Precision Measurements of Charmed Meson Properties at BaBar

David Muller, SLAC
representing the BaBar collaboration

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects
22-26 April, 2013, Marseille

- **Introduction**
- **Analysis techniques**
- **The D^0 mass**
- **The D^{*+}-D^0 mass difference and the D^{*+} natural width**
- **Summary**

new results:

pub. in preparation

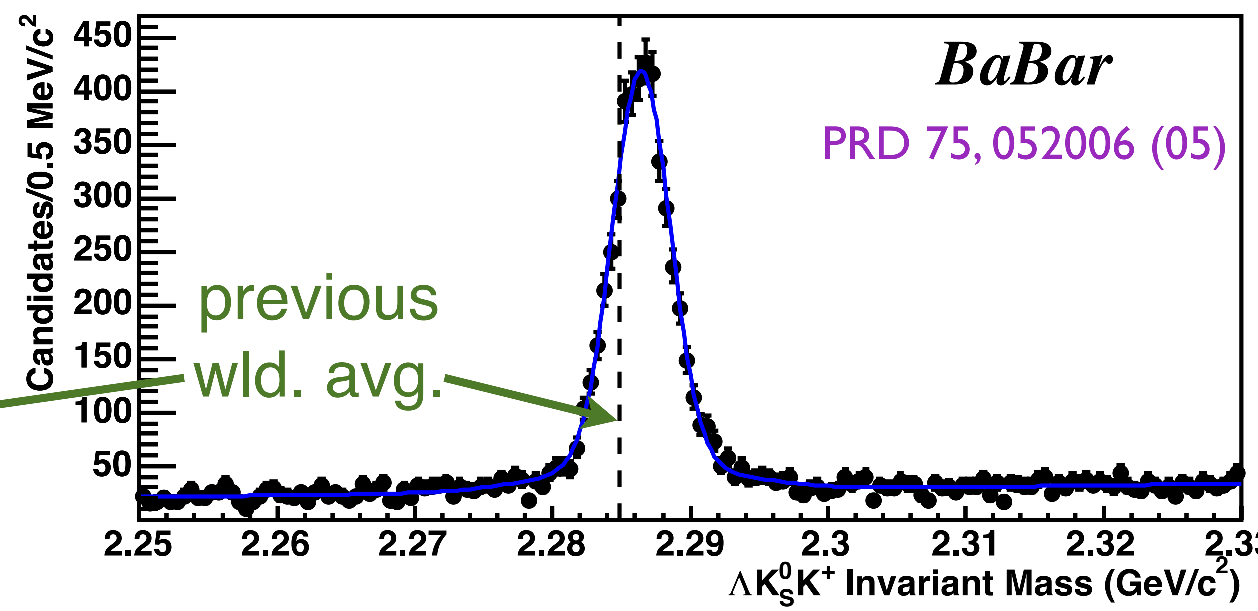
arXiv:1304.5009
submitted to PRD

Introduction

- would like to know masses and lifetimes/widths of all bound states precisely

- the D^0 is the lowest lying pseudoscalar $c\bar{u}$ state
  D^{*+} vector $c\bar{d}$
  → critical to understanding the charm quark
  → foundation for full set of $c\bar{q}$ states

- in 2005, BaBar measured the Λ_c^+ mass
  → nice improvement:
  2286.46 ± 0.14 MeV/c²
  2284.9 ± 0.6
  → remains the standard



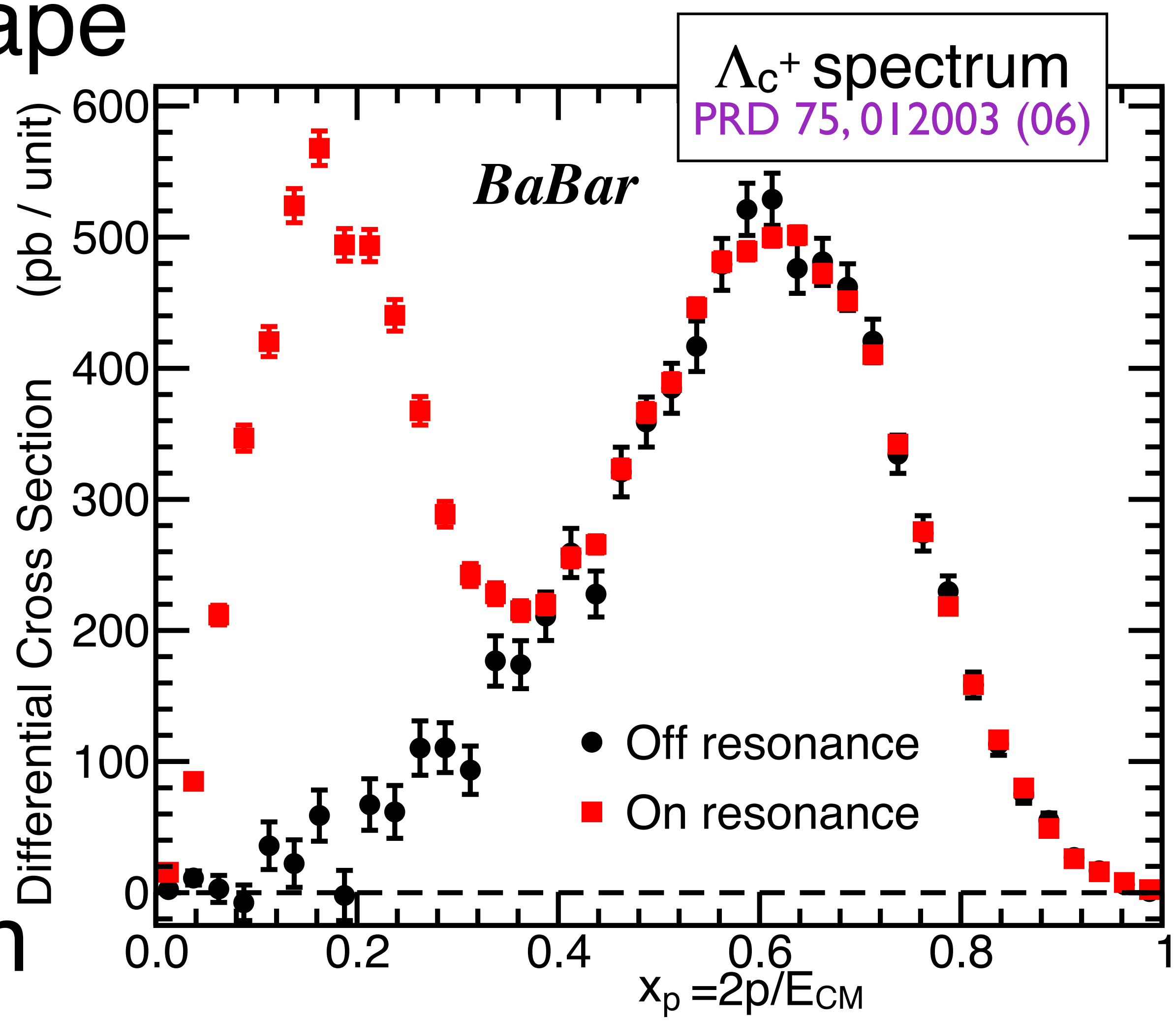
- current world avgs:

$m_{D^0} = 1864.86 \pm 0.13$ MeV/c²
$m_{D^{*+}} - m_{D^0} = 145.421 \pm 0.010$ MeV/c²
$\Gamma_{D^{*+}} = 96 \pm 22$ keV

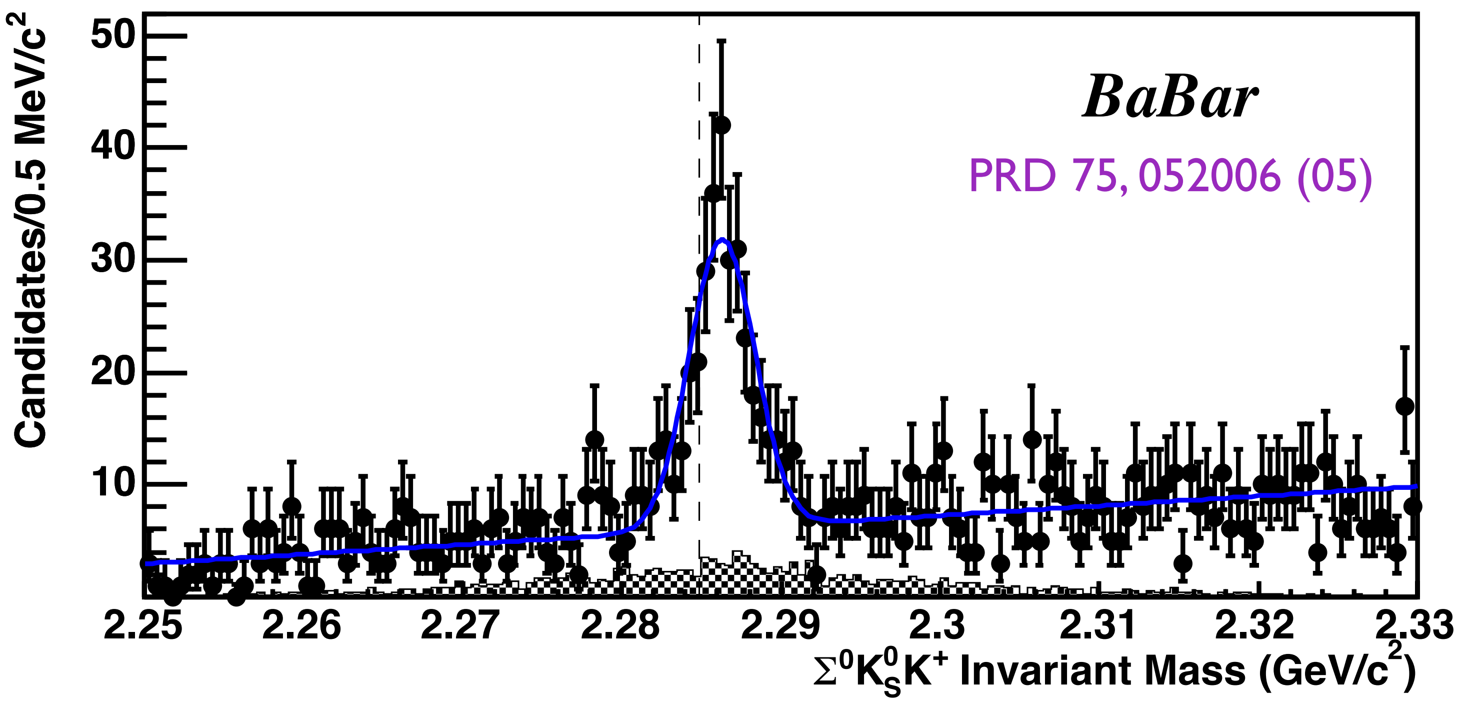
→ can we do better?

Analysis Techniques

- to make precise measurements, we need:
  - → high statistics ...
  - → in a sample with good resolution, systematic control
  - → where simulation, line shapes, etc. are reliable
- focus on signal:noise
  - → less sensitivity to background shape
  - → better control of signal shape
- tight particle identification
- go to high momentum
  - → combinatoric background drops rapidly with p
  - → effectively, use charmed hadrons from $c\bar{c}$ events, not B decays
  - → also helps mass resolution



- use a low Q decay mode
  - ➞ track angles become less important
  - ➞ mass resolution/bias ↔ momentum resolution/scale
  - ➞ $\Lambda_c^+ \to \Sigma^0 K_S^0 K^+$ has the same mass sensitivity as $\Lambda^0 K_S^0 K^+$, with 10% of the statistics

