D^0 and D^+ Hadronic Decays at CLEO

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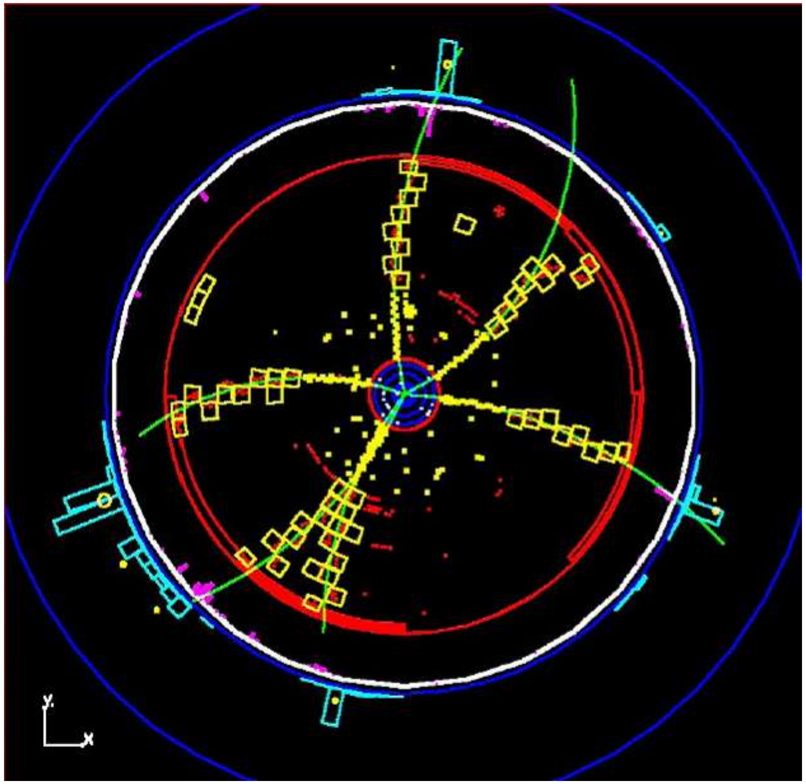
CLEO collaboration

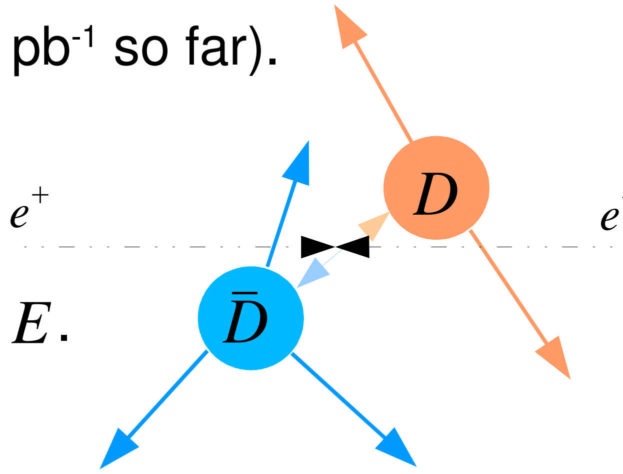
$D^+ \to K^-\pi^+\pi^+$ $D^- \to K^+\pi^-\pi^-$



- D^0 and D^+ branching fractions
- Doubly-Cabibbo-suppressed branching fractions: $D^+ \to K^+\pi^0$ and
  $D \to K^0_S \pi$ vs. $D \to K^0_L \pi$
- Dalitz analyses:
  - $D^+ \to \pi^+\pi^+\pi^-$
  - $D^0 \to K^+K^-\pi^0$

D^0 and D^+ at $\Psi(3770)$

- We collide e^- and e^+ at the $\psi(3770)$ resonance (281 pb^{-1} so far). This energy is just above threshold for $D^0\bar{D}^0$ or D^+D^- production, with no additional massive particles.



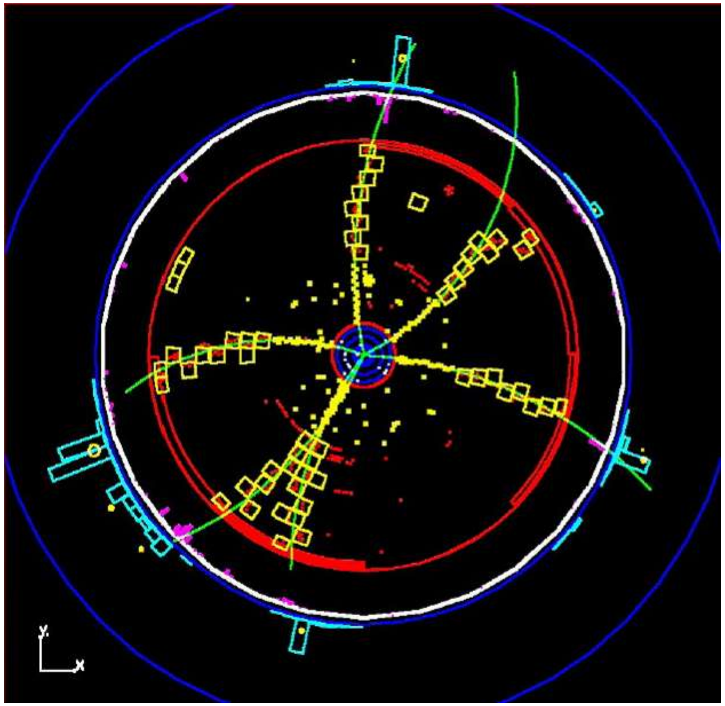
- Identify D's from "beam-constrained mass" (M_{BC}) and ΔE.

$$M_{BC} \equiv \sqrt{(E_{\text{beam}})^2 - |\vec{p}_D|^2}$$ (peaks at D mass)

$$\Delta E \equiv E_D - E_{\text{beam}}$$ (peaks at zero)

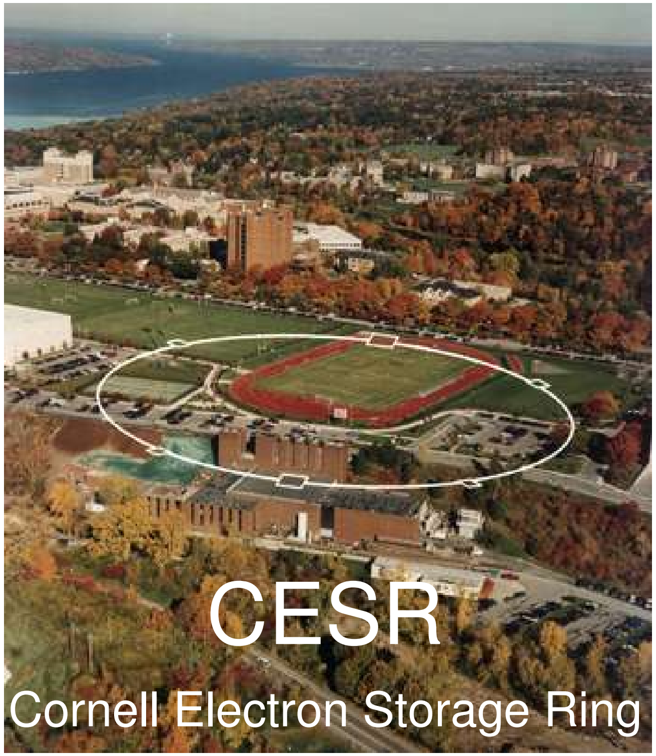
- Three ways to analyze an event:
  - Fully reconstruct one D or $\bar{D}$ ("single tag").
  - Fully reconstruct both D and $\bar{D}$ ("double tag").
  - Reconstruct one $\bar{D}$ as a tag, then look for a particular decay of the D. This is useful when one particle can't be detected (e.g. K_L^0).

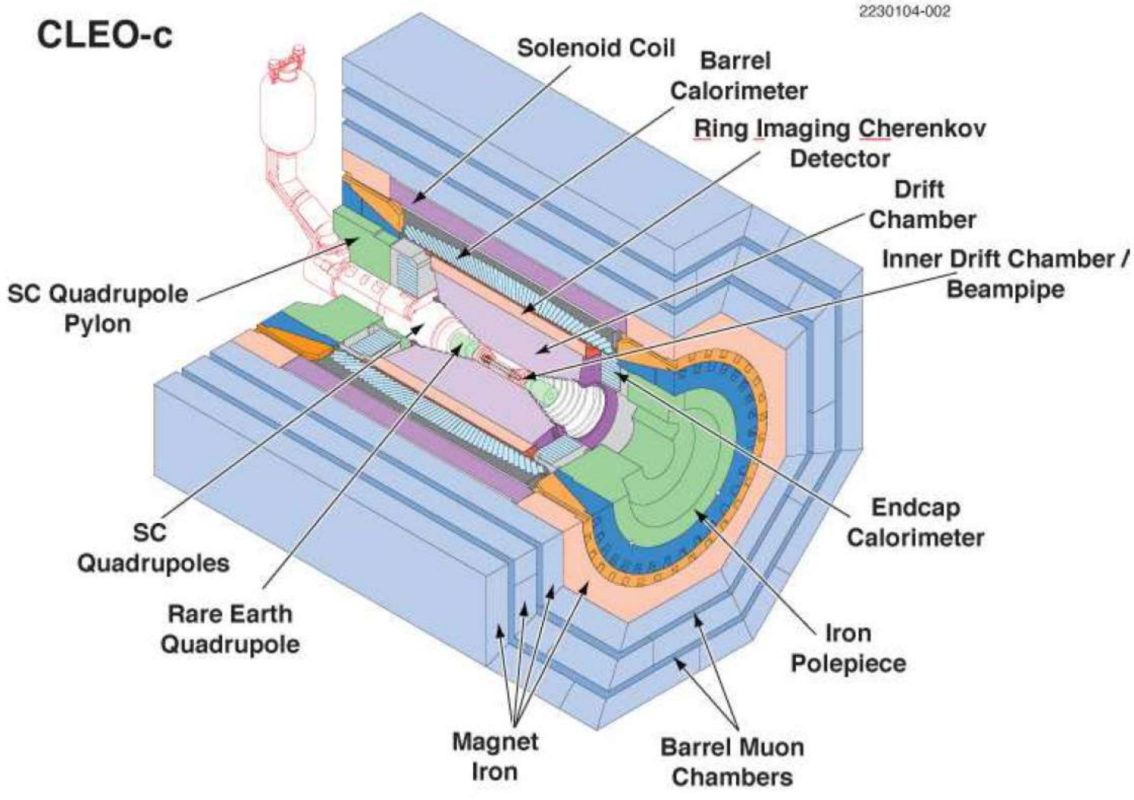
$D^+ \to K^-\pi^+\pi^+$ $D^- \to K^+\pi^-\pi^-$



