Dalitz plot analysis of $D_s \rightarrow \pi^+ \pi^+ \pi^-$

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for the BaBar Collaboration

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Outline

- Motivations
- General analysis overview
- Selection criteria
- Likelihood function description
- Dalitz plot analysis: partial waves
- Fit results
- Systematics
- Conclusions

Motivations

- Charm decays are expected to proceed mainly through quasi two-body states
- Dalitz plot analysis is the best way to shed light on these intermediate states
  - Mainly light mesons, so can do spectroscopy
- Some questions worth investigating:
  - If we believe in the $\kappa(800)$ and $f_0(600)$, what happens to the $J^{PC}=0^{++}$ nonet?
  - Are the $a_0(980)$ and $f_0(980)$ tetraquarks (close to the $KK$ threshold)?
- Measuring BRs and couplings helps to get an answer
- Charm Dalitz plot provides a clean environment to study the $\pi\pi$ S-wave
Analysis of $D_s \rightarrow \pi^+ \pi^+ \pi^-$

• Can study the $s\bar{s}$ coupling to the light scalars
• Describe the $\pi\pi$ S-wave with a MIPWA*
  → Previous analyses didn't have enough statistics to use this method
• Using 384 fb$^{-1}$ of BaBar data
  → Using both Y(4S) and [Y(4S) – 50 MeV] data
• Can use $D_s \rightarrow K^+K^-\pi^+$ as a control sample, once the different efficiencies are kept into account

*See Aitala et al. [E791 Collaboration], Phys. Rev. D 73, 032004 (2006)
Selection criteria

Reconstruct

\[ D_{s}^{*+} \rightarrow D_{s}^{+} \gamma \]
\[ \rightarrow \pi^{+}\pi^{+}\pi^{-} \]
\[ \rightarrow K^{+}K^{-}\pi^{+} \]

- Reconstruct \( D_{s}^{*+} \) to improve purity
- Fit vertex with \( p_{1}(\chi^{2}) > 0.1\% \)
- Refit to beamspot and determine probability \( p_{1} \)

Use CM momentum of \( D_{s}^{*} p^{*} \), \( p_{1}-p_{2} \) and \( d_{xy} \) to construct likelihood ratio to discriminate signal and background

- Background distributions from \( D_{s} \) mass sidebands
- Signal distributions from \( D_{s} \rightarrow K^{+}K^{-}\pi^{+} \) sample
Selection criteria (II)

After the selection cuts, the invariant mass distribution looks like

- Fit with gaussian and 1\textsuperscript{st} order polynomial
- Find $m_{D_s} = 1968.1 \pm 0.09$ MeV/c\textsuperscript{2}, $\sigma_{m_{D_s}} = 7.77 \pm 0.09$ MeV/c\textsuperscript{2}
- We also cut on $\Delta m = m_{D_s^*} - m_{D_s}$ in a 2$\sigma$ region
- About 13k events in 2$\sigma$ region with $\sim$ 80% purity
Likelihood function

Fit data with the likelihood:

\[ \mathcal{L} = \prod_{\text{events}} \left[ x(m) \cdot \eta(m_1^2, m_2^2) \frac{\sum_{i,j} c_i c_j^* A_i A_j^*}{\sum_{i,j} c_i c_j^* I_{A_i A_j^*}} + (1 - x(m)) \frac{\sum_i |k_i|^2 B_i B_i^*}{\sum_i |k_i|^2 I_{B_i B_i^*}} \right] \]

where

- \( m_1, m_2 \) invariant masses
- \( x(m) \) \( D_S \) mass dependent signal fraction
- \( \eta(m_1^2, m_2^2) \) efficiency (2\(^{nd}\) order polynomial)
- \( A_i, B_i \) signal and background amplitudes (background incoherent)
- \( k_i \) real values for background description (fitted from sidebands)
- \( I_{A_i A_j^*} \) normalization integrals
- \( c_i \) complex values varied during fit
Amplitudes parametrization

Each $A_i$ represented by a product of BW and a real angular term* $T$:

$$A = BW\left(m_{\pi\pi}\right) \times T\left(\Omega\right)$$

- BW function includes Blatt-Weisskopf form factors
- $\pi^+\pi^-$ S-wave cannot use BW as resonances are too wide
- For the S-wave we perform a Model Independent Partial Wave Analysis (MIPWA)
  - Divide the $\pi^+\pi^-$ spectrum in 29 bins (30 endpoints)
  - Interpolate between the 30 points:
    $$A_{S\text{-wave}}\left(m_{\pi\pi}\right) = \text{Interp}\left(c_k\left(m_{\pi\pi}\right)e^{i\phi_k\left(m_{\pi\pi}\right)}\right)_{k=1,...,30}$$
  - Amplitude and phase of each endpoint are free parameters
- Choose as a reference amplitude and phase the $f_2(1270)\pi^+$

