Precise measurements of charmed mesons, studies of charmonium-like states

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On behalf of the BABAR collaboration

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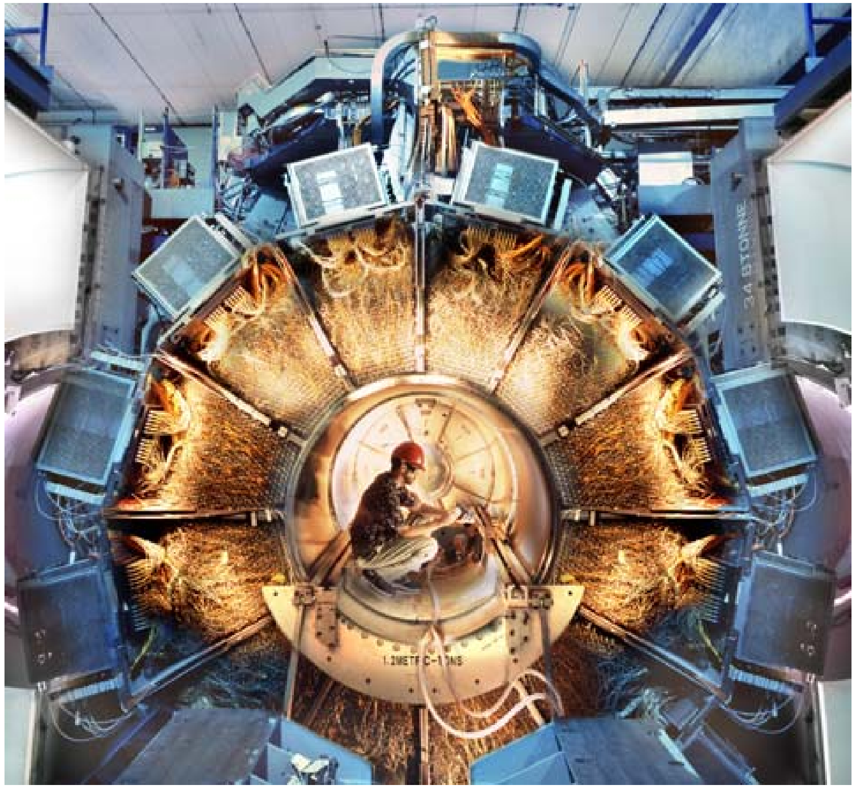
Outline

- BaBar detector and dataset
  - Measurements presented in this talk use the full BaBar dataset

- Precise measurements of D mesons
  - D^0 mass
  - $D^*(2010)^+$ linewidth
    $D^{*+} - D^0$ mass difference

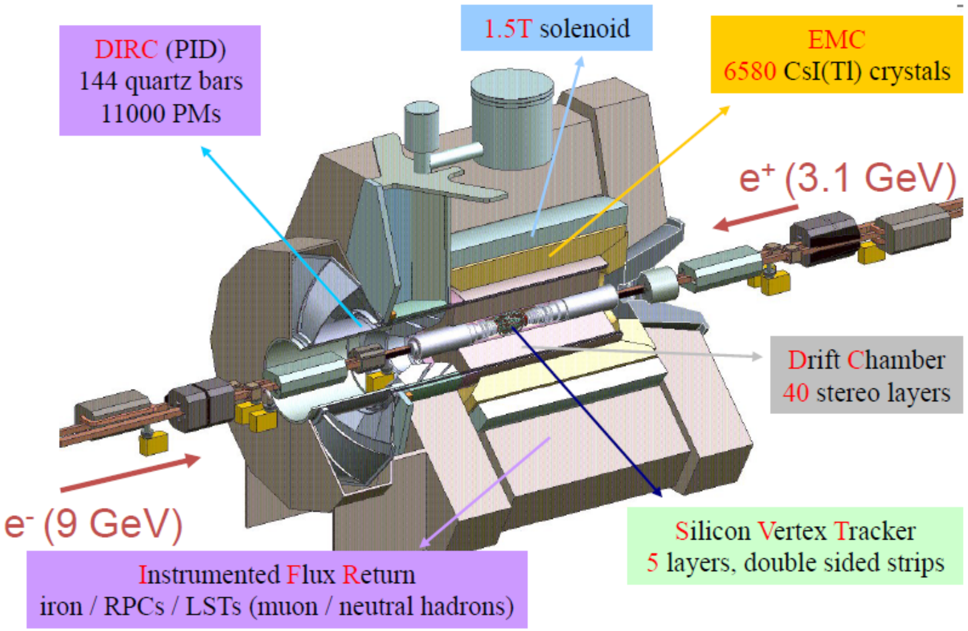
- Recent results for charmonium-like states
  - 1^{--} states: Y(4010), Y(4260),
    Y(4360), Y(4660)

- Summary

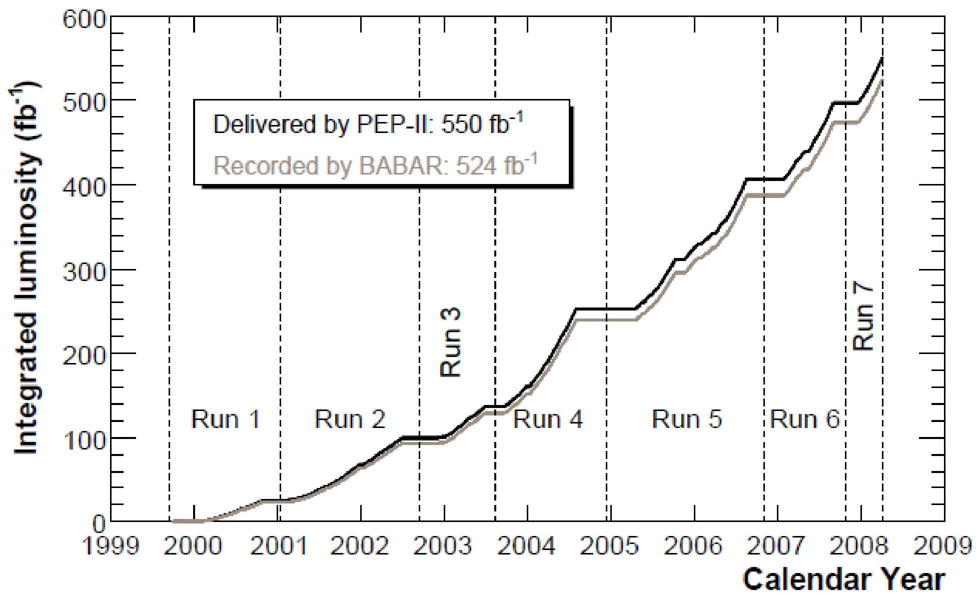


BaBar in a nutshell

- The BaBar detector



- The BaBar dataset



- Final detector paper published recently
  http://dx.doi.org/10.1016/j.nima.2013.05.107

The *BABAR* Detector: Upgrades, Operation and Performance

- 424 fb^{-1} @ $\Upsilon(4S) \Leftrightarrow (471.0 \pm 2.8) \times 10^6$ $B\bar{B}$ pairs – ‘onpeak’
- 44 fb^{-1} recorded 40 MeV below the peak – ‘offpeak’ – to study background
- 30.6 fb^{-1} @ $\Upsilon(3S)$ and 15.0 fb^{-1} @ $\Upsilon(2S)$ – onpeak + offpeak
- ~3.9 fb^{-1} from the final energy scan up to 11.2 GeV

