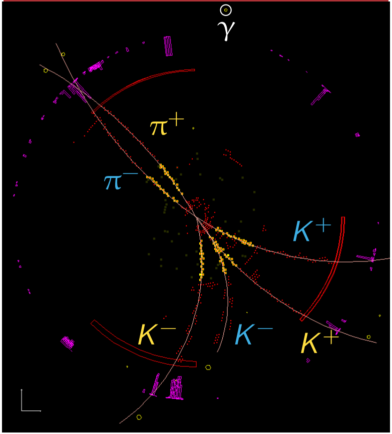
$D_{(s)}$ Hadronic Decays From CLEO-c

$$e^+e^- \to D_s^* D_s \to D_s^+ D_s^- \gamma$$



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Outline

- Scope of hadronic decay analyses (and this talk)
- Analysis techniques
- Results:
  - $D^0/D^+/D_s$ absolute branching fractions
  - $D^0/D^+ \to (m)\pi^\pm(n)\pi^0$
  - $D^+ \to K_{S,L}\pi^+$
  - $D^0/D^+/D_s \to (\phi, \eta, \eta')X$

Scope and Physics

The hadronic decays of charmed mesons are a very active field of study at CLEO-c — multiple talks are covering our results:

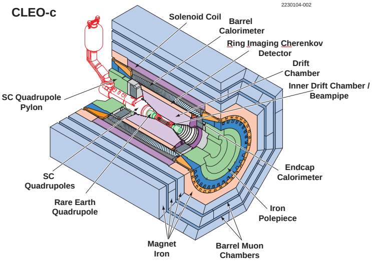
- The Quantum Correlation Analysis (D. Asner)
- Dalitz analyses (M. Dubrovin)
- High energy scan [3.97–4.26 GeV] (R. Poling)

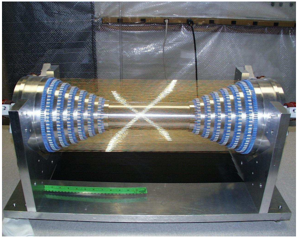
This talk will cover branching fraction results.

Physics from branching fractions:

- Important as engineering numbers:
  - "Reference" modes, e.g. $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, normalize many D and B decays
  - Inclusive rates help disentangle charm content
- Relative rates of decays measure various decay amplitudes, probe final state interactions

CLEO-c



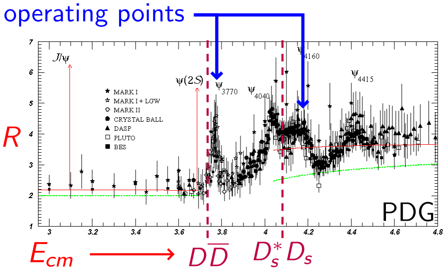


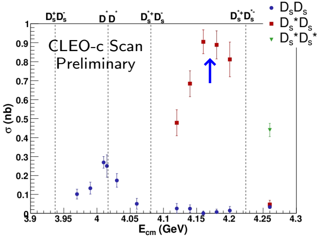
- Detector slightly modified from Υ physics configuration: silicon vertex detector replaced with (all stereo) drift chamber
- Solenoid magnetic field changed from 1.5T to 1.0T to compensate for lower-momentum tracks
- DAQ, trigger, software, etc. from CLEO-III with only minor changes
- Particle ID (from dE/dx, Čerenkov) better due to lower p tracks
- Muon system now only useful for high momentum (e.g. $J/\psi \to \mu^+\mu^-$)

Datasets

CLEO-c has accumulated:

- 281 pb^{-1} at $\psi(3770)$
  - $D\overline{D}$ at 6 nb
  - The D^0/D^+ absolute BFs use 56 pb^{-1} only, are being updated
- $\approx$ 200 pb^{-1} near 4.17 GeV
  - $D_s^* D_s$ at 1 nb, $DD + D^*D + D^*D^*$ at 7 nb
  - Only $\approx$ 75 pb^{-1} used for results here





Analysis techniques

These analyses use "single tag" and "double tag" techniques:

- **Single tag** events reconstruct the signal in events without regard for the rest of the event
- **Double tag** events reconstruct the signal opposite a well-understood (flavor tagging) decay

Single tags:

- ✓ Full statistics available
- × Branching **ratios** only (ratios of ST yields)
- × D^0 BFs affected by quantum correlations, especially CP eigenstates

