Summer student project report: Search for the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ at the LHCb experiment

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Abstract

The summer student project treated the search for the radiative decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ with the 2016 and 2017 data sets collected by the LHCb experiment corresponding to $3.3\,\text{fb}^{-1}$ at a centre-of-mass energy of $13\,\text{TeV}$. For the search the ratio $\text{BR}(D_s^*(2317)^\pm \to D_s^{*\pm}\gamma)/\text{BR}(D_s^*(2317)^\pm \to D_s^\pm\pi^0)$ was investigated, but no hint for the existence of $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ was found.

1 Introduction

The spectroscopy of heavy-light mesons can mostly be described successfully with non-relativistic quark potential models in the limit of Heavy Quark Effective Theory (HQET), in which the mesons can be considered as a hydrogen atom. The limit requires that $m_\text{Q} \to \infty$, which is the mass of the meson's heavy quark. In that case the spin of the heavy quark $\vec{S}_\text{Q}$ is decoupled from the orbital angular momentum $\vec{l}$ between the quarks and states in the spectrum are identified by the quantum numbers $j = L + s_\text{q}$, L and J. Therefore the ${}^jP$-wave ($L = 1$) states are expected to be doubly degenerated in the spin of the heavy quark. Moreover new symmetries called Heavy Flavour Symmetry and Heavy Spin Symmetry come along with the HQET that make it possible to estimate several mass states and branching fractions. [1][2]
The HQET was applied successfully to the spectroscopy of the strange-charmed mesons until the surprising discoveries of the $D_s^*(2317)^+$ and the $D_s^*(2460)^+$ states by the BABAR and CLEO collaborations in 2003. [3][4]. The $D_{s1}^*(2536)^\pm$ and $D_{s2}^*(2573)^\pm$ P-wave states with $j = 3/2$ are known since their discoveries by the ARGUS [5] and the CLEO [6] collaborations and match the mass predictions by HQET very well. Therefore the $D_s^*(2317)^\pm$ and $D_s^*(2460)^\pm$ states are supposed to be the missing $j = 1/2$ P-wave states in $D_s^\pm$ mass spectrum. Most (but not all, e.g. [7]) of the theory papers predict these missing $j = 1/2$ P-wave states to have higher masses than those measured, even above the DK and D^*K mass thresholds [8][9][10] and the widths of these states to be broad (hundreds of MeV) [11]. As they are observed below these thresholds they can decay through the strong interaction only via isospin violating modes. Therefore the radiative processes are expected to have sizeable branching fractions, but they have not been seen so far. All these differences between the measurements and the theory predictions raise the questions of how applicable quark potential models and HQET are in describing these states and whether they are part of the $D_s^\pm$ spectrum or not. Thus the searches for the radiative decays such as $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ are important tools for testing HQET in this application. Several other theoretical papers suggest different approaches to solve these problems by treating the states as hadronic molecules [12][13] or multiquarks compounds such as tetraquarks [14].

2 Former searches for decay channels of the $D_s^*(2317)^\pm$

When the BABAR collaboration found the $D_s^*(2317)^\pm$ resonance, it was seen in the decay channel $D_s^\pm \pi^0$, which is so far the only decay channel found. The existence of the decay channel was confirmed by the CLEO [4] and the BELLE collaborations [15] in the same year. These experiments also searched, among others, for the radiative decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$, but did not find a hint for its existence, so they set upper limits on the ratio

$$R = \frac{\mathrm{BR}(D_s^*(2317)^\pm \to D_s^{*\pm}\gamma)}{\mathrm{BR}(D_s^*(2317)^\pm \to D_s^\pm \pi^0)} \tag{1}$$

to be $\leq 5.9\,\%$ [4] and $\leq 18\,\%$ [15] respectively. The BABAR collaboration performed another search for decay channels of the $D_s^*(2317)^\pm$ and $D_s^*(2460)^\pm$ meson states [16] and set the limit to R to be $\leq 16\,\%$.

