$B \to VV$ decays can be useful

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• A determination of $\alpha [\gamma]$

• Enhanced electroweak penguin (electromagnetic dipole $- O_{\gamma\gamma}^\pm$) contributions in
decays to transversely polarized vector mesons
A determination of $\alpha \ [\gamma]$

$B \rightarrow \rho \rho$ is good, because $P$ is small, and the longitudinal polarization amplitude dominates

$$A_0(B^0 \rightarrow \rho^+ \rho^-) = Te^{i\gamma} + Pe^{i\delta}$$

- three unknowns: $r \equiv \frac{P}{T}$, $\delta$ and $\alpha$
  ($T$ will not be needed, $\beta$ is assumed to be known)

- two observables: $S_L$, $C_L$

- require one further constraint

  - $\text{Br}(B^0 \rightarrow \rho^0 \rho^0) \Rightarrow \text{bound on } |\Delta \alpha_{\text{eff}}| < 11^\circ \Rightarrow \alpha = (96 \pm 13)^\circ$

  - Idea: Use instead longitudinal branching fraction $\text{Br}_L(B^+ \rightarrow K^{*0} \rho^+)$

  - $B \rightarrow VV$ decays can be useful
How is this related to $B \to \rho^+ \rho^-$?

$$|A_0(B^+ \to K^{*0} \rho^+)|^2_{\text{CP-av.}} = \left(\left|\frac{V_{cs}}{V_{cd}}\frac{f_{K^*}}{f_\rho}\right|\right)^2 F P^2 = 21.4 F P^2$$

with $P$ from $A_0(B^0 \to \rho^+ \rho^-)$. This defines $F$. Roughly the ratio of longitudinal penguin amplitudes in $B^+ \to K^{*0} \rho^+$ to the one in $B^0 \to \rho^+ \rho^-$. 

Then the third observable is

$$\mathcal{R} \equiv \left(\left|\frac{V_{cd}}{V_{cs}}\frac{f_\rho}{f_{K^*}}\right|\right)^2 \frac{\Gamma_L(B^+ \to K^{*0} \rho^+) + \Gamma_L(B^- \to K^{*0} \rho^-)}{\Gamma_L(B^0 \to \rho^+ \rho^-) + \Gamma_L(\bar{B}^0 \to \rho^+ \rho^-)}$$

$$= \frac{F r^2}{1 - 2r \cos \delta \cos(\beta + \alpha) + r^2}$$

exp. $$= 0.0080 \pm 0.0023$$

But what is $F$?

$- B \to VV$ decays can be useful $-$
\[
\sqrt{F} = \frac{\hat{\alpha}_4^c - \frac{1}{2} \alpha_{4,EW}^c + \beta_{3,EW}^c + \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \cdots |_{\rho K^*} |_{\rho \rho}}{\hat{\alpha}_4^c + \alpha_{4,EW}^c + 2\beta_4^c - \frac{1}{2} \beta_{3,EW}^c + \frac{1}{2} \beta_{4,EW}^c |_{\rho \rho}}
\]

if

- Doubly CKM suppressed penguins [...] are neglected.
- Colour-suppressed electroweak penguin \( \alpha_{4,EW}^c \) and EW penguin annihilation neglected.
- QCD penguin annihilation \( 2\beta_4^c \) neglected.
- SU(3) breaking in QCD penguin amplitude \( \hat{\alpha}_4^c \) neglected

Standard assumptions in the SU(3) approach. Here want to be more conservative (because \( \hat{\alpha}_4^c \) is smaller for VV, so other effects are relatively larger). Allow

\[0.3 \leq F \leq 1.5\]

i.e. factor 2.23 variation in the amplitude ratio.

N.B. In QCDF obtain \( F = 0.65 \pm 0.36 \) with \(-0.1\) from electroweak penguin and \(-0.2\) from QCD penguin annihilation.

\[ B \to VV \text{ decays can be useful} \]
Main point: need $\mathcal{R}$ and $F$ only to constrain the penguin contamination $r \neq 0$. But experimentally $\mathcal{R} \approx Fr^2$ is small, so almost no effect on

$$S_L = \sin(2\alpha) + \mathcal{O}(r)$$

Hence, even a large theoretical uncertainty of $F$ leads to a small error on $\alpha$. 

