Precise Measurement of D^0 mass and D^* linewidth with BaBar

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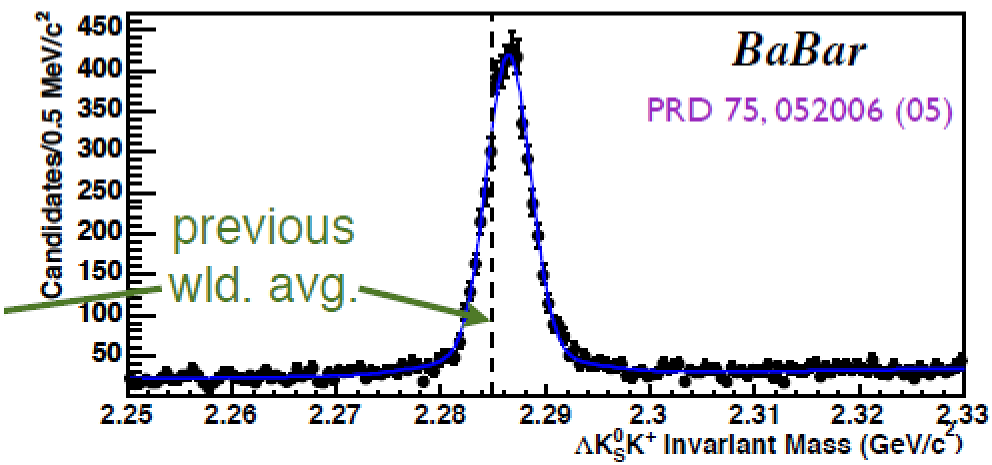
Synopsis

- Introduction
- D^0 Mass [pub. in preparation]
- D^* linewidth and D^*-D^0 mass difference [arXiv:1304.5009 submitted to PRD and arXiv:1304.5657 submitted to PRL]
- Summary

Motivation

- D^0 mass
  - Foundation for a full set of $c\bar{q}$ states, for example D* mass from $\Delta m = m(D^*) - m(D^0)$ and $m(D^0)$
  - X(3872) exotic state very close to D^0D^{*0} threshold: D^0D^{*0} molecule ?
- Measurement of masses of charmed hadrons known with a precision of 0.5-0.6MeV/c^2 based on measurements from the '80s and '90s (<1k events)
- B-Factories are able to improve significantly due to high statistics O(1M events) by increasing the purity and keep sys errors under control
- In 2005 BaBar measured

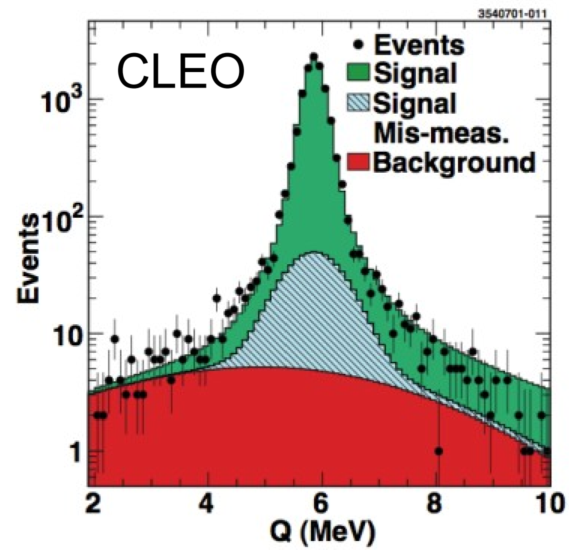
  the Λ_c mass
  - 2286.46 ± 0.14 MeV/c^2 BaBar
  - 2284.9 ± 0.6 MeV/c^2 PDG



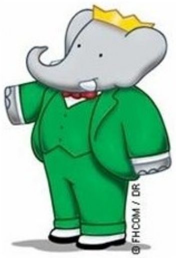
Motivation

- D* linewidth provides a window in non perturbative strong phys.
  - From the D* linewidth one can obtain $g_{D^*D\pi}$ the strong coupling of a heavy charm meson to a pion
  - $g_{D^*D\pi}$ can be related, in chiPT, to the universal strong coupling of a heavy meson to a pion => can be used to obtain the kinematically forbidden $g_{B^*B\pi}$
  - $g_{B^*B\pi}$ is one of the largest contributions to the theoretical uncertainty on $|V_{ub}|$

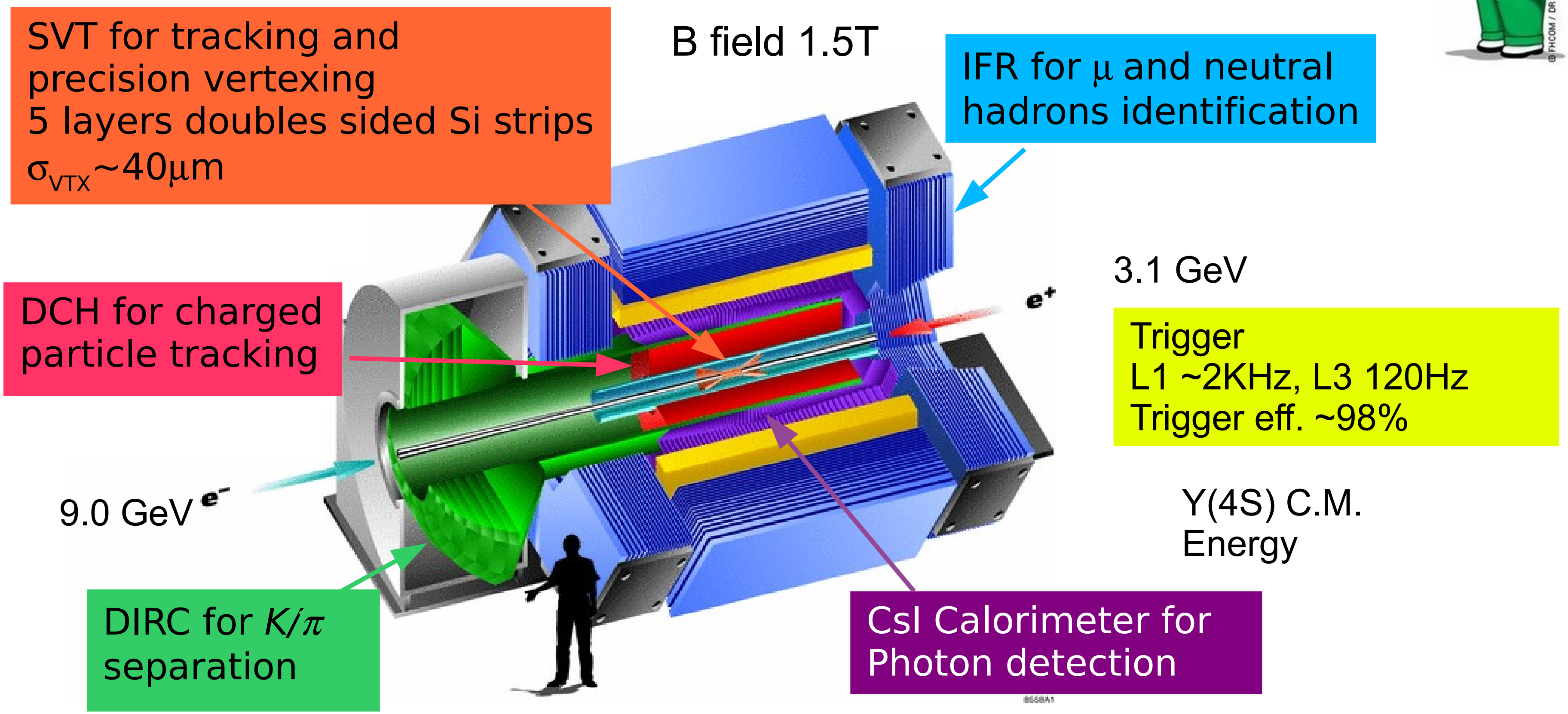
- Previous measurement by CLEO (Phys.Rev.D65:032003,2002):)
  - $\Gamma(D^{*+})$ = 96 ± 4 ± 22 keV
  - 11,000 cand. Sample (9fb^{-1})