3 Strategy for the search

The analysis is based on the full data sets of 2016 and 2017 which refer to an integrated luminosity of $3.3\,\mathrm{fb}^{-1}$. The search of the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ is performed by measuring the ratio R of equation (1). The $D_s^{*\pm}$ is reconstructed in the $D_s^\pm\gamma$ decay channel, while the π^0 goes to $\gamma\gamma$ and $D_s^\pm$ to $K^+K^-\pi^\pm$. Thus the particles in the final states of $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ and $D_s^*(2317)^\pm \to D_s^\pm\pi^0$ are the same, so that a similar selection for both channels is implemented. The advantage of similar selections yields in the cancellation of many systematic uncertainties in the calculation of the branching ratios which gives

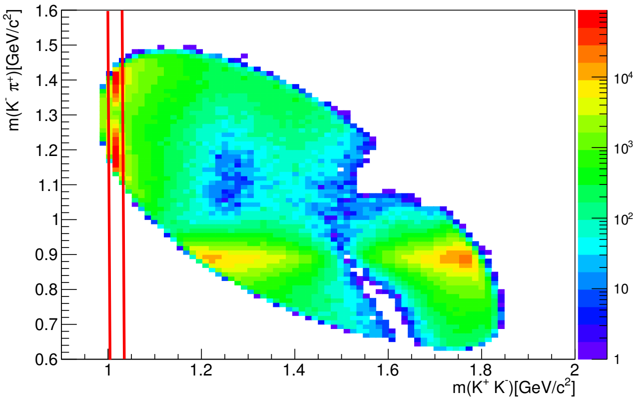
$$\frac{N(D_s^*(2317)^\pm \to D_s^{*\pm}\gamma)}{N(D_s^*(2317) \to D_s^\pm\pi^0)} = \frac{\mathrm{BR}(D_s^*(2317)^\pm \to D_s^{*\pm}\gamma)}{\mathrm{BR}(D_s^*(2317)^\pm \to D_s^\pm\pi^0)} \frac{{\varepsilon_{\mathrm{sel}}}^{\pi^0}}{{\varepsilon_{\mathrm{sel}}}^{2\gamma}} \underbrace{\frac{{\varepsilon_{\mathrm{rec}}}^{\gamma_0}{\varepsilon_{\mathrm{rec}}}^{\gamma_1}}{({\varepsilon_{\mathrm{rec}}}^{\gamma})^2}}_{\approx 1}$$

$$\times \frac{\cancel{\varepsilon_{\mathrm{trig}}}\, \varepsilon_{\mathrm{rec}}^{KK\pi}\, \cancel{\varepsilon_{\mathrm{sec}}^{KK\pi}}}{\cancel{\varepsilon_{\mathrm{trig}}}\, \varepsilon_{\mathrm{rec}}^{KK\pi}\, \cancel{\varepsilon_{\mathrm{sec}}^{KK\pi}}} \frac{\cancel{\mathcal{L}\sigma(pp \to c\bar{c}) f_{Ds(2317)}}}{\cancel{\mathcal{L}\sigma(pp \to c\bar{c}) f_{Ds(2317)}}}, \tag{2}$$

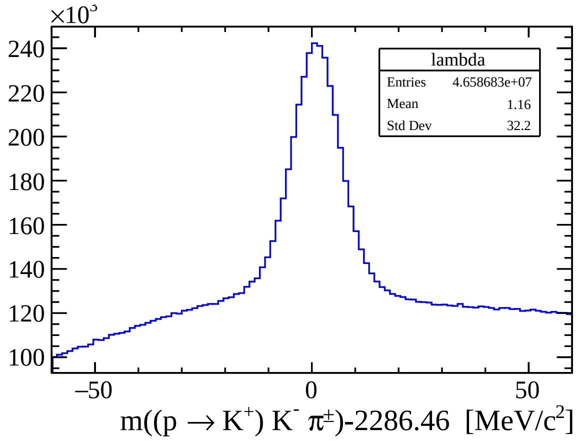
where furthermore the cancellation of some efficiencies is assumed. The $D_s^\pm$ meson is reconstructed in the full-hadronic $\phi(1020)(\to K^+K^-)\pi^\pm$ channel and the selection is tuned by requirements to the kinematics and PID of the charged tracks as well as by avoiding backgrounds. The results are presented in the next section. For the reconstruction of the neutrals the kinematics as well as the angular separation between the neutrals and the $D_s^\pm$ flight directions are studied based on a RapidSim [17] simulation. The small available Q-value in these decays is going to be used to create a cone around the $D_s^\pm$ flight direction that covers the neutrals and excludes background from random photons. For the reconstruction of the $D_s^*(2317)^\pm \to D_s^\pm\pi^0$ channel only resolved π^0 are used. For the $D_s^{*\pm}$ yield an SPlot [18] is performed to extract signal weights. With these weights the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ yield can be built.

