CERN Summer Studentship 2015 — Report

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Abstract. I report on my activities at CERN during the course of my Summer Studentship. My project focused on the spectroscopy of excited charmed meson states at LHCb, and was concluded on the first observation of the $D_{s1}(2460)^+$ meson at a hadron machine, and on the possible observation of the rare radiative decay of $D^*_{s0}(2317)^+ \to D^{*+}_s\gamma$. Further work to expand the results of this project is also pointed out.

1. Project proposal: *Study of charmed mesons decaying to $D^+_s\pi^0$ and $D^+_s\gamma$ final states*

1.1. Introduction

The aim of this project is to look for excited charmed mesons decaying to a D^+_s meson (with quark content $c\bar{s}$) and either a neutral pion or a photon. Two mesons, $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$, have already been observed decaying into these final states, but their natures are still subject of debate. Indeed, it has been pointed out that they could be tetraquarks or molecular states. The baseline of the project is thus to confirm the observation of the aforementioned excited charmed mesons and to measure their productions relative to that of the more familiar D^{*+}_s.

1.2. Theoretical motivations

The $D^*_{s0}(2317)^+$ meson, discovered by the BABAR collaboration in 2006 [1], and the $D_{s1}(2460)^+$ meson, observed by CLEO in 2003 [2], do not conform to conventional models of $c\bar{s}$ meson spectroscopy. These models [3, 4, 5, 6], mostly set up in the limit of heavy c quark mass and treating the $c\bar{s}$ system much like a hydrogen atom, have been successful in explaining the masses of all known D and D_s states, and have even predicted the masses of the $D_{s1}(2546)^+$ and $D^*_{s2}(2573)^+$ mesons to good accuracy. As shown in Figure 1 below, they however predict D_s masses for the lowest mass $J^P = 0^+$ and second lowest mass $J^P = 1^+$ states that were not confirmed experimentally.

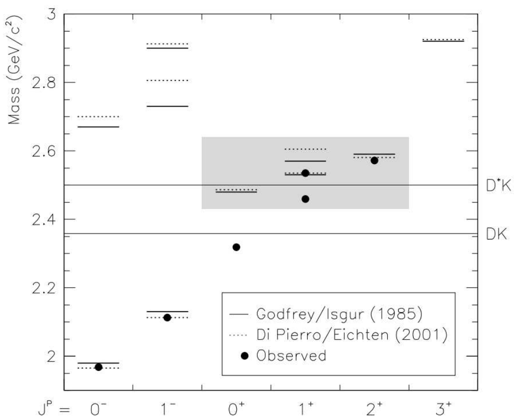

Figure 1. The $c\bar{s}$ meson spectrum, as predicted by Godfrey and Isgur [3] (solid lines), Di Pierro and Eichten [5] (dashed lines), and as observed by experiment (points). The DK and D^*K mass thresholds are indicated by the horizontal lines spanning the width of the plot. [1]

Table 1 below shows the predicted hadronic and radiative transition rates for narrow heavy-light meson states, in the model proposed by Bardeen, Eichten and Hill [7]. As will be described in the following section, it was decided for the purpose of the project not to study the $D_s^+\pi^0$ state, and instead look at the $D_s^+\gamma\gamma$ state where we prohibit the $\pi^0 \to \gamma\gamma$ decay.

Transition	Dependence	Γ (keV)	BR
$0^+ \to 1^- + \gamma$	$r_{\bar{c}s}$	1.74	7.5%
$\mathbf{0^+ \to 0^- + \pi^0}$	$G_A\delta_{\eta\pi 0}$	21.5	**92.5%**
Total		23.2	
$1^+ \to 0^+ + \gamma$	$r'_{\bar{c}s}$	2.74	7.1%
$1^+ \to 0^+ + \pi^0$	$g_A\delta_{\eta\pi 0}$	0.0079	0.02%
$1^+ \to 1^- + \gamma$	$r_{\bar{c}s}$	4.66	12.2%
$\mathbf{1^+ \to 0^- + \gamma}$	$r_{\bar{c}s}$	5.08	**13.3%**
$\mathbf{1^+ \to 1^- + \pi^0}$	$G_A\delta_{\eta\pi 0}$	21.5	**56.3%**
$\mathbf{1^+ \to 0^- + 2\pi}$	$g_A\delta_{\sigma_1\sigma_3}$	4.2	**11.0%**
Total		38.2	

