Extracting γ and Penguin Parameters from $B_s \to J/\psi K_S$

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$\to$ Project with Kristof De Bruyn & Patrick Koppenburg (in progress)

- Setting the Stage
- Picture from the Current Data
- Sensitivity at LHCb: $\to$ a feasibility study
- Concluding Remarks

Setting the Stage

Kristof De Bruyn

Patrick Koppenburg

Introduction

- LHCb has just started to take physics data:

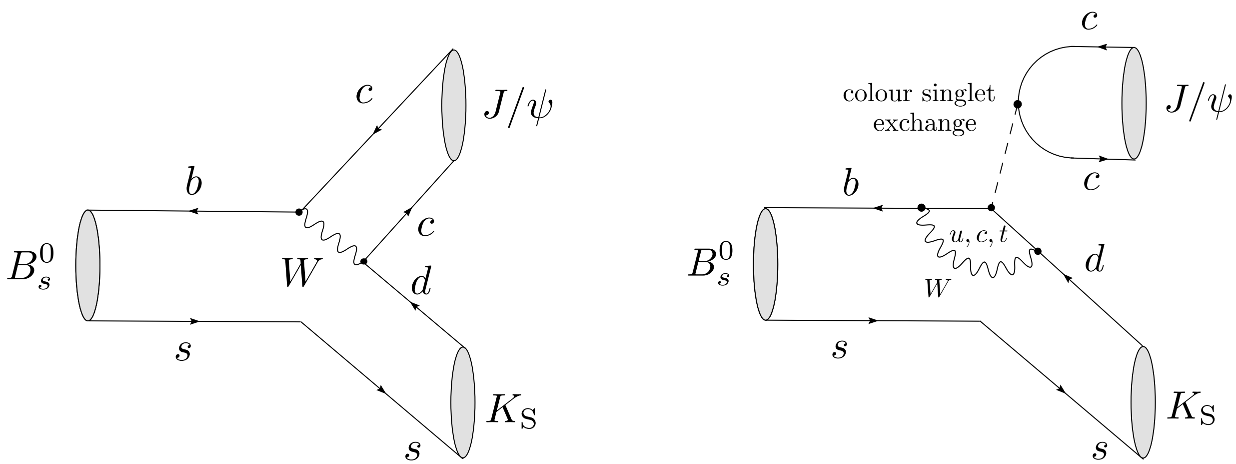
  $\rightarrow$ new era for the exploration of B_s decays

- One of the decays with a promising physics potential: $B_s \to J/\psi K_{\rm S}$
  - Observation was recently announced by CDF @ ICHEP 2010 ...
  - Only information on the BR is available with large errors.
  - CP violation would be an important next step $\rightarrow$ LHCb...

- Physics with $B_s \to J/\psi K_{\rm S}$: U-spin partner of $B_d \to J/\psi K_{\rm S}$ $\Rightarrow$
  - Extraction of the UT angle γ
  - Extraction of hadronic penguin parameters $\Rightarrow$
  - Control of penguin effects in $(\sin 2\beta)_{J/\psi K_{\rm S}}$: needed to match LHCb precision (0.014 and 0.010 for 6fb^{-1} and 50fb^{-1}, respectively).

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

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



- Decay amplitude:

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

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

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

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

$$A \equiv |V_{cb}|/\lambda^2, \quad R_b \equiv \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left|\frac{V_{ub}}{V_{cb}}\right|$$

