Towards New Frontiers in CP Violation in B Decays

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- Setting the Stage
- Focus on two topics:
  - Precision measurements of the B_q^0–$\bar{B}_q^0$ mixing phases
  - CP violation in $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$
- Outlook

Setting the Stage

$\diamond$ *Other theory talks related to CP-B:*

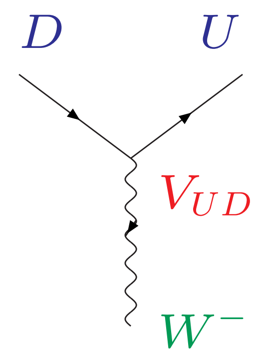
- Hadronic B decays: $\rightarrow$ Guido Bell
- Theory of B mixing: $\rightarrow$ Christoph Bobeth

[Recent detailed overview: G. Borissov, R.F. and M.-H. Schune
Ann. Rev. Nucl. Part. Sci. **63** (2013) 205 [arXiv:1303.5575 [hep-ph]]]

The Quark-Flavour Code

- Quark flavour physics and CP violation in the Standard Model (SM):

$$\text{flavour eigen-states}\left.\right\}\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}\left\{\right.\text{mass eigen-states}$$



quark-mixing matrix, also known as the

Cabibbo–Kobayashi–Maskawa (CKM) matrix

$\rightarrow$ *unitary* matrix; *complex* phase $\rightarrow$ CP violation

$\Rightarrow$ *encoded in weak decays of K, D and B mesons*

- The *key problem:* strong interactions $\rightarrow$ "hadronic" uncertainties
  - The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. B, D and K mesons.
  - In the calculations of the relevant transition amplitudes, we encounter process-dependent, *non-perturbative "hadronic" parameters!?*

- New Physics (NP): typically new sources for flavour and CP violation.

Hierarchy of Scales

$$\underbrace{\Lambda_{\rm NP} \sim 10^{(0\ldots?)}\,\text{TeV} \gg \Lambda_{\rm EW} \sim 10^{-1}\,\text{TeV}}_{\text{(very) short distances}} \ggg \underbrace{\Lambda_{\rm QCD} \sim 10^{-4}\,\text{TeV}}_{\text{long distances}}$$

- Powerful theoretical concepts/techniques:

$\rightarrow$ "Effective Field Theories"

  - Heavy degrees of freedom (NP particles, top, Z, W) are "integrated out" from appearing explicitly: $\rightarrow$ *short-distance loop functions.*
  - Calculation of *perturbative QCD corrections*.
  - *Renormalization group* allows the summation of large $\log(\mu_{\rm SD}/\mu_{\rm LD})$.

- Applied to the SM and various NP scenarios, such as the following:
  - MSSM, UED, WED, LH, LHT, Z' models, ...

[Huge literature... $\rightarrow$ recent review: Buras & Girrbach, arXiv:1306.3775 [hep-ph]]

Theoretical Tool: Low-Energy Effective Hamiltonians

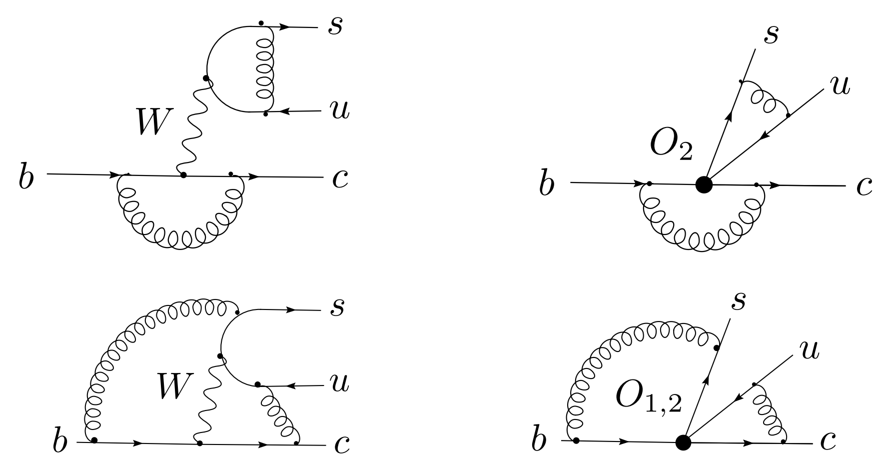
- Separation of short-distance from long-distance contributions (OPE):

$$\langle \overline{f}|\mathcal{H}_{\rm eff}|\overline{B}\rangle = \frac{G_{\rm F}}{\sqrt{2}} \sum_j \lambda^j_{\rm CKM} \sum_k C_k(\mu)\, \langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; Martinelli *et al.* ('90s); ...]

  $\to$ Wilson coefficients $C_k(\mu)$ $\to$ *perturbative* quantities $\to$ known!

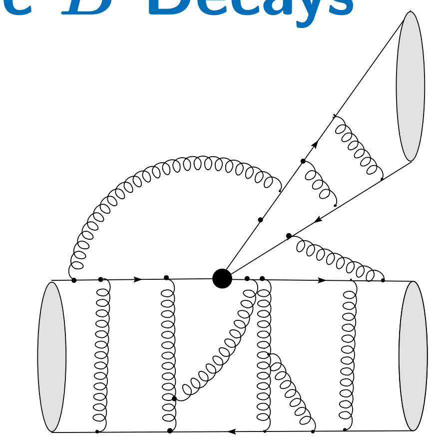


- Long-distance physics:

  $\to$ matrix elements $\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$ $\to$ *non-perturbative* $\to$ "unknown"!?

[Lattice QCD: impressive recent progress, but still challenging for non-leptonic B decays]

Key Player for CP Violation: Non-Leptonic B Decays



$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$

- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (1999–2001); Beneke & Jäger (2005); ...

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

Data $\Rightarrow$ *theoretical challenge remains ...*

[Detailed discussion: $\rightarrow$ talk by Guido Bell]

Circumvent the $\langle \overline{f} | Q_k^j(\mu) | \overline{B} \rangle$ in CP-B Studies:

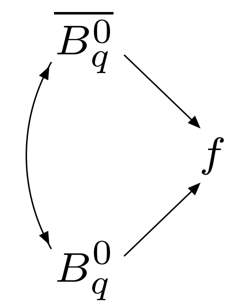
- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\rightarrow$ typically strategies to determine the UT angle γ):

  – *Exact* relations: class of pure "tree" decays (e.g. $B \to DK$).

  – *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_{\mathrm{F}}$:

$$B \to \pi\pi,\ B \to \pi K,\ B_{(s)} \to KK.$$

- Decays of neutral B_d or B_s mesons:



Interference effects through B^0_q–$\overline{B^0_q}$ mixing:

  – Lead to "mixing-induced" CP violation $S(f)$, in addition to "direct" CP violation $C(f)$ (caused by interference between decay amplitudes).

  – If one CKM amplitude dominates:

$$\Rightarrow \ \textit{hadronic matrix elements cancel in } S(f), \textit{ while } C(f) = 0$$

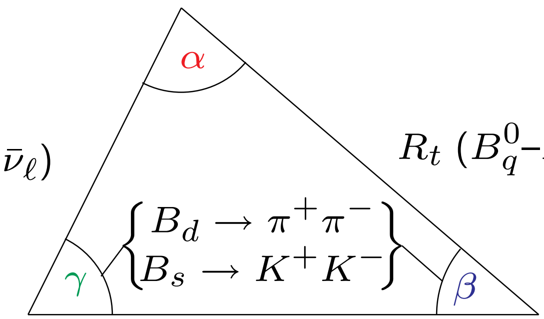
  ∗ Example: $B^0_d \to J/\psi\, K_{\mathrm{S}} \ \Rightarrow\ S(J/\psi K_{\mathrm{S}}) = \sin 2\beta + \mathcal{O}(\lambda^2)$

A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$

$R_b\ (b \to u, c\ell\bar{\nu}_\ell)$



R_t (B_q^0–$\bar{B}_q^0$ mixing)

$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{matrix} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{matrix}\right\} \text{only trees}$$

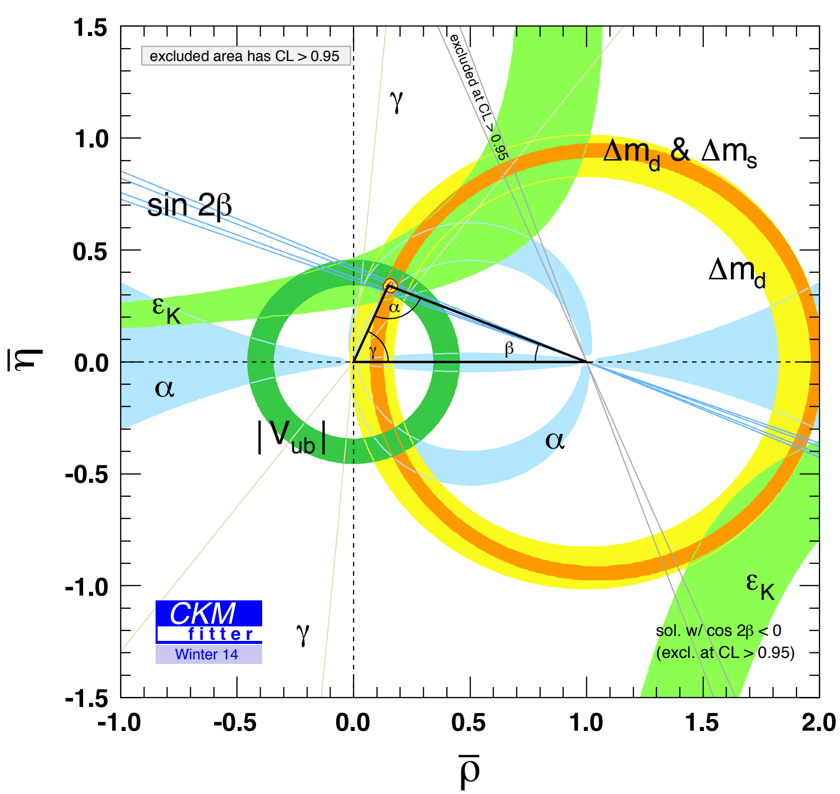
$$\left.\begin{matrix} B_d \to D^{(*)\pm}\pi^\mp : \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \gamma + \phi_s \end{matrix}\right\} \text{only trees}$$

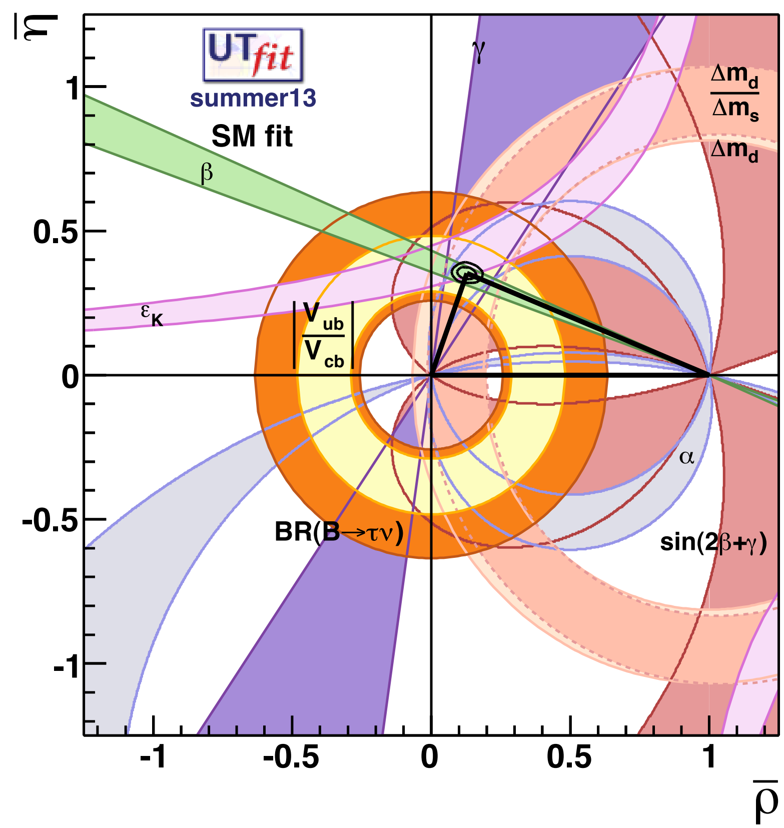
- Moreover "rare" decays: $B \to X_s\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

New Physics (NP) $\Rightarrow$ Discrepancies

Status of the Unitarity Triangle

- Detailed studies and continuous updates:
  - CKMfitter Collaboration [http://ckmfitter.in2p3.fr/];
  - UTfit Collaboration [http://www.utfit.org/UTfit/WebHome]:





Where Do We Stand?

