News on Penguin Effects in CP Violation Benchmark Decays

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- Setting the Stage
- Focus on two decay classes: $\rightarrow$ benchmark modes:
  - $B^0_{s,d} \to J/\psi P$: $B^0_d \to J/\psi K_S \oplus B^0_s \to J/\psi K_S$, ...
  - $B^0_{s,d} \to J/\psi V$: $B^0_s \to J/\psi \phi \oplus B^0_d \to J/\psi \rho^0$, $B^0_s \to J/\psi \overline{K}^{*0}$
- A Penguin Roadmap & Conclusions

Setting the Stage

Where Do We Stand?

- Run I of the LHC: $\rightarrow$ discovery of "Higgs-like" particle, but ...
  - No SM deviations seen at ATLAS and CMS.
  - Some puzzling results in the flavour sector at LHCb but no solid evidence for NP (yet?) ...

- Implications for the general structure of 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!

High-Precision B Physics

- Crucial for resolving smallish effects of New Physics:
  - Have a critical look at theoretical analyses and their approximations:

    $\rightarrow$ key issue: strong interactions: $\rightarrow$ "hadronic" effects

  - Match the experimental and theoretical precisions.

- Benchmark B-meson decays for exploring CP violation:

$$\Rightarrow \; B_d^0 \to J/\psi K_{\rm S} \text{ and } B_s^0 \to J/\psi \phi$$

  - 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...

$\Rightarrow$ How big are they & how can they be controlled?

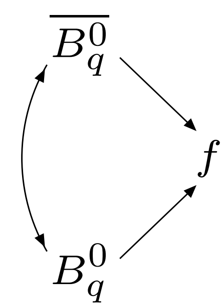
"Penguin Hunting"

This Talk: Direct & Mixing-Induced CP Violation

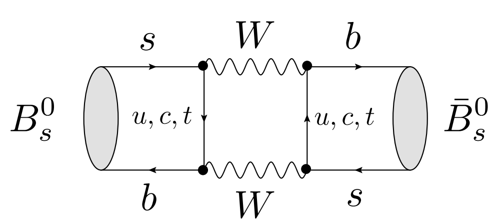
- Direct CP violation: *interference between decay amplitudes*

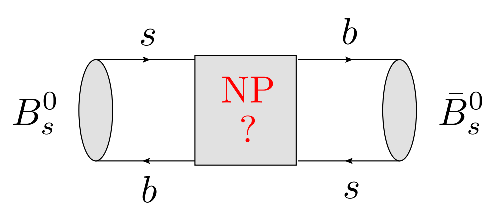
$$\mathcal{A}_{\rm CP} \equiv \frac{\Gamma(B\to f)-\Gamma(\overline{B}\to\overline{f})}{\Gamma(B\to f)+\Gamma(\overline{B}\to\overline{f})} = \frac{|A(B\to f)|^2-|A(\overline{B}\to\overline{f})|^2}{|A(B\to f)|^2+|A(\overline{B}\to\overline{f})|^2}$$

$$= \frac{2|A_1||A_2|\sin(\delta_1-\delta_2)\sin(\varphi_1-\varphi_2)}{|A_1|^2+2|A_1||A_2|\cos(\delta_1-\delta_2)\cos(\varphi_1-\varphi_2)+|A_2|^2}$$



- Mixing-induced CP violation: *neutral B_q decays*





$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}$$

$$\phi_d = \phi_d^{\rm SM} + \phi_d^{\rm NP} = 2\beta + \phi_d^{\rm NP}$$

PhD Student:

$\longrightarrow$ closely involved in the topics discussed in this talk:

Kristof De Bruyn
[Theory $\oplus$ LHCb]

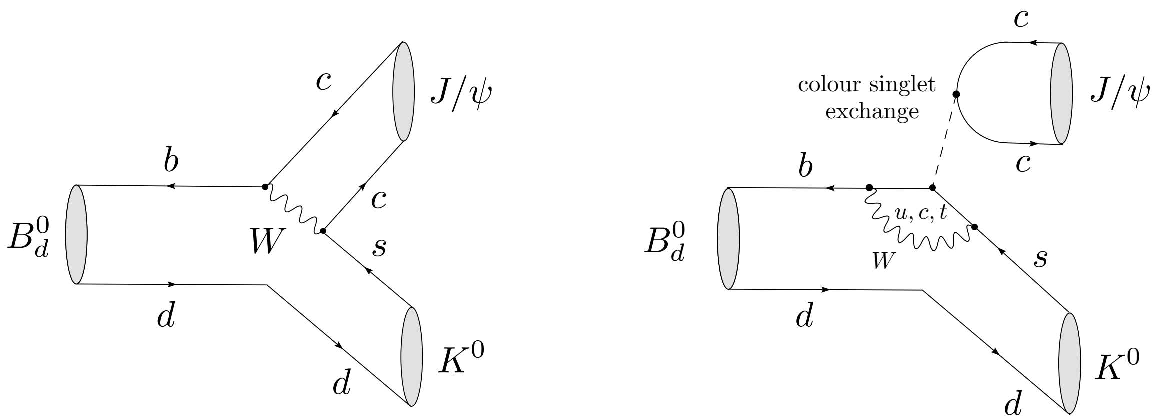
- Details in recent publication:

K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]

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

Picture from current data and prospects?

The $B_d^0 \to J/\psi K_{\rm S}$ Decay



- Decay amplitude in the SM:

$$A(B_d^0 \to J/\psi\, K_{\rm S}) = \lambda_c^{(s)} \left[A_{\rm T}^{(c)'} + A_{\rm P}^{(c)'}\right] + \lambda_u^{(s)} A_{\rm P}^{(u)'} + \lambda_t^{(s)} A_{\rm P}^{t'}$$

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

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

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

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

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

$$\frac{\Gamma(B^0_d \to J/\psi K_S) - \Gamma(\bar{B}^0_d \to J/\psi K_S)}{\Gamma(B^0_d \to J/\psi K_S) + \Gamma(\bar{B}^0_d \to J/\psi K_S)}$$

$$= \mathcal{A}_{CP}^{dir}(B_d \to J/\psi K_S)\cos(\Delta M_d t) + \mathcal{A}_{CP}^{mix}(B_d \to J/\psi K_S)\sin(\Delta M_d t)$$

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

$$\mathcal{A}_{CP}^{dir}(B_d \to J/\psi K_S) = -\frac{2\epsilon a' \sin\theta' \sin\gamma}{1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2}$$

$$-\frac{\mathcal{A}_{CP}^{mix}(B_d \to J/\psi K_S)}{\sqrt{1 - \mathcal{A}_{CP}^{dir}(B_d \to J/\psi K_S)^2}} = \sin(\phi_d + \Delta\phi_d)$$

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

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

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

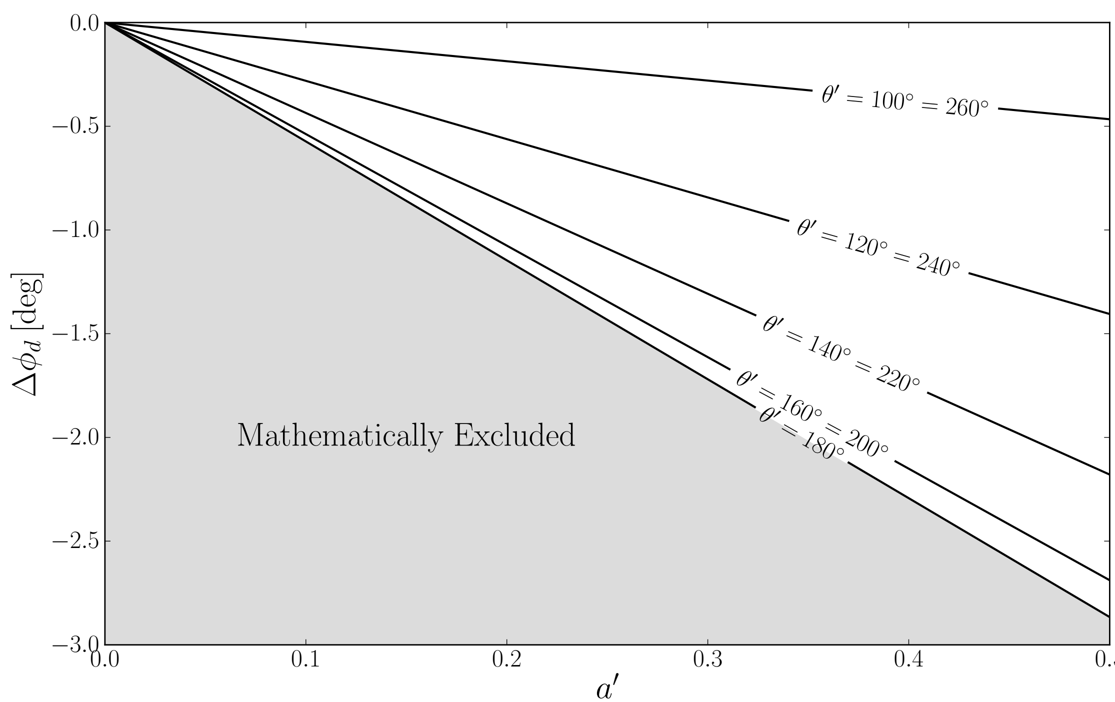
- Current experimental status: [Heavy Flavour Averaging Group (HFAG)]

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi K^0) = -0.670 \pm 0.021$$

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi K^0) = 0.007 \pm 0.020 \;\Rightarrow\; \sqrt{1-(\mathcal{A}_{\rm CP}^{\rm dir})^2} = 0.99998^{+0.00006}_{-0.00034}$$

$$\Rightarrow \quad \boxed{\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi K^0) = -\sin(\phi_d + \Delta\phi_d)}$$

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



$\star$ How can we control $\Delta\phi_d$?