D meson precise measurements

D^{*+}
- arXiv:1304.5009, submitted to PRD
- arXiv:1304.5657, submitted to PRL

D^0 Publication in preparation

Motivation

- D^0: ground state of the $c\bar{u}$ quark system
  D^{*+}: lowest vector state of the $c\bar{d}$ quark system

- Masses and natural decay widths sensitive to both quark contents
  & binding mechanism

- $m(D^{*+}) = m(D^0) + \Delta m$, with Δm being the mass difference $m(D^{*+}) - m(D^0)$

- X(3872) mass very close to the D^0-D^{*0} threshold
  - A D^0–D^{*0} `molecule'?
    $\rightarrow$ Would require $m[X(3872)] < m(D^0) + m(D^{*0})$

- D^* linewidth useful to probe non-perturbative strong physics
  $\rightarrow$ $g_{D^*D\pi}$, the strong coupling of a heavy charm meson to a pion
  $\rightarrow$ The universal strong coupling of a heavy meson to a pion
  $\rightarrow$ $g_{B^*B\pi}$, one of the largest contributions to the theoretical uncertainty on $|V_{ub}|$

  In the framework of the theory of chiral perturbation

Previous measurements

- PDG: $m(D^0) = 1864.86 \pm 0.13$ MeV/c^2

Decay channel with a small Q value

$D^0 \to \phi K^0_s$

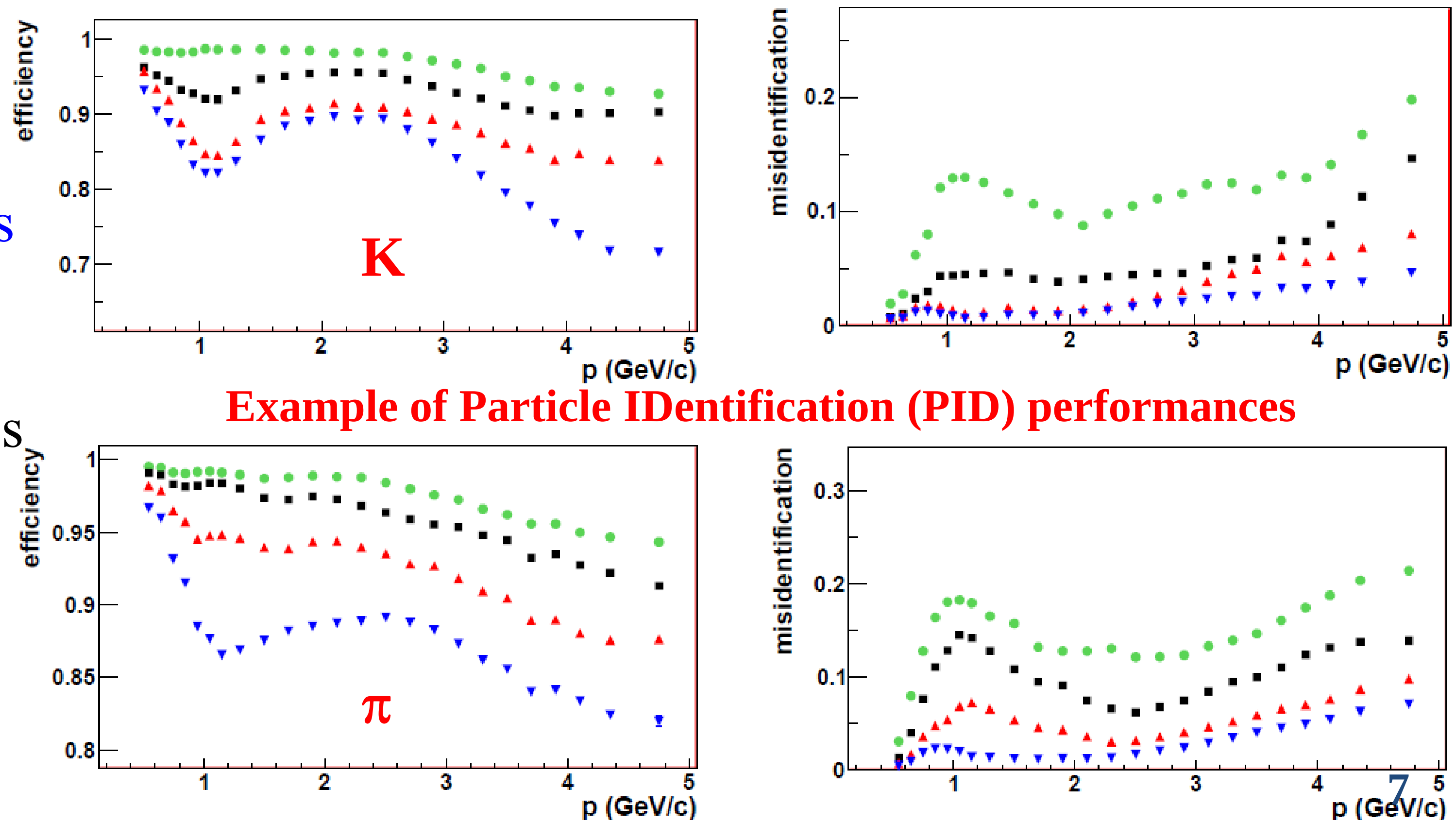
- Fit dominated by CLEO's measurement using 319±18 signal events
  - $m(D^0) = 1864.847 \pm 0.150$ (stat) ± 0.095 (syst) MeV/c^2
- Recent result from LHCb (2013/06) using the same decay channel as BaBar
  - $m(D^0) = 1864.75 \pm 0.15$(stat) ± 0.11(syst) MeV/c^2, using 1 fb^{-1} @ 7 TeV
- Mesurement of the D^{*+} linewidth by CLEO
  - $\Gamma(D^{*+}) = 96 \pm 4 \pm 22$ keV, using a sample of 11,000 candidates (9 fb^{-1})
- B-factories have much larger statistics ⇒ can improve these measurements
  - Tight selections to increase the selected sample purity
  - Control of the systematic errors

Strategy for precise measurements

- Need good tracking measurements
  - Main issues: detector material, magnetic field strength
  - Calibration from data using K_s control sample

    → Empirical corrections of energy losses and momentum scale
- Use low Q-value decays: Σ m(daughter particles) close to m(mother particle)
  - Lower statistics, but better systematics
- Low background
  - Tight PID

    for π and K
  - Use charmed hadrons from $c\bar{c}$ events
    - ✓ Higher momenta
    - ✓ Less combinatorics
  - Cut edges of the angular acceptance : $\cos(\theta_{lab}) < 0.89$



Example of Particle IDentification (PID) performances

Energy loss and momentum scale corrections

- dE/dx ~ 1 + $(m/p_{lab})^2$: large at low p_{lab}!
  - Reconstructed K_S mass lower than PDG value – blue open squares
- Use K_s control sample to fit the correction factors
  - Similar kinematics: $K_S \to \pi^+\pi^-$ from $D^{*+} \to D^0 \pi^+_S$, $D^0 \to K_S \pi^+\pi^-$
  - Systematics computed by varying the `target' K_s mass by $\pm$ 1 σ_{PDG}
- Correct energy loss and momentum scale – red dots