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

- 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

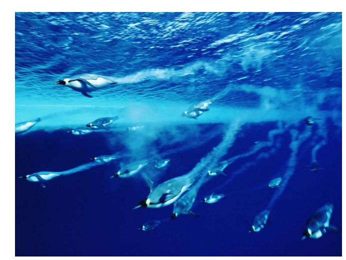
  - Match the experimental and theoretical precisions.

- Benchmark B-meson decays for exploring CP violation:

$$B_d \rightarrow J/\psi K_S,\ B_s \rightarrow J/\psi \phi,\ B_s \rightarrow J/\psi f_0(980)$$

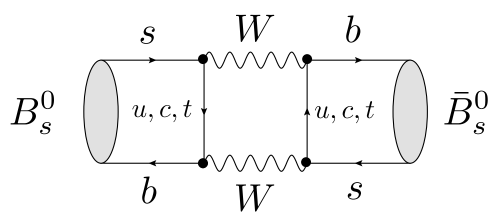
  - Allow measurements of the $B^0_{d,s}$–$\bar{B}^0_{d,s}$ mixing phases $\phi_{d,s}$.
  - Uncertainties from doubly Cabibbo-suppressed *penguin* contributions.
  - These effects are usually neglected; we cannot reliably calculate them...

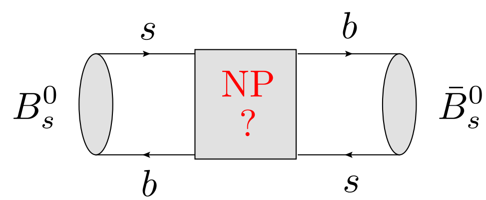
$\Rightarrow$ How big are they & how can they be controlled?



"Penguin Hunting"

Precision Measurements of the B_q^0–$\bar{B}_q^0$ Mixing Phases



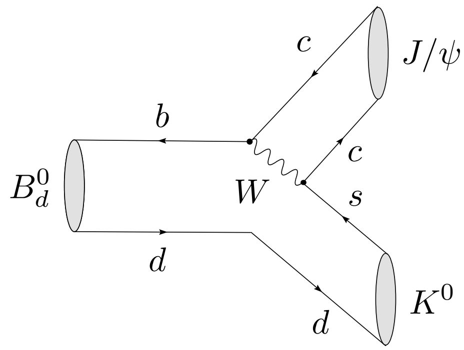


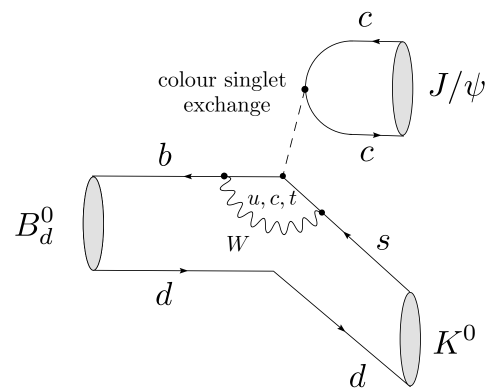
$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}$$

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

[Detailed discussion of B mixing: $\rightarrow$ talk by Christoph Bobeth]

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





- Decay amplitude in the SM:

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

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

$$\Rightarrow \boxed{A(B_d^0 \to J/\psi\, K_{\rm S}) = \left(1 - \lambda^2/2\right) \mathcal{A}' \left[1 + \epsilon\, a' e^{i\theta'} e^{i\gamma}\right]} \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \sim 0.05$$

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

$$\lambda \equiv |V_{us}| \sim 0.22, \;\; A \equiv \frac{|V_{cb}|}{\lambda^2} \sim 0.8, \;\; R_b \equiv \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left|\frac{V_{ub}}{V_{cb}}\right| \sim 0.5$$

- Time-dependent CP asymmetry: $\to$ requires "tagging":

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

- CP-violating observables:

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

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

$$\sin\Delta\phi_d = \frac{2\epsilon a'\cos\theta'\sin\gamma+\epsilon^2a'^2\sin2\gamma}{(1+2\epsilon a'\cos\theta'\cos\gamma+\epsilon^2a'^2)\sqrt{1-C(B_d\to J/\psi K_{\rm S})^2}}$$

$$\cos\Delta\phi_d = \frac{1+2\epsilon a'\cos\theta\cos\gamma+\epsilon^2a'^2\cos2\gamma}{(1+2\epsilon a'\cos\theta'\cos\gamma+\epsilon^2a'^2)\sqrt{1-C(B_d\to J/\psi K_{\rm S})^2}}$$

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

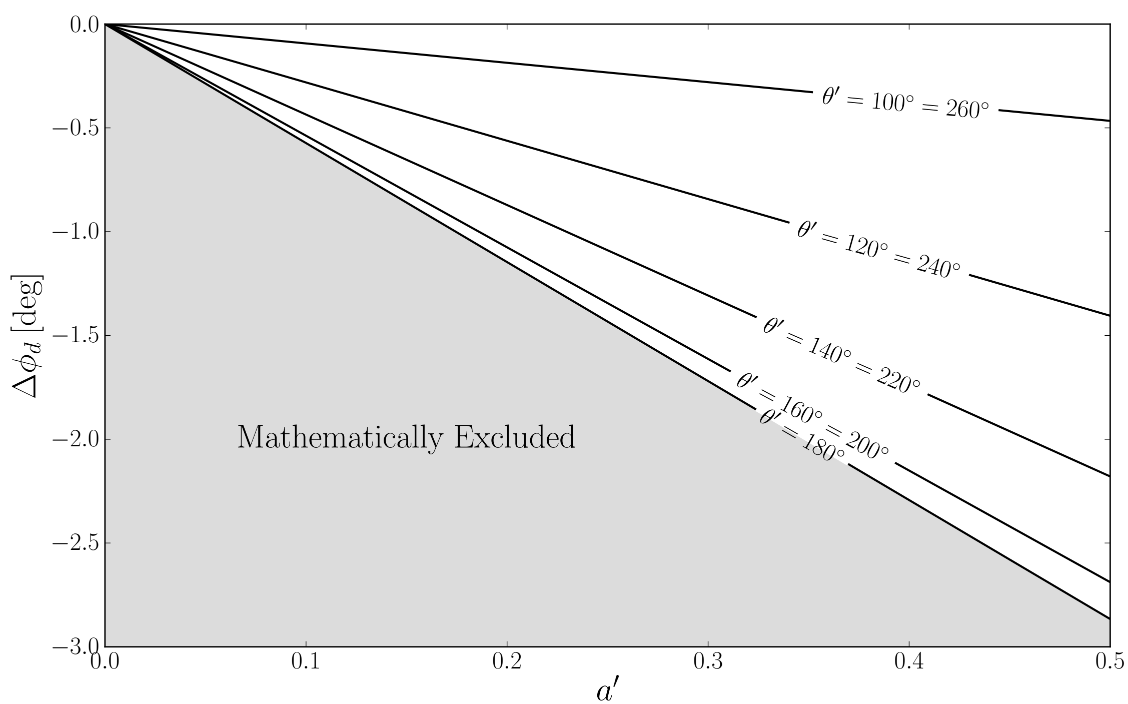
- Experimental status: [Heavy Flavour Averaging Group (HFAG)]

$$S(B_d \to J/\psi K_{\rm S}) = 0.665 \pm 0.024$$

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

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

- 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 $\Delta\phi_d$?

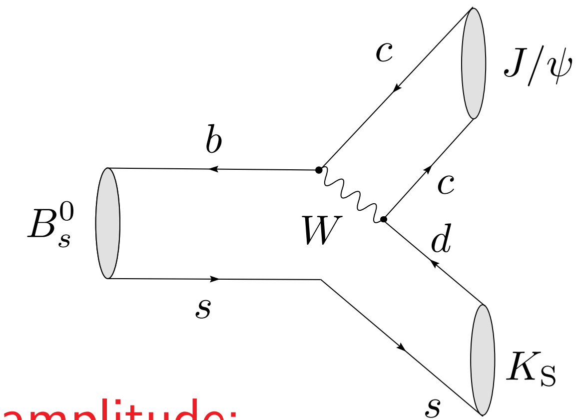
$$\tan\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}$$

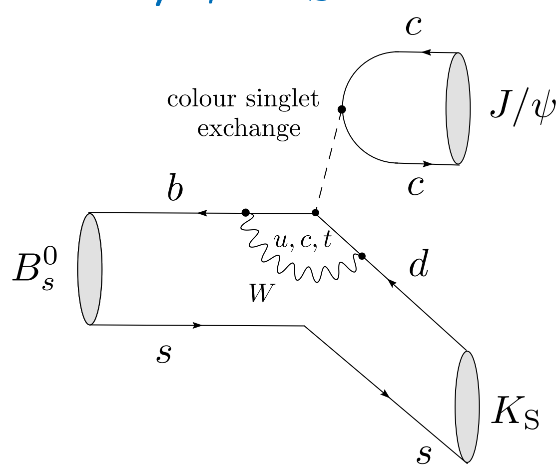
$\rightarrow$ hadronic parameters a', θ' cannot be calculated:

$\Rightarrow$ use control channel(s): $B_s^0 \to J/\psi K_{\rm S}$, ...

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

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





- Decay amplitude:

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

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

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

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

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

$\Rightarrow$ penguin effects are "magnified"!

- Useful quantity: $[\Phi^{s,d}_{J/\psi K_{\rm S}}$: straightforward phase-space factors$]$

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

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

[Subtleties of BR(B_s): De Bruyn, R.F., Knegjens, Koppenburg, Merk & Tuning ('12)]

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

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

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

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

  – 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: [$\rightarrow$ subgroup of $SU(3)_{\rm F}$ relating d and s quarks]

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

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

- Observables:

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

$\Rightarrow$ **γ, a and θ can be extracted from the 3 observables**

- 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

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

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:

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

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 $B_s \to J/\psi K_S$.

[R.F. (1999)]

How big are the penguin effects?

- $B_s^0 \to J/\psi K_S$ has been observed by CDF and LHCb, but not yet CPV.

- Use data for decays with a CKM structure similar to $B_s^0 \to J/\psi K_S$:

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

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

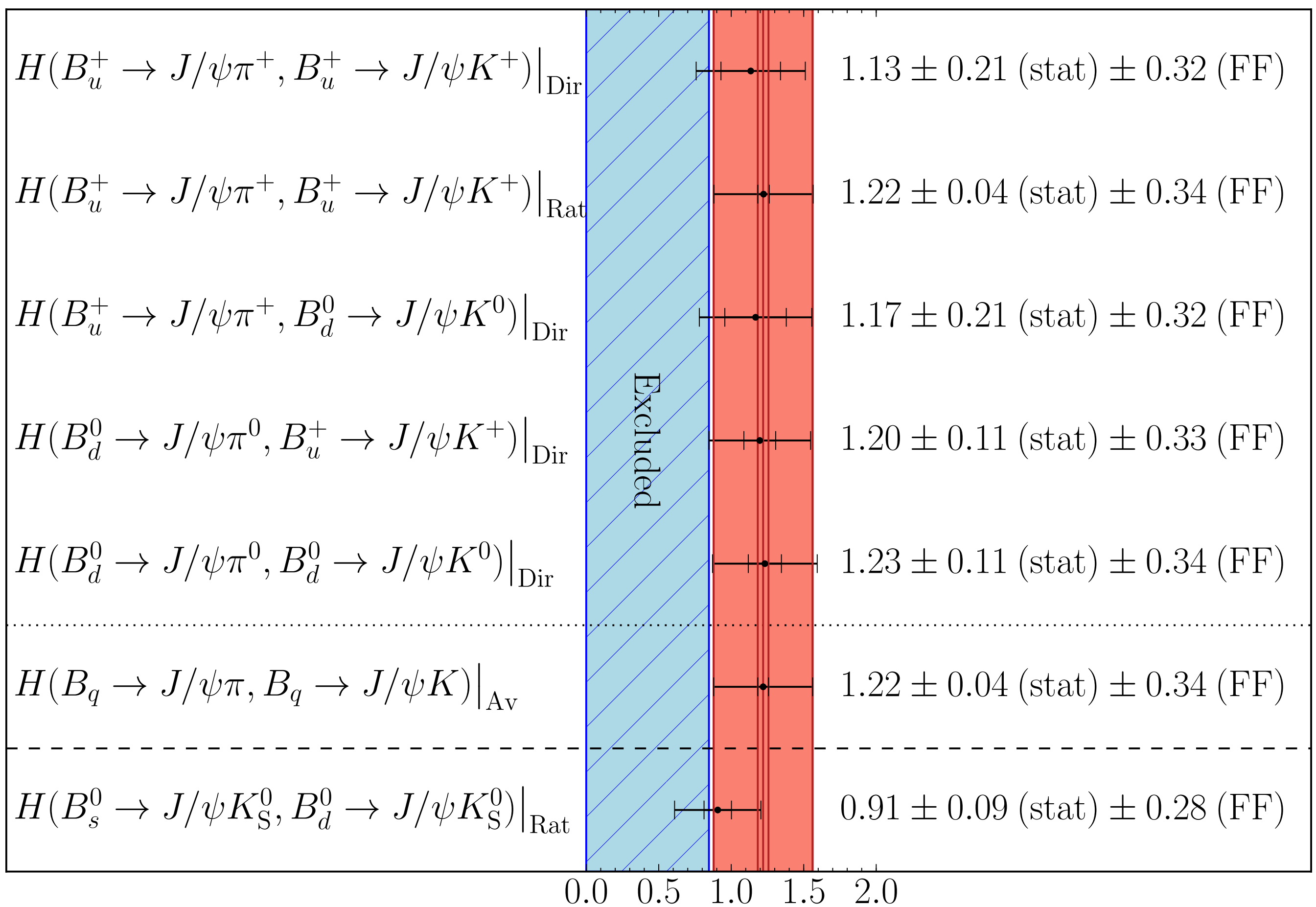
$\Rightarrow$ work in progress with Kristof De Bruyn $\to$ preliminary results:

[See also Ciuchini, Pierini & Silvestrini ('05); Faller, R.F., Jung & Mannel ('08); Jung ('12)]

Compilation of H Observables

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

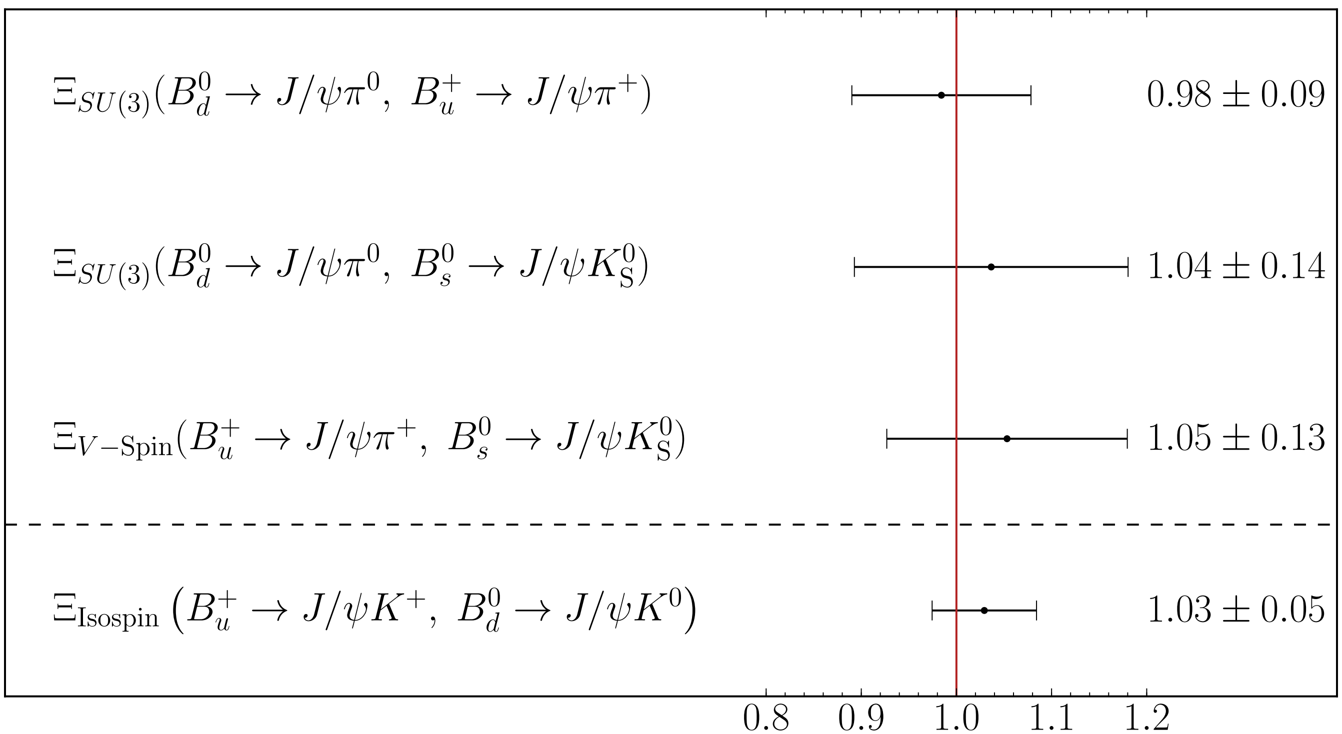
$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\Phi^d_{J/\psi K_S}}{\tau_{B_s}\Phi^s_{J/\psi K_S}}\right] \frac{\mathrm{BR}\,(B_s \to J/\psi K_S)}{\mathrm{BR}(B_d \to J/\psi K_S)}$$



$SU(3)$ Tests

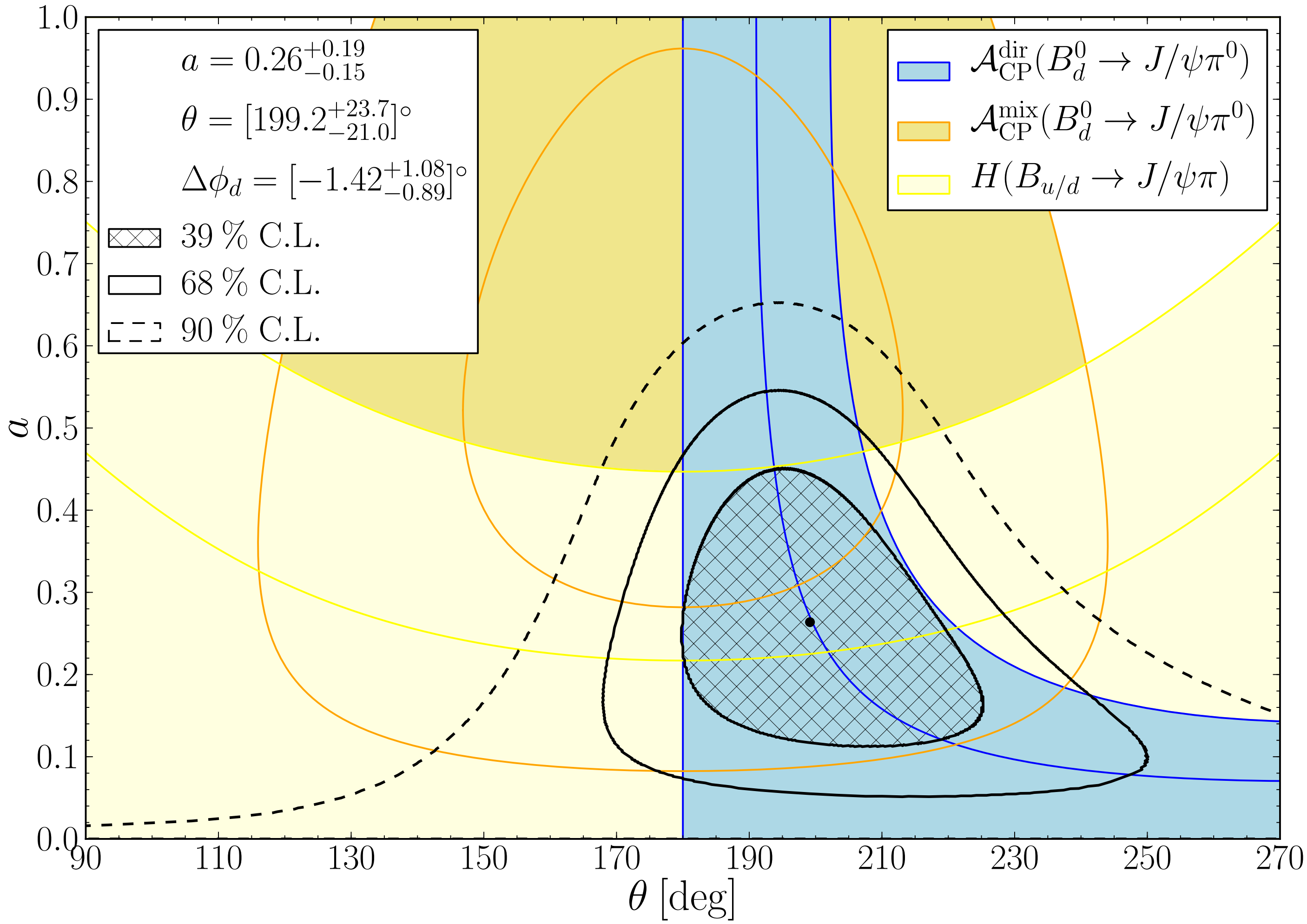
- Neglecting penguin annihilation & exchange topologies:

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



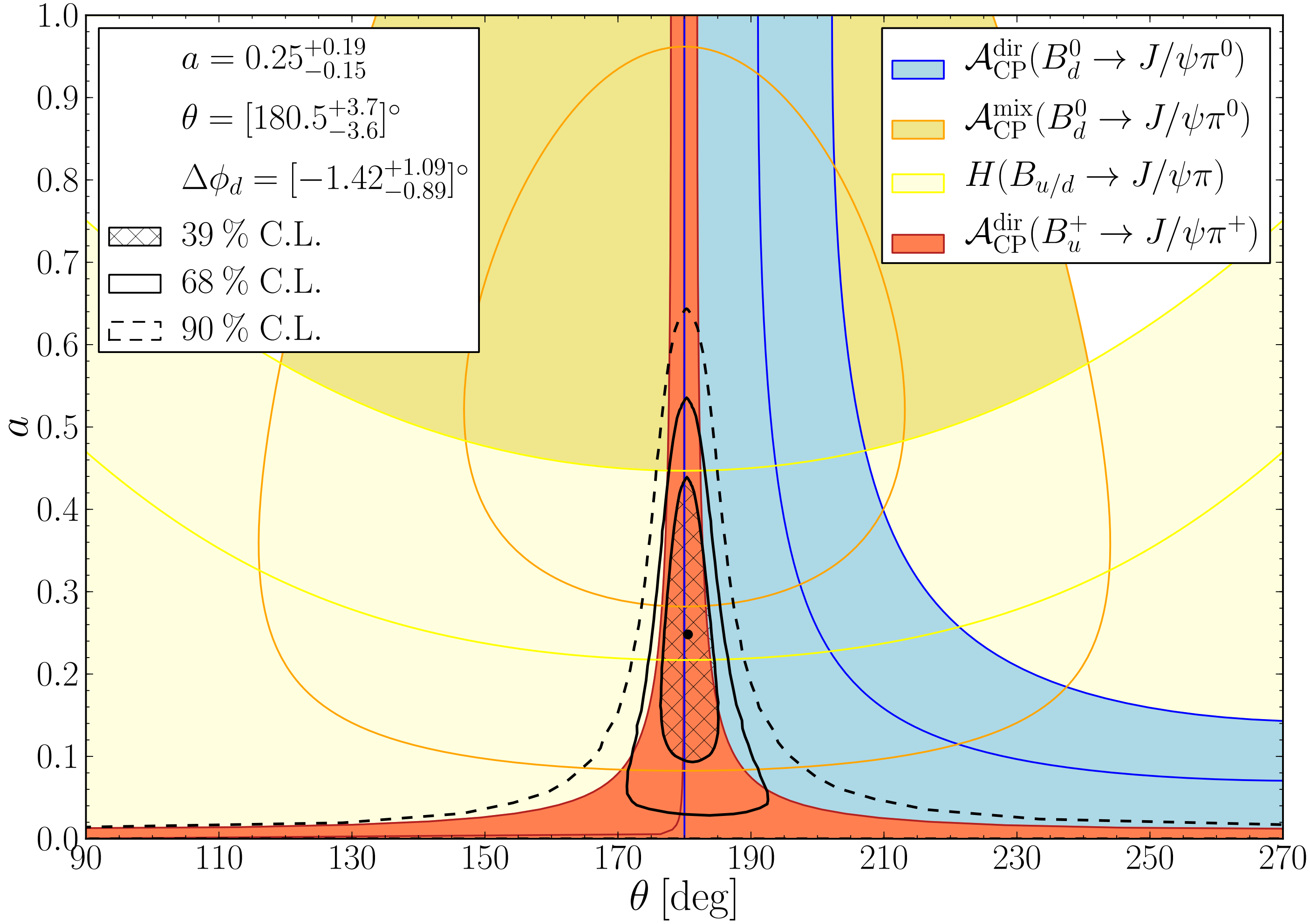
Constraints on Penguin Parameters a, θ

- Current picture: $B_d^0 \to J/\psi\pi^0$, where penguins are *enhanced* ...



