Latest results on $\phi_s$

Diego Martínez Santos
(on behalf of LHCb collaboration)
Introduction

- $\phi_S$ results from LHCb

- Introduction
- Analysis overview
- Results
- Prospects
- Results on penguin pollution
What (and why) $\Phi_s$
**Φ_s from B_s → J/ψ (→μμ) KK**

B_s mass eigenstates:

\[
\begin{align*}
|B^+_L\rangle &= p|B_s\rangle + q|\bar{B}_s\rangle \\
|B^+_R\rangle &= p|B_s\rangle - q|\bar{B}_s\rangle
\end{align*}
\]

- q/p: complex number. |q/p| ≠ 1 → CPV in mixing
- \(A_f, \bar{A}_f\) complex amplitudes. |\(A_f/\bar{A}_f\) ≠ 1 → CPV in decay

Even if not CPV in mixing or decay, you can generate CPV in the interference if

\[
\sin(\phi_s) \equiv \sin\left(-\arg\left(\frac{q A_f}{p \bar{A}_f}\right)\right) \neq 0
\]

Main (but not only) experimental signature of a non-zero \(\phi_s\): it generates wiggles in the time-dependent angular distribution of the \(B_s \rightarrow J/\psi \phi \rightarrow \mu\mu KK\) final state particles. The frequency of the (potential) wiggles is known: \(\Delta m_s\).

\[
|\lambda| \equiv \left|\frac{q A_f}{p \bar{A}_f}\right| \sim 1
\]
**Φ_s : Standard Model and New Physics sensitivity**

SM prediction: \( \Phi_s = -2 \text{arg} \left( -\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*} \right) = -0.0363 \pm 0.0013 \) (*) Neglecting penguin contributions.

It is very precise, and sensitive to Physics Beyond the SM, specially to non-MFV New physics …. which is accessible even if the NP is at a high scales.

→ Illustrative (brute force) test: calculate non-MFV SUSY contributions setting all particle masses \( \sim 10 \) TeV

Those potential effects are within reach of current experimental precision!
Analysis
**Analysis strategy:** Fit the time dependent angular distribution, considering experimental effects:

- **Background:** Events are weighted according to position in $J/\psi KK$ mass spectrum.

- Angular distributions are distorted on data because of **non-flat angular acceptance**. Simulation (weighted according to kinematics seen on data) is used to correct for this.

- **Lifetime acceptance.** Samples from different trigger lines are used to unfold trigger biases. Per event weights are used to correct for track reconstruction biases.
**Φ_s from B_s → J/ψ (μμ) KK**

Analysis strategy: Fit the time dependent angular distribution, considering experimental effects:

- **Lifetime resolution**: Non-perfect time resolution (46 fs, still much smaller than oscillation period, 350 fs) convolved with the pdf. Main effect is a ~25% dilution of the amplitude of the wiggles. Measured on data using prompt J/ψ events.

- **Flavour tagging**: The initial flavour of the B_s is determined either by a lepton/kaon from the other B, and/or by a kaon from the fragmentation. The performance of these taggers is calibrated with control samples such as B^+→J/ψK^+, B_d→D^*+μν and B_s→D_s^−π^+.
$\Phi_s$ from $B_s \to J/\psi (\not>\mu\mu) \pi\pi$

- Similar analysis methodology than $B_s \to J/\psi $KK. Some differences:
  - Deal with several $\pi^+\pi^-$ resonances (implies a time dependent Dalitz analysis)
  - Almost no sensitivity to $\Delta \Gamma_s \rightarrow$ less sensitive to decaytime acceptance
Results and prospects
**Φ_s from B_s → J/ψ (→μμ) hh**

Φ_s (B_s → J/ψππ), 3fb^{-1}

0.070±0.068±0.008 rad

SM prediction: \( \Phi_s = -2\text{arg} \left( \frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*} \right) = -0.0363±0.0013 \) (*)
**\( \Phi_s \) from \( B_s \to J/\psi (\not\mu \mu) \) hh**

**\( \Phi_s (B_s \to J/\psi \pi \pi) \), 3\( \text{fb}^{-1} \)**

\[
0.070 \pm 0.068 \pm 0.008 \text{ rad}
\]

**SM prediction:**

\[
\Phi_s = -2 \arg \left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) = -0.0363 \pm 0.0013^{(*)}
\]

**\( \Phi_s (B_s \to J/\psi \mathrm{KK}) \), 3\( \text{fb}^{-1} \)**

\[
-0.058 \pm 0.049 \pm 0.006 \text{ rad}
\]
**Φ_s from B_s → J/ψ (μμ) hh**

Φ_s (B_s → J/ψππ), 3fb⁻¹

0.070±0.068±0.008 rad

SM prediction: Φ_s = -2arg \left( -\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*} \right) = -0.0363±0.0013(*)

