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UFR DE PHYSIQUE

M1 internship

The polarization of photon in the radiatives decays of D mesons, D(s) $\rightarrow K\pi\pi\gamma$

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Abstract

Flavour-Changing Neutral Currents can be used as a way to test out New Physics. More specifically, the polarisation of the photon in the decay $D \to K\pi\pi\gamma$ can be interesting to study. In D decay, the photon always exhibits left-handed polarisation. On the other hand, in D_s decay, the photon could display right-handed polarition thanks to additional process compared to D decays.
In this report we will study from a theorical point of view these processes and estimate the number of expected events for both decays.

1 Introduction

1.1 Transitions between Quarks

In the current Standard Model of particle physics, there a 6 quarks which are regrouped in three generations : $\begin{pmatrix} u \\ d \end{pmatrix}$, $\begin{pmatrix} c \\ s \end{pmatrix}$ and $\begin{pmatrix} t \\ b \end{pmatrix}$ There are two kinds of transitions between two quarks : transitions which alter the charge and transitions which don't alter the charge.

1.2 Flavour-Changing Charged Current

The quark eigenstates of mass and the quark eigenstates of interaction (denoted with a ') are not the same. This phenomenon is described with the Cabbibo-Kobayashi-Maskawa (CKM) matrix :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1}$$

This matrix is unitary but thanks to experiments, we know its non diagonal-terms are non-zero. Because all the terms are not independent, this matrix can be reduced to 4 parameters :

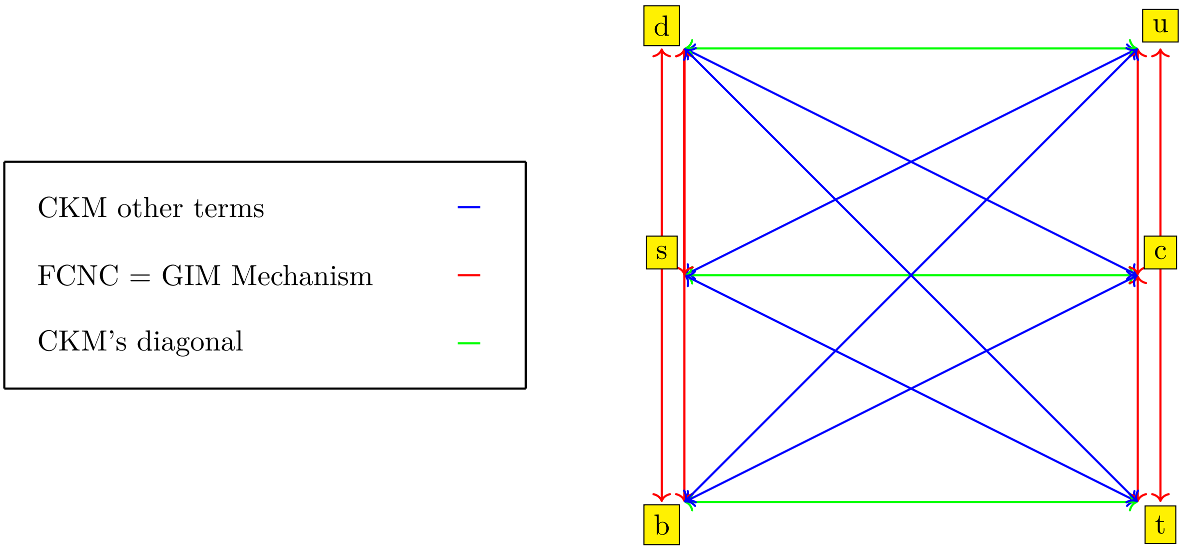
- Three reals parameters which are three angles representing the mixing of the flavour between quarks.
- One complex phase which describes the CP-violation. CP symmetry is the invariance under a symmetry of both parity and charge.

1.3 Flavour-Changing Neutral Current

These transitions don't alter the electric charge. These transitions are suppressed with the GIM mechanism. This mechanism is based upon the introduction of a unitary matrix between the two basis of eigenstates and the fact that quarks come in doublets. They are suppressed at tree level but they are permitted with higher order mechanism such as loop.

1.4 Conclusion on the transitions of quarks

The 6 quarks leads to 15 different transitions :



One thing to note is that we have done all the parametrizations in the (d, s, b) sector. We could have done the same in the (u, c, t) sector and we would have reached the same conclusions.

1.5 The Weak Current

With three generations we have the following current :

$$J^\mu = \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \frac{1}{2}\gamma^\mu(1-\gamma^5)U \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{2}$$

This current is the strength of the interaction coupling two quarks during a process.

- The $\bar{q}$ denotes an outgoing quark, whereas the q denotes an ingoing quark in accordance with the Feynman Rules.
- The $\gamma^\mu(1-\gamma^5)$ leads to the V - A form of the weak interactions. The vector term has been introduced as a direct analogy with the current of QED. The axial vector term describes the CP-violation, which has been experimentally verified.
- The V - A form of the interaction comes from the fact that the weak interaction couples to left-handed particles.
- U is the CKM matrix.

2 Feynman Diagram

We want to study the disintegration of a D meson emitting a photon. In weak interactions the photon emitted is mostly of left polarization. The following diagrams describe the various processes involved in this decay :

- Tree level diagrams which couple two quarks of the same generation, as illustrated in Figure 1.
- Loop Diagrams. They feature a spectator $\bar{s}$ and $\bar{u}$ and a FCNC transition : $c \to u$, Figure 2. We also have the second process for $D^0(c\bar{u}) \to \bar{K}_{res}(s\bar{d})\gamma$ where a loop is involved, Figure 3.
- Others, such as $D^0(c\bar{u}) \to \phi(s\bar{s})\gamma$, Figure 4.

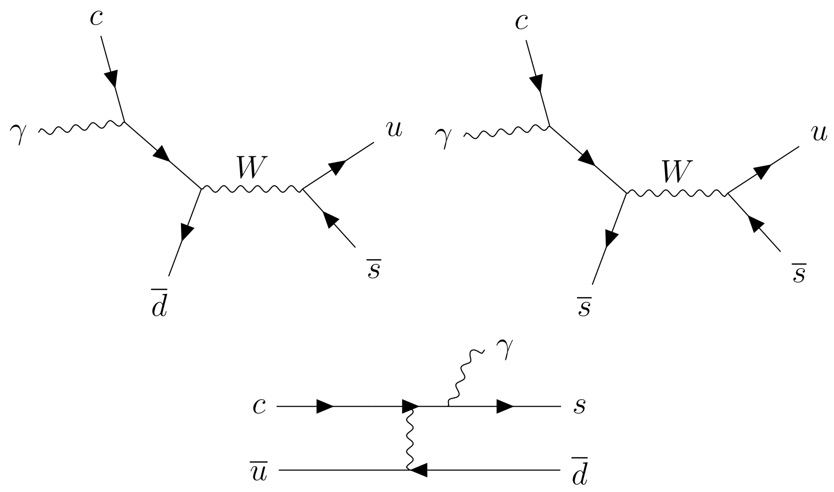


Figure 1: Tree level diagrams for $D^+(c\bar{d}) \to K^+_{res}(u\bar{s})\gamma$, $D^+_s(c\bar{s}) \to K^+_{res}(u\bar{s})\gamma$ and $D^0(c\bar{u}) \to \bar{K^0}_{res}(s\bar{d})\gamma$

