A higher precision measurement of the $D^*(2010)^+ - D^+$ mass difference

$\Rightarrow$ a higher precision measurement of $m(D^+) - m(D^0)$

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Mass difference measurements constrain theory

from J.L. Goity and C.P. Jayalath

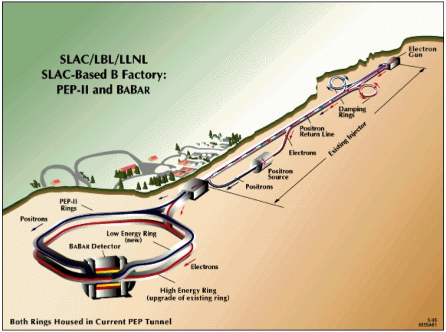
Table 2
Mass contributions by strong hyperfine, light quark masses and electromagnetism in units of MeV. The errors include the uncertainties in the quark mass ratios. The fit has $\chi^2 \sim 1$

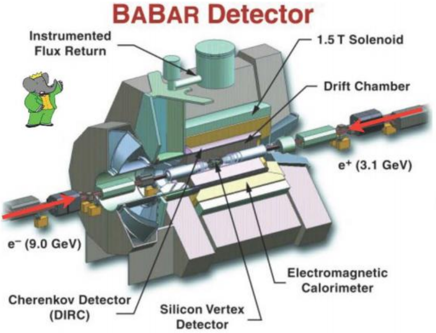
ΔM	Strong HF	Light quark masses	Electromagnetic	Total	PDG [2]
$D^+ - D^0$	0	2.71 ± 0.20	2.07 ± 0.32	4.78 ± 0.25	4.78 ± 0.10
$D_s - D^+$	0	98.85 ± 0.21	0	98.85 ± 0.20	98.85 ± 0.30
$D^{*0} - D^0$	140.98 ± 0.1	0.09 ± 0.01	1.04 ± 0.05	142.12 ± 0.06	142.12 ± 0.07
$D^{*+} - D^+$	140.98 ± 0.1	0.18 ± 0.02	-0.52 ± 0.03	140.64 ± 0.13	140.64 ± 0.10
$D_s^* - D_s$	140.98 ± 0.1	3.30 ± 0.28	-0.52 ± 0.03	143.77 ± 0.15	143.8 ± 0.4
$B^0 - B^-$	0	2.42 ± 0.18	-2.09 ± 0.18	0.33 ± 0.04	0.33 ± 0.28
$B^* - B$	45.70 ± 0.02	0.04 ± 0.01	-0.05 ± 0.01	45.69 ± 0.02	45.78 ± 0.35
$B_s - B$	0	89.34 ± 0.16	-1.04 ± 0.10	88.3 ± 0.15	88.3 ± 1.8
$B_s^* - B_s$	45.70 ± 0.02	0.94 ± 0.11	0.09 ± 0.01	46.73 ± 0.06	45.3 ± 1.5

- Chiral perturbation theory and lattice QCD calculations of heavy-light mesons start in the limit of infinitely heavy *b*- and *c*-quark masses and $SU(3)$ flavor symmetry for the light quarks and consider symmetry breaking associated with (i) the finite masses of the heavy quarks, (ii) the different light quark masses, and (iii) the electromagnetic interactions.
- The symmetry-breaking associated with these sources can be related to mass differences [J.L. Goity and C.P. Jayalath, PLB 650, 22 (2007)].
- Improving mass difference measurements allows more precise understanding of the symmetry-breaking, and should lead to more precise predictions of other quantities.