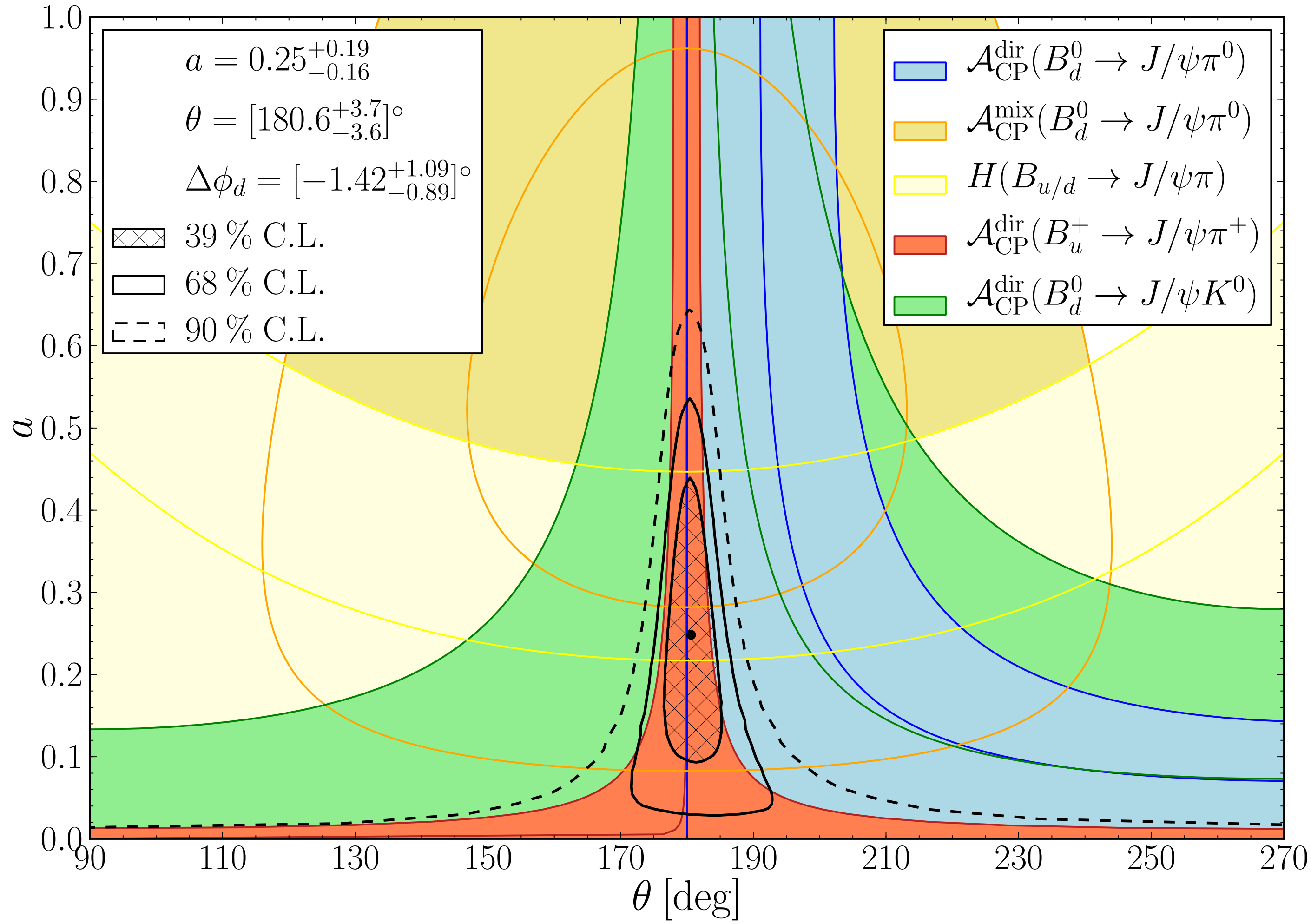
Constraints on Penguin Parameters a, θ

- Current picture: adding $B^+ \to J/\psi\pi^+$ ...



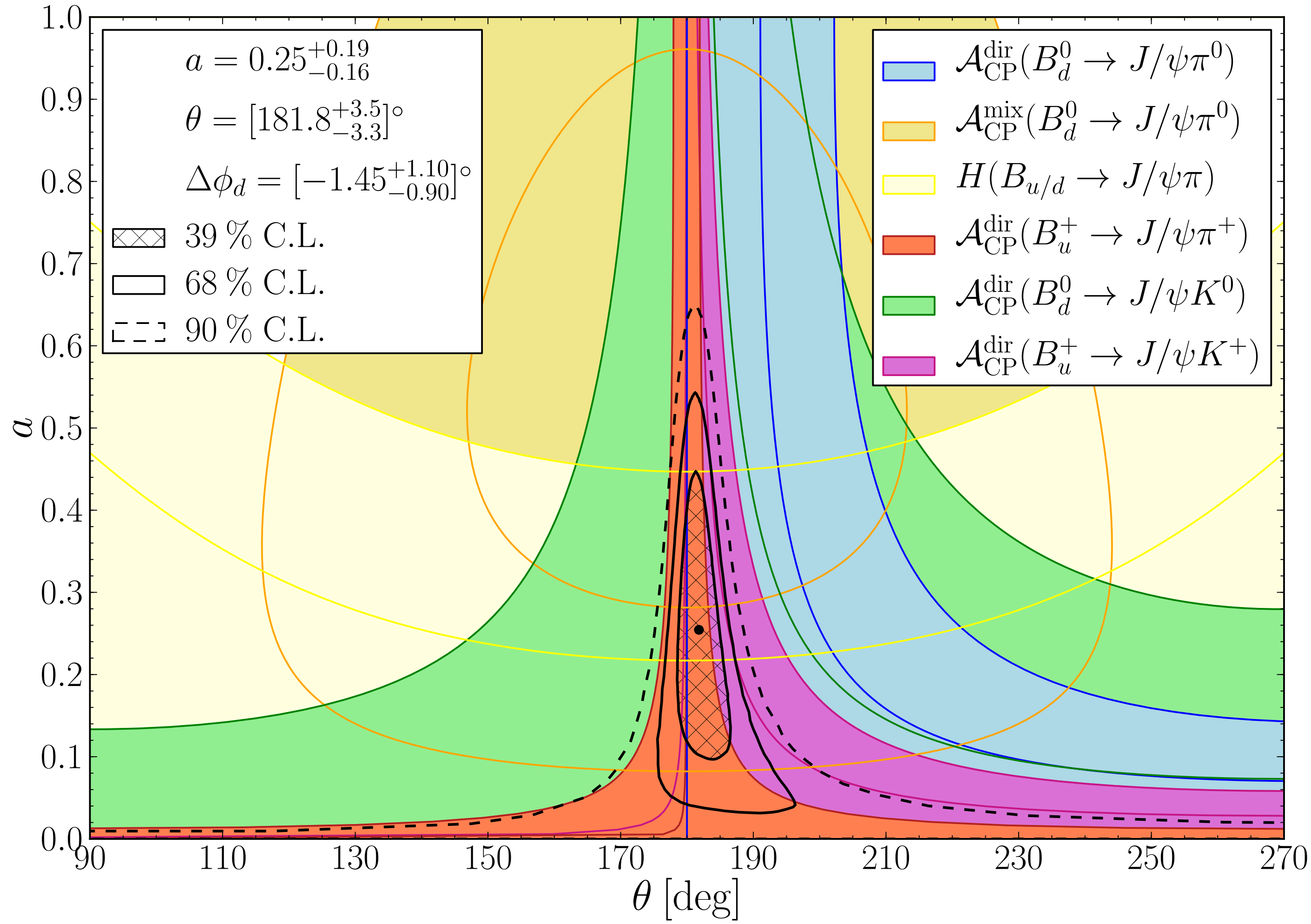
Constraints on Penguin Parameters a, θ

- Current picture: adding $B_d^0 \to J/\psi K^0$ ...



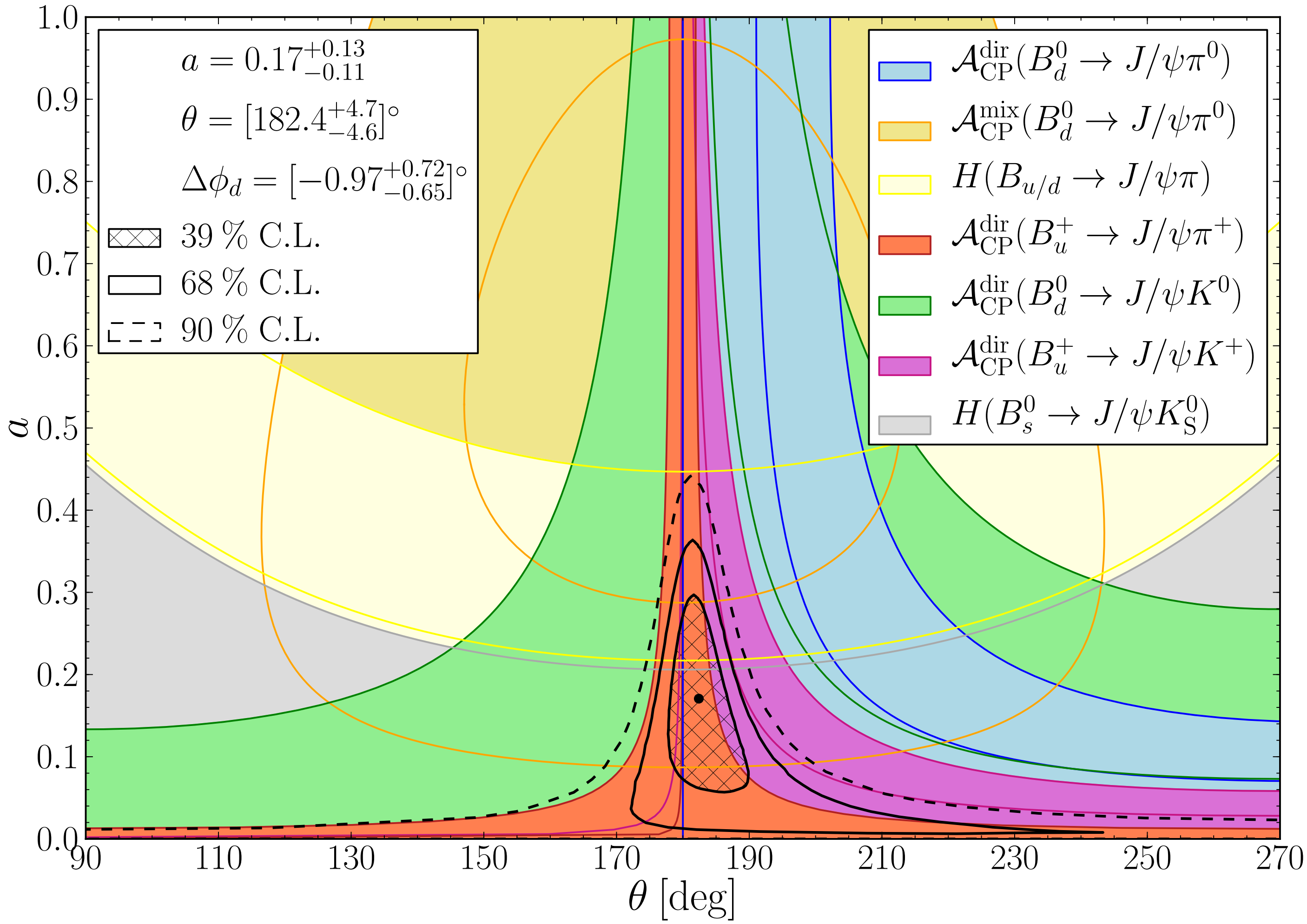
Constraints on Penguin Parameters a, θ

- Current picture: adding $B^+ \to J/\psi K^+$ ...

