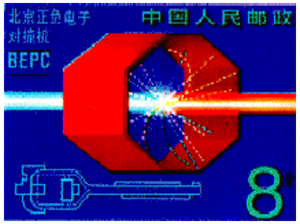
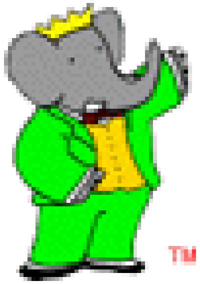
Charm Leptonic and Semileptonic Decays

Peter Zweber
University of Minnesota
(CLEO Collaboration)





Overview

Study of leptonic and semileptonic charm decays is an excellent environment to provide validation and calibration for theory, especially Lattice QCD (LQCD), so it can be applied with confidence to B physics (V_{ub}).

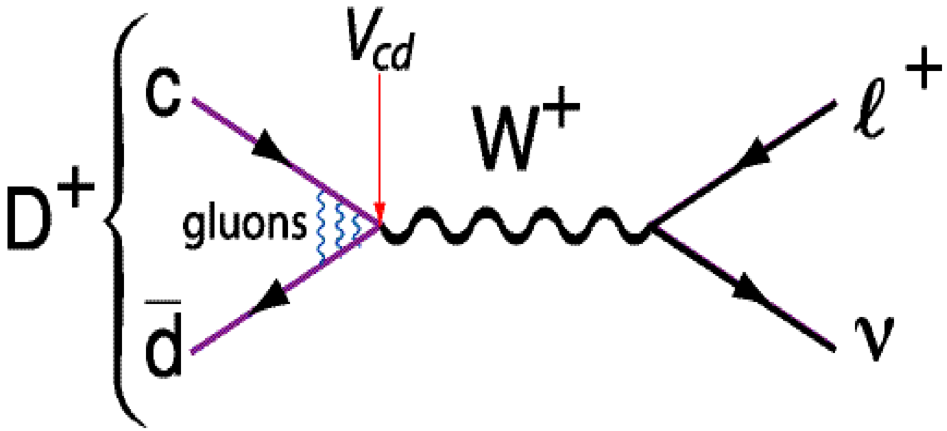
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

A validated theory can be used in precision measurements of V_{cs} and V_{cd}

Measuring f_D, f_{Ds}, and their ratio f_{Ds}/f_D in leptonic charm decays and studying form factors in semileptonic decays provide very stringent constraints on LQCD

$D^+_{(s)}$ Leptonic Decays

Probability for c and $\bar{d}$ ($\bar{s}$) annihilation is proportional to wave function overlap, related to the decay constant $f_{D(s)}$



$$\Gamma\left(D^+_{(s)} \to l^+ \nu\right) = \frac{G_F^2}{8\pi} f^2_{D_{(s)}} m_l^2 M_{D^+_{(s)}} \left(1 - \frac{m_l^2}{M^2_{D^+_{(s)}}}\right)^2 |V_{cd\,(s)}|^2$$

Decays also test Lepton Universality and search for New Physics

Standard Model (SM) predicts

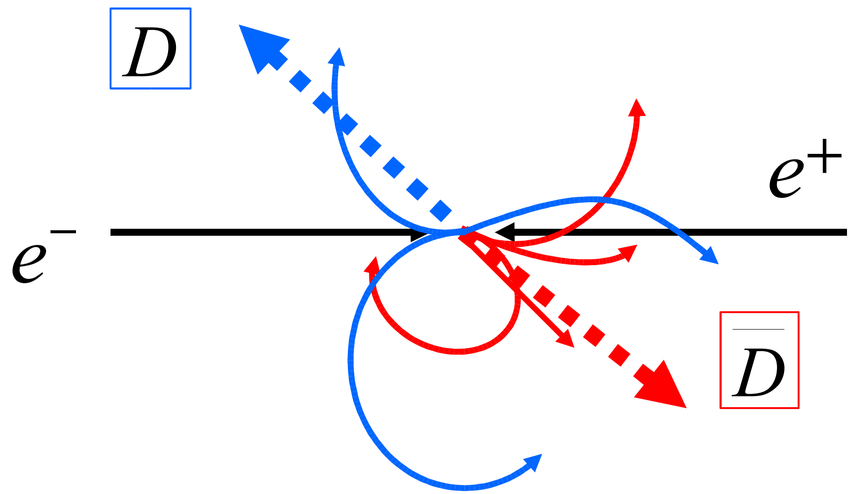
$$\Gamma(D^+ \to l^+\nu) = 2.35\times10^{-5} : 1 : 2.64 \quad (l = e : \mu : \tau)$$
$$\Gamma(D^+_s \to l^+\nu) = 2.35\times10^{-5} : 1 : 9.72 \quad (l = e : \mu : \tau)$$

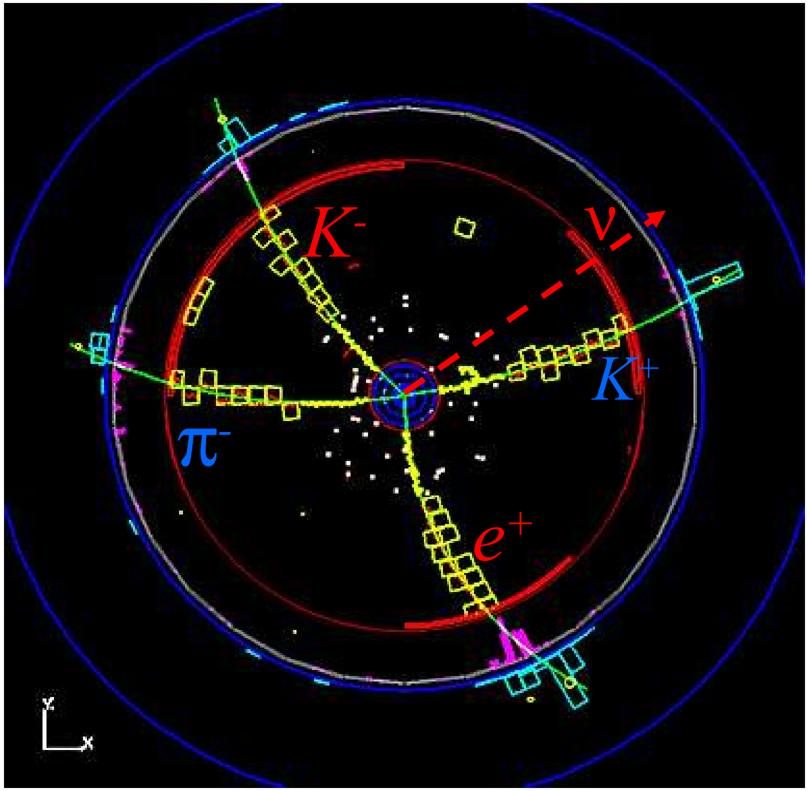
Use $|V_{cd\,(s)}|$ to determine $f_{D(s)}$ for comparison with Lattice QCD

D Tagging

BES, CLEO-c: $e^+e^- \rightarrow \psi(3770) \rightarrow D\,\bar{D}$

"MARK III Method"

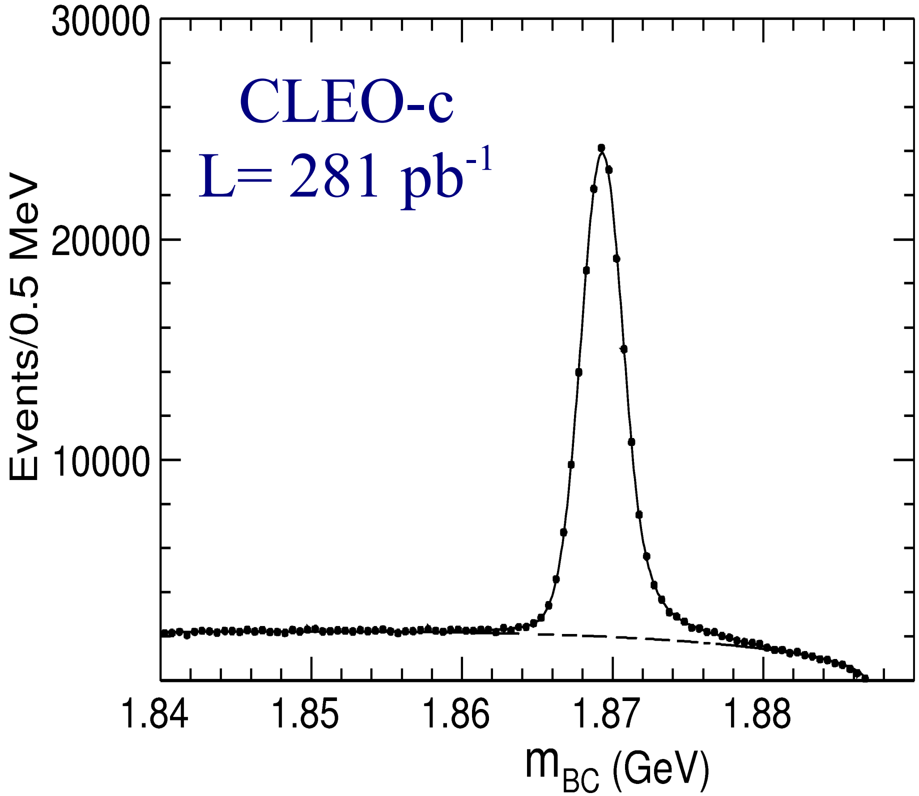




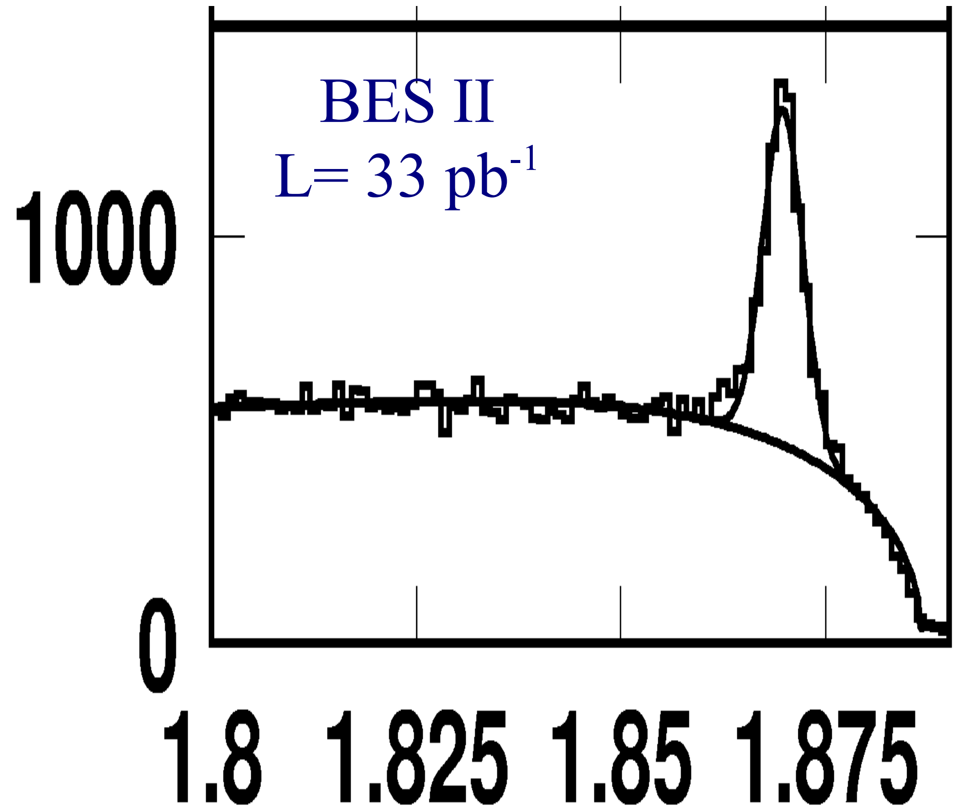
Blue: Tagged D Red: Signal D

Reconstruct hadronic D decay, reconstruct other side and look at neutrino w/ missing mass or $U_{miss} = E_{miss} - |\mathbf{P}_{miss}|$