4 Reconstruction of the $D_s^\pm$ mesons

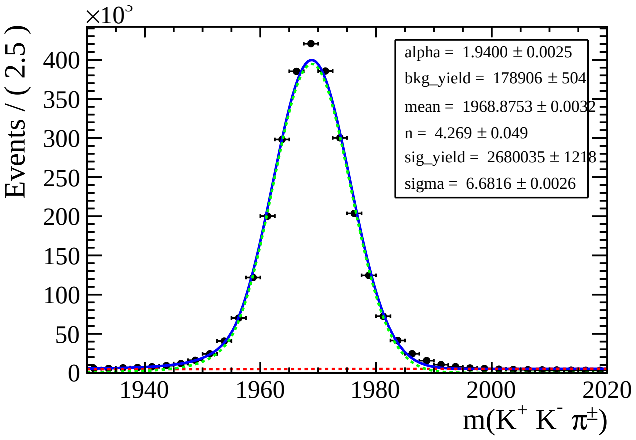
As mentioned before the $D_s^\pm$ are reconstructed in the full-hadronic $\phi(1020)(\to K^+K^-)\pi^\pm$ channel. The data was taken in the stripping line StrippingD2hhhFTCalib_KKPLine in stripping S28r1 for 2016 and S29r2 for 2017. There was a change in the stripping line regarding the invariant mass of the two kaons $m(K^+K^-)$ to be in the $\phi(1020)$ mass range in S29r2 but not in S28r1. Therefore the data sets have been aligned to each other. This is performed by requiring the invariant mass of the two kaons $m(K^+K^-)$ to be within $7\,\mathrm{MeV}/c^2$ of $m_{\phi(1020)} = (1019.461 \pm 0.016)\,\mathrm{MeV}/c^2$ [19]. Reconstruction of $D_s^\pm$ mesons via the $\phi(1020)$-resonance is a common selection that is motivated by the Dalitz plot and aim to get a very pure signal. In figure 1a a Dalitz plot for $D_s^\pm \to K^+K^-\pi^\pm$ of simulated events made with RapidSim for the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ is shown. The red vertical lines qualitatively highlight the requirement to $m(K^+K^-)$.



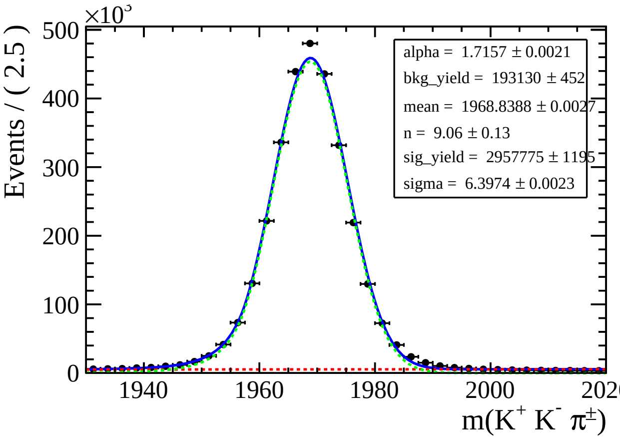
(a) Dalitz plot



(b) $\Lambda_c^+ \to (p \overset{\text{misid.}}{\to} K^+)K^-\pi^+$ background



(c) $D_s^\pm$ yield for 2016



(d) $D_s^\pm$ yield for 2017

Figure 1: (a) Dalitz plot of $D_s^\pm \to K^+K^-\pi^\pm$ from simulated events made with RapidSim for the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ decay channel. (b) contribution of $\Lambda_c^\pm \to pK^-\pi^+$ for the 2016 data set before applying any cuts. $D_s^\pm$ yield after all selection cuts for (c) 2016 and (d) 2017.

