FSR corrections to the FOCUS $D^0 \to \pi\pi$ and $D^0 \to KK$ branching fractions

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1 Introduction

The FOCUS measurement [1] of the branching ratios $\mathcal{B}(D^0 \to \pi^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ and $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ did not include any correction due to final state radiation (FSR). The dominant effect FSR in the analysis is to create a long, low-side tail on the hadronic invariant mass distribution. Of the order of several percent of the decays will have the mass smeared below the range used by FOCUS in their final fit. There will additionally be asymmetric shape biases that interact with the signal and background shapes that FOCUS uses in their fits. The corrections will partially cancel in the branching ratios taken.

The shifts in the reconstructed hadronic invariant mass distributions resulting from FSR will largely be independent of detector-level effects. (There will, of course, be some coupling because of the momentum dependence of tracking system's resolution, but this effect will be small for the subset of decays in which FSR does not shift the invariant mass out of the range fit by FOCUS.) Therefore, it is only necessary to find a correction to the reconstructed yields to account for the smearing and loss due to FSR, and this same correction will apply to the final branching ratios. Using toy Monte Carlo (MC) simulations, I estimate the correction needed to the $\pi^+\pi^-$, K^+K^- and $K^-\pi^+$ yields, which can then be applied to correct the branching ratios.

The general procedure will be the same in each mode. I start with signal and background parameterizations for the $M_{\pi^+\pi^-}$, $M_{K^+K^-}$ and $M_{K^-\pi^+}$ yields obtained from fits to the FOCUS data to provide an initial model for the background and signal distributions for the toy MC. For each decay mode, I also determine the FSR-induced mass biases, shown in Figure 1, using the EvtGen generator [2] coupled with the PHOTOS 2.15 FSR simulation package [3] (including interference terms between radiation from the two separate charged hadrons).

I then iterate over sets of toy experiments to determine the yield correction needed to account for FSR. For each iteration, I generate 400 toy experiments, each with statistics similar to the FOCUS measurement. Initially, the signal parameters, reflecting detector resolution effects, and the backgrounds are taken to be the data fit parameters. FSR-induced shifts are drawn from appropriate distribution in Figure 1, and applied to the masses drawn from the signal resolution parameterization. The mass distribution for each experiment is then fit with signal and background functions identical to the initial fit to the FOCUS data. Based on the average deviations observed in the 400 toy samples relative to the FOCUS fit, the signal and background models are adjusted. For the signal, for example, the downward-only shift from FSR require determination of the upward shift in the mean and a narrowing of the width, in addition to an increase in the total signal yield. Typically only a couple of iterations are required to obtain reasonable agreement between the average fit results of the (or, equivalently, that the average of the 400 toy distributions describe the observed data well).

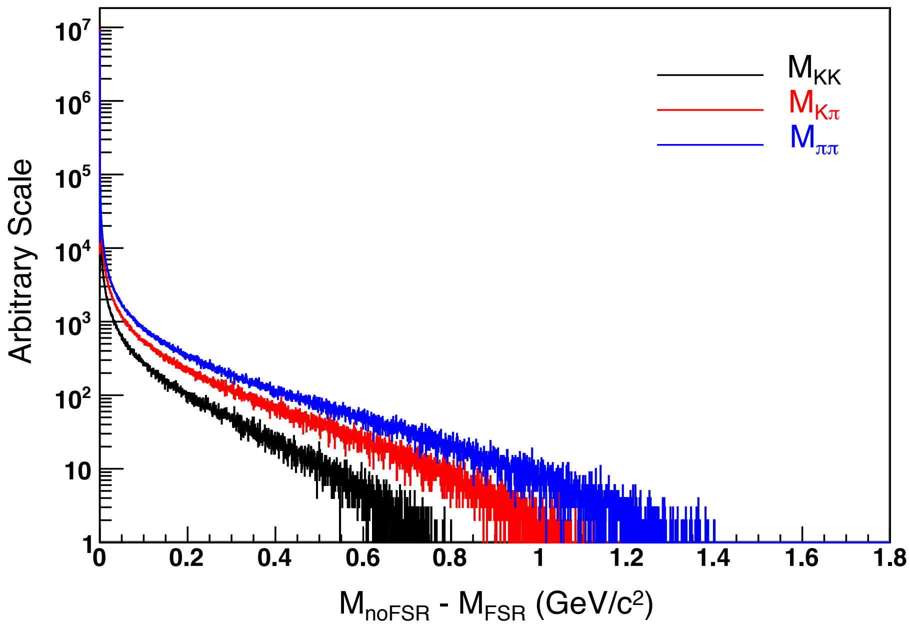

Figure 1: The difference between the nominal hadronic invariant mass (no FSR) and the invariant mass when the FSR process is turned on in $D^0 \to \pi^+\pi^-$, $D^0 \to K^+\pi^-$, and $D^0 \to K^+K^-$ decays.

