Controlling Penguin Effects in B Decays

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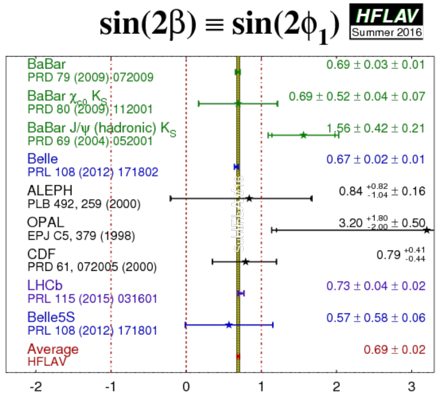
LHCb Implications Workshop

CERN – November 8th, 2017

The B^0–$\bar{B}^0$ Mixing Phase ϕ_d

Experimental Status:



[HFLAV]

Inputs:

Golden Modes . . .

- $B^0 \to J/\psi K^0_S$
- $B^0 \to J/\psi K^0_L$

. . . but also many other $B^0 \to (c\bar{c})K^0$ channels to further boost sensitivity

World Averages:

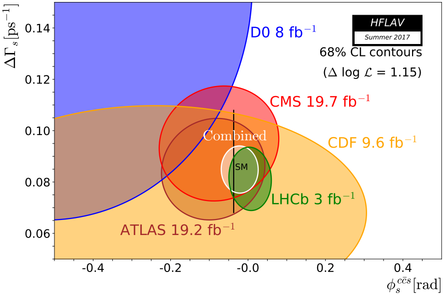
$$\phi_d^{\text{dir}} = [43.7 \pm 1.4]^\circ$$

$$\phi_d^{\text{SM}} = [47.5 \pm 2.3]^\circ$$

[CKMFitter]

The B^0_s–$\bar{B}^0_s$ Mixing Phase ϕ_s

Experimental Status:



[HFLAV]

Inputs:

Golden Mode . . .

- $B^0_s \to J/\psi\,\phi$

. . . but also many other channels to further boost sensitivity, including

- $B^0_s \to D^-_s D^+_s$
- $B^0_s \to K^+ K^-$

World Averages:

$$\phi_s^{\text{dir}} = -0.021 \pm 0.031$$

$$\phi_s^{\text{SM}} = -0.03702^{+0.00064}_{-0.00066}$$

[HFLAV] & [CKMFitter]

Excellent Probes to Search for New Physics

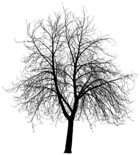
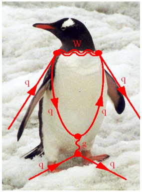
Today:

- Already incredible experimental precision, zooming in on Standard Model expectation

> New physics contributions, if present, will be small
> $\Rightarrow$ Finding it will require much more effort

Tomorrow:

- Entering a new era of precision physics: Aim to reach a precision of $\mathcal{O}(0.5^\circ)$
- Need to have a critical look at assumptions underlying these measurements
- What about subleading contributions?

$|A(B \to f)|^2 = \Big|$  $+ \ \epsilon$ 

$\Big|^2$

> Controlling contributions from penguin topologies becomes mandatory!

Introducing "Penguin Pollution"

Subleading Effects:

- Experimentally measure an effective mixing phase

$$\frac{\mathcal{A}_{CP}^{\rm mix}(B^0_q \to f)}{\sqrt{1 - \left(\mathcal{A}_{CP}^{\rm dir}(B^0_q \to f)\right)^2}} = \sin\left(\phi_q^{\rm eff}\right) = \sin\left(\phi_q^{\rm SM} + \phi_q^{\rm NP} + \Delta\phi_q\right)$$

- Controlling the higher order hadronic corrections is mandatory!
  ...especially if we want to disentangle them from $\phi_q^{\rm NP}$.
- Challenge: Penguin shift $\Delta\phi_q$ is decay mode specific

Dealing with the Strong Interactions

- Non-perturbative, long-distance QCD contributions make determining the shift $\Delta\phi_q$ difficult.
- Theory calculations have been attempted (See for example here or here)
- Preferred option: Data-driven techniques relying on flavour symmetry arguments.

