Measurement of the Branching fraction of the D meson decay in $K^0\omega\pi$ at Belle II

DESY Summer Programm 2022
Matilde Carminati, University of Pisa
Supervisor: Daniel Pitzl

September 7, 2022

Abstract

In this report we present the measurement of the branching fraction of the decay $D \to K^0\pi\omega$ using Belle II data from experiment 12 to 18, with a total integral luminosity of $203.65\,\mathrm{fb}^{-1}$. Using five different reference channels we found an average branching fraction of (0.79 ± 0.03(stat) ± 0.12(syst))% .

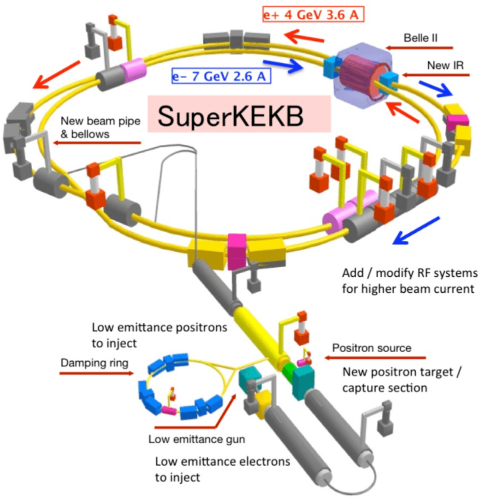
Contents

1. Introduction

In 2001 BaBar and Belle II observed the first large signals for CP violation in the B meson and so it confirmed the hypothesis of Kobayashi and Maskawa. Belle II continues this research of CP violation while improving the precision of measurements of weak interaction parameters and searching for new physics beyond the Standard Model (SM) at the intensity frontier.
Hadronic D decays provide an ideal platform to explore strong and weak effects in decays of hadrons with charm or bottom quarks. The branching fraction of the channel $D \to K^0\pi\omega$ is missing from the PDG, hence the major reason for this measurement is to improve the monte carlo generator for other future measurements, such as the research of CP violation in the channel $D^0 \to K^0_S\omega$, where evidence of it was found in 2014 at a level of 3.1 standard deviations (ref. [3]). Furthermore it can be used as a reference channel for the decay of the B^+ in the same final state.

1.1. SuperKEKB

The SuperKEKB accelerator collides 7 GeV electrons and 4 GeV positrons to have center-of-mass energies in the regions of the Υ resonances ($10.58\,\mathrm{GeVc}^{-2}$), this way we have B mesons pair production where no other particles can be produced.
The boost of the CM system provided by the asymmetric beam allows for time-dependent CP violation measurements. It is slightly less than at KEKB and, even though it requires better vertex reconstruction resolution, it is advantageous for analysis with neutrinos in the final state that requires good detector hermeticity.
SuperKEKB has a design luminosity of $8 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, about 40 times larger that of KEKB's recorded peak. Till now it has achieved a luminosity of $4.7 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a new world record.



Experiment number	Recorded integrated luminosity [fb^{-1}]
12 (2020)	63.58
14 (2020)	15.90
16-18 (2021)	124.17

Table 1: In this analysis we use Belle II data from experiment 12 to 18 for a total integrated luminosity of $204\,\mathrm{fb}^{-1}$. In this table we report the integrated luminosity of each experiment.

1.2. Belle II detector

Like every collider experiment, Belle II has various detectors arranged in cylindrical layers around the beam pipe, but unlike the others it doesn't have an hadronic calorimeter since it doesn't have hadronic jets. The main components of the Belle II detector are:

- vertex detector
- central drift chamber

◇ TOF and ARICH

◇ electromagnetic calorimeter

◇ superconducting solenoid magnet

◇ muon detector

◇ trigger and DAQ system

Since the final particle that we are looking for are charge pions and photons, we mainly use the information coming from the VXD (pixel and strip), the drift chamber, the electronic calorimeter and the TOP and ARICH, for tracking, energy and momentum measurement and particle identification. A better description of the Belle II detector can be found in the *Belle II Physics Book* [1].

