Precise measurement of $m_{D^{*+}} - m_{D^+}$ (and $m_{D^+} - m_{D^0}$)

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Motivation

• Chiral perturbation theory and lattice QCD calculations of heavy-light mesons start in the $m_b = m_c = \infty$ limit and SU(3) flavor symmetry and consider symmetry breaking due to (i) finite $m_b, m_c$, (ii) $m_u \neq m_d \neq m_s$, (iii) EW interactions.

• These SBs can be related to mass differences [Goity & Jayalath, PLB 650, 22]:

<table>
<thead>
<tr>
<th>$\Delta M$</th>
<th>Strong HF</th>
<th>Light quark masses</th>
<th>Electromagnetic</th>
<th>Total</th>
<th>PDG [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ - D^0$</td>
<td>0</td>
<td>2.71 ± 0.20</td>
<td>2.07 ± 0.32</td>
<td>4.78 ± 0.25</td>
<td>4.78 ± 0.10</td>
</tr>
<tr>
<td>$D_s^0 - D_s^+$</td>
<td>98.85 ± 0.21</td>
<td>0.09 ± 0.01</td>
<td>0</td>
<td>98.85 ± 0.20</td>
<td>98.85 ± 0.30</td>
</tr>
<tr>
<td>$D^* - D^0$</td>
<td>140.98 ± 0.1</td>
<td>0.18 ± 0.02</td>
<td>-0.52 ± 0.03</td>
<td>140.64 ± 0.13</td>
<td>140.64 ± 0.10</td>
</tr>
<tr>
<td>$D_s^* - D_s$</td>
<td>140.98 ± 0.1</td>
<td>3.30 ± 0.28</td>
<td>-0.52 ± 0.03</td>
<td>143.77 ± 0.15</td>
<td>143.8 ± 0.4</td>
</tr>
<tr>
<td>$B^0 - B^-$</td>
<td>0</td>
<td>2.42 ± 0.18</td>
<td>-2.09 ± 0.18</td>
<td>0.33 ± 0.04</td>
<td>0.33 ± 0.28</td>
</tr>
<tr>
<td>$B - B^*$</td>
<td>45.70 ± 0.02</td>
<td>0.94 ± 0.11</td>
<td>0.09 ± 0.01</td>
<td>46.73 ± 0.06</td>
<td>45.3 ± 1.5</td>
</tr>
</tbody>
</table>

• Improving mass difference measurements allows more precise understanding of the SB effects, and should lead to more precise predictions of other quantities.
Current charm mass differences

- \( m_{D^{*+}} - m_{D^+} = 140660 \pm 80 \text{ keV} \)
  - CLEO, PRL 69 (1992) 2046
  - Similar technique to one presented here: \( D^{*+} \rightarrow D^+\pi^0 \)

- \( m_{D^+} - m_{D^0} = 4760 \pm 12 \pm 70 \text{ keV} \)
  - LHCb, JHEP 1306 (2013) 065

- \( m_{D^{*+}} - m_{D^0} = 145475.7 \pm 1.7 \text{ keV} \)
  - PDG, dominated by BABAR, PRL 111 (2013) 111801, \( D^{*+} \rightarrow D^0\pi^+ \)
The BABAR detector & dataset

- BABAR ran from 1999 to 2008 at and around the $\Upsilon(4S)$ region.
- The analysis uses $468 \text{ fb}^{-1}$ collected on the $\Upsilon(4S)$
Reconstruction

- Reconstruct $D^{*+} \rightarrow D^+ \pi^0$
  $$\pi^0 \rightarrow \gamma \gamma$$
  $$D^+ \rightarrow K^- \pi^+ \pi^+$$
- $p_{D^{*+}} > 3$ GeV, $E_\gamma > 60$ MeV, $E_{\pi^0} > 200$ MeV

- **Kinematic fit constraints:**
  - $\pi^0$ mass
  - $D^{*+}$ decay at the primary vertex
  - $D^+$ momentum points back to the primary vertex

- **Typical $\pi^0$ has**
  - Momentum $\sim 300$ MeV
  - Energy resolution $\sim 7\%$
  - After the kinematic fit, momentum resolution $\sim 3\%$
How well does $\pi^0$ MC match the data?

- The $\pi^0$ momentum measurement dominates the final uncertainty.
- Use $\pi^0$ mass distribution to understand MC-data differences
- $\pi^0$ mass peak position is correct in data
- But 0.5 MeV too low in the MC, partly due to different calibration method.
- We emulate the data calibration by correcting the MC depending on
  - Photon energy
  - Photon opening angle
  - Data-taking period
- Agreement much better, but peak shape is not identical. Taken into account in fit procedure.
Fit procedure 1

• To obtain $m_{D^{*+}} - m_{D^+}$, we fit the distribution of the difference
  \[ \Delta m \equiv m(K^-\pi^+\pi^+\pi^0) - m(K^-\pi^+\pi^+) \]
  between the reconstructed masses of the $D^{*+}$ and $D^+$ candidates

