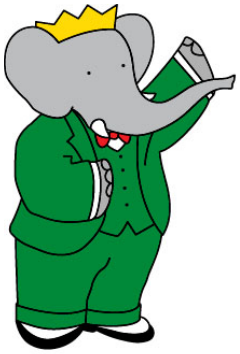

# Precision measurement of the $D^0$ mass and of the natural line width of the $D^{*+}$

**Ray F. Cowan**

**Representing the *BABAR* Collaboration**

**DPF 2013**

**Santa Cruz, California**
**USA**

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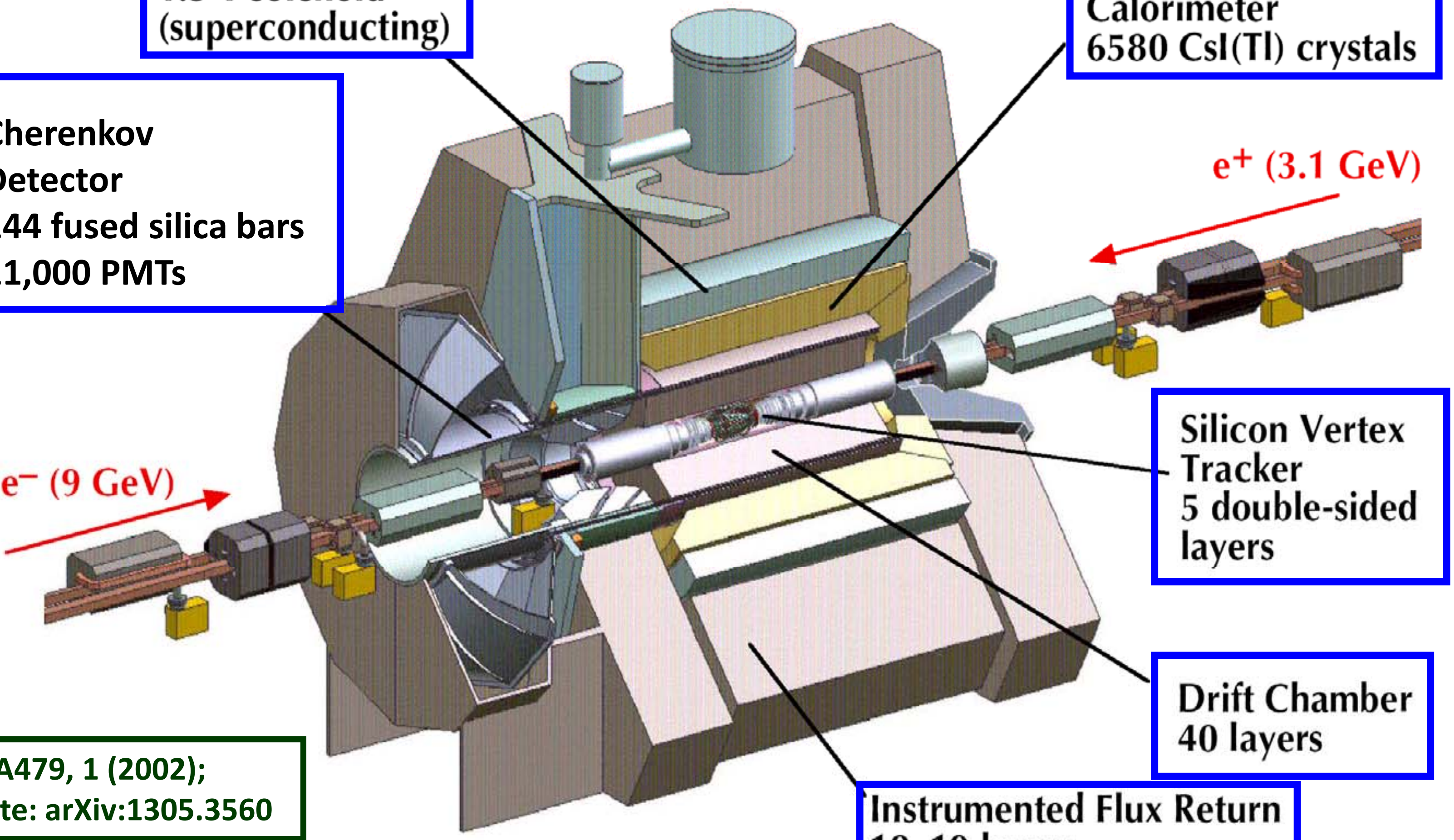
Massachusetts
Institute of
Technology

# Outline

- BaBar detector and dataset
- Motivation for precision $D^0$ and $D^{*+}$ mass and width measurements
- $D^0$ mass
- $D^{*+}$ width and $D^{*+}$–$D^0$ mass difference
- Summary

# The *BaBar* detector at PEP-II



**1.5 T solenoid (superconducting)**

**Calorimeter**
**6580 CsI(Tl) crystals**

**Cherenkov Detector**
**144 fused silica bars**
**11,000 PMTs**

**Silicon Vertex Tracker**
**5 double-sided layers**

**Drift Chamber**
**40 layers**

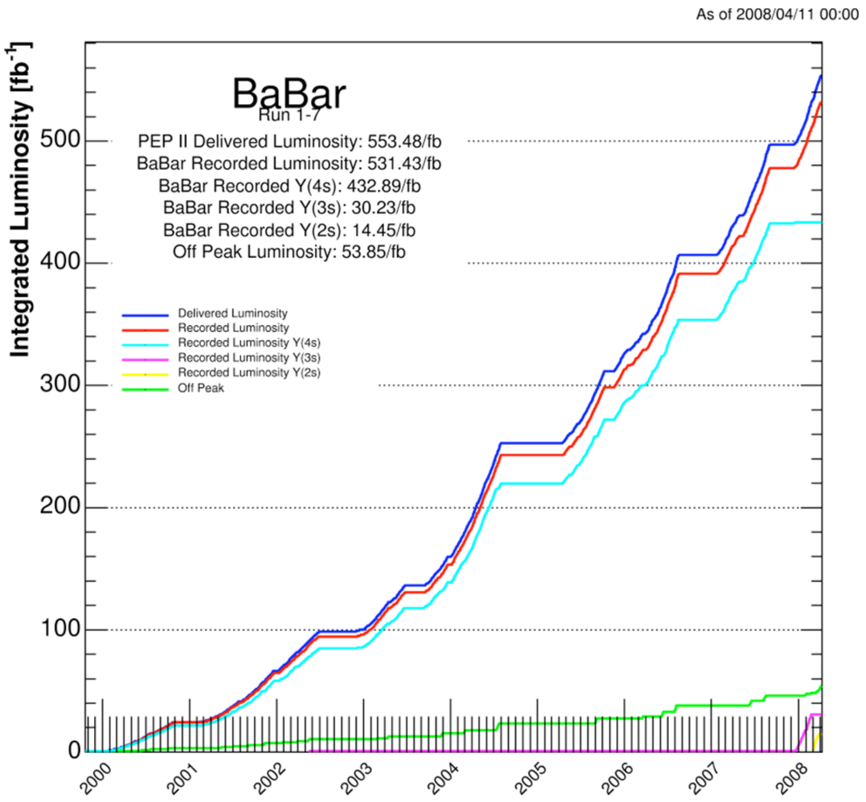
**Instrumented Flux Return**
**18–19 layers**

**NIM A479, 1 (2002);**
**Update: arXiv:1305.3560**

# *BaBar* Datasets

- PEP-II at SLAC is not only a *B* factory but also a charm factory
  - 470 x $10^6$ *B* anti-*B* pairs
  - 690 x $10^6$ *c* anti-*c* pairs
  - 500 x $10^6$ $\tau^+\tau^-$ pairs

| Sample | Integrated $\mathcal{L}$ |
|---|---|
| $\Upsilon(4S)$ | $433\ \mathrm{fb}^{-1}$ |
| $\Upsilon(3S)$ | $30.2\ \mathrm{fb}^{-1}$ |
| $\Upsilon(2S)$ | $14.5\ \mathrm{fb}^{-1}$ |
| Off-peak | $54\ \mathrm{fb}^{-1}$ |
| Scan | $3.9\ \mathrm{fb}^{-1}$ |



