Hunting Penguins: Towards high precision *CP* violation measurements in the *B* meson systems

K. De Bruyn and R. Fleischer, arXiv:1412.6834 (to appear in JHEP)

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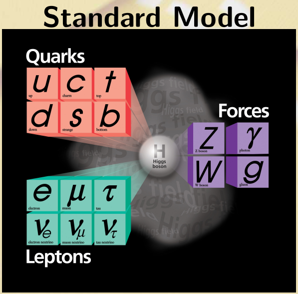
The Standard Model . . .

Neutrino Masses?

Family Symmetry?

Matter–Anti-Matter Asymmetry?



Strong *CP* Problem?

Hierarchy Problem?

Quantize Gravity & General Relativity?

Neutrinos: Dirac or Majorana?

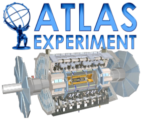
Dark Matter & Dark Energy?

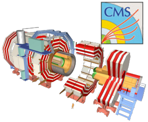
. . . and Beyond: Searching for New Physics

The LHC: Two Complementary Strategies

Direct Observation (Energy Frontier)

Search for new particles



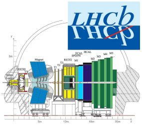


Primary Focus:

- Higgs measurements
- Supersymmetry searches
- . . .

Indirect Evidence (Precision Frontier)

Study quantum loop effects

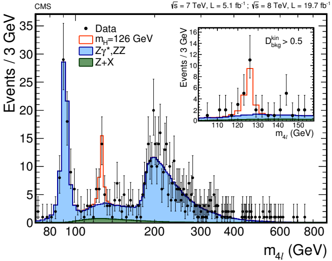


Primary Focus:

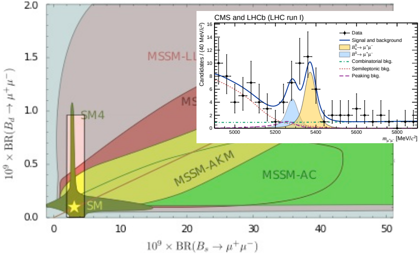
- Flavour physics
- Rare Decays
- *CP* Violation

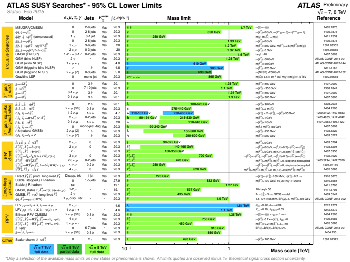
Three Years of LHC Data: Some Highlights

Discovered a Higgs particle

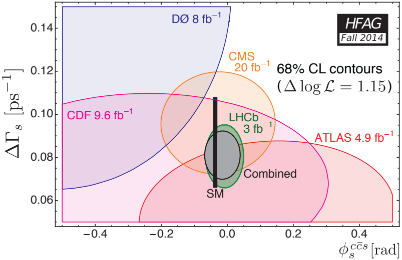


Measured $B_s^0 \to \mu^+\mu^-$ Branching Ratio





Searched for Supersymmetry



Constrained B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s

Searching for New Physics 2: Search Harder

Conclusion:

New physics contributions, if present, will be small

$\Downarrow$

Finding it will require much more effort, both on experimental and theoretical side!

Because: Rely on interplay between

$\swarrow$ $\searrow$

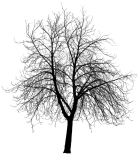
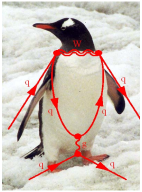
High precision measurements $\Leftrightarrow$ Accurate Standard Model predictions

For Flavour Physics:

- Primary objective for the LHCb and Belle II programmes
- Further input from theory side is needed

Towards High Precision Measurements of ϕ_d and ϕ_s

- The decay channels $B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi \phi$ are key modes to measure the complex phases "ϕ_d" and "ϕ_s"
- Current precision: $\mathcal{O}(2^\circ)$
- Entering a new era of precision physics: aim to improve to $\mathcal{O}(0.5^\circ)$
- Need to have a critical look at assumptions underlying these measurements
- What about subleading contributions?

$$|A(B \to J/\psi X)|^2 = \Big|$$  $$+\ \epsilon$$ 

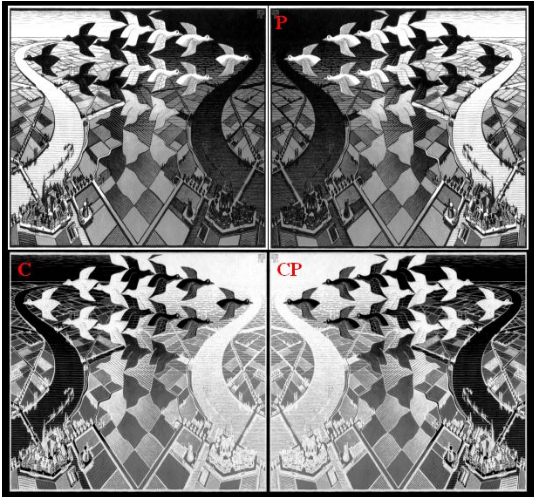
$$\Big|^2$$

- Controlling contributions from penguin topologies becomes mandatory!

Flavour Physics

Charge–Parity Symmetry

An Illustration:



[Escher, *Day and Night*]

Origin of *CP* Violation in the Standard Model

Yukawa Couplings:

- Quark masses in the Standard Model:

$$\mathcal{L}_{\text{Yukawa}} \equiv \sum_{i,j} Y_u^{ij} \left(\overline{Q_{L,i}} \cdot i\sigma_2 H^* \right) u_{R,j} + \sum_{i,j} Y_d^{ij} \left(\overline{Q_{L,i}} \cdot H \right) d_{R,j} + \text{h.c.} \tag{1}$$

$\downarrow$ Spontaneous symmetry breaking

$$\mathcal{L}_{\text{mass}} = \sum_{i,j} m_u^{ij} \overline{u_{L,i}} u_{R,j} + \sum_{i,j} m_d^{ij} \overline{d_{L,i}} d_{R,j} + \text{h.c.} \tag{2}$$

- But in general m_u and m_d are not diagonal ...

