Absolute Hadronic D^0 and D^+ Branching Fractions at CLEO-c

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for the CLEO-c Collaboration

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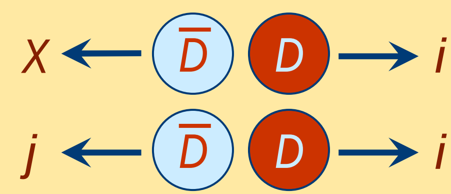
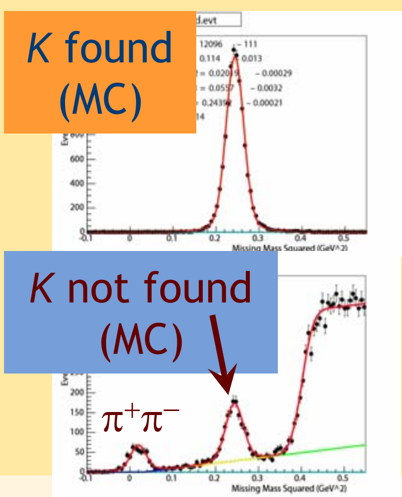
Introduction to analysis techniques
Results from three analyses
Future directions

Overview of Techniques

- $e^+e^- \to \psi(3770) \to D\overline{D}$
- Kinematics analogous to $\Upsilon(4S) \to B\overline{B}$: identify D with
  - $M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$ $\sigma(M_{BC})$ ~ 1.3 MeV, x2 with π^0
  - $\Delta E = E_D - E_{beam}$ $\sigma(\Delta E)$ ~ 7—10 MeV, x2 with π^0
- Single tag (ST): $n_i = N_{DD}\mathcal{B}_i\varepsilon_i$
- Double tag (DT) : $n_{ij} = N_{DD}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$



- Take advantage of low multiplicity, low backgrounds.
- Example: MC tracking, K^0_S, and π^0 efficiency systematics:
  - Missing mass (MM) technique to compare data and MC.
  - Fully reconstruct entire event, but deliberately leave out one particle.
  - Fraction of MM peak where the last particle is found = efficiency.



note different scales

Example: K^- eff from $D^0 \to K^-\pi^+$

$\varepsilon \approx$ 91% in fiducial volume

Three Analyses

Reduce error on V_{cb}

- MARK III double tag technique, using 55.8 pb^{-1}

$$B_i \approx \frac{n_{ij}}{n_j}\frac{\varepsilon_j}{\varepsilon_{ij}} \qquad N_{DD} \approx \frac{n_i n_j}{n_{ij}}\frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

  - Independent of $\mathcal{L}$ and cross sections.
  - Correlated systematic uncertainties cancel.
  - Combine ST and DT yields in χ^2 fit for $\mathcal{B}$ and N_{DD}.
  - Published in **PRL 95, 121801 (2005).**

Probe strong phases

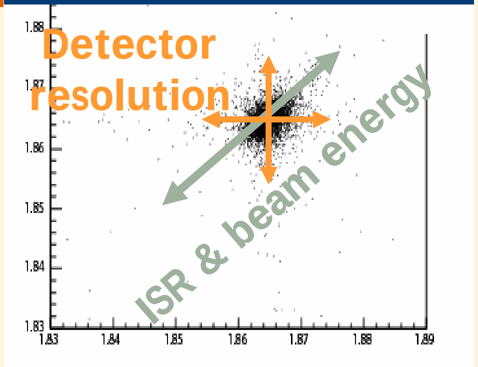
- $D^+ \to K^0\pi^+$, using 281 pb^{-1} PRELIMINARY
  - Reconstruct K^0 inclusively, search for K^0_S / K^0_L asymmetry.
  - Presented at EPS2005, abstract #185.
- $D \to n(\pi^+)\, m(\pi^0)$, using 281 pb^{-1} PRELIMINARY
  - Cabibbo-suppressed transitions, low statistics.
  - Isospin analysis of $D \to \pi\pi$.

