Recent Results From CLEO-c

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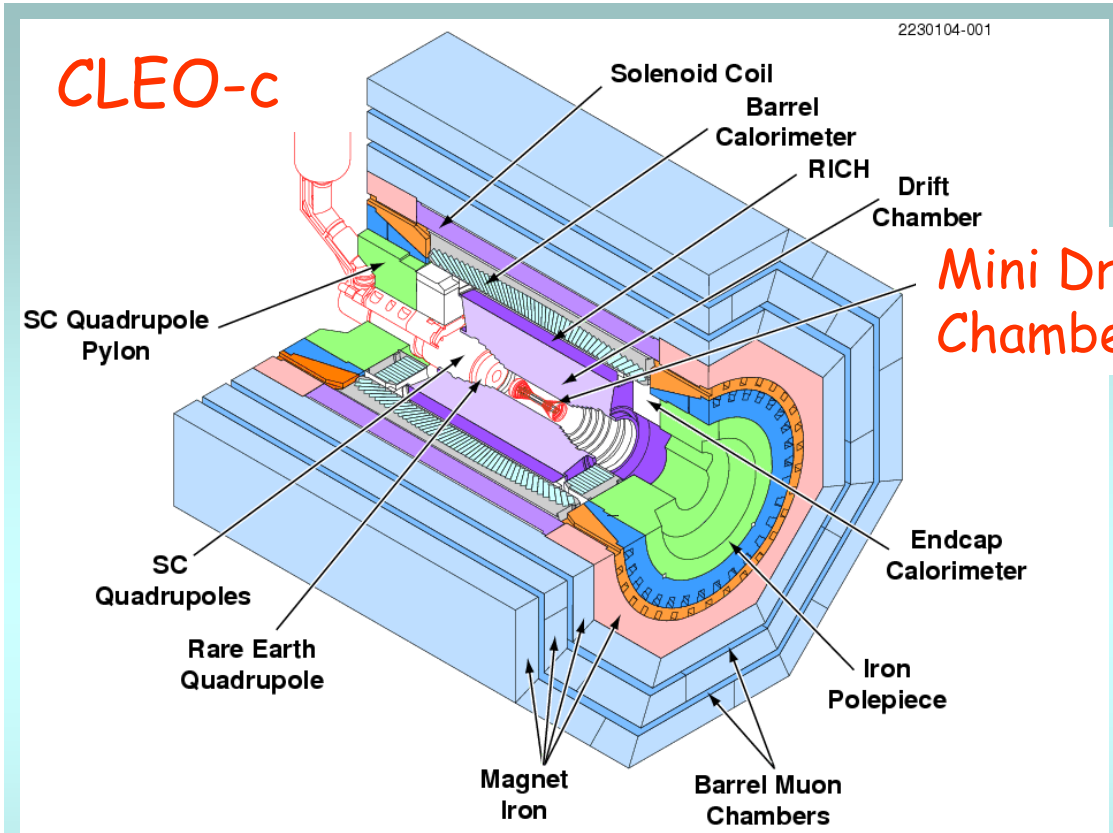
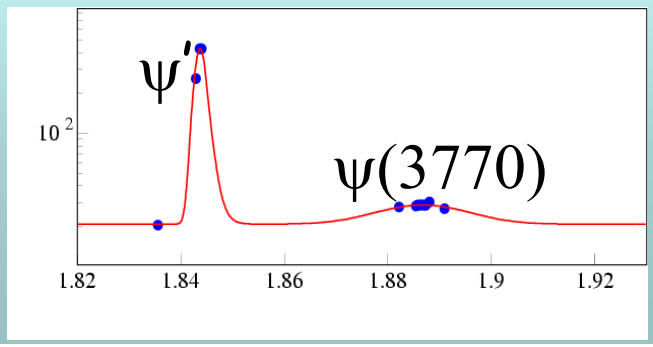
- Motivation
- Leptonic D decays
- Semileptonic D decays
  - Exclusive
  - Inclusive
- D hadronic BR, $\sigma(D\overline{D})$
- Conclusions

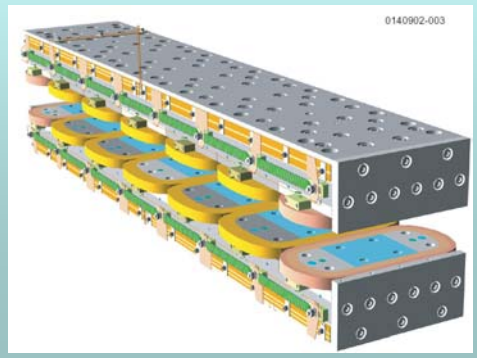
Les Rencontres de Physique de la Vallee D'Aoste
February 27 – March 5, 2005

CLEO-c Detector/CESR-c Accelerator



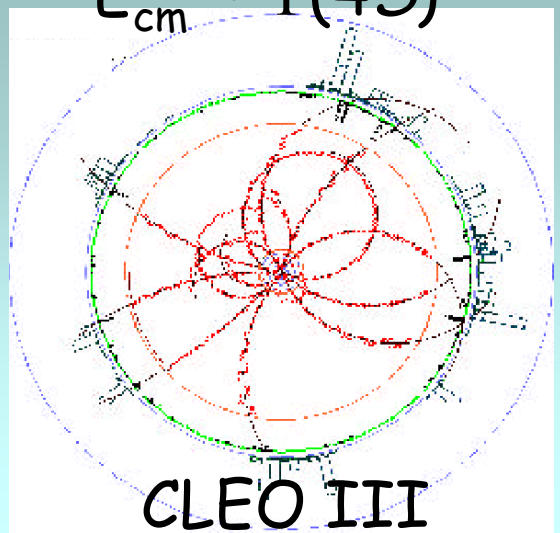
- Ability to run at cms energies from J/ψ up to Υ(5S)
- Simple conversion of detector from Υ(4S) to ψ(3770) running
- Addition of superconducting wigglers to CESR required for low energy running
  - Additional damping to compensate for lower synchrotron radiation





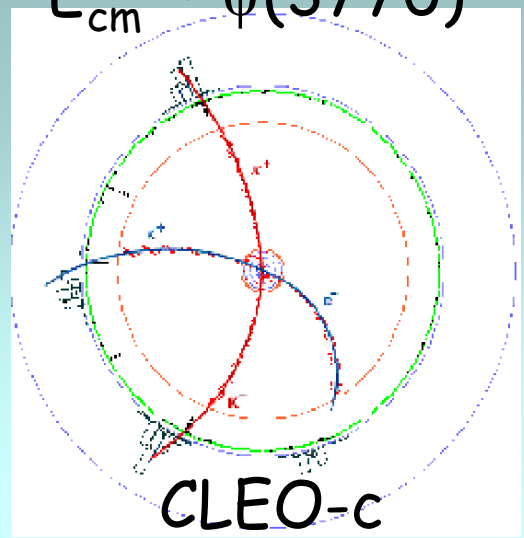
Running at the ψ(3770)

$E_{cm} \sim \Upsilon(4S)$



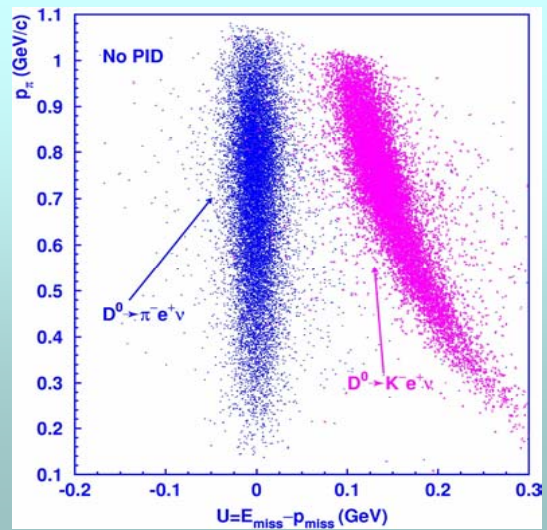
CLEO III

$E_{cm} \sim \psi(3770)$



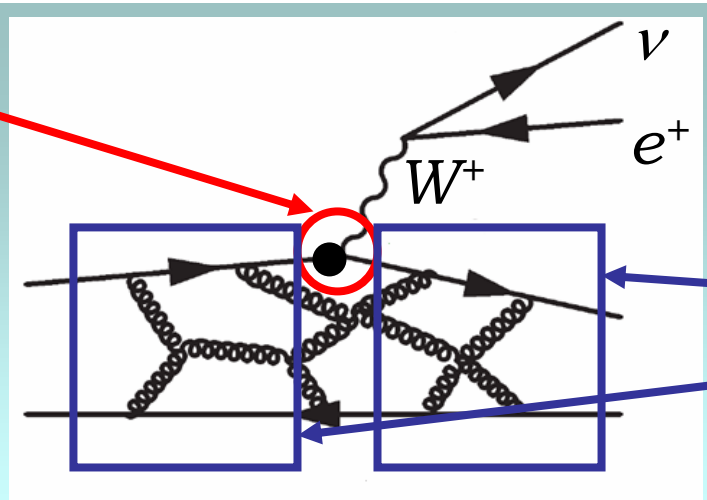
CLEO-c

- No extra energy for fragmentation particles
  - Known/coherent initial state
  - Clean neutrino reconstruction
  - Simple combinatorics
- Large cross section
- Good kinematic particle ID



