Optimising the search for $CP$ violation in $D_s^+ \rightarrow K^+ \pi^+ \pi^-$ decays at LHCb

Using forward-backward asymmetry as a probe for CPV

Summer Project 2021
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Dalitz plot & Isobar model

1) $D_S^+ \rightarrow K^+ \pi^+ \pi^-$  
2) $D_S^+ \rightarrow K^+ \alpha \rightarrow K^+ \pi^+ \pi^-$  
3) $D_S^+ \rightarrow \pi^+ \beta \rightarrow K^+ \pi^+ \pi^-$

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Removing background: BDTG

- $D_S^+$ Impact parameter of primary vertex
- Secondary vertex $\chi^2$
- $D_S^+$ Pseudorapidity
- $D_S^+$ transverse and total momentum
- $D_S^+$ decay length and lifetime
- $D_S^+$ flight distance to primary vertex
- Daughter track isolation variables

Cut a signal efficiency of 75%
→ Background rejection 82%
Resonances:

- $K^*(892)$
- $\rho(770)$
- $\pi N$
- $K^*(1410)$
- $K^*_0(1430)$
- $\rho(1450)$

Incomplete model, missing structure both in $K^+\pi^-$ and $\pi^+\pi^-$ projection

Based on 567 ± 31 events

Improved Model

Resonances:

- $K^*(892)$
- $\rho(770)$
- $NR$
- $K^*(1410)$
- $K_0^*(1430)$
- $\rho(1450)$
- $f_0(980)$
- $f_0(1370)$
- $K_2^*(1430)$
- $\omega(782)$
- $f_2(1270)$

Based on $3.5 \cdot 10^6$ events

Improvement, yet still incomplete. Still useful for sensitivity study!
Regional charge asymmetry

\[ A_{CP} = \frac{\#D_s^+ - \#D_s^-}{\#D_s^+ + \#D_s^-} \]

Forward-Backward charge asymmetry in helicity angle

\[ \pi^- (3) \quad \theta_{23} \quad \pi^+ (2) \]

\[ K^+ (1) \]


→ Twice as much statistics
Simulating CP violation

\[ A_\rho = |A| e^{i\phi} \]

\[ \Delta |A| \in \{-0.2 \%, -0.1 \%, 0 \%, 0.1 \%, 0.2 \%\} \]

\[ \Delta \phi \in \{-0.2^\circ, -0.1^\circ, 0^\circ, 0.1^\circ, 0.2^\circ\} \]
Sensitivity results (1 toy example)

\[ 1.5 \cdot 10^7 D^+_S & 1.5 \cdot 10^7 D^-_S \]

Significance of ACP

- LHCb preliminary
- Amplitude \( \rho(770) = 0.0 \% \)
- Weak phase \( \rho(770) = -0.1^\circ \)
Sensitivity results (1 toy example)

<table>
<thead>
<tr>
<th>$\Delta A$</th>
<th>$\Delta \phi$</th>
<th>Global $A_{CP-FB}$</th>
<th>$\sigma$</th>
<th>Angle</th>
<th>Best Bin</th>
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| 0.0 %     | -0.1°         | (-0.013 ± 0.018)\% | 0.7     | $\theta_{13}$ | 11       | (0.158 ± 0.074)\% | 2.1     | 10       | (-0.388 ± 0.136)\% | 2.9 | $\theta_{12}$
|           | +0.1°         | (-0.018 ± 0.018)\% | 1.0     | $\theta_{12}$ | 12       | (0.614 ± 0.268)\% | 2.3     | 12       | (-0.630 ± 0.268)\% | 2.4 | $\theta_{13}$
| -0.1%     | -0.1°         | (0.030 ± 0.018)\%  | 1.7     | $\theta_{13}$ | 21       | (0.242 ± 0.109)\% | 2.2     | 21       | (-0.253 ± 0.109)\% | 2.3 | $\theta_{13}$
|           | 0.0 °         | (-0.038 ± 0.018)\% | 2.1     | $\theta_{12}$ | 26       | (-0.353 ± 0.119)\% | 3.0     | 26       | (-0.353 ± 0.119)\% | 3.0 | All three
|           | +0.1°         | (-0.043 ± 0.018)\% | 2.4     | $\theta_{23}$ | 11       | (-0.152 ± 0.074)\% | 2.0     | 11       | (-0.152 ± 0.074)\% | 2.0 | $\theta_{12}$ and $\theta_{23}$
| +0.1%     | -0.1°         | (0.028 ± 0.018)\%  | 1.6     | $\theta_{23}$ | 9        | (-0.288 ± 0.103)\% | 2.8     | 21       | (-0.308 ± 0.109)\% | 2.8 | $\theta_{13}$
|           | 0.0 °         | (-0.026 ± 0.018)\% | 1.4     | $\theta_{13}$ | 9        | (-0.215 ± 0.103)\% | 2.1     | 21       | (-0.237 ± 0.109)\% | 2.2 | $\theta_{13}$
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Forward-backward charge asymmetry not twice as sensitive, but in some regions more sensitive than “regular” charge asymmetry
Outlook

With an increased number of MC events
   → Improve BDTG
   → Improve detector efficiency map

In general
   → Introduce CPV in multiple resonances
   → Use K-matrix formalism
   → Performing the CPV analysis on data
Back Up
MC Efficiency for BDTG cut at 0.4
Detector efficiency estimation

\[ m(c\pi^+)^2 \quad [\text{GeV}^2/c^4] \]
\[ m(K^+\pi^-)^2 \quad [\text{GeV}^2/c^4] \]
Example of residual background subtraction

![Graph showing the distribution of events and masses](image)

- $m(K\pi)$: 0.40 - 0.44
- $m(\pi\pi)$: 1.01 - 1.03
Dalitz plot of model by FOCUS Collaboration

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Dalitz plot of Improved model

LHCb preliminary
2018 dataset

LHCb preliminary
Improved model

LHCb preliminary
2018 dataset

LHCb preliminary
Improved model
Uniform binning of DP
Phase over DP: Physical Binning

[Image: A complex 3D graph showing a distribution of data points with various color gradients and labeled phases.]
Phase over DP: Uniform binning
Uniform Binning results

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