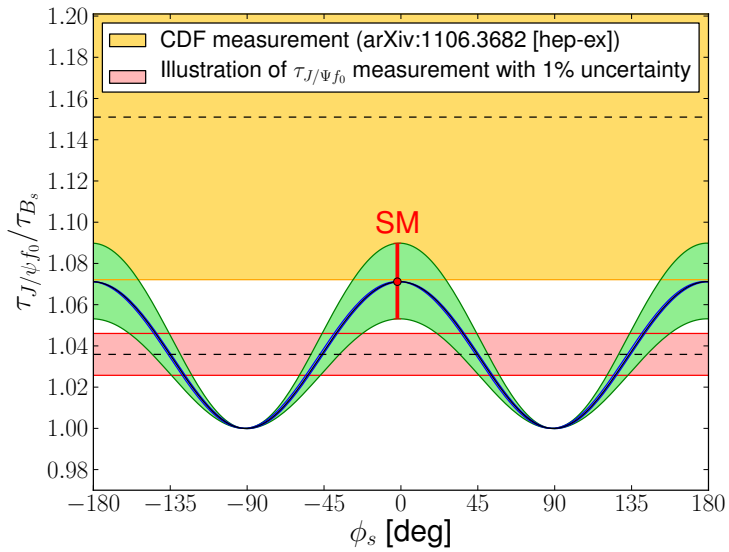
– Conservative range for $b e^{i\theta}$: $0 \le b \le 0.5$, $0^\circ \le \vartheta \le 360^\circ$ $\Rightarrow$

$$\Delta\phi_{J/\psi f_0} \in [-2.9^\circ, 2.8^\circ] \quad \text{(similar error as } \Delta\phi_{K^+K^-}\text{)}$$

Effective $B_s^0 \to J/\psi f_0$ Lifetime

- Theoretical analysis (I):

  $\to$ use theoretical value of $\Delta\Gamma_s^{\rm Th}$ [Lenz & Nierste]: $\to$ dominates the error



$$\tau_{J/\psi f_0}|_{\rm SM} = (1.582 \pm 0.036)\,{\rm ps},$$

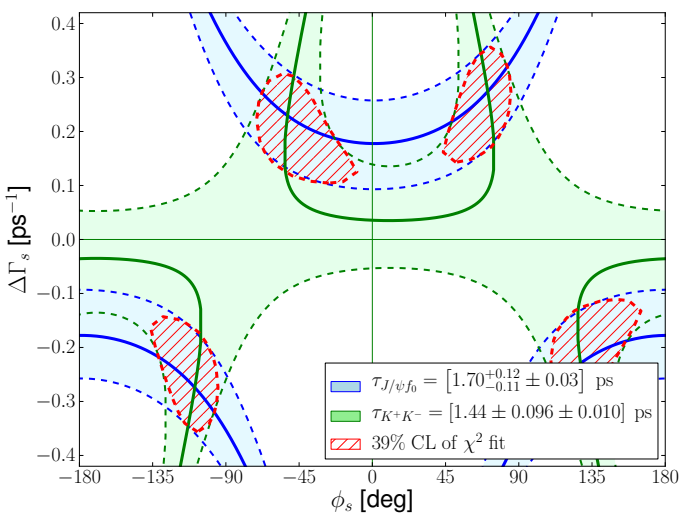
- Theoretical analysis (II):

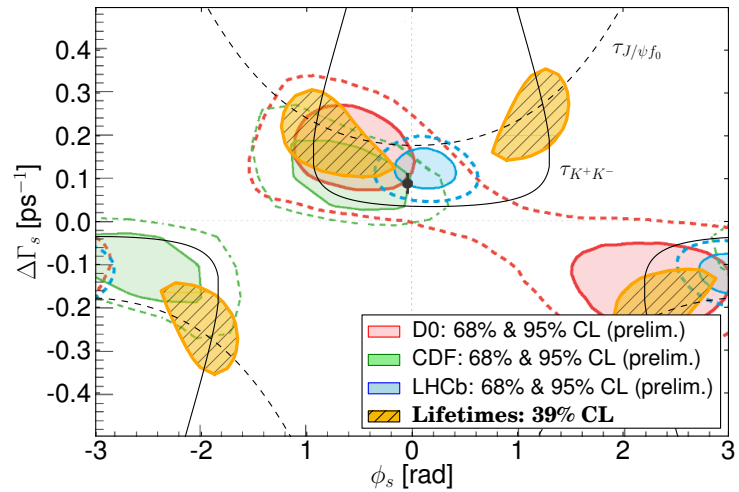
  $\to$ use $\tau_{J/\psi f_0}$ to determine a contour in the ϕ_s–$\Delta\Gamma_s$ plane