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

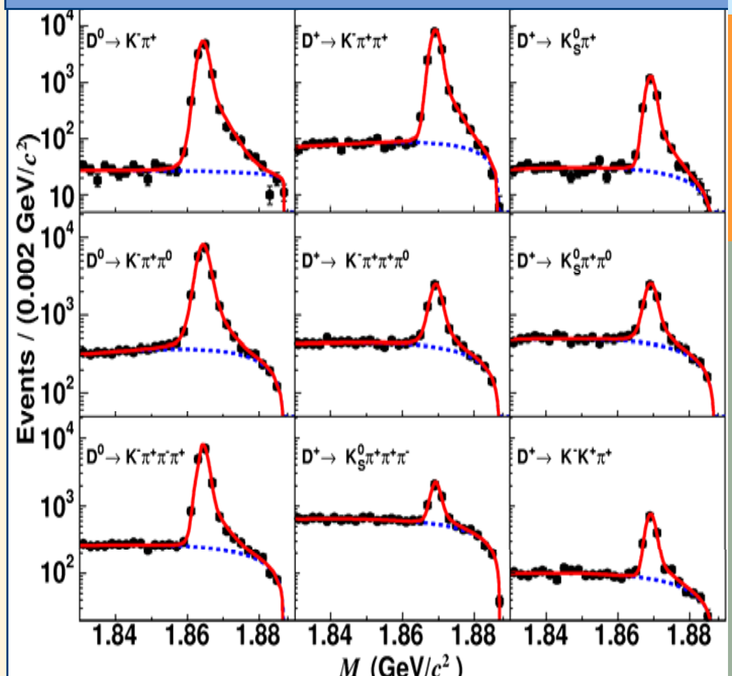
Double Tag Analysis

- Unbinned ML fits to M_{BC} (1D for ST, 2D for DT)
  - Signal function includes ISR, $\psi(3770)$ line shape, beam energy smearing, and detector resolution.
  - Background: phase space ("ARGUS function").
- D and $\overline{D}$ yields and efficiencies separated.

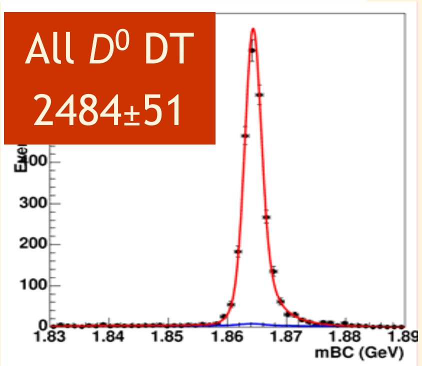
DT signal shape

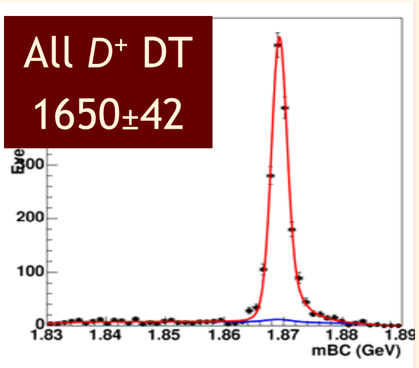


M_{BC} (log scale) for ST modes: $D+\overline{D}$



Mode	N_D (10^3)	$\overline{N}_D$ (10^3)	$<\varepsilon_D>$(%)
$K\pi$	5.11±0.07	5.15±0.07	65.1±0.2
$K\pi\pi^0$	9.51±0.11	9.47±0.11	31.6±0.1
$K\pi\pi\pi$	7.44±0.09	7.43±0.09	43.8±0.1
$K\pi\pi$	7.56±0.09	7.56±0.09	51.0±0.1
$K\pi\pi\pi^0$	2.45±0.07	2.39±0.07	25.7±0.1
$K^0_s\pi$	1.10±0.04	1.13±0.04	45.7±0.3
$K^0_s\pi\pi^0$	2.59±0.07	2.50±0.07	22.4±0.1
$K^0_s\pi\pi\pi$	1.63±0.06	1.58±0.06	31.2±0.1
$KK\pi$	0.64±0.03	0.61±0.03	41.1±0.4