Impact of CLEO-c Measurements

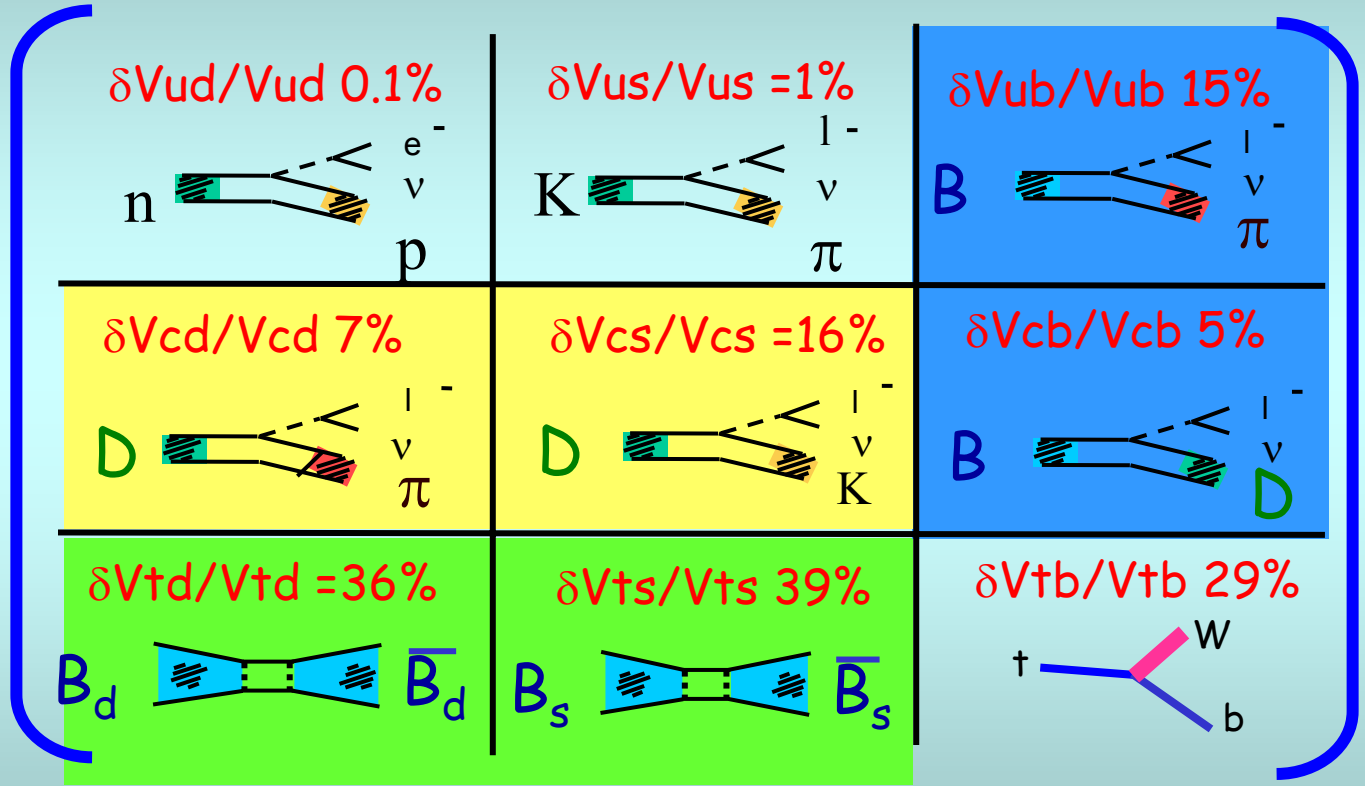
Electroweak Physics



- Calibration and validation of Lattice QCD
- Test theoretical form factor calculations and models
  - Impacts prediction of form factors for B meson decays
- Measurements of $|V_{cs}|$ and $|V_{cd}|$
- Improved decay constants f_B possible from CLEO-c f_D measurement + LQCD
- Improved measurement of many important normalization modes

The Future of Precision Flavor Physics

The Goal: Measure all CKM matrix elements and associated phases in order to over-constrain the unitary triangles



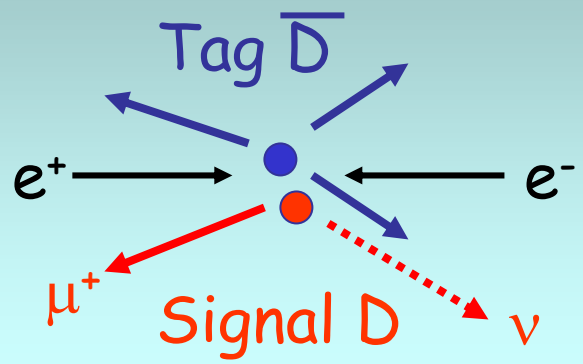
CLEO-c

CLEO-c + Lattice QCD +B factories

CLEO-c + Lattice QCD +B factories + ppbar

D Leptonic Decays: $D^+ \to \mu^+ \nu$

Getting the ABSOLUTE branching fractions... "Other side D" tag

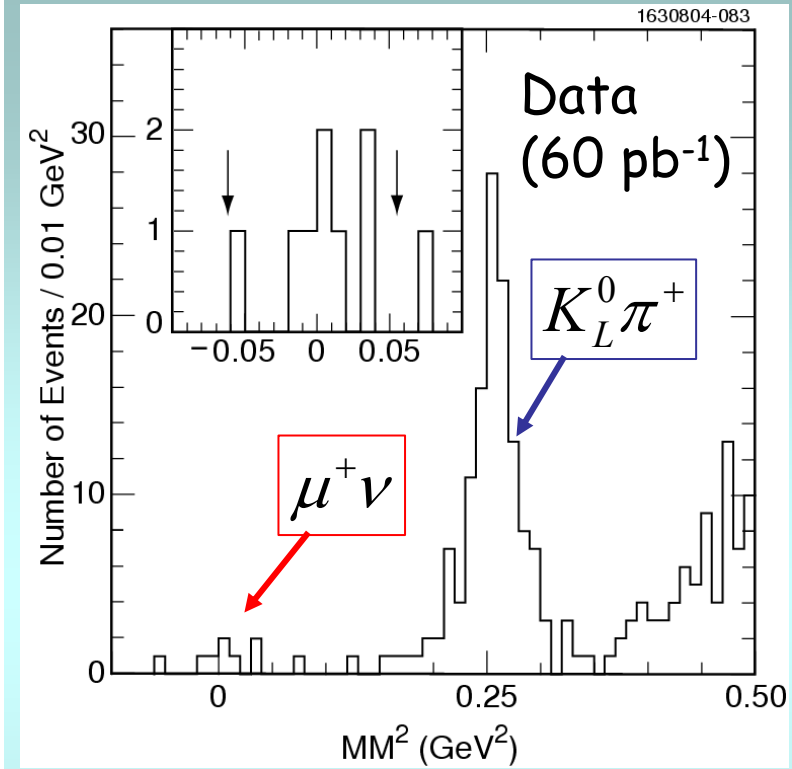


- Tag D decay modes:
  - $D^- \to K^+\pi^-\pi^-$
  - $D^- \to K^+\pi^-\pi^-\pi^0$
  - $D^- \to \overline{K}^0_S\pi^-$
  - $D^- \to \overline{K}^0_S\pi^-\pi^-\pi^+$
  - $D^- \to \overline{K}^0_S\pi^-\pi^0$

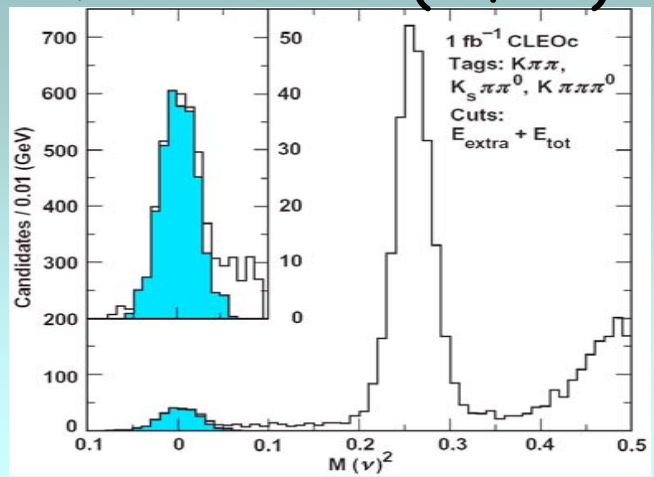
- Many large BR tag modes
  - ~25% Efficiency for reconstructing a tag
- Signal is very pure after tagging
  - 28651 +/-207 tag cand.
- Additional charged track presumed to be μ^+
- Fit for ("missing mass")^2:

$$\mathrm{MM}^2 = \left(E_{\mathrm{beam}} - E_{\mu^+}\right)^2 - \left(-\vec{p}_{D^-} - \vec{p}_{\mu^+}\right)^2$$

D Leptonic Decays: $D^+ \to \mu^+\nu$



Monte Carlo (1 fb^{-1})



8 candidate events

1 background event in signal region

$$B\left(D^+ \to \mu^+\nu\right) = \left(3.5 \pm 1.4 \pm 0.6\right) \times 10^{-4}$$
$$f_{D^+} = \left(202 \pm 41 \pm 17\right)\ \text{MeV}$$

First Observation!