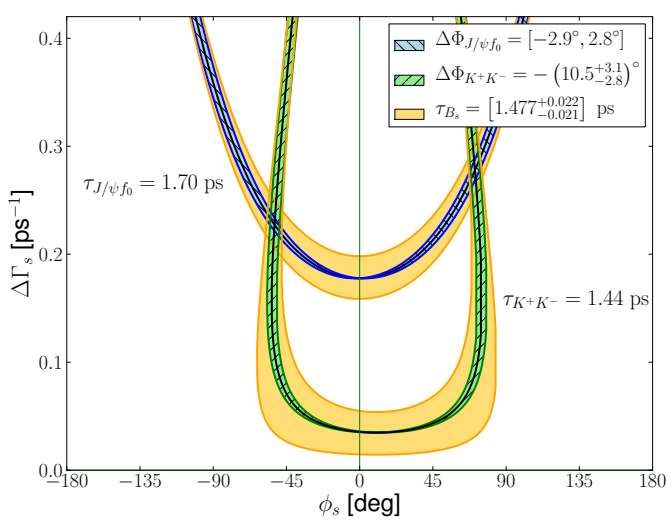
  – Does not rely on $\Delta\Gamma_s^{\rm Th}$.

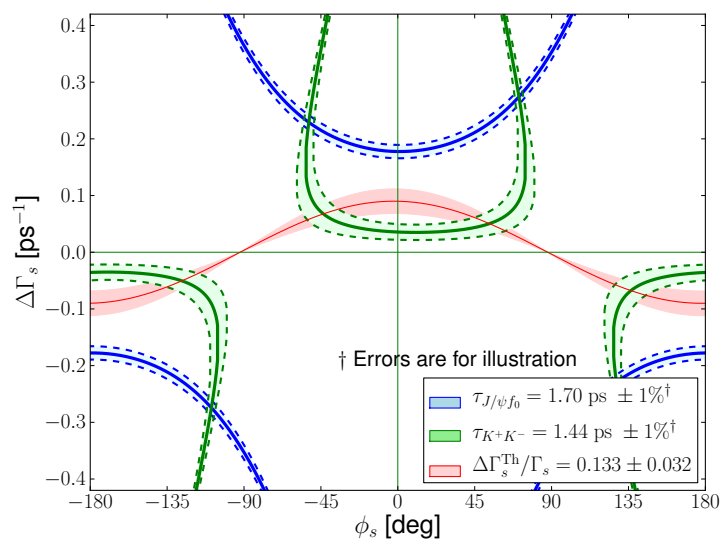
  – Combine $\tau_{J/\psi f_0}$ (CP-odd) with $\tau_{K^+K^-}$ (CP-even) $\Rightarrow$

