Penguin Effects in $\phi_{d,s}$ Determinations

Robert Fleischer

Nikhef & Vrije Universiteit Amsterdam

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- Setting the Stage
- Focus on three different systems: $\rightarrow$ benchmark decays:
  - $B_d^0 \to J/\psi K_{\rm S} \;\oplus\; B_s^0 \to J/\psi K_{\rm S}$
  - $B_s^0 \to J/\psi \phi \;\oplus\; B_s^0 \to J/\psi \bar{K}^{*0}$
  - $B_s^0 \to J/\psi f_0(980) \;\oplus\; B_d^0 \to J/\psi f_0(980)$
- Conclusions

Setting the Stage

Where Do We Stand?

- News from Physics @ LHC: $\rightarrow$ discovery of "Higgs-like" particle, but ...
  - No deviations from the SM in direct searches at ATLAS and CMS ...
  - No solid evidence for NP in the flavour sector ...

- 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).*

- Much more is yet to come: ...

... but prepare to deal with "smallish" NP effects!

Towards New Frontiers in Precision B-Physics

- Crucial for resolving 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.

- Key decays for exploring CP violation:

$$B_d \rightarrow J/\psi K_{\rm S},\ B_s \rightarrow J/\psi\phi,\ B_s \rightarrow J/\psi f_0(980)$$

  - Allow measurements of the $B^0_{d,s}$–$\bar{B}^0_{d,s}$ mixing phases $\phi_{d,s}$.
  - Uncertainties from doubly Cabibbo-suppressed penguin contributions.
  - These effects are usually neglected; we cannot reliably calculate them...

$\Rightarrow$ $\boxed{\text{How big are they \& how can they be controlled?}}$

PhD Students:

$\rightarrow$ involved in topics addressed in this talk:

Kristof De Bruyn
(Theory $\oplus$ LHCb)

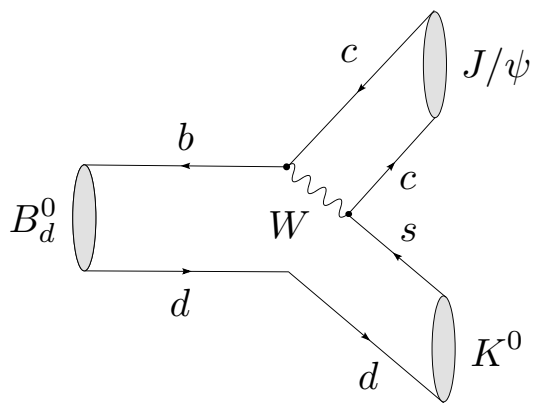
Rob Knegjens
(Theory)

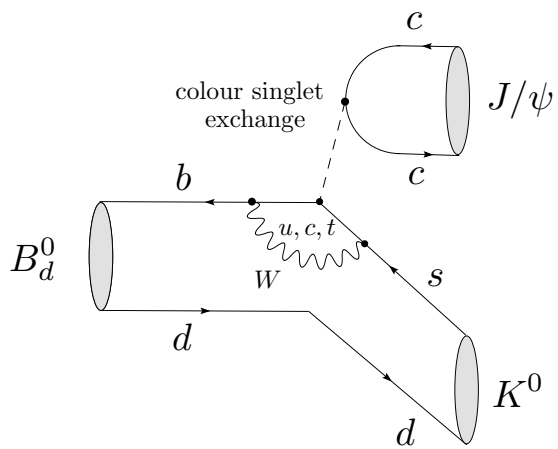
$$\boxed{B_d^0 \to J/\psi K_{\rm S} \oplus B_s^0 \to J/\psi K_{\rm S}}$$

Current picture of the penguin parameters?

[Thanks to Kristof De Bruyn for plots/numerics; work in progress.]

The Decay $B_d \to J/\psi K_S$





- Standard Model (SM) decay amplitude:

$$A(B_d^0 \to J/\psi\, K_S) = \lambda_c^{(s)} \left[A_T^{(c)\prime} + A_P^{(c)\prime} \right] + \lambda_u^{(s)} A_P^{(u)\prime} + \lambda_t^{(s)} A_P^{t\prime}$$

- Unitarity of the CKM matrix: $\Rightarrow \lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \quad [\lambda_q^{(s)} \equiv V_{qs} V_{qb}^*]$:

$$\Rightarrow \quad \boxed{A(B_d^0 \to J/\psi\, K_S) = \left(1 - \lambda^2/2\right) \mathcal{A}' \left[1 + \epsilon\, a' e^{i\theta'} e^{i\gamma} \right]}$$

$$\mathcal{A}' \equiv \lambda^2 A \left[A_T^{(c)\prime} + A_P^{(c)\prime} - A_P^{(t)\prime} \right], \quad a' e^{i\theta'} \equiv R_b \left[\frac{A_P^{(u)\prime} - A_P^{(t)\prime}}{A_T^{(c)\prime} + A_P^{(c)\prime} - A_P^{(t)\prime}} \right]$$

$$A \equiv |V_{cb}|/\lambda^2 \sim 0.8, \;\; R_b \equiv \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \sim 0.5, \;\; \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} = 0.053$$

- Time-dependent CP asymmetry (CP-odd final state):

$$\frac{\Gamma(B_d^0 \to J/\psi K_S) - \Gamma(\bar{B}_d^0 \to J/\psi K_S)}{\Gamma(B_d^0 \to J/\psi K_S) + \Gamma(\bar{B}_d^0 \to J/\psi K_S)}$$
$$= C(B_d \to J/\psi K_S)\cos(\Delta M_d t) - S(B_d \to J/\psi K_S)\sin(\Delta M_d t)$$

- CP-violating observables: $[\phi_d = 2\beta + \phi_d^{\rm NP} \to B_d^0$–$\bar{B}_d^0$ mixing phase$]$

$$C(B_d \to J/\psi K_S) = -\frac{2\epsilon a \sin\theta \sin\gamma}{1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2}$$

$$\frac{S(B_d \to J/\psi K_S)}{\sqrt{1 - C(B_d \to J/\psi K_S)^2}} = \sin(\phi_d + \Delta\phi_d)$$

$$\sin\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{(1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2)\sqrt{1 - C(B_d \to J/\psi K_S)^2}}$$

$$\cos\Delta\phi_d = \frac{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}{(1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2)\sqrt{1 - C(B_d \to J/\psi K_S)^2}}$$

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

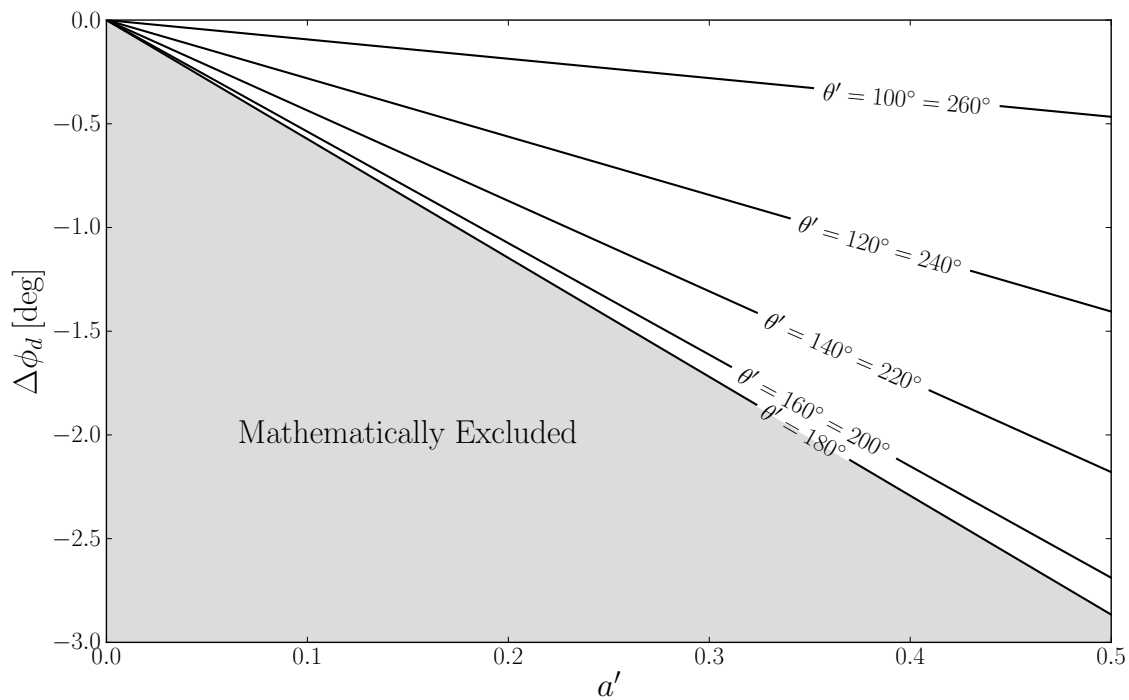
- Current experimental status: [HFAG]

$$S(B_d \to J/\psi K_S) = 0.665 \pm 0.024$$

$$C(J/\psi K_S) = 0.024 \pm 0.026 \quad \Rightarrow \quad \sqrt{1 - C(J/\psi K_S)^2} = 0.99971^{+0.00029}_{-0.00096}$$

$$\Rightarrow \boxed{S(B_d \to J/\psi K_S) = \sin(\phi_d + \Delta\phi_d) = 0.665 \pm 0.024}$$