Published in PRD
Phys. Rev. D, **70**, 112004 (2004)

4X statistics by end of April

Will also measure $D_s^+ \to \mu^+\nu$ in run above $D_s\bar{D}_s$ threshold

Exclusive Semileptonic D Meson Decays

Technique:

- Reconstruct one D meson in hadronic tagging channel
  - $M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$
  - $\Delta E = E_{beam} - E_{candidate}$
- Reconstruct the remaining observable tracks
- Use the missing energy (E_{miss}) and missing momentum ($|P_{miss}|$) in the event to form kinematic fit variable for the neutrino

$$U \equiv E_{\text{miss}} - \left|\vec{P}_{miss}\right|$$

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

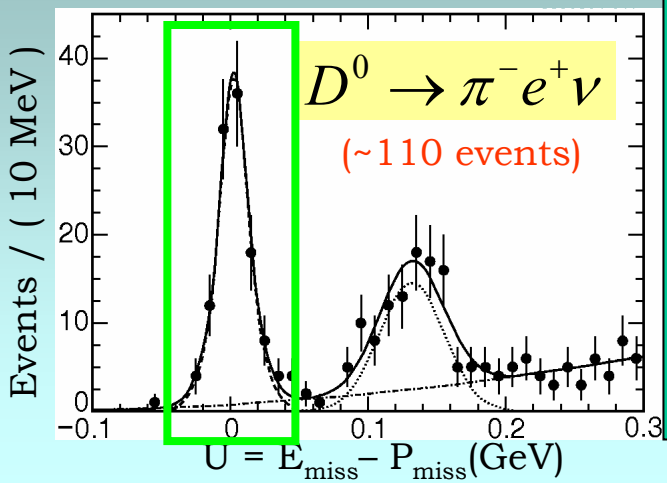
From fit of M_{bc} and ΔE for number of tags

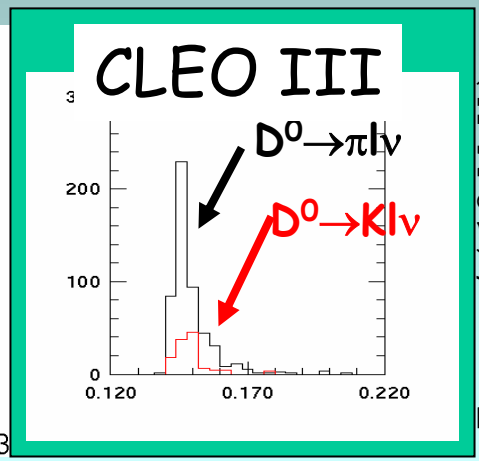
Both flavors combined:

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

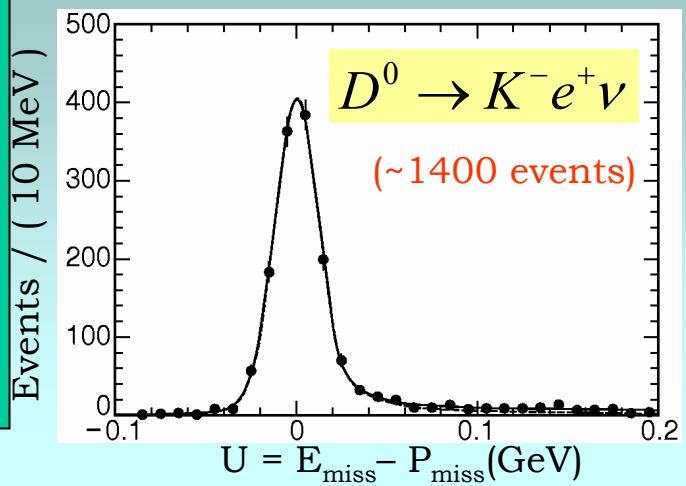
Exclusive Semileptonic D^0 Meson Decays

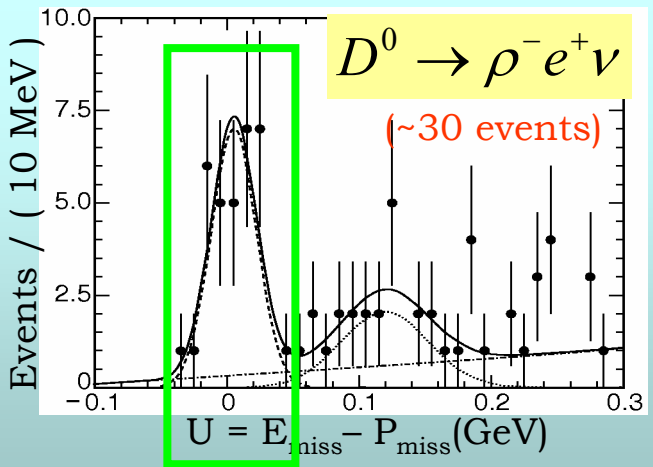
Cabibbo suppressed modes



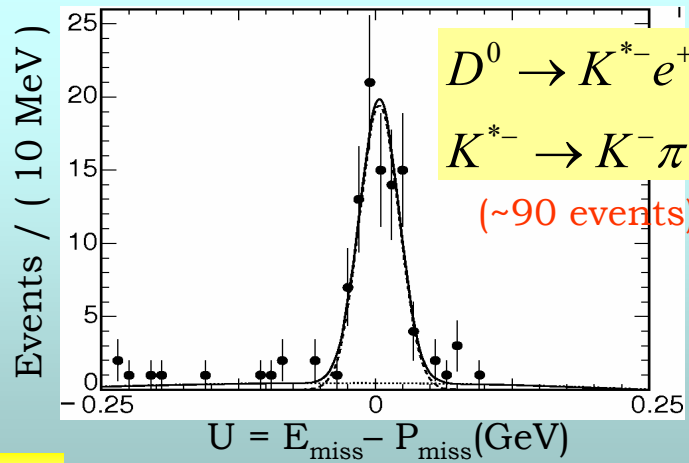


Cabibbo favored modes





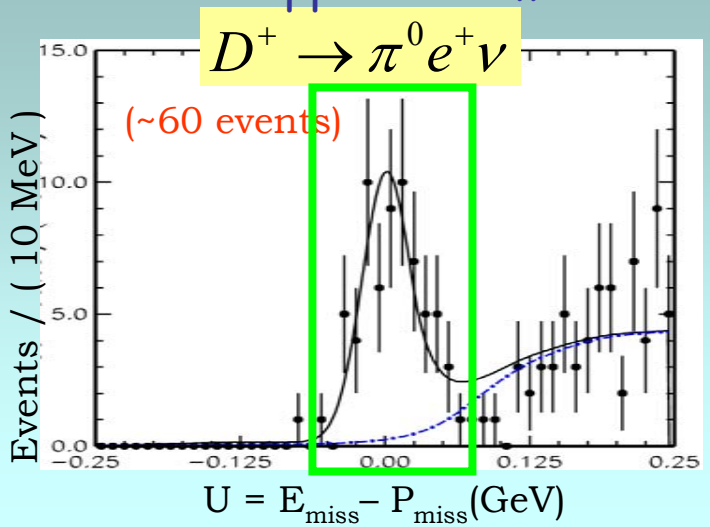
First Observation!