Table 1. Theoretical predictions of the hadronic and electromagnetic transition rates for the $D_{s0}^*(2317)^+$ $J^P = 0^+$ and the $D_{s1}(2460)^+$ $J^P = 1^+$ meson states. The observed decay channels are shown in bold, and the ones studied in the project are shown in red. Note that the radiative transition $0^+ \to 0^- + \gamma$ is forbidden.

2. Project work

2.1. Skills

This project required reading theoretical, phenomenological and experimental papers, studying the kinematics of various decay processes, and understanding and analysing data. `ROOT`, `C`, `C++` and `Python` were extensively used.

2.2. Selecting a D_s^+ candidate

We start by studing 2011 LHCb data, with the following specifications:

```
Stripping 20
DsSel.Inputs = ["/Event/CharmCompleteEvent/Phys/D2hhhControl_KKPLine/Particles"]
Prescale 3%
Luminosity = 1.953 fb-1
```

We reconstruct the invariant mass of the D_s^+ by considering the decay $D_s^+ \to K^+K^-\pi^+$. The invariant mass of the $KK\pi$ system is plotted in Figure 2 below, and fitted to a Gaussian signal function and a flat blackground. The Gaussian mean, $\mu = 1969.7 \pm 0.03$ MeV/c^2 is in good agreement with the PDG value of $M(D_s^+) = 1969.0 \pm 1.4$ MeV/c^2. The Dalitz plot of the D_s^+ phase space is shown on the right, where we can clearly observe two structure bands at $M^2(\phi)$ and $M^2(\overline{K}^*)$. A good D_s^+ candidate is taken to be one with an invariant mass in the $\mu \pm 2\sigma$ range.

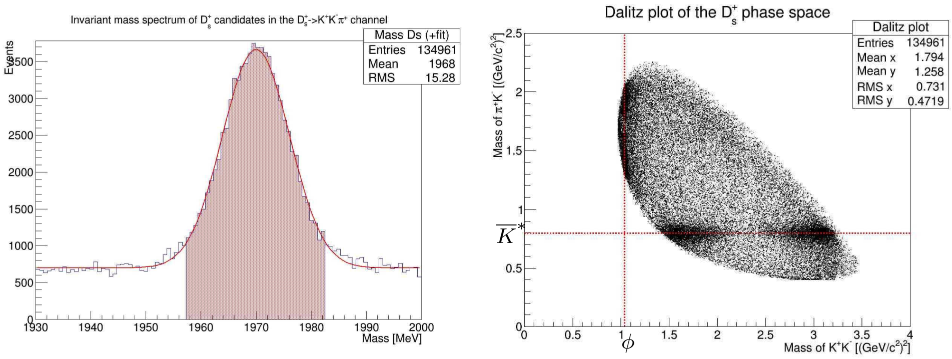

Figure 2. (Left) Invariant mass of the $K^+K^-\pi^+$ system, fitted to a Gaussian signal function with $\mu = 1969.7 \pm 0.03$ MeV/c^2 and $\sigma = 6.08 \pm 0.04$ MeV^2, plus a flat background. The shaded area corresponds to events with an invariant mass in the range $\mu \pm 2\sigma$. (Right) Dalitz plot of the D_s^+ phase space, with the invariant mass squared of the K^+K^- system on the horizontal axis, and the invariant mass squared of the $K^-\pi^+$ system on the vertical axis. Two structures are identifiable, interpreted as the $\overline{K}^*(892)$ and the $\phi(1020)$, decaying to $K^-\pi^+$ and K^+K^- respectively.

