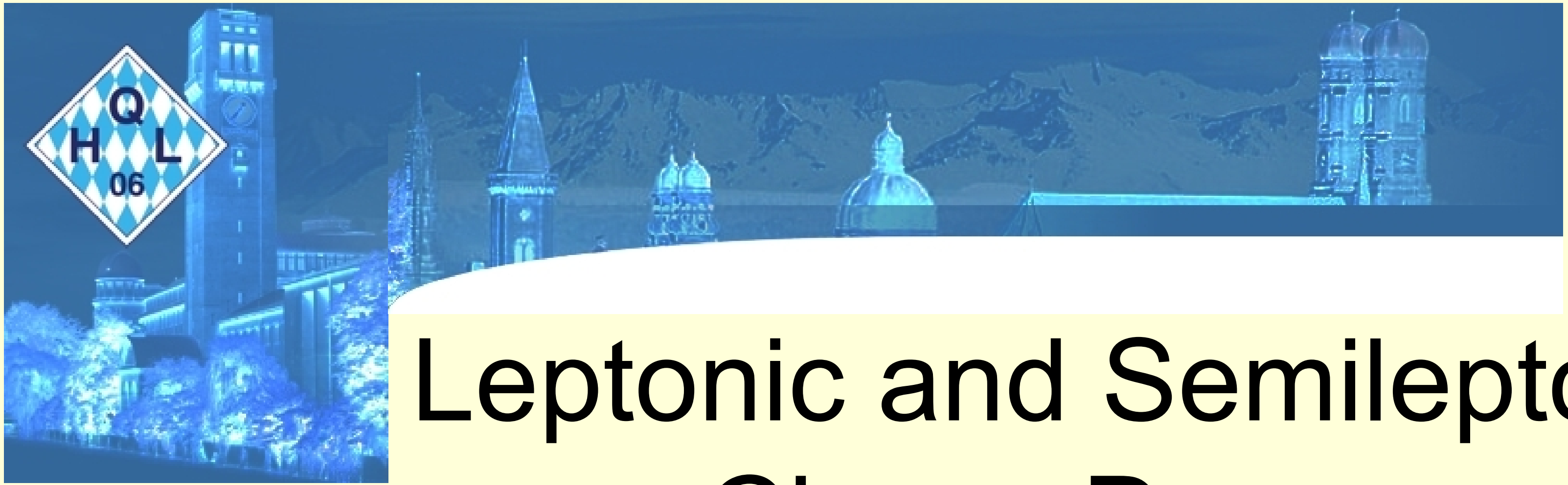
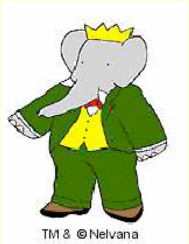
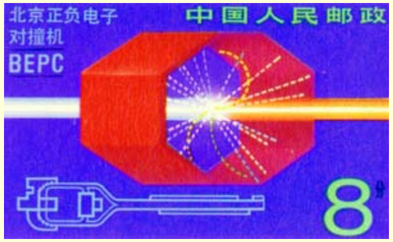


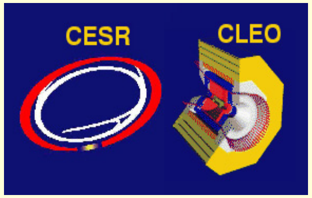
Leptonic and Semileptonic Charm Decays

Hanna Mahlke
Cornell University

Heavy Quarks and Leptons
Munich, Germany
October 2006

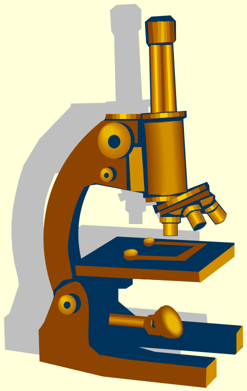




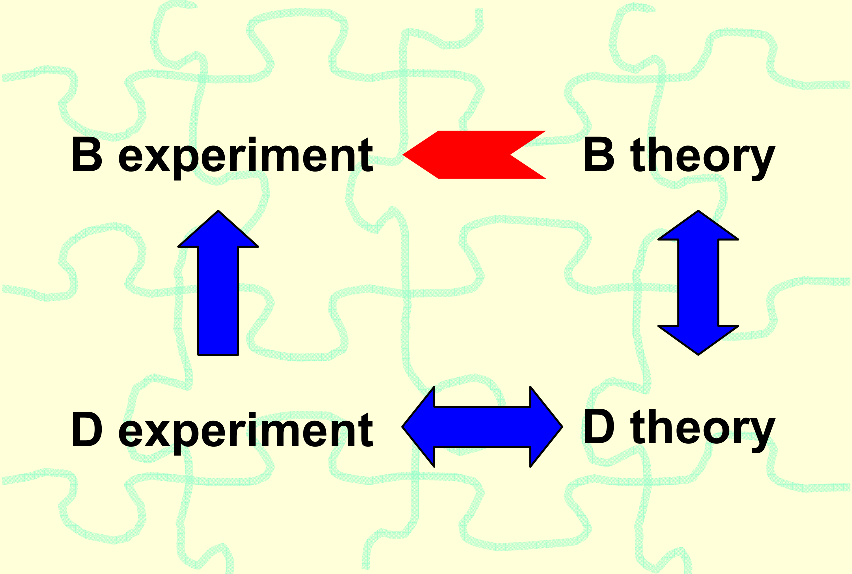


The Big Picture

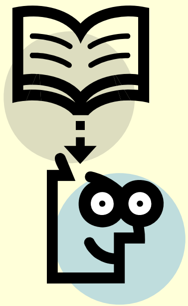
Theory's difficulties in calculating strong phenomena seriously hamper some measurements in the B sector that need such input, eg. V_{ub} from semileptonic or leptonic B decays, extraction of V_{td} from B^0-B^{0bar} mixing measurement.



In addition to being of interest in and of itself, experimental charm results thus have an impact on bottom results.



Both b and c are heavy quarks, similar methods apply, b↔c transfer is"easy".



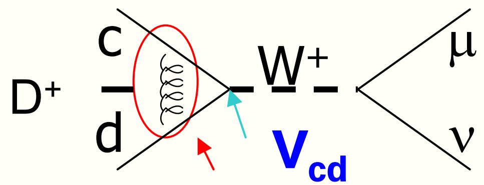
The charm system provides stringent experimental tests of theoretical heavy quark tools at the percent level.

This talk: semileptonic and leptonic D decays

Overview: (Semi-)Leptonic Decays

Examples:

Leptonic:

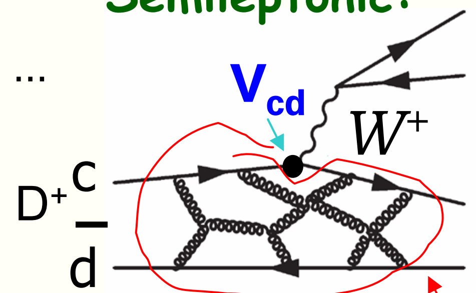


Decay constant f_D

Similar for D_s, B, B_s, ...