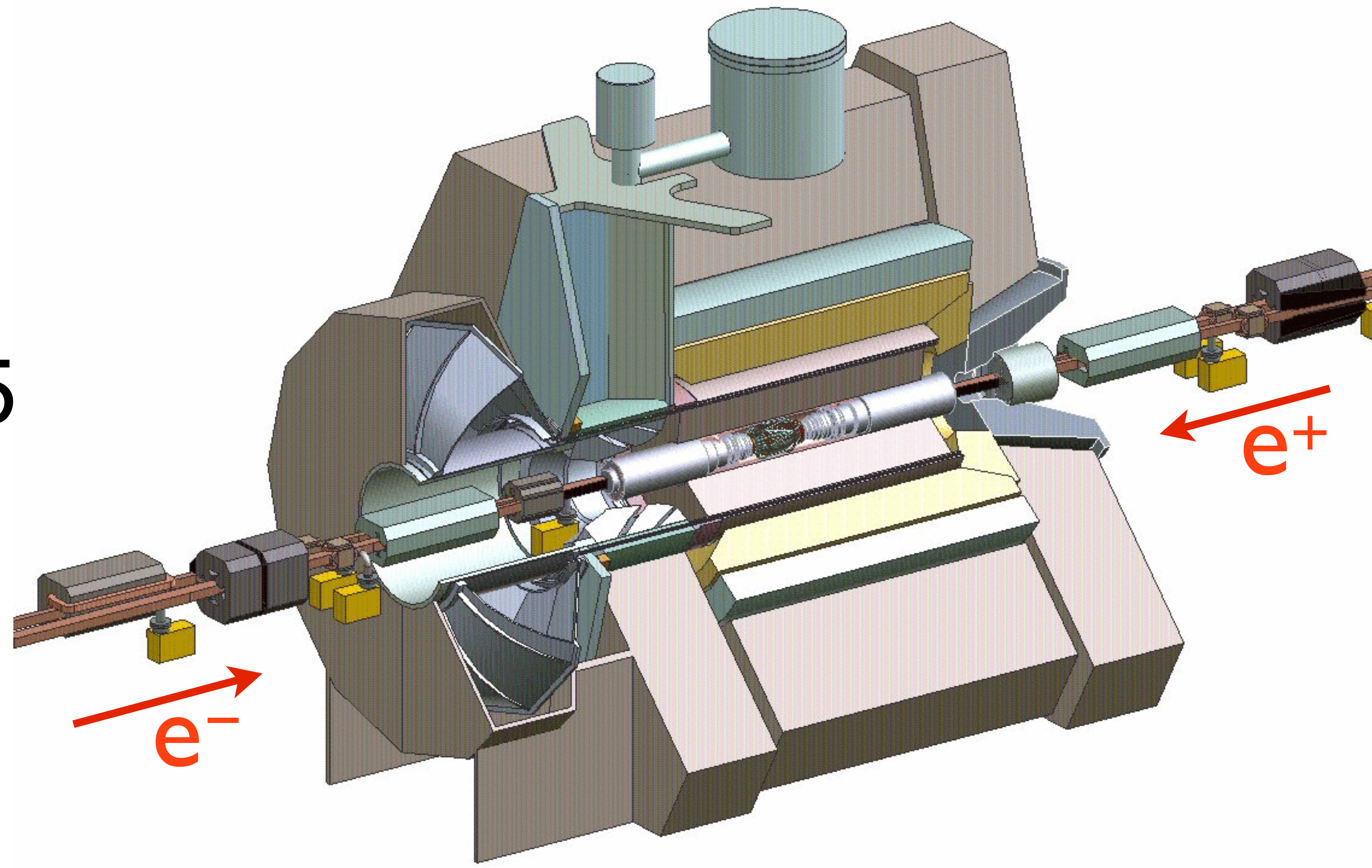


- use only well understood regions of the detector
  - ➞ minimize material interactions, measurement bias
  - ➞ further background suppression
  - ➞ calibrate where possible from the data

The BaBar Experiment

- e^+e^- collisions at E_{CM}=10.6 GeV, designed for CP violation in B decays

- Different beam energies
  - → E_{e^-} = 9.0 GeV
  - → E_{e^+} = 3.1 GeV
  - → c.m.-lab boost, $\beta\gamma$=0.55



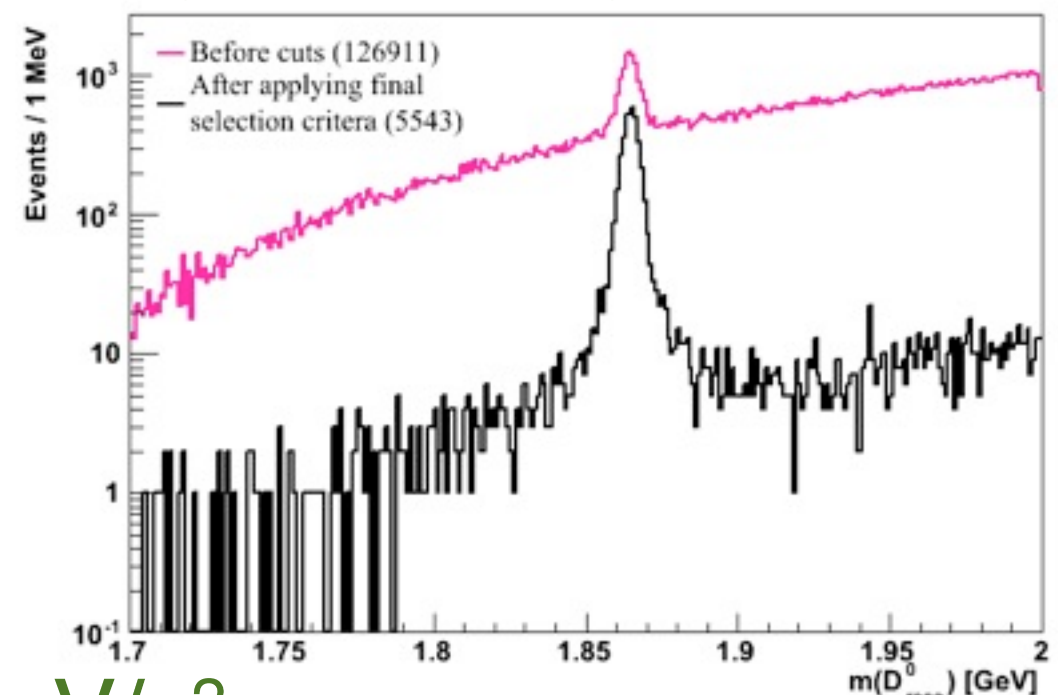
- Asymmetric detector
  - → c.m. frame acceptance $-0.9 \sim \cos\theta^* \sim 0.85$ wrt e^- beam

- with excellent performance
  - → good tracking, mass resolution
  - → good γ, π^0 recon.
  - → full e,μ,π,K,p ID

- High luminosity
  - → ~477 fb^{-1} used
  - ↔450 million Υ(4S) decays
  - ↔650 million $e^+e^-\rightarrow c\bar{c}$ events
  - ↔400 million $D^{*+}\rightarrow D^0\pi^+$

