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 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

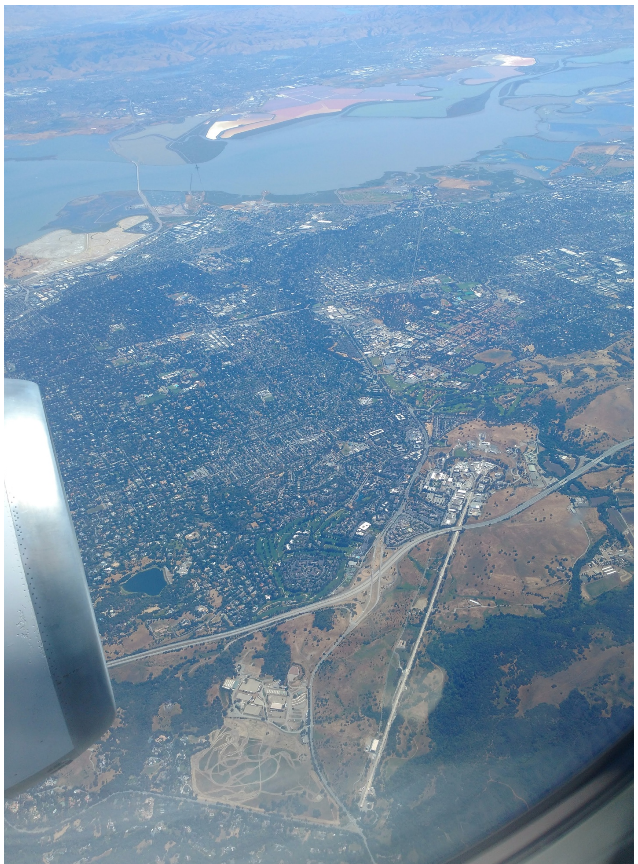
- Improving mass difference measurements allows more precise understanding of the SB effects, and should lead to more precise predictions of other quantities.

Current charm mass differences

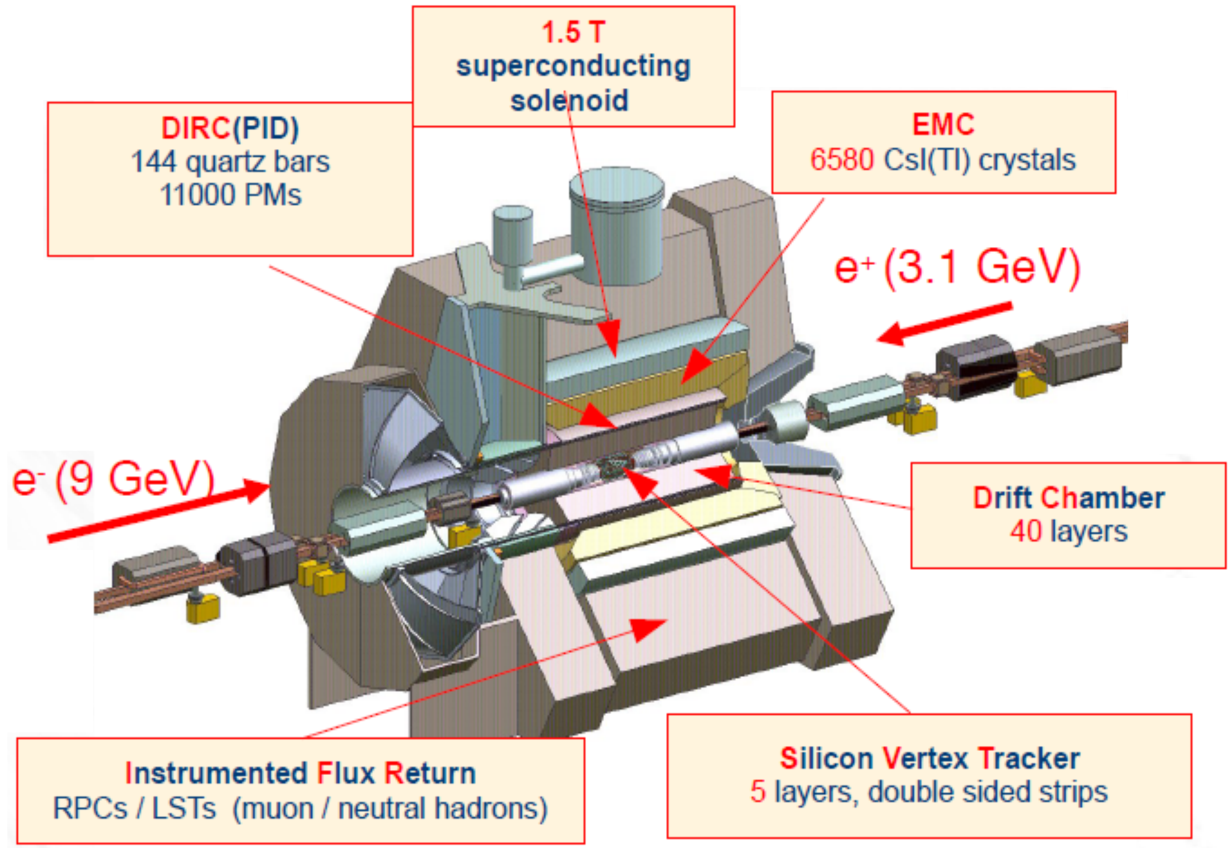
- ⇨ $m_{D^{*+}} - m_{D^+} = 140660 \pm 80$ keV
  - CLEO, PRL 69 (1992) 2046
  - Similar technique to one presented here: $D^{*+} \to D^+\pi^0$
- ⇨ $m_{D^+} - m_{D^0} = 4760 \pm 12 \pm 70$ keV
  - LHCb, JHEP 1306 (2013) 065
- $m_{D^{*+}} - m_{D^0} = 145475.7 \pm 1.7$ keV
  - PDG, dominated by BABAR, PRL 111 (2013) 111801, $D^{*+} \to D^0\pi^+$

