Exclusive Semileptonic D and B Decays from CLEO

- Results for exclusive D semileptonic decays from CLEO-c
- Overview of an exclusive $B \to \pi / \rho \, l \, \nu$ analysis

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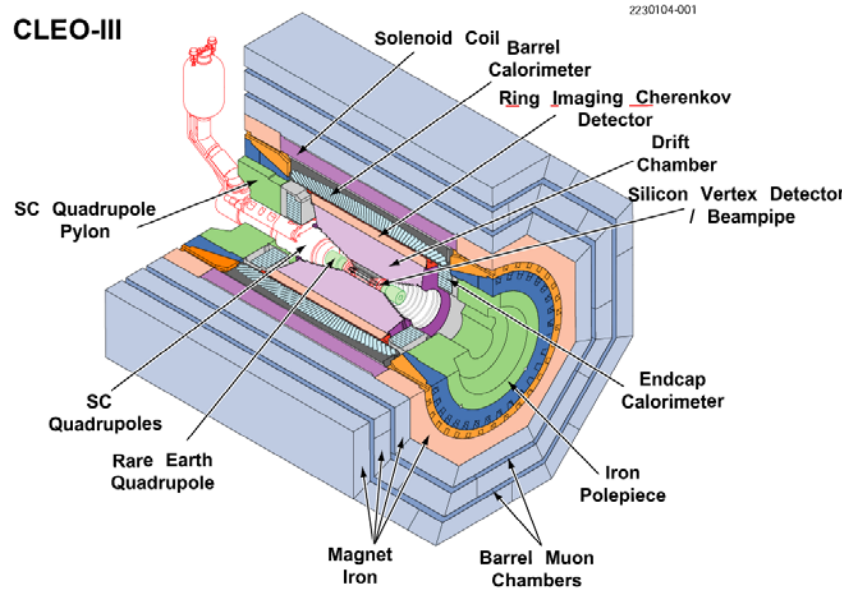
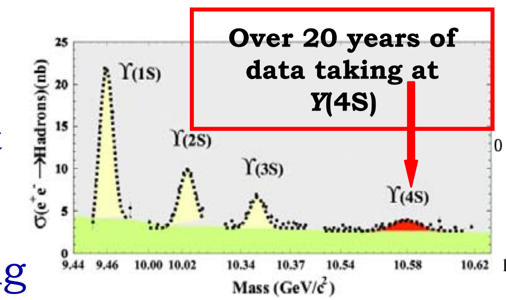
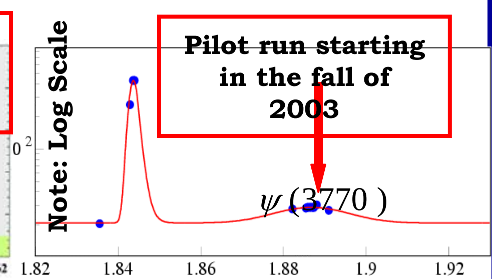
The CLEO detector and data samples

- The CLEO detector was developed for *B* physics at the Υ(4S) at the Cornell Electron Storage Ring (CESR):
  - ✓ B-field: 1.5 T
  - ✓ Gas (drift chamber): He and C_3H_8
  - ✓ Tracking: 93% of 4π, δP/P≈0.6% for a 1.0 GeV track
  - ✓ Hadron particle ID: RICH (80% of 4π) and dE/dx
  - ✓ E/M crystal calorimeter: 93% of 4π, δE/E ≈ 2%(4%) for a 1.0 GeV (100 MeV) photon
  - ✓ Muon Chambers: Proportional chambers at 3, 5 and 7 λ_I.



- Transitions from CLEO III to CLEO-c:
  - ✓ B-field: 1.5 T → 1.0 T
  - ✓ Silicon vtx detector → low mass stereo drift chamber





- CESR is a symmetric e^+e^- collider operating in the region of the Υ resonances. Transition from CESR to CESR-c:
  - ✓ 12 wigglers were installed

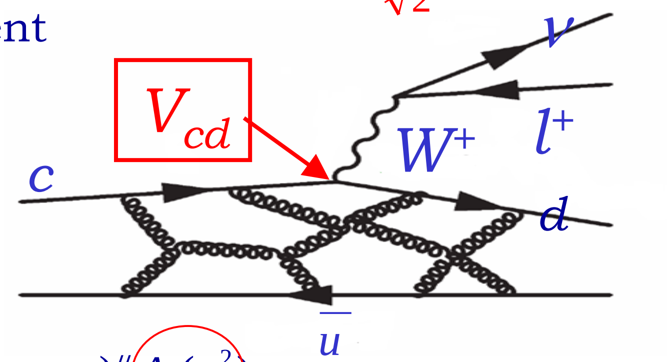
~16 fb^{-1} at the Υ(4S)

~56 pb^{-1} at the ψ(3770) in fall-03/winter-04 (now have 280 pb^{-1})