Determining Penguin Pollution

Decay channels already studied in detail:

- $B^0 \to J/\psi K_S^0$ [Fleischer *et al.*; Ciuchini, Silvestrini *et al.*; Jung]
- $B_s^0 \to J/\psi \phi$ [Fleischer *et al.*]
- $B_s^0 \to D_s^- D_s^+$ [Fleischer *et al.*; Jung & Schacht]
- $B_s^0 \to K^+ K^-$ [Fleischer *et al.*; Ciuchini, Silvestrini *et al.*]

More detailed list of references in the Backup

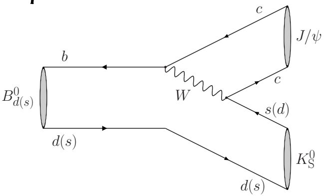
This Talk:

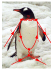
- Briefly discuss each of the four channels
- Will focus on the method(s) proposed by R. Fleischer
- Some numerical updates compared to the latest papers

The Basic Strategy

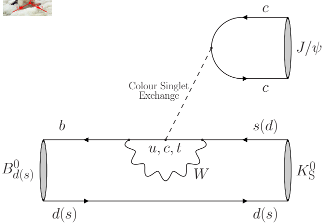
Introducing Trees & Penguins

Tree Topology





Penguin Topology



Decay Amplitude:

$$A(B^0_q \to f) = \mathcal{N}_f \left[1 - b_f e^{i\rho_f} e^{+i\gamma}\right]$$
$$A(\overline{B}^0_q \to f) = \eta_f \mathcal{N}_f \left[1 - b_f e^{i\rho_f} e^{-i\gamma}\right]$$

- $\mathcal{N}_f$: overall normalisation, represents the tree topology,
- b_f: the relative contribution from the penguin topologies,
- ρ_f: the associated strong phase difference,
- γ: UT angle and the associated relative weak phase difference.
- η_f: CP eigenvalue of the final state

Example: $B^0 \to J/\psi K^0_S$ and $B_s^0 \to J/\psi K^0_S$

The Penguin Suppressed Mode:

$$A(B^0 \to J/\psi K^0_S) = \left(1 - \frac{1}{2}\lambda^2\right) \mathcal{A}' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right] , \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.053$$

- Used to measure $\sin\left(\phi_d^{\text{eff}}\right)$

The Penguin Enhanced Mode:

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

- Used to determine a and θ

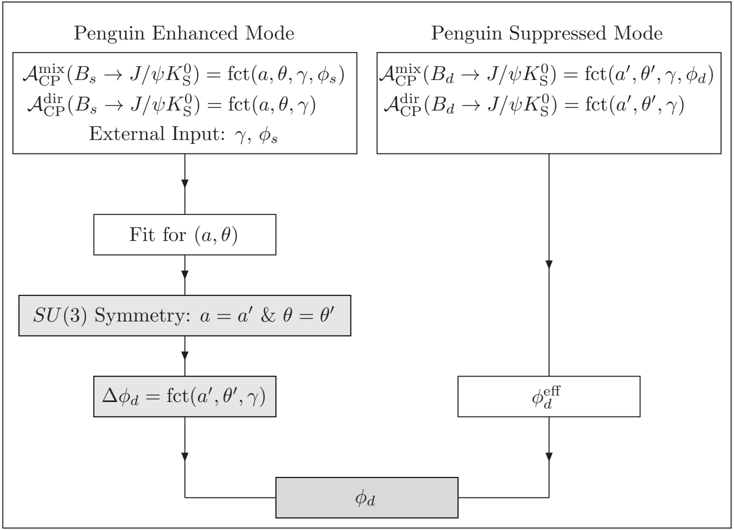
Flavour Symmetry Relation:

- Decays are related via U-spin symmetry: interchange all $s \leftrightarrow d$ quarks
- 1-to-1 correspondance between **all** decay topologies

$$a' = \xi \times a \qquad \& \qquad \theta' = \theta + \delta$$

- ξ and δ are $SU(3)$-breaking parameters; Uncertainty taken to be $\mathcal{O}(20\%)$