BaBar Detector at PEPII



Nucl.Instrum.Meth.A479:1-116,2002

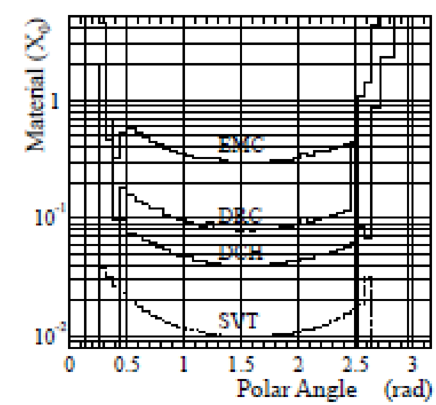


Integrated Luminosity 1999 – 2008

On-Peak 477 fb^{-1} ~4xx MBB

Off-Peak 44 fb^{-1},

100M Υ(2S), 120M Υ(3S), 4fb^{-1} above Υ(4S)

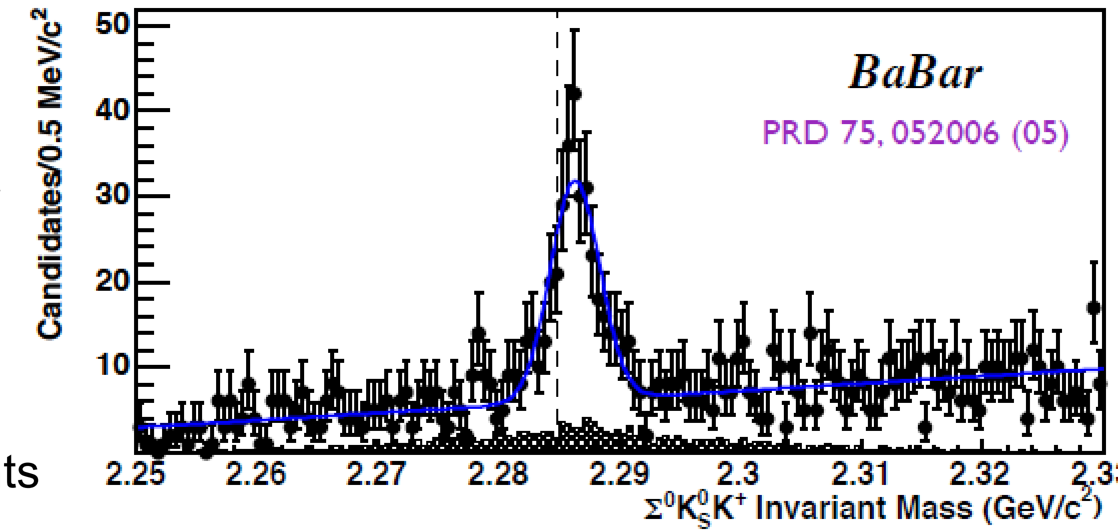


Analysis Strategy

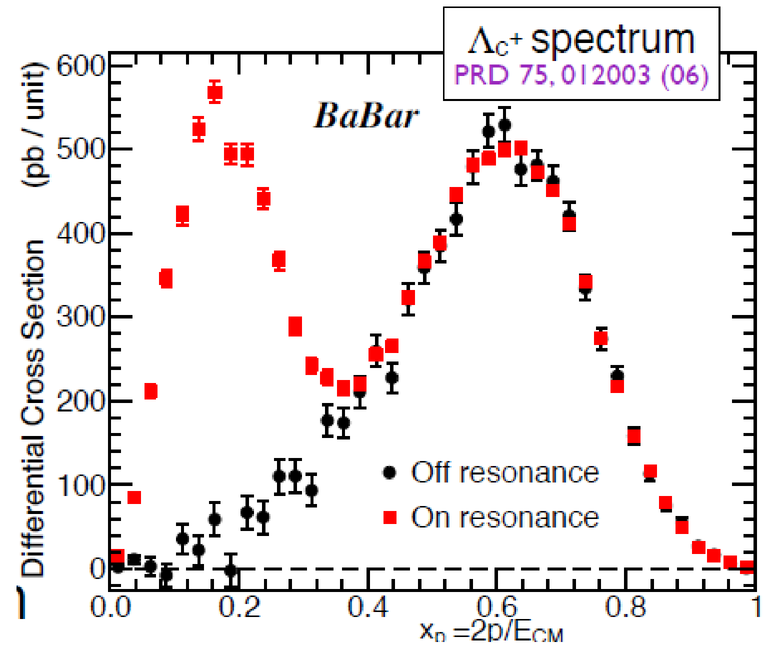
- Precise mass measurements requires
  - Good track momentum and angles measurement
  - High statistics and low background
  - Control over systematic errors
- Track momentum and angles
  - Critical point is energy loss in the material and overall magnetic field strength
  - Seen in K^0_S and Λ^0 mass naive measurement
  - Correcting the material simulation is difficult
    - => Use a low Q-value decay
    - => calibrate energy loss from data

Control over systematic errors

- Low Q-value
  - Track angles become less important
  - Mass resolution/bias ↔ momentum resolution/scale
  - Example: $\Lambda_c^+ \to \Sigma^0 K_S K^+$ has same resolution as $\Lambda^0 K_S K^+$ with 10% events
- Use only well understood regions of the detector - avoid edges of angular acceptance