D^+ Tag Samples @ $\psi(3770)$



$$m_{bc} = \sqrt{(E_{beam} - |\boldsymbol{p}_{\boldsymbol{D}_{tag}}|^2)}$$



<u>CLEO-c</u>

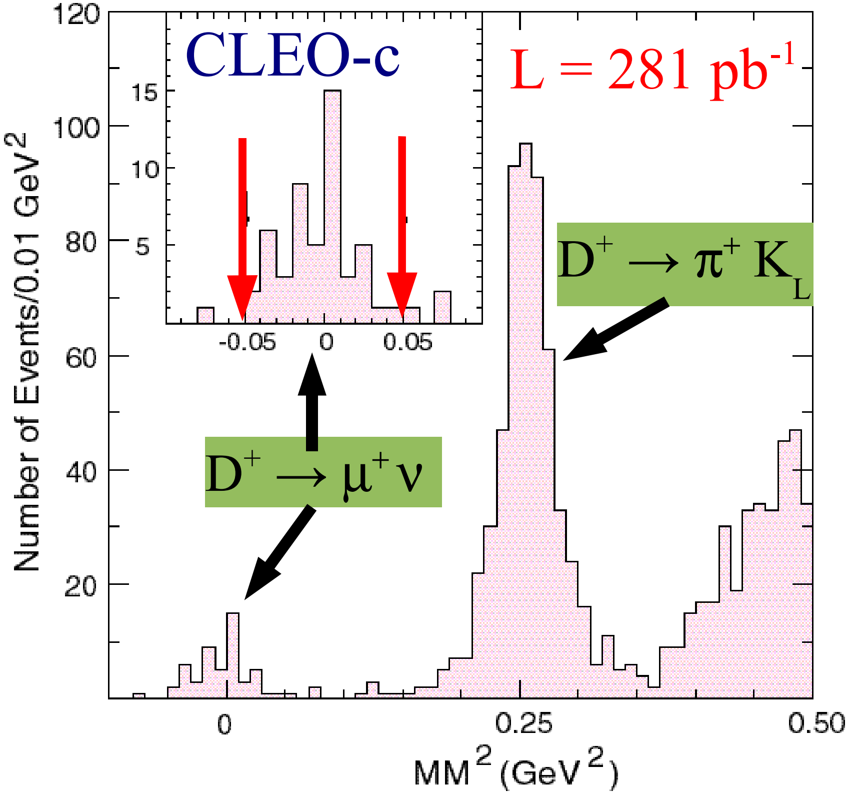
158k D^+ tags (6 modes)

<u>BES II</u>

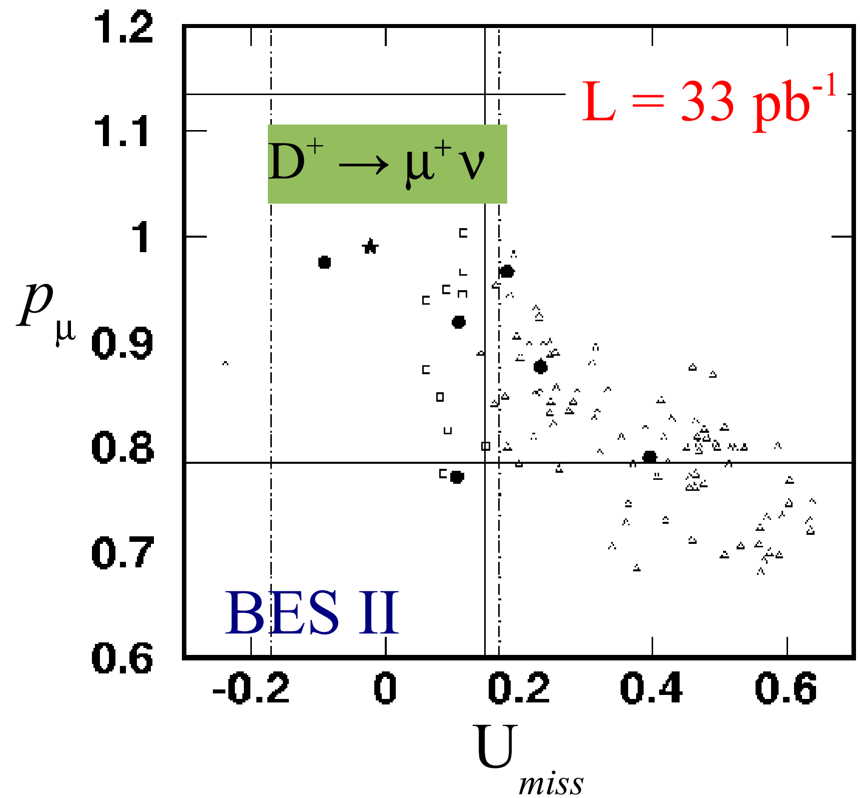
5300 D^+ tags (9 modes)

$D^+ \to \mu^+ \nu$

PRL 95, 251801 (2005)



$$MM^2 = \left(E_{beam} - E_\mu\right)^2 - \left(\boldsymbol{p}_D + \boldsymbol{p}_\mu\right)^2$$



PLB 610, 183 (2005)

$$U_{miss} = E_{miss} - |p_{miss}|$$

50 signal, 2.8 bkgd events

$B(D^+ \to \mu^+\nu) = (4.4 \pm 0.7 \pm 0.1)\times 10^{-4}$

$B(D^+ \to e^+\nu) < 2.3\times 10^{-5}$ (90% CL)

3 signal, 0.3 bkgd events

$B(D^+ \to \mu^+\nu) = (12\,^{+11}_{-5} \pm 1)\times 10^{-4}$

Determination of f_D

Using D lifetime = 1.040 ± 0.007 ps
$|V_{cd}| = 0.2238 \pm 0.0029$

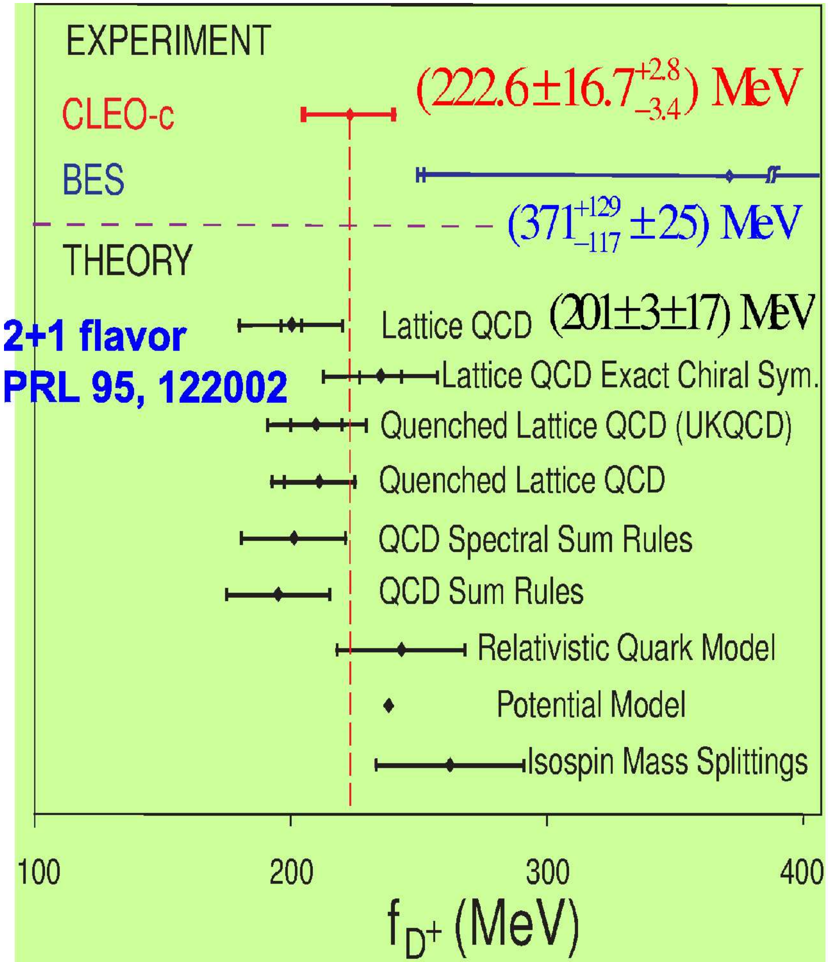
CLEO-c: $f_D = (222.6 \pm 16.7\,^{+2.8}_{-3.4})$ MeV

BES: $f_D = (371\,^{+129}_{-117} \pm 25)$ MeV

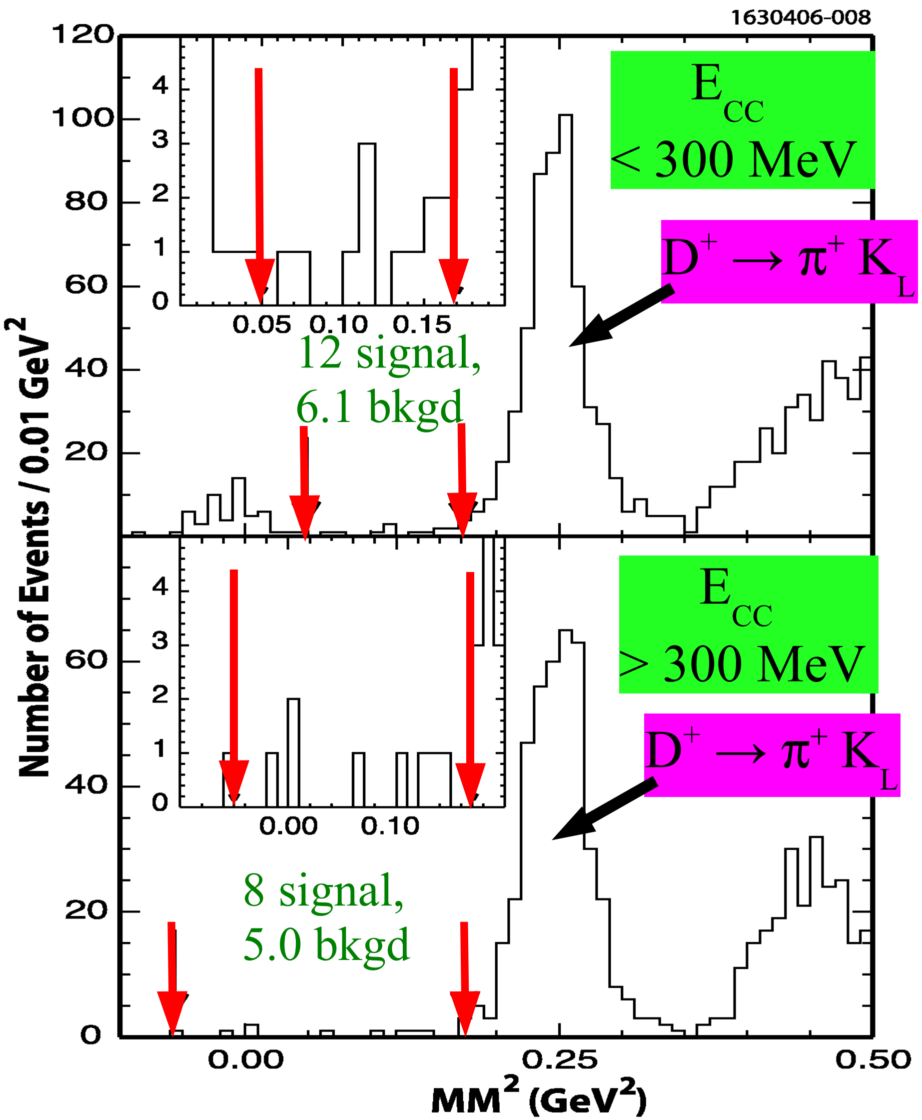
LQCD: $f_D = (201 \pm 3 \pm 17)$ MeV

FNAL/MILC: PRL 95, 122002 (2005)

CLEO-c result is statistics limited, plan to collect a total of ~750 pb^{-1} at ψ(3770) and measure f_D to ~4%



$D^+ \to \tau^+ \nu$



PRD 73, 112005 (2006)

CLEO-c, w/ the same sample, searched for $D^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\nu$

Select π tracks in two regions based on calorimeter (CC) info:

- E_{CC} < 300 MeV
- E_{CC} > 300 MeV

$B(D^+ \to \tau^+\nu) < 2.1\times10^{-3}$ (90% CL)

