D Semileptonic Decays at CLEO-c

- Overview of the CLEO-c data sample and technique
- Current results for D^0 and D^+ semileptonic decays
- Sensitivity of the CLEO-c program to
  - ✓ *D* semileptonic branching fractions and form factors
  - ✓ CKM matrix elements V_{cs} and V_{cd}
- Summary

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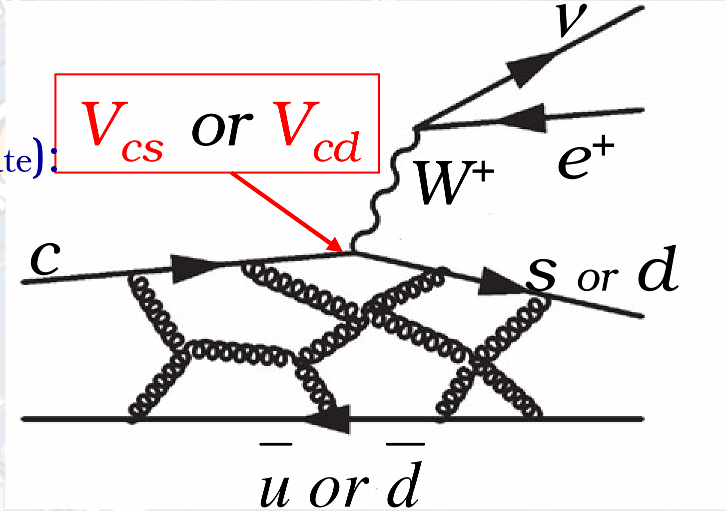
Physics topics associated with D semileptonic decays

- The matrix element for a semileptonic transition is given by

$$\mathcal{M}(M_i \to M_f l\nu) = -i\frac{G_{Fermi}}{\sqrt{2}} V_{Q_i q_f} L^\mu H_\mu$$



- Form Factors (with non-negligible contribution to the decay rate):
  - ✓ P to P transitions (1 FF):

$$\langle M_f(p_f)|V^\mu|M_i(p_i)\rangle = f_+(q^2)(p_i + p_f)^\mu$$

  - ✓ P to V transitions (3 FFs):

$$\langle M_f(p_f,\epsilon)|V^\mu - A^\mu|M_i(p_i)\rangle = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M+m_V}\epsilon^*_\nu p_{f\alpha} p_{i\beta} V(q^2) - (M+m_V)\epsilon^{*\mu} A_1(q^2) + \frac{\epsilon^*\cdot q}{M+m_V}(p_i+p_f)^\mu A_2(q^2)$$

- Measurements of the absolute branching fractions and form factors for semileptonic decays in the D system are important because they provide:
  - ✓ A test of theoretical form factor models
  - ✓ Input for validation and calibration of LQCD
  - ✓ Input on semileptonic form factors in the B system valuable for extraction of V_{ub} from, eg, $B\to\pi e\nu$
  - ✓ Direct measurements of V_{cs} and V_{cd} (with input from theory)

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The CLEO-c detector and data sample

- The main components of the CLEO-c detector were developed for *B* physics at the *Υ*(4S) in the CLEO~II and CLEO~III experiments at the Cornell Electron Storage Ring (CESR):

✓ **B = 1.0 Tesla;**

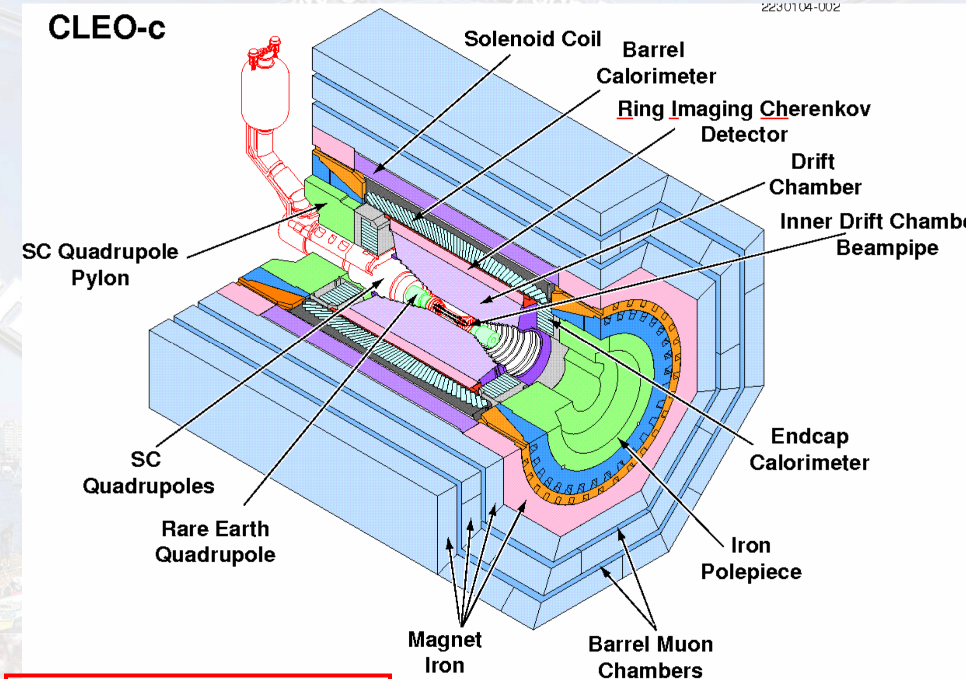
✓ **Gas: mixture of He and C_3H_8;**

✓ **Two tracking chambers: 93% of 4π, achieved δP/P ≈ 0.6% for a 1.0 GeV track;**