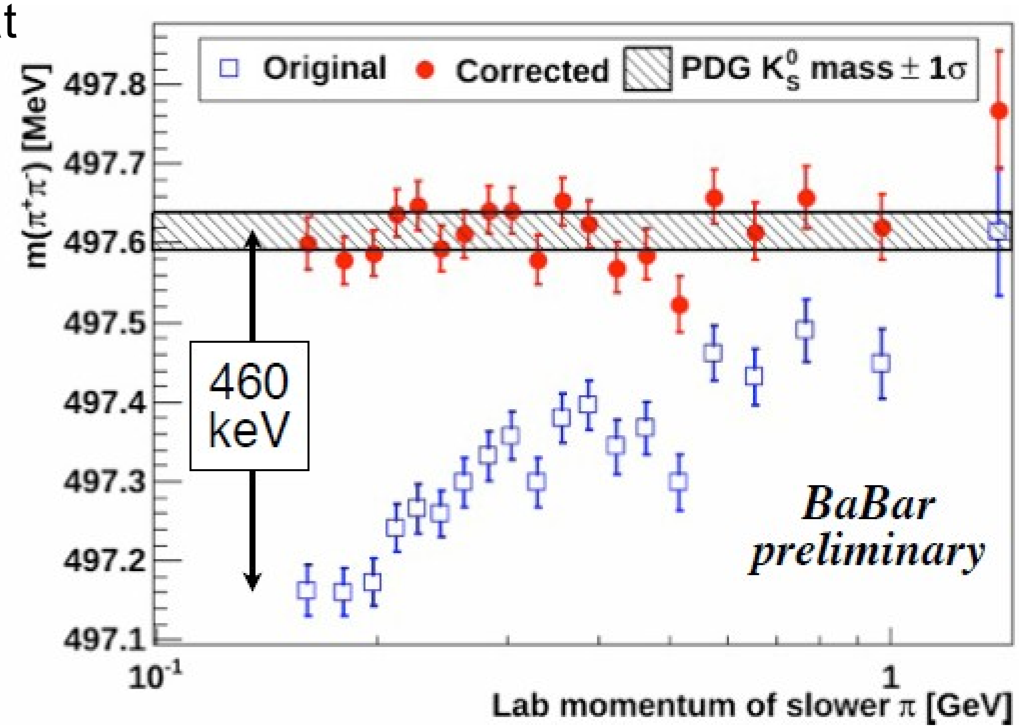


- Low background
  - Tight particle ID
  - High momentum
    - Charmed hadrons from cc events



Energy loss and magnetic field correction

- Energy loss correction especially relevant at low p_{lab} : $dE/dx \sim 1/\beta^2 = 1 + m^2/p^2_{lab}$
- In $D^* \to D^0 \pi^+_S$ the π^+_S can have momentum 50-400MeV/c
- Empirically correct energy loss and momentum scale using data
  - $K_S \to \pi^+\pi^-$ from $D^{*+} \to D^0\pi^-_S$, $D^0 \to K_S\pi^+\pi^-$



- Deviation from PDG value observed at low p_{min}
- E^{bmp}_{loss}, E^{SVT}_{loss} energy loss in material returnd by Kalman fit
- a, b_{bmp}, b_{SVT} fitted on data to minimize difference w.r.t. PDG value
- b_{bmp}=1.8%, b_{SVT}=5.9%, a=0.03%

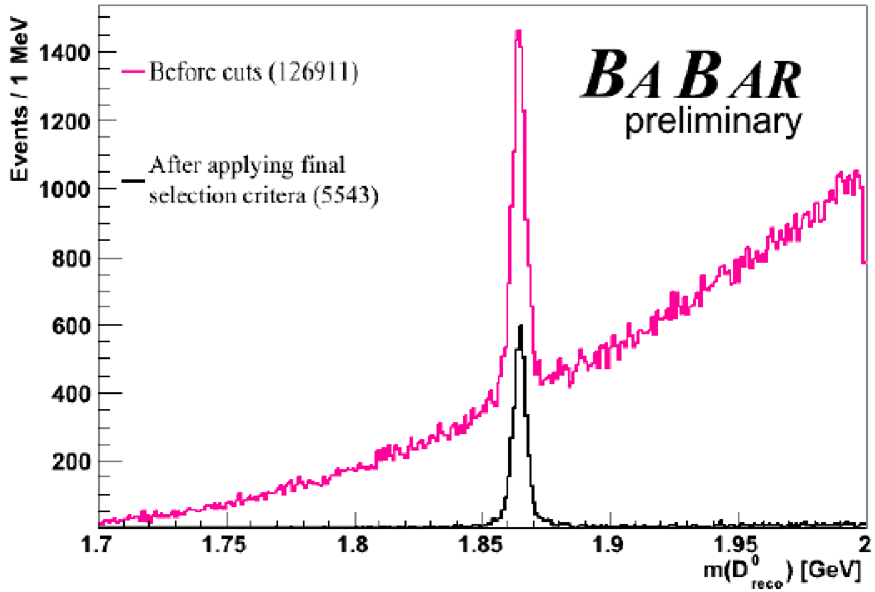
$$E \to E + b_{bmp} E^{bmp}_{loss} + b_{SVT} E^{SVT}_{loss}$$
$$p \to p(1+a)$$

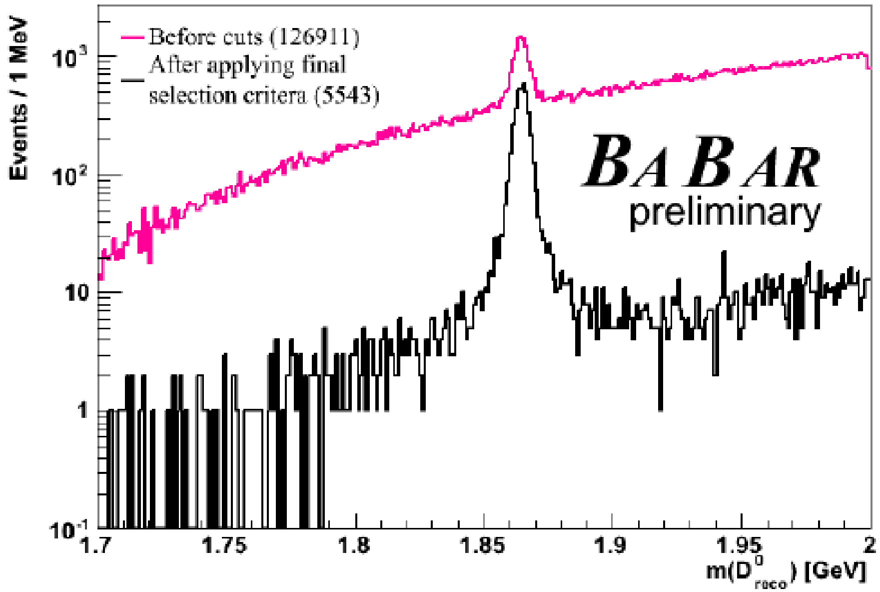
D^0 mass measurement

- World average: $m(D^0)=(1864.86 \pm 0.13)$ MeV/c^2
- Best previous measurement, by CLEO (2007), using 319 signal events $D^0 \rightarrow \phi K^0_S$, precision $(0.15 \oplus 0.09)$ MeV/c^2
- This measurement using 4345 signal events $D^* \rightarrow D^0 \pi^+_s, D^0 \rightarrow K^- K^- K^+ \pi^+$, Q-value~250MeV/$c^2$, BF=$2.2 \times 10^{-4}$,D* tag to reduce background
- Selection optimized on 5% and of data and systematic studies with blind central value to avoid bias
- Tight cuts in order to keep systematic errors under control

D^0 mass: signal selection

- Purity and significance
  - $P_{CM}(D^*)>2.5$ GeV/c^2
  - PID on K and π
- Well understood tracking
  - $P_{LAB}(\pi_S^+)>0.15$GeV/c
  - $\cos(\theta_{LAB})<0.89$
- D*tag
  - $\Delta m=m_{KKK\pi\pi_S}-m_{KKK\pi}$
  - $\Delta m-\Delta m_{PDG}<1.5$ MeV/c^2
  - $\Delta m'=m_{KKK\pi\pi_S}-m_{KKK\pi_S}>150$MeV/$c^2$
- Kinematic fit constraining each vertex to choose best candidate