Using CLEO-c $B(D^+ \to \mu^+\nu)$

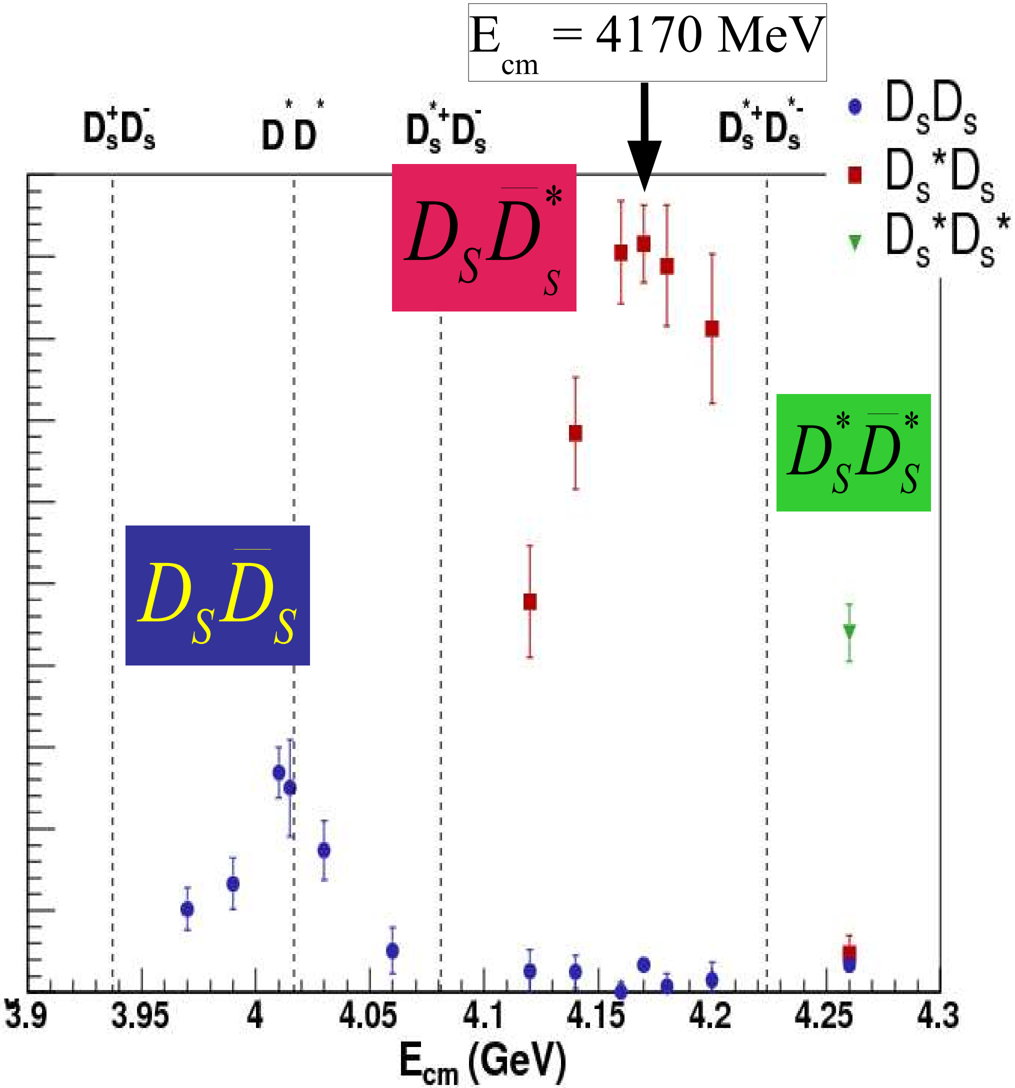
SM: $B(D^+ \to \tau^+\nu) = (1.1 \pm 0.2)\times10^{-3}$

$$\frac{[B(D^+ \to \tau^+\nu)/B(D^+ \to \mu^+\nu)]_{meas}}{[B(D^+ \to \tau^+\nu)/B(D^+ \to \mu^+\nu)]_{SM}} < 1.8$$

(90% CL)

D_s Sample @ CLEO-c

CLEO preliminary



Fall 2005:
Scanned E_{cm} = 3.97 – 4.26 GeV to find optimal D_s production

Optimal E_{cm} = 4170 MeV

Almost all D_s from $e^+e^- \rightarrow D_s\bar{D}_s^*$

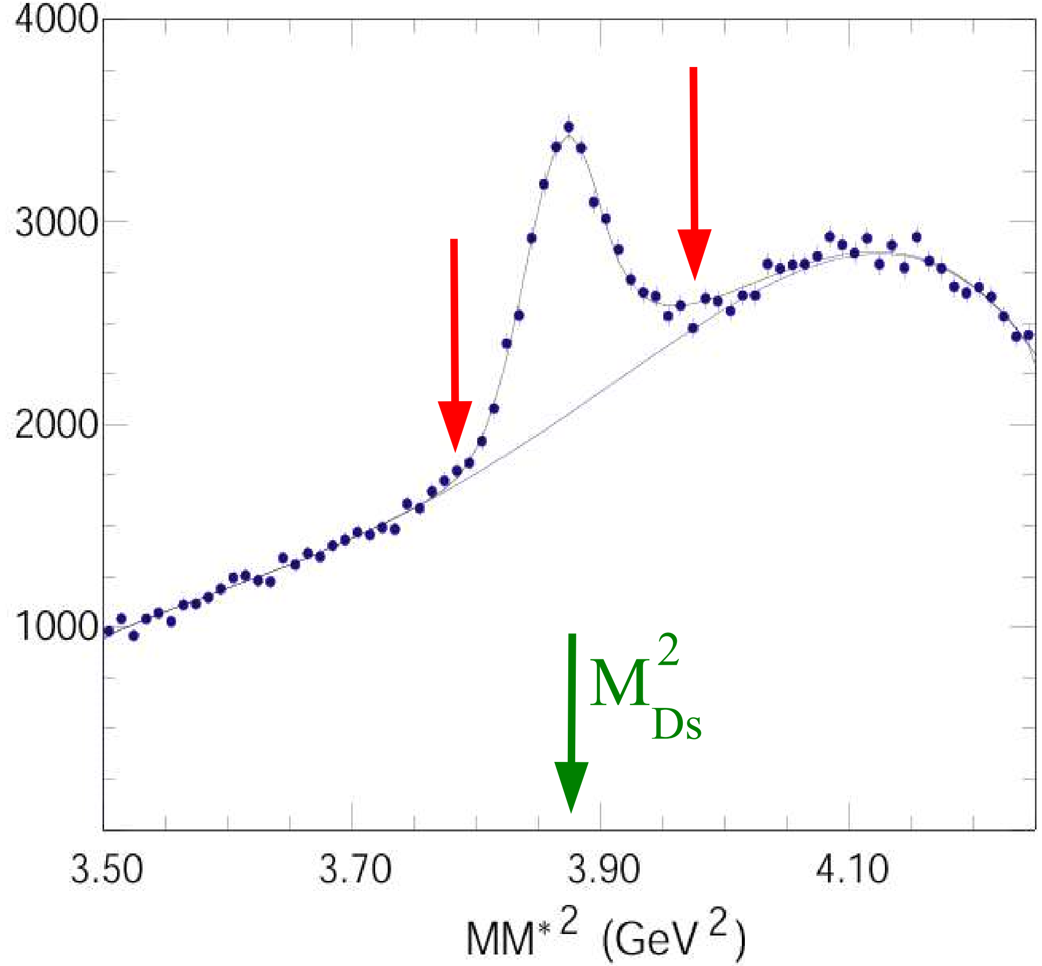
As of Summer 2006,
~320 pb^{-1} collected at 4170 MeV
(Results using ~200 pb^{-1})

D_s Tags from $e^+e^- \to D_s^* D_s$

Study $D_s \to \mu^+\nu$ decays by studying its recoil against D_s tag and γ ("D_s^* tag").

CLEO preliminary

CLEO CONF 06-17



8 D_s hadronic decays (tags):

$D_s \to K^+K^-\pi$, K_sK^+, $\pi^+\pi^+\pi^-$

$\to \pi^+\varphi(K^+K^-)$, $K^{*+}(K_s\pi^+)K^0(K^-\pi^+)$

$\to \pi^+\eta(\gamma\gamma)$, $\rho(\pi^+\pi^-)\eta(\gamma\gamma)$

$\to \pi^+\eta'(\pi^+\pi^-\eta(\gamma\gamma))$

11900 "D_s tags" after MM^{*2} selection

$$MM^{*2} = \left(E_{CM} - E_{D_s} - E_\gamma\right)^2 - \left(\boldsymbol{p}_{D_s} + \boldsymbol{p}_\gamma\right)^2$$

$D_s^+ \to \mu^+\nu, \tau^+\nu$ (I)

Three cases

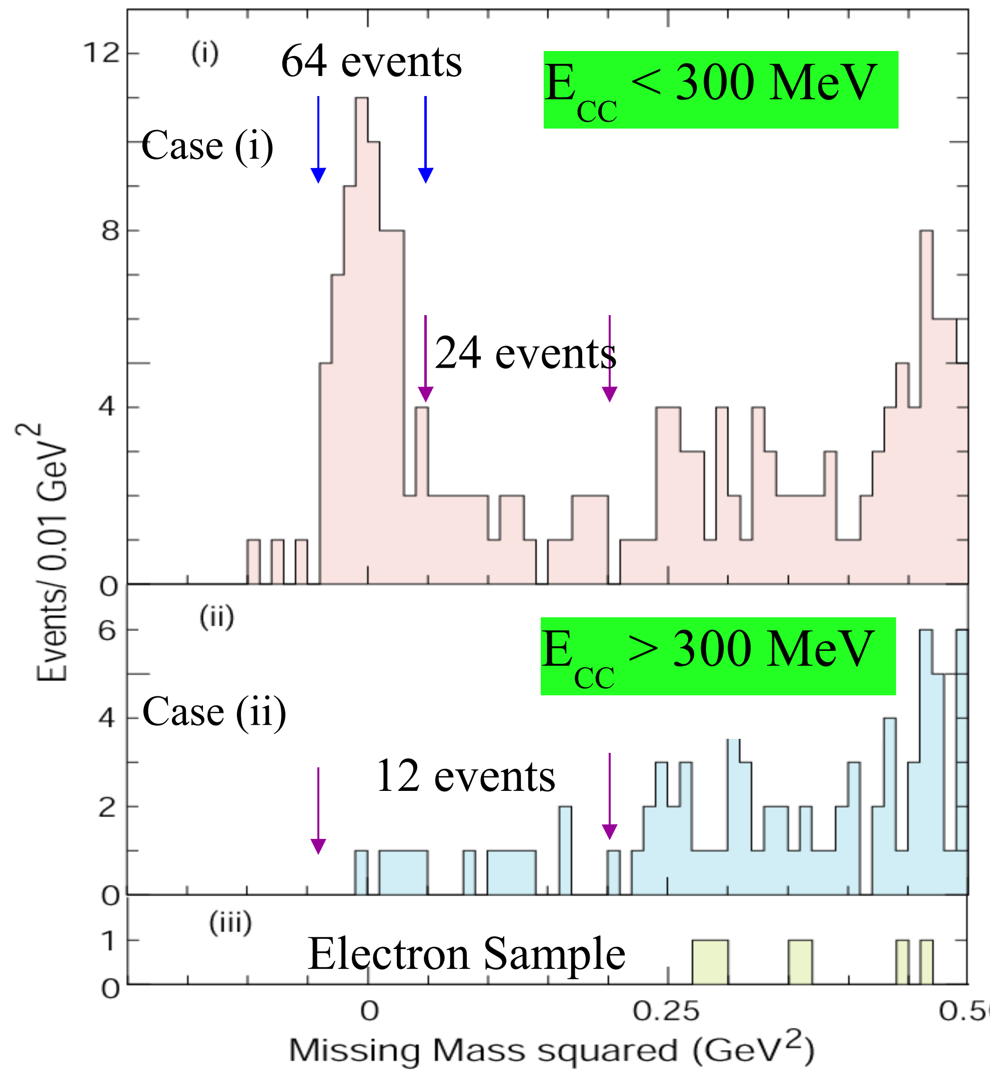
(i) Track has E_{CC} < 300 MeV (μ, π)

(ii) Track has E_{CC} > 300 MeV (π)

(iii) Track consistent with electron

Cases (i) and (ii) allow for simultaneous study of $D_s^+ \to \tau^+\nu$, $(\pi^+\nu)\ \nu$

Look at missing mass squared (MM^2) for enhancements in signal regions



CLEO preliminary

$$MM^2 = \left(E_{CM} - E_{D_s} - E_\gamma - E_\mu\right)^2 - \left(\boldsymbol{p}_{D_s} + \boldsymbol{p}_\gamma + \boldsymbol{p}_\mu\right)^2$$

$D_s^+ \to \mu^+\nu, \tau^+\nu$ (II)

$D_s^+ \to \mu^+\nu$ [Case (i)]

64 signal, 2 bkgd events, use SM for $\tau^+\nu$ yield near $MM^2 = 0$ ($\tau\nu/\mu\nu$ ratio)

$B(D_s^+ \to \mu^+\nu) = (0.66\pm0.09\pm0.03)\%$

$D_s^+ \to \tau^+\nu, (\pi^+\nu)\,\nu$ [Case (i) + Case (ii)]