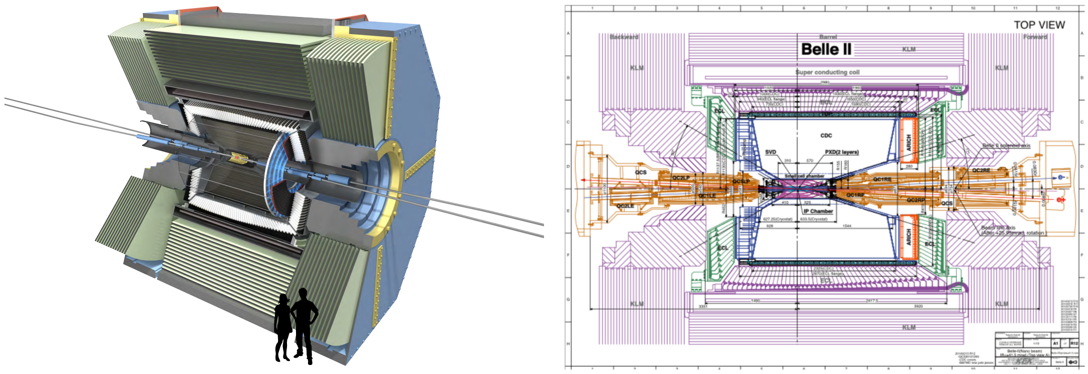


Figure 1: Belle II detector: it is about 10 m wide and just as high, it weighs 1500 tons.

Vertex detector (VXD) The new vertex detector consists of a silicon pixel detector (PXD) and a silicon vertex detector (SVD), with a total of six layers starting at a distance of 14 mm from the beam and finishing at 135 mm (the beam pipe has a 10 mm radius). The first two layers use pixelated sensors of the DEPFET type, the remaining ones are double-sided silicon strip sensors. The combined PXD and SVD system provides average decay-time resolutions of about 60 fs (ref. [2]) for the D^+, that became 20 µm space resolution.

Central drift chamber (CDC) One of the core instruments of the Belle II spectrometer is the central tracking device, a large-volume (inner radius 160 mm, outer radius 1130 mm) drift chamber with small drift cells. The chamber gas consists of a $He : C_2H_6$ 50:50 mixture where 14336 sense wires are arranged in 56 layers. The combination of the wires' orientation, axial (aligned with the solenoidal magnetic field) or stereo (skewed with respect to the axial wires), allow to fully reconstruct a three dimensional helix track. Besides the information about the track, the CDC can do some particle identification by energy loss.

Particle identification (TOP and ARICH) For the particle identification there are two types of Cherenkov detector: a time-of-propagation (TOP) counter followed by a proximity focusing Cherenkov ring imaging detector (ARICH).
The TOP is a special kind of Cherenkov detector where the two-dimensional information of a Cherenkov ring image is given by the time of arrival and impact position of Cherenkov photons at the photo-detector. Each of the 16 modules is composed by a quartz bar (260x45x2 cm^3) with, at the sensor end, a small expansion volume (about 10 cm long) that introduces some additional

pinhole imaging, relaxes slightly the precision timing requirements, and reduces the hit occupancy at the photo-detector. At the exit window of the wedge, two rows of sixteen fast multi-anode photon detectors are mounted. The requested time resolution of 100 ps for a single-photon is achieved by using a 16-channel microchannel plate (MCP) photomultiplier tube (PMT) specially designed for this end.
The ARICH is used to identify charged particles and it requires a low momentum threshold for pions and good separation of pions and kaons from 0.4 GeV/c up to about 4 GeV/c. Thanks to a new method the number of detected Cherenkov photons is increased: two 2 cm-thick layers of aerogel with different refractive indices (n = 1.045 upstream, n = 1.055 downstream) are used to increase the yield without degrading the Cherenkov angle resolution. A hybrid avalanche photon detector (HAPD) is used as the single-photon-sensitive high-granularity sensor, its dimensions are 73×73 mm^2 and it has 144 channels. Here the photo-electrons are accelerated over a potential difference of 8 kV, and are detected in avalanche photodiodes (APD).

Electromagnetic calorimeter (ECL) The electromagnetic calorimeter was designed to detect gamma rays and to identify electrons, i.e. separate electrons from hadrons, in particular pions. It is a highly segmented array of thallium doped caesium iodide CsI(Tl) crystals assembled in a projective geometry. With a total of 8736 crystals distributed in three regions, it covers about 90%of the solid angle in the centre-of-mass system. The energy and the angular resolution it's expected to be similar to the Belle experiment in the absence of background: $\sigma_E/E = 4\%$ at 100 MeV, 1.6% at 8 GeV, 13 mrad (3 mrad) at low (high) energies; π^0 mass resolution was 4.5 MeV/c^2. In the presence of considerably elevated background levels as compared to the operation in Belle, the relatively long decay time of scintillations in CsI(Tl) crystals will considerably increase the overlapping of pulses from neighboring (background) events. Scintillator photo-sensors are equipped with wave-form-sampling readout electronics to mitigate the resulting large pileup noise His performance is expected to be degraded by pile-up noise and radiation damage, specially in the region closer to the beam pipe where there are higher background rates. A possible replacement of CsI(Tl) with considerably faster and radiation tolerant pure CsI is being studied, for this region of the spectrometer.

