Measurements of penguin pollution effects

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Outline

- Introduction and physics motivations
- Controlling penguin topologies
- Prospects & summary
Introduction and physics motivations
• CKM mechanism introduces $CP$ violation and neutral meson mixing phenomena
  ‣ The presence of new heavy particles exchanged in virtual loops could introduce additional phases altering the corresponding measurements
  ‣ Constraining these phases put stringent limits on a large range of NP models

• $CP$ violation is needed to explain baryon asymmetry in the Universe
  ‣ Discovered in 1964 in the kaons, 2004 in the $B$ and each time awarded with Nobel Prizes
  ‣ Still missing 10 orders of magnitudes!

• Experimentally, $CP$ violation observables accessed through ratios of measured quantities
  ‣ Cancelation of many experimental systematics
  ‣ Flagship measurements for LHCb and Belle II
CPV in interference between mixing and decay:

\[ |A(B \rightarrow J/\psi X)|^2 = \phi_{q}^{\text{eff}} + \varepsilon + \delta_{q}^{\text{NP}} \]

- dominant SM “tree” contribution
- higher order “penguin” contributions from non-perturbative hadronic effects that are difficult to calculate in QCD
- NP could be comparable to penguins…

\[ \phi_{q}^{\text{eff}} = \phi_{M} - 2\phi_{D} = \pm 2\beta_{q} + \Delta\phi_{q} + \delta_{q}^{\text{NP}} \]

\[ \beta_{q} = \arg \left( -\frac{V_{tq} V_{tb}^{*}}{V_{cq} V_{cb}^{*}} \right) \]

- \( \phi_{s} \) and \( \phi_{d} \) determination via global fit to experimental results ignoring contributions from penguin diagrams:

\[ \phi_{s}^{\text{SM}} = -2\beta_{s} = [-0.0376^{+0.0007}_{-0.0008}] \text{ rad} \]
\[ \phi_{d}^{\text{SM}} = +2\beta_{d} = [48.6 \pm 2.6]^{\circ} \]

Very precise theoretical predictions!
**Current experimental status**

\[ B^0 - \bar{B}^0 \text{ mixing phase: } \phi_d \]

\[ \sin(2\beta) = \sin(2\phi_d) \]

HFAG 2016

**Golden mode: \( B^0 \rightarrow J/\psi K_S^0 \)**

\[ \phi_{d,J/\psi K_S^0}^{\text{eff}} = [42.2 \pm 1.5]^{\circ} \]

\[ \phi_{d}^{\text{SM}} = [47.8 \pm 2.6]^{\circ} \]

HFAG 2016

**Golden mode: \( B_s^0 - \bar{B}_s^0 \text{ mixing phase: } \phi_s \)**

\[ \Delta \Gamma_s \left[ \text{ps}^{-1} \right] \]

HFAG 2016

\[ \phi_{s,ccs}^{\text{eff}} = [-0.030 \pm 0.033] \text{ rad} = [-1.7 \pm 1.9]^{\circ} \]

\[ \phi_{s}^{\text{SM}} = [-0.0376^{+0.0007}_{-0.0008}] \text{ rad} = [-2.16^{+0.04}_{-0.05}]^{\circ} \]

- **New physics contributions, if present, will be small!!**
- **Entering a new era of precision physics: Aim to reach a precision of \( O(0.5^{\circ}) \) at the end of LHC Run-3**
- **Controlling contributions from penguin topologies becomes mandatory!**

Simon Akar

CKM 16' - Measurement of penguin pollution effects
Controlling penguin topologies
Decay topologies:

- Tree Topology
- Penguin Topology
- Exchange Topology
- Penguin-Annihilation

Decomposition:

- $B^0 \rightarrow J/\psi K^0_S$: $T + P$
- $B_s^0 \rightarrow J/\psi \phi$: $T + P + E + PA$

Assumptions:

- Given the current experimental sensitivities, exchange and annihilation topologies can be ignored (control channels to cross-check this assumption: $B_s^0 \rightarrow J/\psi \pi^0$, $B_s^0 \rightarrow J/\psi \rho^0$)
- Up to now, only penguin contributions are being studied from analyses involving SU(3) counterparts where $T \sim P$: $B_s^0 \rightarrow J/\psi K^0_S$, $B^0 \rightarrow J/\psi \rho^0$, $B_s^0 \rightarrow J/\psi \bar{K}^0$
- Ignore non-factorisable SU(3) breaking
The penguin shift $\Delta \phi_s$