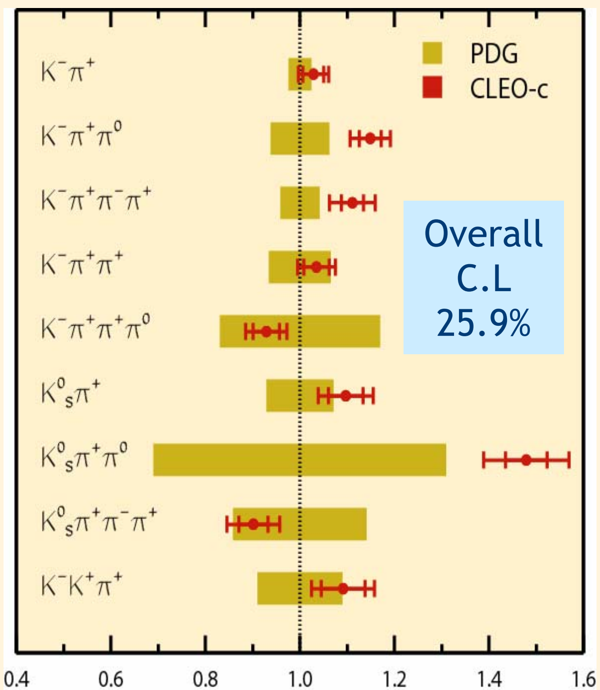
Double Tag Analysis: Fit Results

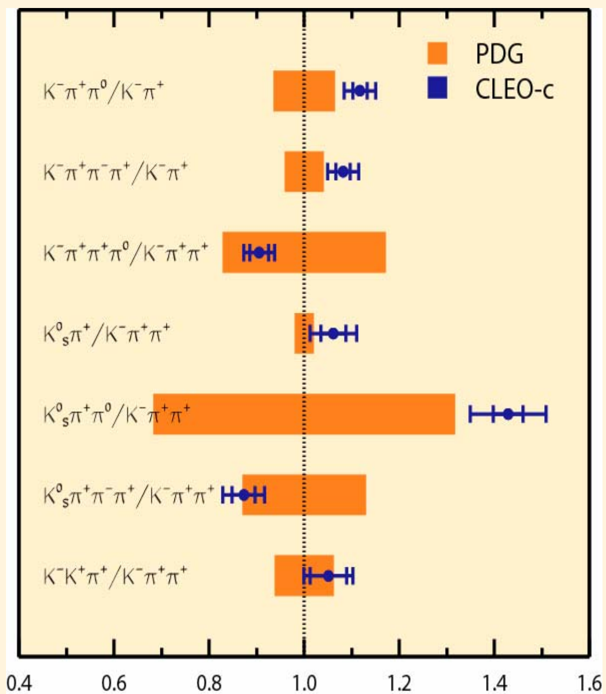
- Fit includes both statistical and systematic errors (with correlations) [arXiv:physics/0503050].
- Precision comparable to PDG WA.
- σ(systematic) ~ σ(statistical).
  - Many systematics measured in data, will improve with time.
- Simulation includes FSR, so we measure $\mathcal{B}$ (final state + nγ).
  - Using efficiencies without FSR correction would lower $\mathcal{B}$.
- N_{DD} includes continuum and resonant production.
- $\mathcal{L}$ = (55.8 ± 0.6) pb^{-1} ⟶ cross sections
  - Consistent with BES measurements.

