Direct CP violation in B decays with $\rho^0 - \omega$ mixing

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Abstract

A complete study of the processes $B \to \pi^+\pi^- V \;\; (V = 1^{--})$ is performed both in the framework of the helicity formalism and the effective lagrangian approach. Emphasis is put on the factorization hypothesis and the importance of the $\rho^0 - \omega$ mixing in enhancing the direct CP violation. New results involving some branching ratios and the ratio of the Penguin/Tree amplitude are given in details.

1 Physical Motivations for the channels $B \to V_1 V_2$ and their Decay Kinematics

In the framework of the LHCb experiment devoted to the search for CP violation and rare B decays, special care is given to the B decays into two vector mesons, $B \to V_1 V_2, \;\; V_i = \; 1^{--}$.

(i) B decays being governed by weak interactions, the vector-mesons are *polarized* and their final states have specific angular distributions; which allows one to cross-check the Standard Model (SM) predictions and to perform tests of models *beyond* the SM.
(ii) In the special case of two neutral vector mesons with $\bar{V}^0 = V^0$; orbital angular momentum ℓ, total spin S and CP eigenvalues are related by the following relations : $\ell = \; S \; = \; 0, 1, 2 \implies CP \; = \; (-1)^{\ell}$, which implies a *mixing of different CP eigenstates*, proving a CP non-conservation process. According to Dunietz *et al* [1], tests of CP violation in a model independent way can be performed and severe constraints on models beyond the SM can be set. Because the B meson has spin 0, the final two vector mesons, V_1 and V_2, have the same helicity $\lambda_1 = \lambda_2 = -1, 0, +1$, and their angular distribution is isotropic in the B rest frame. Let H_w be the weak Hamiltonian describing the B decays. Any transition amplitude between the initial and final states will have the following form:

$$H_\lambda = \langle V_1(\lambda) V_2(\lambda) | H_w | B \rangle \tag{1}$$

where the common helicity is $\lambda = -1, 0, +1$. Then, each vector meson V_i will decay into two pseudo-scalar mesons, a_i and b_i ; $a_i(b_i)$ can be either a pion or a kaon which angular distributions depend on V_i polarization.

The helicity frame of a vector-meson V_i is defined in the B rest frame such that the direction of the Z-axis is given by its momentum $\vec{p}_i$. Schematically, the whole process gets the form:

$$B \longrightarrow V_1 + V_2 \longrightarrow (a_1 + b_1) + (a_2 + b_2) \; .$$

The corresponding decay amplitude, $M_\lambda\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big)$, is factorized according to the relation,

$$M_\lambda\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big) = H_\lambda(B \to V_1 + V_2) \times \prod_{i=1}^{2} A_i(V_i \to a_i + b_i) \; , \tag{2}$$

where the amplitudes $A_i(V_i \to a_i + b_i)$ are related to the decay of the resonances V_i. For a given value of λ and a well defined final state, amplitudes $A_i(V_i \to a_i + b_i)$ are given, according to the Wigner-Eckart theorem, by the following expressions:

$$A_1(V_1 \to a_1 + b_1) = c_1 D^1_{\lambda m_1}(0, \theta_1, 0) \;\; \text{and} \;\; A_2(V_2 \to a_2 + b_2) = c_2 D^1_{\lambda m_2}(\phi, \theta_2, -\phi) \; . \tag{3}$$

In Eq. (3), the c_1 and c_2 coefficients represent respectively the *dynamical decay parameters* of the V_1 and V_2 resonances. The term $D^1_{\lambda m_i}(\phi_i, \theta_i, -\phi_i)$ is the Wigner rotation matrix element for a spin-1

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particle and we let $\lambda(a_i)$ and $\lambda(b_i)$ be the respective helicities of the final particles a_i and b_i in the V_i rest frame. θ_1 is the polar angle of a_1 in the V_1 helicity frame. The decay plane of V_1 is identified with the (X-Z) plane and consequently the azimuthal angle ϕ_1 is set to 0. Similarly θ_2 and ϕ are respectively the polar and azimuthal angles of particle a_2 in the V_2 helicity frame. Finally, the coefficients m_i are defined as $m_i = \lambda(a_i) - \lambda(b_i)$.

