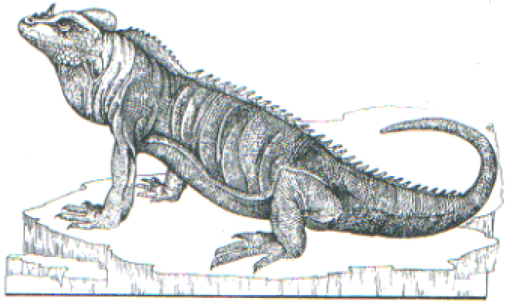
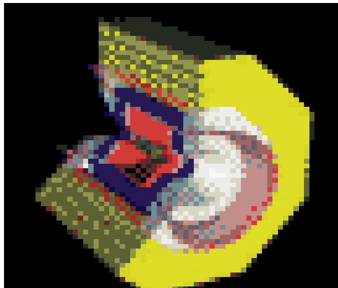


CLEO-c: Open Charm

Dan Cronin-Hennessy
University of Minnesota
May 31, 2006
CIPANP



Talk Overview

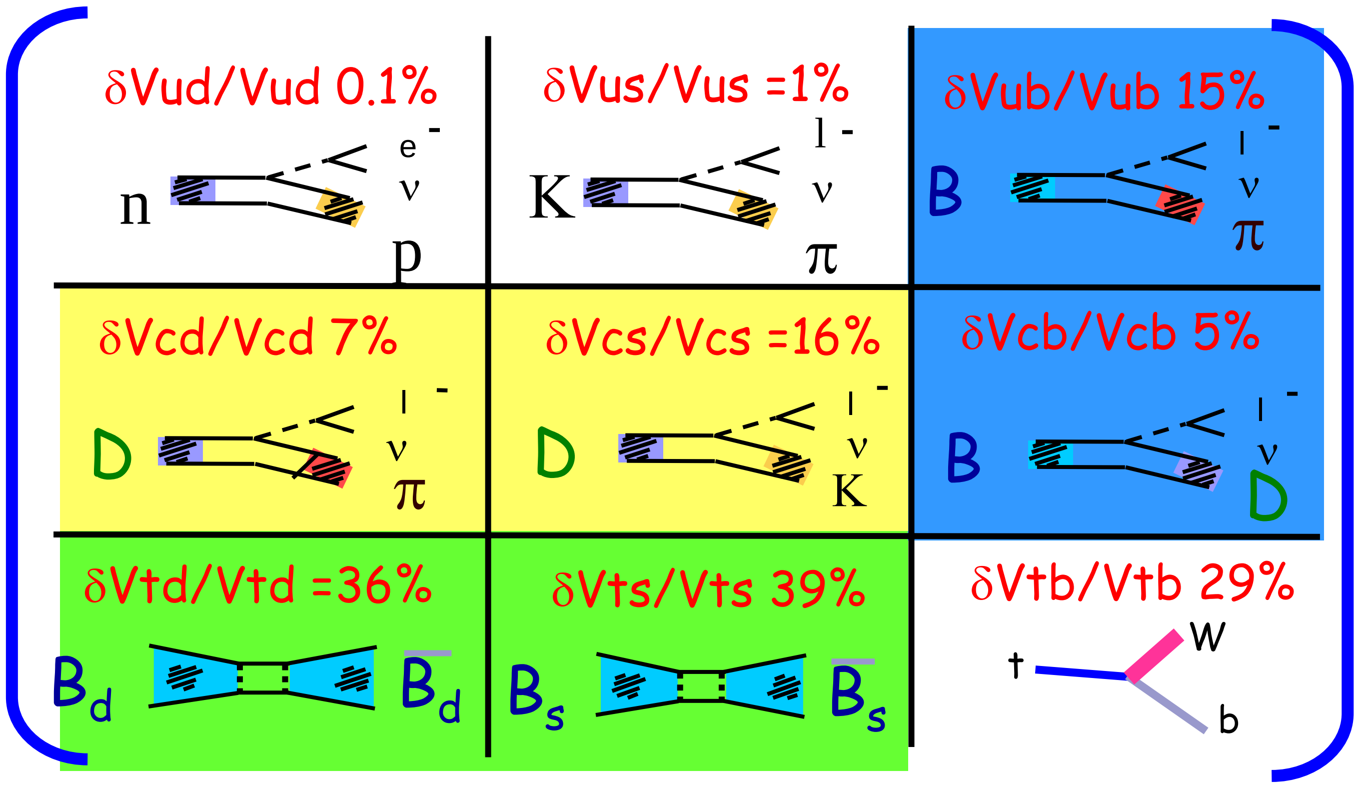
- Program Overview

- CLEO-c Results:

Measurement	**Theory**	**Physics**
D Leptonic	Lattice (f_D)	V_{tx}
D Semileptonic	Lattice (ff)	V_{xb}
	CKM	V_{cx}
D Hadronic/Semilep	Mixing	$\Delta M, \Delta \Gamma$
		new physics

Impact of Physics

- $\psi(3770)$
  - 1000/pb
  - 2M tagged D
  - 100x MARKIII
- = 4170 MeV
  - 1000/pb
  - ~0.1M tagged Ds
  - Scan completed.
- $\psi(3686)$
  - 30 million $\psi(3686)$



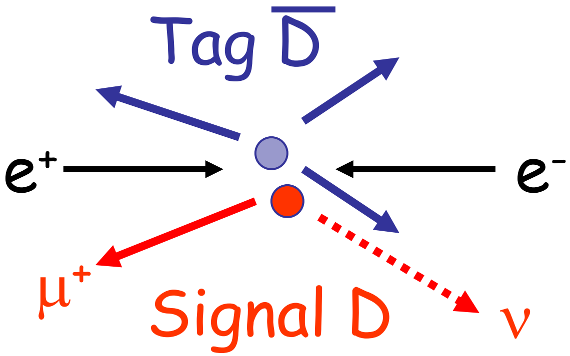
CLEO-c

CLEO-c + Lattice QCD +B factories

CLEO-c + Lattice QCD +B factories + ppbar

D-Tagging

D-Tagging



→Event Shape discrimination no longer a powerful powerful tool in the charm region.