Semileptonic decays

- Semileptonic decays are a principal process for measuring the CKM matrix elements:

$$M(D^0 \to \pi^- l^+ \nu) = -i\frac{G_{Fermi}}{\sqrt{2}} V_{cd}\, L_\mu\, H^\mu$$



- Strong interaction effects reside in the hadronic current only and are parameterized by form factors (assuming charged lepton mass is zero):
  - ✓ for P to P transitions:

$$H^\mu = f_+(q^2)(p_i + p_f)^\mu$$

  - ✓ for P to V transitions three form factors are needed:

$$H^\mu = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M_D + m_V} e^*_\nu p_{f\alpha} p_{i\beta} V(q^2) - (M_D + m_V) e^{*\mu} A_1(q^2) + \frac{e^* \cdot q}{M + m_V}(p_i + p_f)^\mu A_2(q^2)$$

- The theory must predict the absolute normalization of form factors for the CKM matrix element measurements:

theory

$$\Gamma(D^0 \to \pi^- e^+ \nu) = \frac{B(D^0 \to \pi^- e^+ \nu)}{\tau(D^0)} = \gamma\, |V_{cd}|^2 \Rightarrow \frac{\delta V_{cd}}{V_{cd}} = \sqrt{\left(\frac{\delta\Gamma}{2\Gamma}\right)^2 + \left(\frac{\delta\gamma}{2\gamma}\right)^2}$$

experiment

- In charm semileptonic decays $|V_{cs}|$ and $|V_{cd}|$ are tightly constrained by the unitarity of the CKM matrix. Therefore measurements of charm semileptonic decay rates and form factors rigorously test the theory (e.g., LQCD and LCSR).

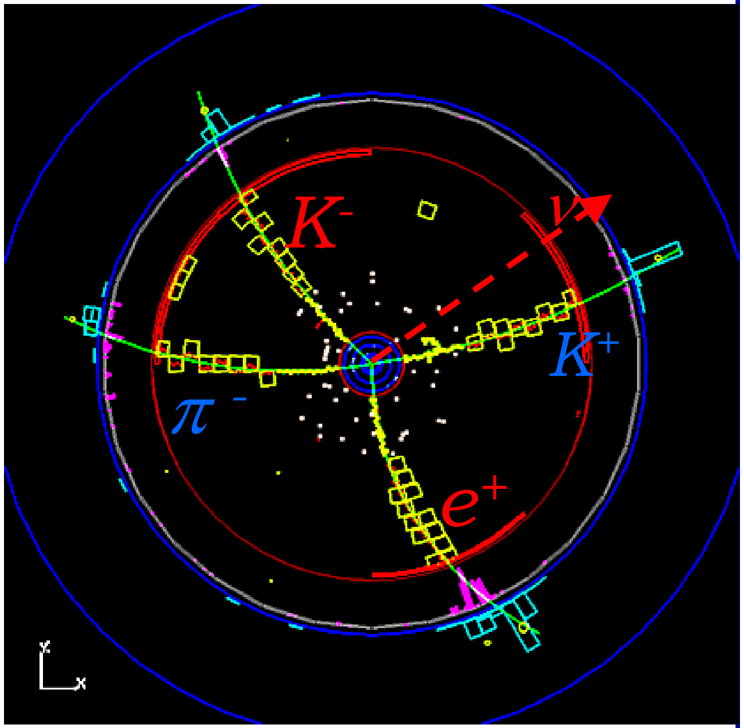
- Testing theoretical predictions for semileptonic form factors is an important task of the CLEO-c program underway at CESR (Ref.: CLNS 01/1742).

D semileptonic decays at $\psi(3770)$

- The $\psi(3770)$ is about 40 MeV above the DD pair production threshold and decay predominantly to DD pairs ($\vec{P}_D = -\vec{P}_{\bar{D}}$)
- One of the two D's is reconstructed in a hadronic decay channel. It is called a tag. Two key variables in the tag reconstruction:
  - ✓ $M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$
  - ✓ $\Delta E = E_{beam} - E_{candidate}$
- From the remaining tracks and showers the semileptonic decay is reconstructed
- $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$ is used to separate signal from backgrond, where E_{miss} and $\boldsymbol{P}_{miss}$ are the missing energy and momentum approximating the neutrino E and $\boldsymbol{P}$. The signal peaks at zero in U.
- Account for the background in the signal region of U. Account for systematic uncertainties.