Diagonalise the Mass Matrix:

- Flavour Changing Charged Current:

$$i \frac{g_{\text{EW}}}{\sqrt{2}} W_\mu^+ \overline{\mathbf{u}}_L \gamma^\mu \mathbf{d}_L + \text{h.c.} \quad \to \quad i \frac{g_{\text{EW}}}{\sqrt{2}} W_\mu^+ \overline{\mathbf{u}}_L^m \mathbf{V}_{\text{CKM}} \gamma^\mu \mathbf{d}_L^m + \text{h.c.} \tag{3}$$

- Basis of Weak interaction is rotated compared to that of Strong and EM:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \mathbf{V}_{\text{CKM}} \begin{pmatrix} d^m \\ s^m \\ b^m \end{pmatrix} \tag{4}$$

The Cabibbo–Kobayashi–Maskawa Quark Mixing

Standard Parametrisation:

$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & |V_{ts}|e^{-i\beta_s} & |V_{tb}| \end{pmatrix} \quad (5)$$

- Expanding [Wolfenstein] the CKM matrix as

$$\boxed{|V_{us}| \equiv \lambda}\,, \qquad |V_{cb}| \equiv A\lambda^2\,, \qquad V_{ub} \equiv A\lambda^3(\rho - i\eta) \quad (6)$$

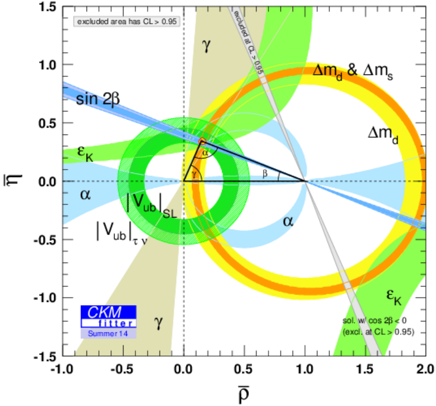
$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (7)$$

The Unitarity Triangle: Visualizing *CP* Violation

- $\mathbf{V}_{\text{CKM}}$ is a unitary matrix: leads to constraints like

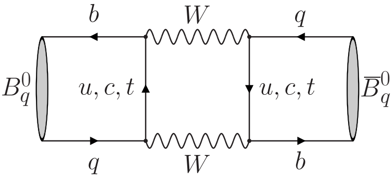
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad (8)$$

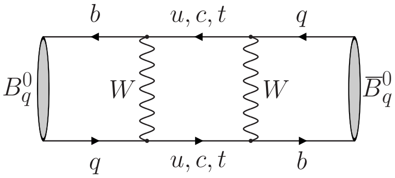
- These form triangles in the complex plane.
- Excellent test for Standard Model & target to search for New Physics



The "B_q^0–$\overline{B}_q^0$ Mixing Phases"

Neutral Meson Mixing





- Complex phase associated with mixing process

$$\phi_q \equiv 2\arg(V_{tq}^* V_{tb}) \tag{9}$$

- In the Standard Model

$$\phi_d^{SM} = 2\beta \quad , \quad \phi_s^{SM} = 2\beta_s = -2\lambda^2\eta = -[0.0364 \pm 0.0016] \text{ rad} \tag{10}$$

- Measured in $B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi \phi$, respectively

[Disclaimer: These quantities are convention dependent, but their associated observables are, of course, not.]

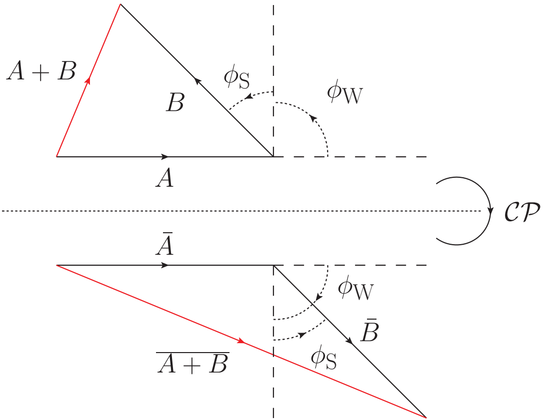
Measuring *CP* Violation: Interfering Paths

Necessary Conditions:

- Two interfering amplitudes

$$\mathcal{A}(P \to f) = A + B\, e^{+i\phi_W}\, e^{+i\phi_S} \quad \overset{\text{CP}}{\longleftrightarrow} \quad \mathcal{A}(\bar{P} \to \bar{f}) = \bar{A} + \bar{B}\, e^{-i\phi_W}\, e^{+i\phi_S} \tag{11}$$

- One relative weak phase (CP odd) + one relative strong phase (CP even)



- "Direct *CP* Violation"

$$|A + B| \neq |\overline{A + B}|$$

Sources of *CP* Violation

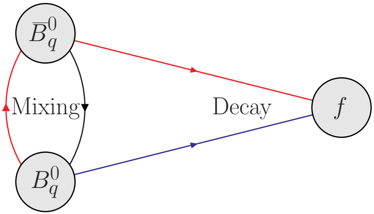
Direct *CP* Violation: $\text{Prob}(B \to f) \neq \text{Prob}(\bar{B} \to \bar{f})$

- Interference between multiple decay paths (for example: Tree + Penguin diagrams)
- Key Measurements: $B_q^0 \to h^+ h^-$; γ from $B^\pm \to D^0 h^\pm$ where $h \in \{\pi, K\}$

CP Violation in Mixing: $\text{Prob}(B_q^0 \to \bar{B}_q^0) \neq \text{Prob}(\bar{B}_q^0 \to B_q^0)$

- Interference through Virtual (loops) and Real (intermediate decay) contributions
- Key Measurements: Semi-leptonic asymmetries a_{sl}^s & a_{sl}^d from $B_q^0 \to D_q^- \mu^+ \nu$

Sources of *CP* Violation



Mixing-Induced *CP* Violation: $\text{Prob}(B_q^0 \to f) \neq \text{Prob}(B_q^0 \to \overline{B}_q^0 \to f)$

- Interference between direct decay and decay after mixing
- Key Measurements: β from $B^0 \to J/\psi\, K_S^0$; ϕ_s from $B_s^0 \to J/\psi\, h^+ h^-$

Time-Dependent *CP* Violation

Decay Time Evolution:

- For the decay into *CP* final state $B \to f$

$$|A(B_q^0(t) \to f)|^2 = |\mathcal{N}|^2 e^{-t/\tau_q}\Big[\cosh(\Delta\Gamma_q t) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t) + \mathcal{A}_{CP}^{\rm dir}\cos(\Delta m_q t) + \mathcal{A}_{CP}^{\rm mix}\sin(\Delta m_q t)\Big] \quad (12)$$

$$|A(\overline{B}_q^0(t) \to f)|^2 = |\mathcal{N}|^2 e^{-t/\tau_q}\Big[\cosh(\Delta\Gamma_q t) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t) - \mathcal{A}_{CP}^{\rm dir}\cos(\Delta m_q t) - \mathcal{A}_{CP}^{\rm mix}\sin(\Delta m_q t)\Big] \quad (13)$$

- where $\Delta m_q \equiv m_{\rm H} - m_{\rm L}$, $\Delta\Gamma_q \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$ and
- Thus $|A(B_q^0(t) \to f)|^2 \neq |A(\overline{B}_q^0(t) \to f)|^2$

CP Asymmetry:

$$a_{\rm CP}(t) \equiv \frac{|A(B_q^0(t) \to f)|^2 - |A(\overline{B}_q^0(t) \to f)|^2}{|A(B_q^0(t) \to f)|^2 + |A(\overline{B}_q^0(t) \to f)|^2} = \frac{\mathcal{A}_{CP}^{\rm dir}\cos(\Delta m_q t) + \mathcal{A}_{CP}^{\rm mix}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)} \quad (14)$$

[Conversion rules for the HFAG convention: $\mathcal{A}_{CP}^{\rm dir} = C_f$ and $\mathcal{A}_{CP}^{\rm mix} = -S_f$.]