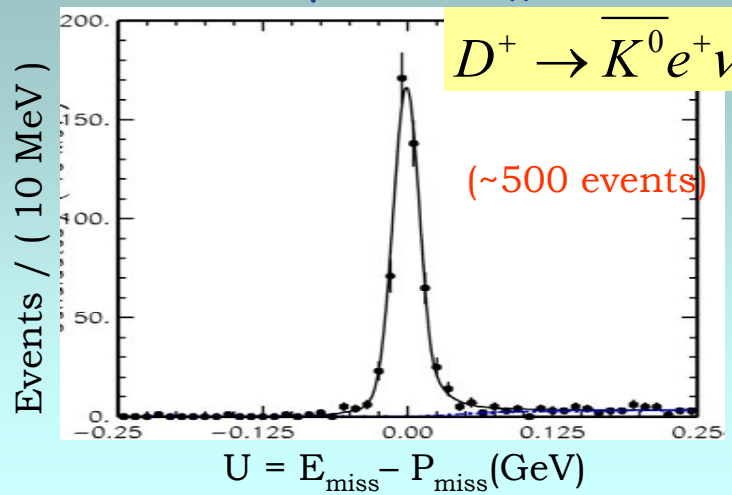
Preliminary

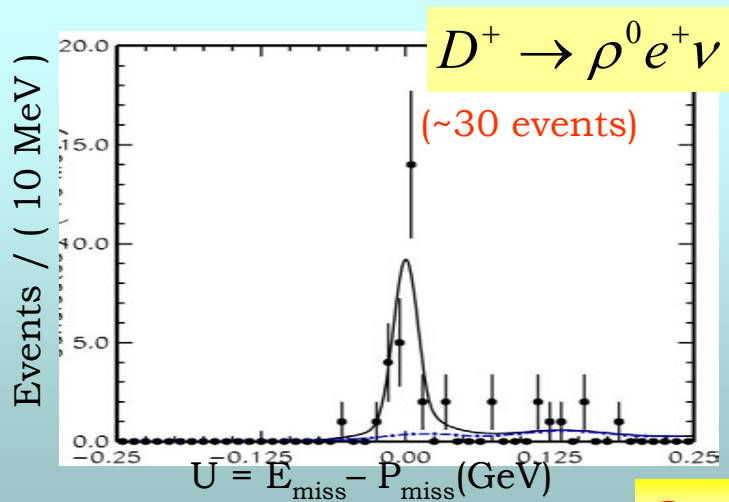
Exclusive Semileptonic D^+ Meson Decays

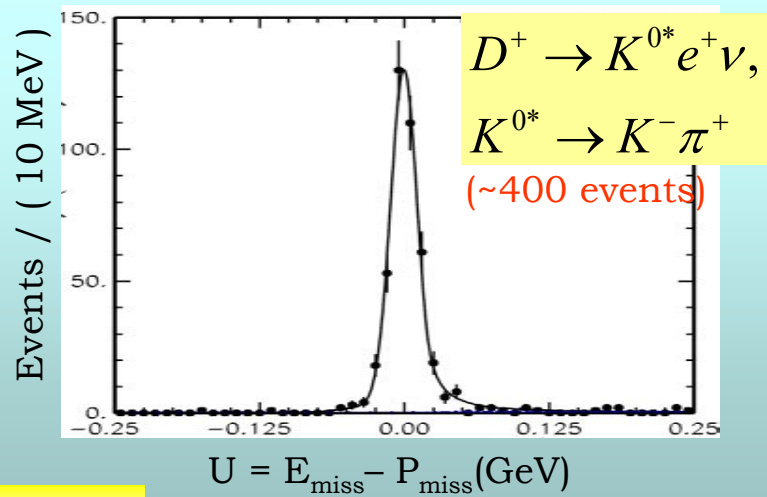
Cabibbo suppressed modes:



Cabibbo favored modes:



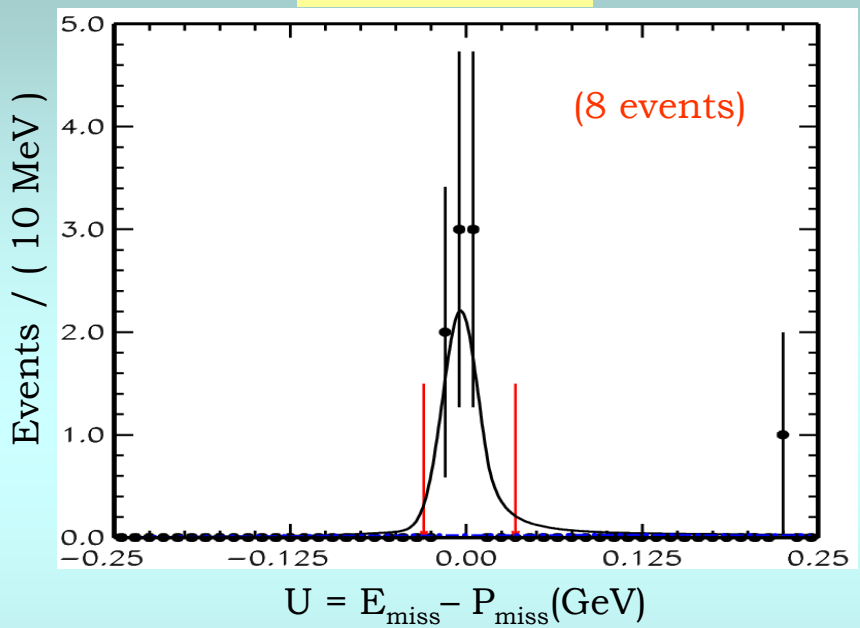




Preliminary

Exclusive Semileptonic D^+ Meson Decays

$D^+ \to \omega e^+ \nu$



First Observation!

Preliminary

Exclusive Semileptonic D^0 Decays

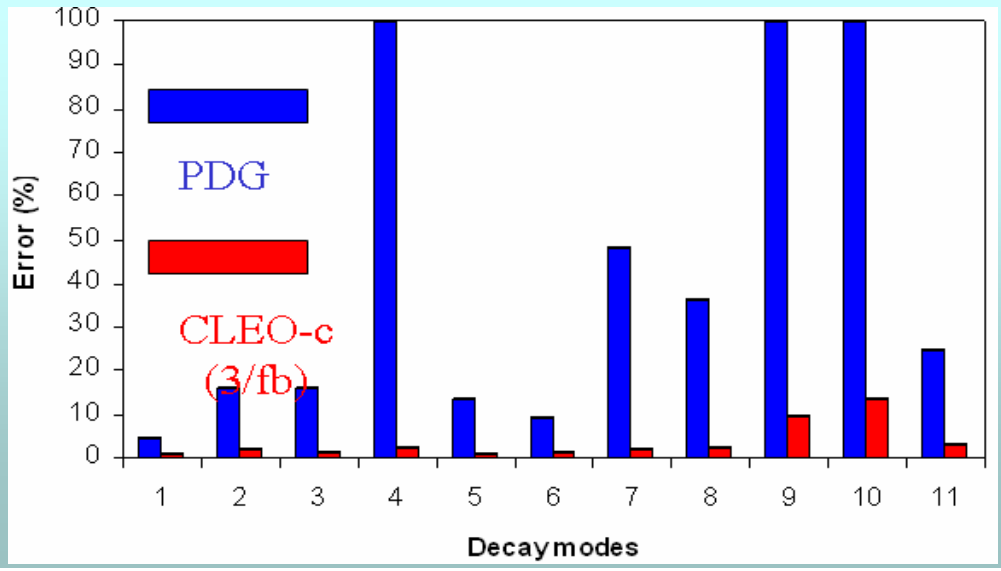
Now (~60 pb^{-1}):

Preliminary

Form factor measurements still to come—stay tuned!

CLEO-c goal:

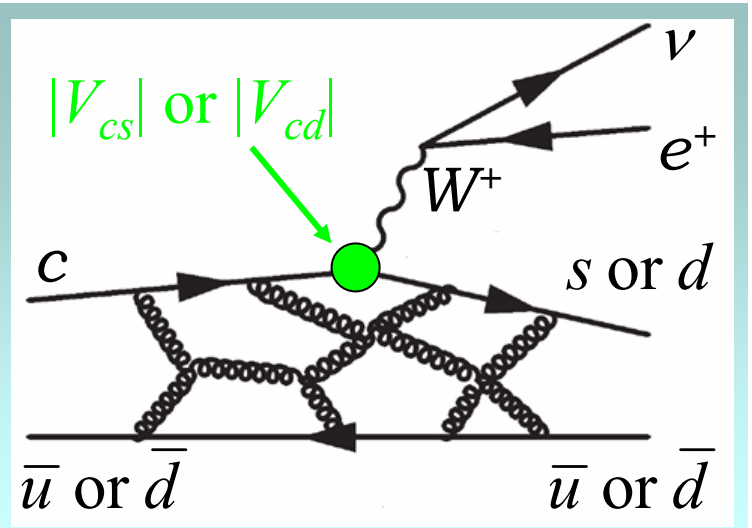
Decay Mode	$\mathcal{B}$ (%) (here)	$\mathcal{B}$ (%) (PDG-04)
$D^0 \to \pi^- e^+ \nu$	$0.25 \pm 0.03 \pm 0.02$	0.36 ± 0.06
$D^0 \to K^- e^+ \nu$	$3.52 \pm 0.10 \pm 0.25$	3.58 ± 0.18
$D^0 \to K^{*-}(K^-\pi^0) e^+ \nu$	$2.07 \pm 0.23 \pm 0.18$	2.15 ± 0.35
$D^0 \to \rho^- e^+ \nu$	$0.19 \pm 0.04 \pm 0.02$	N/A
$D^+ \to \bar{K}^0 e^+ \nu$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \bar{K}^{*0}(K^-\pi^+) e^+ \nu$	$5.70 \pm 0.28 \pm 0.25$	5.5 ± 0.7
$D^+ \to \pi^0 e^+ \nu$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \rho^0(\pi^+\pi^-) e^+ \nu$	$0.21 \pm 0.04 \pm 0.02$	0.25 ± 0.10
$D^+ \to \omega(\pi^+\pi^-\pi^0) e^+ \nu$	$0.17 \pm 0.06 \pm 0.01$	N/A



Extracting Decay Constants, FF, $|V_{cs}|$ and $|V_{cd}|$

Use ratio of semileptonic to leptonic branching ratios to eliminate CKM element and isolate hadronic terms:

$$\frac{\frac{d\Gamma}{dq^2}\left(D^+ \to \bar{K}^0 e^+ \nu_e\right)}{\Gamma\left(D^+ \to \mu^+ \nu_\mu\right)} = \left(3\pi^2 m_D m_\mu^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right)\right)^{-1} p_{\bar{K}^0}^3 \frac{\left|f_+\left(q^2\right)\right|^2}{f_{D^+}^2}$$



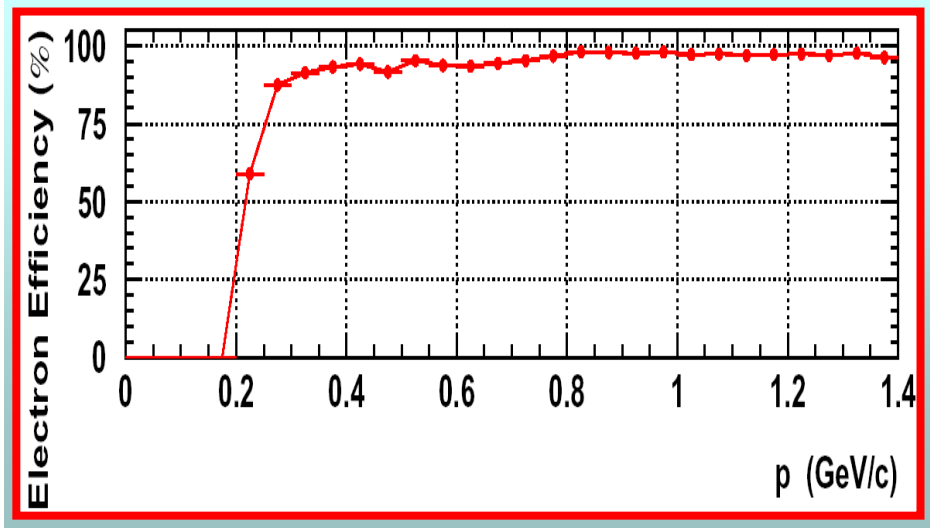
Theory is calibrated/tested with this data