The BABAR detector & dataset

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

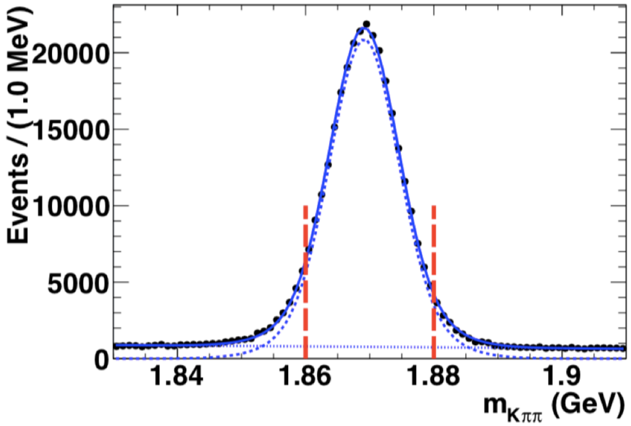


SLAC yesterday



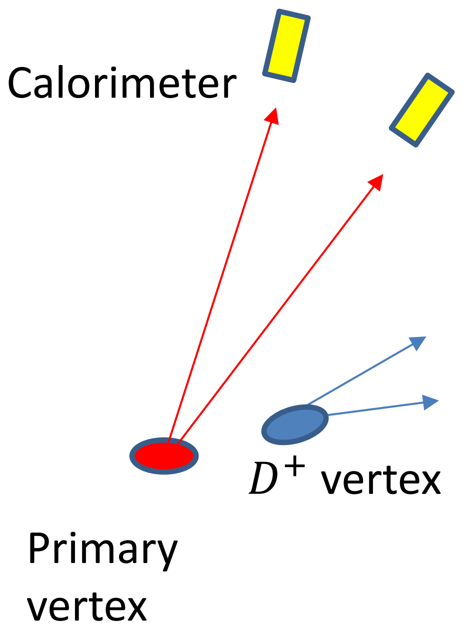
Reconstruction

- Reconstruct $D^{*+} \to D^{+}\pi^{0}$
  $\pi^{0} \to \gamma\gamma$
  $D^{+} \to K^{-}\pi^{+}\pi^{+}$