✓ **RICH: 80% of 4π;**

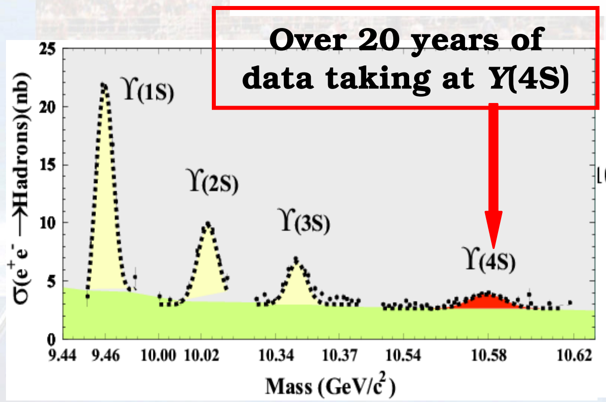
✓ **E/M crystal calorimeter: 93% of 4π, δE/E ≈ 2.0% (4.0)% for a 1.0 GeV (100 MeV) photon;**

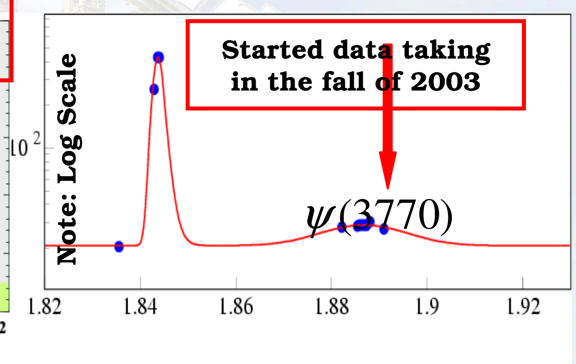
✓ **Muon Chambers: Proportional chambers at 3, 5 and 7 λ_I .**



Hadronic particle identification is based on the dE/dx and RICH information (over 90% efficient and fake rates below 5%)

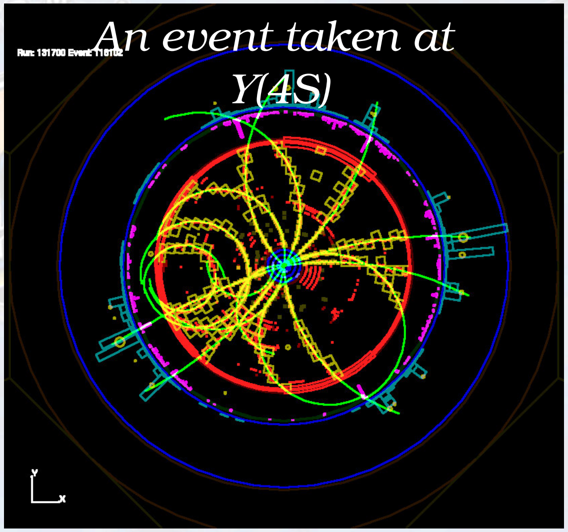
Electron identification uses the dE/dx, RICH and CC information (~95% efficient above 300 MeV with fake rates below ~0.2%)

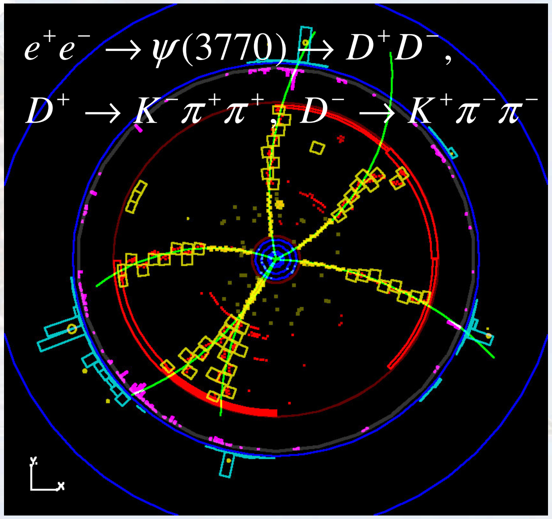




The CLEO-c detector and data sample (2)

- Analyzed data sample: ~57/pb collected with the CLEO-c detector during the running period of October, 2003, through January, 2004 at the $\psi(3770)$ resonance
- The 57/pb sample contains about 2.0×10^5 and 1.6×10^5 of neutral and charged D pairs respectively
- The generic MC sample corresponds to about 50 times the luminosity of the data sample
- The $\psi(3770)$ decays to a pair of D mesons and no extra particles ($E_D = E_{\text{beam}}$, $\vec{P}_D = -\vec{P}_{\bar{D}}$).
- Events at $\psi(3770)$ have about 50% of track and photon multiplicities compared to those at the $Y(4S)$ energy (figures on the left) $\Rightarrow$ small combinatorial background
- Hermeticity of the CLEO-c detector and large D tagging branching fractions lead to high D tagging efficiency





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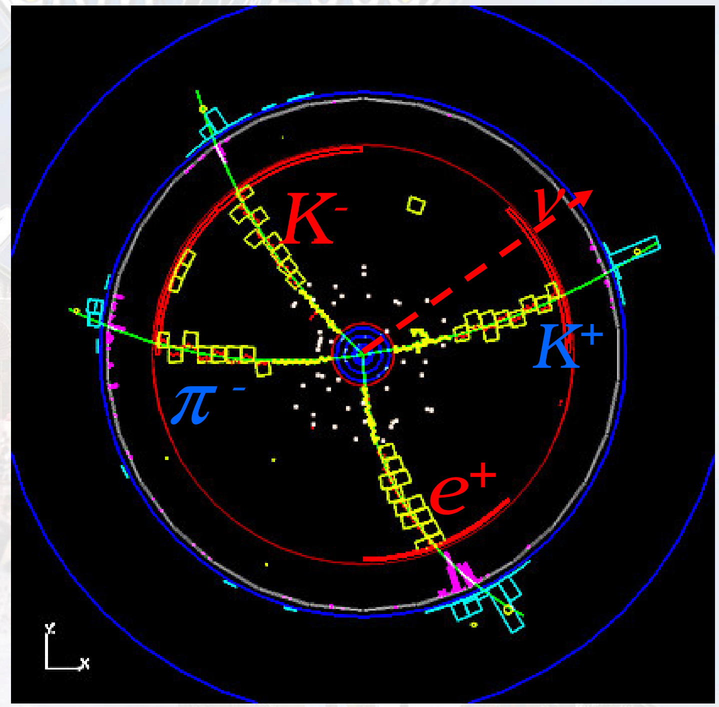
Overview of the analysis

- Reconstruct one of the two *D*'s in a hadronic decay channel. It is called a tagging *D* or a tag. Two key variables in the tagging *D* reconstruction are:
  - ✓ $M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$
  - ✓ $\Delta E = E_{beam} - E_{candidate}$
- Reconstruct from the remaining tracks and showers the observable particles in the final state of a semileptonic decay.
- Define an observable that can be used to separate signal and background as $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$, where E_{miss} and $\boldsymbol{P}_{miss}$ are the missing energy and momentum in the event, approximating the neutrino *E* and ***P***. The signal peaks at zero in *U*.
- Account for the background in the signal region of *U*.
- Account for systematic effects.