Assuming a precision of ~3% for the SL form factors and ~1% for the decay constants is achieved by the theory:

- Error on $|V_{cd}|$ of ~1.4% (presently 7%) from $D^+ \to \mu^+\nu$ and $D \to \pi e \nu$
- Error on $|V_{cs}|$ of ~1.1% (presently 16%) from $D_s^+ \to \mu^+\nu$, $D_s^+ \to \tau^+\nu$ and $D \to Kl\nu$

Inclusive Semileptonic D Meson Decays

D-tag mode	Yield (10^3)
$D^0 \to K^-\pi^+$	9.1
$D^0 \to K^-\pi^+\pi^0$	12.5
$D^0 \to K^-\pi + \pi^0\pi^0$	2.7
$D^0 \to K^-\pi + \pi + \pi-$	13.8
Sum of all D^0 modes	38.1
$D^+ \to K^-\pi^+\pi^+$	13.9
$D^+ \to K^-\pi^+\pi^+\pi^0$	3.5
$D^+ \to K^0_S\pi^+$	1.8
$D^+ \to K^0_S\pi^+\pi^0$	2.6
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	2.4
$D^+ \to K^-K^+\pi^+$	1.2
Sum of all D^+ modes	25.5



Technique:

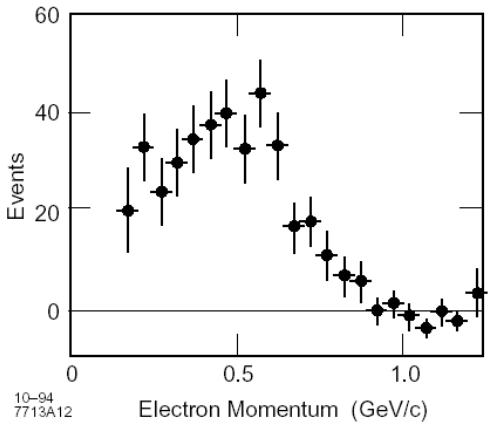
- Tag opposite side D meson
- Identify electron
  - Select correct *e* charge using opposite side D meson:
    - Charge of K for D^0
    - D meson charge for $D^{+/-}$
- Correct for electron efficiency and backgrounds
  - Efficiency from reweighted radiative Bhabhas
  - Fake rates

Inclusive Semileptonic D Meson Decays

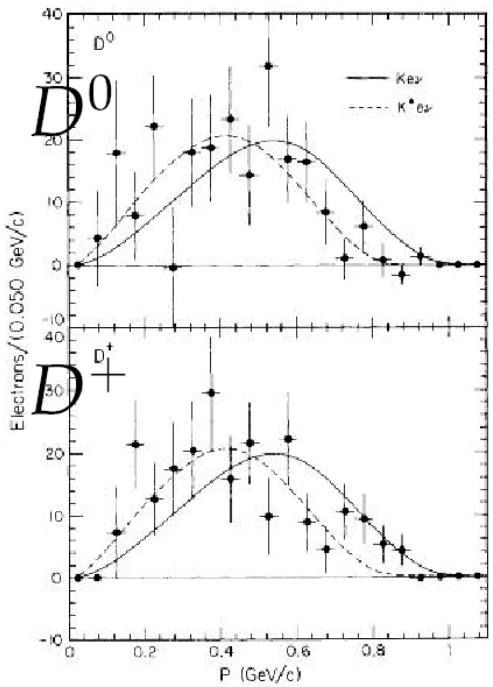
PDG $\mathcal{B}(D^0 \to e^+ X) = 6.87 \pm 0.28\%$
PDG $\mathcal{B}(D^+ \to e^+ X) = 17.2 \pm 1.9\%$