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

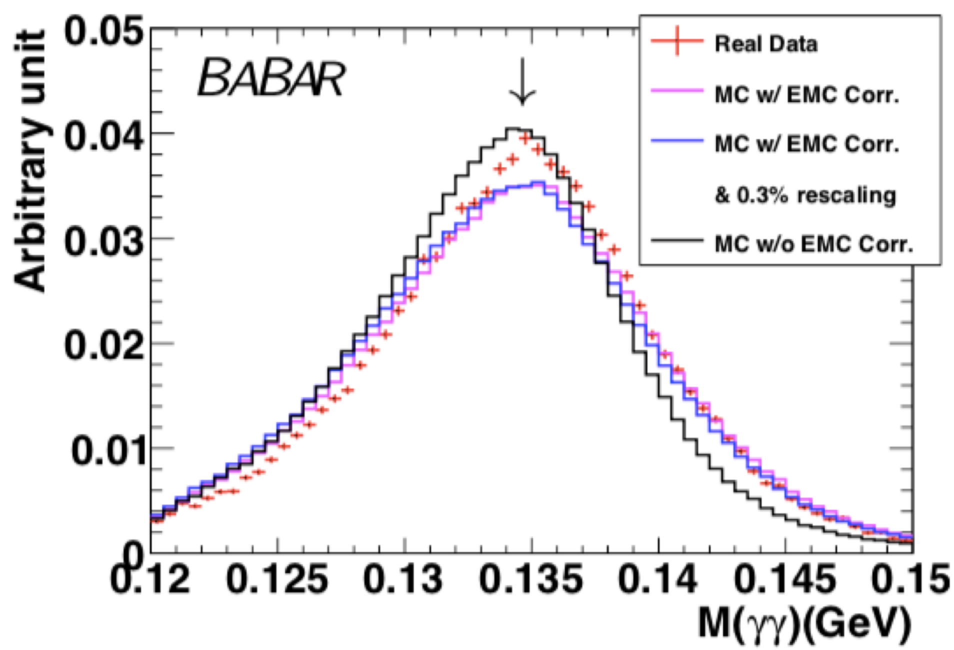
- Kinematic fit constraints:
  - π^{0} mass
  - D^{*+} decay at the primary vertex
  - D^{+} momentum points back to the primary vertex



- Typical π^{0} has
  - Momentum ~ 300 MeV
  - Energy resolution ~7%
  - After the kinematic fit, momentum resolution ~ 3%

How well does π^0 MC match the data?

- The π^0 momentum measurement dominates the final uncertainty.
- Use π^0 mass distribution to understand MC-data differences
- π^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

$$\Delta m \equiv m(K^- \pi^+ \pi^+ \pi^0) - m(K^- \pi^+ \pi^+)$$

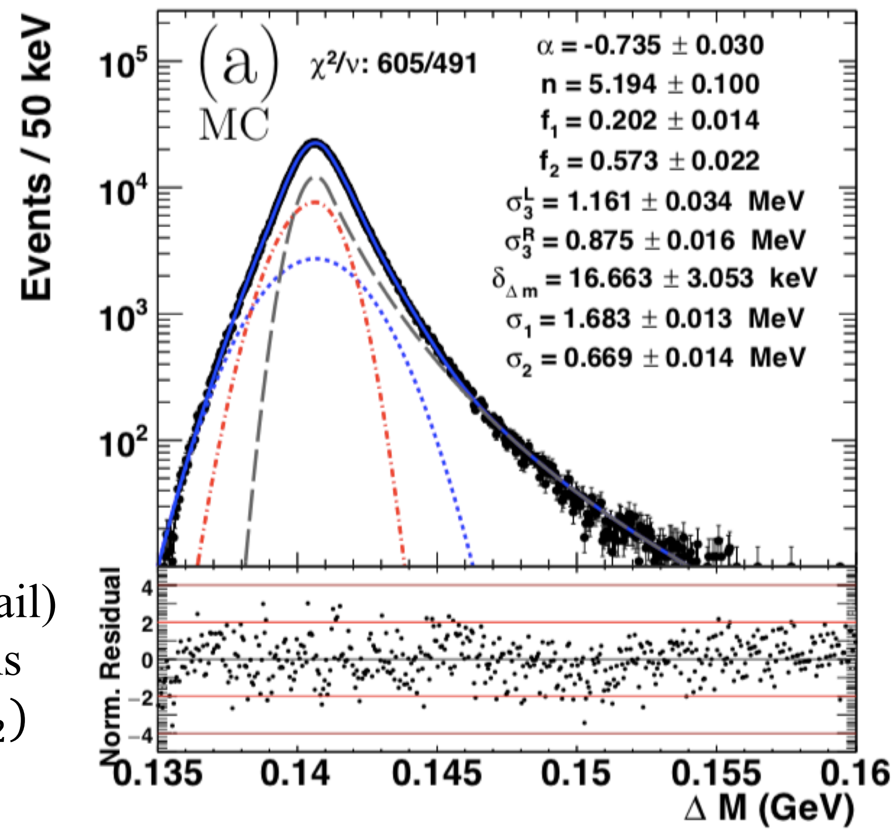
between the reconstructed masses of the D^{*+} and D^{+} candidates