The CLEO-c Detector

- Good momentum resolution: 0.6% at 1 GeV
- Good photon detection: π^0 mass resolution ~ 6 MeV
- Good particle ID: RICH (Cherenkov) & dE/dx $\Rightarrow$ excellent π^+/K^+ separation
- Run primarily at E_{CM} = 3.77 GeV for $D\bar{D}$ production (this talk) and at E_{CM} = 4.17 GeV for D_s production.





D Hadronic BFs: Overview

- The $D\bar{D}$ environment at CLEO-c is ideal for measurement of absolute D^0 and D^+ hadronic branching fractions.
  - Results do not depend on the luminosity or cross section.
- These branching fractions are an important input for B physics.
- We measure 3 D^0 and 6 D^+ decay modes, including the two reference modes $D^0 \to K^- \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$.
- We previously published* results based on 56 pb^{-1}, and we are now updating with ~5x more data: 281 pb^{-1}. Both statistical and systematic uncertainties have improved.

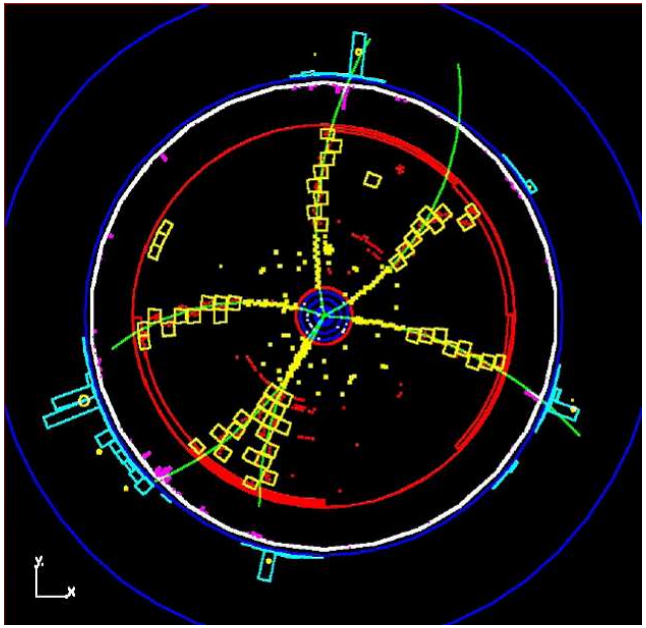
Modes:

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

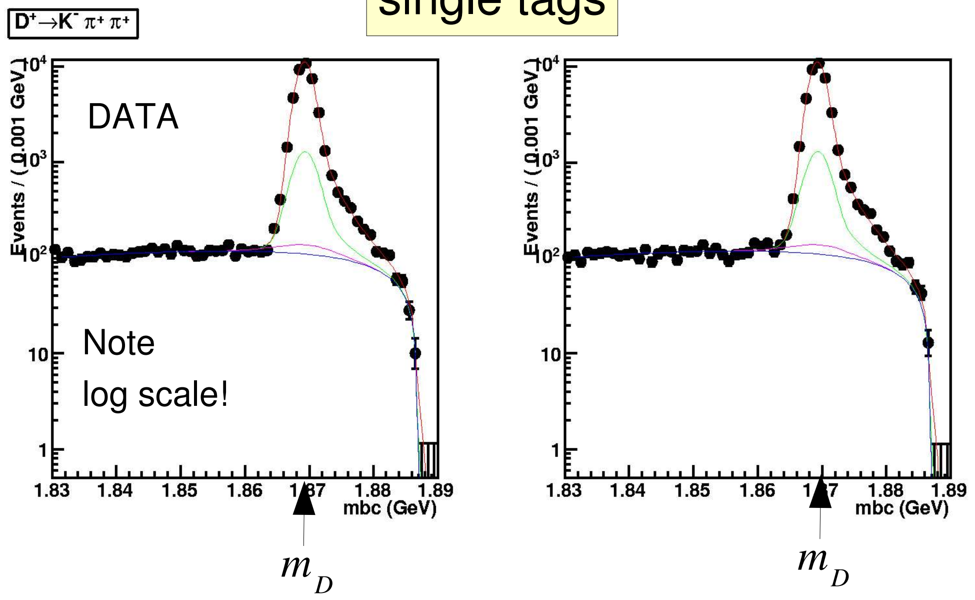
* Q. He *et al.*, Phys. Rev. Let. **95**, 121801 (2005).

D Hadronic BFs: Method

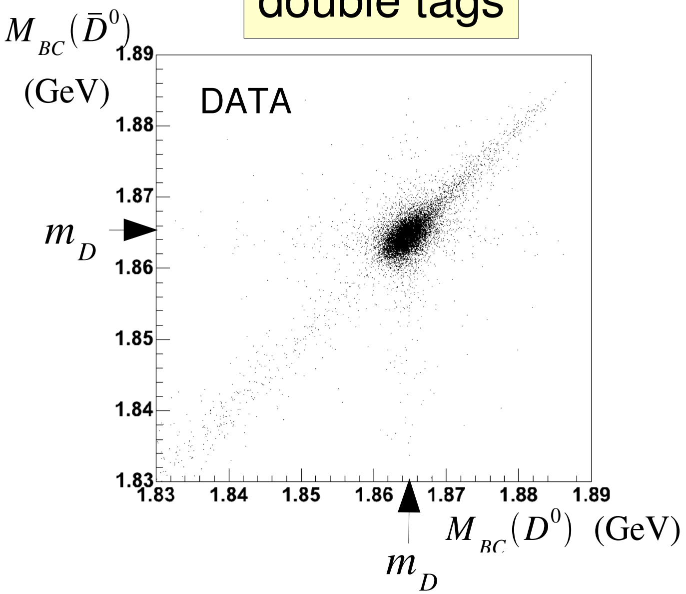
- Reconstruct single-D candidates (single tags) and $D\bar{D}$ candidates (double tags) from the final-state particles.
- Require ΔE consistent with zero.
- Extract single and double tag yields by fitting M_{BC} plots.
- Using single and double tag yields, do a χ^2 fit for branching fractions and $N_{D\bar{D}}$.