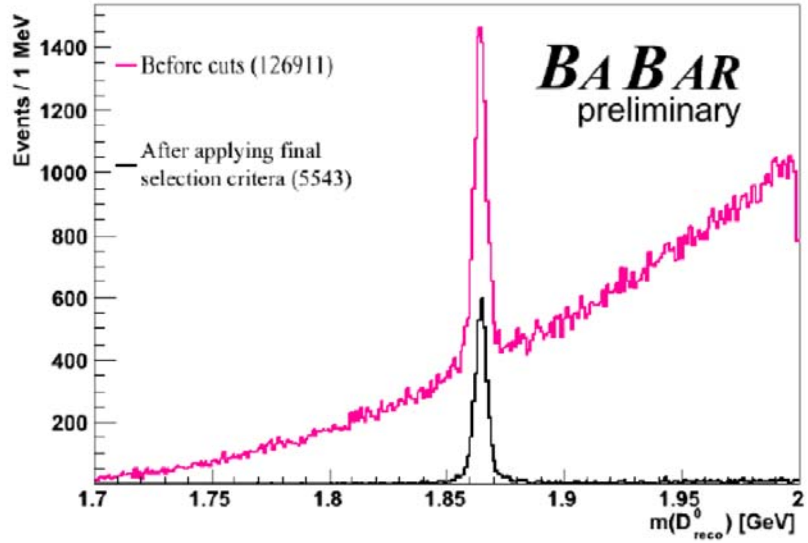
# Motivation — $D^0$ mass

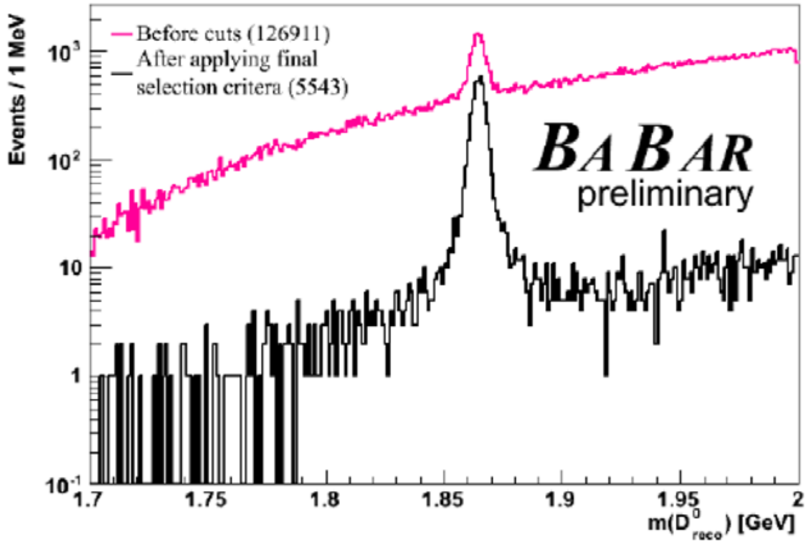
- $D^0$ is a ground state of the charm mesons
  - Sets the mass scale for higher-mass, excited states
  - Used in determining D*+ mass
    - $m(D^{*+}) = m(D^0) + \Delta m(D^{*+} - D^0)$
  - Used to extract mixing parameters from mass-constrained Dalitz plots in time-dependent amplitude analyses
    - E.g., $D^0 \rightarrow K_S\pi^+\pi^-$ and $K_SK^+K^-$
  - Precision value of the $D^0$ mass is used in detector magnetic field studies
  - Used to determine $D^0$-anti-$D^{*0}$ threshold for studies of the $X(3872)$
    - $X(3872)$ binding energy $E_b = m(X(3872)) - 2m(D^0) - \Delta m(D^{*+}\text{-}D^0)$
- $D^0$ mass current world average
  - $m(D^0) = 1864.86 \pm 0.13$ MeV/c$^2$ [1]
- Previous most precise single measurement
  - $m(D^0) = 1864.847 \pm 0.150 \pm 0.095$ MeV/c$^2$ [2]
  - Used (319 ± 18) $D^0 \rightarrow \varphi K_s$ signal events
- This measurement
  - Uses $D^0 \rightarrow K^-K^-K^+\pi^+$ decays
    - Small $Q$ value (244.2 MeV) minimizes systematic uncertainties and reduces backgrounds
    - Integrated luminosity 60x larger, 477 fb$^{-1}$
    - Data sample 15x previous after cuts, 4345 ± 70 signal events
  - Reduces overall uncertainty by > 2x

[1] J. Beringer *et al.* (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012)
[2] C. Cawlfield *et al*. (CLEO), *Phys. Rev. Lett.* **98**, 092002 (2007)

# $D^0$ mass — event selection

- Purity and significance
  - $p_{\mathrm{CM}}(D^{*+}) > 2.5$ GeV/$c$
  - Tight particle ID on $K$ and $\pi$
- Well understood tracking
  - $p_{\mathrm{LAB}}(\pi_S^+) > 150$ MeV/$c$
  - $\cos(\theta_{\mathrm{LAB}}) < 0.89$
- Tag the $D^{*+}$
  - $\Delta m \equiv m(KKK\pi\pi_s) - m(KKK\pi)$
  - $\Delta m - \Delta m_{\mathrm{PDG}} < 1.5$ MeV/$c^2$
- Use a kinematic fit that constrains each vertex to choose best candidate



