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

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Outline

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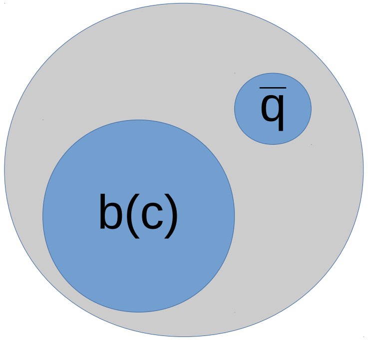
- Analysis details
- Our results [PRL 119, 202003 (2017)]
- Summary

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 **S**ymmetry-**B**reaking due to finite m_b & m_c, $m_u \neq m_d \neq m_s$, and EM interactions

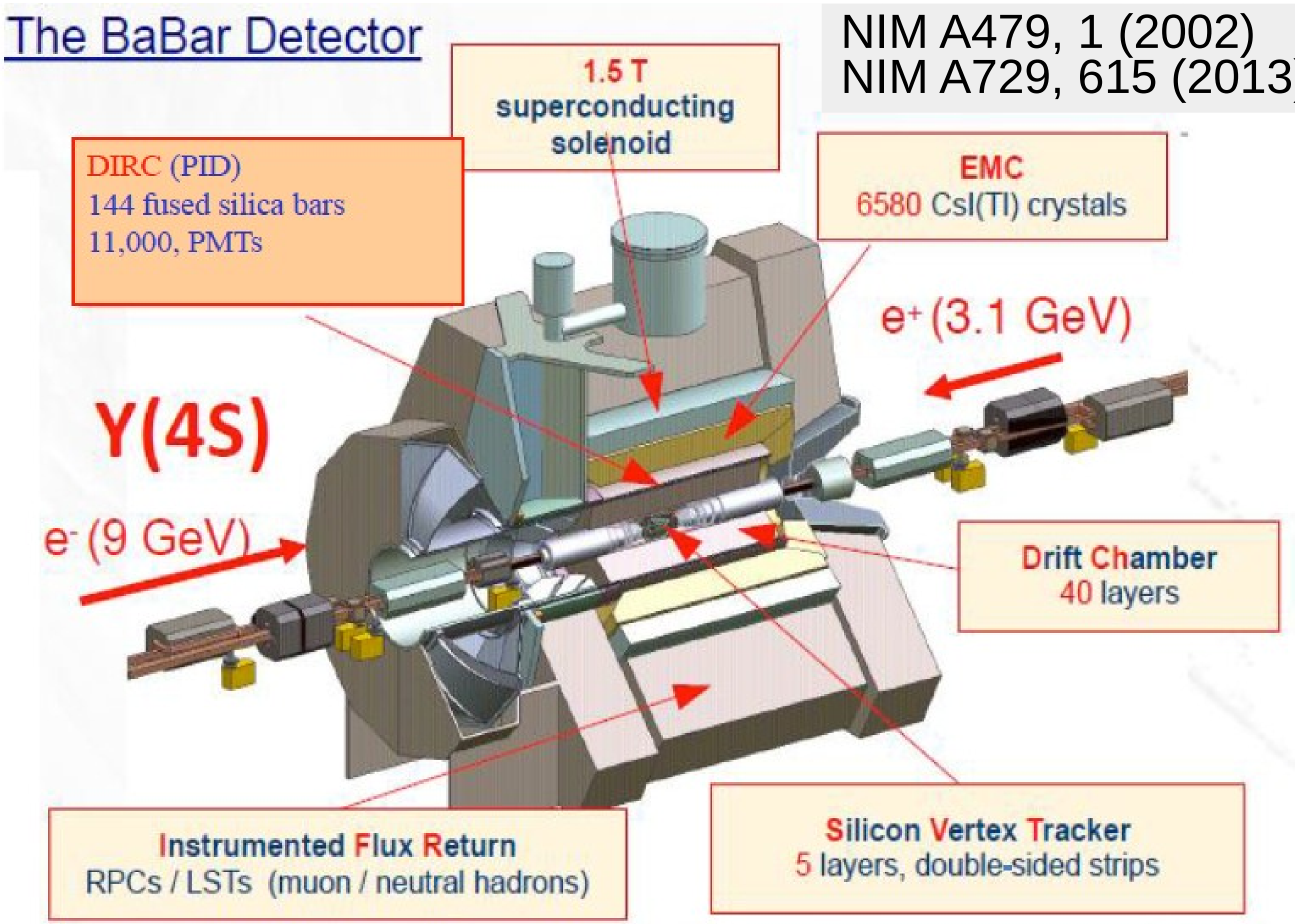
- SB can be related to mass differences [Goity & Jayalath, PLB 650, 22 (2007)]