1.3. D physics

D mesons are the lightest mesons containing a single charm (anti)quark, for this reason they must change the charm (anti)quark into an (anti)quark of another type to decay. Such transitions involve a change of the internal charm quantum number, and can take place only via the weak interaction, the charm quark preferentially changes into a strange quark via an exchange of a W particle, therefore the D meson preferentially decays into kaons and pions.

$$D^+ = \overline{d}c \rightarrow \overline{d}(u\overline{d}s) = \pi^+ K^0$$

In this type of decay is possible that the color charge is not conserved and two other (anti)quark emerge from the sea and another light meson is added to the decay of the D, for example $D^+ \rightarrow K^0\pi^0\pi^+$, $D^+ \rightarrow K^0\eta\pi^+$ or $D^+ \rightarrow K^0\omega\pi^+$. In this analysis we measure the branching fraction of $D \rightarrow K^0\omega\pi$, and we use as reference channels $D^0 \rightarrow K^0\pi^0$, $D^0 \rightarrow K^0\omega$, $D \rightarrow K^0\pi$, $D \rightarrow K^0\pi^0\pi$, $D^* \rightarrow K^0\pi^0\pi$ and $D^* \rightarrow K^0\omega\pi$.

2. Data analysis

2.1. Method

The equation for the production rate of a particular D decay is

$$N = \sigma_D L A \epsilon B$$

where σ is the production cross section, L is the luminosity, A is the detector selection acceptance, ϵ is the detection efficiency and B the branching fraction . For the reference channels we assume a good generator and a good detector simulation, i.e.:

$$(\sigma_D A \epsilon B)_{data} = (\sigma_D A \epsilon B)_{sim}.$$

This way we can calculate the ratio of data and simulation luminosity and, assuming a similar hypothesis for the signal channel $(\sigma_D A \epsilon)_{data} = (\sigma_D A \epsilon)_{sim}$), we calculate the branching ratio by using the next equation:

$$\frac{B^{ref}_{data}}{B^{ref}_{sim}} = \frac{N^{sig}_{data}}{N^{sig}_{sim}} / \frac{N^{ref}_{data}}{N^{ref}_{sim}} \tag{1}$$

where $B^{ref}_{sim} = 0.19255\%$ is the branching fraction used in the events generator.
In this analysis we don't distinguish between the particle and the antiparticle of the D mesons and the charged pions, hence their sign will not be specified.

2.2. K^0_S finding

We search for the K^0 in its decay in two charge pions, that means we are looking for K^0_S (from now on just called K^0). Since the K^0 doesn't decay right away we are looking for displaced (at least 3 sigma from the beam spot) charged pions with intersected tracks. We choose as pions those signals with track which are clearly not protons and kaons using the particle ID given by the ECL, TOF and ARICH. First we verify that the two circle tracks have an intersection in the transverse plane, but since the two circles intersect each other at two points (and the transverse plane is just a projection) we also have to match the z coordinates, so we cut on the difference between the two z coordinates within 8 sigma. Also the flight direction of the K^0 has to be the same as the momentum direction, that's why we define the decay length dl with a sign and we only choose the events with dl> 0. Due to the energy leakage in the EMC of the Belle II detector, we need to correct the energy of the reconstructed particle by using the kinematic constraint of the mass, not just for the K^0 but also for the pions and the omega.