→Backgrounds at $\psi(3770)$: continuum (18 nb), τ pair (3 nb), radiative return (~1.5 nb)

→D meson has large branchings to low multiplicity modes.

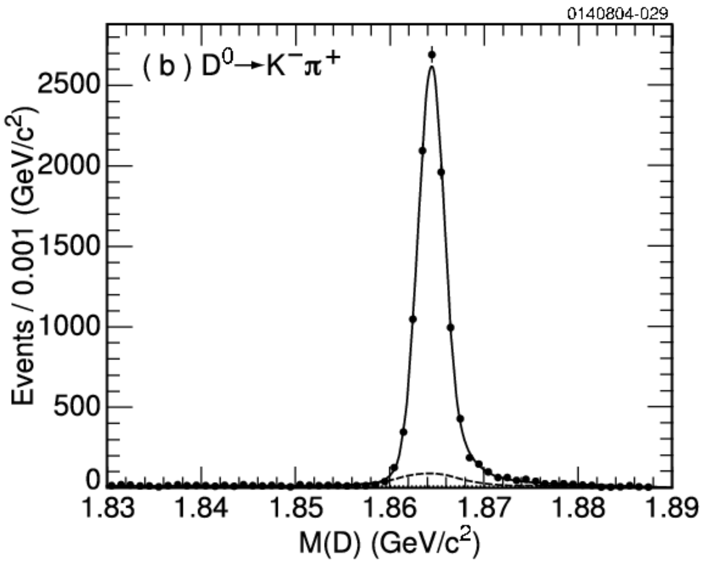
→Requiring a reconstructed D provides background suppression.

→D-Tagging removes half the event (only a single D remains).

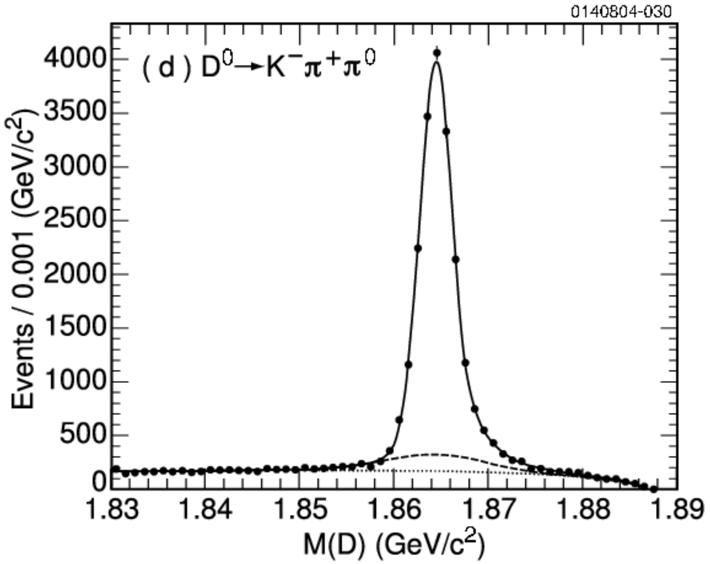
→Simultaneously provides 4-vector of other D meson.

D-Tagging

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



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

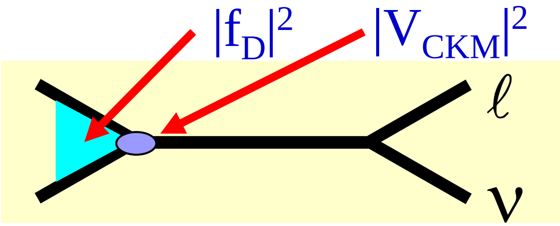


$$M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$$

$$\Delta E = E_{beam} - E_{candidate}$$

Weak Annihilation: $D^+ \rightarrow \mu^+ \nu_\mu$

$$\Gamma(D_q^+ \to l\,\upsilon) = \frac{1}{8\pi} G_F^2 M_{D_q^+} m_l^2 \left(1 - \frac{m_l^2}{M_{D+}^2}\right) f_{D+}^2 |V_{cq}|^2$$

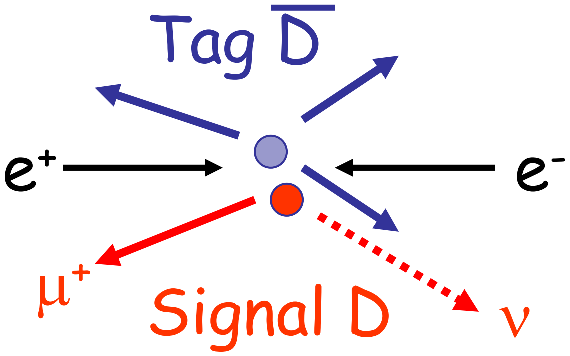


$$\Delta M_d = 0.50\,ps^{-1} \left[\frac{\sqrt{B_{B_d}}\, f_{B_d}}{200 MeV} \right]^2 \left[\frac{|V_{td}|}{8.8 \times 10^{-3}} \right]^2$$

Improvement in mixing constraints with better f_B
Ideally one would measure $B^+ \rightarrow l^+ \nu$ (rate too low).
Realistic alternative: Measure f_D,f_{Ds}.