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

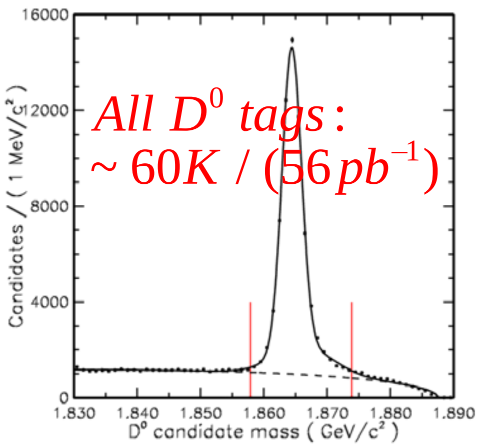
$\bar{D}^0 \to K^+\pi^-$, $D^0 \to K^- e^+ \nu$

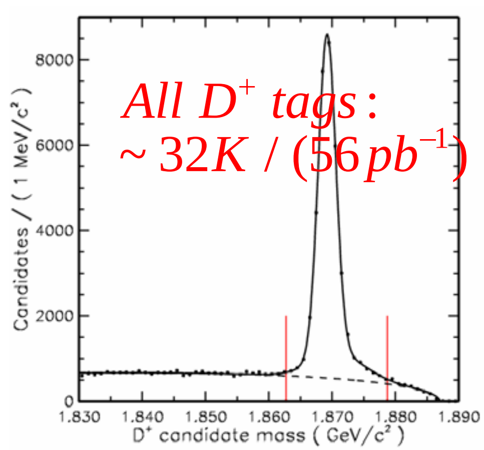


D^0 and D^+ tag yields in 56 pb^{-1} of DATA

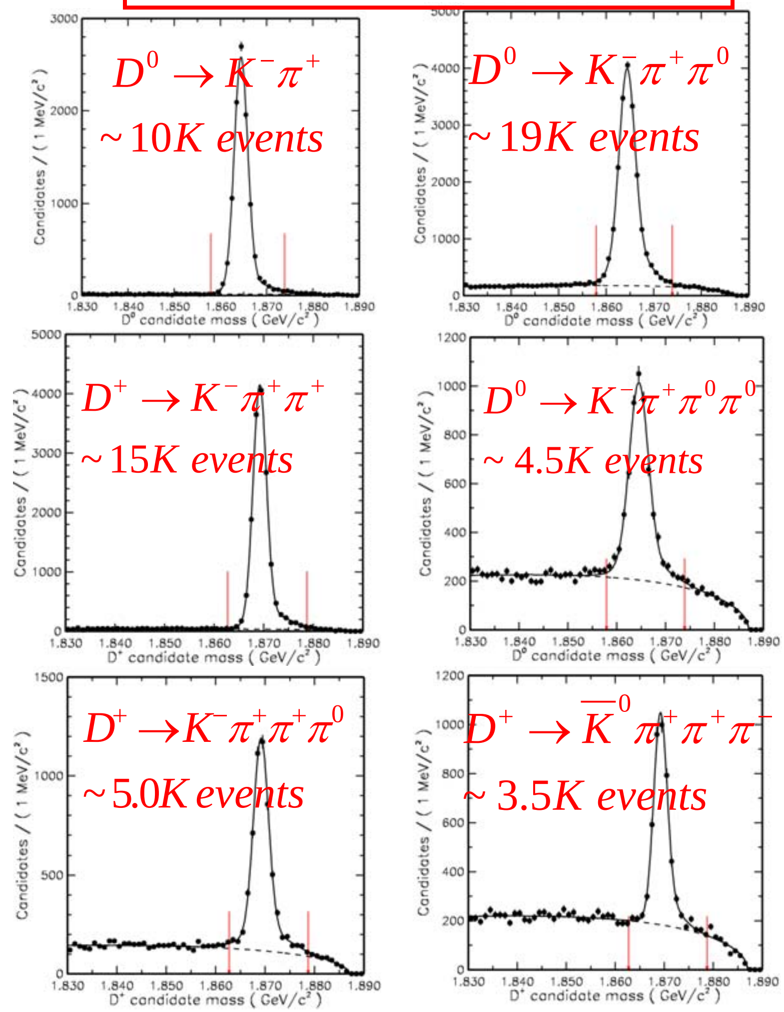
D^0 Decay Mode	$\mathcal{B}$ (%) PDG
$D^0 \to K^-\pi^+$	(3.80 ± 0.09)
$D^0 \to K^-\pi^+\pi^0$	(13.1 ± 0.9)
$D^0 \to K^-\pi^+\pi^0\pi^0$	
$D^0 \to K^-\pi^+\pi^+\pi^-$	(7.46 ± 0.31)
$D^0 \to \overline{K^0}\pi^0$	(2.28 ± 0.22)
$D^0 \to \overline{K^0}\pi^+\pi^-$	(5.92 ± 0.35)
$D^0 \to \overline{K^0}\pi^+\pi^-\pi^0$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





Examples of Mbc for tag modes in the data



~30% tagging efficiency

~20% tagging efficiency

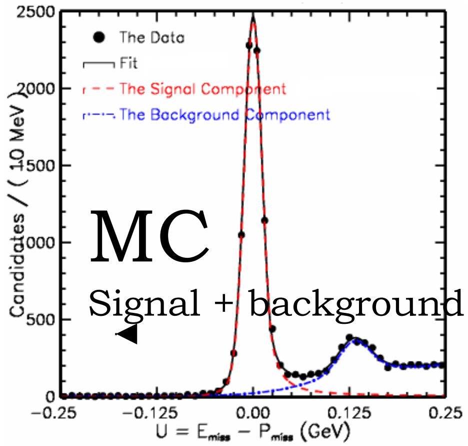
Tagging creates a single beam of D mesons with known momentum