single tags

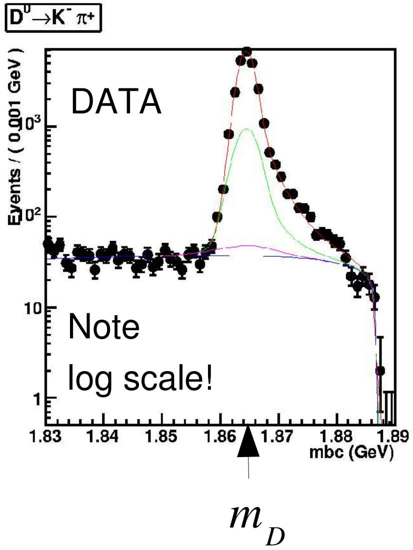


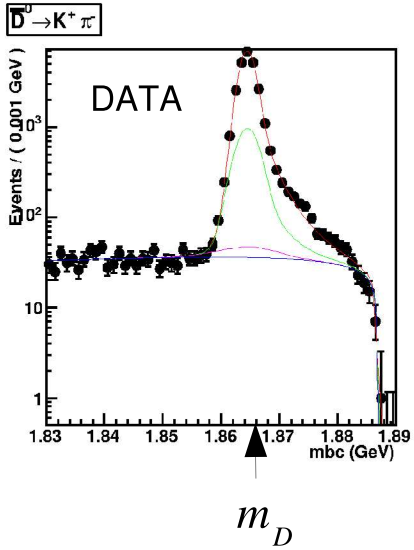
double tags

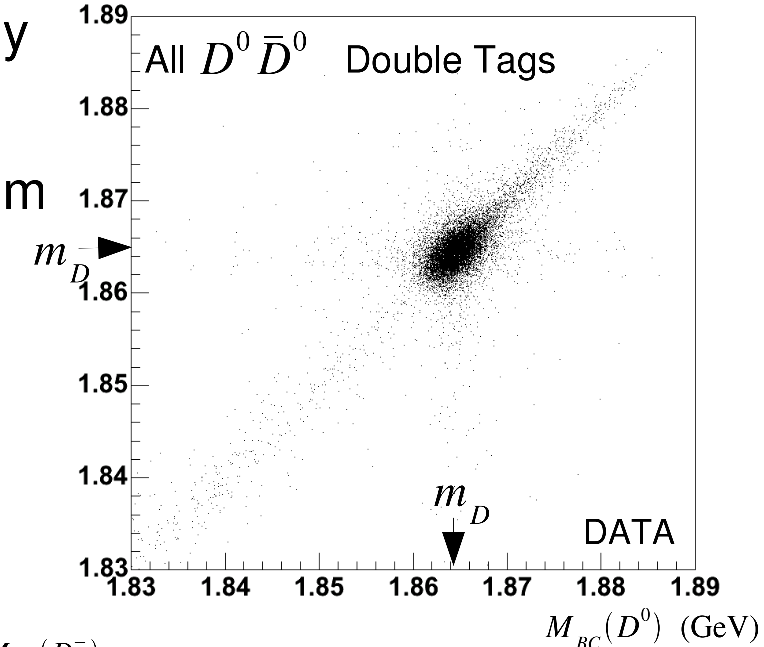


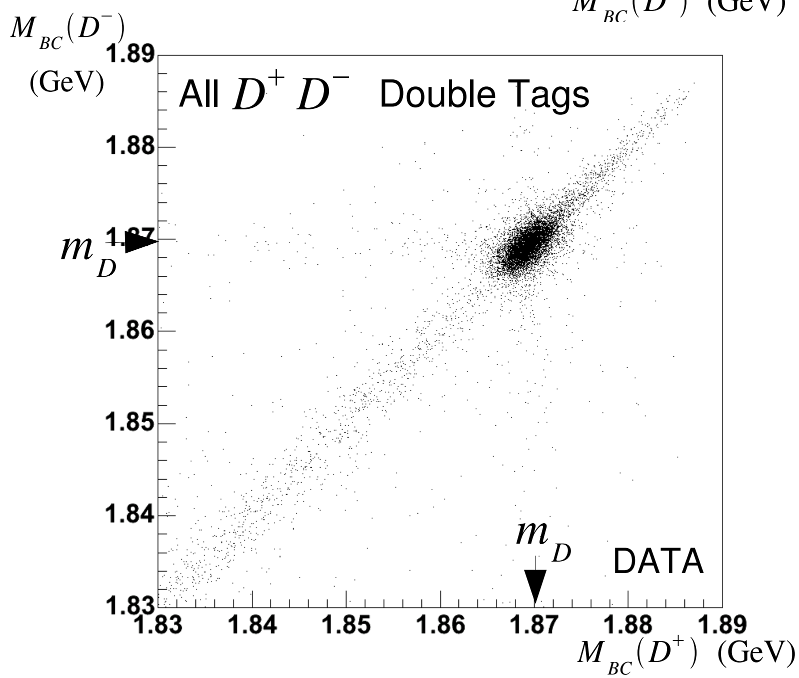
D Hadronic BFs: Yield Extraction

- We fit single and double tag peaks with a theoretically derived M_{BC} peak shape that includes the effects of initial state radiation, beam energy spread, momentum resolution, and the $\psi(3770)$ line shape.
- Double tag yields are obtained from a 2-dimensional fit of $M_{BC}(D)$ vs. $M_{BC}(\bar{D})$.
- Single tag yields are obtained from a 1-dimensional fit of M_{BC} . D and $\bar{D}$ yields are extracted separately.





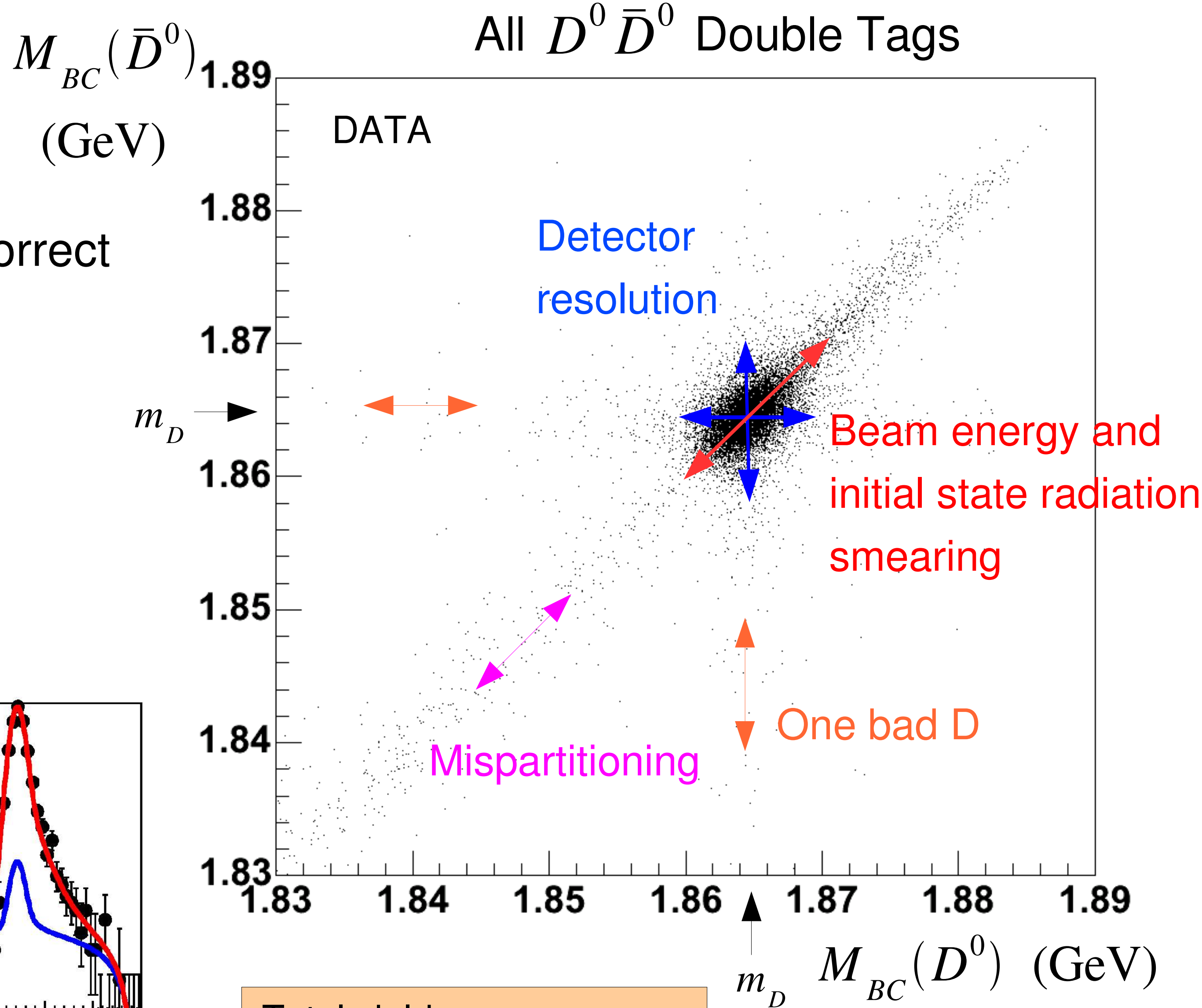




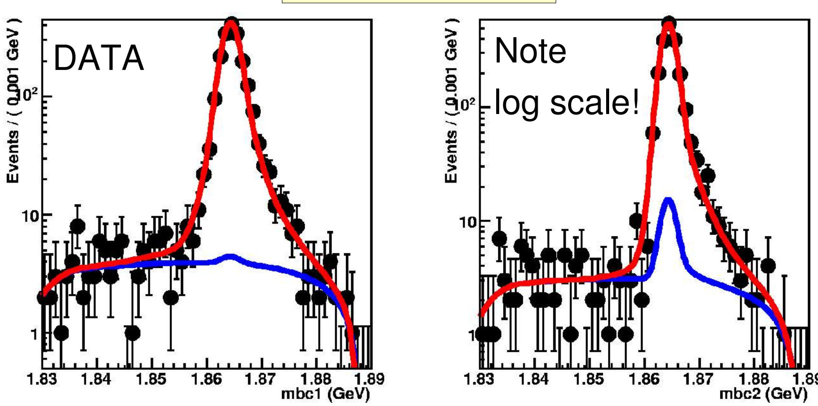
D Hadronic BFs: Double Tag Yields

- Fit components:
  - Signal peak
  - One D correct, one incorrect
  - Mispartitioning
  - Both D 's incorrect