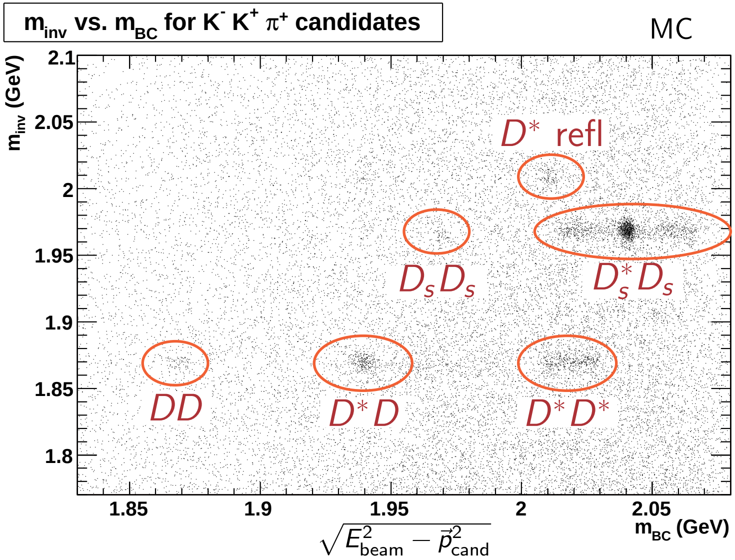
Double tags:

- ✓ Very clean
- ✓ Branching **fractions** from ratios of DT and ST yields
- ✓ Can infer K_L^0
- ✓ Flavor tags minimize quantum correlations
- × Tag efficiency $\sim \mathcal{O}(10)\%$

Tagging at different energies

- At $\psi(3770)$, only open charm channels are $D^0\overline{D}^0$, D^+D^-
  - Cut on $\Delta E \equiv E_{\text{cand}} - E_{\text{beam}}$, fit in $m_{BC} \equiv \sqrt{E_{\text{beam}}^2 - |\vec{p}_{\text{cand}}|^2}$
- At $E_{cm} = 4.17$ GeV, multiple open channels. For D_s we use $D_s^* D_s$
  - We use m_{BC} as a proxy for momentum to choose the $D_s^* D_s$ two-body decay
  - Fits are in invariant mass
- Charged K, π distinguished using dE/dx (all momenta) and Čerenkov (for high momentum)
- Find π^0's by combining pairs of isolated showers in the CsI calorimeter, requiring 3σ consistency with π^0 mass ($\sigma \sim 6$ MeV)
- Find K_S's by combining pairs of tracks that lie within a mass window

Kinematic Separation at $E_{cm} = 4.17$ GeV



$D_{(s)}$ Absolute Hadronic Branching Fractions: Overview

- D^0/D^+ reference decay modes are $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
- The classic D_s reference decay has been the exclusive mode $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$
- This causes problems since ϕ signal is ambiguous given the precision we will soon achieve. **All results here are inclusive branching fractions only.**

Decay	PDG 2004 fit	Rel uncert
$D^0 \to K^-\pi^+$	3.80%	2.4%
$D^0 \to K^-\pi^+\pi^0$	13.0%	6.2%
$D^0 \to K^-\pi^+\pi^+\pi^-$	7.46%	4.2%
$D^+ \to K^-\pi^+\pi^+$	9.2%	6.5%
$D^+ \to K^-\pi^+\pi^+\pi^0$	6.5%	17%
$D^+ \to K_S\pi^+$	1.41%	6.7%
$D^+ \to K_S\pi^+\pi^0$	4.85%	31%
$D^+ \to K_S\pi^+\pi^+\pi^-$	3.55%	14%
$D^+ \to K^-K^+\pi^+$	0.89%	9.0%
$D_s^+ \to K_S K^+$	1.8%	31%
$D_s^+ \to K^-K^+\pi^+$	4.3%	28%
$D_s^+ \to K^-K^+\pi^+\pi^0$	—	—
$D_s^+ \to \pi^+\pi^+\pi^-$	1.00%	28%

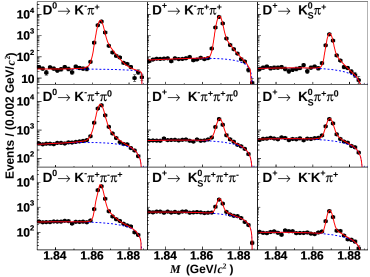
BaBar has a 2005 $\phi\pi^+$ measurement, 34% higher than the PDG, with 13% errors.

