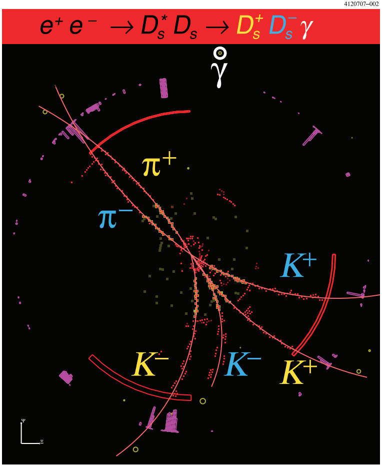

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CLEO Collaboration

LBNL Research Progress Meeting
20 Nov 2007

Cornell University
Laboratory for Elementary-Particle Physics

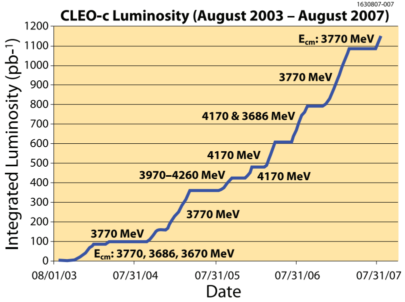
Outline

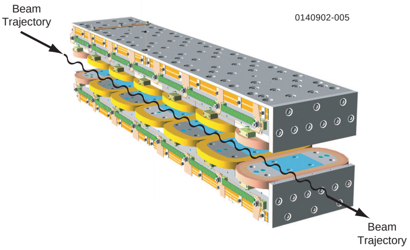
- CLEO-c/CESR-c
- The Whys and Hows of Branching Fractions
- The Analyses
  - D^0/D^+ at $E_{cm} = 3.77$ GeV
  - D_s^+ at $E_{cm} = 4.17$ GeV

CESR

- 768 m symmetric e^+e^- storage ring
- Provides collisions for **CLEO** and x-ray beams for the **C**ornell **H**igh **E**nergy **S**ynchrotron **S**ource
- Designed to operate at $E_{cm} =$ 9–16 GeV, ran at Υ resonances with (at the time) world-record luminosities
- CESR-c: upgrade to provide collisions down to $E_{cm} = 3.7$ GeV

CESR-c Upgrade & Run Plan



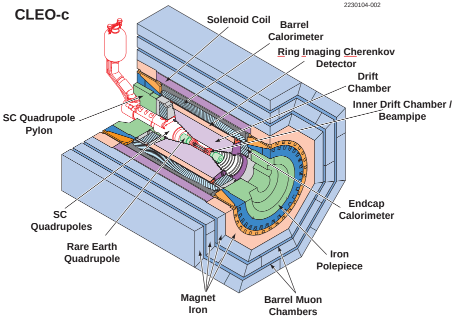


- Insufficient beam cooling at low energy with old CESR (synchrotron power $\propto E^4$)
  - CLEO can no longer run simultaneously with CHESS
- Solution: 12 wiggler magnets installed to cool beam
  - CESR-c an interesting testbed for wiggler-dominated rings (e.g. ILC damping rings)
- Charm physics running ends March 30, 2008; last run period begins early December for D_s physics

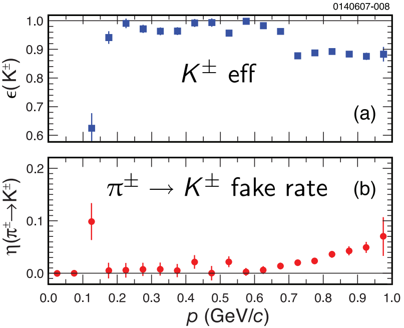
CLEO-c Detector

- General-purpose symmetric detector
- Particle ID (dE/dx, Ring Imaging Cherenkov) excellent in our momentum region

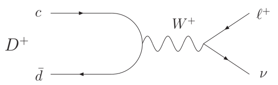
- Tracking: $\delta p/p = 0.6\%$ at 1 GeV
- CsI calorimeter: $\delta E/E \sim 5\%$ at 100 MeV