$\psi(3770) \to D^0\, \overline{D}{}^0$

$\overline{D}{}^0 \to K^+\pi^-,\ D^0 \to K^- e^+ \nu$



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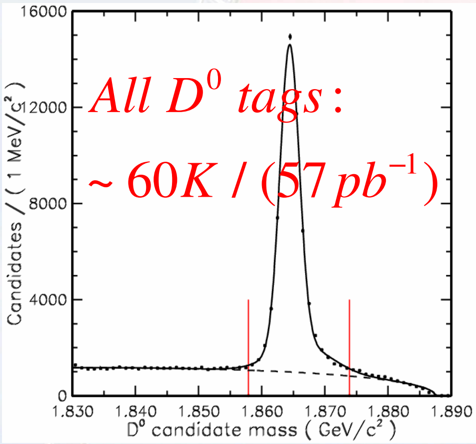
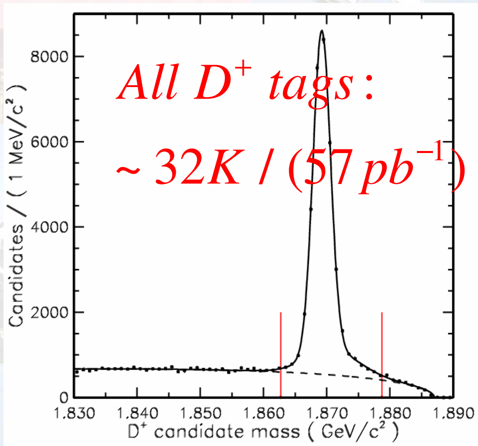
D^0 and D^+ tag yields in 57/pb of DATA

D^0 Decay Mode	$\mathcal{B}$ (%) PDG
$D^0 \to K^-\pi^+$	(3.80 ± 0.09)
$D^0 \to K^-\pi^+\pi^0$	(13.1 ± 0.9)
$D^0 \to K^-\pi^+\pi^0\pi^0$	
$D^0 \to K^-\pi^+\pi^+\pi^-$	(7.46 ± 0.31)
$D^0 \to \overline{K^0}\pi^0$	(2.28 ± 0.22)
$D^0 \to \overline{K^0}\pi^+\pi^-$	(5.92 ± 0.35)
$D^0 \to \overline{K^0}\pi^+\pi^-\pi^0$	(10.8 ± 1.3)
$D^0 \to K^+K^-$	(0.41 ± 0.01)

D^+ Decay Mode	$\mathcal{B}$ (%) PDG
$D^+ \to \overline{K^0}\pi^+$	(2.77 ± 0.18)
$D^+ \to K^-\pi^+\pi^+$	(9.1 ± 0.6)
$D^+ \to \overline{K^0}\pi^+\pi^0$	(9.7 ± 3.0)
$D^+ \to K^-\pi^+\pi^+\pi^0$	(6.4 ± 1.1)
$D^+ \to \overline{K^0}\pi^+\pi^+\pi^-$	(7.0 ± 0.9)
$D^+ \to K^+K^-\pi^+$	(0.9 ± 0.1)



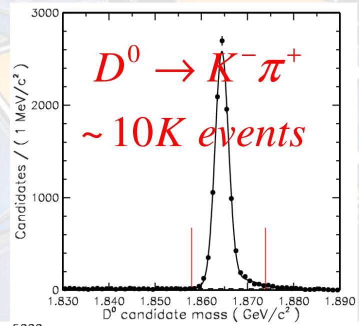


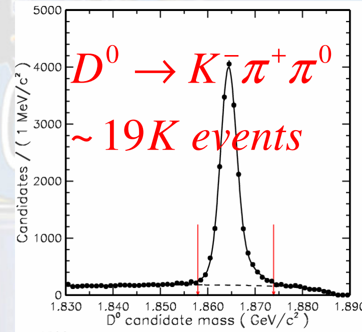
~30% tagging efficiency

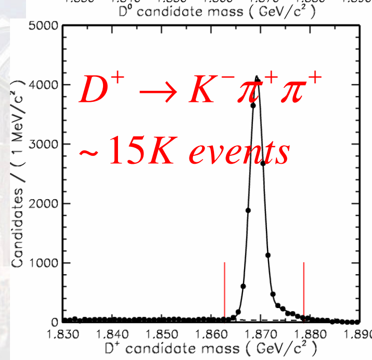
~20% tagging efficiency

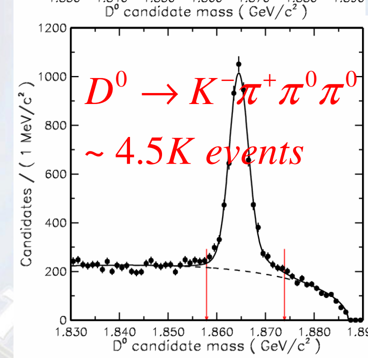
Tagging creates a beam of D mesons with known momentum

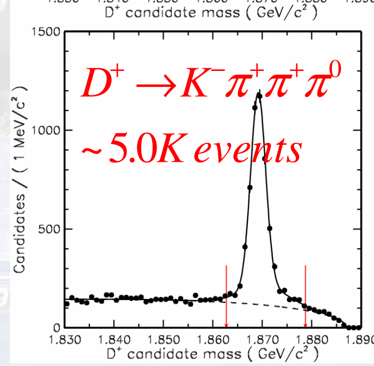
Examples of Mbc for tag modes in the data