Preliminary

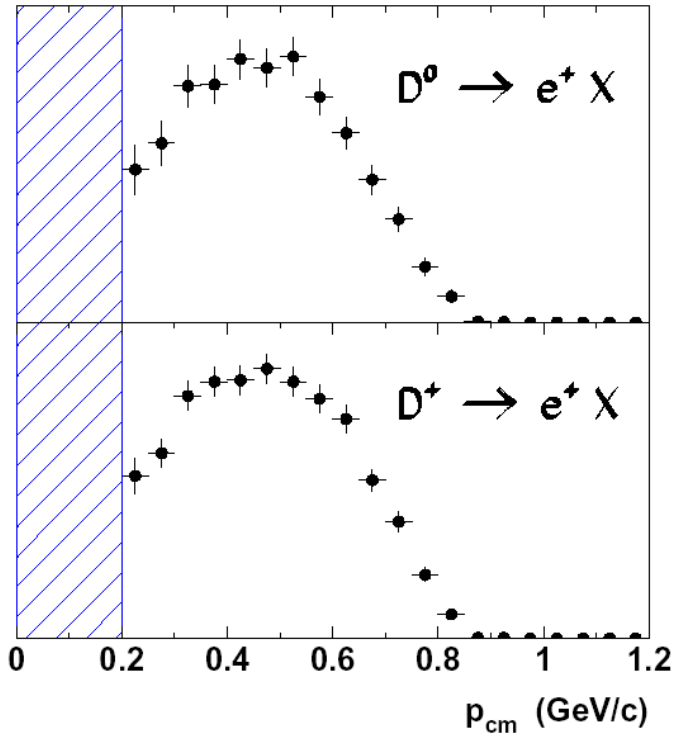
D^0/D^+



'79 DELCO

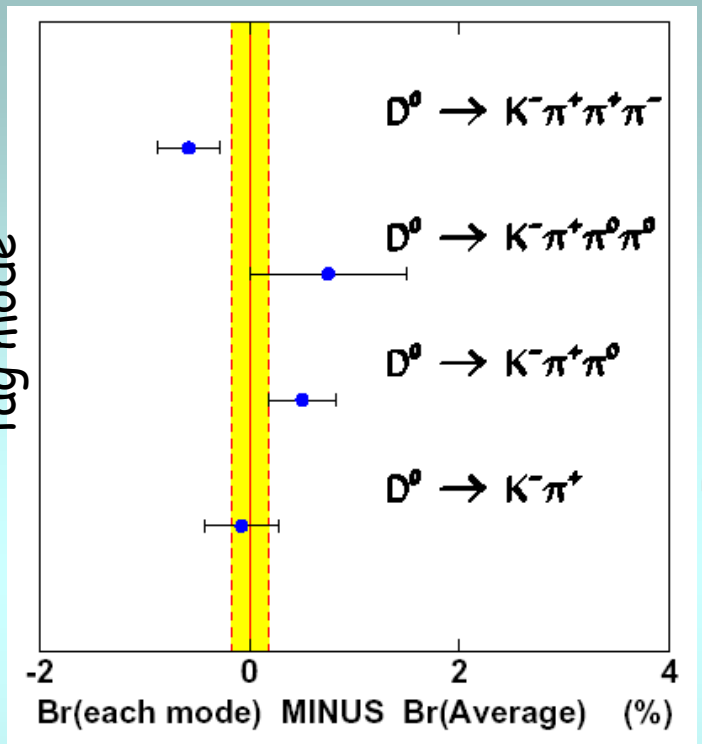


'85 MARK III

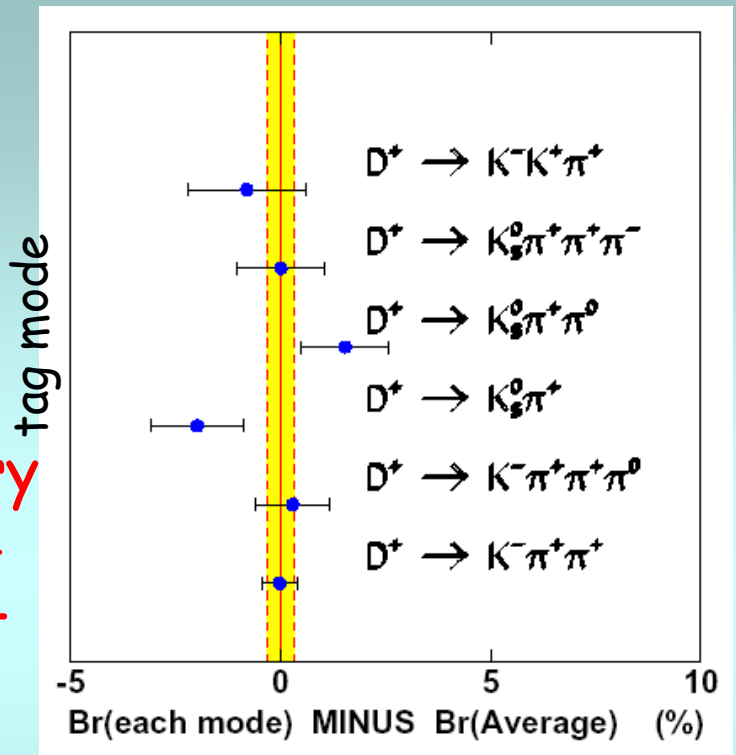


CLEO-c
(in D rest frame)
~60 pb^{-1}

Inclusive Semileptonic D Meson Decays



Preliminary Results--- No BR yet



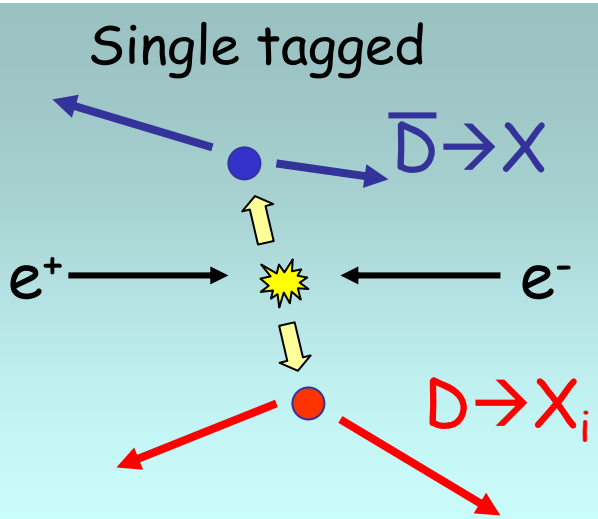
Combining tag modes:

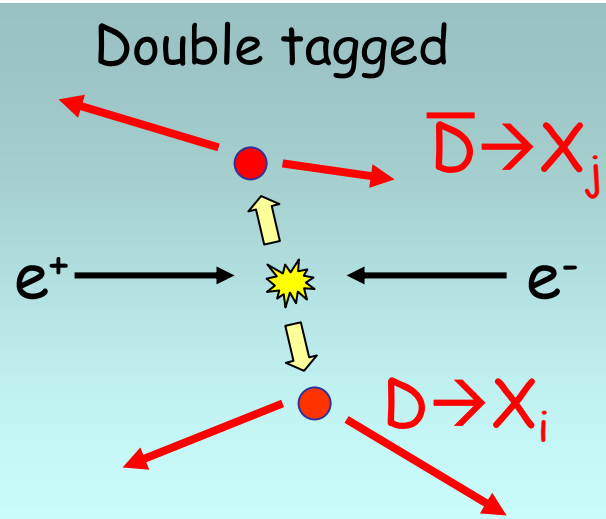
$$D^0 \to e^+X: \begin{cases} \text{CLEO-c:} & \sigma_{BR}(\text{stat}) \sim 0.2\% \\ \text{PDG:} & \sigma_{BR}(\text{stat} \oplus \text{sys}) \sim 0.3\% \end{cases}$$

$$D^+ \to e^+X: \begin{cases} \text{CLEO-c:} & \sigma_{BR}(\text{stat}) \sim 0.3\% \\ \text{PDG:} & \sigma_{BR}(\text{stat} \oplus \text{sys}) \sim 1.9\% \end{cases}$$

~60 pb^{-1}

D Hadronic BR's and Production Cross Sections





$$N_i = N_{D\overline{D}} B_i \varepsilon_i \qquad N_{ij} = N_{D\overline{D}} B_i B_j \varepsilon_{ij}$$

$$N_{D\overline{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

Independent of integrated luminosity!

D Hadronic BR's and Production Cross Sections

Fitting technique

- A simultaneous fit for all BR and cross sections is performed
  - Charged and neutral modes fit simultaneously

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

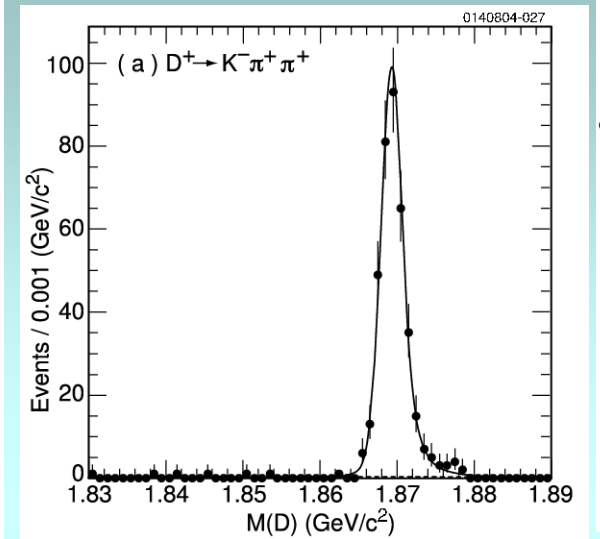
$$D^+ \to K^-\pi^+\pi^+,\ K^0_S\pi^+$$

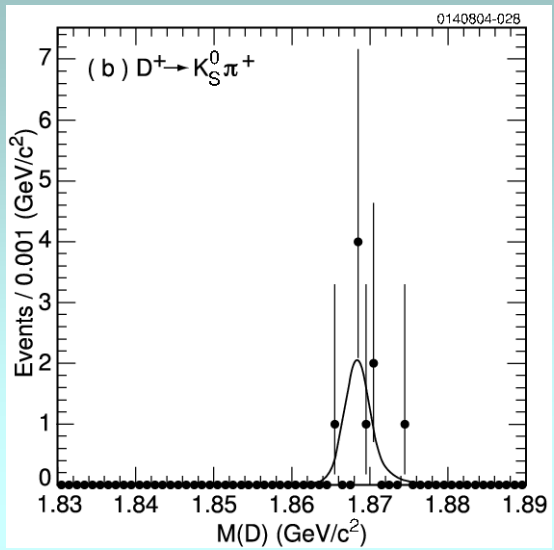
  - All correlations taken into account
    - These systematic errors are included in the fit
- Efficiencies
  - Denominator of efficiency may be determined using missing mass in data and MC (all particles measured)
    - Uncertainty on charged track efficiencies will go down by factor of four
    - Improvements to uncertainties on π^0 and K_S^0 efficiencies nearing completion

D Hadronic BR's and Production Cross Sections

Preliminary

Double Tag Yields





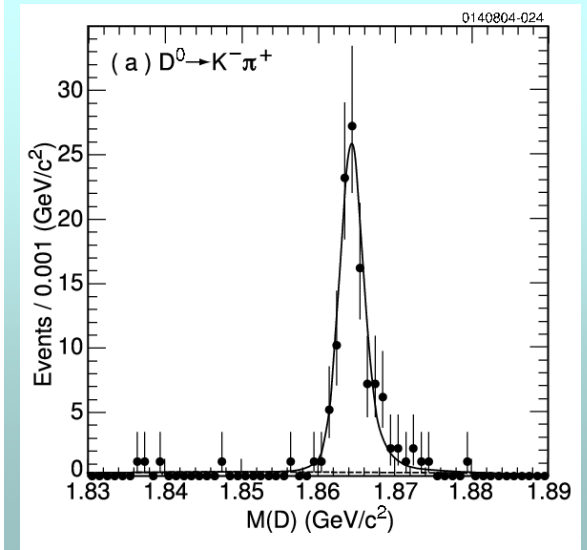
Key Variables for extracting yields:

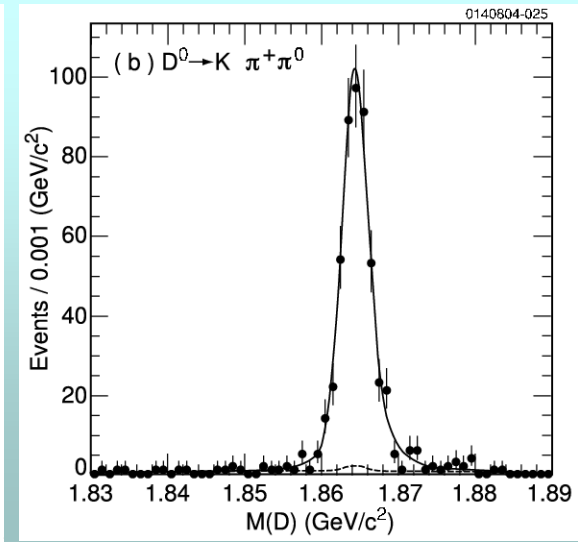
$$\Delta E = \left(E_K + E_\pi\right) - E_{beam}$$

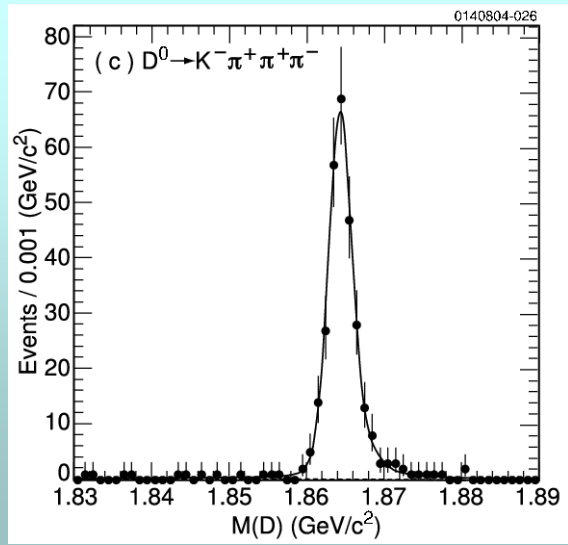
$$M_{bc} = \sqrt{E_{beam}^2 - \left(\vec{P}_K + \vec{P}_\pi\right)^2}$$

