Taming Penguins: Towards High Precision Measurements in ϕ_d and ϕ_s

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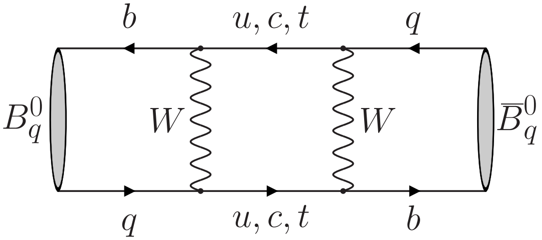
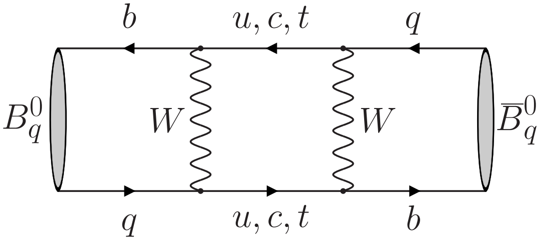
Mixing Between Neutral B_q^0 and $\bar{B}_q^0$ Mesons

- SM process: Flavour Changing Neutral Current



- Associated phase:
  - B_d system: $\phi_d^{\text{SM}} \equiv 2\arg\left(V_{td}^* V_{tb}\right) = 2\beta$
  - B_s system: $\phi_s^{\text{SM}} \equiv 2\arg\left(V_{ts}^* \; V_{tb}\right) = -2\lambda^2\eta$
- Important test of SM paradigm
- Sensitive to Beyond the Standard Model processes

- SM process: Flavour Changing Neutral Current



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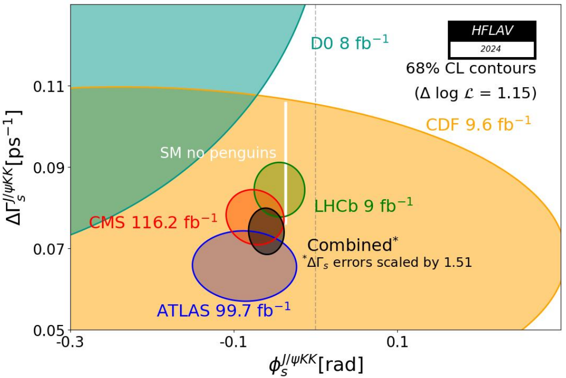
- Important test of SM paradigm
- Sensitive to Beyond the Standard Model processes

- High profile measurements for

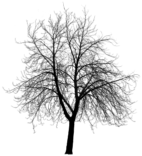
  Tevatron, B-factories, LHC experiments



HFLAV

- Experimentally looking for: high yield & “simple” interpretation
  - Measuring ϕ_d: $B_d^0 \to J/\psi K^0$
  - Measuring ϕ_s: $B_s^0 \to J/\psi \phi$
- At leading order

$$|A(B_q^0 \to f)|^2 = \left| \qquad \right|^2$$



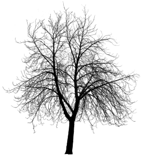
- Time-dependent CP asymmetry

$$a_{\rm CP}(t) \equiv \frac{|A(B_q^0(t) \to f)|^2 - |A(\bar{B}_q^0(t) \to f)|^2}{|A(B_q^0(t) \to f)|^2 + |A(\bar{B}_q^0(t) \to f)|^2} \qquad \propto \qquad \sin\phi_q \sin(\Delta m_q t)$$

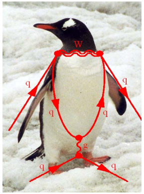
Penguins Muddying the Waters

- Aiming for high precision measurements (Belle-II, HL-LHC)
- Important to take into account next-to-leading order effects! $(\epsilon \approx 0.052)$

$$|A(B_q^0 \to f)|^2 = \Bigg|$$



$$+ \ \epsilon$$



$$\Bigg|^2$$

- Time-dependent CP asymmetry

$$a_{\rm CP}(t) \equiv \frac{|A(B_q^0(t) \to f)|^2 - |A(\bar{B}_q^0(t) \to f)|^2}{|A(B_q^0(t) \to f)|^2 + |A(\bar{B}_q^0(t) \to f)|^2} = \frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta m_q t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)}$$