- Illustration of the impact of the penguin topologies: $a' e^{i\theta'} \sim R_b \left[\frac{\text{“pen”}}{\text{“tree”}} \right]$



How can we control $\Delta\phi_d$?

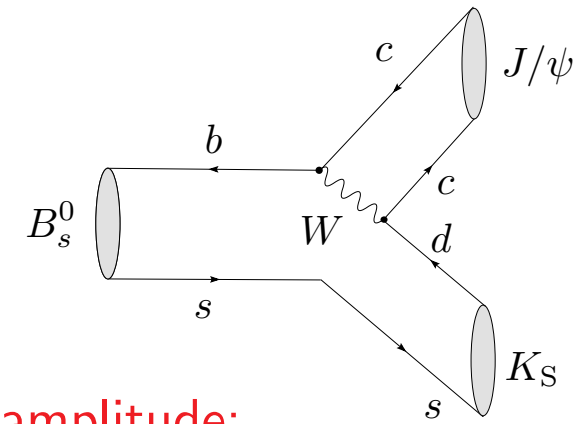
$$\tan\Delta\phi_d = \frac{2\epsilon a'\cos\theta'\sin\gamma + \epsilon^2 a'^2\sin 2\gamma}{1 + 2\epsilon a'\cos\theta\cos\gamma + \epsilon^2 a'^2\cos 2\gamma}$$

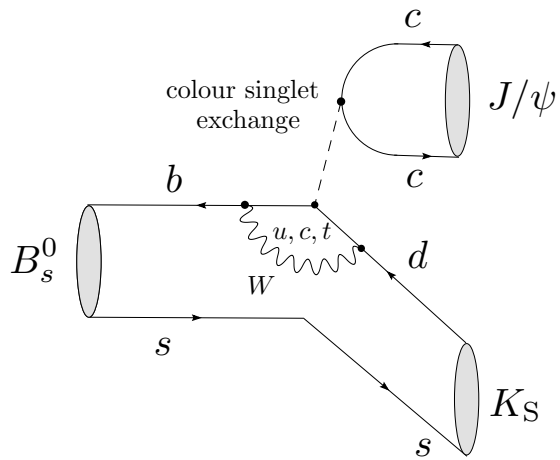
$\rightarrow$ hadronic parameters a', θ' cannot be calculated:

$\Rightarrow$ use control channel(s): $B_s^0 \rightarrow J\psi K_{\rm S} \oplus U$-spin symmetry

[R.F., Eur. Phys. J. C **10** (1999) 299 [hep-ph/9903455]]

The Decay $B_s \to J/\psi K_S$





- Decay amplitude:

$$A(B_s^0 \to J/\psi\, K_S) = \lambda_c^{(d)} \left[A_T^{(c)} + A_P^{(c)} \right] + \lambda_u^{(d)} A_P^{(u)} + \lambda_t^{(d)} A_P^t$$

- Unitarity of the CKM matrix: $\lambda_t^{(d)} = -\lambda_c^{(d)} - \lambda_u^{(d)}$

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

$$\mathcal{A} \equiv \lambda^2 A \left[A_T^{(c)} + A_P^{(c)} - A_P^{(t)} \right], \quad a e^{i\theta} \equiv R_b \left[\frac{A_P^{(u)} - A_P^{(t)}}{A_T^{(c)} + A_P^{(c)} - A_P^{(t)}} \right]$$

- In contrast to $B_d^0 \to J/\psi K_S$, $a e^{i\theta}$ is *not* suppressed by $\epsilon = 0.05$:

$\Rightarrow$ penguin effects are "magnified"!

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

$$\langle\Gamma(B_s(t)\to f)\rangle \propto \left[\cosh\left(\frac{y_s\,t}{\tau_{B_s}}\right)+\mathcal{A}^f_{\Delta\Gamma}\,\sinh\left(\frac{y_s\,t}{\tau_{B_s}}\right)\right]$$

  - "Experimental" branching ratio: $[y_s \equiv \Delta\Gamma_s/(2\,\Gamma_s)\sim 0.1]$

$$\mathrm{BR}\,(B_s\to f)_{\mathrm{exp}} \equiv \frac{1}{2}\int_0^\infty \langle\Gamma(B_s(t)\to f)\rangle\,dt$$

  - "Theoretical" branching ratio: $\to$ *will be used below ...*

$$\mathrm{BR}\,(B_s\to f)_{\mathrm{theo}} \equiv \frac{\tau_{B_s}}{2}\langle\Gamma(B_s^0(t)\to f)\rangle\Big|_{t=0}$$

- Conversion between both BRs: $\to$ effective decay lifetime τ_f useful:

$$\mathrm{BR}\,(B_s\to f)_{\mathrm{theo}} = \left[\frac{1-y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}\,y_s}\right]\mathrm{BR}\,(B_s\to f)_{\mathrm{exp}}$$

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

[De Bruyn, R.F., Knegjens, Koppenburg, Merk & Tuning (2012)]

- Useful quantity: [$\Phi^s_{J/\psi K_S}$, $\Phi^d_{J/\psi K_S}$: phase-space factors]

$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\Phi^d_{J/\psi K_S}}{\tau_{B_s}\Phi^s_{J/\psi K_S}}\right] \frac{\mathrm{BR}\,(B_s \to J/\psi K_S)_{\mathrm{theo}}}{\mathrm{BR}(B_d \to J/\psi K_S)_{\mathrm{theo}}}$$

$$= \frac{1 - 2a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2}$$

- Further $B^0_s \to J/\psi K_S$ observables from *tagged* time-dependent rates:

$$\frac{\Gamma(B^0_s \to J/\psi K_S) - \Gamma(\bar{B}^0_s \to J/\psi K_S)}{\Gamma(B^0_s \to J/\psi K_S) + \Gamma(\bar{B}^0_s \to J/\psi K_S)}$$
$$= \frac{C(B_s \to J/\psi K_S)\cos(\Delta M_s t) - S(B_s \to J/\psi K_S)\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_S)\sinh(\Delta\Gamma_s t/2)}$$

$$\Rightarrow \quad C, \quad S, \quad \mathcal{A}_{\Delta\Gamma}$$

  - Note that these observables are not independent: $C^2 + S^2 + \mathcal{A}^2_{\Delta\Gamma} = 1$.

Extraction of γ and Penguin Parameters

- U-spin flavour symmetry:

$$a = a', \quad \theta = \theta'$$

$$\Rightarrow \qquad \mathcal{A}' = \mathcal{A}$$

- Observables:

$$\begin{aligned} H &= \text{function}(a, \theta, \gamma) \\ C(B_s \to J/\psi K_{\rm S}) &= \text{function}(a, \theta, \gamma) \\ S(B_s \to J/\psi K_{\rm S}) &= \text{function}(a, \theta, \gamma; \phi_s) \end{aligned}$$

$\Rightarrow$ $\boxed{\gamma,\ a \text{ and } \theta \text{ can be extracted from the 3 observables}}$

[ϕ_s denotes the B_s^0–$\bar{B}_s^0$ mixing phase, with $\phi_s^{\rm SM} = -2\lambda^2\eta \sim -2^\circ$]

- Change of focus of interest since 1999:
  - Extraction of γ @ LHCb is feasible but probably not competitive ...
  - Assume that γ is know $\Rightarrow$ clean determination of the penguin parameters a, θ from C and S (further info from H).