Challenge: understand QCD portion in a “simple” weak process

Semileptonic:



q^2: momentum transfer or $m(W^*)$

Form factor $f_+(q^2)$

✓$D^+ \to \mu\nu$ ✓$D_s^+ \to \mu\nu$

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

✗ FCNC, LFV

✓ $D^+ \to K/\pi/\rho/\eta/\eta'/\omega/K\pi\pi + \ell\nu$

✓ $D_s^+ \to \phi + e\nu$

* BR measurements

and/or

* Form factors ($K/\pi/\rho/\phi$)

Experimental Issues for precision studies of $D_{[s]} \rightarrow \ell\nu$, $h\ell\nu$ decays

B Factories:

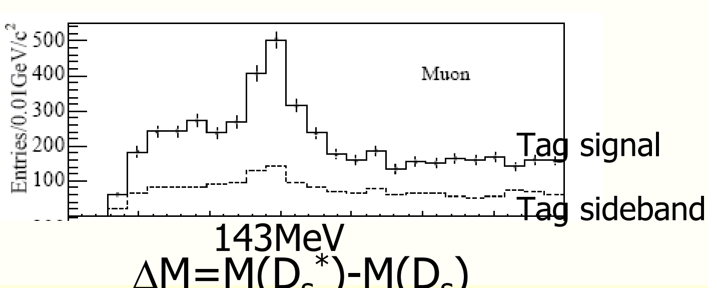
- Use charm from $e^+e^- \rightarrow c c^{bar}$ (separate from $b b^{bar}$ through topological requirements)
- D from $D^{*+} \rightarrow \pi_S D^0$, D_s^+ from $D_s^{*+} \rightarrow \gamma D_s^+$, check $D_{(s)}^*$-$D_{(s)}$ mass difference
- Can tag, or not tag, "the other D"
- Normalization: mostly reference mode

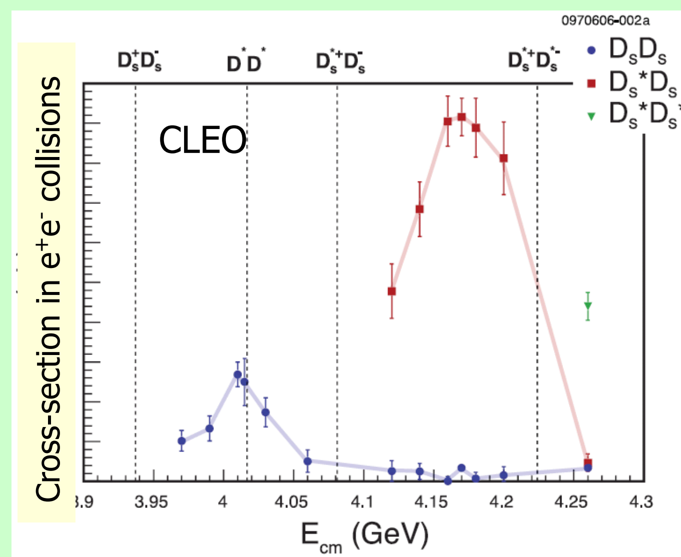
Running at charm threshold (CLEO-c, BES):

- Very clean event environment, well-defined kinematics
- D from $\psi(3770) \rightarrow D^+D^-$, D^0D^{0bar}; D_s from $e^+e^- \rightarrow D_s^* D_s \rightarrow \gamma D_s D_s$
- DD^{bar} analyses mostly identify one D through a well-known decay mode ("tagged"), but untagged turned out to work very well, too
- Normalization: number of decays

Belle $D_s \rightarrow \mu\nu$ using tagged D_s events

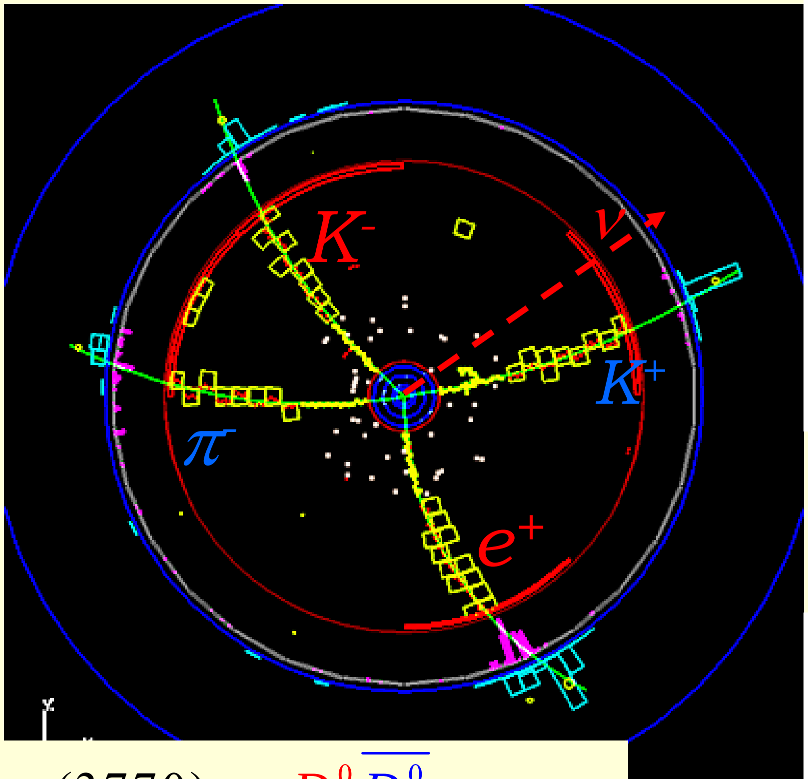
hep-ex/0607094





Reconstruction of (semi)leptonic decays at $\psi(3770)$

$281 pb^{-1}$: ~310k D^+, ~160k D^0 tags

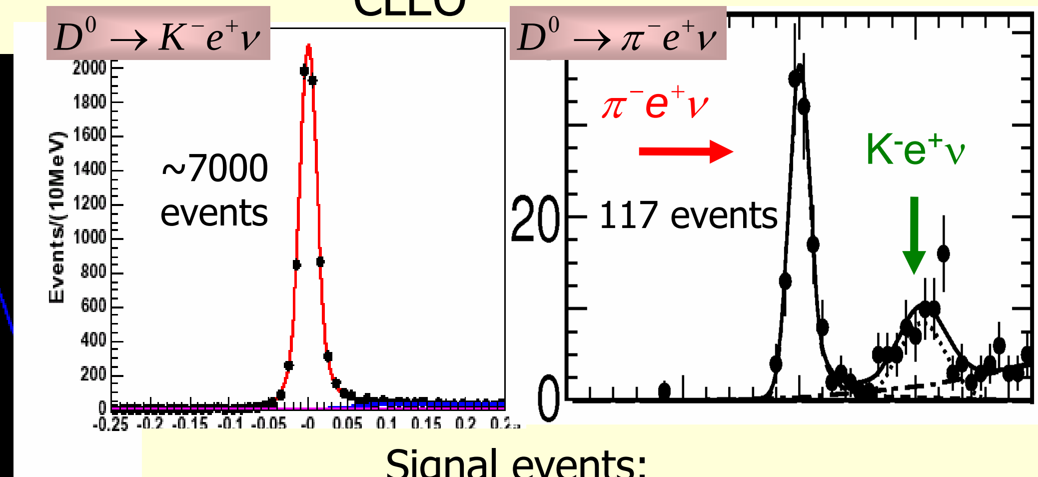


$$\psi(3770) \to D^0 \overline{D^0}$$

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

Tagging creates a single D beam of known 4-momentum.