Parameter	Value	no FSR
$N_{D^0\bar{D}^0}$	$(2.01\pm0.04\pm0.02)\times10^5$	-0.2%
$\mathcal{B}(K^-\pi^+)$	$(3.91\pm0.08\pm0.09)\%$	-2.0%
$\mathcal{B}(K^-\pi^+\pi^0)$	$(14.9\pm0.3\pm0.5)\%$	-0.8%
$\mathcal{B}(K^-\pi^+\pi^+\pi^-)$	$(8.3\pm0.2\pm0.3)\%$	-1.7%
$N_{D^+D^-}$	$(1.56\pm0.04\pm0.01)\times10^5$	-0.2%
$\mathcal{B}(K^-\pi^+\pi^+)$	$(9.5\pm0.2\pm0.3)\%$	-2.2%
$\mathcal{B}(K^-\pi^+\pi^+\pi^0)$	$(6.0\pm0.2\pm0.2)\%$	-0.6%
$\mathcal{B}(K_S^0\pi^+)$	$(1.55\pm0.05\pm0.06)\%$	-1.8%
$\mathcal{B}(K^0_S\pi^+\pi^0)$	$(7.2\pm0.2\pm0.4)\%$	-0.8%
$\mathcal{B}(K^0_S\pi^+\pi^-\pi^+)$	$(3.2\pm0.1\pm0.2)\%$	-1.4%
$\mathcal{B}(K^+K^-\pi^+)$	$(0.97\pm0.04\pm0.04)\%$	-0.9%
$\sigma(D^0\overline{D^0})$	$(3.60\pm0.07^{+0.07}_{-0.05})$ nb	-0.2%
$\sigma(D^+D^-)$	$(2.79\pm0.07^{+0.10}_{-0.04})$ nb	-0.2%
$\sigma(+-)/\sigma(00)$	$0.776\pm0.024^{+0.014}_{-0.008}$	+0.0%

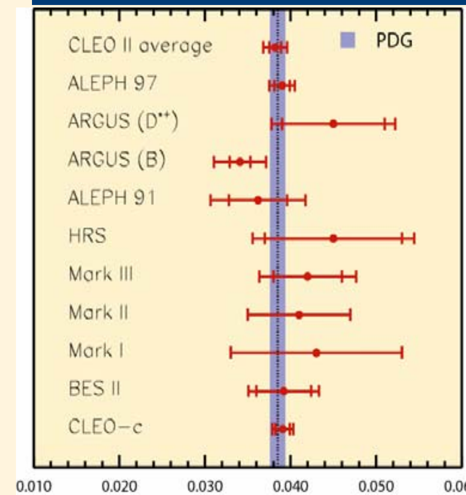
Comparison with PDG 2004

- Measurements and errors normalized to PDG.
- PDG global fit includes ratios to $K^-\pi^+$ or $K^-\pi^+\pi^+$.
- No FSR corrections in PDG measurements.
- Our measurements also correlated (statistics and efficiency systematics).

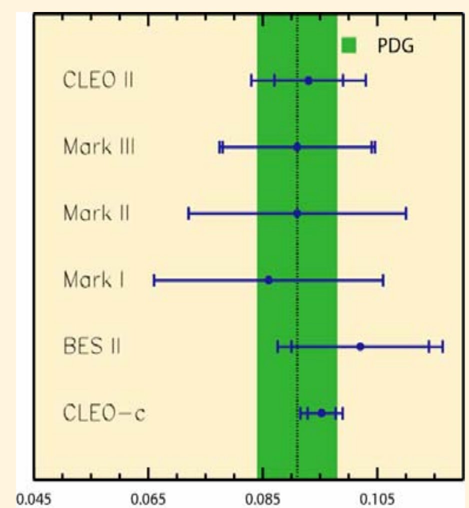




Other *direct* meas.