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

- 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



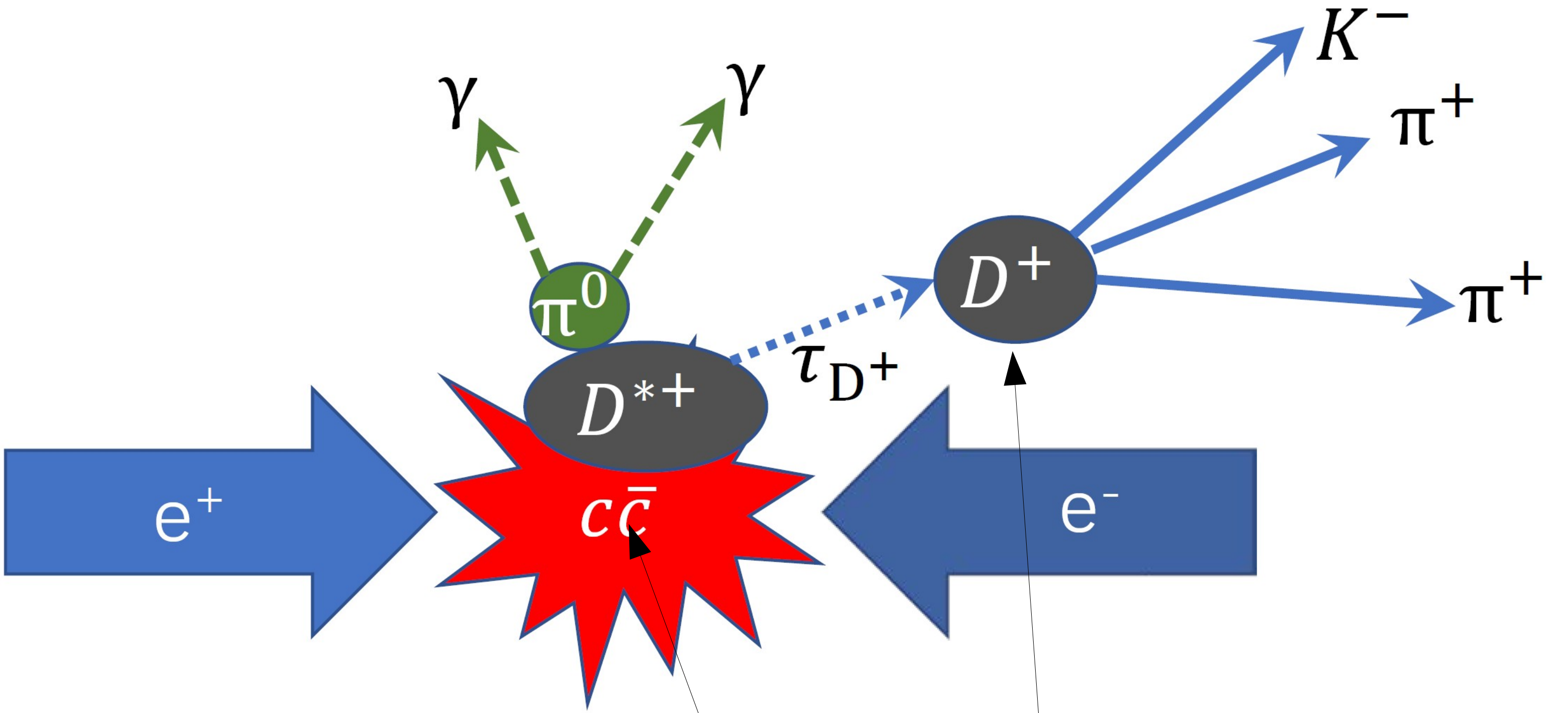
NIM A479, 1 (2002)
NIM A729, 615 (2013)

Data taking period from 1999 to 2008:

- $\sim 1.3\times10^9$ $e^+e^- \to c\bar{c}$
- $\sim 0.5\times10^9$ $e^+e^- \to B\bar{B}$

- 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 $\pi/\mu/K/p$

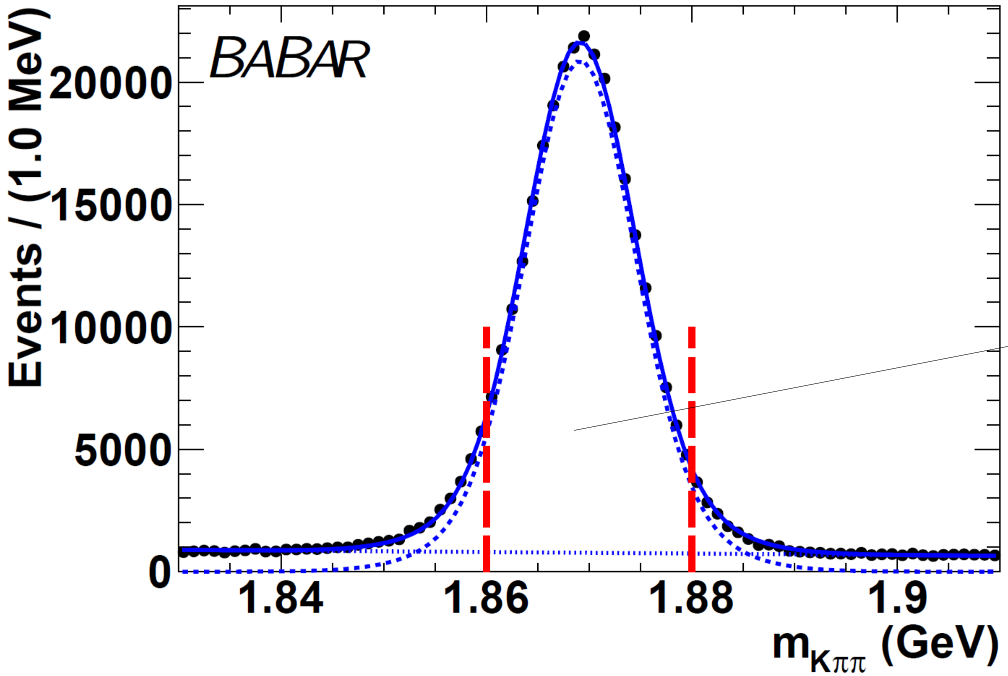
Reconstructing $D^*(2010)^+ \rightarrow D^+\pi_s^0$