Φ_s (B_s → J/ψKK), 3fb⁻¹

-0.058±0.049±0.006 rad

**NEW**

Combined, 3fb⁻¹

φ_s = -0.010±0.040 rad

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LHCb-PAPER-2014-059
In preparation
Other observables from $B_s \to J/\psi KK$

<table>
<thead>
<tr>
<th>Observable</th>
<th>value</th>
</tr>
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<tbody>
<tr>
<td>$\Gamma_s [ps^{-1}]$</td>
<td>$0.6603 \pm 0.0027 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s [ps^{-1}]$</td>
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<td>\lambda</td>
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(NEW: world’s most precise measurements of basic $B_s$ physics observables)
Other observables from $B_s \to J/\psi KK$

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First polarization dependent results (to study penguin pollutions)

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<tr>
<td>$</td>
<td>\lambda_0</td>
<td>$</td>
<td>$1.012 \pm 0.058 \pm 0.013$</td>
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<tr>
<td>$</td>
<td>\lambda_{</td>
<td></td>
<td>}/\lambda_0</td>
</tr>
<tr>
<td>$</td>
<td>\lambda_{\perp}/\lambda_0</td>
<td>$</td>
<td>$1.02 \pm 0.12 \pm 0.05$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda_S/\lambda_0</td>
<td>$</td>
<td>$0.86 \pm 0.12 \pm 0.03$</td>
</tr>
</tbody>
</table>

Everything compatible with no polarization dependence
In addition to $B_s \rightarrow J/\psi KK$ and $B_s \rightarrow J/\psi \pi \pi$ LHCb measured $\Phi_s$ in $B_s \rightarrow D_s D_s$:

$$\phi_s = 0.02 \pm 0.17 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ rad}, \quad |\lambda| = 0.91 \pm 0.18 \text{ (stat)} \pm 0.02 \text{ (syst)}$$

arXiv:1409.4619

See M.Jung’s talk at 12.05: [https://indico.cern.ch/event/324660/session/4/contribution/43](https://indico.cern.ch/event/324660/session/4/contribution/43)

And also plans to:

- $B_s \rightarrow \psi(2S)KK$ (~10% of the statistics power of $B_s \rightarrow J/\psi KK$)
- $B_s \rightarrow J/\psi KK$ (high KK mass)
- $B_s \rightarrow J/\psi KK$ with the $J/\psi$ going to electrons

Altogether could give an extra ~25% reduction of the uncertainty in $\Phi_s$
ATLAS and CMS also study $B_s \to J/\psi \phi \to \mu\mu KK$.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lumi. (fb$^{-1}$)</th>
<th>$\Delta \Gamma_s$ (ps$^{-1}$)</th>
<th>$\Phi_s$ (rad)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>4.9</td>
<td>$0.053 \pm 0.021 \pm 0.010$</td>
<td>$0.12 \pm 0.25 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>$0.096 \pm 0.014 \pm 0.007$</td>
<td>$-0.03 \pm 0.11 \pm 0.03$</td>
</tr>
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\( \Phi_s \) (world average)

ATLAS and CMS also study \( B_s \rightarrow J/\psi \Phi \rightarrow \mu\mu KK \)

HFAG private/unofficial world average yields

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<td>0.096( \pm )0.014( \pm )0.007</td>
<td></td>
</tr>
<tr>
<td>( \Phi_s ) (rad)</td>
<td>0.12( \pm )0.25( \pm )0.05</td>
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<td></td>
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</table>

arxiv.org/abs/1407.1796

CMS-PAS-BPH-13-012

HFAG world average, unofficial

\( \Phi_s = -0.015\pm0.036 \) rad
Prospects

\[ \text{Bs} \to \text{J/}\psi \text{KK} \]
\[ \text{Bs} \to \text{J/}\psi \text{KK} + \text{Bs} \to \text{J/}\psi\pi\pi \]

~2016

~ end of Run-II

… and with LHCb upgrade the sensitivity can go below 0.01 rad
Prospects

$\text{Bs} \rightarrow \text{J}/\psi KK$
$\text{Bs} \rightarrow \text{J}/\psi KK + \text{Bs} \rightarrow \text{J}/\psi \pi \pi$

$\sim 2016$
$\sim \text{end of Run-II}$

... and with LHCb upgrade the sensitivity can go below 0.01 rad
Penguin Pollutions
Penguin contributions to $\Phi_s$, are usually neglected because they are doubly Cabibbo suppressed.

