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Strong and electromagnetic J/ψ and ψ(2*S*) 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/ψ and ψ(2*S*) resonances in combination with resonance parameters determination. The implementation to the Monte Carlo event generator PHOKHARA of the J/ψ and ψ(2*S*) 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/ψ and ψ(2*S*) 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/ψ and ψ(2*S*) decays alone [2, 3] or in combination with form factor measurements close to ψ(2*S*) [4] it has been argued that this phase is close to 90° or 270° (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-IIIexperiment.

Also the radiative return method gives possibility of competitive experimental investigations of the properties of J/ψ and ψ(2*S*) 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/ψ and ψ(2*S*). 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 $e^+e^-\to P\bar{P}$ can then be written as

$$\sigma\left(e^+e^-\to P\bar{P}\right) = \frac{\pi\alpha^2}{3s}|F_P|^2\ \beta^3\times\left|\frac{1}{1-\Delta\alpha}+\sum_R\frac{3\sqrt{s}}{\alpha}\frac{\Gamma_e^R(1+c_P^R)}{s-M_R^2+i\Gamma_R M_R}\right|^2=\frac{\pi\alpha^2}{3s}|F_P|^2\ \beta^3\times$$

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$$\left(\frac{1}{(1-\Delta\alpha)^2}+\sum_R\left\{\frac{9s}{\alpha^2}\frac{(\Gamma_{\rm e}^{\rm R})^2}{(s-M_{\rm R}^2)^2+\Gamma_{\rm R}^2M_{\rm R}^2}\times\left[|1+c_{\rm P}^{\rm R}|^2+\frac{2\alpha M_{\rm R}}{3\sqrt{s}(1-\Delta\alpha)}\frac{\Gamma_{\rm R}}{\Gamma_{\rm e}^{\rm R}}{\rm Im}(c_{\rm P}^{\rm R})\right]+\right.\right.$$

$$\left.\left.\frac{6\sqrt{s}\Gamma_{\rm e}^{\rm R}}{\alpha(1-\Delta\alpha)}\frac{(1+{\rm Re}(c_{\rm P}^{\rm R}))\,(s-M_{\rm R}^2)}{(s-M_{\rm R}^2)^2+\Gamma_{\rm R}^2M_{\rm R}^2}\right\}\right), \tag{1}$$

where

$$\beta=\sqrt{1-\frac{4m_{\rm P}^2}{s}}$$

and R stands for J/ψ 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 $|F_{\rm P}|$ close to the resonance from one measurement only as the cross section depends also on unknown strong complex coupling $c_{\rm P}^{\rm R}$. Thus at least three data points are necessary to obtain the desired values. Such data are not currently available and using all available experimentally information one gets [7] for $\psi(2S)$

$$\begin{aligned} &0.052<|F_{{\rm K}^+}|<0.073\\ &|c_+|=2.94\pm0.99\\ &|F_{{\rm K}^0}|<0.0282\pm0.0003\\ &|F_{{\rm K}^0}\cdot {\rm c}_0|<0.174\pm0.009\pm0.024. \end{aligned} \tag{2}$$

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

If a second measurement of $\sigma({\rm e^+e^-}\to{\rm K^+K^-})$ closer to the $\psi(2S)$ would be available a model independent determination of ${\rm Re}c_+$, $|F_{{\rm K}^+}|^2$ with a twofold solution for ${\rm Im}c_+$ 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 $\mathcal{B}(\psi(2S)\to{\rm K^+K^-}) = (6.3\pm0.35)\cdot10^{-5}$. As it is clear from Fig. 1, a remarkable accuracy for $|c_+|$, $|F_{{\rm K}^+}|^2$ and ϕ_+ 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.