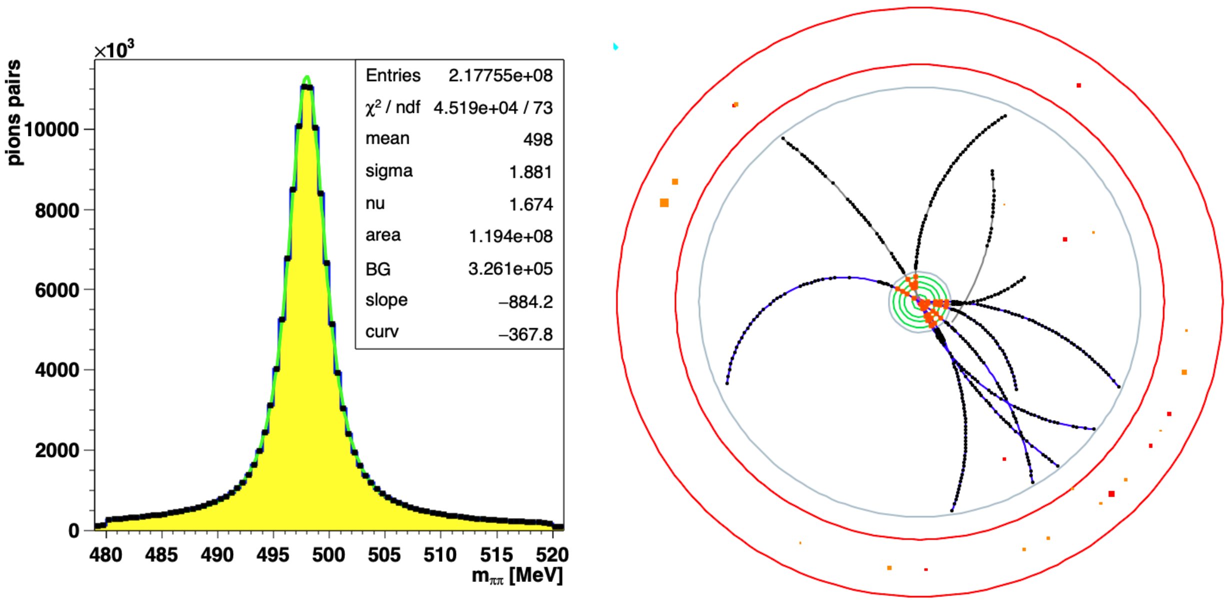


Figure 2: In this analysis we are using pre-selected hadron data with at least one K^0, given that the channels under focus have a K^0 in the final state. Hence we are looking at events like on the plot on the right.

2.3. π^0 finding

The main decay of the neutral pion is into two photons. For this reason we are going to look at the invariant mass of every possible combination of two photons for each event.

For the selection of the photons we search for particles who leave a signal in the ECL (the cluster has to be narrow and distant from other tracks for it to be consistent with electromagnetic shower) without a track. We also add a minimum energy cut because the region near zero is highly populated by background noise caused by the electronics. In later analysis the cut will be increased for improving signal over background.

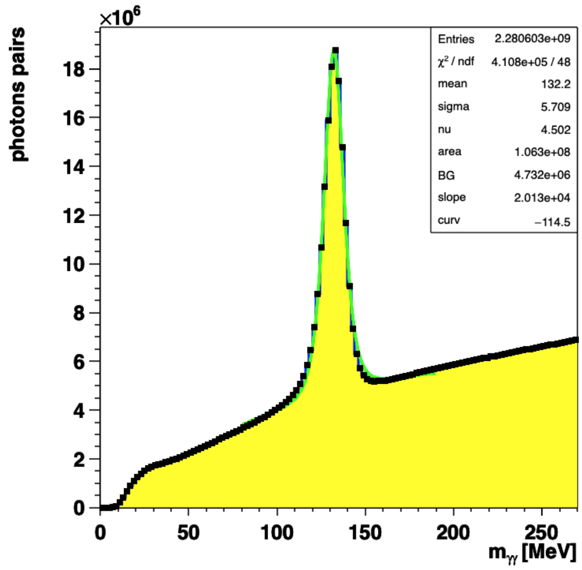


Figure 3: Peak of the π^0 in the invariant mass of two photons. The mean given by the fit is slightly less than the mass in the PDG, this is cause by energy leakage in the ECL.

2.4. ω finding

The main decay of the omega is into three pions, that's why we search for omegas in this final state. Likewise for the pions coming from the K^0, we select the charged pions looking at tracked particles rejecting the ones that are clearly protons or kaons, but in this case the pions are coming from the beam. In the spectrum of this decay we can also find the particle η. Since $D^+ \to K^0\eta\pi^+$ was measured by BES III in 2020, we could have used it as a cross checking channel. Unfortunately our monte carlo generator is not updated yet and doesn't include this new measurement.