All $D^0 \bar{D}^0$ Double Tags



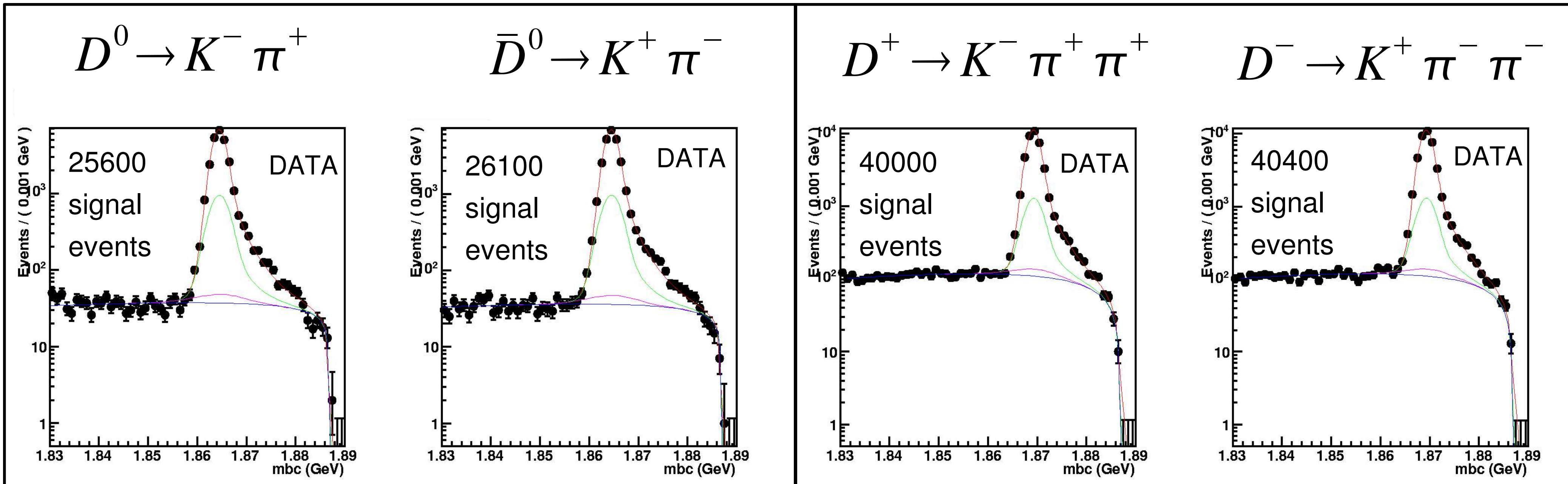
Projections



$D^0 \rightarrow K^- \pi^+ \pi^0$ vs. $\bar{D}^0 \rightarrow K^+ \pi^- \pi^- \pi^+$

Total yields:
13600 $D^0 \bar{D}^0$ double tags
8900 $D^+ D^-$ double tags

D Hadronic BFs: Single Tag Yields



Note log scale!

Total yields:

230000 D^0 and $\bar{D}^0$ single tags

167000 D^+ and D^- single tags

D Hadronic BFs: Branching Fraction Fit

$$N_i = \epsilon_i B_i N_{D\bar{D}}$$
$$\bar{N}_j = \bar{\epsilon}_j B_j N_{D\bar{D}}$$
$$N_{ij} = \epsilon_{ij} B_i B_j N_{D\bar{D}}$$

$$\Rightarrow \quad N_{D\bar{D}} = \frac{N_i \bar{N}_j}{N_{ij}} \frac{\epsilon_{ij}}{\epsilon_i \bar{\epsilon}_j} \qquad B_i = \frac{N_{ij}}{\bar{N}_j} \frac{\bar{\epsilon}_j}{\epsilon_{ij}}$$

- We are determining 9 branching fractions, as well as the number of $D^0 \bar{D}^0$ and $D^+ D^-$ pairs, from 18 single tag yields and 45 double tag yields, so we do a χ^2 fit.
- This fit includes background subtractions on the yields and cross-feeds between modes.
- Systematic errors are included in the fit. When appropriate, they are correlated between tag modes (ex. tracking efficiencies).
  - Many systematics in $N_{D\bar{D}}$ cancel, as do systematics on the other-side D in branching fraction calculations.

D Hadronic BFs: Preliminary Results

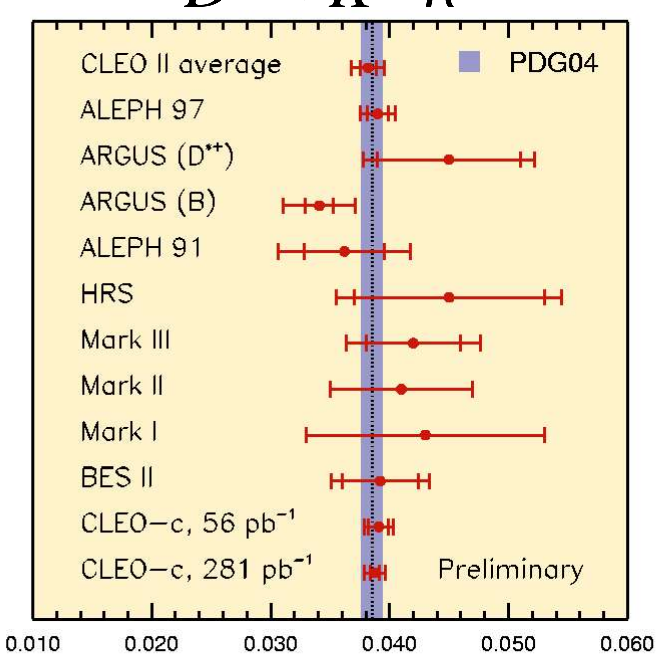
Mode	Branching Fraction
$D^0 \to K^- \pi^+$	(3.876 ± .035 ± .085)%
$D^0 \to K^- \pi^+ \pi^0$	(14.57 ± .12 ± .42)%
$D^0 \to K^- \pi^+ \pi^+ \pi^-$	(8.26 ± .07 ± .29)%
$D^+ \to K^- \pi^+ \pi^+$	(9.18 ± .10 ± .25)%
$D^+ \to K^- \pi^+ \pi^+ \pi^0$	(5.98 ± .08 ± .21)%
$D^+ \to K^0_S \pi^+$	(1.549 ± .022 ± .047)%
$D^+ \to K^0_S \pi^+ \pi^0$	(7.22 ± .09 ± .30)%
$D^+ \to K^0_S \pi^+ \pi^+ \pi^-$	(3.134 ± .05 ± .14)%
$D^+ \to K^- K^+ \pi^+$	(0.928 ± .016 ± .029)%

- Our results are consistent with our previous measurements and those of other experiments.
- We are systematics-limited (stat. precision ~ 1%), but we expect to improve some systematics.

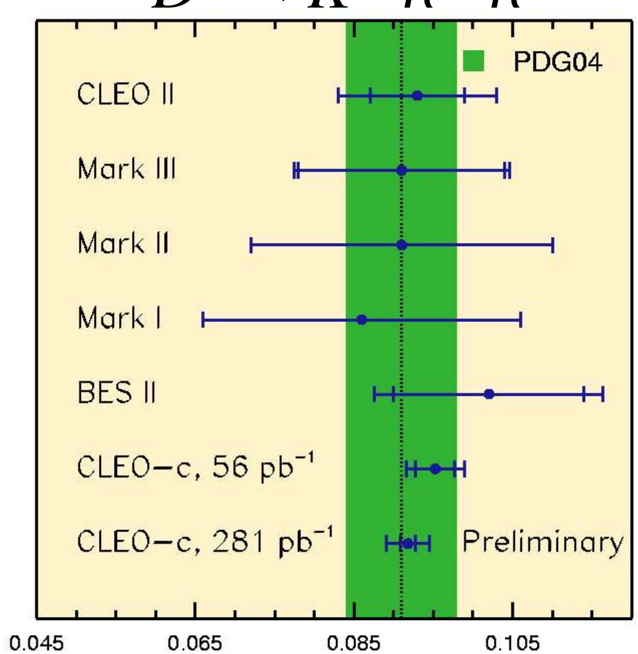
230000 D^0 single tags
167000 D^+ single tags
13600 $D^0 \bar{D}^0$ double tags
8900 $D^+ D^-$ double tags

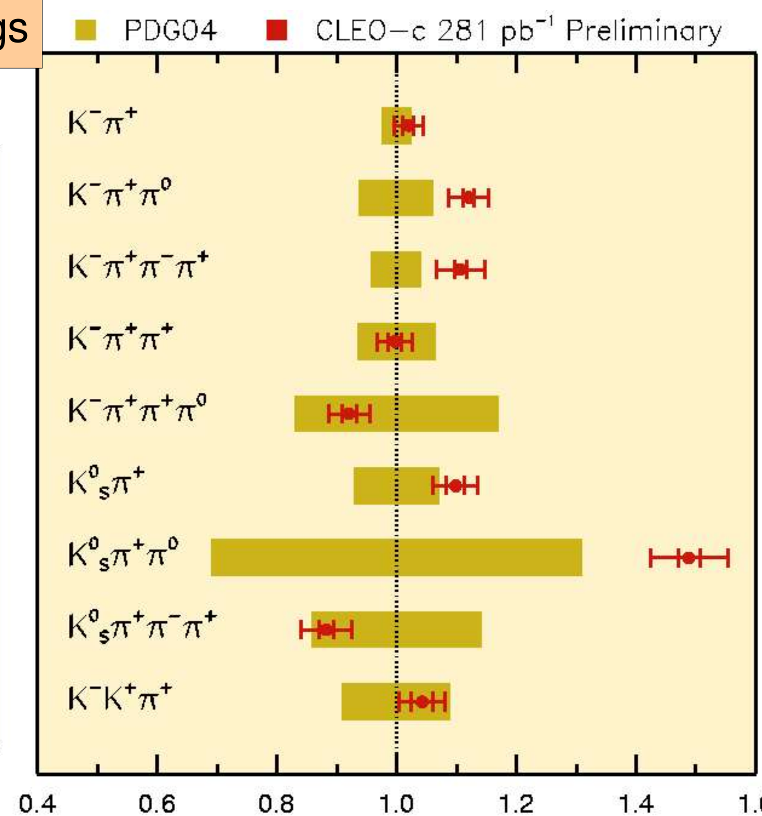
PRELIMINARY

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



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

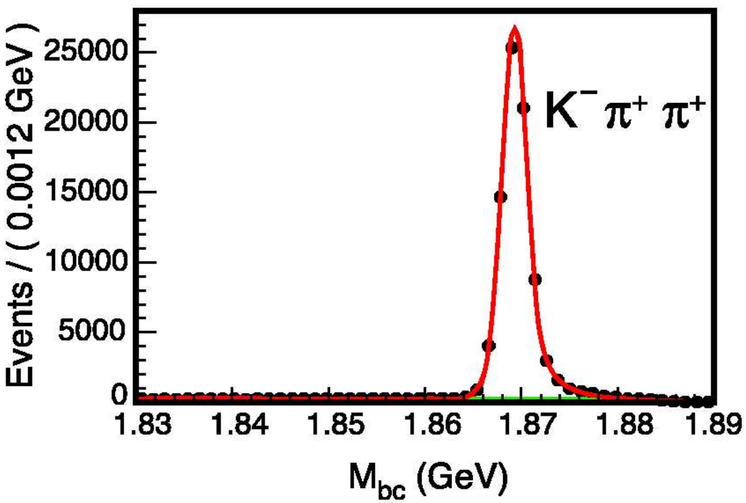




$D^+ \to K^+ \pi^0$

- Reconstruct $D^+ \to K^+ \pi^0$ single tags, measure rate relative to $D^+ \to K^- \pi^+ \pi^+$:

$$\frac{B(D^+ \to K^+ \pi^0)}{B(D^+ \to K^- \pi^+ \pi^+)} = \frac{Y((D^+ \to K^+ \pi^0))/\epsilon(D^+ \to K^+ \pi^0)}{Y(D^+ \to K^- \pi^+ \pi^+)/\epsilon(D^+ \to K^- \pi^+ \pi^+)}$$



- We find

$B(D^+ \to K^+ \pi^0)$ = (2.28 ± 0.36 ± 0.15 ± 0.08)x10^{-4} *

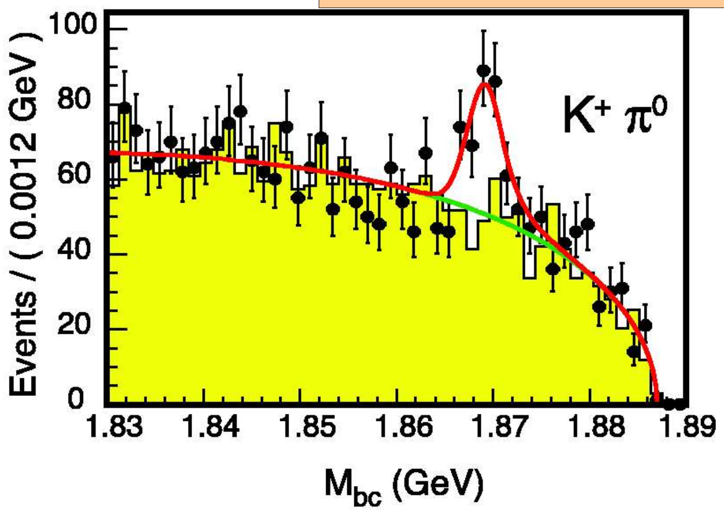
BABAR: (2.52 ± 0.47 ± 0.25 ± 0.08)x10^{-4} **

first measurement

148 ± 23 signal events

efficiency = 44.5%

- Test isospin symmetry:
  - Expect $$\frac{\Gamma(D^+ \to K^+ \pi^0)}{\Gamma(D^0 \to K^+ \pi^-)} = 0.5$$
  - With our result and PDG values, $$\frac{\Gamma(D^+ \to K^+ \pi^0)}{\Gamma(D^0 \to K^+ \pi^-)} = 0.64 \pm 0.12$$



** B. Aubert *et al.* , Phys. Rev. D **74**, 011107(R) (2006).

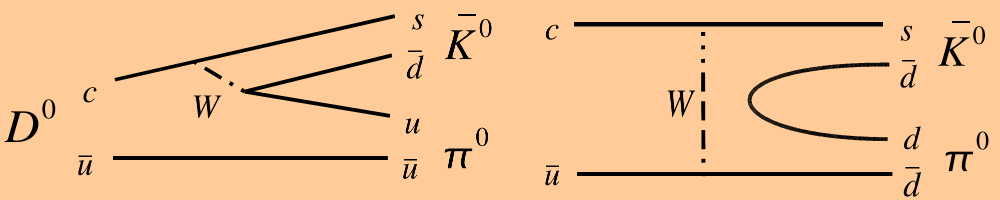
* S.A. Dytman *et al.*, Phys. Rev. D **74**, 071102(R) (2006).

$D \to K_S^0 \pi$ vs. $D \to K_L^0 \pi$

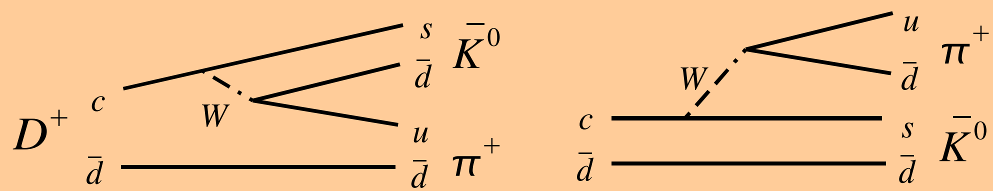
- To first order, $B(D \to K_S^0 \pi) \approx B(D \to K_L^0 \pi)$ (from $D \to \bar{K}^0 \pi$).
- Interference from doubly-Cabibbo-suppressed process $D \to K^0 \pi$ has opposite sign for $K_S^0 \approx (1/\sqrt{2})(\bar{K}^0 - K^0)$ and $K_L^0 \approx (1/\sqrt{2})(\bar{K}^0 + K^0)$.
- This produces an asymmetry between the decay rates (Bigi & Yamamoto):

$$R(D) \equiv \frac{B(D \to K_S^0 \pi) - B(D \to K_L^0 \pi)}{B(D \to K_S^0 \pi) + B(D \to K_L^0 \pi)} \sim \tan^2 \theta_C$$

$D^0 \to \bar{K}^0 \pi^0$



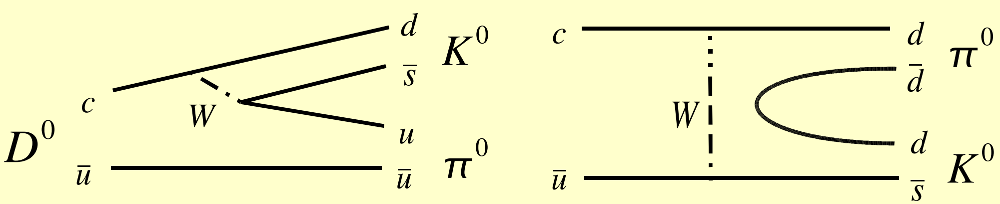
$D^+ \to \bar{K}^0 \pi^+$



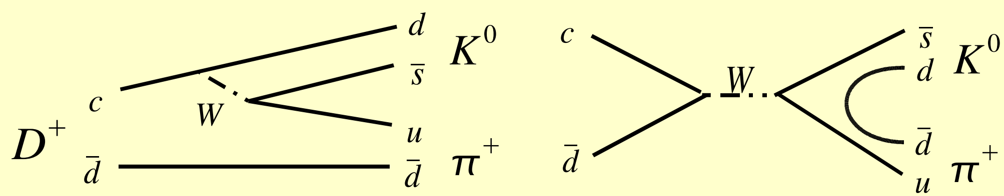
SU(3) prediction → $R(D^0) = 2 \tan^2 \theta_C$

$R(D^+) = (?) \tan^2 \theta_C$

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



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



Quantum Correlation for D^0 and $\bar{D}^0$

- Since $D^0\bar{D}^0$ is produced through a virtual photon (C=-1), decays of D^0 and $\bar{D}^0$ are correlated. (For example, they can't decay to states with the same CP.)
- Apparent "branching fraction" for a D^0 decay depends on how the $\bar{D}^0$ decayed, especially for CP eigenstates like $K_S^0\pi^0$ and $K_L^0\pi^0$.
- What we can measure:

  $\lesssim 1\%$

  $$y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad r_f e^{i\delta_f} = \frac{\langle f|\bar{D}^0\rangle}{\langle f|D^0\rangle}$$

  - Untagged $D^0 \to K_S^0\pi^0$ gives $B(D^0 \to K_S^0\pi^0)(1+y)$
  - $D^0 \to K_S^0\pi^0$, tagged by $\bar{D}^0 \to \bar{f}$, gives $B(D^0 \to K_S^0\pi^0)(1-2r_f\cos\delta_f + r_f^2)$
  - $D^0 \to K_L^0\pi^0$, tagged by $\bar{D}^0 \to \bar{f}$, gives $B(D^0 \to K_L^0\pi^0)(1+2r_f\cos\delta_f + r_f^2)$

  $\sim 0.3\%$

  - (Untagged $D^0 \to K_L^0\pi^0$ would give $B(D^0 \to K_L^0\pi^0)(1-y)$, but our technique for finding $D^0 \to K_L^0\pi^0$ requires a tag.)
- Strategy:

  $f = K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

  - Measure untagged $D^0 \to K_S^0\pi^0$, and $D^0 \to K_S^0\pi^0$ and $D^0 \to K_L^0\pi^0$ tagged by 3 modes.
  - Use these, with y and r_f^2, to calculate $B(D^0 \to K_S^0\pi^0)$, $2r_f\cos\delta_f$, and $B(D^0 \to K_L^0\pi^0)$.