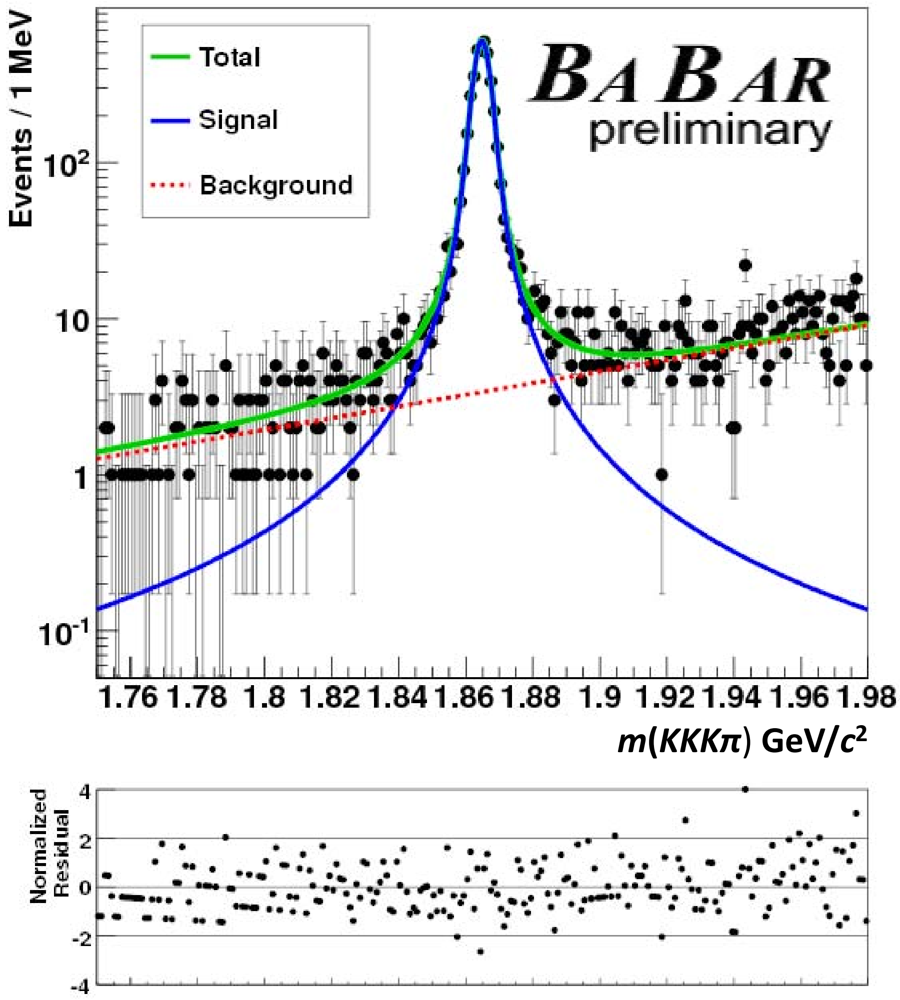


# $D^0$ mass — fit

- Fit function
  - Signal: Voigtian

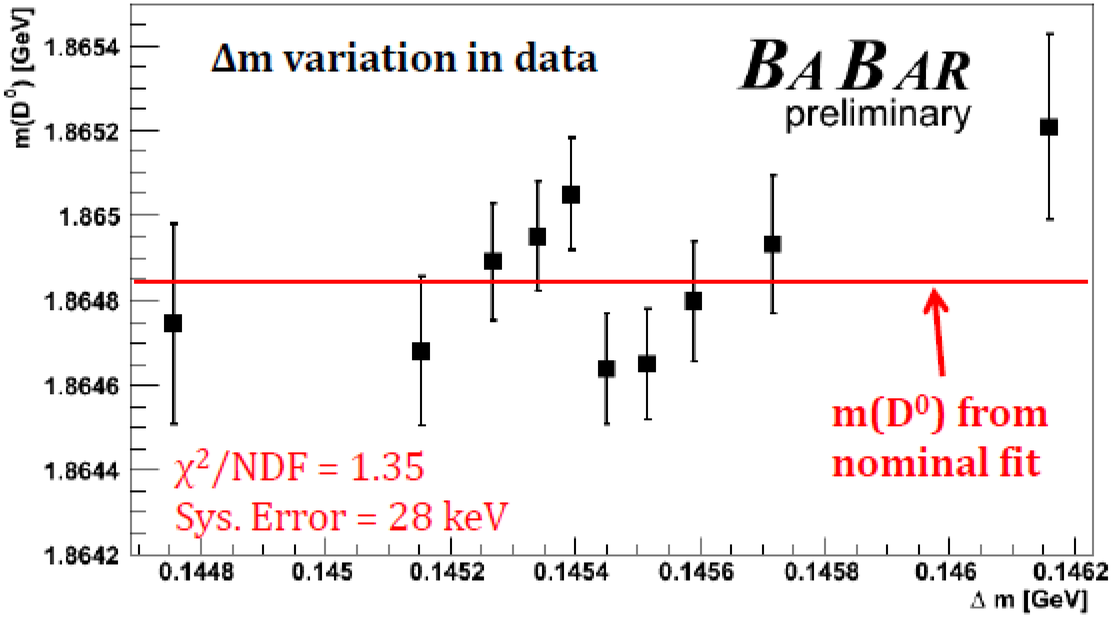
$$V(m; m_D, \gamma, \sigma) = \frac{1}{(m-m_d)^2+\frac{1}{4}\gamma^2} \otimes \exp\left[-\frac{1}{2}\frac{(m-m_d)^2}{\sigma^2}\right]$$

  - Background:
    - Exponential in $m(KKK\pi)$
- Unbinned max. like. fit
- Fitted values
  - $m(D^0) = 1864.841 \pm 0.048$ MeV/$c^2$
  - $\gamma = 2.596 \pm 0.152$ MeV
  - $\sigma = 1.762 \pm 0.086$ MeV
- Events in signal
  - 4345 ± 70



# $D^0$ mass — systematic uncertainties

- Consistency check
  - Split dataset into 10 disjoint subsamples
    - Azimuth angle
    - $p_{\mathrm{LAB}}(D^0)$
    - $\Delta m$
- If $\chi^2/N_{\mathrm{DOF}} > 1$, use the PDG scale factor method to assign the systematic error



$$\sigma^2 = \sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{syst}}$$

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

Scale factor $S^2 = \chi^2/N_{\mathrm{DoF}}$

Systematic error $\sigma_{syst} = \sigma_{stat}\sqrt{S^2 - 1}$

# $D^0$ mass — systematic uncertainties

- The largest systematic: $K^{\pm}$ mass uncertainty
  - Reconstruction uses known $K^{\pm}$ mass
  - Uncertainty is ± 16 keV/$c^2$, but there are 3 kaons
  - Assess effect by varying within ± 1σ (PDG), refit, and take average

**Summary of Systematic Errors**

| **Source** | **$\sigma_{sys}$ [keV]** |
|---|---|
| $K^{\pm}$ mass uncertainty | 46 |
| Magnetic field & material model | 31 |
| Background model | 5 |
| Azimuthal angle φ variation | 0 |
| $p_{lab}(D^0)$ variation | 0 |
| Δm variation | 28 |
| **Total** | **62** |

# $D^0$ mass — results

- Dominant systematic error from $K^+$ mass uncertainty (16 keV/$c^2$) yields
  - 46 keV/$c^2$ (3 kaons)
- Magnetic field and energy loss calibration
  - 31 keV/$c^2$
- Systematic variation in $\Delta m$
  - 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 a more precise $D^0$ mass with improved $K$ mass value
- Result is approximately twice as precise as the current world average
  - 1864.841 ± 0.078 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

Binding energy
$E_b = m(X(3872)) - 2m(D^0) - \Delta m(D^{*+}\text{-}D^0)$
This result: $E_b = 0.12 \pm 0.24$ MeV
PDG: $E_b = 0.16 \pm 0.32$ MeV

# Motivation — $D^{*+}$ line width, $\Delta m(D^{*+}\text{-}D^0)$ mass difference

- The $D^{*+}$ line width explores nonperturbative strong physics where the heavy meson involves the charm quark
  - Provides a check on models of the *D*-meson mass spectrum
  - Provides information on the $D^{*+}$ coupling $g_{D^*D\pi}$ to the $D$-$\pi$ system
    - Which can be related to $g_{B^*B\pi}$ which is not accessible directly (no phase space for $B^* \rightarrow B\pi$)
      - Needed for model-independent measurement of $|V_{ub}|$
      - And is a large contributor to the theoretical uncertainty of $|V_{ub}|$
  - Extracted values of the universal coupling constant *g* are not consistent with chiral perturbation theory
- Previously only one measurement [3]
  - $\Gamma(D^{*+}) = 96 \pm 4 \pm 22$ keV
  - Used $D^0 \rightarrow K^-\pi^+$ decays, 9 $\text{fb}^{-1}$
- This measurement uses $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ decays
  - And 50x more data
  - Permits tight event selection to control backgrounds
  - Permits precision understanding of systematics

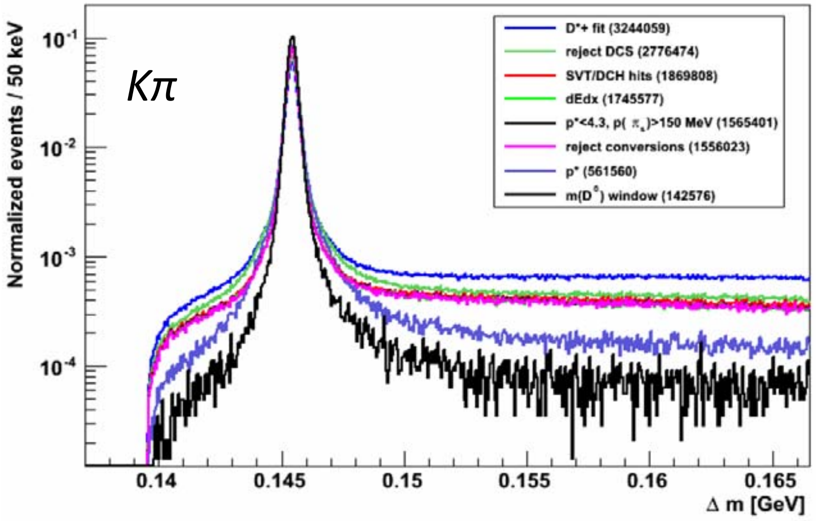
[3] A. Anastassov et al. (CLEO Collaboration), *Phys. Rev. D***65**, 032003 (2002).