Kinematic fitting of the full decay chain with the constraints:
- Nominal π^0 mass
- D^{*+} (D^+) decay at the Primary (Secondary) Vertex
- D^+ momentum pointing back to the PV

$D^*(2010)^+ \to D^+\pi_s^0$: event selection

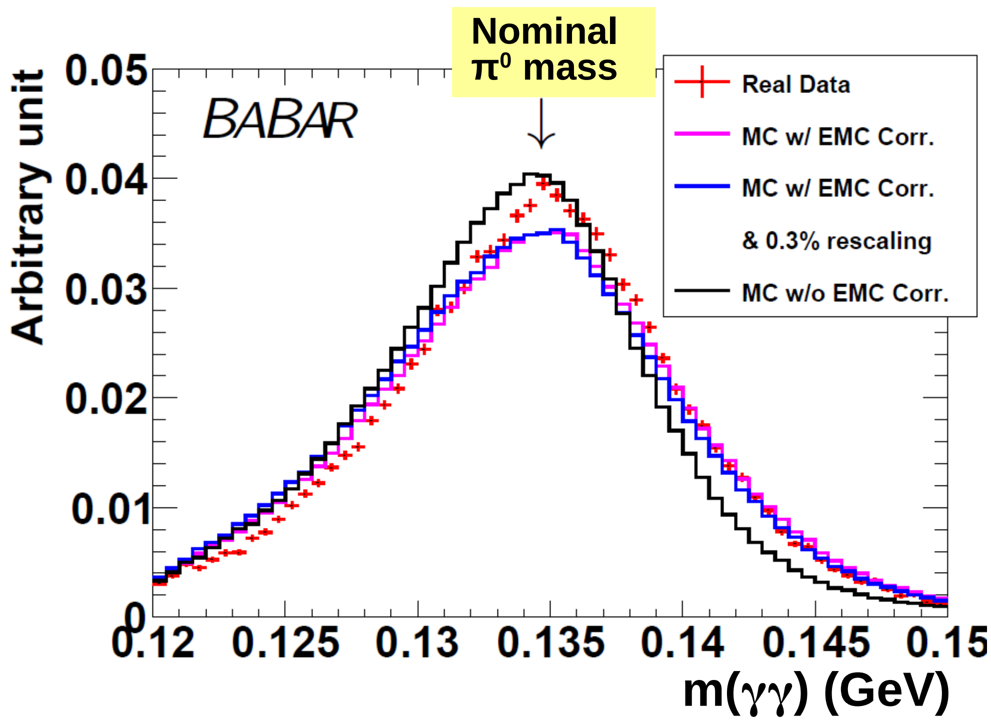
- D^+ is reconstructed from $D^+ \to K^-\pi^+\pi^+$
  - Well-measured tracks with kaon or pion identification
  - Requiring $1.86 < m_{K\pi\pi} < 1.88$ GeV
  - The mass window is varied as a sanity check → no significant variation in the final result



Fraction of candidates with a correctly reconstructed D^+ in the mass window: ~95%

$D^*(2010)^+ \to D^+\pi_s^0$: event selection

- Slow pion π_s^0 is reconstructed from $\pi^0 \to \gamma\gamma$
  - Requiring two photons each with E_γ > 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