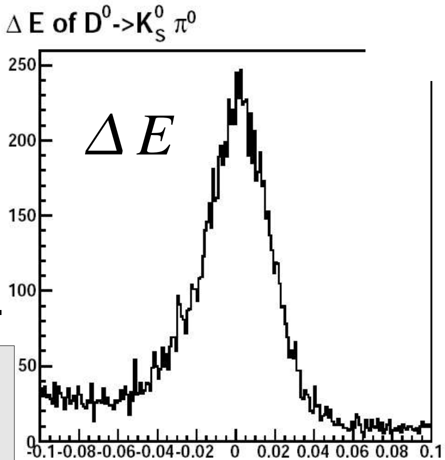
$D \to K^0_S \pi$ Measurements

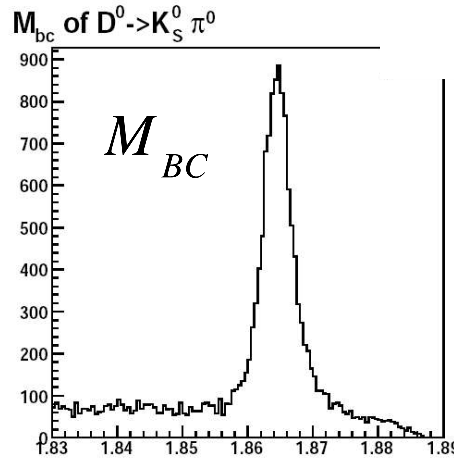
- Take $B(D^+ \to K^0_S \pi^+)$ from the D hadronic BF analysis (described earlier).
- Measure $B(D^0 \to K^0_S \pi^0)(1+y)$ from untagged direct reconstruction via $K^0_S \to \pi^+\pi^-$, $\pi^0 \to \gamma\gamma$
  - Subtract ΔE and $M(\pi^+\pi^-)$ sidebands.
  - Result:

$B(D^0 \to K^0_S \pi^0)$ =
(1.262 ± 0.017 ± 0.041 ± 0.048)%

due to π^0 efficiency, cancels in asymmetry

PDG 2006: (1.14 ± 0.12)%





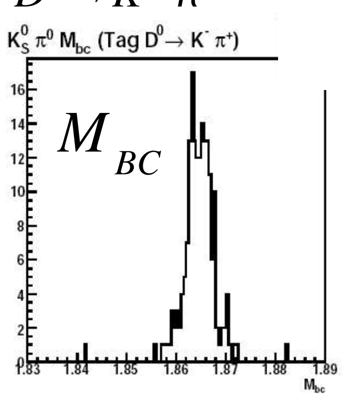
7487 ± 99 signal events
efficiency = 30.5%

- Measure $B(D^0 \to K^0_S \pi^0)(1 - 2 r_f \cos\delta_f + r_f^2)$ for each tag mode $\bar{f}$ by also requiring a found $\bar{D}^0 \to \bar{f}$ decay.
  - Result:

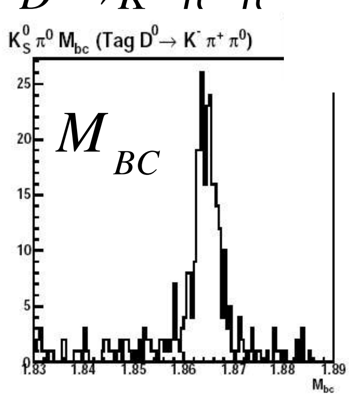
PRELIMINARY

Mode $\bar{f}$	$2 r_f \cos\delta_f$
$\bar{D}^0 \to K^+\pi^-$	0.181 ± 0.074
$\bar{D}^0 \to K^+\pi^-\pi^0$	0.192 ± 0.069
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	0.073 ± 0.063

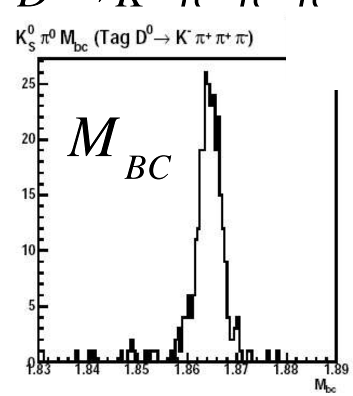
$\bar{D}^0 \to K^+\pi^-$



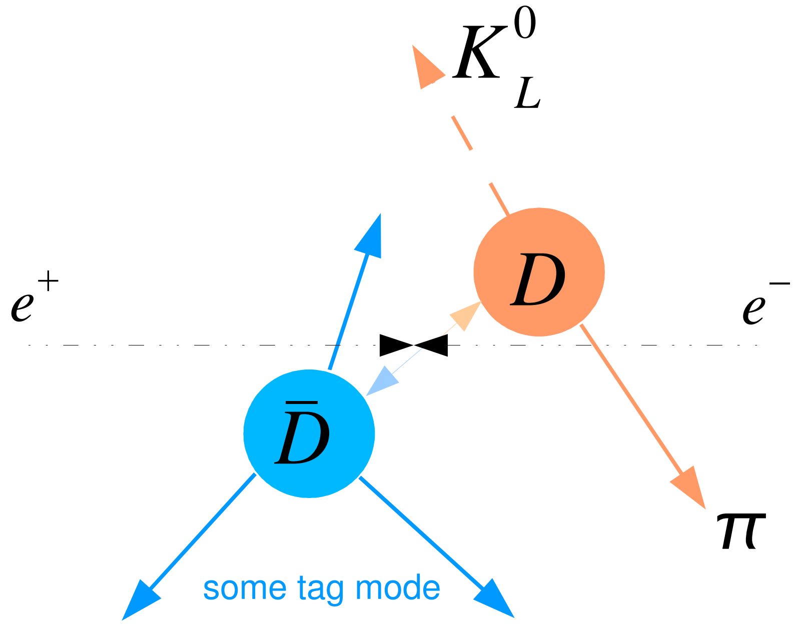
$\bar{D}^0 \to K^+\pi^-\pi^0$



$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$



$D \to K^0_L \pi$ Analysis Technique



- Reconstruct all particles except the K^0_L.
- Form missing mass squared:

$$M^2_{\text{miss}} \equiv (p_{\text{event}} - p_{\bar{D}} - p_{\pi})^2$$

peaks an the kaon mass squared for $D \to K^0_L \pi$ and $D \to K^0_S \pi$.

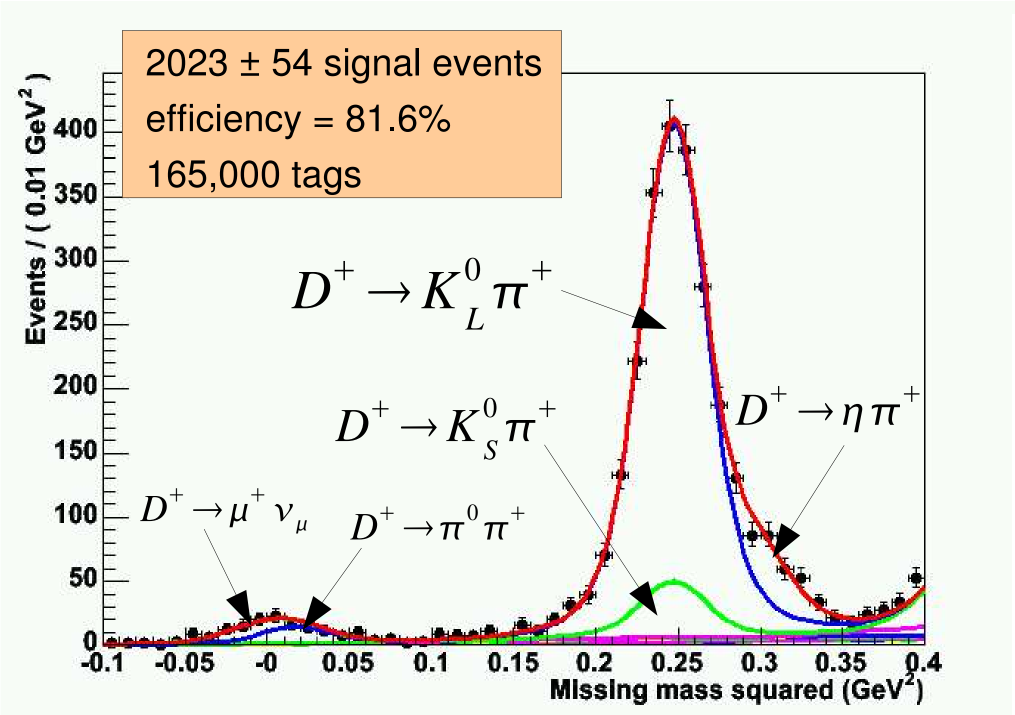
- Remove $D \to K^0_S \pi$ by vetoing events with extra tracks or π^0's.
- Determine number of tags from M_{BC} and ΔE of tag $\bar{D}$ candidates, and number of signal events from peak in missing mass squared.