CLEO

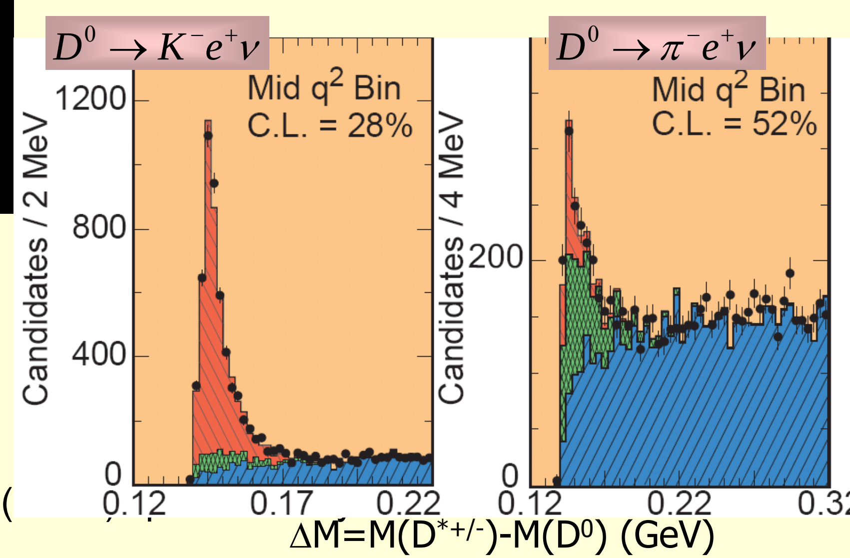


Signal events:

$U = E_{miss} - |P_{miss}| = 0$

Compare cleanliness at $\Upsilon(4S)$:

CLEO PRL94, 011802 (2005)



Signal

Peaking background

Other background

Leptonic Decays

$D \rightarrow \mu\nu$

$D \rightarrow \tau\nu$

$D_s \rightarrow \mu\nu$

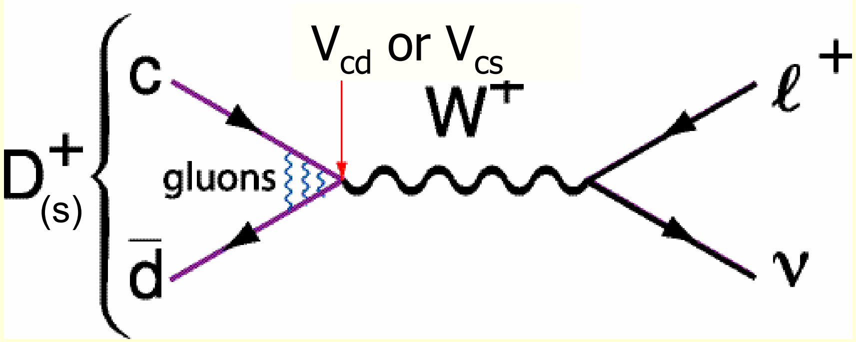
$D_s \rightarrow \tau\nu$

Leptonic Decays: $D_{(s)}^+ \to \ell^+\nu$

c and $\overline{q}$ can annihilate,
probability is $\propto$ to wave function overlap

Hadronic interaction described by decay constant f_D – challenge for theory

Goals: 1) put calculations to the test,
2) check lepton universality



General case for pseudoscalars:

$$\Gamma\left(P^+ \to \ell^+ \nu\right) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 \left|V_{Qq}\right|^2$$

Other mesons:
f_π=131.73±0.15MeV (0.1%),
f_K=160.6±1.3MeV (0.8%)

Calculate, or measure if V_{Qq} is known

$\tau : \mu : e$ is 9.72:1:0.00002 for $P=D_s^+$
2.65:1:0.00002 for $P= D^+$

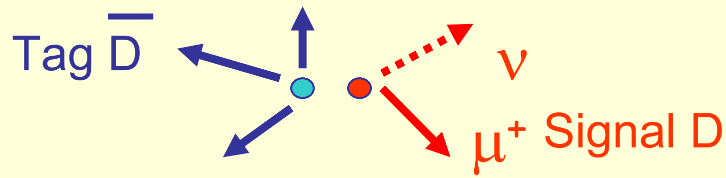
τ most copiously produced, but is not stable
$\Rightarrow \mu$ preferable experimentally, esp. for D^+

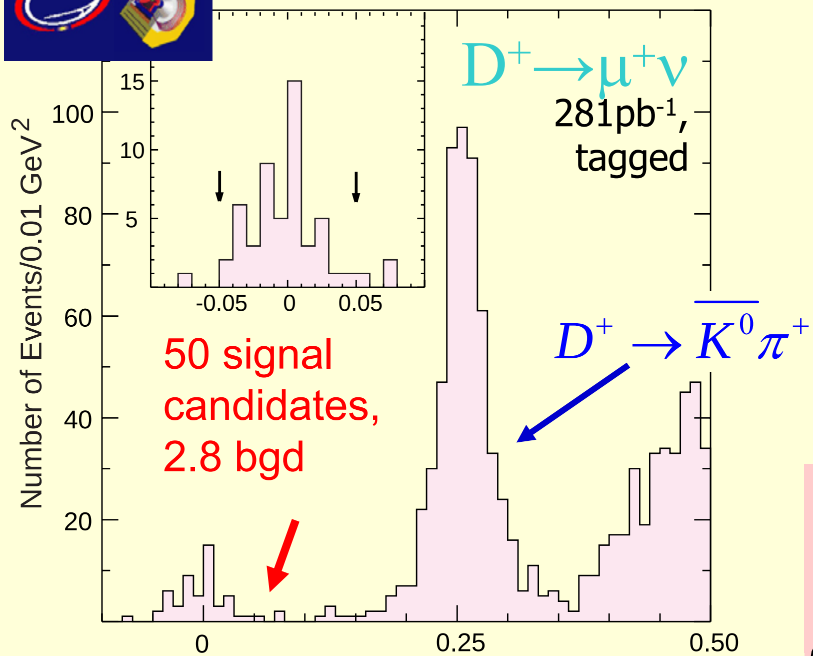
V_{cq} is O(1) $P=D_s^+$
O(0.1) for $P= D^+$

D_s^+ leptonic BR's larger than D^+
(lifetimes only a factor of two apart)

$D^+ \to \ell^+\nu$ from experiment

$(\Rightarrow BR \Rightarrow f_D)$





Missing mass^2 = $(E_{beam}-E_{mu})^2-(p_D-p_m)^2$ (GeV)^2

Variations:

* Similar technique applied to measure $D \to \tau\nu$ with $\tau \to \pi\nu$; 20 candidates on 11 background
* Require e instead of μ

$\Rightarrow$ no candidates, upper limit set

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

$BR(D \to e\nu) < 2.4 \times 10^{-5}$ — Times SM ratio: 1×10^{-8}

$BR(D \to \tau\nu) < 3.1 \times 10^{-3}$ — 2×10^{-3}

BES, 33pb^{-1}, tagged (3 signal, 0.3 bgd):
$BR(D \to \mu\nu) = (12^{+11}_{-5} \pm 1) \times 10^{-4}$

With D^+ lifetime of 1.040+-0.0007ps, $|V_{cd}|$=0.2238+-0.0029

$f_D = 222.6 \pm 16.7\ ^{+2.8}_{-3.4}$ MeV **(11%)**

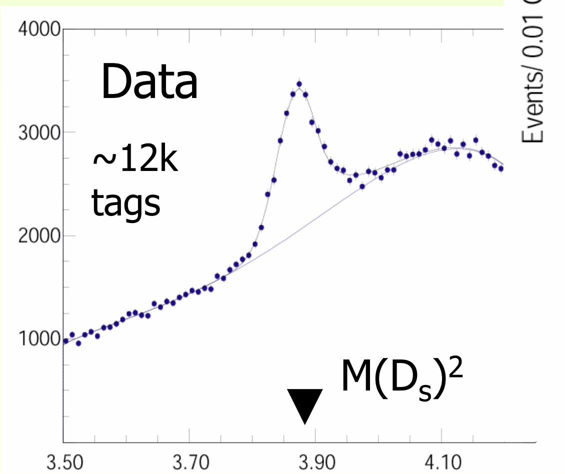
Background:
$D^+ \to \pi^+\pi^0$, $\tau^+(\to \pi\ \nu)\nu$, $K_0\pi^+$,
estimated from data or MC