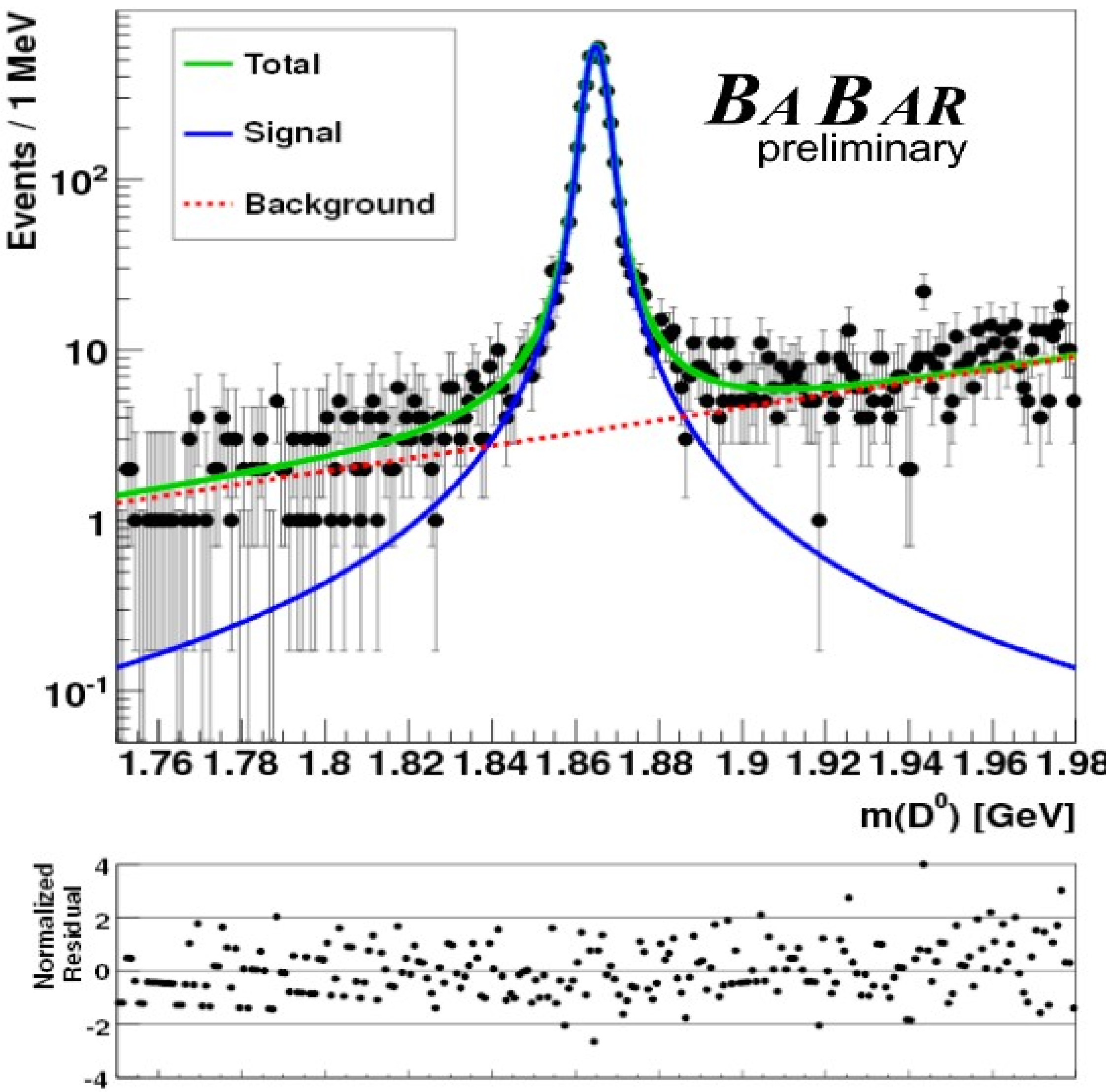
Signal model

- $D^0 \to K^- K^- K^+ \pi^+$
- Unbinned ML fit of $m(K^- K^- K^+ \pi^+)$ with Voigtian signal p.d.f. and exponential background p.d.f.

$$V\left(m; m_D, \gamma, \sigma\right) = \frac{1}{\left(m - m_D\right)^2 + \frac{1}{4}\gamma^2} \otimes \exp\left[-\frac{1}{2}\frac{\left(m - m_D\right)^2}{\sigma^2}\right]$$

- All parameters free in fit, σ and γ ad-hoc parameters to model resolution
- Results insensitive to choice of function
  - Double Gaussian gives no change

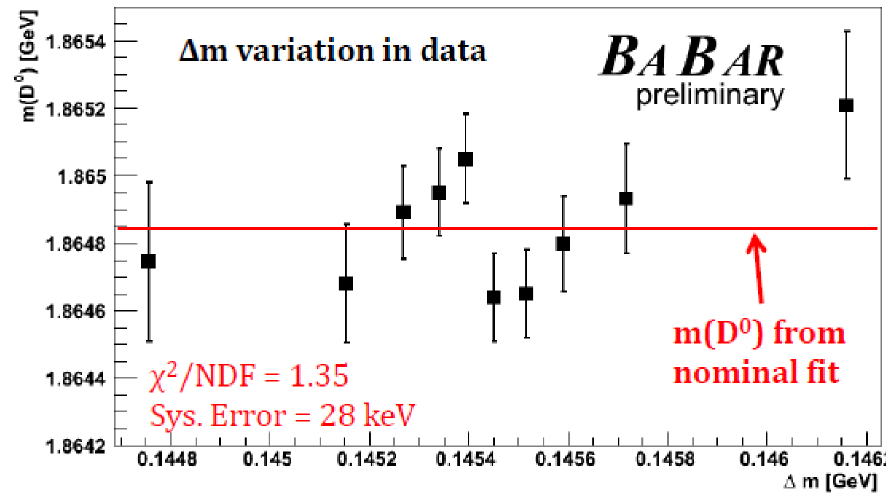
$D^0 \to K^- K^- K^+ \pi^+$ fit to data



- D0 mass 1864.841 ± 0.048 MeV/c^2
- S=4345±70
- Resolution parameters consistent with simulation
- Normalized residuals show good quality of fit

D^0 mass systematic errors

- Split dataset into disjoint subsamples → check consistency
  - Azimuth angle
  - $p_{lab}(D^0)$
  - Δm



$$\sigma^2 = \sigma^2_{stat} + \sigma^2_{sys}$$

- If $\chi^2/_{NDOF}$>1 use the PDG scale factor method to assign a systematic error