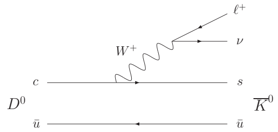


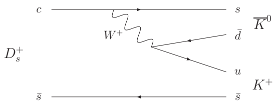
Combined PID performance



Open Charm Decays at CLEO-c







Leptonic decays:

- Probe wavefunction at origin (decay constants f_D, f_{D_s})
  - Test lattice QCD and meson structure models

Semileptonic decays:

- Probe overlap of initial and final hadron states (form factors $f_+(q^2)$ ...)
  - Test LQCD and decay models

Hadronic decays:

- Reference modes normalize decays
- QCD dynamics
- Search for new phenomena: CP violation, D^0–$\overline{D}^0$ mixing

Why Branching Fractions are Needed

How do we study processes with unstable particles in the final state?

- "Exclusive" analyses that reconstruct entire decay chain are often the experimentally cleanest way
- To get absolute *rates* this way, you need probabilities — branching fractions — of intermediate steps
- Charm quarks hadronize, so need to measure branching fractions for easily-reconstructed final states

In this talk:

- A **branching fraction** will always be an *absolute* probability $\mathcal{B}(X \to YZ)$,
- A **branching ratio** will always be a *relative* ratio $\mathcal{B}(X \to YZ)/\mathcal{B}(X \to Y'Z')$.

The Role of Charm

Sampler of measurements that need charm branching fractions:

- Exclusive $|V_{cb}|$ from $B \to D^* \ell \nu$ or $B \to D \ell \nu$
- $|V_{cd}|$ from charm production in neutrino interactions
- $R_c \equiv \mathcal{B}(Z^0 \to c\bar{c})/\mathcal{B}(Z^0 \to \text{ hadrons})$ at LEP experiments
- $\Delta\Gamma$ in B_s^0 system from $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$

Four independent scales characterize open charm branching fractions:

	D^0 $(c\bar{u})$	D^+ $(c\bar{d})$	D_s^+ $(c\bar{s})$	Λ_c^+ (udc)
Reference decay	$K^-\pi^+$	$K^-\pi^+\pi^+$	$\phi\pi^+$	$pK^-\pi^+$
PDG Uncertainty (excl CLEO-c)	2.4%	6.5%	9%	26%

CLEO-c has the data to contribute for the mesons.

Measuring Branching Fractions

- If luminosity and $X \to YZ$ yield/efficiency known, can measure

$$\sigma(X)\mathcal{B}(X \to YZ) = \frac{N(X \to YZ)}{\epsilon}\frac{1}{\mathcal{L}}$$

  and combine with external $\sigma(X)$ (e.g. $|V_{tb}|$ from single top).
- If it's possible to reconstruct *all* major decays of a particle, branching ratios + constraint $\sum \mathcal{B} = 1 \to$ branching fractions (e.g. η, K_L^0).
- Use some characteristic of X production as a "tag" — can then determine total number of produced X and number of $X \to YZ$ in same sample (analyses I'll discuss).

Tagging for Charm Decays

B-factory/LEP measurements of charm branching fractions:

- D^0: tag low-momentum pions from $D^{*+} \to D^0\pi^+$
- D^+: use D^0 measurement, with an estimation of $\mathcal{B}(D^{*+} \to D^+\pi^0)$ (isospin broken due to phase space!)
- D_s^+: Partially reconstruct $B \to D_s^{(*)} D^{(*)}$

The CLEO-c procedure follows early branching fraction measurements by Mark III

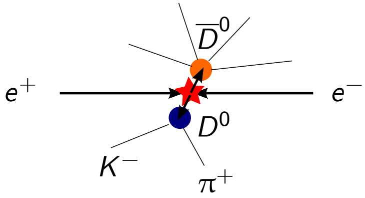
Near threshold, not enough phase space to produce extra particles:

- At 3.77 GeV, can make D^+D^- and $D^0\overline{D}^0$, but not $D^-D^0\pi^+$;
- At 4.17 GeV, can make $D_s^*D_s$, but not D_sDK.