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

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

- CP-violating observables: $[C^2 + S^2 + \mathcal{A}_{\Delta\Gamma}^2 = 1]$

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

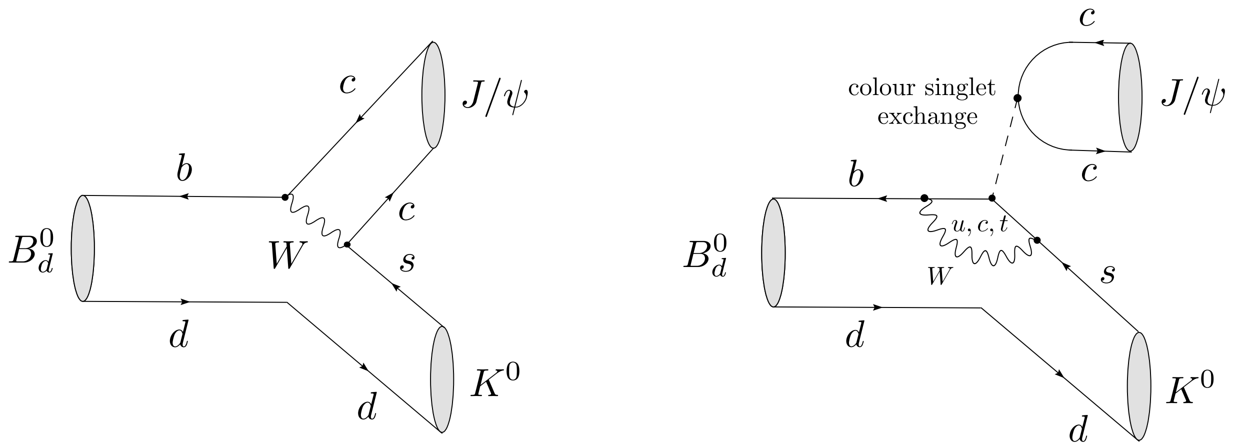
$$S(B_s \to J/\psi K_S) = \frac{\sin\phi_s - 2a\cos\theta\sin(\phi_s+\gamma) + a^2\sin(\phi_s + 2\gamma)}{1 - 2a\cos\theta\cos\gamma + a^2}$$

$$\mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_S) = \frac{\cos\phi_s - 2a\cos\theta\cos(\phi_s+\gamma) + a^2\cos(\phi_s + 2\gamma)}{1 - 2a\cos\theta\cos\gamma + a^2}$$

- ϕ_s is the CP-violating B_s^0–$\bar{B}_s^0$ mixing phase:

$\phi_s^{\rm SM} = -2\lambda^2\eta \sim -2°$, but may be enhanced by NP (CDF, DØ?).

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



- Amplitude:

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

$$\epsilon \equiv \lambda^2/(1-\lambda^2) = 0.053$$

- Hadronic parameters straightforwardly from the $B_s \to J/\psi K_S$ definitions:

$$a \to -a', \quad \theta \to \theta', \quad \mathcal{A} \to \mathcal{A}', \quad \mathcal{N} \to \mathcal{N}' \equiv -\frac{1}{\sqrt{\epsilon}} \frac{\mathcal{A}'}{\mathcal{A}} \mathcal{N}$$

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

$$H \equiv \frac{1}{\epsilon} \frac{\langle \Gamma(B_s \to J/\psi K_S) \rangle}{\langle \Gamma(B_d \to J/\psi K_S) \rangle} \left| \frac{\mathcal{A}'}{\mathcal{A}} \right|^2 \frac{\Phi^d_{J/\psi K_S}}{\Phi^s_{J/\psi K_S}} = \frac{1 - 2a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2}$$

Extraction of γ and Penguin Parameters

- U-spin flavour symmetry:

$$a = a', \quad \theta = \theta' \tag{1}$$

$$\Rightarrow \qquad \mathcal{A}' = \mathcal{A} \tag{2}$$

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

- Transparent implementation in terms of contours in the γ–a plane:
  - C and S give a theoretically clean contour;
  - H and S give another contour (affected by $SU(3)$ corrections);
  - Intersection of contours (U-spin) gives γ and a, yields then also θ.

Picture from the Current Data

Observation of $B_s \to J/\psi K_S$

- CDF has recently reported the following result: [CDF Note 10240 (2010)]

$$\frac{\text{BR}(B_s \to J/\psi K_S)}{\text{BR}(B_d \to J/\psi K_S)} = 0.0405 \pm 0.0070(\text{stat.}) \pm 0.0041(\text{syst.}) \pm 0.0050(\text{frag.})$$

  - The last error is associated with the ratio f_s/f_d of the B_s and B_d fragmentation functions [$\to$ N. Serra's WG III talk for new strategy @ LHCb].
  - The PDG value $\text{BR}(B_d^0 \to J/\psi K^0) = (8.71 \pm 0.32) \times 10^{-3}$ yields

$$\text{BR}(B_s^0 \to J/\psi \bar{K}^0) = (3.53 \pm 0.61 \pm 0.35 \pm 0.43 \pm 0.13(\text{PDG})) \times 10^{-5}$$