2 Decay Dynamics and Basis for Simulations

The most general form of the decay amplitude $\mathcal{M}\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big)$ is a *linear superposition* of the previous amplitudes $M_\lambda\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big)$ denoted by:

$$\mathcal{M}\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big) = \sum_{\lambda} M_\lambda\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big) \ . \tag{4}$$

The decay width $\Gamma(B \to V_1 V_2)$ can be computed by taking the square of the modulus, $|\mathcal{M}\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big)|$, which involves the three kinematic parameters, θ_1, θ_2 and ϕ. This leads to the following general expression:

$$d^3\Gamma(B \to V_1 V_2) \propto \Big|\sum_{\lambda} M_\lambda\big(B \to \sum_{i=1}^{2}(a_i + b_i)\big)\Big|^2 = \sum_{\lambda,\lambda'} h_{\lambda,\lambda'} F_{\lambda,\lambda'}(\theta_1) G_{\lambda,\lambda'}(\theta_2, \phi) \ , \tag{5}$$

which gives rise to **three density-matrices** $h_{\lambda\lambda'}, F_{\lambda\lambda'}(\theta_1)$ and $G_{\lambda\lambda'}(\theta_2, \phi)$: (i) The factor $h_{\lambda\lambda'} = H_\lambda H^*_{\lambda'}$ is an element of the density-matrix related to the B decay; (ii) $F_{\lambda\lambda'}(\theta_1)$ represents the density-matrix of the decay $V_1 \to a_1 + b_1$ and (iii) $G_{\lambda\lambda'}(\theta_2, \phi)$ represents the density-matrix of the decay $V_2 \to a_2 + b_2$. The analytic expression in Eq. (5) exhibits a **very general form**. It depends on neither the specific nature of the intermediate resonances nor their decay modes (except for the spin of the final particles).

The previous calculations are illustrated by the reaction $B^0 \to K^{*0}\rho^0$ where $K^{*0} \to K^+\pi^-$ and $\rho^0 \to \pi^+\pi^-$. In this channel, since all the final particles have spin zero, the coefficients m_1 and m_2, defined previously, are equal to zero. The three-fold differential width has the following form :

$$\begin{aligned}\frac{d^3\Gamma(B \to V_1 V_2)}{d(\cos\theta_1) d(\cos\theta_2) d\phi} &\propto \big(h_{++} + h_{--}\big)\sin^2\theta_1 \sin^2\theta_2/4 + h_{00}\cos^2\theta_1\cos^2\theta_2 \\ &+ \Big\{\mathscr{R}e(h_{+0})\cos\phi - \mathscr{I}m(h_{+0})\sin\phi + \mathscr{R}e(h_{0-})\cos\phi - \mathscr{I}m(h_{0-})\sin\phi\Big\}\sin 2\theta_1 \sin 2\theta_2/4 \\ &+ \Big\{\mathscr{R}e(h_{+-})\cos 2\phi - \mathscr{I}m(h_{+-})\sin 2\phi\Big\}\sin^2\theta_1\sin^2\theta_2/2 \ . \end{aligned}\tag{6}$$

It is worth noticing that the expression in Eq. (6) is *completely symmetric* in θ_1 and θ_2 and consequently the angular distribution of a_1 in the V_1 frame is *identical* to that of a_2 in the V_2 frame. From Eq. (6) the normalized probability distribution functions (pdf) of θ_1, θ_2 and ϕ can be derived and one finds :

$$f(\cos\theta_{1,2}) \ = (3h_{00} - 1)\cos^2\theta_{1,2} + (1 - h_{00}) \ , \quad g(\phi) \ = 1 + 2\ \mathscr{R}e(h_{+-})\cos 2\phi - 2\ \mathscr{I}m(h_{+-})\sin 2\phi \ . \tag{7}$$

A practical way to compute the matrix elements is to use the Effective Hamiltonian approach based on the general hamiltonian :

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM} C_i(\mu) O_i(\mu) \ , \tag{8}$$

where G_F is the Fermi constant, V_{CKM} is the CKM matrix element, $C_i(\mu)$ are the Wilson Coefficients (W.C.), $O_i(\mu)$ are the operators associated to the **tree, QCD-penguin and EW-penguin** diagrams and, finally μ is the renormalization energy scale taken equal to m_B.