Total of 36 signal, 4.8 bkgd events

$B(D_s^+ \to \tau^+\nu) = (7.1\pm1.4\pm0.3)\%$

Using SM $\tau\nu/\mu\nu$ ratio to average,

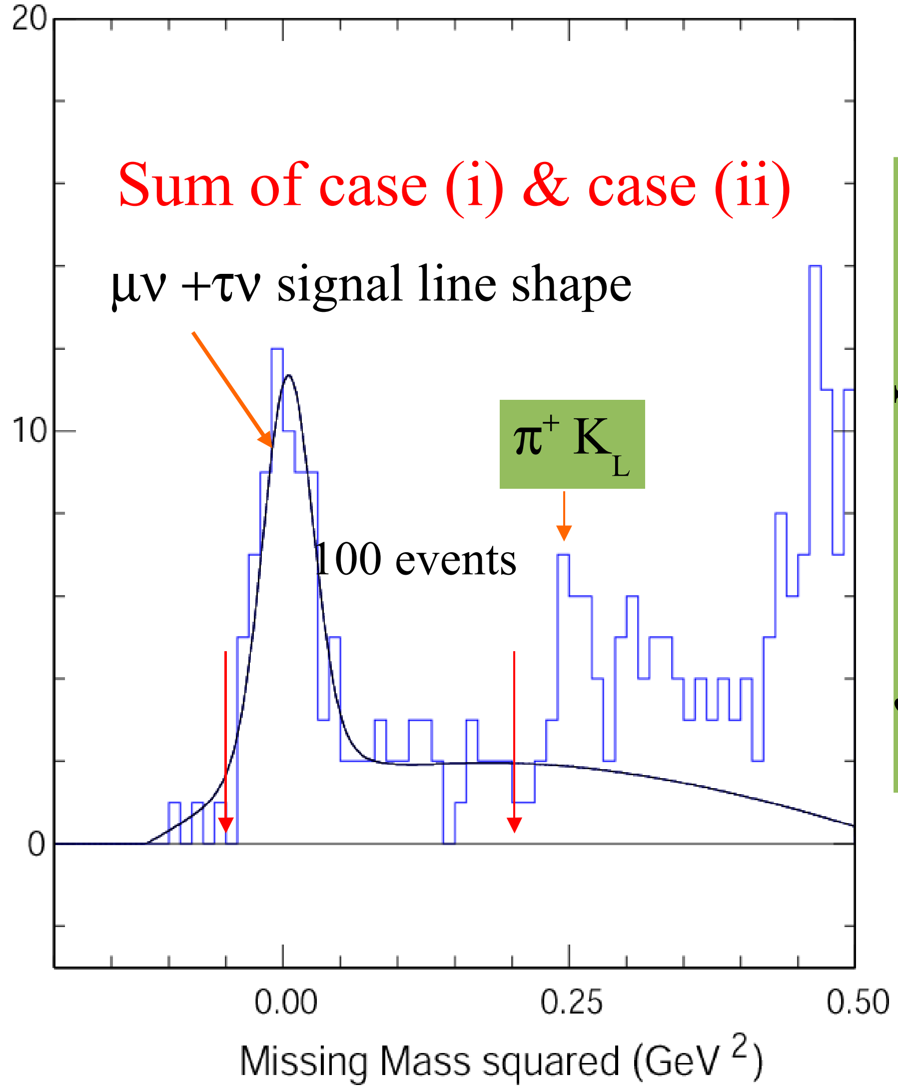
$B(D_s^+ \to \mu^+\nu) = (0.664\pm0.076\pm0.028)\%$

$B(D_s^+ \to \mu^+\nu) = (0.61\pm0.19)\%$ PDG06

$D_s^+ \to e^+\nu$ [Case (iii)]

No events in signal region

$B(D_s^+ \to e^+\nu) < 3.1\times10^{-4}$ (90% CL)



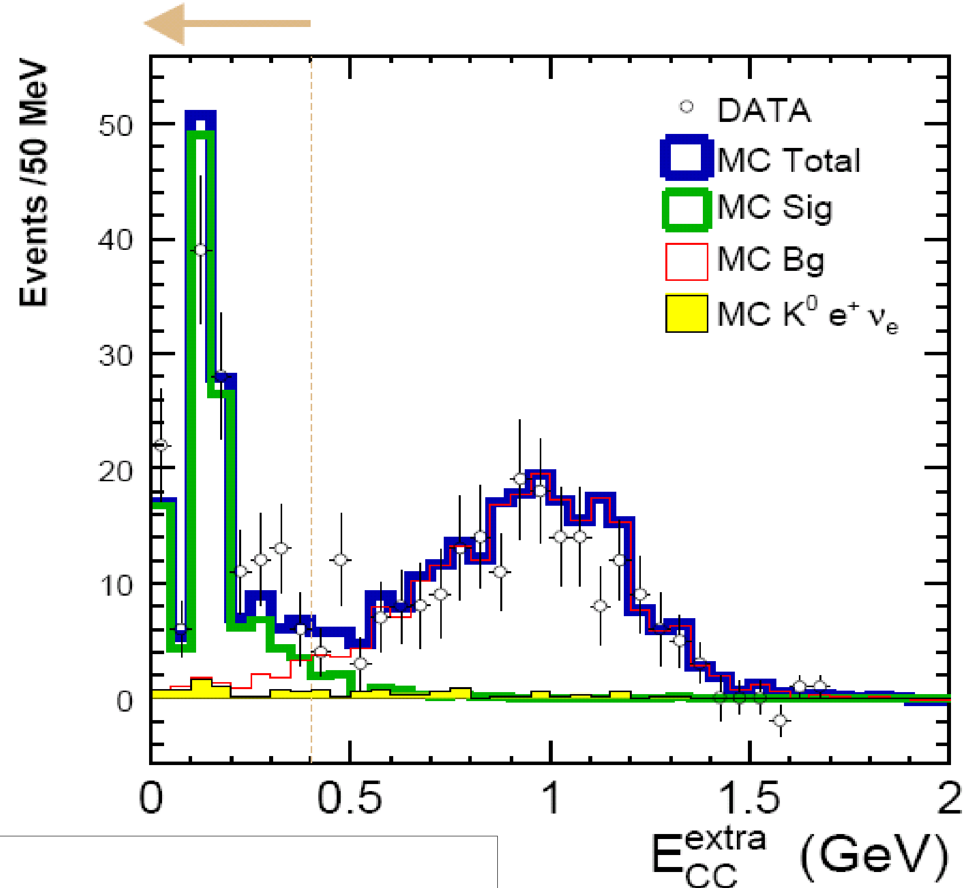
CLEO preliminary

$D_s^+ \to \tau^+\nu \to (e^+\nu\bar{\nu})\,\nu$

Complementary Analysis

$B(D_s^+ \to \tau^+\nu) \times B(\tau^+ \to e^+\nu\bar{\nu}) \sim 1.3\%$,
"large" compared to expected
$B(D_s^+ \to X e^+\nu) \sim 8\%$

Technique is to find events with
1) an e^+ candidate opposite D_s^- tags
2) Total energy in calorimeter not associated with D_s tag or e^+ (E_{CC}^{extra}) < 400 MeV



CLEO preliminary

<u>Summary</u>

$B(D_s^+ \to \tau^+\nu) = (6.3 \pm 0.8 \pm 0.5)\%$ from $\tau^+ \to e^+\nu\bar{\nu}$ analysis
$B(D_s^+ \to \tau^+\nu) = (7.1 \pm 1.4 \pm 0.3)\%$ from $\tau^+ \to \pi^+\nu$ analysis
[$B(D_s^+ \to \tau^+\nu) = (6.4 \pm 1.5)\%$ PDG06]

$D_s^+ \to \mu^+ \nu$ (BaBar)

hep-ex/0607094, subm to PRL

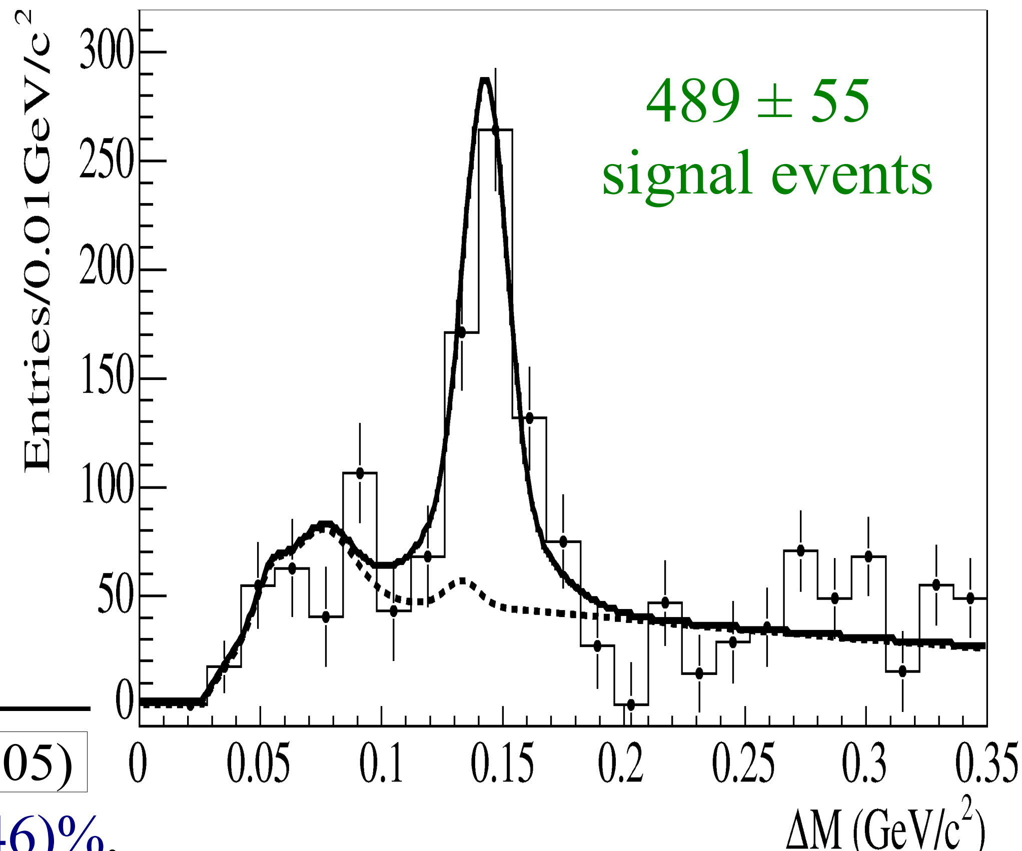
BaBar ($L = 230\ fb^{-1}$)

Reconstruct 13 tag modes in $e^+e^- \to D_s^* D_{tag} X$ events

Select $D_s^{*+} \to D_s^+ \gamma \to (\mu^+\nu)\gamma$ events

Measure partial width w.r.t. $\phi\pi^+$

$$\frac{\Gamma(D_s^+ \to \mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.143 \pm 0.018 \pm 0.006$$



$$\Delta M = M_{D_s^*} - M_{D_s^+}$$

PRD 71, 091104 (2005)

Using BaBar's $B(D_s^+ \to \phi\pi^+) = (4.71 \pm 0.46)\%$,

$B(D_s^+ \to \mu^+\nu) = (0.67 \pm 0.08 \pm 0.03 \pm 0.07)\%$

Using PDG04 $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9)\%$,

$B(D_s^+ \to \mu^+\nu) = (0.52 \pm 0.06 \pm 0.02 \pm 0.13)\%$

$B(D_s^+ \to \mu^+\nu) = (0.61 \pm 0.19)\%$ PDG06

f_{Ds} Summary

CLEO preliminary

Weighted CLEO-c Results:

$f_{Ds} = (280 \pm 12 \pm 6)$ MeV,

Using the CLEO-c f_D result,

$f_{Ds}/f_D = 1.26 \pm 0.11 \pm 0.03$

LQCD: $f_{Ds}/f_D = 1.24 \pm 0.07$

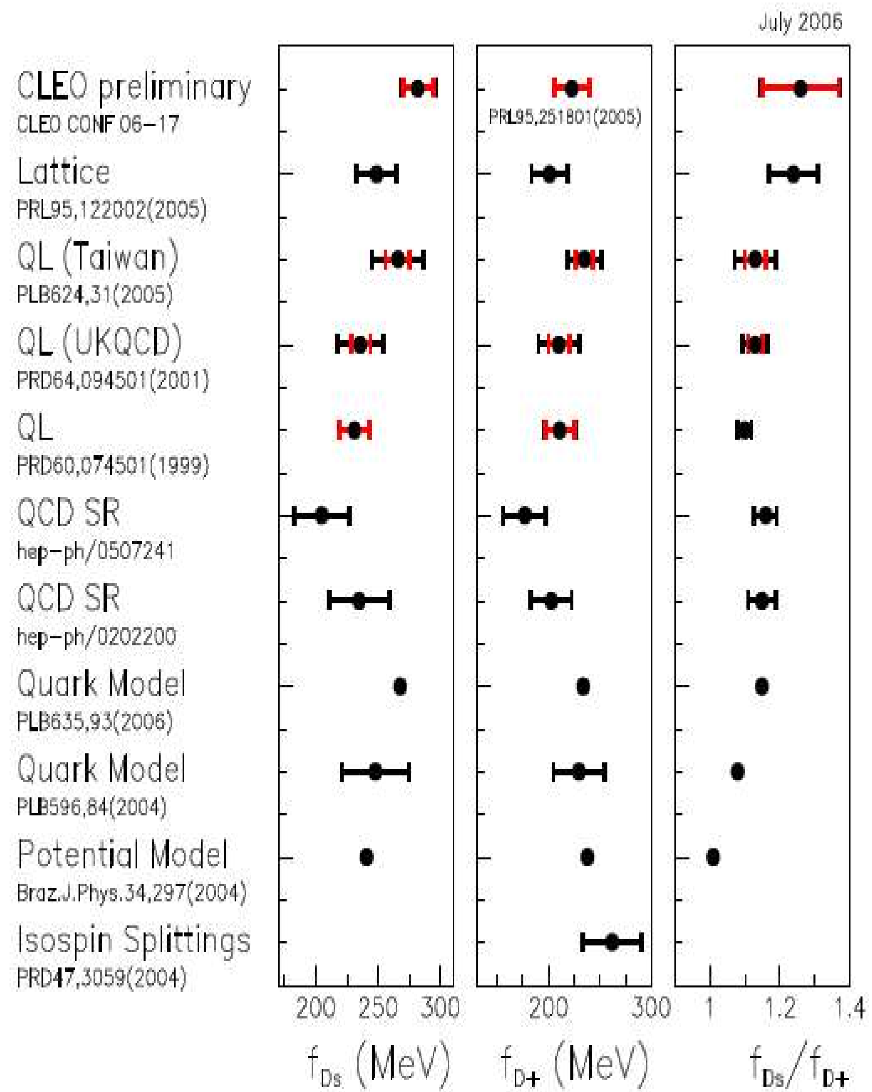
FNAL/MILC: PRL 95, 122002 (2005)

BaBar: $f_{Ds} = (283 \pm 17 \pm 4 \pm 14)$ MeV

[w/ BaBar $D_s \rightarrow \varphi\pi$ result]

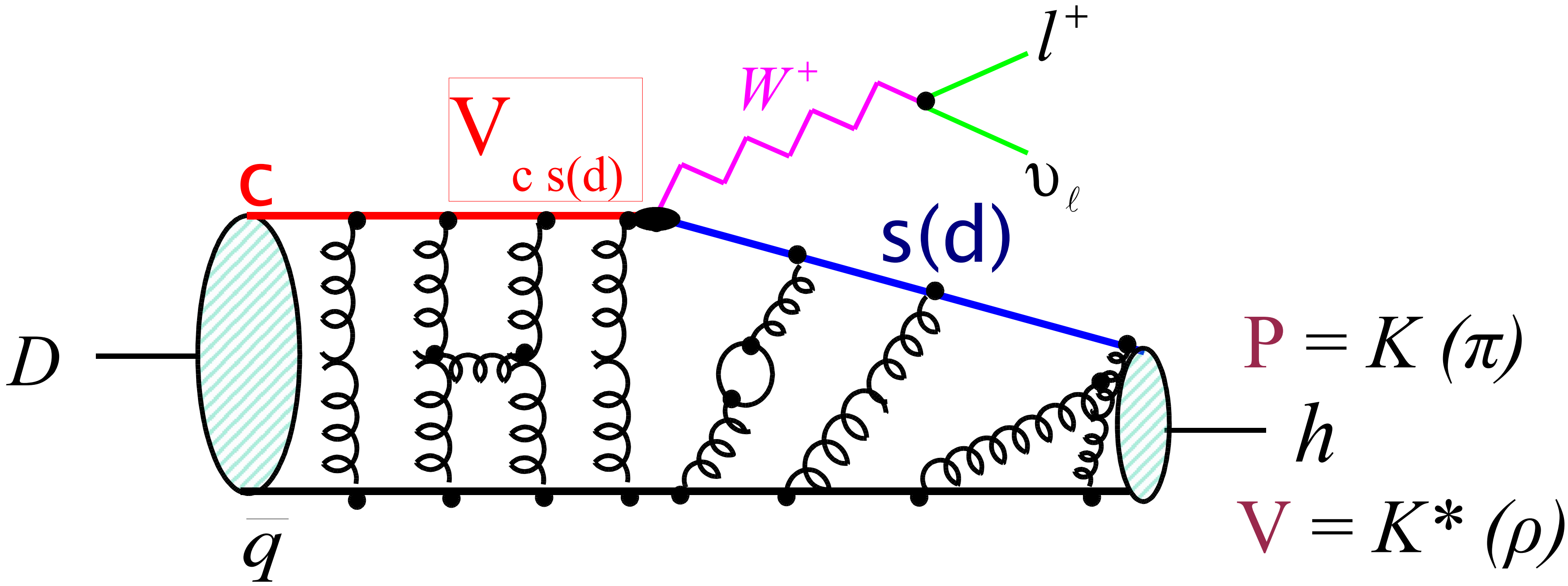
BaBar: $f_{Ds} = (248 \pm 15 \pm 6 \pm 31)$ MeV

[w/ PDG04 $D_s \rightarrow \varphi\pi$ result]



Watch for CLEO-c exclusive D_s hadronic branching fraction results

D Semileptonic Decays



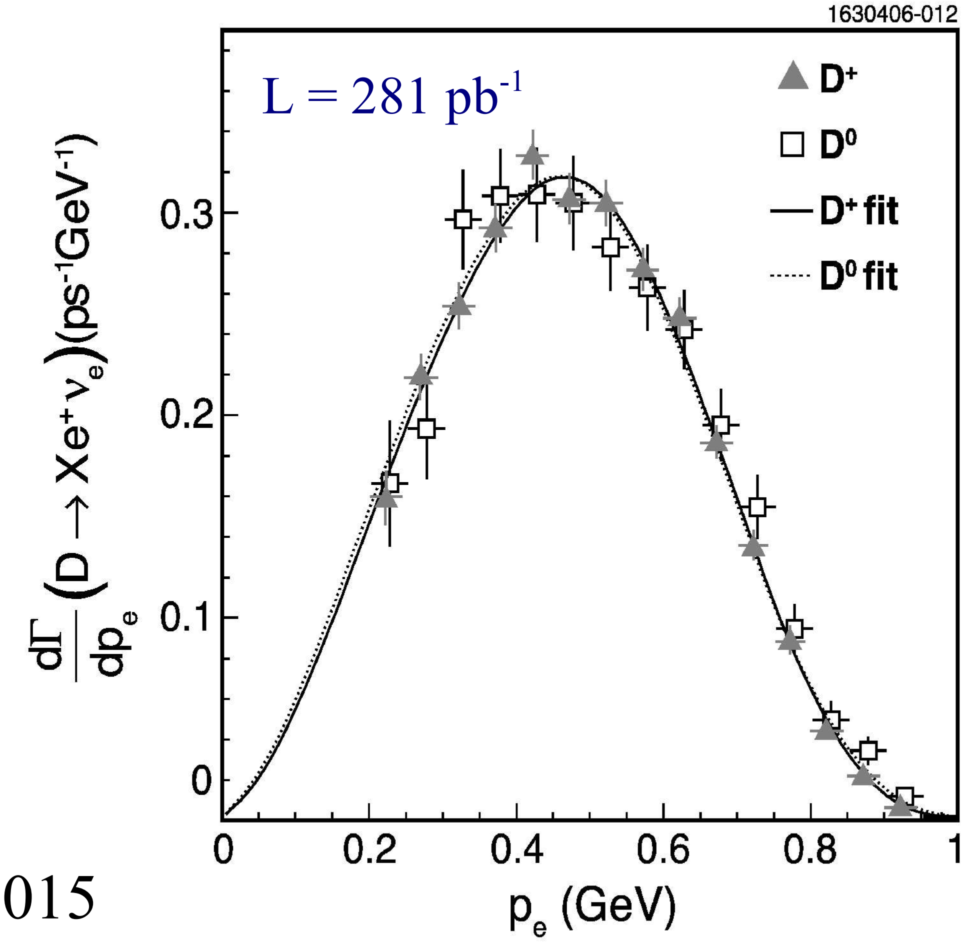
e.g., for pseudoscalars (P)

$$\frac{d\,\Gamma}{dq^2} = \frac{G_F^2}{24\,\pi^3}\left|V_{c\,q}\right|^2 p_P^3\,\left|f_+(q^2)\right|^2$$

Inclusive $D \rightarrow Xe\nu$

hep-ex/0604044, subm to PRL

Mode	Branching Fraction
$D^0 \rightarrow Xe^+\nu$	$(6.46\pm0.17\pm0.13)\%$
$\Sigma_{excl}\ B(D^0 \rightarrow Xe^+\nu)$	$(6.1\pm0.2\pm0.2)\%$
$D^+ \rightarrow Xe^+\nu$	$(16.13\pm0.20\pm0.33)\%$
$\Sigma_{excl}\ B(D^+ \rightarrow Xe^+\nu)$	$(15.1\pm0.5\pm0.5)\%$



Consistent with known exclusive modes saturating the inclusive branching fraction

$$\frac{\Gamma^{SL}_{D^+}}{\Gamma^{SL}_{D^0}} = \frac{B^{SL}_{D^+}}{B^{SL}_{D^0}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985\pm0.028\pm0.015$$

Consistent with isospin invariance

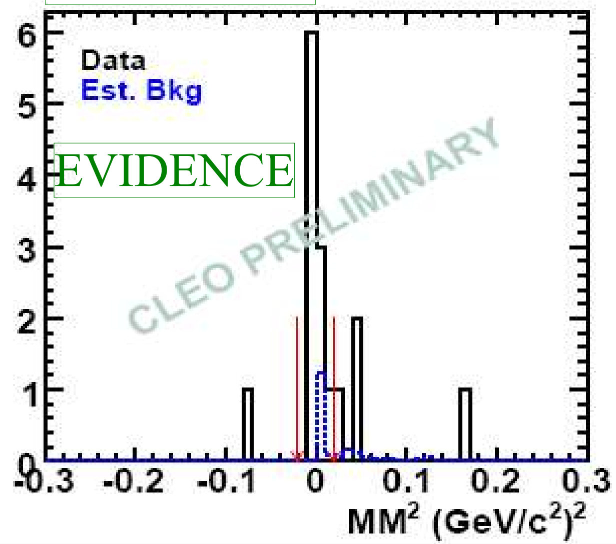
Rare Semileptonic D Decays

ALL
CLEO preliminary

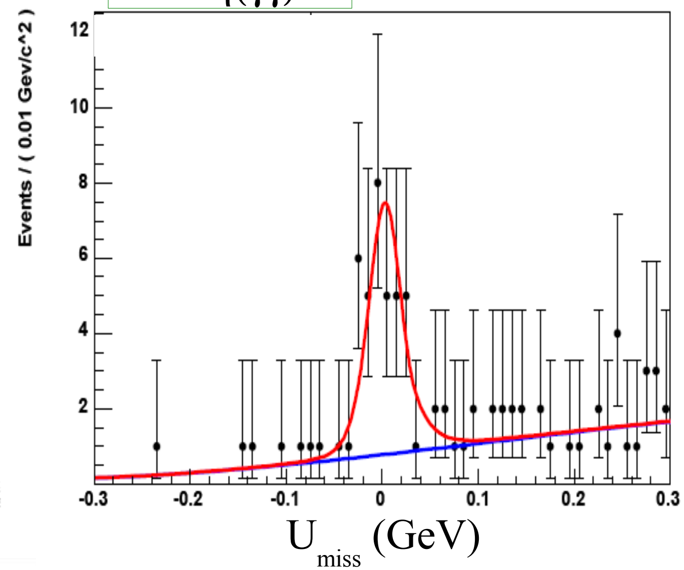
Mode	BF(10^{-4})
$\eta\, e^+\nu$	$12.9\pm1.9\pm0.7$
$\eta' e^+\nu$	< 3 (90% CL)
$\varphi\, e^+\nu$	< 2 (90% CL)
$K^-\pi^+\pi^- e^+\nu$	$2.9^{+1.5}_{-1.1}\pm0.5$
$K_1(1270)\, e^+\nu$	$2.2^{+1.4}_{-1.0}\pm0.2$
$\omega\, e^+\nu$	$14.9\pm2.7\pm0.5$

