# Exclusive Semileptonic Decays of D Mesons Produced at Threshold

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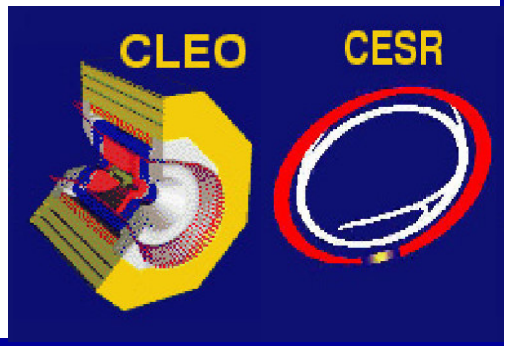
- Introduction
- Overview of the data sample
- Overview of the technique
- *D* tagging side:
  - ✓ $D^0$ tags
  - ✓ $D^+$ tags
- Semileptonic decays:
  - ✓ $D^0$ semileptonic decays
  - ✓ $D^+$ semileptonic decay
- Sensitivity of the CLEO-c program to
  - ✓ *D* semileptonic decay branching fractions
  - ✓ *D* semileptonic decay form factors
  - ✓ CKM matrix elements *Vcs* and *Vcd*
- Summary and Outlook



# Introduction

- The matrix element for a semileptonic *D* transition is

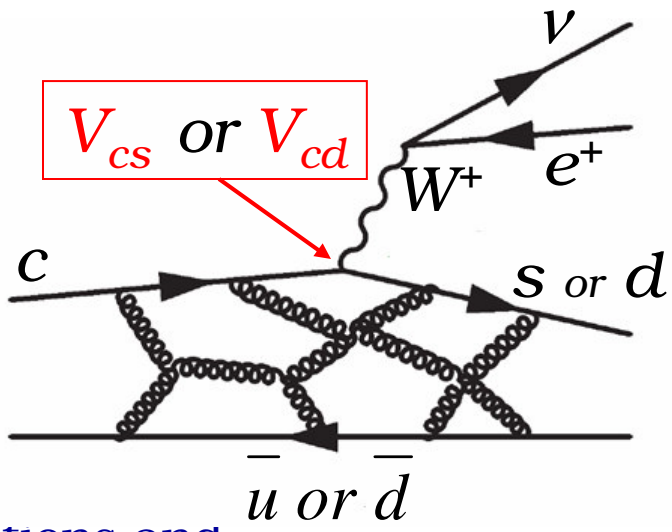
$$\mathcal{M}(M_i \to M_f l\nu) = -i\frac{G_{Fermi}}{\sqrt{2}} V_{Q_i\, q_f} L^{\mu} H_{\mu}$$

- Form Factors:
  - ✓ *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):

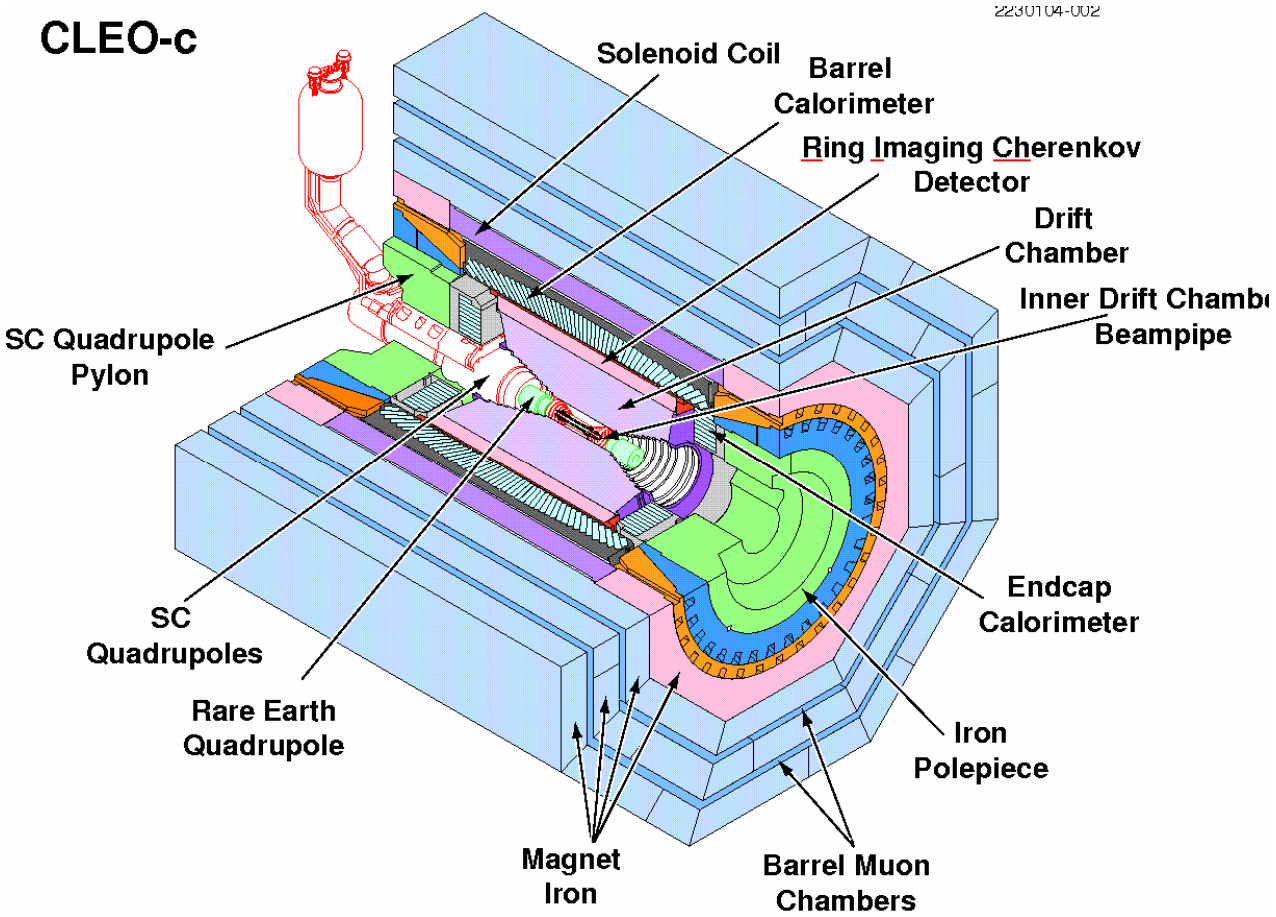
$$\langle M_f(p_f,\epsilon)|V^{\mu}-A^{\mu}|M_i(p_i)\rangle = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M+m_V}\epsilon^*_{\nu}p_{f\alpha}p_{i\beta}V(q^2) - (M+m_V)\epsilon^{*\mu}A_1(q^2) + \frac{\epsilon^*\cdot q}{M+m_V}(p_i+p_f)^{\mu}A_2(q^2)$$