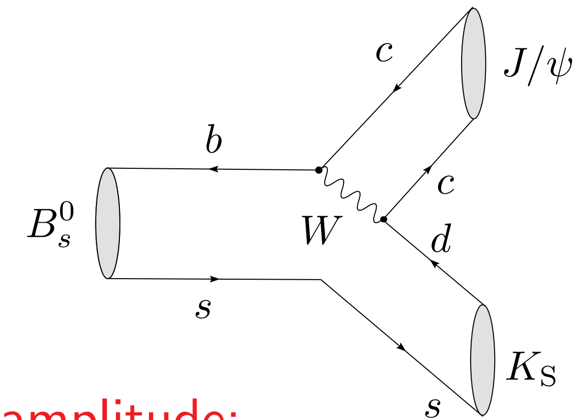
$$\tan\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}$$

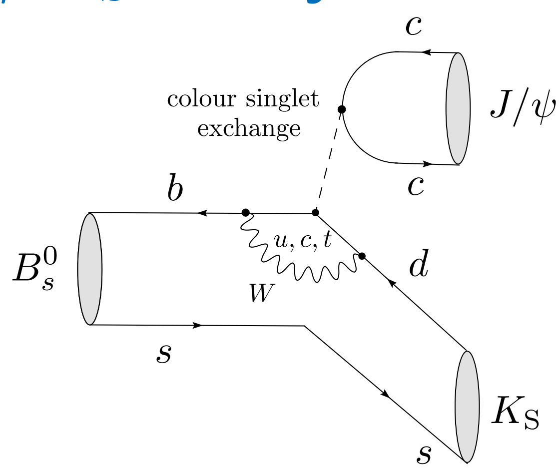
$\rightarrow$ hadronic parameters a', θ' cannot be calculated:

$\Rightarrow$ use control channel(s): $B_s^0 \to J/\psi K_S \oplus U$-spin symmetry

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

The $B_s^0 \to J/\psi K_{\rm S}$ Decay





- Decay amplitude:

$$A(B_s^0 \to J/\psi\, K_{\rm S}) = \lambda_c^{(d)} \left[A_{\rm T}^{(c)} + A_{\rm P}^{(c)}\right] + \lambda_u^{(d)} A_{\rm P}^{(u)} + \lambda_t^{(d)} A_{\rm P}^{t}$$

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

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

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

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

$\Rightarrow$ penguin effects are “magnified”!

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

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

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

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

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

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

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

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

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

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

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

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

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

- Further $B^0_s \to J/\psi K_{\rm S}$ observables from *tagged* time-dependent rates:

$$\frac{\Gamma(B^0_s \to J/\psi K_{\rm S}) - \Gamma(\bar{B}^0_s \to J/\psi K_{\rm S})}{\Gamma(B^0_s \to J/\psi K_{\rm S}) + \Gamma(\bar{B}^0_s \to J/\psi K_{\rm S})}$$

$$= \frac{\mathcal{A}^{\rm dir}_{\rm CP}(B_s \to J/\psi K_{\rm S})\cos(\Delta M_s t) + \mathcal{A}^{\rm mix}_{\rm CP}(B_s \to J/\psi K_{\rm S})\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_{\rm S})\sinh(\Delta\Gamma_s t/2)}$$

$$\Rightarrow \quad \mathcal{A}^{\rm dir}_{\rm CP}, \quad \mathcal{A}^{\rm mix}_{\rm CP}, \quad \mathcal{A}_{\Delta\Gamma}$$

  – Observables are not independent: $(\mathcal{A}^{\rm dir}_{\rm CP})^2 + (\mathcal{A}^{\rm mix}_{\rm CP})^2 + (\mathcal{A}_{\Delta\Gamma})^2 = 1.$

Extraction of γ and Penguin Parameters

- U-spin flavour symmetry:

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

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

- Observables:

$$\begin{aligned} H &= \text{function}(a, \theta, \gamma) \\ \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi K_{\rm S}) &= \text{function}(a, \theta, \gamma) \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to J/\psi K_{\rm S}) &= \text{function}(a, \theta, \gamma; \phi_s) \end{aligned}$$

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

[ϕ_s denotes the B^0_s–$\bar{B}^0_s$ 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 $\mathcal{A}_{\rm CP}^{\rm dir}$ and $\mathcal{A}_{\rm CP}^{\rm mix}$ (further info from H).

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

$\star$ Current information on the penguin parameters?

- $B_s^0 \to J/\psi K_{\rm S}$ observed by CDF and LHCb. Recent *first* analysis of CP violation by LHCb, but still large uncertainties [arXiv:1503.07055 [hep-ex]].

- 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.

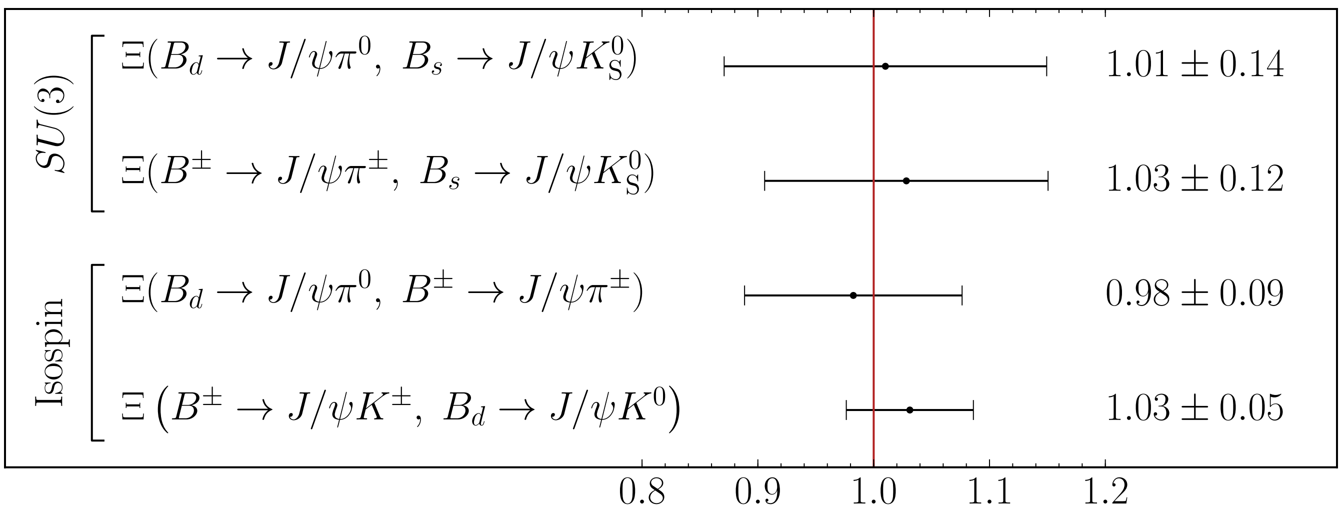
[K. De Bruyn and R.F. (2014)
See also: Ciuchini, Pierini & Silvestrini (2005);
Faller, R.F., Jung & Mannel (2008); Jung (2012);
Frings, Nierste & Wiebusch (2015)]

First Tests of Flavour Symmetries

- Neglecting penguin annihilation & exchange topologies:

$$\Xi(B_q \to J/\psi X, B_{q'} \to J/\psi Y)$$

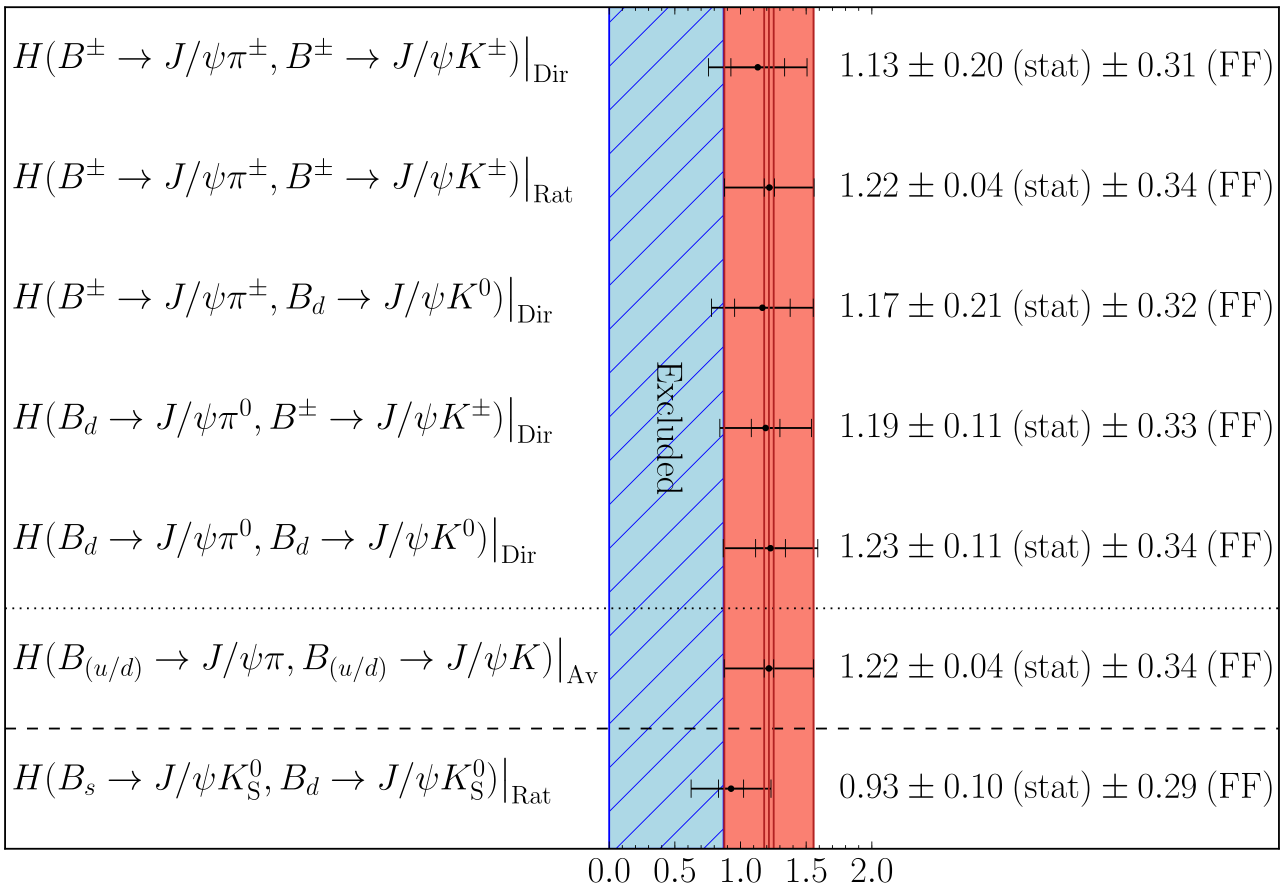
$$\equiv \frac{\mathsf{PhSp}\left(B_{q'} \to J/\psi Y\right)}{\mathsf{PhSp}\left(B_q \to J/\psi X\right)} \frac{\tau_{B_{q'}}}{\tau_{B_q}} \frac{\mathcal{B}\left(B_q \to J/\psi X\right)_{\mathrm{theo}}}{\mathcal{B}\left(B_{q'} \to J/\psi Y\right)_{\mathrm{theo}}} \xrightarrow{SU(3)} 1$$