CLEO: PRL96, 251801 (2005)
BES: PLB610, 183 (2005)

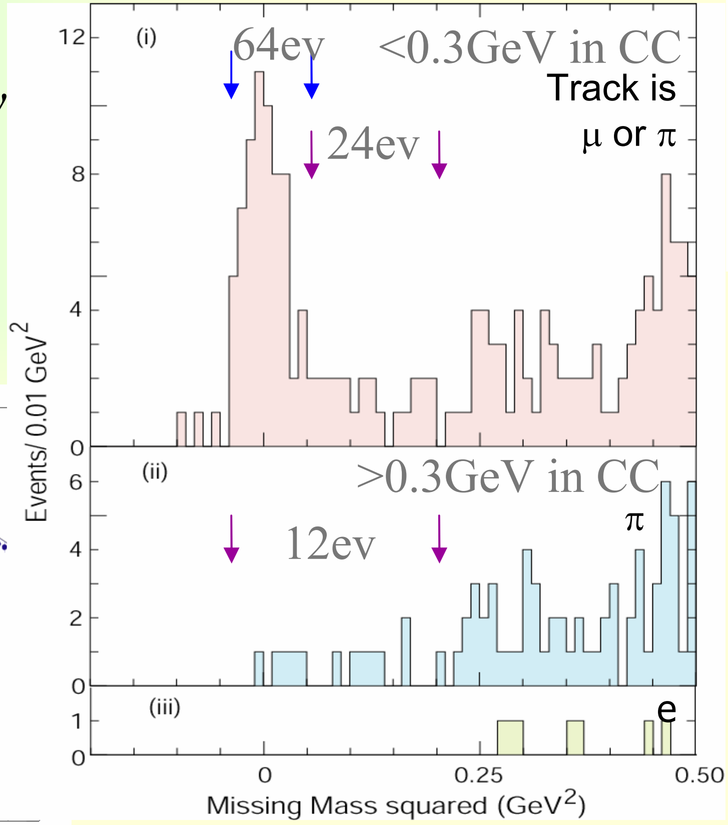
$D_S^+ \to \mu^+\nu$ and $\tau^+\nu$ (1)

~200pb^{-1} at 4170MeV, D_s tags, CLEO preliminary

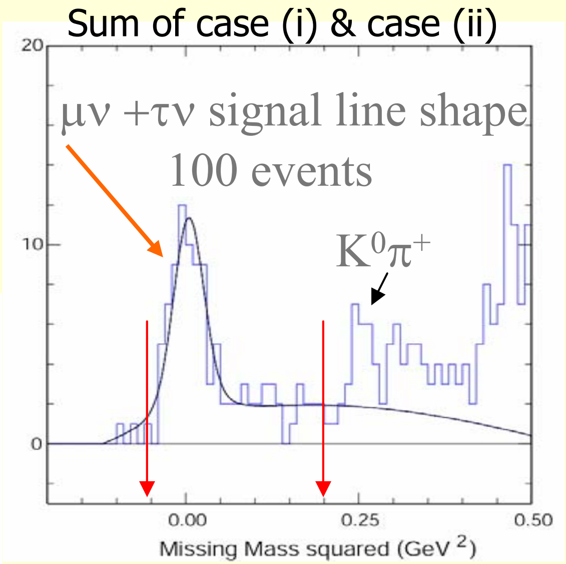
$e^+e^- \to D_s^* D_s \to \gamma D_s D_s$, find…
… D_s tag,
… γ,
… $D_s \to \mu\nu$ or $\tau(\to \pi\nu)\nu$ or $e\nu$; distinguish by energy deposition in calorimeter



$$MM^{*2} = (E_{CM} - E_{Ds} - E_\gamma)^2 - (-\vec{p}_{Ds} - \vec{p}_\gamma)^2$$



$B(D_S^+ \to e^+\nu) < 3.1 \times 10^{-4}$



CLEO preliminary results using SM $\mu\nu/\tau\nu$ ratio of 1:9.72:

Combined fit for $\mu+\tau$

$B(D_S^+ \to \mu^+\nu) =$
$(0.657 \pm 0.090 \pm 0.028)\%$

$B(D_S^+ \to \tau^+\nu) =$
$(7.1 \pm 1.4 \pm 0.3)\%$

Combining μ and τ:

$B^{eff}(D_S^+ \to \mu^+\nu) =$
$(0.664 \pm 0.076 \pm 0.028)\%$

$f_{Ds} = 282 \pm 16 \pm 7$ MeV (6%)

$D_S^+ \to \tau^+\nu$ (2)

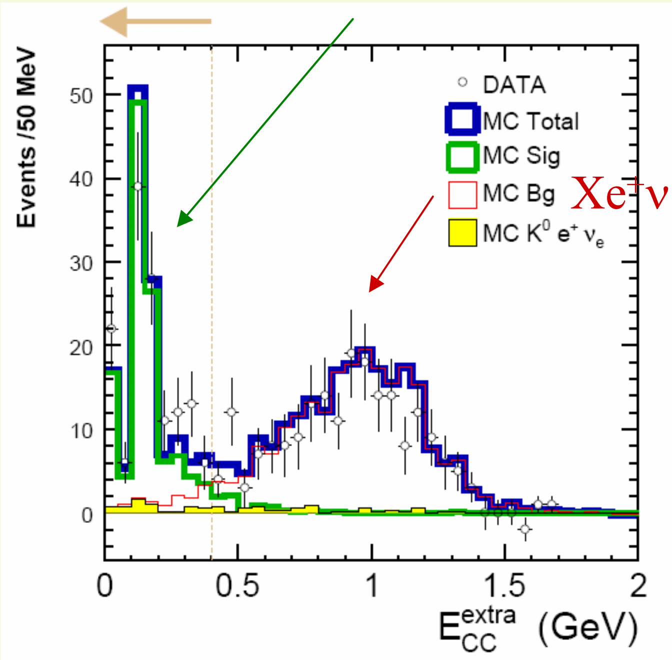
using $\mathbf{D_S^+ \to \tau^+\nu,\ \tau^+ \to e^+\nu\nu}$

$B(D_S^+\to\tau^+\nu)\times B(\tau^+\to e^+\nu\nu)$ ~1.3%; "large" compared with expected $B(D_S^+\to Xe^+\nu)$~8%

Signal candidates:
- (1) e^+ opposite D_S^- tag,
- (2) no other tracks,
- (3) Σ calorimeter energy < 400 MeV

(don't care about the 140MeV photon)

$200\,pb^{-1}$, DTagged at 4170MeV, $e^+e^- \to D_s^* D_s \to \gamma D_s D_s$



- **This analysis:**

$B(D_S^+\to\tau^+\nu) = (6.3\pm0.8\pm0.5)\%$

f_{Ds} = (278±17±12) MeV (7%)

- **Recall from previous slide:**

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

f_{Ds}=(282 ± 16 ± 7) MeV (6%)

CLEO preliminary

- **Combined:**

$\mathbf{f_{Ds}}$ = **(280±12±6) MeV** (5%)

$f_D = 222.6 \pm 16.7\ ^{+2.8}_{-3.4}$ MeV **(11%)**:

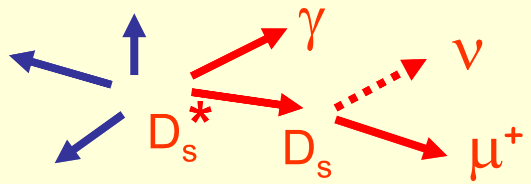
$\mathbf{f_{Ds}/f_D = 1.26 \pm 0.11 \pm 0.03}$ **CLEO (9%)**

$\mathbf{f_{Ds}/f_D = 1.24 \pm 0.07}$ **FNAL/MILC/HPQCD (6%)**

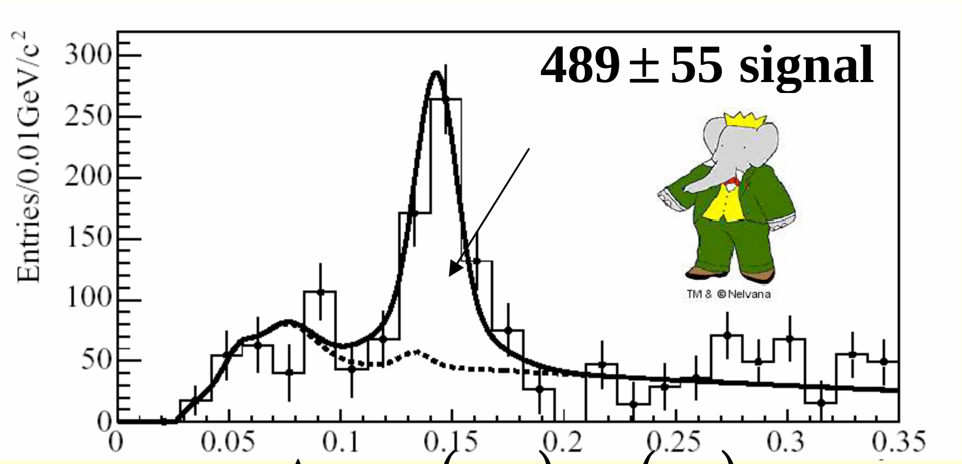
BaBar $D_s \to \mu\nu$

hep-ex/0607094, subm to PRL

Tag: D, D_s, D^* (13 modes)



$D_S^* \to \gamma D_s^+ \to \gamma(\mu\nu)$ at $\Upsilon(4S)$



$\Delta m = m(\gamma\mu\nu) - m(\mu\nu)$

- 230fb^{-1} of data in the Υ(4S) region from $e^+e^- \to c\bar{c}$ (cc^{bar})
- Use kinematic constraints: invariant masses, angle(muon,D_s)
- Peak in $m(D_S^*)-m(D_S)$ ~ 143 MeV signifies decay chain
- ~50k charm tags, ~500 signal events
- Normalization: D_s^* production rate in cc^{bar} fragmentation unknown; measure partial width ratio to $\phi\pi$

$$\frac{\Gamma(D_s^+ \to \mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.143 \pm \underset{13\%}{0.018} \pm \underset{4\%}{0.006}$$

Largest sys:
bgd shape parametrization

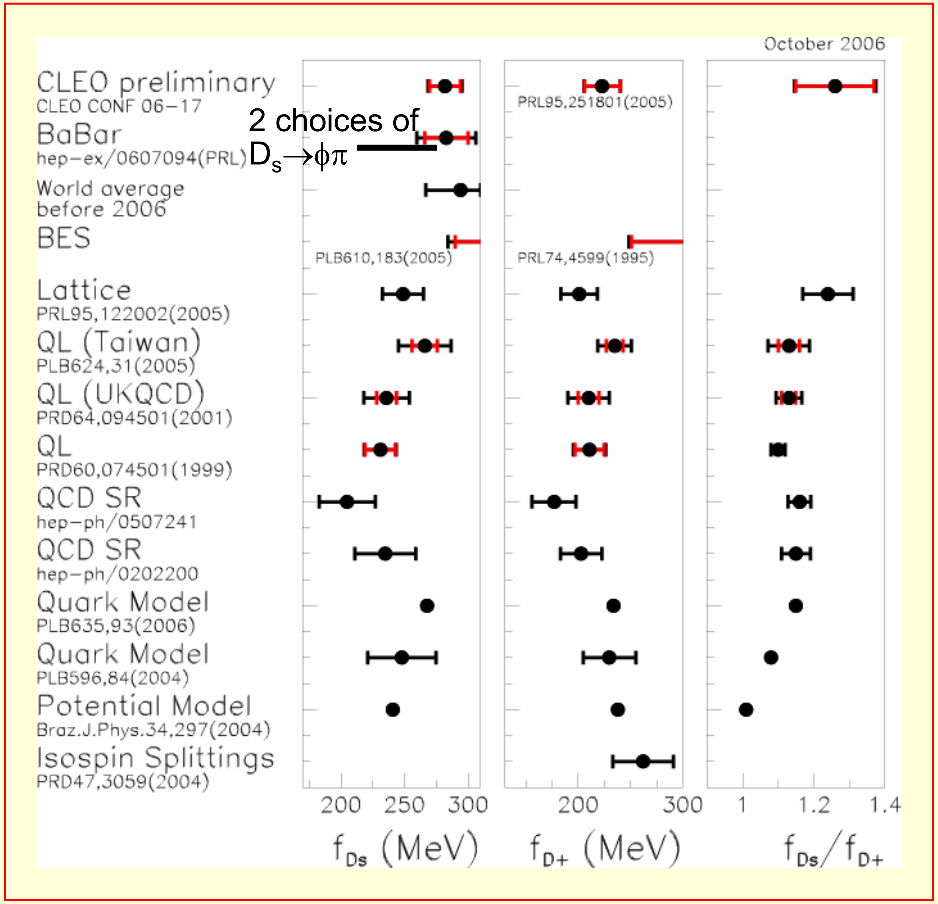
$BR(D_s^+ \to \phi\pi^+) = (4.71 \pm 0.46)\%$ ("BaBar ave"):

$BR(D_s^+ \to \mu^+\nu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$

$f_{Ds} = (283 \pm 17 \pm 7 \pm 14)$MeV (8%)

$BR(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9)\%$ (PDG04):
$BR(D_s^+ \to \mu^+\nu) = (5.15 \pm 0.63 \pm 0.20 \pm 1.29) \times 10^{-3}$
$f_{Ds} = (248 \pm 15 \pm 6 \pm 31)$MeV (14%)

Decay Constants, Summary



Leptonic charm decays:

$D \to \mu\nu$: fairly precise measurement of f_D (8%)

$D \to e,\tau\nu$: upper limits on BF

$D_s \to \mu\nu,\tau\nu$: two nice new measurements of f_{Ds} (5% CLEO, 8% BaBar)

Dominant errors are statistical (BaBar also normalization) $\Rightarrow$ error reduction “easy”

Most precise calculations are matching the experimental precision, but systematics limited

Semileptonic Decays

$D\to\phi\ell\nu$

$D\to\rho\ell\nu$

$D\to\eta(')\ell\nu$

$D\to\pi\ell\nu$

$D\to\omega\ell\nu$

$D\to K\ell\nu$

$D\to K^{*}\ell\nu$

$D\to X\ell\nu$

$D_s\to\phi\ell\nu$

$D\to K\pi\pi\ell\nu$

Topics:

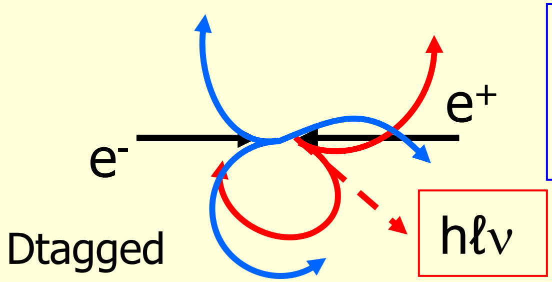
rare decays

precision BR

form factors

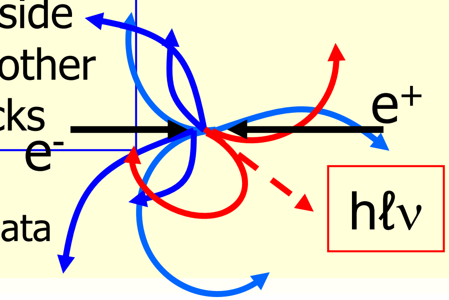
incl vs excl

$D \to \pi/Ke\nu$ Branching Fractions & Form Factors

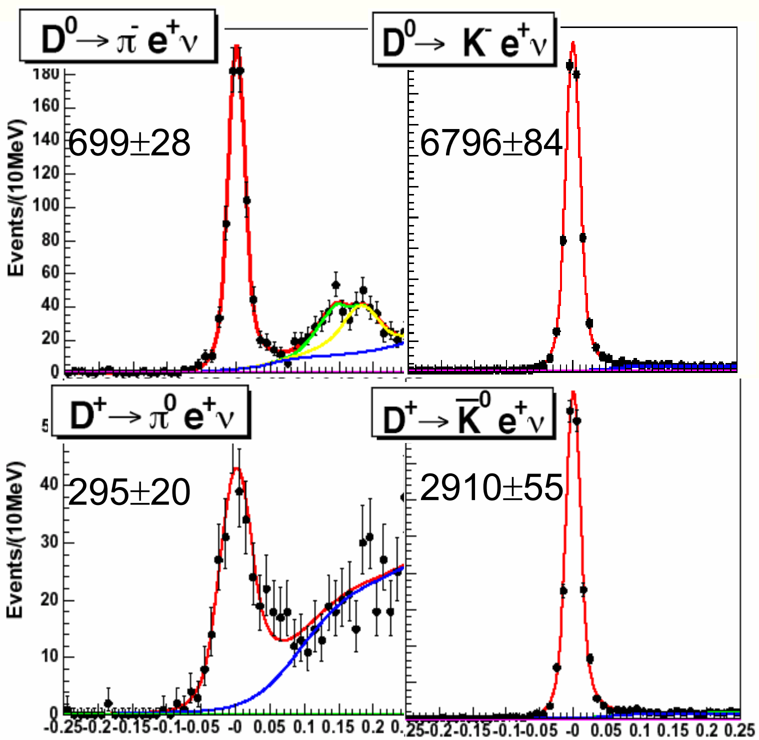


Specific D decay modes, "D tags"

Unspecified other-side D decay, collect all other showers and tracks

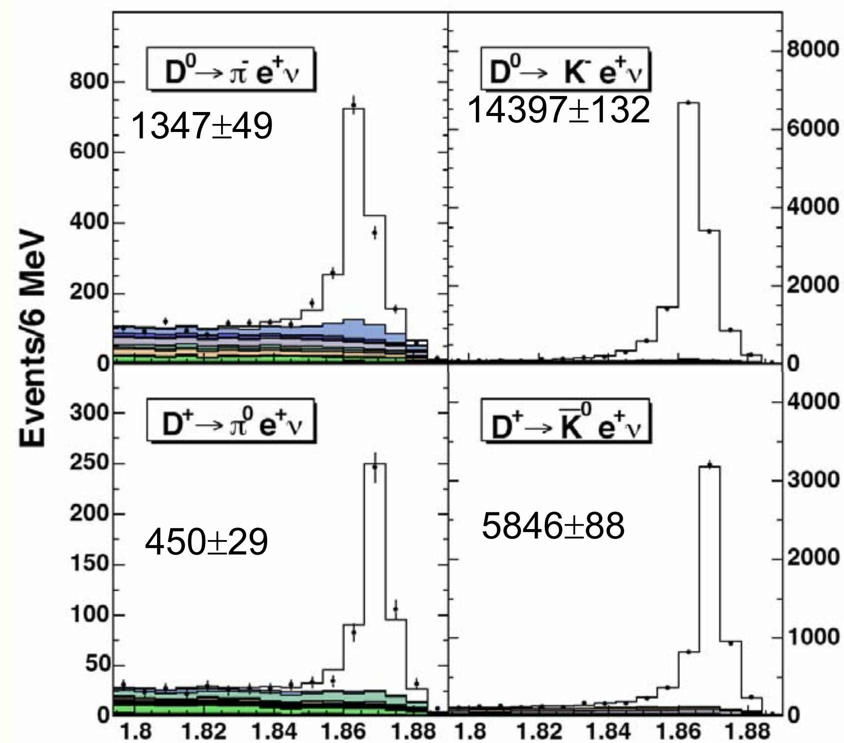


Neutrino reconstruction like $B\to\pi/\rho\ell\nu$ in Y(4S) data



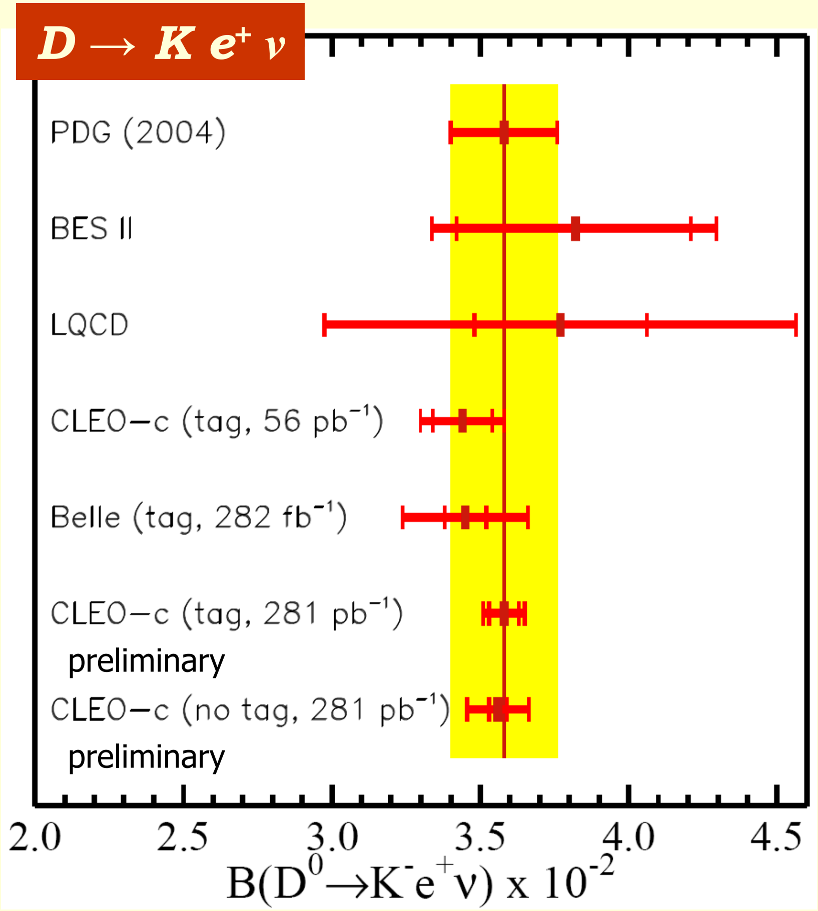
$U = E_{miss} - |P_{miss}|$ (GeV)