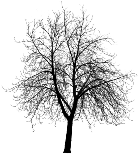
Contributions from Penguin Topologies

The Famous $\sin 2\beta$ Measurement

B-Factory Precision:

- The mode $B^0 \to J/\psi K_S^0$:

$|A(B^0 \to J/\psi K_S^0)|^2 = \Bigg|$



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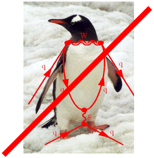

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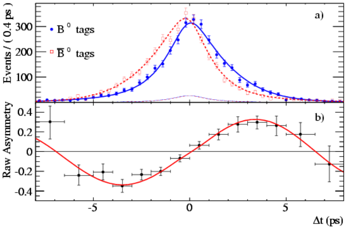
- Achievable precision justifies the approximation:

$$\mathcal{A}_{CP}^{\rm dir} \approx 0$$

$$a_{\rm CP}(t) \approx \eta \mathcal{A}_{CP}^{\rm mix} \cdot \sin(\Delta m_d t) = \sin(2\beta) \sin(\Delta m_d t)$$

- detector effects dampen the oscillation



[BaBar, arXiv 0808.1903]

Entering a New Era for Precision Measurements

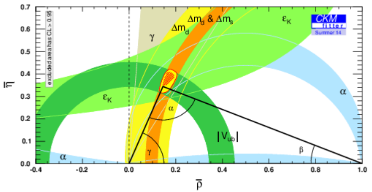
Subleading Effects:

- Current precision: $\phi_d(B^0 \to J/\psi K_S^0) = (42.1 \pm 1.6)^\circ$
- Goal for LHCb upgrade + Belle II: $\sigma_{\phi_d}(B^0 \to J/\psi K_S^0) = \mathcal{O}(0.5^\circ)$
- Need to have a critical look at assumptions underlying these measurements

- Experimentally measure an effective mixing phase

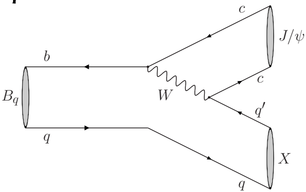
$$\phi_d^{\text{eff}}(B^0 \to J/\psi K_S^0) = \phi_d + \Delta\phi_d$$

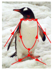
- $\Delta\phi_d = \mathcal{O}(1^\circ)$ is a shift due to penguin topologies
- Controlling these higher order hadronic effects becomes mandatory!



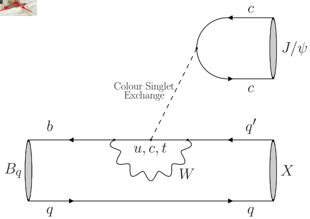
Introducing Trees & Penguins

Tree Topology





Penguin Topology



Decay Amplitude:

$$A(B_q^0 \to f) = \mathcal{N}_f \left[1 - b_f e^{\rho_f} e^{+i\gamma}\right] \quad (15)$$

$$A(\overline{B}_q^0 \to f) = \eta_f \mathcal{N}_f \left[1 - b_f e^{\rho_f} e^{-i\gamma}\right] \quad (16)$$

- $\mathcal{N}_f$ represents the tree topology, b_f the relative contribution from the penguins, ρ_f the associated strong phase difference and γ the relative weak phase difference.

Observables

Penguin Shift:

$$\sin \Delta\phi_q^f = \frac{-2\, b_f \cos\rho_f \sin\gamma + b_f^2 \sin 2\gamma}{\left(1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2\right)\sqrt{1 - \left(\mathcal{A}_{CP}^{\rm dir}(B \to f)\right)^2}} \quad (17)$$

$$\cos \Delta\phi_q^f = \frac{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2 \cos 2\gamma}{\left(1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2\right)\sqrt{1 - \left(\mathcal{A}_{CP}^{\rm dir}(B \to f)\right)^2}} \quad (18)$$

CP Asymmetries:

$$\mathcal{A}_{CP}^{\rm dir}(B_q \to f) = \frac{2\, b_f \sin\rho_f \sin\gamma}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2} \quad (19)$$

$$\mathcal{A}_{CP}^{\rm mix}(B_q \to f) = \eta_f \left[\frac{\sin\phi_q - 2\, b_f \cos\rho_f \sin(\phi_q + \gamma) + b_f^2 \sin(\phi_q + 2\gamma)}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2}\right] \quad (20)$$

$$\mathcal{A}_{\Delta\Gamma}(B_q \to f) = -\eta_f \left[\frac{\cos\phi_q - 2\, b_f \cos\rho_f \cos(\phi_q + \gamma) + b_f^2 \cos(\phi_q + 2\gamma)}{1 - 2\, b_f \cos\rho_f \cos\gamma + b_f^2}\right] \quad (21)$$

- Not all independent

$$\left[\mathcal{A}_{CP}^{\rm dir}\right]^2 + \left[\mathcal{A}_{CP}^{\rm mix}\right]^2 + \left[\mathcal{A}_{\Delta\Gamma}\right]^2 = 1 \quad (22)$$

Controlling Penguin Effects

Strategy:

1. Measure the CP observables

$$\Downarrow$$

2. Determine b and ρ from the CP observables

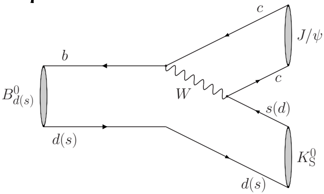
$$\Downarrow$$

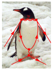
3. Calculate the shift $\Delta\phi(b, \rho)$ with b and ρ

- Now we only need a decay that is sensitive to b and ρ

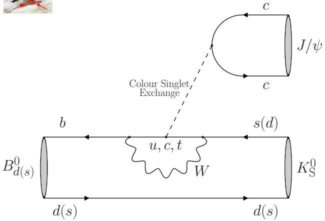
From Topologies to Penguin Parameters: Hadronic Amplitudes

Tree Topology





Penguin Topology



Filling in the Details:

$$A(B^0 \to J/\psi\, K_S^0) = V_{cs}V_{cb}^* \left(A_{\rm tree}^c + A_{\rm pen}^c\right) + V_{us}V_{ub}^*\, A_{\rm pen}^u + V_{ts}V_{tb}^*\, A_{\rm pen}^t \qquad (23)$$

