Search for the decay $D_s^*(2317)^{\pm} \rightarrow D_s^{*\pm} \gamma$

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LHCb Collaboration, CERN & Fakultät Physik, TU Dortmund
Who am I?

- Master student at TU Dortmund, Germany
- Bachelor thesis in LHCb Group of Dortmund → likelihood-based test statistics for upper limit setting
- Besides physics: collecting jazz records, playing trumpet, pool and snooker
Motivation for strange-charmed meson spectroscopy

- most heavy-light meson states successfully predicted by quark potential models in HQET limit
- expectation of $jP_J$-wave states doubly degenerated in spin of the heavy quark
- HQET calculations expect width of the $1/2^+ P_J$-states to be broad and above the $DK/D^*K$ threshold
- conventional excited states are expected to decay with large BR via radiative transitions
- $D_{s}^*(2317)^{\pm}$ and $D_{s}^*(2460)^{\pm}$ were a surprising discovery

Current Status of $D_s^*(2317)^+$ measurements

- $D_s^*(2317)^+$ first seen by the BABAR Collaboration in the channel $D_s^+\pi^0$[3]
- confirmation by CLEO Collaboration, search for $D_s^*(2317)^+ \rightarrow D_s^{*-}\gamma$

$$R = \frac{BR(D_s^*(2317)^+ \rightarrow D_s^{*-}\gamma)}{BR(D_s^*(2317)^+ \rightarrow D_s^{*-}\pi^0)} < 0.059^4$$

- confirmed by BELLE Collaboration, compatible with mass measured by BABAR and CLEO

$$R = \frac{BR(D_s^*(2317)^+ \rightarrow D_s^{*-}\gamma)}{BR(D_s^*(2317)^+ \rightarrow D_s^{*-}\pi^0)} < 0.18^5$$

- theory predictions on $R$ give 0.06-0.16

Open questions

- Why can’t we measure the radiative transition?
- How are the low masses explainable?

Proposed solutions

- hadronic DK molecule supported by absence of large total width and radiative transitions
- multiquark compound

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Strategy for search

- goal is to measure radiative decay
- search via measurement of

\[ R = \frac{\text{BR}(D_s^*(2317)^{\pm} \to D_s^{\pm}\gamma, D_s^{\pm} \to D_s^{\pm}\gamma)}{\text{BR}(D_s^*(2317)^{\pm} \to D_s^{\pm}\pi^0, \pi^0 \to \gamma\gamma)} \]

- performing a common \( D_s^{\pm} \to K^+K^-\pi^\pm \) selection
- select neutrals by profiting from small phase space and studying narrow cone around \( D_s^{\pm} \) flight direction to reduce background
- using resolved \( \pi^0 \) to build \( D_s^*(2317)^{\pm} \to D_s^{\pm}\pi^0 \)
- build \( D_s^{\pm} \), fit the peak and performing SPlot to extract sweights
- build \( D_s^*(2317)^{\pm} \to D_s^{*\pm}\gamma \) with weights
- taking advantage from the similarity of the selections to cancel uncertainties
Reconstruction of the $D_{s}^{\pm}$ mesons

- using data collected in 2016 and 2017 in StrippingD2hhhFTCalib_KKPLine
- Reconstruction in the channel
  \[ D_{s}^{\pm} \rightarrow \phi(1020)\pi^{\pm}, \phi(1020) \rightarrow K^{+}K^{-} \]
- from stripping S28r1 to S29r2 change based on Dalitz structure\[6\]:
  \[ m(K^{+}K^{-}) \in [1012.461, 1026.461] \text{MeV} \]
  \[ \rightarrow \text{within} \pm 7 \text{MeV of the } \phi(1020)-\text{mass} \]
- excluding background from
  \[ \Lambda_{c}^{\pm} \rightarrow (p \rightarrow K^{+})K^{-}\pi^{\pm} \text{ by assigning } m_{p} \text{ to } K^{+} \text{ and recalculating energy} \]

\[6\]LHCb StrippingD2hhhFTCalib_KKPLine stripping lines: stripping28r1 stripping29r2