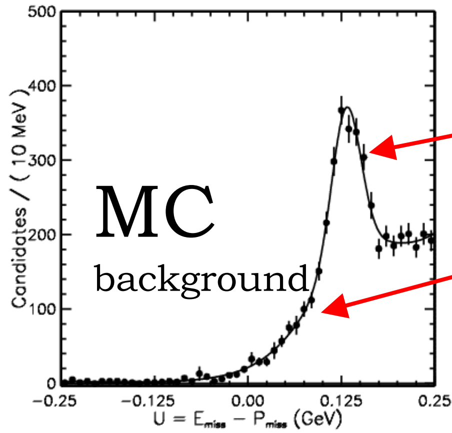
Reconstruction of semileptonic decays

- Semileptonic modes listed in the table are reconstructed
- Electron identification (muons are not used):
  - ✓ 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
- Hadron identification is based on dE/dx (all momenta) and RICH (above 700 MeV)
- 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 the signal D is approximated by $(E_{beam}, -\sqrt{E_{beam}^2 - m_D^2}\ \hat{p}_{D\,tag})$
- One entry per U plot per D tag mode is chosen based on $K^*/\rho/\omega$ and/or π^0 masses
- Again, semileptonic decays peak at zero in $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$
- Semileptonic branching fractions are obtained as $B(D^0 \to \pi^- e^+ \nu) = \dfrac{N(\pi^- e^+ \nu)}{\varepsilon(\pi^- e^+ \nu) N(\overline{D}^0_{tag})}$ (independent of the luminosity)

	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.	$D^+ \to \omega(\pi^+ \pi^- \pi^0) e^+ \nu$

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



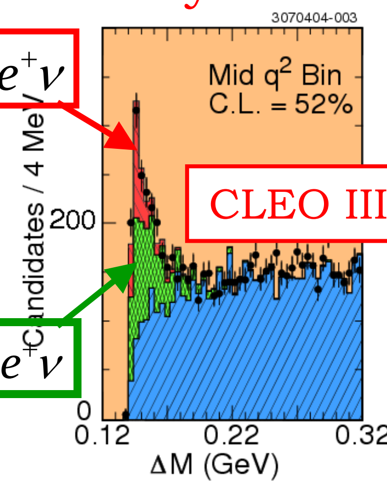


Main background sources:

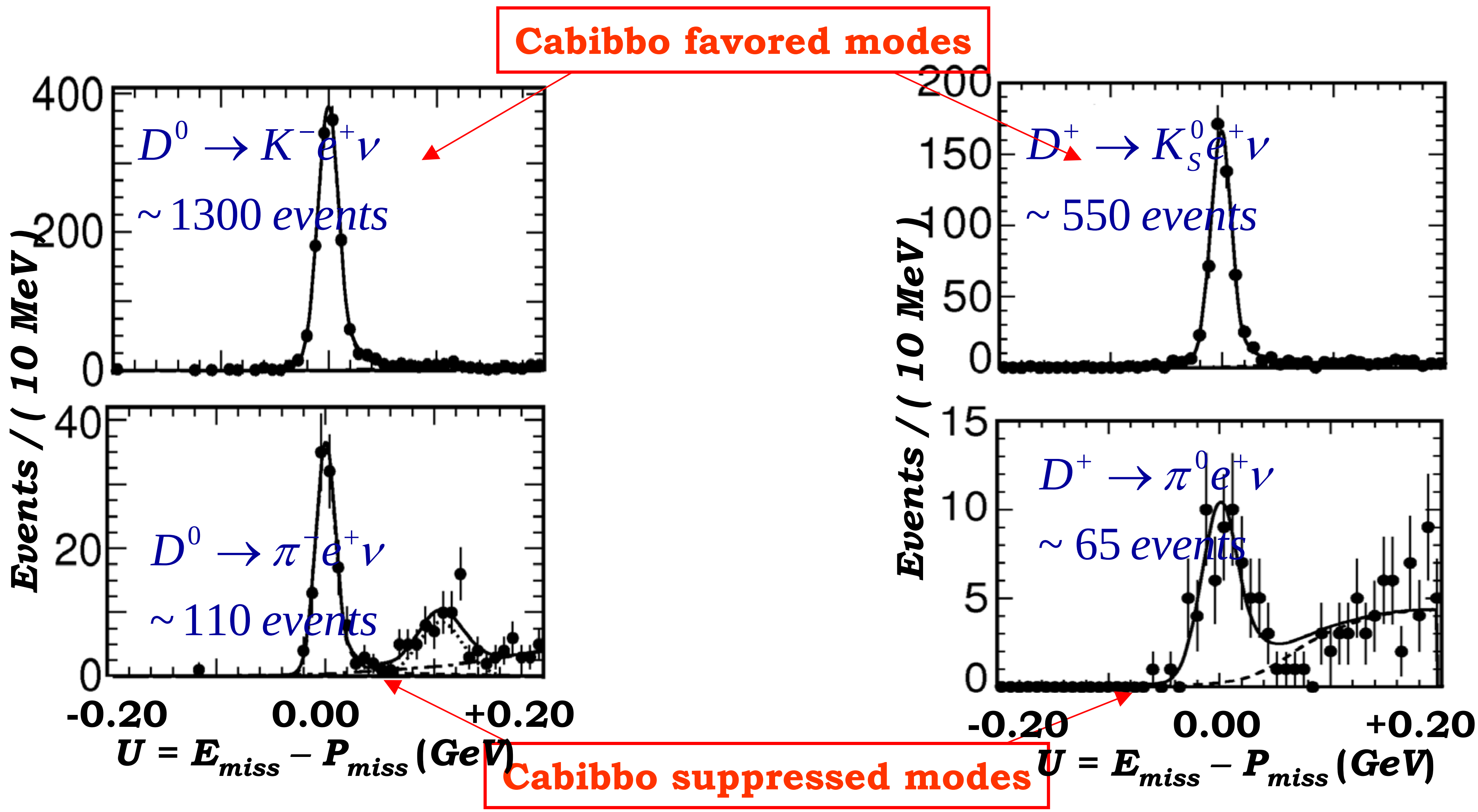
$D^0 \to K^- e^+ \nu$

$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$

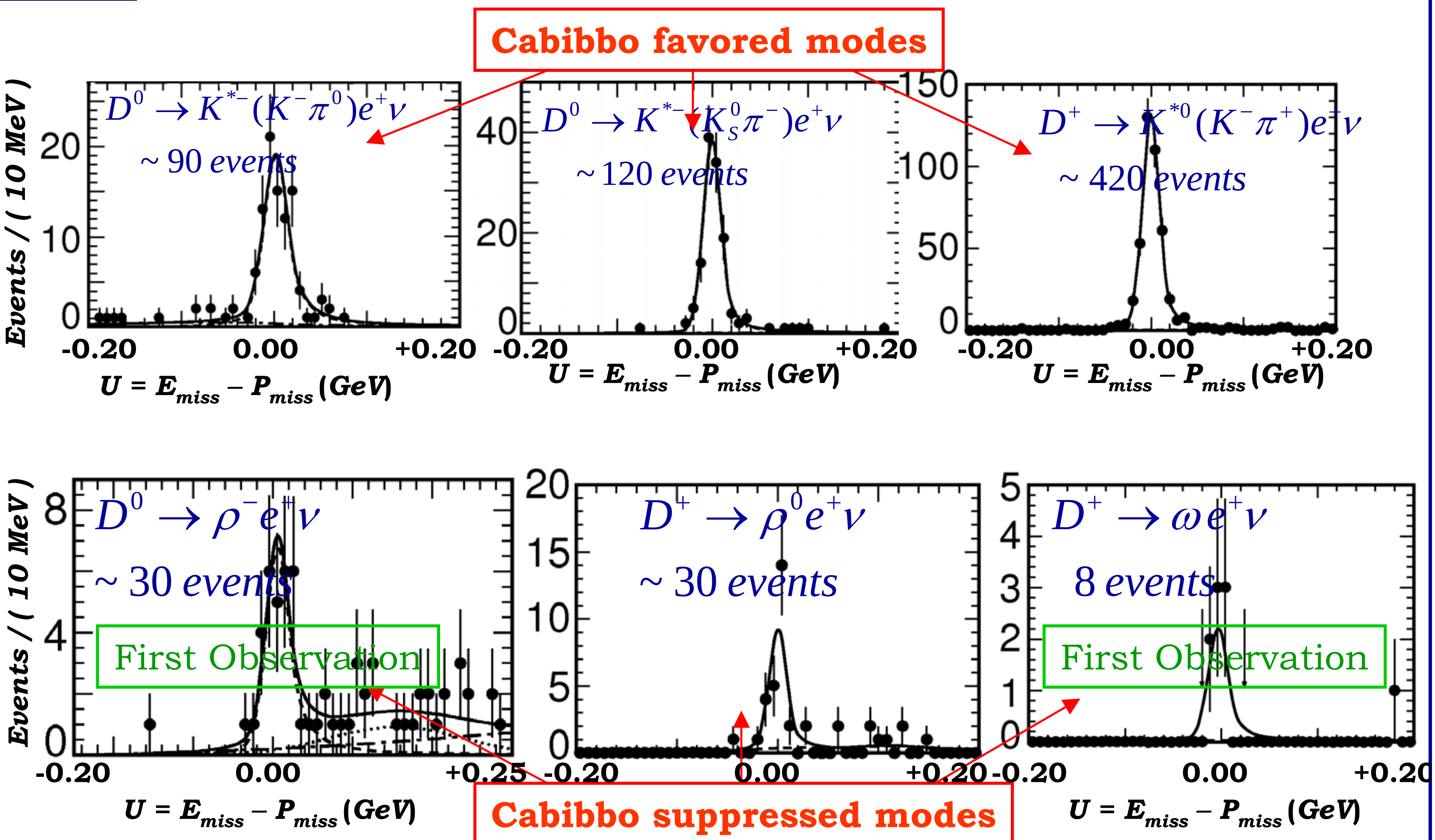
- Background is small and peaks outside the signal region (kinematic separation)
- Most background comes from cross-feed among *D* semileptonic decays
- In other experimental configurations the momentum of the parent *D* meson is unmeasured because of the neutrino, which leads to poorer separation between signal and background
- For example, in a CLEO III analysis using Υ(4S) data (PRL **94**, 011802 (2005)) to reduce background $D^0 \to \pi e^+ \nu$ 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