[R.F. (1999); De Bruyn, R.F. & Koppenburg (2010)]

through

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

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

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

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

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

Consequently, we obtain

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

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:

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

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 $B_s \to J/\psi K_S$.

Current information on the penguin parameters?

- $B_s^0 \to J/\psi K_{\rm S}$ has been observed by CDF and LHCb, but only BR.
- Use data for decays with a CKM structure similar to $B_s^0 \to J/\psi K_{\rm S}$:

$$B_d^0 \to J/\psi \pi^0,\ B^+ \to J/\psi \pi^+$$

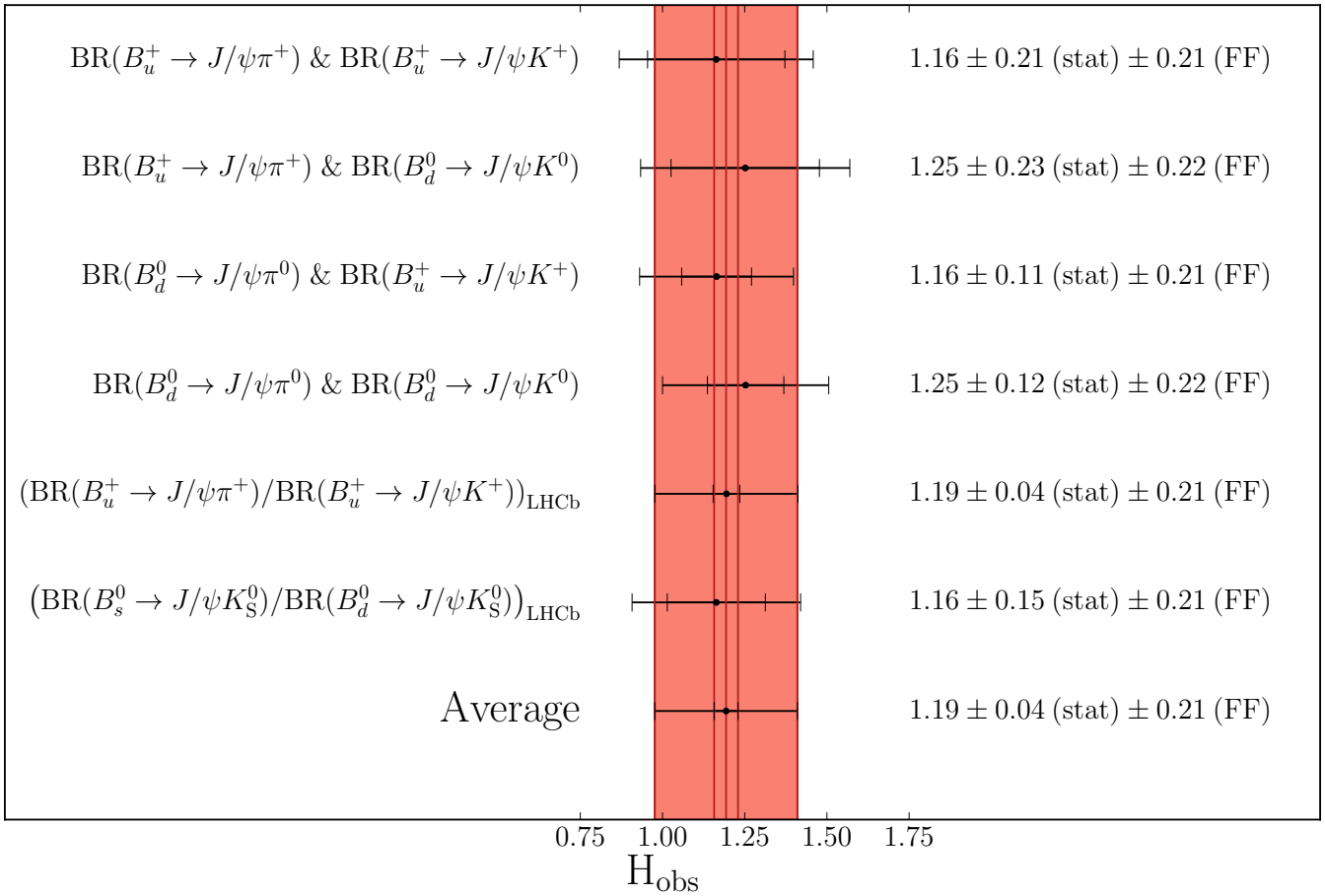
... and complement with data for $B_d^0 \to J/\psi K^0$, $B^+ \to J/\psi K^+$ decays.

Work in progress with K. De Bruyn & P. Koppenburg
see also Ciuchini, Pierini & Silvestrini (2005);
Faller, R.F., Jung & Mannel (2008);
Jung (2012)

Compilation of H Observables

- BR ratios, including factorizable $SU(3)$-breaking corrections:

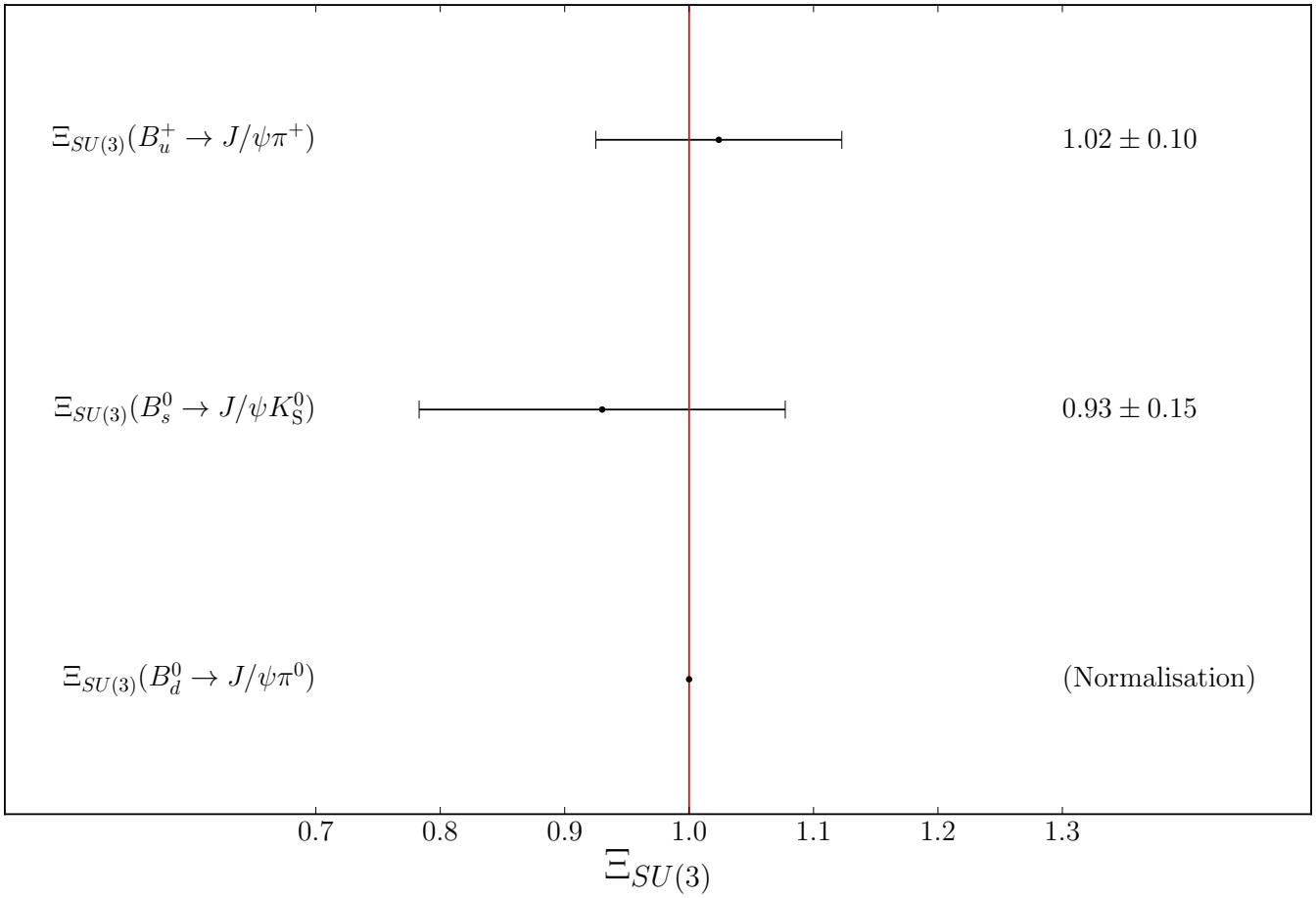
$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\Phi^d_{J/\psi K_S}}{\tau_{B_s}\Phi^s_{J/\psi K_S}}\right] \frac{\mathrm{BR}\left(B_s \to J/\psi K_S\right)_{\mathrm{theo}}}{\mathrm{BR}(B_d \to J/\psi K_S)_{\mathrm{theo}}}$$