- Which can be rewritten as

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

$$\mathcal{A}' \equiv \lambda^2 A \left(A_{\rm tree}^c + A_{\rm pen}^c - A_{\rm pen}^t\right), \qquad \epsilon = \frac{\lambda^2}{1-\lambda^2} \approx 0.053 \qquad (24)$$

$$a'\, e^{i\theta'} = R_b \left(1 - \frac{\lambda^2}{2}\right) \left(\frac{A_{\rm pen}^u - A_{\rm pen}^t}{A_{\rm tree}^c + A_{\rm pen}^c - A_{\rm pen}^t}\right) \qquad (25)$$

Controlling Penguin Effects

$B^0 \to J/\psi K_S^0$ Again:

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

- Not sensitive to a' and θ' (Penguin contribution are suppressed)

The Little Brother: $B_s^0 \to J/\psi K_S^0$:

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

- Sensitive to a and θ (No suppression of penguin contribution)

Symmetry Relation:

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

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

How Good is U-Spin Symmetry?

Factorisation Framework:

- U-spin breaking comes in two flavours:

  factorisable effects and non-factorisable effects

- Non-factorisable effects are suppressed
- Factorisable effects can affect the amplitudes A_{tree} and A_{pen}

Amplitudes:

$$\mathcal{A}^{(\prime)} \equiv \lambda^2 A(A^c_{\text{tree}} + A^c_{\text{pen}} - A^t_{\text{pen}}) \propto f^+_{B_{d/s} \to K}(q^2 = M^2_{J/\psi}) \qquad (26)$$

- Affected by factorisable U-spin breaking: $f^+_{B \to K} / f^+_{B_s \to K} = 1.16 \pm 0.18$

Penguin Parameters:

$$a\, e^{i\theta} \equiv R_b \left(1 - \frac{\lambda^2}{2}\right) \left(\frac{A^u_{\text{pen}} - A^t_{\text{pen}}}{A^c_{\text{tree}} + A^c_{\text{pen}} - A^t_{\text{pen}}}\right) \qquad (27)$$

- Factorisable effects drop out in the ratio

Strategies based on $SU(3)$ Symmetry Relations: Part I

Strategies for $B^0 \to J/\psi K_S^0$:

1. $B_s^0 \to J/\psi K_S^0$: R. Fleischer, arXiv:hep-ph/9903455.
   - Theoretically cleanest option
   - Only possible for the LHCb Upgrade
2. $B^0 \to J/\psi \pi^0$: S. Faller *et al*, arXiv:0809.0842 [hep-ph]
3. Global fit to $B^0 \to J/\psi K_S^0$, $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$ and $B^0 \to J/\psi \pi^0$
   - Largest theoretical uncertainty
   - Smallest statistical uncertainty

Strategy 3: Global Fit for $\Delta\phi_d^{J/\psi K_S^0}$

Global Fit to the $B_q \to J/\psi P$ Data

Group I: Cabibbo-Allowed Penguins:

- $B^+ \to J/\psi \pi^+$: $\mathcal{B}$, $\mathcal{A}_{CP}^{\rm dir}$
- $B^0 \to J/\psi \pi^0$: $\mathcal{B}$, $\mathcal{A}_{CP}^{\rm dir}$, $\mathcal{A}_{CP}^{\rm mix}$
- $B_s^0 \to J/\psi K_S^0$: $\mathcal{B}$

$$A(B \to J/\psi f) = -\lambda \mathcal{A}\left[1 - a\, e^{i\theta} e^{i\gamma}\right]$$

$$\mathcal{N} \to -\lambda \mathcal{A}\,, \qquad b\, e^{i\rho} \to -a\, e^{i\theta}$$

Group II: Cabibbo-Suppressed Penguins:

- $B^+ \to J/\psi K^+$: $\mathcal{B}$, $\mathcal{A}_{CP}^{\rm dir}$
- $B^0 \to J/\psi K_S^0$: $\mathcal{B}$, $\mathcal{A}_{CP}^{\rm dir}$, $\mathcal{A}_{CP}^{\rm mix}$

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

$$\mathcal{N} \to \left(1 - \tfrac{1}{2}\lambda^2\right) \mathcal{A}\,, \qquad b\, e^{i\rho} \to \epsilon a\, e^{i\theta}$$

Assumptions:

- Ignore non-factorisable $SU(3)$ breaking: There is one universal a and θ variable
- Exchange & (Penguin-)Annihilation contributions are small and can be ignored
- We have control channels to cross-check this assumption: $B_s^0 \to J/\psi \pi^0$ and $B_s^0 \to J/\psi \rho^0$

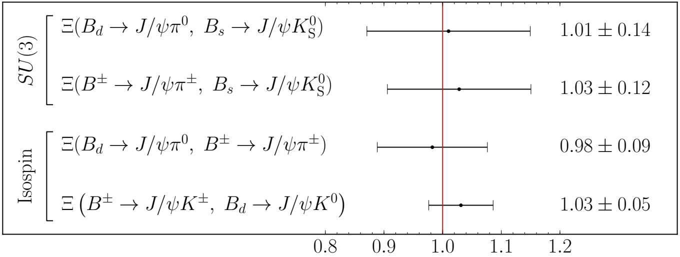
Consistency Tests of the Data: $SU(3)$ Limit

Ratio Test:

- Define

$$\Xi(B_q \to J/\psi X, B_{q'} \to J/\psi Y) \equiv \frac{\text{PhSp}\,(B_{q'} \to J/\psi Y)}{\text{PhSp}\,(B_q \to J/\psi X)} \frac{\tau_{B_{q'}}}{\tau_{B_q}} \frac{\mathcal{B}\,(B_q \to J/\psi X)_{\text{theo}}}{\mathcal{B}\,(B_{q'} \to J/\psi Y)_{\text{theo}}}\,, \tag{28}$$

- In $SU(3)$ limit and neglecting additional topologies:
  Phase-space corrected branching ratios of similar decay modes should be identical



- Picture supported by the data

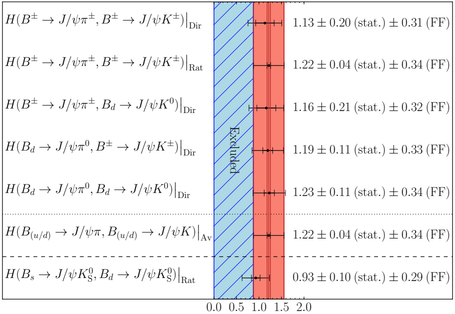
Consistency Tests of the Data: H Observable

One More Observable:

- Decay rate information can be included in the fit via

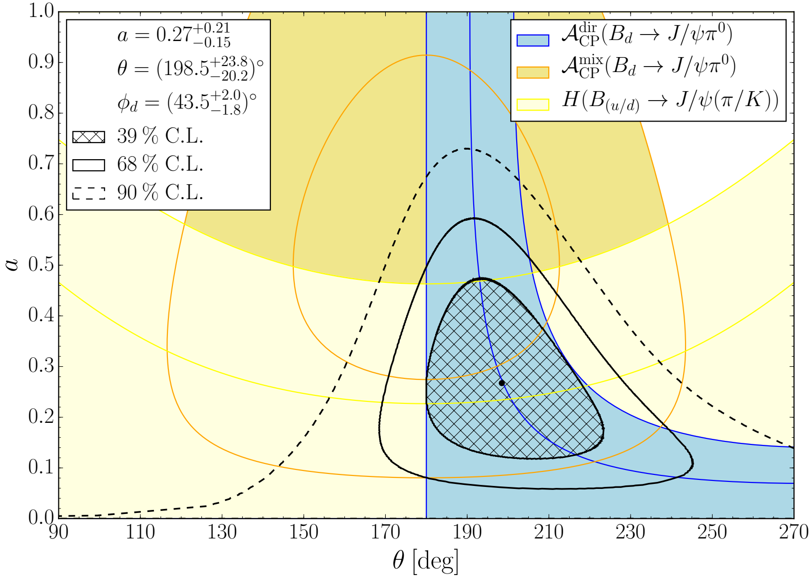
$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \frac{\mathrm{PhSp}\left(B_d \to J/\psi K_S^0\right)}{\mathrm{PhSp}\left(B_s \to J/\psi K_S^0\right)} \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{\mathcal{B}\left(B_s \to J/\psi K_S^0\right)_{\mathrm{theo}}}{\mathcal{B}\left(B_d \to J/\psi K_S^0\right)_{\mathrm{theo}}}, \quad (29)$$

- Within the assumptions made: H observable should be universal

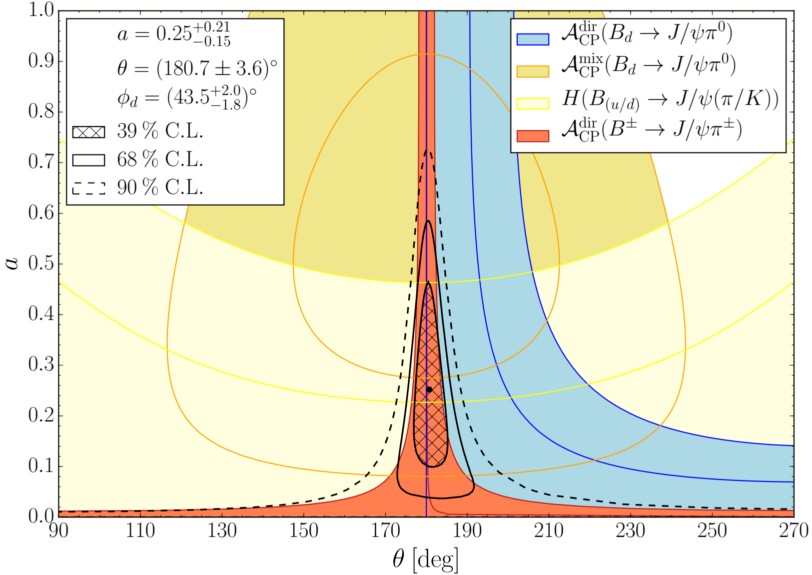


Within current precision, there are no indications of large non-fact. $SU(3)$ breaking