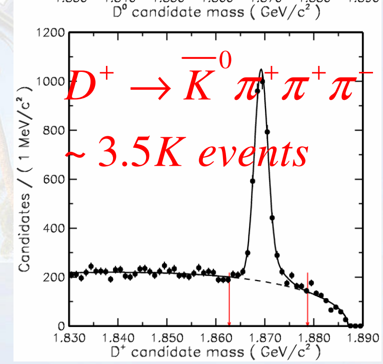












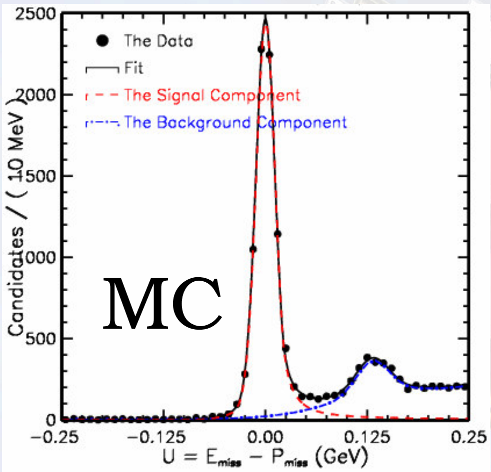
Reconstruction of semileptonic decays

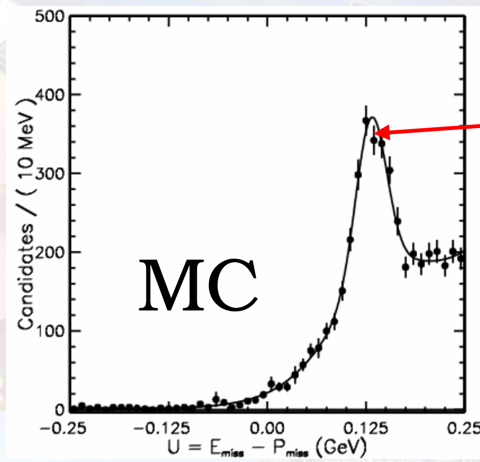
- Semileptonic modes listed in the table are reconstructed

	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(K^0_S \pi^-) e^+ \nu$
5.	$D^0 \to \rho^- e^+ \nu$
6.	$D^+ \to \pi^0 e^+ \nu$
7.	$D^+ \to \bar{K}^0 e^+ \nu$
8.	$D^+ \to \bar{K}^{*0}(K^- \pi^+) e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \omega(\pi^+ \pi^- \pi^0) e^+ \nu$

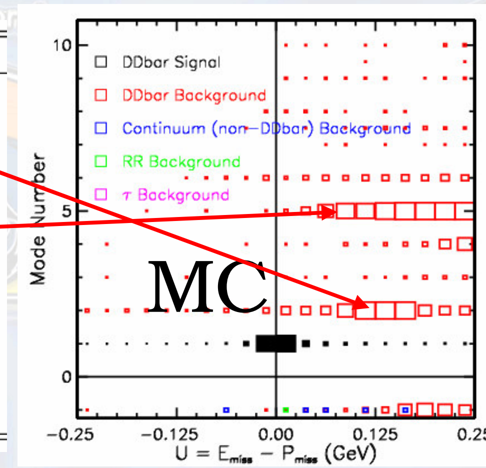
- Electron identification:
  - ✓ Likelihood function built from E/P, dE/dX and RICH information (~95% efficient above 300 MeV with fake rates below ~0.2%)
  - ✓ Bremsstrahlung photons for electrons are recovered
- K^*, ρ, and ω have 100, 150 and 20 MeV mass window cuts respectively
- Events with extra tracks are vetoed
- The crossing angle is accounted for and the 4-mometum of D is approximated by $(E_{beam}, -\sqrt{E^2_{beam} - m^2_D}\, \hat{p}_{D\,tag})$
- One entry per U plot per D tag mode is chosen based on resonance and π^0 masses
- Semileptonic decays peak at zero in $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$
- Semileptonic branching ratio are obtained as $B(D^+ \to \overline{K}^0 e^+ \nu) = \dfrac{N(\overline{K}^0 e^+ \nu)}{\varepsilon^*(\overline{K}^0 e^+ \nu) N(D^-_{tag})}$

Example for $D^0 \to \pi^- e^+ \nu$



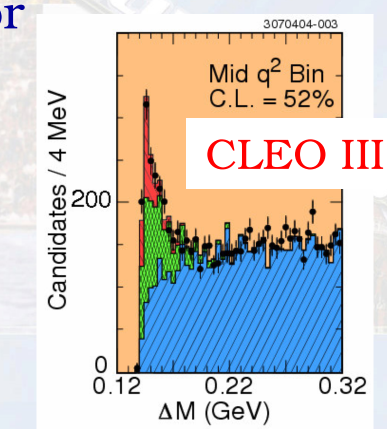


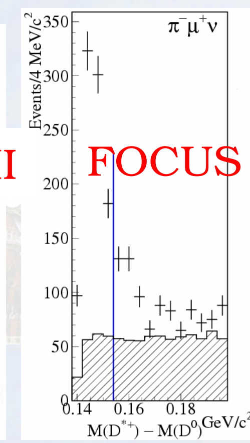
	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\bar{K}^0 \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \bar{K}^0 e^+ \nu$
7.	$D^+ \to \bar{K}^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \omega(\pi^+ \pi^- \pi^0) e^+ \nu$



- Background is small and peaks outside the signal region (kinematic separation)
- Most background comes from cross-feed among *D* semileptonic decays