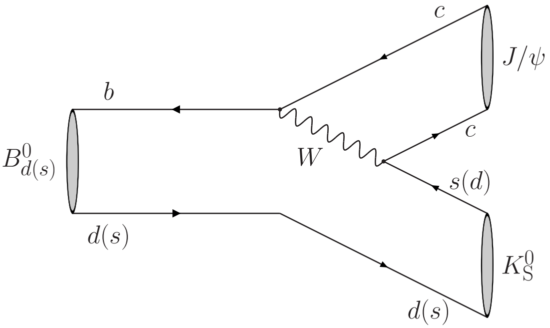
- Measure an effective mixing phase

$$\phi_{q,f}^{\rm eff} \equiv \phi_q + \Delta\phi_q^f = \phi_q^{\rm SM} + \phi_q^{\rm NP} + \Delta\phi_q^f \ ,$$

- $\phi_q^{\rm NP}$ and $\Delta\phi_q^f$ could be of the same order

- $\Delta\phi_q^f$ is dominated by non-perturbative, long-distance QCD contributions
- Preferred strategy: Data-driven techniques relying on $SU(3)$ flavour symmetry arguments:

  In the limit of massless quarks, QCD does not differentiate between u, d and s



Example

- $B_d^0 \to J/\psi K_S^0$ is related to $B_s^0 \to J/\psi K_S^0$ by exchanging all $d \leftrightarrow s$ quarks
- Same QCD effects (Assumption)
- Different CKM dependence

Data-Driven $SU(3)$ Flavour Symmetry Strategy

1. Find a control channel where contributions from penguin topologies are not suppressed
2. Experimentally measure the CP asymmetries of the control mode
3. Estimate the size of the penguin effects using these CP asymmetries
4. Invoke $SU(3)$ flavour symmetry to relate the results back to the decay channel measuring ϕ_q^{eff}
5. Estimate $\Delta\phi_q^f$ ... based on the size of the penguin effects in the control mode
6. Main systematic uncertainty: $SU(3)$ symmetry breaking

Introducing the Penguin Parameters

The Penguin-Suppressed Mode:

$$A(B_d^0 \to J/\psi K_S^0) = \left(1 - \frac{1}{2}\lambda^2\right) \mathcal{A}' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right] , \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.052$$

- $\mathcal{A}'$: overall normalisation, dominated by contribution from the tree topology
- a': the relative contribution from the penguin topologies
- θ': the associated strong phase difference
- γ: UT angle and the associated relative weak phase difference.

The Penguin-Enhanced Mode:

$$A(B_s^0 \to J/\psi K_S^0) = -\lambda \mathcal{A} \left[1 - a e^{i\theta} e^{i\gamma}\right] , \qquad \lambda \approx 0.223$$

Applying the $SU(3)$ Flavour Symmetry Strategy

1. Use CP asymmetries in $B_s^0 \to J/\psi K_S^0$ to determine a and θ (theoretically clean)

$$\mathcal{A}_{\rm CP}^{\rm dir} = \text{function}(a, \theta, \gamma)$$

$$\mathcal{A}_{\rm CP}^{\rm mix} = \text{function}(a, \theta, \gamma, \phi_s)$$

- γ and ϕ_s are external inputs

2. Use $SU(3)$ symmetry relation (assumption)

$$a' = a \qquad \& \qquad \theta' = \theta$$

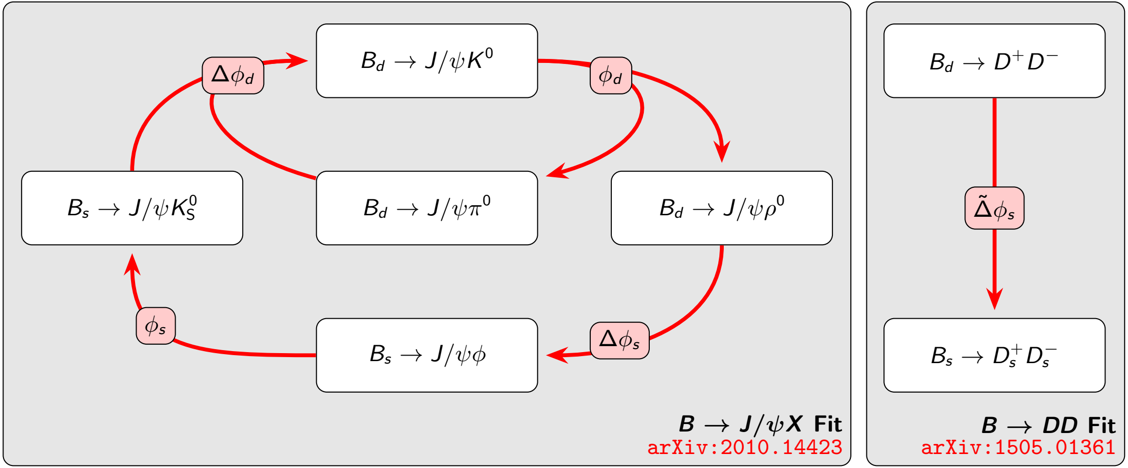
3. Determine the penguin shift $\Delta\phi_d$