- 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 $V_{cd}$

# The CLEO-c detector and data sample

- Data Sample: ~60/pb collected with the CLEO-c detector last fall/winter (October, 2003, through January, 2004) at $\psi(3770)$

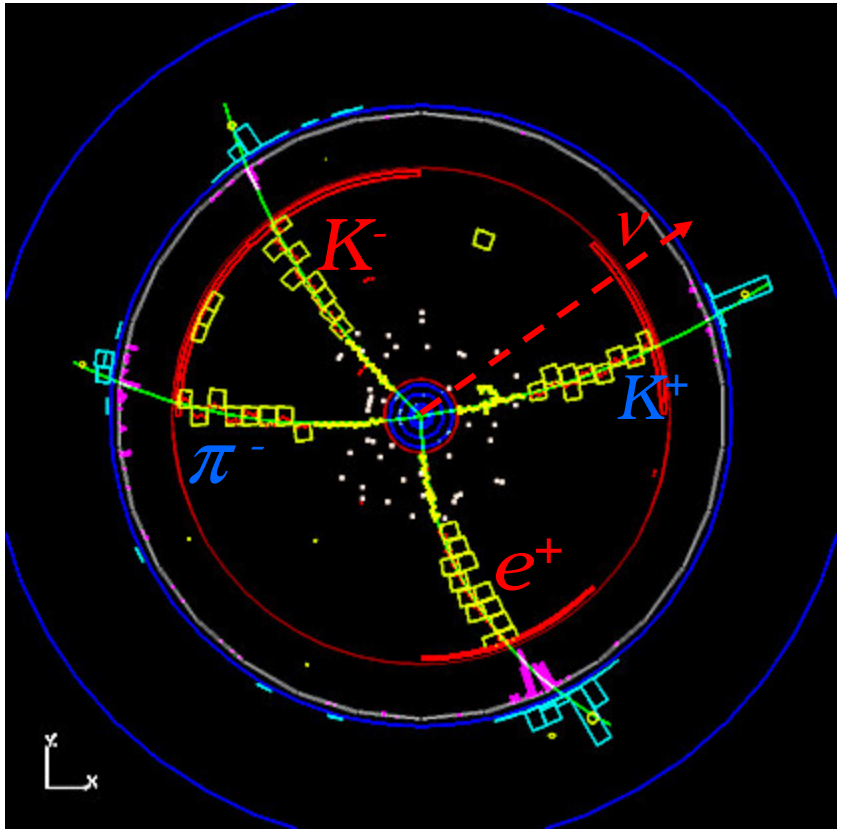


# Overview of the technique

- Reconstruct one of the two $D$'s in a hadronic decay channel. It is called the tagging $D$. Two key variables in the tagging $D$ reconstuction 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 $\boldsymbol{P}$. The signal peaks at zero in $U$.
- Account for the background in the signal region of $U$.
- Account for the systematic effects.

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

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



# Overview of reconstruction

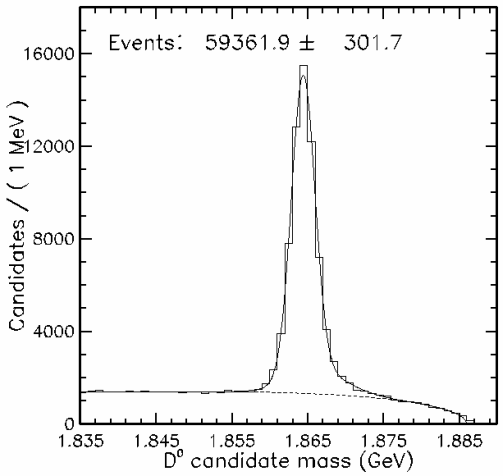
- The selection of *D* tags was described in the previous talk. In events with *D* tags passing ~3σ cuts on Mbc and ΔE, the reconstruction of the semileptonic side is attempted.

## Requirements for the semileptonic side:

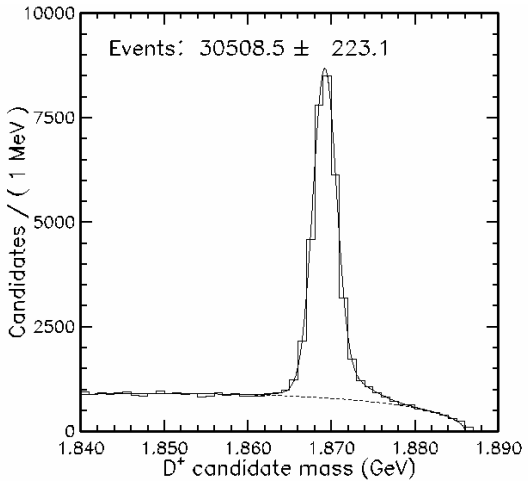
- Standard selection of tracks, showers and $\pi^0$.
- Hadronic particle ID:
  - ✓ Low mometa: dE/dX
  - ✓ Momenta above 0.6 GeV: likelihood function built from the dE/dX and RICH information
- Electron ID:
  - ✓ Likelihood function built from E/P, dE/dX and RICH information
- Bremsstrahlung photons for electrons are recovered, whenever possible.
- Events with extra tracks are vetoed.
- The 4-mometum of the tagging *D* is used to calculate $E_{\mathrm{miss}}$ and $P_{\mathrm{miss}}$.
- Semileptonic decays peak at zero in $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$.