- $B \toVV$ decays can be useful -
Input:

\[ C_{L,\rho\rho} = -0.03 \pm 0.17 \]
\[ S_{L,\rho\rho} = -0.21 \pm 0.22 \]
\[ R = 0.0080 \pm 0.0023 \]

<table>
<thead>
<tr>
<th>( \alpha[^\circ] )</th>
<th>( r )</th>
<th>( \delta[^\circ] )</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>91.2(^+9.1)(^{-6.6})</td>
<td>0.098(^+0.014)(^{-0.016})</td>
</tr>
<tr>
<td>(2)</td>
<td>100.6(^+6.4)(^{-8.3})</td>
<td>0.090(^+0.012)(^{-0.013})</td>
</tr>
<tr>
<td>(3)</td>
<td>175.3(^+7.2)(^{-7.9})</td>
<td>0.102(^+0.017)(^{-0.022})</td>
</tr>
<tr>
<td>(4)</td>
<td>172.9(^+6.4)(^{-6.3})</td>
<td>0.088(^+0.018)(^{-0.014})</td>
</tr>
</tbody>
</table>

\( F = 0.9 \)

Lower figure:
\( \chi^2 = 1 \) contours for \( F = 0.3, 0.9, 1.5 \).
Including \( F = 0.9 \pm 0.6 \) gives (assuming \( |\delta| < \pi/2 \))

\[ \alpha = [91.2\(^+9.1\)\(^{-6.6}\) \text{ (exp)} +1.2 \text{ (th)}][^\circ] \]

- \( B \to VV \) decays can be useful -
In good agreement with the global fit:

$$
(91^{+9}_{-8})^\circ \text{ vs. } (97 \pm 5)^\circ \text{ global}
$$

Accurate measurement of $C_L$ isolates one of the two solutions near $90^\circ$. Phase assumption can be relaxed.

Imagine exp. error on $C_{L,\rho\rho}$, $S_{L,\rho\rho}$ decreases by factor of 2. Then (see right figures)

$$
\alpha = [91.2 \pm 3.5 \text{ (exp)}^{+1.2}_{-3.9} \text{ (th)}]^\circ
$$

(projection to the future)

competitive with global fit.

$B \rightarrow VV$ decays can be useful –
Electroweak penguins and transverse polarization

$B \toVV$ has three helicity amplitudes $A_0$, $A_-$, $A_+$

Naive expectation ($\bar{B}$ decay)

$$A_0 : A_- : A_+ = 1 : \frac{\Lambda}{m_b} : \left(\frac{\Lambda}{m_b}\right)^2$$

due to

- V-A interactions
- large $m_b/\Lambda$

$\Rightarrow$ probe helicity structure of flavour-violating interactions

Experimentally

$$A_0 \gg A_- \gg A_+ \quad \text{tree decays}$$

$$A_0 \approx A_- \gg A_+ \quad \text{penguin decays}$$
Theoretical status

- Hierarchy

\[ A_0 : A_- : A_+ = 1 : \frac{\Lambda}{m_b} : \left(\frac{\Lambda}{m_b}\right)^2 \]

parametrically confirmed in QCD factorization.

- Not numerically. \( P_- / P_0 \sim 1 \) is possible due to weak annihilation \([\text{Kagan}]\). Large transverse polarization in penguin decays is attributed to this effect.

- Parametric hierarchy not true for electromagnetic interactions \([\text{MB, Rohrer, Yang}]\). Instead

\[ A_0 : A_- : A_+ = 1 : \frac{m_b}{\Lambda} : 1 \]

Enhancement of transverse polarization by \((m_b/\Lambda)^2\).

\[ - B \rightarrow VV \text{ decays can be useful} - \]
• left: $\gamma$ always off-shell, $q^2 \sim m_b^2$

• right: $\gamma$ nearly on-shell, $q^2 = m_{V_2}^2 \sim \Lambda^2$
  - $V_2$ longitudinal $\Rightarrow$ photon propagator is cancelled $\Rightarrow$ effective local four-quark interaction
  - for $V_2$ transverse no cancellation $\Rightarrow$ local $b \to D\gamma$ transition followed by long-distance $\gamma \to V_2$ transition $\Rightarrow$ enhanced by large photon propagator

New operator in SCET$_1$ (leading in heavy quark power counting, same as in $B \to V\gamma$)

$$\left[ \bar{\xi} W_{\gamma\perp\mu}(1 \mp \gamma_5)h_\nu \right](0) \left[ W_{\gamma}^\dagger iD^{\mu}_{\gamma\perp} W_{\gamma} \right](0),$$

