B → J/ψK Penguin Pollution

Kristof De Bruyn

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A Victory for the Standard Model?

-0.5 -0.3 -0.1 0.1 0.3
ccs
s [rad]
0.05
0.07
0.09
0.11
0.13

LHCb 4.9 fb
ATLAS 99.7 fb
CMS 116.1 fb
CDF 9.6 fb
D0 8 fb
Combined*
* s errors scaled by 1.77

SM
68% CL contours
(Δ log L = 1.15)

HFLAV
PDG 2021

B → J/ψ K Penguin Pollution

24-11-2021 (CKM 2021)
This is Not the End of the Game!

▶ There is more room for New Physics than you think!

▶ The measurements are affected by “penguin pollution”

▶ Naive average is spot on Standard Model … but misleading

▶ A more careful analysis is necessary
Introducing “Penguin Pollution”

- Time-dependent CP asymmetry

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

- At leading order

\[ |A(B^0_q \to f)|^2 = \]

- Introducing the dependence on the \( B^0_q - \bar{B}^0_q \) mixing phase

\[ A_{CP}^{dir} = 0 \quad \text{and} \quad \eta_f A_{CP}^{mix} = \sin \phi_q \]
Introducing “Penguin Pollution”

- Time-dependent CP asymmetry

\[ a_{CP}(t) \equiv \frac{|A(B^0_q(t) \rightarrow f)|^2 - |A(\bar{B}^0_q(t) \rightarrow f)|^2}{|A(B^0_q(t) \rightarrow f)|^2 + |A(\bar{B}^0_q(t) \rightarrow f)|^2} = \frac{A_{dir}^CP \cos(\Delta m_q t) + A_{mix}^CP \sin(\Delta m_q t)}{\cosh(\Delta \Gamma q t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma q t/2)} \]

- At next-to-leading order

\[ |A(B^0_q \rightarrow f)|^2 = |A_{dir}^CP| + \epsilon \]

- So you measure an effective mixing phase

\[ A_{CP}^{dir} \neq 0 \quad \text{and} \quad \frac{\eta_f A_{mix}^CP(B_q \rightarrow f)}{\sqrt{1 - (A_{CP}^{dir}(B_q \rightarrow f))^2}} = \sin (\phi_q^{eff}) = \sin (\phi_q + \Delta \phi_q) \]
The Penguin Shift $\Delta \phi$

\[
\frac{\eta_f A_{\text{CP}}^{\text{mix}}(B_q \rightarrow f)}{\sqrt{1 - (A_{\text{CP}}^{\text{dir}}(B_q \rightarrow f))^2}} = \sin\left(\phi_{\text{eff}}\right) = \sin\left(\phi_{q}^{\text{SM}} + \phi_{q}^{\text{NP}} + \Delta \phi_{q}\right)
\]

- Penguin shift $\Delta \phi_{q}$ is affected by non-perturbative, long-distance QCD contributions
  \[\Rightarrow \Delta \phi_{q} \text{ is decay mode specific}\]

- Spoiler: $\Delta \phi_{d}^{J/\psi K^0} = -\left(0.73_{-0.91}^{+0.60}\right)^{\circ}$ and $\Delta \phi_{s}^{J/\psi \phi} = \left(0.14_{-0.70}^{+0.54}\right)^{\circ}$

- Controlling $\Delta \phi_{q}$ is mandatory to constrain $\phi_{q}^{\text{NP}}$

- If no action is taken, could easily become the leading systematic uncertainty for the Hi-Lumi LHC.
Non-perturbative, long-distance QCD contributions make it difficult to determine $\Delta \phi_q$ from first principles.


Preferred strategy: Data-driven techniques relying on $SU(3)$ flavour symmetry arguments.