Method in Detail

Common CLEO-c technique:

- reconstruct common, clean D "tag" decays
- search for signal $\overline{D} \rightarrow X$ in these events
- $\mathcal{B}(\overline{D} \rightarrow X) = \frac{N(\overline{D}\rightarrow X)}{\epsilon} \frac{1}{N(\text{tags})}$



However —

- The tag modes are our signal → must be more sophisticated
- Find yields for one D ("single tag") or two Ds ("double tag")
- 3 D^0, 6 D^+, and 8 D_s^+ decays used as tags

Method Numerics

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

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

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

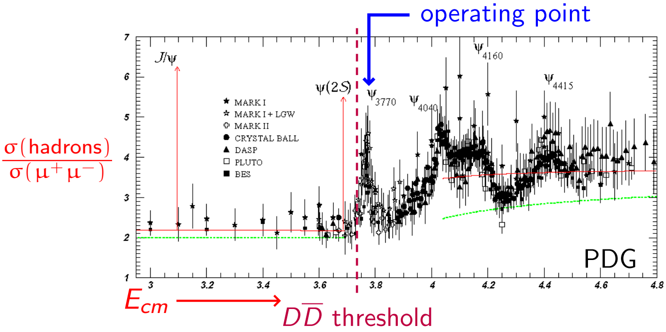
- In practice, we fit all the yields simultaneously
  - Maximizes power: limiting statistical uncertainty is $\sqrt{\text{total double tags}}$ in *every* mode
  - Adding more decay channels helps every measurement
  - Bad $\chi^2 \rightarrow$ something wrong...

D^0/D^+ Analysis

(arXiv:0709.3783, accepted by PRD)

Data Used

- $\mathcal{L} = (281 \pm 3)\ \mathrm{pb}^{-1}$ at $E_{cm} \approx 3.773$ GeV, on the $\psi(3770)$ resonance
- Also exploit ψ' data for systematics studies



D Hadronic Decay Overview

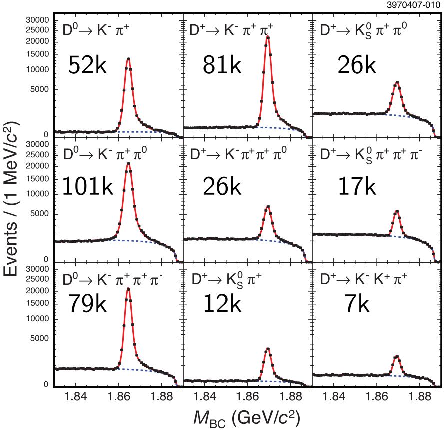
- 3 D^0, 6 D^+ decay channels:
  - $D^0 \to K^-\pi^+$
  - $D^0 \to K^-\pi^+\pi^0$
  - $D^0 \to K^-\pi^+\pi^+\pi^-$
  - $D^+ \to K^-\pi^+\pi^+$
  - $D^+ \to K^-\pi^+\pi^+\pi^0$
  - $D^+ \to K^0_S\pi^+$
  - $D^+ \to K^0_S\pi^+\pi^0$
  - $D^+ \to K^0_S\pi^+\pi^+\pi^-$
  - $D^+ \to K^-K^+\pi^+$
- We get 18 single tag, 45 $(3^2 + 6^2)$ double tag modes
- Fit D^0 and D^+ simultaneously to include correlations
- In addition to two reference modes, get the other seven branching fractions and $N_{D^0\overline{D}^0}$, $N_{D^+D^-}$ as output

The CLEO-c D-Hunter's Guide

- K, π ID: dE/dx (all momenta) and Čerenkov (for high momentum)
- π^0: pairs of isolated showers in the CsI calorimeter within 3σ of π^0 mass ($\sigma \sim 6$ MeV)
- K_S: pairs of tracks that lie within a mass window (no displaced vertex required)
- Two crucial kinematic variables:
  - "Beam-constrained mass" $M_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^2}$: is total momentum of candidate right?
  - $\Delta E = E_D - E_{beam}$: is particle ID right? are we missing particles?