Rescaled error $\sigma^2 = S^2\sigma^2_{stat}$

Scale factor $S^2 = \chi^2/NDF$

Sys. error $\sigma_{sys} = \sigma_{stat}\sqrt{S^2 - 1}$

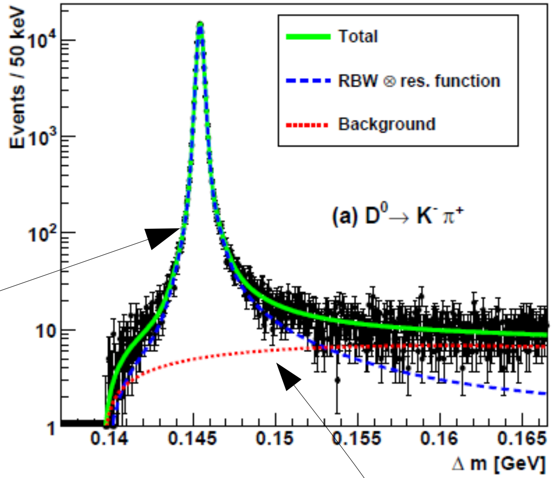
D^0 mass results

- Dominant systematic error from K+ mass uncertainty (16 keV/c^2) results in
  - 46 keV/c^2 (3 Kaons)
- Magnetic field and energy loss calibration
  - 31 keV/c^2
- Systematic variation in Δm
  - 28 KeV/c^2
- $Q = m(D^0)-3m(K)-m(\pi) = 244.240 \pm 0.048 \pm 0.041$ MeV/c^2
- $M(D^0) = 1864.841 \pm 0.048 \pm 0.062$ MeV/c^2
- Can recalculate more precise D^0 mass with improved K mass value
- Twice more precise than current world average
  - 1864.84±0.08 MeV/c^2 This measurement
  - 1864.86 ± 0.13 MeV/c^2 PDG fit
  - 1864.91 ± 0.17 MeV/c^2 PDG average
  - 1864.847 ± 0.178 MeV/c^2 CLEO

X(3872)
$Eb=m(D^0)+m(D^{*0})-m(X3872)$
Eb =(0.12 ± 0.24) MeV This
=(0.16 ± 0.32) MeV PDG

D* linewidth measurement

- $D^* \to D^0 \pi^+_s$, $D^0 \to K^- \pi^+$, $D^0 \to k^- \pi^- \pi^+ \pi^+$
- Signal: relativistic P-wave Breit-Wigner convolved with resolution function. All BW parameters fitted from data
- Fit distribution of $\Delta m = D^* - D^0$ mass difference for Γ and $\Delta m_0 = m_0 - m(D^0)$



$$\frac{dN}{dm} = \left(\frac{p}{p_0}\right)^3 \left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2}\right) \frac{(m_0 \Gamma_0)^2}{(m_0^2 - m^2)^2 + (m_0 \Gamma_{\text{Total}}(m))^2}$$

$$\Gamma_{\text{Total}}(m) = \Gamma_{D^* D\pi}(m) + \Gamma_{D^* D\gamma}(m) \approx \Gamma_{D^* D\pi}(m)$$

$$\Gamma_{D^* D\pi}(m) = \Gamma_0 \left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2}\right) \left(\frac{p}{p_0}\right)^3 \left(\frac{m}{m_0}\right)$$

r = Blatt-Weisskopf radius = 1.6 GeV (≈0.3 fm)

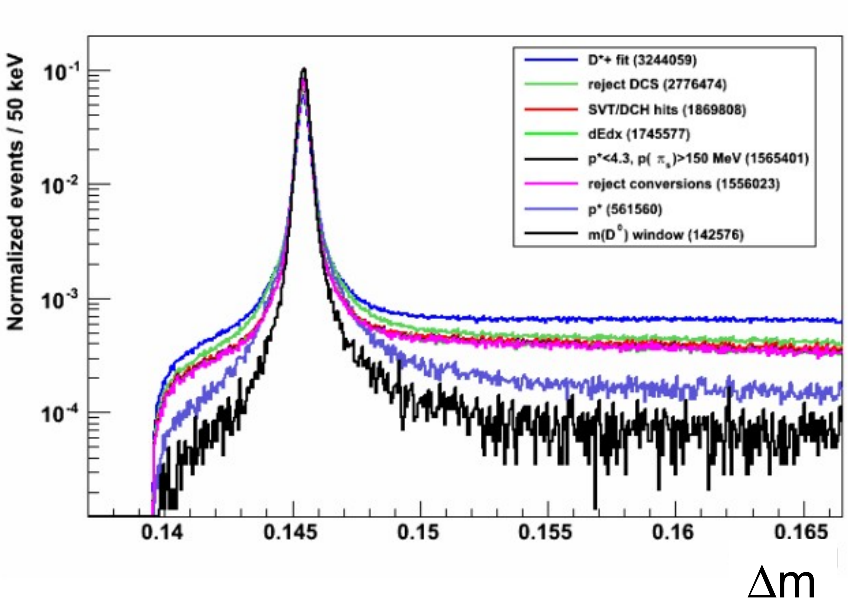
From Phys. Lett. B 308, 435 (1993)