# The tagging $D$ side of the event

| $D^0$ Decay Mode | $\mathcal{B}$ (%) (PDG-02) |
|---|---|
| $D^0 \to K^-\pi^+$ | $(3.80 \pm 0.09)$ |
| $D^0 \to K^-\pi^+\pi^0$ | $(13.1 \pm 0.9)$ |
| $D^0 \to K^-\pi^+\pi^0\pi^0$ | |
| $D^0 \to K^-\pi^+\pi^+\pi^-$ | $(7.46 \pm 0.31)$ |
| $D^0 \to \overline{K^0}\pi^0$ | $(2.28 \pm 0.22)$ |
| $D^0 \to \overline{K^0}\pi^+\pi^-$ | $(5.92 \pm 0.35)$ |
| $D^0 \to \overline{K^0}\pi^+\pi^-\pi^0$ | $(10.8 \pm 1.3)$ |
| $D^0 \to \pi^+\pi^-\pi^0$ | $(1.1 \pm 0.4)$ |
| $D^0 \to K^+K^-$ | $(0.41 \pm 0.01)$ |




| $D^+$ Decay Mode | $\mathcal{B}$ (%) (PDG-02) |
|---|---|
| $D^+ \to \overline{K^0}\pi^+$ | $(2.77 \pm 0.18)$ |
| $D^+ \to K^-\pi^+\pi^+$ | $(9.1 \pm 0.6)$ |
| $D^+ \to \overline{K^0}\pi^+\pi^0$ | $(9.7 \pm 3.0)$ |
| $D^+ \to K^-\pi^+\pi^+\pi^0$ | $(6.4 \pm 1.1)$ |
| $D^+ \to \overline{K^0}\pi^+\pi^+\pi^-$ | $(7.0 \pm 0.9)$ |
| $D^+ \to K^+K^-\pi^+$ | $(0.9 \pm 0.1)$ |




The total number of $D^0$ tags approximately is 60K in 60/pb

The total number of $D^+$ tags approximately is 30K in 60/pb

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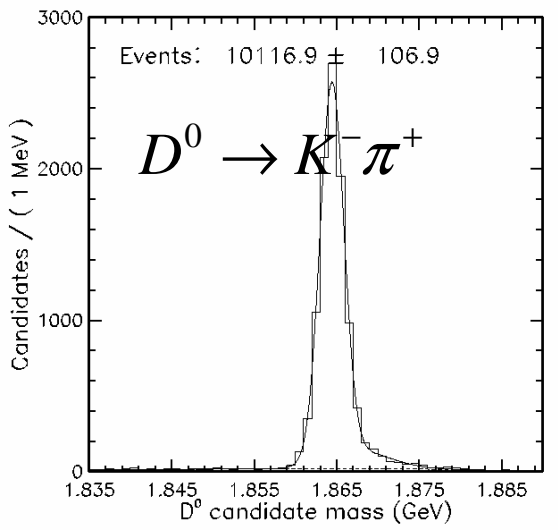
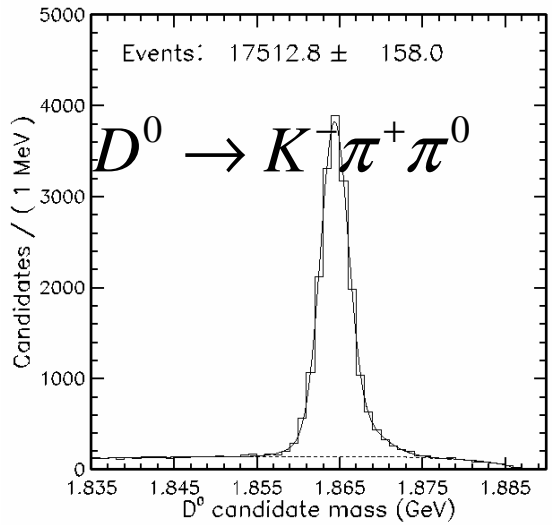
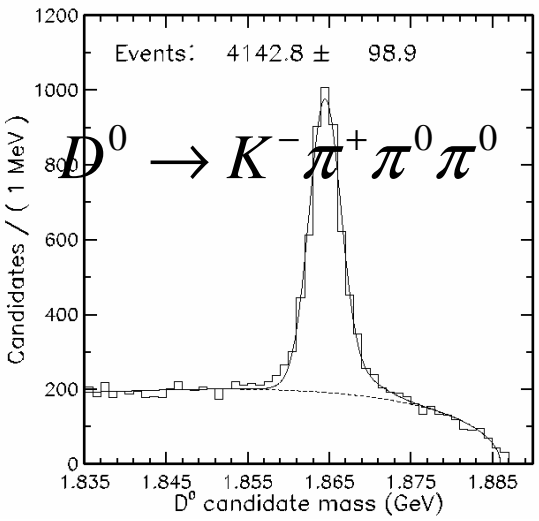
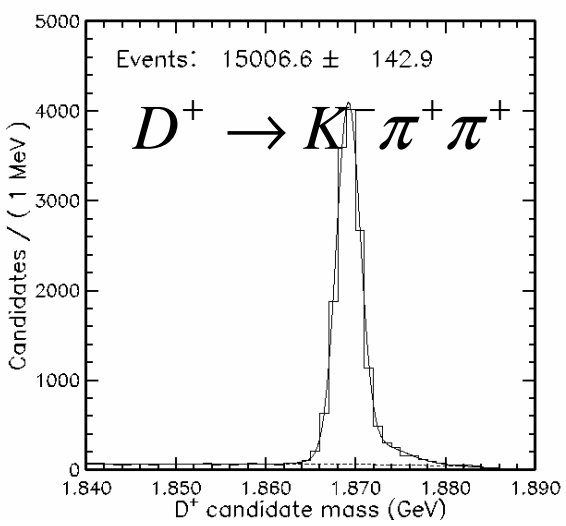
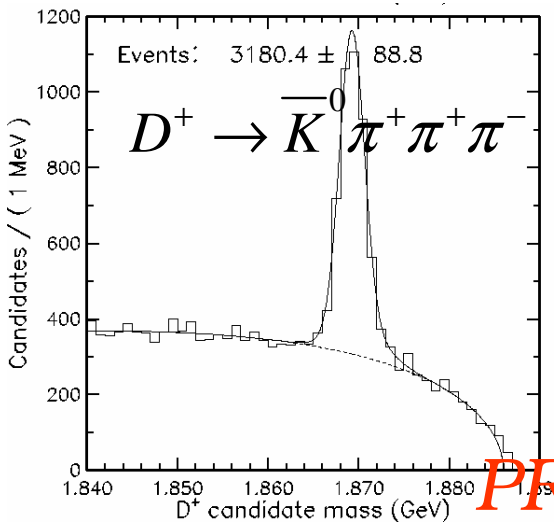
# Representative plots of the $M_{bc}$ distributions for $D^0$ and $D^+$ tags in 60/pb of DATA