Figure: Dalitz plot of $D_{s}^{+} \rightarrow K^{+}K^{-}\pi^{+}$ on RapidSim\[7\][8] simulation with 5 million events.
Simulations with RapidSim

RapidSim\textsuperscript{[7][8]}

- Framework to generate Monte Carlo for heavy-quark hadrons rapidly
- predefined LHCb geometry for acceptance but no interaction with detector

Tasks

- studying kinematics for $D_s^*(2317)\pm \rightarrow D_s^\pm \pi^0$ and $D_s^*(2317)\pm \rightarrow (D_s^*\pm \rightarrow D_s^\pm \gamma_0)\gamma_1$
- verify that cone size $\Delta R = 0.4$ around the $D_s^\pm$ flight direction covers both photons
- calculating selection efficiencies

- using RapidSim simulation because real Monte Carlo not available
- cone size described by angular separation $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \varphi)^2}$
- looking for a $p_T$ cutoff value and asymmetry between the two photons $A_{pT}(\gamma_0, \gamma_1) = \frac{p_T(\gamma_0) - p_T(\gamma_1)}{p_T(\gamma_0) + p_T(\gamma_1)}$

\textsuperscript{[8]} https://github.com/gcowan/RapidSim
Results for $D_s^*(2317)^\pm \rightarrow D_s^{\pm\pi^0}, \pi^0 \rightarrow \gamma\gamma$

- transverse momenta identical, because photons indistinguishable
- $\pi^0$ are mainly resolved → cut on $p_T \in [0.2, 1.5]$GeV to exclude merged $\pi^0$
- cone size of $\Delta R = 0.4$ contains most of the signal
Results for $D_s^*(2317)^\pm \rightarrow D_s^{*\pm}\gamma_0, D_s^{*\pm} \rightarrow D_s^{\pm}\gamma_1$

- cuts on $p_T$ between 0.2 GeV and 1.5 GeV reasonable to exclude background from merged $\pi^0$
- transverse momentum distributions slightly different, asymmetry tends to $p_T(\gamma_0) > p_T(\gamma_1)$
Results for $D_s^*(2317)^\pm \to D_s^{*\pm}\gamma_0$, $D_s^{*\pm} \to D_s^{\pm}\gamma_1$

- mass veto in $\pi^0$ mass range possible without losing much signal
- $m_{\gamma\gamma}$ limited by available phase space $\to$ cut on $m_{\gamma\gamma}$ can reduce background from random photons
- cut on cone size at $\Delta R = 0.4$ covers most of the photons
Conclusion of results from simulation

For both channels

- narrow cone size of $\Delta R = 0.4$ covers most of the photons, so that the small phase space can be used to reduce background
- cut on $p_T$ between 0.2 GeV and 1.5 GeV can be applied to exclude high energetic and very low energetic photons
- selection efficiencies $\varepsilon_{\text{sel}}^{\pi^0} = 45.56\%$ and $\varepsilon_{\text{sel}}^{2\gamma} = 27.49\%$

$D_s^*(2317)^\pm \rightarrow D_s^\pm \pi^0$

- resolved pions expected, no asymmetry in transverse momentum

$D_s^*(2317)^\pm \rightarrow D_s^{*\pm} \gamma$

- small asymmetry between the $p_T$ of the two photons $\rightarrow p_T(\gamma_0) > p_T(\gamma_1)$, identify $\gamma_0$ as photon with maxPT inside the cone, and $\gamma_1$ as the one with secPT
Overview of the applied cuts