The Basic Strategy for Controlling Penguin Effects



Quantity is *Theoretically Clean*   Affected by $SU(3)$-Breaking Effects

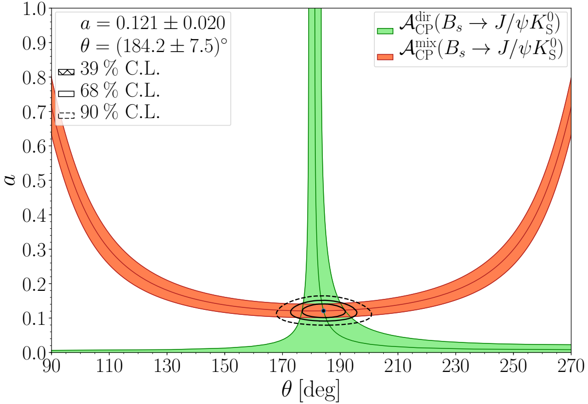
An Illustration for the LHCb Upgrade Phase II (300 fb^{-1})

Hypothetical Scenario:

$$\mathcal{A}_{CP}^{\rm dir}(B_s \to J/\psi K^0_S) = 0.016 \pm 0.028\,, \qquad \gamma = (72.1 \pm 0.4)^\circ$$

$$\mathcal{A}_{CP}^{\rm mix}(B_s \to J/\psi K^0_S) = -0.183 \pm 0.034\,, \qquad \phi_s = -(2.1 \pm 0.5|_{\rm exp} \pm 0.3|_{\rm theo})^\circ$$

Penguin Parameters:

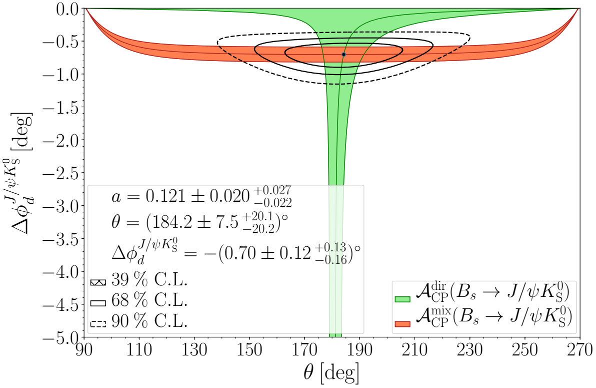


An Illustration for the LHCb Upgrade II Phase (300 fb^{-1})

Translate to $B^0 \to J/\psi K^0_S$:

- Non-factorisable U-spin-breaking corrections enter

$$a' = \xi \times a\,, \qquad \theta' = \theta + \delta \qquad \text{with} \qquad \xi = 1 \pm 0.2\,, \qquad \delta = [0 \pm 20]^\circ$$



- We will be able to control the penguin contributions!

About $SU(3)$ Symmetry Breaking

Amplitudes:

- In terms of the individual amplitudes

$$\mathcal{N}_f \propto \mathcal{A}^{(\prime)} \propto A^c_{\text{tree}} + A^c_{\text{pen}} - A^t_{\text{pen}}$$

- and

$$b_f\, e^{i\rho_f} \propto a^{(\prime)} e^{i\theta^{(\prime)}} \propto R_b \left(\frac{A^u_{\text{pen}} - A^t_{\text{pen}}}{A^c_{\text{tree}} + A^c_{\text{pen}} - A^t_{\text{pen}}} \right)$$

Factorisation Framework:

- $SU(3)$ symmetry breaking in A_{tree} and A_{pen} comes in two flavours:
  factorisable effects and non-factorisable effects
- Non-factorisable effects are suppressed
- Leading contribution to $\mathcal{N}_f$ is factorisable $SU(3)$ symmetry breaking: Dangerous
- But factorisable effects drop out in the ratio b_f: A lot less affected