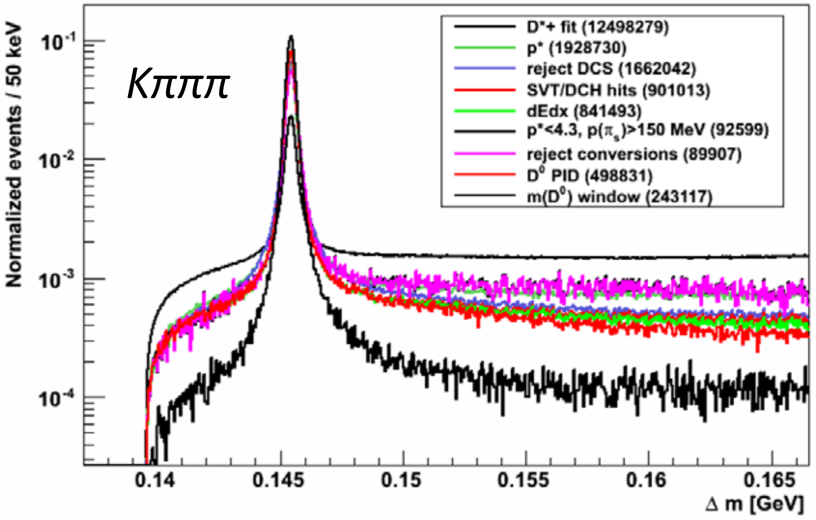
# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — procedure

- Use $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ decays
- Describe signal by a relativistic Breit-Wigner (RBW) convolved with a resolution function
  - RBW: $\frac{d\Gamma(m)}{dm} = \left(\frac{p}{p_0}\right)^{2J+1}\left(\frac{1+r^2p_0^2}{1+r^2p^2}\right)\frac{(m_0\Gamma_0)^2}{(m_0^2-m^2)^2+(m_0\Gamma^2_{\text{Total}}(m))^2}$
  - Resolution function derived from simulation
- Describe background by
  - A threshold function: $B(\Delta m) = \Delta m\sqrt{\Delta m/m_\pi - 1}\,\exp(c\sqrt{\Delta m/m_\pi - 1})$
- Fit the $D^{*+}\text{-}D^0$ mass difference distribution for $\Gamma(D^{*+})$ and $\Delta m(D^{*+}\text{-}D^0)$

# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — event selection

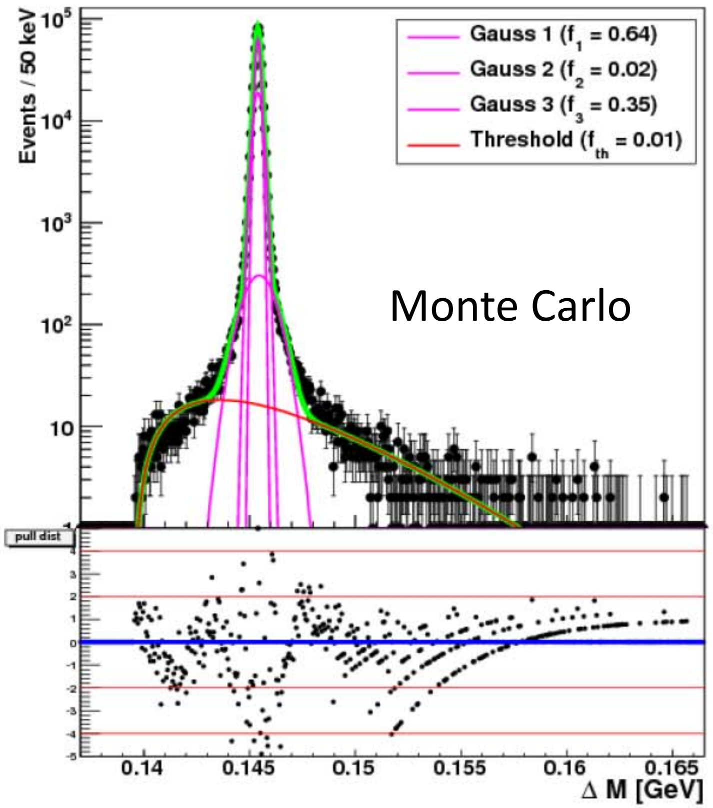
- $D^{*+} \rightarrow D^0\pi_s^+$, $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
  - Q = 6 MeV, total B.F. = 8%
- Cuts for purity and significance
  - $3.6\ \text{GeV}/c < p_{\text{CM}}(D^{*+}) < 4.6\ \text{GeV}/c$
  - Tight particle ID restrictions on $K$ and $\pi$ daughters
- Cuts for highest-quality tracking
  - $p_{\text{LAB}}(\pi_s^+) > 150\ \text{MeV}/c$
  - $\cos(\theta_{\text{LAB}}) < 0.89$
- D0 selection
  - $1.86\ \text{GeV}/c^2 < m(K\pi(\pi\pi)) < 1.87\ \text{GeV}/c^2$
- Apply kinematic fit to each vertex
  - Choose best candidate



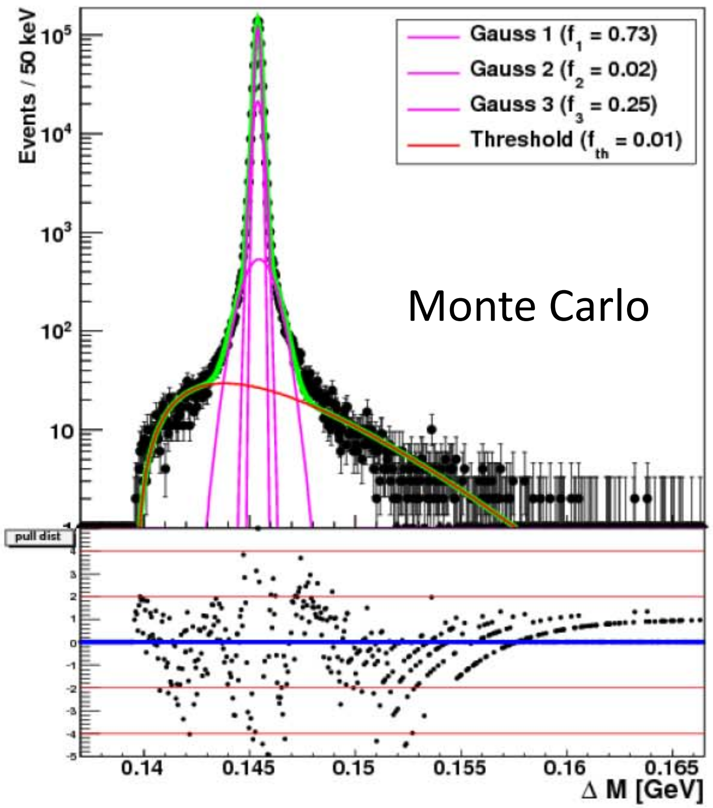


# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — resolution function

- No control sample from data is available
- Use triple Gaussian
  - Extract parameters from simulation fit
- Model slow pion decays $\pi_s^+ \rightarrow \mu^+\nu$ with a threshold function
- Scale widths using scale factor ε
  - $\sigma \rightarrow \sigma\,(1 + \varepsilon)$