Then, applying the Operator Product Expansion (OPE) method pioneered by Wilson, the W.C. C_i are calculated perturbatively at the Next to Leading Order (NLO) for an energy scale $\geq m_B$ [4]. The non-perturbative effects which are related to the operators O_i and representing physical processes at an energy $\leq m_B$ are introduced through a set of form factors. The latters are explicitly computed in the framework of the pioneering BSW models [5]. However some free parameters remain like : (i) the ratio $q^2/{m_b}^2$ where q^2 is the squared invariant mass of the gluon appearing in the penguin diagrams and (ii) the effective number of colors ${N_c}^{eff}$.

Final State Interactions and $\rho^0 - \omega$ Mixing

Hadrons produced from B decays are scattered again by their mutual strong interactions, which could modify completely their final wave-function. Computations of the branching ratios $B \to$ hadrons must take account of the final state interactions (FSI) [3] which are generally divided into two regimes : *perturbative* and *non-perturbative*. These two aspects have been already mentioned above in the framework of the OPE method. However an important question arises: how to deal with the FSI in a simple and practical way in order to perform realistic and rigorous simulations?

The method which has been followed for the computations is largely developed in [2] and [6] and it is based on the hypothesis of **Naive Factorization**, which can be summarized as follows :

$\star$ In the Feynman diagrams describing the B decays into hadrons like *tree or penguin* diagrams, the soft gluons exchanged among the quark lines are *neglected*.

$\star$ The color number N_c is no longer fixed and equal to 3. It is modified according to the relation : $\frac{1}{(N_c^{eff})} = \frac{1}{3} + \xi$ where ξ is an operator representing the non-perturbative effects.

$\star$ The QCD-penguin diagram introduces an intrinsic phase-shift, $\delta_{P/T}$, by comparison with the tree one (BSS mechanism [7]). Thus, the total amplitude gets an *absorptive part*, which is an illustration of the FSI in the perturbative regime.

$\star$ Another important effect which appears in the channels $B \to \pi^+\pi^- V$ is the $\rho^0 - \omega$ **mixing**, which is an unavoidable quantum process. Indeed, the tree amplitude A^T and the penguin one, A^P, are modified according to the following relations :

$$\langle K^*\pi^-\pi^+|H^T|B\rangle = \frac{g_\rho}{s_\rho s_\omega}\tilde{\Pi}_{\rho\omega}t_\omega + \frac{g_\rho}{s_\rho}t_\rho \quad , \quad \langle K^*\pi^-\pi^+|H^P|B\rangle = \frac{g_\rho}{s_\rho s_\omega}\tilde{\Pi}_{\rho\omega}p_\omega + \frac{g_\rho}{s_\rho}p_\rho \tag{9}$$

Here t_V ($V = \rho$ or ω) and p_V are respectively the tree and penguin amplitudes for producing a vector meson V , g_ρ is the coupling for $\rho^0 \to \pi^+\pi^-$, $\tilde{\Pi}_{\rho\omega}$ is the effective $\rho^0 - \omega$ mixing amplitude and s_V is the inverse propagator of the vector meson V , $s_V = s - m_V^2 + im_V\Gamma_V$ where $\sqrt{s}$ is the invariant mass of the $\pi^+\pi^-$ pair.