"D Tagging will solve the world's problems and make it sunny in Ithaca" - Anon.

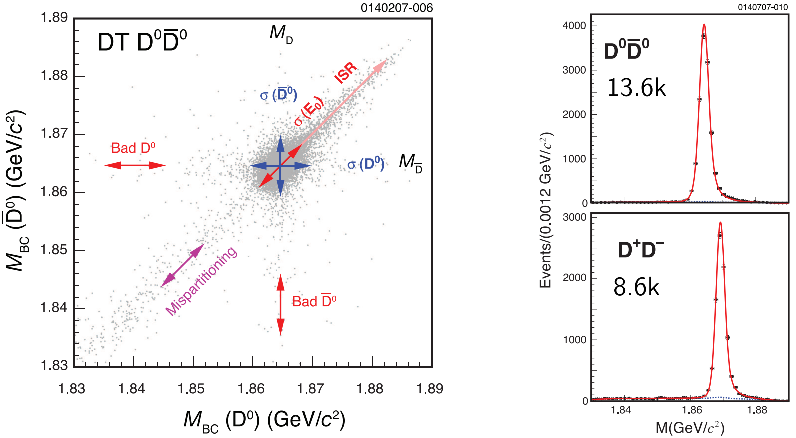
DATA: Single tags



Note square root scale

- 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 ($< 2\%$)

Yield Extraction - Double Tags

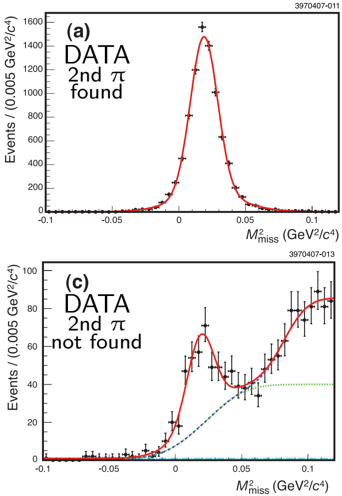


Double tags: fit 2D plane of $M_{BC}(1)$ vs. $M_{BC}(2)$, with appropriate correlations

Efficiency Systematics Studies

- Clean decays used to compare tracking, K_S^0, π^0 efficiencies in MC and data
- Example (π^+ efficiency from $D^+ \to K^-\pi^+\pi^+$):
  - Tag D^-candidate
  - Find K^-, π^+
  - Find recoil mass of $D^-K^-\pi^+$ system; has a peak at π^+ mass
  - Find fraction of such events with other pion reconstructed
  - Compare data and MC

$D^+ \to K^-\pi^+\pi^+$, $p_{\pi^+} > 0.2$ GeV$/c$



$\epsilon_{MC}/\epsilon_{data} - 1 = +0.30 \pm 0.30 \pm 0.05\%$

Final State Radiation

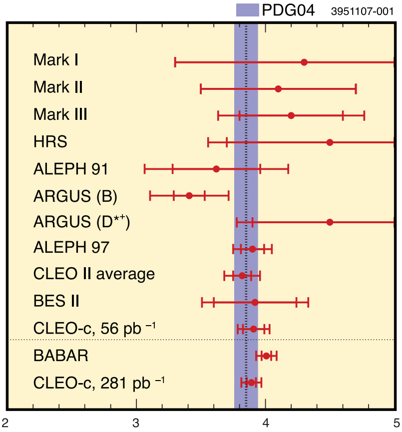
- We report branching fractions which include soft photons radiated off the daughter particles, e.g. $\mathcal{B}(D^0 \to K^-\pi^+)$ includes $D^0 \to K^-\pi^+ + n\gamma$
- We use `PHOTOS` to model radiation from the hadrons
  - `PHOTOS` modifies the already-generated physics process and is necessarily inexact
- Predict that 2.8% of $D^0 \to K^-\pi^+$ decays radiate more than 30 MeV; these fail the ΔE cut and are lost
- This depends on `PHOTOS` implementation of interference between radiation from the two daughters
- We take 30% of the total FSR effect as a systematic uncertainty: 0.9% uncertainty for $D^0 \to K^-\pi^+$
- Correlated between experiments!

