Charm mixing with $D^0 \rightarrow K \pi \pi^0$

Summer Student 2016 - LHCb

Serena Maccolini
Supervisor: Angelo Di Canto
August 30, 2016
About me

- I’m from Italy!
- Bachelor in Physics at University of Bologna.
- Now I’m an undergraduate student in Nuclear and Subnuclear Physics.
Mixing of neutral mesons

- Flavour and mass eigenstates are different.

\[ |P_{1,2}\rangle = p |P^0(t)\rangle \pm q |\bar{P}^0(t)\rangle \]

- This causes \( P^0 \leftrightarrow \bar{P}^0 \) transitions described by

\[
\begin{align*}
    x &= \frac{m_1 - m_2}{\Gamma} \\
    y &= \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\end{align*}
\]

\[
|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]
\]

\[
|\langle P^0(0)|\bar{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]
\]
How can you measure mixing?

- Look at rate of wrong-sign (WS) \( D^* \rightarrow D^0 (\rightarrow K\pi\pi^0)\pi_S \) decays with respect to right-sign (RS) decays.

- Time-dependent analysis to disentangle mixing from DCS rate.

\[
R(t) = \frac{WS(t)}{RS(t)} \approx R_D + \alpha \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \frac{x^2 + y^2}{4} \left( \frac{t}{\tau} \right)^2
\]

\[y' = y \cos(\delta) - x \sin(\delta)\]

- Most of the sensitivity to mixing comes from the interference term.
Dataset and event selection

Dataset

- Started to look at 2012 data

Resolved $\pi^0$

\(\gamma\gamma\) in different clusters of the ECAL.

Merged $\pi^0$

\(\gamma\gamma\) in the same cluster of the ECAL.
Selected candidates

In addition to provide the flavour at production, the $D^*$ decay also helps to reject lots of background (very small Q-value).

Resolved $\pi^0$

Merged $\pi^0$

The background is given by correct $D^0$ but wrong $\pi_S$
BDT training

- Implement a BDT selection to suppress the large random-$\pi$ background of the WS sample.
- Train on RS data (more abundant and cleaner)
- Identify input variables that have good separation between signal and background but also low correlation with $M_{D^0\pi_S}$ and with Dalitz plot.

Resolved $\pi^0$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>$&lt; S^2 &gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(D^0)$</td>
<td>8.3%</td>
</tr>
<tr>
<td>$\cos\theta_{XY}(p_K \pi vsp_{\pi^0})$</td>
<td>6.5%</td>
</tr>
<tr>
<td>$CL(\pi^0)$</td>
<td>4.8%</td>
</tr>
<tr>
<td>$P(\pi_S \rightarrow \pi)$</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\log(DTF1_V\chi^2)$</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Merged $\pi^0$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>$&lt; S^2 &gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\pi_S)$</td>
<td>7.4%</td>
</tr>
<tr>
<td>$P(\pi_S \rightarrow \pi)$</td>
<td>6.7%</td>
</tr>
<tr>
<td>$p(\pi_S)$</td>
<td>1.6%</td>
</tr>
<tr>
<td>$\log(DTF1_V\chi^2)$</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
BDT distribution and ROC curve

Resolved $\pi^0$:  

Merged $\pi^0$:  

BDT separation: 0.184  

BDT separation: 0.151  

Serena Maccolini  
$D^0 - D^0$ mixing  
August 30, 2016
BDT optimization

Choose the BDT cut that minimises the uncertainty of the time integrated WS/RS ratio.

20% improvement in precision for candidates with resolved $\pi^0$, while only a marginal gain for the merged sample.
Overlap between WS and RS candidates

Additional background reduction when removing WS candidates whose $D^0$ is also used to reconstruct a good RS candidate.
Final samples

Resolved

In WS fitting, the signal shape is fixed with RS values.

Merged
Time-dependent WS/RS ratio

$$R(t) \approx R_D + \alpha \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \frac{x^2 + y^2}{4} \left( \frac{t}{\tau} \right)^2$$

No mixing:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>$(XX \pm 0.0058)%$</td>
</tr>
</tbody>
</table>

$\chi_0^2 / NDF = 30.3 / 19$

Mixing:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>$(XX \pm 0.034)%$</td>
</tr>
<tr>
<td>$\alpha y'$</td>
<td>$(XX \pm 0.62)%$</td>
</tr>
<tr>
<td>$1/4(x^2 + y^2)$</td>
<td>$(XX \pm 0.0055)%$</td>
</tr>
</tbody>
</table>