$SU(3)$ flavour symmetry: In the limit of massless quarks, QCD does not differentiate between $u$, $d$ and $s$
SU(3) Flavour Symmetry Strategy

1. Find a control channel where contributions from penguin topologies are not suppressed

2. Estimate the size of the penguin effects using the CP asymmetries of the control mode

3. Use $SU(3)$ flavour symmetry to relate the result to the mode measuring $\phi_q^{\text{eff}}$

4. Estimate $\Delta \phi_q$ based on the size of the penguin effects in the control mode

5. Main systematic uncertainty: $SU(3)$ symmetry breaking
## Current Status on Controlling Penguin Effects

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Control Mode</th>
<th>Latest Penguin Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_d \to J/\psi K^0$</td>
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<td>[L.Bel, KDB, R.Fleischer, M.Mulder, N.Tuning arXiv:1505.01361]</td>
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<tr>
<td>$B^0_s \to J/\psi f_0(980)$</td>
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<td>[R.Fleischer, R.Knegjens, G.Ricciardi arXiv:1109.1112]</td>
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<tr>
<td>$B^0_s \to J/\psi (2S)\phi$</td>
<td>$B^0_s \to J/\psi (2S)\rho^0$</td>
<td>Control mode not yet measured</td>
</tr>
<tr>
<td>$B^0_s \to J/\psi K^- K^+</td>
<td>_{m(K^- K^+)&gt;1.05}$</td>
<td>$B^0_s \to J/\psi (2S)\rho^0$</td>
</tr>
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</table>

- Many groups involved, see references in the listed papers
- $B^0_s \to J/\psi \bar{K}^{*0}$ as an alternative for $B^0_d \to J/\psi \rho^0$
  But measures only direct CP asymmetry, making it more difficult to determine the penguin effects cleanly
- This talk focuses on $B^0_d \to J/\psi K^0$ and $B^0_s \to J/\psi \phi$
In pursuit of new physics with $B_d^0 \rightarrow J/\psi K^0$ and $B_s^0 \rightarrow J/\psi \phi$ decays at the high-precision Frontier

Marten Z Barel$^1$, Kristof De Bruyn$^{1,2,*}$, Robert Fleischer$^{1,3}$ and Eleftheria Malami$^1$
Finding $SU(3)$ Partners

$\phi_d$: $B_d^0 \to J/\psi K^0$ has partner $B_s^0 \to J/\psi K_S^0$

$\phi_s$: $B_s^0 \to J/\psi \phi$ has partner $B_d^0 \to J/\psi \rho^0$

Decays are related via $U$-spin symmetry: interchange all $s \leftrightarrow d$ quarks

1-to-1 correspondence between all decay topologies

$\phi_d$: $B_d^0 \to J/\psi K^0$ has a second partner $B_d^0 \to J/\psi \pi^0$

$(q = d$ and $q' = s)$ versus $(q = s$ and $q' = d)$

$(q = s$ and $q' = s)$ versus $(q = d$ and $q' = d)$
Penguin Parameters for $B^0_d \rightarrow J/\psi K^0$

The Penguin Suppressed Mode:

$A(B^0_d \rightarrow J/\psi K^0) = \left(1 - \frac{1}{2}\lambda^2\right)\mathcal{A}' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right], \quad \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} \approx 0.052$

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

The Penguin Enhanced Mode:

$A(B^0_s \rightarrow J/\psi K^s_0) = -\lambda A \left[1 - a e^{i\theta} e^{i\gamma}\right], \quad \lambda \approx 0.225$

$A(B^0_d \rightarrow J/\psi \pi^0) = -\lambda A \left[1 - a e^{i\theta} e^{i\gamma}\right]$

Kristof De Bruyn (RUG)
**SU(3) Flavour Symmetry Strategy for $B^0_d \rightarrow J/\psi K^0$**

1. Use CP asymmetries in $B^0_s \rightarrow J/\psi K^0_s$ and $B^0_d \rightarrow J/\psi \pi^0$ to determine $a$ and $\theta$

   \[ A_{\text{CP}}^{\text{dir}} = \text{function}(a, \theta, \gamma) \]
   \[ A_{\text{CP}}^{\text{mix}} = \text{function}(a, \theta, \gamma, \phi_s) \]

2. $\gamma$ and $\phi_s$ are external inputs

3. Use $SU(3)$ symmetry relation

   \[ a' = a \quad \& \quad \theta' = \theta \]

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

   \[ \Delta \phi_d = \text{function}(a', \theta', \gamma) \]

5. Correct $\phi_d^{\text{eff}}$

   \[ \phi_d = \phi_d^{\text{eff}} - \Delta \phi_d \]
Penguin Parameters for $B^0_s \to J/\psi \phi$