~2500 Double Tagged D^0

~500 Double Tagged D^+



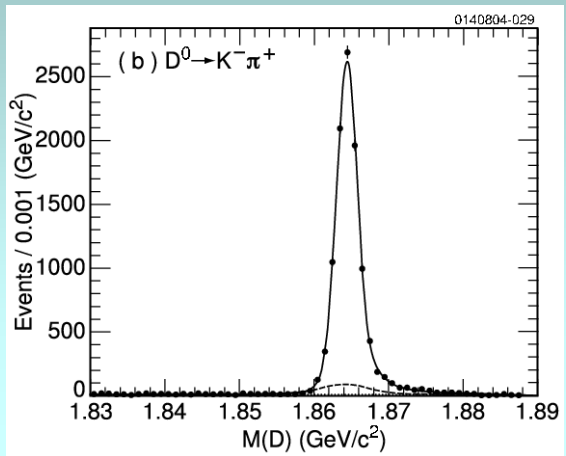




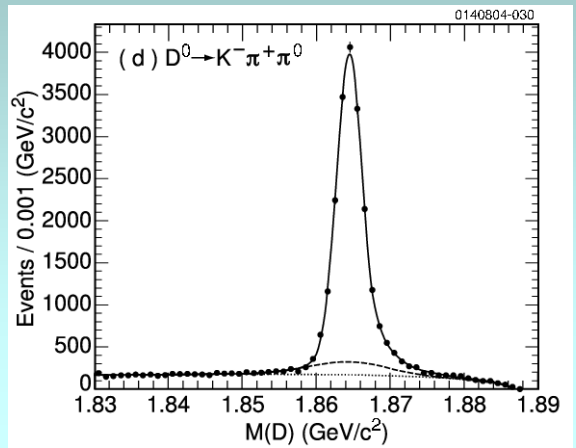
D Hadronic BR's and Production Cross Sections

Single Tag Yields

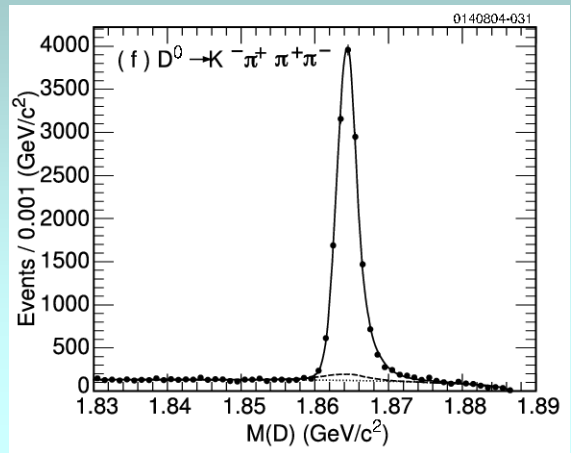
$D^0 \to K^-\pi^+$



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

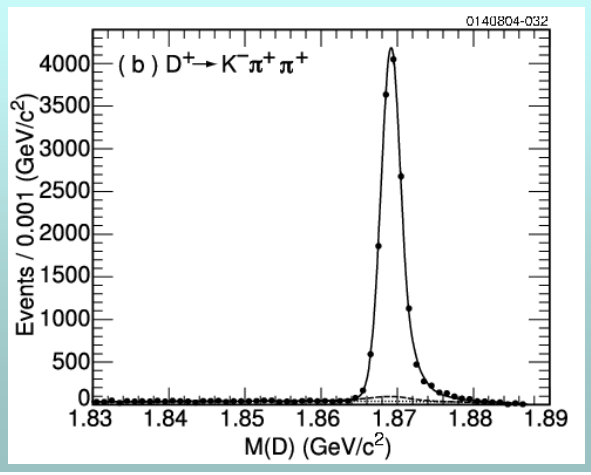


$D^0 \to K^-\pi^+\pi^-\pi^+$

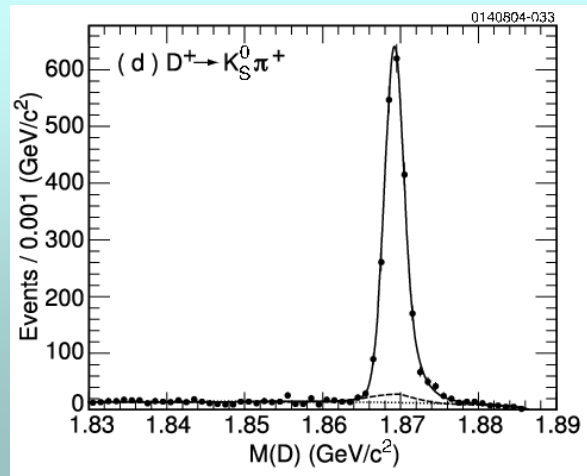


Preliminary

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



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



D Hadronic BR's and Production Cross Sections

Global Fit Results : $\begin{cases} \chi^2/N_{\text{dof}} = 9.0/16 \\ \text{C.L.} = 91.4\% \end{cases}$

Preliminary

~60 pb^{-1}

Cross sections:

$\sigma(e^+e^- \to D^0\bar{D}^0)$	3.47 ± 0.07 ± 0.15 nb
$\sigma(e^+e^- \to D^+D^-)$	2.59 ± 0.11 ± 0.11 nb
$\sigma(e^+e^- \to D\bar{D})$	6.06 ± 0.13 ± 0.22 nb
$N_{D^+D^-} / N_{D^0\bar{D}^0}$	0.75 ± 0.04 ± 0.02

Charged Modes:

$N_{D^+D^-}$	(1.48 ± 0.06 ± 0.04) x 10^5
$K^-\pi^+\pi^+$	0.098 ± 0.004 ± 0.008
$K_S^0\pi^+$	0.0161 ± 0.0008 ± 0.0015

Stat. Errors ~ 4.5%

Neutral Modes:

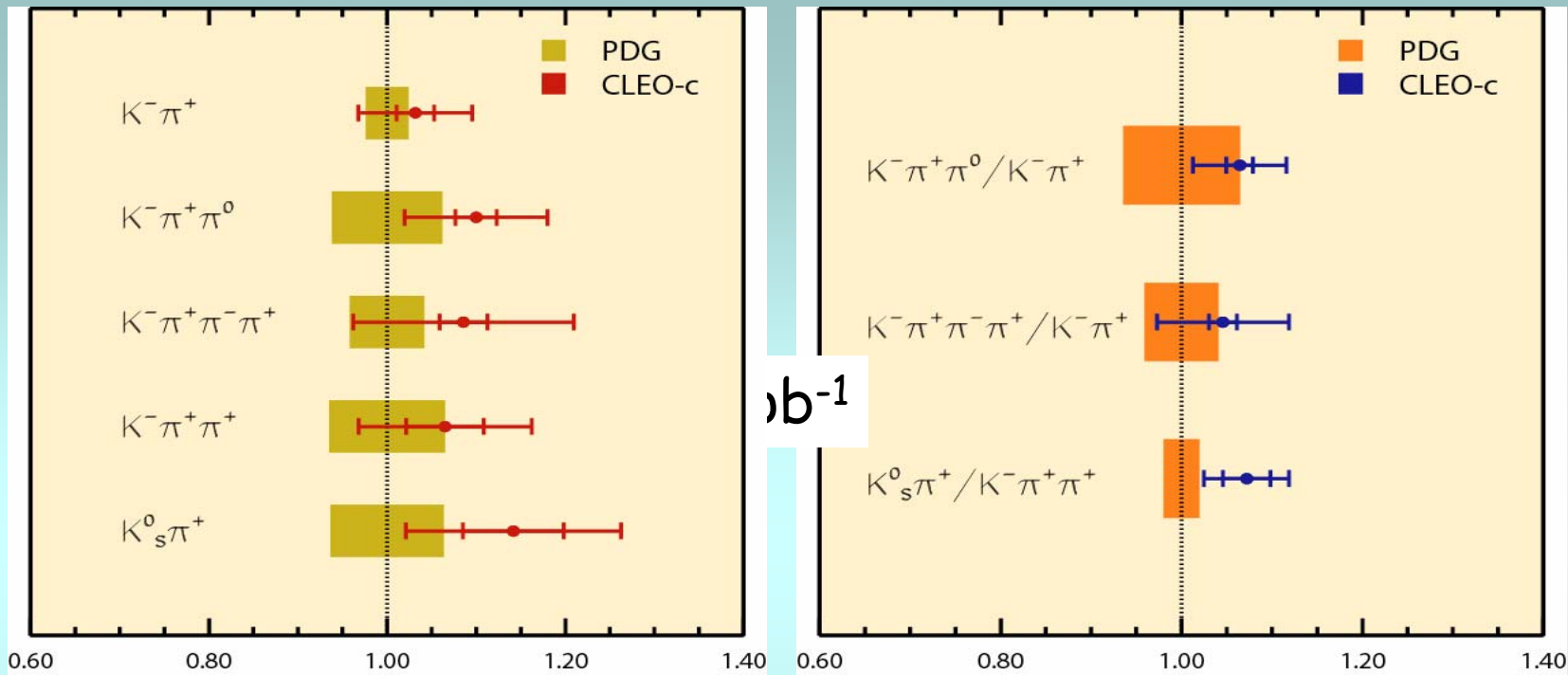
$N_{D^0\bar{D}^0}$	(1.98 ± 0.04 ± 0.03) x 10^5
$K^-\pi^+$	0.0392 ± 0.0008 ± 0.0023
$K^-\pi^+\pi^0$	0.143 ± 0.003 ± 0.010
$K^-\pi^+\pi^+\pi^-$	0.081 ± 0.002 ± 0.009