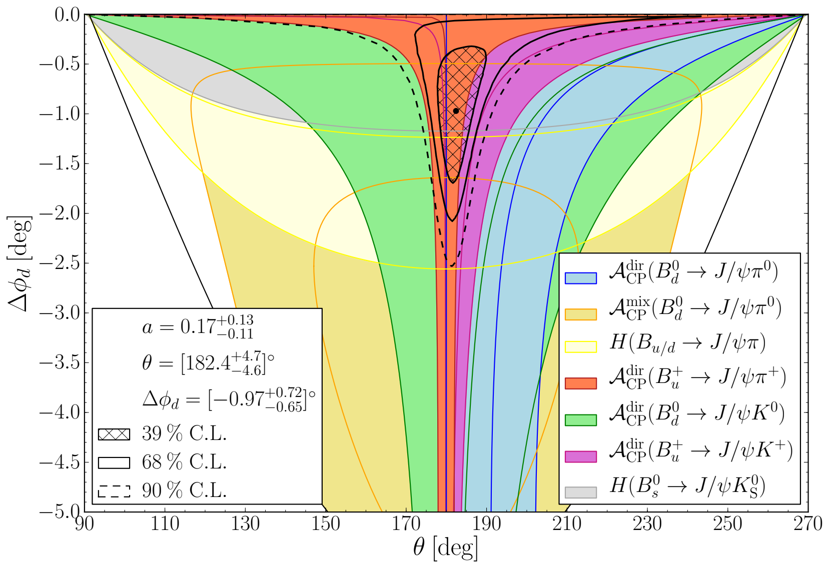


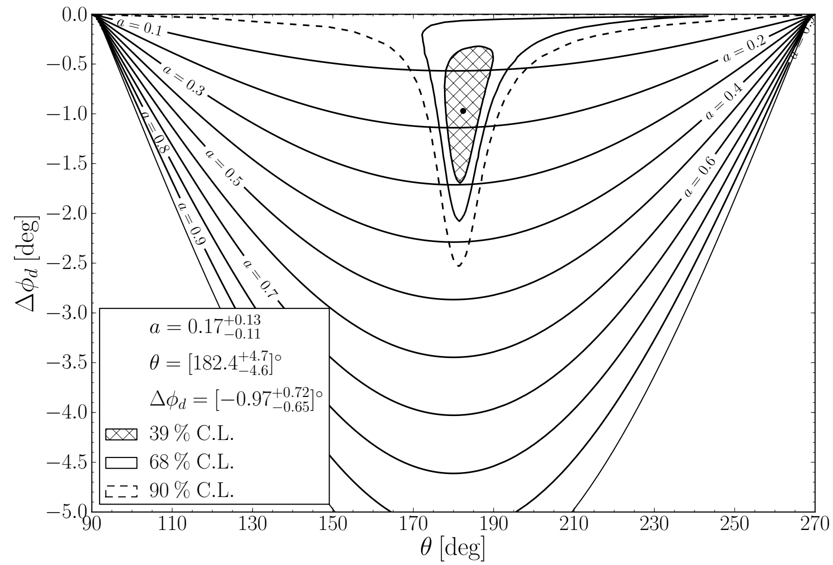
Constraints on Penguin Parameters a, θ

- Current picture: adding $B_s^0 \to J/\psi K_{\rm S}$ ...



Constraints on $\Delta\phi_d$





$$\boxed{\Delta\phi_d = (-0.97^{+0.72}_{-0.65})^\circ}$$

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

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

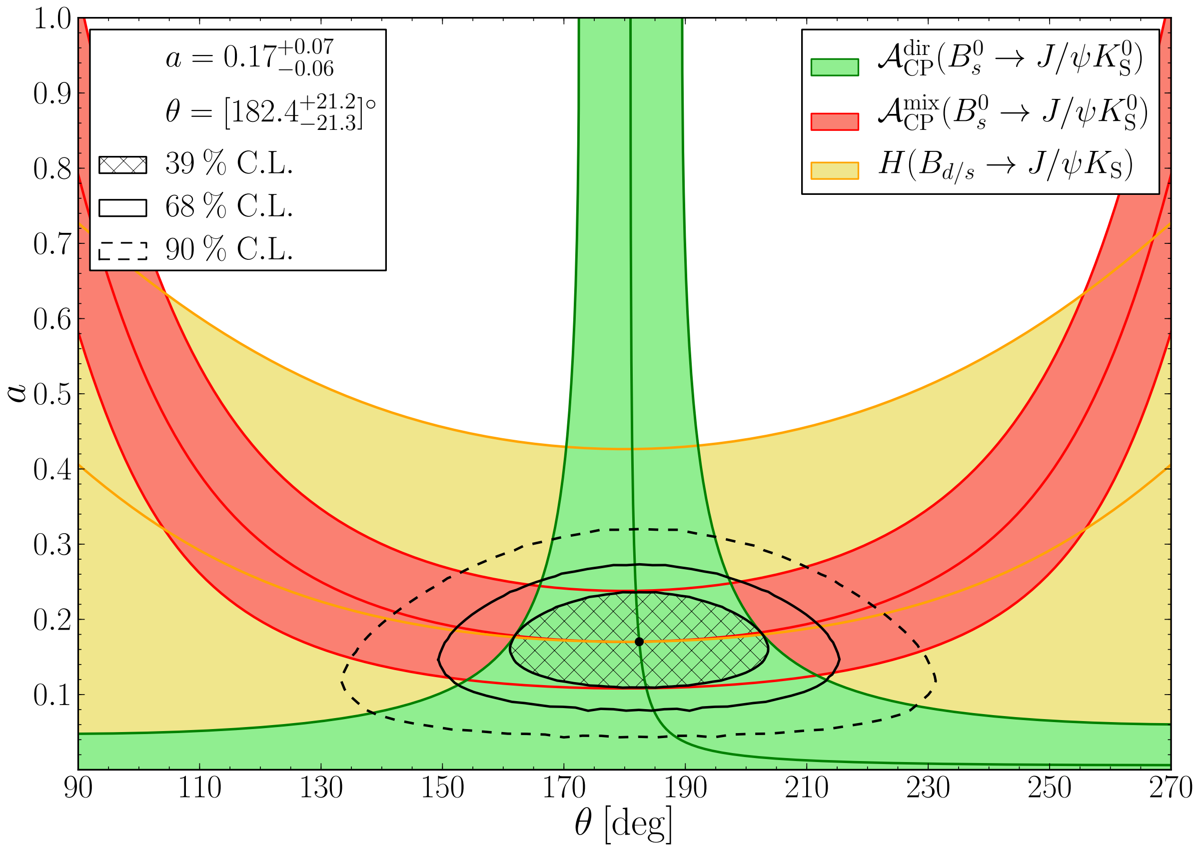
$$\phi_d = (42.7 \pm 1.7|_S \pm 0.7|_{\Delta\phi_d})^\circ = (43.0 \pm 1.8)^\circ$$

- 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 the LHCb Upgrade

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



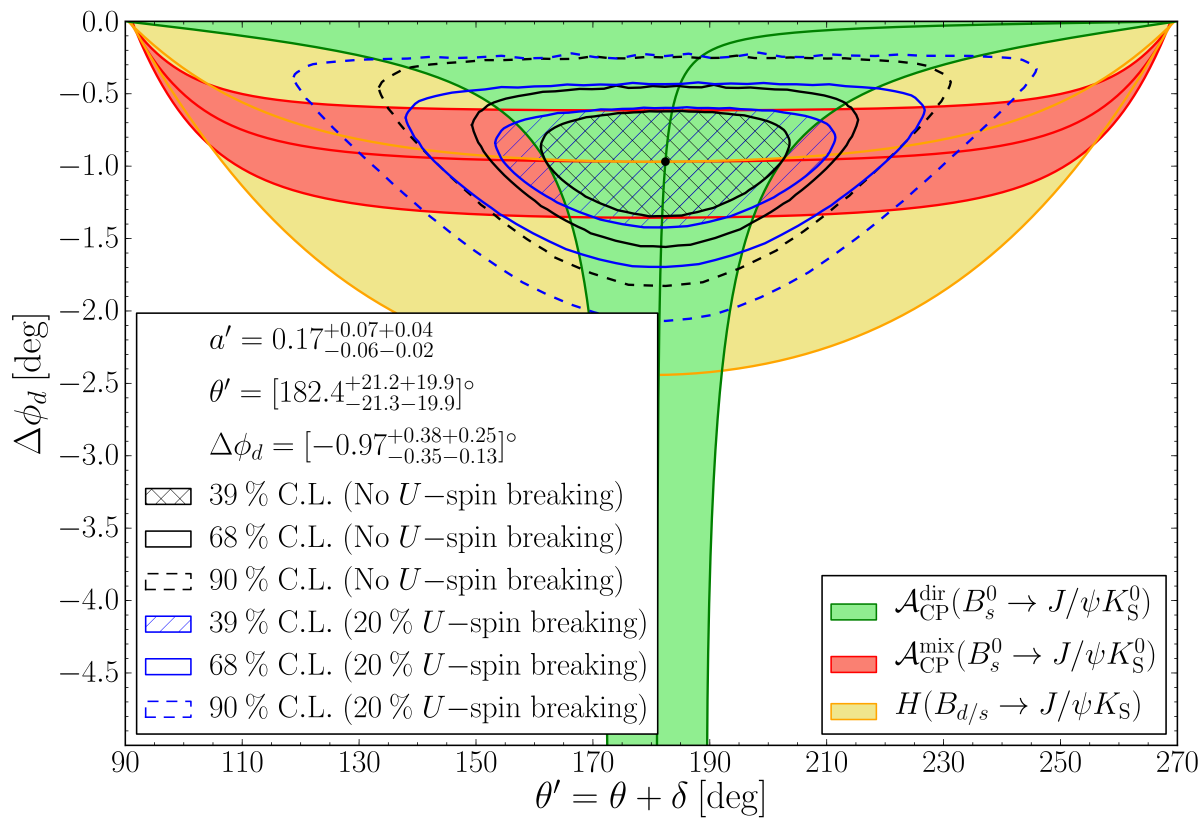
- Comments:
  - This determination of a and θ is theoretically clean.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\rm S}$) through U-spin symmetry.