Penguin Contributions to $B^0 \to J/\psi\, K^0_{\mathrm{S}}$

Current Constraints from $B^0_s \to J/\psi K^0_S$

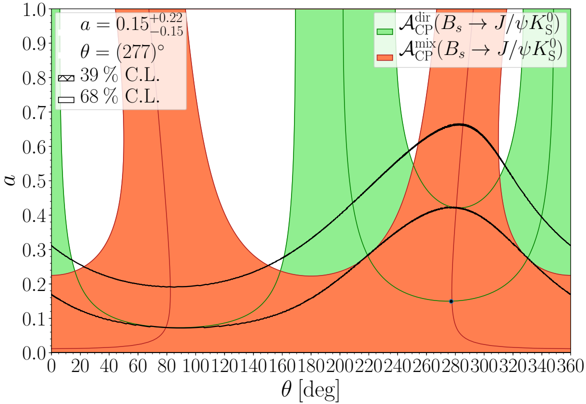
Inputs:

$$\mathcal{A}_{CP}^{\rm dir}(B_s \to J/\psi K^0_S) = -0.28 \pm 0.42\,, \qquad \gamma = (72.1 \pm 5.8)^\circ$$

$$\mathcal{A}_{CP}^{\rm mix}(B_s \to J/\psi K^0_S) = 0.08 \pm 0.41\,, \qquad \phi_s = -(3.3 \pm 2.8)^\circ$$

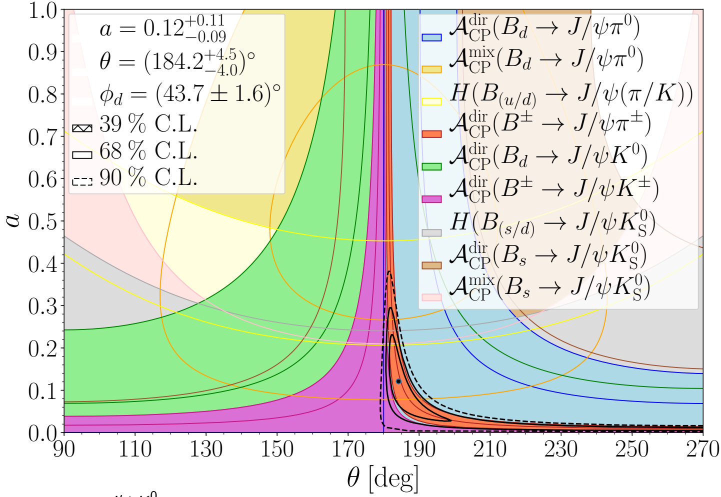
[LHCb, arxiv:1503.07055 [hep-ex]]

Penguin Parameters:



Current Constraints from $B^0_q \to J/\psi P$ Decays

- Additional assumptions apply

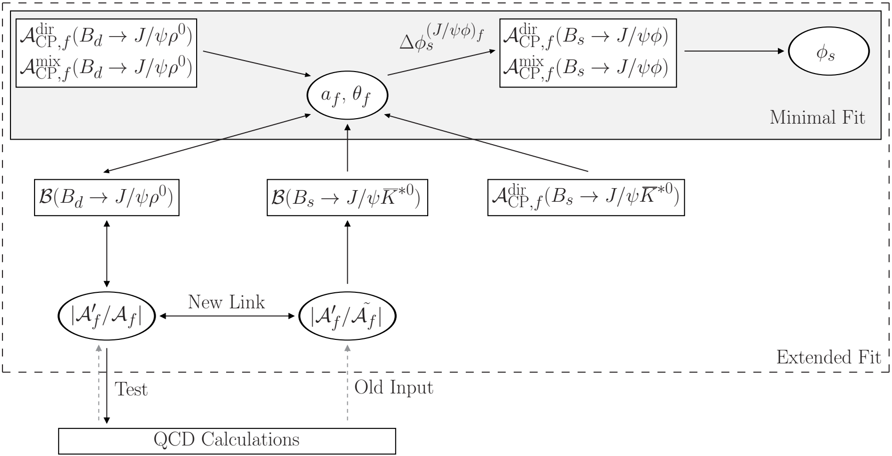


- Obtain $\Delta\phi_d^{J/\psi K^0_S} = -(0.71^{+0.56}_{-0.65})^\circ$, ignoring possible $SU(3)$ breaking

updated from [KDB, R. Fleischer, arxiv:1412.6834 [hep-ph]]