Stat. Errors ~ 2.0%

Ratios:

$K^-\pi^+\pi^0 / K^-\pi^+$	3.64 ± 0.05 ± 0.17
$K^-\pi^+\pi^+\pi^- / K^-\pi^+$	2.05 ± 0.03 ± 0.14
$K_S^0\pi^+ / K^-\pi^+\pi^+$	0.164 ± 0.004 ± 0.006

D Hadronic BR's and Production Cross Sections

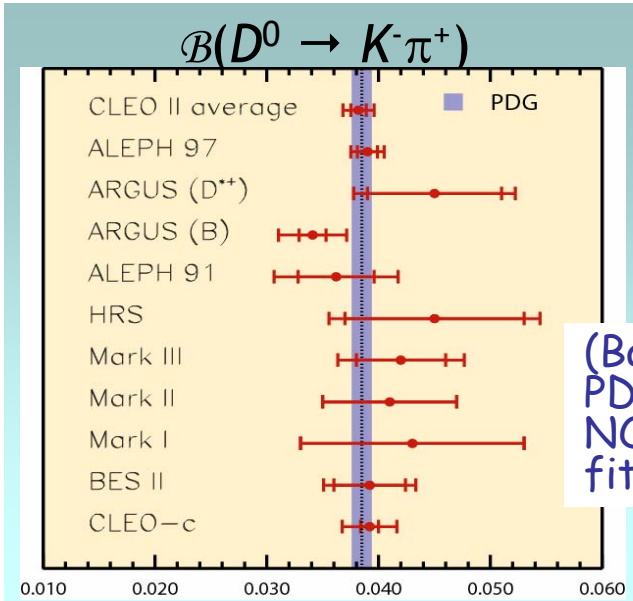


Results shown normalized to PDG values

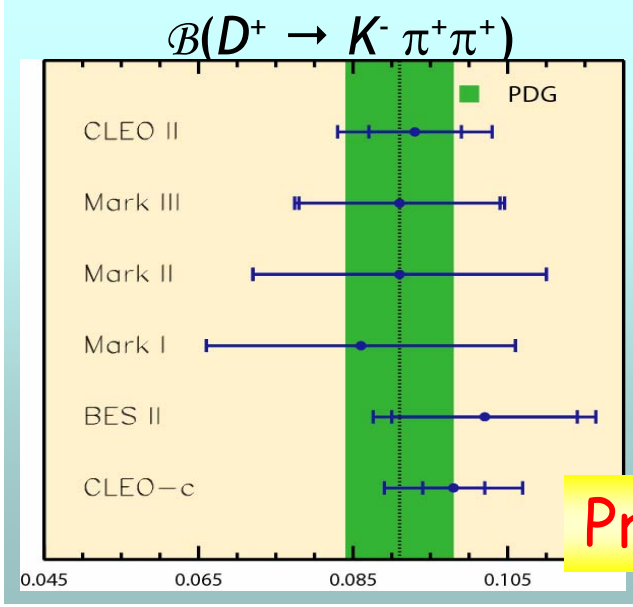
Preliminary

- PDG global fit includes ratios to $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
  - Charged and neutral modes are correlated in that fit
- Our results higher than PDG
  - Final state radiation (FSR) included in our results and not in PDG results
    - 1-2% increase depending on mode

D Hadronic BR's and Production Cross Sections



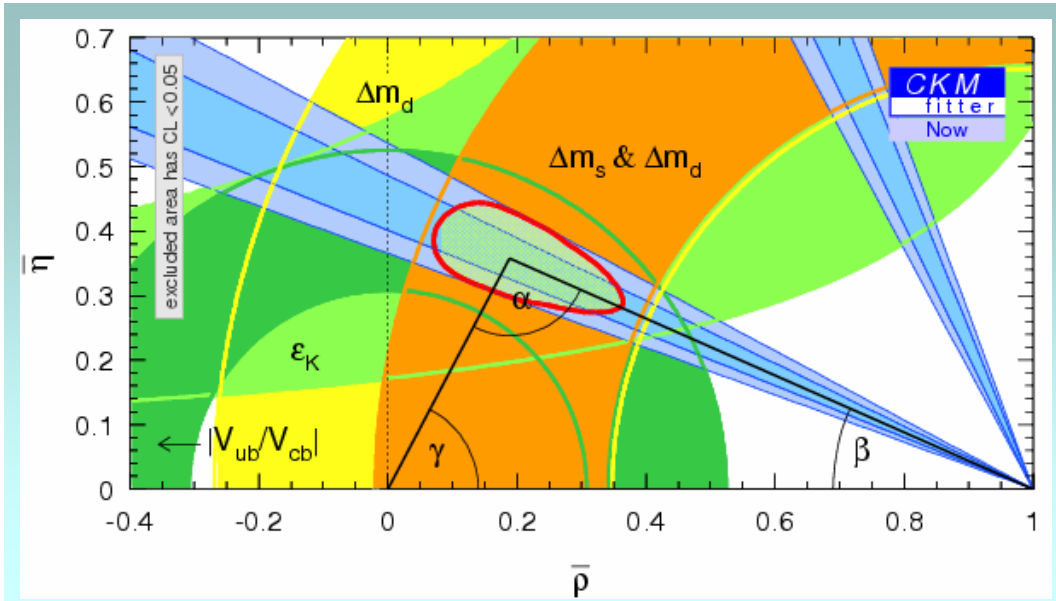
(Bands are PDG average, NOT global fit)



Preliminary

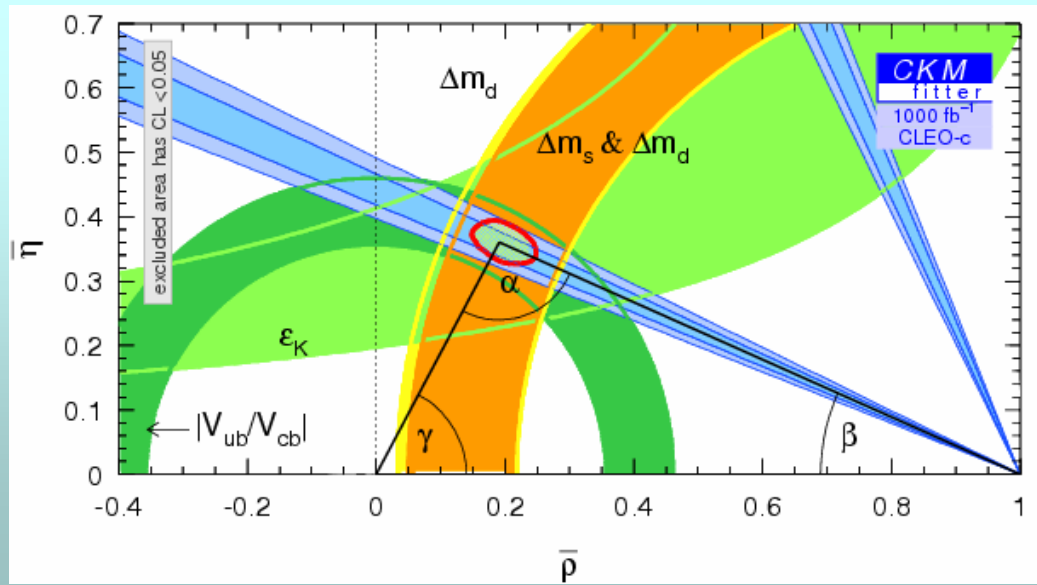
- Branching fractions and cross sections are competitive with world averages with only ~60 pb^{-1}
- Results are presently systematics limited but improving
  - Dominant per track systematic error recently improved by factor of 4!
  - Most systematic errors will improve with luminosity, however
- Four more D^+ modes being added (3X DT statistics)
- These measurements will impact the determination of $|V_{cb}|$ (from $B \to D^* l\nu$)

CLEO-c Impact on the Unitarity Triangle



Now: Theory uncertainties dominate

With few % theory errors made possible by CLEO-c and 500 fb^{-1} each from the B factories:



Other CLEO-c Physics Not Covered in This Talk

- $\psi(3770)$
  - Data still coming in, luminosity improving
- ψ'
  - Large sample collected… lots of results
  - Observation of h_c
- E_{cm} ~ 4140 MeV (just above D_s pair threshold)
  - f_{Ds} from $D_s^+ \rightarrow \mu^+\nu$
  - D_s semileptonic decays
- J/ψ
  - Sample of 10^9 J/ψ's anticipated
  - Radiative J/ψ decays
  - Glueball candidates, hybrids, …

Summary

- CLEO-c is producing results that will have a broad impact on the field
  - These measurements are essential for other measurements at the B Factories and Tevatron to realize their full potential
- With only 60 pb^{-1} of $\psi(3770)$ data analyzed many measurements are already the best
- Exciting results on the horizon
  - More data on $\psi(3770)$
  - Data at E_{cm} above $2M_{Ds}$ threshold
  - J/ψ radiative decays