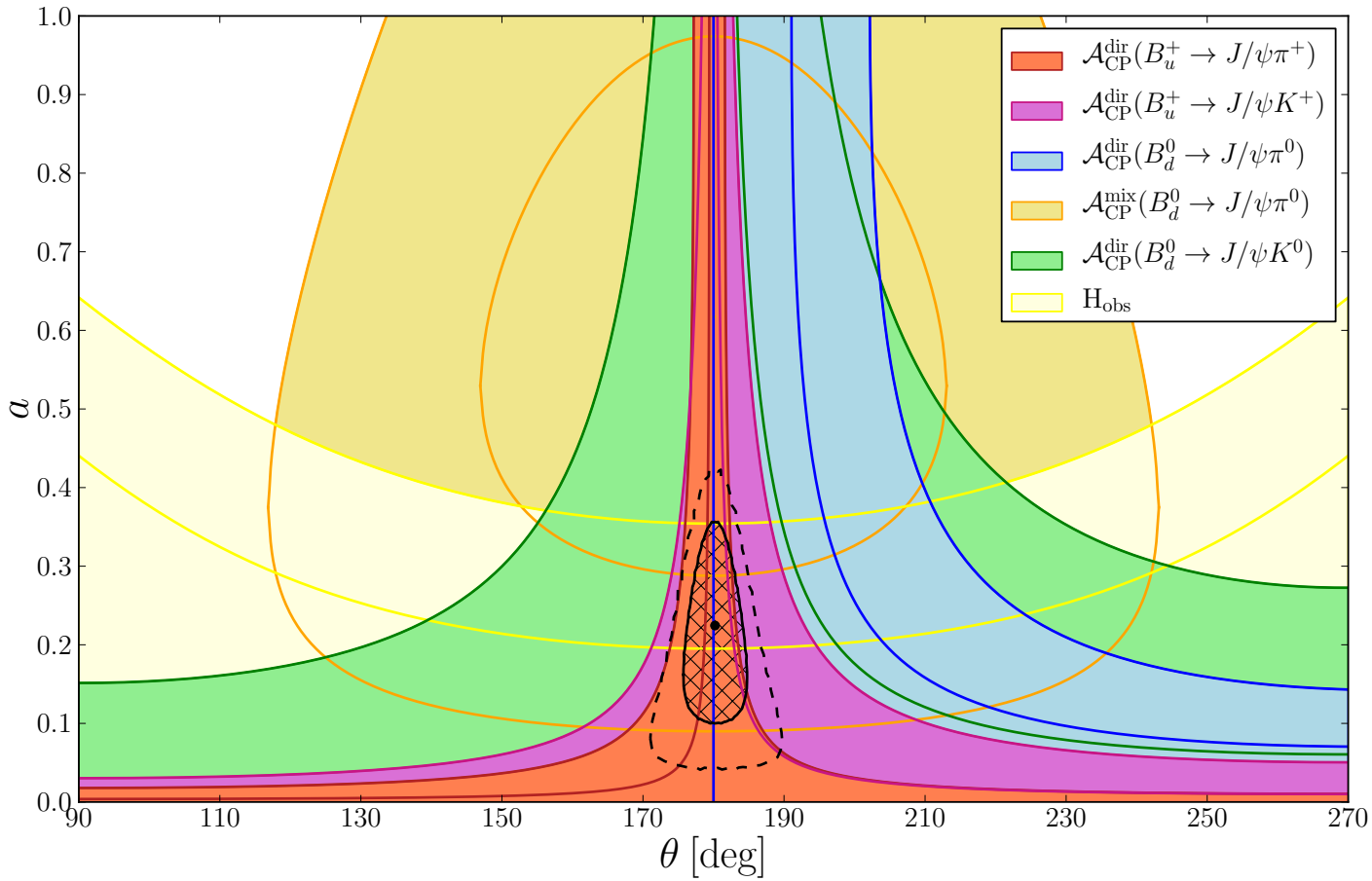
$SU(3)$ Tests

- Neglecting penguin annihilation & exchange topologies:

$$\Xi_{SU(3)} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi \bar{K}^0)_{\mathrm{theo}}}{2\mathrm{BR}(B_d^0 \to J/\psi \pi^0)_{\mathrm{theo}}} \frac{\tau_{B_d}}{\tau_{B_s}} \frac{\Phi^d_{J/\psi\pi^0}}{\Phi^s_{J/\psi K_{\mathrm{S}}}} \xrightarrow{SU(3)} 1$$



Constraints on Penguin Parameters



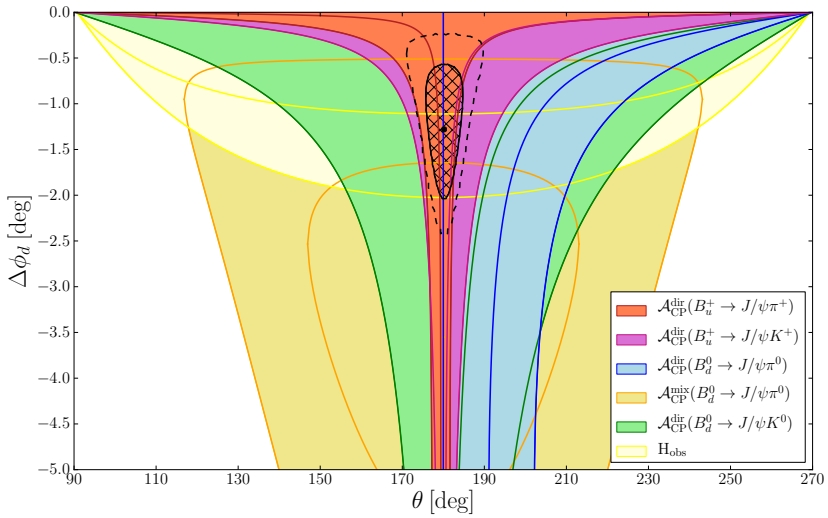
[39% and 68% C.L.]