Penguin Contributions to $B_s^0 \to J/\psi \phi$

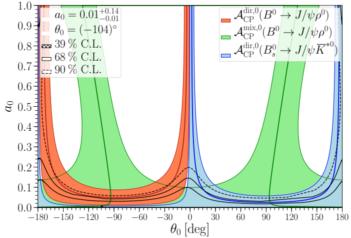
$B^0_q \to J/\psi V$ Fit Strategy



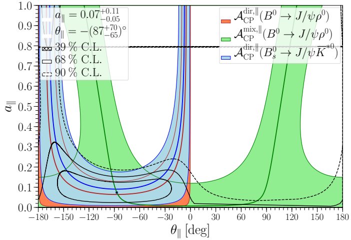
[KDB, R. Fleischer, arxiv:1412.6834 [hep-ph]]

Current Constraints from $B_q^0 \to J/\psi\, V$ Decays

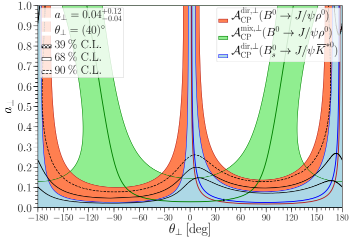
Longitudinal



Parallel



Perpendicular



$$\Delta\phi_s^{(J/\psi\,\phi)_0} = -\left(0.01^{+0.79}_{-0.59}\right)^\circ$$

$$\Delta\phi_s^{(J/\psi\,\phi)_\parallel} = \left(0.02^{+0.67}_{-0.94}\right)^\circ$$

$$\Delta\phi_s^{(J/\psi\,\phi)_\perp} = \left(0.17^{+0.68}_{-0.93}\right)^\circ$$

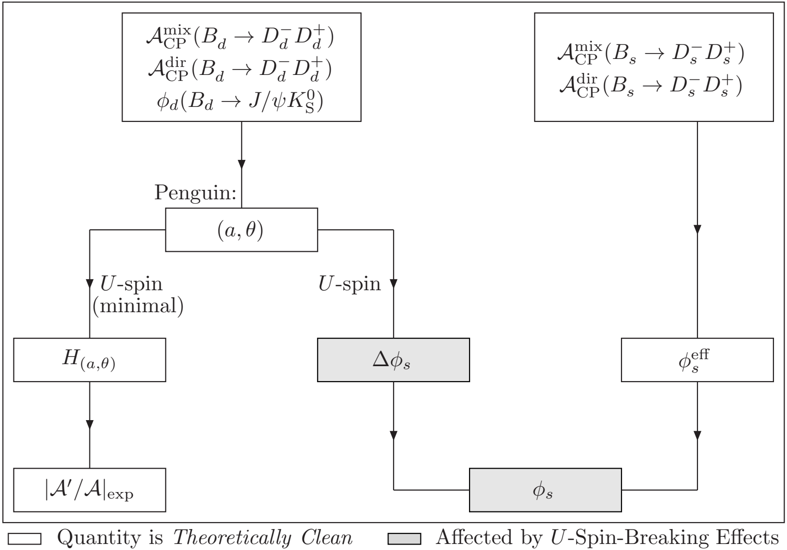
updated from

[LHCb, arxiv:1509.00400 [hep-ex]]

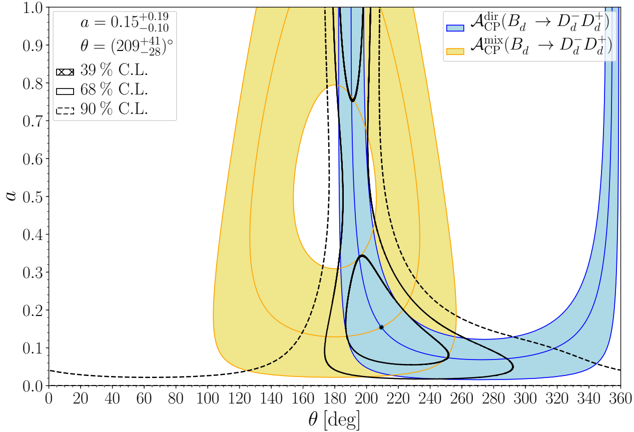
We can already control the penguin effects!