Fit results

\( m^2(\pi^+\pi^-)_{\text{low/high}} \) is the softer/harder dipion combination

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Decay fraction(%)</th>
<th>Amplitude</th>
<th>Phase(rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_2(1270)\pi^+ )</td>
<td>10.1±1.5±1.1</td>
<td>1.(Fixed)</td>
<td>0.(Fixed)</td>
</tr>
<tr>
<td>( \rho(770)\pi^+ )</td>
<td>1.8±0.5±1.0</td>
<td>0.19±0.02±0.12</td>
<td>1.1±0.1±0.2</td>
</tr>
<tr>
<td>( \rho(1450)\pi^+ )</td>
<td>2.3±0.8±1.7</td>
<td>1.2±0.3±1.0</td>
<td>4.1±0.2±0.5</td>
</tr>
<tr>
<td>( S\text{-wave} )</td>
<td>83.0±0.9±1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>97.2±3.7±3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \chi^2/NDF = \frac{437}{422-64} = 1.2 \)

Fit fraction defined as:

\[
f_i = \frac{|c_i|^2 \int |A_i|^2 dm_1^2 dm_2^2}{\sum_{j,k} c_j c_k^* \int A_j A_k^* dm_1^2 dm_2^2}
\]

The decay is dominated by the S-wave contribution

Additional resonant contributions do not improve the fit quality significantly
Comparison with previous experiments

From:
Aitala et al. [E791 Coll.], PRL 86 (2001) 765

FOCUS results seem in good agreement with BaBar.
What about the S-wave?

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>E687 0.1k</th>
<th>E791 0.6k</th>
<th>FOCUS 1.5k</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2(1270)\pi^+$</td>
<td>10.1 ± 1.5 ± 1.0</td>
<td>14.7 ± 5.3</td>
<td>9.74 ± 4.49 ± 2.63</td>
</tr>
<tr>
<td>$\rho(770)\pi^+$</td>
<td>1.8 ± 0.5 ± 1.0</td>
<td>—</td>
<td>5.8 ± 2.3 ± 3.7</td>
</tr>
<tr>
<td>$\rho(1450)\pi^+$</td>
<td>2.3 ± 0.8 ± 1.7</td>
<td>—</td>
<td>4.4 ± 2.1 ± 0.2</td>
</tr>
<tr>
<td>$S$-wave</td>
<td>83.0 ± 0.9 ± 1.9</td>
<td>&quot;118.9 ± 14.5&quot;</td>
<td>87.04 ± 5.60 ± 4.17</td>
</tr>
<tr>
<td>TOT.</td>
<td>97.2 ± 3.7 ± 3.8</td>
<td>133.6 ± 19.8</td>
<td>103.34 ± 13.52 ± 10.17</td>
</tr>
</tbody>
</table>
The $\pi^+\pi^-$ S-wave

- $f_0(600)$ contribution absent, doesn't couple with $s\bar{s}$
- S-wave amplitude and phase show dominantly the $f_0(980)$
- Further structure present in the $f_0(1370)/f_0(1500)$ region
- Our result seems more in agreement with the K-matrix approach (the full amplitudes and phases are in the backup slides)
Spherical harmonic moments

- Use $Y_L^0$ to further test our amplitudes description
- Plot on the $\pi^+\pi^-$ axis as function of the helicity angle
- Weight each event on $\pi^+\pi^-$ axis using the $Y_L^0$
Branching fraction measurement

The channels $D_s \rightarrow \pi^+\pi^-\pi^+$ and $D_s \rightarrow K^+K^-\pi^+$ have similar topologies, so small systematic error in the ratio

We measure

$$BR = \frac{\sum_{x,y} N_1(x,y)}{\sum_{x,y} N_0(x,y)} \frac{\epsilon_1(x,y)}{\epsilon_0(x,y)}$$

where

- 0 is $D_s \rightarrow K^+K^-\pi^+$ and 1 is $D_s \rightarrow \pi^+\pi^-\pi^+$
- $\epsilon_i$ is the efficiency for the $i_{th}$ channel
- $N_i$ is the measured number of events

We find

$$\frac{\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^-\pi^+)}{\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+)} = 0.199 \pm 0.004 \pm 0.009$$

PDG reports

$0.265 \pm 0.041 \pm 0.031$

CLEO-c

$0.202 \pm 0.011 \pm 0.009$

Systematics

Studied systematics effects considering:

- Background estimation using only one mass sideband
- Vary Blatt-Weisskopf parameters
- Consider additional resonances with similar sum of fractions but worse likelihood
- Signal purity, resonances parameters and efficiency varied within the error
- $\rho$ parametrization using Gounaris-Sakurai model
- Change binning of the S-wave parametrization
Conclusions

- $D_s \rightarrow \pi^+ \pi^- \pi^+$ provides new hints on the light scalar mesons behavior
  - $f_0(600)$ doesn't seem to couple to $s\bar{s}$
  - $f_0(980)$ is the dominant contribution in the S-wave
    - And the S-wave dominates $D_s \rightarrow \pi^+ \pi^- \pi^+$...
  - $f_0(1370)/f_0(1500)$ is seen
  - $f_2(1270)$ has a somewhat large contribution
- A detailed analysis of $D_s \rightarrow K^+ K^- \pi^+$ S-wave will bring new knowledge to the $f_0(980)$ coupling to $\pi\pi/KK$
- Hopefully this can help in understanding the light mesons zoo
Backup slides
The $\pi^+\pi^-$ S-wave

<table>
<thead>
<tr>
<th>Interval</th>
<th>Mass (GeV/c^2)</th>
<th>Amplitude</th>
<th>Phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.28</td>
<td>2.7 ± 1.5</td>
<td>-3.4 ± 1.0 ± 1.3</td>
</tr>
<tr>
<td>2</td>
<td>0.448</td>
<td>2.2 ± 1.2</td>
<td>-3.9 ± 0.5 ± 0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>3.2 ± 0.8</td>
<td>-3.7 ± 0.3 ± 0.3</td>
</tr>
<tr>
<td>4</td>
<td>0.647</td>
<td>3.3 ± 0.7</td>
<td>-3.7 ± 0.2 ± 0.3</td>
</tr>
<tr>
<td>5</td>
<td>0.736</td>
<td>5.0 ± 0.7</td>
<td>-3.4 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>6</td>
<td>0.803</td>
<td>5.1 ± 0.7</td>
<td>-2.9 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>7</td>
<td>0.873</td>
<td>6.7 ± 0.7</td>
<td>-2.6 ± 0.1 ± 0.3</td>
</tr>
<tr>
<td>8</td>
<td>0.921</td>
<td>10.7 ± 1.0</td>
<td>-2.2 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>9</td>
<td>0.951</td>
<td>16.3 ± 1.6</td>
<td>-1.9 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>10</td>
<td>0.968</td>
<td>22.9 ± 2.3</td>
<td>-1.4 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>11</td>
<td>0.981</td>
<td>27.2 ± 2.7</td>
<td>-0.8 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>12</td>
<td>0.993</td>
<td>20.4 ± 2.0</td>
<td>-0.3 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>13</td>
<td>1.024</td>
<td>11.8 ± 1.2</td>
<td>0.1 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>14</td>
<td>1.078</td>
<td>8.8 ± 0.9</td>
<td>0.4 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>15</td>
<td>1.135</td>
<td>7.4 ± 0.7</td>
<td>0.3 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>16</td>
<td>1.193</td>
<td>6.3 ± 0.5</td>
<td>1.1 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>17</td>
<td>1.235</td>
<td>7.0 ± 0.5</td>
<td>1.4 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>18</td>
<td>1.267</td>
<td>6.9 ± 0.5</td>
<td>1.4 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>19</td>
<td>1.297</td>
<td>6.1 ± 0.6</td>
<td>1.8 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>20</td>
<td>1.323</td>
<td>6.7 ± 0.6</td>
<td>1.7 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>21</td>
<td>1.35</td>
<td>7.0 ± 0.8</td>
<td>1.8 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>22</td>
<td>1.376</td>
<td>7.5 ± 0.8</td>
<td>2.0 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>23</td>
<td>1.402</td>
<td>9.2 ± 1.0</td>
<td>2.1 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>24</td>
<td>1.427</td>
<td>9.1 ± 1.0</td>
<td>2.3 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>25</td>
<td>1.455</td>
<td>9.1 ± 1.0</td>
<td>2.6 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>26</td>
<td>1.492</td>
<td>7.0 ± 0.9</td>
<td>3.1 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>27</td>
<td>1.557</td>
<td>2.3 ± 0.5</td>
<td>4.3 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td>28</td>
<td>1.64</td>
<td>2.8 ± 1.1</td>
<td>4.7 ± 0.3 ± 0.7</td>
</tr>
<tr>
<td>29</td>
<td>1.735</td>
<td>3.1 ± 1.1</td>
<td>6.0 ± 0.5 ± 1.4</td>
</tr>
</tbody>
</table>

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