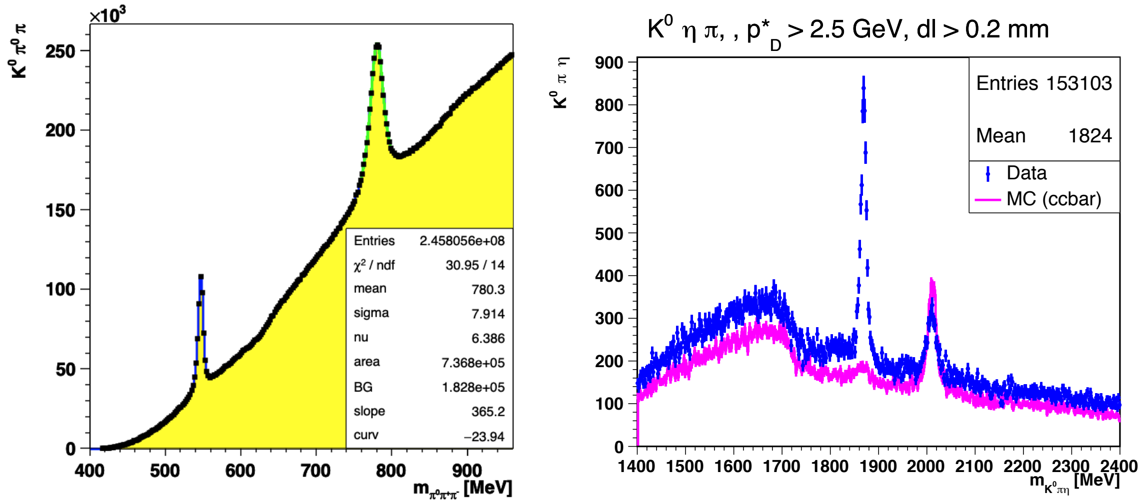


Figure 4: On the left the spectrum of the invariant mass of three pions ($\pi^+\pi^-\pi^0$), with the peaks of the *eta* and the ω. On the right the spectrum for data (blue) and monte carlo (magenta) of the invariant mass of $K^0\eta\pi$. We can see that the peak of the D meson is missing from the monte carlo for this decay.

2.5. Fitting

As a fitting function we use a T-student distribution for the signal and a polynomial function for the background. T-student distribution results from compounding a Gaussian distribution and a Breit-Wigner, the parameter ν tell us if our data fit more one or the other: $\nu < 1$ BW distribution, $\nu = 3$ t-student distribution, $\nu > 5$ gaussian distribution.

$$p(x) = A\frac{\delta m_{bin}}{\sigma\sqrt{\nu\pi}}\frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2})}(1+t^2/\nu)^{-\frac{\nu+1}{2}} + B + m(x-\mu)$$

where A is the area of the signal, $\delta \mathrm{m}_{\mathrm{bin}}$ is the bin width of the histogram, B is the background at the value of the mean and $t = (x-\mu)/\sigma$.

2.6. Reference channels

In the study of our reference channels we add some more conditions for the selection of the events:

- impact parameters
- use of the nominal mass for energy correction
- D momentum cut in the center of mass frame

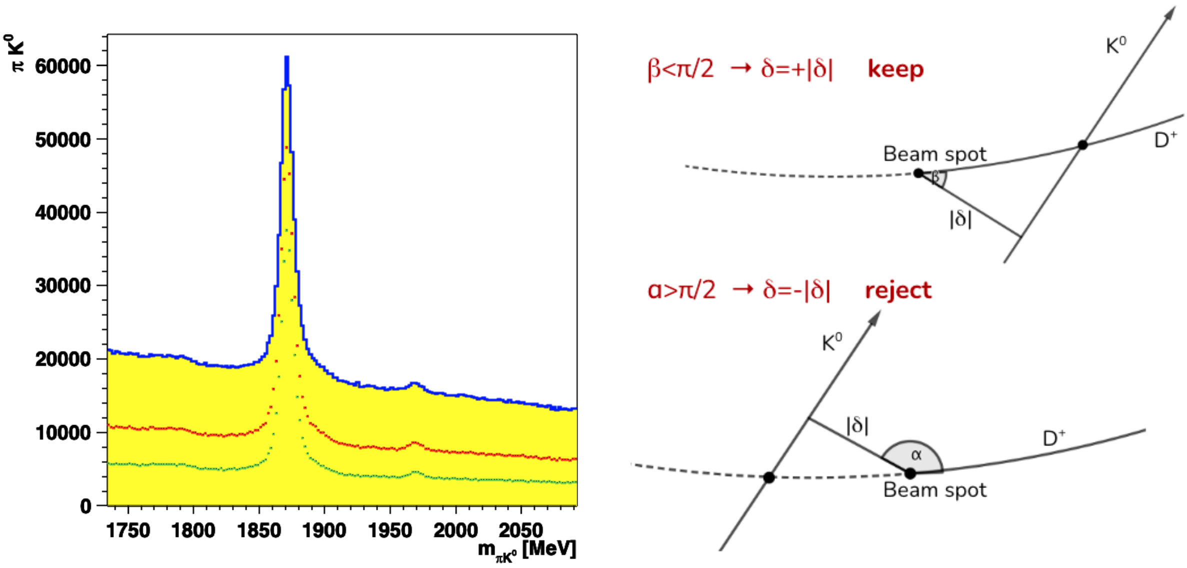


Figure 5: On the left we can see the effect of the cut on the impact parameter for K^0 and π. On the right a sketch to understand in which case we have a negative or positive impact parameter.