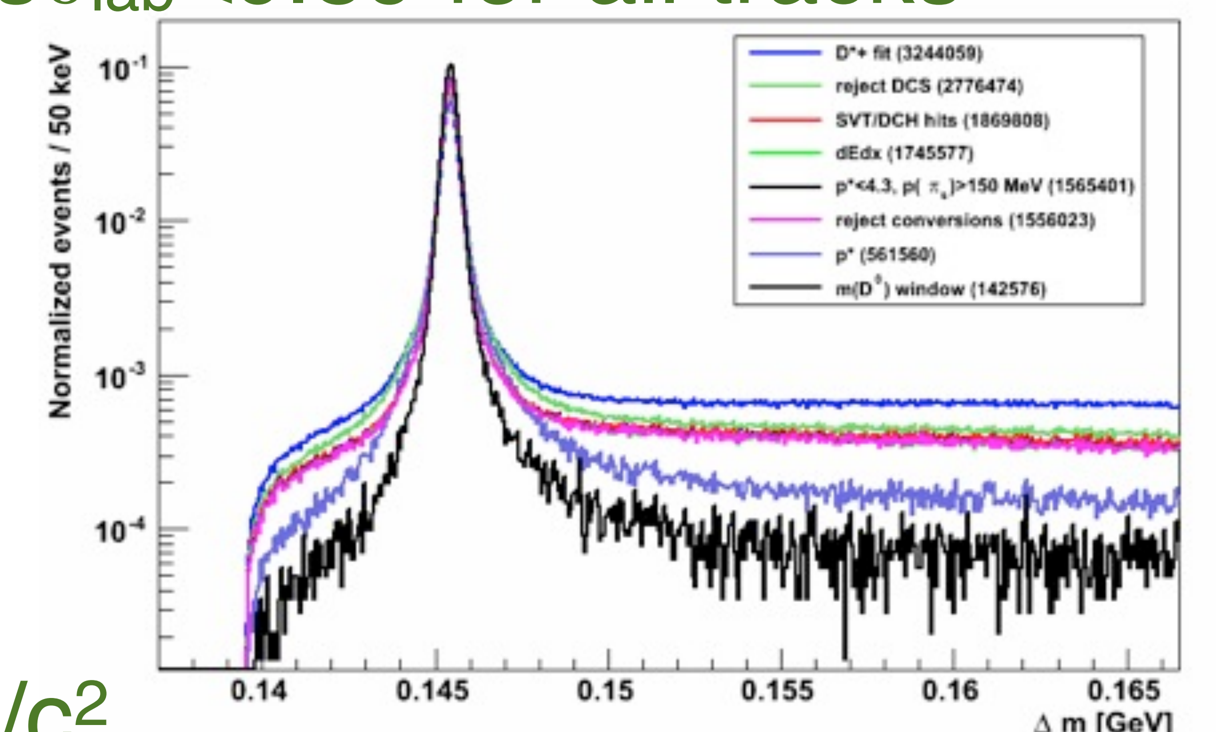
D^0 Selection for the m_{D^0} Measurement

- use the decay chain $D^{*+} \to D^0 \pi_s^+$, $D^0 \to K^- K^+ K^- \pi^+$ (&c.c.)
  - → $Q = 250$ MeV/c^2, $BF = 2.2 \times 10^{-4}$
  - → D^* tag reduces backgrounds
- particle identification: two identified K^-, one K^+, two π^+
- optimize S:N and mass resolution
  - → $K^- K^+ K^- \pi^- \pi_s^+$ momentum >2.5 GeV/c in the c.m. frame
  - → π_s^+ momentum > 0.15 GeV/c in the lab frame
  - → $\cos\theta_{lab} < 0.89$ for all tracks
- kinematic fits
  - → constrain all vertices
  - → choose best χ^2 if <20
- D^* tag
  - → $\Delta m = m_{KKK\pi\pi_s} - m_{KKK\pi} < 150$ MeV/c^2
  - → $\Delta m' = m_{KKK\pi\pi_s} - m_{KKK\pi_s} > 150$ MeV/c^2



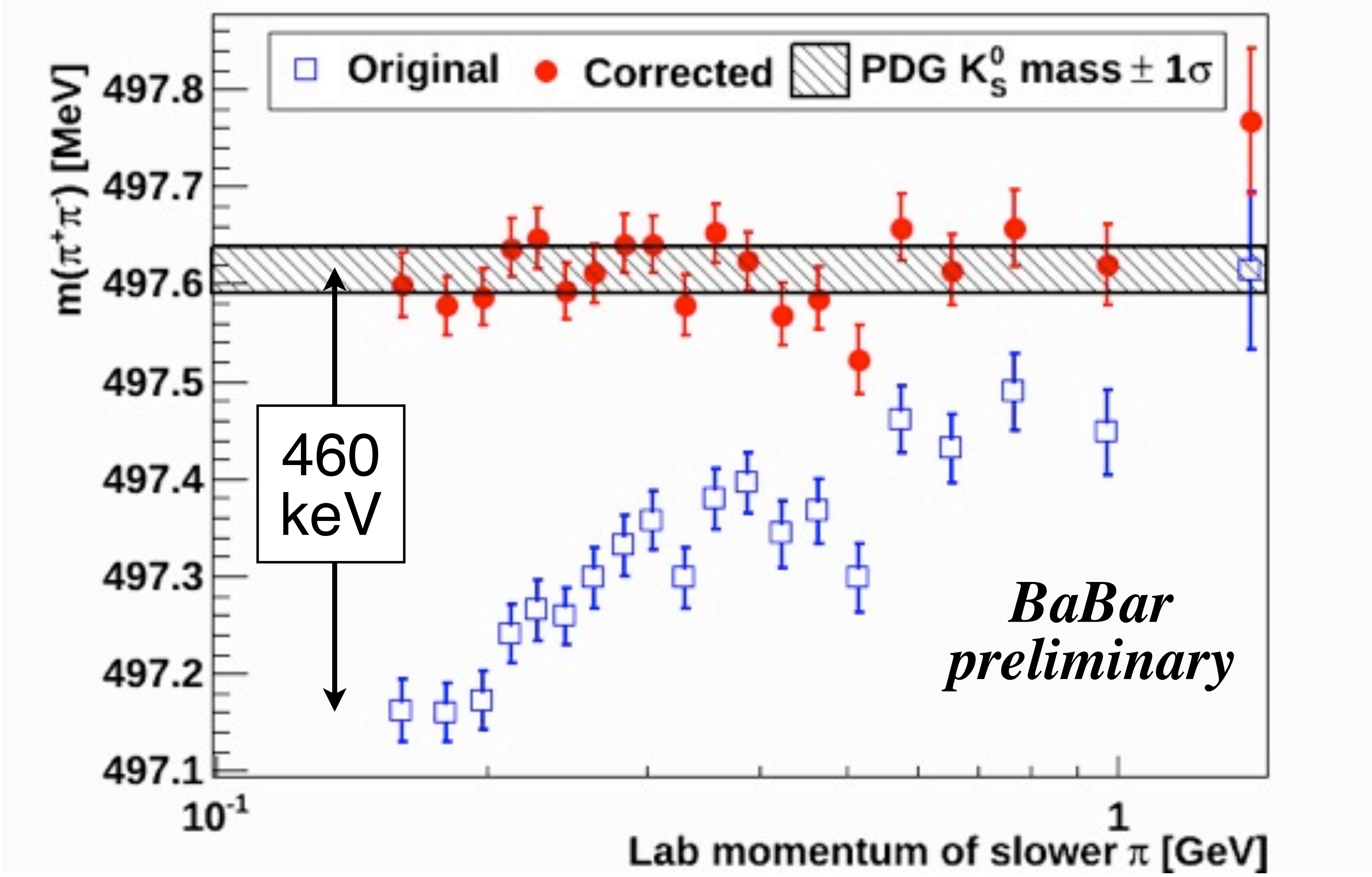
D^{*+} Selection for the Δm, Γ Measurements