Additionally cuts to the kinematics of the charged tracks and to the particle identification (PID) of the kaons were applied to increase the purity of the $D_s^\pm$. These require for the transverse momenta $p_{\mathrm{T}}(K^+, K^-, \pi^\pm) > 1.5\,\mathrm{GeV}/c$, $p_{\mathrm{T}}(D_s^\pm) > 5\,\mathrm{GeV}/c$ and for the PID ProbNNk$(K^+, K^-) > 0.8$. There is also cut applied to avoid contaminations in the signal window from $\Lambda_c^+ \to (p \overset{\text{misid.}}{\to} K^+)K^-\pi^+$ where the proton is misidentified as a K^+. This is made by assigning the proton mass to the positively charged kaons and recalculating their energy and the invariant mass $m(K^+K^-\pi^+)$. The cut requires that $|m((p \overset{\text{misid.}}{\to} K^+)K^-\pi^\pm) - m(\Lambda_c^\pm)| > 33\,\mathrm{MeV}$. In figure 1b the resulting background before applying any cuts is shown for the 2016 data set. The final resulting yields for the $D_s^\pm$ after all these cuts are shown in the figures 1c and 1d. The peak is modelled by a Crystall Ball (CB) function, whereas for the background Chebychev polynomials are used.

5 Simulations with RapidSim

For studying the kinematics of the neutrals and the angular separations between the neutrals and $D_s^\pm$ flight directions RapidSim simulations are performed because LHCb Monte Carlo for these decays was not available. RapidSim provides tools for fast simulations of heavy-quark hadron decays. However, no interaction with the LHCb detector is simulated, but the particles are forced to decay in the acceptance of the LHCb detector. For the $D_s^\pm$ decays a Dalitz model of EVTGEN is used. The simulations are also used to estimate the selection efficiencies for the $D_s^*(2317)^\pm \to D_s^\pm\pi^0$ and $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ decay channels. The angular separation of the flight directions of two particles is a Lorentz-invariant quantity and is defined by

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} \tag{3}$$

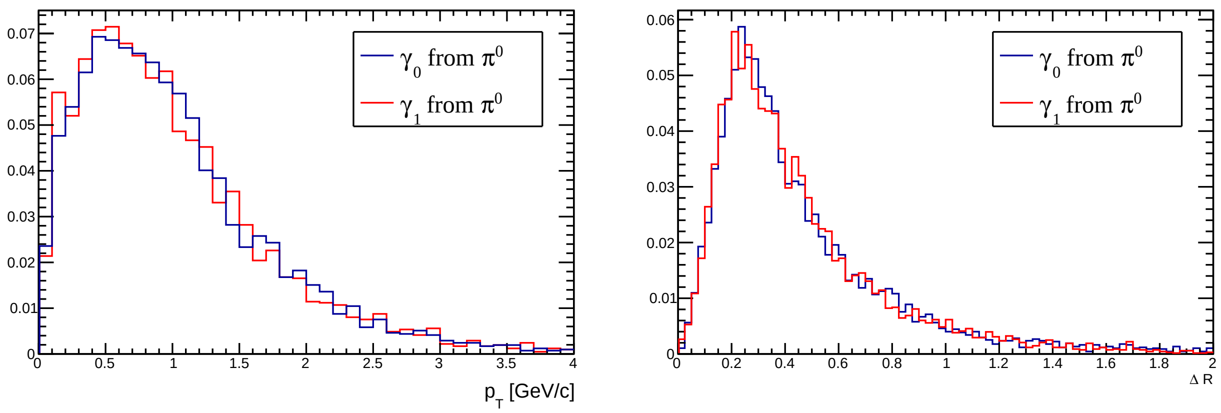
where is $\Delta\eta$ is the difference in the particles pseudorapidities and $\Delta\varphi$ the difference in their polar angles with respect to the beam axis. The purpose of studying this quantity is to profit from the small Q-value in the decays and to verify that a cone size of $\Delta R = 0.4$ around the $D_s^\pm$ is reasonable to exclude background from random photons without losing too much signal. This specific cone size is motivated by a former analysis of $B_s \to D_s^*\mu\nu_\mu$. For investigating the kinematics of the two photons in the final state of each decay the transverse momenta are compared and the their asymmetries are considered. The asymmetry in the transverse momentum is defined by

$$A_{\mathrm{PT}} = \frac{p_{\mathrm{T}}(\gamma_0) - p_{\mathrm{T}}(\gamma_1)}{p_{\mathrm{T}}(\gamma_0) + p_{\mathrm{T}}(\gamma_1)}. \tag{4}$$

For the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ channel γ_0 refers to the photon coming from the $D_s^*(2317)^\pm$ and γ_1 to the one coming from the $D_s^{*\pm}$.

5.1 Results for $D_s^*(2317)^\pm \to D_s^\pm\pi^0$

In the figures 2a and 2b the results for transverse momentum and angular separation distributions of the two photons are shown.