Conversion into $\Delta\phi_d$

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

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

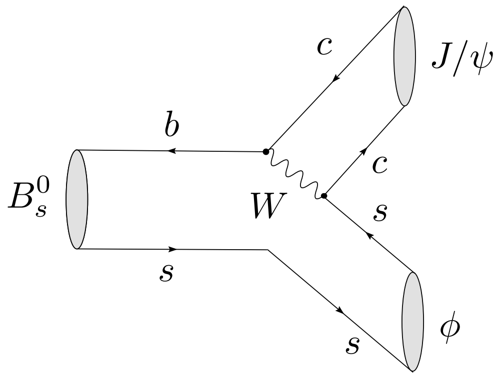
$$\Rightarrow \tan\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}$$

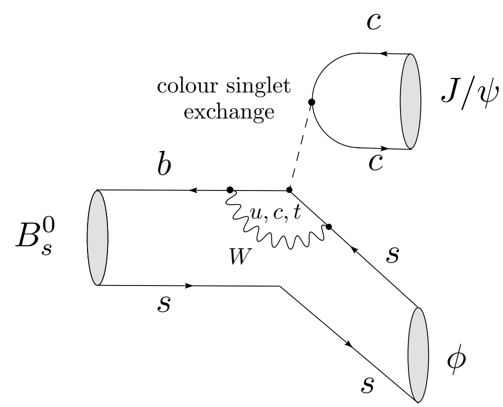


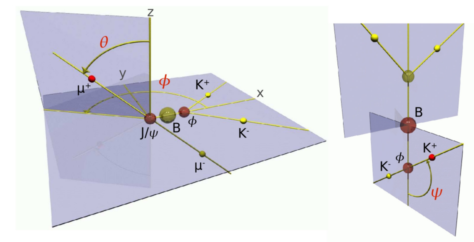
$$\boxed{B_s \to J/\psi\phi:}$$

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

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

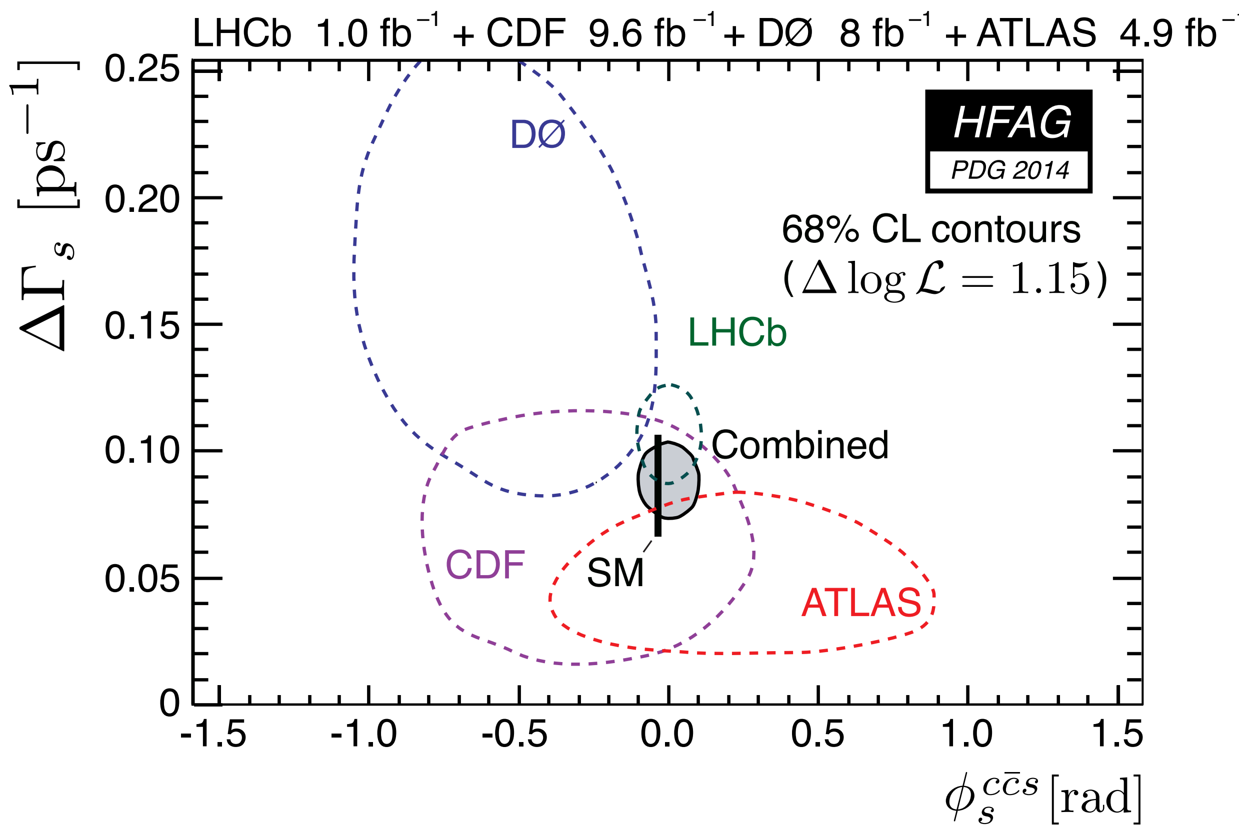
- Impact of SM penguin contributions (which are usually neglected):

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

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

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

Experimental Situation

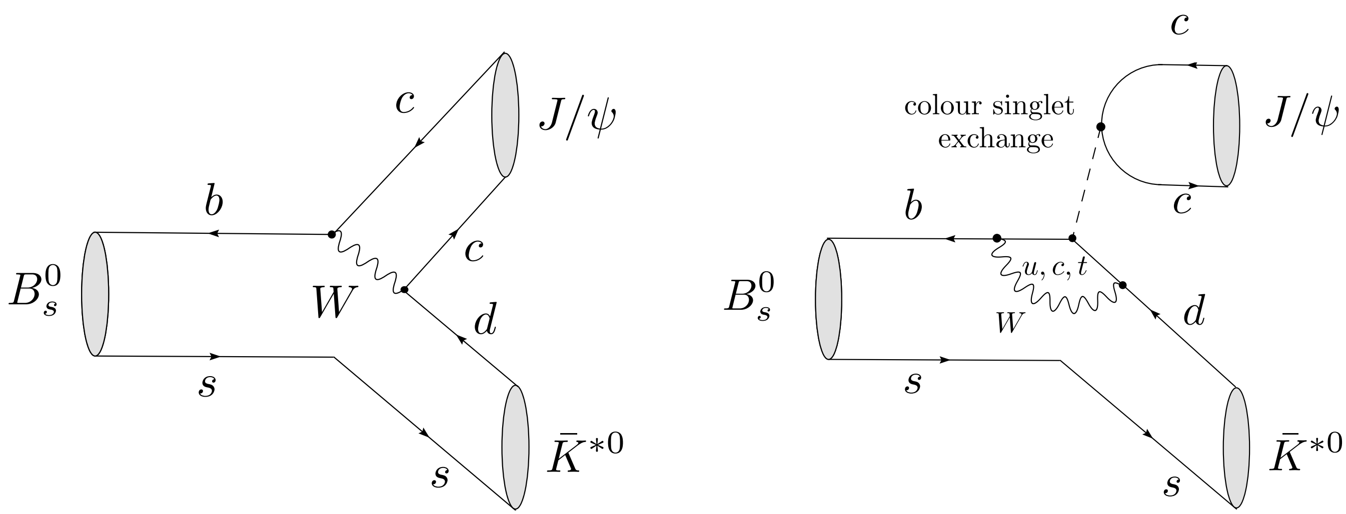


$$[\phi_s^{c\bar{c}s} \equiv \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}]$$

- The data indicate a "smallish" B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s:

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

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 (penguin annihilation) and E (exchange) topologies 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 + direct CP violation.
  - Angular analysis is required to disentangle final states $f \in \{0, \parallel, \perp\}$

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

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 $B_d^0 \to J/\psi K^{*0}$.
- Another control channel: $B_d^0 \to J/\psi \rho^0$: offers mixing-induced CPV!

$\Rightarrow$ look forward to future data... [LHCb, arXiv:1404.5673 [hep-ex]]

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

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

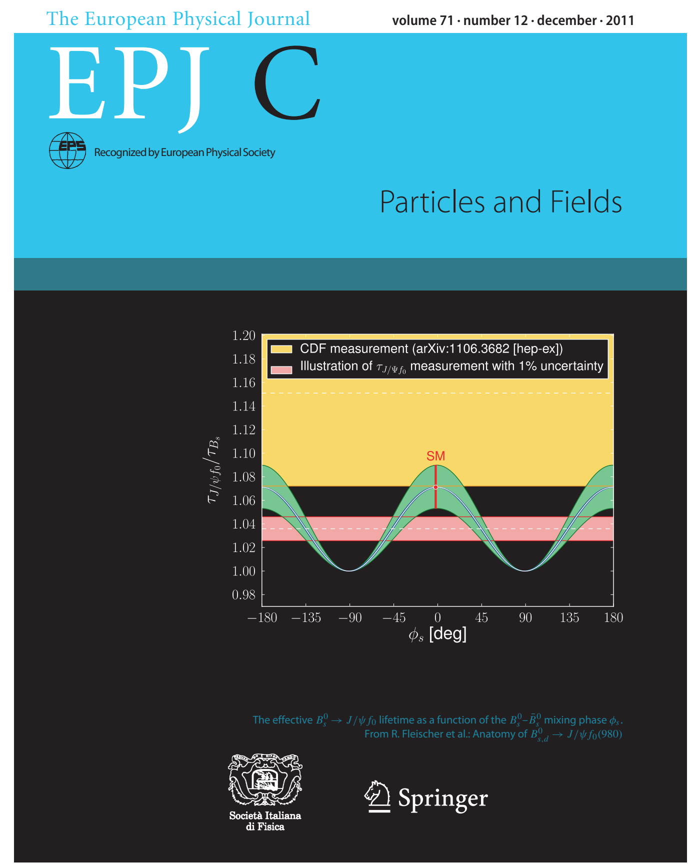
  - Data for $B \to J/\psi \pi, J/\psi K$ decays with a similar dynamics:

$$\Delta\phi_d = (-0.97^{+0.72}_{-0.65})^\circ$$

  - Such phase shifts may mimic New Physics: $\mathcal{A}_{\mathrm{CP,f}}^{\mathrm{mix}} = \sin(\phi_s + \Delta\phi_s^f)$

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

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



$\rightarrow$ very interesting decay

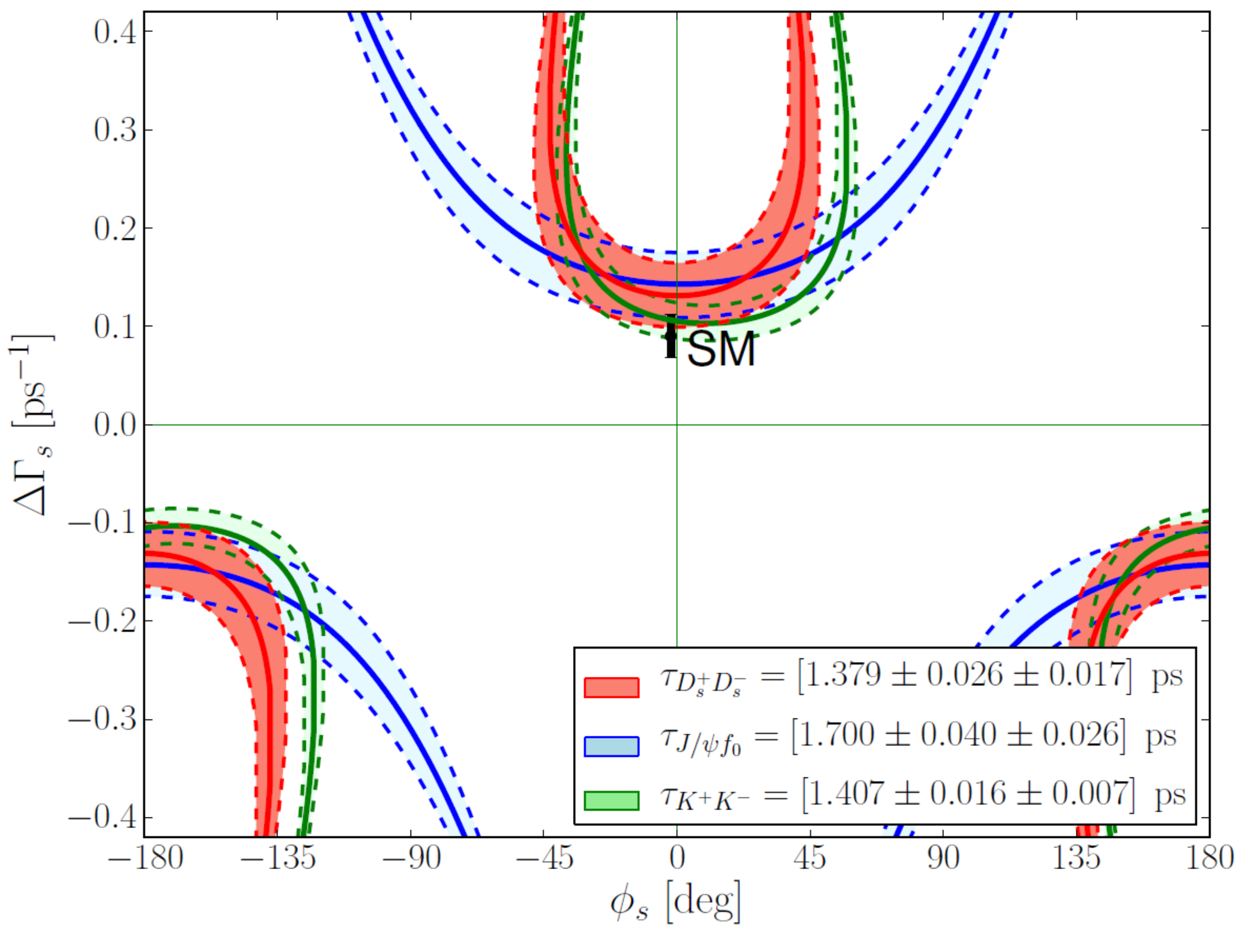
[S. Stone & L. Zhang (2009)]

Hadronic structure of $f_0(980)$!?