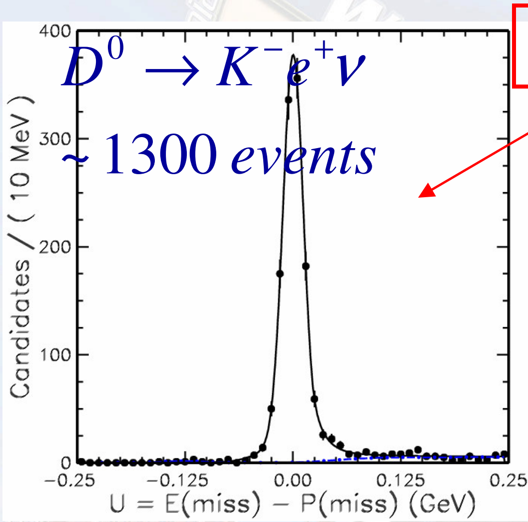
- In other experimental configurations (at the Y(4S) or fix target expts) the momentum of the parent *D* meson is unmeasured, which leads to poorer separation between signal and background
- For example in (CLEO, PRL **94**, 011802 (2005)) and (FOCUS, PL B **607**, 51 (2005)), to reduce background, $D^0 \to \pi^- e^+(\mu^+)\, \nu$ is tagged with π_{slow} : $D^{*+} \to D^0\, \pi_{slow}$
- Fits are made to $\Delta M \equiv M(D^{*+}) - M(D^0)$ in bins of q^2 (CLEO) or simultaneously with q^2 (FOCUS)

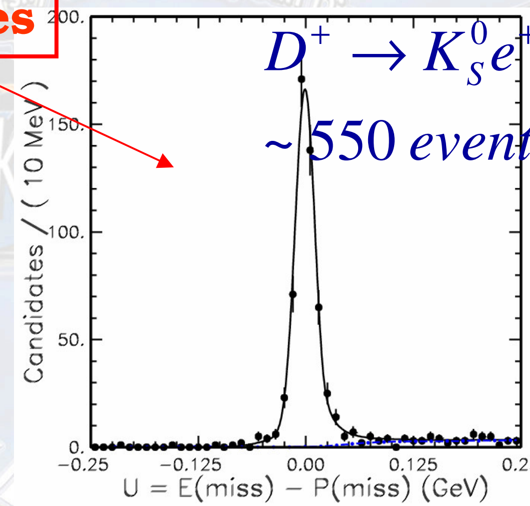




U distributions for $P \to P$ semileptonic transitions (DATA)

Cabibbo favored modes

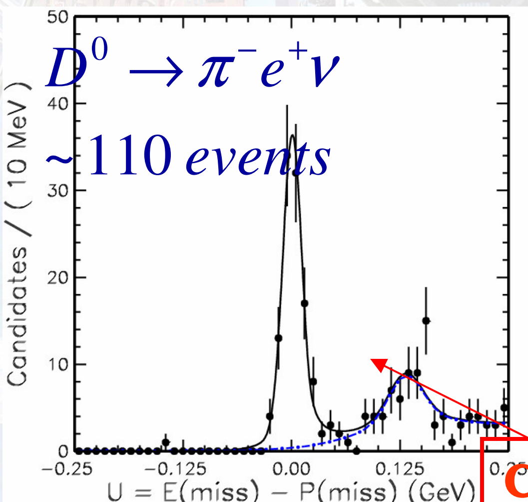


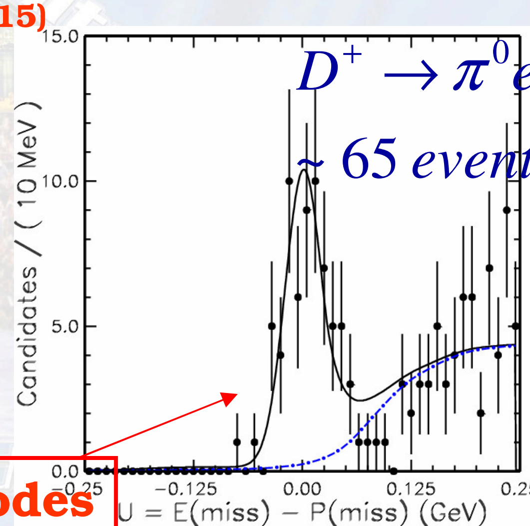


PRELIMINARY

(CLNS 05-1906 and CLNS 05-1915)

(*to be submitted to PRL*)

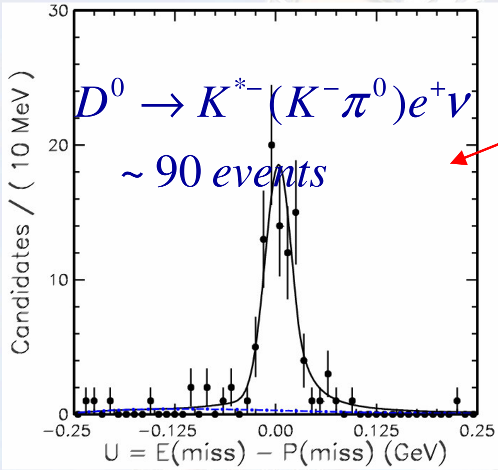


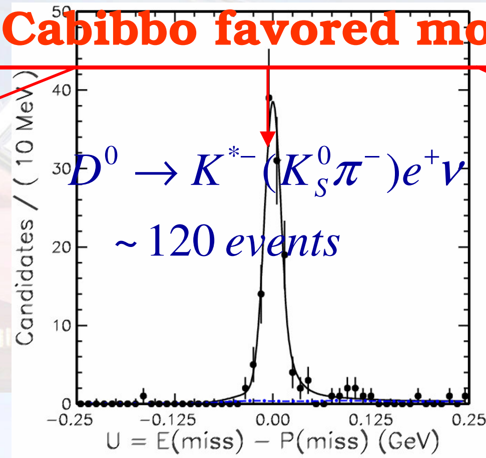


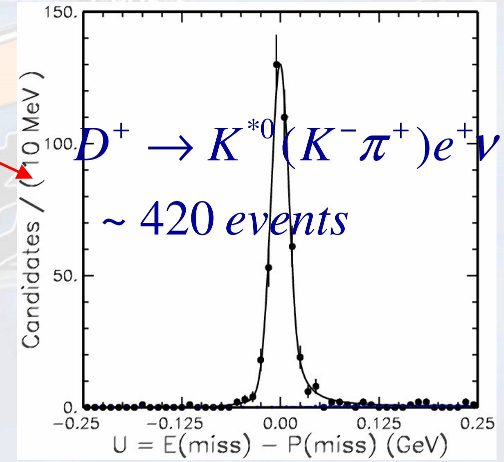
Cabibbo suppressed modes

U distributions for $P \to V$ semileptonic transitions (DATA)