- use the decay chains $D^{*+} \to D^0 \pi_s^+$, $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^- \pi^+$
  - → $Q = 145$ MeV/c^2, total BF=8%
  - → D^0 decay modes chosen for high S:N
- particle identification: one identified K^-, two or four $\pi^\pm$
- optimize S:N and momentum resolution
  - → $K^- \pi^+ (\pi^- \pi^+) \pi^- \pi_s^+$ $p_{cm} > 3.6$ and < 4.3 GeV/c
  - → additional quality cuts, $\cos\theta_{lab} < 0.89$ for all tracks
  - → π_s^+ $p_{lab} > 0.15$ GeV/c
- kinematic fits
  - → constrain all vertices
  - → best χ^2 C.L. if >0.001
- D^0 tag
  - → $1.86 < m_{K\pi(\pi\pi)} < 1.87$ GeV/c^2
  - → (both) $\Delta m' = m_{K\pi\pi\pi\pi_s} - m_{K\pi\pi\pi_s} > 166.5$ MeV/c^2



Energy Loss Corrections

- energy loss in the detector material must be understood
  - → especially at low p_{lab}
  - → … including all π_s^+
- study K_S^0 mass vs. lower track momentum, p_{min}
  - → $K_S^0 \to \pi^+\pi^-$ candidates from the chain $D^{*+} \to D^0\pi_s^+ \to K_S^0\pi^+\pi^-$
  - → deviation from PDG value at low p_{min}



- correct empirically: $E \to E + b_{bmp}E_{loss}^{bmp} + b_{SVT}E_{loss}^{SVT}$
  $p \to p(1+a)$

E_{loss}^{bmp}, E_{loss}^{SVT} are the losses returned by the Kalman filter at the beampipe and vertex tracker

a, b_{bmp}, b_{SVT} are free parameters

→ correction from fit to center of the PDG error band
→ uncertainty edges

D^0 Fitting Function

- width and mass results depend critically on correct signal and background shapes, respectively

$D^0 \to K^- K^+ K^- \pi^+$

- fit to the distribution of $K^- K^+ K^- \pi^+$ masses, m
- use a Voigtian signal PDF

$$P(m) = \frac{1}{(m - m_D)^2 - \gamma^2/4} \otimes \exp(-(m - m_D)^2/2\sigma^2)$$

→ all parameters free in fit
→ result insensitive to choice of function

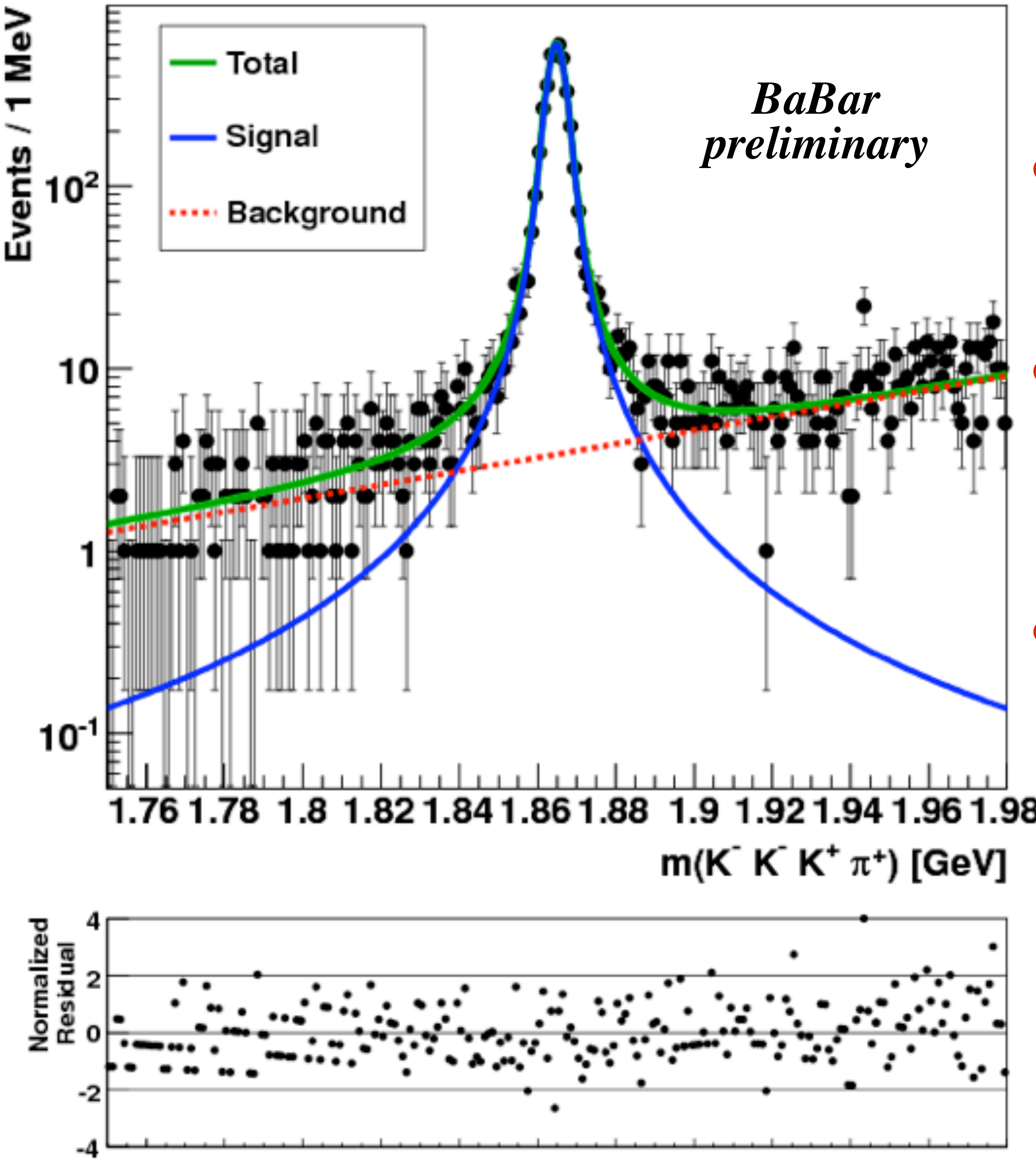
- and an exponential background PDF

$$B(m) = Ae^{Cm}$$

→ A, C free
→ small sensitivity to shape, since background is low

$D^0 \rightarrow K^-K^+K^-\pi^+$ Fit

- unbinned maximum likelihood fit



→ fit has good quality

- 4345±70 signal events
  → largest such sample

- resolution parameters consistent with simulation

- result: m_{D^0} =
  1864.841 ± 0.048 (stat.)