Compilation of H Observables

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

$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\mathsf{PhSp}(B_d \to J/\psi K_{\rm S})}{\tau_{B_s}\mathsf{PhSp}(B_s \to J/\psi K_{\rm S})}\right] \frac{\mathcal{B}\,(B_s \to J/\psi K_{\rm S})_{\rm theo}}{\mathcal{B}(B_d \to J/\psi K_{\rm S})_{\rm theo}}$$

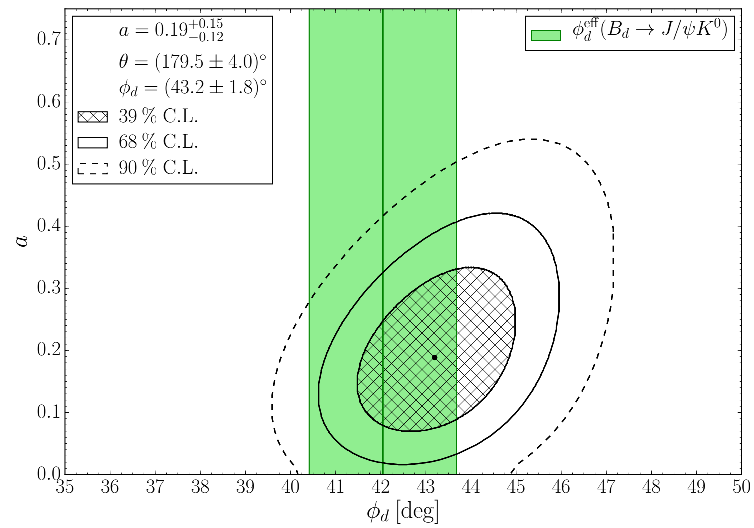


Constraints on the Penguin Parameters: χ^2 Fit

- $\mathcal{A}_{\rm CP}^{\rm mix}(B_d^0 \to J/\psi\pi^0)$ depends on ϕ_d, while CP violation of $B_d^0 \to J/\psi K_{\rm S}^0$ determines only the effective mixing phase:

$$\phi_{d,\psi K_{\rm S}^0}^{\rm eff} = \phi_d + \Delta\phi_d^{\psi K_{\rm S}^0} = (42.1 \pm 1.6)^\circ \ldots$$

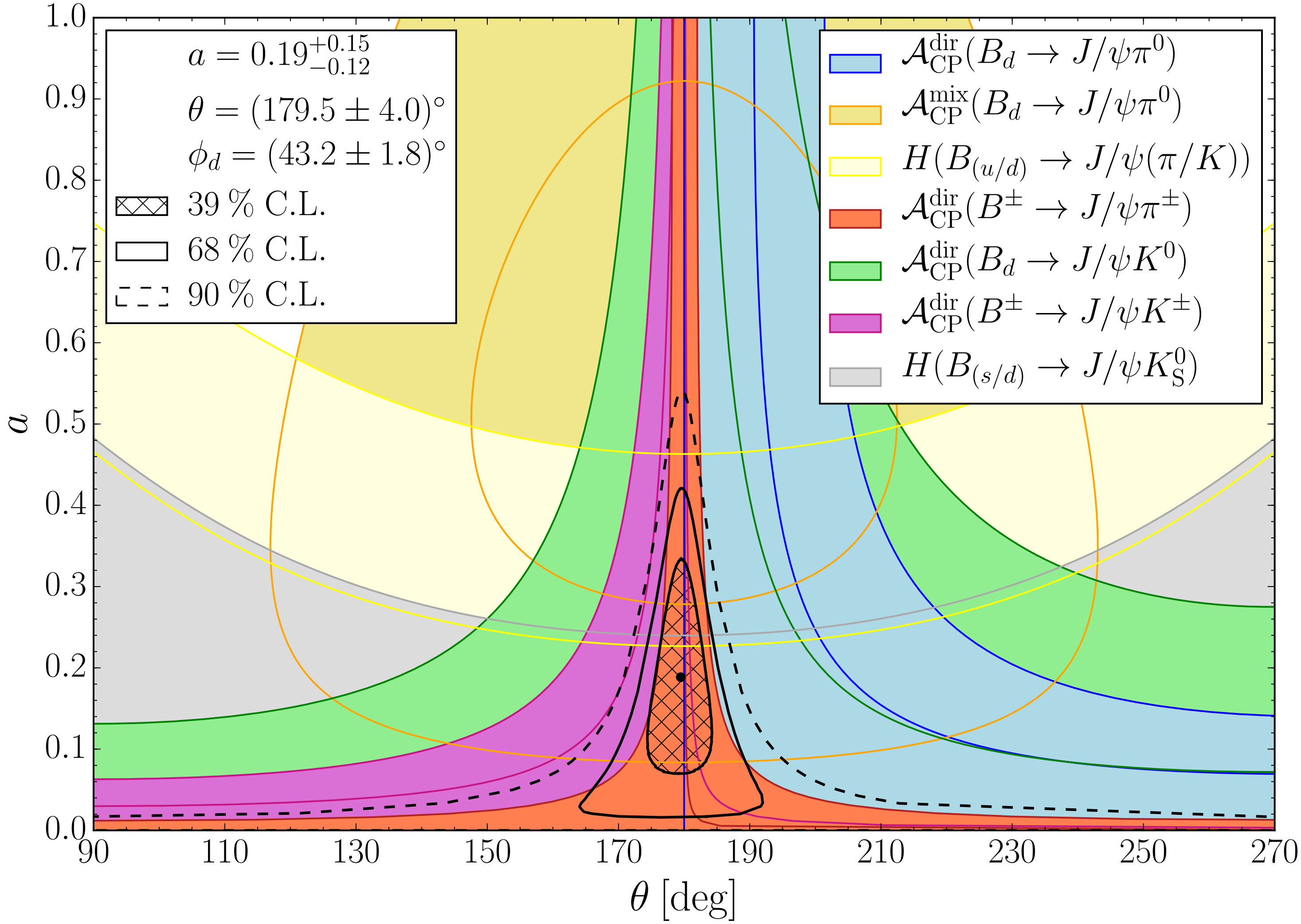
$\Rightarrow$ express $\Delta\phi_d^{\psi K_{\rm S}^0}$ in terms of (a, θ) and add to the fit:



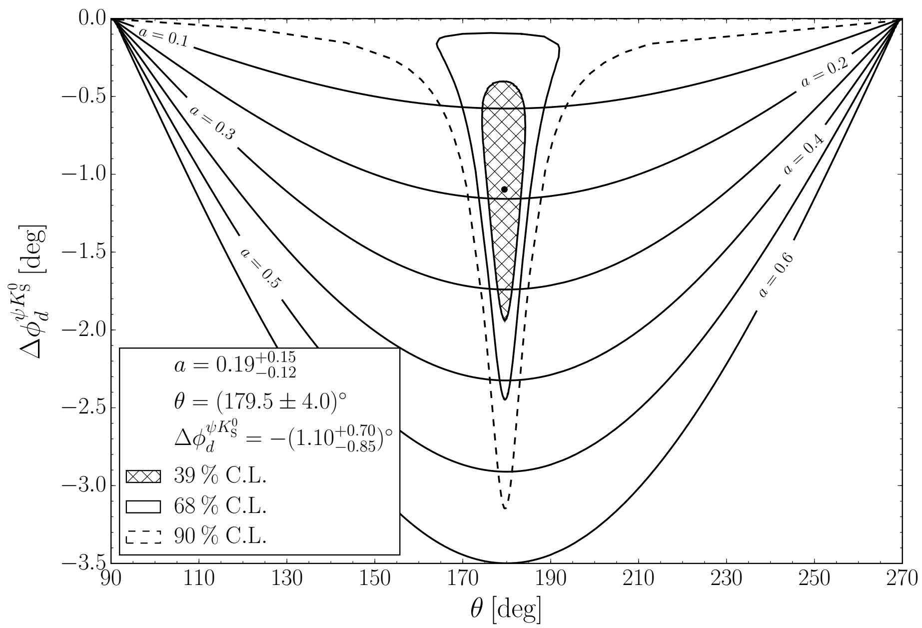
- The global fit yields $\chi^2_{\rm min} = 2.6$ for four degrees of freedom $(a, \theta, \phi_d, \gamma)$, indicating good agreement between the different input quantities:

$$a = 0.19^{+0.15}_{-0.12}\,, \qquad \theta = (179.5 \pm 4.0)^\circ\,, \qquad \boxed{\phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ}$$