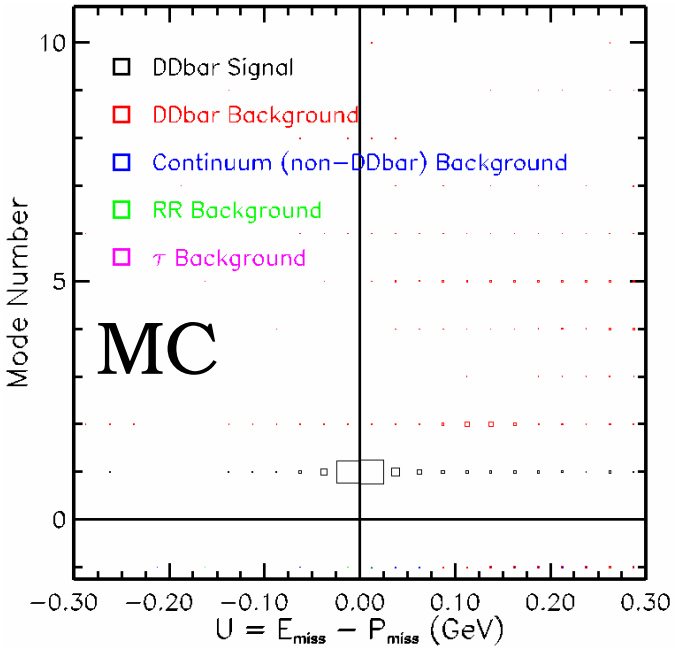




*PRELIMINARY*

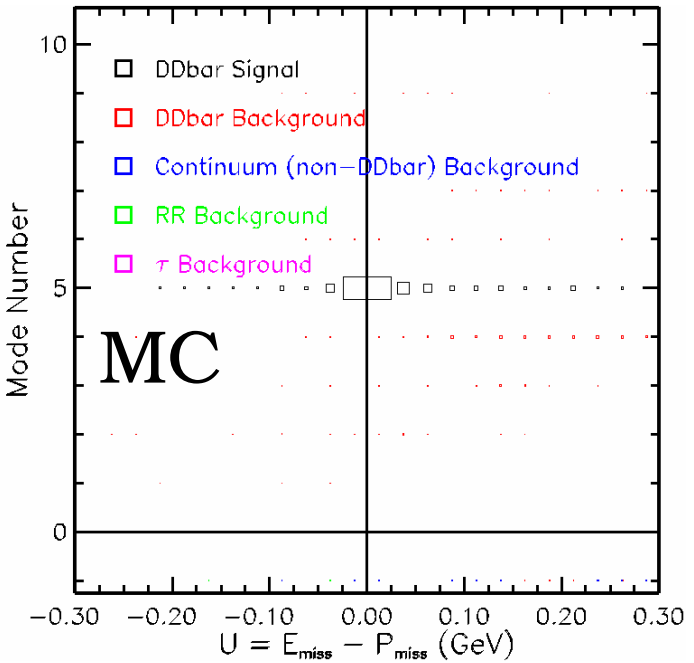
# Composition of the background

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




| Mode | 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. | $D^0 \to K^{*-}(\overline{K^0}\pi^-) e^+ \nu$ |
| 5. | $D^0 \to \rho^-(\pi^-\pi^0) e^+ \nu$ |
| 6. | $D^+ \to \overline{K^0} e^+ \nu$ |
| 7. | $D^+ \to K^{*0}(K^-\pi^+) e^+ \nu$ |
| 8. | $D^+ \to \pi^0 e^+ \nu$ |
| 9. | $D^+ \to \rho^0(\pi^+\pi^-) e^+ \nu$ |
| 10. | $D^+ \to \eta(\gamma\gamma) e^+ \nu$ |
| -1. | all other decays |

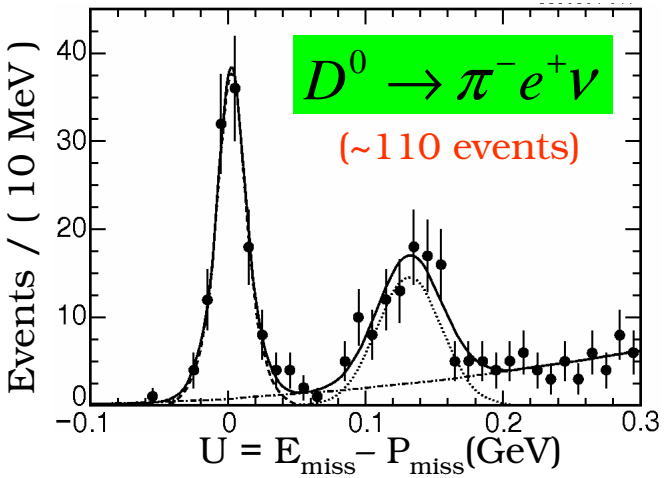
$D^0 \to \rho^- e^+ \nu$

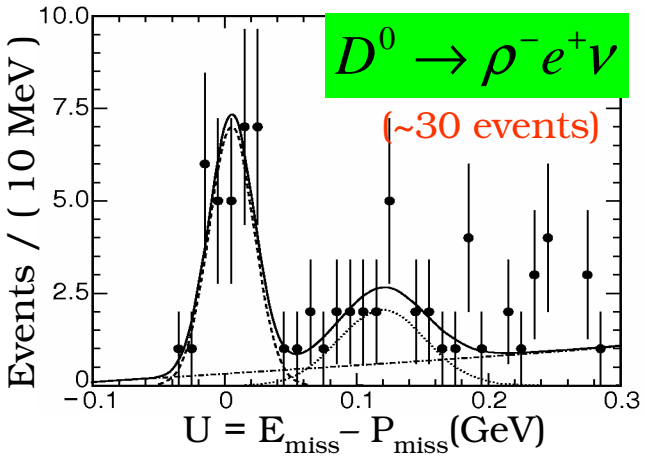



- Background is small and peaks outside the signal region.
- Most of the background comes from cross-feed among *D* semileptonic decays.