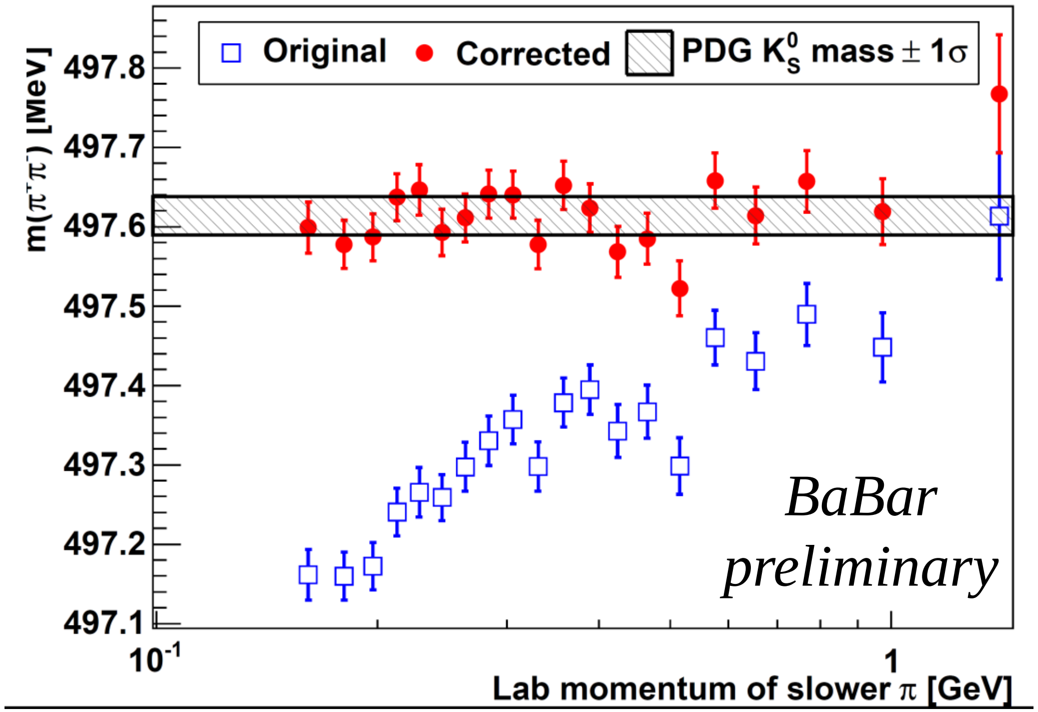
$$p \to p\,(1+a)$$

$$E \to E + b_{\rm bmp} \underbrace{E^{\rm bmp}_{\rm loss}} + b_{\rm svt} \underbrace{E^{\rm svt}_{\rm loss}}$$

Provided by the tracking (Kalman fit)

- Fit results:

a	0.00030
$b_{\rm bmp}$	0.018
$b_{\rm svt}$	0.059



D^0 mass measurement

- Decay chain: $D^* \to D^0 \pi^+_s$, $D^0 \to K^- K^- K^+ \pi^+$
  - Q-value ~250MeV/c^2
  - π_s: `slow' pion (limited phase space available), require $p_{lab}(\pi^+_s) > 0.15$ GeV/c

- Selection optimized using
  - Large Monte-Carlo (MC) datasets
  - and 5% of the data sample – discarded for the mass measurement

- Selection
  - D^* tag to reduce background
    - ✓ $|\Delta m - \Delta m_{PDG}| < 1.5$ MeV/c^2, with $\Delta m = m_{KKK\pi\pi s} - m_{KKK\pi}$
    - ✓ $\Delta m' = m_{KKK\pi\pi s} - m_{KKK\pi s} > 150$ MeV/c^2
  - $p_{CM}(D^*) > 2.5$ GeV/c^2
  - Kinematic fit constraining all vertices

    → Choose candidate with the smallest χ^2

D^0 mass measurement

- Unbinned maximum likelihood fit of $m(K^-K^-K^+\pi^+)$
  - Signal: Vogtian PDF

    $\rightarrow$ Cauchy function convoluted with a Gaussian distribution

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

, σ and γ resolution ad-hoc parameters

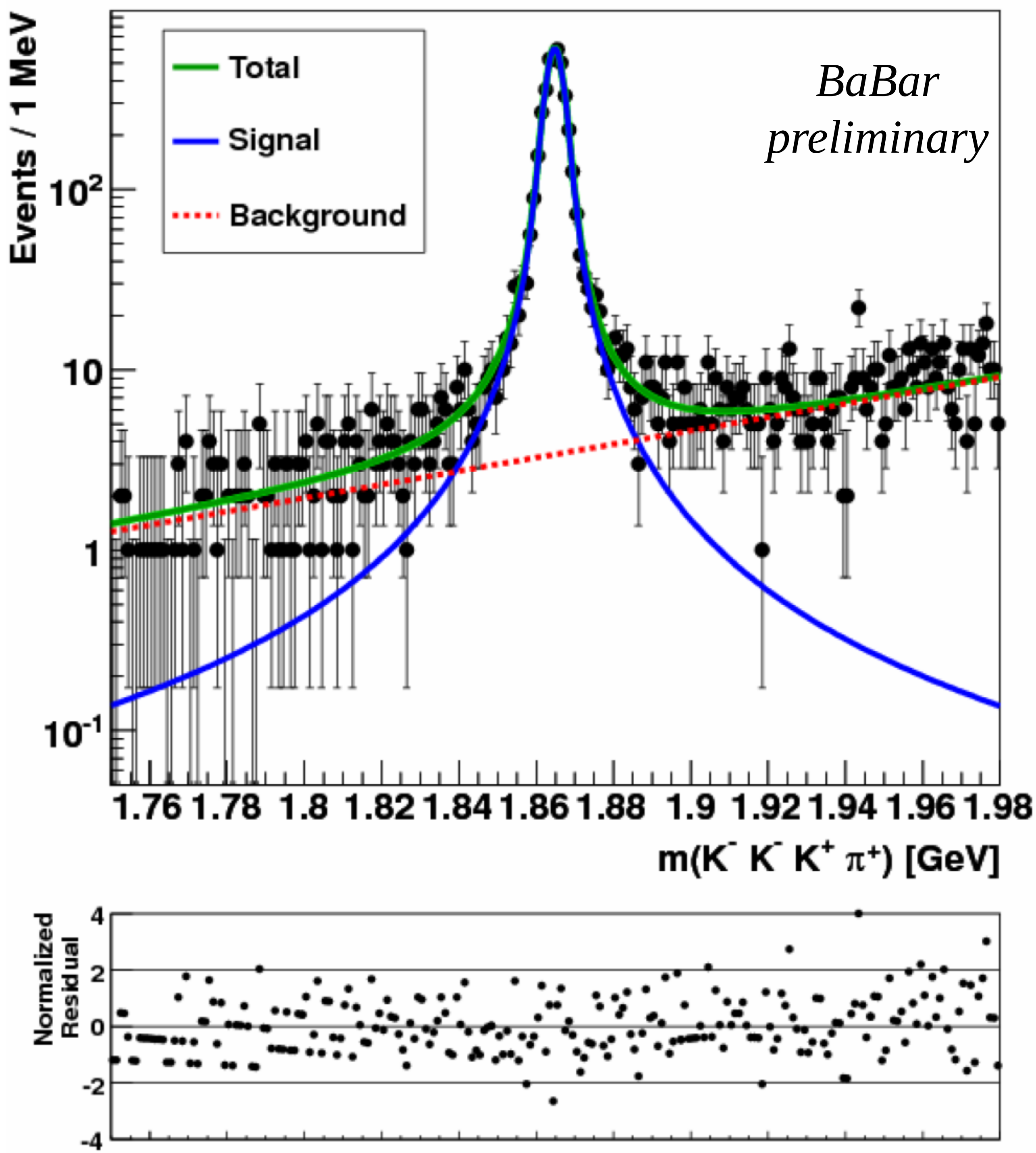
  - Background: exponential PDF: $a \times e^{bm}$