The ratio A^P/A^T, which is a complex number, gets the final expression :

$$re^{i\delta}e^{i\phi} = \frac{\tilde{\Pi}_{\rho\omega}p_\omega + s_\omega p_\rho}{\tilde{\Pi}_{\rho\omega}t_\omega + s_\omega t_\rho} \ , \tag{10}$$

where δ is the *total strong phase* arising both from the $\rho^0 - \omega$ resonance mixing and the penguin diagram quark loop, and ϕ is the weak angle resulting from the CKM matrix elements.

3 Main Results and Comparison with Recent Experimental Data

Owing to the presence of resonances with large widthes, the mass of each resonance is generated according to a *relativistic Breit-Wigner* distribution :

$$\frac{d\sigma}{dM^2} \propto \frac{\Gamma_R M_R}{\left(M^2 - M_R^2\right)^2 + \left(\Gamma_R M_R\right)^2} \ ,$$

M_R and Γ_R being respectively the mass and the width of the vector meson.

Then, combining both the Wilson Coefficients and the BSW formalism and including the $\rho^0 - \omega$ mixing, the helicity amplitude (computed in the B meson rest-frame) is given by the following expression :

$$\begin{aligned} H_\lambda\big(B \to \rho^0(\omega)V_2\big) &= iB^\rho_\lambda(V_{ub}V^*_{us}c^\rho_{t_1} - V_{tb}V^*_{ts}c^\rho_{p_1}) + iC^\rho_\lambda(V_{ub}V^*_{us}c^\rho_{t_2} - V_{tb}V^*_{ts}c^\rho_{p_2}) + \\ &\frac{\tilde{\Pi}_{\rho\omega}}{(s_\rho - m^2_\omega) + im_\omega\Gamma_\omega}\Big[iB^\omega_\lambda(V_{ub}V^*_{us}c^\omega_{t_1} - V_{tb}V^*_{ts}c^\omega_{p_1}) + iC^\omega_\lambda(V_{ub}V^*_{us}c^\omega_{t_2} - V_{tb}V^*_{ts}c^\omega_{p_2})\Big] \ , \end{aligned} \tag{11}$$

where the terms $B_\lambda^{V_i}$ and $C_\lambda^{V_i}$ are combinations of different form factors. Their explicit expressions, corresponding to the helicity values ($\lambda = -1, 0, +1$), are given in Ref. [2]. This expression allows to deduce the dynamical density-matrix elements $h_{\lambda\lambda'}$ given by :

$$h_{\lambda\lambda'} = H_\lambda\big(B \to \rho^0(\omega)V_2\big)H^*_{\lambda'}\big(B \to \rho^0(\omega)V_2\big)\ .$$

Because of the *hermiticity* of the DM, only six elements need to be calculated. The main results are :
1) The matrix elements h_{ij} depend essentially on the **masses** of the resonances. Their spectrum of is too wide because of the resonance widths, especially the ρ^0 width $\Gamma_\rho = 150$ MeV/c^2.
2) The longitudinal polarization, $h_{00} = |H_0|^2$, is **largely dominant**. In the case of $B^0 \to \rho^0(\omega)K^{*0}$, the mean value of h_{00} is $\approx 87\%$ while for $B^+ \to \rho^0(\omega)\rho^+$, its mean value is $\approx 90\%$ (Fig.1). These results have been confirmed recently by both BaBar [8] and Belle collaborations [9].
3) The matrix element $h_{--} = |H_{-1}|^2$ is very tiny, $\leq 0.5\%$.
4) The non-diagonal matrix elements h_{ij} are mainly characterized by : (i) The **smallness** of both their real and imaginary parts. (ii) The ratio $\mathscr{I}m/\mathscr{R}e \approx 0.001 \to 0.1$. (iii) In the special case of $B^+ \to \rho^0(\omega)\rho^+$, $\mathscr{I}\mathrm{m(h_{ij})} \approx 0.0$. Our conclusion is that there is a kind of *universal behavior* of the density-matrix elements, whatever the decay $B \to \pi^+\pi^- V$ is ($V = K^{*0}, K^{*\pm}$, $\rho^\pm$).
• Consequences on the Angular Distributions :
In the helicity frame of each vector-meson V_i , the angular distributions given above (see Eq. (7)) become simplified : because of the small value of $\langle h_{+-}\rangle$, the azimuthal angle distribution $g(\phi)$ is rather **flat**. In the expression of $f(\cos\theta_{1,2})$, the longitudinal part h_{00} being largely dominant, the polar angle distribution is $\approx \cos^2\theta$.