However, these contributions cannot be calculated reliably from QCD.

S. Faller, R. Fleischer, T. Mannel arXiv:0810.4248 [hep-ph] propose a method to calculate the penguin pollution to $\Phi_s$ by analysing $B \rightarrow J/\psi \rho$ and/or $B_s \rightarrow J/\psi K^*$ data.
**Penguin pollution**

\( \mathbf{B} \rightarrow \mathbf{J/ψρ} \) analysed full dataset

- CPV in time dependent Dalitz analysis, measure an effective \( 2β, \) \( 2β_{\text{eff}} \)

\[
\lambda_i \equiv \frac{q_i}{p_i} A_i, \quad 2β_{\text{eff}}^i \equiv -\arg(η_i λ_i)
\]

- Apply SU(3) symmetry (\( θ' \rightarrow θ, a' \rightarrow -εa \)) to convert result into estimate of penguin pollution in \( Φ_s \) or \( 2β^\psi K_s \)

\[
δ_P = -\arg \left( \frac{1 + εa_f e^{iθ_f} e^{-iγ}}{1 + εa_f e^{iθ_f} e^{iγ}} \right)
\]

\( ε = |V_{us}|^2/(1-|V_{us}|^2) = 0.0534 \)

\( δ_P \approx -ε \Delta 2β_f \)

\[
\Gamma(t) = N e^{-Γ dt} \left\{ \frac{|A|^2 + |A|^2}{2} + \frac{|A|^2 - |A|^2}{2} \cos(Δm dt) - i m(A^*A) \sin(Δm dt) \right\}
\]

\[
\Gamma(t) = N e^{-Γ dt} \left\{ \frac{|A|^2 + |A|^2}{2} - \frac{|A|^2 - |A|^2}{2} \cos(Δm dt) + i m(A^*A) \sin(Δm dt) \right\}
\]

\[
A = \sum_i A_i \quad \text{(sum over } π^+π^- \text{ resonant transversity amplitudes)}
\]

Using formalism PLB, 719, 383 (2013)
**Penguin pollution**

\[ B \rightarrow J/\psi \rho \] analysed full dataset

Obtained:

\[ |\delta_P| < 0.02 \text{ rad @ 95\% CL} \]

( half of the uncertainty on \( \Phi_s \)

- The above limit depends linearly on SU(3) breaking factor \( a/a' \)

- Consistent with theory estimations

PRELIMINARY
**Penguin pollution**

\( B_s \to J/\psi K^* \) experimental status

- Analysed with 370pb\(^{-1}\)
- Branching fraction
- Polarization amplitudes

\[
\begin{align*}
  f_L &= 0.50 \pm 0.08 \pm 0.02 \\
  f_\parallel &= 0.19^{+0.10}_{-0.08} \pm 0.02
\end{align*}
\]

\[
\frac{\text{BR}(B_s \to J/\psi K^{*0})}{\text{BR}(B_d \to J/\psi K^{*0})} = (3.43^{+0.34}_{-0.36} \pm 0.50)\%
\]

\[
\mathcal{B}(B_s^0 \to J/\psi K^{*0}) = (4.4^{+0.5}_{0.4} \pm 0.8) \times 10^{-5}
\]

**SM expectations**

\[
\begin{align*}
  \text{BR}(B_s \to J/\psi K^{*0}) &\approx 0.0333 \\
  \text{BR}(B_d \to J/\psi K^{*0}) &\approx 0\%
\end{align*}
\]

Expected similar penguin sensitivity than \( J/\psi \pi \pi \), but depends on central values
Conclusions

- New $\Phi_s$ result presented, in excellent agreement with the Standard Model

$\phi_s = -0.010\pm0.040 \text{ rad} \quad \text{(preliminary)}$
Conclusions

• New $\Phi_s$ result presented, in excellent agreement with the Standard Model

$$\phi_s = -0.010 \pm 0.040 \text{ rad} \quad (\text{preliminary})$$

• Precision can improve to $<0.02$ rad in Run-II, and $<0.01$ rad with LHCb upgrade

• Excellent experimental sensitivity to penguin contamination, need theory input for SU(3) factors