Constraints from the $B_s^0 \to J/\psi f_0, K^+K^-$ Lifetimes







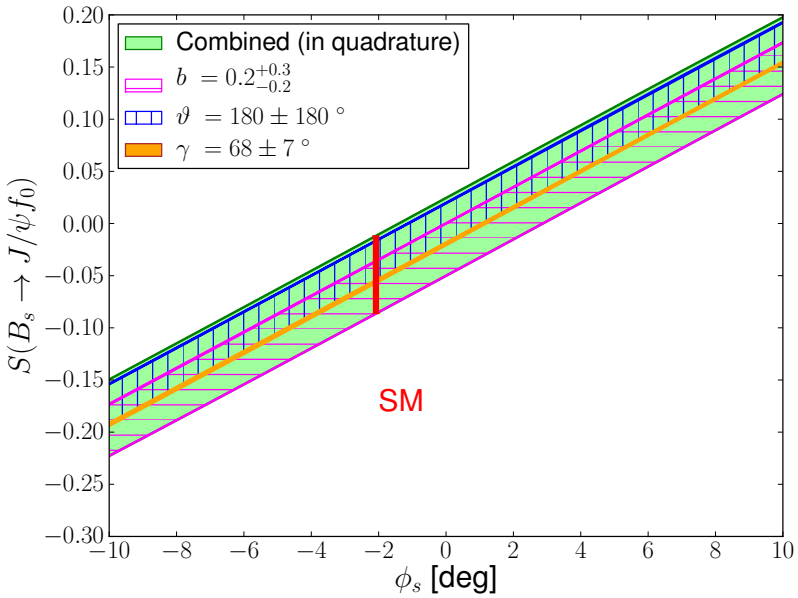


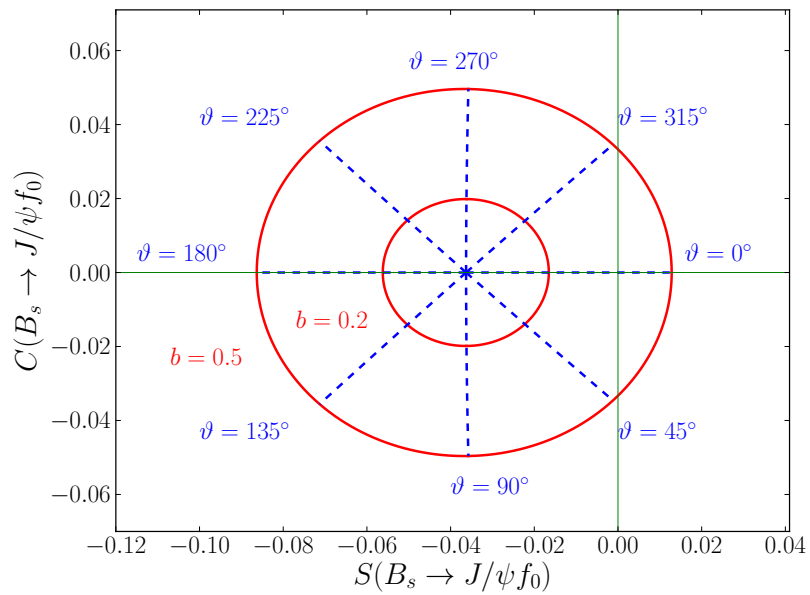
$\Rightarrow$ future lifetime measurements with 1% uncertainty most interesting!

[R.F. & R. Knegjens, arXiv:1109.5115 [hep-ph]]

CP Violation in $B_s^0 \to J/\psi f_0$

$$\frac{\Gamma(B_s(t) \to J/\psi f_0) - \Gamma(\bar{B}_s(t) \to J/\psi f_0)}{\Gamma(B_s(t) \to J/\psi f_0) + \Gamma(\bar{B}_s(t) \to J/\psi f_0)} = \frac{C\cos(\Delta M_s t) - S\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$





- Mixing-induced CP asymmetry: $\boxed{S = \sqrt{1 - C^2}\sin(\phi_s + \Delta\phi)}$
  - Naïve SM value: $(\sin\phi_s)|_{\rm SM} = -0.036 \pm 0.002$;
  - Allowing for hadronic effects: $S(B_s^0 \to J/\psi f_0)\big|_{\rm SM} \in [-0.086, -0.012]$

Comments

- Should smallish CPV $-0.1 \lesssim S \lesssim 0$ be found:

$\Rightarrow$ $\boxed{\text{crucial to constrain hadronic corrections to disentangle NP from SM}}$

- First (preliminary) LHCb result for ϕ_s from $B_s^0 \to J/\psi f_0$:

$$\phi_s = -(25 \pm 25 \pm 1)^\circ, \text{ corrsponds to } S = -0.43^{+0.43}_{-0.34}.$$

  – Hadronic corrections were not taken into account; still some way to go until we may eventually enter the limiting range $-0.1 \lesssim S \lesssim 0$.

- Average with $B_s^0 \to J/\psi\phi$: $\Rightarrow$ $\phi_s = +(1.7 \pm 9.2 \pm 4.0)^\circ$

  – Increase of exp. precision: average is problematic because of hadronic effects and their different impact on $B_s^0 \to J/\psi f_0$ and $B_s^0 \to J/\psi\phi$.

  – It will actually be interesting to compare the individual measurements, which may also provide insights into the hadronic corrections.