U distributions for $P \rightarrow P$ decays in 56 pb^{-1} of data



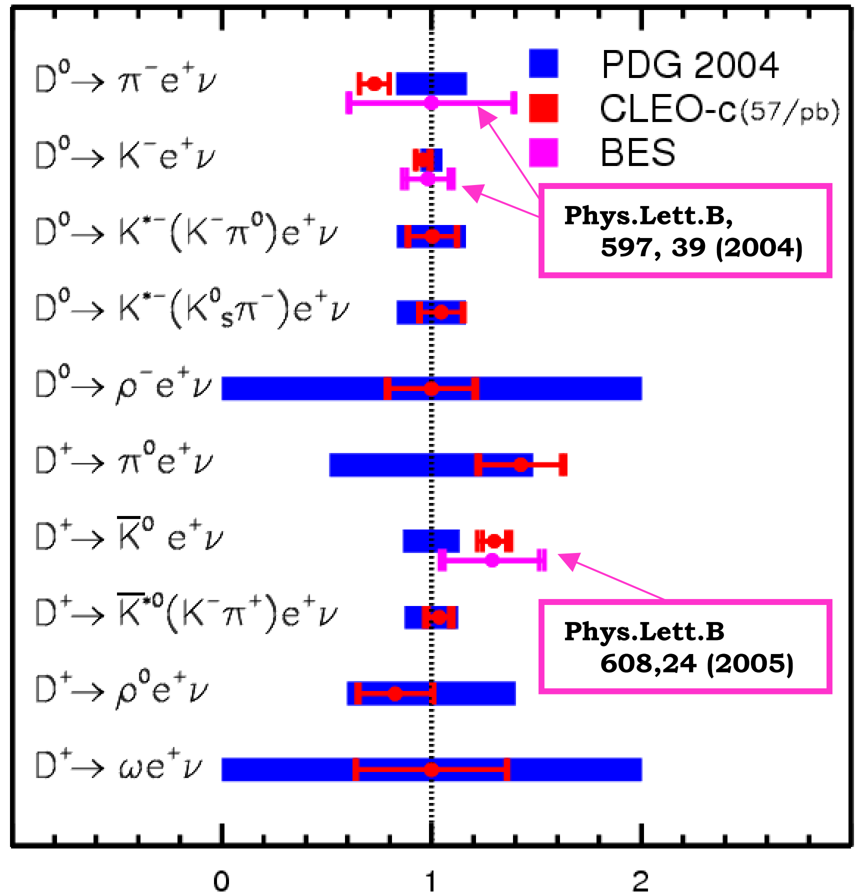
U distributions for $P \to V$ decays in 56 pb^{-1} of data



Absolute branching fractions for D semileptonic decays

Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to \pi^- e^+ \nu_e$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to K^{*-}(K^-\pi^0) e^+ \nu_e$	$2.11 \pm 0.23 \pm 0.10$	2.15 ± 0.35
$D^0 \to K^{*-}(\bar{K}^0\pi^-) e^+ \nu_e$	$2.19 \pm 0.20 \pm 0.11$	2.15 ± 0.35
$D^0 \to \rho^- e^+ \nu_e$	$0.19 \pm 0.04 \pm 0.01$	—
$D^+ \to \pi^0 e^+ \nu_e$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	$5.56 \pm 0.27 \pm 0.23$	5.5 ± 0.7
$D^+ \to \rho^0 e^+ \nu_e$	$0.21 \pm 0.04 \pm 0.01$	0.25 ± 0.10
$D^+ \to \omega e^+ \nu_e$	$0.16^{+0.07}_{-0.06} \pm 0.01$	—

- *BF* for $D^0 \to \pi^- e^+ \nu$ ($D^+ \to \bar{K}^0 e^+ \nu$) is measured to be somewhat 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)). 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
- Most systematic uncertainties are measured in data and will be reduced with a larger data sample.