- It is interesting to compare this result with $\text{BR}(B_d \to J/\psi \pi^0)$:
  - If we neglect penguin annihilation and exchange topologies (can be probed through $B_s^0 \to J/\psi \pi^0$), the $SU(3)$ flavour symmetry implies

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

  - The data give the following value:

$$\boxed{\Xi_{SU(3)} = 1.01 \pm 0.25 \;\to\; \text{agrees very well with the } SU(3) \text{ expectation}}$$

Penguin Parameters & $S(B_s \to J/\psi K_\mathrm{S})$

- In view of the value of $\Xi_{SU(3)} \sim 1$, we will use the hadronic parameters extracted from CP violation in $B_d^0 \to J/\psi\pi^0$ as a guideline:

$$a \in [0.15, 0.67], \quad \theta \in [174, 213]^\circ \quad [\text{correspond to } \gamma = (65 \pm 10)^\circ]$$

[S. Faller, M. Jung, R.F. & T. Mannel (2008); see also Ciuchini *et al.* (2005)]

- The observables of the $B_s^0 \to J/\psi K_\mathrm{S}$ channel read then as follows:

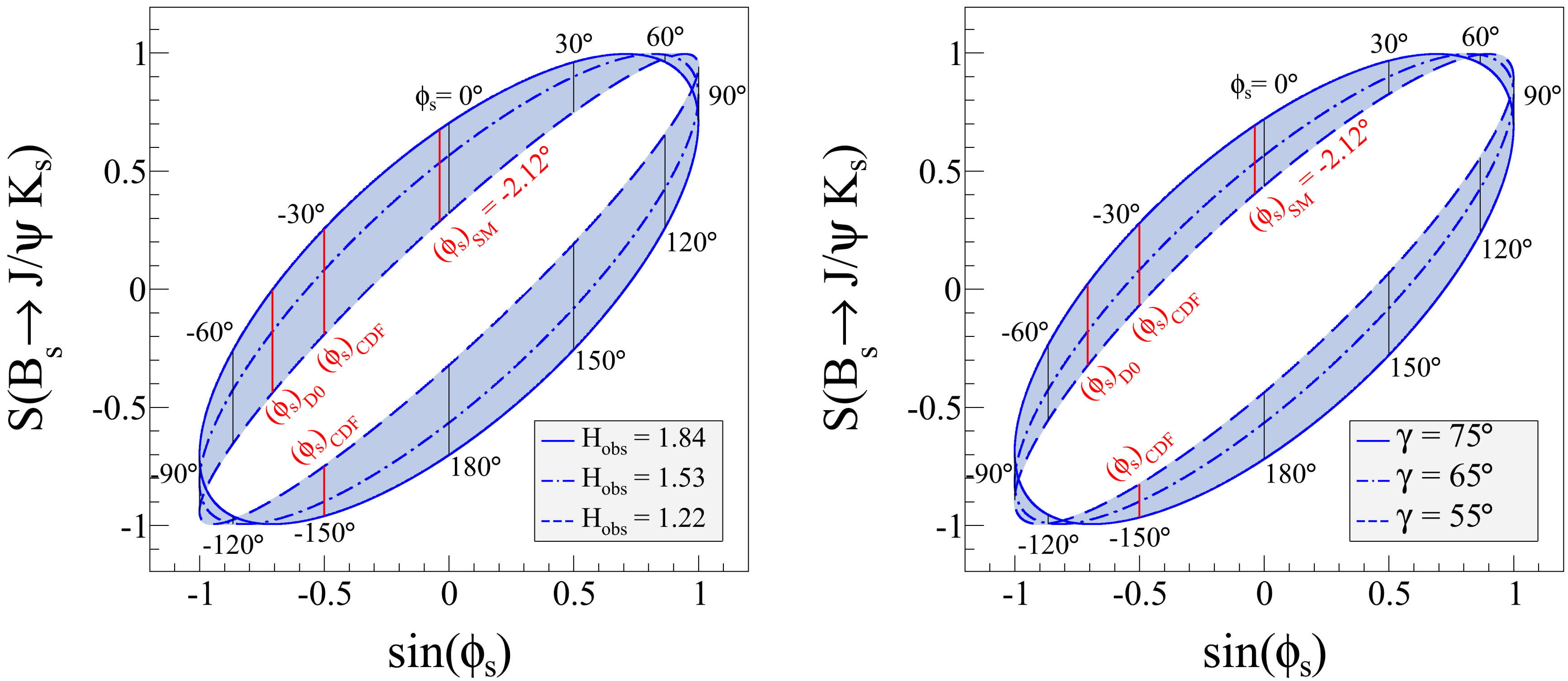
$$H = 1.53 \pm 0.31$$

$$C \equiv C(B_s \to J/\psi K_\mathrm{S}) = C(B_d \to J/\psi\pi^0) = -0.10 \pm 0.13.$$