Bone, you are hard…

… but I am patient…

source: google osso duro
<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
<th>Transversity fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>65.6 ± 1.9</td>
<td>56.7 ± 1.8</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>20.1 ± 0.7</td>
<td>1</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>7.8 ± 0.6</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>0.64$^{+0.19}_{-0.13}$</td>
<td>44 ± 14</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>9.0 ± 1.8</td>
<td>47 ± 11</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>3.1 ± 0.7</td>
<td>29 ± 12</td>
</tr>
</tbody>
</table>
\( \phi_{s}^{\phi\phi} \) from \( B_s \rightarrow \phi\phi \)

\[ \phi_{s}^{\phi\phi} \equiv \text{arg} \left( \frac{q A (B_s \rightarrow \phi\phi)}{p A (B_s \rightarrow \phi\phi)} \right) \]

different quantity than the \( \Phi \)s I presented at the beginning of my talk
SM expectation is \( \phi_{s}^{\phi\phi} < 0.02 \)

Also measured through time dependent angular analysis. We have analysed the full 3 fb\(^{-1}\) dataset:

\[ \phi_{s}^{\phi\phi} = -0.17 \pm 0.15 \pm 0.03 \]

In very good agreement with SM
$\Phi_s$ from $B_s \rightarrow J/\psi (\phi \mu \mu) \pi \pi$

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\phi_s$ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay time acceptance</td>
<td>±0.6</td>
</tr>
<tr>
<td>Mass acceptance</td>
<td>±0.3</td>
</tr>
<tr>
<td>Background time PDF</td>
<td>±0.2</td>
</tr>
<tr>
<td>Background mass distribution PDF</td>
<td>±0.6</td>
</tr>
<tr>
<td>Resonance model</td>
<td>±6.0</td>
</tr>
<tr>
<td>Resonance parameters</td>
<td>±0.7</td>
</tr>
<tr>
<td>Other fixed parameters</td>
<td>±0.4</td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>±5.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±8.4</td>
</tr>
</tbody>
</table>
Apart from the wiggles, there are other terms in the pdf that have some sensitivity to $\Phi_s$:
## $\Phi_s$ from $B_s \to J/\psi (\not\tau \mu \mu)$ KK

| Source                                      | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_\perp|^2$ | $|A_0|^2$ | $\delta_{||}$ [rad] | $\delta_{\perp}$ [rad] | $\phi_s$ [rad] | $|\lambda|$ | $\Delta m_s$ [ps$^{-1}$] |
|--------------------------------------------|------------------------|-------------------------------|--------------|-----------|---------------------|---------------------|---------------|-----------|---------------------|
| Total stat. uncertainty                    | 0.0027                 | 0.0091                        | 0.0049       | 0.0034    | $^{+0.10}_{-0.17}$ | $^{+0.14}_{-0.15}$ | 0.049         | 0.019     | $^{+0.055}_{-0.057}$ |
| Mass factorisation                         | –                      | 0.0007                        | 0.0031       | 0.0064    | 0.05                | 0.05                | 0.002         | 0.001     | 0.004               |
| Signal weights (stat.)                     | 0.0001                 | 0.0008                        | –            | 0.0001    | –                   | –                   | –             | –         | –                   |
| Resonant background                        | 0.0001                 | 0.0004                        | 0.0004       | 0.0002    | 0.02                | 0.02                | 0.002         | 0.003     | 0.001               |
| $B_c^+$ background                          | 0.0005                 | –                             | –            | –         | –                   | –                   | –             | –         | –                   |
| Angular resolution bias                    | –                      | –                             | 0.0006       | 0.0001    | $^{+0.02}_{-0.03}$ | 0.01                | –             | –         | –                   |
| Ang. efficiency (reweighting)              | 0.0001                 | –                             | 0.0011       | 0.0020    | 0.01                | –                   | 0.001         | 0.005     | 0.002               |
| Ang. efficiency (stat.)                    | 0.0001                 | 0.0002                        | 0.0011       | 0.0004    | 0.02                | 0.01                | 0.004         | 0.002     | 0.001               |
| Decay time resolution                      | –                      | –                             | –            | –         | –                   | –                   | 0.002         | 0.001     | 0.005               |
| Trigger efficiency (stat.)                 | 0.0011                 | 0.0009                        | –            | –         | –                   | –                   | –             | –         | –                   |
| Track reconstruction (simul.)              | 0.0007                 | 0.0029                        | 0.0005       | 0.0006    | $^{+0.01}_{-0.02}$ | 0.002               | 0.001         | 0.001     | 0.006               |
| Track reconstruction (stat.)               | 0.0005                 | 0.0002                        | –            | –         | –                   | –                   | –             | –         | 0.001               |
| Length and momentum scales                 | 0.0002                 | –                             | –            | –         | –                   | –                   | –             | –         | 0.005               |
| S-P coupling factors                       | –                      | –                             | –            | –         | 0.01                | 0.01                | –             | –         | 0.001               |
| Fit bias                                   | –                      | –                             | 0.0005       | –         | 0.01                | –                   | 0.001         | –         | –                   |
| Quadratic sum of syst.                     | 0.0015                 | 0.0033                        | 0.0036       | 0.0067    | $^{+0.06}_{-0.07}$ | 0.06                | 0.006         | 0.007     | 0.011               |
Mainly two observables:

\[ F(|V_{us}|) \]