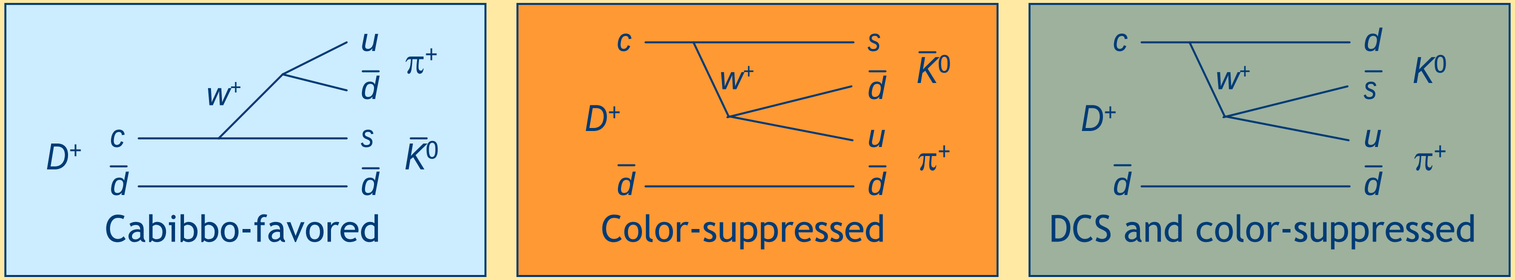
$\mathcal{B}(D^0 \to K^-\pi^+)$



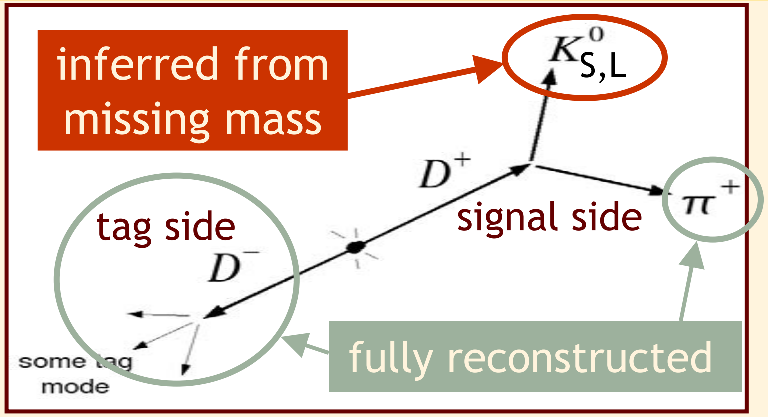
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$

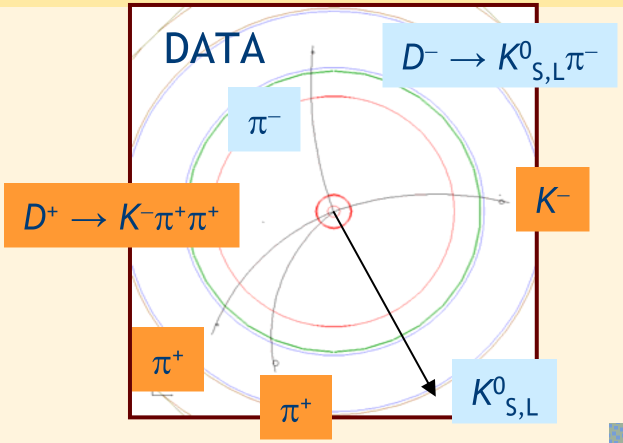
$D^+ \to K^0_{S,L}\pi^+$

- Search for asymmetry between K^0_S and K^0_L branching fractions.
  - Caused by interference: constructive for K^0_L, destructive for K^0_S.