$f_{D\ CLEO-c}$ and $(f_B/f_D)_{lattice} \rightarrow f_B$
(And f_D/f_{Ds} checks f_B/f_{Bs})

$D^+ \rightarrow \mu^+ \nu_\mu$



→**One D fully reconstructed:**
reconstructed:

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

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

$$D^- \rightarrow \overline{K}^0_S\pi^-$$

$$D^- \rightarrow \overline{K}^0_S\pi^-\pi^-\pi^+$$

$$D^- \rightarrow \overline{K}^0_S\pi^-\pi^0$$

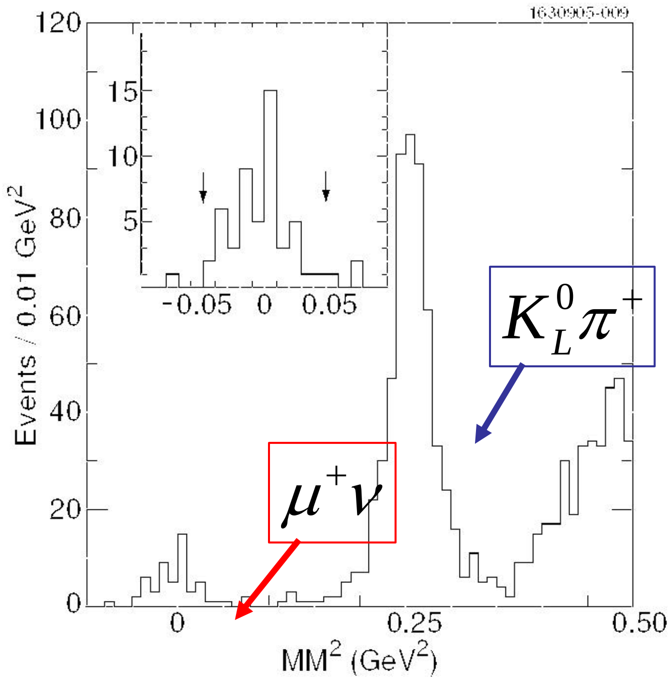
→**Require single track on other side: μ**

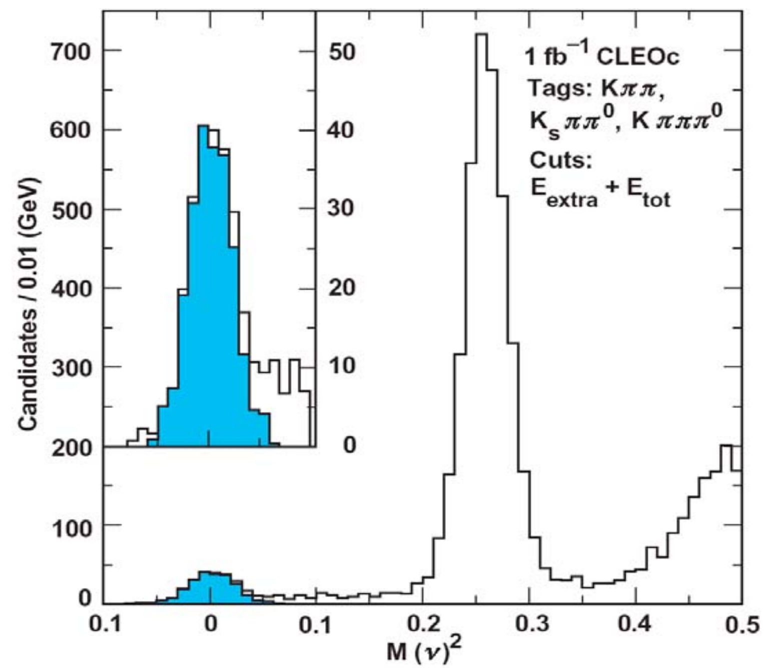
- **PID suppresses K**
- **Calorimeter suppresses π^+**
- **Require low energy in CC**

Use D 4-vector to calculate missing mass (~0 for ν).

$D^+ \to \mu^+ \nu_\mu$

Data (281 pb^{-1}) **Monte Carlo (1 fb^{-1})**





Mode	Events
Data	50
$D^+ \to \pi^+ \pi^0$	1.4
$D^+ \to K_{long}\, \pi^+$	0.33
$D^+ \to \tau^+ \nu_\tau$	1.08
Total Bck:	2.81

$$B(D^+ \to \mu^+ \upsilon) = (4.40 \pm 0.66\,^{+0.09}_{-0.12}) \times 10^{-4}$$

CLEO-c

$$f_{D^+} = (222.6 \pm 16.7\,^{+2.8}_{-3.4})MeV$$

PRL 95 251801 (2005)

Lattice

$$f_{D^+} = (201 \pm 3 \pm 17)MeV$$

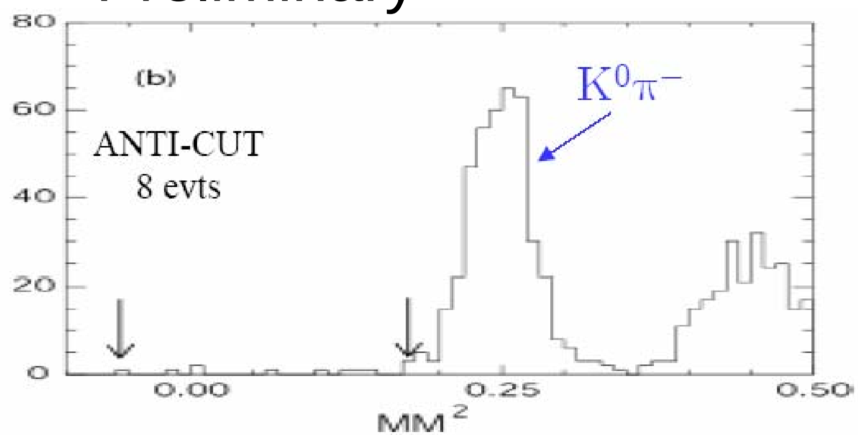
PRL 95 122002 (2005)

$D^+ \to \tau^+ \nu_\tau \; (\tau \to \pi\nu)$

Data (281 pb^{-1})

$$\frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} \neq \frac{m_\tau^2\left(1-m_\tau^2/M_D^2\right)^2}{m_\mu^2\left(1-m_\mu^2/M_D^2\right)^2}$$

Preliminary



$$R = \frac{\Gamma_{Measured}(D^+ \to \tau^+\nu)}{\Gamma_{SM}(D^+ \to \tau^+\nu)}$$

R<1.8 @90%

Submitted to PRD

Anti-cut analysis vetoes
CC energy associated with track
That is consistent with muon.