Systematic uncertainties

Source	Fractional uncertainty (%)
$\pi^+/K^+/K^0_S/\pi^0$	0.3/0.7/1.8/2.0 per particle
Particle ID	0.25 per π, 0.3 per K
Trigger efficiency	0.0–0.2
ΔE cut	0.5–1.0 per D
FSR modeling	0.1–0.9 per D
ST signal shape	0.3–1.3 per ST yield
ST background shape	0.4–1.5 per ST yield
DT signal shape	0.2 per DT yield
Resonant substructure	0.0–1.3
Event environment	0.0–0.8
Lepton veto	0.1 in $K^-\pi^+$ ST
Double DCSD interference	0.8 in D^0 DT

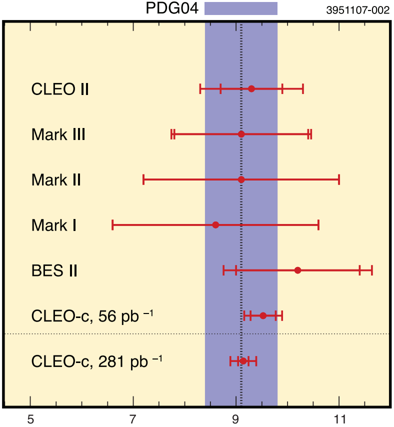
Results

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



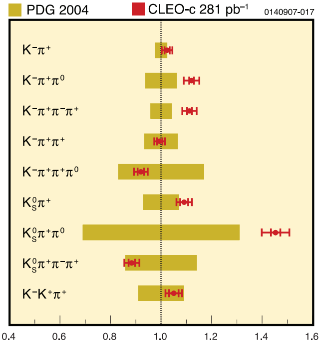
$(3.891 \pm 0.035 \pm 0.059 \pm 0.035)\%$
(stat, syst, FSR)

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



$(9.14 \pm 0.10 \pm 0.16 \pm 0.07)\%$
(stat, syst, FSR)

Results



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

CP asymmetry search:

$$\mathcal{A}_{CP} \equiv \frac{N(D) - N(\overline{D})}{N(D) + N(\overline{D})}$$

Account for charge-dependent detector effects

Mode	CLEO-c (%)	Previous (%)
$D^0 \to K^-\pi^+$	$-0.4 \pm 0.5 \pm 0.9$	
$D^0 \to K^-\pi^+\pi^0$	$0.2 \pm 0.4 \pm 0.8$	-3.1 ± 8.6
$D^0 \to K^-\pi^+\pi^+\pi^-$	$0.7 \pm 0.5 \pm 0.9$	
$D^+ \to K^-\pi^+\pi^+$	$-0.5 \pm 0.4 \pm 0.9$	
$D^+ \to K^-\pi^+\pi^+\pi^0$	$1.0 \pm 0.9 \pm 0.9$	
$D^+ \to K_S^0\pi^+$	$-0.6 \pm 1.0 \pm 0.3$	$-1.6 \pm 1.5 \pm 0.9$
$D^+ \to K_S^0\pi^+\pi^0$	$0.3 \pm 0.9 \pm 0.3$	
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$0.1 \pm 1.1 \pm 0.6$	
$D^+ \to K^+K^-\pi^+$	$-0.1 \pm 1.5 \pm 0.8$	0.7 ± 0.8