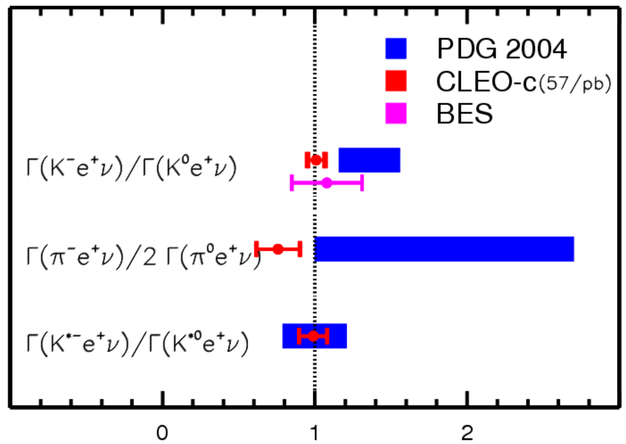


References:
hep-ex/0506052 and hep-ex/0506053
Both submitted to PRL

Isospin tests and a comparison with inclusive measurements

- The widths of the isospin conjugate exclusive semileptonic decays are related due to the isospin invariance of the hadronic current. We find:

Ratio	Measured Value
$\Gamma(D^0 \to K^- e^+ \nu)/\Gamma(D^+ \to \bar{K}^0 e^+ \nu)$	$1.00 \pm 0.05 \pm 0.04$
$\Gamma(D^0 \to \pi^- e^+ \nu)/[2 \cdot \Gamma(D^+ \to \pi^0 e^+ \nu)]$	$0.75^{+0.14}_{-0.11} \pm 0.04$
$\Gamma(D^0 \to K^{*-} e^+ \nu)/\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu)$	$0.98 \pm 0.08 \pm 0.04$



- Isospin averaged semileptonic decay widths:

Decay Mode	$\Gamma\ (10^{-2} \cdot \mathrm{ps}^{-1})$
$D \to K\ e^+ \nu_e$	$8.38 \pm 0.20 \pm 0.23$
$D^0 \to \pi^- e^+ \nu_e$	$0.68 \pm 0.05 \pm 0.02$
$D \to K^*\ e^+ \nu_e$	$5.32 \pm 0.21 \pm 0.20$
$D^0 \to \rho^- e^+ \nu_e$	$0.43 \pm 0.06 \pm 0.02$

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

$$\sum B(D^0_{excl\ semil}) = (6.1 \pm 0.2 \pm 0.2)\% \quad and \quad \sum B(D^+_{excl\ semil}) = (15.1 \pm 0.5 \pm 0.5)\%$$

These are consistent with the CLEO-c inclusive semileptonic branching fractions (Ref.: CLEO-CONF 05-3, LP2005-429):

$$B(D^0_{incl\ semil}) = (6.5 \pm 0.2 \pm 0.2)\% \quad and \quad B(D^+_{incl\ semil}) = (16.2 \pm 0.2 \pm 0.4)\%$$

which excludes the possibility of additional *D* semileptonic modes with large branching fractions.

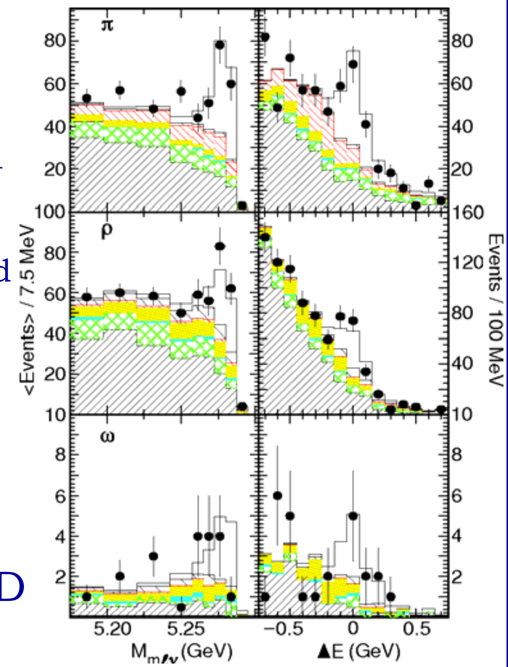
B semileptonic decays at CLEO (1)

- CLEO is finishing studies of $B \to X_u l \nu$ with the complete CLEO II, II.V and III data sample of 15.4 million BB events. Two analyses are ongoing:
  - ✓ Weak annihilation in $B \to X_u l \nu$ (preliminary results are given in the talk by I.Shipsey in "Heavy Flavors" later today)
  - ✓ An update for exclusive $B \to \pi/\rho\, l \nu$ and $|V_{ub}|$