My goal is to be careful enough with the interaction between the FSR-smeared signal and the fit background levels to keep procedural systematic contributions small relative to the full FOCUS systematic. Then the dominant systematic in the process should be from the PHOTOS FSR-prediction, which will be fully correlated with the same systematic uncertainty in other experiments.

2 $K\pi$ yield bias

Given the relatively low background in the $K\pi$ mode and the double gaussian signal function needed to describe the line shape, the broadening of the low side of mass distribution by FSR interacted in a more complicated fashion with the fitting in this mode. The yield correction procedure must therefore allow for the possibility that the FSR-smeared signal could result in over-estimation of the background level and hence a larger under-estimate of the signal yield. In terms of the $\pi\pi/k\pi$ ratio, this additional underestimate will be beneficial – it will lead to a larger cancellation of the FSR effect in the ratio.

My first pass with the toy MC's focussed on estimating the level of FSR smearing into the region that would be essentially pure background without the FSR contribution. Ignoring the interaction between FSR and background levels, I iterated until the averages over the 400 toy samples for the yields and mean mass reproduced the initial data fit results, while wide and narrow widths and their relative areas were close. (It was difficult to exactly reproduce those three parameters particularly since the needed corrections were highly correlated.) The resulting FSR-smeared signal distribution, averaged over the 400 sets of toy experiments, is shown in Figure 2. We fit the $M_{K\pi}$ range from 1.76 to 1.80 GeV to estimate the level and shape of signal that FSR smears into this region (in which in the nominal FOCUS fit contains pure background). From comparison to the background function from the FOCUS fit, the smearing is an appreciable fraction the apparent background in that low mass region.

To obtain the final yield corrections, I obtain a new background function by refitting the FOCUS

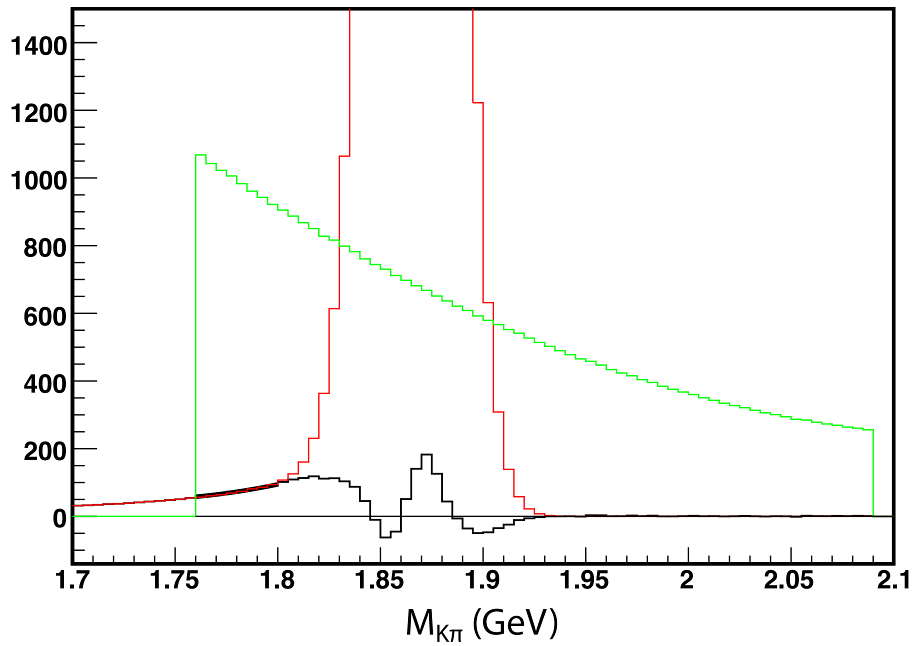

Figure 2: The FSR-smeared $M_{K\pi}$ lineshape for signal (red), the background lineshape (green), and the difference (black) between the FSR-smeared signal lineshape and the nominal FOCUS double gaussian lineshape. The bold curve from 1.76 to 1.80 GeV is a fit to the FSR-smeared signal in that region.

data. In the refit, however, the signal peak region from 1.80 to 1.92 GeV is excluded. The contribution from the FSR-smeared signal determined above is included as a fixed contribution. This new background function is then used in the toy MC procedure. After iteration, the yield parameter needs a scaling of 1.0298 ± 0.0001 to reproduce the fitted FOCUS yield. The widths are scaled down from the nominal FOCUS fit by 0.98, and a mean shift of 0.00059 GeV is needed to account for the unidirectional bias in the FSR smearing. The FOCUS data with the FOCUS fit and the average of the 400 toy MC samples is shown in Figure 3. The corrected yield changed by well under 0.1% from the initial estimation used to determine the background function.