- $B \to VV$ decays can be useful -
Consider electromagnetic dipole operators including both chiralities

\[ Q_{7\gamma}^\pm = -\frac{e\bar{m}_b}{8\pi^2} \bar{D} \sigma_{\mu\nu} (1 \pm \gamma_5) F^{\mu\nu} b, \]

Contributes to the electroweak penguin amplitudes

\[ P_{\pm}^{\text{EW}} (V_1 V_2) = C_7 + C_9 + \frac{1}{N_c} (C_8 + C_{10}) \mp \frac{2\alpha_{\text{em}}}{3\pi} C_{7\gamma,\text{eff}}^{\pm} R_\pm \frac{m_B \bar{m}_b}{m_{V_2}^2} + \ldots \]

with \( R_- \) a form factor ratio that equals 1 in the heavy-quark limit and \( R_+ \sim m_b / \Lambda \).

Compare leading QCD penguin to EW penguin amplitude (in some units)

\[ P_-(\rho K^*) \approx -1 \quad P_{\pm}^{\text{EW}} (\rho K^*) \approx -0.3 + 0.7 \quad \text{[new]} \]

A very large effect.

For positive helicity \( 0.7 \rightarrow 0.7 \times (10 - 20) \times \frac{C_{7\gamma}^+}{C_{7\gamma,\text{eff}}^-} \)

\(- B \rightarrow VV \) decays can be useful -
The $B \rightarrow \rho K^*$ system

\[ \mathcal{A}_h(\rho^- K^{*0}) = P_h \]
\[ \sqrt{2} \mathcal{A}_h(\rho^0 K^{*0}) = [P_h + P_{h^{EW}}] + e^{-i\gamma} [T_h + C_h] \]
\[ \mathcal{A}_h(\rho^+ K^{*0}) = P_h + e^{-i\gamma} T_h \]
\[ -\sqrt{2} \mathcal{A}_h(\rho^0 \bar{K}^{*0}) = [P_h - P_{h^{EW}}] + e^{-i\gamma} [-C_h], \]

$T_h, C_h$ CKM suppressed.

Consider CP-averaged negative helicity decay rate ratio ($p_{h^{EW}} = P_{h^{EW}} / P_h$)

\[ R \equiv \frac{\bar{\Gamma}_-(\rho^0 K^{*0})}{\bar{\Gamma}_-(\rho^0 \bar{K}^{*0})} = \left( \frac{1 + p_{h^{EW}}}{1 - p_{h^{EW}}} \right)^2 + \Delta = \left\{ \begin{array}{c} 3.0 \pm 0.7 \\ 0.6 \pm 0.1 \end{array} \right\} \text{ without dipole operator} \]

(Fit $P_-$ to data, use QCDF for the other amplitudes)

$-B \rightarrow VV$ decays can be useful
Available data (HFAG values 12/05 – not updated):

<table>
<thead>
<tr>
<th></th>
<th>$\text{Br}_{\text{Av}}/10^{-6}$</th>
<th>$A_{\text{CP}}$</th>
<th>$f_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^- K^{*0}$</td>
<td>10.6 ± 1.9</td>
<td>−0.14 ± 0.43</td>
<td>0.66 ± 0.07</td>
</tr>
<tr>
<td>$\rho^0 K^{*-}$</td>
<td>10.6$^{+3.8}_{-3.5}$</td>
<td>0.20$^{+0.32}_{-0.29}$</td>
<td>0.96$^{+0.06}_{-0.15}$</td>
</tr>
</tbody>
</table>

$$\mathcal{F} \equiv \frac{f_-(\rho^0 \bar{K}^{*-})}{f_-(\rho^- \bar{K}^{*0})} \text{ exp.} = 0.12^{+0.44}_{-0.11}$$

$$\mathcal{F} \text{ th.} = \left\{ \begin{array}{l} 0.4 \pm 0.1 \\ 0.8 \pm 0.1 \end{array} \right. \text{ without dipole operator}$$

Detecting physics beyond the Standard Model

★ New Physics could enhance $Q_{7\gamma}^+$ through new flavour-changing neutral currents

★ $Q_{7\gamma}^+$ contribution to $\bar{A}_+$ is suppressed only by $C_{7\gamma}^+/C_{7\gamma}^-$, while other contributions have additional $\Lambda/m_b$ suppression ⇒ Sensitivity to $C_{7\gamma}^+ \approx 0.1$ may be possible.

★ An alternative to studies of photon polarization in $B \to K^*\gamma$. Here the $\rho$ meson (decay) acts as the polarization analyzer.

--- $B \to VV$ decays can be useful ---