- All parameters free in fit

- Fit results insensitive to the shape of the signal PDF
  - Same result using a double Gaussian

Fit result

- 4345 ± 70 signal events
- $m(D^0) =$ 1864.841 ± 0.048 MeV/c^2
- Resolution parameters consistent with simulation:
  - $\gamma = 2.596 \pm 0.152$ MeV/c^2
  - $\sigma = 1.762 \pm 0.086$ MeV/c^2
- Statistical errors only
- Fit quality shown by normalized residuals:
  - Almost all of them within $\pm 2\sigma$



Systematic errors

- Energy loss and momentum scale
  - See previous slides

- Vary PDF shapes and parameters

- Split dataset in disjoint subsamples in three variables:
  - Azimuthal angle of the D^0 momentum – 2 points per BaBar sextant → 12 in total
  - D^0 lab momentum
  - Δm

  (lab momentum and Δm:) 10 bins each, with roughly equal numbers of signal events

  → Goal: check detector response uniformity
  - If $S^2 = \chi^2/NDF > 1$, additional systematic error : $\sigma_{sys} = \sigma_{stat}\sqrt{S^2 - 1}$

    PDG prescription

- Three dominant systematics

Source	σ_{sys} (MeV)	
$K^{\pm}$ mass uncertainty	0.046	(3 kaons)
Magnetic field and material model	0.031	
Disjoint Δm bin variation	0.028	→ PDG prescription

Final result

- D^0 mass measurement: $m(D^0) = 1864.841 \pm 0.048\ (\text{stat}) \pm 0.062\ (\text{syst})\ \text{MeV}/c^2$
  - Consistent and twice as precise as the current world average from PDG

Experiment	**CLEO**	**LHCb**	**BaBar**
Year	2007	2013	2013
D^0 mass (MeV/c^2)	$1864.847 \pm 0.150 \pm 0.095$	$1864.75 \pm 0.15 \pm 0.11$	$1864.841 \pm 0.048 \pm 0.062$

- $m(D^0) + m(D^{*0}) - m[X(3872)] = 0.12 \pm 0.24\ \text{MeV}/c^2$

- Given that the largest uncertainty comes from the K^+ mass, one can express the result in terms of:

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

→ Improving $m(K^+)$ would directly lead to an improved $m(D^0)$

D^{*+} linewidth – event selection

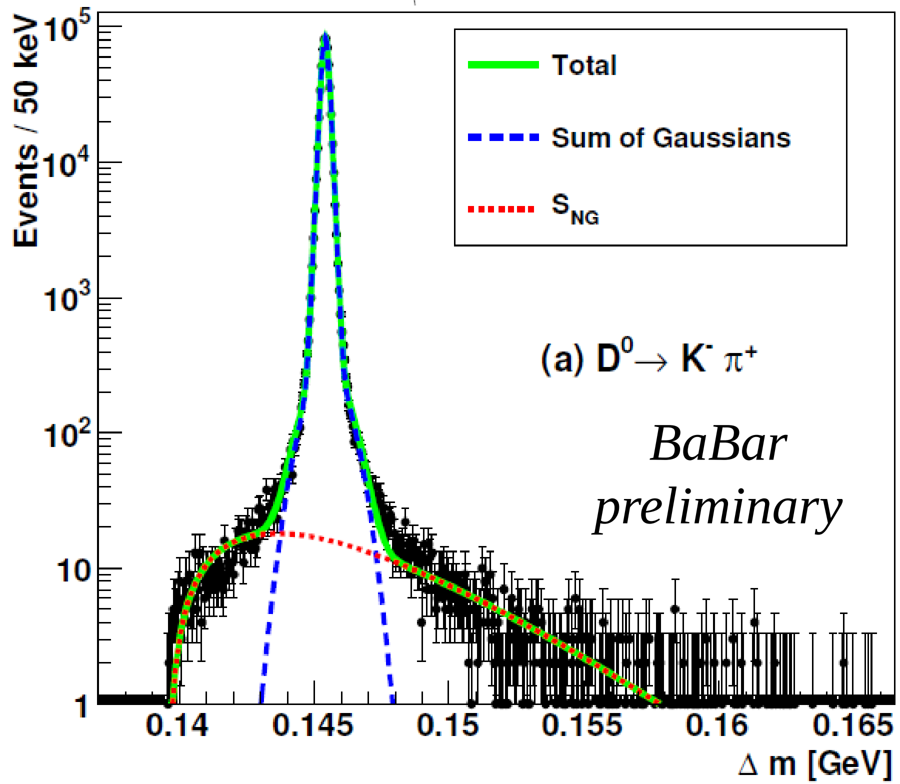
- Decay chain: $D^{*+} \to D^0 \pi^+_s$, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^-\pi^+\pi^+$
  - Q value ~145 MeV/c^2
- Similar selection criteria as for the D^0 mass measurement
  - K and π PID
  - Good tracking – only keep the `best' tracks:
    → Many hits required in both the vertex detector and the drift chamber
  - Kinematic fit constraining each decay vertex
  - Beam spot constrain
- D^* selection
  - $3.6 < p_{CM}(D^*) < 4.3$ GeV/c
    - ✓ Lower bound to reduce combinatorial background
    - ✓ Poor data-MC agreement above this range
  - $0.14 < \Delta m < 0.17$ GeV/c^2
  - Cut mis-reconstructed events
    - ✓ slow pion exchanged with a D^0 π–daughter for K3π mode
- D tag: $1.86 < m_{K\pi(\pi\pi)} < 1.87$ GeV/c^2

Fit functions

- Fit distribution of Δm for Γ and $\Delta m_0 = m_0 - m(D^0)$
- Signal: relativistic P-wave Breit-Wigner convolved with a resolution function
- Resolution function
  - No control sample available on data
    $\rightarrow$ Triple Gaussian with parameters given by truth-matched MC (5× data stat.)
  - Free common scale factor ε for the RMS of the three Gaussian functions
  - Additional term to take into account π^+_s decays in flight: $\Delta m\, u^q e^{cu}, u = \Delta m / m_\pi - 1$
    $\rightarrow$ Improve model near the mass peak
- Background: a threshold function