- ◇ D projected decay length cut
- ◇ particle id
- ◇ kinematic constrained

The impact parameter is the distance of the track's backward extension of the secondary particles, as kaons and pions, from the beam spot (see Fig. 5 on the right). We give a sign to this quantity: positive if the kaon or the pion came in fact from the decay of the meson D, negative if the intersection is between the extension of the tracks and not the real one. This can be done by looking at the sign of the vector product between the D momentum and the K^0(or π) momentum. this way we reject the event with K^0 and π that are not coming from the D.

2.7. Signal channels

As in the reference channels we make:

- ◇ an harder cut on the photons energy from the π^0
- ◇ a cut on the momentum of the D meson in the CM frame
- ◇ a cut on the projected decay length of the D

In addition, since we have three charged particles we can do a vertex fit to reduce the background noise.

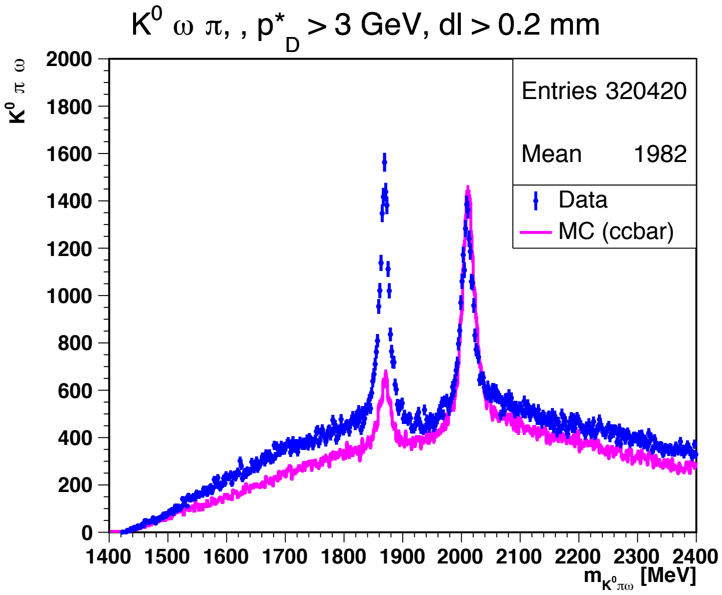


Figure 6: The spectrum for data (blue) and monte carlo (magenta) of the invariant mass of $K^0\omega\pi$, the peak of our channel is smaller in montecarlo

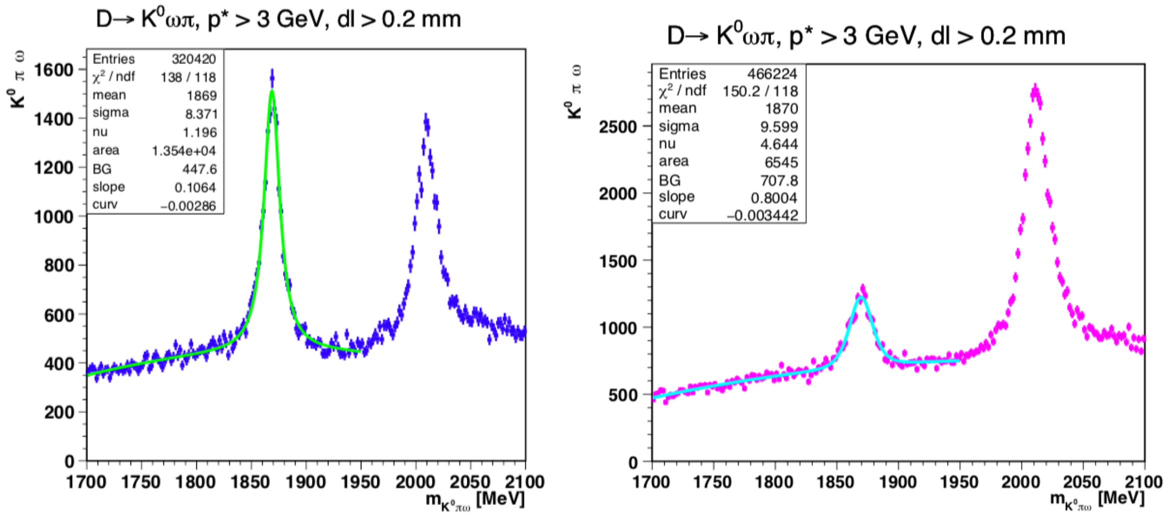


Figure 7: Fit to the peak of our signal in data and montecarlo.