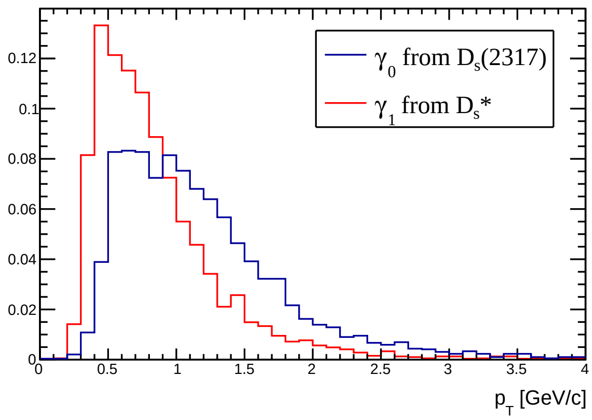
(a) transverse momentum **(b)** angular separation

Figure 2: Distributions for the transverse momenta (a) and angular separation (b) in the $D_s^*(2317)^\pm \to D_s^\pm\pi^0$ channel.

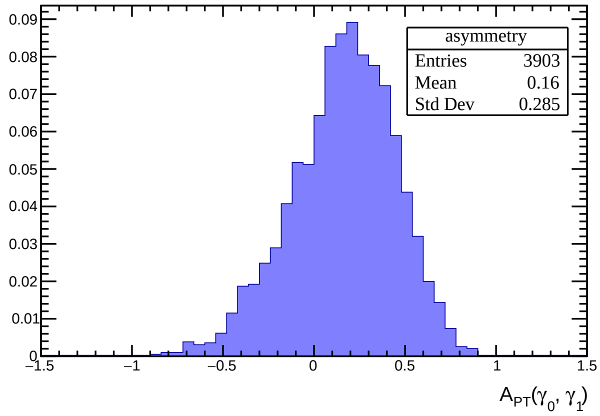
It is observable that most of the photons have transverse momenta below 1.5 GeV/c and that the two photons coming from the π^0 have the same transverse momentum distribution as expected because they are indistinguishable. From this observation a cut $p_{\mathrm{T}}(\gamma_0, \gamma_1) < 1.5\,\mathrm{GeV}/c$ is applied to get rid of merged π^0. Moreover the confidence level of the PID of the photons is required to be $\mathrm{CL}(\gamma) > 0.6$ which comes along with excluding low energetic photons, so that the cut $p_{\mathrm{T}}(\gamma_0, \gamma_1) > 0.2\,\mathrm{GeV}/c$ is applied. From the angular separation distributions it is visible that the cone size of $\Delta R = 0.4$ is reasonable.

5.2 Results for $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$

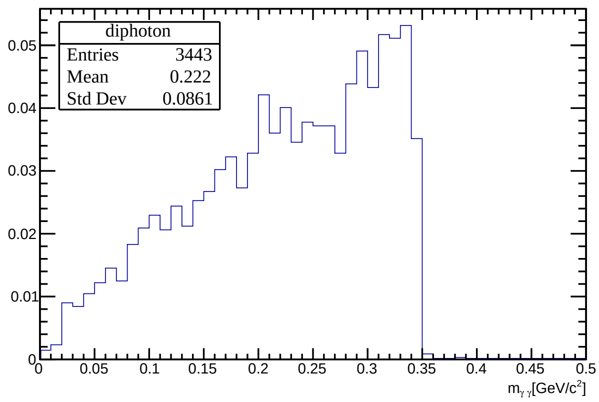
Figures 3a and 3b show the resulting transverse momentum distributions of the two photons and their asymmetry, whereas figure 3c and 3d show results for the invariant mass of the two photons and the cone size in the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ channel. The distributions of the transverse momenta show that the same cut $0.2\,\mathrm{GeV}/c < p_\mathrm{T}(\gamma_0, \gamma_1) < 1.5\,\mathrm{GeV}/c$ as in the $D_s^*(2317)^\pm \to D_s^\pm \pi^0$ channel can be applied. Furthermore the asymmetry of the transverse momenta towards the γ_0 shows that the photon with the highest transverse momentum in the cone can be identified as the photon coming from the $D_s^*(2317)^\pm$ and the one with second highest transverse momentum as the one coming from the $D_s^{*\pm}$. This implies that the asymmetry is required to be $A_\mathrm{PT}(\gamma_0, \gamma_1) > 0$. From the distribution of the invariant mass of the two photons $m_{\gamma\gamma}$ it visible that a mass veto for the π^0 mass range such as $|m_{\gamma\gamma} - m_{\pi^0}| > 25\,\mathrm{MeV}/c^2$ can be used. Besides that a cutoff value of $m_{\gamma\gamma} < 500\,\mathrm{MeV}/c^2$ can be extracted which is functional to further reduce background from random photon combinations. The cone size proves itself to be reasonable also for this decay channel, so that both photons can be covered with the same cone around the $D_s^\pm$ flight direction.