Absolute Hadronic Branching Fractions: General Method

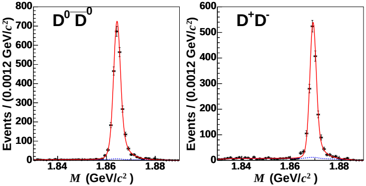
(Follows pioneering analysis at $\psi(3770)$ by Mark III...)

- Exploit low-energy production processes:
  - At 3.77 GeV, open charm *only* produced as $D^0\overline{D}^0$ and D^+D^-
  - At 4.17 GeV, D_s produced almost entirely as $D_s^*D_s$
- Single tags pin down ratios between modes, double tags establish absolute BF scale
  - Use a χ^2 (D^0/D^+) or maximum likelihood (D_s) fit to the observed yields to extract maximum information
- For D^0/D^+, double tags reconstruct entire event. For D_s, we only reconstruct the $D_s^+D_s^-$ (the γ or π^0 from the $D_s^* \to D_s$ transition is ignored)

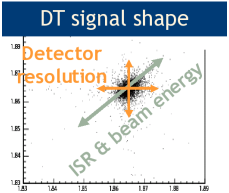
DATA: Single tags



DATA: Double tag projections



- Fit signal with a priori function of **physical** parameters (detector momentum resolution, beam energy spread, $\psi(3770)$ lineshape, ISR spectrum)
- Smooth backgrounds fit as combinatoric phase space ("ARGUS function")
- Peaking backgrounds estimated from known BFs and subtracted
- In double tags, fit 2D plane of $M_{BC}(1)$ vs. $M_{BC}(2)$



D^0/D^+ Systematic Uncertainties

(56 pb^{-1} analysis)

Source	Fractional uncertainty (%)
Tracking/K_S/π^0	0.7/3.0/2.0 per particle
Particle ID	0.3 per π, 1.3 per K
Trigger efficiency	< 0.2
ΔE cut	1.0–2.5 per D
FSR modeling	0.5 per single tag
ψ'' width	0.6
Resonant substructure	0.4–1.5
Event environment	0.0–1.3
Yield fit functions	0.5
Misc. event selection	0.3
Double DCSD interference	0.8 in neutral double tags

$D^0 \to K^- \pi^+$ uncert 2.3%, $D^+ \to K^- \pi^+ \pi^+$ uncert 2.8%

For these, largest contributors are kaon PID and ΔE cut

D^0/D^+ Results

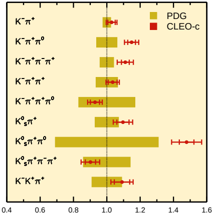
Branching fractions ...

Mode	Value
$\mathcal{B}(D^0 \to K^-\pi^+)$	**(3.91± 0.08± 0.09)%**
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$(14.9 \pm 0.3 \pm 0.5)\%$
$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$	$(8.3 \pm 0.2 \pm 0.3)\%$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	**(9.5± 0.2± 0.3)%**
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$(6.0 \pm 0.2 \pm 0.2)\%$
$\mathcal{B}(D^+ \to K_S\,\pi^+)$	$(1.55 \pm 0.05 \pm 0.06)\%$
$\mathcal{B}(D^+ \to K_S\,\pi^+\pi^0)$	$(7.2 \pm 0.2 \pm 0.4)\%$
$\mathcal{B}(D^+ \to K_S\,\pi^+\pi^+\pi^-)$	$(3.2 \pm 0.1 \pm 0.2)\%$
$\mathcal{B}(D^+ \to K^+K^-\pi^+)$	$(0.97 \pm 0.04 \pm 0.04)\%$

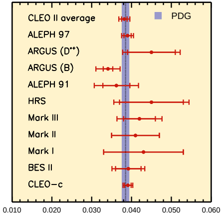
$\sigma_{D^+D^-}$ (nb)	$\sigma_{D^0\overline{D}^0}$ (nb)	$\sigma_{D\overline{D}}$ (nb)	$\sigma_{D^+D^-}/\sigma_{D^0\overline{D}^0}$
$2.79 \pm 0.07^{+0.10}_{-0.04}$	$3.60 \pm 0.07^{+0.07}_{-0.05}$	$6.39 \pm 0.10^{+0.17}_{-0.08}$	$0.776 \pm 0.024^{+0.014}_{-0.006}$

... and cross sections from 55.8 pb^{-1} (PRL 95 121801)