3 $\pi\pi$ yield bias and branching ratio correction

A similar procedure was followed to determine the $\pi\pi$ yield correction, though I used 1600 toy MC samples. To account for the FSR loss/smearing, the $\pi\pi$ yield requires a correction of 1.062 ± 0.001 in order to reproduce the FOCUS fitted yield. The mean $M_{\pi\pi}$ shift required for the toy MC generation was 0.59 MeV as in the $K\pi$ case, and the signal width required a scaling by 0.99. The FOCUS data with the FOCUS fit and the average of the 1600 toy MC samples is shown in Figure 4

The measured $\mathcal{B}(D^0 \to \pi^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ branching ratio must therefore be scaled by $1.062/1.0298 = 1.031$. This changes the published measurement of $0.0353 \pm 0.0012 \pm 0.0006$ to $0.0364 \pm 0.0012 \pm 0.0006$. The systematic uncertainty does not include any additional uncertainty due to the level of FSR predicted by PHOTOS (which will be an uncertainty common to all measurements used in the HFAG average).

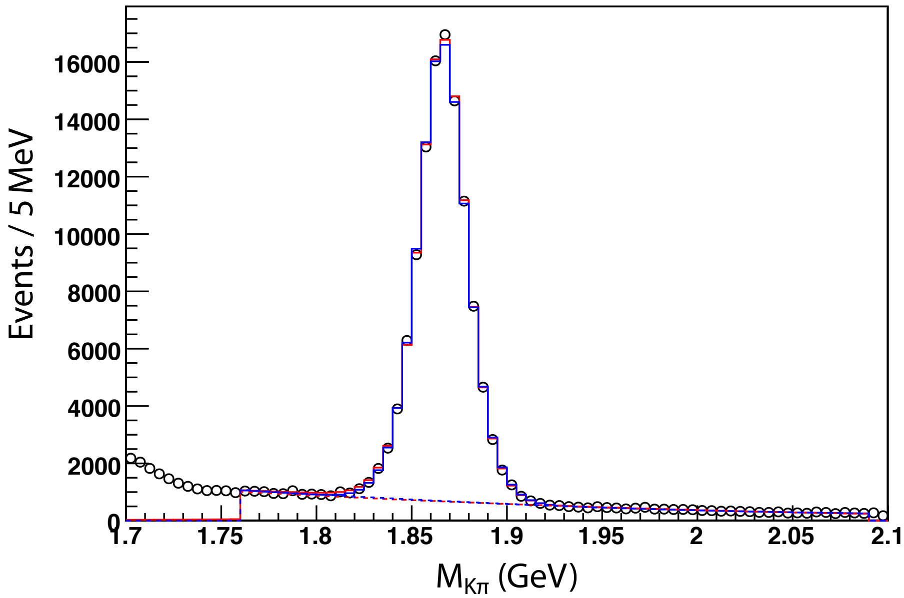

Figure 3: The $M_{K\pi}$ lineshape for the combined background and signal (solid red), tuned and with FSR-smearing, compared to signal (circles) and the nominal FOCUS lineshape (solid blue). The backgrounds in the two cases are shown separately as dashed lines.

4 K^+K^- yield bias and branching ratio correction

The procedure to determine the K^+K^- yield correction was identical to the $\pi\pi$ procedure. In this case, the K^+K^- required a correction of 1.0183 ± 0.0003 to reproduce the FOCUS fitted yield after FSR has been introduced. The mean $M_{K^+K^-}$ mass shift needed in the toy MC was 0.39 MeV in this case. The FOCUS K^+K^- data, as well as the original fit and the average toy MC distribution is shown in Figure 5. The yield correction was stable at the level of 0.02% as the background shape used in the generation of the toy MC was modified in the procedure.

The measured $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ branching ratio must be scaled by $1.0183/1.0298 = 0.9888$. This changes the published measurement of $0.0993 \pm 0.0014 \pm 0.0014$ to $0.0982 \pm 0.0014 \pm 0.0014$. As in the $\pi^+\pi^-$ case, the systematic uncertainty does not include any additional uncertainty due to the level of FSR predicted by PHOTOS (which will be an uncertainty common to all measurements used in the HFAG average).