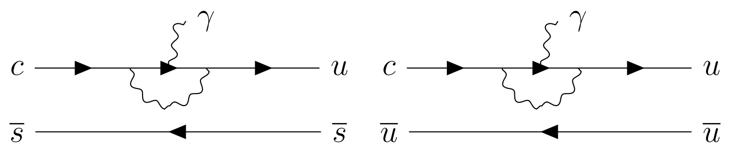


Figure 2: Loop diagrams concern the two transitions : $D^+_s(c\bar{s}) \to K^+_{res}(u\bar{s})\gamma$ and $D^0(c\bar{u}) \to \rho^0(u\bar{u})\gamma$

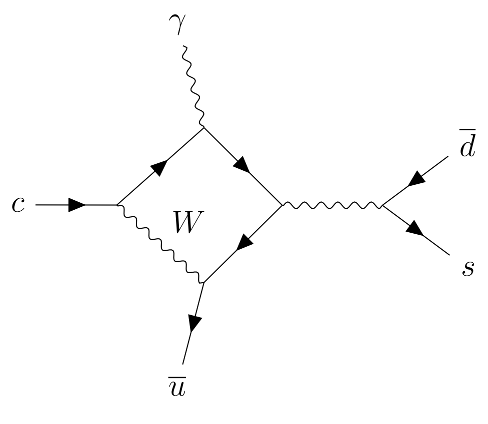


Figure 3: Second process for $D^0(c\bar{u}) \to \bar{K^0}(s\bar{d})\gamma$

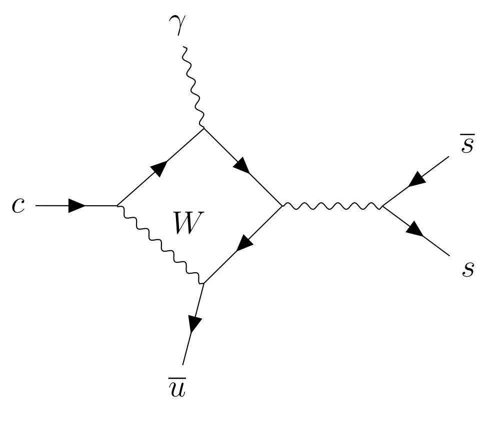


Figure 4: Process for $D^0(c\bar{u}) \to \phi(s\bar{s})\gamma$

3 Beyond the Standard Model with D^+ and D_s decays

3.1 The importance of the photon's polarization

We will focuse especially on the two following decays :

- $D^+ \to K_1^+(\to K\pi\pi)\gamma$
- $D_s^+ \to K_1^+(\to K\pi\pi)\gamma$

As seen previously, D^+ and D_s both share tree-level contributions and those contributions produce left-handed photons because it is a weak decay. However, there may be contributions of gluons which alter the polarization of photons and thus we can have some right-handed photons.
Up to the U-spin (particles of the same multiplet that share the same hypercharge and exhibit different charges, [3]) limit, the gluon contributions are the same for both D^+ ans D_s.
However, while the first decay only occurs at tree level, the second level can occur at loop level. While loop levels have smaller rates than tree levels, they can lead to the creation of unknownn particles and for example, it could leads to a phenomenon implying a new kind of coupling boson. This wouldn't be a weak interaction and thus the emited photon wouldn't have to be left polarized but could have a right-handed polarization.
Thus, these decay can be a mean of production of photons that can deviate from the expected asymmetry. These photons can be either right-handed or left-handed, but the proportions should be different as the gluons interactions differ only at tree level process.

3.2 Amplitude for the $D \to K_1\gamma$ decay

A formula is written in [1] for a $b \to s$ transition. We can take inspiration from it for a $c \to u$ decay and thus write :

$$\mathcal{M}(D \to K_1\gamma) = \frac{-4G_F}{\sqrt{2}} V_{cb}^* V_{ub}(C_L \langle K_1\gamma| \mathcal{O}_7 |D\rangle + C_R \langle K_1\gamma| \mathcal{O}_7' |D\rangle) \tag{3}$$

$\mathcal{O}_7$ and $\mathcal{O'}_7$ are the following operators :

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_c \bar{u}_{\alpha L} \sigma^{\mu\nu} c_{\alpha R} F_{\mu\nu} \tag{4a}$$

$$\mathcal{O'}_7 = \frac{e}{16\pi^2} m_c \bar{u}_{\alpha R} \sigma^{\mu\nu} c_{\alpha L} F_{\mu\nu} \tag{4b}$$

With : α as the colour indice, $q_{L,R}$ denotes a quark with a left or right chirality, $\sigma^{\mu\nu} = [\gamma^\mu, \gamma^\nu]$ and $F^{\mu\nu}$ the electromagnetic tensor.
These operators translates the coupling between an ingoing charm and an outgoing up, with different chirality each.
In the Standard Model, $C_R = 0$ because we study weak decays which couple left-handed particles.
The polarization of the photon, λ, can be written with C_R and C_L in the following manner :

$$\lambda = \frac{|C_R|^2 - |C_L|^2}{|C_R|^2 - |C_L|^2} \tag{5}$$

In the Standard Model, this polarization has always a value of ± 1. If New Physics intervene, its value could differ from this value.

3.3 Asymmetry

As will be seen in the section 4.2, photons are emitted along the $\hat{z}$ axis and can be emitted upward or downward. What we can measure is the asymmetry, which is related to the number of photons

emitted in one direction or the other. We note $\lambda = \pm 1$ the photon polarization
This asymmetry can be calculated by :

$$\mathcal{A} = \frac{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} \mathrm{d}\cos(\theta) - \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} \mathrm{d}\cos(\theta)}{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} \mathrm{d}\cos(\theta) + \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} \mathrm{d}\cos(\theta)} = \frac{3\lambda B}{8A} \tag{6}$$

This asymmetry is non-zero if λ is non-zero. Because we need A and B to mesure λ, we will see in the following that this asymmetry can be written in two different manners.

4 Computation of the Amplitude

4.1 Quasi-two bodies decay

When considering the following decay : $K_1 \to K\pi\pi\gamma$, we treat it as a subsequent two-body decay. This mean that the initial K_1 doesn't decay in three pseudoscalar ($J^p = 0^-$) mesons at once but it occurs in two steps : first, the K_1 decays to a vector meson V ($J^p = 1^-$) and one of the meson (P_3) and then this meson V decays in the two other pseudoscalar mesons : P_1 and P_2

For a given decay, there are several possible intermediate vector mesons, such as ρ or K^*. Thus the amplitude for each decay channel is the sum (with Clebsh-Gordan coefficients) of the amplitude of the decay for every possible V meson.
Each one of these amplitude is itself the product of three terms :

- The amplitude of the first decay : $K_1 \to VP_3$.
- The amplitude of the second decay : $V \to P_1P_2$.
- A Breit-Wigner factor to take into account the vector meson resonance (describes the distribution of mass that a meson can effectively have during a short time long enough so that the transition can occur).