(a) $D^0 \rightarrow K\pi$

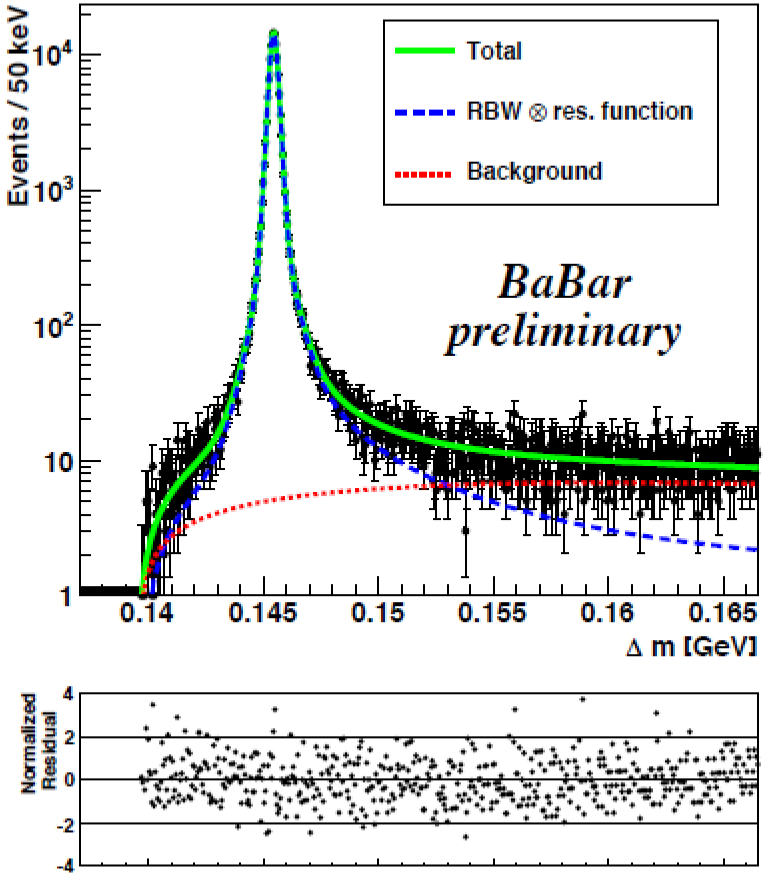


(b) $D^0 \rightarrow K3\pi$

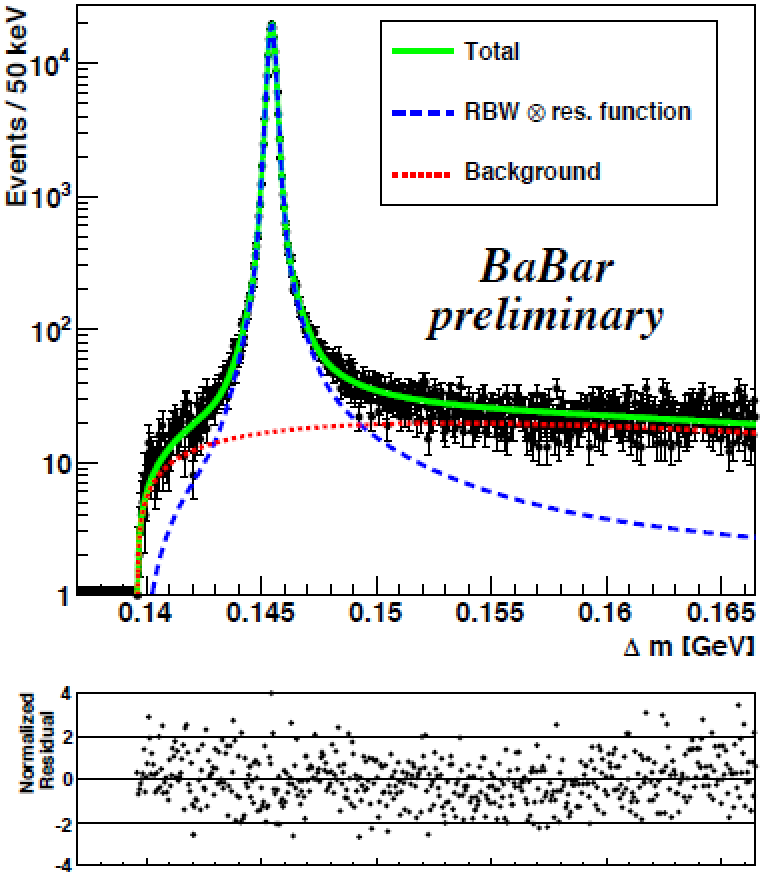
# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — fits