A Dalitz plot analysis of the decay of $D_s^+ \to K^+K^-\pi^+$, conducted by the BABAR Collaboration [8], reports a decay fraction of $D_s^+ \to \overline{K}^*K^+$ at the level of $(47.9 \pm 0.5 \pm 0.5)\%$, and $D_s^+ \to \phi\pi^+$ at $(41.4 \pm 0.8 \pm 0.5)\%$. Hence, selecting one of these two regions in the Dalitz plot greatly reduces the background in the distribution of the invariant mass of D_s^+ (better candidate selection). We now study 2012 LHCb data:

```
Stripping 21
DsSel.Inputs = ["/Event/CharmCompleteEvent/Phys/Ds2KKpi4Spectr_Line/Particles"]
Not Prescaled
Luminosity = 1.953 fb-1
(No stripping line in Stripping 21r1)
```

Again, we fit the distribution of the invariant mass of the $KK\pi$ system, with a flat background and a Gaussian signal function characterized by a mean $\mu = 1969.8 \pm 0.03$ MeV/c^2, in good agreement with the PDG value. Candidate selection is made in the shaded area of Figure 3, corresponding to the region $\mu \pm 2\sigma$. The Dalitz plot shown on the right contains only a narrow band around the invariant mass squared of the $\phi(1020)$.

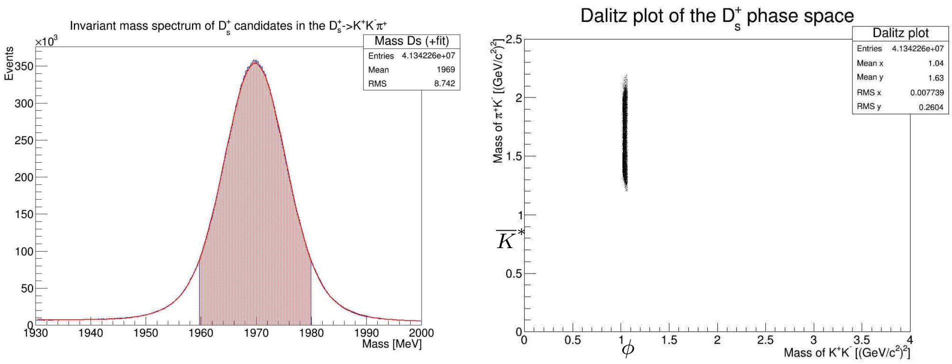

Figure 3. (Left) Invariant mass of the $K^+K^-\pi^+$ system, fitted to a Gaussian signal function with $\mu = 1969.8 \pm 0.03$ MeV/c^2 and $\sigma = 5.06 \pm 0.03$ MeV^2, plus a flat background. The shaded area corresponds to events with an invariant mass in the range $\mu \pm 2\sigma$. (Right) Dalitz plot of the D_s^+ phase space, with the invariant mass squared of the K^+K^- system on the horizontal axis, and the invariant mass squared of the $K^-\pi^+$ system on the vertical axis. The data wasn't prescaled, but only the $\phi(1020)$ band was kept.

2.3. *Analysis of the $D_s^+\gamma$ final state*

Having selected D_s^+ candidates as described above, we combine them with a photon taken from the `StdLooseAllPhotons` container, which only applies a loose cut on the transverse momentum: $P_T(\gamma) > 200$ MeV/c. The raw distribution of the invariant mass of the $D_s^+\gamma$ system is shown on the left of Figure 4 below. We observe a peak around 2112 MeV/c^2, well-known mass of the D_s^{*+} $J^P = 1^-$ meson state, and two bumps around 2310 MeV/c^2 and 2460 MeV/c^2.

To investigate these bumps, we now apply cuts on the photon. After multiple attempts, optimal results are obtained for $P_T(\gamma) > 1.4$ GeV/c^2 (kinematic cut). From the particle identification perspective, we require that the variable describing the confidence level of the cluster being associated to a photon (and not to an electron, or a jet) be greater than 80%: $CL > 0.8$ (PID cut). Furthermore, to make sure we are not dealing with a photon coming from the decay of a π^0, we combine the photon with all the other photons in the event, and keep it only if no combination returns an invariant mass in a small window around the π^0 mass. This is done by constraining a Boolean variable: `VetoPi0Resolved` $== 0$.