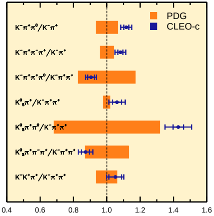
D^0/D^+ Result Comparison



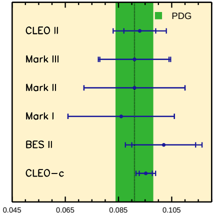
$$\frac{\mathcal{B}(\text{CLEO-c})}{\mathcal{B}(\text{PDG})}$$



$\mathcal{B}(D^0 \to K^-\pi^+)$ previous absolute measurements and PDG fit



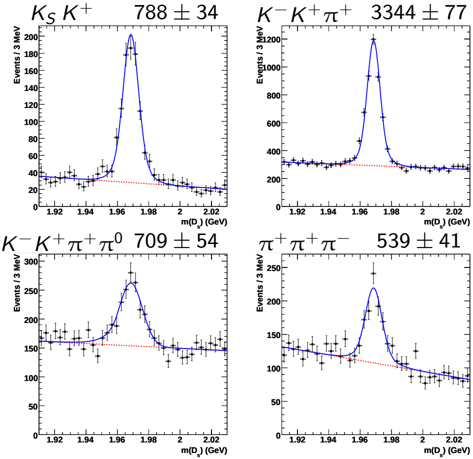
$$\frac{\text{Br. Ratio}(\text{CLEO-c})}{\text{Br. Ratio}(\text{PDG})}$$



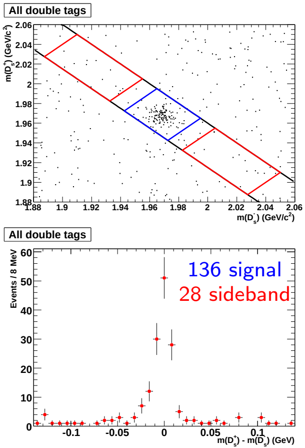
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$ previous absolute measurements and PDG fit

D_s Data Yields

Single Tags



Double Tags



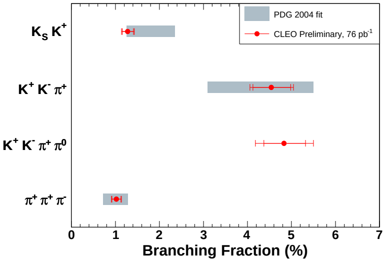
D_s Systematic Uncertainties

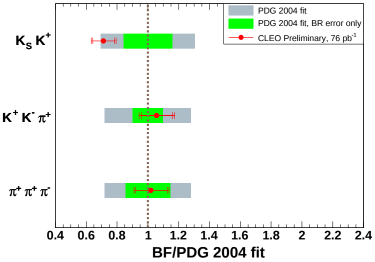
Source	Fractional uncertainty (%)
Tracking/K_S/π^0	0.35/1.1/5.0 per particle
Particle ID	0.3–1.4 correlated by decay
Resonant substructure	0–6.0 correlated by decay
Fit procedure	3.5 in fit result
Event environment	3.5 in $KK\pi\pi^0$
Initial state radiation correction	0–5 per single tag
$\mathcal{B}(D_s^{*+} \to \pi^0 D_s^+)$	0.7 in $KK\pi\pi^0$, $\pi\pi\pi$

D_s Results

Preliminary

Mode	CLEO-c (%)	PDG 2004 fit (%)
$\mathcal{B}(K_S K^+)$	$1.28^{+0.13}_{-0.12} \pm 0.07$	1.8 ± 0.55
$\mathcal{B}(K^- K^+ \pi^+)$	$4.54^{+0.44}_{-0.42} \pm 0.25$	4.3 ± 1.2
$\mathcal{B}(K^- K^+ \pi^+ \pi^0)$	$4.83^{+0.49}_{-0.47} \pm 0.46$	—
$\mathcal{B}(\pi^+ \pi^+ \pi^-)$	$1.02^{+0.11}_{-0.10} \pm 0.05$	1.00 ± 0.28





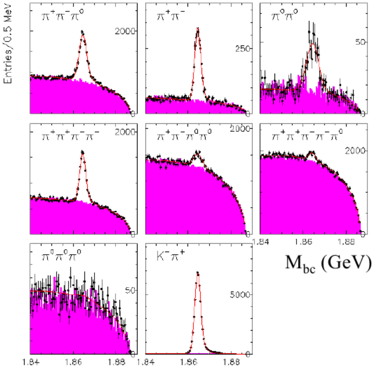
Absolute Branching Fractions Summary and Outlook