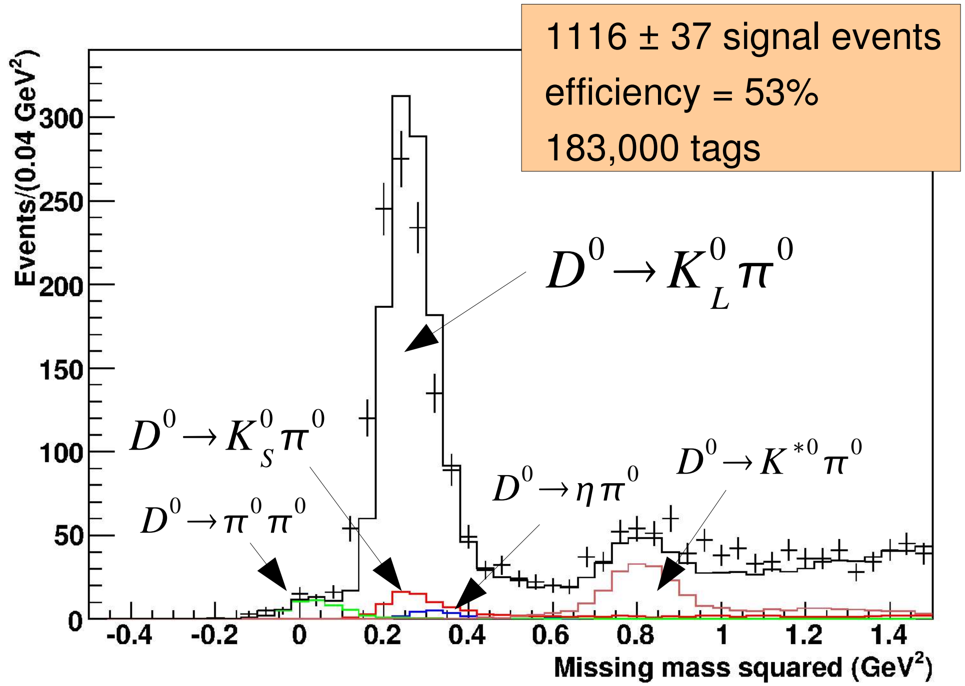
$$B(D \to K^0_L \pi) = \frac{Y(\text{signal})}{Y(\text{tags}) \times \epsilon} \times R$$

(R – 1) ~ few %
accounts for easier tag reconstruction
when the other D decays to $K^0_L \pi$

efficiency for finding signal
given that tag was found

$D \to K_L^0 \pi$ Results





PRELIMINARY

Measure $B(D^0 \to K_L^0 \pi^0)(1 + 2 r_f \cos\delta_f + r_f^2)$, then calculate $B(D^0 \to K_L^0 \pi^0)$.

$B(D^+ \to K_L^0 \pi^+)$

= (1.460 ± 0.040 ± 0.035 ± 0.006)%

due to input value of $B(D^+ \to K_S^0 \pi^+)$

$B(D^0 \to K_L^0 \pi^0)$

= (0.987 ± 0.048 ± 0.034 ± 0.038)%

due to π^0 efficiency, cancels in asymmetry

primary systematics: signal peak shapes and veto efficiencies

$D \to K_S^0 \pi$ vs. $D \to K_L^0 \pi$ Asymmetry

PRELIMINARY

- Compare rates by calculating asymmetry:

$$R(D) \equiv \frac{B(D \to K_S^0 \pi) - B(D \to K_L^0 \pi)}{B(D \to K_S^0 \pi) + B(D \to K_L^0 \pi)}$$

- Comparing $B(D^0 \to K_S^0 \pi^0)$ and $B(D^0 \to K_L^0 \pi^0)$,

$$R(D^0) = 0.122 \pm 0.024 \pm 0.030$$

(Expect $R(D^0) = 2\tan^2\theta_C = 0.109 \pm 0.001$ from U-spin symmetry.*)

* J.L. Rosner, Phys. Rev. D **74**, 057502 (2006).

- Comparing $B(D^+ \to K_S^0 \pi^+)$ and $B(D^+ \to K_L^0 \pi^+)$,

$$R(D^+) = 0.030 \pm 0.016 \pm 0.021$$

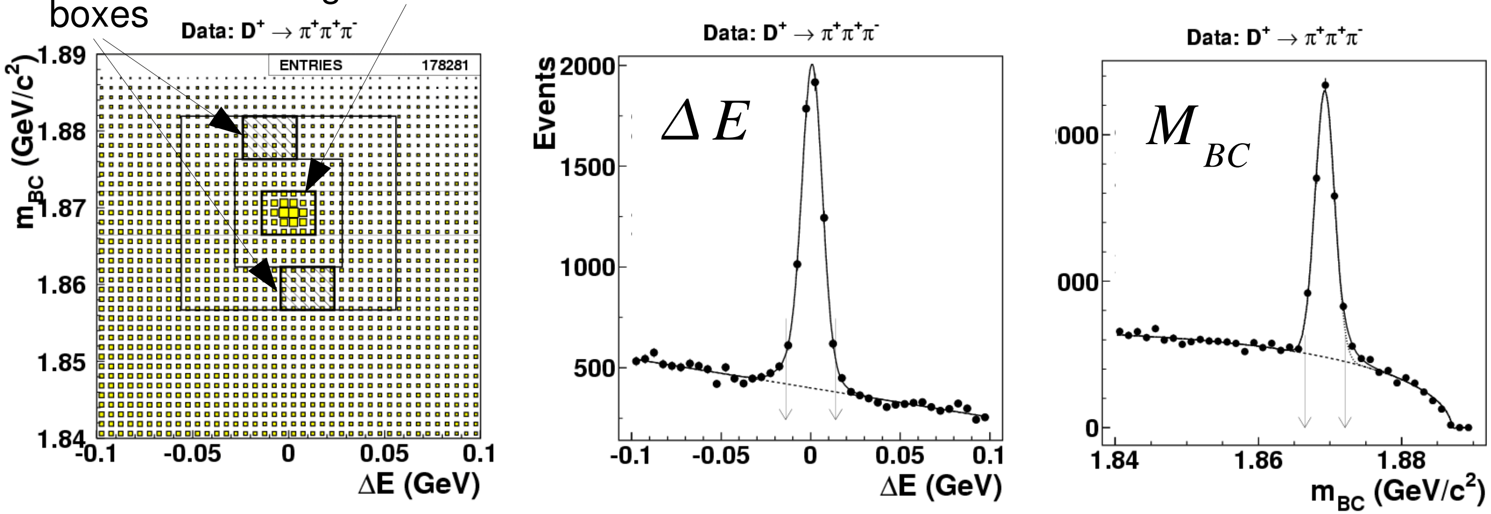
(No simple prediction.)

Final results will be submitted to PRL.

$D^+ \to \pi^+ \pi^+ \pi^-$ Dalitz Analysis

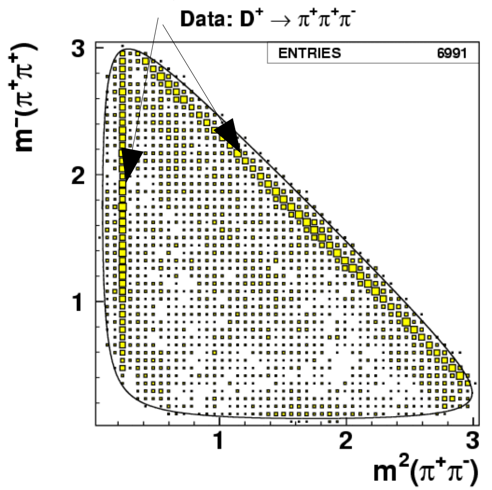
- E791 and FOCUS have analyzed $D^+ \to \pi^+ \pi^+ \pi^-$.
  - Fit by E791 finds σ enhancement (low-mass $\pi\pi$ S-wave) in the Dalitz plot.
  - FOCUS uses K-matrix approach.
- CLEO reconstructs this decay in $D^+ D^-$ events, without tagging.

D^+ candidate selection



Dalitz plot

$D^+ \to K_S^0 \pi^+$



$N(K_S\pi^+)$ ~ 2240

$N_{background}$ ~ 2150

$N(\pi^+\pi^+\pi^-)$ ~ 2600

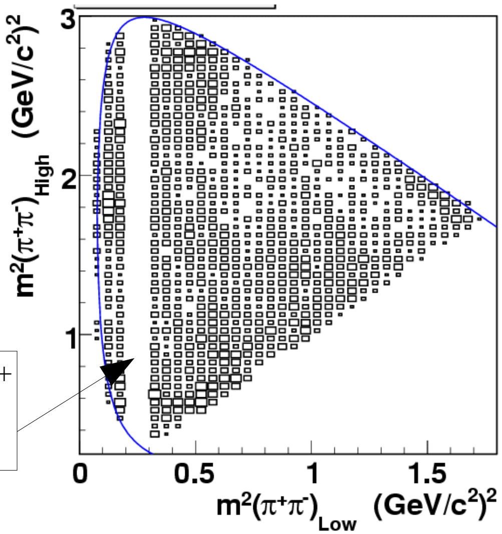
$D^+ \to \pi^+ \pi^+ \pi^-$ Dalitz Results

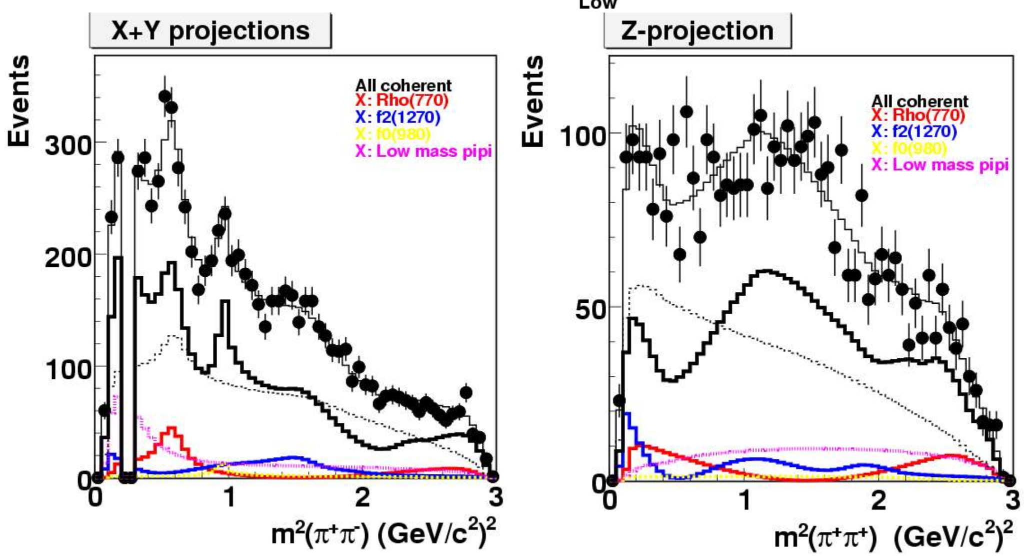
$m^2(\pi_1^+ \pi^-)$

vs.