The result of these cuts is shown on the right of Figure 4, where the background has been greatly reduced. We still observe the D_s^{*+} resonance, but the bumps are now much clearer. The first bump is not a signal, but actually a feed-down (reflection) of two decay channels: $D_{s1}(2460)^+ \to D_s^+\pi^0$ and $D_{s0}^*(2317) \to D_s^{*+}\pi^0$, which shows the limited efficiency of the cut on the Boolean variable `VetoPi0Resolved`. The second bump is however much more promising, and correspond to a $D_{s1}(2460)^+$ decaying to $D_s^+\gamma$.

A fit of this distribution was attempted, but yielded only very crude results, due to technical difficulties when trying to fit several gaussian signals at the same time in `ROOT`, and is not reproduced here.

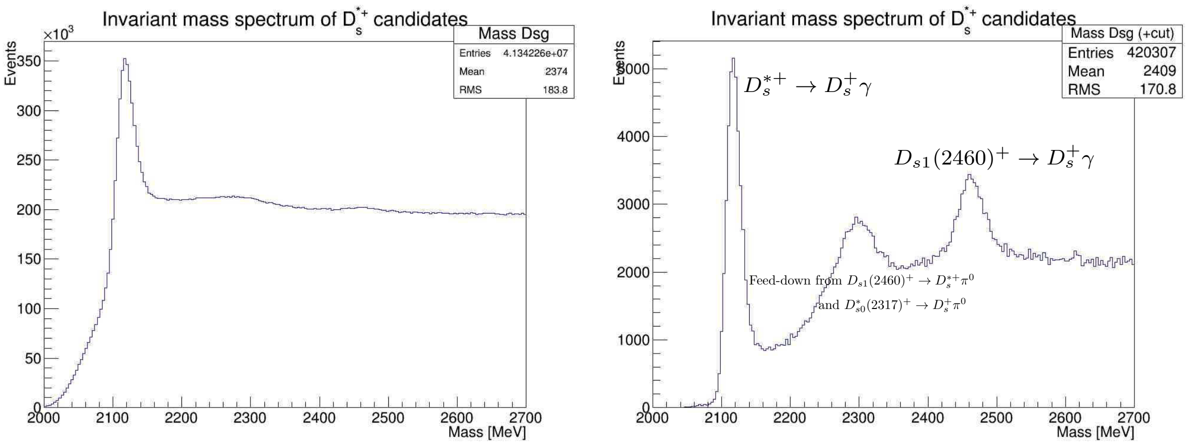

Figure 4. (Left) Raw invariant mass distribution of the $D_s^+\gamma$ system, after selection of a suitable D_s^+ candidate. (Right) Same distribution, after applying kinematic and PID cuts on the photon, and trying to suppress the π^0 decay channel. Three structures are observed: a $D_s^*(2112)^+$, a feed-down structure from $D_{s1}(2460)^+ \to D_s^*\pi^0$ and $D_{s0}^*(2317)^+ \to D_s^+\pi^0$, and a true $D_{s1}(2460)^+ \to D_s^+\gamma$ signal.

2.4. *Selecting a $D_s^*(2112)^+$ candidate*

As shown in Figure 5 below, we focus on the 2000–2200 MeV/c^2 region of the $D_s^+\gamma$ invariant mass distribution. D_s^{*+} candidates are taken to have an invariant mass between 2095 and 2150 MeV/c^2, based on the asymetric distribution around the 2112 MeV/c^2 peak.