Detailed analysis: R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph];
see also arXiv:1110.5490 [hep-ph], giving a discussion of $B_{s,d} \to J/\psi \eta^{(\prime)}$

Nice Playground: Effective B_s Decay Lifetimes

$$\tau_f \equiv \frac{\int_0^\infty t\, \langle \Gamma(B_s(t) \to f) \rangle\, dt}{\int_0^\infty \langle \Gamma(B_s(t) \to f) \rangle\, dt}$$



[R.F. and R. Knegjens (2011); updated plot from talk by P. Gandini @ Beauty 2014]

Comments for the LHCb Upgrade Era

- In view of hadronic effects, it is important to give values of ϕ_s for the *individual* decay channels $B_s^0 \to f$, i.e. $B_s^0 \to J/\psi\phi$, $J/\psi f_0$, ...:

  $\Rightarrow$ pattern of $(\phi_s)_f$ may provide insights into the hadronic effects:

  – Differences in the values of ϕ_s would indicate hadronic effects.

  – Should no differences between the individual ϕ_s emerge, we would have negligible hadronic effects or a universal hadronic phase shift.

- Time-dependent analysis of CP violation in $B_s^0 \to J/\psi K_{\rm S}$:

  $\Rightarrow$ *clean* extraction of the relevant penguin parameters:

  – Significant penguin parameters would indicate a *potential problem* in the measurement of ϕ_s from $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi f_0$, ...

  – Conversely, smallish parameters would give us *confidence* for the measurement of ϕ_s (but still different final states ...).

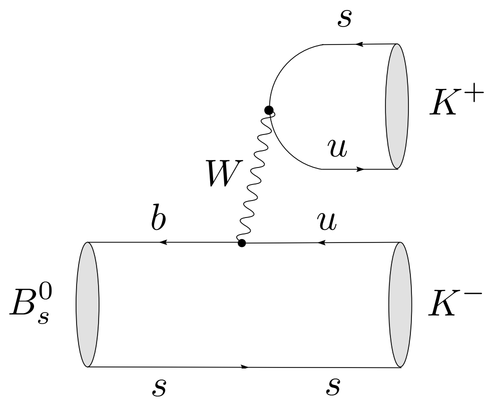
$$B_s \to K^+K^-$$

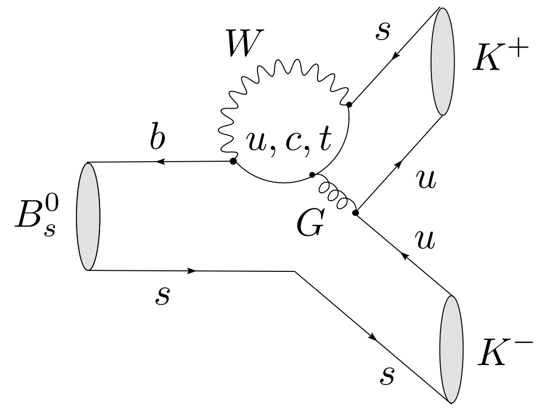
$\oplus$ U-Spin Partner

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

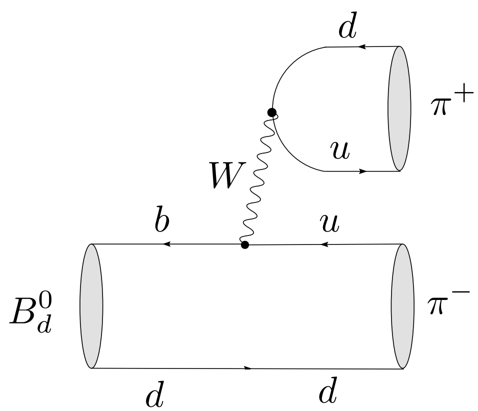
Decay Topologies & Amplitudes

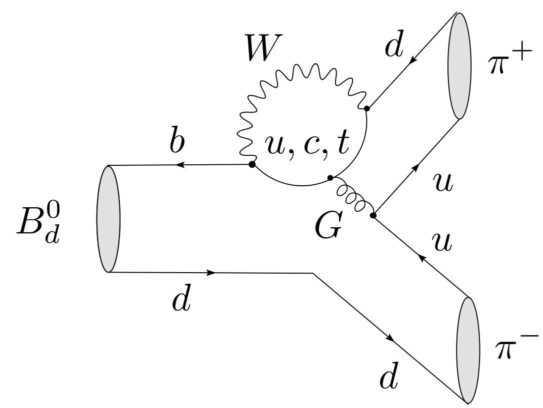
- $B_s^0 \to K^+K^-$: $$A(B_s^0 \to K^+K^-) \propto \mathcal{C}' \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d' e^{i\theta'} \right]$$





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





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

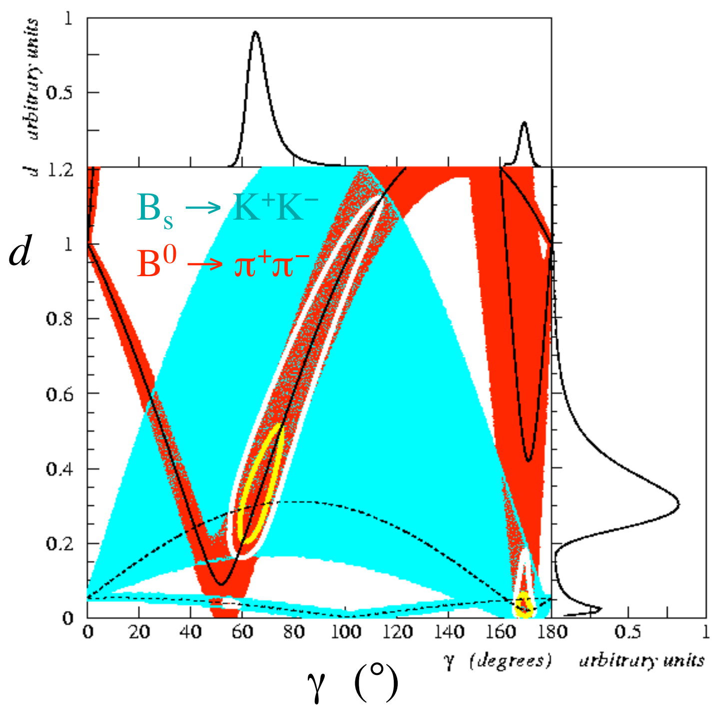
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

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

  - 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, 2007)]

- 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]

Picture from Current Data:

$\rightarrow$ update of R.F. & Knegjens (2010), R. Knegjens, PhD thesis (2013)

[See the talk by Marco Ciuchini @ Beauty 2014 for an interesting variant of the method, following Ciuchini, Franco, Mishima & Silvestrini (2012)]

Measurements of CP Violation

- CP-violating observables of the time-dependent decay rate:

$$\frac{\Gamma(B_q^0(t) \to f) - \Gamma(\bar{B}_q^0(t) \to f)}{\Gamma(B_q^0(t) \to f) + \Gamma(\bar{B}_q^0(t) \to f)}$$

$$= \left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f)\,\cos(\Delta M_q t) + \mathcal{A}_{\rm CP}^{\rm mix}(B_q \to f)\,\sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2) + \mathcal{A}_{\Delta\Gamma}(B_q \to f)\,\sinh(\Delta\Gamma_q t/2)}\right]$$

- CP violation in $B_d \to \pi^+\pi^-$: $\to$ HFAG average of BaBar, Belle, LHCb:

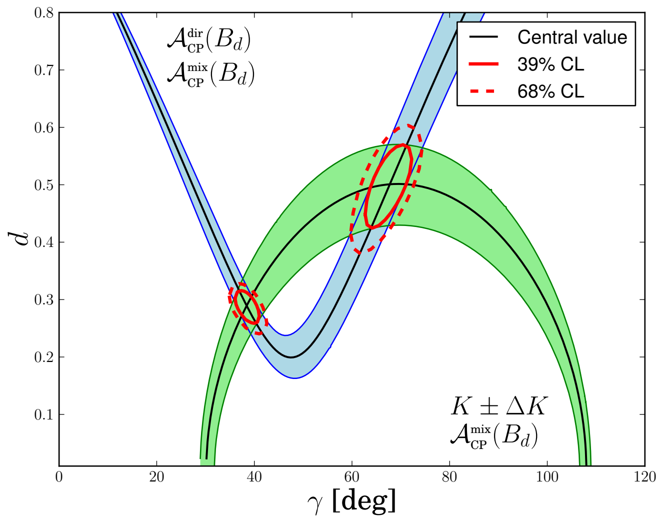
$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) &= -0.29 \pm 0.06 \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) &= +0.65 \pm 0.06 \end{aligned}$$

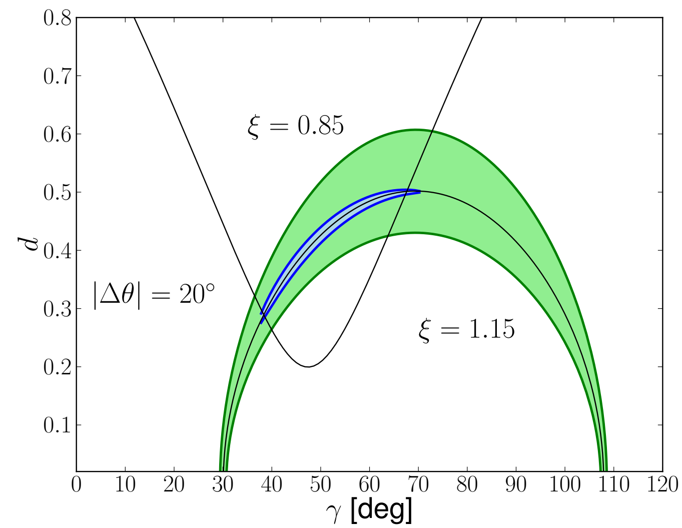
- First LHCb measurement [arXiv:1308.1428] of CP violation in $B_s \to K^+K^-$:

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) &= +0.14 \pm 0.11 \pm 0.03 \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) &= -0.30 \pm 0.12 \pm 0.04 \end{aligned}$$

Extraction of γ

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





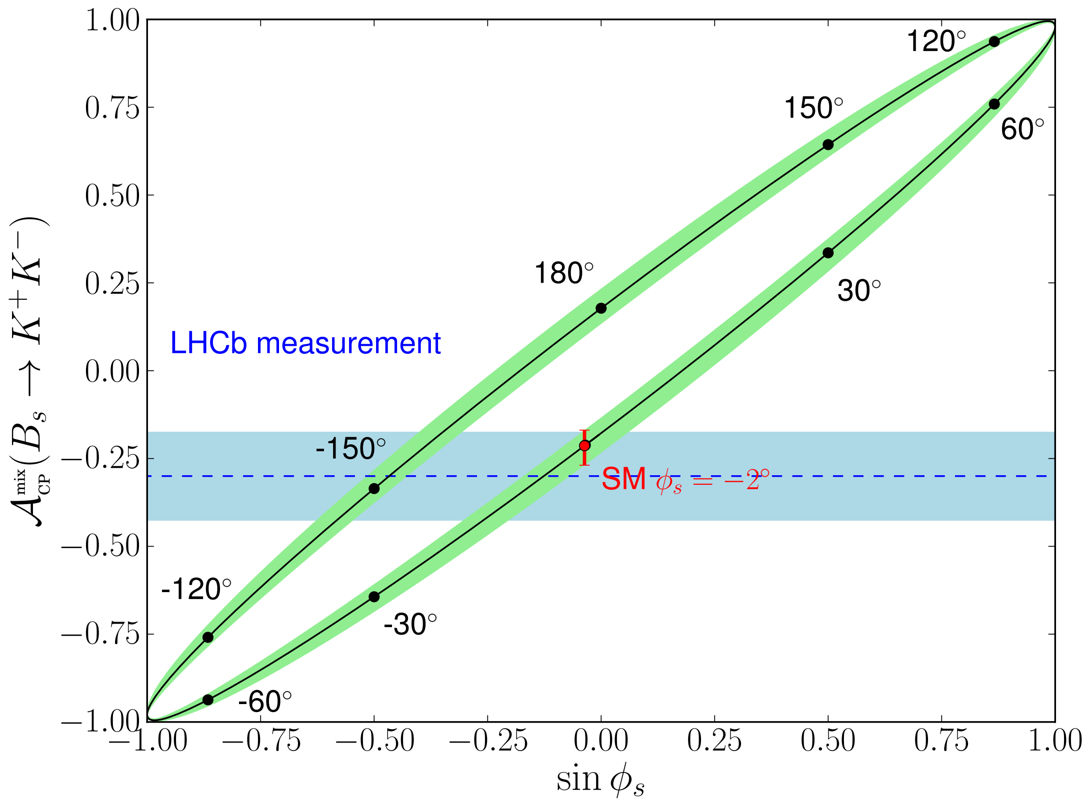
$$\Rightarrow \boxed{\gamma = \left(67.7^{+4.5}_{-5.0}\big|_{\rm input}{}^{+5.0}_{-3.7}\big|_{\xi}{}^{+0.1}_{-0.2}\big|_{\Delta\theta}\right)^\circ}$$

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

- "Tree-level" results: $\gamma = (70.0^{+7.7}_{-9.0})^\circ$ (CKMfitter), $(69.4 \pm 7.1)^\circ$ (UTfit).