Exclusive Semileptonic Decays

Motivation

→Direct access to CKM elements (V_{cs},V_{cd})

→High resolution measurement of q^2 spectrum. Confronts form factor predictions. ➔ Better extraction of V_{xb} from exclusive semileptonic B decays.

→ Opportunity for first observations.

Exclusive Semileptonic Decays

Technique

→D-Tag event
→Identify electron
→Reconstruct the hadronic component
→Check for consistency with neutrino
$U=E_{miss}-|P_{miss}|$

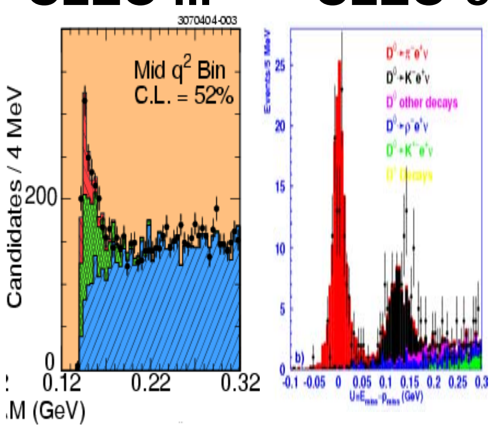
Signal component from fit to variable U

$$B(D^+ \to \overline{K}^0 e^+ \nu) = \frac{N(\overline{K}^0 e^+ \nu)}{\varepsilon(\overline{K}^0 e^+ \nu)\, N(D^-)}$$