The Penguin Suppressed Mode:

$$A(B^0_s \to J/\psi \phi) = \left(1 - \frac{1}{2} \lambda^2\right) A'_V \left[1 + \epsilon a'_V e^{i\theta'_V} e^{i\gamma}\right], \quad \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} \approx 0.052$$

- $A'_V$: overall normalisation, represents the tree topology,
- $a'_V$: the relative contribution from the penguin topologies,
- $\theta'_V$: the associated strong phase difference,
- $\gamma$: UT angle and the associated relative weak phase difference.

The Penguin Enhanced Mode:

$$A(B^0_d \to J/\psi \rho^0) = -\lambda A_V \left[1 - a_V e^{i\theta_V} e^{i\gamma}\right], \quad \lambda \approx 0.225$$
**SU(3) Flavour Symmetry Strategy for $B_s^0 \rightarrow J/\psi\phi$**

1. Use CP asymmetries in $B_d^0 \rightarrow J/\psi\rho^0$ to determine $a$ and $\theta$

\[
A_{CP}^{dir} = \text{function}(a_V, \theta_V, \gamma) \\
A_{CP}^{mix} = \text{function}(a_V, \theta_V, \gamma, \phi_d)
\]

2. $\gamma$ and $\phi_d$ are external inputs

3. Use $SU(3)$ symmetry relation

\[
a'_V = a_V \quad \& \quad \theta'_V = \theta_V
\]

4. Determine the penguin shift $\Delta\phi_s$

\[
\Delta\phi_s = \text{function}(a'_V, \theta'_V, \gamma)
\]

5. Correct $\phi_s^{eff}$

\[
\phi_s = \phi_s^{eff} - \Delta\phi_s
\]
Interplay between $\phi_d$ and $\phi_s$

\[ \Delta \phi_d \]
\[ \begin{array}{c}
B^0_d \rightarrow J/\psi K_S^0 \\
B^0_s \rightarrow J/\psi K^0_S
\end{array} \]
\[ \begin{array}{c}
B^0_d \rightarrow J/\psi \pi^0 \\
B^0_s \rightarrow J/\psi \phi
\end{array} \]
\[ \begin{array}{c}
B^0_d \rightarrow J/\psi \rho^0 \\
\Delta \phi_s
\end{array} \]
Interplay between $\phi_d$ and $\phi_s$:

$$B^0_d \rightarrow J/\psi K^0_S$$
$$B^0_s \rightarrow J/\psi K^0_S$$
$$B^0_s \rightarrow J/\psi \phi$$
$$B^0_d \rightarrow J/\psi \pi^0$$
$$B^0_d \rightarrow J/\psi \rho^0$$

Assumptions:

1. Ignore contributions from Exchange and Penguin-Annihilation topologies
2. Ignore polarisation-dependent effects (due to lack of data)
3. Ignore $SU(3)$-breaking effects
Fit to Current Data

\[ a = 0.14^{+0.17}_{-0.11}, \quad \theta = \left(173^{+35}_{-45}\right)^\circ, \quad \phi_d = \left(44.4^{+1.6}_{-1.5}\right)^\circ, \]

- Compare with \( \phi_{d,J/\psi K^0}^{\text{eff}} = (43.6 \pm 1.4)^\circ \)
$a_V = 0.044^{+0.085}_{-0.038}$, \quad $\theta_V = \left(306^{+48}_{-112}\right)^\circ$, \quad $\phi_s = -0.074^{+0.025}_{-0.024} = (-4.2 \pm 1.4)^\circ$

▶ Compare with $\phi_{s,J/\psi}^{\text{eff}} = -0.071 \pm 0.022 = (-4.1 \pm 1.3)^\circ$
Searching for New Physics

- Experimentally measure
  \[ \phi_{s,J/\psi\phi}^{\text{eff}} = -0.071 \pm 0.022 = (-4.1 \pm 1.3)^\circ \]

- Correct penguin pollution
  \[ \Delta \phi_s = 0.003^{+0.010}_{-0.012} = (0.14^{+0.54}_{-0.70})^\circ \]
  \[ \phi_s = -0.074^{+0.025}_{-0.024} = (-4.2 \pm 1.4)^\circ \]