- 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

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



G_1 =Gaussian
CB =Crystal Ball (Gaussian + RHS exponential tail)
G_2 =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:

$$a_1 G_1(\Delta m;\ m_{D^{*+}} - m_{D^+} + \delta, \sigma_1)$$
$$+a_2 CB(\Delta m;\ m_{D^{*+}} - m_{D^+} + \delta, \sigma_2, \alpha, n)$$
$$+a_3 G_2(\Delta m;\ m_{D^{*+}} - m_{D^+} + \delta, \sigma_3^L, \sigma_3^R)$$

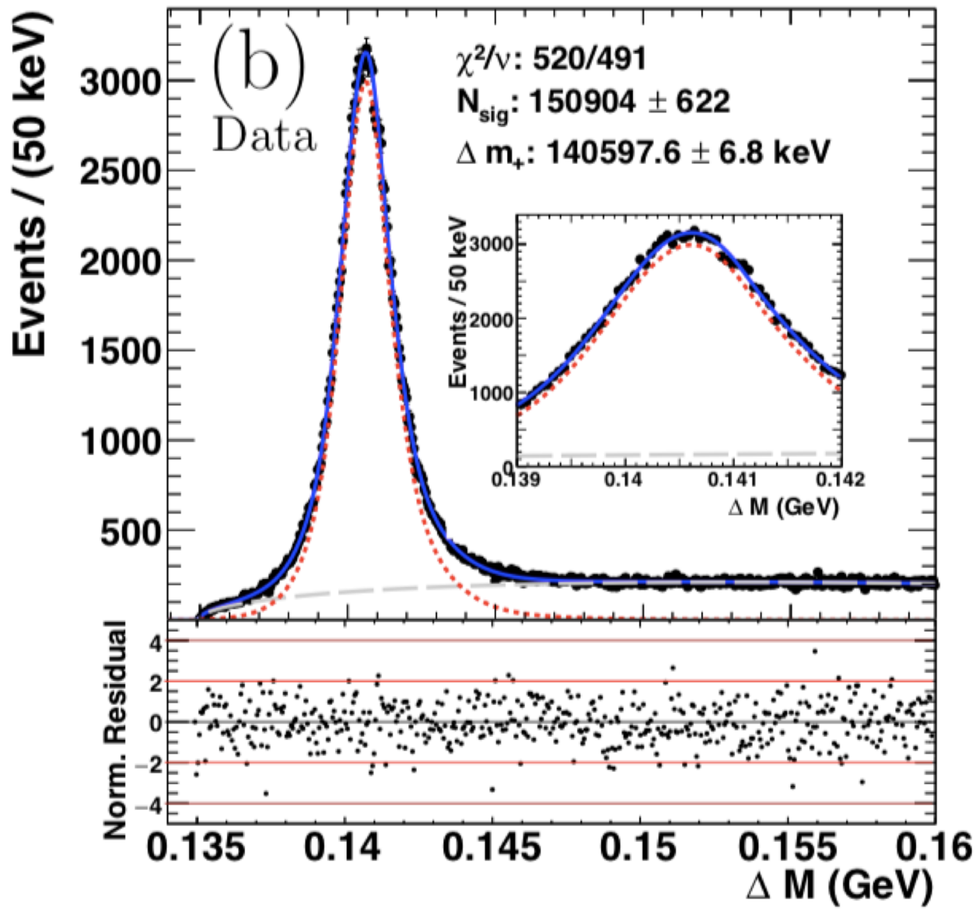
- Plus a background threshold function

$$\Delta m\sqrt{(\Delta m/m_{\pi^0})^2 - 1}\, e^{k(\Delta m/m_{\pi^0})}$$

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

- With this correction, we obtain

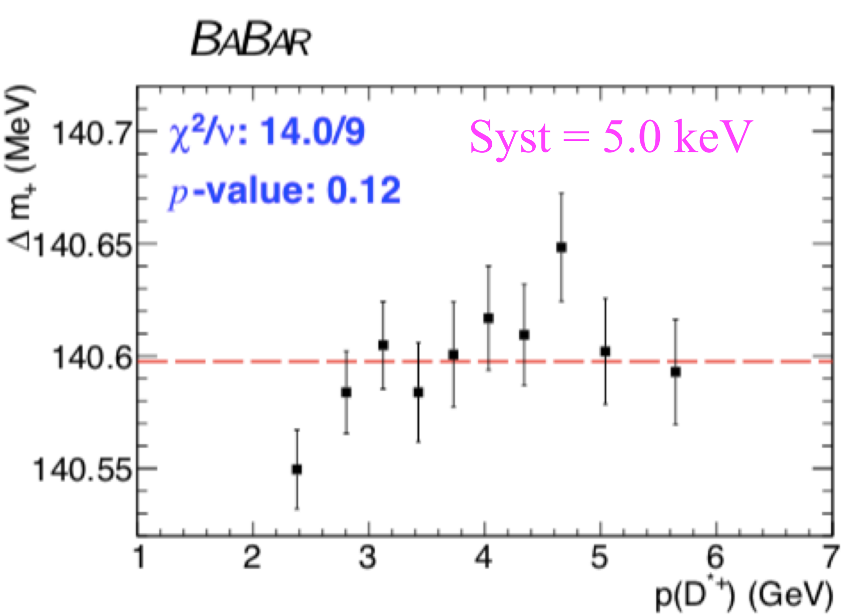
$$m_{D^{*+}} - m_{D^+} =$$
$$140{,}601.0 \pm 6.8\ \text{(stat)}\ \ \text{keV}$$



