Observing matter antimatter asymmetries
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Introduction

- Searches for CP violation can be carried out using Dalitz plot analysis techniques.
- Aim is to determine the parameters that affect the sensitivity of methods and then optimise them.
- Two different methods are compared, a binned χ² test known as S_CP and a novel unbinned method known as the energy test.
- Analysis performed using a toy model X → ABC with several intermediate resonances.
- These methods can be applied in experiments performed at detectors such as LHCb and Belle II.

Toy model

- Model used in previous comparison of these two methods [1].
- Particle X with mass 1 GeV, particles A, B, C with mass 0.1 GeV.
- Several intermediate resonances, given in the table below.
- Samples generated using Laura++ [2].

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (GeV)</th>
<th>Width</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>0.3</td>
<td>0.025</td>
<td>62%</td>
</tr>
<tr>
<td>AB</td>
<td>0.6</td>
<td>0.05</td>
<td>2%</td>
</tr>
<tr>
<td>AC</td>
<td>0.4</td>
<td>0.04</td>
<td>18%</td>
</tr>
<tr>
<td>AC</td>
<td>0.7</td>
<td>0.1</td>
<td>43%</td>
</tr>
<tr>
<td>BC</td>
<td>0.35</td>
<td>0.01</td>
<td>10%</td>
</tr>
<tr>
<td>BC</td>
<td>0.75</td>
<td>0.02</td>
<td>17%</td>
</tr>
</tbody>
</table>

Dalitz Plots

- Contains kinematic information of decays.
- Generate a plot for the X particle decay and another for the X decay.
- Plots can then be compared. CP violation shown up as a difference between the two plots.
- Use a goodness of fit (g.o.f) analysis method to compare.

![An example Dalitz plot for the X → ABC decay.](Image)

S_CP

- Each Dalitz plot is divided into bins, and the significance of the difference in number of events between X and X̄ in each bin calculated [3]:

\[
S_{CP} = \frac{N_i(X) - \alpha N_i(X \bar{X})}{\sqrt{N_i(X) + \alpha N_i(X \bar{X})}}, \quad \alpha = \frac{\sum_i N_i(X)}{\sum_i N_i(X \bar{X})},
\]

(1)

- The χ² value is then the sum of \(S_{CP}^2\), from which a p value for the no CP violation hypothesis can be calculated.
- The choice of binning is the important parameter in determining sensitivity.
- Plotting p value against number of bins per axis tells us the optimum number of bins to use.

![p value against number of bins for a few different scenarios. Here we see 3 bins per axis is much more sensitive than any other choice consistently for all scenarios. This is fewer than normally used.*](Image)

Energy test

- Calculate T value of the combined X and X̄ samples to compare the Dalitz plots [1]:

\[
T = \frac{1}{n(n-1)} \sum_{i,j \neq i} n \psi(\Delta \bar{E}_{ij}) + \frac{1}{n(n-1)} \sum_{i,j \neq i} \hat{n} \psi(\Delta \bar{E}_{ij}) - \frac{1}{n^2} \sum_{i,j} \psi(\Delta \bar{E}_{ij})
\]

(2)

where \(\psi(\Delta \bar{E}_{ij}) = e^{-\Delta \bar{E}_{ij}/\sigma^2}\).

- No CP violation would give a T value of 0, and any CP violation would increase T.
- Randomly re-tagging events as X or X̄ provides permutation T values to compare the original value to in order to test the significance of the deviation from the no CP violation hypothesis.
- Use a generalised extreme value (GEV) function [4] to calculate p value for the no CP violation hypothesis from permutation T values.
- This method has only recently been applied to real data from LHCb [5].
- The value of \(\sigma\) in the weighting function is a free choice, and determines the sensitivity of the method.
- Plotting p value against \(\sigma\) for different scenarios tells us how the optimum value of \(\sigma\) changes depending on the sample.

![p value against \(\sigma\) for a few different scenarios. Here we see a strong dependence of sensitivity on \(\sigma\), with an optimum value around 0.15 GeV. This value doesn’t change noticeably in the different scenarios.](Image)

Sensitivity studies

Both methods appear comparable in sensitivity in most cases, with S_CP with a small number of bins performing better in some.

References