- Illustration through intersecting contours for the different observables:



Constraints on $\Delta\phi_d^{\psi K_S^0}$

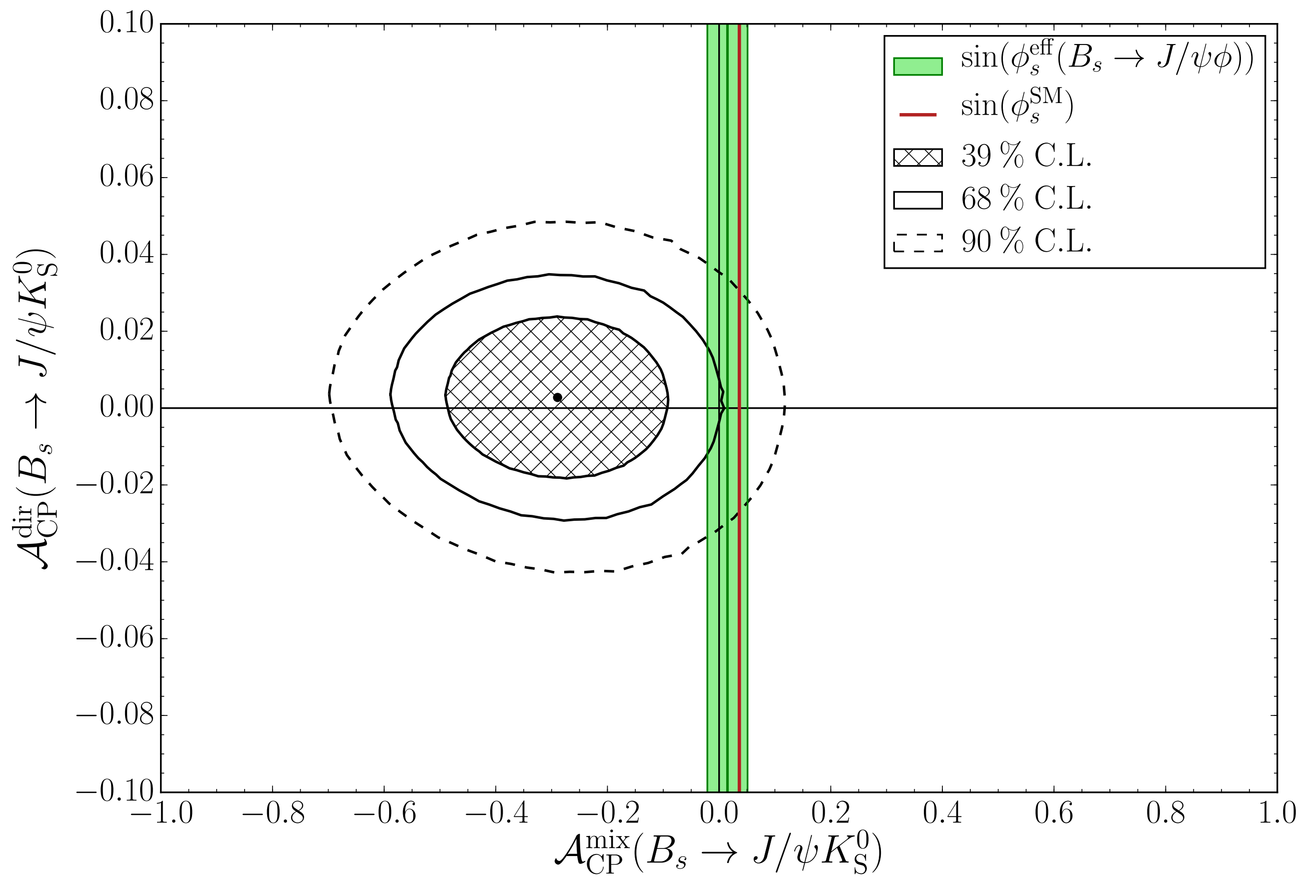


$$\Delta\phi_d^{\psi K_S^0} = -\left(1.10^{+0.70}_{-0.85}\right)^\circ$$

- χ^2 fit gives "guidance" for the importance of penguin effects.
- Go for CP violation in $B_s^0 \to J/\psi K_S$: $\to$ SM predictions:

$$\begin{aligned}
\mathcal{A}_{CP}^{dir}(B_s \to J/\psi K_S^0) &= 0.003 \pm 0.021 \\
\mathcal{A}_{CP}^{mix}(B_s \to J/\psi K_S^0) &= -0.29 \pm 0.20 \\
\mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_S^0) &= 0.957 \pm 0.061
\end{aligned}$$

- Confidence contours for the CP asymmetries of $B_s^0 \to J/\psi K_S^0$ in the Standard Model following from the global χ^2 fit:



⋆ Benchmark Scenario for the $B^0_{d,s} \to J/\psi K^0_{\rm S}$ Analysis:

→ points to the LHCb upgrade era:

- Assumes the following future measurements: [see also arXiv:1208.3355]
  - Clean γ determination from tree decays $B \to D^{(*)}K^{(*)}$: $\gamma = (70 \pm 1)^\circ$
  - ϕ_s measured from $B^0_s \to J/\psi\phi$ and penguin strategies (see below):

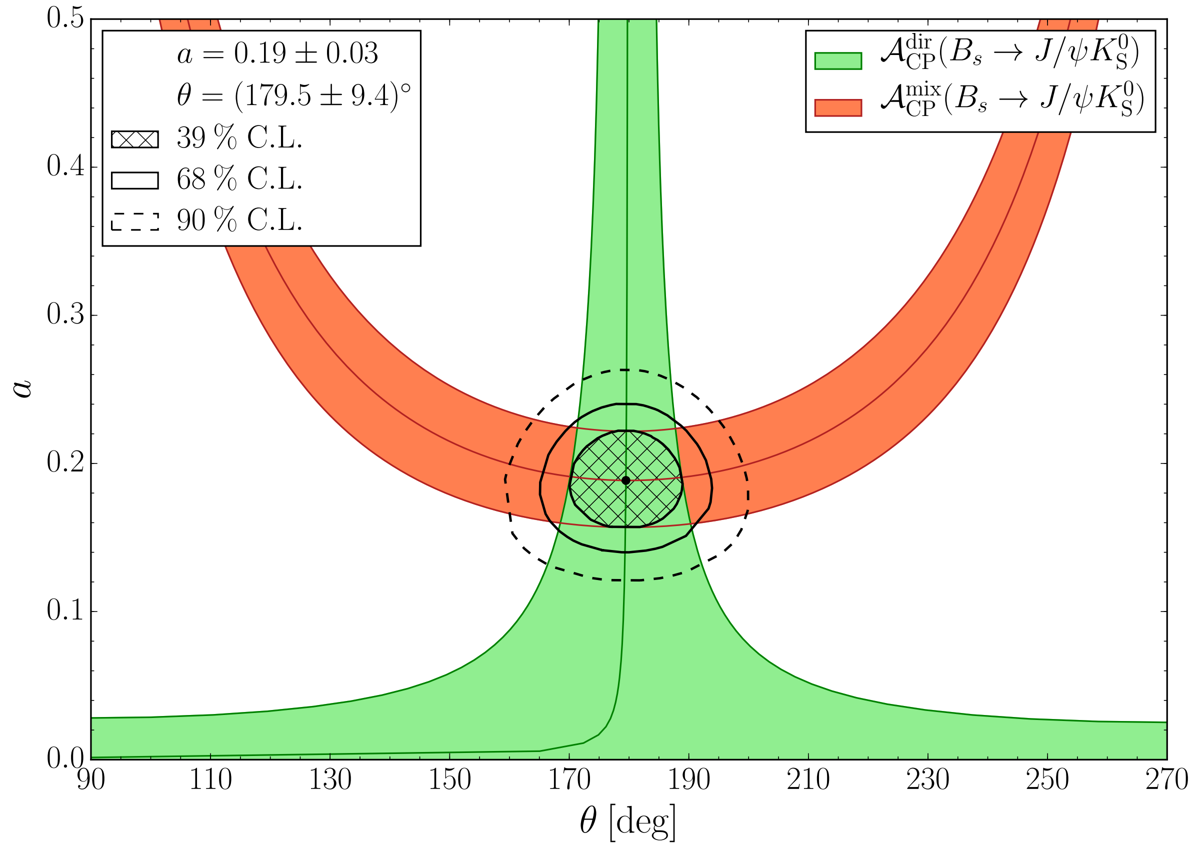
$$\phi_s = -\left(2.1 \pm 0.5|_{\rm exp} \pm 0.3|_{\rm theo}\right)^\circ = -(2.1 \pm 0.6)^\circ\,.$$

  - CP violation in the $B_s \to J/\psi K^0_{\rm S}$ decay:[1]

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi K^0_{\rm S}) &= 0.00 \pm 0.05 \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to J/\psi K^0_{\rm S}) &= -0.28 \pm 0.05 \end{aligned}$$

[1] These uncertainties were extrapolated from the current LHCb measurements of the CP violation in $B^0_s \to D_s^\mp K^\pm$ decays, corrected for the $B^0_s \to J/\psi K^0_{\rm S}$ event yield (no *official* LHCb study).