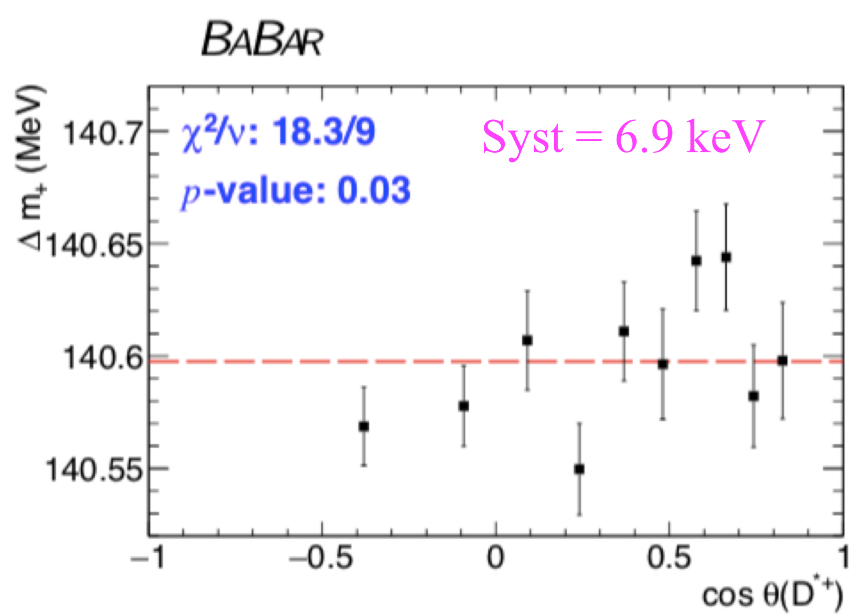
Systematic uncertainties

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

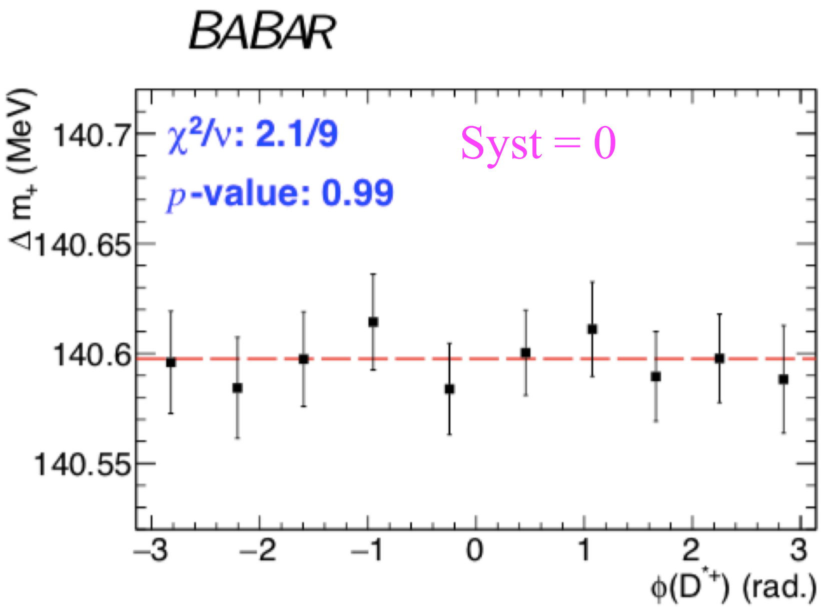
D^{*+} momentum



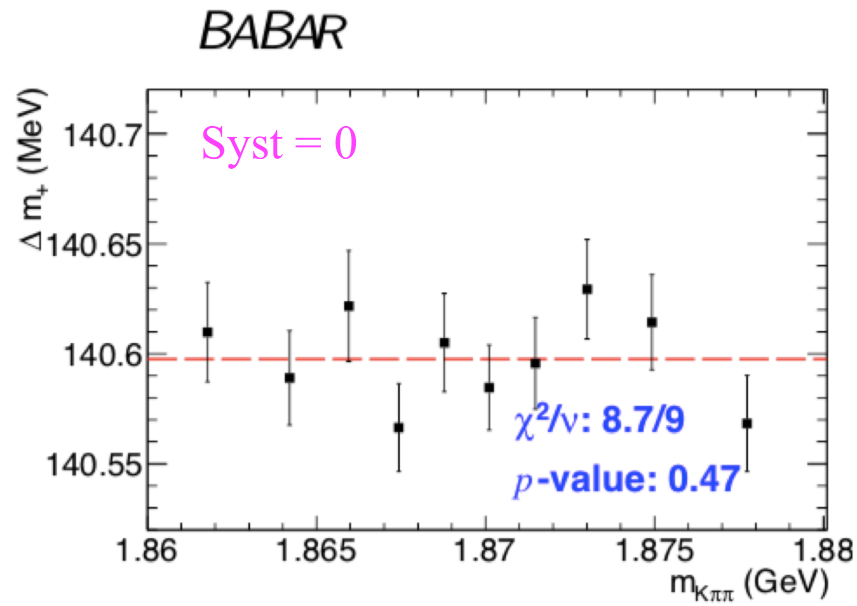
D^{*+} polar angle



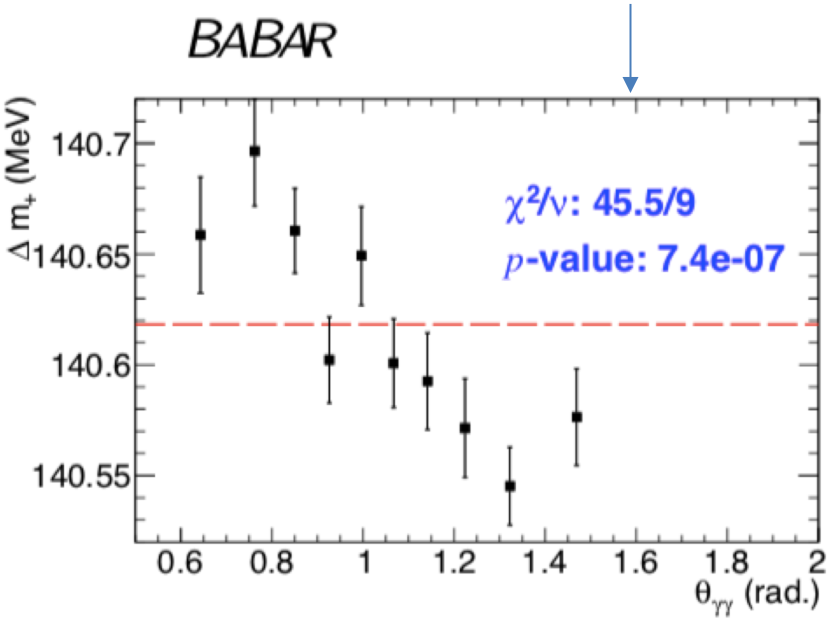
D^{*+} azimuthal angle

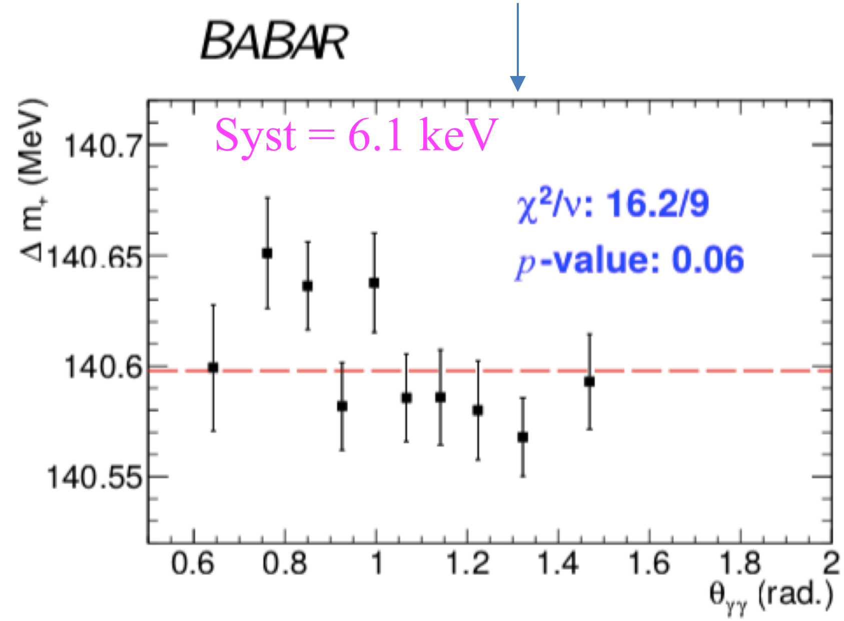


$m(K^-\pi^+\pi^+)$



Large dependence on $\gamma\gamma$ opening angle mostly accounted for by the calibration emulation





Systematic uncertainties

Source	Δm_+ systematic [keV]
Fit bias	1.7
D^{*+} $p_{\rm lab}$ dependence	5.0
D^{*+} $\cos\theta$ dependence	6.9
D^{*+} ϕ dependence	0.0
$m(D^+_{\rm reco})$ 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

Half the bias → Fit bias

Evaluate δ for different periods. No dependence → Run period dependence

Vary fixed fit parameters, accounting for correlations with toy MC → Signal model parametrization

Rescaling of γ energies by 0.3%, from data-MC m_{π^0} peak-position difference → EMC calibration

MC statistics in MC-to-data p_{π^0}-scaling parameters → MC π^0 momentum rescaling

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*!