Precise Measurement of the $D^{*}(2010)^{+} - D^{+}$ Mass Difference

Liang Sun (Wuhan University)
On behalf of the BABAR Collaboration

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Outline

- Motivation
- The $BABAR$ experiment
- Analysis details
- Our results [PRL 119, 202003 (2017)]
- Summary
Motivation

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

- SB can be related to mass differences [Goity & Jayalath, PLB 650, 22 (2007)]

<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^0 )</td>
<td>140.98 ± 0.1</td>
<td>0.09 ± 0.01</td>
<td>1.04 ± 0.05</td>
<td>142.12 ± 0.06</td>
<td>142.12 ± 0.07</td>
</tr>
<tr>
<td>( B^* - B )</td>
<td>45.70 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>−0.05 ± 0.01</td>
<td>45.69 ± 0.02</td>
<td>45.78 ± 0.35</td>
</tr>
<tr>
<td>( B_s - B )</td>
<td>0</td>
<td>89.34 ± 0.16</td>
<td>−1.04 ± 0.10</td>
<td>88.3 ± 0.15</td>
<td>88.3 ± 1.8</td>
</tr>
</tbody>
</table>

- Improving mass difference measurements → better understanding of SB → more precise predictions of other quantities expected.

- BABAR has already measured \( D^*(2010)^+ - D^0 \) mass difference with \(~2\) keV precision [PRL 111, 111801 (2013) and PRD 88, 052003 (2013)]
**BABAR Experiment**

Data taking period from 1999 to 2008:
- $\sim1.3\times10^9 \text{ e}^+\text{e}^- \rightarrow \text{c}\bar{\text{c}}$
- $\sim0.5\times10^9 \text{ e}^+\text{e}^- \rightarrow \text{B}\bar{\text{B}}$

- **SVT, DCH**: charged particle tracking: good vertex & momentum resolution
- **EMC**: Information related to $\gamma/e/\pi^0/\eta$
- **DIRC, IFR, DCH**: charged particle ID on $\pi/\mu/K/p$

**The BaBar Detector**

- **DIRC (PID)**: 144 fused silica bars, 11,000, PMTs
- **1.5 T superconducting solenoid**
- **EMC**: 6580 CsI(Tl) crystals
- **Drift Chamber**: 40 layers
- **Silicon Vertex Tracker**: 5 layers, double-sided strips
- **Instrumented Flux Return**: RPCs/LSTs (muon/neutral hadrons)
Reconstructing $D^*(2010)^+ \rightarrow D^+\pi^0_s$

Kinematic fitting of the full decay chain with the constraints:

- Nominal $\pi^0$ mass
- $D^{**+}$ ($D^+$) decay at the Primary (Secondary) Vertex
- $D^+$ momentum pointing back to the PV
$D^*(2010)^+ \rightarrow D^+\pi^0$: event selection

- $D^+$ is reconstructed from $D^+ \rightarrow K^-\pi^+\pi^+$
  - Well-measured tracks with kaon or pion identification
  - Requiring $1.86 < m_{K\pi\pi} < 1.88$ GeV
  - The mass window is varied as a sanity check → no significant variation in the final result

Fraction of candidates with a correctly reconstructed $D^+$ in the mass window: $\sim 95\%$
D*(2010)^+ \to D^+ \pi_s^0: event selection

- Slow pion $\pi_s^0$ is reconstructed from $\pi^0 \to \gamma \gamma$
  - Requiring two photons each with $E_\gamma > 60$ MeV
  - Requiring $0.12 < m_{\gamma\gamma} < 0.15$ GeV
  - The background-subtracted data are compared to MC signals with different correction methods on EMC energies

- MC signals with nominal corrections on EMC energies used to improve data/MC agreement
- Additional 0.3% rescaling on photon energies applied on MC signals to determine systematic uncertainty related to EMC calibration (see p14)
$\pi^0_s$: additional correction

- For signal MC events, reconstructed $\pi^0_\gamma$ momentum distributions do not peak at the generated values.
- Observed variation accounted for by making a momentum scale correction in each of 10 bins of $\gamma\gamma$ laboratory opening angle $\theta_{\gamma\gamma}$.

As will be seen later, this correction largely mitigates an observed variation of $\Delta m_\gamma$ with $\theta_{\gamma\gamma}$. 

PRL 119, 202003 (2017)
Signal shape of $\Delta m \equiv m(D^+\pi_s^0) - m(D^+)$

- Signal shape modeled based on simulation defined as: A sum of three Gaussian-like PDFs with a common mean
  - Standard Gaussian (G) + Crystal-Ball (CB) + Bifurcated Gaussian (BfG):

$$S(\Delta m) = f_1 G(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_1)$$
$$+ (1 - f_1) \left[ f_2 CB(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_2, \alpha, n) + (1 - f_2) BfG(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_3^L, \sigma_3^R) \right],$$

- PDF parameters are determined in the fit to MC signals, except for $\Delta m_+$, which is fixed to the generated value of 140.636 MeV
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  - PDF parameters are determined in the fit to MC signals, except for $\Delta m_+$, which is fixed to the generated value of 140.636 MeV
Data fit for $\Delta m_+ \equiv m(D^{*+}) - m(D^+)$