D^{*+} Fitting Function

$D^{*+} \rightarrow D^0 \pi^+$

- fit to the distribution of mass differences masses, Δm
- for background, use a threshold PDF

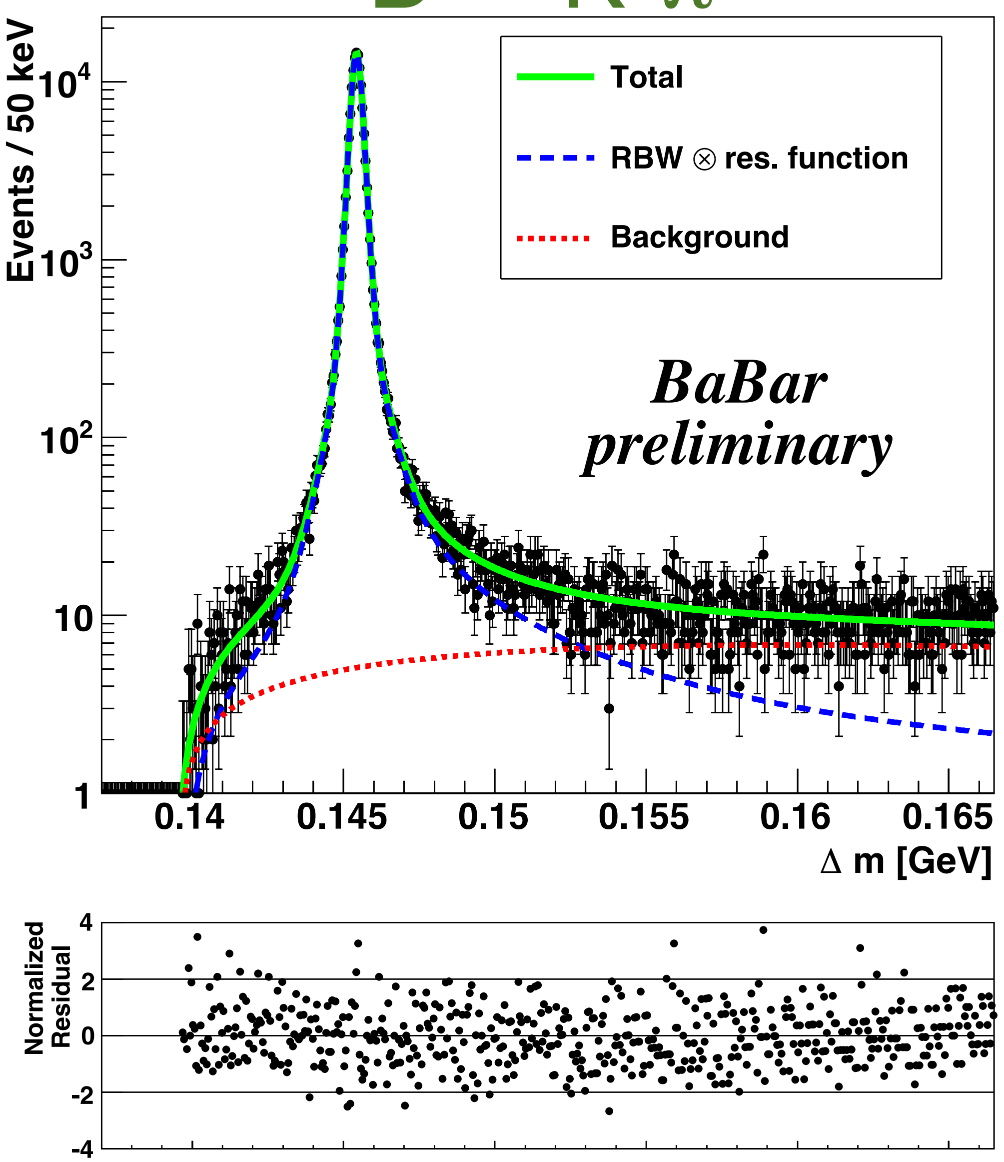
$$B(\Delta m) = \Delta m \sqrt{u} e^{cu}, \quad u = (\Delta m / m_\pi) - 1$$

  → c is the one free parameter
  → tested on simulation, data in other decay modes