Due to the two-body coupling, the amplitude $\mathcal{M}(D \to (K_1 \to K\pi\pi)\gamma)$ is the product of the amplitudes $\mathcal{M}(D \to K_1\gamma)$ and $\mathcal{M}(K_1 \to K\pi\pi)$.

4.2 Generalities on the second decay

We can note for starters that the studying $\mathcal{M}(K_1 \to K\pi\pi)$ doesn't take into account whether the K_1 originates from a D or a D_s.
For this subsection we consider the general decay $\mathcal{M}(K_1 \to P_1P_2P_3)$. As we said at the subsection 4.1, the amplitude $\mathcal{M}(K_1 \to P_1P_2P_3)$ is the sum of the amplitude for different vector mesons. The coefficients being Clebsh-Gordan coefficients. We can put it under the following form :

$$\mathcal{M} = J^\mu \epsilon_\mu \tag{7}$$

where we introduced the polarization of the kaonic resonance : $\epsilon_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm i \\ 0 \end{pmatrix}$ and the helicity J :
$J^\mu = \mathcal{C}_1 p_1^\mu - \mathcal{C}_2 p_2^\mu$
The $\mathcal{C}$ coefficients thus arise from the sum (which differs from one decay to another) of the amplitudes which are themselves sum for different intermediate vector meson :
We consider the 4 followings decays, named I to IV :

$$\begin{cases} K_1^+ &= \pi^0(\vec{p}_1)\pi^+(\vec{p}_2)K^0(\vec{p}_3) \\ K_1^+ &= \pi^-(\vec{p}_1)\pi^+(\vec{p}_2)K^+(\vec{p}_3) \\ K_1^0 &= \pi^0(\vec{p}_1)\pi^-(\vec{p}_2)K^+(\vec{p}_3) \\ K_1^0 &= \pi^+(\vec{p}_1)\pi^-(\vec{p}_2)K^0(\vec{p}_3) \end{cases}$$

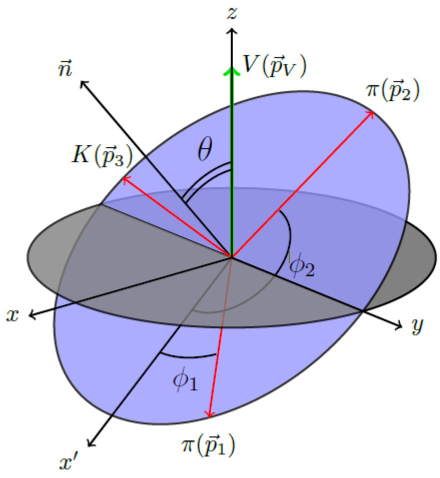


Figure 5: The $K\pi\pi$ plane

$$\begin{cases} \mathcal{C}_1^{I,III} = \frac{\sqrt{2}}{3}(a_{13}^{K^*} - b_{13}^{K^*}) + \frac{\sqrt{2}}{3}b_{23}^{K^*} + \frac{1}{\sqrt{3}}a_{12}^{\rho}, & \mathcal{C}_1^{II,IV} = -\frac{2}{3}(a_{13}^{K^*} - b_{13}^{K^*}) - \frac{1}{\sqrt{6}}a_{12}^{\rho} \\ \mathcal{C}_2^{I,III} = \frac{\sqrt{2}}{3}b_{13}^{K^*} + \frac{\sqrt{2}}{3}(a_{23}^{K^*} - b_{23}^{K^*}) - \frac{1}{\sqrt{3}}b_{12}^{\rho}, & \mathcal{C}_2^{II,IV} = -\frac{2}{3}b_{13}^{K^*} + \frac{1}{\sqrt{6}}b_{12}^{\rho} \end{cases} \tag{8}$$

a_{ij} and b_{ij} being two parameters used to parametrize the different amplitudes and written under the following form : $a_{ij}^V = gBW_V f$ and $b_{ij}^V = gBW_V f'$.
g being a coupling constant, BW_V the Breit-Wigner put under the following form : $BW_V = \frac{1}{M_V^2 - s - i\sqrt{s}\Gamma}$
and f and f' are functions depending of the parameters of the hadronic tensor and the Energies.
For the following section, we just need to keep in mind that $\mathcal{C}_1$ and $\mathcal{C}_2$ are complex numbers.

5 Study of the $K_1 \to K\pi\pi$ decay

5.1 Derivation of the invariant amplitude

Our frame of reference is the rest frame of the Kaonic resonance. The $K\pi\pi$ trajectories are within the same plane, parametrized by $\vec{n}$ and $\vec{x}'$. The photon (V) is emitted along an axis $\hat{z}$ which is not in this plane. We will project the plane in the Cartesian coordinates x, y and z, as follows : This leads to the impulsions of the pions, named 1 and 2 :

$$\vec{p}_{1,2} = |\vec{p}_{1,2}| \begin{pmatrix} \cos(\theta)\cos(\phi_{1,2}) \\ \sin(\phi_{1,2}) \\ -\sin(\theta)\cos(\phi_{1,2}) \end{pmatrix} \tag{9}$$

As we said in the last section, we have $\mathcal{M} = \frac{1}{\sqrt{2}}(J_x \pm iJ_y)$. Where $J_x = \mathcal{C}_1|\vec{p}_1|\cos(\phi_1)\cos(\theta) - \mathcal{C}_2|\vec{p}_2|\cos(\phi_2)\cos(\theta)$ and $J_y = \mathcal{C}_1|\vec{p}_1|\sin(\phi_1) - \mathcal{C}_2|\vec{p}_2|\sin(\phi_2)$.
This directly leads us to the following differential rate :

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos(\theta)\mathrm{d}\phi_1} \equiv |\mathcal{M}|^2 = \frac{1}{2}(|J_x|^2 + |J_y|^2 \pm 2\,\mathrm{Im}(J_x^* J_y)) \tag{10}$$

The expression (10) can be rewritten in two different ways.