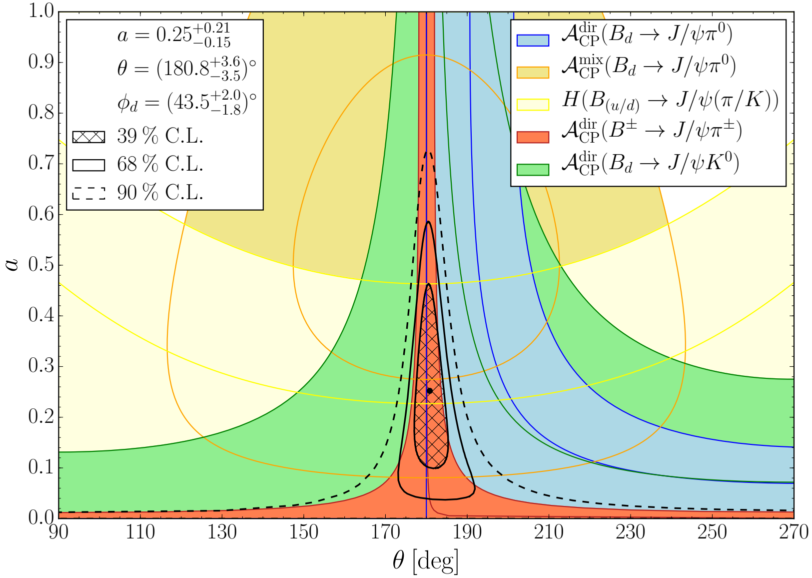
Grand Fit: Contours



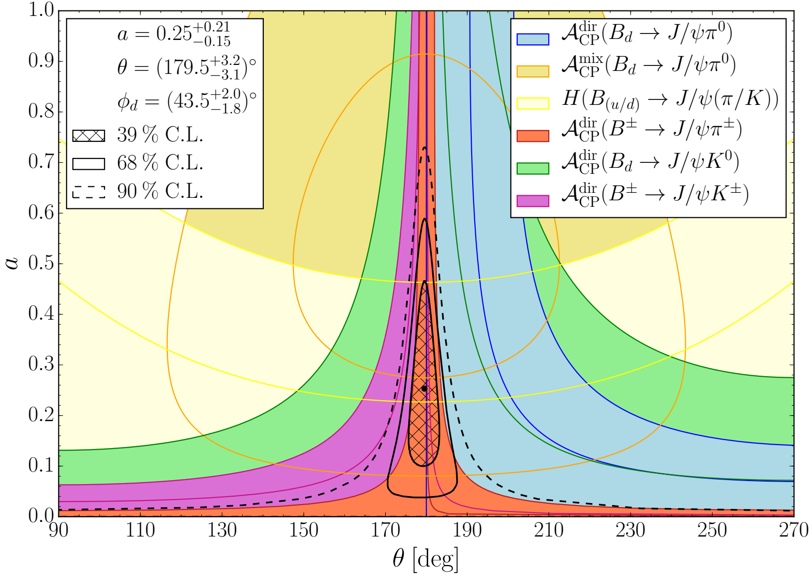
Grand Fit: Contours



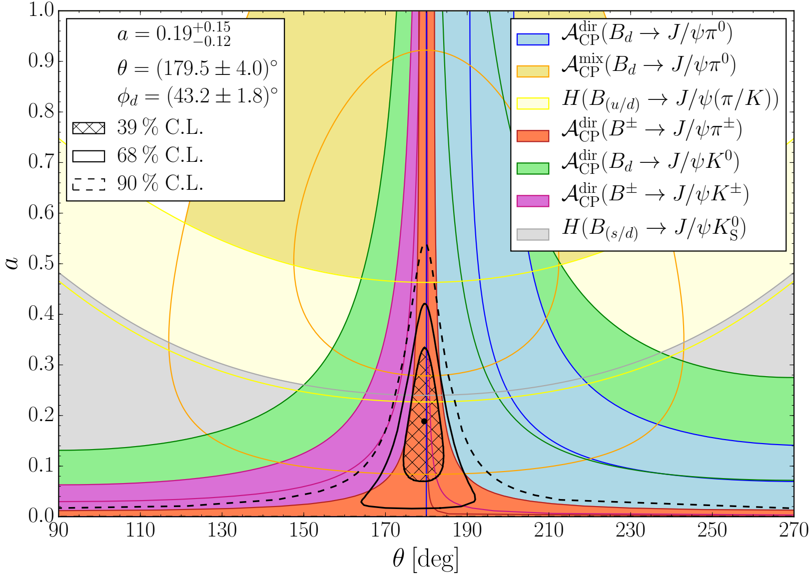
Grand Fit: Contours



Grand Fit: Contours



Grand Fit: Contours



Grand Fit: Setup & Results

Inputs:

- CP asymmetries & branching ratios listed previously
- Gaussian constraint: $\gamma = \left(70.0^{+7.7}_{-9.0}\right)^\circ$

Caveats:

- $\mathcal{A}_{CP}^{\rm mix}(B^0 \to J/\psi \pi^0)$ and $\mathcal{A}_{CP}^{\rm mix}(B^0 \to J/\psi K_S^0)$ depend on ϕ_d
- Directly determined in the fit by explicitly including $\Delta\phi_d(a,\theta,\gamma)$
- Time-integrated $B_s^0 \to J/\psi K_S^0$ branching ratio is converted to the theoretical one

Fit Results:

$$a = 0.19^{+0.15}_{-0.12}\,, \qquad \theta = (179.5 \pm 4.0)^\circ\,,$$

$$\phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ\,, \qquad \gamma = \left(70.9^{+7.6}_{-8.5}\right)^\circ\,,$$

- with $\chi^2_{\rm min} = 2.6$ for 4 degrees of freedom
- This corresponds to

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

Strategy 1: A Benchmark Scenario of $B_s^0 \to J/\psi K_S^0$

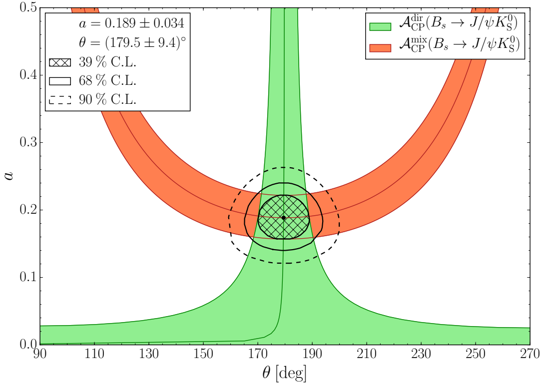
Benchmark for the LHCb Upgrade: Penguin Parameters

Hypothetical Scenario for End of LHCb Upgrade:

$$\mathcal{A}_{CP}^{\rm dir}(B_s \to J/\psi\, K_S^0) = 0.00 \pm 0.05\,, \qquad \gamma = (70 \pm 1)^\circ \tag{30}$$

$$\mathcal{A}_{CP}^{\rm mix}(B_s \to J/\psi\, K_S^0) = -0.29 \pm 0.05\,, \qquad \phi_s = -(2.1 \pm 0.5|_{\rm exp} \pm 0.3|_{\rm theo})^\circ \tag{31}$$

Penguin Parameters:



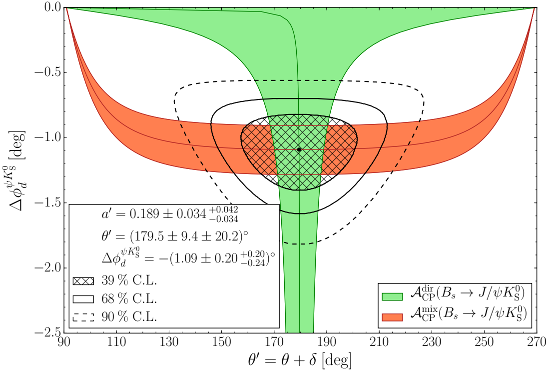
$a = 0.189 \pm 0.034$

$\theta = (179.5 \pm 9.4)^\circ$

Benchmark for the LHCb Upgrade: Penguin Shift

Including $SU(3)$-Breaking Corrections:

$$a' = \xi \cdot a \,, \qquad \theta' = \theta + \delta \tag{32}$$



$$\Delta\phi_d^{J/\psi K_S^0} = -\left(1.09 \pm 0.20\,(\text{stat})^{+0.20}_{-0.24}\,(\text{U-spin})\right)^\circ , \tag{33}$$

Benchmark for the LHCb Upgrade: Hadronic Parameters

Constraining Hadronic Amplitudes:

- The penguin parameters predict

$$H_{(a,\theta)} = 1.172 \pm 0.037\,(a,\theta) \pm 0.0016\,(\xi,\delta) \tag{34}$$

- Compare with branching ratio information

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \sqrt{\epsilon\, H_{(a,\theta)} \frac{\text{PhSp}\,(B_s \to J/\psi\, K_S^0)}{\text{PhSp}\,(B_d \to J/\psi\, K_S^0)} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{\mathcal{B}\,(B_d \to J/\psi\, K_S^0)_{\text{theo}}}{\mathcal{B}\,(B_s \to J/\psi\, K_S^0)_{\text{theo}}}} \tag{35}$$

- This leads to

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|_{\text{exp}} = 1.160 \pm 0.035 \tag{36}$$

- LCSR calculations give

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|_{\text{fact}} = 1.16 \pm 0.18 \tag{37}$$

B Decays Into Two Vector Mesons

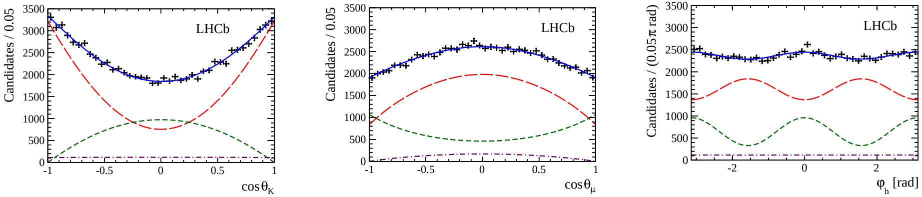
Strategies based on $SU(3)$ Symmetry Relations: Part II

Strategies for $B_s^0 \to J/\psi\, \phi$:

1. $B^0 \to J/\psi\, \rho^0$: R. Fleischer, arXiv:hep-ph/9903540
   - Theoretically cleanest option
2. $B_s^0 \to J/\psi\, \overline{K}^{*0}$: R. Fleischer, arXiv:0810.4248 [hep-ph]
   - Requires decay rate information
3. Combined fit of $B^0 \to J/\psi\, \rho^0$ and $B_s^0 \to J/\psi\, \overline{K}^{*0}$:
   - Does not require input from QCD calculations (Form factors, factorisation assumption, ...)