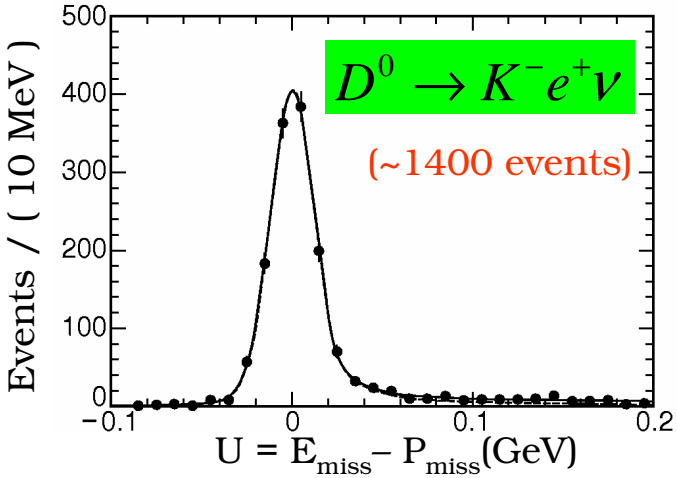
# $U$ distributions for $D^0$ modes in the DATA

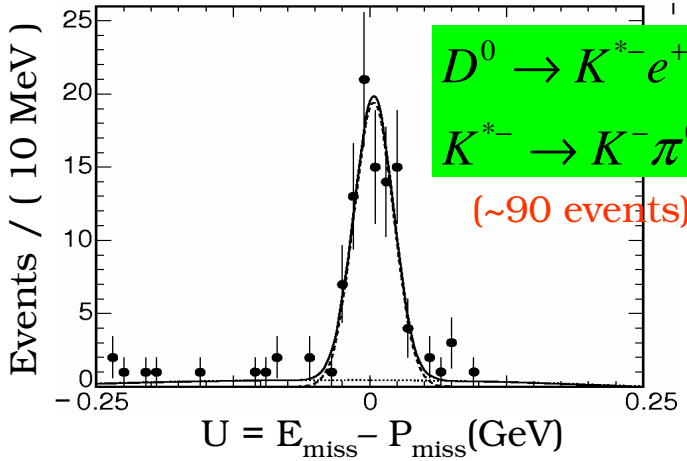
Cabibbo suppressed modes:




Cabibbo favored modes:

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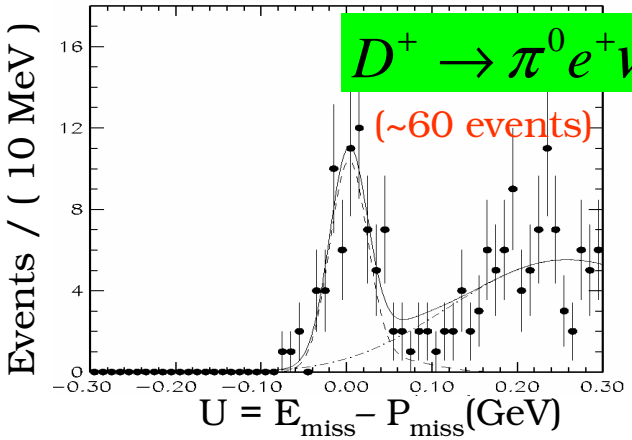
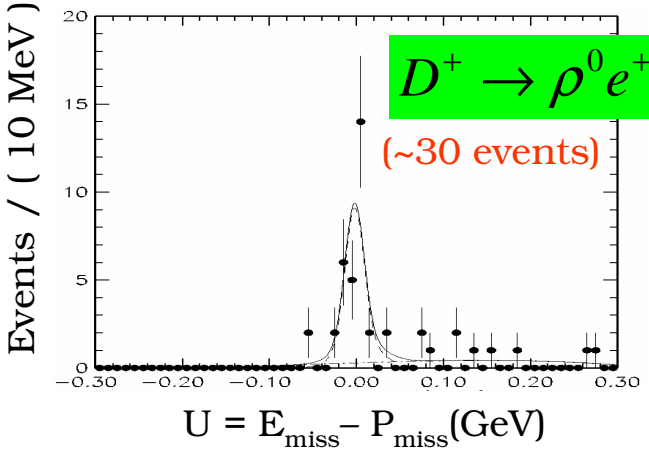
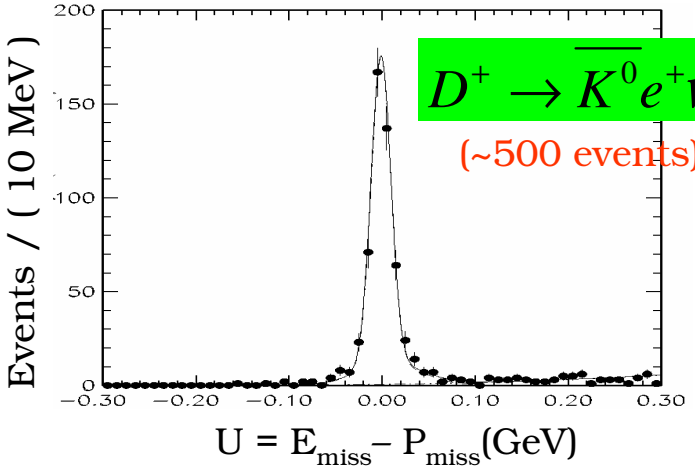
# $U$ distributions for $D^+$ modes in the DATA

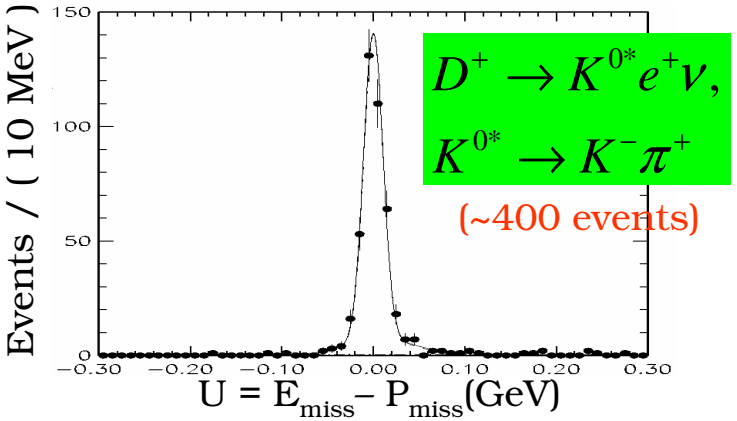
Cabibbo suppressed modes:




Cabibbo favored modes:

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# Major systematic uncertainties (the ICHEP status)

| Source of systematic error | Value (%) |
|---|---|
| Electron ID efficiency | 2.0 |
| Hadron ID efficiency | 1.0 |
| Track finding efficiency | 3.0/track |
| $\pi^0$ finding efficiency | $4.4/\pi^0$ |
| $K^0_S$ finding efficiency | $3.0/K^0_S$ |
| Form factor modeling | from 2 to 5 (mode dependent) |

- Most of the systematic uncertainties are expected to be significantly reduced with further study.