- Mixing-induced CP violation $S \equiv S(B_s \to J/\psi K_\mathrm{S})$:
  - Given values of H and C allow us to calculate S as a function of ϕ_s.
  - We obtain the following SM prediction:

$$S(B_s \to J/\psi K_\mathrm{S})|_\mathrm{SM} = 0.54^{+0.14}_{-0.25}\big|_H{}^{+0.00}_{-0.01}\big|_C{}^{+0.16}_{-0.13}\big|_\gamma = 0.54^{+0.21}_{-0.28}$$

- Target space for the first measurements of $S(B_s \to J/\psi K_{\rm S})$:



- Consequently, first experimental info on S would be very interesting!
- Correlation between $S(B_s \to K^+K^-)$ and $\sin\phi_s$: → R.F. @ WG VI

Sensitivity at LHCb

$\rightarrow$ a feasibility study

General Framework for the Study

- Input parameters:

$$a = 0.41, \quad \theta = 194^\circ \quad \text{and} \quad \gamma = 65^\circ \quad \text{(see above)}$$

- The LHCb precision estimates are based on the following assumptions:
  - We extrapolate from published results [CERN-LHCC-2003-030].
  - We consider integrated luminosities of $6\,\mathrm{fb}^{-1}$ (~2014–15) and $50\,\mathrm{fb}^{-1}$ (conservative assumption for an LHCb upgrade).
  - We use the number of expected $B_d \to J/\psi K_\mathrm{S}$ events and the corresponding BRs to determine the $B_s \to J/\psi K_\mathrm{S}$ signal yield:

    $\Rightarrow$ 7000 and 60000 signal events for $6\,\mathrm{fb}^{-1}$ and $50\,\mathrm{fb}^{-1}$, respectively.
  - The background is modeled as the sum of a prompt J/ψ component and a combinatorial background with a non-zero lifetime.
  - A toy MC study is performed to simulate the relevant observables.