Branching Ratios and Asymmetries

⋆ The energy E_i and the momentum p_i of each vector meson vary significantly according to the generated event. So, the width of each channel is computed by Monte-Carlo methods from the fundamental relation :

$$d\Gamma(B \to V_1V_2) \ = \ \frac{1}{8\pi^2 M}\ |\mathcal{M}(B \to V_1V_2)|^2\ \frac{d^3\vec{p}_1}{2E_1}\ \frac{d^3\vec{p}_2}{2E_2}\ \delta^4(P - p_1 - p_2) \tag{12}$$

from which the specific branching ratios are deduced.
⋆ For a fixed value of $q^2/{m_b}^2$, the BRs depend strongly on the Form Factor models. They could vary up to a **factor 2**.
⋆ The relative difference between two conjugate branching ratios, $Br(B \to f)$ and $Br(\bar{B} \to \bar{f})$, is almost *independent* of the form-factor models. The *global asymmetry* defined by :

$$\mathcal{A}_{CP} = \frac{Br(B \to f) - Br(\bar{B} \to \bar{f})}{Br(B \to f) + Br(\bar{B} \to \bar{f})}$$

is usually $\leq 2\%$
⋆ However, an interesting effect is found in the variation of the **differential asymmetry** with respect to the $\pi\pi$ invariant mass. This parameter defined as :

$$a_{CP}(m) = \frac{\Gamma_m(B \to f) - \bar{\Gamma}_m(\bar{B} \to \bar{f})}{\Gamma_m(B \to f) + \bar{\Gamma}_m(\bar{B} \to \bar{f})}$$

is **amplified** in the in the vicinity of the ω resonance mass (± 20 MeV/c^2 around $M_\omega = 782$MeV/c^2). $a_{CP}(m)$ is $\approx 15\%$ in the case of $B^0 \to K^{*0}\rho^0(\omega)$ and equal to 24% in the channel $B^\pm \to \rho^\pm\rho^0(\omega)$.

This kind of asymmetry is almost independent of the form factor models. It is worth noticing that this novel effect has been predicted analytically in the channel $B \to VP \to \pi^+\pi^-\pi$ by Leitner et al [11] and its only explanation is the *mixing* process of the two vector-mesons ρ^0 and ω.

Ratio Penguin/Tree

The ratio Penguin/Tree is given by the following relation derived from equation (11) :

$$\frac{P}{T} = re^{i\delta}e^{i\phi} \quad , \quad r = r'|\frac{V_{tb}V_{tq}^*}{V_{ub}V_{uq}^*}|$$

where r' is the "naked" ratio P/T . It is almost constant over the $\pi\pi$ interval mass, but it varies *very sharply* in the ω interval, from 760 MeV $\rightarrow$ 820 MeV, especially in the channel $B^0 \rightarrow K^{*0}\rho^0(\omega)$ where it reaches 60%. Its variation is almost independent of q^2/m_b^2 but it depends on N_c^{eff}.

Channel	Usual Values	ω Interval
$B^0 \rightarrow K^{*0}\rho^0(\omega)$	$0.08 \leq r' \leq 0.30$	0.60
$B^+ \rightarrow K^{*+}\rho^0(\omega)$	$0.04 \leq r' \leq 0.05$	0.06
$B^+ \rightarrow \rho^+\rho^0(\omega)$	$r' \approx 0.016$	0.05