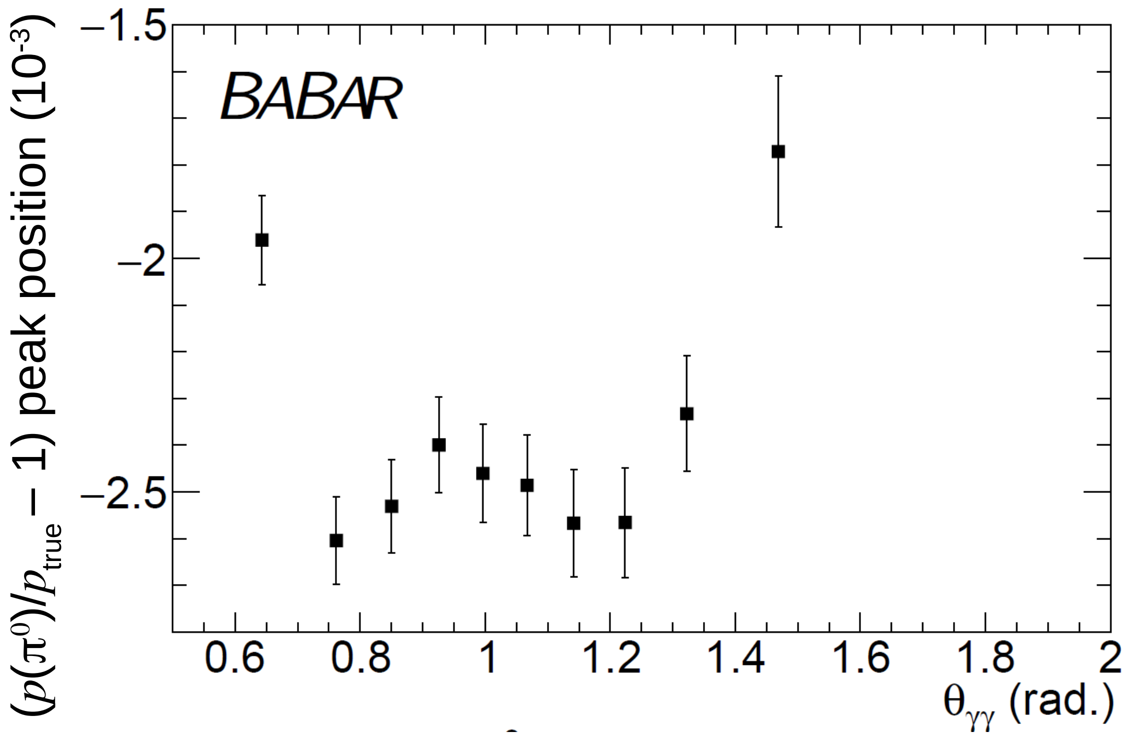


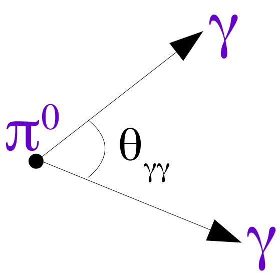
- MC signals with nominal corrections on EMC energies used to improve data/MC agreement
- Additional 0.3% rescaling on photon energies applied on MC signals to determine systematic uncertainty related to EMC calibration (see p14)

PRL 119, 202003 (2017)

π_s^0: additional correction

- For signal MC events, reconstructed π^0 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 $\theta_{\gamma\gamma}$





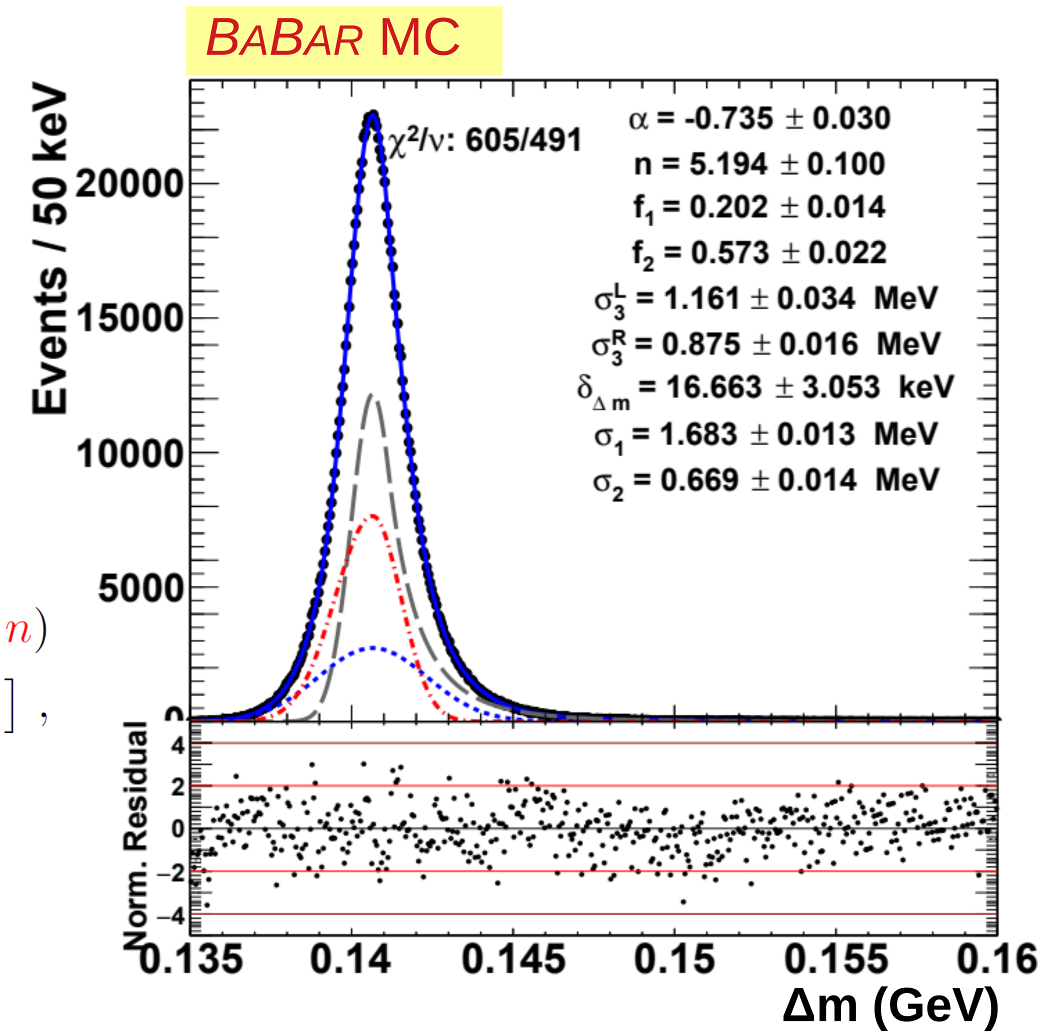
As will be seen later, this correction largely mitigates an observed variation of Δm_+ with $\theta_{\gamma\gamma}$

Signal shape of $\Delta m \equiv m(D^+\pi_s^0)\text{-}m(D^+)$

- 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):

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

  - PDF parameters are determined in the fit to MC signals, except for Δm_+, which is fixed to the generated value of **140.636 MeV**



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):