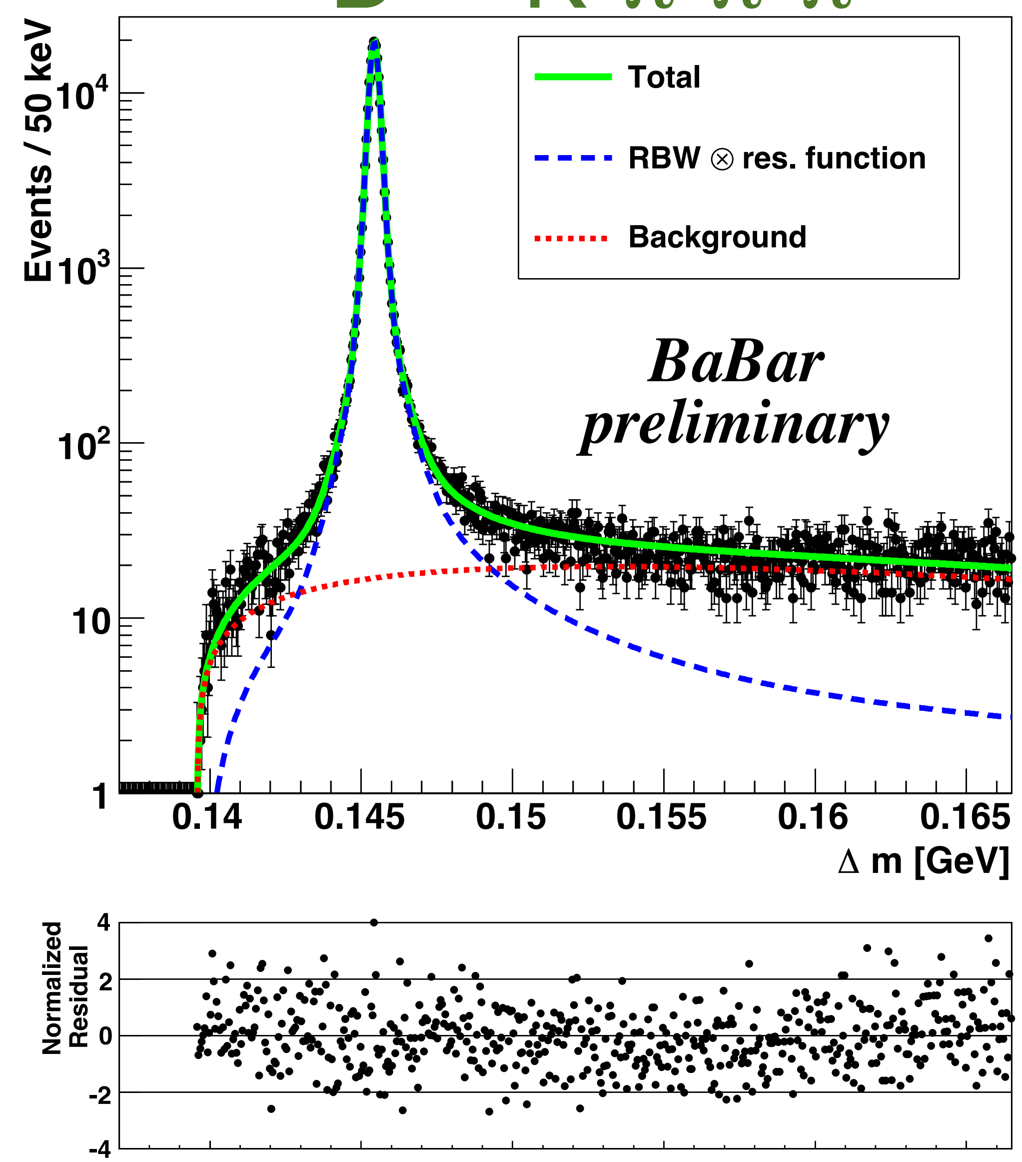
- for signal, use a relativistic P-wave Breit Wigner x phase space convolved with a resolution function
  → resolution function is a sum of three Gaussian fcns
  → ...and a $\Delta m u^q e^{au}$ term to account for $\pi_s^\pm$ decay in flight
  → most resolution parameter values fixed from simulation
  → an overall width scale factor and the BW parameters are left free

$D^{*+} \rightarrow D^0\pi^+$ Fits

$D^0 \rightarrow K^-\pi^+$



$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$



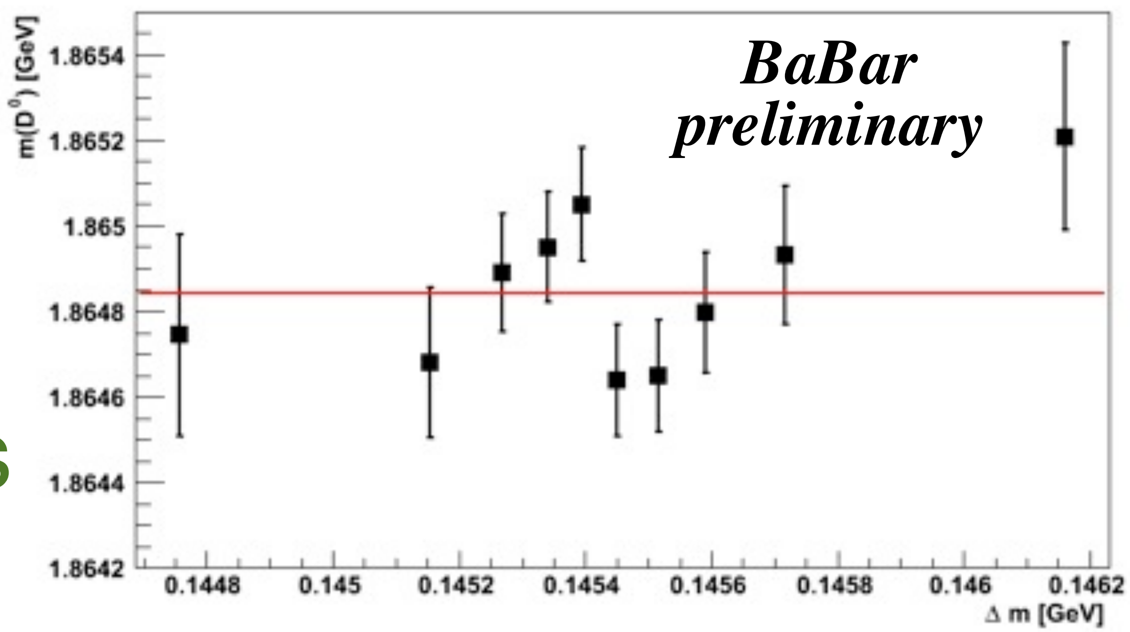
good quality fits

$D^0 \rightarrow K^-\pi^+$		$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
138,539±109	signal events	174,286±50
1.06±0.01	resolution scale factor	1.08±0.01
0.8	S:B at 155.4 MeV/c^2	0.3

- width extracted from Breit-Wigner tails

Systematic Uncertainties

- vary energy loss correction based on PDG K^0_S mass
  - → important for masses, not for widths
- vary form and parameters of signal, background PDFs
  - → small sensitivity to Blatt-Weisskopf radius, most resolution parameters
  - → width is sensitive to range of fit
- disjoint subsets in ϕ, $D^{(*)}$ momentum, Δm or m_{D0}
  - → ϕ is the azimuthal direction of the $D^{(*)}$ in the detector
  - → these three quantities chosen in advance as indicators of specific potential problems
  - → compare subsets, if χ^2/ndf > 1 then inflate error using PDG method
  - → example shown contributes ± 28 keV/c^2 to m_{D0} error



D^0 Mass Results

- $Q = m_{D^0} - 3m_{K^\pm} - m_{\pi^\pm} = 244.240 \pm 0.048 \pm 0.041$ MeV/c^2
  (stat.) (syst.)

  → systematic uncertainty dominated by
  energy loss calibration (31 keV/c^2)
  disjoint subsets (28)

- $m_{D^0} = 1864.841 \pm 0.048 \pm 0.041 \pm 0.046$ MeV/c^2
  (stat.) (inst.) ($m_{K^\pm}$)

  → total uncertainty sensitive to the PDG $K^\pm$ mass error!