Finally, the $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(D^0 \to \pi^+\pi^-)$ branching ratio is scaled by $1.0183/1.062 = 0.959$. This correction brings the published branching fraction of $2.81 \pm 0.10 \pm 0.06$ to $2.69 \pm 0.10 \pm 0.06$, again with no additional systematic added for the uncertainty in the PHOTOS prediction.

References

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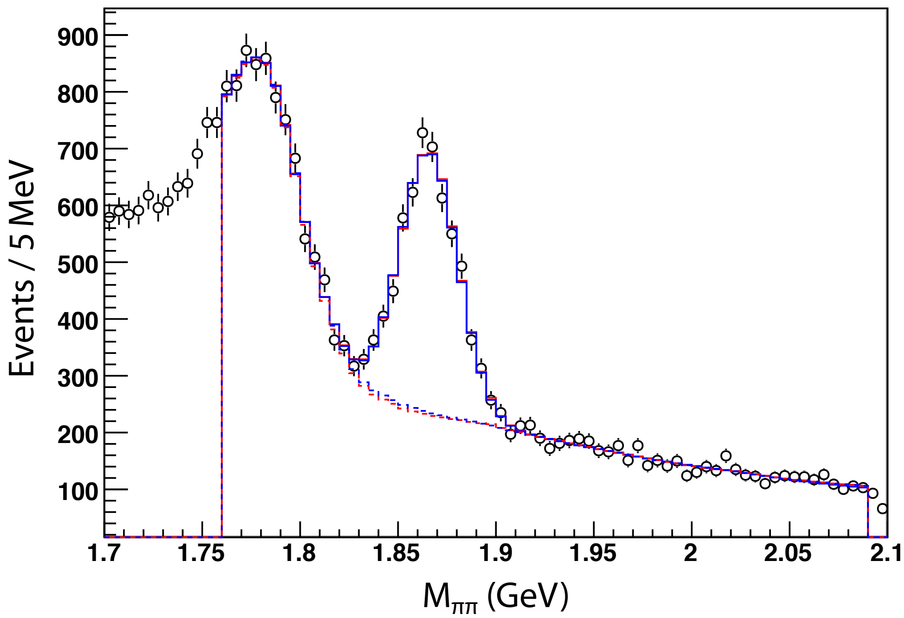

Figure 4: The $M_{\pi^+\pi^-}$ lineshape for the combined background and signal (solid red), tuned and with FSR-smearing, compared to signal (circles) and the nominal FOCUS lineshape (solid blue). The backgrounds in the two cases are shown separately as dashed lines.

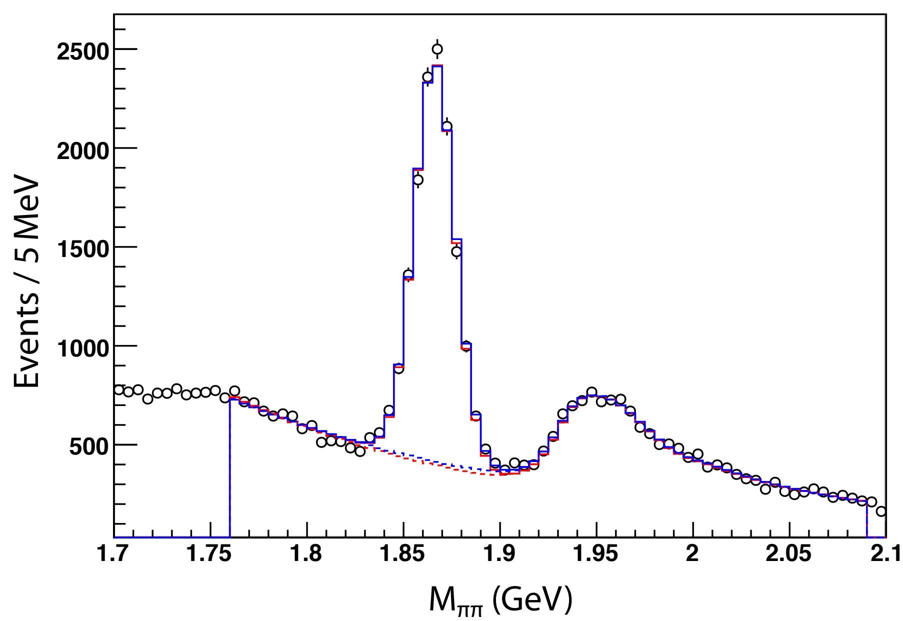

Figure 5: The $M_{K^+K^-}$ lineshape for the combined background and signal (solid red), tuned and with FSR-smearing, compared to signal (circles) and the nominal FOCUS lineshape (solid blue). The backgrounds in the two cases are shown separately as dashed lines.