From Monte Carlo/Data

From fit of M_{bc} and ΔE for number of tags

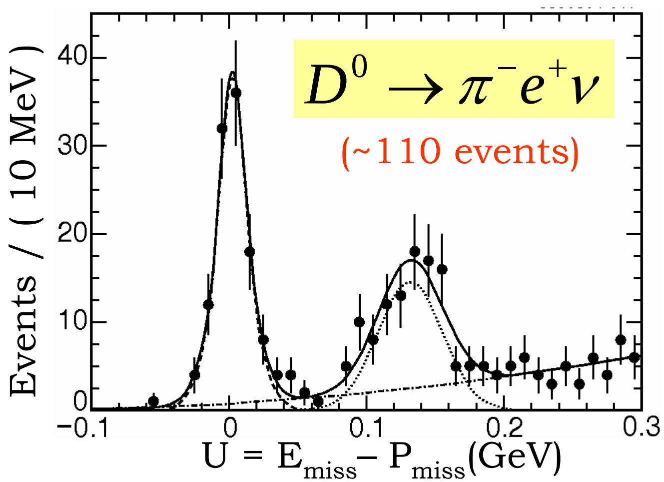
CLEO III **CLEO-c**

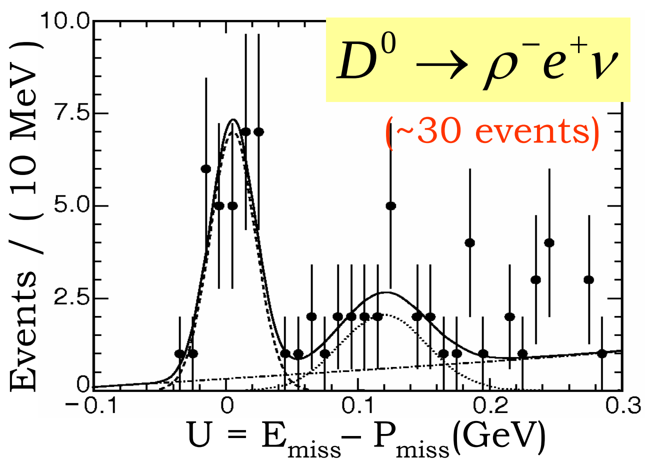


D→π l ν

Exclusive Semileptonic Decays

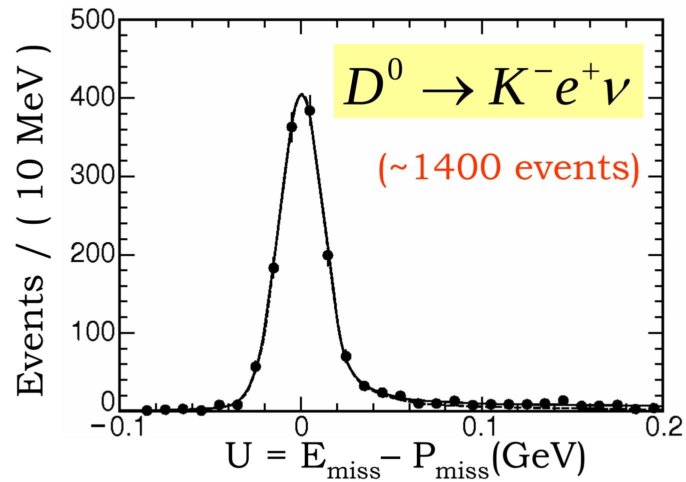
Cabibbo suppressed

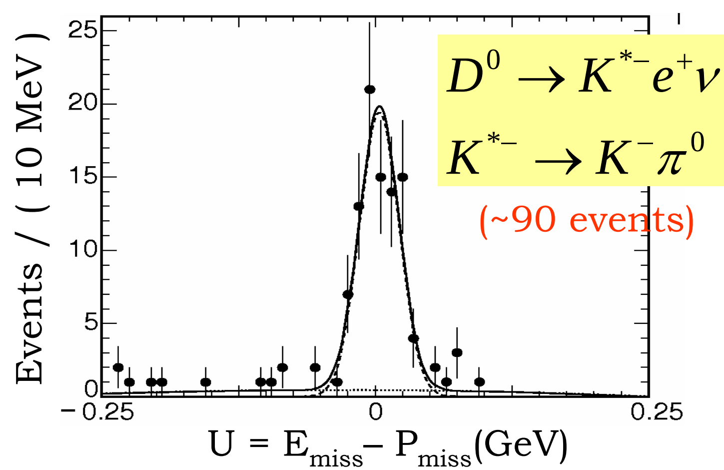




First Observation

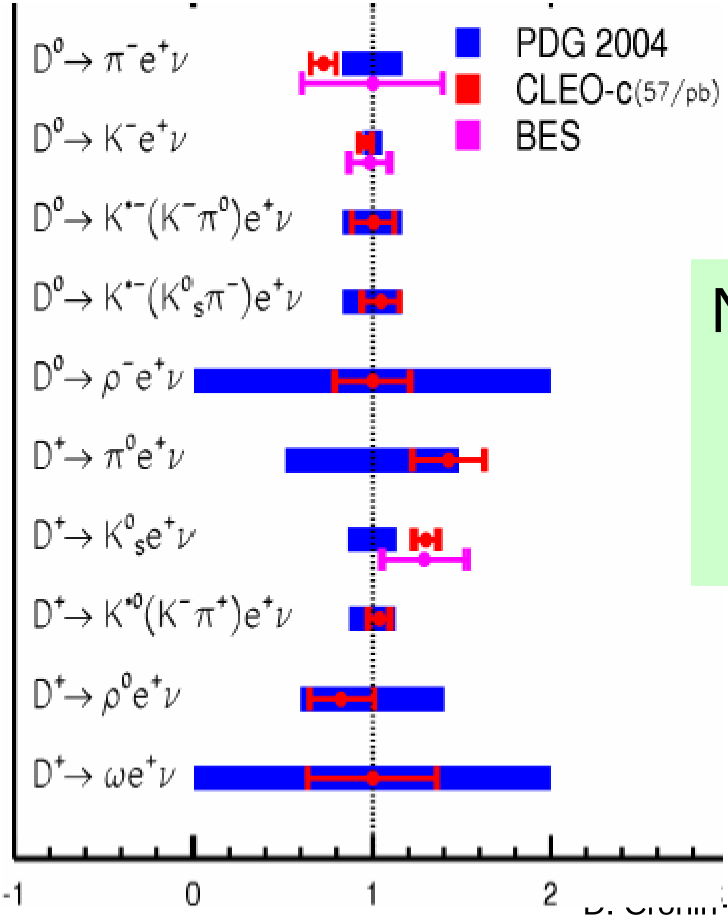
Cabibbo favored modes





Exclusive Semileptonic Decays

Results from 57/pb



PRL 95 181802 (2005) D^o

PRL 95 181801 (2005) D^+

Next:
- Form Factors from 281/pb
- $K e \nu$ and $\pi e \nu$
- q^2 resolution < 0.025 GeV^2

Inclusive Semileptonic Decays

Motivation:

→BR(D→Xlν)

→Precision measurement of lepton momentum spectrum.

→Compare $\Gamma_{sl}(D^0)/\Gamma_{sl}(D^+)$

→Test HQT with $\Gamma_{sl}(D^0)/\Gamma_{sl}(D_s)$

Technique:

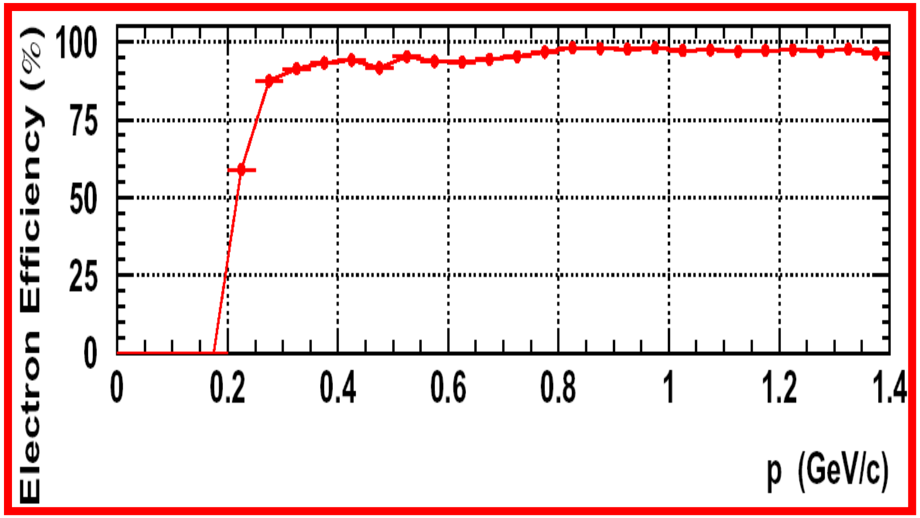
→D-Tag

→Electron ID

→Gold DTags only

- $K^-\pi^+$ and $K^-\pi^+\pi^+$

→Charge correlation

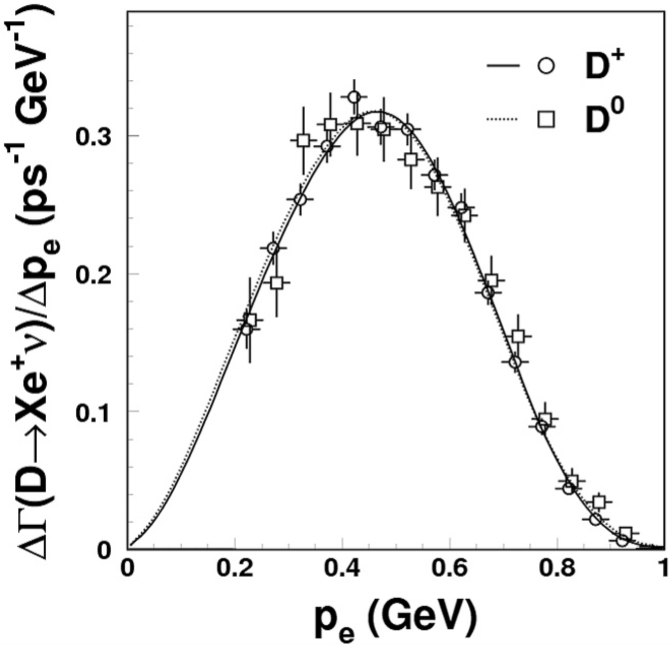


Inclusive Semileptonic Decays

From 281/pb

$\mathcal{B}$ ($D^+ \rightarrow Xe^+\nu$) = ($16.13 \pm 0.20 \pm 0.34$)%
(Σ D^+ exclusive =15.1 %)

$\mathcal{B}$($D^0 \rightarrow Xe^+\nu$) = ($6.46 \pm 0.17 \pm 0.12$)%
(Σ D^0 exclusive =6.1%)



$\Gamma_{sl}(D^+)/\Gamma_{sl}(D^0) = 0.985 \pm 0.028 \pm 0.015$

Submitted to PRL

Exclusive Semileptonic Decays Using Neutrino Reconstruction

Using the reconstructed ν and a signal K or π, reconstruct D in the usual way:

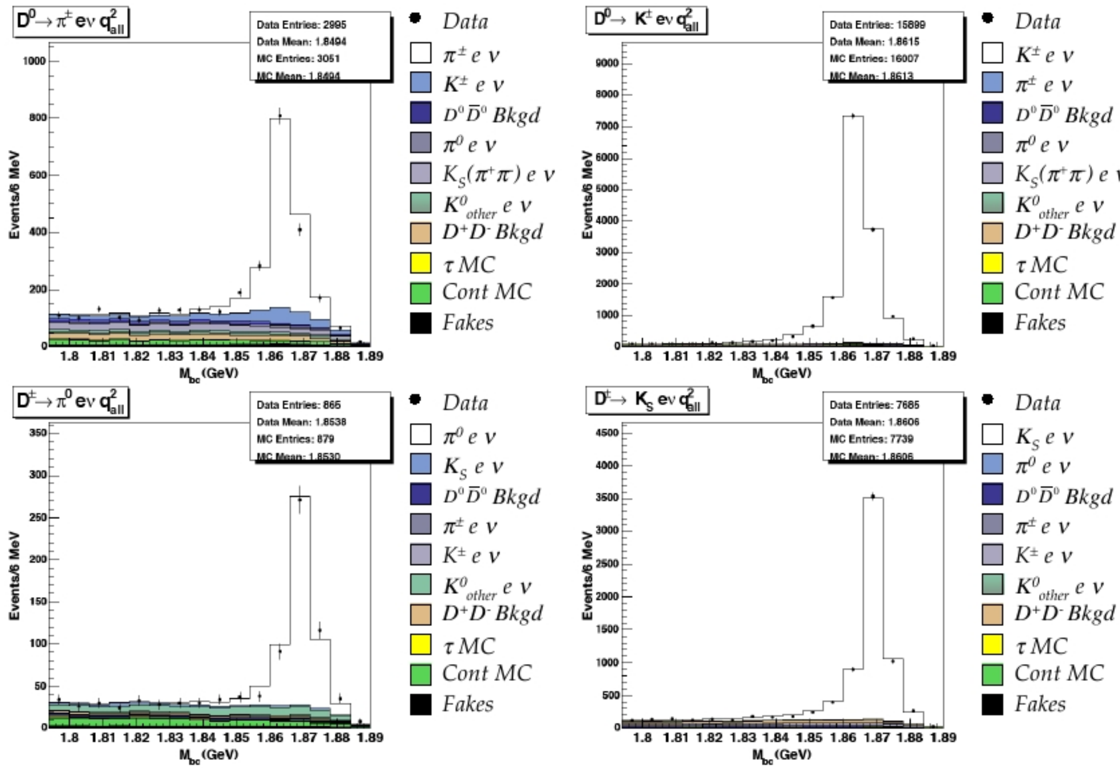
$$\Delta E = E_K + |\boldsymbol{p}_{\text{miss}}| - E_{\text{beam}}$$

$$M_{\text{bc}} = \sqrt{E^2_{\text{beam}} - (\boldsymbol{p}_K + \boldsymbol{p}_e + \boldsymbol{p}'_{\text{miss}})^2}$$

M_{bc} distributions fitted simultaneously in 5 q^2 bins to obtain $d(\text{BF})/dq^2$. Integrate to get branching fractions and fit to obtain form-factor parameters.