$L = 281\ pb^{-1}$

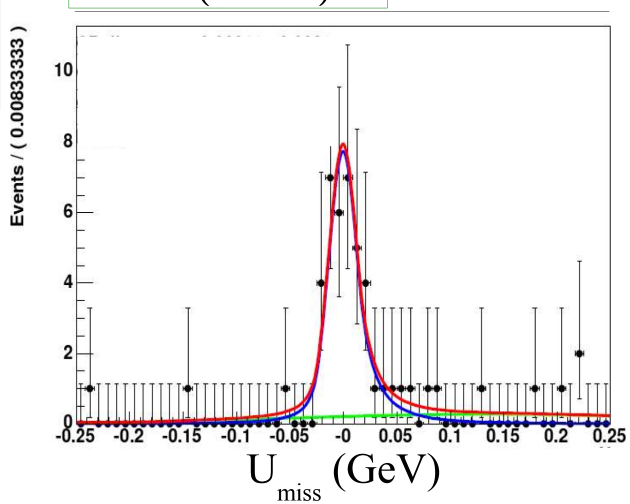
$D^0 \to K^-\pi^+\pi^- e^+\nu$



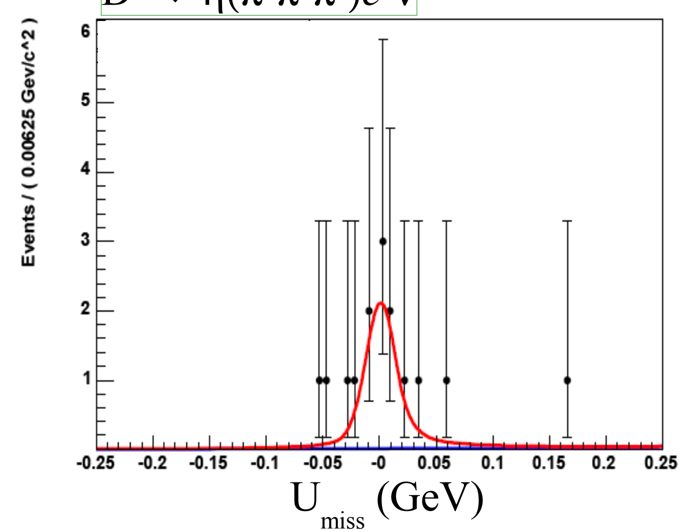
$D^+ \to \eta(\gamma\gamma) e^+\nu$



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



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



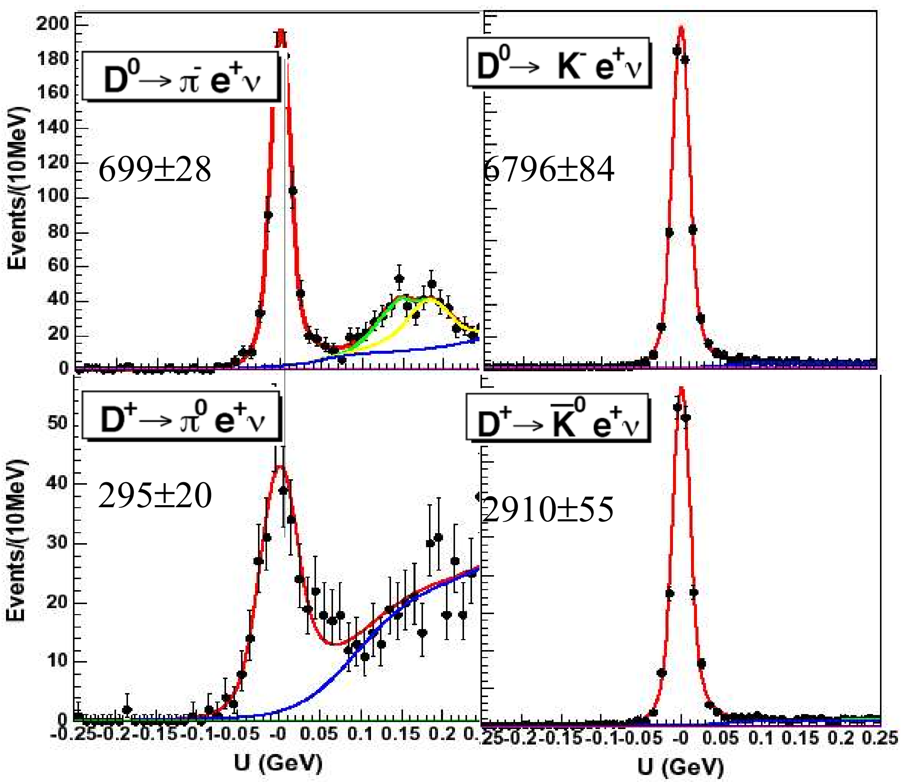
D $\rightarrow K/\pi\, e^{+}\nu$ Intro

CLEO preliminary

Two methods

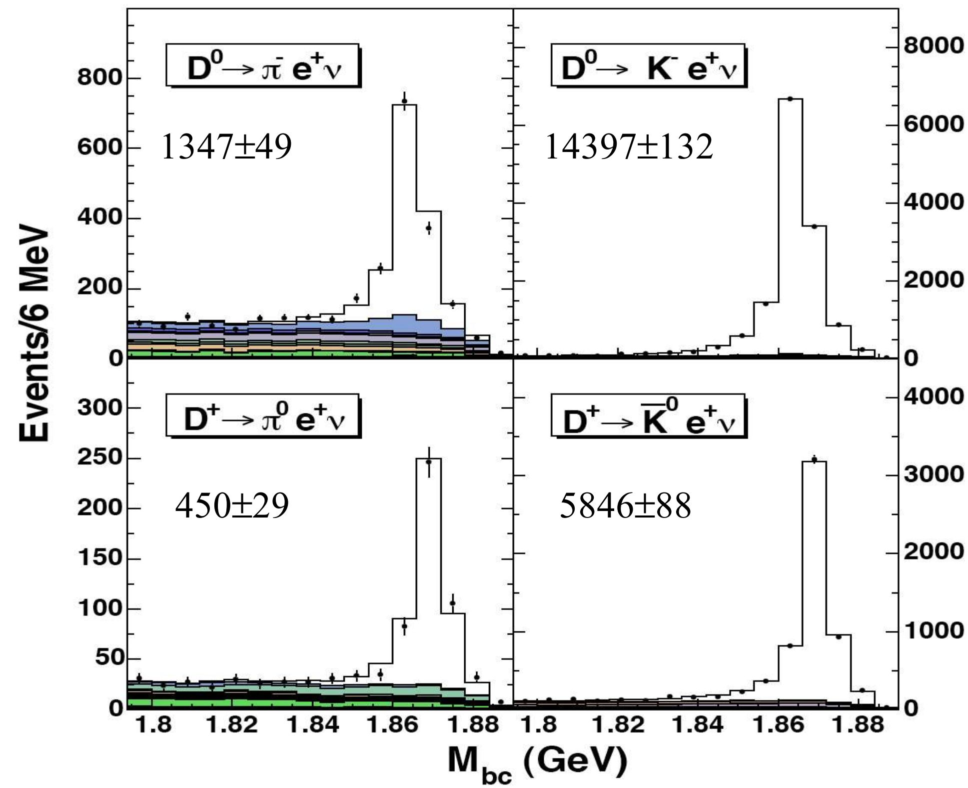
Methods have 40% overlap, do NOT average

Standard D Tags (Tag)



$$U_{miss} = E_{miss} - |\boldsymbol{p}_{miss}|$$

Neutrino reconstruction (Untagged)

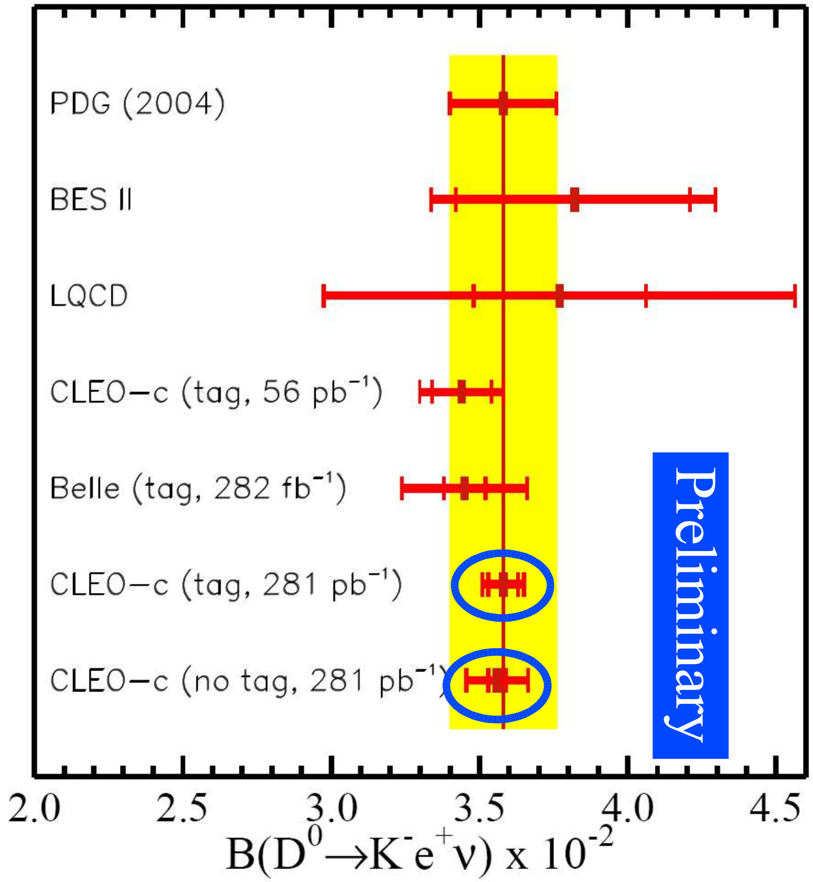


$$M_{bc} = \sqrt{\left(E_{beam}^2 - \left(\boldsymbol{p}_{K(\pi)} + \boldsymbol{p}_e + \xi\, \boldsymbol{p}_{miss}\right)^2\right)}$$