5.2 Rewriting with the Dalitz angle

By introducing the angles $\delta = \phi_2 - \phi_1$ and $\phi = \frac{\phi_2 + \phi_1}{2}$, this leads us to :

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos(\theta)\mathrm{d}\phi} = \frac{1}{4}[2a - (a + a_2\cos(2\phi) + a_3\sin(2\phi))\sin^2(\theta) \pm b\cos(\theta)] \tag{11}$$

where :

$$\begin{cases} a &= |\mathcal{C}_1|^2|\vec{p}_1|^2 + |\mathcal{C}_2|^2|\vec{p}_2|^2 - 2\,\mathrm{Re}(\mathcal{C}_1\mathcal{C}_2^*)|\vec{p}_1||\vec{p}_2|\cos(\delta) \\ a_2 &= (|\mathcal{C}_1|^2|\vec{p}_1|^2 + |\mathcal{C}_2|^2|\vec{p}_2|^2)\cos(\delta) - 2\,\mathrm{Re}(\mathcal{C}_1\mathcal{C}\mathcal{C}_2^*)|\vec{p}_1||\vec{p}_2| \\ a_3 &= (|\mathcal{C}_1|^2|\vec{p}_1|^2 - |\mathcal{C}_2|^2|\vec{p}_2|^2)\sin(\delta) \\ b &= 8i\,\mathrm{Im}(\mathcal{C}_1\mathcal{C}_2^*)|\vec{p}_1||\vec{p}_2|\sin(\delta) \end{cases}$$

After integrating over ϕ, we find : $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} = \frac{1}{4}[2\pi a(1+\cos^2(\theta)) \pm 2\pi b\cos(\theta)]$
We can compare this expression to the following form : $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} = A[1+\cos^2(\theta)) + \lambda B\cos(\theta)]$, where $\lambda = \pm 1$ for a right-handed (respectively left-handed) polarization.
This leads to : $A = \frac{1}{2}\pi a$ and $B = \frac{1}{2}\pi b$.

5.3 Rewriting with the helicity J

We can calculate $\mathcal{M}$ using J' instead of J, where J' is the helicity in the referential of the K_1 decay. Following [1], we can find the following expression of the rate, in function of the helicity, after integration over ϕ

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} = \frac{1}{4}[|J|^2(1+\cos^2(\theta)) \pm 2\,\mathrm{Im}(\vec{n}\cdot(\vec{J}\wedge\vec{J}^*))\cos(\theta)] \tag{12}$$

5.4 Condition for having a non-zero asymmetry

Thus we can directly write the Asymmetry both in term of the helicity or in terms of a and b :

$$\mathcal{A} = \frac{3\lambda\,\mathrm{Im}(\vec{n}\cdot(\vec{J}\wedge\vec{J}^*)}{4|J|^2} = \frac{3\lambda b}{8a} \tag{13}$$

This asymmetry is non-zero if and only if the imaginary part doesn't vanish. As we seen in figure 5.2, this imaginary part is non-zero if and only if $\mathcal{C}_1\mathcal{C}_2^*$ is non zero.
If we compute $\mathrm{Im}(\mathcal{C}_1\mathcal{C}_2^*)$, by looking at their expression in (8), we find that we have numerous kinds of terms :

- Factors that mix neither V, nor a/b or the energy : they gives 0.
- Factors that don not mix V, but that mix any combination of a, b with the same or the different energy are of the form : $|BW_V|^2\,\mathrm{Im}(ff'^*)$. Because f and f' are real, those terms gives 0.
- Factors that do not mix the K^* meson, but because they are different energy, they do not give 0.
- Factors wich mix K^* and ρ

Thus we can have a non-zero asymmetry for systems featuring K^* only but they need to be of different energy for system mixing ρ and K^*. Systems which do not mix ρ (all the ρ mesons have the same energy) gives 0.

6 Statistics

6.1 Motivation

In the $D \to (K_1 \to K\pi\pi)\gamma$ decay, the K_1 exists in two states of mass, at both 1270 and 1400 GeV.
There are two final $K\pi\pi$ systems : $D^+ \to K^+\pi^+\pi^-\gamma$ (decay I) and $D^+ \to K^0\pi^+\pi^0\gamma$ (decay II)
As seen in [2], the Asymmetry depends of the invariant mass of the $K\pi\pi$ system, as seen on figure 6 We want to study the evolution of the rate in terms of the asymmetry. Keeping in mind that $\mathcal{A}/\lambda = 3b/a$ is given by :

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos(\theta)} = \frac{\pi}{2}a[(1+\cos^2(\theta)) + \frac{8\mathcal{A}}{3}\lambda\cos(\theta)] \tag{14}$$

The plot 7 was done using the value of the asymmetry for the rest mass as the value of the invariant mass for the two states of mass of K_1 for both decay.

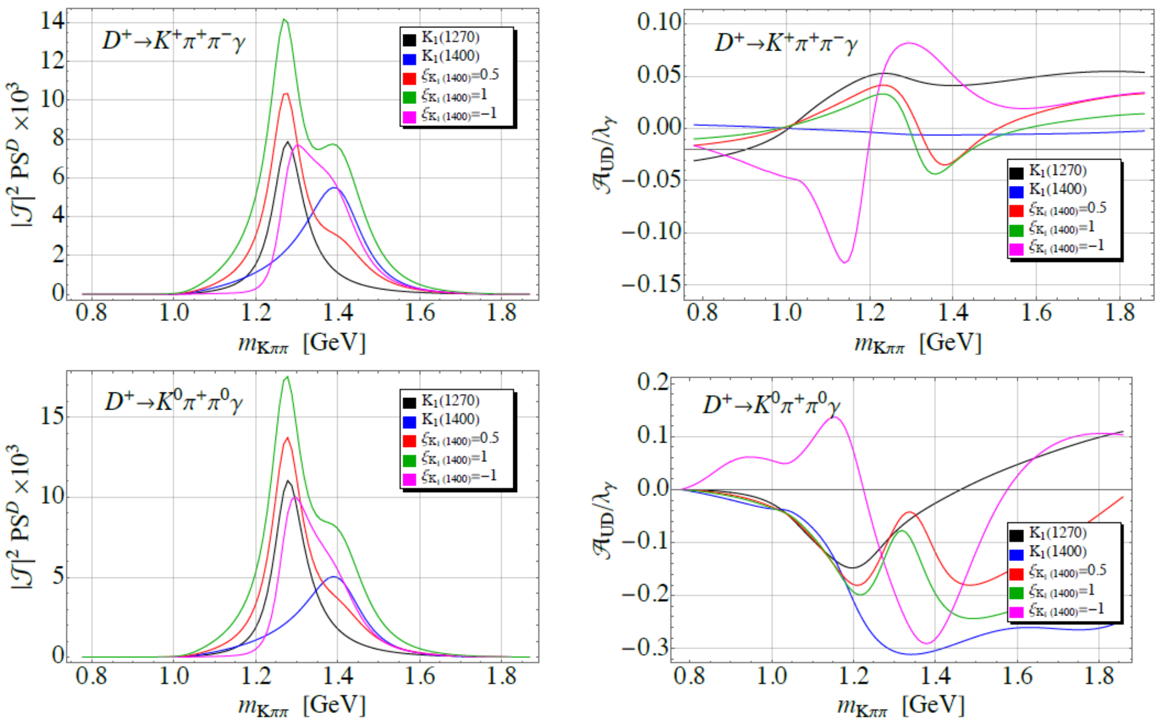


Figure 6: Invariant $K^+\pi^+\ \pi^-$ (upper plots) and $K^0\pi^+\pi^0$ (lower plots) mass dependance of $|\vec{J}|^2$ plots to the left) and $\mathcal{A}/\lambda$ (plots to the right) for K_1 (1270,1400) resonances separately and with relative fraction of the $K_1(1400)$: $\chi_{K_1(1400)}$