Final Phase-Shift δ

The strong phase δ which is the phase difference between the Penguin and Tree diagrams is the main ingredient of the *absorptive part* of the B decay amplitude. Its physical origin is related to the : (i) Intrinsic pahse-shift induced by the Top quark in the Penguin diagram, (ii) the complex Wilson Coefficients, and (iii) essentially the $\rho^0 - \omega$ mixing in the $\pi\pi$ final state interactions. It depends on the ratio $q^2/m_b{}^2$ and *strongly* on N_c^{eff}. Usually, δ is almost constant in all the $\pi\pi$ invariant mass interval except in the ω resonance window, 770 $\rightarrow$ 790 MeV, where it undergoes a variation of $80° \rightarrow 100°$ in the $K^{*0}\rho^0(\omega)$ channel and a variation of $5° \rightarrow 25°$ in the $K^{*+}\rho^0(\omega)$ one.

• Very interesting physical consequences can be inferred from the exhaustive study of the parameters P/T and δ with the $\pi\pi$ invariant mass. The direct CP asymmetry parameter is defined according to the relation :

$$a_{CP}^{dir} = \frac{A^2 - \bar{A}^2}{A^2 + \bar{A}^2} = \frac{-2\ r\ \sin\delta\ \sin\phi}{1 + r^2 + 2\ r\ \cos\delta\ \cos\phi}\ . \tag{13}$$

where Φ is one of the weak mixing angle deduced from the CKM matrix elements. In the channel $B \rightarrow \rho^0(\omega)K^*$, angle Φ is identified with $Arg[V_{tb}V_{ts}^*/V_{ub}V_{us}^*] = \gamma$; while in the channel $B \rightarrow \rho^0(\omega)\rho$, angle Φ is given by $Arg[V_{tb}V_{td}^*/V_{ub}V_{ud}^*] = \ \beta + \gamma \ = \Pi - \alpha$. So, the theoretical knowledge of r and δ and the experimental measurements of a_{CP}^{dir} according to the $\pi\pi$ invariant mass allow to extract angle(s) Φ from the above equation (13).

These results could be seen as *experimental challenges* for the future LHC experiments in the field of B physics like LHCB.

Recent Experimental Results

Recently, B factories like BaBar and Belle experiments published interesting results related to the charmless decays $B \rightarrow V_1V_2$. They both agree on the fact that the longitudinal part of the decay amplitude is *very dominant*, which is one of our essential results. However, these collaborations do not take into account the process of $\rho^0 - \omega$ mixing in the estimation of the branching ratios and the asymmetries. By computing the branching ratios from relation (12) and comparing them with those published in ref. [8] and [9], we can summarize the main results in the table 1

4 Conclusion and Perspectives

Helicity formalism has been used very successfully for a full computation and numerical simulations of the channels $B \rightarrow \pi^+\pi^-V$ with $V = \ K^{*0}, K^{*\pm}, \rho^{\pm}$. Naive factorization is very useful for weak hadronic B decays despite its theoretical uncertainties. Furthermore, interesting results have been obtained like : (i) The important role of the *form factor models*, (ii) The longitudinal polarization is largely dominant, whatever the form factor model. (iii) The $\rho^0 - \omega$ mixing is the main ingredient in the *enhancement* of the direct CP violation. (iv) A new way to look for direct CP Violation is found and it can help to develop

Channel	Br($\times 10^{-6}$)	$f_L = \lvert H_0 \rvert^2$	A_{CP}
$\rho^0 K^{*+}$(BaBar)	$10.6^{+3.0}_{-2.6}\pm 2.4$	$0.96^{+0.04}_{-0.15}\pm 0.04$	$0.20^{+0.32}_{-0.29}\pm 0.04$
Our results	$2.3 \rightarrow 5.8$	87%	$-6.4\% \rightarrow -22\%$
$\rho^0 \rho^+$(BaBar)	$22.5^{+5.7}_{-5.4}\pm 5.8$	$0.97^{+0.03}_{-0.07}\pm 0.04$	$-0.19\pm 0.23\pm 0.03$
$\rho^0 \rho^+$(Belle)	$31.7^{+3.8}_{-6.7}\pm 7.1$	$0.95\pm 0.02\pm 0.11$	$0.00\pm 0.22\pm 0.03$
Our results	$11.0 \rightarrow 20.0$	90%	$-8.5\% \rightarrow -10\%$