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

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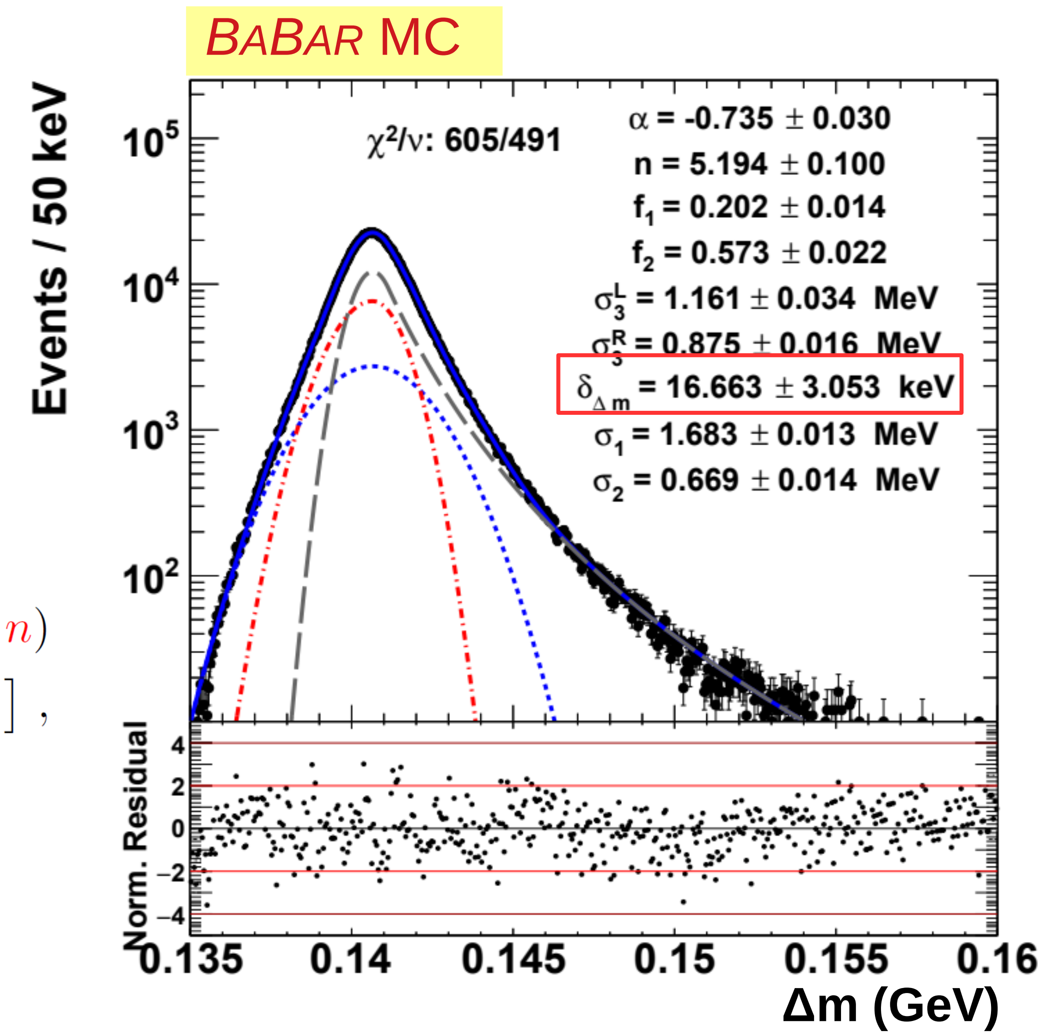


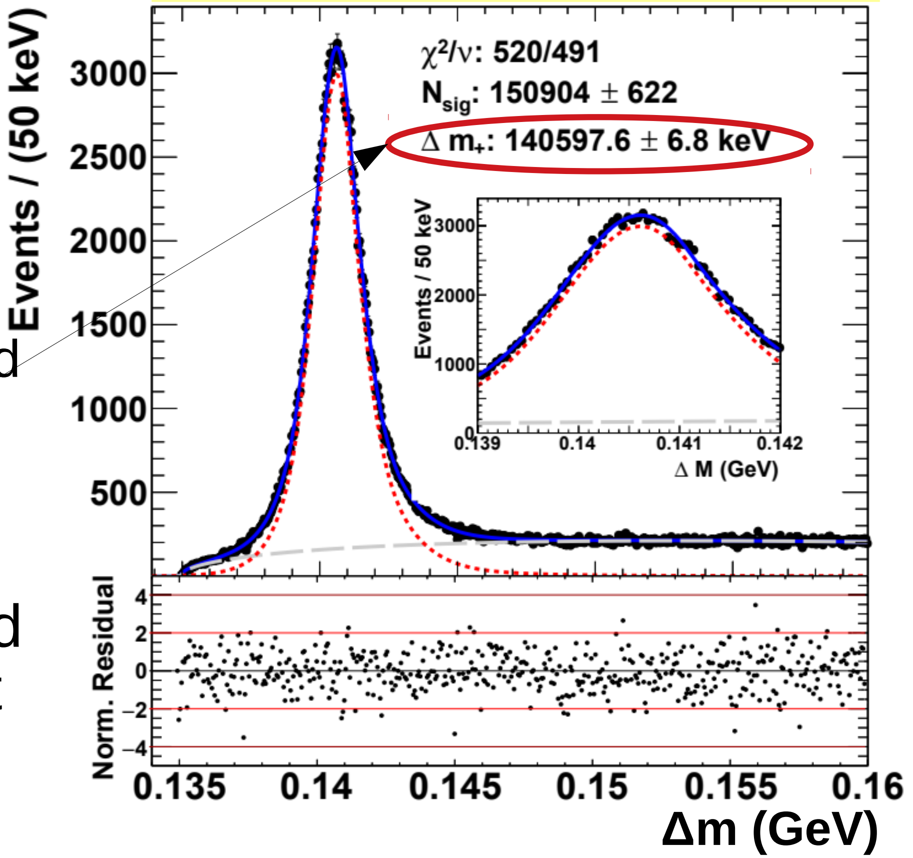
Data fit for $\Delta m_+ \equiv m(D^{*+})-m(D^+)$