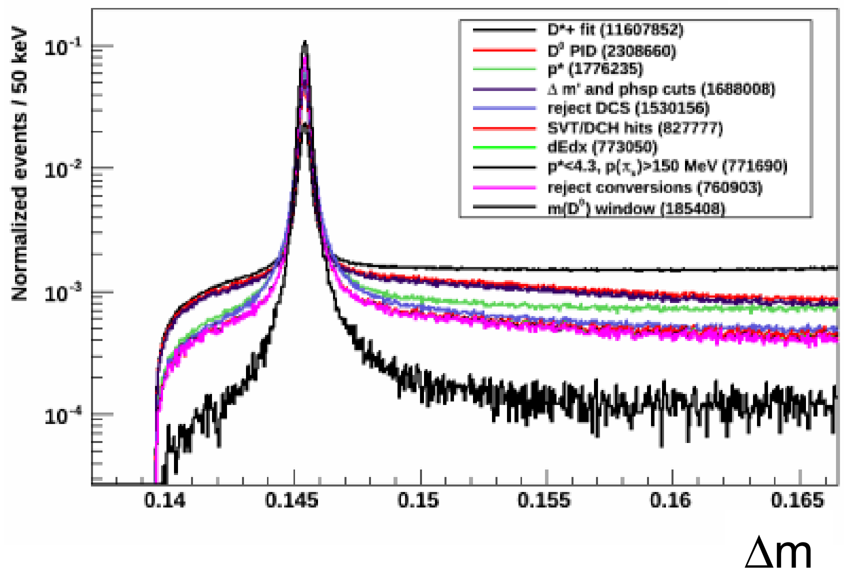
- Background: threshold function

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

D* selection

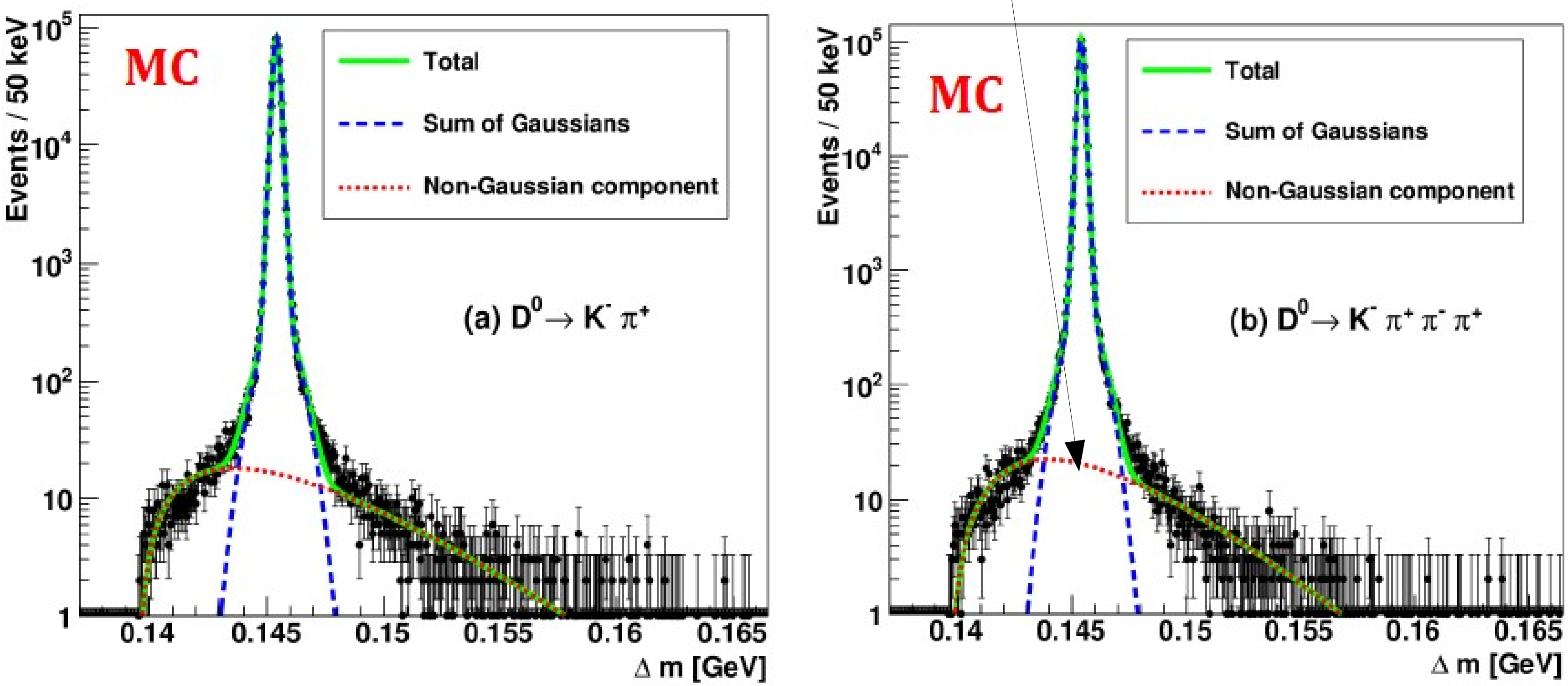
- $D^* \to D^0 \pi^+_s$, $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^-\pi^+\pi^+$
  - Q=6 MeV/c^2, total BF=8%
- Purity and significance
  - $P_{CM}(D^*)$>3.6GeV/c^2 and <4.6GeV/c^2
  - PID on K and π
- Well understood tracking
  - $P_{LAB}(\pi_S^+)$>0.15GeV/c
  - $\cos(\theta_{LAB})$<0.89
- D^0 tag
  - 1.86 GeV/c^2<$m_{K\pi(\pi\pi)}$<1.87 GeV/c^2
  - $\Delta m'=m_{K\pi\pi\pi\pi_s}-m_{K\pi\pi\pi_s}$ >166.5MeV/c^2
- Kinematic fit constraining each vertex to choose best candidate





Resolution function

- No control sample on data is available
- Triple Gaussian with parameters extracted from truth-matched MC
- π+ decays in flight modeled with $\Delta m\, u^{q} e^{cu}, u = \Delta m / m_{\pi} - 1$
- Scale factor ε for errors σ*(1+ε) fitted fitted from data



$D^{*+} \rightarrow D^0\pi^+$ Δm Fits

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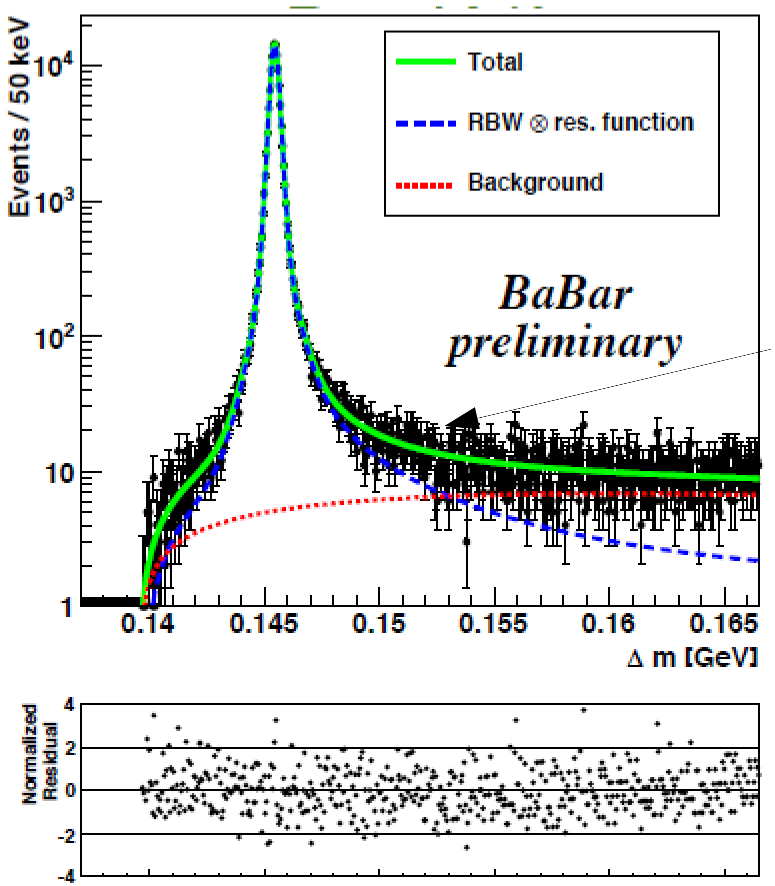
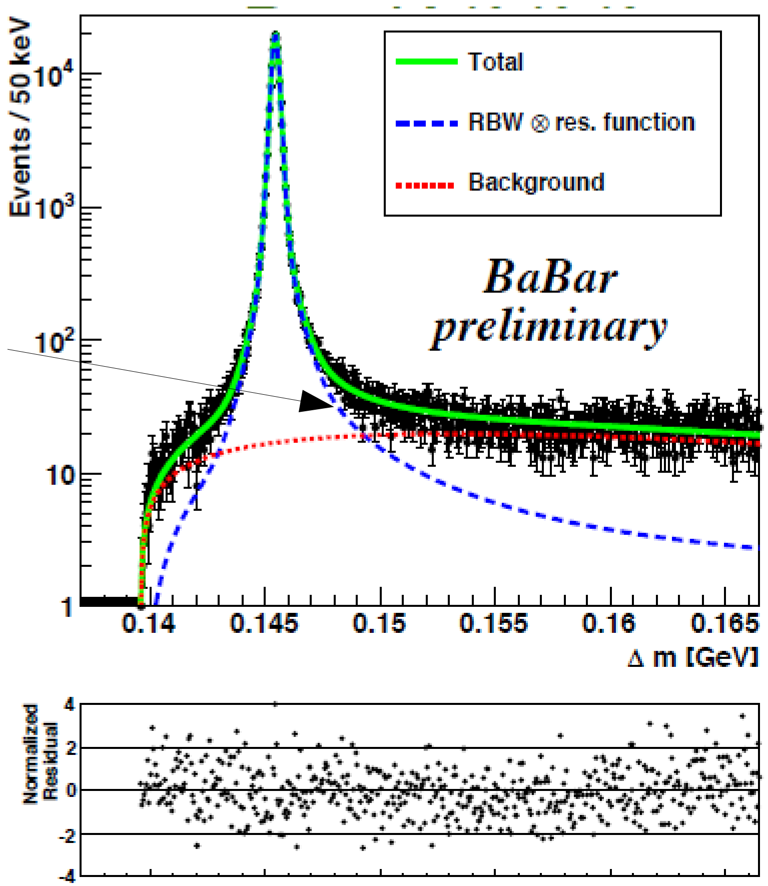
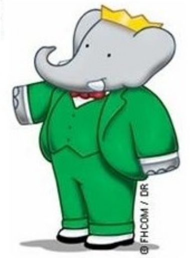




Sensitivity to Γ from tails of Δm distrib.