[Remember discussions about averages for CP asymmetries in $b \to s$ penguin modes]

Control Channel: $B_d^0 \to J/\psi f_0(980)$

- Leading contributions emerge from the $d\bar{d}$ component of the $f_0(980)$:

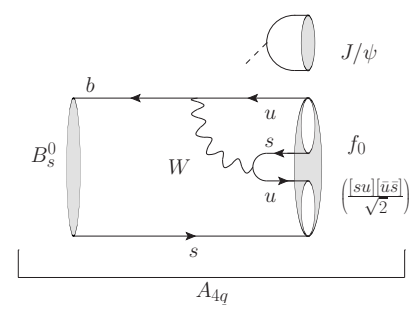
$$A(B_d^0 \to J/\psi f_0) = -\lambda \mathcal{A}' \left[1 - b' e^{i\vartheta'} e^{i\gamma}\right]$$

- Measurement of branching ratio and CP-violating asymmetries:

$$\Rightarrow \boxed{b' \text{ and } \vartheta' \text{ can be (cleanly) determined}}$$

- Relation to the b and ϑ hadronic parameters of $B_s^0 \to J/\psi f_0$:
  - $q\bar{q}$ interpretation of the $f_0(980)$: $\to b \approx b'$, $\vartheta \approx \vartheta'$ through $SU(3)$ if mixing angle is significantly different from 0° or 180°.
  - Tetraquark description: topology contributing to $B_s^0 \to J/\psi f_0$ does not have a counterpart in $B_s^0 \to J/\psi f_0$ $\to$ how important is it!?

$$\to \boxed{\text{hadronic } f_0 \text{ structure !?}}$$



- Please add $B_d^0 \to J/\psi f_0$ to the experimental agenda:

$$\text{BR}(B_d^0 \to J/\psi f_0; f_0 \to \pi^+\pi^-) = \mathcal{O}(10^{-6})$$

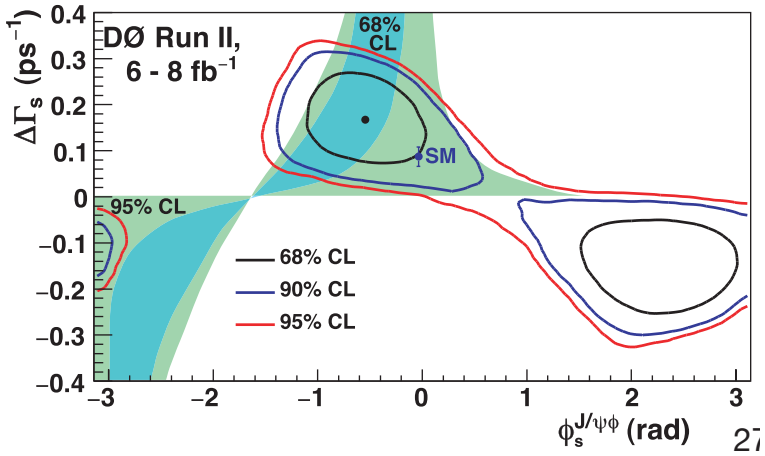
[Details: R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph]]

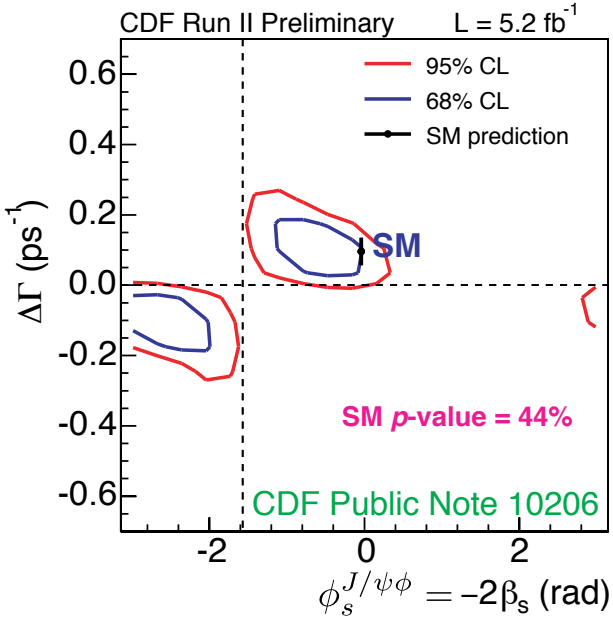
$$\boxed{B_s \to J/\psi\phi:}$$

$\to$ experimentally best studied decay

Tevatron $B_s^0 \to J/\psi\phi$ Results

- Interesting results on this channel since 2008 ...
- Picture in the Summer of 2011:





$$\phi_s^{\mathrm{D\emptyset}} = -\left(31.5^{+20.6}_{-21.8}\right)^\circ \qquad \phi_s^{\mathrm{CDF}} = [-59.6^\circ, -2.3^\circ]\ (68\%\ \mathrm{C.L.})$$