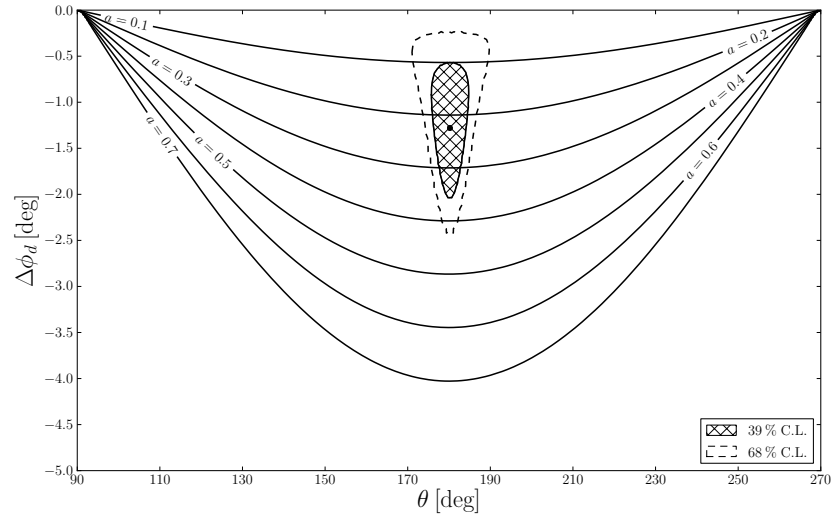
$$a = 0.22 \pm 0.13, \quad \theta = (180.2 \pm 4.5)^\circ$$

[1σ ranges]

[Comparison with Faller, R.F., Jung & Mannel ('08): $a \in [0.15, 0.67]$, $\theta \in [174, 213]^\circ$]

Constraints on $\Delta\phi_d$





$$\boxed{\Delta\phi_d = -(1.28 \pm 0.74)^\circ}$$

$$S(B_d \to J/\psi K_{\rm S}) = \sin(\phi_d + \Delta\phi_d) = 0.665 \pm 0.024 \Rightarrow$$

$$\phi_d + \Delta\phi_d = (41.7 \pm 1.7)^\circ \Rightarrow$$

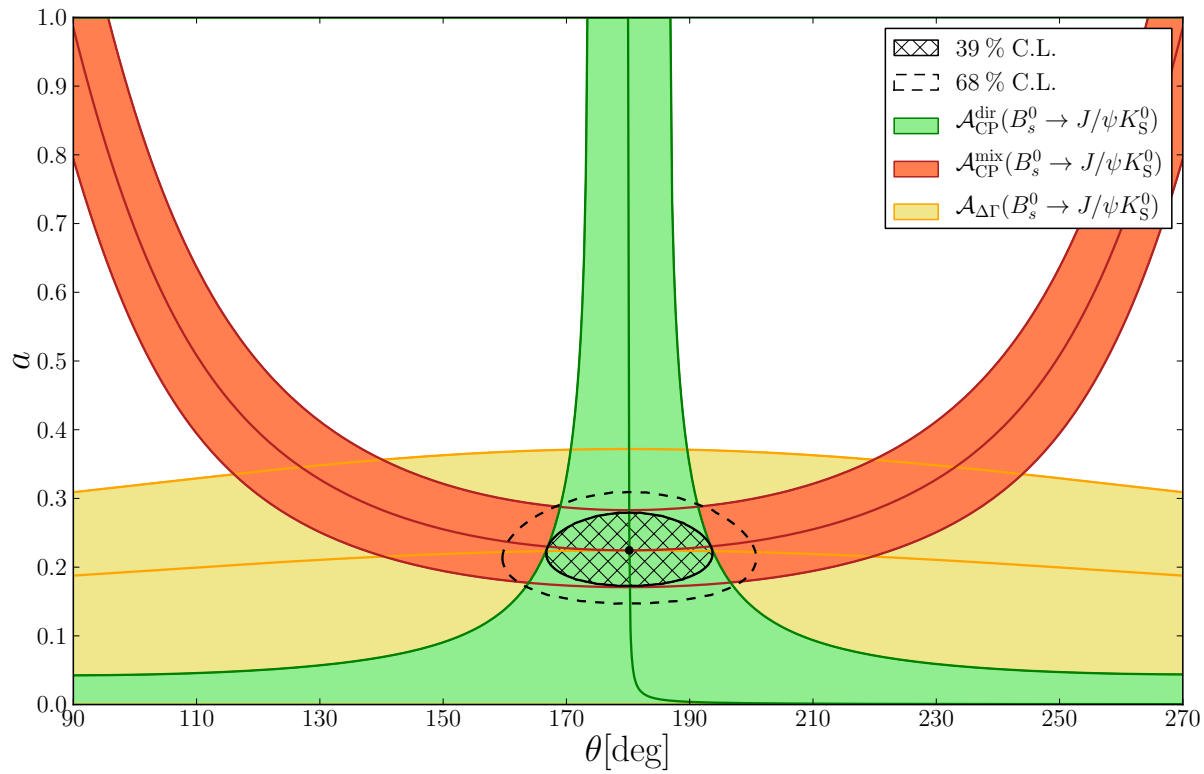
$$\phi_d = (43.0 \pm 1.7|_S \pm 0.7|_{\Delta\phi_d})^\circ = (43.0 \pm 1.8)^\circ$$

- Situation is similar in the extraction of ϕ_s from $B_s \to J/\psi\phi$ ...
- LHCb strategy document [arXiv:1208.3355]:

  $\to$ theory uncertainty of ϕ_s measurement quoted as $\sim 0.003 = 0.17^\circ$!?

Prospects for LHCb Upgrade

- Extrapolation from toy study (i.e. not official LHCb):



- Comments:
  - This determination of a and θ is theoretically clean.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\rm S}$) through U-spin symmetry.

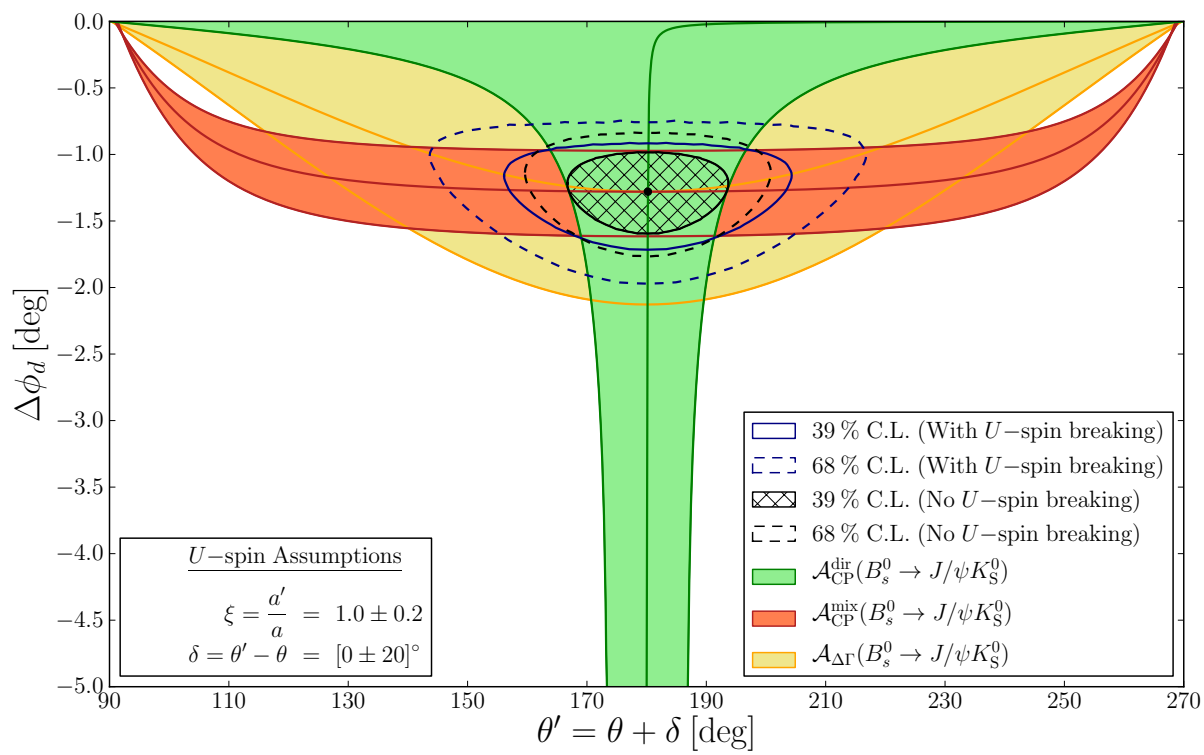
[Update of De Bruyn, R.F. & Koppenburg (2010)]