Determination of Penguin Parameters



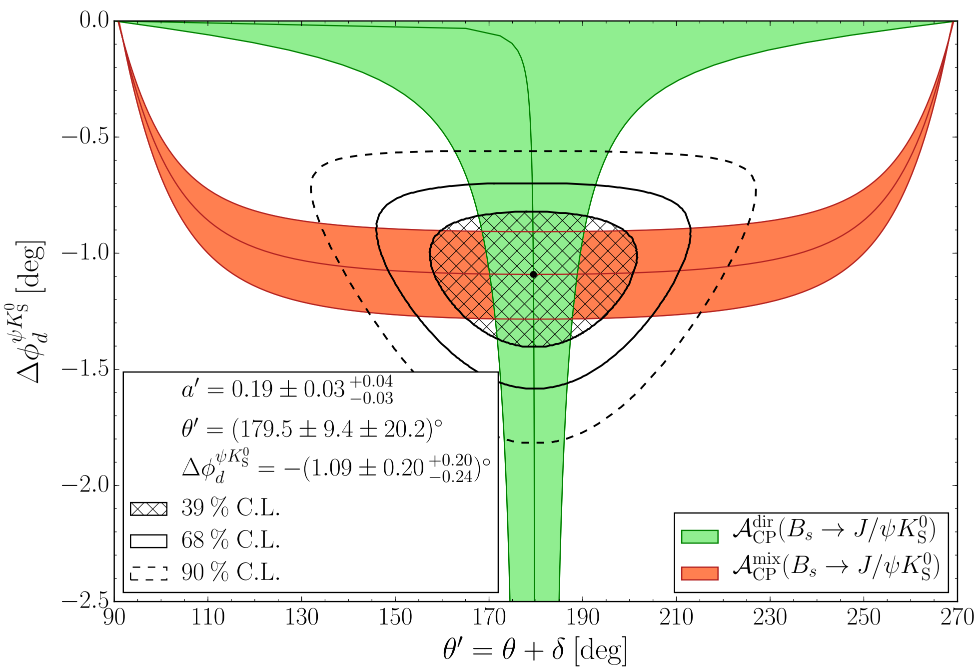
- <u>Comments:</u>
  - This determination of a and θ is *theoretically clean*.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\mathrm{S}}$) through U-spin symmetry.

... conversion into $\Delta\phi_d$

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

$$a' = \xi a \,, \qquad \theta' = \theta + \delta$$

$\to$ allow for U-spin breaking (non-fact.): $\xi = 1.00 \pm 0.20$, $\delta = (0 \pm 20)^\circ$:



$$\Delta\phi_d^{\psi K_S^0} = -\left[1.09 \pm 0.20\,(\text{stat})^{+0.20}_{-0.24}\,(\text{U spin})\right]^\circ = -\left[1.09 \pm 0.30\right]^\circ$$

Using Branching Ratio Information

It is important to emphasise that H is not required in this analysis ...

- Knowing (a,θ) ($\rightarrow$ clean!), H can rather be determined:

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

$$\Rightarrow \quad H_{(a,\theta)} = 1.172 \pm 0.037\,(a,\theta) \pm 0.0016\,(\xi,\delta)$$

- We may then determine the following amplitude ratio from the BRs:

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \sqrt{\epsilon\,H_{(a,\theta)}\frac{\mathrm{PhSp}\,(B_s\to J/\psi K^0_{\mathrm{S}})}{\mathrm{PhSp}\,(B_d\to J/\psi K^0_{\mathrm{S}})}\frac{\tau_{B_s}}{\tau_{B_d}}\frac{\mathcal{B}\,(B_d\to J/\psi K^0_{\mathrm{S}})_{\mathrm{theo}}}{\mathcal{B}\,(B_s\to J/\psi K^0_{\mathrm{S}})_{\mathrm{theo}}}}$$

- $\mathcal{B}(B_s\to f)$ measurements @ LHCb limited by $f_s/f_d = 0.259 \pm 0.015$:

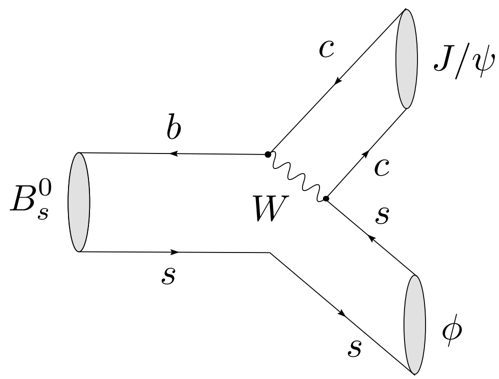
  $\rightarrow$ assuming no improvement of f_s/f_d, which is conservative $\Rightarrow$

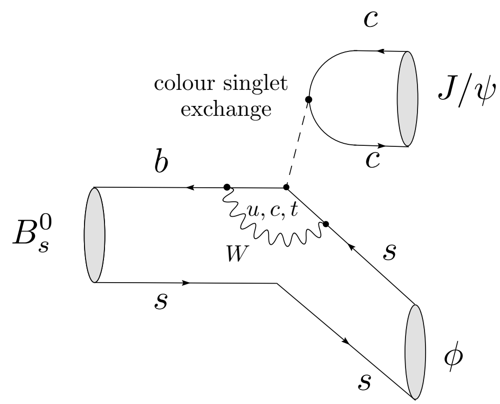
$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|_{\mathrm{exp}} = 1.160 \pm 0.035 \quad \text{vs} \quad \left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^{\mathrm{LCSR}}_{\mathrm{fact}} = 1.16 \pm 0.18 \quad (!)$$

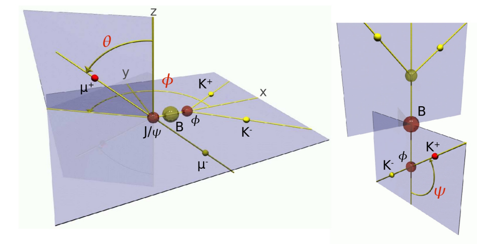
$B^0_{s,d} \to J/\psi V$ Decays:

- $B^0_s \to J/\psi\phi$: benchmark decay to extract ϕ_s
- $B^0_d \to J/\psi\rho^0$: penguin probe $\to$ CPV @ LHCb
- $B^0_s \to J/\psi\bar{K}^{*0}$: yet another penguin probe

The $B_s^0 \to J/\psi\phi$ Decay







- 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: $f \in \{0, \|, \perp\}$

$$A\left(B_s^0 \to (J/\psi\phi)_f\right) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}'_f\left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

  $\star$ CP-violating observables $\Rightarrow$ $\phi^{\rm eff}_{s,(\psi\phi)_f} = \phi_s + \Delta\phi_s^{(\psi\phi)_f}$

- 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)]

News on $B_s^0 \to J/\psi\phi$

- Penguin parameters:
  - (a'_f, θ'_f) are expected to differ for different final-state configurations f.
  - Simplified arguments along the lines of factorisation:

$$\Rightarrow a'_f \equiv a'_{\psi\phi}\,, \qquad \theta'_f \equiv \theta'_{\psi\phi} \qquad \forall f \in \{0, \|, \perp\}$$

$\to$ **interesting to test through data!** [R.F. (1999)]

- New LHCb results for $B_s \to J/\psi\phi$: [LHCb, arXiv:1411.3104]
  - First polarisation-dependent results for $\phi_{s,f}^{\rm eff}$: $\to$ *pioneering character:*

$$\begin{aligned}
\phi_{s,0}^{\rm eff} &= -0.045 \pm 0.053 \pm 0.007 &= -(2.58 \pm 3.04 \pm 0.40)^\circ \\
\phi_{s,\|}^{\rm eff} - \phi_{s,0}^{\rm eff} &= -0.018 \pm 0.043 \pm 0.009 &= -(1.03 \pm 2.46 \pm 0.52)^\circ \\
\phi_{s,\perp}^{\rm eff} - \phi_{s,0}^{\rm eff} &= -0.014 \pm 0.035 \pm 0.006 &= -(0.80 \pm 2.01 \pm 0.34)^\circ
\end{aligned}$$

  - Assuming a universal value of $\phi_s^{\rm eff}$:

$$\phi_s^{\rm eff} = \phi_s + \Delta\phi_s = -0.058 \pm 0.049 \pm 0.006 = -(3.32 \pm 2.81 \pm 0.34)^\circ$$

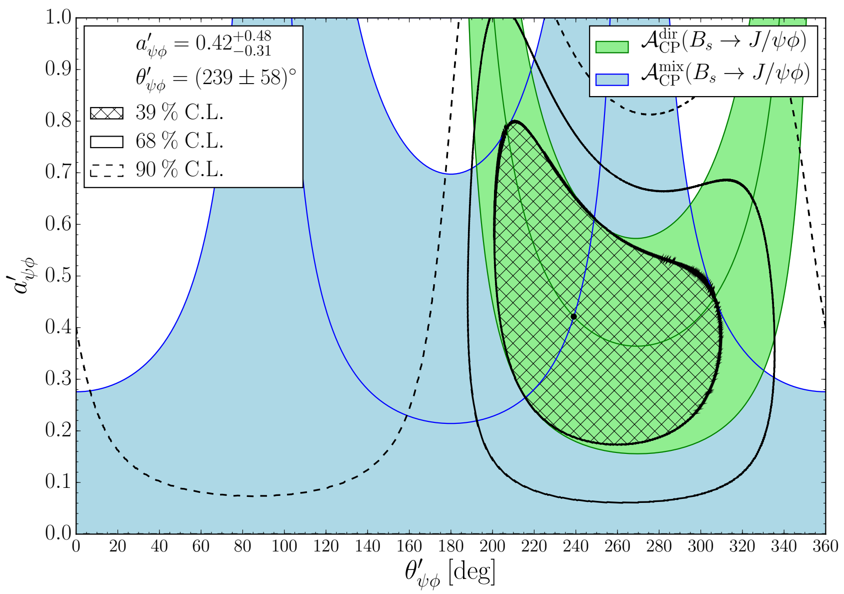
- Further polarisation-dependent LHCb results for $B_s^0 \to J/\psi\phi$:

$$|\lambda_f| \equiv \left|\frac{A(\bar{B}_s^0 \to (J/\psi\phi)_f}{A(B_s^0 \to (J/\psi\phi)_f}\right| = \left|\frac{1+\epsilon a'_f e^{i\theta'_f} e^{-i\gamma}}{1+\epsilon a'_f e^{i\theta'_f} e^{+i\gamma}}\right|$$

$$\begin{aligned} |\lambda^0| &= 1.012 \pm 0.058 \pm 0.013 \\ |\lambda^\perp/\lambda^0| &= 1.02 \pm 0.12 \pm 0.05 \\ |\lambda^\parallel/\lambda^0| &= 0.97 \pm 0.16 \pm 0.01 \end{aligned}$$