- Compare with a SM prediction
  \[ \phi_s^{\text{SM}} = -0.0351 \pm 0.0021 = (-2.01 \pm 0.12)^\circ \]

- Space left for New Physics
  \[ \phi_s^{\text{NP}} = -0.039 \pm 0.025 = (-2.2 \pm 1.4)^\circ \]
Future Prospects

Based on

\[
\phi_d^{SM} = (45.7 \pm 2.8)^\circ \\
\phi_s^{SM} = -0.0351 \pm 0.0021 = (-2.01 \pm 0.12)^\circ
\]

Could still uncover NP in \(\phi_s\) with 5\(\sigma\) significance

Requires equal (relative) improvements to both \(B_s^0 \rightarrow J/\psi \phi\) and \(B_d^0 \rightarrow J/\psi \rho^0\)

Situation less favourable for \(\phi_d\):
Dominated by uncertainty in SM prediction
Hadronic effects are polarisation-dependent → thus also the penguin pollution

With a $\times 5$ improvement in precision we could see differences between the polarisation states

Need polarisation-dependent measurements

Illustration based on polarisation-dependent results in $B^0_d \rightarrow J/\psi \rho^0$ [LHCb, arXiv:1411.1634]
**SU(3) Symmetry Breaking**

- SU(3) symmetry only exact in the limit \( m_q \to 0 \)

- Main theoretical uncertainty comes from the breaking of SU(3) symmetry since \( m_s \gg m_d \)

- Generically, SU(3) broken at 20% level (for example: \( f_K/f_\pi = 1.1932 \pm 0.0021 \) [FLAG])

\[
ae^{i\theta} \equiv R_b \left[ \frac{\text{Pen}(u) - \text{Pen}(t)}{\text{Tree} + \text{Pen}(c) - \text{Pen}(t)} \right],
\]

- Factorisable effects affect both Tree and Penguin and drop out in the ratio

- Non-factorisable effects remain, but are smaller
A Closer look at the Branching Fractions

\[ 2 B(B_d^0 \rightarrow J/\psi \pi^0) = \tau_{B_d} \frac{G_F^2}{32\pi} |V_{cd}|^2 m_{B_d}^3 \left[ f_{J/\psi} f_{B_d^0 \rightarrow \pi}^+ (m_{J/\psi}^2) \right]^2 \Phi \left( \frac{m_{J/\psi}}{m_{B_d}}, \frac{m_{\pi^0}}{m_{B_d}} \right)^3 \times (1 - 2a \cos \theta \cos \gamma + a^2) \times a_2(B_d^0 \rightarrow J/\psi \pi^0)^2, \]

Contributions:

- Coupling constants & known quantities
- Input from Lattice QCD or Semileptonic $B$-decays
- Decay kinematics
- Penguins
- $a_2$: Effective colour suppression factor ... includes non-factorisable corrections

$\Rightarrow$ Everything except $a_2$ is now known
Non-Factorisable Effects

- Naive Factorisation predicts
  \[ a_2 = 0.21 \pm 0.05 \]

- Deviations from factorisation around 30% to 40%

- This is a non-trivial result!

- Factorisation is not expected to work well here.
Non-Factorisable $SU(3)$-Breaking

- Deviations from factorisation around 30% to 40%
- $SU(3)$-Symmetry is broken at 20% level
- Thus have non-factorisable $SU(3)$-breaking at 5% to 8%
- Illustrated by these ratios

$\Rightarrow$ $SU(3)$-symmetry approach is robust
Conclusion

- Effects due to penguin pollution in $B^0_d \to J/\psi K^0$ and $B^0_s \to J/\psi \phi$ are small . . .
  
  . . . but fast approaching the experimental precision where that still matters

- Effects due to penguin pollution are decay channel specific
  
  → Requires careful analysis when combining experimental results

- Discussed a robust $SU(3)$-symmetry-based strategy to control penguin contributions

- There is still room for physics beyond the Standard Model in $\phi_d$ and $\phi_s$ . . .
  
  . . . but we will only find it if we take good care of the Penguins!