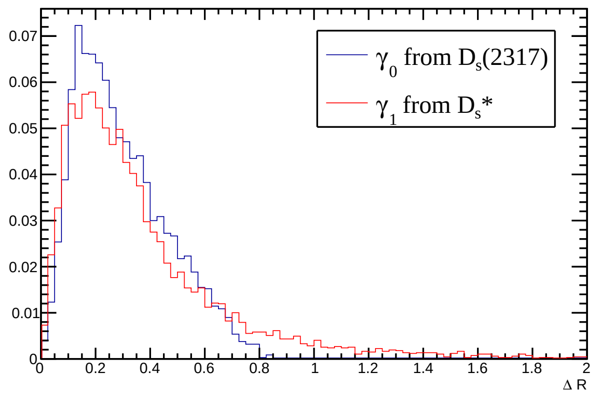
(a) transverse momentum



(b) asymmetry



(c) invariant mass of the photons

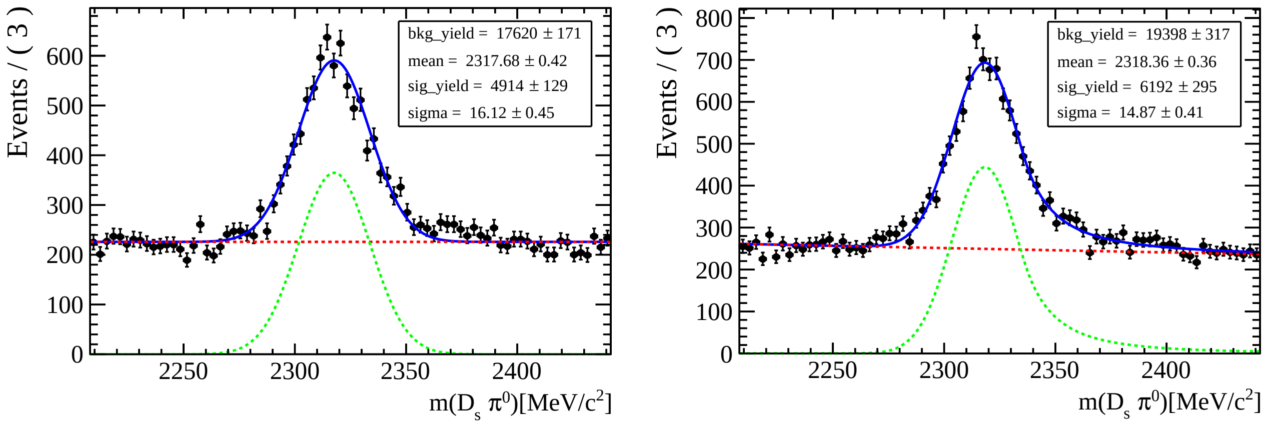


(d) angular separation

Figure 3: Distributions for (a) the transverse momenta, (b) the asymmetry of the transverse momenta, (c) the invariant mass of the the two photons and (d) the angular separation in the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ channel.