Good Quality



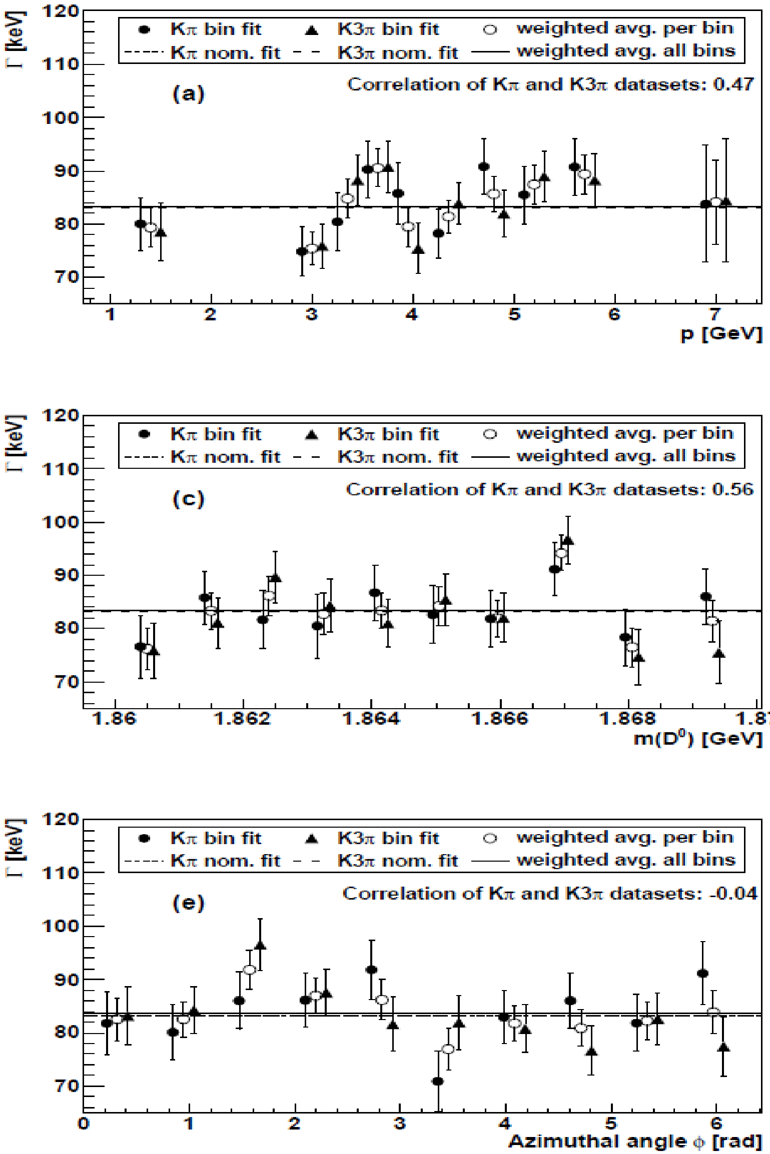
Fit Results

- Binned fit

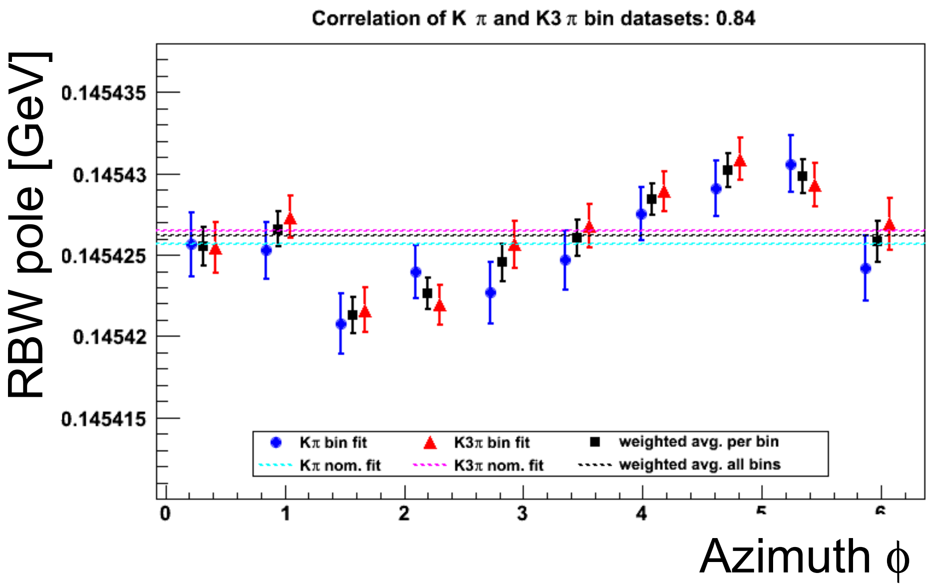
Parameter	$D^0 \to K\pi$	$D^0 \to K\pi\pi\pi$
Number of signal events	$138\,539 \pm 109$	$174\,286 \pm 150$
Γ (keV)	83.5 ± 1.7	83.2 ± 1.5
scale factor, $(1+\epsilon)$	1.06 ± 0.01	1.08 ± 0.01
Δm_0 (keV)	$145\,425.6 \pm 0.6$	$145\,426.6 \pm 0.5$
S/B at peak ($\Delta m = 0.14542$ (GeV))	2700	1130
S/B at tail ($\Delta m = 0.1554$ (GeV))	0.8	0.3
χ^2/ν	$574/535$	$556/535$