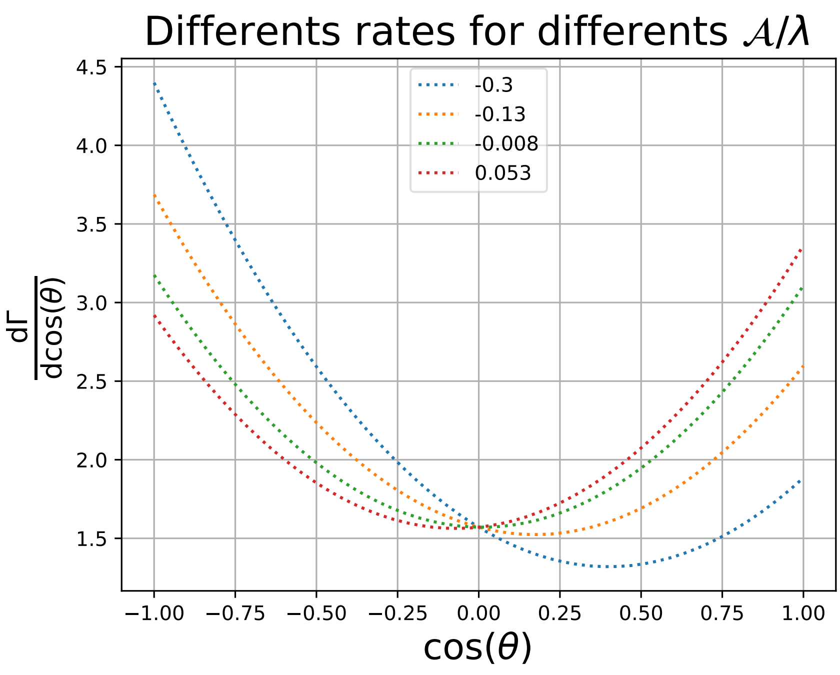


Figure 7: Plot of the rate for different asymmetries. The K_1 at 1270 Gev (respectively at 1400 GeV) has an asymmetry of 0.05 (resp. -0.008) in decay I and an asymmetry of -0.013 (resp. -0.3) in decay II.

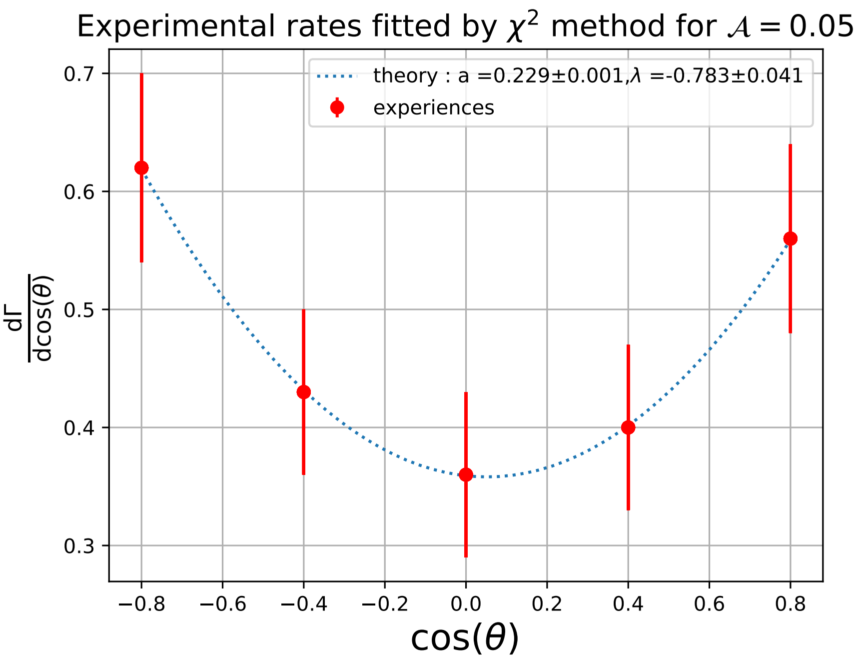


Figure 8: Fit of the rate using the least χ^2 method for an asymmetry of 0.05

6.2 Fit

Using a list of experimental points, we fitted the equation (14) using the least χ^2 method, to find a and λ the best fit we have is on figure 8.

7 Monte-Carlo Simulation

7.1 Event Generation

We will first generate our signal : $D^+ \to (K_1^+ \to K^+\pi^-\pi^+)\gamma$.
As described in part 4.1, this decay can occur in three different ways, the first two implying an intermediate vector mesons and the third one being a direct three-body decay :

- $D^+ \to [K_1^+ \to (\rho^0 \to \pi^-\pi^+)K^+]\gamma$
- $D^+ \to [K_1^+ \to (K^* \to \pi^-K^+)\pi^+]\gamma$
- $D^+ \to [K_1^+ \to \pi^-K^+\pi^+]\gamma$

The generations will be the following, for each mode using a Monte-Carlo generator : we start by a $e^+e^- \xrightarrow{\gamma^*} c\bar{c}$ final state from which we filter 10000 events, where at least is present a D^+.
Then we reconstruct the final states of these decay through the assigned mass and momentum of simulated final states. We aim to estimate the number of D^+ that could actually be reconstructed.

7.2 The combinatorial background

The measured first concern is the combinatorial background which dictates that most of the reconstructed particles are not D^+. This term designates a partially reconstructed signal where the pions or the gamma is not from the D signal.
For example, when we look at the distribution of the mass of the D meson, the events which have the right invariant mass can be in a really small number compared to events all happening at an other mass. What we need is to reduce it.

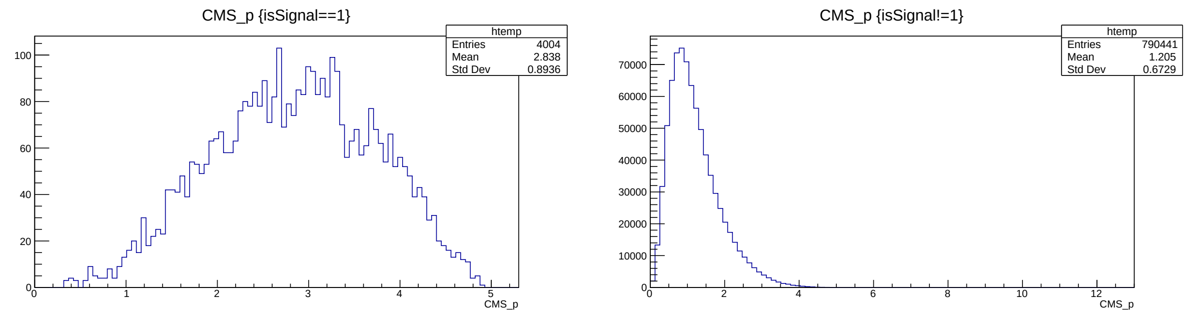


Figure 9: Momentum in the center of mass of both the reconstructed D mesons in the Signal and in the Combinatorial Noise