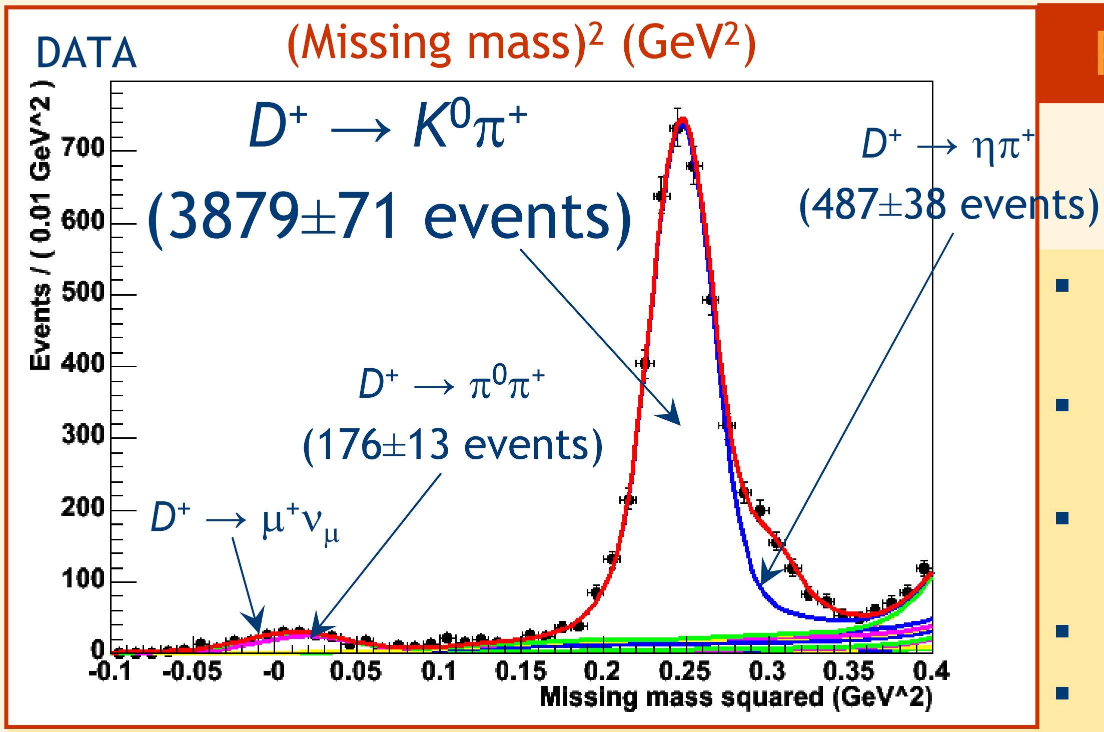


  - O(10%) predicted by Bigi & Yamamoto [PLB 349 (1995) 363-366].
  - Depends on relative strong phases between amplitudes.
- $D^+ \to K^0_S\pi^+$ already measured in double tag analysis.
- Now, reconstruct $K^0_S + K^0_L$ inclusively in missing mass (MM) recoiling against π^+.