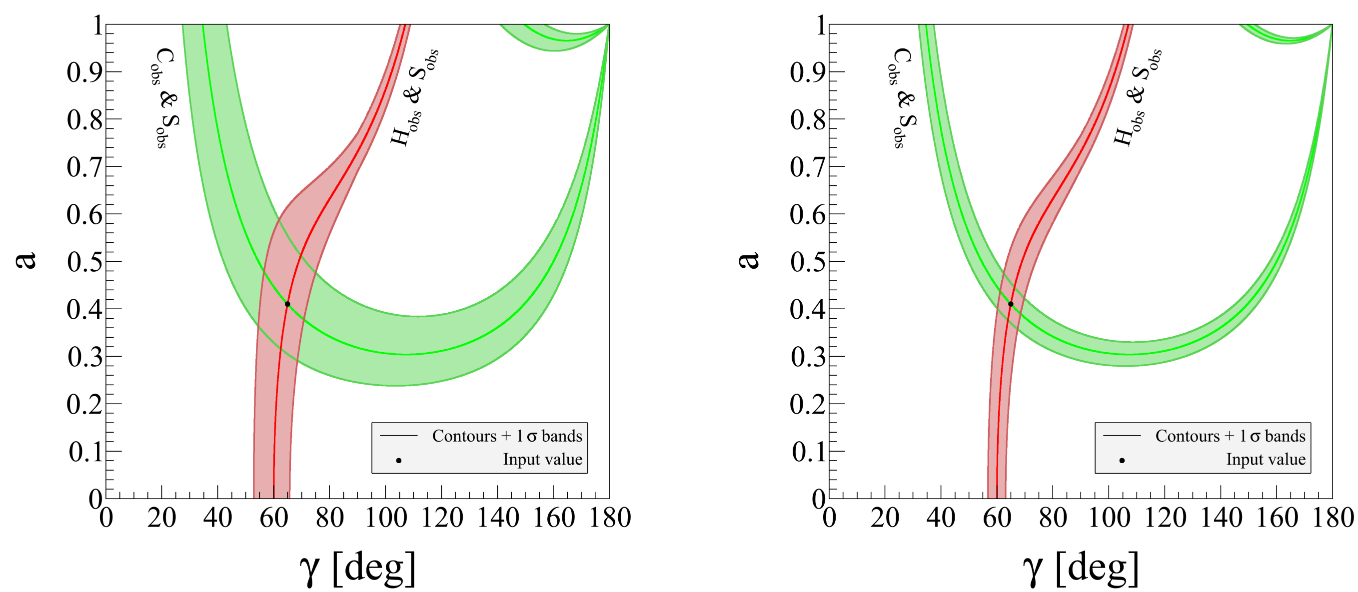
Extraction of γ at LHCb

- First information about γ could in principle be obtained from H:

$$H \geq \left[1 - 2\epsilon \cos^2\gamma + \mathcal{O}(\epsilon^2)\right] \sin^2\gamma$$

  – However, as the data indicate $H > 1$, the corresponding bound on γ seems not to be effective. [R.F. & T. Mannel ('97); R.F. & Recksiegel ('05)]

- Contours in the γ–a plane: $[6\,\text{fb}^{-1}$ and $50\,\text{fb}^{-1}]$



- Numerical results: [only statistical sensitivity]

$$6\,\text{fb}^{-1}: \quad \gamma = (65.0 \pm 7.4)^\circ, \quad a = 0.410 \pm 0.060, \quad \theta = (194 \pm 13)^\circ,$$

$$50\,\text{fb}^{-1}: \quad \gamma = (65.0 \pm 3.3)^\circ, \quad a = 0.410 \pm 0.024, \quad \theta = (194.0 \pm 4.3)^\circ.$$

Controlling Penguin Effects in $(\sin 2\beta)_{J/\psi K_{\rm S}}$ at LHCb

- Generalized expressions: $[\phi_d = 2\beta + \phi_d^{\rm NP}]$

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

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

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

with $N \equiv 1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2$,

- Current data: [averages over $B_d \to J/\psi K_{\rm S}$ and $B_d \to J/\psi K_{\rm L}$]

$$S(B_d \to J/\psi K^0) = 0.655 \pm 0.024, \quad C(J/\psi K^0) = -0.003 \pm 0.020$$

