Strong and electromagnetic \( J/\psi \) and \( \psi(2S) \) decays into pion and kaon pairs*

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Abstract  We discuss interference effects important for the form factors extraction in the vicinity of \( J/\psi \) and \( \psi(2S) \) resonances in combination with resonance parameters determination. The implementation to the Monte Carlo event generator PHOKHARA of the \( J/\psi \) and \( \psi(2S) \) contributions to the muon, pion and kaon pairs production associated with a photon at next-to-leading order is also described.

Key words  narrow resonances, radiative return, Monte Carlo generators

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1 Introduction

For many years exclusive decays of \( J/\psi \) and \( \psi(2S) \) into pseudoscalar meson pairs attract attention from both the theoretical and the experimental side. In the case of \( \pi^+\pi^- \) the branching ratio was used to determine the pion form factor (see for example [1]). For charged and neutral kaons both strong and electromagnetic interactions are of the similar size and the branching ratio depends on their relative phase. In earlier phenomenological studies, based on \( J/\psi \) and \( \psi(2S) \) decays alone [2, 3] or in combination with form factor measurements close to \( \psi(2S) \) [4] it has been argued that this phase is close to \( 90^\circ \) or \( 270^\circ \) (see also [5, 6]). The recent model independent analysis [7] shows that this conclusion depends crucially on the model assumptions and new data would be highly desirable to clarify the situation. For earlier studies in this direction see [6]. In Section 2, using the results obtained in [7], we further elaborate the possibility of performing this measurement at BES-I\( \text{II} \) experiment.

Also the radiative return method gives possibility of competitive experimental investigations of the properties of \( J/\psi \) and \( \psi(2S) \) resonances, as evident already from [8]. The Monte Carlo tools used in these analysis usually ([9]) do not contain contributions from photon(s) emission from the final states. As shown in [10, 11] (for more recent investigations see [12, 13]) the final state emission might be important and in [14] its role was studied for the case of \( J/\psi \) and \( \psi(2S) \). In [14] details were given only for \( \mu^+\mu^- \) final state and in Section 3 we discuss the charged kaon case. Section 4 contains a short summary.

2 Form factors and resonance parameters extraction

Following the notation from [7], the cross section for the reaction \( e^+e^- \rightarrow P\bar{P} \) can then be written as

\[
\sigma(e^+e^- \rightarrow P\bar{P}) = \frac{\pi\alpha^2}{3s}|F_P|^2 \beta^3 \times \left( \frac{1}{1-\Delta\alpha} + \sum_R \frac{3\sqrt{s}}{\alpha} \frac{f_R^R(1+c_R^R)}{s-M_R^2+i\Gamma_R M_R} \right)^2 = \frac{\pi\alpha^2}{3s}|F_P|^2 \beta^3 \times
\]

\[
\left( \frac{1}{1-\Delta\alpha} + \sum_R \frac{3\sqrt{s}}{\alpha} \frac{f_R^R(1+c_R^R)}{s-M_R^2+i\Gamma_R M_R} \right)^2
\]

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\[
\left(\frac{1}{(1-\Delta \alpha)^2} + \sum_R \left\{ \frac{9s}{\alpha^2} \left( \frac{(I_R^{aj})^2}{(s-M_R^2)^2+I_R^2} \right) \times \left[ 1+|c_F|^2 + \frac{2\alpha M_R}{3\sqrt{s} (1-\Delta \alpha)} \frac{F_R}{K^*} \text{Im}(|c_F^s|) \right] + \frac{6\sqrt{s} I_R}{\alpha(1-\Delta \alpha)} \frac{(1+\text{Re}(|c_F^s|))(s-M_R^2)}{(s-M_R^2)^2+I_R^2} \right\} \right),
\]

where
\[
\beta = \sqrt{1-\frac{4m_{K^*}^2}{s}}
\]

and \( R \) stands for \( J/\psi \) and \( \Psi(2S) \). The narrow resonances are well separated, thus in Eq. (1) their interferences are neglected. We also neglect small contributions from the imaginary part of \( \Delta \alpha \).