⋆ Assuming a universal $|\lambda^f| \equiv |\lambda_{\psi\phi}|$: $\Rightarrow$ $|\lambda_{\psi\phi}| = 0.964 \pm 0.019 \pm 0.007$

- Constraints in the $\theta'_{\psi\phi}$–$a'_{\psi\phi}$ plane following from the "universal" LHCb values of $\phi_s^{\rm eff}$ and $|\lambda_{\psi\phi}|$, assuming the SM value of ϕ_s:



⋆ Controlling the Penguin Effects in $B_s^0 \to J/\psi\phi$:

- Use the $SU(3)$ flavour symmetry.

- Neglect certain E and PA topologies:

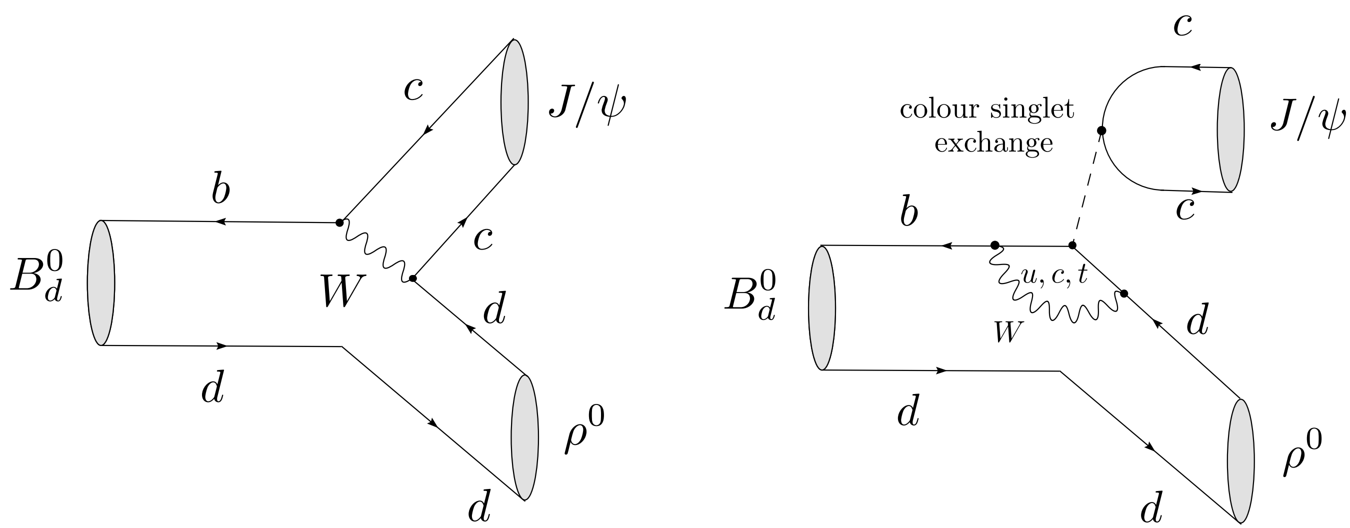
  – Probed through $B_d^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\rho^0$.

  – No evidence for enhancement in LHCb data:

$\to$ stronger bounds in the future

[R.F. (1999), Faller, R.F. & Mannel (2008), De Bruyn & R.F. (2014)]

The $B_d^0 \to J/\psi\rho^0$ Decay



- Decay amplitude:

$$\sqrt{2}\, A\left(B_d^0 \to (J/\psi\rho^0)_f\right) = -\lambda \mathcal{A}_f \left[1 - a_f e^{i\theta_f} e^{i\gamma}\right]$$

- CKM structure similar to $B_s^0 \to J/\psi K_{\rm S}$ and $B_d^0 \to J/\psi \pi^0$:

$\to$ "magnified penguin contributions"

  – Hardonic parameters in $B_{s,d}^0 \to J/\psi K_{\rm S}^0$ and $B_d^0 \to J/\psi\rho^0$ are generally expected to differ from one another.

- CP violation: $\to \phi_{d,f}^{\rm eff} \equiv 2\beta_f^{\rm eff}$ (in general polarisation dependent)

- First experimental results for CP violation in the $B_d^0 \to J/\psi\rho^0$ channel:

$\to$ *pioneering polarisation-dependent analysis:*

$$\begin{aligned} \phi_{d,0}^{\rm eff} &= +\left(44.1 \pm 10.2^{+3.0}_{-6.9}\right)^\circ \\ \phi_{d,\parallel}^{\rm eff} - \phi_{d,0}^{\rm eff} &= -\left(0.8 \pm 6.5^{+1.9}_{-1.3}\right)^\circ \\ \phi_{d,\perp}^{\rm eff} - \phi_{d,0}^{\rm eff} &= -\left(3.6 \pm 7.2^{+2.0}_{-1.4}\right)^\circ \end{aligned}$$

[L. Zhang and S. Stone, arXiv:1212.6434; LHCb, arXiv:1411.1634]

- Assuming *polarisation-independent* penguin parameters: $\Rightarrow$

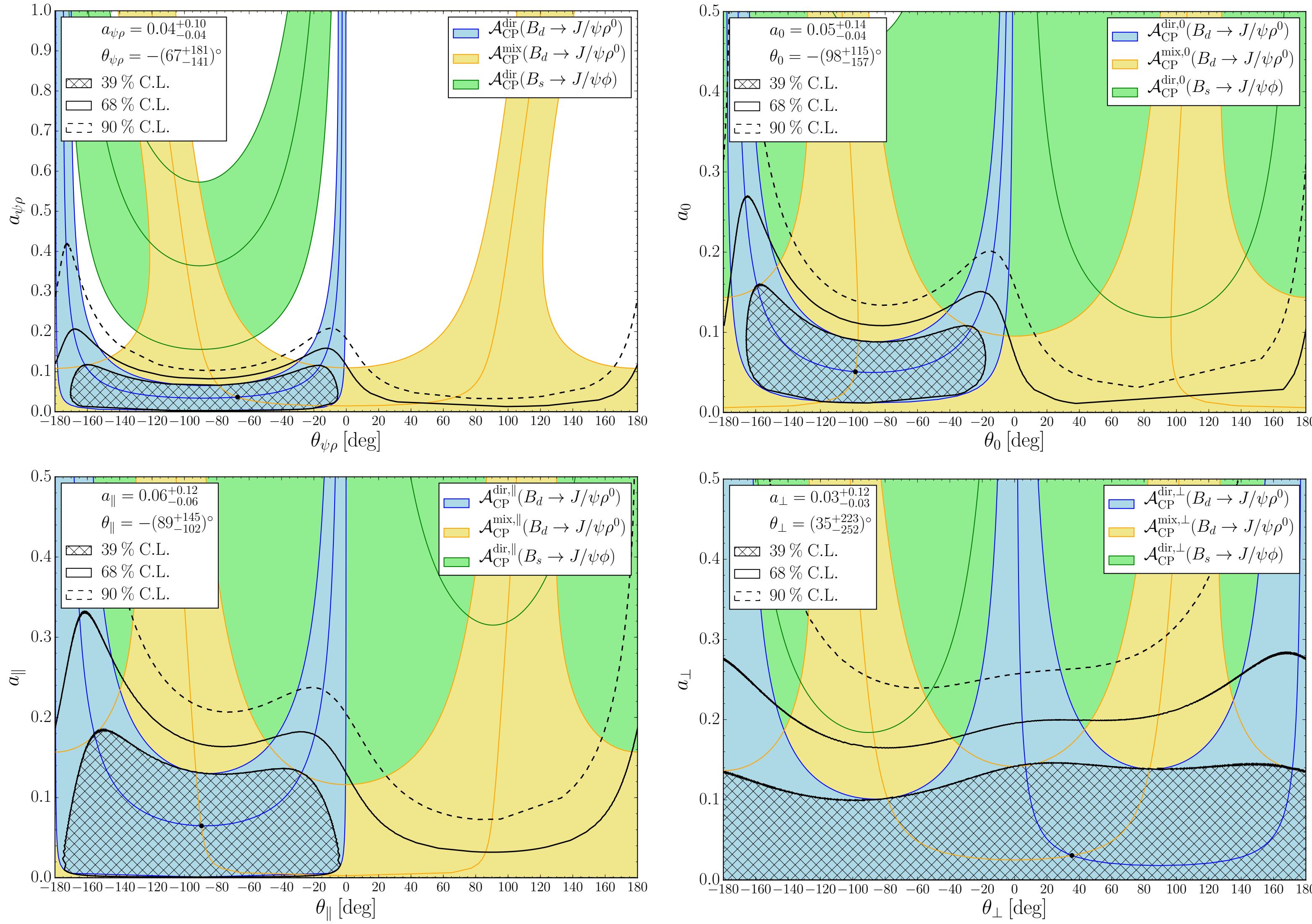
$$\phi_d^{\rm eff} = \left(41.7 \pm 9.6^{+2.8}_{-6.3}\right)^\circ$$