$B^0_s \rightarrow J/\psi \phi$:

$$A(B^0_s \rightarrow (J/\psi \phi)_i) = \left(1 - \frac{\lambda^2}{2}\right)A'_i \left[1 + \epsilon a'_i e^{i\theta'_i} e^{i\gamma}\right]$$

$$\epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} = 0.0536$$

- $a'_i$ and $\theta'_i$: magnitude and phase of the penguin contributions
- Amplitudes are polarisation dependent: $i \in \{0, \parallel, \perp\}$
- Penguin contributions are doubly Cabbibo-suppressed
- Will ignore Exchange and Penguin-Annihilation contributions
- Differences in hadronisation dynamics: $\Delta \phi_s$ can be polarisation dependent (but so far no indication of that in the data)
The penguin shift \( \Delta \phi_s \)

- **Partner 1: \( B_s^0 \to J/\psi \, \bar{K}^* \)**
  
  \[
  A \left( B_s^0 \to J/\psi \, \bar{K}^* \right) = -\lambda A_i \left[ 1 - a_i e^{i\theta_i} e^{i\gamma} \right]
  \]

  - Reconstructed using flavor specific final state, only access to direct CP violation, \( A_{\text{CP}}^{\text{dir}} \)
  - Need additional information from branching fractions

- **Partner 2: \( B^0 \to J/\psi \rho^0 \)**
  
  \[
  A \left( B^0 \to J/\psi \rho^0 \right) = -\lambda A_i \left[ 1 - \tilde{a}_i e^{i\tilde{\theta}_i} e^{i\gamma} \right]
  \]

  - Access to both \( A_{\text{CP}}^{\text{dir}} \) and mixing induced CP violation \( A_{\text{CP}}^{\text{mix}} \)
  - Branching fraction information is optional

Ignoring non-factorisable SU(3) breaking:

- There is **one universal** set of \( a \) and \( \theta \): \( a_i = \tilde{a}_i = a'_i \); \( \theta_i = \tilde{\theta}_i = \theta'_i \)
- The penguin shift can be expressed in terms of the penguin parameters:

\[
\tan(\Delta \phi_{s,i}) = \frac{2\epsilon a_i \cos \theta_i \sin \gamma + \epsilon^2 a_i^2 \sin(2\gamma)}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2 \cos(2\gamma)}
\]
Analysis of $B_s^0 \to J/\psi \bar{K}^{*0}$ decays

- **Analysis overview:**
  - Perform an **angular analysis** using full Run-I data sample and measure the polarisation dependent fractions $f_i$, the direct CP asymmetries, and the branching fraction.

- **Results:**

  $$B(B_s^0 \to J/\psi \bar{K}^{*0}) = \left(4.13 \pm 0.16 \text{ (stat)} \pm 0.25 \text{ (syst)} \pm 0.24 \left(\frac{f_d}{f_s}\right)\right) \times 10^{-5}$$

  $f_0 = 0.497 \pm 0.025 \text{ (stat)} \pm 0.025 \text{ (syst)}$

  $f_\parallel = 0.179 \pm 0.027 \text{ (stat)} \pm 0.013 \text{ (syst)}$

  $A_{0CP}(B_s^0 \to J/\psi \bar{K}^{*0}) = -0.048 \pm 0.057 \text{ (stat)} \pm 0.020 \text{ (syst)}$

  $A_{CP}(B_s^0 \to J/\psi \bar{K}^{*0}) = 0.171 \pm 0.152 \text{ (stat)} \pm 0.028 \text{ (syst)}$

  $A_{1CP}(B_s^0 \to J/\psi \bar{K}^{*0}) = -0.049 \pm 0.096 \text{ (stat)} \pm 0.025 \text{ (syst)}$

- **Accessing penguin parameters:**

  - $A_{iCP} = \frac{\Gamma(B_s^0 \to J/\psi(K^+\pi^-)_{i}) - \Gamma(B_s^0 \to J/\psi(K^-\pi^+)_{i})}{\Gamma(B_s^0 \to J/\psi(K^+\pi^-)_{i}) + \Gamma(B_s^0 \to J/\psi(K^-\pi^+)_{i})} = -\frac{2a_i \sin \theta_i \sin \gamma}{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}$