- D^0/D^+:
  - Branching fractions from 56 pb^{-1} have precision comparable to world averages
  - Updating to 281 pb^{-1}: we will be systematics-limited
  - Aiming for $< 1.5\%$ uncertainty on reference modes
- D_s:
  - Preliminary absolute branching fractions for four D_s decay modes from 76 pb^{-1} of data
    - Precision about 11% for all-charged modes
    - Inclusive $K^-K^+\pi^+\pi^0$ is a first measurement
  - The measured BFs are consistent with the PDG 2004 fit
  - We are actively working on adding more modes (especially decays with η, η')
  - We are aiming for $< 4\%$ uncertainties with full CLEO-c dataset
  - Have more than 120 pb^{-1} additional data on tape

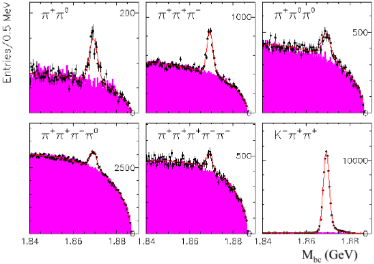
$D^0/D^+ \to (m)\pi^\pm(n)\pi^0$ (281 pb^{-1})

- Motivations:
  - Cabibbo-suppressed BFs badly known, in particular for modes with π^0's
  - Isospin analysis from $D \to \pi\pi$ probes final state interactions
  - Find resonant contributions and tune MC
- Single tag analysis provides full reach for these low rate modes
- Branching ratios measured relative to $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

$D^0/D^+ \to (m)\pi^{\pm}(n)\pi^0$



D^0



D^+

Shaded histogram is normalized sideband

Signals seen in all channels except $D^0 \to \pi^0\pi^0\pi^0$

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

Mode	$\mathcal{B}$ (10^{-3})	PDG (10^{-3})
$\pi^+\pi^-$	$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$	1.38 ± 0.05
$\pi^0\pi^0$	$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$	0.84 ± 0.22
$\pi^+\pi^-\pi^0$	$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$	11 ± 4
$\pi^+\pi^+\pi^-\pi^-$	$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$	7.3 ± 0.5
$\pi^+\pi^-\pi^0\pi^0$	$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$	
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$	
$\omega\pi^+\pi^-$	$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$	
$\eta\pi^0$	$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$	
$\pi^0\pi^0\pi^0$	< 0.35 (90% CL)	
$\omega\pi^0$	< 0.26 (90% CL)	
$\eta\pi^+\pi^-$	< 1.9 (90% CL)	
$\pi^+\pi^0$	$1.25 \pm 0.06 \pm 0.07 \pm 0.04$	1.33 ± 0.22
$\pi^+\pi^+\pi^-$	$3.35 \pm 0.10 \pm 0.16 \pm 0.12$	3.1 ± 0.4
$\pi^+\pi^0\pi^0$	$4.8 \pm 0.3 \pm 0.3 \pm 0.2$	
$\pi^+\pi^+\pi^-\pi^0$	$11.6 \pm 0.4 \pm 0.6 \pm 0.4$	
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$1.60 \pm 0.18 \pm 0.16 \pm 0.06$	1.73 ± 0.23
$\eta\pi^+$	$3.61 \pm 0.25 \pm 0.23 \pm 0.12$	3.0 ± 0.6
$\omega\pi^+$	< 0.34 (90% CL)	

For $\pi\pi$ decays, obtain amplitude ratios for A_2 $(\Delta I = 3/2)$ and A_0 $(\Delta I = 1/2)$:

$$\left|\frac{A_2}{A_0}\right| = 0.420 \pm 0.014 \pm 0.016$$

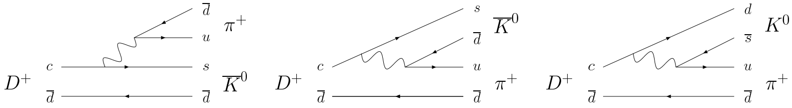
$$\arg(A_2/A_0) = (86.4 \pm 2.8 \pm 3.3)^\circ$$

(Errors: stat, syst, normalizing mode, [CP correlation])

PRL 96, 081802

$D^+ \to K_{S,L}\pi^+$ (281 pb^{-1})

Usually assume $\mathcal{B}(D \to K_L X) = \mathcal{B}(D \to K_S X)$ — but this is not strictly true...