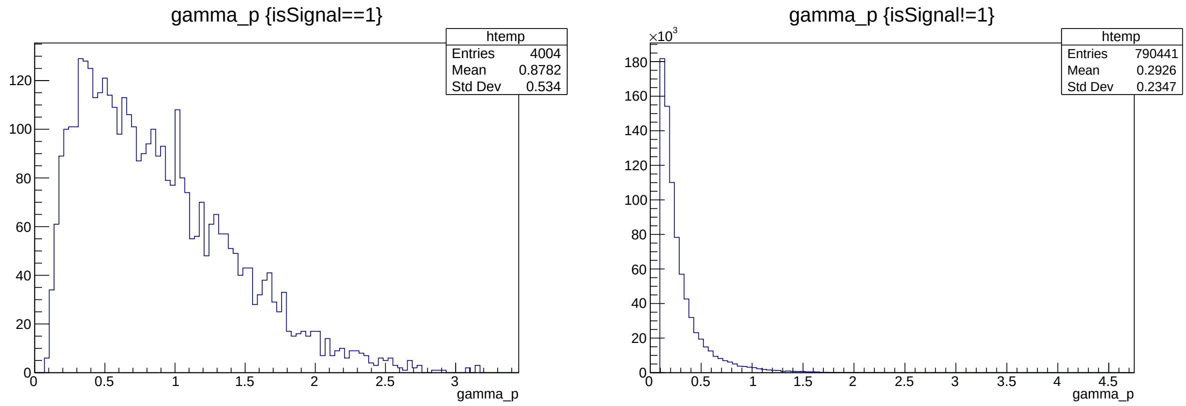


Figure 10: Energy of the photons produced both in the signal (left) and in the combinatorial background (right)

The combinatorial noise is visible in every distribution we produce. It is possible to separate it from the real signal in a very efficient way after the processing is done. This can be achieved by using a variable which tracks which particles are from the signal and which ones are from the combinatorial noise (with a certain confidence level). However, this variable is of course only accessible for a simulation of this kind. What we need is to find, using this variable, what differs in the distributions of the observables of both the signal and the combinatorial background, to apply cuts on the observables of the sum of the two (the raw signal).
The difficulty of applying cuts to our simulated data to extract the purest signal is that the purer the signal will be, the less events it will have. We thus need to find a compromise between a pure signal and a number of events high enough so that we have enough statistics.

8 Selection

8.1 Selection on the center of mass momentum

As we can see on figure 9, the distribution of the momentum from the combinatorial noise has a decreasing exponential shape. This means that the lower the momentum of the particles from the signal is, the more they are buried under the combinatorial noise. At a high enough center of mass momentum (about 2.5 GeV), we can keep the recorded events. Under this momentum, all particles will be cut, regardless they are part of the signal or not.

8.2 Selection on the energy of the photons

As representend on 10, most of the photons produced in the signal display an energy of above 0.4 GeV while most of the photons produced in the combinatorial background features an energy of under 0.4

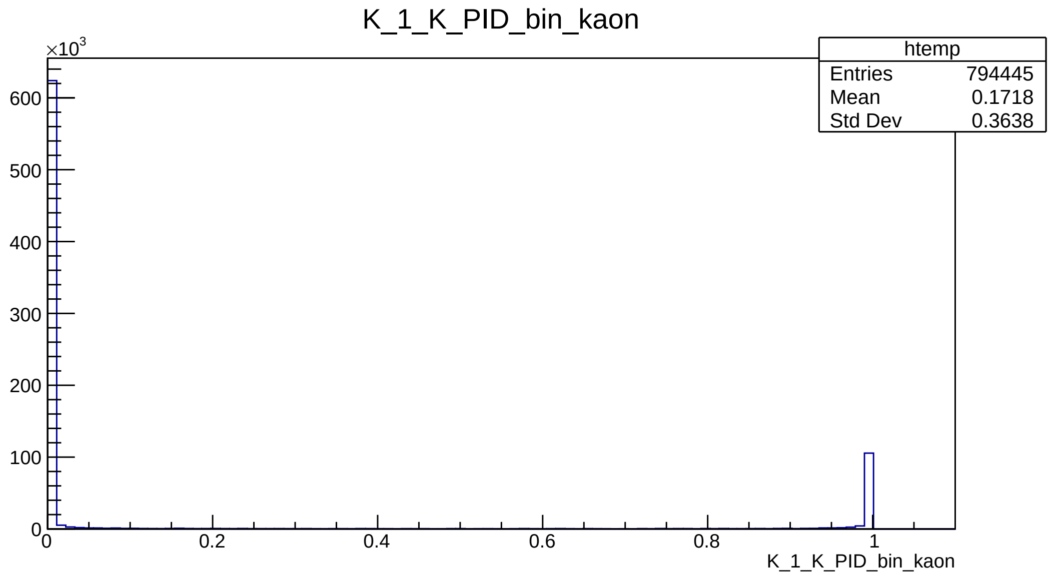


Figure 11: Fit

GeV. Thus, we can remove from our raw signal the events that produce photons of insufficient levels of energy.

8.3 Quality of the reconstruction of the Kaons

There are some particles which are not correctly reconstructed. For example, Kaons which are reconstructed as pions. While Kaons and Pions are similar, the difference in mass between the two can blurr the data. Hopefully, it is possible, with the Particle Identification Detector, to remove from the events considered from the raw signal the events where the Kaons have not been reconstructed with enough confidence. This value is represented on 11 Typically, if the particle that has been reconstructed as a Kaon has a confidence level below 90 %, then it is remove from the statistics from the raw signal.

9 Masses plots

To reconstruct the masses of the intermediate vector meson, we have from the conservation of the Energy and the 3-momentum for the $K\pi$ system :

$$(\sqrt{m_K^2 + p_K^2} + \sqrt{m_\pi^2 + p_\pi^2})^2 - \sum_i [(p_K)_i + (p_\pi)_i]^2 = m_{K\pi}^2 = m_{K^*}^2 \tag{15}$$

We expect this equation to give the invariant mass of the K^*. In the same way,we have an analogous formula for the $\pi\pi$ that we expect to give the invariant mass of the ρ^0. Through our simulation, we can have direct access to the mass of the D meson and the remaining combinatorial noise (figure 12), the K_1 (figure 13) and the intermediate vector meson when there is one (figure 14).
The D's mass distribution was done using only the part of the raw signal which has been identified as the signal. In the same way, the distribution of mass of the remaining combinatorial noise after applying the cuts was done the parts of the raw signal which were identified as being not the signal.

As we can see, we can expect around 624 events for the three-body mode, around 1229 events for the K^* mode and 1676 events for the ρ mode. As seen on [7], the D_s has a fraction of about the half of the one one the D^+. This mean we can expect to have about two times less D_s than D mesons.