  - $H_i \propto \frac{1}{\epsilon \left(\frac{A_i'}{A_i}\right)} \left(\frac{B(B_s^0 \to J/\psi \bar{K}^{*0}) f_i}{B(B_s^0 \to J/\psi \phi)}\right) f_i' = \frac{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}{1 + 2\epsilon a_i' \cos \theta_i \cos \gamma + \epsilon^2 a_i'^2}$

  Ratio of hadronic amplitudes calculated using latest results from QCD LCSR [arXiv:1503.05534]
Analysis of $B^0 \to J/\psi \pi^+ \pi^-$ decays

Analysis overview:
- Perform a time-dependent flavor-tagged angular analysis using full Run-I data sample and measure the direct and mixing-induced CP violation parameters
- $\rho^0$ disentangled from the $\pi^+ \pi^-$ spectrum using technique from [Phys. Lett. B719 (2013) 383]

Results: (using $\rho^0$ events)

\[
2\beta_{\text{eff}}(B^0 \to J/\psi \rho^0) = (41.7 \pm 9.6(\text{stat})^{+2.8}_{-6.3}(\text{syst}))^{\circ}
\]
\[
\alpha_{CP}(B^0 \to J/\psi \rho^0) = -(32 \pm 28(\text{stat})^{+7}_{-9}(\text{syst})) \times 10^{-3}
\]

\[
\alpha_{CP} = \frac{1 - |\lambda_f|}{1 + |\lambda_f|}
\]

Accessing penguin parameters:

\[
\Delta \phi_s = - \arg \left( \frac{\lambda_f e^{2i\gamma} - 1 + \epsilon(\lambda'_f - 1)}{(\lambda_f e^{2i\gamma} - 1) + \epsilon(\lambda'_f - 1)e^{2i\gamma}} \right) \quad \lambda'_f \equiv |\lambda_f|e^{-i\Delta 2\beta}
\]
\[
\Delta 2\beta = \left( 2\beta_{J/\psi \rho} - 2\beta_{J/\psi K^0_S} \right) = (-0.9 \pm 9.7(\text{stat})^{+2.8}_{-6.3}(\text{syst}))^{\circ}
\]
Combining $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ & $B^0 \rightarrow J/\psi \rho^0$

Using the extended fit method proposed in: [JHEP 1503 (2015) 145]

- $A_{\text{dir}}^{\psi}(B_d \rightarrow J/\psi \rho^0)$
- $A_{\text{mix}}^{\psi}(B_d \rightarrow J/\psi \rho^0)$
- $\Delta \phi_s^{(\psi \rho)}$
- $A_{\text{dir}}^{\psi}(B_s \rightarrow J/\psi \phi)$
- $A_{\text{mix}}^{\psi}(B_s \rightarrow J/\psi \phi)$
- $B(B_d \rightarrow J/\psi \rho^0)$
- $B(B_s \rightarrow J/\psi \bar{K}^{*0})$
- $\mathcal{A}_{\text{dir}}^{\psi}(B_s \rightarrow J/\psi \bar{K}^{*0})$

Minimal Fit

- $a_f, \theta_f$

Extended Fit

- New Link
- Old Input
- Test

QCD Calculations

Extract ratio of hadronic amplitudes from data
Combining $B_s^0 \to J/\psi \bar{K}^{*0}$ & $B^0 \to J/\psi \rho^0$

Using the extended fit method proposed in: [JHEP 1503 (2015) 145]

- Assuming: 
  \[ \frac{\mathcal{A}_i'(B_s^0 \to J/\psi \phi)}{\mathcal{A}_i(B_s^0 \to J/\psi \bar{K}^{*0})} = \frac{\mathcal{A}_i'(B_s^0 \to J/\psi \rho^0)}{\mathcal{A}_i(B^0 \to J/\psi \rho^0)} \]

Complete set of results on following slide
Combining $B_s^0 \rightarrow J/\psi \ K^{*0}$ & $B^0 \rightarrow J/\psi \ \rho^0$

Using the extended fit method proposed in: [JHEP 1503 (2015) 145]

- Assuming: \[
\frac{\mathcal{A}'_i(B_s^0 \rightarrow J/\psi \phi)}{\mathcal{A}_i(B_s^0 \rightarrow J/\psi \ K^{*0})} = \frac{\mathcal{A}'_i(B_s^0 \rightarrow J/\psi \phi)}{\mathcal{A}_i(B^0 \rightarrow J/\psi \ \rho^0)}
\]

Penguin effects in $B_s^0$ mixing are under control!