$$\Delta\phi_d^{J/\psi K} = \text{function}(a', \theta', \gamma)$$

4. Correct effective mixing phase

$$\phi_d = \phi_{d,J/\psi K}^{\rm eff} - \Delta\phi_d^{J/\psi K}$$

Fit Scenarios



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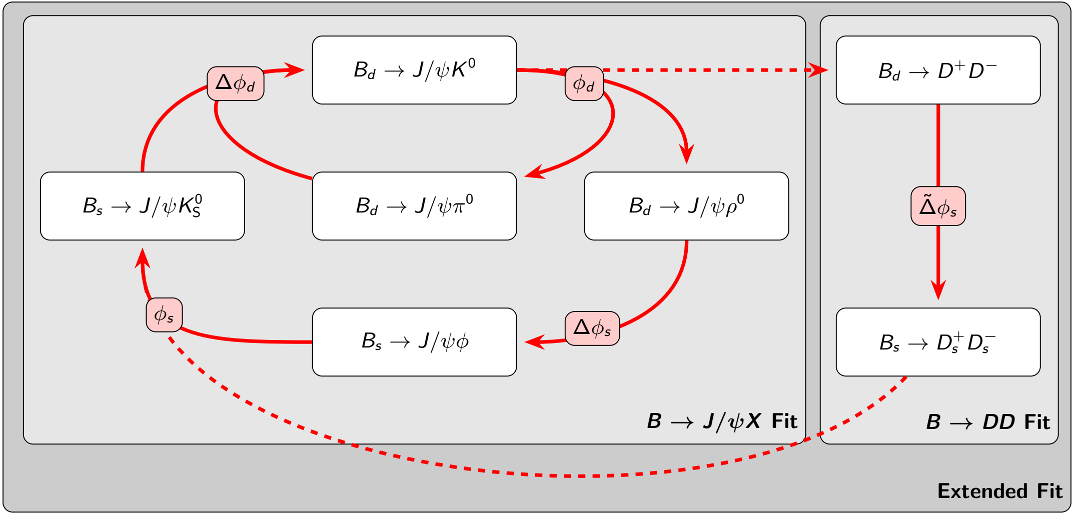


What's New?

$B_d^0 \to J/\psi\pi^0$

- New CP asymmetry measurement from Belle-II arXiv:2410.08622

$$\mathcal{A}_{\text{dir}}^{\text{CP}}(B_d^0 \to J/\psi\pi^0) = 0.13 \pm 0.12(\text{stat}) \pm 0.03(\text{syst})$$
$$\eta_{\text{CP}}\mathcal{A}_{\text{mix}}^{\text{CP}}(B_d^0 \to J/\psi\pi^0) = 0.88 \pm 0.17(\text{stat}) \pm 0.03(\text{syst})$$

- Similar precision to the HFLAV world average (BaBar + Belle)

$B_d^0 \to D^+D^-$ and $B_s^0 \to D_s^+D_s^-$

- New CP asymmetry measurements from LHCb arXiv:2409.03009

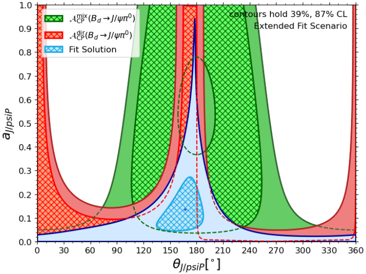
$$\mathcal{A}_{\text{dir}}^{\text{CP}}(B_d^0 \to D^+D^-) = 0.128 \pm 0.103(\text{stat}) \pm 0.010(\text{syst})$$
$$\eta_{\text{CP}}\mathcal{A}_{\text{mix}}^{\text{CP}}(B_d^0 \to D^+D^-) = 0.552 \pm 0.100(\text{stat}) \pm 0.010(\text{syst})$$

- Similar precision to the HFLAV world average (BaBar + Belle + LHCb)