Cabibbo favored modes

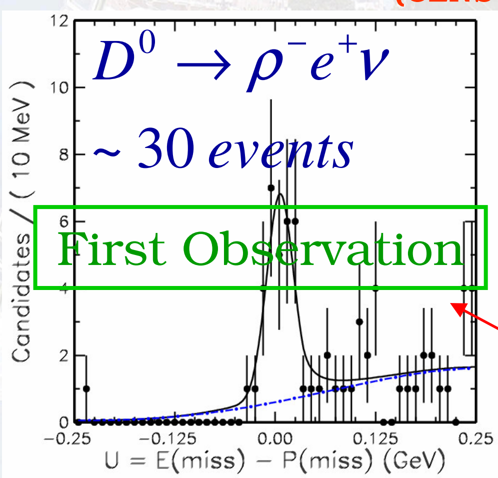


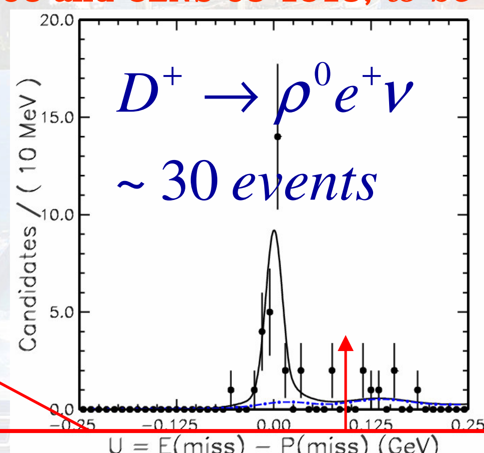


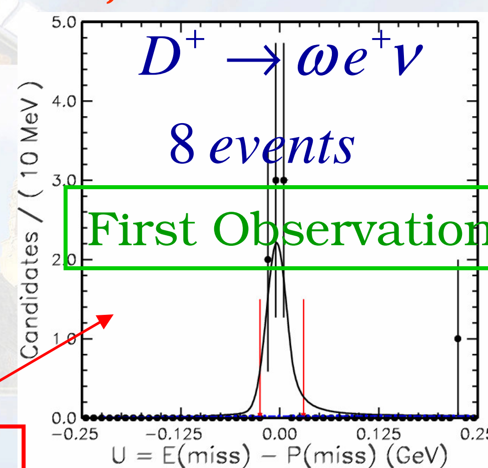


PRELIMINARY

(CLNS 05-1906 and CLNS 05-1915, *to be submitted to PRL***)**







Cabibbo suppressed modes

Systematic uncertainties

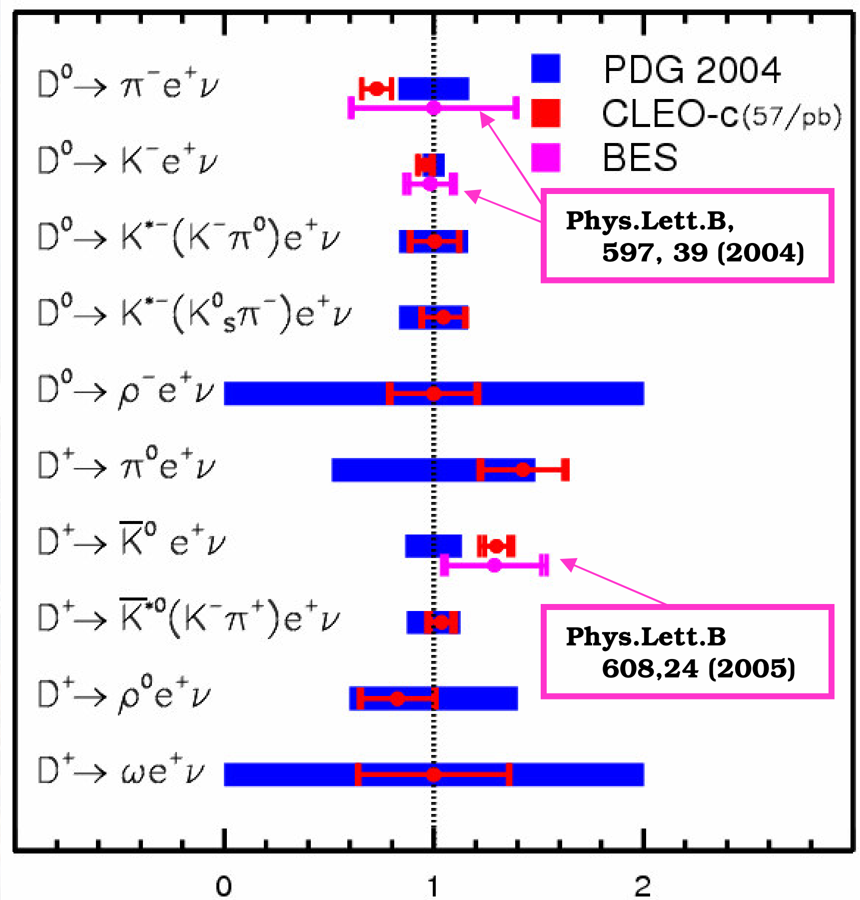
Sources of systematic uncertainty include:

- ✓ Electron and hadron identification efficiencies and fake rates
- ✓ Track, π^0 and *K*s finding efficiencies
- ✓ Number of *D* tags
- ✓ Simulation of form factors
- ✓ Signal shape and background shapes in fitting
- ✓ Simulation of FSR
- ✓ Non-resonant background the P to V modes
- ✓ Simulation of spurious tracks

- ❑ Total systematic uncertainty ranges from about 3.0% to 8.0% depending on the mode
- ❑ Many systematic uncertainties are measured in the data and therefore will decrease with a larger data set ($\sim \sqrt{L}$).