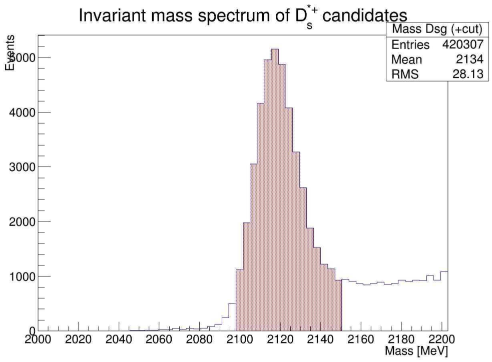

Figure 5. Distribution of the invariant mass of $D_s^+\gamma$. The shaded area corresponds to the selection range of $D_s^*(2112)^+$ candidates, between 2095 and 2150 MeV/c^2.

2.5. *Analysis of the* $D_s^{*+}\,(\rightarrow D_s^+\gamma)\,\gamma$ *final state*

Having selected D_s^{*+} candidates as described above, we combine them with a photon taken from the `StdLooseAllPhotons` container, which only applies a loose cut on the transverse momentum: $P_T(\gamma) > 200$ MeV/c. The raw distribution of the invariant mass of the $D_s^{*+}\,(\rightarrow D_s^+\gamma)\,\gamma$ system is shown on the left of Figure 6 below. A bump is observed at the top of the distribution, near 2317 MeV/c^2.

To investigate this bump further, we apply similar cuts on the second photon as we did in the previous sections, by requiring `VetoPi0Resolved` $== 0$ and $CL > 0.8$. However, the kinematic cut is relaxed to $P_T(\gamma_2) > 0.5$ GeV/c. The invariant mass distribution after these cuts is shown on the right of Figure 6. No signal is evident at 2460 MeV/c^2, but a structure is present in the vicinity of 2317 MeV/c^2 (red line).

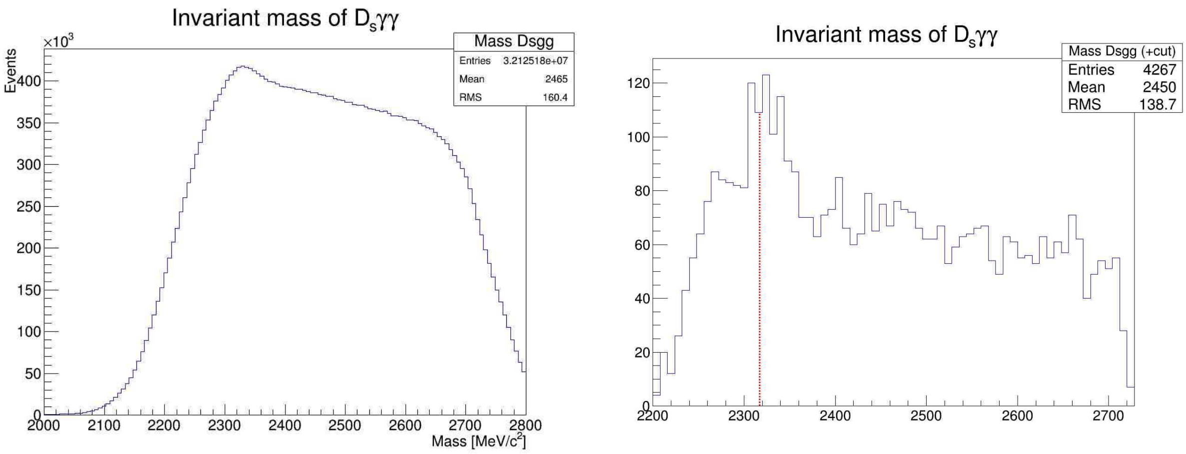

Figure 6. (Left) Raw invariant mass distribution of the $D_s^+\gamma\gamma$ system, after selection of a suitable D_s^{+*} candidate. (Right) Same distribution, after applying kinematic and PID cuts on the second photon, and trying to suppress the π^0 decay channel. A structure is observed, seemingly at a mass near 2317 MeV/c^2 (red line). No clear signal is visible near 2460 MeV/c^2.