- Sensitivity to width comes from tails of the distribution

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

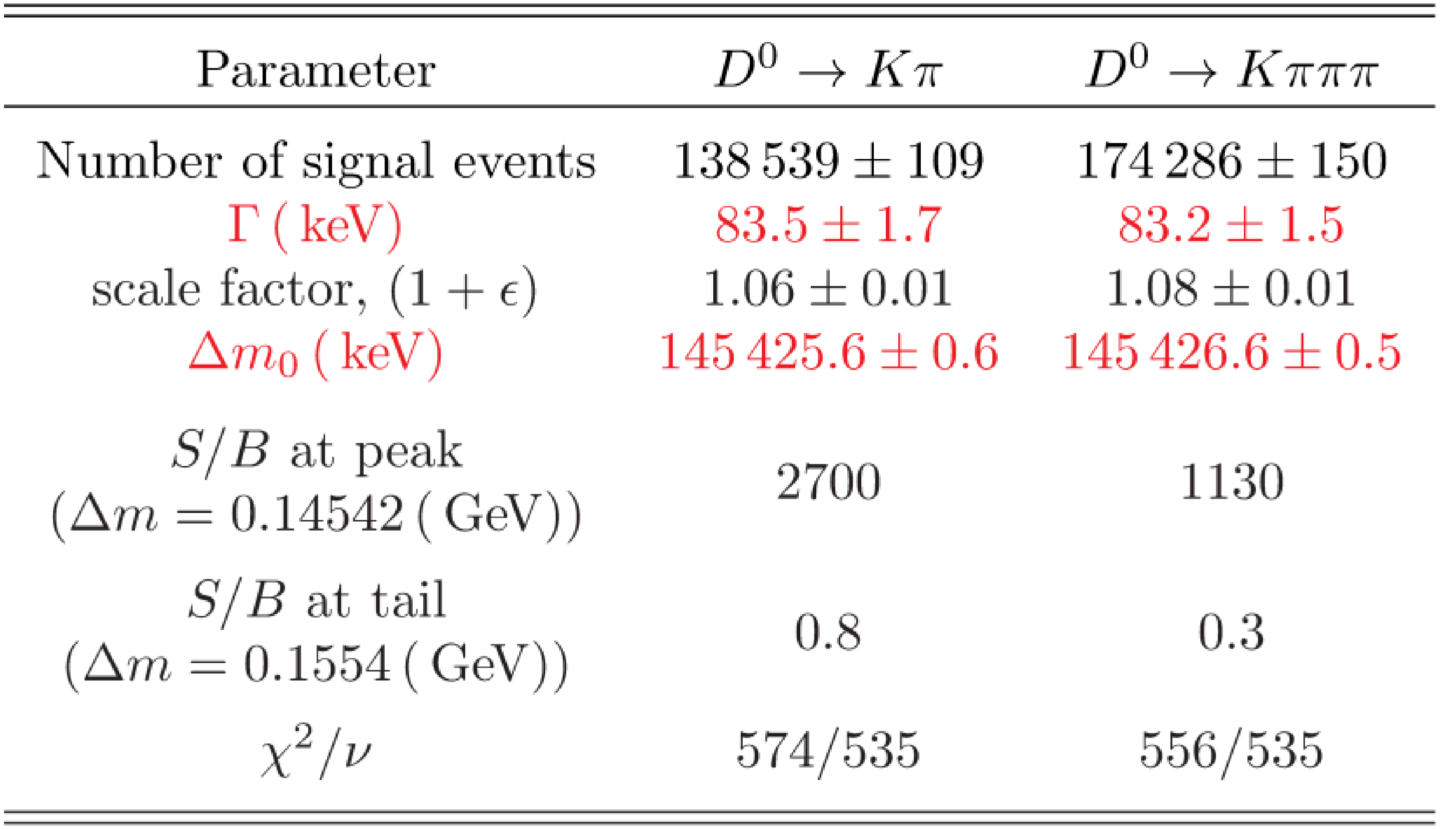


$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$



# $\Gamma(D^{*+})$, $\Delta m(D^{*+}-D^0)$ — fit results

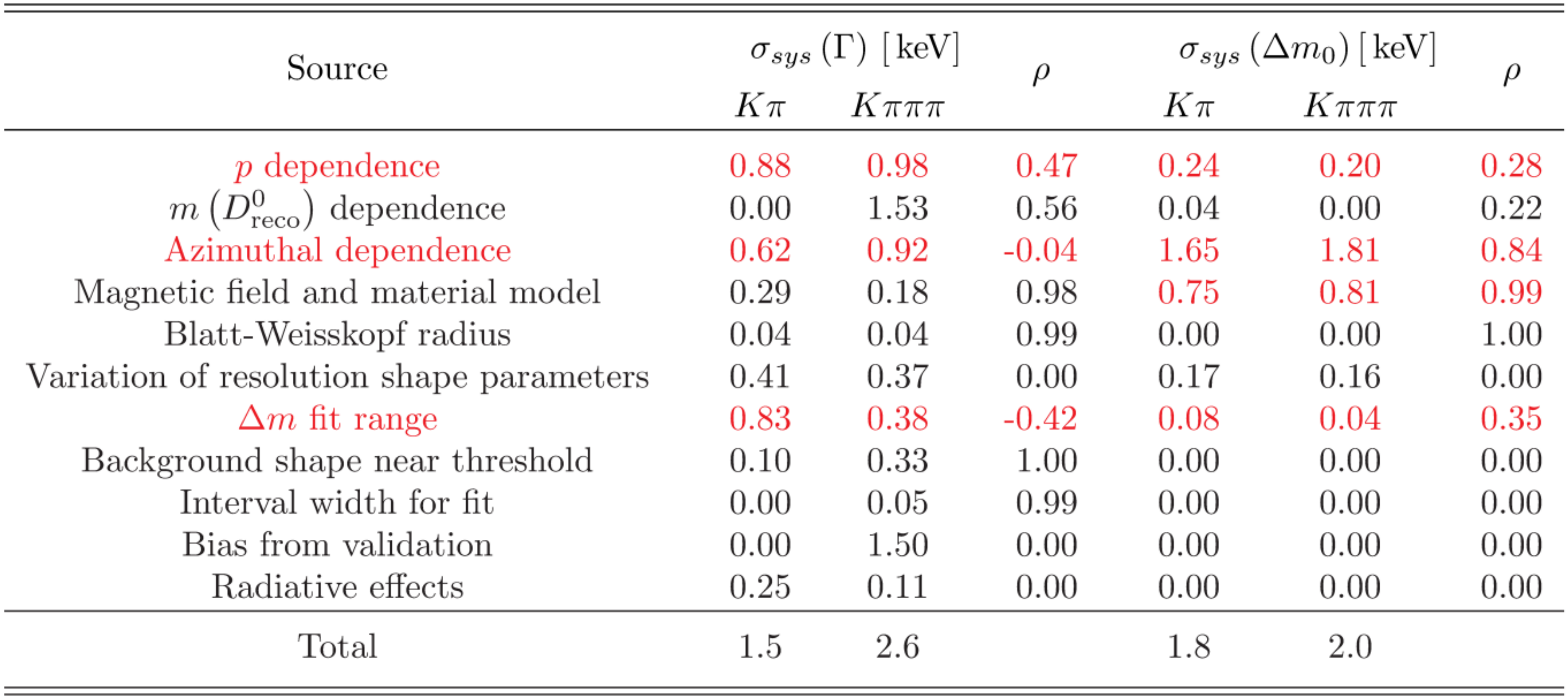
- From binned fits



| Parameter | $D^0 \to K\pi$ | $D^0 \to K\pi\pi\pi$ |
|---|---|---|
| Number of signal events | $138\,539 \pm 109$ | $174\,286 \pm 150$ |
| $\Gamma$ ( keV) | $83.5 \pm 1.7$ | $83.2 \pm 1.5$ |
| scale factor, $(1+\epsilon)$ | $1.06 \pm 0.01$ | $1.08 \pm 0.01$ |
| $\Delta m_0$ ( keV) | $145\,425.6 \pm 0.6$ | $145\,426.6 \pm 0.5$ |
| $S/B$ at peak<br>$(\Delta m = 0.14542\,(\,\mathrm{GeV}))$ | 2700 | 1130 |
| $S/B$ at tail<br>$(\Delta m = 0.1554\,(\,\mathrm{GeV}))$ | 0.8 | 0.3 |
| $\chi^2/\nu$ | 574/535 | 556/535 |

# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — systematics

- Larger systematics are shown in red
- Systematics include correlation factor $\rho$ between the $K\pi$ and $K\pi\pi\pi$ subsamples



| Source | $\sigma_{sys}(\Gamma)$ [keV] |  | $\rho$ | $\sigma_{sys}(\Delta m_0)$ [keV] |  | $\rho$ |
|---|---|---|---|---|---|---|
|  | $K\pi$ | $K\pi\pi\pi$ |  | $K\pi$ | $K\pi\pi\pi$ |  |
| $p$ dependence | 0.88 | 0.98 | 0.47 | 0.24 | 0.20 | 0.28 |
| $m\left(D^0_{\text{reco}}\right)$ 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 |
| $\Delta m$ 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 |  |

# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^0)$ — results

- Combined results from $K\pi$ and $K\pi\pi\pi$ subsamples
- Combined using weighted average taking correlations into account
  - $\Delta m = m(D^{*+}) - m(D^0)$ = 145425.8 ± 0.5 (stat.) ± 1.8 (syst.) keV/$c^2$
  - Contrast with
    - CLEO: 145.412 ± 0.012 MeV/$c^2$
    - PDG: 145.410 ± 0.010 MeV/$c^2$
  - $\Gamma(D^{*+})$ = 83.3 ± 1.3 (stat.) ± 1.4 (syst.) keV
  - Contrast with
    - CLEO: 96 ± 4 ± 22 keV