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# Results for $D^0$ modes (ICHEP-04 / arXiv:hep-ex/0408077)

| Decay mode | This work: $\mathcal{B}$ (%) | PDG: $\mathcal{B}$ (%) |
|---|---|---|
| $D^0 \to \pi^- e^+ \nu$ | $0.25 \pm 0.03 \pm 0.02$ | $0.36 \pm 0.06$ |
| $D^0 \to K^- e^+ \nu$ | $3.52 \pm 0.10 \pm 0.25$ | $3.58 \pm 0.18$ |
| $D^0 \to \rho^- e^+ \nu$ | $0.19 \pm 0.04 \pm 0.02$ | none |
| $D^0 \to K^{*-} e^+ \nu$ | $2.07 \pm 0.23 \pm 0.18$ | $2.15 \pm 0.35$ |
| $\frac{D^0 \to \pi^- e^+ \nu}{D^0 \to K^- e^+ \nu}$ | $7.0 \pm 0.7 \pm 0.3$ | $10.1 \pm 1.8$ |

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- $B(D^0 \to \pi^- e^+ \nu)$ is measured to be lower than the PDG value.
- $\frac{B(D^0 \to \pi^- e^+ \nu)}{B(D^0 \to K^- e^+ \nu)}$ compares favorably with the CLEO III result of (8.2±0.6±0.5)% (arXiv:hep-ex/0407035, accepted by PRL).
- This is the first observation of $D^0 \to \rho^- e^+ \nu$ .
- Branching fractions for the $D^+$ modes will be made available soon.

# CLEO-c reach (1)

- The ~60/pb data sample collected in fall-2003/winter-2004 by the CLEO-c detector already gives measurements of BRs for all modes considered today with statistical uncertainties smaller than the total uncertainties in PDG-2004.
- CLEO-c is expected to collect 50 times more (~3/fb) data on $\psi(3770)$ as well as ~3/fb of data at $E_{cm}$ ~ 4140 MeV for studies of $D_s$ mesons.
- The CLEO-c data will dramatically improve knowledge of the BRs of charm mesons (CLNS 01/1742 ):