2.6. *Monte Carlo analysis*

In order to make sure that the signals we observe are not reflections from other decay channels or artefacts of our selection criteria, we run Monte Carlo simulations, with inclusive D_s^+ and D_s^{*+} events. Figure 7 below shows the result of the Monte Carlo simulation for the $D_s^+\gamma$ final state, with no contribution from either $D_{s0}^*(2317)^+$ or $D_{s1}(2460)^+$, and where the same kinematic and PID cuts were applied, confirming our observation of a true $D_{s1}(2460)^+$ plus.

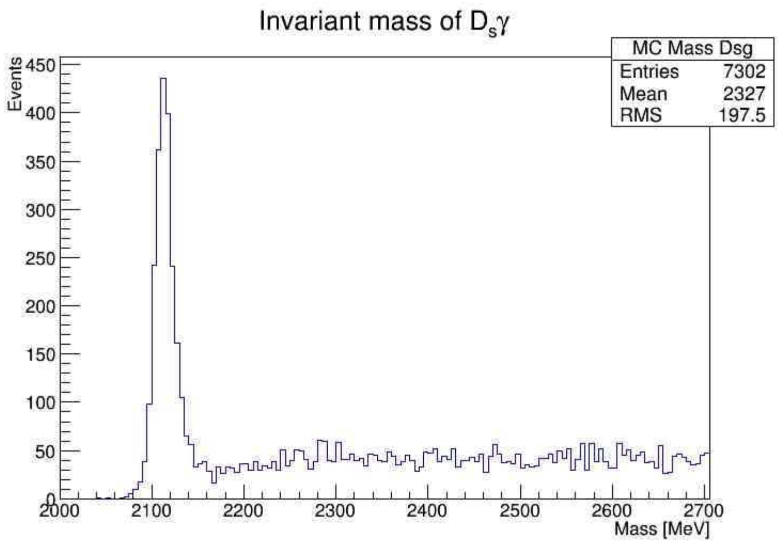

Figure 7. Invariant mass distribution of the $D_s^+\gamma$ final state, obtained by Monte Carlo simulations excluding the contributions of the 0^+ and 1^+ states.

However, the inclusive D_s^{*+} Monte Carlo $D_s^+\gamma\gamma$ sample seems to reproduce the same bump that was observed in the previous section, as is shown in Figure 8 below. It is still important to point out that we do not have much Monte Carlo statistics, and even fewer events left in the analysis of the actual data, after applying the various cuts and selections. Further Monte Carlo requests are in progress at the time of writing, covering all possible decay channels of both $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$: radiative, hadronic (with missed π^0), resonant (with D_s^{*+}) and non-resonant (directly to $\gamma\gamma$).

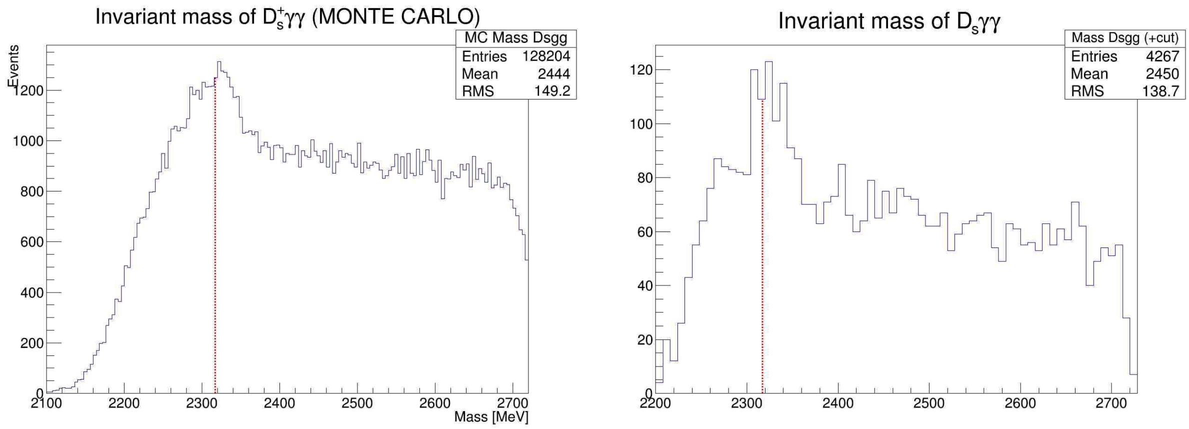

Figure 8. (Left) Invariant mass distribution of the $D_s^+\gamma\gamma$ final state, obtained by Monte Carlo simulations excluding the contributions of the 0^+ and 1^+ states. (Right) Distribution from actual data. (Both) The red vertical line is situated at 2317 MeV/c^2. A similar structure near this threshold is observed in both cases.