• Fit truth-matched signal-MC candidates (~7 times data size) with the function
  \[ a_1 G_1(\Delta m; m_{D^{*+}} - m_{D^+} + \delta, \sigma_1) \]
  \[ + a_2 CB(\Delta m; m_{D^{*+}} - m_{D^+} + \delta, \sigma_2, \alpha, n) \]
  \[ + a_3 G_2(\Delta m; m_{D^{*+}} - m_{D^+} + \delta, \sigma_3^L, \sigma_3^R) \]

  Fixed to the generated value

  $\delta = \text{floating correction}$
  (How well the PDF give the peak)

$G_1 = \text{Gaussian}$
$CB = \text{Crystal Ball (Gaussian + RHS exponential tail)}$
$G_2 = \text{Gaussian with different RHS and LHS widths}$
$a_1 = f_1$, $a_2 = (1 - f_1)f_2$, $a_3 = (1 - f_1)(1 - f_2)$
Fit procedure 2

- Fit the data, fixing some shape parameters to MC, floating the widths:
  \[ a_1 G_1(\Delta m; m_{D^+} - m_{D^*} + \delta, \sigma_1) \]
  \[ + a_2 CB(\Delta m; m_{D^*} - m_{D^*} + \delta, \sigma_2, \alpha, n) \]
  \[ + a_3 G_2(\Delta m; m_{D^*} - m_{D^*} + \delta, \sigma_3^L, \sigma_3^R) \]

- Plus a background threshold function
  \[ \Delta m \sqrt{(\Delta m/m_{\pi^0})^2 - 1} e^{k(\Delta m/m_{\pi^0})} \]

- Parameterized MC experiments show a fit bias of 3.4 keV.

- With this correction, we obtain
  \[ m_{D^*} - m_{D^*} = 140,601.0 \pm 6.8 \text{ (stat) keV} \]
Systematic uncertainties

- Study dependence of $m_{D^*+} - m_{D^+}$ on several kinematic quantities to identify sources of detector mis-simulation.
- If $\chi^2/n_{dof} > 1$ for the no-dependence hypothesis given the statistical uncertainty $\sigma_{\text{stat}}$, apply a systematic $\sigma_{\text{syst}} = \sigma_{\text{stat}}\sqrt{\chi^2/n_{dof} - 1}$

$D^*$ momentum

$D^*$ polar angle

![Graph showing $D^*$ momentum distribution with systematic uncertainty of 5.0 keV](image1)

![Graph showing $D^*$ polar angle distribution with systematic uncertainty of 6.9 keV](image2)
Large dependence on $\gamma\gamma$ opening angle mostly accounted for by the calibration emulation.
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta m_+ \text{ systematic [keV]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit bias</td>
<td>1.7</td>
</tr>
<tr>
<td>$D^{*+}$ $p_{\text{lab}}$ dependence</td>
<td>5.0</td>
</tr>
<tr>
<td>$D^{*+}$ $\cos \theta$ dependence</td>
<td>6.9</td>
</tr>
<tr>
<td>$D^{*+}$ $\phi$ dependence</td>
<td>0.0</td>
</tr>
<tr>
<td>$m(D^{+}_\text{reco})$ dependence</td>
<td>0.0</td>
</tr>
<tr>
<td>Diphoton opening angle dependence</td>
<td>6.1</td>
</tr>
<tr>
<td>Run period dependence</td>
<td>0.0</td>
</tr>
<tr>
<td>Signal model parametrization</td>
<td>2.1</td>
</tr>
<tr>
<td>EMC calibration</td>
<td>7.0</td>
</tr>
<tr>
<td>MC $\pi^0$ momentum rescaling</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.9</strong></td>
</tr>
</tbody>
</table>

- Half the bias
- Evaluate $\delta$ for different periods. No dependence
- Vary fixed fit parameters, accounting for correlations with toy MC
- Rescaling of $\gamma$ energies by 0.3%, from data-MC
- $m_{\pi^0}$ peak-position difference
- MC statistics in MC-to-data $p_{\pi^0}$-scaling parameters

Additional cross checks: vary fit ranges and cuts
Summary

• We measure

\[ m_{D^{*+}} - m_{D^+} = 140601.0 \pm 6.8 \pm 12.9 \text{ keV} \]

• 5.5 times better than previous result (CLEO)

• Combine with previous BABAR result

\[ m_{D^{*+}} - m_{D^0} = 145425.1 \pm 0.5 \pm 1.8 \text{ keV}, \]

gives

\[ m_{D^+} - m_{D^0} = 4824.9 \pm 14.6 \text{ keV}, \]
also 5.5 times better than previous result (LHCb)

• To be compared with

\[ m_{\pi^+} - m_{\pi^0} = 4539.6 \pm 0.5 \]
\[ m_{K^+} - m_{K^0} = -3934 \pm 20 \]

– Note: uncertainty for \( D \) smaller than for \( K \)!