- Together with a threshold function to model the background, we fit to real data to extract $\Delta m_+$ in the signal model:
  \[
  S(\Delta m) = f_1 G(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_1 ) \\
  + (1 - f_1) \left[ f_2 CB(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_2, \alpha, n ) \\
  + (1 - f_2) BfG(\Delta m; \Delta m_+ + \delta_{\Delta m_+}, \sigma_3^L, \sigma_3^R) \right],
  \]
  - CB shape parameters, fractions $f_1$ & $f_2$, and $\delta_{\Delta m_+}$ fixed to MC values
  - Resolution parameters allowed to vary to account for possible data/MC differences

- The fitted $\Delta m_+$ central value is corrected by the bias of $3.4 \text{ keV}$ in our nominal fit model, based on a set of pseudoexperiments

- The central value becomes $\Delta m_+ = 140\, 601.0 \text{ keV}$

BABAR Data: ~151 K signals

Observed FWHM of the signal shape: ~2 MeV
Searching for anomalous variations – I
Data divided into 10 disjoint sets of $p(D^{*+})$ and of $\cos \theta(D^{*+})$

- Variations in fit results as functions of kinematic variables to identify possible sources of detector/simulation differences. Systematics assigned by mimicking the PDG scale factor method for inflating errors.
- If the fit results from a given dependence study are compatible with a constant value, in the sense that $\chi^2/\nu < 1$, no systematic uncertainty is assigned.
- If $\chi^2/\nu > 1$, an uncertainty of $\sigma_{sys} = \sigma_{stat}\sqrt{\chi^2/\nu - 1}$ is ascribed to account for unidentified detector effects.
- The variations observed as functions of $p(D^{*+})$ and $\cos \theta(D^{*+})$ lead to $\pm 5.0$ keV and $\pm 6.9$ keV systematic uncertainties in $\Delta m_+$, respectively.

**BABAR**

$p(D^{*+})$ (GeV) vs $\Delta m_+$ (MeV)

**BABAR**

$\cos \theta(D^{*+})$ vs $\Delta m_+$ (MeV)
Searching for anomalous variations – II
Data divided into 10 disjoint sets of $\phi(D^{*+})$ and of $m(K\pi\pi)$

- The variations seen with these variables are "consistent" with being purely statistical (i.e., $\chi^2/\nu < 1$)
- Therefore, the systematic uncertainties in $\Delta m_+$ associated with these variations are zero
Searching for anomalous variations – III
Data divided into 10 disjoint sets of π⁰ opening angle θ_{γγ}

- As mentioned previously, the MC momentum scale correction leads to a smaller χ²/ν value related to π⁰ opening angle dependence
- We assign ±6.1 keV systematic uncertainties in Δm⁺ on the variation observed as a function of θ_{γγ}

Before (left) and after (right) the correction in MC π⁰ momentum scale
Summary of $\Delta m_+\,$ systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>syst. [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>Total</td>
<td>12.9</td>
</tr>
</tbody>
</table>

$\Rightarrow \Delta m_+ = (140\, 601.0 \pm 6.8 \pm 12.9)\,$ keV

Our final result!
Previous *BABAR* results on $\Delta m_0 \equiv m(D^{**}) - m(D^0)$

- Two reconstruction channels:
  
**Previous BABAR results on $\Delta m_0 \equiv m(D^{**}) - m(D^0)$**

- Two reconstruction channels:

**Combined result:**

$\Rightarrow \Delta m_0 = (145,425.9 \pm 0.4 \pm 1.7) \text{ keV}$
Summary of our results

- By combining the BABAR results on $\Delta m_+\,$ and $\Delta m_0\,$, we have

  $\Delta m_+ \equiv m(D^*(2010)^+) - m(D^+) = (140\,601.0 \pm 6.8 \,[\text{stat}] \pm 12.9 \,[\text{syst}])\,\text{keV}$
  
  $\Delta m_0 \equiv m(D^*(2010)^+) - m(D^0) = (145\,425.9 \pm 0.4 \,[\text{stat}] \pm 1.7 \,[\text{syst}])\,\text{keV}$
  
  $\Delta m_D \equiv m(D^+) - m(D^0) = (4\,824.9 \pm 6.8 \,[\text{stat}] \pm 12.9 \,[\text{syst}])\,\text{keV}$

- These results are compatible with and $\sim$5x more precise than the current PDG averages

<table>
<thead>
<tr>
<th>parameter</th>
<th>prior WA</th>
<th>present measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_+$</td>
<td>$(140,670 \pm 80),\text{keV}$</td>
<td>$(140,601 \pm 15),\text{keV}$</td>
</tr>
<tr>
<td>$\Delta m_D$</td>
<td>$(4,750 \pm 80),\text{keV}$</td>
<td>$(4825 \pm 15),\text{keV}$</td>
</tr>
</tbody>
</table>

- Our results can be compared with the corresponding values for the pion and kaon systems reported by PDG

  $\Delta m_{\pi} = (4\,593.6 \pm 0.5)\,\text{keV}$
  
  $\Delta m_K = (-3\,934 \pm 20)\,\text{keV}$