$\Delta \phi^{J/\psi \phi}_{s,0} = 0.000^{+0.009}_{-0.011} \ (\text{stat})^{+0.004}_{-0.009} \ (\text{syst})$

$\Delta \phi^{J/\psi \phi}_{s,\parallel} = 0.001^{+0.010}_{-0.014} \ (\text{stat})^{+0.007}_{-0.008} \ (\text{syst})$

$\Delta \phi^{J/\psi \phi}_{s,\perp} = 0.003^{+0.010}_{-0.014} \ (\text{stat})^{+0.007}_{-0.008} \ (\text{syst})$

$a_0 = 0.01^{+0.10}_{-0.01}$
$a_{\parallel} = 0.07^{+0.11}_{-0.05}$
$a_{\perp} = 0.04^{+0.12}_{-0.04}$

$\theta_0 = - (82^{+98}_{-262})^\circ$
$\theta_{\parallel} = - (85^{+71}_{-63})^\circ$
$\theta_{\perp} = (38^{+142}_{-218})^\circ$
- **Accessing Hadronic Parameters:**
  - Using the branching ratio information and solutions for \((a_i, \theta_i)\) as inputs
  - Get information on hadronic amplitudes as a nice byproduct of the fit:

<table>
<thead>
<tr>
<th></th>
<th>Fact./LCSR</th>
<th>LHCb Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{A}'_0(B_s \to J/\psi \phi) )</td>
<td>1.15 ± 0.15</td>
<td>1.195_{-0.056}^{+0.074}</td>
</tr>
<tr>
<td>( \mathcal{A}_0(B_d \to J/\psi \rho^0) )</td>
<td>1.25 ± 0.15</td>
<td>1.238_{-0.080}^{+0.104}</td>
</tr>
<tr>
<td>( \mathcal{A}'_1(B_s \to J/\psi \phi) )</td>
<td>1.13 ± 0.10</td>
<td>1.042_{-0.063}^{+0.081}</td>
</tr>
<tr>
<td>( \mathcal{A}_1(B_d \to J/\psi \rho^0) )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[JHEP 08 (2016) 098] [JHEP 11 (2015) 082]
Strategy:
- Similarly as for $\Delta \phi_s$, the decay mode $B_s^0 \to J/\psi K_S^0$ can be used to control $\Delta \phi_d$
Analysis of $B_s^0 \rightarrow J/\psi K_S^0$ decays

Analysis overview:
- First **flavor-tagged time-dependent** analysis of $B_s^0 \rightarrow J/\psi K_S^0$ decays

<table>
<thead>
<tr>
<th>Yield</th>
<th>Long $K_S^0$ (ps)</th>
<th>Downstream $K_S^0$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi K_S^0$</td>
<td>27 801 ± 168</td>
<td>51 351 ± 231</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi K_S^0$</td>
<td>307 ± 20</td>
<td>601 ± 30</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>658 ± 37</td>
<td>2 852 ± 74</td>
</tr>
</tbody>
</table>

Results:

\[
A_{\Delta \Gamma} (B_s^0 \rightarrow J/\psi K_S^0) = 0.49 \pm 0.77^{+0.65}_{-0.65} \text{ (stat)} \pm 0.06 \text{ (syst)}
\]
\[
C_{\text{dir}} (B_s^0 \rightarrow J/\psi K_S^0) = -0.28 \pm 0.41 \text{ (stat)} \pm 0.08 \text{ (syst)}
\]
\[
S_{\text{mix}} (B_s^0 \rightarrow J/\psi K_S^0) = -0.08 \pm 0.40 \text{ (stat)} \pm 0.08 \text{ (syst)}
\]

- Successful proof of concept waiting for more statistics
- Can be used to estimate the penguin shift $\Delta \phi_d$
Prospects and summary
Prospects on penguin shift $\Delta \phi_d$