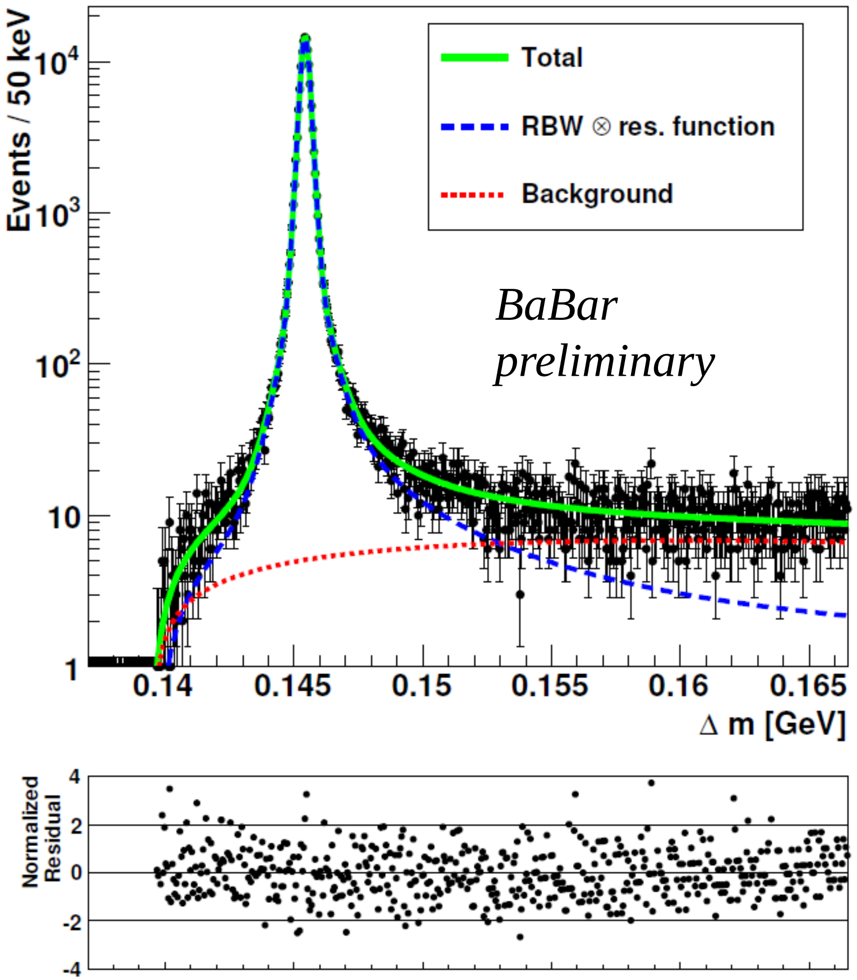
$$\mathcal{B}(\Delta m) = \Delta m\ \sqrt{u}\ e^{cu}$$

- Tails of the distribution used to measure the D^{*+} width
  - Detector resolution (FWHM ~300 keV) larger than the width
  - Tails need to be well-modeled
- Binned maximum likelihood fits

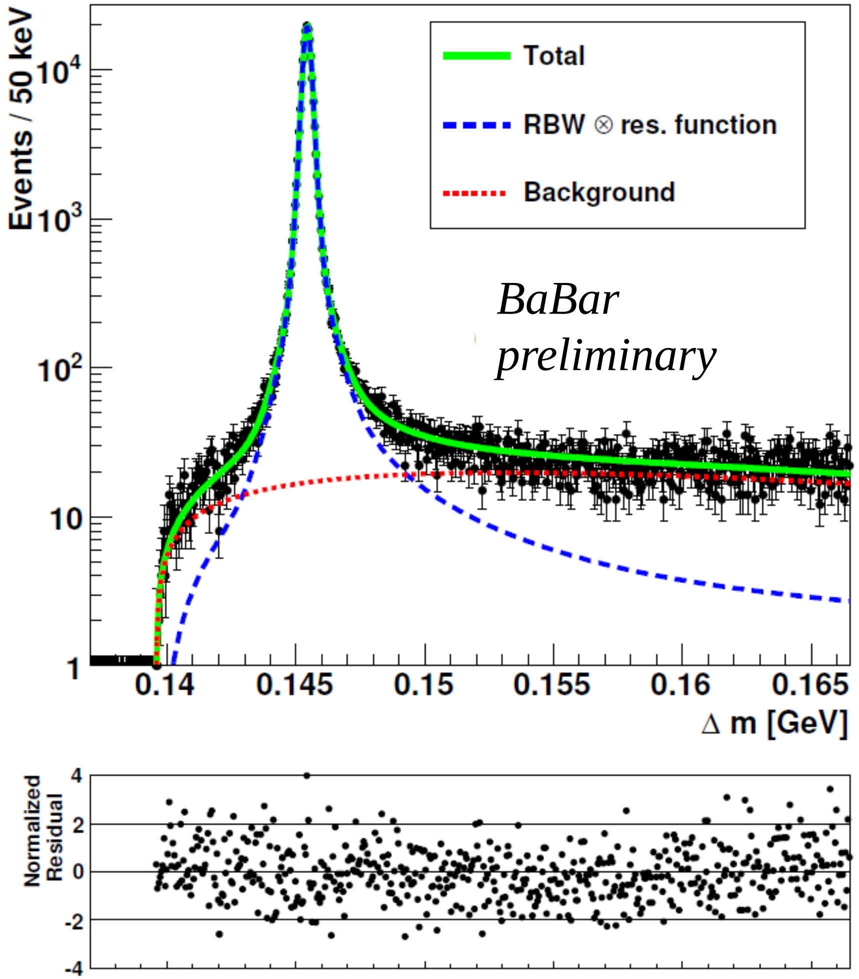


Fit results

$D^0 \to K\pi$



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



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

Systematic errors

- Similar approach to the D^0 mass measurement
- Energy loss correction and momentum scale
  - Most important for the pole position
- Split dataset into disjoint subsamples
  - D^0 track azimuth, lab momentum and mass
  - Add `PDG-like' syst. error if subsample fit results not consistent with a constant
  - Pole mass varies with ϕ – variation of magnetic field w.r.t. the measured map
    Width does not
- Vary shapes and parameters of the PDFs

Summary of systematic errors

Source	$\sigma_{sys}(\Gamma)$ [keV]		ρ	$\sigma_{sys}(\Delta m_0)$ [keV]		ρ
	$K\pi$	$K\pi\pi\pi$		$K\pi$	$K\pi\pi\pi$	
Disjoint D^{*+} momentum bin variation	0.88	0.98	0.47	0.24	0.20	0.28
Disjoint $m\left(D^0_{\rm reco}\right)$ bin variation	0.00	1.53	0.56	0.04	0.00	0.22
Disjoint azimuthal variation	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	

Results and interpretation

- Weighted average of the two (consistent) fit results, taking correlations into account
- $\Delta m = m(D^*) - m(D^0) = 145425.8 \pm 0.5 \pm 1.8$ keV/c^2
  - Consistent with the PDG average, and 5 times more precise
- $\Gamma(D^*) = 83.3 \pm 1.3 \pm 1.4$ keV/c^2
  - Consistent with CLEO measurement, and a factor of 12 more precise
- Results can be used to test a prediction from the chiral perturbation theory of a universal coupling constant $\hat{g} = g_{D^{*+}D^0\pi^+} f_\pi / \left(2\sqrt{m_{D^0} m_{D^{*+}}}\right)$

BaBar

Di Pierro & Eichten, PRD 64, 114004 (2001)

State	Width (Γ)	$R = \Gamma/\hat{g}^2$ (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

Not consistent with a universal coupling constant

- Private communication from Rosner (to appear in arXiv)
  - Experimental D^{*+} and $D_2(2460)$ widths in agreement with updated model based on single quark-transition hypothesis
    Ex: $\Gamma(D^*)^{predicted} = 80.5 \pm 0.1$ keV/c^2

Y charmonium-like states

$Y \rightarrow J/\psi\ \pi^+\pi^-$

Phys. Rev. D 86, 051102(R) (2012)