9.1 Number of Expected Events

As seen on [6], Belle II is expected to reach an integrated luminosity of $L = 50 \times 10^{-46} ab^{-1}$. If we know the cross-section, σ and the fraction f, we can estimate the number of expected D and D_s mesons by

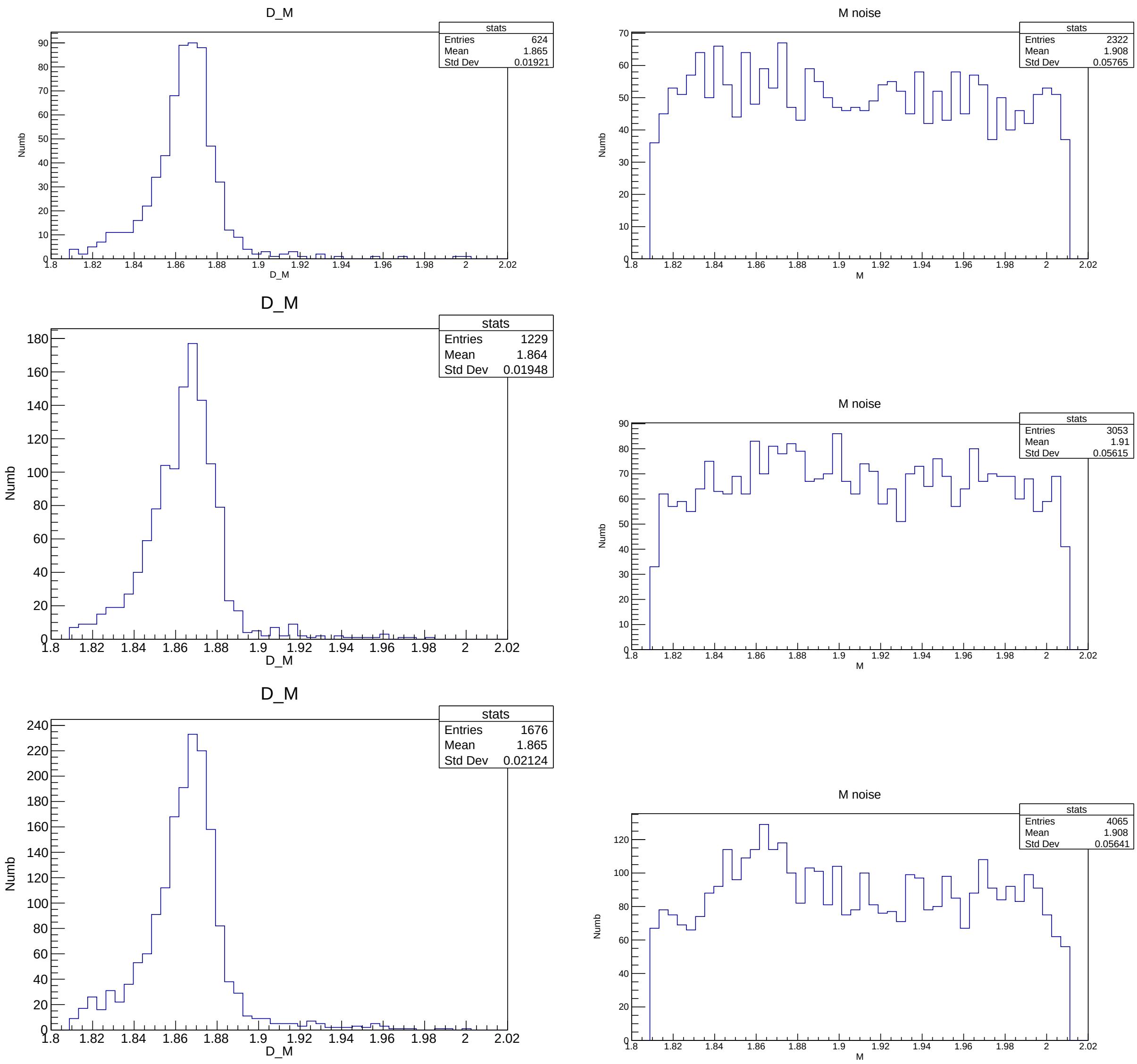


Figure 12: On left, masses for the D (mass of around 1.869 GeV) meson for the three channels. From left to right : 3-body decay, K^* and ρ^0 and on right what's left after applying the cuts.

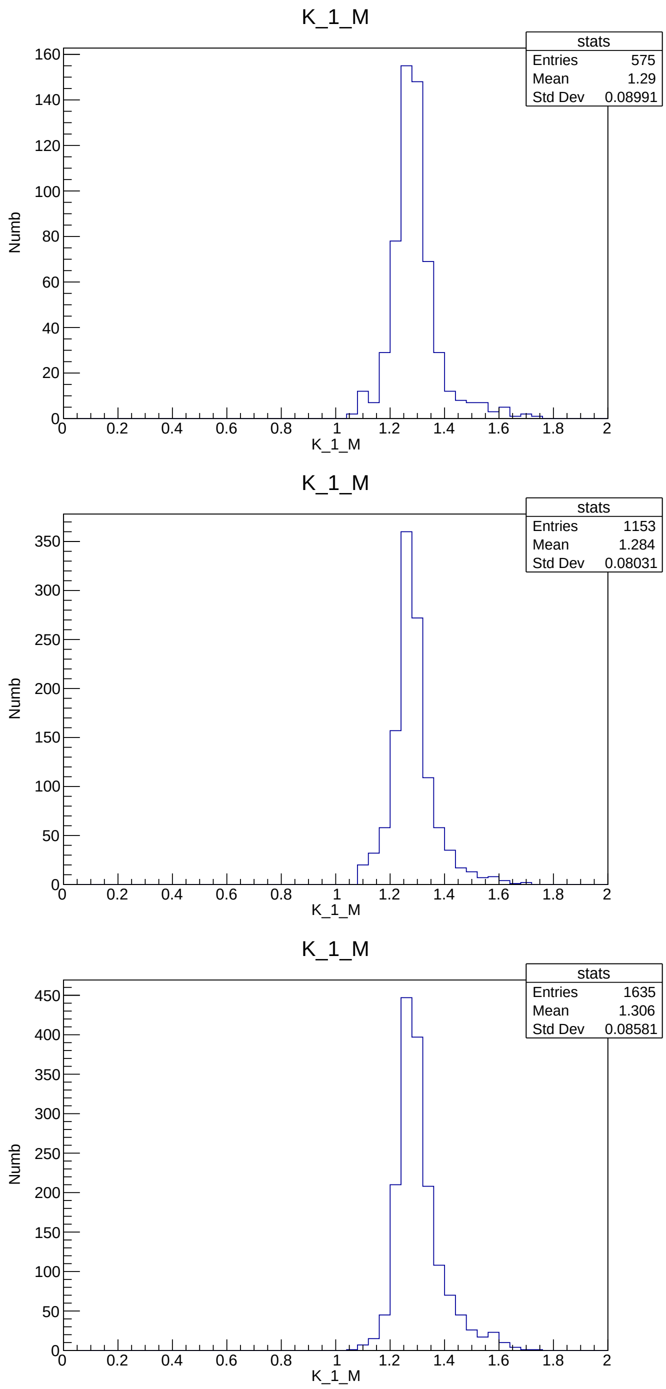


Figure 13: Masses for the intermediate $K_1(1270)$ for the three channels. From left to right : 3-body decay, K^* and ρ^0