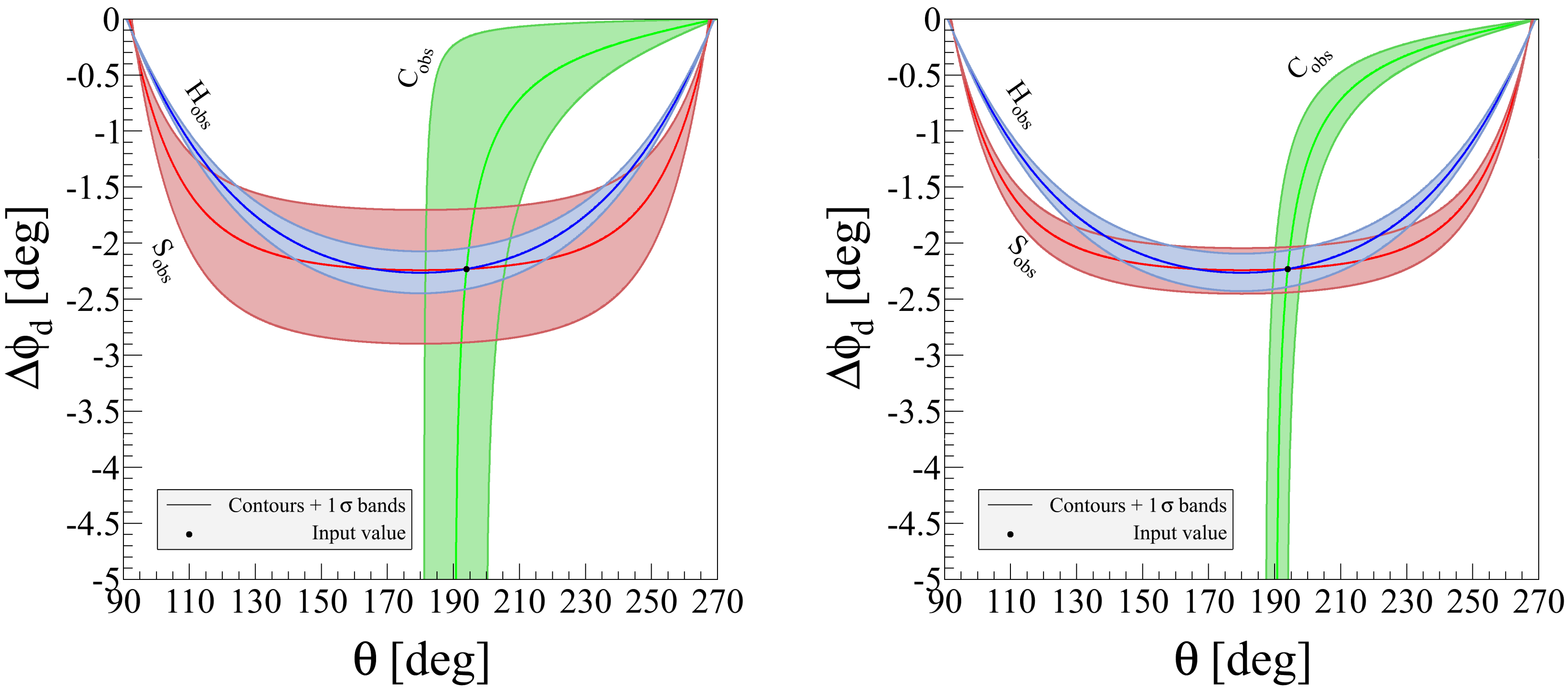
$B_d \to J/\psi \pi^0 \quad \Rightarrow \quad \Delta\phi_d \in [-6.7^\circ, 0.0^\circ]$ (softens tension in fits of UT)

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

- We use γ as an input ($\rightarrow$ LHCb):

$$6\ \text{fb}^{-1}: \quad \gamma = (65.0 \pm 3.1)^\circ, \qquad 50\ \text{fb}^{-1}: \quad \gamma = (65.0 \pm 1.3)^\circ$$

- Within our study we arrive at the following picture: [$6\,\text{fb}^{-1}$ and $50\,\text{fb}^{-1}$]