... Conversion into $\Delta\phi_d$

- Use U-spin symmetry between $B_s^0 \to J/\psi K_S$ and $B_d^0 \to J/\psi K_S$:

$$a' = a, \quad \theta' = \theta$$

$$\Rightarrow \tan\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}$$

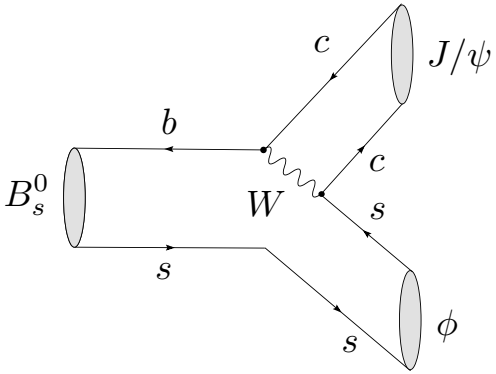


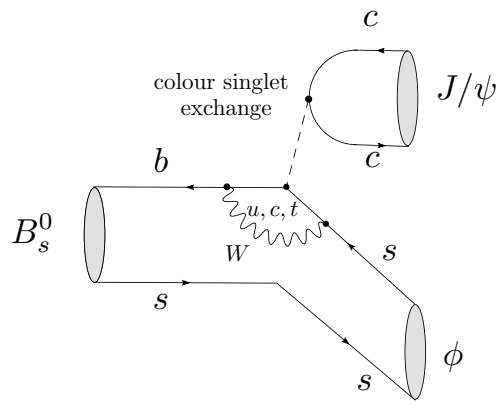
$$\boxed{B_s \to J/\psi\phi:}$$

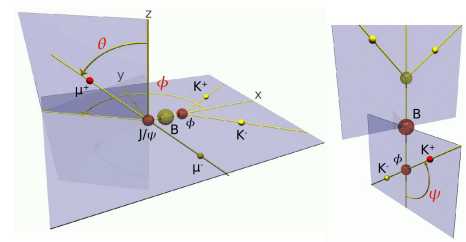
$\Rightarrow$ B_s counterpart of $B_d \to J/\psi K_{\rm S}$

[See talks by Rob Harr, Gerhard Raven and Maria Smizanska]

CP Violation in $B_s \to J/\psi\phi$







- Final state is mixture of CP-odd and CP-even states:

  $\to$ disentangle through $J/\psi[\to \mu^+\mu^-]\phi[\to\ K^+K^-]$ angular distribution

- Impact of SM penguin contributions (which are usually neglected):

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

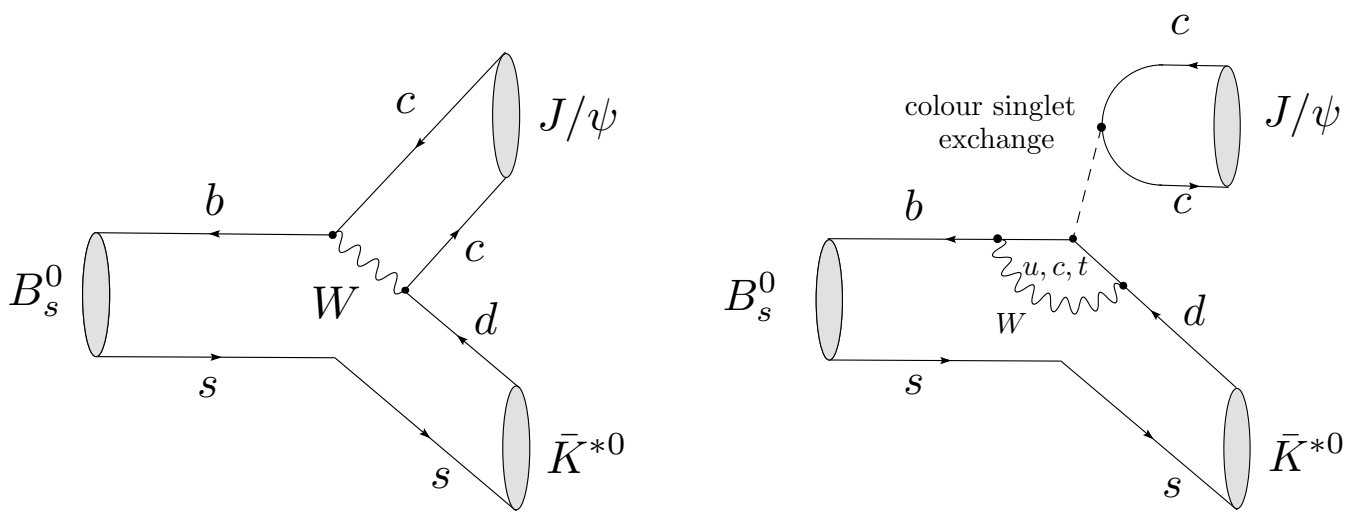
$$\mathcal{A}_{\mathrm{CP},f}^{\mathrm{mix}} = \sin\phi_s \ \to\ \sin(\phi_s + \Delta\phi_s^f)$$

- Smallish B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s (indicated by data ...):

  $\Rightarrow\ \ \Delta\phi_s^f$ at the 1° level would have a significant impact ...

[Faller, R.F. & Mannel (2008)]

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



- Decay amplitude: $A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$
  - 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 $f \in \{0, \|, \perp\}$

Comments

- $B_s^0 \to J/\psi \bar{K}^{*0}$ was observed by CDF and LHCb [arXiv:1208.0738]:
  - Branching ratio $(4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$ agrees well with the prediction $(4.6 \pm 0.4) \times 10^{-5}$ from $B_d \to J/\psi \rho^0$ [Faller, R.F. & Mannel (2008)].
  - Polarization fractions agree well with those of $B_d^0 \to J/\psi K^{*0}$.
  - Angular observables of $B \to VV$ decays offer plenty of information! [R.F. (1999); Bhattacharya, Datta & London (2012)]

$\Rightarrow$ **look forward to future data...**

- Sensitivity at the LHCb upgrade (50 fb^{-1}) [arXiv:1208.3355]:

$$\Delta\phi_s|_{\rm exp} \sim 0.008 = 0.46^\circ$$

  - Theoretical uncertainty quoted as $\Delta\phi_s|_{\rm theo} \sim 0.003 = 0.17^\circ$ (!), ...
  - Data for $B \to J/\psi\pi, J/\psi K$ decays with a similar dynamics:
    $$\Delta\phi_d = -(1.28 \pm 0.74)^\circ$$
  - Such phase shifts may mimic New Physics: $\mathcal{A}_{\rm CP,f}^{\rm mix} = \sin(\phi_s + \Delta\phi_s^f)$

$\Rightarrow$ **we have to get a handle on the penguin effects ...**

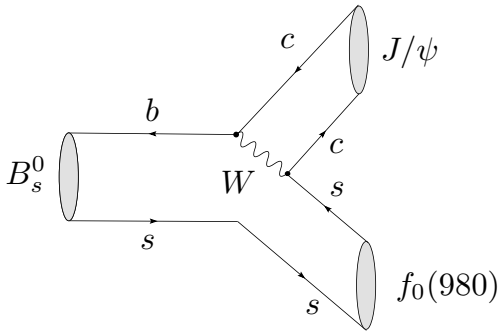
$$\boxed{B_s \to J/\psi f_0(980):}$$

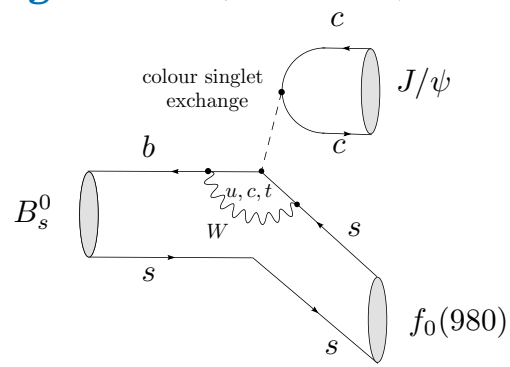
$\to$ interesting new decay!