- Together with a threshold function to model the background, we fit to real data to extract Δm_+ in the signal model:

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

  - 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 Δm_+ central value is corrected by the bias of **3.4 keV** in our nominal fit model, based on a set of pseudoexperiments
- The central value becomes Δm_+ = **140 601.0 keV**

BABAR Data: ~151 K signals

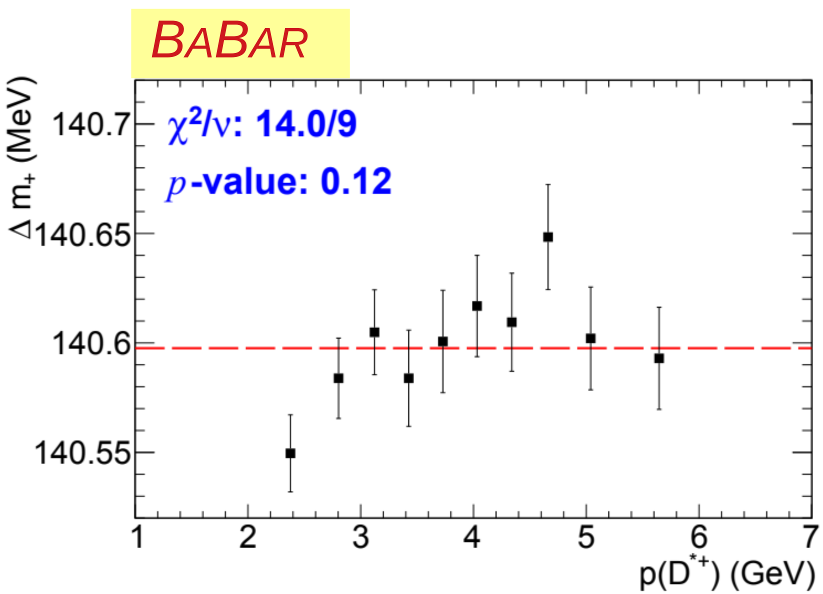


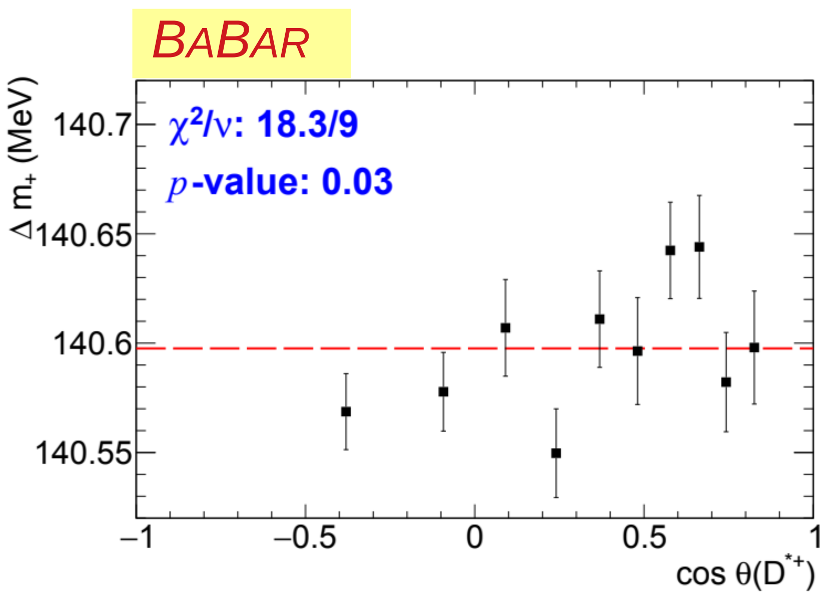
Observed FWHM of the signal shape: ~ 2 MeV

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 ±5.0 keV and ±6.9 keV systematic uncertainties in Δm_+, respectively