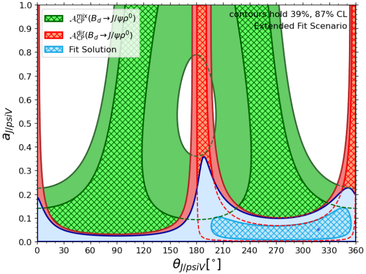
$$\phi_s^{\text{eff}} = -0.055 \pm 0.090(\text{stat}) \pm 0.021(\text{syst})$$
$$\lambda_{D_sD_s} = 1.054 \pm 0.099(\text{stat}) \pm 0.020(\text{syst})$$

Fit Results: Penguin Parameters

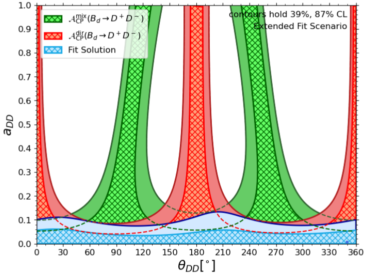
$B \to J/\psi$+Pseudo-Scalar



$B \to J/\psi$+Vector



$B \to DD$



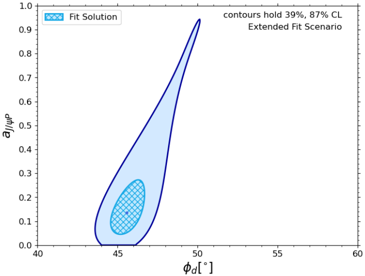
$$a_{J/\psi P} = 0.14^{+0.14}_{-0.09} \qquad a_{J/\psi V} = 0.052^{+0.092}_{-0.045} \qquad a_{DD} = 0.007^{+0.054}_{-0.007}$$

$$\theta_{J/\psi P} = \left(167^{+21}_{-32}\right)^\circ \qquad \theta_{J/\psi V} = \left(317^{+38}_{-120}\right)^\circ \qquad \theta_{DD} = \left(350^{+10}_{-350}\right)^\circ$$

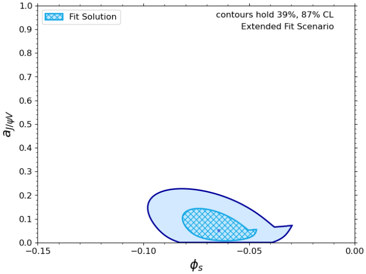
- Current data suggests the penguin effects are small, but improved precision more than welcome!

Fit Results: Mixing Phases

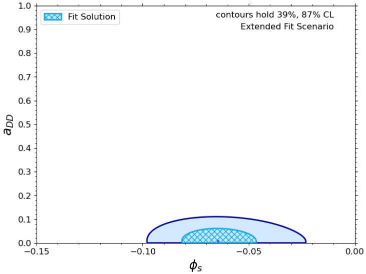
$B \to J/\psi$+Pseudo-Scalar



$B \to J/\psi$+Vector



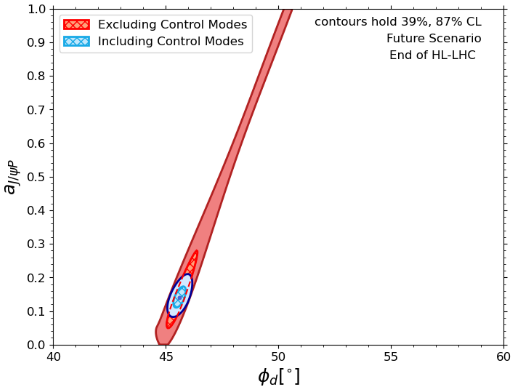
$B \to DD$

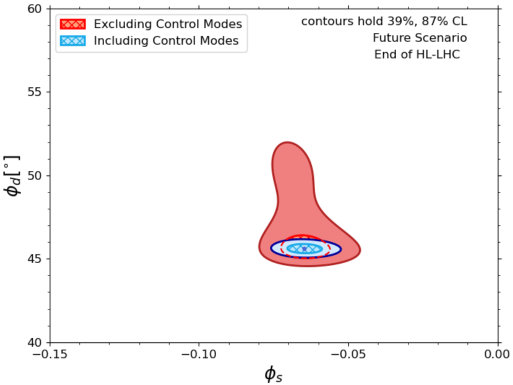


$$\phi_d = \left(45.6^{+1.1}_{-1.0}\right)^\circ \quad \text{vs} \quad \phi_d^{\text{eff}} = (45.12 \pm 0.94)^\circ$$

$$\phi_s = -0.065^{+0.019}_{-0.017} \quad \text{vs} \quad \phi_s^{\text{eff}} = -0.061 \pm 0.014$$

A Look into the Future: What could we get after the HL-LHC?