2.7. Technical issue

We detected an apparent bug in the *Decay Tree Fitter* algorithm, used to reconstruct the tracks of daughter particles to fit exactly the nominal invariant mass of the mother. This issue has already been reported to the DaVinci mailing list and at several meetings (including Calo). The variables labelled `_DTF_Ds_PV` (refitted to the invariant mass of the D_s^+) give a worse signal resolution than standard variables, when (for example) reconstructing the invariant mass of the $D_s\gamma$ system (Figure 9 below). A negative mass of $\sim -35 \times 10^{36}$ MeV/c^2 is attributed by the algorithm to the D_s^{*+} in about 1% of the events.

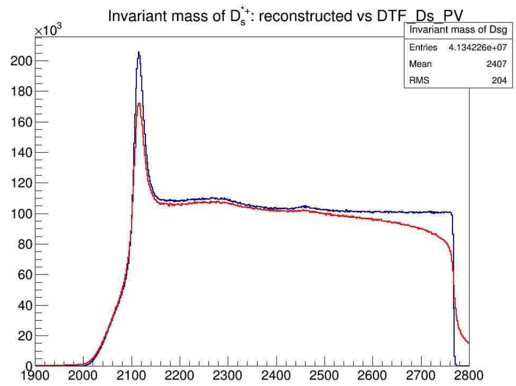

Figure 9. Distribution of the invariant mass of $D_s^+\gamma$. (Blue) Using the standard variables. (Red) Using the DTF variables.

2.8. Summary

What was done: Analysis of the $D_s^+\gamma$ and $D_s^+\gamma\gamma$ final states. First observation of a $D_{s1}(2460)^+$ at a hadron machine. Possible observation of a radiative decay of $D_{s0}(2317)^+ \to D_s^{*+}\gamma$. Monte Carlo simulations. Partial fits.

What could be done: Improve fits. Further Monte Carlo analysis for $D_s^+\gamma\gamma$. Production measurement of D_{sJ}^+ relative to D_s^{*+}. Measurement of $\frac{\mathcal{B}\left(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma\right)}{\mathcal{B}\left(D_{s0}^*(2317)^+ \to D_s^+\pi^0\right)}$.

3. The CERN Summer Studentship

Throughout these thirteen weeks spent at CERN, I have had the opportunity to attend a series of lectures given by world-leading researchers, in both theoretical and experimental particle physics, to visit various experiments and sites (control rooms, LHCb and CMS caverns, SPS, data center, etc.), to engage in challenging and rewarding research within the LHCb group, and to meet and form friendships with many students from diverse backgrounds and nationalities.

I have also been able to attend seminars and conferences, to give a couple of presentations to the LHCb team and the charm working group, and talk to many physicists, engineers, computer scientists and PhD students. All in all, not only have I enhanced my programming skills and developed specialized knowledge in high energy particle physics phenomenology, but I also have had the chance to witness at first hand the life, work and organization of a world-leading particle laboratory, gaining valuable insight and contacts in the field of professional research.

Acknowledgments

I thank the Summer Student Team and my supervisors, Marco Pappagallo and Vladimir Gligorov, without whom this adventure wouldn't have been possible. I would also like to show gratitude to the LHCb Collaboration for taking me in two summers in a row, and acknowledge in particular Monica Pepe Altarelli, Loïc Brarda, Angelo Di Canto, Gloria Corti, Joël Closier, Cindy Denis, Carnita Hervet, Chris Parkes and Heinrich Schindler. And of course, all my Summer Student friends.

References

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