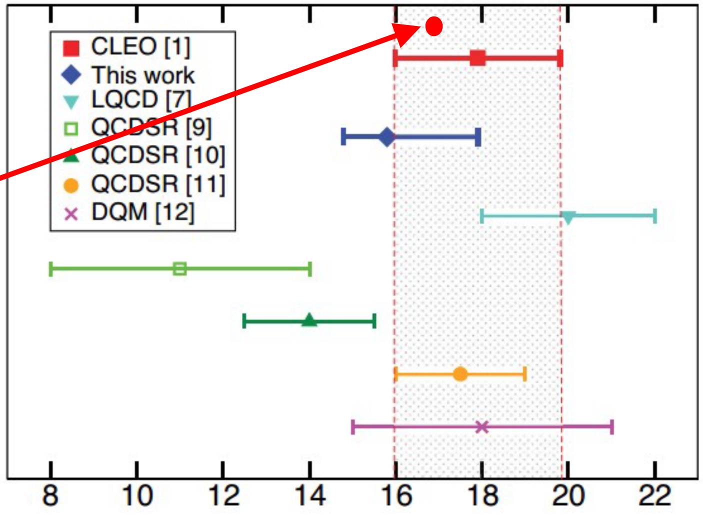
# Vector meson coupling to pion

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

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

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

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



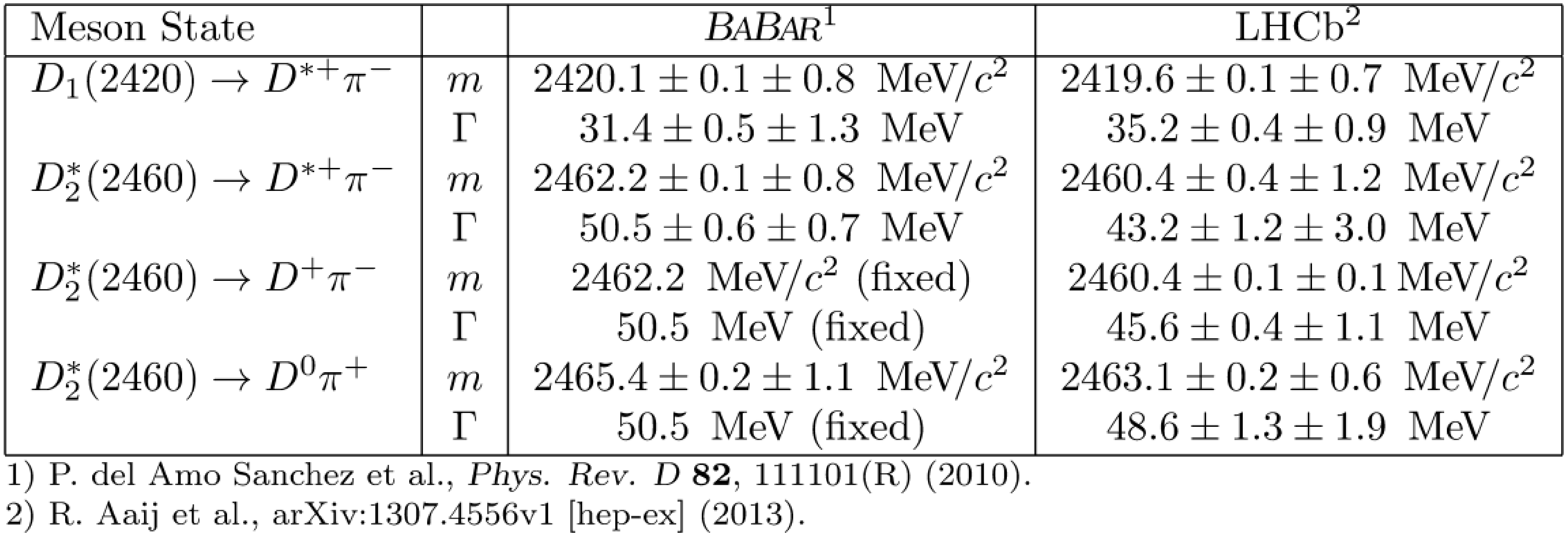
- Test predictions of chiral perturbation theory
- Use *R* from Di Pierro and Eichten, PRD **64**, 114004 (2001)
- Use widths from this measurement and from PRD **82**, 111101(R) (2010)
- Extracted values of *g* are not constant for different *D* meson excited states; this contradicts the prediction of the Di Pierro & Eichten potential model
- Measurements are inconsistent with chiral perturbation theory

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

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

# $D_1$(2420) and $D_2$*(2460) masses and widths

- LHCb and *BABAR* results are reasonably consistent
- Width measurements from LHCb lead to substantial disagreement with calculated values of the coupling constant
- And with the model expectation that these values should be the same for the three states
- The order of magnitude increase in precision of these measurments confirms the observed inconsistency with the chiral quark model (on previous slide)

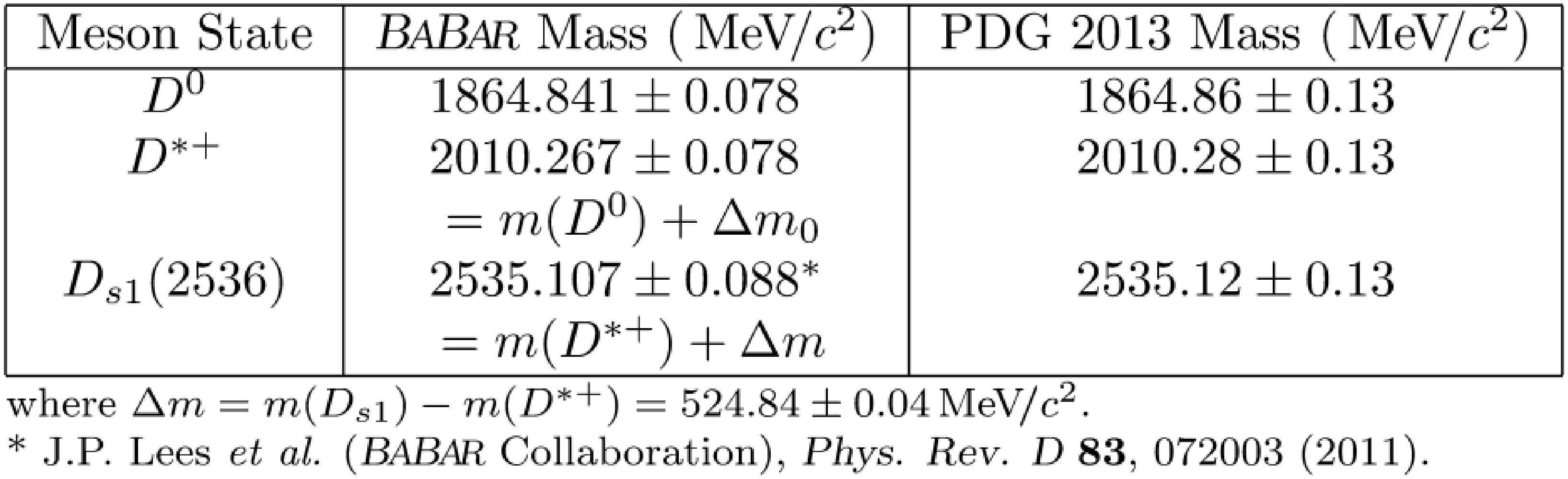


| Meson State | | *BABAR*[1] | LHCb[2] |
|---|---|---|---|
| $D_1(2420) \to D^{*+}\pi^-$ | $m$ | $2420.1 \pm 0.1 \pm 0.8$ MeV/$c^2$ | $2419.6 \pm 0.1 \pm 0.7$ MeV/$c^2$ |
| | $\Gamma$ | $31.4 \pm 0.5 \pm 1.3$ MeV | $35.2 \pm 0.4 \pm 0.9$ MeV |
| $D_2^*(2460) \to D^{*+}\pi^-$ | $m$ | $2462.2 \pm 0.1 \pm 0.8$ MeV/$c^2$ | $2460.4 \pm 0.4 \pm 1.2$ MeV/$c^2$ |
| | $\Gamma$ | $50.5 \pm 0.6 \pm 0.7$ MeV | $43.2 \pm 1.2 \pm 3.0$ MeV |
| $D_2^*(2460) \to D^{+}\pi^-$ | $m$ | 2462.2 MeV/$c^2$ (fixed) | $2460.4 \pm 0.1 \pm 0.1$ MeV/$c^2$ |
| | $\Gamma$ | 50.5 MeV (fixed) | $45.6 \pm 0.4 \pm 1.1$ MeV |
| $D_2^*(2460) \to D^{0}\pi^+$ | $m$ | $2465.4 \pm 0.2 \pm 1.1$ MeV/$c^2$ | $2463.1 \pm 0.2 \pm 0.6$ MeV/$c^2$ |
| | $\Gamma$ | 50.5 MeV (fixed) | $48.6 \pm 1.3 \pm 1.9$ MeV |

1) P. del Amo Sanchez et al., *Phys. Rev. D* **82**, 111101(R) (2010).
2) R. Aaij et al., arXiv:1307.4556v1 [hep-ex] (2013).

# Summary

- *BABAR* has made precision measurements in the charm sector
- The $D^0$ mass
  - $m(D^0)$ = 1864.841 ± 0.048 (stat.) ± 0.062 (syst.) MeV/$c^2$
- The $D^{*+} - D^0$ mass difference
  - $\Delta m_0 = m(D^{*+}) - m(D^0)$ = 145425.8 ± 0.5 (stat.) ± 1.8 (syst.) MeV/$c^2$
- The $D^{*+}$ line width
  - $\Gamma(D^{*+})$ = 83.3 ± 1.3 (stat.) ± 1.4 (syst.) keV
- Combining $m(D^0)$ and $\Delta m$ yield the most precise value of the $D^{*+}$ mass
  - Better than PDG in terms of precision
- *BABAR* measured the mass difference $\Delta m(D_{s1}(2536)\text{-}D^{*}+)$ earlier
  - Using that value, we also have the most precise $D_{s1}(2536)$ mass



| Meson State | BABAR Mass (MeV/$c^2$) | PDG 2013 Mass (MeV/$c^2$) |
|---|---|---|
| $D^0$ | $1864.841 \pm 0.078$ | $1864.86 \pm 0.13$ |
| $D^{*+}$ | $2010.267 \pm 0.078$<br>$= m(D^0) + \Delta m_0$ | $2010.28 \pm 0.13$ |
| $D_{s1}(2536)$ | $2535.107 \pm 0.088^*$<br>$= m(D^{*+}) + \Delta m$ | $2535.12 \pm 0.13$ |