2.8. Physics and detector simulation

The version of the event generator that we use is number 14. For the data simulation we used $c\bar{c}$ monte carlo data from experiment 12 to 18, from the server of Germany, France, Italy and America. Even if our data are not only $c\bar{c}$ the simulation described our reference channels and background well: the main background for this pair production is himself, we can see that by looking at the shape of the background in data and monte carlo. The simulation doesn't describe our channel well: in the experimental data there is a larger signal. However it seems pretty good at describing the Belle II detector, e.g. in the invariant mass of two photons the monte carlo algorithm simulates the energy leakage in the ECL that leads to tails in photon energy distributions and impacts on reconstructed π^0 mass.

2.9. Systematic uncertainties

To estimate the systematic uncertainties of the cuts we take half of the maximum range and weighted average of the values to convert it into a percentage error. From the cut on the decay length we found a 3.4% error, and 7.3% from the one on the D momentum.

signal cuts	**peak area data** $[10^3]$	**peak area MC** $[10^3]$	**Data/MC**	**Stability**
$p* > 2.5$, $dl > 0.2$	16.1 ± 0.9	8.9 ± 0.7	1.80 ± 0.17	1.15 ± 0.14
$p* > 3.5$, $dl > 0.2$	8.0 ± 0.5	4.22 ± 0.25	1.88 ± 0.16	1.10 ± 0.13
$p* > 3$, $dl > 0.2$	13.5 ± 0.9	6.54 ± 0.34	2.07 ± 0.17	1.00 ± 0.11
$p* > 3$, $dl > 0.1$	16.7 ± 1.3	8.2 ± 0.6	2.03 ± 0.22	1.02 ± 0.14
$p* > 3$, $dl > 0.3$	11.1 ± 0.6	5.7 ± 0.4	1.94 ± 0.17	1.07 ± 0.13

Table 2: Area peak fit results in data and montecarlo for different cuts.

We use the same method for the other assumption that we have made in the section 2.1 (good generator and good detector simulation) by looking at the variation of luminosity in the reference channels, and we found an error of 12.9%.

Channel	**peak area data** $[10^3]$	**peak area MC** $[10^3]$	**data / MC**
ref $D \to K^0_S \pi^0 \pi$	227.1 ± 1.3	379.6 ± 2.2	L $= 0.598 \pm 0.005$
ref $D^0 \to K^0_S \omega$	117.9 ± 0.8	221.0 ± 0.9	L $= 0.533 \pm 0.004$
ref $D^0 \to K^0_S \pi^0$	245.2 ± 1.3	442.6 ± 1.2	L $= 0.554 \pm 0.003$
ref $D^* \to K^0_S \pi^0 \pi$	227.1 ± 1.3	379.6 ± 2.2	L $= 0.598 \pm 0.005$
ref $D^* \to K^0_S \omega \pi$	25.95 ± 0.21	57.1 ± 0.3	L $= 0.454 \pm 0.004$

Table 3: Area peak fit results in data and montecarlo for different reference channel.

2.10. Result

The K^0_S branching fraction used for the event's generator is 0.19255%, the result for each reference channel, is reported in Tab. 4

Reference channel	**Double ratio**	**BF** $(D \to K^0_S \omega \pi)$ [%]
$D \to K^0_S \pi^0 \pi$	3.46 ± 0.28	0.67 ± 0.05
$D^0 \to K^0_S \omega$	3.88 ± 0.32	0.75 ± 0.06
$D^0 \to K^0_S \pi^0$	3.73 ± 0.30	0.72 ± 0.06
$D^* \to K^0_S \pi^0 \pi$	4.4 ± 0.4	0.84 ± 0.07
$D^* \to K^0_S \omega \pi$	4.6 ± 0.4	0.88 ± 0.07

Table 4: Branching fraction calculated from different reference channels. For double ratio we mean the one described in Eq. 1.

Assuming that the branching fraction distribution is a Gaussian, the average between these results is 0.79(3) %. Adding the systematic uncertainties summed up in quadrature, we measure as branching fraction of the decay $D \to K^0 \pi \omega$ be $(0.79 \pm 0.03(\text{stat}) \pm 0.12(\text{syst}))\%$, for a total of 15.7% percentage error .

3. Acknowledgements

I would like to thank my supervisor, Daniel Pitzl, for giving me the opportunity to work with the DESY Belle II group, for providing me with an exciting project and supporting me during these weeks.
I would also like to thank the DESY Belle II group for welcoming me into the group, always being friendly, available and helpful.
I would also like to thank Olaf Behnke and and the entire organizing team for enable us to experience the vibrant working environment here at DESY, ensuring that the program ran smoothly and that our stay was entertaining.
Finally, I want to thank my friends Valerio Bertacchi and Irene Falcitelli for pushing me and supporting me to have this amazing experience.