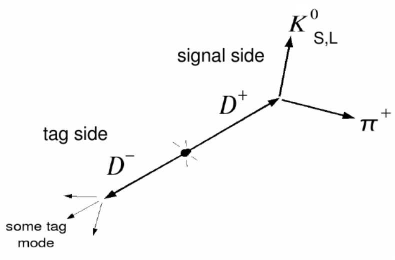


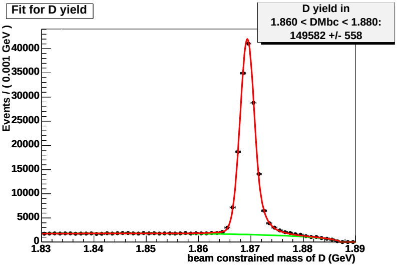
Can produce both Cabibbo-allowed $\overline{K}^0$ and doubly-Cabibbo-suppressed K^0, and their amplitudes for producing K_L and K_S interfere with opposite signs; thus we expect K_L and K_S decays to have unequal rates (Bigi & Yamamoto, PL B349, 363)

Interference $\Rightarrow$ effect $\propto \tan^2(\theta_C)$

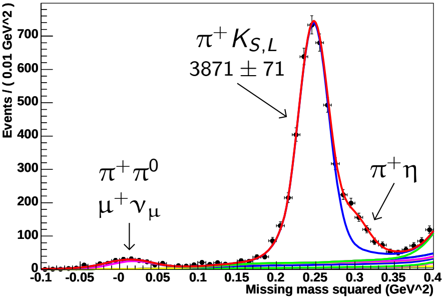
Expect $\mathcal{B}(D^+ \to K_S\pi^+) \neq \mathcal{B}(D^+ \to K_L\pi^+)$ by up to $\sim 10\%$

- Double tag analysis
  - Tag D^+, find extra pion
  - Form missing mass^2 of rest of system: fit for peak at kaon mass^2 — independent of whether it's K_L or K_S
- Careful understanding of background shapes required
- Combine with absolute $D^+ \to K_S\,\pi^+$ BF to form asymmetry





$D^+ \to K_{S,L}\pi^+$



$$\mathcal{B}(K_S\pi^+) + \mathcal{B}(K_L\pi^+) = (3.055 \pm 0.057 \pm 0.158)\%$$

$$\frac{\mathcal{B}(K_L\pi^+) - \mathcal{B}(K_S\pi^+)}{\mathcal{B}(K_L\pi^+) + \mathcal{B}(K_S\pi^+)} = -0.01 \pm 0.04 \pm 0.07$$

$$\mathcal{B}(D^+ \to \eta\pi^+) = (0.391 \pm 0.031 \pm 0.033)\%$$

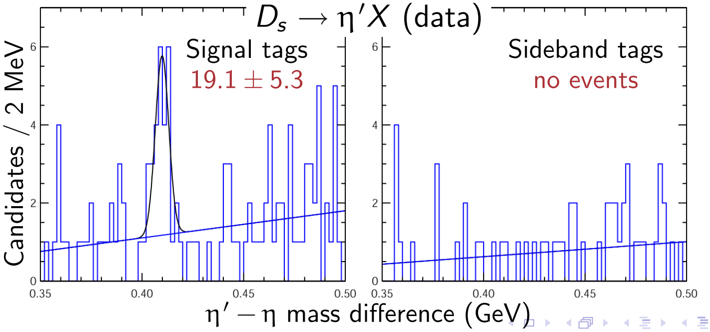
Preliminary

$D^0/D^+/D_s \to (\phi, \eta, \eta')X$

- Inclusive D^0/D^+ branching fractions to mesons with large $s\bar{s}$ content extremely poorly known
- D_s final states have more $s\bar{s}$ content, hence expect larger η, η', ϕ branching fractions
- Inclusive rates help disentangle decay chains through open charm ($\to$ e.g. understand B_s from $\Upsilon(5S)$)
- Uses 281 pb^{-1} for D^0/D^+ and 71 pb^{-1} for D_s