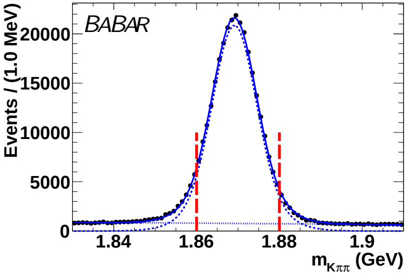
The data come from the BaBar experiment

ran 1999 - 2008; $\mathcal{L}_{\rm int} \approx 468~{\rm fb}^{-1}$ recorded at, and 40 MeV below, the $\Upsilon(4S)$ resonance

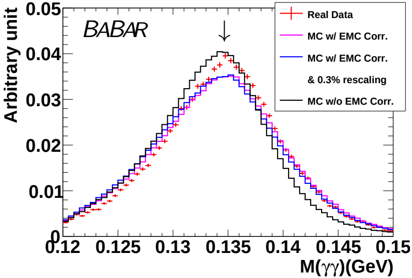




$D^{*+} \to D^+\pi^0$: the D^+ and π^0 candidates

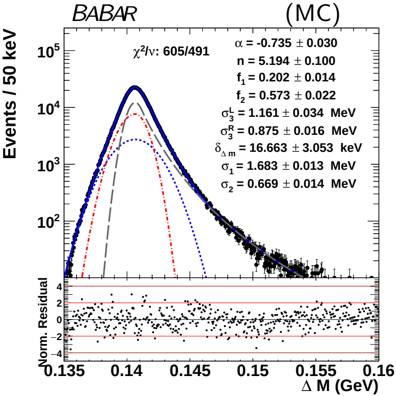


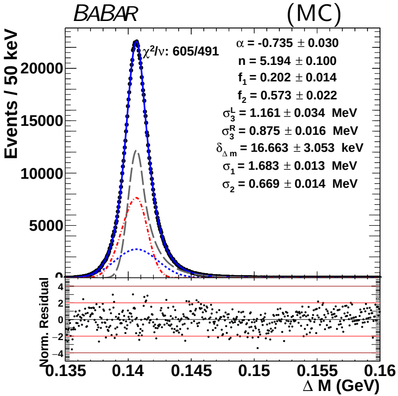
- These are the $D^+ \to K^-\pi^+\pi^+$ candidates from which the D^{*+} candidates are built.
- The vertical red lines indicate the mass range used for the nominal fit.
- As a sanity check, we vary the mass window used in the analysis and find no significant variation in the final result.



- The background-subtracted $\gamma\gamma$ invariant mass spectrum from real data is shown in red.
- The truth-matched MC spectrum with no energy scale corrections is shown in black.
- The MC spectra with nominal energy corrections and with an additional 0.3% rescaling are shown in blue and magenta, respectively.

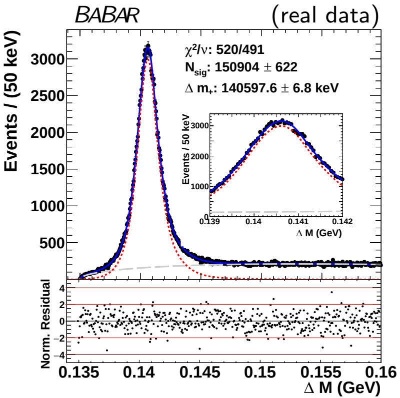
Simulated $\Delta m_+ \equiv m(D^{*+}) - m(D^+)$





Signal shape parameters are derived from truth-matched Monte Carlo simulation. When fitting the real data, most of the fit model parameters are taken directly from the MC. However, several of the resolution terms are allowed to vary to account for possible differences between data and simulation.

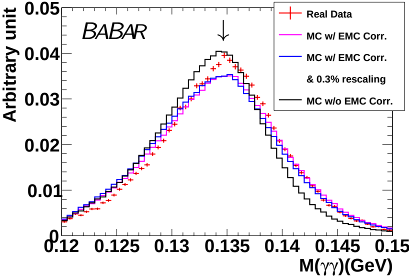
Real data: $\Delta m_+ \equiv m(D^{*+}) - m(D^+)$

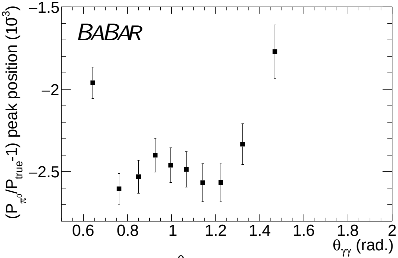


- Fitting simulated data sets generated with signal and background PDFs corresponding to those in our nominal fit produces a bias of 3.4 keV with a very small nominal uncertainty.
- We add this bias to the directly fitted value and assign a systematic uncertainty of 1.7 keV to this shift.
- Thus, the central value becomes **$\Delta m_+ = 140\,601.0$ keV**
- Varying the "'fixed" fit model parameters according to their reported covariance matrices produces an rms spread of 2.1 keV in the central fit value. We assign this as another systematic uncertainty.