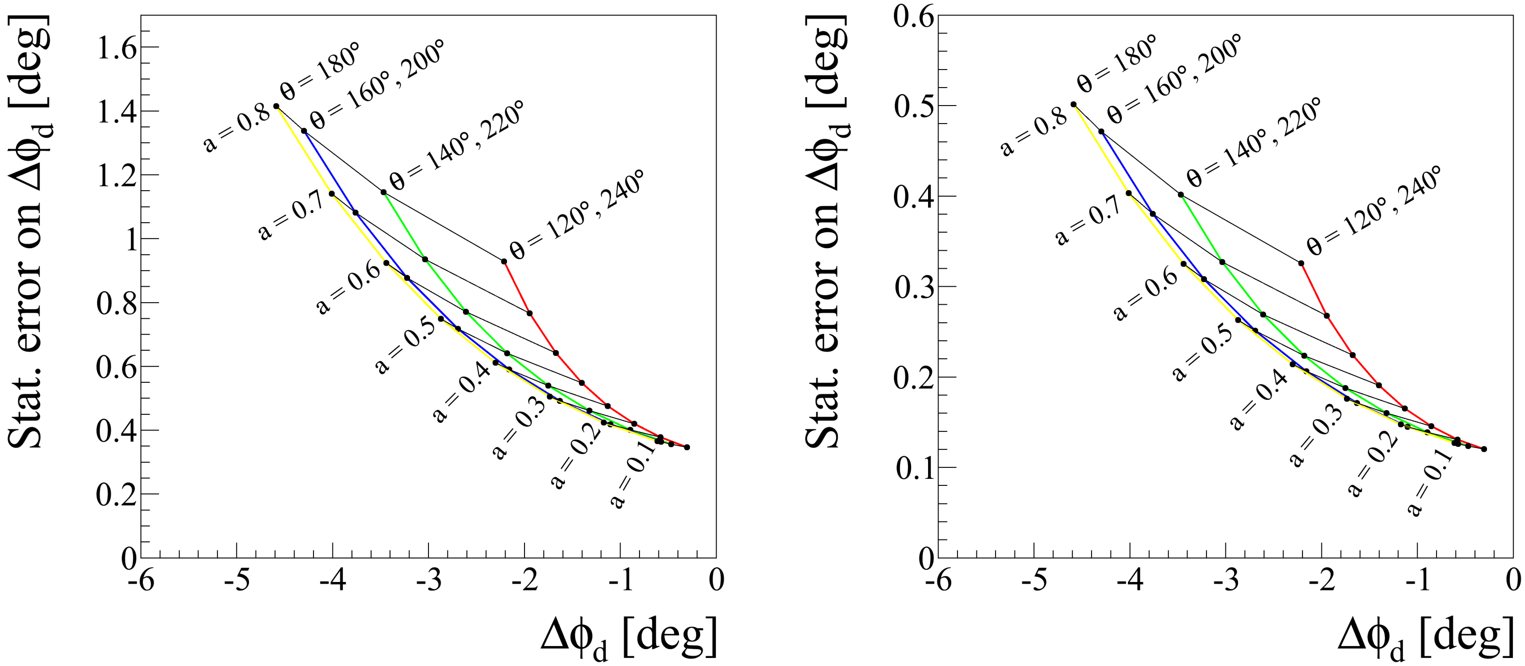


– Numerical results (use only the C and S contours):

$$6\ \text{fb}^{-1}: \Delta\phi_d = \left[-2.23 \pm 0.59\ (\text{stat.}) \pm 0.12\ (\gamma)\ {}^{+0.29}_{-0.40}(\xi)\ {}^{+0.33}_{-0.07}(\Delta\theta)\right]^\circ$$
$$50\ \text{fb}^{-1}: \Delta\phi_d = \left[-2.23 \pm 0.21\ (\text{stat.}) \pm 0.05\ (\gamma)\ {}^{+0.29}_{-0.40}(\xi)\ {}^{+0.33}_{-0.07}(\Delta\theta)\right]^\circ$$

– $SU(3)$-breaking: $\xi \equiv a/a' = 1 \pm 0.15 \quad , \quad \Delta\theta \equiv \theta - \theta' = \pm 20^\circ.$

- Dependence on the penguin parameters a and θ: $[6\,\text{fb}^{-1}$ and $50\,\text{fb}^{-1}]$



- This matches nicely the LHCb precision for $S(B_d \to J/\psi K_S)$:

$$\Delta(\phi_d + \Delta\phi_d) \sim 1^\circ\ (6\,\text{fb}^{-1}), \quad (0.4\text{–}0.8)^\circ\ (50\,\text{fb}^{-1})$$

Concluding Remarks

- $B_s^0 \to J/\psi K_{\rm S}$ is the U-spin partner of the "golden" $B_d^0 \to J/\psi K_{\rm S}$ mode and allows an extraction of γ and the corresponding penguin parameters.

- The $B_s^0 \to J/\psi K_{\rm S}$ decay has recently been observed by CDF, with a BR which agrees well with an $SU(3)$ relation to $B_d^0 \to J/\psi \pi^0$:

$$\Xi_{SU(3)} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi \bar{K}^0)}{2\mathrm{BR}(B_d^0 \to J/\psi \pi^0)} \frac{\tau_{B_d}}{\tau_{B_s}} \frac{\Phi^d_{J/\psi\pi^0}}{\Phi^s_{J/\psi K_{\rm S}}} = 1.01 \pm 0.25 \stackrel{SU(3)}{\longrightarrow} 1,$$

- We obtain an interesting correlation between $S(B_s \to J/\psi K_{\rm S})$ and $\sin\phi_s$ which serves as a "target region" for the first CPV measurement in $B_s \to J/\psi K_{\rm S}$ and shows an interesting pattern for $(\phi_s)_{\rm tevatron}$.

- Our LHCb feasibility study shows:
  - The $B_{s,d} \to J/\psi K_{\rm S}$ strategy offers another extraction of γ.
  - The major application will be the control of the penguin effects in $(\sin 2\beta)_{J/\psi K_{\rm S}}$, which will allow us to match the experimental precision:

$\to$ may eventually allow us to resolve NP in B_d^0–$\bar{B}_d^0$ mixing.