$Y \rightarrow \psi(2S)\ \pi^+\pi^-$

arXiv: 1211.6271, submitted to PRD-RC

Analysis method and background

- Decay chain:
  - $e+e- \rightarrow \gamma_{ISR}$ X, γ_{ISR} not reconstructed – effective scan of energies
  - X $\rightarrow \pi^+\pi^-$ [J/ψ or ψ(2S)]: mode highly-supressed above the open charm threshold if X is a charmonium state
    $\rightarrow$ Exotic state seen as enhancement in these modes
  - J/ψ $\rightarrow l^+l^-$ or ψ(2S) $\rightarrow \pi^+\pi^-$ J/ψ, with J/ψ$\rightarrow l^+l^-$
    ψ(2S) $\rightarrow l^+l^-$

- Analysis using the full dataset available
  - Supercede previous results

- Y(4260): observed by BaBar – J/ψ decay mode
  confirmed by CLEO and Belle [+ second enhancement: Y(4008)]

- Y(4350) observed by BaBar – ψ(2S) decay mode
  confirmed by Belle [+ another state: Y(4660)]

⇒ Twofold BaBar goal with the new analysis:
  - Improve measurements of states previously observed
  - Look for Belle's Y(4008) and Y(4660)

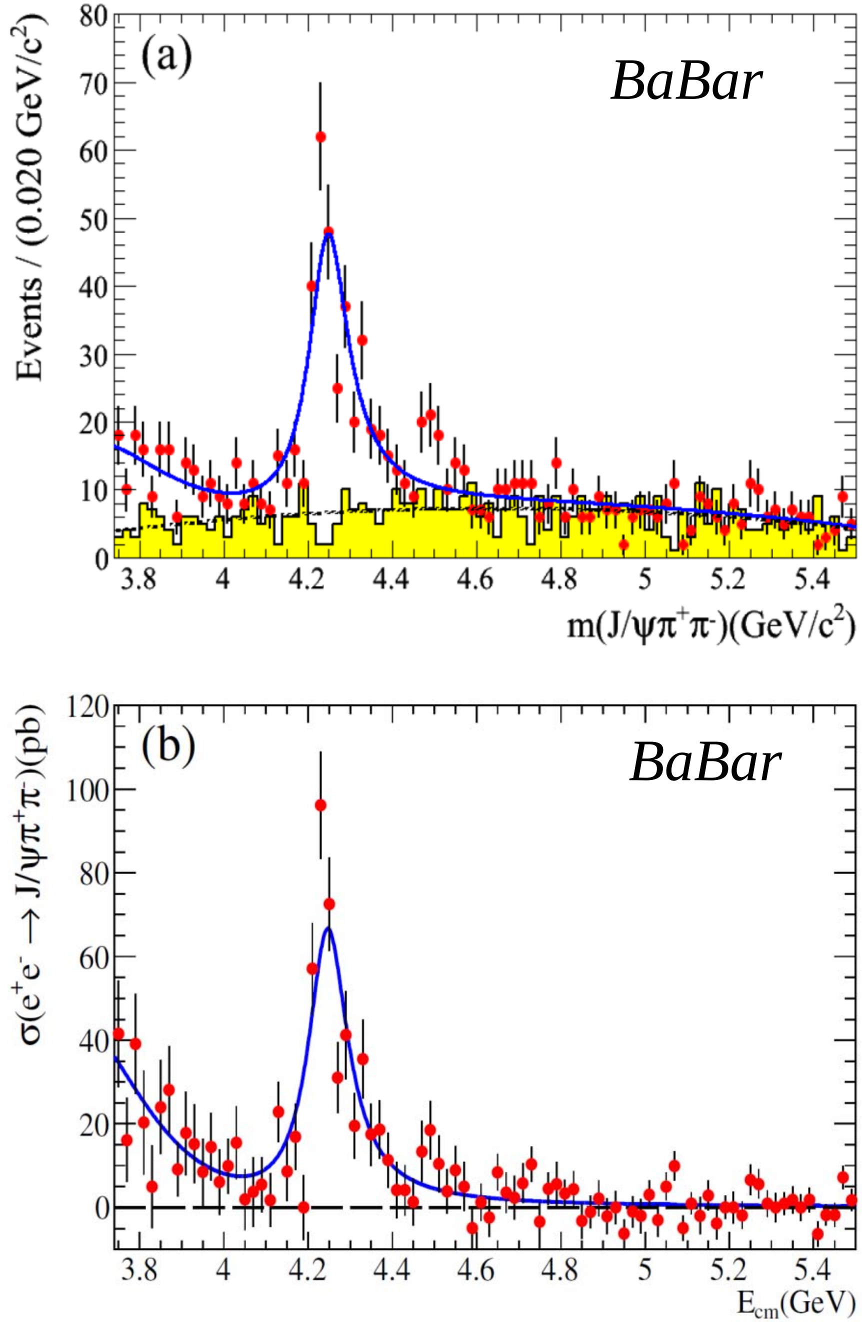
Results for $X \rightarrow J/\psi\, \pi^+\pi^-$

- Top plot: fit
  Bottom plot: cross-section
- Clear Y(4260) signal

$$m_Y = 4245 \pm 5 \text{ (stat) } \pm 4 \text{ (syst) MeV}/c^2$$

$$\Gamma_Y = 114\ ^{+16}_{-15} \text{ (stat) } \pm 7 \text{ (syst) MeV}$$

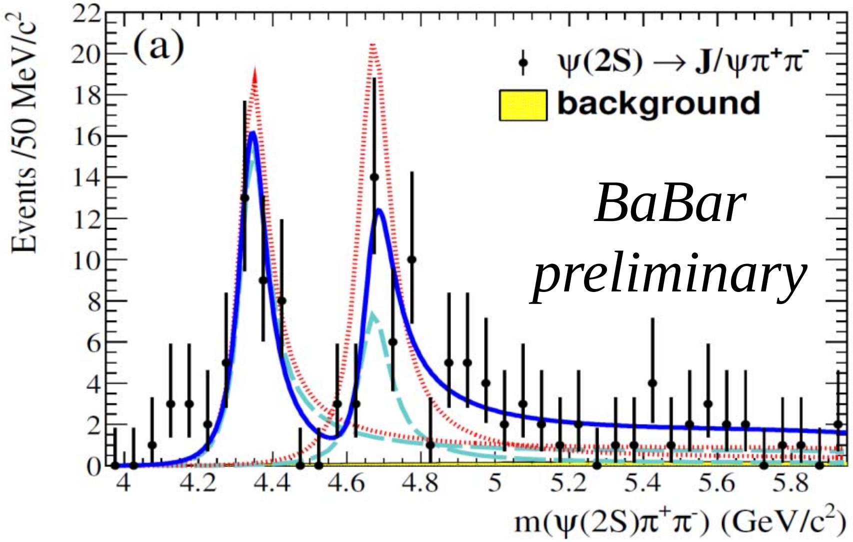
- Consistent with Belle result
- No sign of the Y(4008) enhancement
- Cross-section enhancement at low energy of unknown origin
- $\pi^+\pi^-$ invariant mass distribution reasonably well-modeled by the interference between $f_0(980)$ [(17±13)%] and continuum