Penguin Contributions to $B^0_s \to D^-_s D^+_s$ Decays

Classic Strategy



Current Constraints from $B^0 \to D_d^- D_d^+$



$$\phi_{s,D_s^- D_s^+}^{\rm eff} = (1.1 \pm 9.7 \pm 1.1)^\circ$$

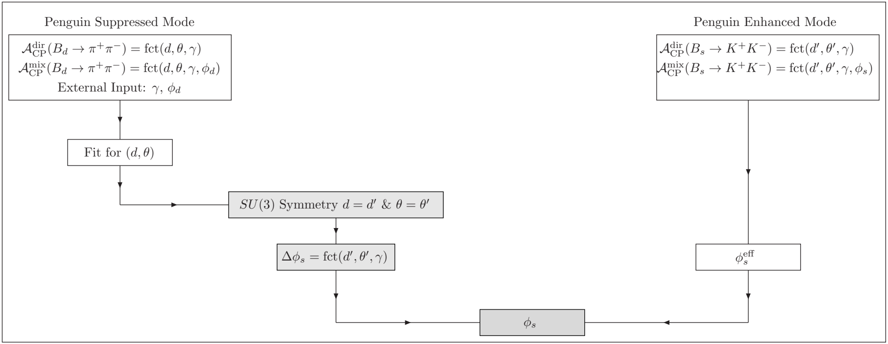
$$\Delta\phi_s^{D_s^- D_s^+} = -(0.78^{+0.65}_{-1.14}\,(\text{stat})^{+0.15}_{-0.33}\,(U\text{-spin}))^\circ$$

$$\phi_s = (0.36 \pm 9.87\,(\text{stat}) \pm 0.34\,(U\text{-spin}))^\circ$$

updated from [L. Bel, KDB, R. Fleischer, M. Mulder, N. Tuning, arxiv:1505.01361 [hep-ph]]

Penguin Contributions to $B^0_s \to K^+K^-$

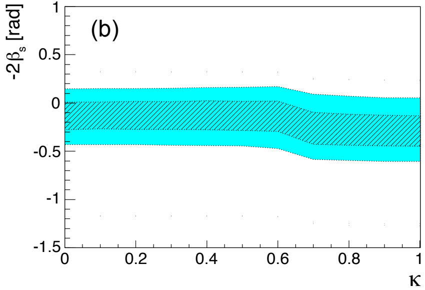
Classic Strategy



Quantity is *Theoretically Clean* | Affected by $SU(3)$-Breaking Effects

Classic Strategy

- Strategy already adopted by LHCb

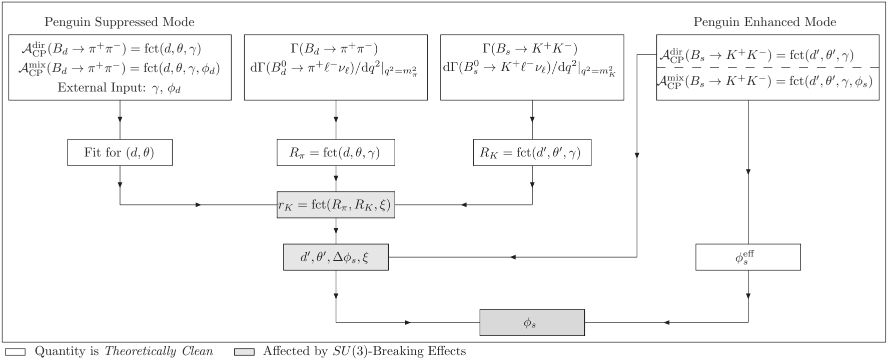


$$\phi_s = -\left(6.9^{+9.2}_{-8.0}\right)^\circ$$

[LHCb, arxiv:1408.4368 [hep-ex]]