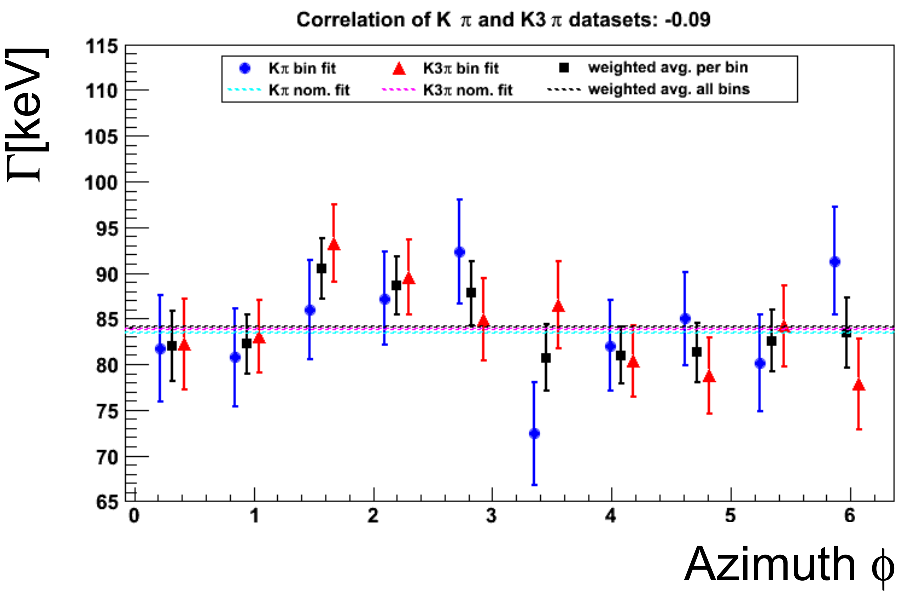
Systematic uncertainties

- Split dataset into disjoint subsamples → check consistency
  - $p_{lab}(D^0)$
  - $m(D^0)$
  - Azimuth angle
- If $\chi^2/_{NDOF}>1$ use the PDG scale factor method to assign a systematic error
- vary energy loss correction based on PDG Ks 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



Variation with azimuthal angle





- Sinusoidal variation of Δm with phi, average value unbiased

  => assign a systematic error
- Seen also in Ks calibration, interpreted as a variation of magnetic field with respect to the measured map
- Γ shows almost insignificant variation

Systematic uncertainties

Source	$\sigma_{sys}(\Gamma)$ [keV] $K\pi$	$\sigma_{sys}(\Gamma)$ [keV] $K\pi\pi\pi$	ρ	$\sigma_{sys}(\Delta m_0)$ [keV] $K\pi$	$\sigma_{sys}(\Delta m_0)$ [keV] $K\pi\pi\pi$	ρ
p dependence	0.88	0.98	0.47	0.24	0.20	0.28
$m\left(D^0_{\mathrm{reco}}\right)$ dependence	0.00	1.53	0.56	0.04	0.00	0.22
Azimuthal dependence	0.62	0.92	-0.04	1.65	1.81	0.84
Magnetic field and material model	0.29	0.18	0.98	0.75	0.81	0.99
Blatt-Weisskopf radius	0.04	0.04	0.99	0.00	0.00	1.00
Variation of resolution shape parameters	0.41	0.37	0.00	0.17	0.16	0.00
Δm fit range	0.83	0.38	-0.42	0.08	0.04	0.35
Background shape near threshold	0.10	0.33	1.00	0.00	0.00	0.00
Interval width for fit	0.00	0.05	0.99	0.00	0.00	0.00
Bias from validation	0.00	1.50	0.00	0.00	0.00	0.00
Radiative effects	0.25	0.11	0.00	0.00	0.00	0.00
Total	1.5	2.6		1.8	2.0	

D* mass and width combined results

- Results consistent between the two modes
- Combined using weighted average taking correlations into account

- $\Delta m = m(D^*) - m(D^0) = 145425.8 \pm 0.5 \pm 1.8$ keV/c^2

  145410 $\pm$ 10 keV/c^2 PDG

  145412 $\pm$ 12 keV/c^2 CLEO

- $\Gamma(D^*) = 83.3 \pm 1.3 \pm 1.4$ keV/c^2 BaBar

  96 $\pm$ 4 $\pm$ 22 keV/c^2 CLEO

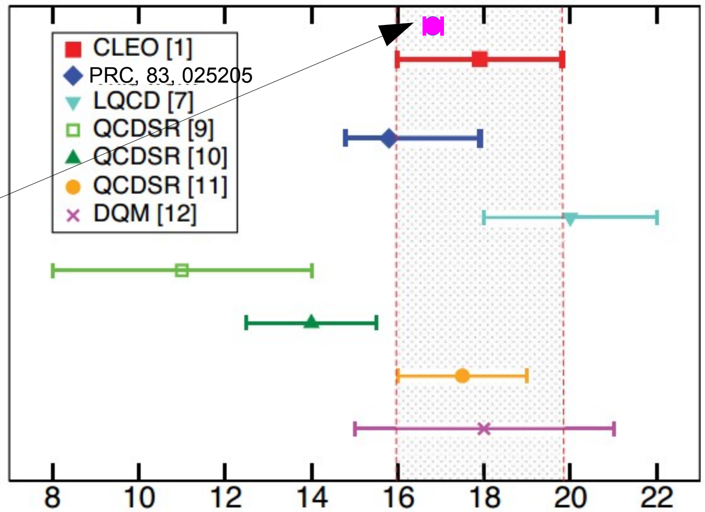
Vector meson coupling to pion

PHYSICAL REVIEW C **83**, 025205 (2011)

$$\Gamma = \Gamma\left(D^0\pi^+\right) + \Gamma\left(D^+\pi^0\right) + \Gamma\left(D^+\gamma\right)$$
$$\approx \Gamma\left(D^0\pi^+\right) + \Gamma\left(D^+\pi^0\right)$$
$$\approx \frac{g^2_{D^*D^0\pi^+}}{24\pi m^2_{D^{*+}}} p^3_{\pi^+} + \frac{g^2_{D^*D^+\pi^0}}{24\pi m^2_{D^{*+}}} p^3_{\pi^0}$$

$$g_{D^*D^0\pi^+} = -\sqrt{2} g_{D^*D^+\pi^0}$$

$$g^{\mathrm{exp}}_{D^*D^0\pi^+} = 16.92 \pm 0.13 \pm 0.14$$



$$R = \Gamma/\hat{g}^2 \qquad \hat{g} = g_{D^*D^0\pi^+} f_\pi / \left(2\sqrt{m_D m_{D^*}}\right)$$

State	Width (Γ)	R (model)	$\hat{g}$
$D^*(2010)^+$	$83.3 \pm 1.3 \pm 1.4$ keV	143 keV	0.76 ± 0.01
$D_1(2420)^0$	$31.4 \pm 0.5 \pm 1.3$ MeV	16 MeV	1.40 ± 0.03
$D_2^*(2460)^0$	$50.5 \pm 0.6 \pm 0.7$ MeV	38 MeV	1.15 ± 0.01

- Test of prediction of a universal coupling g from χPT
  - using R from Di Pierro and Eichten PRD 64, 114004 (01)
  - Widths from this measurement and from Phys. Rev. D 82, 111101(R) (2010).
  - g not consistent between D states
  - Measurements are inconsistent with xPT

Conclusions

- BaBar measured precisely
  - the mass of the D0 using a low Q-value decay mode
    - $M(D^0) = 1864.841 \pm 0.048 \pm 0.062$ MeV/c^2
    - $Q = m(D^0)-3m(K)-m(\pi) = 244.240 \pm 0.048 \pm 0.041$ MeV/c^2
    - Dominant systematic errors come from energy loss and magnetic field calibration
    - Publication being submitted
  - D* linewidth and pole position
    - $\Delta m=m(D^*)-m(D^0)=145425.8 \pm 0.5 \pm 1.8$ keV/c^2
    - $\Gamma(D^*) = 83.3 \pm 1.3 \pm 1.4$ keV/c^2
    - Inconsistent with universal coupling from xPT