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 $f_0 \to \pi^+\pi^-$.
- Observation of $B_s^0 \to J/\psi f_0$ at LHCb, Belle, DØ and CDF:

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

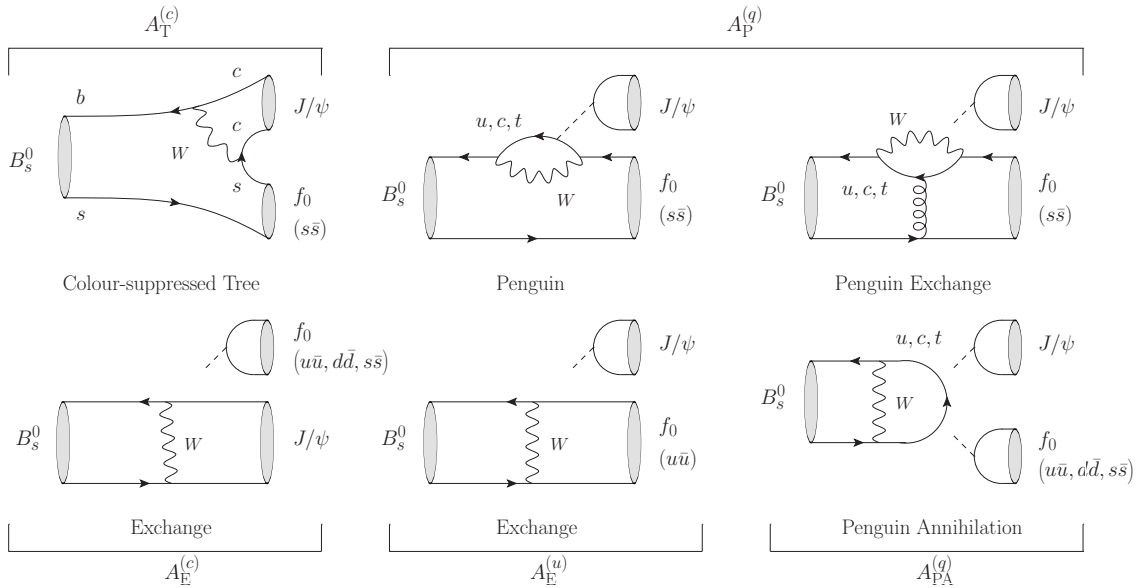
... but as no angular analysis is required:

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

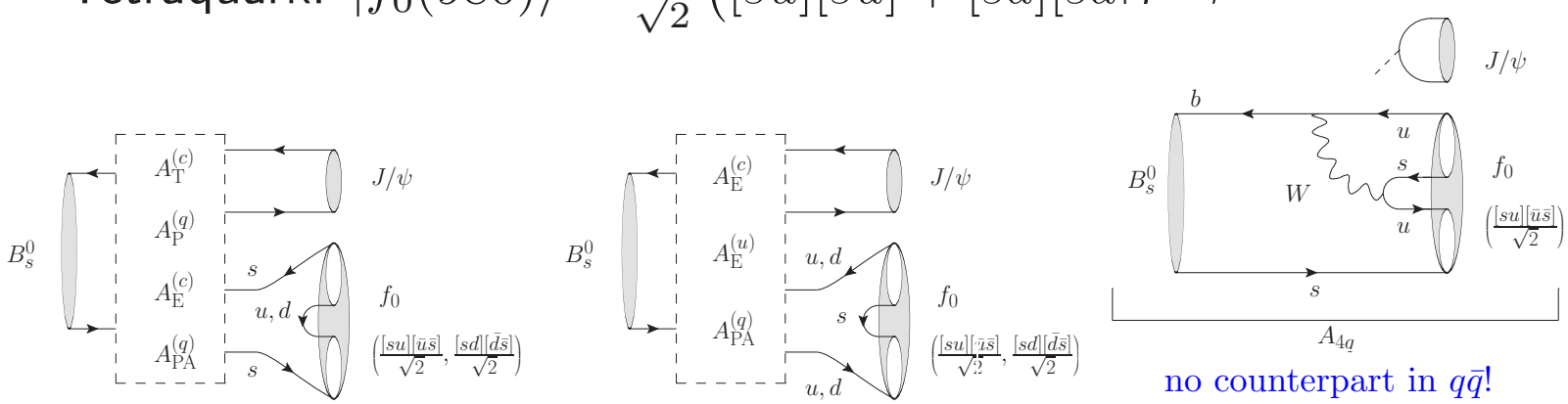
[S. Stone & L. Zhang (2009)]

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:

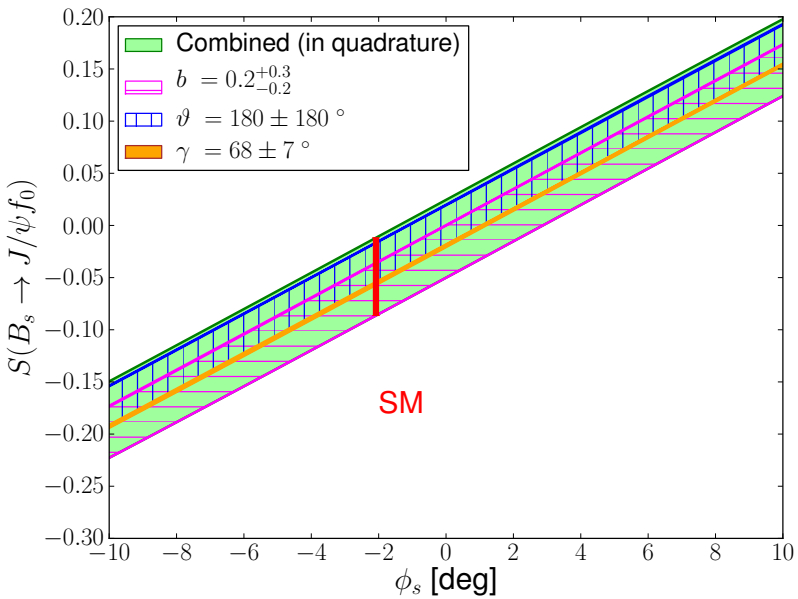
$$\tan \Delta\phi_{J/\psi f_0} = \frac{2\epsilon b \cos\vartheta \sin\gamma + \epsilon^2 b^2 \sin 2\gamma}{1 + 2\epsilon b \cos\vartheta \cos\gamma + \epsilon^2 b^2 \cos 2\gamma}$$

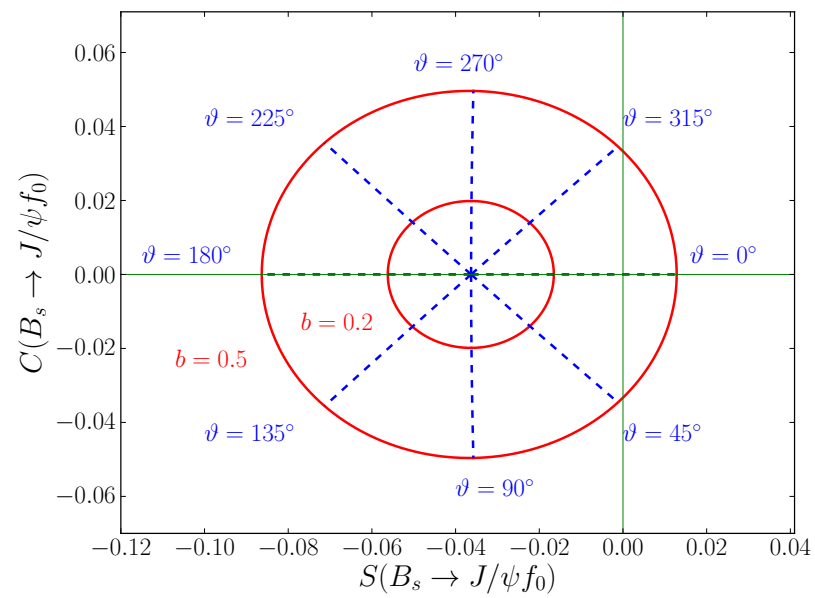
– Conservative range for $b e^{i\theta}$: $0 \le b \le 0.5$, $0^\circ \le \vartheta \le 360^\circ$ $\Rightarrow$

$$\Delta\phi_{J/\psi f_0} \in [-2.9^\circ, 2.8^\circ]$$

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

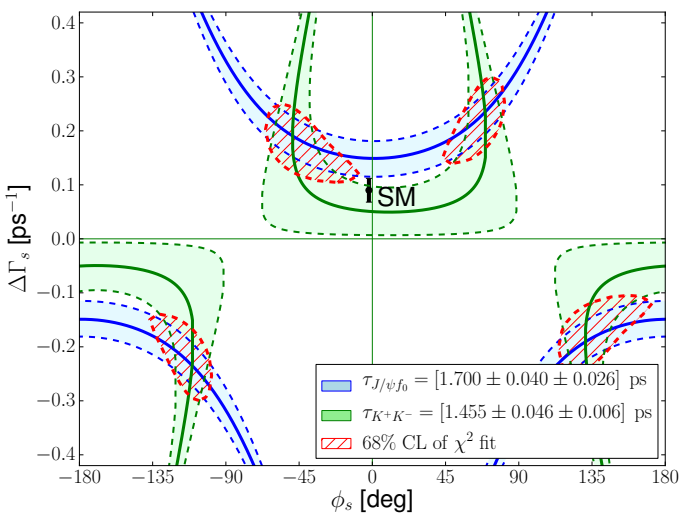
$$\frac{\Gamma(B_s(t) \to J/\psi f_0) - \Gamma(\bar{B}_s(t) \to J/\psi f_0)}{\Gamma(B_s(t) \to J/\psi f_0) + \Gamma(\bar{B}_s(t) \to J/\psi f_0)} = \frac{C\cos(\Delta M_s t) - S\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