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

- Contour in the $\sin\phi_s$–$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$ plane:

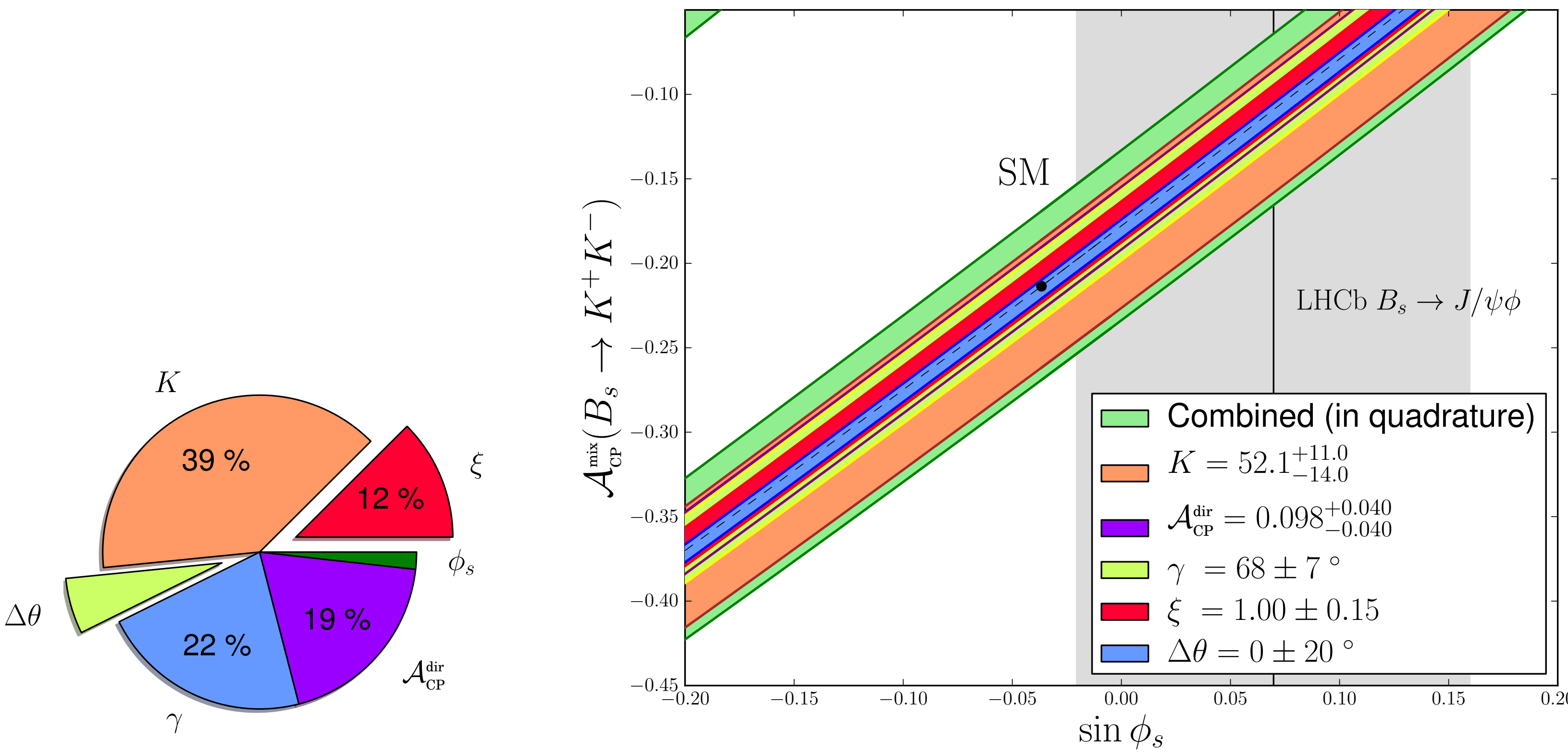


  – Measured value of $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) \Rightarrow -0.25 \lesssim \sin\phi_s \lesssim 0$

- SM prediction: $$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)|_{\rm SM} = -0.220^{+0.042}_{-0.054}$$

... while $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) \approx \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\pm K^\pm) = 0.082 \pm 0.04$.

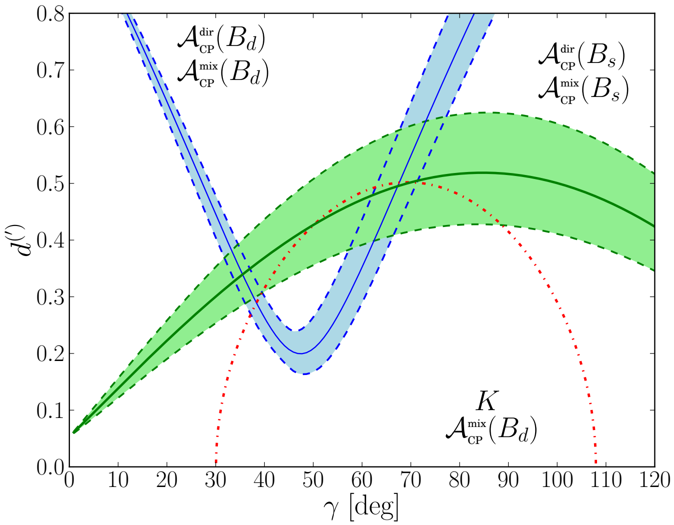
- The analysis takes uncertainties due to input parameters and observables as well as U-spin-breaking corrections into account:



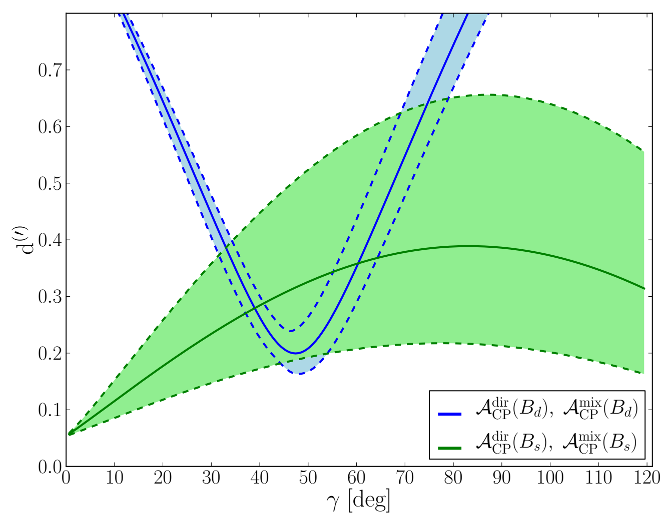
Final Goal: Optimal Determination of γ

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

$\Rightarrow$ theoretically clean contour in the γ–d' plane: $\Rightarrow$ K is not needed:



Green bands: current SM projection



current LHCb result

- 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.

Outlook

$\diamond$ Many More Topics in CP-B:

$\rightarrow$ two examples:

- CP violation in $B_s^0 \rightarrow \phi\phi$:
  - Pure penguin decay caused by $b \rightarrow s\bar{s}s$ quark-level transitions.
  - First time-dependent angular analysis @ LHCb:

$\Rightarrow$ *experimental CP-B highlight of the summer 2014:*

$$\Rightarrow \phi_s = -0.17 \pm 0.15(\mathrm{stat}) \pm 0.03(\mathrm{syst}) = -(9.7 \pm 8.8)^\circ$$

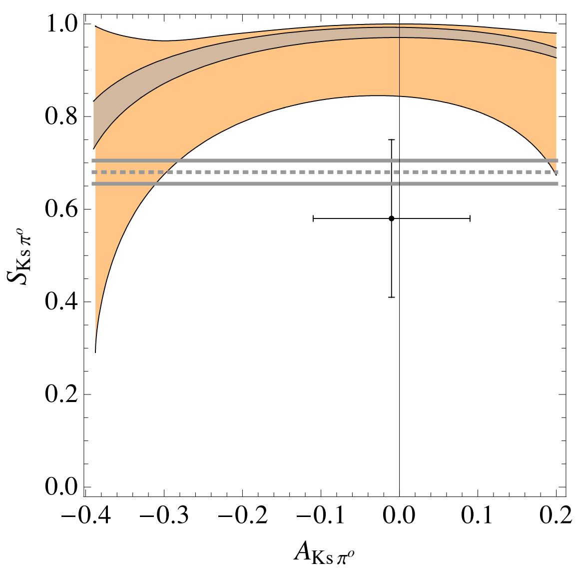
$\rightarrow$ no sign of NP (yet!?) ...

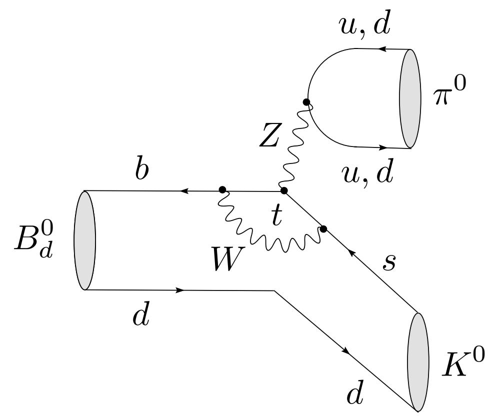
$\rightarrow$ stay tuned

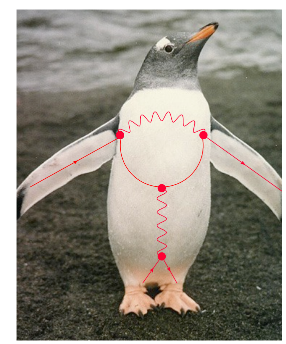
[Recent theory paper: Bhattacharya, Datta, Duraisamy & London ('13)]

- CP violation in $B^0 \to \pi^0 K_S$: $\to$ interesting decay for Belle II:

$$\frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) - \Gamma(B^0(t) \to \pi^0 K_S)}{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) + \Gamma(B^0(t) \to \pi^0 K_S)}$$
$$= A_{\pi^0 K_S} \cos(\Delta M_d t) + S_{\pi^0 K_S} \sin(\Delta M_d t)$$







"penguin" contribution $\to$ NP?

[R.F., S. Jäger, D. Pirjol & J. Zupan ('08)]

◇ Towards New Frontiers:

$\Rightarrow$ *new high-precision era:*

- Still no signals for New Physics @ LHC:
  - Impressive (also frustrating ...), but more is yet to come!
  - Many studies of CP violation in B decays: many more strategies than discussed in this talk (time constraints) ...
  - Prepare to deal with "smallish" NP effects:

$\Rightarrow$ Challenge: matching of the exp. and theo. precisions!