Illustration the era of the LHCb Upgrade:
- Results from [JHEP 1503 (2015) 145] using the following extrapolated inputs:

\[
\begin{align*}
A_{CP}^{\text{dir}}(B_s \rightarrow J/\psi K^0_S) &= 0.004 \pm 0.065, \\
A_{CP}^{\text{mix}}(B_s \rightarrow J/\psi K^0_S) &= -0.274 \pm 0.065,
\end{align*}
\]

$\gamma = (73.2 \pm 1.0)^\circ$

$\phi_s = -(2.1 \pm 0.5|_{\text{exp}} \pm 0.3|_{\text{theo}})^\circ$

\[
\Delta \phi_d = -(1.02 \pm 0.24(\text{stat})^{+0.17}_{-0.24}(\text{SU(3)}))^\circ
\]
Prospects on penguin shift $\Delta \phi_d$:

- Illustration the era of the LHCb Upgrade:

We will be able to control the penguin effects in $B^0$ mixing!
Modes to be investigated in the future:

- **Control Modes for $B_s^0 \to J/\psi \phi$:**
  1. High precision CP analysis of $B^0 \to J/\psi \rho^0$: Determination of penguin parameters
  2. Search for $B_s^0 \to J/\psi \rho^0$ and/or $B^0 \to J/\psi \phi$: Control contribution from E + PA
  3. High precision CP analysis of $B_s^0 \to J/\psi \bar{K}^*0$: Cross-check

- **Control Modes for $B^0 \to J/\psi K_S^0$:**
  1. High precision CP analysis of $B_s^0 \to J/\psi K_S^0$: Determination of penguin parameters
  2. High precision CP analysis of $B^0 \to J/\psi \pi^0$: Determination of penguin parameters
  3. Search for $B_s^0 \to J/\psi \pi^0$: Control contributions from E + PA in $B^0 \to J/\psi \pi^0$
We entered in the era of high-precision for the measurement of the \(B^0 - \bar{B}^0\) and \(B_s^0 - \bar{B}_s^0\) mixing phases.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(\phi_d [^\circ])</td>
<td>(B^0 \rightarrow J/\psi K^0_S)</td>
<td>2.2</td>
<td>1.2</td>
<td>0.4</td>
<td>(~ 0.2)</td>
<td>(~ 2.6)</td>
</tr>
<tr>
<td>(\phi_s [\text{rad}])</td>
<td>(B_s^0 \rightarrow J/\psi K^+K^-)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.008</td>
<td>(~ 0.004)</td>
<td>(~ 0.001)</td>
</tr>
<tr>
<td></td>
<td>(B_s^0 \rightarrow J/\psi \pi^+\pi^-)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>(~ 0.005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combination</td>
<td>0.039</td>
<td>0.020</td>
<td>0.007</td>
<td>(~ 0.003)</td>
<td></td>
</tr>
</tbody>
</table>

- Controlling higher order corrections to \(\phi_d\) and \(\phi_s\) becomes mandatory.

- Demonstrated that we can control the penguin effects sufficiently well for the Upgrade Era:

\[ \Delta \phi_s \sim 0.001 \pm 0.020 \text{ rad} \]

\[ \phi_{s,c\bar{c}s}^{\text{eff}} = -0.030 \pm 0.033 \text{ rad} \]

- ...but more work might still be needed for a 300 fb\(^{-1}\) Upgrade.
"-ϕ mixing:

Octet and Singlet Contributions:
- ϕ being a pure s̅s̅ state, hence an admixture of octet and singlet state
- In the current framework, only the octet contribution is considered:
  - Only needed for the H observable to relate the form factors of $B_s^0 \rightarrow \phi$
  - and $B_s^0 \rightarrow \bar{K}^{*0}$ or $B^0 \rightarrow \rho^0$ (+ E & PA contributions are ignored)

Mixing:
- Can mix with the orthogonal ω state: parametrised by mixing angle δ

\[ \mathcal{B}(B_s^0 \rightarrow J/\psi \omega) = \tan^2 \delta \times \mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \]

- Challenging, but LHCb should be able to perform a measurement of this branching fraction allowing to get insight on the mixing angle δ
Penguin pollution in $\phi_s$ with $B_s^0 \rightarrow J/\psi K^{*0}$