$D^0/D^+/D_s \to (\phi, \eta, \eta')X$

- Double tag: find $D^0/D^+/D_s$; reconstruct ϕ, η, η' with remaining showers and tracks
  - Use $\phi \to K^-K^+$, $\eta \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta \to \pi^+\pi^-\gamma\gamma$
- Use sidebands in ΔE (D^0/D^+) and m_{BC} (D_s) of the tag side to get the background spectrum
- Fit invariant mass of ϕ and η, and $\eta' - \eta$ mass difference



$D^0/D^+/D_s \to (\phi, \eta, \eta')X$

Preliminary

	$\mathcal{B}(\phi X)$ (%)	$\mathcal{B}(\eta X)$ (%)	$\mathcal{B}(\eta' X)$ (%)
D^0	$1.0 \pm 0.1 \pm 0.1$	$9.4 \pm 0.4 \pm 0.6$	$2.6 \pm 0.2 \pm 0.2$
D^+	$1.1 \pm 0.1 \pm 0.2$	$5.7 \pm 0.5 \pm 0.5$	$1.0 \pm 0.2 \pm 0.1$
D_s	$15.1 \pm 2.1 \pm 1.5$	$32.0 \pm 5.6 \pm 4.7$	$11.9 \pm 3.3 \pm 1.2$

- η signals include feeddown from η'
- All except $D^0/D_s \to \phi X$ are first measurements
- Known D_s exclusive modes essentially saturate inclusive measurements

Summary

- Excellent detector, clean events, and large data sample $\Rightarrow$ branching fractions for open charm decays with precision $\gtrsim$ world averages
- BF measurements help normalize D and B physics, probe strong interaction physics
- CLEO-c plans on taking 1.5 fb^{-1} of open charm data over the next two years, aims for absolute BF precision of 1.5% for D^0, $D^+$and 4% for D_s

Backup Slides

Method Numerics

Single tag yields: $N_i = N_{D\overline{D}} \mathcal{B}_i \epsilon_i$

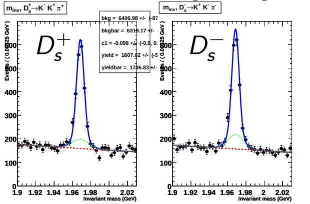
Double tag yields: $N_{ij} = N_{D\overline{D}} \mathcal{B}_i \mathcal{B}_j \epsilon_{ij}$

$\Rightarrow$ **Branching fractions:** $\mathcal{B}_j = \frac{N_{ij}}{N_i} \frac{\epsilon_i}{\epsilon_{ij}}$

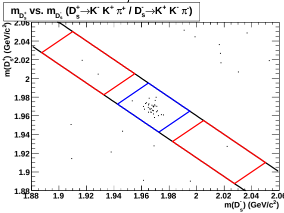
- In practice, we fit all the yields simultaneously
  - Maximizes power: limiting statistical uncertainty is $\sqrt{\text{total double tags}}$ in *every* mode
  - Bad $\chi^2 \rightarrow$ something wrong...
- Can correlate systematics
- Obtain cross-section as well

Yield extraction

DATA: $KK\pi$ Single Tags



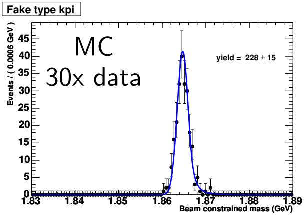
DATA: $KK\pi^+/KK\pi^-$ Double Tag



- Fit single tag signals with double Gaussian or Crystal Ball function (parameters fixed from Monte Carlo) plus a linear background
  - Each charge done separately
- In double tags, count events in signal and sideband boxes
  - Combinatoric background is flat in $m(D_s^+) - m(D_s^-)$, has structure in $m(D_s^+) + m(D_s^-)$

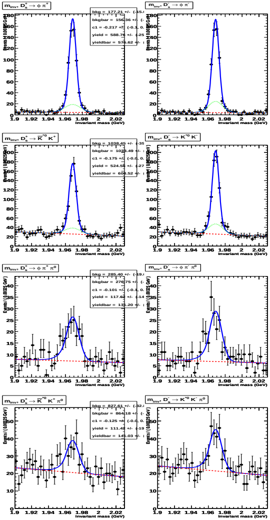
Backgrounds

- Non-peaking backgrounds removed in the yield fit
- Peaking backgrounds are from crossfeed between modes we consider, and contamination from other modes
  - Latter dominated by Cabibbo-suppressed decays in K_S modes, e.g. prompt $D^+ \to 5\pi$ fakes $D^+ \to K_S 3\pi$; in some modes up to 3% correction
- Estimate backgrounds to single and double tags with PDG branching fractions and efficiencies from MC, subtract from measured yields