$D^+ \to K^0_{S,L}\pi^+$: Results



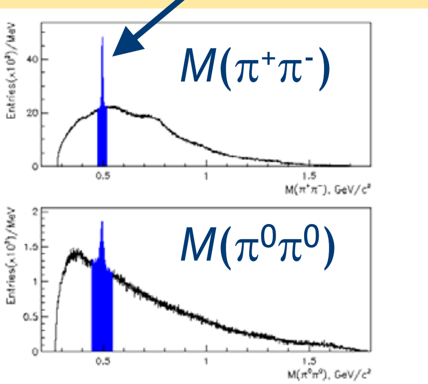
PRELIMINARY

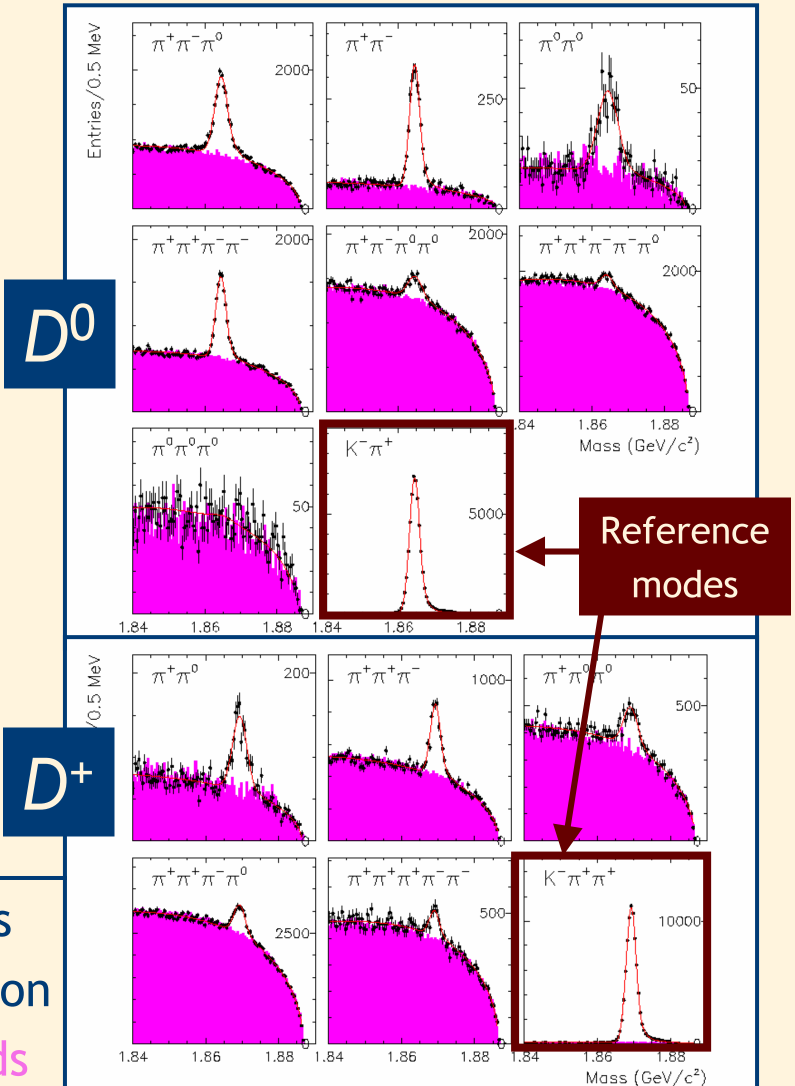
- Dominant background from $\eta\pi^+$.
- Many small backgrounds from other D^+ decays.
- All shapes determined from MC.
- Statistical error 1.9%
- Systematic error 5.2%

- $\mathcal{B}(D^+ \to K^0_S\pi^+) + \mathcal{B}(D^+ \to K^0_L\pi^+) = (3.06 \pm 0.06 \pm 0.16)\%$
- Asymmetry = $(K^0_L - K^0_S)/(K^0_L + K^0_S) = -0.01 \pm 0.04 \pm 0.07$
  - Consistent with O(10%) prediction.
- Also, $\mathcal{B}(D^+ \to \eta\pi^+) = (0.39 \pm 0.03 \pm 0.03)\%$ [PDG2004 has $(0.30 \pm 0.06)\%$].

$D \to n(\pi^+)\ m(\pi^0)$

- Study Cabibbo-suppressed *D* decays with single tags only.
  - Double tag technique not as profitable—statistics too low.
  - Normalize $\mathcal{B}$s to reference modes.
- MC tuned to match $\pi\pi$ mass spectra in data.
- Background from Cabibbo-favored decays with $K^0_S \to \pi^+\pi^-$, $\pi^0\pi^0$.
  - Veto $M(\pi\pi)$ near K^0_S mass.