6 Resulting $D_s^*(2317)^\pm$ yield in the $D_s^*(2317)^\pm \to D_s^\pm \pi^0$ channel

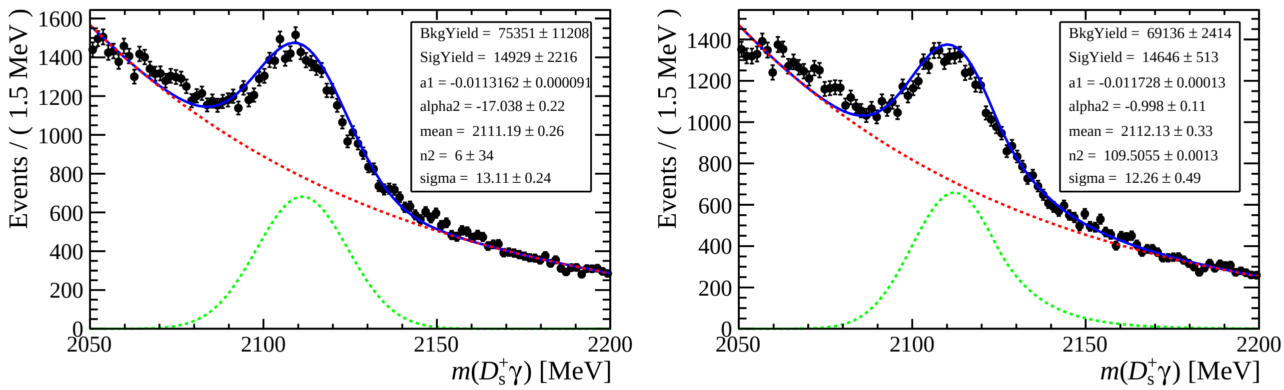
For the $D_s^*(2317)^\pm \to D_s^\pm \pi^0$ channel the measured masses of the $D_s^\pm$ and π^0 are substracted from and their nominal values $m_{D_s^\pm} = 1968.34\,\mathrm{MeV}/c^2$ and $m_{\pi^0} = 134.977\,\mathrm{MeV}/c^2$ [19] are added to the invariant mass $m(D_s^\pm \pi^0)$. This procedure improves the resolution of the peak, so that this is more significant and narrower. The signal is modelled by a CB function, whereas the backgound is described by an exponential. The results are shown in the figures 4a and 4b. The fit yields in 4914 ± 129 signal events for 2016 and 6192 ± 295 for 2017. Combining the years this results in more than 11000 events which is the largest yields ever observed in this channel.



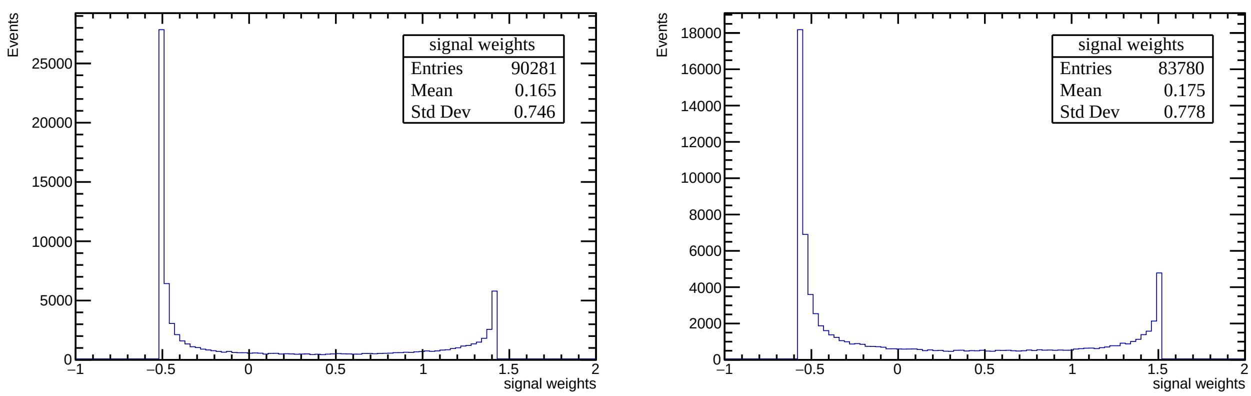
(a) 2016 **(b)** 2017

Figure 4: Fitted yields for (a) 2016 and (b) 2017 in the $D_s^*(2317)^\pm \to D_s^\pm \pi^0$ channel.