π^0 candidates in data and MC

differences, correction factors, and associated systematic uncertainties



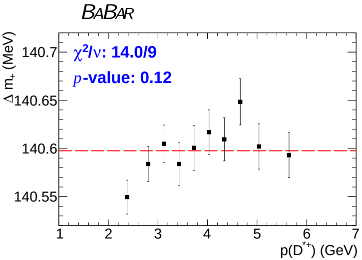


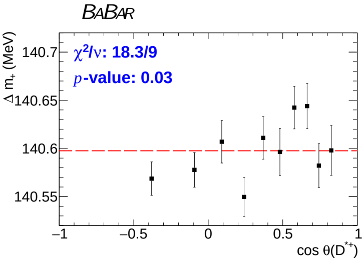
- The "calibrated" energy scales in the data and MC simulation, at higher energy scales than observed here, differ by $(-0.35 \pm 0.09)\%$ [NIM A729, pp 615-701 (2013)].
- Making a similar 0.3% MC photon energy correction improves the data/MC agreement in the $m_{\gamma\gamma}$ distribution shown above.
- Varying the correction by $\pm 0.3\%$, and trying other MC neutrals corrections, leads to a **$\pm$7.0 keV systematic uncertainty in Δm_+**.

- Truth-matched π^0 momentum distributions observed in MC samples do not peak at the generated momenta.
- The observed variation is accounted for by making a momentum scale correction in each of 10 bins of $\gamma\gamma$ laboratory opening angle.
- As will be seen later, this largely mitigates an observed variation of Δm_+ with $\theta_{\gamma\gamma}$.
- Varying the MC π^0 momentum scale values according to the errors in each bin leads to a **$\pm$0.5 keV systematic uncertainty in Δm_+**.

Searching for anomalous variations - I

divide the data into 10 disjoint sets of $p(D^{*+})$ and of $\cos\theta(D^{*+})$

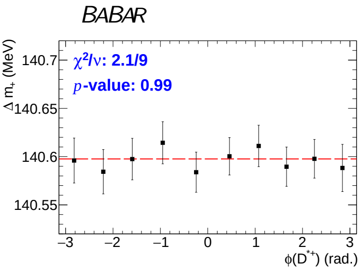


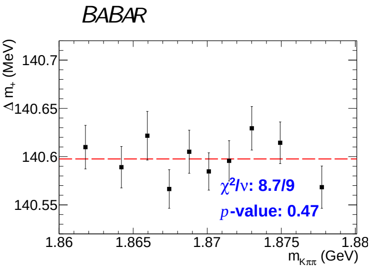


- We study variations in fit results as functions of kinematic variables to identify possible sources of detector/simulation differences. We assign systematics mimicking the PDG scale factor method for inflating errors.
- If the fit results from a given dependence study are compatible with a constant value, in the sense that $\chi^2/\nu < 1$, where ν is the number of degrees of freedom, we assign no systematic uncertainty.
- If $\chi^2/\nu > 1$, we ascribe an uncertainty of $\sigma_{\rm sys} = \sigma_{\rm stat}\sqrt{\chi^2/\nu - 1}$ 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 Δm_+**, respectively.

Searching for anomalous variations - II

divide the data into 10 disjoint sets of $\phi(D^{*+})$ and of $m(K\pi\pi)$

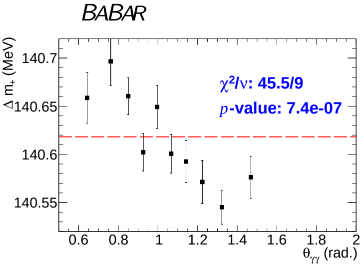




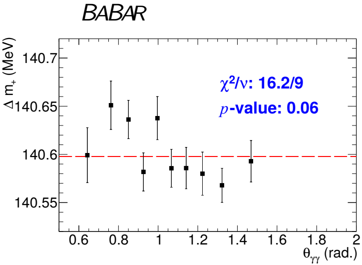
- The variations seen with these variables are "consistent" with being purely statisical (i.e., $\chi^2/\nu < 1$).
- Therefore, **the systematic uncertainties in Δm_+ associated with these variations are zero**.