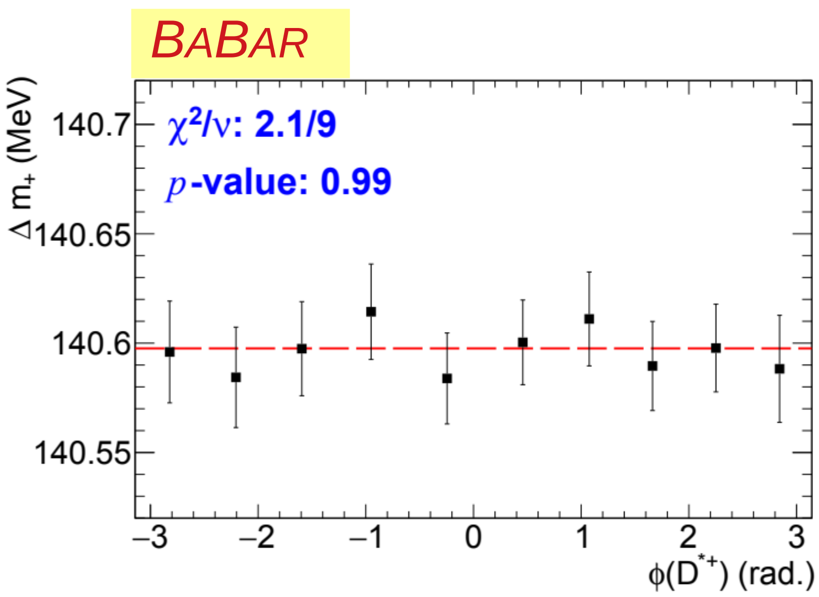


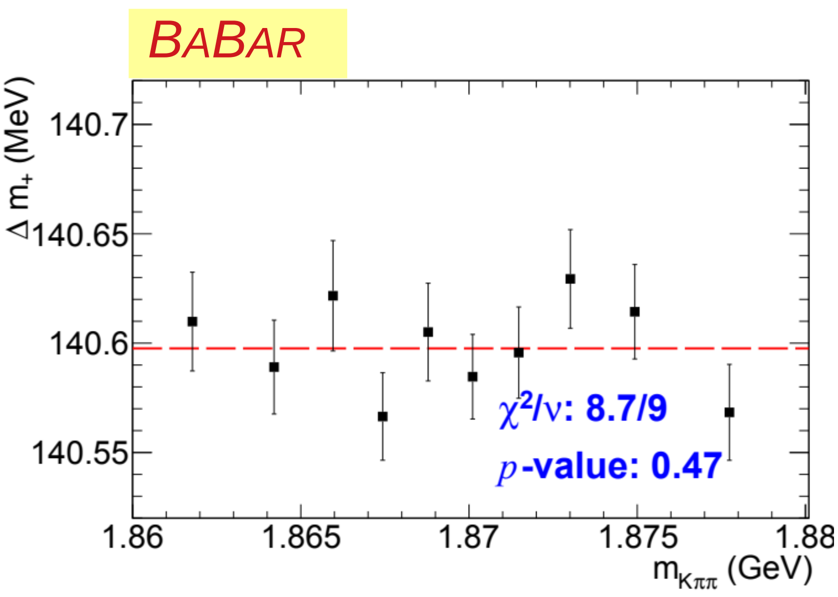


Searching for anomalous variations – II

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 Δm_+ associated with these variations are zero

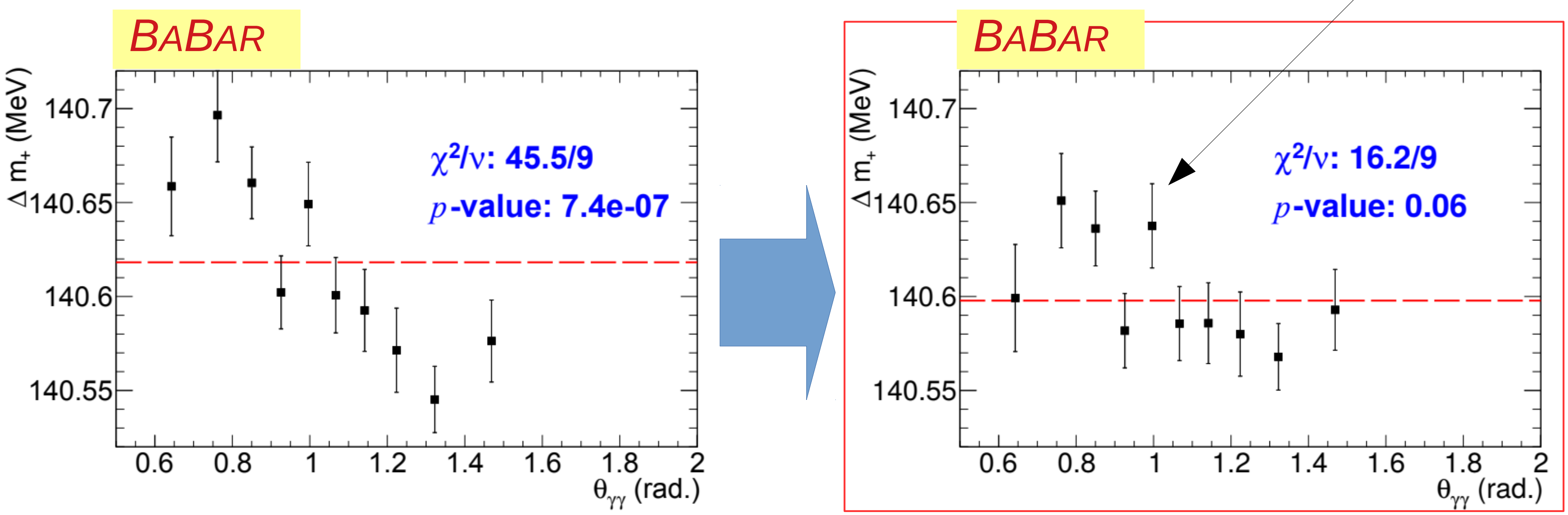




Searching for anomalous variations – III

Data divided into 10 disjoint sets of π^0 opening angle $\theta_{\gamma\gamma}$

- As mentioned previously, the MC momentum scale correction leads to a smaller χ^2/ν value related to π^0 opening angle dependence
- We assign ±6.1 keV systematic uncertainties in Δm_+ on the variation observed as a function of $\theta_{\gamma\gamma}$



Before (left) and after (right) the correction in MC π^0 momentum scale

Summary of Δm_+ systematic uncertainties

BABAR

Source	syst. [keV]
Fit bias	1.7
D^{*+} p_{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