Strategy 1: Analysis of $B^0 \to J/\psi\, \rho^0$

PRL 114 (2015), arXiv:1411.3104



Nominal Setup:

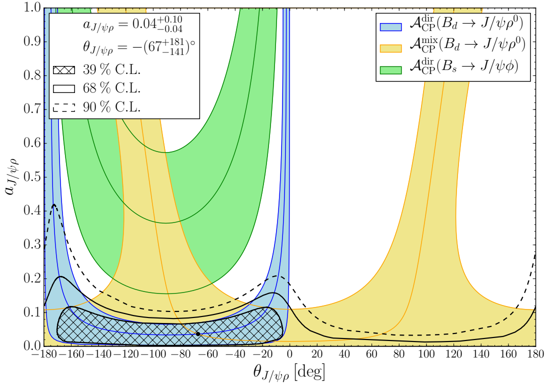
$$B^0 \to J/\psi\, \rho^0 : \; b_f e^{i\rho_f} \to a_k e^{i\theta_k} \,, \qquad \mathcal{N}_f \to -\frac{\lambda}{\sqrt{2}}\mathcal{A}_k \,, \qquad \text{with } k \in \{0, \parallel, \perp\} \qquad (38)$$

- Expect in general $a_0 \neq a_\parallel \neq a_\perp$, because of
- Polarisation-dependent hadronisation dynamics and non-factorisable effects

Simplified Setup:

- No polarisation dependence seen in current data
- Assume universal set of penguin parameters: $a_0 = a_\parallel = a_\perp = a_{J/\psi\, \rho}$

Polarisation-Independent Fit for $B^0 \to J/\psi\, \rho^0$



Results from χ^2 fit:

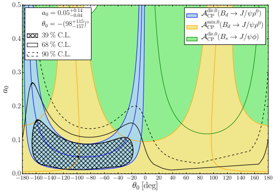
$$a_{J/\psi\,\rho} = 0.037^{+0.097}_{-0.037}\,, \qquad \theta_{J/\psi\,\rho} = -\left(67^{+181}_{-141}\right)^\circ, \qquad \Delta\phi_d^{J/\psi\,\rho} = -\left(1.5^{+12}_{-10}\right)^\circ\,,$$

corresponding to a shift

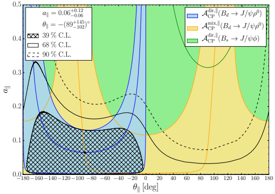
$$\Delta\phi_s^{J/\psi\,\phi} = \left(0.08^{+0.56}_{-0.72}\,(\text{stat.})^{+0.15}_{-0.13}\,(SU(3))\right)^\circ\,.$$

Polarisation-Dependent Fit for $B^0 \to J/\psi\,\rho^0$

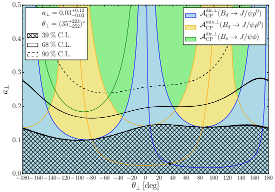
Longitudinal



Parallel



Perpendicular



Results from χ^2 fit:

$$a_0 = 0.051^{+0.140}_{-0.041}\,, \quad \theta_0 = -\left(98^{+115}_{-157}\right)^\circ, \; \Delta\phi_s^{(J/\psi\,\phi)_0} = -\left(0.04^{+0.60}_{-0.81}\,(\text{stat.})^{+0.15}_{-0.18}\,(SU(3))\right)^\circ,$$

$$a_\parallel = 0.065^{+0.116}_{-0.064}\,, \quad \theta_\parallel = -\left(89^{+145}_{-102}\right)^\circ, \; \Delta\phi_s^{(J/\psi\,\phi)_\parallel} = \left(0.00^{+0.67}_{-0.95}\,(\text{stat.})^{+0.19}_{-0.21}\,(SU(3))\right)^\circ,$$

$$a_\perp = 0.031^{+0.118}_{-0.031}\,, \quad \theta_\perp = \left(35^{+223}_{-252}\right)^\circ, \; \Delta\phi_s^{(J/\psi\,\phi)_\perp} = \left(0.14^{+0.68}_{-0.94}\,(\text{stat.})^{+0.17}_{-0.14}\,(SU(3))\right)^\circ.$$

Strategy 1: Analysis of $B^0 \to J/\psi \rho^0$

Additional Opportunities:

- Penguin fit of $B^0 \to J/\psi \rho^0$ does not use decay rate information
- Get experimental access to ratio of hadronic amplitudes

$$\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right| = \sqrt{\epsilon\, H_{(a,\theta)} \frac{\text{PhSp}\,(B_q \to J/\psi\, X)}{\text{PhSp}\,(B_s \to J/\psi\, \phi)} \frac{\tau_{B_q}}{\tau_{B_s}} \frac{\mathcal{B}\,(B_s \to J/\psi\, \phi)_{\text{theo}}}{\mathcal{B}\,(B_q \to J/\psi\, X)_{\text{theo}}} \frac{f_i'}{f_i}}\,. \tag{39}$$

- where f_i is the polarisation fraction

Results:

P. Ball and R. Zwicky, arXiv:hep-ph/0412079

$$\left|\frac{\mathcal{A}_0'(B_s \to J/\psi\, \phi)}{\mathcal{A}_0(B_d \to J/\psi\, \rho^0)}\right|_{\text{exp}} = 1.06 \pm 0.07\,(\text{stat.}) \pm 0.04\,(a_0, \theta_0)\,, \qquad \left|\frac{\mathcal{A}_0'(B_s \to J/\psi\, \phi)}{\mathcal{A}_0(B_d \to J/\psi\, \rho^0)}\right|_{\text{fact}} = 1.43 \pm 0.42$$

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

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

- This is already competitive!