D^0/D^+ Summary and Outlook

- Branching fractions from 281 pb^{-1} have precision exceeding world averages
- Analysis is systematics-limited
- Final state radiation modeling is a large component of uncertainty
- All CLEO-c D^0/D^+ data have been taken

D_s Analysis
(Preliminary)

D_s Hadronic Decay Overview

- D_s decays have large $s\bar{s}$ components: large ϕ, η, η' fraction, unique detector challenges
- Classic reference decay is $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$
- With CLEO-c's precision, "ϕ" signal is ambiguous due to underlying scalar
- We instead measure $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$
- $K_S^0 K^+$ might also be a useful reference mode

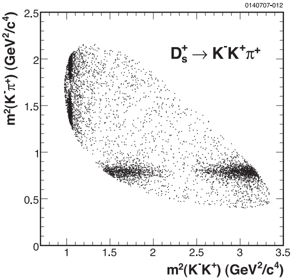
Our 8 modes:

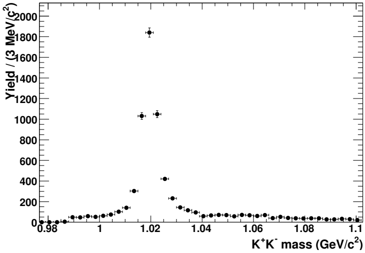
- $D_s^+ \to K_S^0 K^+$
- $D_s^+ \to K^-K^+\pi^+$
- $D_s^+ \to K^-K^+\pi^+\pi^0$
- $D_s^+ \to K_S^0 K^-\pi^+\pi^+$
- $D_s^+ \to \pi^+\pi^+\pi^-$
- $D_s^+ \to \pi^+\eta$
- $D_s^+ \to \pi^+\eta'$
- $D_s^+ \to K^+\pi^+\pi^-$

Reconstruct $\eta \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta$.

The $\phi\pi^+$ problem

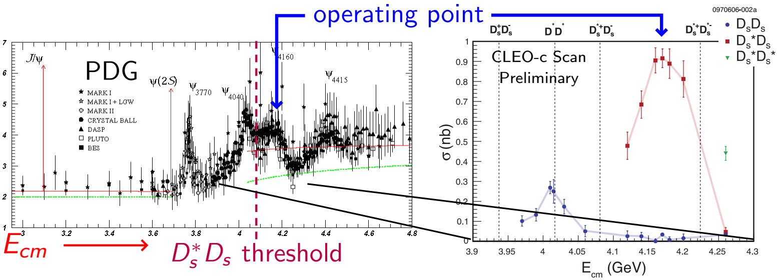
- Observe a broad scalar contribution in the ϕ mass region
- Contribution is $\gtrsim 5\%$ — but depends on mass window, resolution, angular cuts
- We report partial branching fractions for various mass cuts around the ϕ





Dataset and Landscape

- Use 298 pb^{-1} of data at $E_{cm} = 4170$ MeV
  - Chose optimal D_s production energy with a scan
- D_s dominantly produced via $D_s^* D_s$, ≈ 1 nb
- Major background of D^0, D^+ events produced at ≈ 7 nb



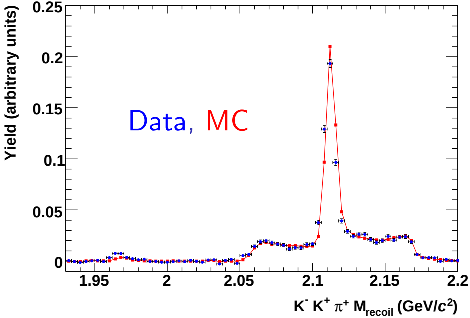
Production Channel

- Use events with the topology $e^+e^- \to D_s^{*\pm} D_s^{\mp} \to D_s^+ D_s^- (\gamma, \pi^0)$. The γ or π^0 is *not* reconstructed.
- Use the momentum of the D_s candidates to select events consistent with $D_s^* D_s$ production.