Exclusive Semileptonic Decays Using Neutrino Reconstruction

From 281/pb Preliminary



Yields and Branching Fractions (281pb^{-1})

D Decay	Yield (Eff. Corr.)	Yield (Uncorr.)	Br. Frac.
$D^0 \to K^{\pm} e\ \nu$	$72076 \pm 663 \pm 1230$	14395 ± 78	$3.56 \pm 0.03 \pm 0.10$ %
$D^0 \to \pi^{\pm} e\ \nu$	$6097 \pm 223 \pm 139$	1346 ± 28	$0.301 \pm 0.011 \pm 0.010$ %
$D^{\pm} \to K^0 e\ \nu$	$136736 \pm 2054 \pm 2415$	5842 ± 54	$8.70 \pm 0.13 \pm 0.27$ %
$D^{\pm} \to \pi^0 e\ \nu$	$5988 \pm 385 \pm 176$	450 ± 17	$0.381 \pm 0.025 \pm 0.015$ %

Exclusive Semileptonic Decays Form Factors and V_{cx}

From 281/pb, Preliminary

$$f^+(q^2) = \frac{f^+(0)}{\left(1 - q^2/m_{pole}^2\right)}$$

Simple Pole

Decay Mode	$\lvert V_{cx}\rvert f^+(0)$	m_{pole}
$D^0 \to \pi^\pm e\nu$	$0.146 \pm 0.004 \pm 0.003$	$1.87 \pm 0.03 \pm 0.01$
$D^0 \to K^\pm e\nu$	$0.736 \pm 0.005 \pm 0.010$	$1.98 \pm 0.03 \pm 0.02$
$D^\pm \to \pi^0 e\nu$	$0.152 \pm 0.007 \pm 0.004$	$1.97 \pm 0.07 \pm 0.02$
$D^\pm \to K^0 e\nu$	$0.719 \pm 0.009 \pm 0.012$	$1.97 \pm 0.05 \pm 0.02$

Decay Mode	$\lvert V_{cx}\rvert \pm (stat) \pm (syst) \pm (theory)$	PDG (HF) Value
$D^0 \to \pi^\pm e\nu$	$0.221 \pm 0.013 \pm 0.004 \pm 0.028$	0.224 ± 0.012
$D^0 \to K^\pm e\nu$	$1.006 \pm 0.042 \pm 0.013 \pm 0.103$	0.996 ± 0.013 (0.976 ± 0.014)
$D^\pm \to \pi^0 e\nu$	$0.235 \pm 0.016 \pm 0.006 \pm 0.029$	0.224 ± 0.012
$D^\pm \to K^0 e\nu$	$0.984 \pm 0.042 \pm 0.017 \pm 0.101$	0.996 ± 0.013 (0.976 ± 0.014)

Extract $\lvert V_{cx}\rvert$ *using* *f*(0) from LQCD

PRL 94, 011601 (2005)

Precision comparable to exclusives with tags; much independent information.

Quantum Coherence and D Decays

	Definition	Current knowledge
y	$(\Gamma_2-\Gamma_1)/2\Gamma = \mathcal{B}(CP+)-\mathcal{B}(CP-)-\Sigma\, \mathcal{B}_f\, r_f\, z_f$	0.008 ± 0.005
x	$(M_2-M_1)/\Gamma$ sensitive to NP	$x' < 0.018$
R_M	$(x^2+y^2)/2$	$< \sim 1 \times 10^{-3}$
r	$K\pi$ DCS-to-CF rel. amplitude	0.061 ± 0.001
δ	$K\pi$ DCS-to-CF relative phase	π(weak) + ? (strong)
z	$2\cos\delta$	None
w	$2\sin\delta$	None

- Hadronic rates (flavored and *CP* eigenstates) depend on mixing/DCSD.
- Semileptonic modes ($r = \delta = 0$) resolve mixing and DCSD.
- Rate enhancement factors, to leading order in x, y and r^2:

	f	$l+$	$CP+$	$CP-$
$\bar{f}$	R_M/r^2			
f	$1+r^2(2-z^2)$			
$l-$	1	1		
$CP+$	$1+rz$	1	0	
$CP-$	$1-rz$	1	2	0
X	$1+rzy$	1	$1-y$	$1+y$

Technique

- Use fitter from CLEO-c *D* absolute hadronic branching fraction analysis [**physics/0503050**].
- Based on MARK III double tag technique using:
  - single tags ($n_i \sim N_{DD}\mathcal{B}_i\varepsilon_i$) and double tags ($n_{ij} \sim N_{DD}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$)

$\Gamma \sim n/\varepsilon$

$$B_i \approx \frac{n_{ij}}{n_j}\frac{\varepsilon_j}{\varepsilon_{ij}}$$

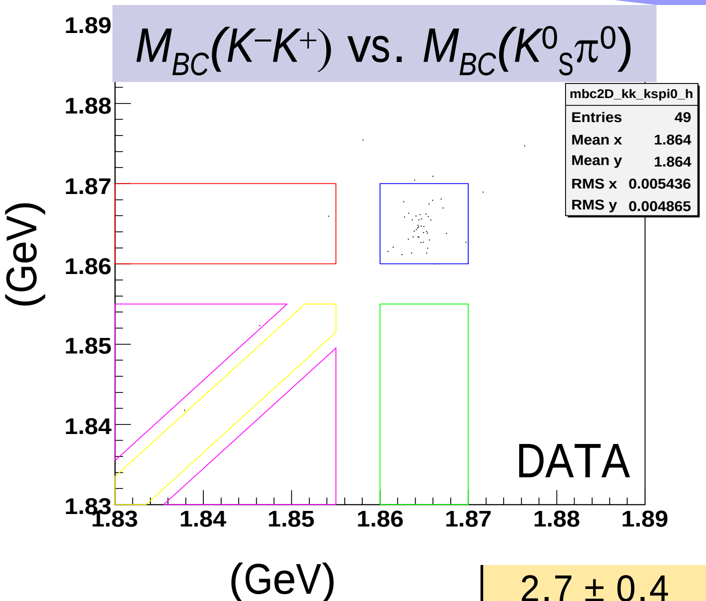
$$y + rz \approx \frac{\Gamma_{f,\bar{f}}}{4\Gamma_{\bar{f},X}}\left(\frac{\Gamma_{CP-,X}}{\Gamma_{CP-,f}} - \frac{\Gamma_{CP+,X}}{\Gamma_{CP+,f}}\right)$$

- 281 pb^{-1} = 1.0 x 10^6 C= -1 D^0D^0 pairs.
- Limiting statistics: *CP* tags—our focus is not on $\mathcal{B}$s.
- Kinematics analogous to Υ(4S)→$B\bar{B}$: identify *D* with
  - $M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$ $\quad\sigma(M_{BC}) \sim$ 1.3 MeV, x2 with π^0
  - $\Delta E = E_{beam} - E_D$ $\quad\sigma(\Delta E) \sim$ 7—10 MeV, x2 with π^0
- Procedure tested with *CP*-correlated MC.