Searching for anomalous variations - III

divide the data into 10 disjoint sets of $\theta_{\gamma\gamma}$



This is the variation with $\gamma\gamma$ opening angle before the MC momentum scale correction is made.



This is the variation with $\gamma\gamma$ opening angle after the MC momentum scale correction is made.

The variations observed as a function of $\theta_{\gamma\gamma}$ lead to a **$\pm$6.1 keV systematic uncertainty in Δm_+**.

Overview of Systematic Uncertainties for Δm_+

Table: Systematic errors for Δm_+, from all considered sources.

Source	syst. [keV]
Fit bias	1.7
D^{*+} $p_{\rm lab}$ dependence	5.0
D^{*+} $\cos\theta$ dependence	6.9
D^{*+} ϕ dependence	0.0
$m(D^+_{reco})$ dependence	0.0
Diphoton opening angle dependence	6.1
Run period dependence	0.0
Signal model parametrization	2.1
EMC calibration	7.0
MC π^0 momentum rescaling	0.5
Total	12.9

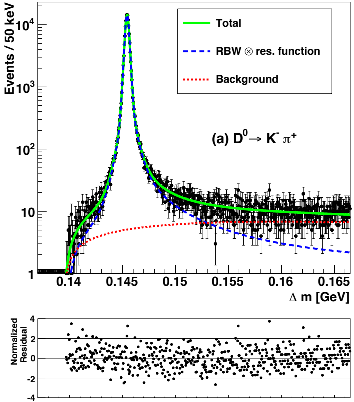
Table: These are the p-values for the hypothesis that observed variations in the value of Δm_+ for the disjoint subsets of data are consistent with statistical fluctuation.

Source	p-value
D^{*+} $p_{\rm lab}$ dependence	0.12
D^{*+} $\cos\theta$ dependence	0.03
D^{*+} ϕ dependence	0.99
$m(D^+_{reco})$ dependence	0.47
Diphoton opening angle dependence	0.06
Average	0.33

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

Previously published: $\Delta m_0 \equiv m(D^{*+}) - m(D^0)$

see Phys. Rev. Lett. 111, 111801 (2013) and Phys. Rev. D 88, 052003 (2013)



$\Rightarrow \boldsymbol{\Delta m_0 = (145\,425.9 \pm 0.4 \pm 1.7)}$ **keV**

Derived value for $\Delta m_D \equiv m(D^+) - m(D^0)$

more details of the analysis available in Phys. Rev. Lett. **119**, 202003 (2017)

Combining the BaBar measurements of Δm_+ and Δm_0, we find:

$$\Delta m_+ = (140\,601.0 \pm 6.8 \pm 12.9)\ \text{keV}$$

$$\Delta m_0 = (145\,425.9 \pm 0.4 \pm 1.7)\ \text{keV}$$

$$\Delta m_D = (4\,824.9 \pm 6.8 \pm 12.9)\ \text{keV}$$

Table: Prior world-average (WA) values [PDG, 2016], accessed online 7 April 2018, compared to our measured values.

parameter	prior WA	present measurement
Δm_+	$(140\,670 \pm 80)$ keV	$(140\,601 \pm 15)$ keV
Δm_D	$(4\,750 \pm 80)$ keV	(4825 ± 15) keV

Other world-average measurements [PDG, 2016]:

$$m(D^0) = (1864.83 \pm 0.05)\ \text{MeV}$$

$$m(D^+) = (1869.59 \pm 0.09)\ \text{MeV}$$

$$\Delta m_\pi = (4\,593.6 \pm 0.5)\ \text{keV}$$

$$\Delta m_K = (-3\,934 \pm 20)\ \text{keV}$$