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\rho) \equiv C_{J/\psi\rho} &= -0.063 \pm 0.056^{+0.019}_{-0.014} \\ -\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\rho) \equiv S_{J/\psi\rho} &= -0.66^{+0.13+0.09}_{-0.12-0.03} \end{aligned}$$

- Using $\gamma = (70.0^{+7.7}_{-9.0})^\circ$ [CKMfitter] and $\phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ$ determined from our $B \to J/\psi P$ analysis (see above), a χ^2 fit to the data yields:

$$\boxed{a_{\psi\rho} = 0.037^{+0.097}_{-0.037}\,, \quad \theta_{\psi\rho} = -\left(67^{+181}_{-141}\right)^\circ\,, \quad \Delta\phi_d^{J/\psi\rho^0} = -\left(1.5^{+12}_{-10}\right)^\circ}$$

- Illustration of the determination of a_f and θ_f from the χ^2 fit through intersecting contours derived from the CP observables in $B_d^0 \to J/\psi\rho^0$:



[K. De Bruyn & R.F. (2014)]

⋆ *Further Implications of the $B_d^0 \to J/\psi\rho^0$ Analysis:*

- Conversion into the $B_s^0 \to J/\psi\phi$ penguin parameters:

$$a'_{\psi\phi} = \xi a_{\psi\rho} \quad \theta'_{\psi\phi} = \theta_{\psi\rho} + \delta \quad [\xi = 1.00 \pm 0.20,\ \delta = (0 \pm 20)^\circ]$$

$$\Rightarrow \quad \boxed{\Delta\phi_s^{\psi\phi} = \left[0.08^{+0.56}_{-0.72}\,(\text{stat})^{+0.15}_{-0.13}\,(\text{SU(3)})\right]^\circ} \quad (!)$$

... to be compared with $\phi_s^{\text{eff}} = \phi_s + \Delta\phi_s^{\psi\phi} = -(3.32 \pm 2.81 \pm 0.34)^\circ$.

- Extraction of hadronic amplitude ratios: [$\to B_{s,d}^0 \to J/\psi K_{\rm S}$ discussion]

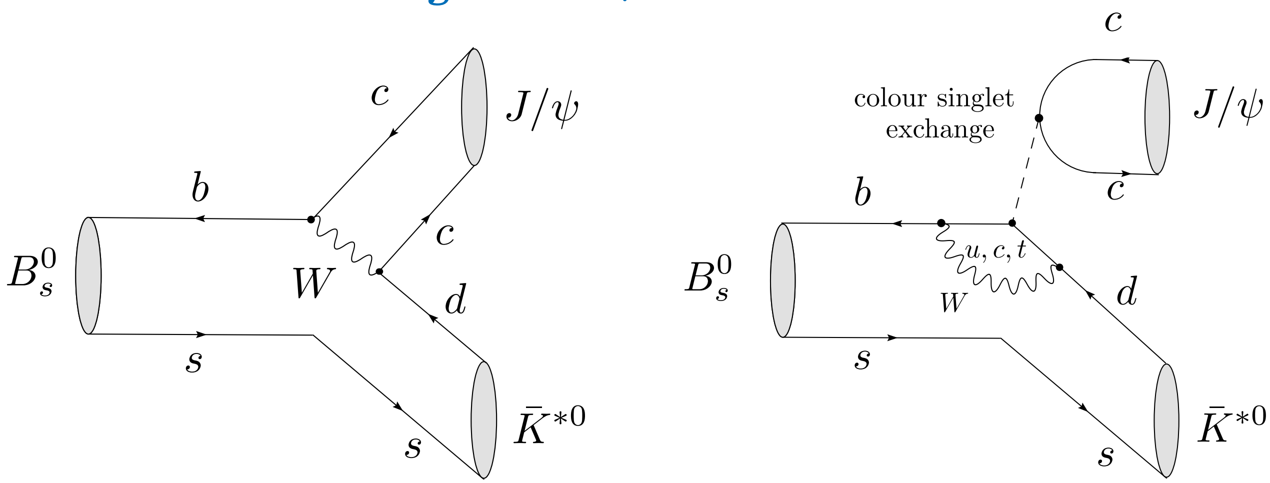
$$\left|\frac{\mathcal{A}'_0(B_s \to J/\psi\phi)}{\mathcal{A}_0(B_d \to J/\psi\rho^0)}\right| = 1.06 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{a}_0, \theta_0) \stackrel{\text{fact}}{=} 1.43 \pm 0.42$$

$$\left|\frac{\mathcal{A}'_{||}(B_s \to J/\psi\phi)}{\mathcal{A}_{||}(B_d \to J/\psi\rho^0)}\right| = 1.08 \pm 0.08\,(\text{stat}) \pm 0.05\,(\text{a}_{||}, \theta_{||}) \stackrel{\text{fact}}{=} 1.37 \pm 0.20$$

$$\left|\frac{\mathcal{A}'_{\perp}(B_s \to J/\psi\phi)}{\mathcal{A}_{\perp}(B_d \to J/\psi\rho^0)}\right| = 1.24 \pm 0.15\,(\text{stat}) \pm 0.06\,(\text{a}_{\perp}, \theta_{\perp}) \stackrel{\text{fact}}{=} 1.25 \pm 0.15$$

[Naive "fact" refers to LCSR form factors [Ball & Zwicky ('05)];
recent PQCD calculation: X. Liu, W. Wang and Y. Xie (2014)]

The $B_s^0 \to J/\psi \overline{K}^{*0}$ Decay



- Decay amplitude: $A(B_d^0 \to (J/\psi \overline{K}^{*0})_f) = -\lambda \tilde{\mathcal{A}}_f \left[1 - \tilde{a}_f e^{i\tilde{\theta}_f} e^{i\gamma}\right]$

- $SU(3)$ and neglect of PA and E topologies:

$$\tilde{a}_f e^{i\tilde{\theta}_f} = a_f e^{i\theta_f} \,, \qquad \tilde{\mathcal{A}}_f = \mathcal{A}_f \,.$$

- Important *difference/disadvantage* with respect to $B_d^0 \to J/\psi \rho^0$:

$$\to \textit{no mixing-induced CP violation} \Rightarrow$$

  – Untagged rate measurement $\oplus$ direct CP violation.
  – Angular analysis is required to disentangle final states $f \in \{0, \parallel, \perp\}$

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

- In more detail: *untagged rate measurement* $\rightarrow$

$$\tilde{H}_f \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'_f}{\tilde{\mathcal{A}}_f}\right|^2 \frac{\mathrm{PhSp}\,(B_s \to J/\psi\phi)}{\mathrm{PhSp}(B_s \to J/\psi \overline{K}^{*0})} \frac{\mathcal{B}(B_s \to J/\psi \overline{K}^{*0})_{\mathrm{theo}}}{\mathcal{B}(B_s \to J/\psi\phi)_{\mathrm{theo}}} \frac{\tilde{f}^{\mathrm{exp}}_{\mathrm{VV},f}}{f^{\mathrm{exp}}_{\mathrm{VV},f}}$$

$$f^{\mathrm{exp}}_{\mathrm{VV},f} \equiv \frac{\mathcal{B}(B_s \to (f)_f)_{\mathrm{exp}}}{\sum_f \mathcal{B}(B_s \to (f)_f)_{\mathrm{exp}}}$$

$\tilde{H}_f$ requires $|\mathcal{A}'_f/\tilde{\mathcal{A}}_f| \rightarrow$ hadronic uncertainties...

[Experimental analysis: CDF (2011); LHCb, arXiv:1208.0738]