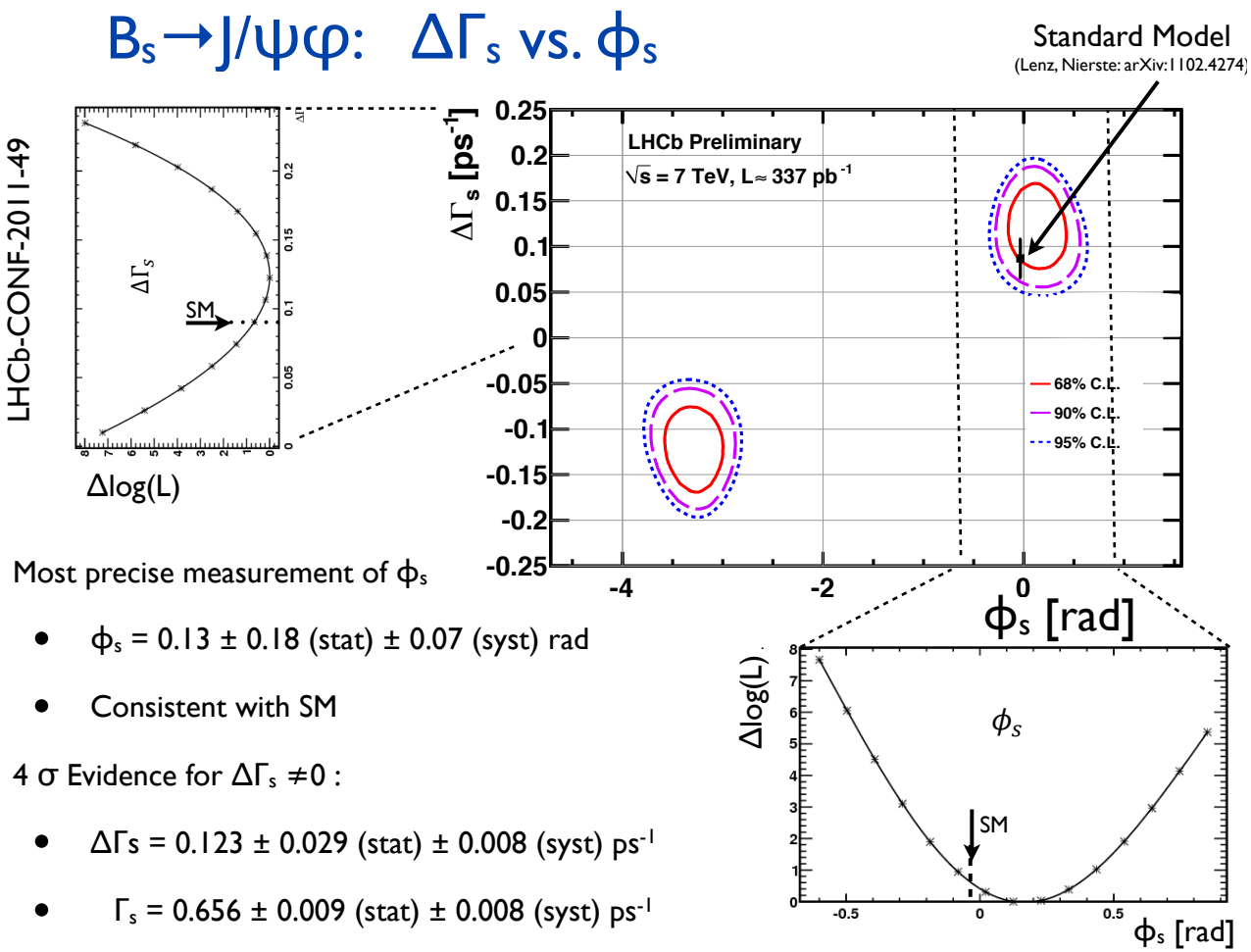
- DØ includes also the anomalous like-sign dimuon charge asymmetry;
- CDF plot uses only $B_s \to J/\psi\phi$ data.