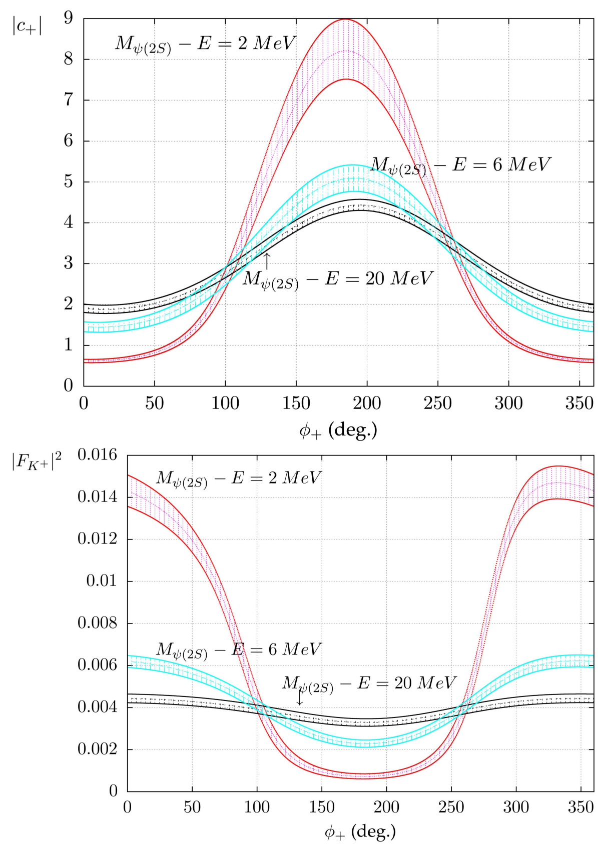

Fig. 1. Allowed regions of $|c_+|$, $|F_{{\rm K}^+}|^2$ and ϕ_+ assuming $\sigma({\rm e^+e^-}\to{\rm K^+K^-}) = 5.55(28)$ pb, 5.74(29) pb and 7.68(38) pb at 20 MeV, 6 MeV and 2 MeV below the $\psi(2S)$ resonance.

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/ψ 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.

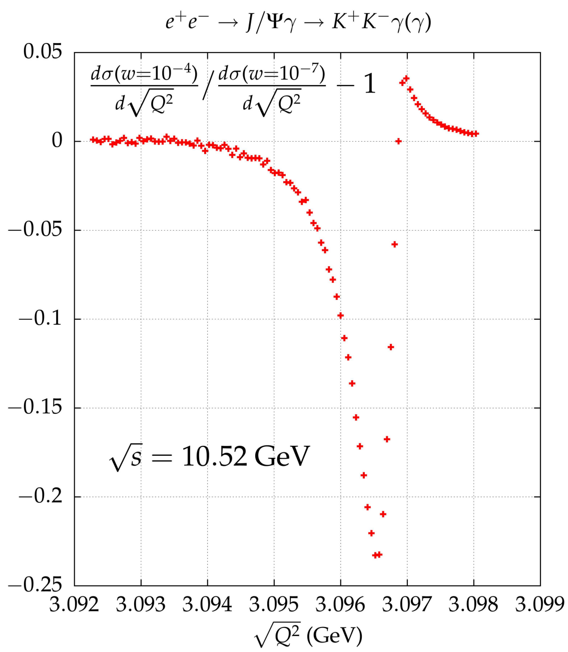

Fig. 2. The relative difference between the invariant kaon pair mass distributions obtained with separation parameter $w=10^{-4}$ and $w=10^{-7}$.

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 ϕ 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 chosing to big value of the separation parameter w.