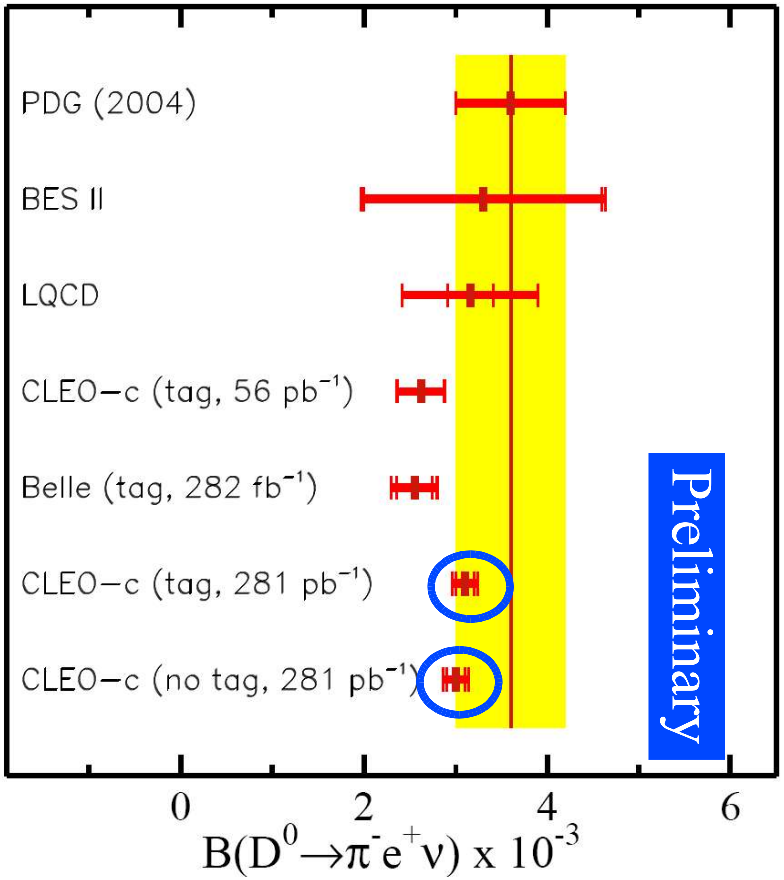
$D^0 \to K/\pi\ e^+\nu$ BR Comparison

July 2006

$D \to K e^+ \nu$



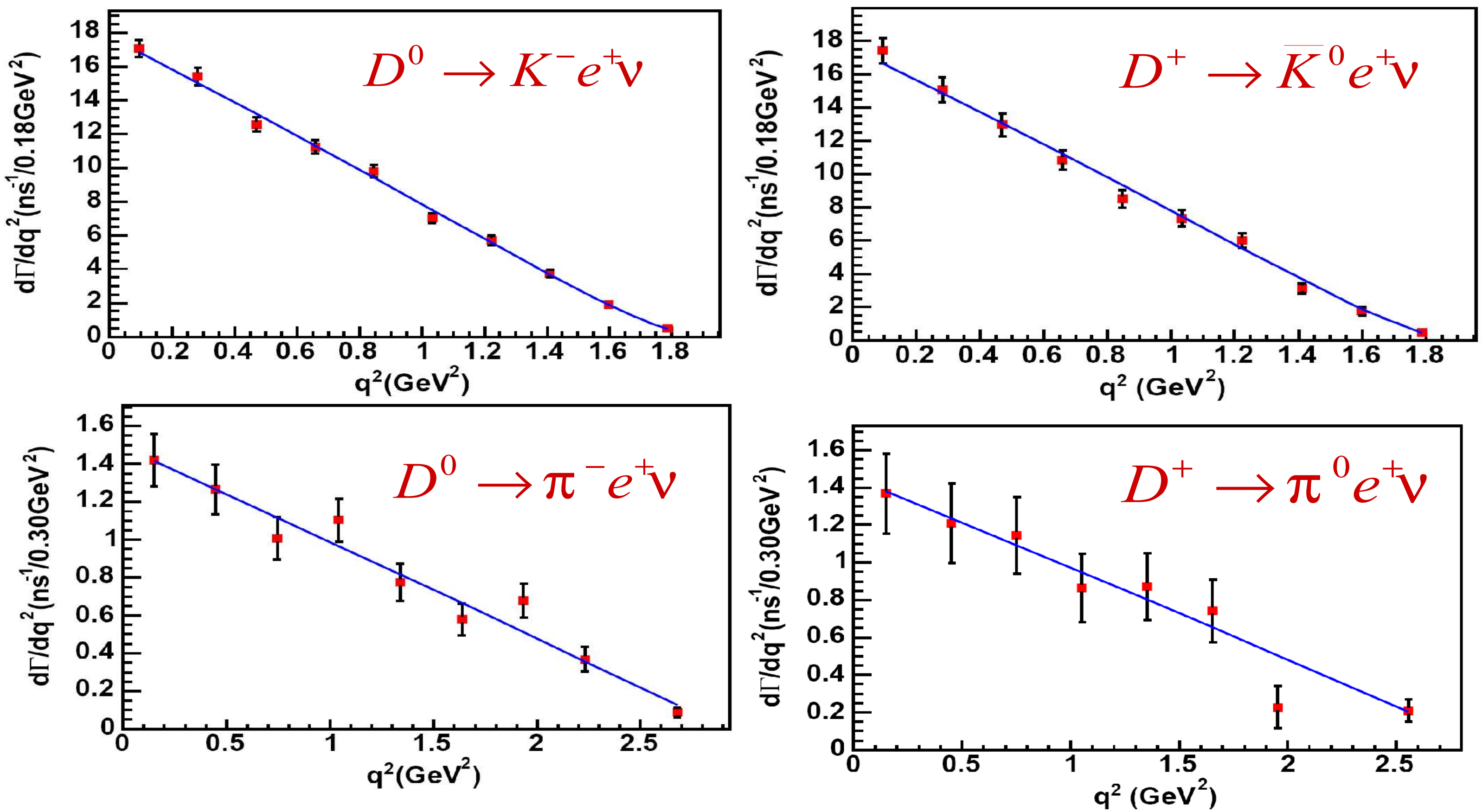
$D \to \pi e^+ \nu$



Good consistency between measurements.
LQCD precision lags experiment.

Form Factor Fit (Tag)

Form factor fit plots



CLEO preliminary

Simple Pole Model

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

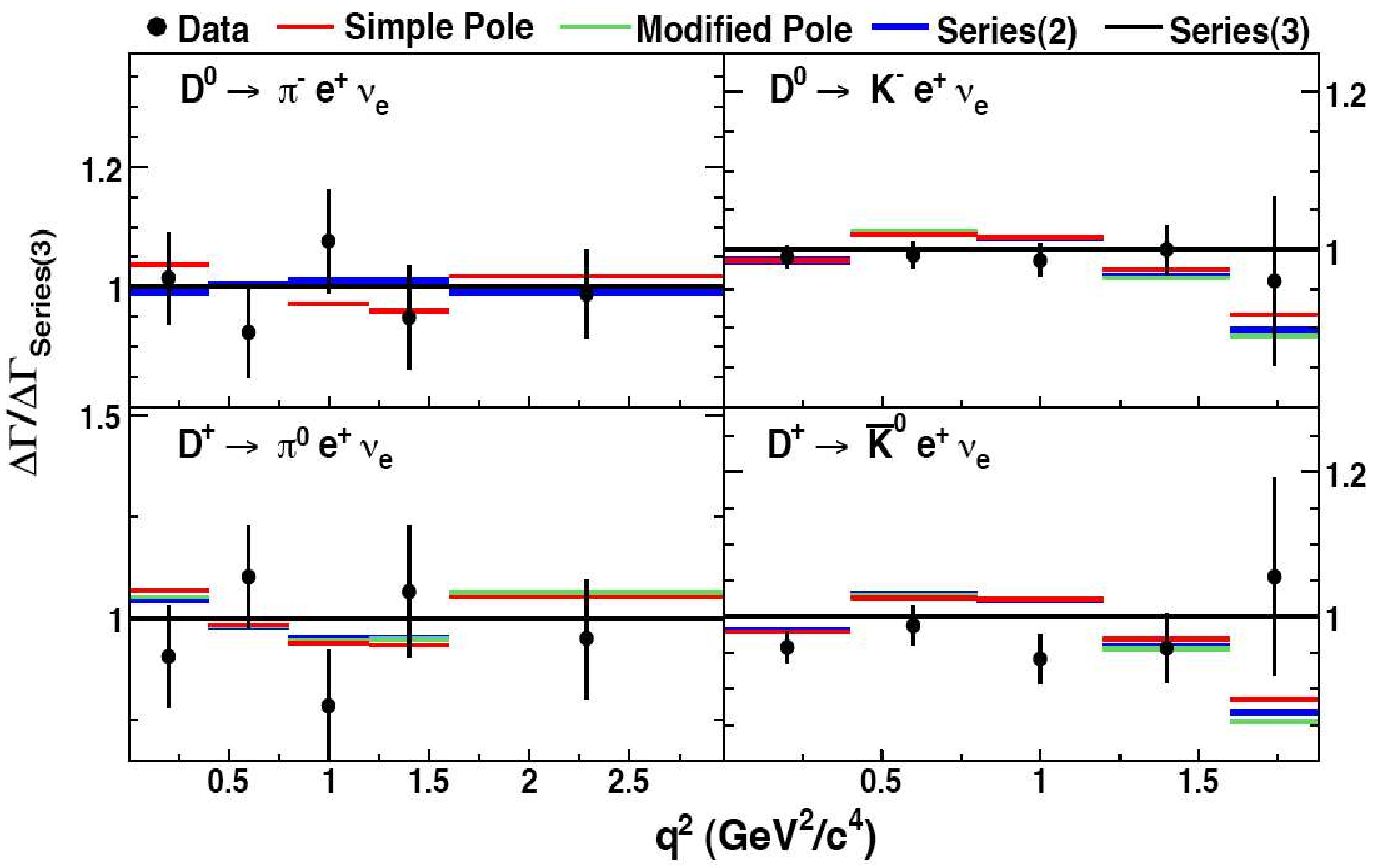
Modified Pole Model

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

Hill series expansion PLB 633, 61 (2005)

Tagged Modified Pole (BK) Model shown

Form Factor Fits (Untagged)



CLEO preliminary

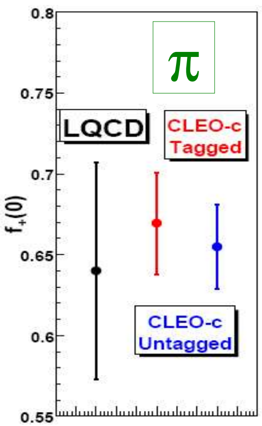
Data vs. LQCD Comparison

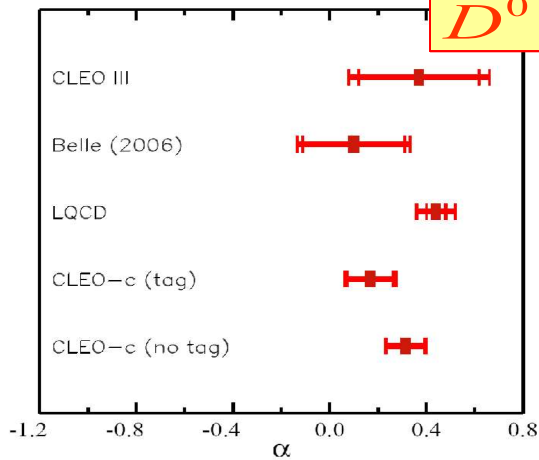
$f_+(0)$

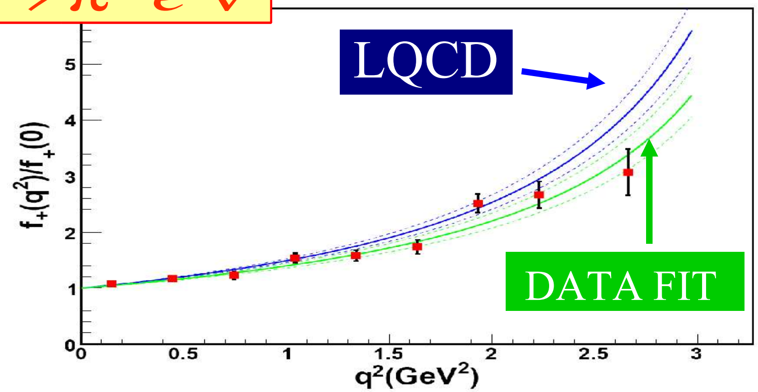
α_{pole}

LQCD [PRL **94,** 011601 (2005)]

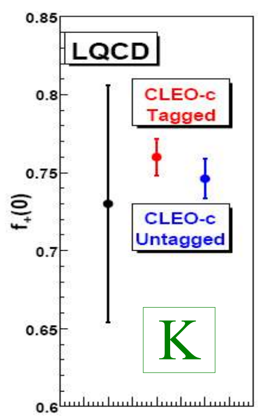
$D^0 \to \pi^- e^+ \nu$

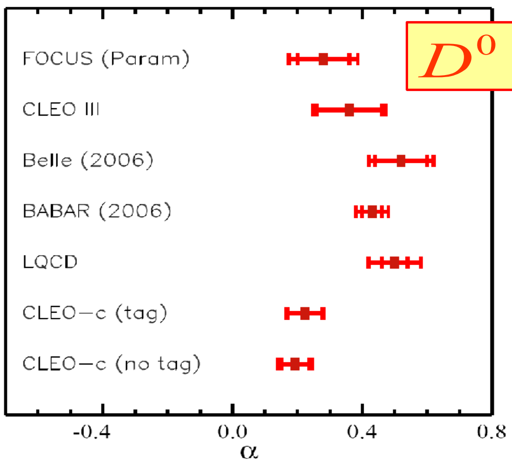


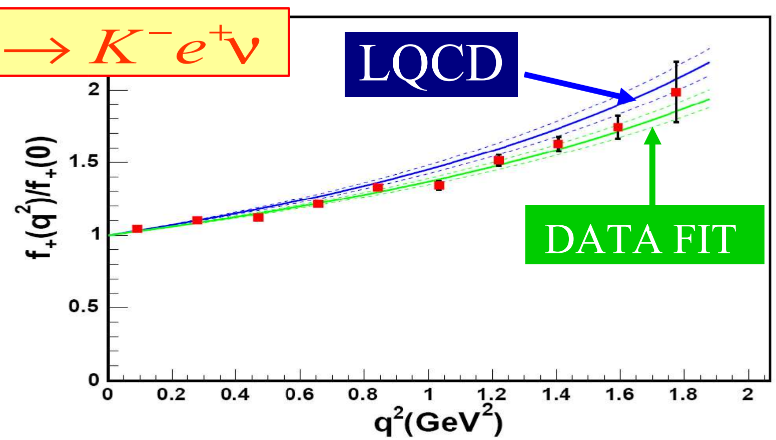




$D^0 \to K^- e^+ \nu$







CLEO preliminary

V_{cd} and V_{cs} Results

Combine $|V_{cx}|f_+(0)$ values from fits with unquenched LQCD results for $f_+(0)$ [**PRL 94, 011601 (2005)**] *to extract $|V_{cs}|$ and $|V_{cd}|$.*