CKM angle

Penguin pollution

Experimental input. Basically

\[ \frac{(BR \cdot f_f)_{J/\psi K^*}}{(BR \cdot f_f)_{J/\psi \phi}} \]

Penguin pollution

\[ f = \text{polarization state} \]

Direct CP asymmetry (difference of yields)
Mainly two observables:

\[ F(|V_{us}|) \]

CKM angle

Experimental input. Basically (modulo lifetimes)

\begin{align*}
H_c &= \frac{1}{\epsilon} \left| \frac{A_f}{A'_f} \right|^2 \frac{\Gamma[f, t = 0]'}{\Gamma[f, t = 0]} = \frac{1 - 2a'_f \cos \theta'_f \cos \gamma + a^2_f}{1 + 2\epsilon a_f \cos \theta_f \cos \gamma + \epsilon^2 a^2_f} \\
\end{align*}

penguin stuff

\[ \left( \frac{BR \cdot f_f}{BR \cdot f_f} \right)_{J/\psi K^*} \]

\[ \left( \frac{BR \cdot f_f}{BR \cdot f_f} \right)_{J/\psi \phi} \]

Direct CP asymmetry (difference of yields)

\[ \tan \Delta \phi_f = \frac{2\epsilon a_f \cos \theta_f \sin \gamma + \epsilon^2 a^2_f \sin 2 \gamma}{1 + 2\epsilon a_f \cos \theta_f \cos \gamma + \epsilon^2 a^2_f \cos 2 \gamma} \]

SU(3) \implies a' = a, \theta' = \theta

...and plug here
Penguin pollution

Mainly two observables:

$$H_f \equiv \frac{1}{\epsilon} \left| \frac{A_f}{A'_f} \right|^2 \frac{\Gamma[f, t = 0]}{\Gamma[f, t = 0]} = \frac{1 - 2 \alpha'_f \cos \theta'_f \cos \gamma + \alpha'^2_f}{1 + 2 \epsilon \alpha_f \cos \theta_f \cos \gamma + \epsilon^2 \alpha^2_f}$$

This other stuff are SU(3) breaking effects which are currently poorly known

$$\left| \frac{A'_0}{A_0} \right|^2 = 0.42 \pm 0.27,$$

$$\left| \frac{A'_\parallel}{A_\parallel} \right|^2 = 0.70 \pm 0.29,$$

$$\left| \frac{A'_\perp}{A_\perp} \right|^2 = 0.38 \pm 0.16.$$
Mainly two observables:

\[
H_f \equiv \frac{1}{\epsilon} \left| \frac{\mathcal{A}_f}{\mathcal{A}'_f} \right|^2 \frac{\Gamma[f, t = 0]}{\Gamma[f, t = 0]} = \frac{1 - 2a_f' \cos \theta_f' \cos \gamma + a_f'^2}{1 + 2\epsilon a_f' \cos \theta_f' \cos \gamma + \epsilon^2 a_f'^2}
\]

This other stuff are SU(3) breaking effects which are currently poorly known.

Or maybe not so poorly?

\[
\left| \frac{\mathcal{A}'_0}{\mathcal{A}_0} \right|^2 = 0.42 \pm 0.27 ,
\]

\[
\left| \frac{\mathcal{A}'_\parallel}{\mathcal{A}_\parallel} \right|^2 = 0.70 \pm 0.29 ,
\]

\[
\left| \frac{\mathcal{A}'_\perp}{\mathcal{A}_\perp} \right|^2 = 0.38 \pm 0.16 .
\]

arXiv:0810.4248

\[ -\sqrt{2}A(B^0 \rightarrow (J/\psi \rho)_{f}) = \lambda A'_f \left[ 1 - a'_f e^{i\theta'_f} e^{i\gamma} \right] \frac{V_{cd}V_{cb}^*}{|V_{cd}V_{cb}^*|}, \]

where the \( CP \)-conserving hadronic parameters are

\[ A'_f \equiv \lambda^2 A \left[ A_T^{(c)f} + A_P^{(c)f} - A_P^{(t)f} \right] \]

and

\[ a'_f e^{i\theta'_f} \equiv R_b \left[ \frac{A_P^{(u)f} - A_P^{(t)f}}{A_T^{(c)f} + A_P^{(c)f} - A_P^{(t)f}} \right]. \]