Preliminary Results (1)

	Decay Mode	$\mathcal{B}$ (%) (CLEO-c/(57/pb))	$\mathcal{B}$ (%) (PDG-04)
1.	$D^0 \to \pi^- e^+ \nu$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
2.	$D^0 \to K^- e^+ \nu$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
3.	$D^0 \to K^{*-}(K^-\pi^0) e^+ \nu$	$2.16 \pm 0.24 \pm 0.11$	2.15 ± 0.35
4.	$D^0 \to K^{*-}(K^0_S\pi^-) e^+ \nu$	$2.25 \pm 0.21 \pm 0.11$	2.15 ± 0.35
5.	$D^0 \to \rho^- e^+ \nu$	$0.19 \pm 0.04 \pm 0.02$	—
6.	$D^+ \to \pi^0 e^+ \nu$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
7.	$D^+ \to \bar{K}^0 e^+ \nu$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
8.	$D^+ \to \bar{K}^{*0}(K^-\pi^+) e^+ \nu$	$5.70 \pm 0.28 \pm 0.25$	5.5 ± 0.7
9.	$D^+ \to \rho^0(\pi^+\pi^-) e^+ \nu$	$0.21 \pm 0.04 \pm 0.02$	0.25 ± 0.10
10.	$D^+ \to \omega(\pi^+\pi^-\pi^0) e^+ \nu$	$0.17 \pm 0.06 \pm 0.01$	—

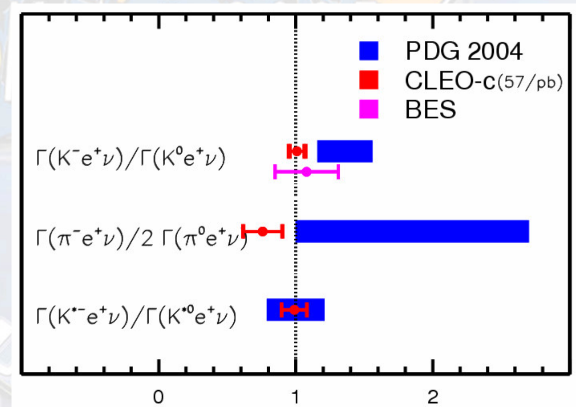


- $D^0 \to \pi^- e^+ \nu$ ($D^+ \to K^0 e^+ \nu$) is measured to be lower (higher) than the PDG value
- $B(D^0 \to \pi^- e^+ \nu)/B(D^0 \to K^- e^+ \nu) = (7.6 \pm 0.8 \pm 0.2) \times 10^{-2}$ compares favorably with the CLEO III result of $(8.2 \pm 0.6 \pm 0.5) \times 10^{-2}$ (CLEO, PRL **94**, 011802 (2005)) and the results of $(7.4 \pm 0.8 \pm 0.7) \times 10^{-2}$ by FOCUS (FOCUS, PLB, 607, 51 (2005)). The PDG-04 value for this ratio is 0.101 ± 0.017.
- The following two modes $D^0 \to \rho^- e^+ \nu$ and $D^+ \to \omega e^+ \nu$ are observed for the first time
- This set of results allows to test a variety of relations among semileptonic D^0 and D^+ decay widths (some shown on the next slide).

Preliminary Results (2)

- The widths of the isospin conjugate exclusive semileptonic decay modes are expected to be equal due to the isospin invariance of the hadronic current. We find:

Ratio	Expected Value	Measured Value	PDG-04
$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu)}$	1.0	$1.01 \pm 0.05 \pm 0.04$	1.36 ± 0.20
$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{2\Gamma(D^+ \to \pi^0 e^+ \nu)}$	1.0	$0.76^{+0.14}_{-0.11} \pm 0.04$	$1.5^{+1.2}_{-0.5}$
$\frac{\Gamma(D^0 \to K^{*-})}{\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu)}$	1.0	$0.99 \pm 0.09 \pm 0.03$	1.00 ± 0.21
$\frac{\Gamma(D^0 \to \rho^- e^+ \nu)}{2\Gamma(D^+ \to \rho^0 e^+ \nu)}$	1.0	$1.19^{+0.42}_{-0.31} \pm 0.07$	—



- Summing up all exclusive semileptonic branching fractions measured in this analysis we find:

$$\sum B(D^0_{excl\ semil}) = (6.1 \pm 0.2 \pm 0.2)\% \quad and \quad \sum B(D^+_{excl\ semil}) = (15.2 \pm 0.5 \pm 0.6)\%$$

These are smaller than the PDG-04 inclusive semileptonic branching fractions:

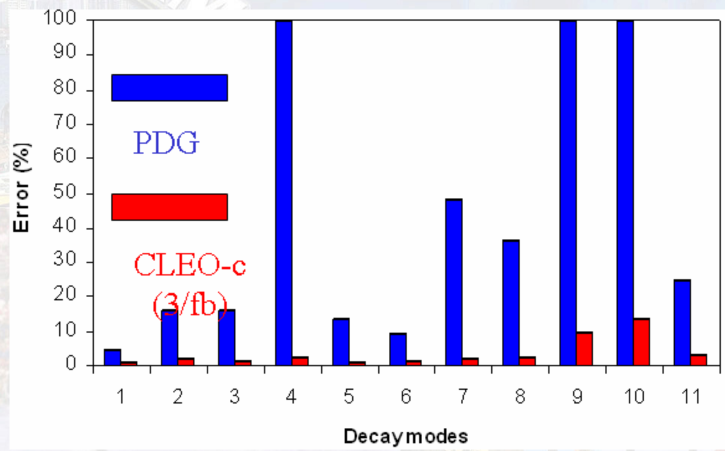
$$B(D^0_{incl\ semil}) = (6.9 \pm 0.3)\% \quad and \quad B(D^+_{incl\ semil}) = (17.2 \pm 1.9)\%$$

which is indicative that new semileptonic modes await discovery.