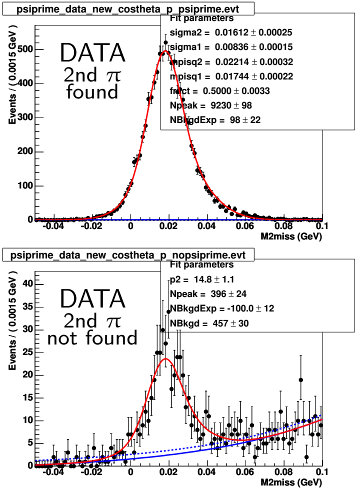
DCSD decay $\overline{D}^0 \to K^-\pi^+$ faking $D^0 \to K^-\pi^+$ in 30x MC sample. In data, contributes $\approx 0.15\%$ of observed peak.

- Our Monte Carlo has some reasonable mixture of intermediate resonances
- Our efficiencies depend on the intermediate state
- We reweight the expected efficiencies by comparing data yields with MC expectations
  - Size of correction is largest systematic for $K^- K^+ \pi^+ \pi^0$
- The correction for a given mode affects that mode's BF *only*



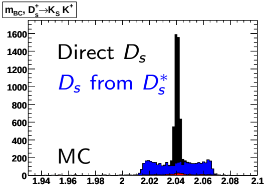
Systematics studies using ψ'

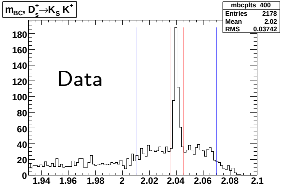
- Clean decays $\psi' \to J/\psi\,\pi^+\pi^-$ and $J/\psi\,\pi^0\pi^0$ used to compare tracking and π^0 efficiencies in MC and data
- Reconstruct J/ψ and one pion; compute recoil mass: peaks at pion mass
- Find fraction of such events with other pion reconstructed
- Right: Plots for $J/\psi\,\pi^+\pi^-$, $0.15 < \cos\theta_\pi < 0.55$
  - $\epsilon = (95.89 \pm 0.20)\%$; agrees with MC within statistics



Production Channel

- We use events with the topology $e^+e^- \to D_s^{*\pm} D_s^{\mp} \to D_s^+ D_s^- (\gamma, \pi^0)$.
- We do **not** reconstruct the γ or π^0.
- We use the momentum of the D_s candidates to select for events with an intermediate D_s^*. (The quantity $m_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^2}$ is a proxy for momentum.)
- We can use a loose cut to include the daughters of D_s^*, or a tight cut for the directly produced D_s

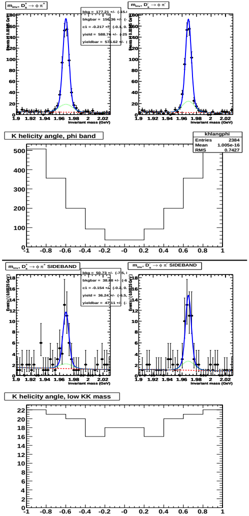




The $\phi\pi^+$ problem

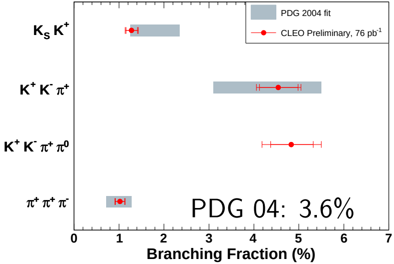
- Expect $(f_0(980) \to K^- K^+)\pi^+$ to contribute to any ϕ mass region, with badly controlled parameters
- Correction might be on the order of 5% or more — but depends on experiment's mass window, resolution, angular distribution requirements!

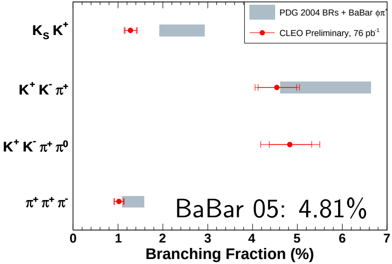
Looking at low-mass KK pairs ($m(KK) < 1.005$ GeV) we see evidence for scalar production by looking at helicity angle



Can we compare with the BaBar $\mathcal{B}(D_s^+ \to \phi\pi^+)$ result?

- We can use the PDG fit branching ratios...





- We are more consistent with 3.6% than 4.8%