- Bad news: situation is (still...) not conclusive (?)

[R. van Kooten @ Lepton–Photon 2011]

LHCb $B_s^0 \to J/\psi\phi$ Results

- Update at Lepton–Photon 2011:



Most precise measurement of ϕ_s

- $\phi_s = 0.13 \pm 0.18$ (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma_s = 0.123 \pm 0.029$ (stat) ± 0.008 (syst) ps^{-1}
- $\Gamma_s = 0.656 \pm 0.009$ (stat) ± 0.008 (syst) ps^{-1}

- $\phi_s = (7.4 \pm 10.3 \pm 4.0)^\circ$ consistent with $\phi_s^{\rm SM} = -2.1^\circ \to$ stay tuned ...

[G. Raven @ Lepton–Photon 2011]

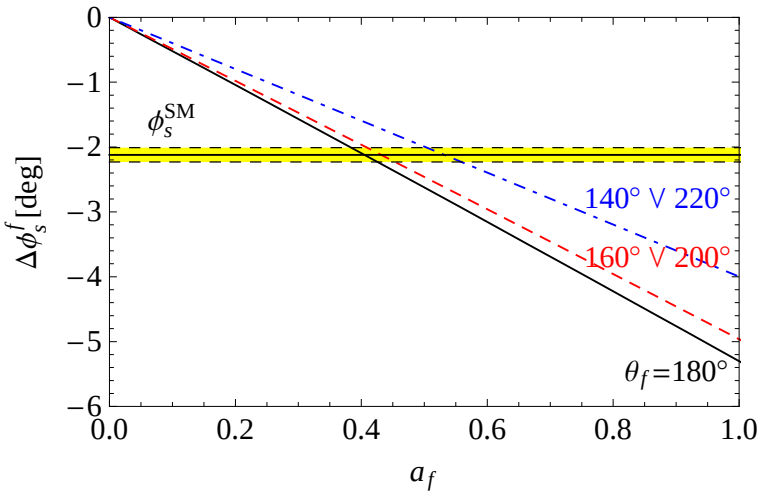
Prospects for $B_s \to J/\psi\phi$

- Experimental reach @ LHCb: *very impressive ...*
  - End of first phase of LHCb ($5\,\text{fb}^{-1} \sim 2015$): $\sigma(\phi_s)_{\rm exp} \sim 1^\circ$
  - LHCb upgrade ($50\,\text{fb}^{-1}$): $\sigma(\phi_s)_{\rm exp} \sim 0.3^\circ$ [Marcel Merk @ Beauty 2011]

- However: *SM penguin effects were so far fully neglected:*

$$A(B_s^0 \to (J/\psi\phi)_f) \propto \mathcal{A}_f \left[1 + \lambda^2 (a_f e^{i\theta_f}) e^{i\gamma}\right]$$

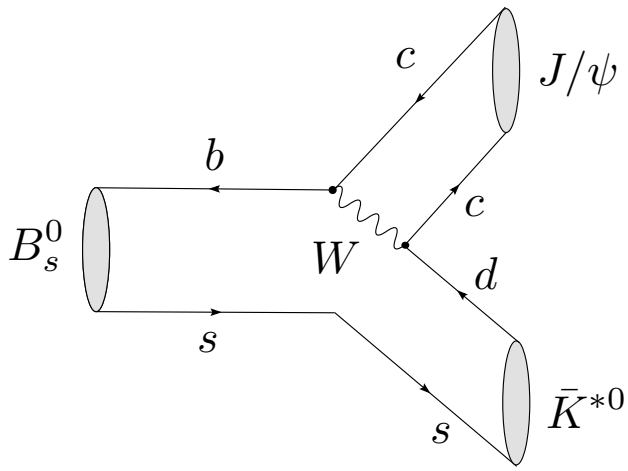
  - Impact of these corrections: $\mathcal{A}_{\rm CP}^{\rm mix} = \sin\phi_s \;\to\; \sin(\phi_s + \Delta\phi_s^f)$.