Actually use recoil mass

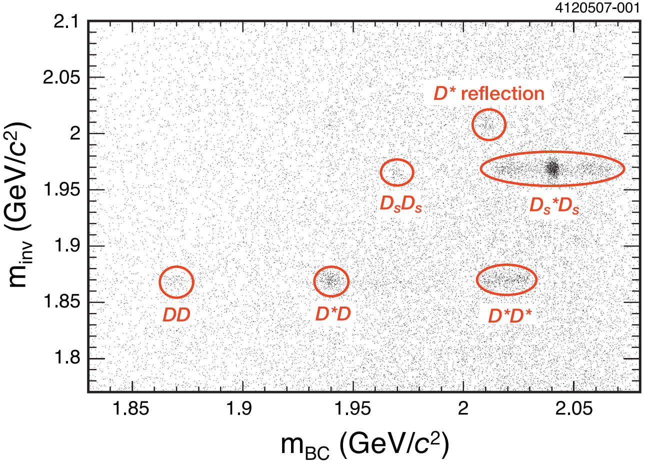
$$m_{\rm rec}^2 = \left(E_{cm} - \sqrt{\vec{p}_{D_s}^{\,2} + m_{D_s}^2}\right)^2 - (\vec{p}_{cm} - \vec{p}_{D_s})^2$$

as a momentum proxy. Expect $m_{\rm rec} \sim m(D_s^*) = 2.112$ GeV.



Kinematic Separation

MC: reconstructed $K^-K^+\pi^+$ candidates, before cuts



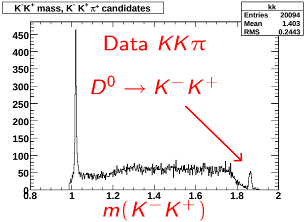
$$= \sqrt{E_{\text{beam}}^2 - \vec{p}_{D_s}^{\,2}}$$

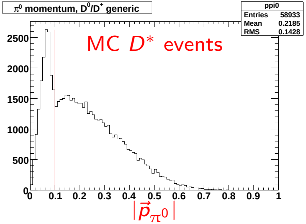
$D_s^* D_s$ Branching Fraction Fit

- We do a binned maximum likelihood fit for all the observed yields (utilizing Poisson statistics for double tags)
- Maximizing statistical power important given relatively low D_s cross-section
  - The $KK\pi$ mode is 46% of total ST yield, but $KK\pi/KK\pi$ is only 17% of total DT yield

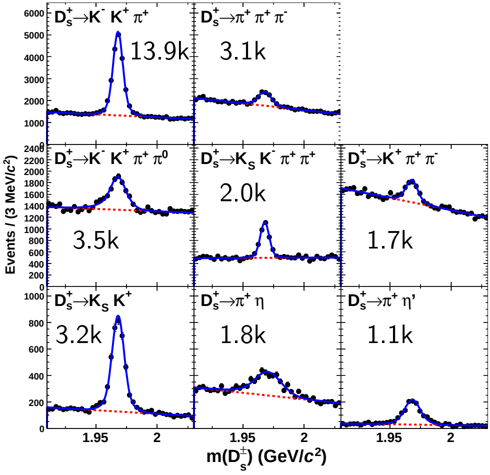
Backgrounds and Reflections

- Crossfeed between D_s modes from $K_S^0 \leftrightarrow \pi^+\pi^-$ is Cabibbo-suppressed
  - Use vetoes and sidebands
- Peaking structure from reflections, e.g. $D^{*+} \to D^0\pi^+ \to K^-K^+\pi^+$
  - We veto certain mass regions; e.g. for $KK\pi$ we reject events consistent with $D^0 \to KK$
  - Require $|\vec{p}_\pi| > 100$ MeV to remove slow pions from D^*
  - Doesn't affect signal but makes background easier to model





Yield extraction



Preliminary

Cut on candidate recoil mass, fit invariant mass

Fit single tag signals with empirical functions (parameters fixed from Monte Carlo) plus a linear background