From Eq. (1) it is evident that it is impossible to extract the modulus of the form factor \(|F_F|\) close to the resonance from one measurement only as the cross section depends also on unknown strong complex coupling \( c_F^s \). Thus at least three data points are necessary to obtain the desired values. Such data are not currently available and using all available experimental information one gets [7] for \( \Psi(2S) \)
\[
0.052 < |F_{K^+}| < 0.073
\]
\[
|c_+| = 2.94 \pm 0.99
\]
\[
|F_{K^0}| < 0.0282 \pm 0.0003
\]
\[
|F_{K^0} \cdot c_0| < 0.174 \pm 0.009 \pm 0.024. \tag{2}
\]

To obtain these values an assumption on the isospin symmetry \( A_{2\text{CD}}^P(K^+K^-) = A_{2\text{CD}}^P(K^0\bar{K}^0) \) was used. The phase of \( c_+ \) is not determined.

If a second measurement of \( \sigma(e^+e^- \to K^+K^-) \) closer to the \( \Psi(2S) \) would be available a model independent determination of \( \text{Re}c_+ \), \(|F_{K^+}|^2\) with a twofold solution for \( \text{Im}c_+ \) would be feasible. This is illustrated in Fig. 1 for an analysis based on three fictitious measurements 20 MeV, 6 MeV and 2 MeV below \( \Psi(2S) \) resonance with 5\% relative error, and combined with an improved determination of \( B(\Psi(2S) \to K^+K^-) = (6.3 \pm 0.35) \times 10^{-5} \). As it is clear from Fig. 1, a remarkable accuracy for \(|c_+|\), \(|F_{K^+}|^2\) and \(\phi_+\) can be expected.

Due to beam spread of about 2 MeV of the BES-III machine it will be difficult to measure as close as 2 MeV from the \( \Psi(2S) \) and in this case it is better to perform a scan below the resonance to obtain better sensitivity. The measurements above the resonance would suffer from the radiative return to the resonance. In this case the control of the theoretical accuracy is more difficult as it involves the modeling of the photon emission from kaons.

\[\text{Fig. 1. Allowed regions of } |c_+|, |F_{K^+}|^2 \text{ and } \phi_+ \text{ assuming } \sigma(e^+e^- \to K^+K^-) = 5.55(28) \text{ pb, 5.74(29) pb and 7.68(38) pb at 20 MeV, 6 MeV and 2 MeV below the } \Psi(2S) \text{ resonance.} \]

### 3 Narrow resonances and the radiative return

In [14] models of pion and kaon (charged and neutral) form factors, improved as compared to [15], were constructed. They take into account all existing experimental data and a special care was devoted to proper modeling of the form factors at high energies, especially in the vicinity of \( J/\psi \) and
ψ(2S) resonances. The results of [7] were also used. The form factors and the narrow resonance contributions to muon, pion and kaon pair production were implemented into Monte Carlo event generator PHOKHARA. The main goal of this implementations was to study the influence of final state photon emission at the next-to-leading order. The measurements performed so far were not taking them into account and, as the experimental accuracy was quite good, the quantitative detailed studies of these left over corrections is important.

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The implementation of the NLO FSR part is however tricky. With the standard choice of the separation parameter between soft and hard part, \( w = 10^{-4} \), which corresponds to the photon energy \( E_\gamma = 1 \) MeV for \( \sqrt{s} = 10 \) GeV, the ‘soft’ integral receives contributions from the whole resonance region, as a consequence of the small width \( (\Gamma_{J/\psi} = 93.4 \) keV). For this choice of the separation parameter, the part of the matrix element which multiplies the soft emission factor is rapidly varying and the basic assumption underlying the whole approach, that the soft emission can be integrated analytically with the multiplicative remainder being constant, is not longer valid. Chosing an extremely small value of the separation parameter, say \( 10^{-7} \), solves this problem. However, in this case negative weights appear. A simple approach, which gives correct distributions, when convoluted with an energy resolution of a typical detector at a \( \phi \) or \( B \)-meson factory, was adopted in [14] to cure this problem.