Strategy 2: Analysis of $B_s^0 \to J/\psi \overline{K}^{*0}$

Inputs:

- Flavour-specific final state
- Only direct *CP* violation in this decay [Not yet measured]

⇒ Interesting new constraint

- Need to complement this with decay rate information

$$H_i \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}_f'}{\mathcal{A}_f}\right|^2 \frac{\text{PhSp}\,(B_s \to J/\psi\,\phi)}{\text{PhSp}(B_s \to J/\psi\,\overline{K}^{*0})} \frac{\mathcal{B}(B_s \to J/\psi\,\overline{K}^{*0})_{\text{theo}}}{\mathcal{B}(B_s \to J/\psi\,\phi)_{\text{theo}}} \frac{f_i}{f_i'} \tag{40}$$

Challenge:

1. Requires theory input for $|\mathcal{A}'/\mathcal{A}|$

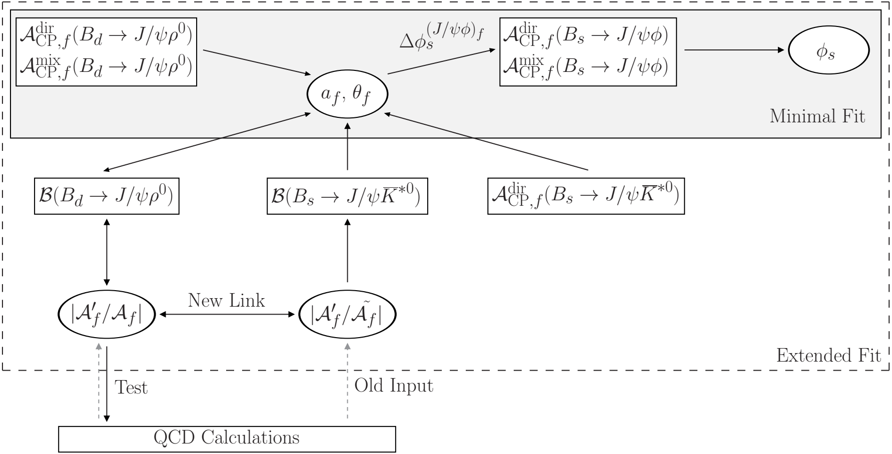
⇒ Currently form factors only poorly known from LCSR (or Lattice)

2. Affected by factorisable & non-factorisable effects

⇒ Theoretically not a clean observable

Given the performance of $B^0 \to J/\psi\,\rho^0$, what extra insights can $B_s^0 \to J/\psi\,\overline{K}^{*0}$ provide?

Strategy 3: $B_q^0 \to J/\psi V$ Fit Strategy



Strategy 3: $B_q^0 \to J/\psi\, V$ Fit

Hadronic Amplitudes:

- Combined fit assumes

$$\left|\frac{\mathcal{A}_i'(B_s^0 \to J/\psi\,\phi)}{\mathcal{A}_i(B^0 \to J/\psi\,\rho^0)}\right| = \left|\frac{\mathcal{A}_i'(B_s^0 \to J/\psi\,\phi)}{\mathcal{A}_i(B_s^0 \to J/\psi\,\overline{K}^{*0})}\right| \tag{41}$$

- No input from QCD calculations necessary

Results from Current Data:

$$\left|\frac{\mathcal{A}_0'}{\mathcal{A}_0}\right| = 1.073^{+0.094}_{-0.073}\,, \qquad a_0 = 0.05^{+0.14}_{-0.04}\,, \qquad \theta_0 = -\left(98^{+115}_{-157}\right)^\circ\,,$$

$$\left|\frac{\mathcal{A}_\parallel'}{\mathcal{A}_\parallel}\right| = 1.088^{+0.114}_{-0.085}\,, \qquad a_\parallel = 0.06^{+0.12}_{-0.06}\,, \qquad \theta_\parallel = -\left(89^{+145}_{-102}\right)^\circ\,,$$

$$\left|\frac{\mathcal{A}_\perp'}{\mathcal{A}_\perp}\right| = 1.21^{+0.18}_{-0.13}\,, \qquad a_\perp = 0.03^{+0.12}_{-0.03}\,, \qquad \theta_\perp = \left(35^{+223}_{-252}\right)^\circ\,.$$

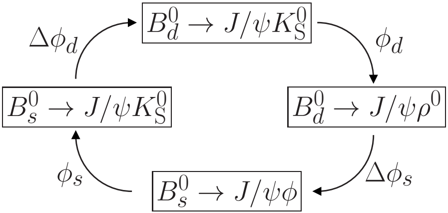
Roadmap for LHCb Upgrade

Connecting ϕ_d and ϕ_s

High Precision Constraints:

- $\Delta\phi_d$ from $B_s^0 \to J/\psi K_S^0$
- $\Delta\phi_s$ from $B^0 \to J/\psi \rho^0$

Subtle Interplay:



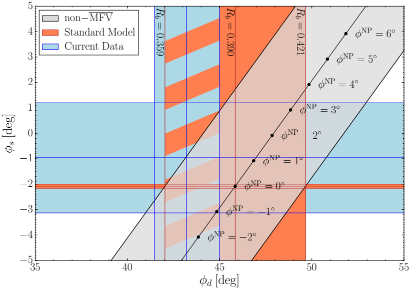
- Could benefit from one complex fit . . .

Connecting ϕ_d and ϕ_s

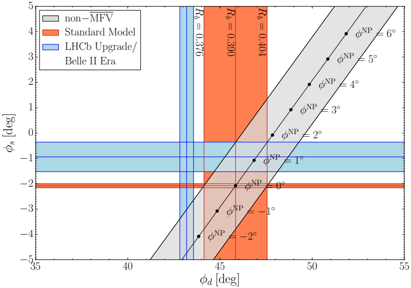
Hunting New Physics:

- We need both ϕ_d and ϕ_s to pin down new physics
- R_b will be the show stopper

Current



LHCb Upgrade/Belle II



- Illustration for flavour-universal *CP*-violating new physics (non-$\overline{\text{MFV}}$ models)

$$\phi_s^{NP} = \phi_d^{NP} \equiv \phi^{NP}, \tag{42}$$

- leading to

$$\phi_s = \phi_d + \left(\phi_s^{SM} - \phi_d^{SM}\right), \tag{43}$$

Conclusion

- Controlling higher order corrections to ϕ_d and ϕ_s becomes mandatory
- Illustrated strategies to get these corrections directly from data based on $SU(3)$ flavour symmetry
- Key players: $B_s^0 \to J/\psi K_S^0$, $B^0 \to J/\psi \rho^0$, $B_s^0 \to J/\psi \overline{K}^{*0}$
- Highlighted new possibilities to get insights into ratio of hadronic amplitudes $|\mathcal{A}'/\mathcal{A}|$

Credit: David and Sarah Cousens