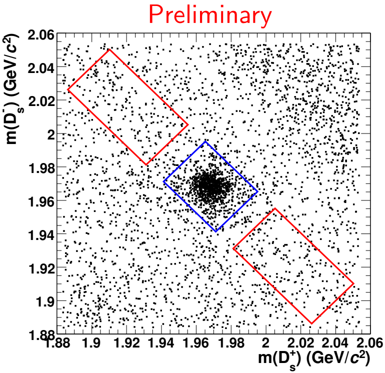
Each charge done separately; charges combined in this plot

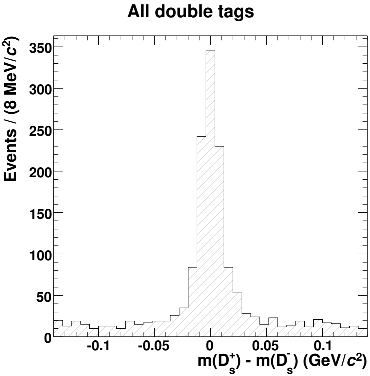
Total single tag yield $\approx$ 30k events

Yield Fits

In double tags, count events in signal and sideband boxes

- Combinatoric background is flat in $m(D_s^+) - m(D_s^-)$, has structure in $m(D_s^+) + m(D_s^-)$





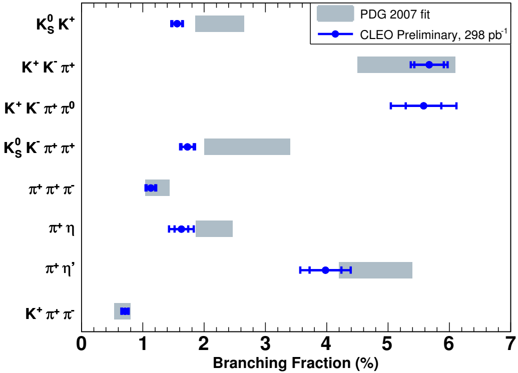
Total double tag yield 976 ± 33 events

Systematic uncertainties

Preliminary

Source	Fractional uncertainty (%)
$\pi^{\pm}/K^{\pm}/K_S^0/\pi^0/\eta$	0.3/0.7/1.8/2.0/3.5 per particle
η/η' branching fractions	0.7/3.1 per particle
Particle ID	0.3–1.4
Resonant substructure	0–6.0
Event environment	0.1–1.4 per ST
Initial state radiation model	0–1.2 per ST
ST lineshapes	0.3–11.3 per ST
DT lineshapes	0–8 per DT
Final state radiation model	0.8

Preliminary Results for D_s



Partial branching fractions for
$D_s \to K^- K^+ \pi^+$

$|m(K^- K^+) - m_\phi| < \Delta M$

ΔM	Partial $\mathcal{B}$ (%)
5 MeV	$1.75 \pm 0.08 \pm 0.06$
10 MeV	$2.07 \pm 0.10 \pm 0.05$
15 MeV	$2.22 \pm 0.11 \pm 0.06$
20 MeV	$2.32 \pm 0.11 \pm 0.06$

$$\mathcal{B}(D_s^+ \to K^- K^+ \pi^+) = (5.67 \pm 0.24 \pm 0.18)\%$$

Largely consistent with PDG average —
comparison now limited by PDG branching ratios

Overall Summary

	D^0	D^+	D_s^+	D_s^+	Λ_c
Reference decay	$K^-\pi^+$	$K^-\pi^+\pi^+$	$\phi\pi^+$	$K^-K^+\pi^+$	$pK^-\pi^+$
PDG Uncertainty (excl CLEO-c)	2.4%	6.5%	9%	15%	26%
CLEO-c	2.0%	2.2%		5.3%†	—

†Preliminary

- CLEO-c has measurements of charmed meson branching fractions with precision exceeding world averages.
- D^0/D^+ analysis is systematics-limited.
- D_s^+ analysis is statistics-limited and we expect to take $\sim 2\times$ more data in our last run period.