Table 1: Predicted results compared to experimental data from BaBar and Belle

new methods for measuring the angles γ and α.
What remains to be done is to cross-check these predictions with experimental data coming soon from the LHC exoeriments.
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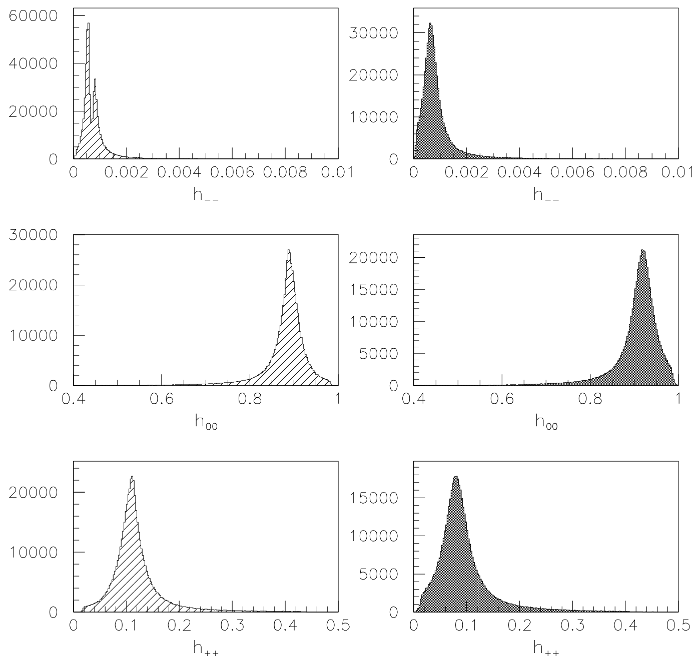

Figure 1: Spectrum of h_{--}, h_{00}, h_{++} : $B^0 \rightarrow \rho^0(\omega)K^{*0}$ (left) $B^+ \rightarrow \rho^0(\omega)\rho^+$ (right)

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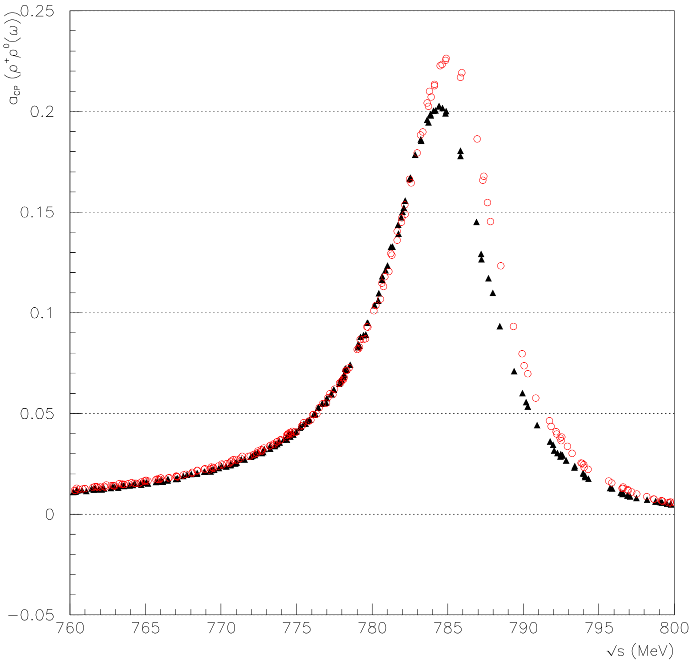

Figure 2: CP-violating asymmetry parameter, $a_{CP}(m)$, as a function of the $\pi^+\pi^-$ invariant mass in the vicinity of the ω mass region for the channel $B^+ \to \rho^0(\omega)\rho^+$ for two different form factor models.

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