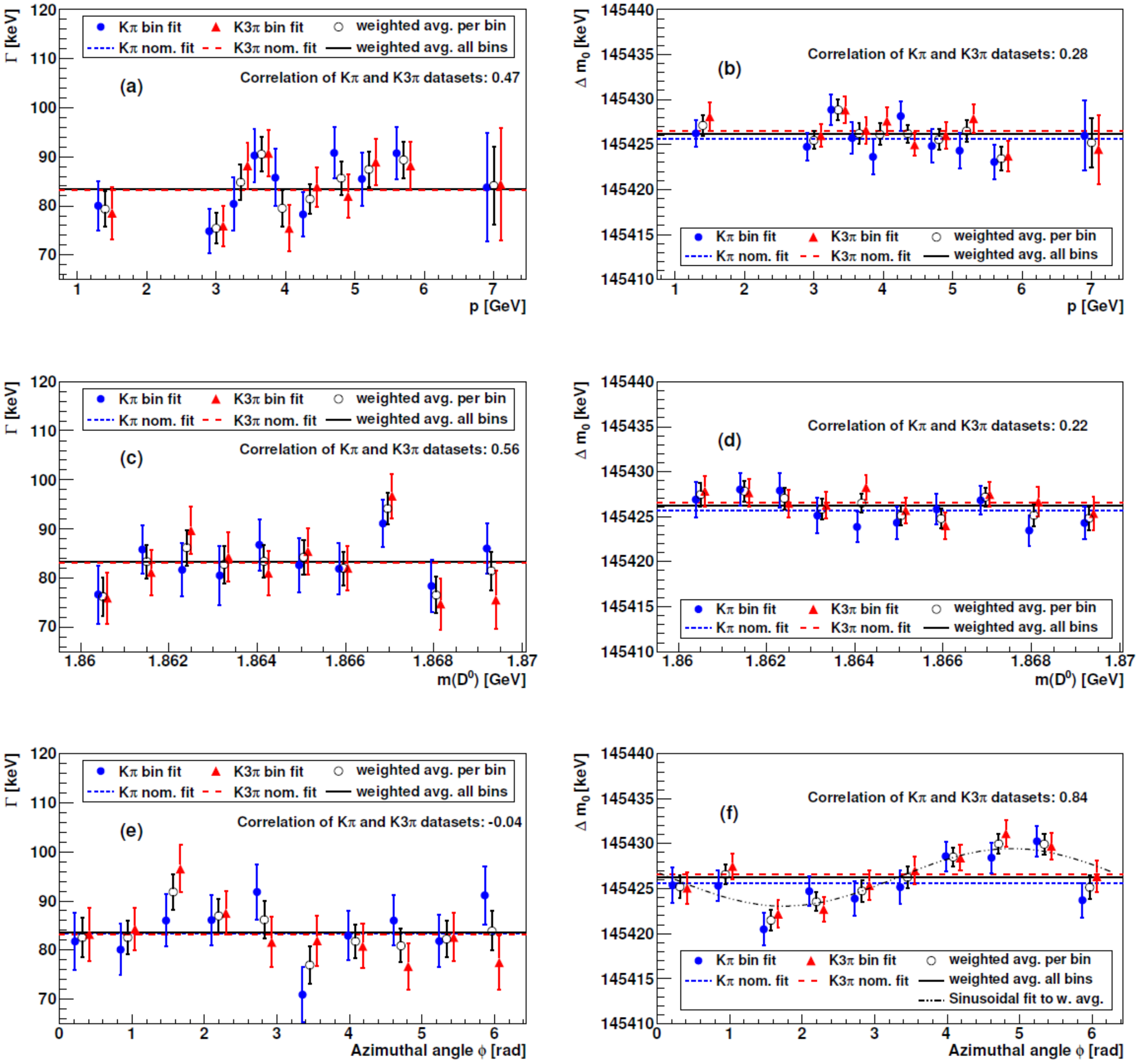
where $\Delta m = m(D_{s1}) - m(D^{*+}) = 524.84 \pm 0.04$ MeV/$c^2$.

* J.P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **83**, 072003 (2011).

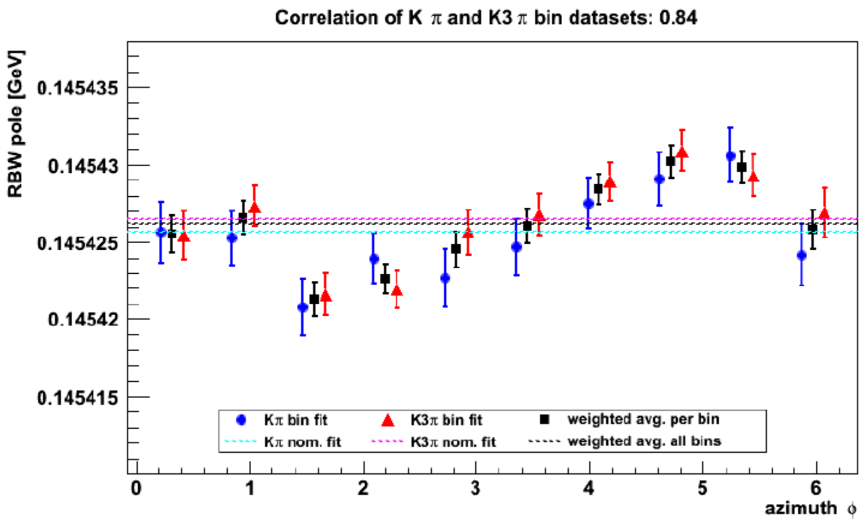
# Backup slides

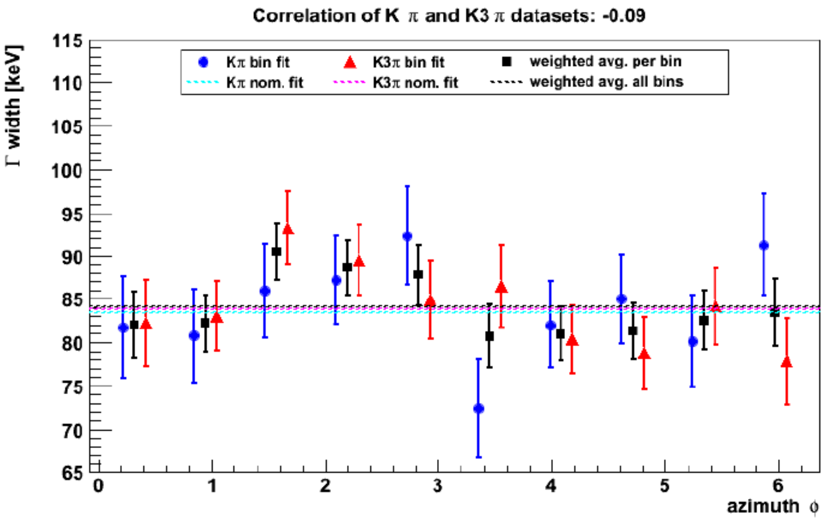
# $\Gamma(D^{*+})$, $\Delta m(D^{*+}$-$D^0)$ — checks and systematics

- Checks
  - Split data into 10 disjoint subsamples
  - Check $p_{\text{lab}}(D^0)$, $m(D^0)$, azimuthal angle
- Systematics
  - If $\chi^2/N_{\text{DOF}} > 1$, use PDG scale factor method
  - Vary energy loss correction based on PDG value for $K_S$ mass
    - Needed for masses, not widths
  - Vary form, parameters of signal and background PDFs
    - Small sensitivity to Blatt-Weisskopf radius and most resolution parameters
    - Width is sensitive to range of fit



# $\Gamma(D^{*+})$, $\Delta m(D^{*+}\text{-}D^{0})$ — checks and systematics





- Azimuthal angle variation of RBW pole and width
  - Sinusoidal variation of $\Delta m$ with $\varphi$, average value is unbiased
    - Assign as systematic error
  - Seen in $K_S$ calibration, interpreted as a variation of magnetic field with respect to the measured map
- $\Gamma$ shows an insignificant variation