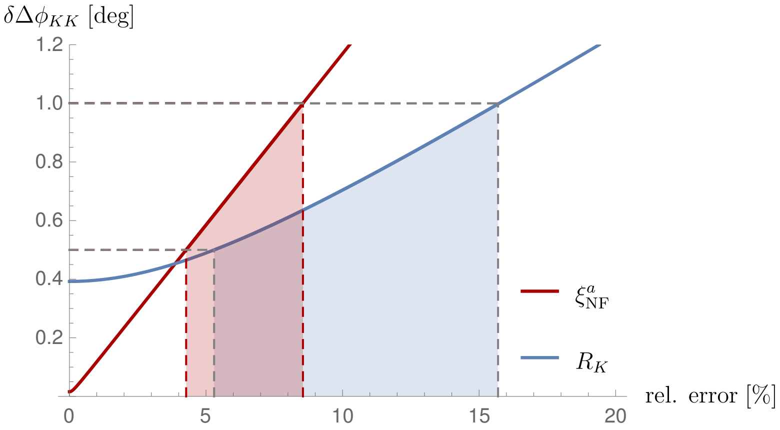
- Compared to $B \to J/\psi X$ and $B \to D\bar{D}$, different CKM structure for decay topologies
- Will quickly be limited by $SU(3)$-breaking uncertainties
- Challenging to reduce uncertainties below $\mathcal{O}(5^\circ)$
- This strategy cannot match the experimental precision in the upgrade era

New Strategy using Semileptonic Decays



[R. Fleischer, R. Jaarsma, K. Vos, arxiv:1608.00901 [hep-ph]]

New Strategy using Semileptonic Decays



[R. Fleischer, R. Jaarsma, K. Vos, arxiv:1608.00901 [hep-ph]]

Conclusion

- Controlling higher order corrections to ϕ_d and ϕ_s becomes mandatory
- Illustrated various strategies to get these corrections directly from data based on $SU(3)$ flavour symmetry
  - $B^0 \to J/\psi\, K^0_{\rm S}$
  - $B_s^0 \to J/\psi\, \phi$
  - $B_s^0 \to D_s^- D_s^+$
  - $B_s^0 \to K^+ K^-$
- With current data, penguin effects in many channels already controlled at $\mathcal{O}(1^\circ)$
- With these strategies we will be able to control the penguin effects sufficiently well for the Upgrade Era

Back-up

References

- General framework/Multiple decay channels

[R. Fleischer, arxiv:hep-ph/9903455]

[R. Fleischer, arxiv:hep-ph/9908340]

- $B \to J/\psi X$ Decays: High Precision measurements of ϕ_d and ϕ_s

[M. Ciuchini, M. Pierini, L. Silvestrini, arxiv:hep-ph/0507290]

[S. Faller, R. Fleischer, M. Jung, T. Mannel, arxiv:0809.0842 [hep-ph]]

[S. Faller, R. Fleischer, T. Mannel, arxiv:0810.4248 [hep-ph]]

[M. Ciuchini, M. Pierini, L. Silvestrini, arxiv:1102.0392 [hep-ph]]

[M. Jung, arxiv:1212.4789 [hep-ph]]

[KDB, R. Fleischer, arxiv:1412.6834 [hep-ph]]

[P. Frings, U. Nierste, M. Wiebusch, arxiv:1503.00859 [hep-ph]]

References

- $B \to D\overline{D}$ Decays: Precision measurements of ϕ_s

[R. Fleischer, arxiv:0705.4421 [hep-ph]]
[M. Jung, S. Schacht, arxiv:1410.8396 [hep-ph]]
[L. Bel, KDB, R. Fleischer, M. Mulder, N. Tuning, arxiv:1505.01361 [hep-ph]]

- $B \to hh$ Decays: Precision measurements of ϕ_s

[R. Fleischer, arxiv:0705.1121 [hep-ph]]
[R. Fleischer, R. Knegjens, arxiv:1011.1096 [hep-ph]]
[M. Ciuchini, E. Franco, S. Mishima, L. Silvestrini, arxiv:1205.4948 [hep-ph]]
[R. Fleischer, R. Jaarsma, K. Vos, arxiv:1608.00901 [hep-ph]]
[R. Fleischer, R. Jaarsma, K. Vos, arxiv:1612.07342 [hep-ph]]