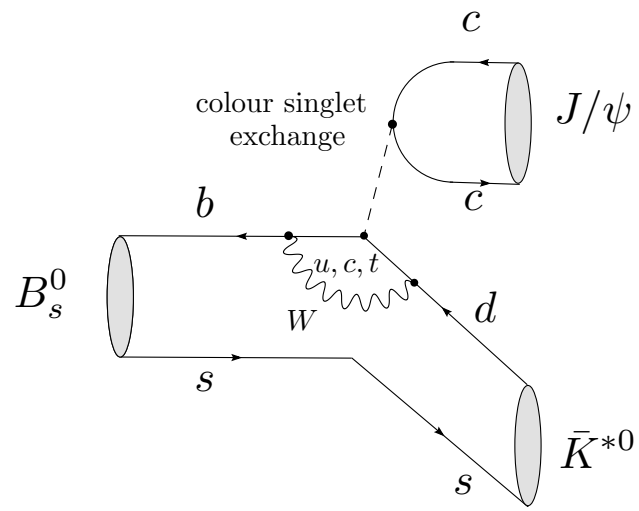


$\Rightarrow$ towards new frontiers in terms of precision: $\to$ control penguins...

[S. Faller, R.F. & T. Mannel, arXiv:0810.4248 [hep-ph]]

Control Channel: $B_s^0 \to J/\psi \bar{K}^{*0}$





- Decay amplitude:[2] $A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$
  - Neglect PA and E topologies [upper bound on BR$(B_d^0 \to J/\psi\phi) \Rightarrow |E + PA|/|T| \lesssim 0.1$] and use the $SU(3)$ flavour symmetry:

$$\Rightarrow \quad |\mathcal{A}_f| = |\mathcal{A}'_f| \quad \text{and} \quad a_f = a'_f, \quad \theta_f = \theta'_f.$$

- Implementation: $\to$ no mixing-induced CP in $B_s^0 \to J/\psi \bar{K}^{*0}$, but ...
  - Untagged rate measurement $\oplus$ direct CP violation.
  - Angular analysis is required to disentangle final states $f \in \{0, \|, \perp\}$

[2] Advantage with respect to $B_{s,d}^0 \to J/\psi f_0(980)$: not affected by the hadronic f_0 structure (?).

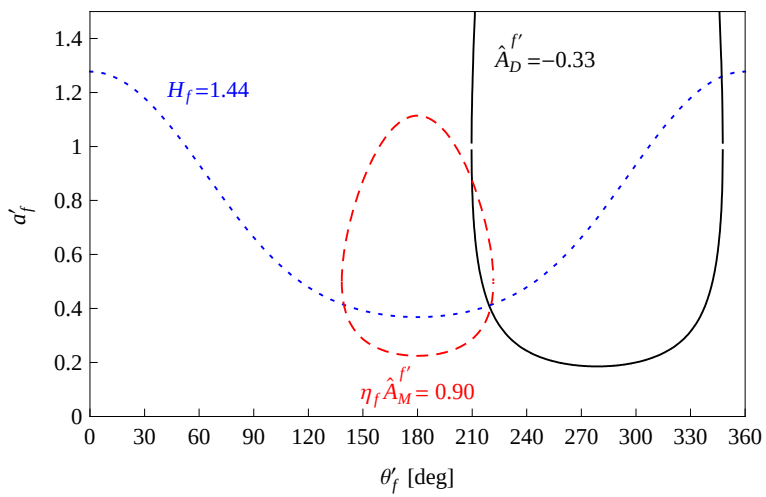
A Closer Look

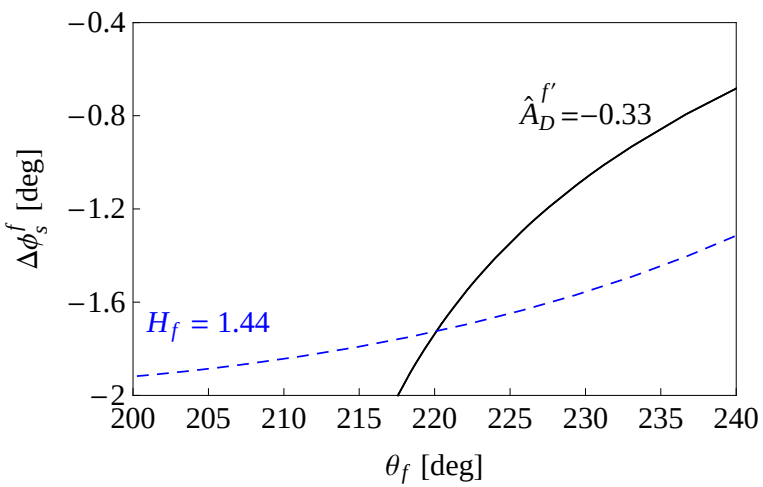
- Observables:
  - Ratio of the CP-averaged "untagged" rates $\Gamma[f,t=0]'$ and $\Gamma[f,t=0]$ of the $B_s^0 \to J/\psi \bar{K}^{*0}$ and $B_s^0 \to J/\psi\phi$ modes, respectively:

$$H_f \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}_f}{\mathcal{A}'_f}\right|^2 \frac{\Gamma[f,t=0]'}{\Gamma[f,t=0]} = \frac{1-2a'_f\cos\theta'_f\cos\gamma + a'^2_f}{1+2\epsilon a_f\cos\theta_f\cos\gamma+\epsilon^2 a_f^2}$$

  - Direct CP asymmetries $\hat{A}_{\rm D}^{f'}$

- Numerical Illustration: $\gamma = 65^\circ$, $a'_f = 0.4$, $\theta'_f = 220^\circ$ (consistent with $a' \in [0.15, 0.67]$ and $\theta' \in [174^\circ, 213^\circ]$ following from a $B^0 \to J/\psi\pi^0$ analysis).





- Further control channel: $B_d^0 \to J/\psi\rho^0 \to$ mix.-ind. CP asymmetry $\hat{A}_{\rm M}^{f'}$

Comments & Observations

- $\Delta\phi_s^f$ is favoured to have negative sign:

$$\Rightarrow \boxed{\text{interferes } \textit{constructively} \text{ with } \phi_s^{\rm SM} = -(2.08 \pm 0.09)^\circ}$$

  - Consequently, the phase shift $\Delta\phi_s^f = -1.7^\circ$ of our example yields

$$\eta_f \hat{A}_{\rm M}^f = -6.7\% \quad \Rightarrow \quad \sim 2 \times \text{naïve SM value!}$$

  - Without the analysis described above: $\Rightarrow$ *misinterpretation* as $\sim 6\,\sigma$ signal for NP at the LHCb upgrade with $\sigma(\phi_s)_{\rm exp} \sim 0.3^\circ$.
  - Cannot exclude that the hadronic penguin effects are actually more significant than in our example, could lead to $\eta_f \hat{A}_{\rm M}^f \sim -10\%$ ...
  - They could also be smaller, but we have to check this ...

- Scenarios: [$\Delta\phi_s^f$ must in any case be controlled to match future LHCb accuracy]
  - *Optimistic:* $|\mathcal{A}_{\rm CP}^{\rm mix}| \sim 40\%$ would be an unambiguous signal of NP!
  - *Pessimistic:* $\mathcal{A}_{\rm CP}^{\rm mix} \sim -(5...10)\%$ would require further work from theorists and experimentalists to clarify the picture ...

Concluding Remarks

Challenges & Perspectives

- Still no signals for New Physics @ LHCb (as from the direct searches):
  - Impressive (also frustrating ...), but we are still at the beginning.
  - We will continue to see more and more precise measurements ...

$\Rightarrow$ prepare to deal with "smallish" NP effects

- (Still a) promising probe for CP-violating NP: B_s^0–$\bar{B}_s^0$ mixing
  - Effective B_s decay lifetimes very interesting: $\rightarrow$ untagged studies
  - CP-violating asymmetries: $\rightarrow$ tagged studies.

$$B_s^0 \to K^+K^-,\ B_s^0 \to J/\psi f_0,\ B_s^0 \to J/\psi\phi,\ (\oplus \text{ other decays ...})$$

$\rightarrow$ may eventually give us first unambiguous signals for NP @ LHCb

- Recent LHCb measurements of CP violation in $B_s^0 \to J/\psi\phi$:
  - Future data may fall into the region where we need a handle on penguin effects to disentangle (smallish) NP from SM contributions.
  - Study penguin "control" channels (theoretically & experimentally): $B_s^0 \to J/\psi K_{\rm S}$, $B_s^0 \to J/\psi \bar{K}^{*0}$, $B_d^0 \to J/\psi\rho^0$, $B_d^0 \to J/\psi f_0$, ...

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