$1: D^0 \to K^- e^+ \nu$

$2: D^0 \to K^{*-} e^+ \nu$

$3: D^0 \to \pi^- e^+ \nu$

$4: D^0 \to \rho^- e^+ \nu$

$5: D^+ \to \overline{K}^0 e^+ \nu$

$6: D^+ \to \overline{K}^{0*} e^+ \nu$

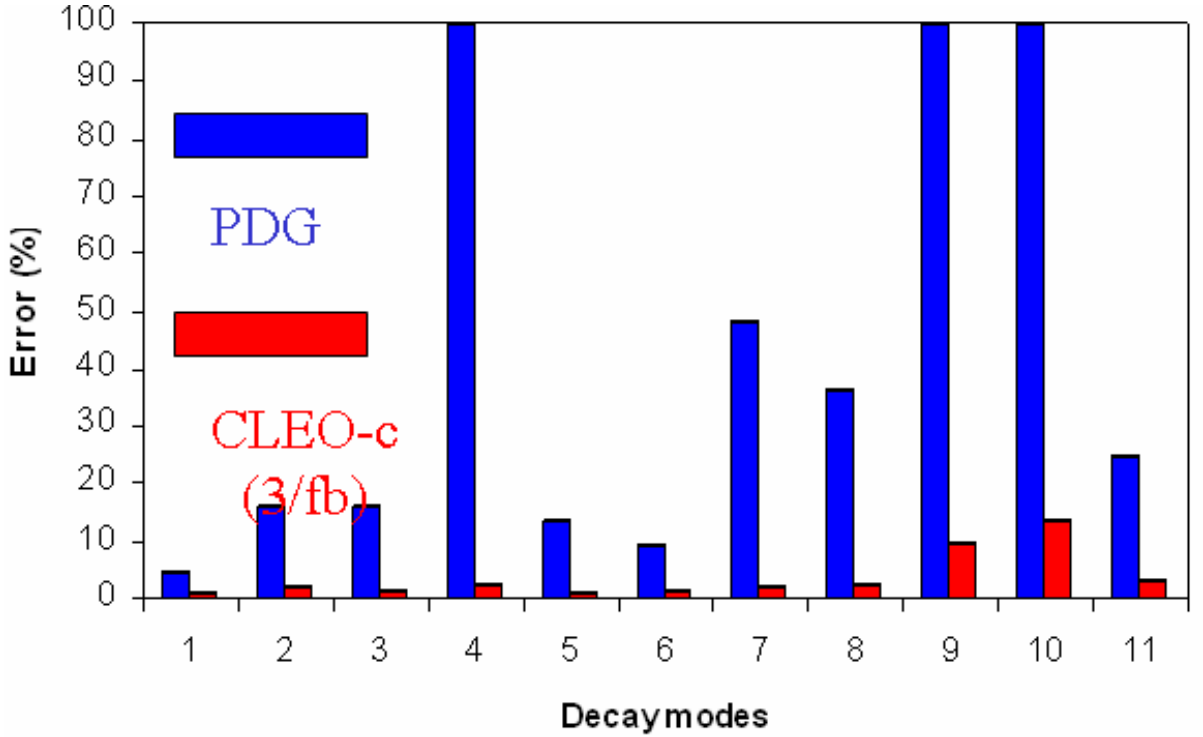
$7: D^+ \to \pi^0 e^+ \nu$

$8: D^+ \to \rho^0 e^+ \nu$

$9: D_s \to K^0 e^+ \nu$

$10: D_s \to K^{*0} e^+ \nu$

$11: D_s \to \phi e^+ \nu$



# CLEO-c reach (2)

- CLEO-c semileptonic events allow precision studies of semileptonic decay form factors (predictions for 3/fb, CLNS 01/1742):
  - ✓ *P* to *P*: $f_+(q^2) = f_+(0)\, e^{\alpha q^2}, \quad \frac{\delta\alpha}{\alpha} \approx 2-3\%, \quad for\ both\ D^0 \to K^- e^+ \nu\ and\ D^0 \to \pi^- e^+ \nu$
  - ✓ *P* to *V*: $R_V = \frac{V(0)}{A_1(0)} \approx 2-3\% \quad and \quad R_2 = \frac{A_2(0)}{A_1(0)} \approx 2.5-3.5\% \quad for\ both\ D^+ \to K^{*0} e^+ \nu\ and\ D^+ \to \rho^0 e^+ \nu$

  (Plots on the next slide)
- The form factor measurements are essential for testing form factor models and calibrating LQCD, input from which is required for measurements of *Vcs* and *Vcd*:

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

theory

experiment

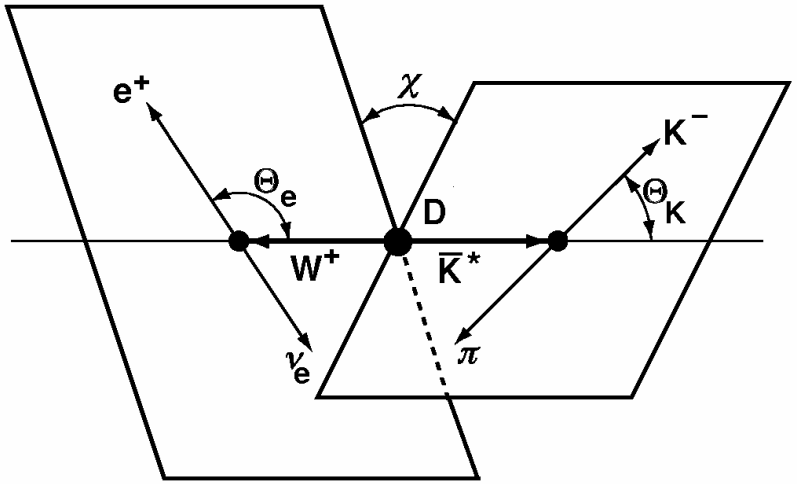
- Using the future CLEO-c measurements of BRs and the world average for *D* meson lifetimes, and assuming theory errors on $\gamma_s$ and $\gamma_d$ of 3%, the following uncertainties for *Vcs* and *Vcd* from a 3/fb data sample are within reach:

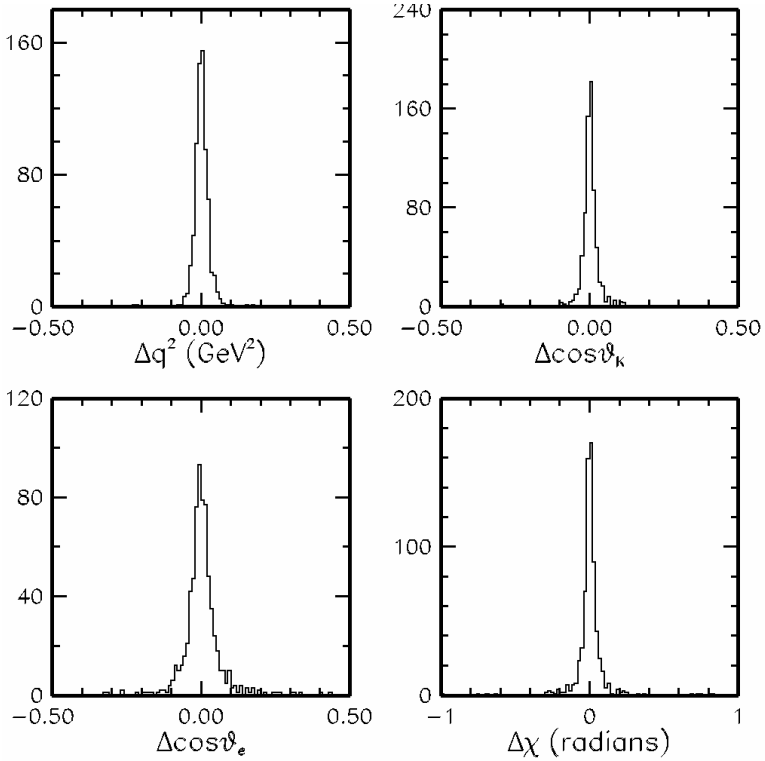
$$\frac{\delta V_{cs}}{V_{cs}} = 1.6\%\ (now\ 11\%) \quad and \quad \frac{\delta V_{cd}}{V_{cd}} = 1.7\%\ (now\ 7\%)$$

# Resolution of kinematic variables

- The kinematic constraints in the *DDbar* system produced at threshold lead to at least a 10 fold improvement in the resolution of kinematic variables (compared to the resolution on the Y(4S) resonance):

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




- This improvement is essential for form factor measurements

# Summary and Outlook

- First exclusively reconstructed CLEO-c $D^0$ and $D^+$ semileptonic decays from the ~60/pb data sample collected on $\psi(3770)$ in 2003/04 have been presented. Expect finalized results from this data sample by the end of the year.
- The CLEO-c detector is functioning as expected.
- It is planned to collect 50 times more data on $\psi(3770)$ and the same amount of data at $E_{cm}$ ~ 4140 MeV. This data sample will play an important role in particle physics as
  - ✓ validation and calibration data for LQCD – a theory capable of solving strongly coupled field theory equations
  - ✓ input data to the *B*-factories and other experiments increasing their potential
- The CLEO-c detector is collecting more data.