7 Reconstruction of the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$



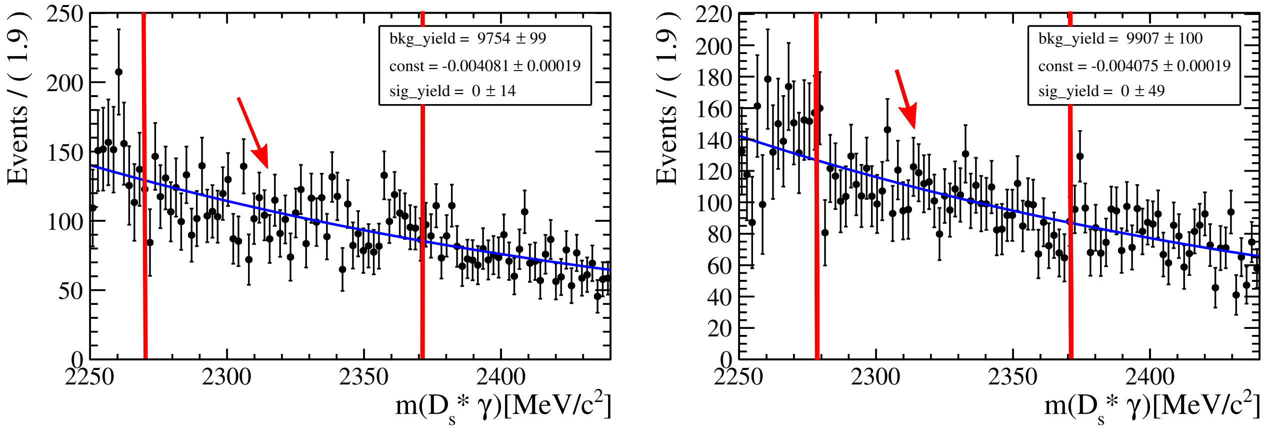
(a) 2016 **(b)** 2017



(c) 2016 **(d)** 2017

Figure 5: Fitted yields for $D_s^{*\pm} \to D_s^\pm \gamma_1$ with the total (a) 2016 and (b) 2017 data sets and signal weights for the (c) 2016 and (d) 2017 data sets. Here for γ_1 only photons with the second highest p_T in the cone are considered.

For the reconstruction of decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ the analysis is performed as follows: First the $D_s^{*\pm}$ are reconstructed from the $D_s^\pm$ and the γ with second highest p_T in the cone. The same method as for the $D_s^*(2317)^\pm \to D_s^\pm \pi^0$ peak is done to increase the peak resolution, but here only the $D_s^\pm$ mass is substracted from $m(D_s^\pm \gamma)$. For the $D_s^{*\pm}$ a SPlot is performed to extract signal weights. With those weights the $D_s^*(2317)^\pm$ mass is built. The $D_s^{*\pm}$ peak is modelled by a CB function again, whereas for the background an exponential is used. The resulting fits and yields for the years 2016 and 2017 are shown in the figures 5a and 5b. The extracted signal weights from the SPlot are shown in the figures 5c and 5d. With those signal weights the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ is now reconstructed. For this only the photon with highest p_T in the cone is used. The results are shown in the figures 6a and 6b. The red vertical lines mark the signal window that is observed in $D_s^\pm\pi^0$ channel and the arrow the expected peak position.



(a) 2016 **(b)** 2017

Figure 6: Fitted yields for (a) 2016 and (b) 2017 in the $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ channel with applied signal weighting.

From the fits it is visible that no hint for the existence of the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ can be found. Taking the 11000 events, the selection efficiencies and the current best limit at least 1000 events are expected in this decay channel.

8 Conclusion and outlook

This summer student project covered a search for the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$ at the LHCb experiment with the full 2016 and 2017 data sets corresponding to an integrated luminosity of 3.3 fb^{-1} at $\sqrt{s} = 13\,\mathrm{TeV}$. A common $D_s^\pm \to K^+K^-\pi^\pm$ selection was performed and tuned by constraints to the kinematics, PID and possible contaminations of the signal by $\Lambda_c^+ \to pK^-\pi^+$. Moreover a selection for the $D_s^*(2317)^\pm$ decaying to $D_s^\pm\pi^0$ and $D_s^{*\pm}\gamma$ respectively was developed. This includes that the neutrals can be covered by a narrow cone around the $D_s^\pm$ flight direction and avoiding contributions from random photons by this. The existence of the decay $D_s^*(2317)^\pm \to D_s^\pm\pi^0$ was confirmed and the largest yield ever in this channel consisting of more than 11000 events was observed. However, there was no hint for the existence of the decay $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma$. The search will be continued by using data from another stripping line for meson spectroscopy. Background contaminations from $D_s^*(2460)^\pm \to D_s^{*\pm}\pi^0$ have to be studied as well as selection efficiencies have to be evaluated and determined on the LHCb Monte Carlo. With that an upper limit on the ratio R can be set.

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