- The technique described in Phys.Rev. D **68** 072003 (2003) is used for the latter analysis:
  - ✓ Neutrino reconstruction: $(E_\nu, \boldsymbol{P}_\nu) = (|\boldsymbol{P}_{miss}|, \boldsymbol{P}_{miss})$
  - ✓ Rates are measured in q^2 bins (to minimize the uncertainty from form factors on the branching fractions)
  - ✓ Simultaneous binned ML fit to all modes (to account for cross-feed among modes) using isospin or constituent quark model constraints for the branching fractions (results from 2003):

$$B(B^0 \to \pi^- l^+ \nu) = (1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07) \times 10^{-4};$$
$$B(B^0 \to \rho^- l^+ \nu) = (2.17 \pm 0.34\,^{+0.47}_{-0.54} \pm 0.41 \pm 0.01) \times 10^{-4}$$

  - ✓ $|V_{ub}|$ is extracted using LCSR for $q^2 \in [0;16)$ GeV^2 and LQCD for $q^2 \in [16; q^2_{max}]$ GeV^2.



B semileptonic decays at CLEO (2)

- In the current $B \to \pi / \rho\, l\, \nu$ analysis, significant improvements in the systematic uncertainty related to the $B \to \rho l \nu$ modeling are expected:
  - ✓ The lepton momentum cut is lowered to 1.0 GeV from 1.5 GeV
  - ✓ The region $cos(\theta_l) < 0.0$ is included in the fit
- Changes to the q^2 binning are being considered
- Recent unquenced lattice calculation for the $B \to \pi\, l\, \nu$ form factor is used (Shigemitsu, *et al.*, hep-lat/0408019)
- *Final* CLEO results on $|V_{ub}|$ using 15.4 million BB pairs are forthcoming.

Summary and Outlook

- The analysis of absolute D semileptonic branching fractions from the first ~56 pb^{-1} data sample collected at the $\psi(3770)$ by CLEO-c is completed. All measurements are most precise to date.
- CLEO is finishing studies of $B \to X_u l \nu$ with the full $\Upsilon(4S)$ data set of 15.4 million BB events
- Analyses of semileptonic form factors with 280 pb^{-1} of new CLEO-c data are ongoing.
- CLEO-c is going to collect a much larger data sample at the $\psi(3770)$ as well as data above the $D_s D_s$ threshold. This data sample will play an important role in particle physics as
  - ✓ validation and calibration data for LQCD and other theories and models
  - ✓ input data to the B factories and other experiments increasing their potential in the search for new physics

Extra slides

CLEO-c prospects

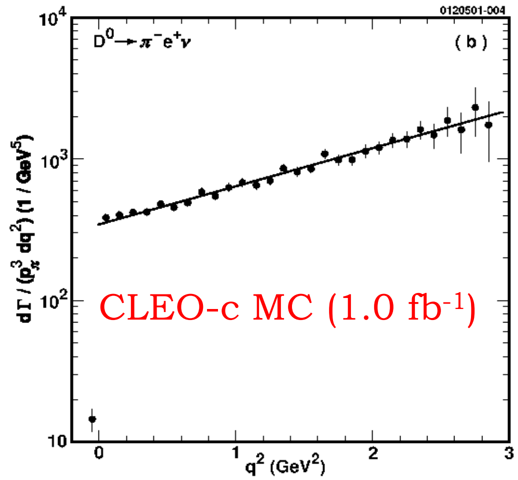
(Ref.: CLNS 01/1742)

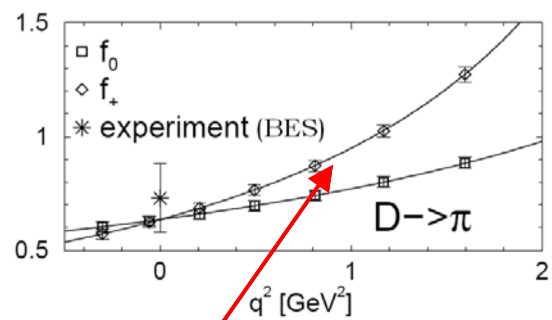
- The ~56 pb^{-1} data sample collected in fall-2003/winter-2004 by the CLEO-c detector already gives measurements of absolute branching fractions for all modes considered today with uncertainties smaller than the uncertainties in PDG-2004.

- CLEO-c is going to collect a much larger data sample at the $\psi(3770)$ and data at slightly higher energies for studies of D_s mesons.

- 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 will measure form factors at a percent level in $P \to P$ transitions and at a few percent level in $P \to V$ transitions.
  - ✓ 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 (V_{cs} and V_{cd} 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 $\Gamma(D^+ \to \pi(K)\, l\nu) / \Gamma(D^+ \to l\nu)$

- 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 V_{cs} and V_{cd} from D semileptonic decays at CLEO-c sample are possible: $\frac{\delta V_{cs}}{V_{cs}} \approx 1.6\%$ *and* $\frac{\delta V_{cd}}{V_{cd}} \approx 1.7\%$





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