Allowing for SU(3) flavor symmetry breaking:

$$a'_i = \xi \times a_i, \quad \theta'_i = \theta_i + \delta$$
Penguin pollution in $\phi_s$ with $B^0 \rightarrow J/\psi \rho^0$

Allowing for SU(3) flavor symmetry breaking:

\[ \Delta \phi_s \text{ 95\% CL region [deg]} \]

\[ \theta - \theta' \text{ [deg]} \]

LHCb

$B^0 \rightarrow J/\psi \pi^+ \pi^-$: Resonance constant

- $\pi^+ \pi^-$ invariant-mass spectrum:

![Graph showing the invariant-mass spectrum with data points, fits, and signal and background contributions.](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
<td>65.6 ± 1.9</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>20.1 ± 0.7</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>7.8 ± 0.6</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.64^{+0.19}_{-0.13}$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>9.0 ± 1.8</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>3.1 ± 0.7</td>
</tr>
</tbody>
</table>
The LHCb experiment

- Forward General-Purpose Detector at the LHC
- ~30% of heavy quark production cross-section with just 4% of solid angle

**Vertex Detector**
reconstruct vertices
decay time resolution: 46 fs
IP reconstruction: 20 μm

**Tracking System**
momentum resolution
Δp/p = 0.4% — 0.6%

**Collisions**
@ 40 MHz

**~12 MHz**
Visible Interactions (2012)

**Dipole Magnet**
4 Tm
normal conducting regular polarity switches

**RICH Detectors**
K/π/p separation

**Muon System**

**Calorimeters**
energy measurement
particle identification
Measurement ingredients

- **Time-dependent CP asymmetry:**

\[
\mathcal{A}_{CP}(t) = \frac{\Gamma (\bar{B}_q^0(t) \to f) - \Gamma (B_q^0(t) \to f)}{\Gamma (\bar{B}_q^0(t) \to f) + \Gamma (B_q^0(t) \to f)} = \frac{S_f \sin (\Delta mt) - C_f \cos (\Delta mt)}{\cosh (\frac{\Delta \Gamma t}{2}) + A_{\Delta \Gamma} \sinh (\frac{\Delta \Gamma t}{2})}
\]

- **Mixing parameters:**

\[
\Delta m = m_H - m_L \quad \Delta \Gamma = \Gamma_L - \Gamma_H
\]

- **CP observables:**

\[
S_f = \frac{2 \Im (\lambda f)}{1 + |\lambda f|^2}, \quad C_f = \frac{1 - |\lambda f|^2}{1 + |\lambda f|^2}, \quad A_{\Delta \Gamma} = -\frac{2 \Re (\lambda f)}{1 + |\lambda f|^2}
\]

\[
\lambda_f = \frac{\eta_f q}{p} A(\bar{B}_q^0(t) \to f) = \eta_f |\lambda_f| e^{i\phi_q}
\]

\[
S_f = -\eta_f \frac{2 |\lambda_f| \sin (\phi_s)}{1 + |\lambda f|^2}, \quad A_{\Delta \Gamma} = \eta_f \frac{2 |\lambda_f| \cos (\phi_s)}{1 + |\lambda_f|^2}
\]
Measurement ingredients

- Tagging, resolution and other nuisance effects:

\[ A_{\text{meas}}(t) = A_{\text{CP}}(t) \times D_{\text{res}} \times D_{\text{tag}} \pm A_{\text{det/prod}} \]

- Decay time resolution (~45 fs):

\[ D_{\text{res}} = e^{-\frac{\Delta m^2 \sigma_t^2}{2}} \]

- Tagging dilution:

\[ D_{\text{tag}} = (1 - 2\omega) \]
  - Initial B flavor efficiency: \( \epsilon_{\text{tag}} \)
  - Wrong tag rate: \( \omega \)
  - Effective reduction in statistical power:

\[ \epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1 - 2\omega)^2 \sim \mathcal{O}(\%) \]

\[ \sigma_{\text{stat}}(\phi_s) \propto \frac{1}{\sqrt{\epsilon_{\text{eff}} N}} \]

- Also need to account for detection/production asymmetries, acceptance effects on time and angular variables (P \( \rightarrow \) VV), ...