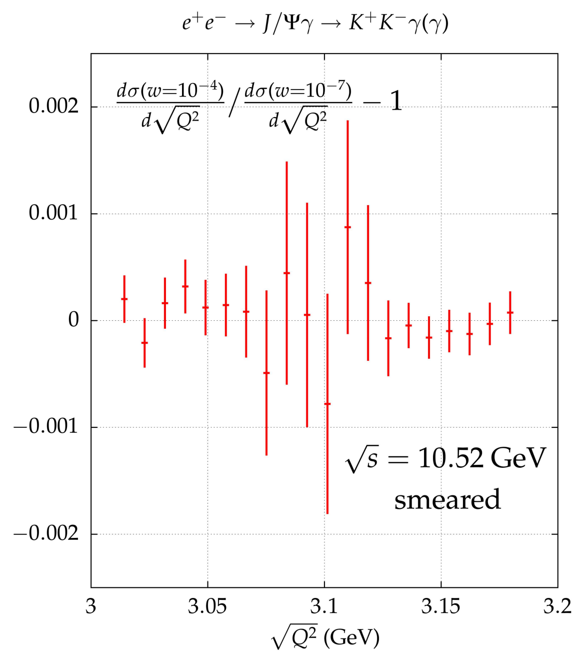

Fig. 3. The relative difference between the invariant kaon pair mass distributions obtained with separation parameter $w = 10^{-4}$ and $w = 10^{-7}$. Both distributions are smeared with a Gaussian distribution assuming invariant mass spread 14 MeV.

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 residual dependence at the level of 0.1%–0.2% remained. This should be taken as an intrinsic error of the applied 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 muons (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 section for kaons is varying slower then for muons and the aforementioned problems with factorization of the soft photon contributions are less severe.

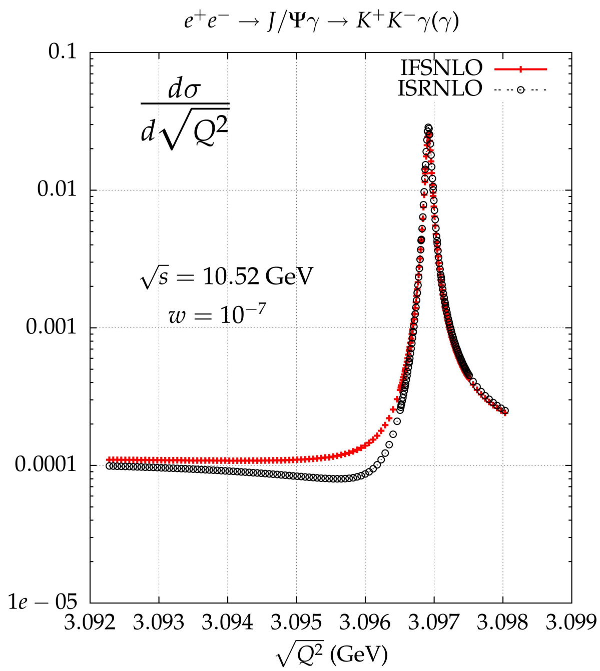

Fig. 4. The invariant kaon pair mass distribution with and without FSR NLO corrections.

Having solved the technical problems one can discuss 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 parameters of ρ and the narrow resonances are dramatically different the effect is also expected to be quantitatively different. In Fig. 4 we see that the the FSR corrections to the invariant mass distribution are enhanced 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 ($\sigma_{\rm ISRNLO} = 2.450\cdot10^{-5}$ nb, $\sigma_{\rm IFSNLO} = 2.442\cdot10^{-5}$ nb). Thus in case only the integral over the whole resonance region is used to obtain branching ratios, the final state emission at the next