- compare m_{D^0} =

1864.841	$\pm$ 0.078 MeV/c^2	BaBar
1864.86	$\pm$ 0.13	PDG fit
1864.91	$\pm$ 0.17	PDG avg.
1864.847	$\pm$ 0.178	CLEO=best previous

D^{*+} Mass and Width Results

- results from the two D^0 decay modes are consistent
  → weighted averages taking all correlations into account
- $\Delta m = m_{D^{*+}} - m_{D^0} =$ 145 425.8 ± 0.5 (stat.) ± 1.8 (syst.) keV/c^2
  c.f. 145 410 ± 10 PDG
  145 412 ± 12 CLEO=best previous
- $\Gamma_{D^{*+}} =$ 83.3 ± 1.3 (stat.) ± 1.4 (syst.) keV
  cf. 96 ± 4 ± 22 PDG=CLEO=best prev.
- test prediction of a universal coupling $g=\Gamma/R$ from χPT
  → R from Di Pierro and Eichten PRD 64, 114004 (01)

State	Γ	R	g
$D^*(2010)^+$	83.3 ± 1.9 keV	143 keV	0.76 ± 0.01
$D_1(2420)^0$	31.4 ± 1.4 MeV	16 MeV	1.40 ± 0.03
$D_2^*(2460)^0$	50.5 ± 0.9 MeV	38 MeV	1.15 ± 0.01

→ confirm discrepancy seen in other excited D states

Summary

- BaBar continues to make precise measurements of heavy hadron masses and widths
  → very high statistics
  → well understood detector

- new measurement of the D^0 meson mass:
  1864.841 ± 0.048 (stat.) $\pm$ 0.062 (syst.) MeV/c^2
  → 1.7x more precise than current world average
  → statistical error ≈ effect of error on $K^\pm$ mass

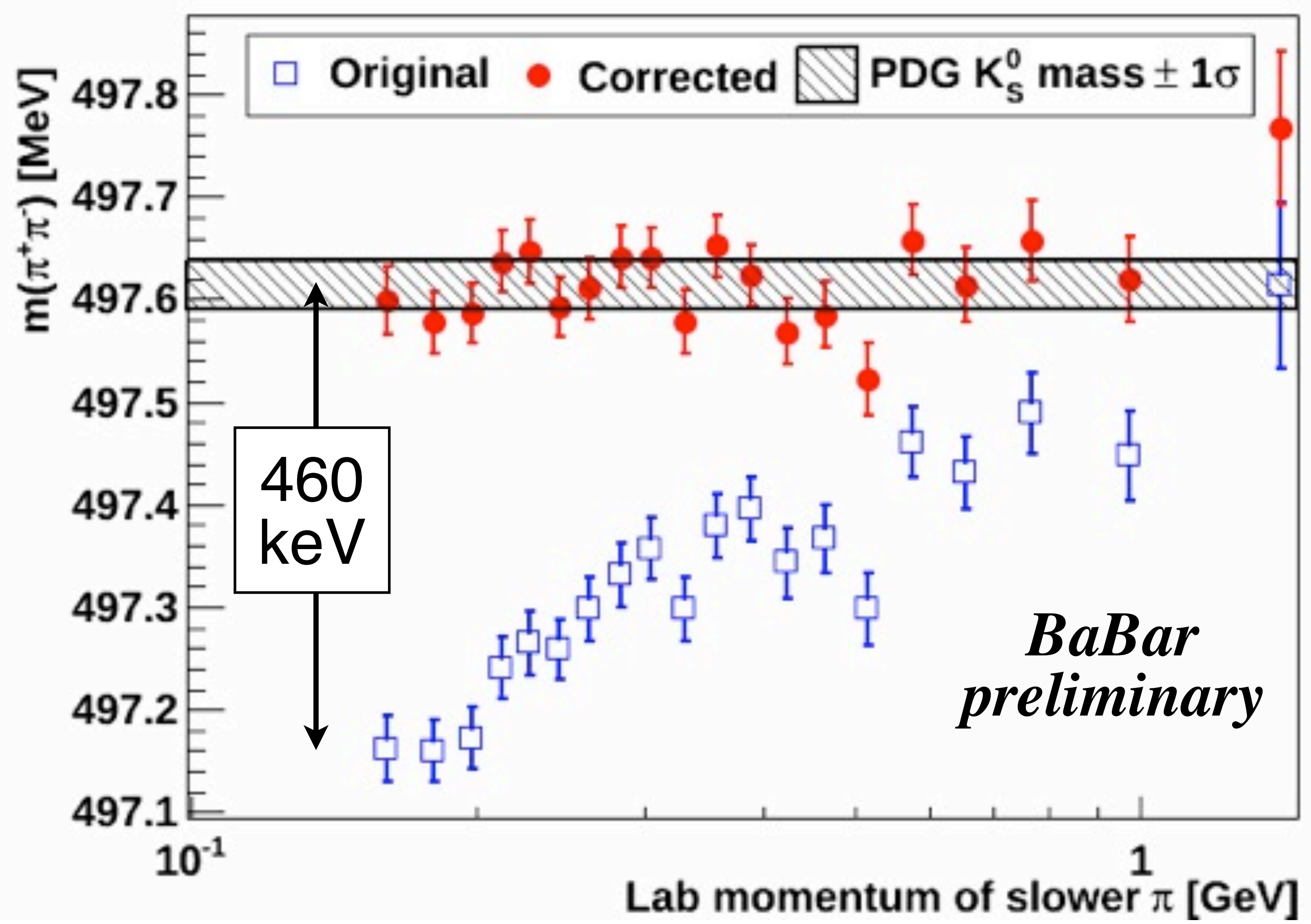
- new measurement of the D^{*+}-D^0 mass difference:
  $145\,425.8 \pm 0.5$ (stat.) $\pm$ 1.8 (syst.) keV/c^2
  → 5x more precise than current world average

- new measurement of the D^{*+} meson width:
  83.3 ± 1.3 (stat.) $\pm$ 1.4 (syst.) keV
  → 12x more precise than current world average
  → inconsistent with the model of Di Pierro and Eichten

Backup Slides

Energy Loss Details

- combination of studies suggests possible problems with
  - → beampipe material description in Kalman filter
  - → SVT material description in Kalman filter
  - → B field scale
- choose correction values by matching to PDG K^0_S mass
  - → find a=0.003; 0.002 uncertainty on B field
  - → b_{bmp}=0.018
    b_{SVT}=0.059
    consistent with expectations



- energy loss is well constrained by tracks in our data with characteristics similar to our signal tracks
  - → PDG K^0_S mass error → our largest systematic on mass measurements