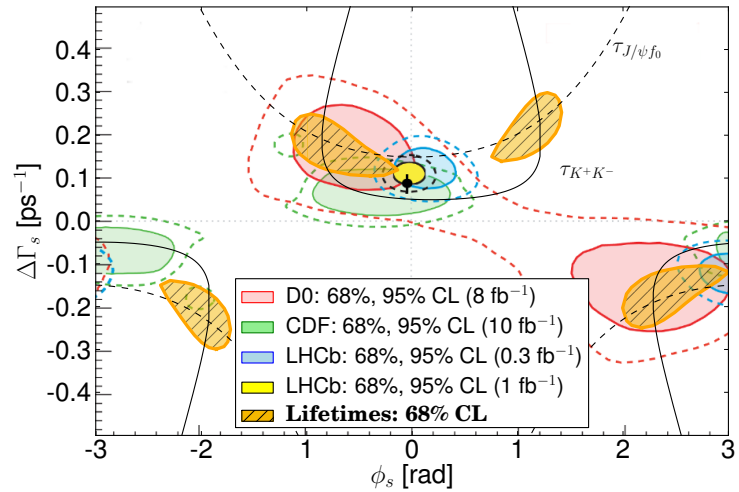


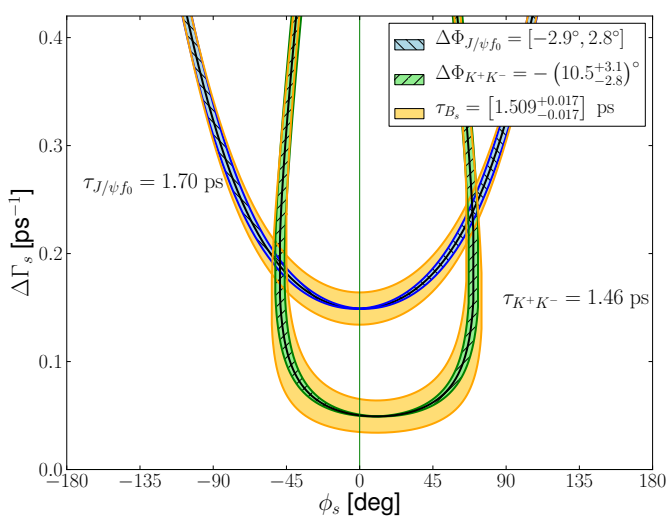


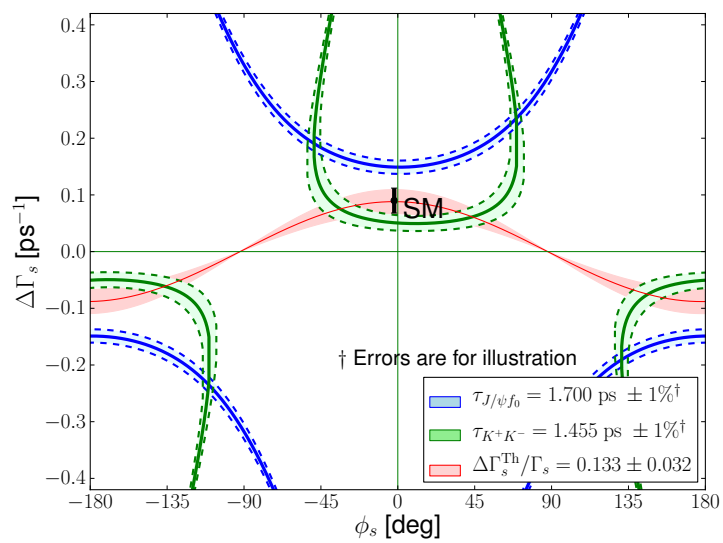
- Mixing-induced CP asymmetry: $\boxed{S = \sqrt{1 - C^2}\sin(\phi_s + \Delta\phi)}$
  - Naïve SM value: $(\sin\phi_s)|_{\rm SM} = -0.036 \pm 0.002$;
  - Allowing for hadronic effects: $S(B_s^0 \to J/\psi f_0)\big|_{\rm SM} \in [-0.086, -0.012]$

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









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

[R.F. & Knegjens, arXiv:1109.5115 [hep-ph]; update: Knegjens, arXiv:1209.3206 [hep-ph]]

Comments

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

$\Rightarrow$ crucial to constrain hadronic corrections to disentangle NP from SM

- LHCb result for ϕ_s from $B_s^0 \to J/\psi f_0$: [$\to$ talk by Gerhard Raven]

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

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

$$S = \sqrt{1 - C^2}\sin(\phi_s + \Delta\phi); \quad \Delta\phi_{J/\psi f_0} \in [-2.9^\circ, 2.8^\circ]$$

  - LHCb [arXiv:1208.3355]: theory uncertainty of $\sim 0.01 = 0.57^\circ$!?

- Average with $B_s^0 \to J/\psi\phi$:
  - 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.

[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 $f_0(980)$:

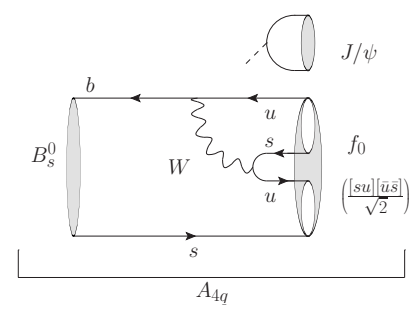
$$A(B_d^0 \to J/\psi f_0) = -\lambda \mathcal{A}' \left[1 - b' e^{i\vartheta'} e^{i\gamma}\right]$$

- 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]]

Conclusions

◇ New Frontiers in Precision:

- Still no signals for New Physics @ LHC:
  - Impressive (also frustrating ...), but more is yet to come!
  - Prepare to deal with "smallish" NP effects:

$\Rightarrow$ Match experimental with theoretical precisions!

Towards Controlling Penguins

- Penguin parameters following from current $B \to J/\psi\pi, J/\psi K$ data:

$$a = 0.22 \pm 0.13,\ \theta = (180.2 \pm 4.5)^\circ \ \Rightarrow\ \Delta\phi_d = -(1.28 \pm 0.74)^\circ$$

- Interesting penguin probe for the LHCb upgrade era: $\boxed{B_s^0 \to J/\psi K_{\rm S}}$
  - CP asymmetries allow clean extraction of a and θ.
  - Relation to $B_d^0 \to J/\psi K_{\rm S}$ through U-spin symmetry.
- Penguin uncertainties in $B_s^0 \to J/\psi\phi$:
  - $\Delta\phi_d = -(1.28 \pm 0.74)^\circ \sim \Delta\phi_s^f$ vs. $\phi_s^{\rm SM} = -2^\circ$ and $\Delta\phi_s|_{\rm exp} \sim 0.46^\circ$.
  - Control channels: $B_s^0 \to J/\psi \bar{K}^{*0}$ (and $B_d^0 \to J/\psi\rho^0$, not this talk).
- Penguin uncertainties in $B_s^0 \to J/\psi f_0(980)$:
  - Hadronic structure of $f_0(980)$ matters here!?
  - Conservative range: $S(B_s^0 \to J/\psi f_0)\big|_{\rm SM} \in [-0.086, -0.012]$.
  - Interesting future channel: $B_d^0 \to J/\psi f_0(980)$.
- Further observables and decay channels: effective B_s decay lifetimes, angular correlations in $B \to VV$ decays, $B_{s,d} \to D_{s,d}^{(*)+} D_{s,d}^{(*)-}$....