A. Some more plots

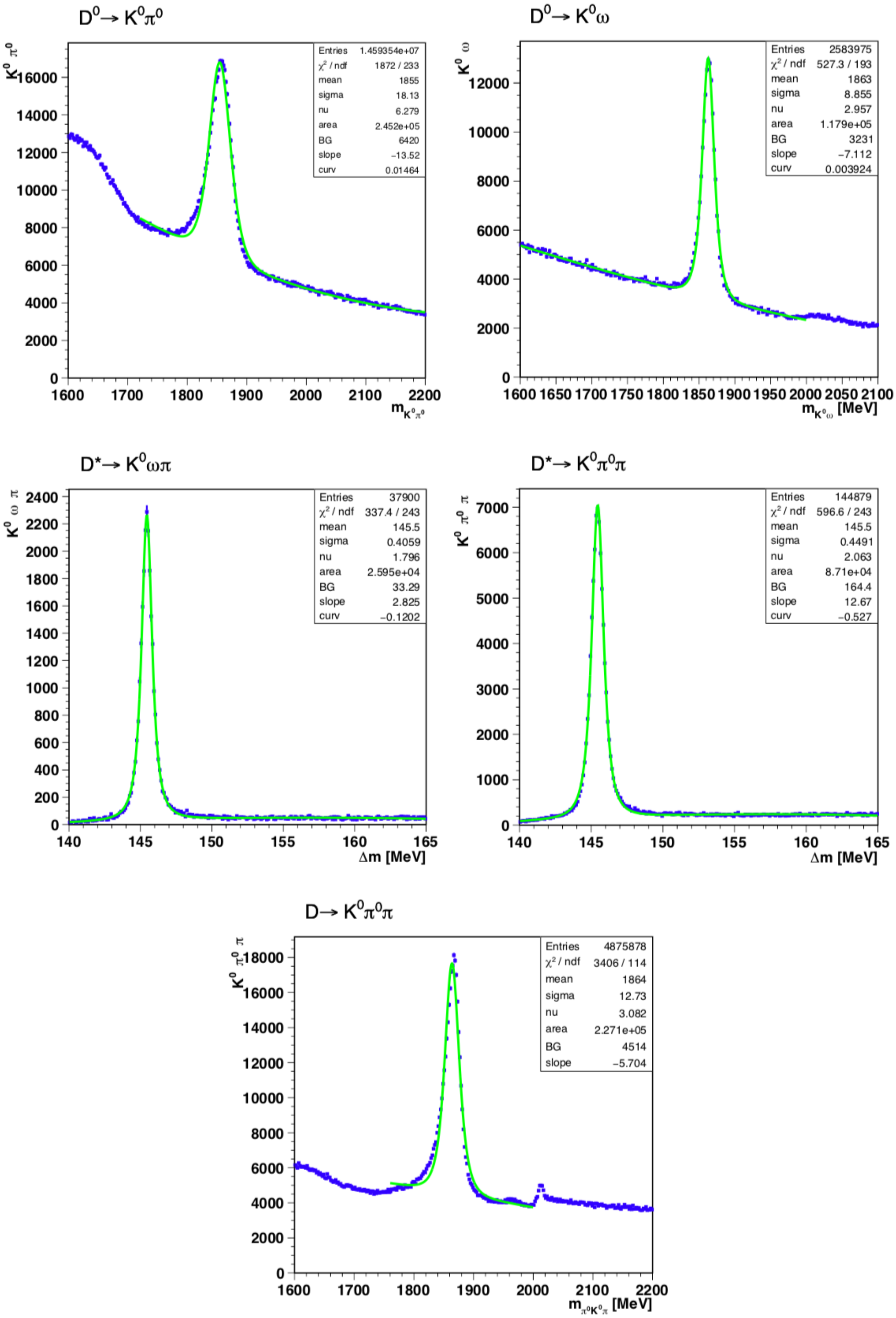


Figure 8: Here we can find the fit for the reference channels.

References

[1] The Belle II Physics Book

[2] *Precise measurement of the D^0 and D^+ lifetimes at Belle II*, Phys.Rev.Lett. 127 (2021) 21, 211801

[3] *Measurement of branching fractions and CP violation parameters in $B \to \omega K$ decays with first evidence of CP violation in $B^0 \to \omega K_S^0$*, Belle Collaboration, Phys.Rev.D 90 (2014) 1, 012002