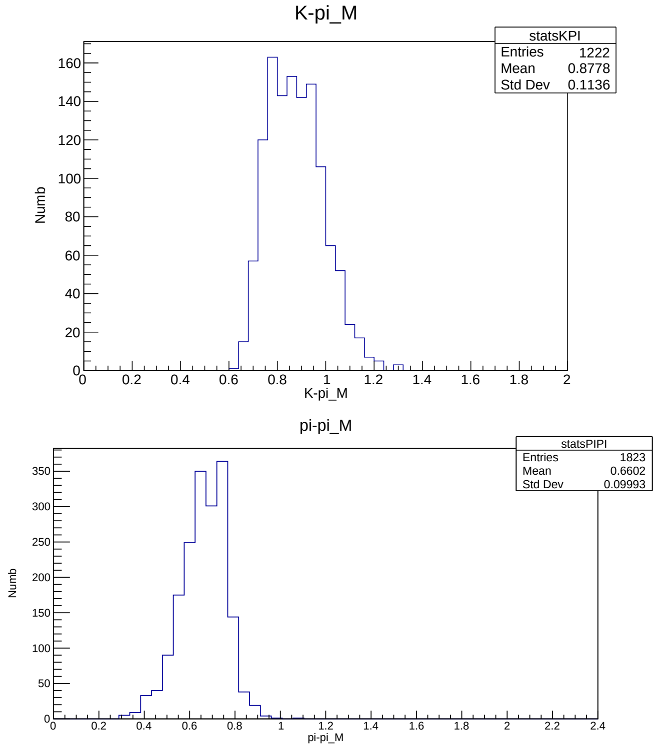


Figure 14: Masses for the intermediate vector meson. For the K^* channel, the $K\pi$ system gives the K^* mass and for the ρ^0 channel, the $\pi\pi$ system gives the ρ^0 mass

calculating : $L \times \sigma \times f$. For the D and D_s mesons, $\sigma = 1.3nb$. The fraction for the D is 0.23 and for the D_s it is 0.10 (as seen on [7]). This gives us an expected number of 1.5×10^{10} events for the D and an expected number of 6.5×10^9 events for the D_s.
To estimate the number of events that can effectively be measured, we need to take into account that only a portion of the events can be seen. As shown on the plots of the masses, we only have about 1000 events that survived the selection with the cuts out of 10000 events. Thus we can only have access to 10% of the events.
Finaly, we need into account the interesting rate to see how much D or D_s actually decay into $K\pi\pi$. As seen on [8], the expected rates are :

- $(2.1 \pm 0.5)\times10^{-4}$ for the ρ^0 mode
- $(2.5 \pm 0.4)\times10^{-4}$ for the K^* mode

We thus can expect around 6.75×10^5 and 2.925×10^5 events for the decays in which we are interested in.

10 Dalitz plots

10.1 Principles

Dalitz plots are visual representation of the phase-space of a three-body decay involving only spin-0 particles.
Let's consider a 3 bodies decay from a mother particle of mass M to 3 particles of masses 1,2 and 3. There are 3 four-vectors in the final state which leads to 12 degrees of freedom. Thanks to the 4-momentum conservation, the 3 masses and the 3 Euler angles, this leads to a grand total of only 2 degree of freedom. We have in the center of mass of the mother particle the following relation for any permutation of i,j,k=1,2,3 :

$$m_{ij}^2 = (p_i^\mu + p_j^\mu)^2 = (p^\mu + p_k^\mu) = M^2 + m_k^2 - 2ME_k \tag{16}$$

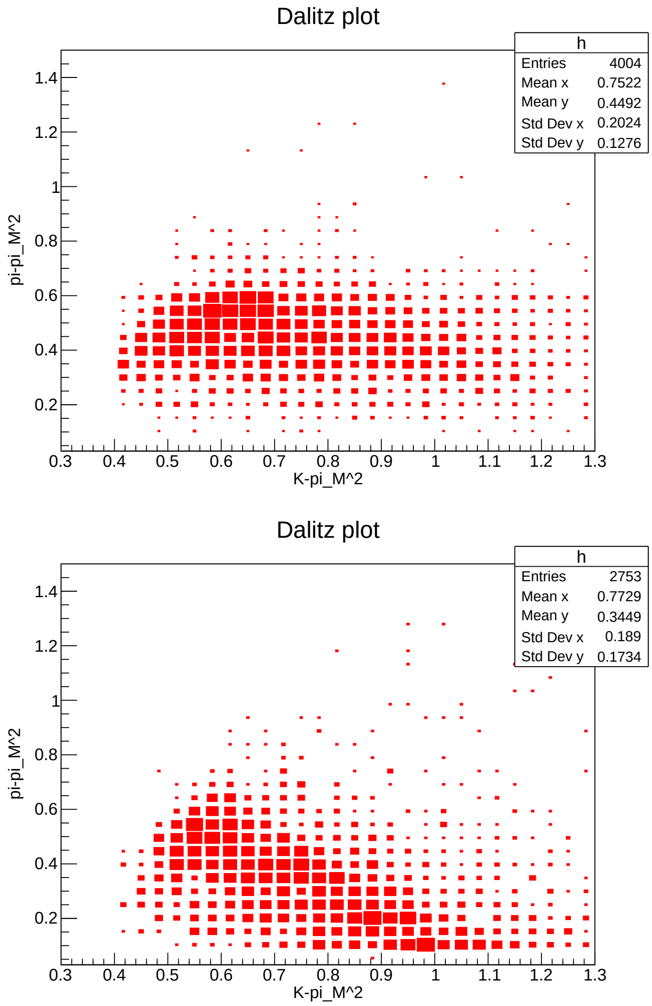


Figure 15: Dalitz plot for the ρ^0 mode and the K^* mode

As seen in [4], the sum $m_{12}^2+m_{23}^2+m_{31}^2$ is a constant. The Dalitz Plot is plotting two out of these three variables, such as m_{12}^2 versus m_{23}^2 The different plots are thus linked to the norm and the directions of the different momenta.
Futhermore as seen in [5], the number of times 0 is crossed is linked to the spin of the particle and the shape of the plot is linked to how relativistic our decay is. The closer it is to a triangle shape, the more it is in a relativistic regime.

10.2 Dalitz Plot

By projecting on the $\pi\pi$ (respectively on the K^π) plane the ρ (respectively the K^*) mass for the ρ (respectively the K^*) mode a straight, we expect to see a line, perpendicular to the axis of projection. The outcome was as can be seen on 15. As we can see on the Dalitz Plots, the invariant masses of the Kaon and of the Pion are the minimum threshold of the phase space. The masses are not really well-defined. This may be due to the K_1 which cut the phase space at the nominal masses of its products.

Conclusion

Although the additional loop-level contributions to the decay of $D_s \to K\pi\pi\gamma$ in comparison to the decay $D \to K\pi\pi\gamma$ represent an interesting gateway to the study of New Physics, these events are tricky to study experimentally. Indeed, they are part of a very open system, the masses are not well-defined and thus, the signal is hard to extract. Further research could focus on the major source of noise $D \to K\pi^+\pi^-\pi^0$ to determine whether or not this decay possesses a sufficient rate to warrant experimentation.

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