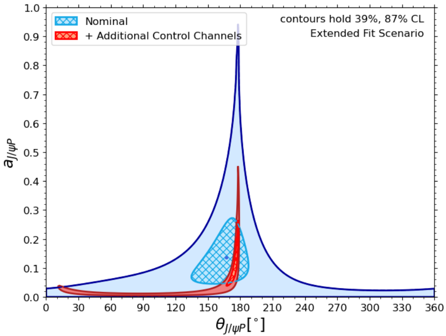
- The penguin control modes need to get higher priority at HL-LHC/Belle-II if we want to capitalise on the increased statistics they will offer.
- ϕ_d: expect 30% improvement, another 25% to 50% when updating penguin control modes
- ϕ_s: expect 50% improvement, another 15% to 30% when updating penguin control modes

Can we add more penguin control modes?

- Additional $SU(3)$-symmetry partners:
  - $B^+ \to J/\psi\pi^+$
  - $B^+ \to J/\psi K^+$
  - $B_s^0 \to J/\psi\bar{K}^{*0}$
- Additional assumptions
- New CP asymmetry measurement from LHCb
  arXiv:2411.12178

$$\mathcal{A}_{\rm dir}^{\rm CP}(B^+ \to J/\psi\pi^+) = (1.51 \pm 0.50({\rm stat}) \pm 0.08({\rm syst})) \times 10^{-2}$$

$B \to J/\psi$+Pseudo-Scalar



$$a_{J/\psi P} = 0.14^{+0.14}_{-0.09} \Rightarrow 0.13^{+0.13}_{-0.09}$$

$$\theta_{J/\psi P} = \left(167^{+21}_{-32}\right)^\circ \Rightarrow \left(176.0^{+0.6}_{-9.7}\right)^\circ$$

Conclusion

- Data-driven $SU(3)$ flavour symmetry strategy to control penguin contributions to ϕ_d^{eff} and ϕ_s^{eff} from
  - $B_d^0 \to J/\psi K^0$
  - $B_s^0 \to J/\psi \phi$
  - $B_s^0 \to D_s^+ D_s^-$
- Results from Current Data

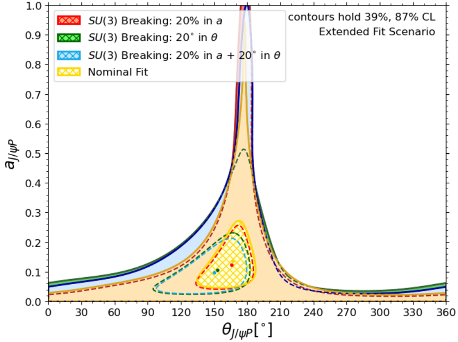
$$\phi_s = -0.065^{+0.019}_{-0.017}\,(\text{fit}) \pm 0.002\,(\text{syst}) = \left(-3.72^{+1.09}_{-0.97}\,(\text{fit}) \pm 0.11\,(\text{syst})\right)^\circ$$

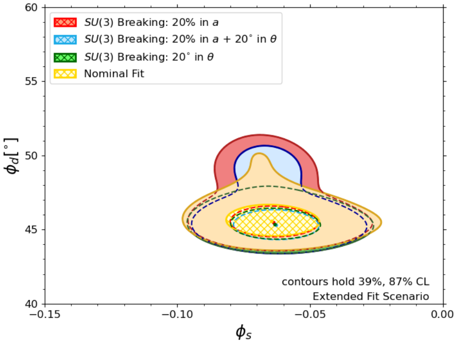
$$\phi_d = \left(45.6^{+1.1}_{-1.0}\,(\text{fit}) \pm 0.3\,(\text{syst})\right)^\circ$$

- Including recent measurements of penguin control modes from Belle-II and LHCb
- Improving our understanding of the penguin effects with future data is critical to benefit from HL-LHC and Belle-II programmes.

Backup

Impact of Potential $SU(3)$ Symmetry Breaking





- Let's assume the $SU(3)$ symmetry relation is not perfect

$$a = x_{SU(3)} \cdot a' \,, \qquad \theta = \theta' + y_{SU(3)}$$

- Add $x_{SU(3)}$ and $y_{SU(3)}$ as external constraints
- Introduces shifts to the penguin parameters
- But almost no impact on ϕ_d and ϕ_s