CLEO-c reach (1)

- The ~57/pb data sample collected in fall-2003/winter-2004 by the CLEO-c detector already gives measurements of absolute branching fractions for all modes considered today with uncertainties smaller than the uncertainties in PDG-2004.
- The goal is collect 50 times more (~3/fb) data at the $\psi(3770)$ as well as ~3/fb of data at E_{cm} ~ 4140 MeV for studies of D_s mesons.
- This CLEO-c data will significantly improve knowledge of the branching fractions of charm mesons (CLNS 01/1742):

1) $D^0 \to K^- e^+ \nu$ 2) $D^0 \to K^{*-} e^+ \nu$
3) $D^0 \to \pi^- e^+ \nu$ 4) $D^0 \to \rho^- e^+ \nu$
5) $D^+ \to \overline{K}^0 e^+ \nu$ 6) $D^+ \to \overline{K}^{0*} e^+ \nu$
7) $D^+ \to \pi^0 e^+ \nu$ 8) $D^+ \to \rho^0 e^+ \nu$
9) $D_s \to K^0 e^+ \nu$ 10) $D_s \to \overline{K}^{*0} e^+ \nu$
11) $D_s \to \phi e^+ \nu$



- Knowledge of absolute semileptonic branching fractions is needed measurements of form factor shapes and form factor absolute normalizations

CLEO-c reach (2)

(predictions for 3/fb, CLNS 01/1742)

- An important aspect of the CLEO-c program is testing the LQCD predictions as well as predictions of models or other theories for semileptonic form factors
- CLEO-c semileptonic events will provide precision measurements of semileptonic decay form factor shapes and ratios:
  - ✓ *P* to *P*: $f_+(q^2) = f_+(0)\, e^{\alpha q^2}, \quad \frac{\delta\alpha}{\alpha} \approx 2-3\%, \quad for \;\; D^0 \to \pi^-(K^-)e^+\nu$
  - ✓ *P* to *V*: $R_V = \frac{V(0)}{A_1(0)} \approx 2-3\% \quad and \quad R_2 = \frac{A_2(0)}{A_1(0)} \approx 2.5-3.5\% \;\; for \;\; D^+ \to \rho^0(\overline{K}^{*0})e^+\nu$
- Theory (e.g., LQCD) predictions for the absolute normalization of form factors (e.g., $f_+(0)$) can be tested if one assumes the unitarity of the CKM matrix (Vcs and Vcd become known to 0.1% and 1.0% respectively)
- Theory can be tested further without uncertainties associated with the CKM couplings or assumptions of the CKM unitarity using the following ratio of decay rates $\Gamma(D^+ \to \pi(K) l\nu) \,/\, \Gamma(D^+ \to l\nu)$
- Once theory is tested, its predictions can be used for extraction of CKM matrix elements, for example for Vcs:

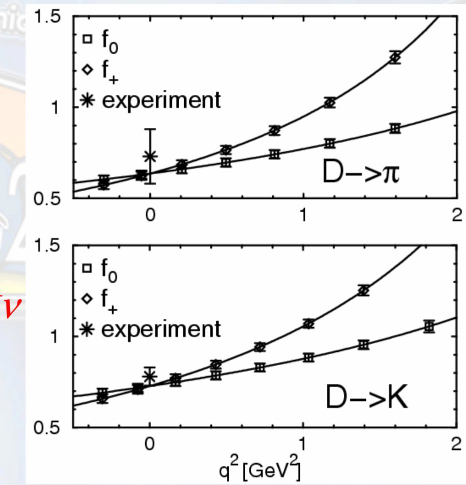
$$\Gamma(D^0 \to K^- e^+\nu) = \frac{B(D^0 \to K^- e^+\nu)}{\tau(D^0)} = \gamma_s |V_{cs}|^2 \;\Rightarrow\; \frac{\delta V_{cs}}{V_{cs}} = \sqrt{\left(\frac{\delta\Gamma}{2\Gamma}\right)^2 + \left(\frac{\delta\gamma_s}{2\gamma_s}\right)^2}$$

theory

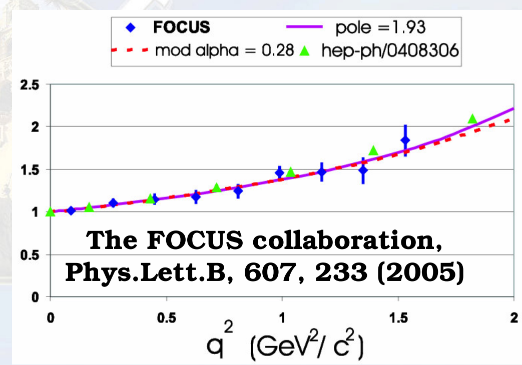
experiment

- Using future CLEO-c measurements of branching fractions for $D \to \pi e\nu$ and $D \to K e\nu$ (1.2% and 1.5% uncerts) and the world averages for *D* meson lifetimes, and assuming theory errors on γ_s and γ_d, of 3%, the following uncertainties for *Vcs* and *Vcd* from a 3/fb data sample are within reach:

$$\frac{\delta V_{cs}}{V_{cs}} \approx 1.6\% \quad and \quad \frac{\delta V_{cd}}{V_{cd}} \approx 1.7\%$$



First unquenched LQCD calculation for $D \to \pi/K e\nu$ (PRL **94**, 011601 (2005))



The FOCUS collaboration, Phys.Lett.B, 607, 233 (2005)

Summary and Outlook

- I have shown preliminary results for D^0 and D^+ exclusive semileptonic decays from the first ~57/pb data sample collected at the $\psi(3770)$ in fall-03/winter-04 at CLEO-c. These results will be submitted for publication during the next few weeks.
- The CLEO-c detector is functioning (at lower energies) as expected
- It is hoped to obtain first results for form factors (in $D \to \pi e \nu$ and $D \to K e \nu$) for the summer conferences using a larger (~285/pb) data set.
- The goal is to collect 3/fb at the $\psi(3770)$ and the same amount of data at E_{cm} ~ 4140 MeV over the next three years. This data sample will play an important role in particle physics as
  - ✓ validation and calibration precision data for LQCD (a theory capable of solving strongly coupled field theory equations) as well as for models and other theories
  - ✓ input data to the *B*-factories and other experiments increasing their potential
- The CLEO-c detector is collecting more data at this moment.