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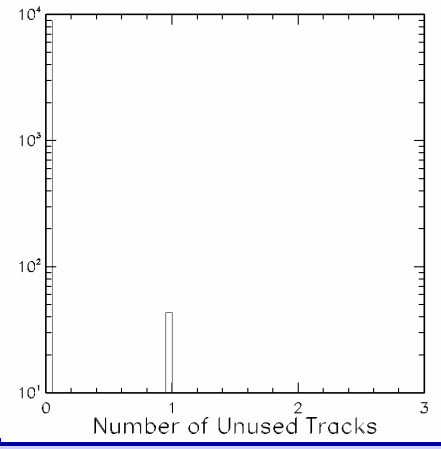
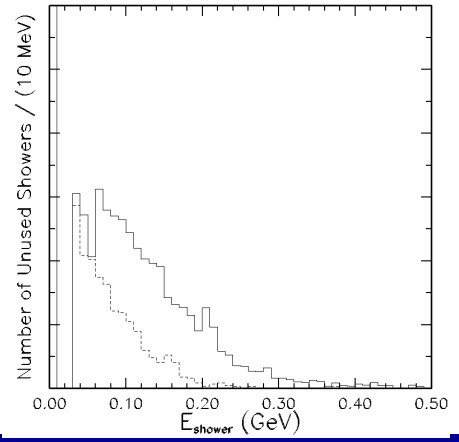
# An overview of reconstruction

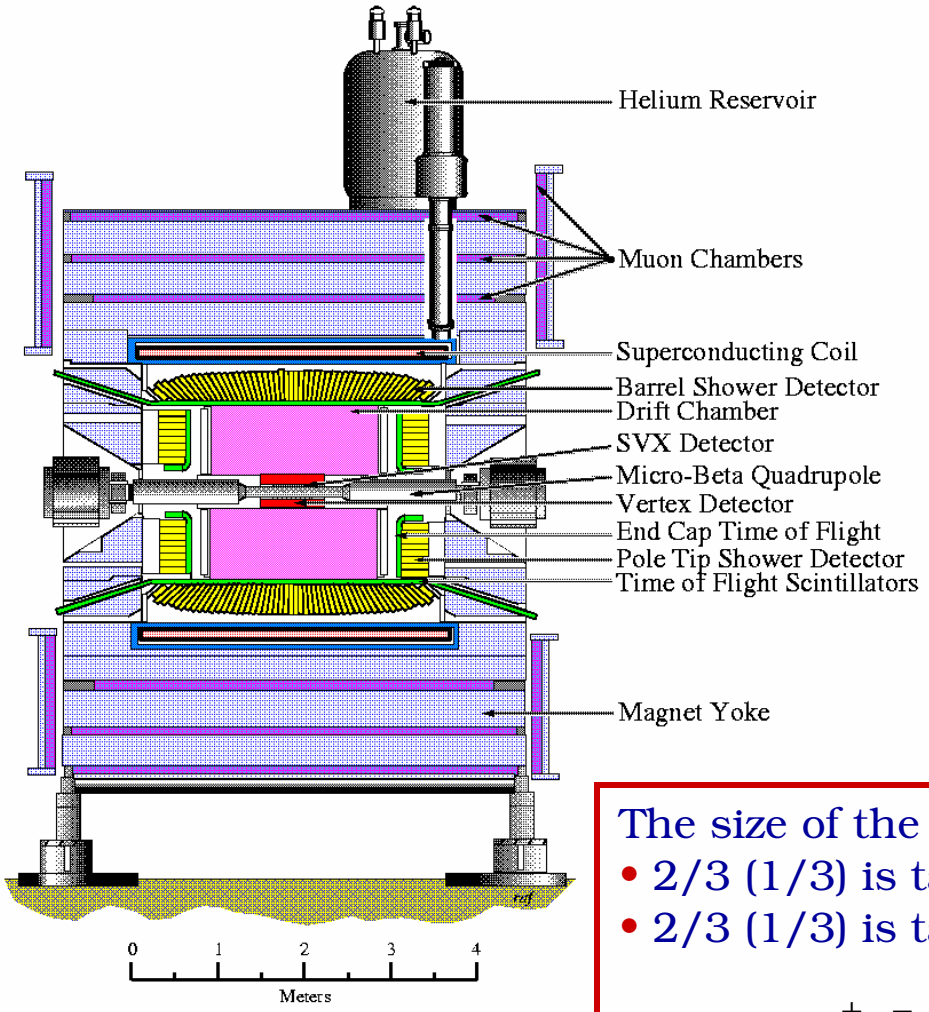
- Selection of tracks:
  - ✓ Track quality criteria
  - ✓ Hadronic PID criteria are based on
    - ➢ the dE/dX information
    - ➢ the RICH information
- Selection of showers and $\pi^0$:
  - ✓ unmatched to tracks showers
  - ✓ $E_{shower} > 30\ (50)\ MeV$
  - ✓ hot crystals are excluded
  - ✓ $-3.5\sigma < |M(\pi^0)| < 3.0\sigma$
- Electron ID is based on a likelihood built from:
  - ✓ the ratio of $E/P$
  - ✓ the $dE/dX$ information
  - ✓ the RICH information
- Bremsstrahlung photons for electrons are recovered

- Two important variables in the $D$ tag reconstuction:
  - ✓ $\Delta E = E_{beam} - E_{cand}$
  - ✓ $M_{bc} = \sqrt{E^2_{beam} - P^2_{cand}}$
- Require $|\Delta E| < 35 MeV$ and $|M_{bc} - M_D| < 8 MeV$
- All tracks found in the event must be used in reconstruction
- Require for unused showers $E_{shower} < 0.30\ (0.15)\ GeV$
- Loose cuts on $E_{miss}$ and $P_{miss}$



# The CLEO II and II.V detector




- **Tracking system:**
  SVX (3 layers) or Gas Vertex Detector,
  Vertex Detector, Drift Chamber
  (B=1.5T, $Ar_2$+$C_2H_6$ or $He_2$+$C_3H_8$)
  ($\delta p/p \sim 0.6\%$ for a 2 GeV track)
- **Time of Flight system**
  Scintillating plastic ($\delta t \sim 170$ps)
- **Crystal Calorimeter**
  CsI crystals($\delta E/E \sim 2\%$ for a 2 GeV photon
- **Muon chambers**
  Proportional chambers at 3, 5 and 7 $\lambda_I$

The size of the data sample is 13.7 $fb^{-1}$.
- 2/3 (1/3) is taken with CLEOII.V (CLEOII).
- 2/3 (1/3) is taken ON (50 MeV OFF) Y(4S).

~10M of $e^+e^- \to B\overline{B}$ and ~18M of $e^+e^- \to c\overline{c}$ events.