$m^2(\pi_2^+ \pi^-)$

$D^+ \to K_S^0 \pi^+$ removed





Likelihood Fit including: Amplitude, phase, spin-dependent PW (*ie.* BW), angular distribution, Blatt-Weiskopf angular momentum penetration factor.

Mode	Fit Values		
	Relative Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)\pi^+$	1.0	0	20.0±2.3±0.9
$f_0(980)\pi^+$	1.4±0.2±0.2	12±10±5	4.1±0.9±0.3
$f_2(1270)\pi^+$	2.1±0.2±0.1	237±6±3	18.2±2.6±0.7
$f_0(1370)\pi^+$	1.3±0.4±0.2	-21±15±14	2.6±1.8±0.6
$f_0(1500)\pi^+$	1.1±0.3±0.2	-44±13±16	3.4±1.0±0.8
σ pole	3.7±0.3±0.2	-3±4±2	41.8±1.4±2.5
	Limits on Other Contributing Modes		
$\rho(1450)\pi^+$	0.9±0.5	51±22	<2.4
$f_0(1710)\pi^+$	1.0±1.5	-17±90	<3.5
$f_0(1790)\pi^+$	1.0±1.1	23±58	<2.0
Non-resonant	0.17±0.14	-17±90	<3.5
I=2 $\pi^+\pi^+$ S-wave	0.17±0.14	23±58	<3.7

- Consistent with E791:
  - E791 BW σ Fit Fraction = **(46.3±9.0±2.1)%**
- Also try two S-wave models to replace σ and $f_0(980)$. Data are consistent with both.

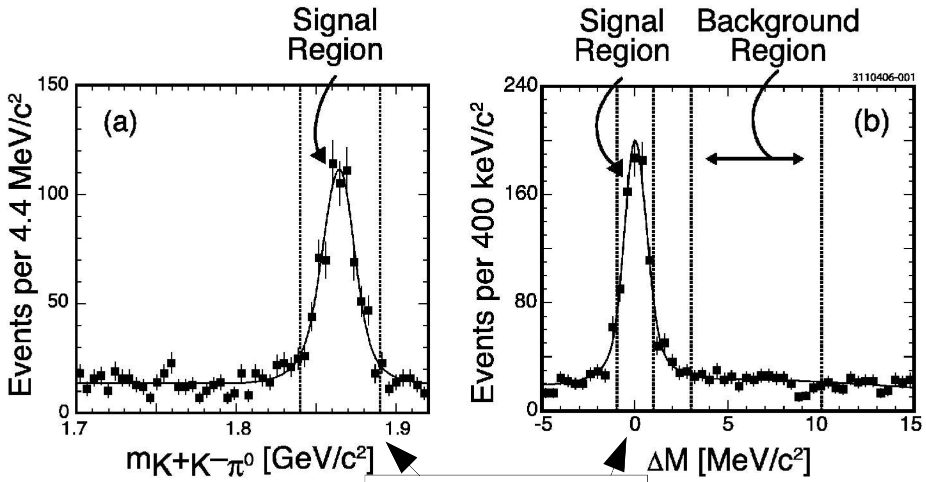
CLEO preliminary: hep-ex/0607069

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

- Motivation:
  - Measurement of CKM angle γ (ϕ_3) from *B* decays requires input values of r_D and δ_D:

$$\frac{A(\bar{D}^0 \to K^{*+} K^-)}{A(D^0 \to K^{*+} K^-)} = r_D e^{i\delta_D}$$

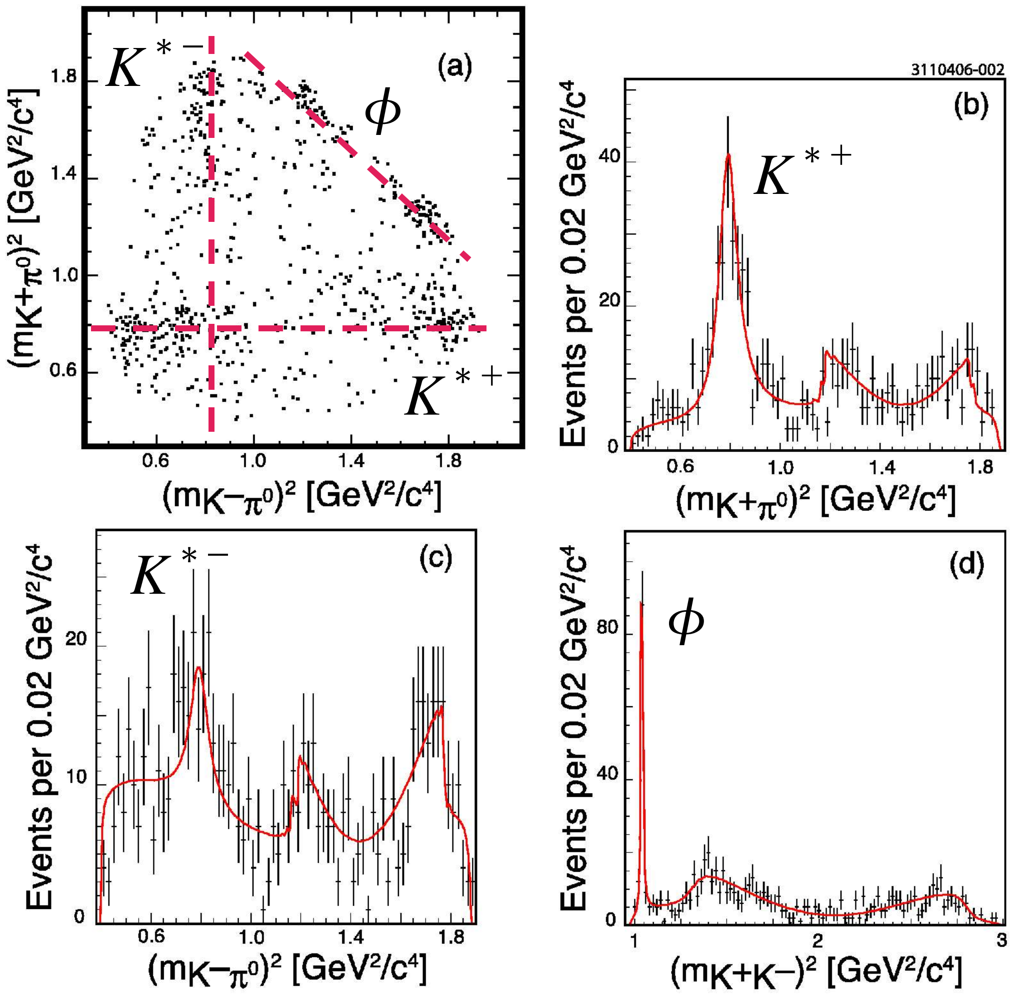
  - r_D and δ_D can be determined from the $D^0 \to K^+ K^- \pi^0$ Dalitz plot.
- Method:
  - 9 fb^{-1} collected near $\Upsilon(4S)$ with CLEO III detector
  - Consider D^0's from $D^{*+} \to D^0 \pi^+$, tagging flavor of the D^0 by the pion's charge.



735 candidates

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

Dalitz plot and projections



Mode	Fit Values		
	Relative Amplitude	Phase (degrees)	Fit Fraction (%)
$K^{*+}K^-$	1.0	0	46.1±3.1
$K^{*-}K^+$	0.52±0.05±0.04	332±8±11	12.3±2.2
$\phi\pi^0$	0.64 ±0.04	326±9	14.9±1.6
NR	5.62±0.45	220±5	36.0±3.7

Read off the values from the DP fit:

$r_D = 0.52 \pm 0.05 \pm 0.04$

$\delta_D = (332 \pm 8 \pm 11)^o$

- ❑ First measurement of δ_D.
- ❑ Significant improvement on r_D over previous value using K*K BF's

C. Cawlfield *et al.*, Phys. Rev. D **74**, 031108(R) (2006).

Summary

- CLEO continues to generate measurements of D^0 and D^+ decays.
- Absolute *D* hadronic branching fractions set the scale for *D* decays.
- Measurements of $D^+ \to K^+ \pi^0$ and $D \to K_S^0 \pi$ vs. $D \to K_L^0 \pi$ provide a complete set of measurements for the doubly-Cabibbo-suppressed $D \to K \pi$ decays.
- Dalitz analyses measure substructure of *D* decays, including input for measurement of CKM angle γ from *B* decays.
- We will approximately triple our $\psi(3770)$ dataset over the next year, so more results will be coming.