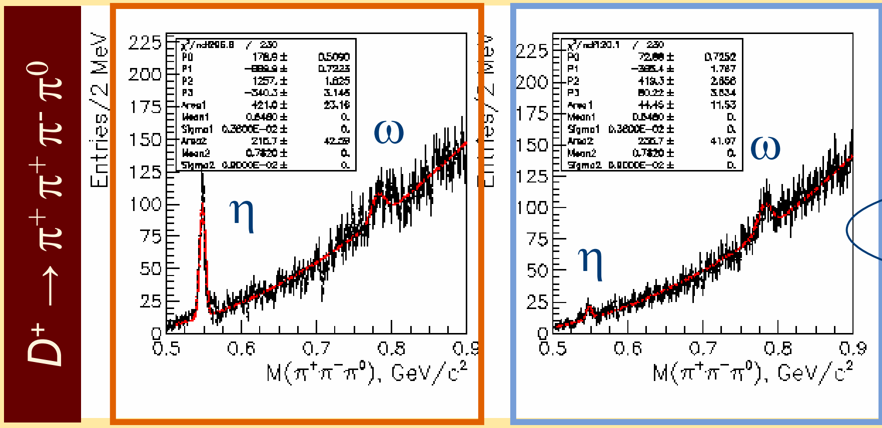




M_{BC} distributions in ΔE signal region and ΔE sidebands

$D \to n(\pi^+)\, m(\pi^0)$: Results

- Some first observations (circled).
- Use PDG04 + CLEO-c for reference $\mathcal{B}$s.
- Also search for substructure: η, ω
  - Compare $M(\pi^+\pi^-\pi^0)$ in ΔE **signal** and **sideband** regions.



- $\mathcal{B}(\eta\pi^+)$ consistent with MM analysis.
- Isospin analysis of $\pi\pi$:
  - $A_2/A_0 = 0.423 \pm 0.014 \pm 0.055$
  - $\cos\delta = 0.10 \pm 0.05 \pm 0.11$
  - Evidence for final state interactions.

PRELIMINARY

Mode	$\mathcal{B}$ ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$\pi^+\pi^-$	$1.40 \pm 0.04 \pm 0.03$	1.38 ± 0.05
$\pi^0\pi^0$	$0.78 \pm 0.05 \pm 0.04$	0.84 ± 0.22
$\pi^+\pi^-\pi^0$	$13.3 \pm 0.2 \pm 0.5$	11 ± 4
$\pi^0\pi^0\pi^0$	< 0.30	---
$\pi^+\pi^+\pi^-\pi^-$	$7.42 \pm 0.14 \pm 0.27$	7.3 ± 0.5
$\pi^+\pi^-\pi^0\pi^0$	$10.2 \pm 0.6 \pm 0.7$	---
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$4.31 \pm 0.44 \pm 0.18$	---
$\pi^+\pi^0$	$1.23 \pm 0.06 \pm 0.06$	1.33 ± 0.22
$\pi^+\pi^+\pi^-$	$3.36 \pm 0.10 \pm 0.16$	3.1 ± 0.4
$\pi^+\pi^0\pi^0$	$4.80 \pm 0.27 \pm 0.34$	---
$\pi^+\pi^+\pi^-\pi^0$	$11.7 \pm 0.4 \pm 0.7$	---
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$1.67 \pm 0.18 \pm 0.17$	1.82 ± 0.25
$\eta\pi^+$	$3.56 \pm 0.24 \pm 0.21$	3.0 ± 0.6
$\eta\pi^0$	$0.61 \pm 0.14 \pm 0.05$	---
$\omega\pi^+\pi^-$	$1.66 \pm 0.47 \pm 0.10$	---

Summary and Future Directions

- One major goal of CLEO-c: measure hadronic D branching fractions.
  - Reduce error on V_{cb}.
  - Test CKM unitarity.
  - Provide insight on strong interactions (long- and short-distance).
- Branching fractions in current data sample competitive with world averages.
  - $\mathcal{B}(D^0 \to K^-\pi^+)$ measured to 3.1% (PDG 2.4%).
  - $\mathcal{B}(D^+ \to K^- \pi^+\pi^+)$ measured to 3.9% (PDG 6.5%).
  - First observations of some multibody pionic channels.
- Two+ more years of data taking.
  - Will lower statistical *and* systematic errors.
- D_s branching fractions with $\sqrt{s} \sim 4$ GeV running.