Dependence on Penguin Parameters

CP Asymmetries:

$$\mathcal{A}_{CP}^{\rm dir}(B_q \to f) = \frac{2\, b_f \sin\rho_f \sin\gamma}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2}$$

$$\mathcal{A}_{CP}^{\rm mix}(B_q \to f) = \eta_f \left[\frac{\sin\phi_q - 2\, b_f \cos\rho_f \sin(\phi_q + \gamma) + b_f^2 \sin(\phi_q + 2\gamma)}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2}\right]$$

$$\mathcal{A}_{\Delta\Gamma}(B_q \to f) = -\eta_f \left[\frac{\cos\phi_q - 2\, b_f \cos\rho_f \cos(\phi_q + \gamma) + b_f^2 \cos(\phi_q + 2\gamma)}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2}\right]$$

Penguin Shift:

$$\sin\Delta\phi_q^f = \frac{-2\, b_f \cos\rho_f \sin\gamma + b_f^2 \sin 2\gamma}{\left(1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2\right)\sqrt{1 - \left(\mathcal{A}_{CP}^{\rm dir}(B \to f)\right)^2}}$$

$$\cos\Delta\phi_q^f = \frac{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2 \cos 2\gamma}{\left(1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2\right)\sqrt{1 - \left(\mathcal{A}_{CP}^{\rm dir}(B \to f)\right)^2}}$$

The H Observable

One More Observable:

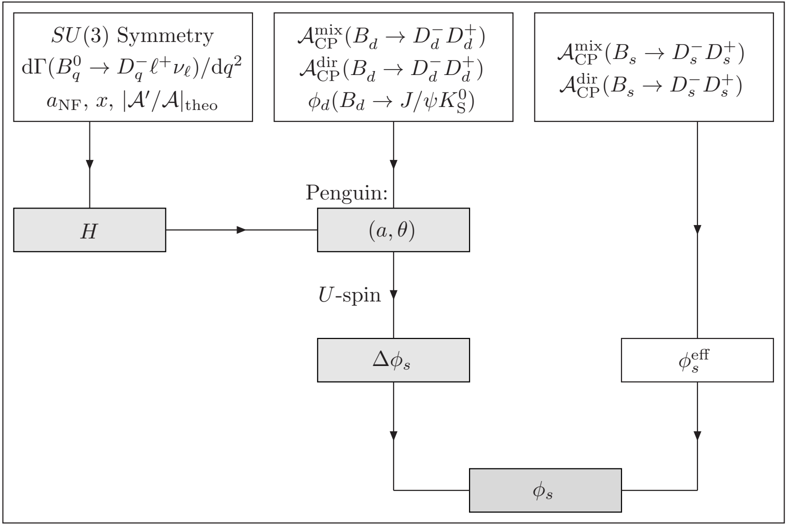
- Also decay rate contains information on the penguin parameters

$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \frac{\text{PhSp}\left(B_d \to J/\psi K^0_S\right)}{\text{PhSp}\left(B_s \to J/\psi K^0_S\right)} \frac{\tau_{B^0}}{\tau_{B^0_s}} \frac{\mathcal{B}\left(B_s \to J/\psi K^0_S\right)}{\mathcal{B}\left(B_d \to J/\psi K^0_S\right)}$$
$$= \frac{1 - 2\, a \cos\theta \cos\gamma + a^2}{1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2}$$

- Affected by factorisable $SU(3)$ symmetry breaking through $|\mathcal{A}'|/|\mathcal{A}|$
- Today: Necessary to constrain penguin effects with available data
- Tomorrow: avoid as input

→ Use it to experimentally constrain $|\mathcal{A}'|/|\mathcal{A}|$ instead

Alternative Strategy for $B_s^0 \to D_s^- D_s^+$



Quantity is *Theoretically Clean* — Affected by U-Spin-Breaking Effects