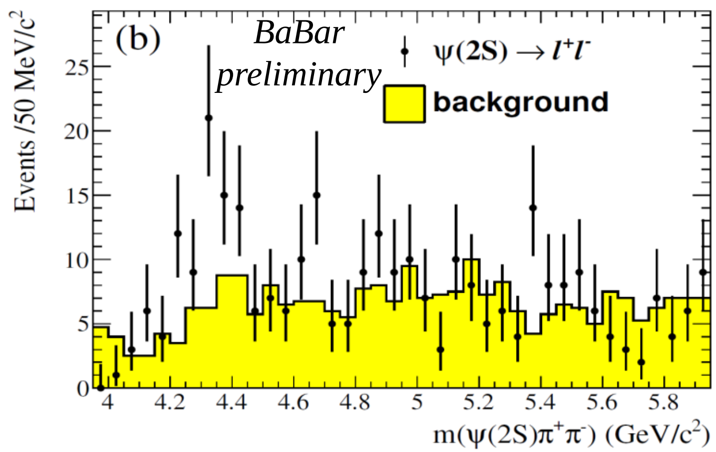
Results for X → $\psi(2S)\,\pi^+\pi^-$

- $\psi(2S) \rightarrow \pi^+\pi^-\, J/\psi$, with $J/\psi \rightarrow l^+l^-$
  - Improved measurement of Y(4360)
  - Belle's Y(4660) confirmed

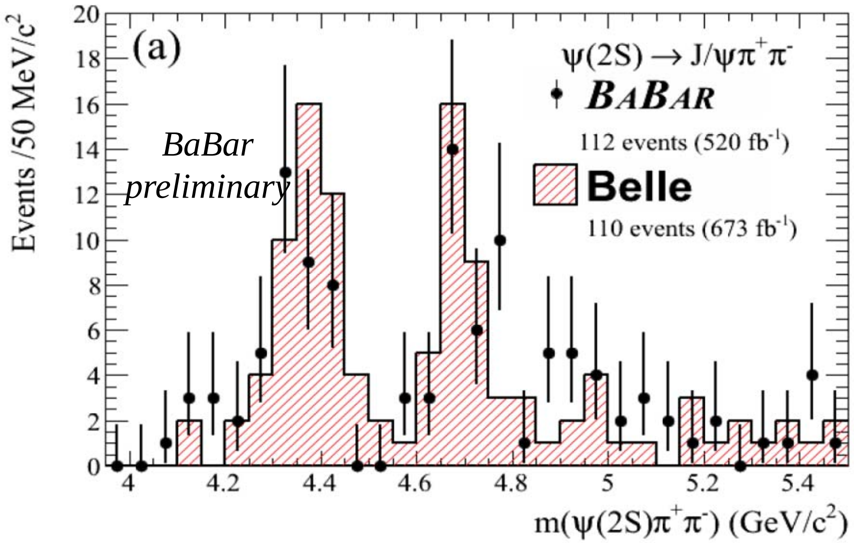
Resonance	Y(4360)	Y(4660)
Mass (MeV/c^2)	4340 ± 16 ± 9	4669 ± 21 ± 3
Width (MeV/c^2)	94 ± 32 ± 13	104 ± 48 ± 10



- $\psi(2S) \rightarrow l^+l^-$
  - More data but much more background ⇒ No fit



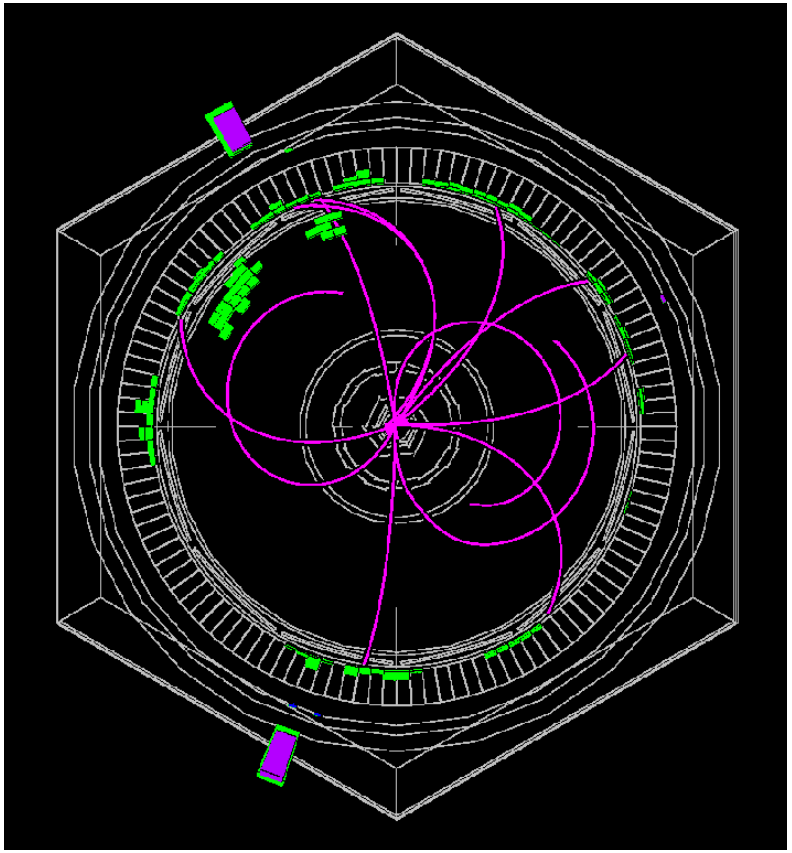
- BaBar and Belle spectra in nice agreement
  - Total dataset: 1.2 ab^{-1}



Outlook

- Improved BaBar measurements on charm mesons
  - D^0 mass
  - D^{*+} mass difference and linewidth

- Three charmonium-like states JPC=1^{--} observed by BaBar and Belle in the region [4.2;4.7] GeV/c^2
- The nature of these states remains a mystery to date



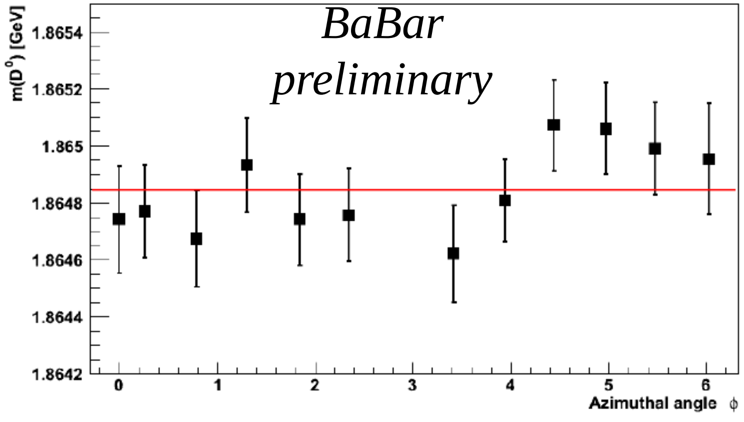
$B \rightarrow D^* D^*$ event

Backup

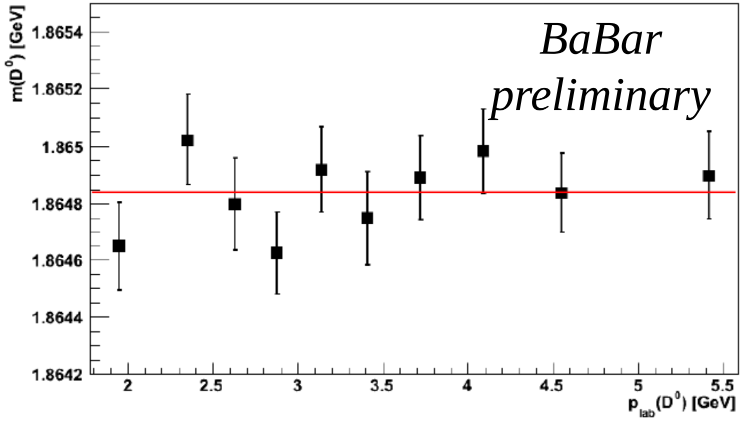
Disjoint subsamples fit [D^0 mass measurement]