Modes	
f	$K^-\pi^+$
	$K^+\pi^-$
CP+	K^-K^+
	$\pi^-\pi^+$
	$K^0_S\pi^0\pi^0$
CP-	$K^0_S\pi^0$
ℓ	$X^-e^+\nu$
	$X^+e^-\nu$

CLEO-c Preliminary

Hadronic DT Yields



- No-QC expectation
- Observed in data

Statistcal Unc Only

Yields	$K^-\pi^+$	$K^+\pi^-$	K^-K^+	$\pi^-\pi^+$	$K^0_S\pi^0\pi^0$	$K^0_S\pi^0$
$K^0_S\pi^0$						9.7 ± 0.5 3.0 ± 1.7
$K^0_S\pi^0\pi^0$					1.2 ± 0.2 1.0 ± 1.0	7.3 ± 0.4 19.0 ± 4.4
$\pi^-\pi^+$				1.1 ± 0.2 0.2 ± 1.4	2.2 ± 0.2 1.6 ± 1.3	5.8 ± 0.4 14.0 ± 3.7
K^-K^+			5.2 ± 0.4 -2.2 ± 1.9	4.5 ± 0.3 0.1 ± 0.9	5.7 ± 0.4 1.6 ±1.3	16.0 ± 0.6 39.6 ± 6.3
$K^+\pi^-$		2.7 ± 0.4 2.0 ± 1.4	64.7 ± 2.1 53.0 ± 7.3	30.6 ± 1.4 24.3 ± 5.0	32.3 ± 1.5 37.6 ± 6.2	85.0 ± 2.4 77.0 ± 8.8
$K^-\pi^+$	2.5 ± 0.4 2.0 ± 0.4	622 ± 7 599 ± 25	62.3 ± 2.1 70.6 ± 8.4	25.3 ± 1.3 24.0 ± 4.9	31.2 ± 1.4 38.7 ± 6.2	78.3 ± 2.3 90.4 ± 9.5

Semileptonic modes measured by searching for electron accompanying hadronic tag

Fitter Results

CLEO-c Preliminary

- Fit inputs: 6 ST, 14 hadronic DT, 10 semileptonic DT, efficiencies, crossfeeds, background branching fractions and efficiencies.
- χ^2 = 17.0 for 19 d.o.f. (C.L. = 59%).
- Fitted r^2 unphysical. If constrain to WA, cosδ = 1.08 ± 0.66 ± ?.
- Limit on C=+1 contamination:
  - Fit each yield to sum of C=-1 & C=+1 contribs.
  - Include CP+/CP+ and CP-/CP- DTs in fit.
  - No significant shifts in fit parameters.
  - C=+1 fraction = 0.06 ± 0.05 ± ?.
- Some branching fracs competitive with PDG.

Uncertainties are statistical *only*

Parameter	Value	PDG or CLEO-c
$N_{D^0 D^0}$	$(1.09 \pm 0.04 \pm ?)\times10^6$	$(1.01 \pm 0.02)\times10^6$
y	$-0.057 \pm 0.066 \pm ?$	$(8 \pm 5)\times10^{-3}$
r^2	$-0.028 \pm 0.069 \pm ?$	$(3.74 \pm 0.18)\times10^{-3}$ PDG + Belle + FOCUS
rz	$0.130 \pm 0.082 \pm ?$	
R_M	$(1.74 \pm 1.47 \pm ?)\times10^{-3}$	$< \sim1\times10^{-3}$
$\mathcal{B}(K^-\pi^+)$	$(3.80 \pm 0.29 \pm ?)\%$	$(3.91 \pm 0.12)\%$
$\mathcal{B}(K^-K^+)$	$(0.357 \pm 0.029 \pm ?)\%$	$(0.389 \pm 0.012)\%$
$\mathcal{B}(\pi^-\pi^+)$	$(0.125 \pm 0.011 \pm ?)\%$	$(0.138 \pm 0.005)\%$
$\mathcal{B}(K^0_S\pi^0\pi^0)$	$(0.932 \pm 0.087 \pm ?)\%$	$(0.89 \pm 0.41)\%$
$\mathcal{B}(K^0_S\pi^0)$	$(1.27 \pm 0.09 \pm ?)\%$	$(1.55 \pm 0.12)\%$
$\mathcal{B}(X^-e^+\nu)$	$(6.21 \pm 0.42 \pm ?)\%$	$(6.87 \pm 0.28)\%$

Summary

CLEO-c:

Update on $D^+ \rightarrow \mu^+\nu$

Limit on $D^+ \rightarrow \tau^+\nu$ (preliminary)

Exclusive semileptonic D branchings using D Tags

- two “first observations”

Inclusive semileptonic D branchings

- Ratio for charged to neutral semileptonic widths ~1

Exclusive semileptonic D branchings using n reconstruction

- CLEO-c first FF extraction and V_{cx}

Mixing parameter extractions exploiting quantum coherence

- demonstration of approach