BABAR

Source	p-value
D^{*+} p_{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

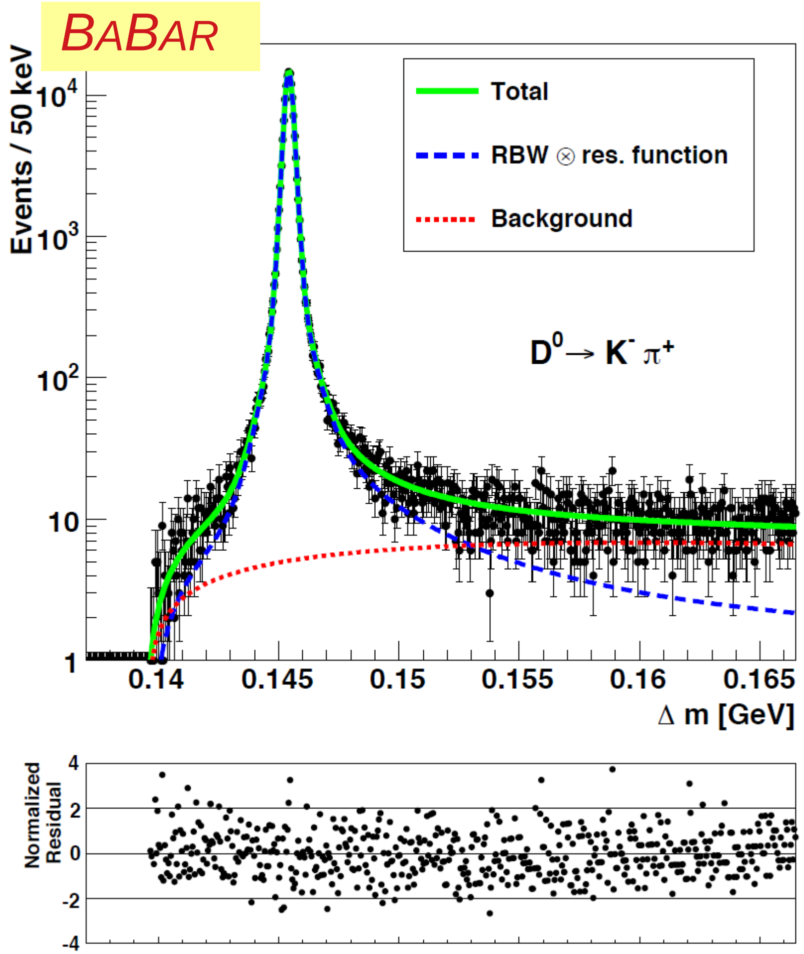
$$\Rightarrow \Delta m_+ = (140\,601.0 \pm 6.8 \pm 12.9)\ \mathrm{keV}$$

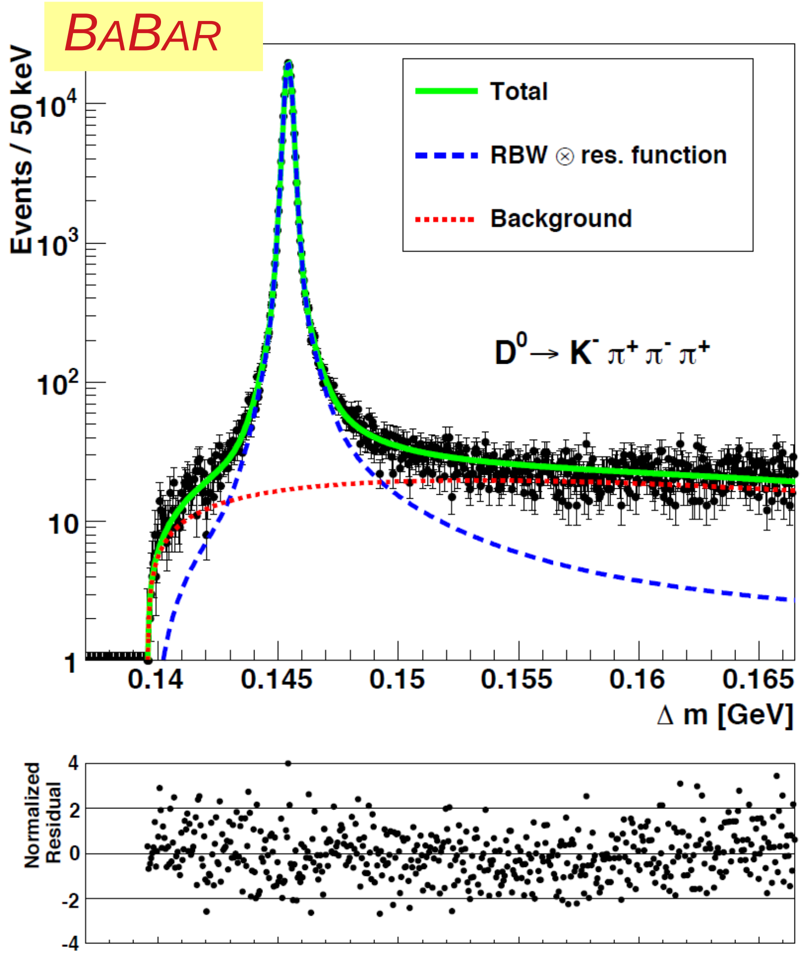
Our final result!

Previous *BaBar* results on $\Delta m_0 \equiv m(D^{*+}) - m(D^0)$

PRL 111, 111801 (2013)
PRD 88, 052003 (2013)

- 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 Δm_+ and Δm_0, we have

$$\Delta m_+ \equiv m(D^*(2010)^+) - m(D^+) = (140\,601.0 \pm 6.8[stat] \pm 12.9[syst])\,keV$$

$$\Delta m_0 \equiv m(D^*(2010)^+) - m(D^0) = (145\,425.9 \pm 0.4[stat] \pm 1.7[syst])\,keV$$

$$\boldsymbol{\Delta m_D \equiv m(D^+) - m(D^0) = (4\,824.9 \pm 6.8[stat] \pm 12.9[syst])\,keV}$$

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

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

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

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

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