$\chi_2^2 / NDF = 16.1 / 17$

$\Delta \chi^2 / \Delta NDF \to 3.3 \sigma$
Conclusion and future projects

First attempt to measure $D^0 - \bar{D}^0$ mixing using $D^0 \rightarrow K\pi\pi^0$ decays at LHCb:

- Results seem to be competitive with other measurements of these decays, but will have a marginal impact on the world average.
- Could increase sensitivity with more statistics and/or a time-dependent Dalitz-plot analysis.
- **Left to be done:** look at Run 2 data and particularly at the 2016 sample (higher cross-section and dedicate triggers)

<table>
<thead>
<tr>
<th>Year</th>
<th>$N_{RS}/L$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>2'700'000</td>
</tr>
<tr>
<td>2015</td>
<td>6'400'000</td>
</tr>
<tr>
<td>2016</td>
<td>?</td>
</tr>
</tbody>
</table>
Thank you!
$D^0$ mixing formalism

- Eigenstate can have different masses and decay width

$$\langle D_{1,2} \rangle = p \langle D^0(t) \rangle \pm q \langle \bar{D}^0(t) \rangle$$

$$x = \frac{m_1 - m_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad \text{with} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- The time evolution is described by

$$\langle D^0(t) \rangle = g_+ \langle D^0(0) \rangle + \frac{q}{p} g_- \langle \bar{D}^0(0) \rangle$$

$$\langle \bar{D}^0(t) \rangle = g_+ \langle \bar{D}^0(0) \rangle + \frac{q}{p} g_- \langle D^0(0) \rangle$$

with

$$g_+(t) = e^{-\imath Mt - \Gamma t/2} \cos \left( \frac{x}{2} \Gamma t - \frac{\imath y}{2} \Gamma t \right)$$

and

$$g_-(t) = e^{-\imath Mt - \Gamma t/2} \imath \sin \left( \frac{x}{2} \Gamma t - \frac{\imath y}{2} \Gamma t \right)$$
Dataset and event selection

Dataset

- 2012 sample candidates reconstructed using DstarToHHPi0_Kpipi0_R_Line and DstarToHHPi0_Kpipi0_M_Line from Stripping21, Stripping24 and Stripping26.

Decay Tree Fitter

- constraining the $D^0\pi_S$ vertex to the primary vertex
- constraining the $\pi^0$ mass to the PDG value.

Additional cuts

- $KPID_K > 8$;
- $\pi PID_K < -5$;
- $D^0 IP \chi^2 < 9$.
- $1825 < M_{D^0} < 1910$ MeV (resolved $\pi^0$)
- $1800 < M_{D^0} < 1950$ MeV (merged $\pi^0$)
BDT training variables distributions

Resolved

Input variable: $D^0_P$

Input variable: $K_{\pi\pi\pi0\cos\theta_{XY}}$

Input variable: $CL_{\pi0}$

Input variable: $\pi_S\text{ProbNN}_\pi$

Input variable: $\log_{DTF1_V\chi2}$
BDT training variables distributions (Merged)

Input variable: $\pi_S P_T$

Input variable: $\pi_S \text{ProbNN}_\pi$

Input variable: $\pi_S P$

Input variable: $\log_{\text{DTF1}} V_{\chi2}$

$\text{U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%}$
BDT training variables correlation matrices (Resolved)

Correlation Matrix (background)

Correlation Matrix (signal)

Serena Maccolini  

$D^0 - D^0$ mixing  

August 30, 2016  19 / 24
BDT training variables correlation matrices (Merged)

Correlation Matrix (background)

Correlation Matrix (signal)
Low correlation of BDT check with $M_{D^0\pi_S}$ and Dalitz plot

Resolved $\pi^0$:  

Merged $\pi^0$:  

Serena Maccolini  
$D^0 - D^0$ mixing  
August 30, 2016  
21 / 24
The fit

- The **signal** is parametrize with a linear combination of a Johnson SU distribution and **three Gaussian** distributions.

  **Johnson SU**: transformation of the normal distribution
  
  \[ z = \gamma + \delta \sinh^{-1} \left( \frac{x - \xi}{\lambda} \right) \text{ where } z \sim \mathcal{N}(0, 1). \]

- The **background**, given by a random soft pion $\pi_S$, is parametrized using the function:

  \[(m - m_0)^\alpha e^{\beta (m - m_0)} \text{ with } m = M_{D^0 \pi_S} \text{ and } m_0 = m_{D^0} + m_\pi.\]
→ I found the minimum uncertainty for $BDT_{cut} = 0.09$
I chose $BDT_{\text{cut}} = -0.1$

The uncertainty has not improved but the significance has.