<table>
<thead>
<tr>
<th>$D_s^{\pm} \rightarrow K^+ K^- \pi^{\pm}$</th>
<th>$D_s^{\ast}(2317)^{\pm} \rightarrow D_s^{\pm} \pi^0$</th>
<th>$D_s^{\ast}(2317)^{\pm} \rightarrow D_s^{\ast\pm} \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>kinematics</td>
<td>photon likelihood</td>
<td>photon likelihood</td>
</tr>
<tr>
<td>$p_T(K^+, K^-, \pi^{\pm}) &gt; 1.5 \text{ GeV}$</td>
<td>$CL(\gamma) &gt; 0.6$</td>
<td>$CL(\gamma) &gt; 0.6$</td>
</tr>
<tr>
<td>$p_T(D_s^{\pm}) &gt; 5 \text{ GeV}$</td>
<td>exclude merged pions</td>
<td>exclude merged pions</td>
</tr>
<tr>
<td>$\phi$ mass range</td>
<td>$p_T(\gamma_{1/2}) &lt; 1.5 \text{ GeV}$</td>
<td>$p_T(\gamma_{1/2}) \in [0.2, 1.5] \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>m(K^+ K^-) - m_\phi</td>
<td>\leq 7 \text{ MeV}$</td>
</tr>
<tr>
<td>Particle identification</td>
<td>cone around $D_s$</td>
<td>$</td>
</tr>
<tr>
<td>$\text{ProbNNk}(K^+, K^-) &gt; 0.8$</td>
<td>$\Delta R(D_s, \gamma) &lt; 0.4$</td>
<td>$m(\gamma \gamma) &lt; 0.5 \text{ GeV}$</td>
</tr>
<tr>
<td>exclude $\Lambda_c^{\pm}$</td>
<td></td>
<td>cone around $D_s$</td>
</tr>
<tr>
<td>$</td>
<td>m((K^+ \rightarrow p)K^-\pi^{\pm}) - m(\Lambda_c^{\pm})</td>
<td>&gt; 33 \text{ MeV}$</td>
</tr>
</tbody>
</table>

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$D_s^*(2317)^\pm$ yield in $D_s^\pm \pi^0$ channel

- $m(D_s^\pm \pi^0) - m(D_s^\pm) + 1968.27$ MeV $- m(\pi^0) + 134.9766$ MeV to get a better peak resolution
- signal peak modelled with Crystall Ball and background with Exponential
- combining data from 2016 and 2017 yields in approximately 11000 events → largest yield ever observed in this channel

(2016)

(2017)
SPlot for the $D_s^{*\pm}$

- $m(D_s^\pm \gamma) - m(D_s^\pm) + 1968.27$ MeV to get a better peak resolution
- performing an SPlot\textsuperscript{[9]} of the reconstructed $D_s^{*\pm}$ to weigh each event’s likelihood of being signal

\[2016\]
\[2017\]

\[\text{bkg\_yield} = 55908 \pm 342\]
\[\text{mean} = 2111.04 \pm 0.97\]
\[\text{sig\_yield} = 10618 \pm 288\]
\[\text{sigma} = 12.9 \pm 2.3\]

\[\text{bkg\_yield} = 64018 \pm 15\]
\[\text{mean} = 2112.617 \pm 0.015\]
\[\text{sig\_yield} = 10889.5 \pm 9.9\]
\[\text{sigma} = 12.931 \pm 0.014\]

Yield for $D_s^*(2317)^\pm \rightarrow D_s^{*\pm}\gamma$

- reconstruction with sweighted $D_s^{*\pm}$
- $m(D_s^{*\pm}\gamma) - m(D_s^{*\pm}) + 2112.1 \text{ MeV}$ to get a better peak resolution

considering theory predictions for the decay rate (6-16 %) at least 1000 events are expected
Conclusion and outlook

- evolved common $D_s^{\pm} \rightarrow K^\pm K^- \pi^\pm$ selection and developed a selection for the $D_s^*(2317)^\pm$ decay channels

- existence of $D_s^*(2317)^\pm \rightarrow D_s^{\pm}\pi^0$ confirmed with largest ever observed yield in this channel

- no hint for the decay $D_s^*(2317)^\pm \rightarrow D_s^{*\pm}\gamma$

- setting expected upper limit on $BR(D_s^*(2317)^\pm \rightarrow D_s^{*\pm}\gamma)/BR(D_s^*(2317)^\pm \rightarrow D_s^{\pm}\pi^0)$ with the CL$_s$ method

- requesting real Monte Carlo to evaluate and determine efficiencies and systematic uncertainties