(a) Azimuthal angle dependence
(b) Lab momentum dependence
(c) Δm dependence
- $S^2 = 1.35 \Rightarrow$ 28 keV systematic error

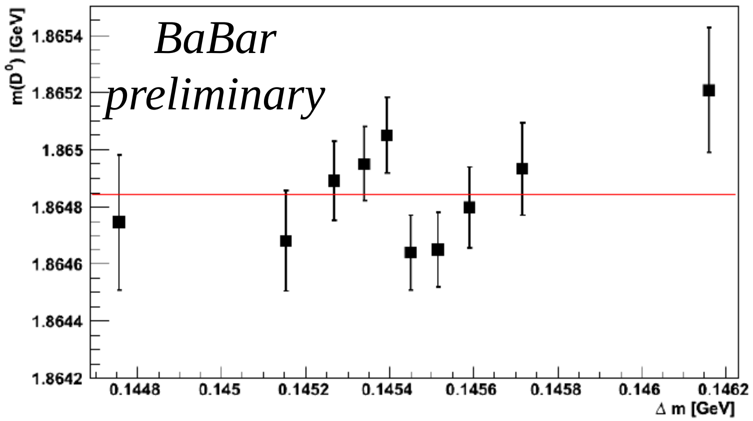
- The red line shows the nominal fit result



(a)



(b)



(c)

D* lineshape fit functions

- $l = 1$
- Blatt-Weisskopf radius r = 1.6 GeV (≈ 0.3 fm)
- $\Gamma_{total} \approx \Gamma_{D^*D\pi}$
- The subscript « $_0$ » denotes a quantity measured at the pole

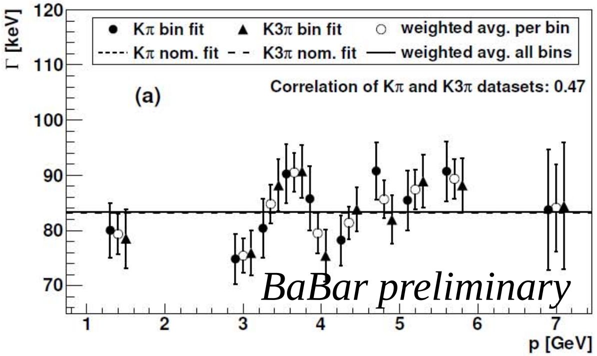
$$\frac{d\Gamma(m)}{dm} = \frac{m\Gamma_{D^*D\pi}(m)\; m_0\Gamma}{(m_0^2 - m^2)^2 + (m_0\Gamma_{\mathrm{Total}}(m))^2},$$

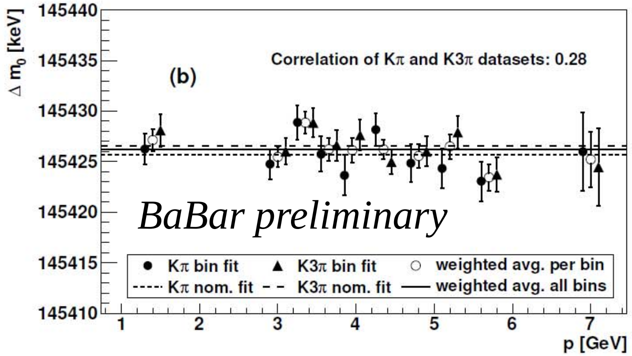
$$\Gamma_{D^*D\pi}(m) = \Gamma\left(\frac{\mathcal{F}^{\ell}_{D\pi}(p_0)}{\mathcal{F}^{\ell}_{D\pi}(p)}\right)^2\left(\frac{p}{p_0}\right)^{2\ell+1}\left(\frac{m_0}{m}\right)$$

Disjoint subsamples – D* analysis

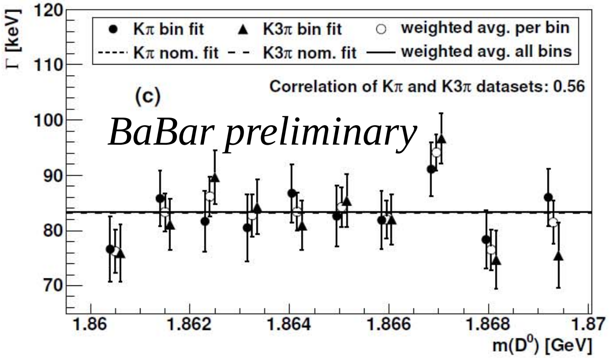
D* width Γ | **Pole mass Δm_0**

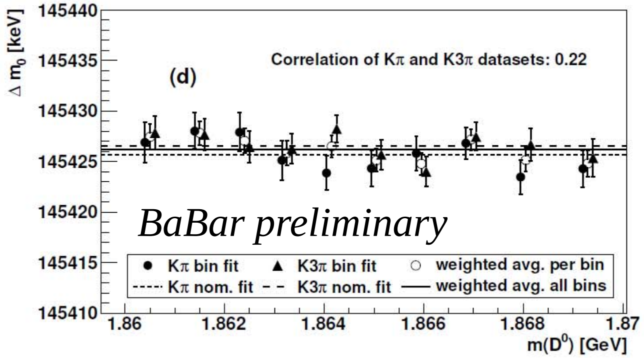
Laboratory momentum



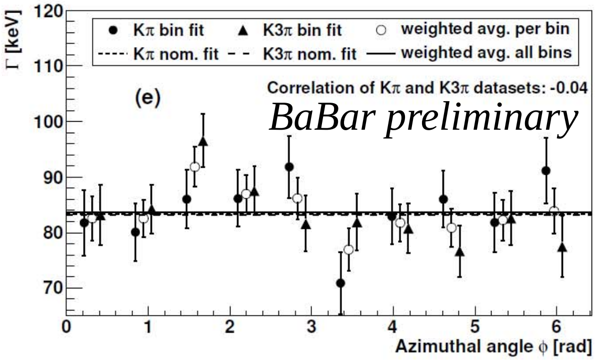


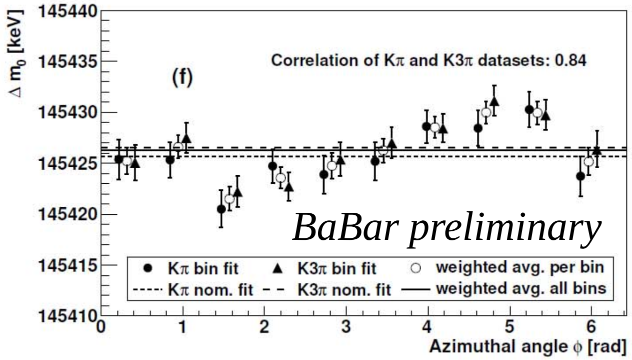
M(D⁰)





Azimuthal angle





`Sinusoidal'-like variation