In the following we discuss tests of this approach for \( K^+K^- \) final state. Details for the \( \mu^+\mu^- \), where the problem is more severe numerically, are given in [14]. In Fig. 2 the relative difference between the invariant kaon pair mass distributions obtained with separation parameter \( w = 10^{-4} \) and \( w = 10^{-7} \) is shown. The difference between the distributions obtained with \( w = 10^{-7} \) and \( w = 10^{-8} \), not shown in a plot, is consistent with zero within Monte Carlo statistical errors of a small fraction of a per mill. Moreover, the integrals over the whole spectrum are identical for all choices of the separation parameters. This supports the statement that the whole problem is caused by choosing to big value of the separation parameter \( w \).

In a realistic experiment one never observes the distribution shown in Fig. 4, but the one convoluted with a detector resolution shown in Fig. 5. Using resolution of the BABAR detector [8] we compared the invariant mass distributions, convoluted with the Gaussian detector spread function, obtained with separation parameter \( w = 10^{-4} \) and \( w = 10^{-7} \). As evident from Fig. 3, the realistic distributions are not affected by the dependence on the separation parameter up to a precision well below 0.1%. For the muon...
case [14] the differences were more severe and a resid-
ual dependence at the level of 0.1%–0.2% remained. 
This should be taken as an intrinsic error of the ap-
plied method. The difference between muon and kaon 
cases is caused by the absence (muons) or presence 
(kaons) of the direct strong coupling of J/ψ to the 
upons (kaons). For kaon studies the relative phase of 
100° between electromagnetic and strong amplitudes 
was used, resulting with smaller, then in the muon 
case, interference effects. Consequently, the cross sec-
tion for kaons is varying slower then for muons and 
the aforementioned problems with factorization of the 
soft photon contributions are less severe.

Having solved the technical problems one can dis-

cuss the influence of the final state emission at the 
next to leading order. As demonstrated in [10, 11], 
the final state emission at the next to leading order 
can be enhanced by the presence of a resonance (ρ in 
the studied case). However, as the resonance param-
ders of ρ and the narrow resonances are dramatically 
different the effect is also expected to be quantita-
tively different. In Fig. 4 we see that the the FSR 
corrections to the invariant mass distribution are en-
hanced a lot below the resonance as it was observed 
[10, 11] for the ρ case. However, they become small, 
when the detector smearing effects are taken into 
account (Fig. 5). It reaches at most 2.5% as shown 
in Fig. 6. The difference between integrated cross 
sections is even smaller ($\sigma_{\text{ISRNL0}} = 2.442 \times 10^{-5} \text{ nb}$). Thus in case only the inte-
gral over the whole resonance region is used to obtain 
branching ratios, the final state emission at the next 

![Fig. 4. The invariant kaon pair mass distri-
bution with and without FSR NLO corrections.](image1)

![Fig. 5. The invariant kaon pair mass distri-
bution with and without FSR NLO corre-
cctions. Both distributions are smeared with 
a Gaussian distribution assuming invariant 
mass spread 14 MeV.](image2)

![Fig. 6. The relative difference between invari-
ant kaon pair mass distributions with and 
without FSR NLO corrections. Both distribu-
tions are smeared with a Gaussian distribution 
assuming invariant mass spread 14 MeV.](image3)
to leading order can be neglected. In case the invariant mass distributions are used one expects a few percent corrections, which might be important for precise experimental data. For the muon case the corrections to the invariant mass distribution can reach 12\% [14]. The results change only slightly when the BABAR angular cuts are imposed (see Fig. 7).

The results presented here are obtained with new version of the Monte Carlo event generator PHOKHARA - PHOKHARA7.0. Details of the implementation can be found in [14]. Besides the new features discussed here it contains also an upgrade of the $4\pi$ channels according to the model described in [16].

4 Summary

We emphasize the importance of interference effects for the form factors extraction in the vicinity of $J/\psi$ and $\psi(2S)$ resonances in combination with resonance parameters determination. We describe the implementation of the $J/\psi$ and $\psi(2S)$ contributions to muon, pion and kaon pairs production associated with a photon at next-to-leading order into Monte Carlo event generator PHOKHARA.

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