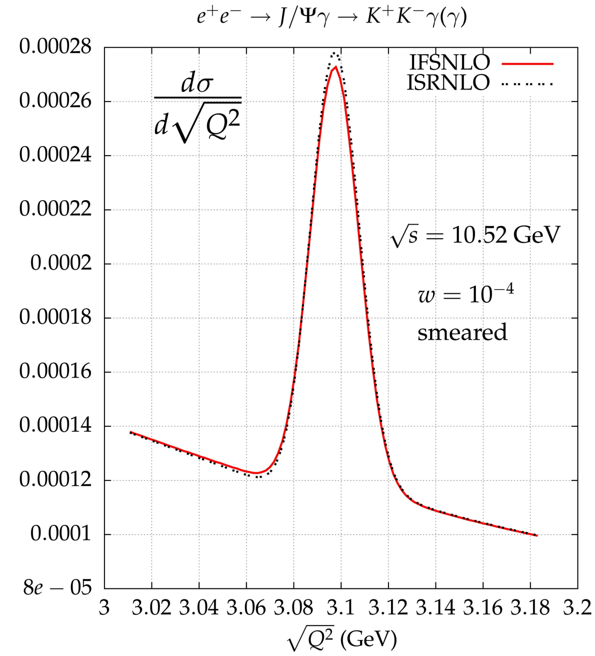

Fig. 5. The invariant kaon pair mass distribution with and without FSR NLO corrections. Both distributions are smeared with a Gaussian distribution assuming invariant mass spread 14 MeV.

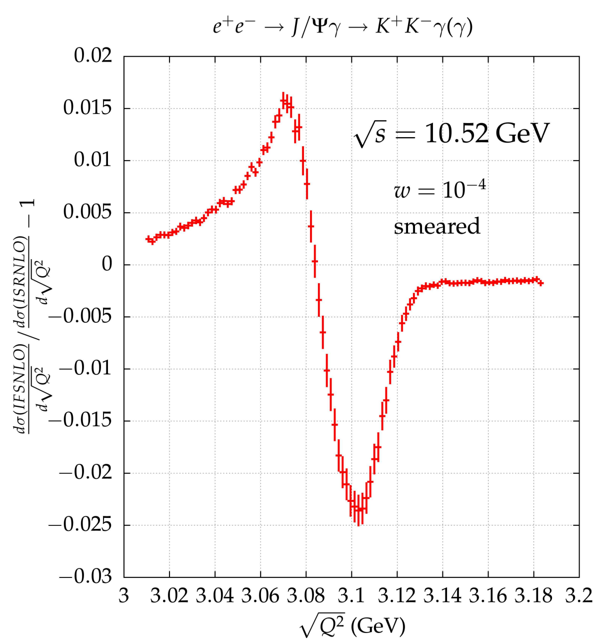

Fig. 6. The relative difference between invariant kaon pair mass distributions with and without FSR NLO corrections. Both distributions are smeared with a Gaussian distribution assuming invariant mass spread 14 MeV.

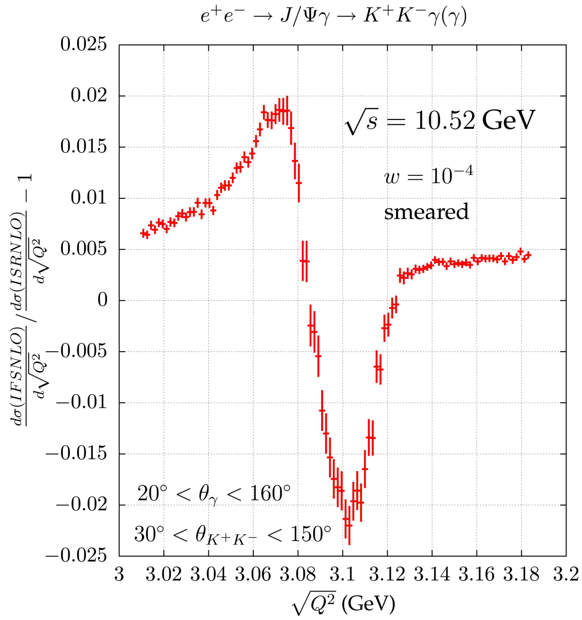

Fig. 7. The relative difference between invariant kaon pair mass distributions with and without FSR NLO corrections. Both distributions are smeared with a Gaussian distribution assuming invariant mass spread 14 MeV.

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 4π 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/ψ and ψ(2S) resonances in combination with resonance parameters determination. We describe the implementation of the J/ψ and ψ(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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