Decay Mode	$\|V_{cx}\| \pm (stat) \pm (syst) \pm (theory)$	*PDG (2006)*
$D \to \pi e\nu$ *(tagged)*	$0.234 \pm 0.010 \pm 0.004 \pm 0.024$	
$D \to \pi e\nu$ *(untagged)*	$0.229 \pm 0.007 \pm 0.005 \pm 0.024$	0.2271 ± 0.0010
$D \to K e\nu$ *(tagged)*	$1.014 \pm 0.013 \pm 0.009 \pm 0.106$	
$D \to K e\nu$ *(untagged)*	$0.996 \pm 0.008 \pm 0.015 \pm 0.104$	0.97296 ± 0.00024

CLEO preliminary

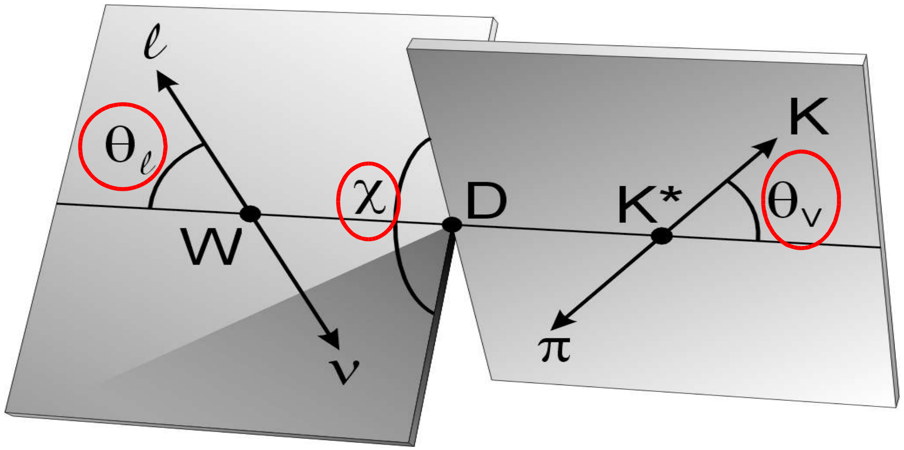
Tagged and untagged consistent.

40% of events are common to both analyses: DO NOT AVERAGE!

Uncertainties: experiment: V_{cs} <2%, V_{cd}~4% / LQCD: 10%

V_{cs} ($W \to cs$ LEP) and V_{cd} (νN) well measured ⇒ good agreement between PDG (HF) and CLEO-c results primarily a check of the LQCD value for $f_+(0)$. Nevertheless, the most precise & robust V_{cs} & V_{cd} determinations using semileptonic decays to date.

$D^+ \to (V = K^-\pi^+)\, e^+ \nu$



Spectroscopic pole dominance

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

$$M_V = 2.1 \text{ GeV} \qquad M_{A1} = M_{A2} = 2.5 \text{ GeV}$$

$$R_V = \frac{V(0)}{A_1(0)} \qquad R_2 = \frac{A_2(0)}{A_1(0)}$$

$$\int |A|^2 d\chi = \frac{1}{8} q^2 \begin{Bmatrix} \left((1+\cos\theta_l)\sin\theta_V\right)^2 |H_+(q^2)|^2 |BW|^2 \\ +\left((1-\cos\theta_l)\sin\theta_V\right)^2 |H_-(q^2)|^2 |BW|^2 \\ +\left(2\sin\theta_l \cos\theta_V\right)^2 |H_0(q^2)|^2 |BW|^2 \\ +8\left(\sin^2\theta_l \cos\theta_V\right) H_0(q^2) h_o(q^2) \mathrm{Re}\left\{A e^{-i\delta} BW\right\} \\ +O(A^2) \end{Bmatrix}$$

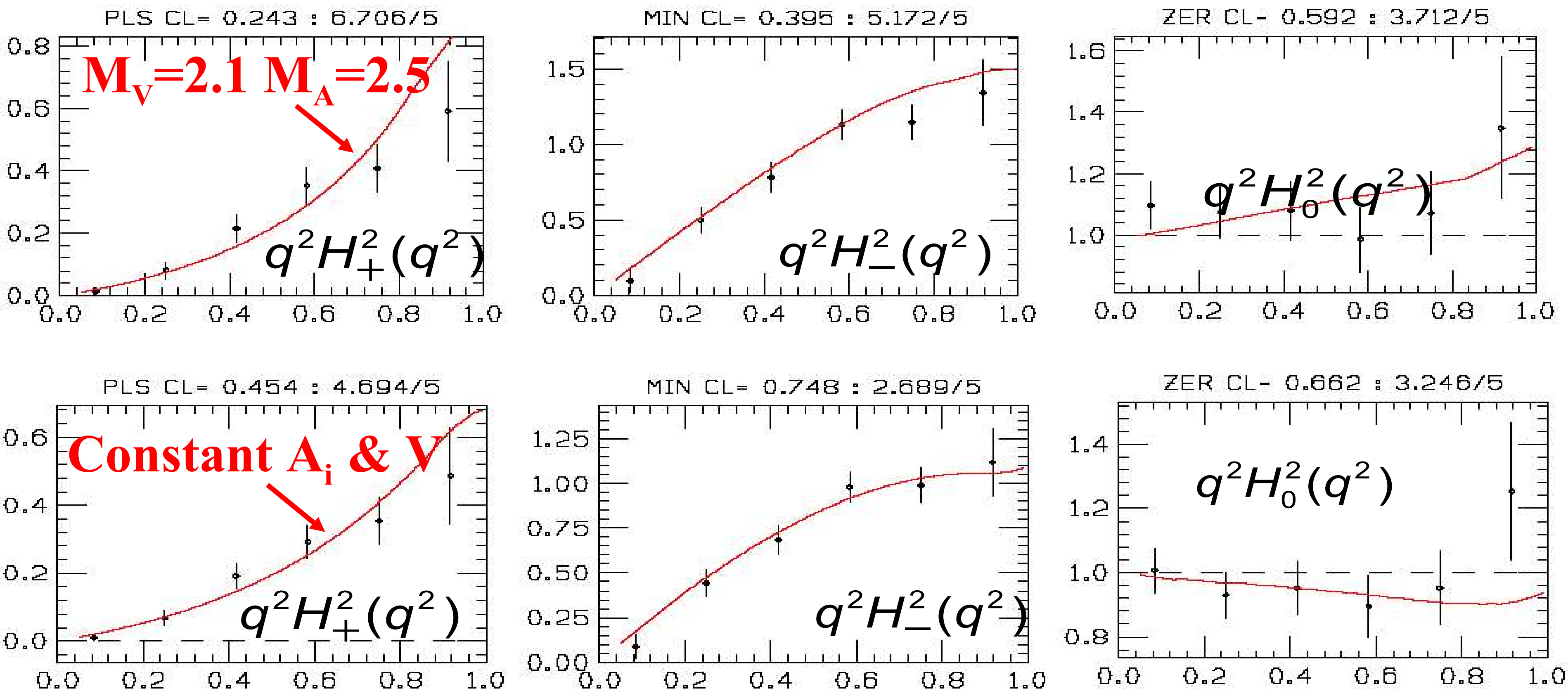
Present in K* l nu

$H_0(q^2)$, $H_+(q^2)$, $H_-(q^2)$ are **helicity-basis form factors** computable by LQCD

A new factor **$h_0(q^2)$** is needed to describe **s-wave interference piece in K* *l* ν**.

$D^+ \to K^- \pi^+ e^+ \nu$ Form Factors

PRD 74, 052001 (2006)

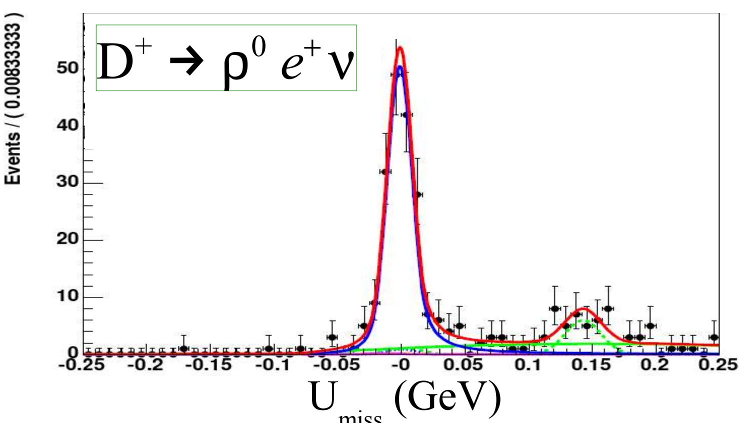


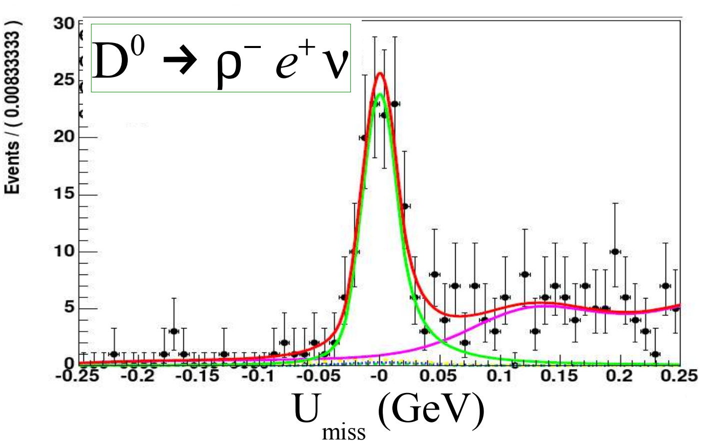
Data fits spectroscopic poles and constant form factors equally well.
No evidence for d- or f-wave contributions.

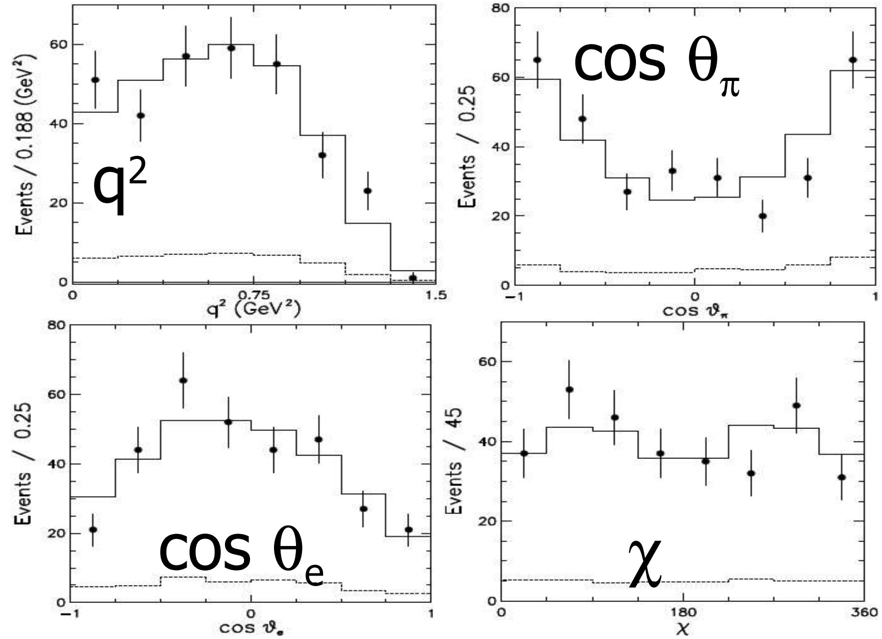
$D \to \rho\, e^{+} \nu$

CLEO preliminary

1st measurement of FF in Cabibbo suppressed charm PS→ V decay







Line is projection for fitted R_V, R_2

$B(D^0 \to \rho^- e^+ \nu) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$

$B(D^+ \to \rho^0 e^+ \nu) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$

Isospin average:

$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2}\ ps^{-1}$ [CLEO-c this result]

$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.44 \pm 0.06 \pm 0.04 \pm 0.02) \times 10^{-2}\ ps^{-1}$

[FOCUS: PLB 637, 32 (2006)]

Simultaneous fit to $D^+ \to \rho^0 e \nu$, $D^0 \to \rho^- e \nu$

$R_v = 1.40 \pm 0.25 \pm 0.03$, $R_2 = 0.57 \pm 0.18 \pm 0.06$

Summary

Experiments are placing very stringent constraints on the decay constants f_D and f_{Ds} and the form factors for $D \to K/\pi\, l\, \nu$ decays

Upcoming CLEO-c results will increase the precision once the complete D and D_S data samples are collected