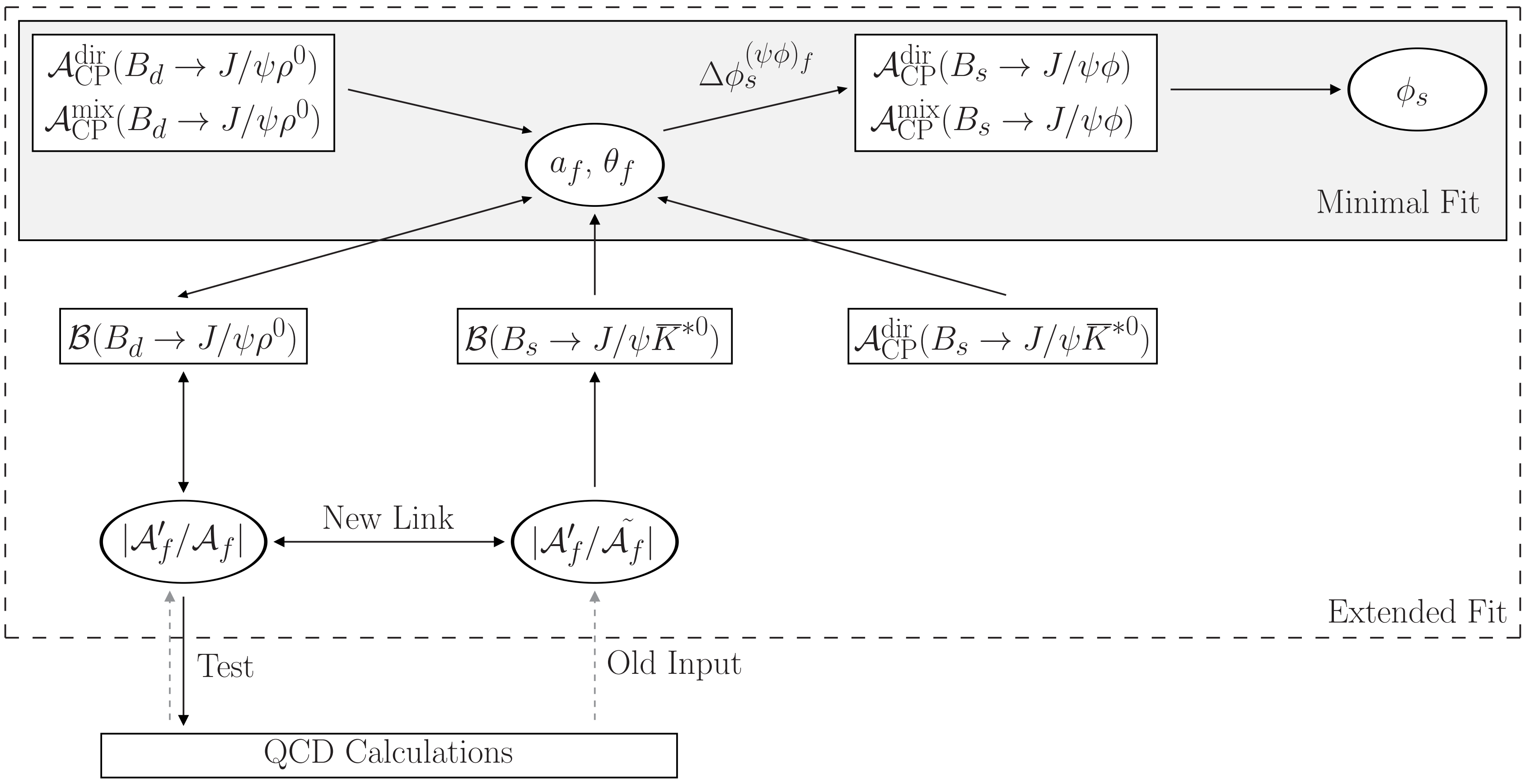
- Important next step: *CP violation measurements* $\rightarrow$
  - We expect them to approximately equal those of $B^0_d \to J/\psi\rho^0$:

$$\begin{aligned}
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s \to J/\psi \overline{K}^{*0})_0 &= -0.094 \pm 0.071 \\
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s \to J/\psi \overline{K}^{*0})_\parallel &= -0.12 \pm 0.12 \\
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s \to J/\psi \overline{K}^{*0})_\perp &= 0.03 \pm 0.22
\end{aligned}$$

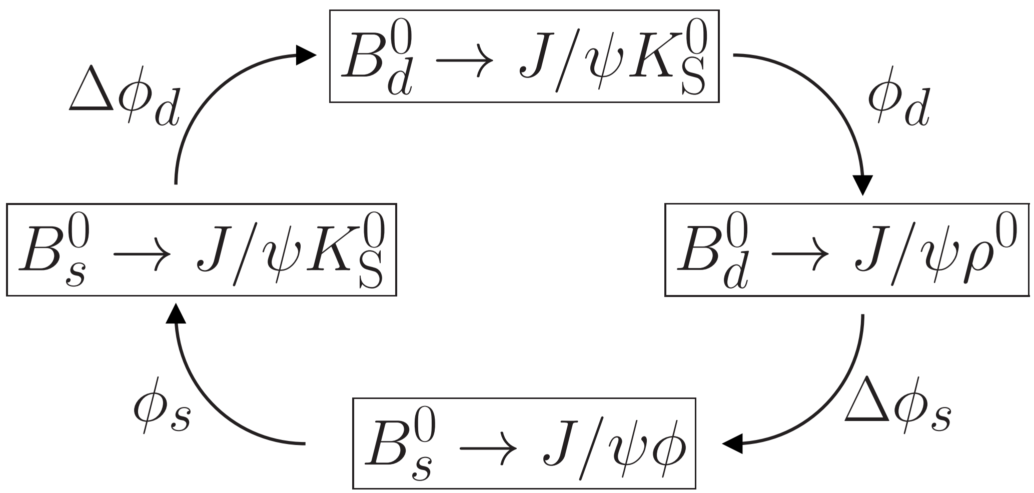
  - Look forward to compare with future LHCb measurements ...

A Penguin Roadmap

- Flow chart of the combined $B_d^0 \to J/\psi\rho^0$, $B_s^0 \to J/\psi\overline{K}^{*0}$, $B_s^0 \to J/\psi\phi$ analysis to simultaneously determine the penguin parameters, the $SU(3)$-breaking ratio of strong amplitudes, and the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s:



- Interplay between the decays to measure the B_q^0–$\bar{B}_q^0$ mixing phases and the channels needed to control the corresponding penguin contributions:



- Illustration of the correlation between ϕ_s and ϕ_d for non-$\overline{\text{MFV}}$ models:

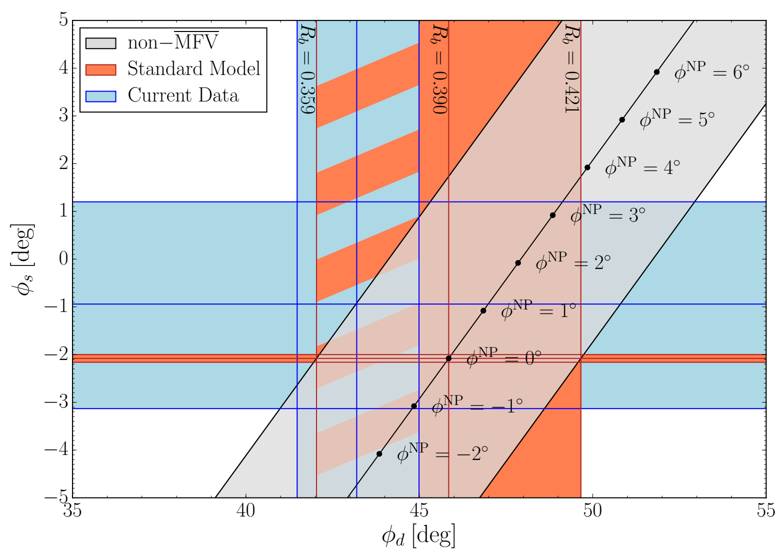
  – Non-MFV models with flavour-universal CP-violating NP phases:

$$\phi_s^{\rm NP} = \phi_d^{\rm NP} \equiv \phi^{\rm NP} \quad \Rightarrow \quad \phi_s = \phi_d + \left(\phi_s^{\rm SM} - \phi_d^{\rm SM}\right)$$

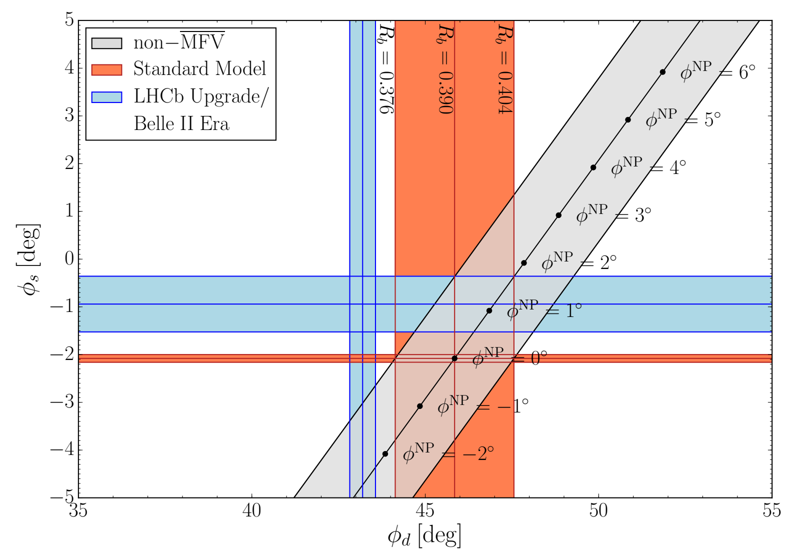
[Ball & R.F. (2006); Buras & Guadagnoli (2008); Buras & Girrbach (2014)]

  – Current situation and extrapolation to the LHCb upgrade era:

$$\sin 2\beta = \frac{2R_b \sin\gamma(1 - R_b\cos\gamma)}{(R_b\sin\gamma)^2 + (1 - R_b\cos\gamma)^2} \Rightarrow R_b \text{ key limitation for } \phi_d^{\rm SM} = 2\beta\text{:}$$



[current situation]



[LHCb upgrade era]

Conclusions

- Moving towards new frontiers in precision of CP violation measurements:

$\Rightarrow$ match experimental with theoretical precisions

- $B^0_{s,d} \to J/\psi P$: $B^0_d \to J/\psi K_{\rm S} \oplus B^0_s \to J/\psi K_{\rm S}$, ...
  - χ^2 fit to current data: $\phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ$, $\Delta\phi_d^{\psi K^0_{\rm S}} = -\left(1.10^{+0.70}_{-0.85}\right)^\circ$
  - Promising prospects for $B^0_s \to J/\psi K_{\rm S}$ at the LHCb upgrade.

- $B^0_{s,d} \to J/\psi V$: $B^0_s \to J/\psi \phi \oplus B^0_d \to J/\psi \rho^0$, $B^0_s \to J/\psi \bar{K}^{*0}$
  - Pioneering polarisation-dependent measurements by LHCb.
  - CPV in $B^0_d \to J/\psi \rho^0$ very powerful penguin probe:

    $a_{\psi\rho} = 0.037^{+0.097}_{-0.037}$, $\Delta\phi_s^{\psi\phi} = \left[0.08^{+0.56}_{-0.72}\,(\text{stat})^{+0.15}_{-0.13}\,(\text{SU}(3))\right]^\circ$
  - New method for combined analysis, using also $B^0_s \to J/\psi \overline{K}^{*0}$.

$\to$ stay tuned ...