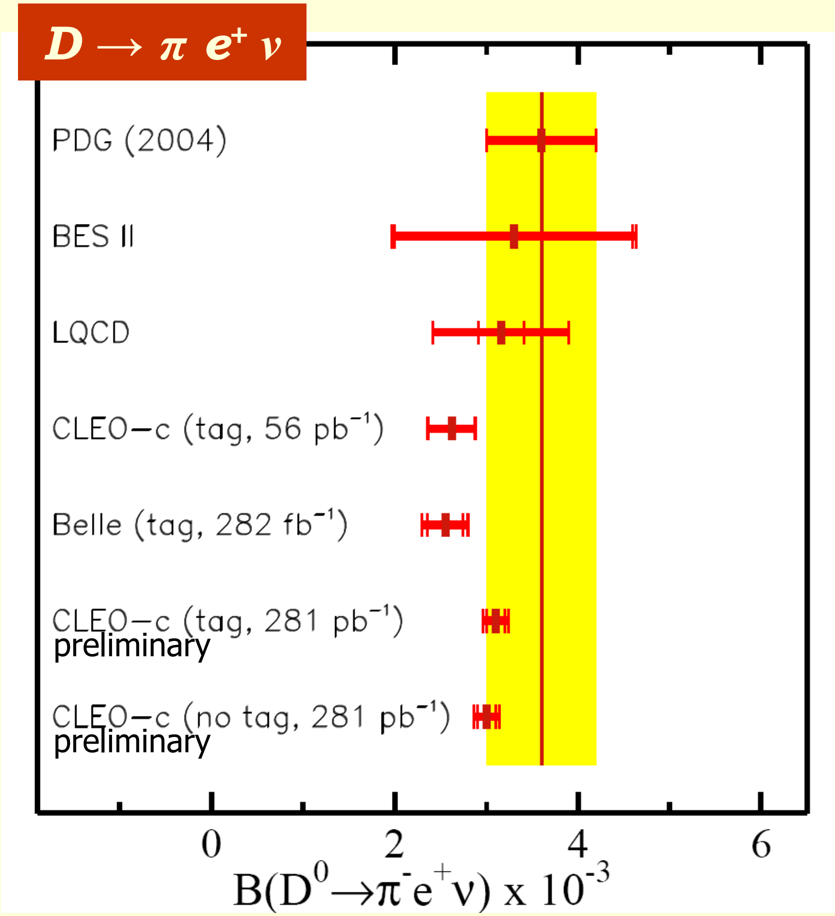
281pb^{-1}, plots, caution: samples overlap!



Reconstructed D candidate mass (substituting E_{beam} for E_D)

D $\to \pi, K e \nu$ Branching Fractions Comparison





Good consistency between measurements.
LQCD precision lags experiment.

Rare semileptonic D decays

CLEO preliminary

Dtagged, 281pb^{-1}

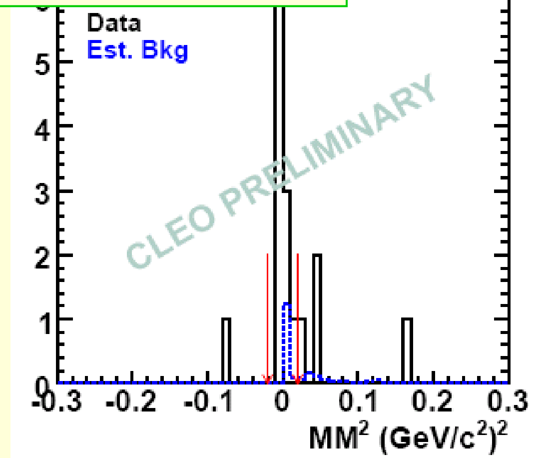
Mode	BR (10^{-4})
* $\eta e^+\nu$	$12.9\pm1.9\pm0.7$
** $\eta' e^+\nu$	<3 (90%CL)
** $\phi e^+\nu$	<2 (90%CL)
* $K^-\pi^+\pi^-e^+\nu$ $K_1(1270)e^+\nu$	$2.9^{+1.5}_{-1.0}\pm0.5$ $2.2^{+1.4}_{-1.0}\pm0.2$
*** $\omega e^+\nu$	$14.9\pm2.7\pm0.5$

* First observation

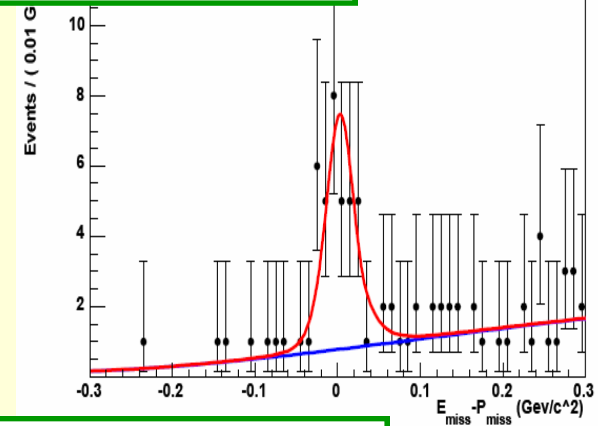
** Improved UL (factor 100)

*** Error improved by factor of two

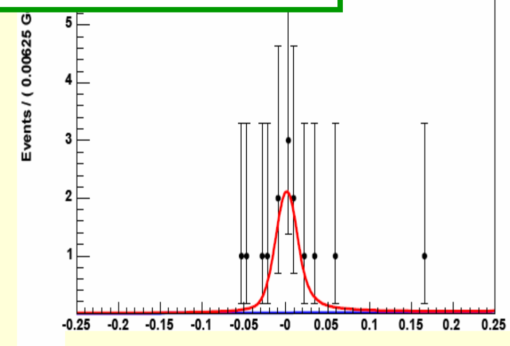
$D^0\to K^-\pi^+\pi^-e^+\nu_\varepsilon$ $8.5^{+4.5}_{-3.2}$



$D^+\to\eta(\gamma\gamma)e^+\nu_e$ 32.7 ± 6.7

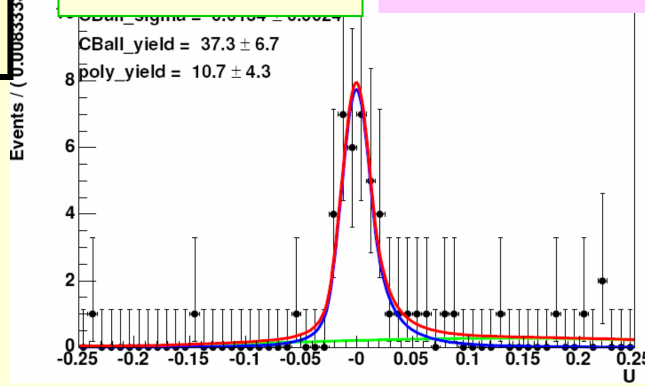


$D^+\to\eta(\pi^+\pi^-\pi^0)e^+\nu_e$ 13.3 ± 4.0



E_{miss}-P_{miss} (GeV^2)

$D^+\to\omega e^+\nu$ 37.3 ± 6.7



Two predictions:

B($D^+\to\eta$ [η'] $e^+\nu$)=…

…10 [1.6] $\times10^{-4}$

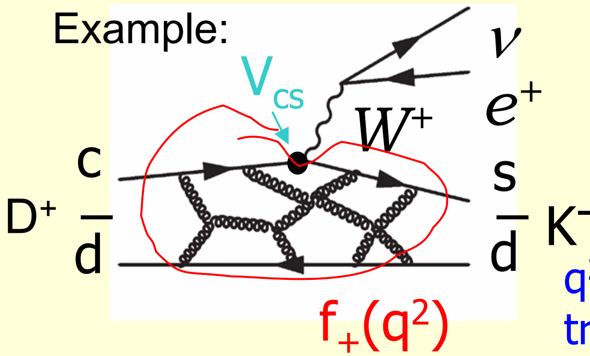
Fajfer & Kamenik, PRD71, 014020

…16 [5] $\times10^{-4}$

Scora & Isgur, RD52, 2783

Form factors

Example:



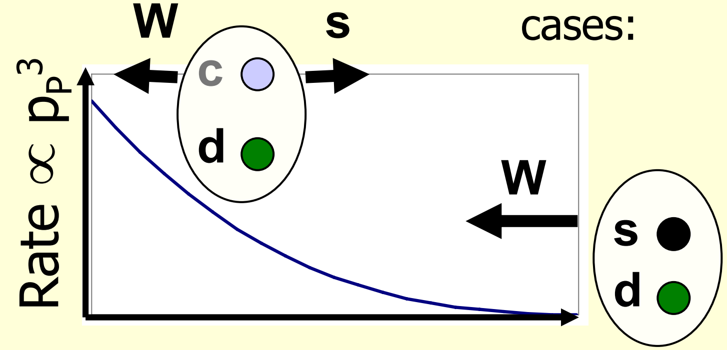
$$\frac{d\Gamma}{dq^2}(D \to \pi \ell \nu)$$

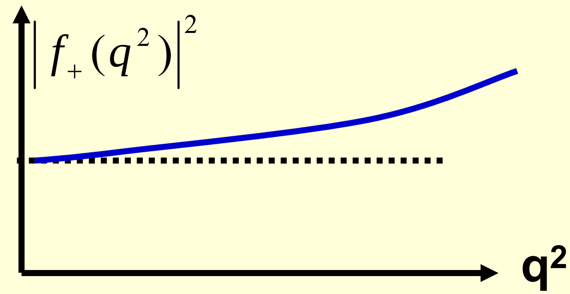
$$\propto \left| f_+^{\pi}(q^2) \right|^2 p_\pi^3 \left| V_{cd} \right|^2$$

$q^2 = m_{W*}$: momentum transfer to the W*

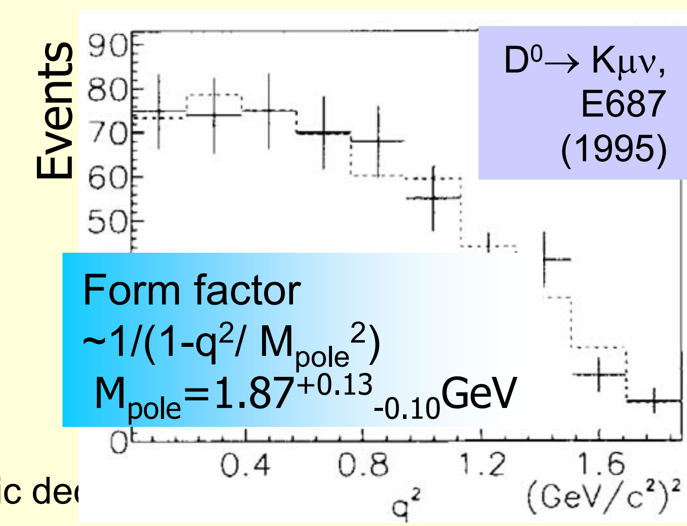
$f_+(q^2)$: form factor function

2 special cases:





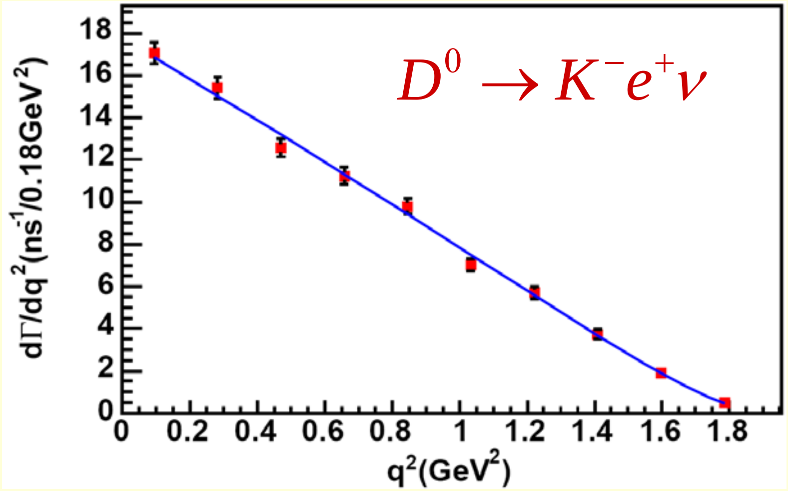
- Cannot calculate from first principles
- Many different parametrizations on the market
- Quantities of interest: shape *and* normalization
- Experiment can only determine $V_{cq} \times f(0)$
- Unitarity constrains V_{cq}, hence stringent tests possible
- HQET links D and B decay
- q^2 resolutions down to $O(0.01 GeV^2)$ have been achieved

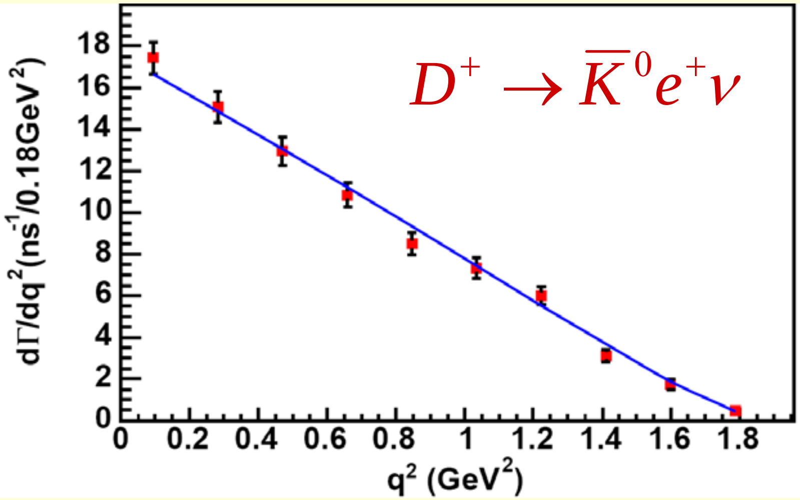


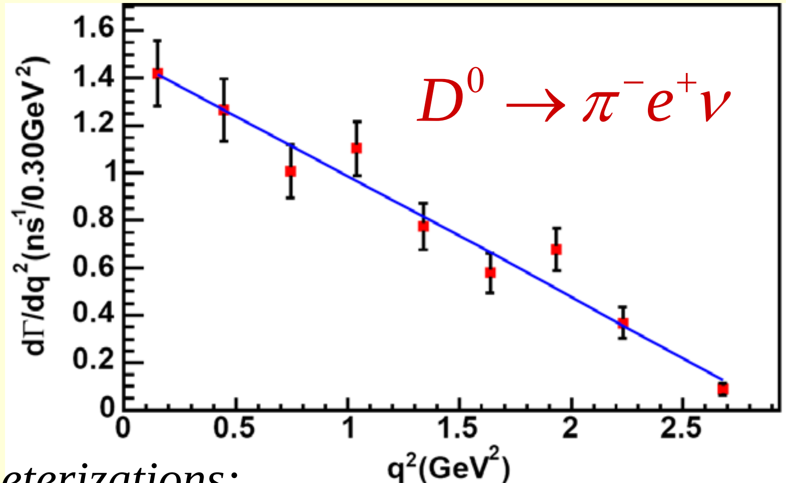
E687, PLB 364, 127 (1995)

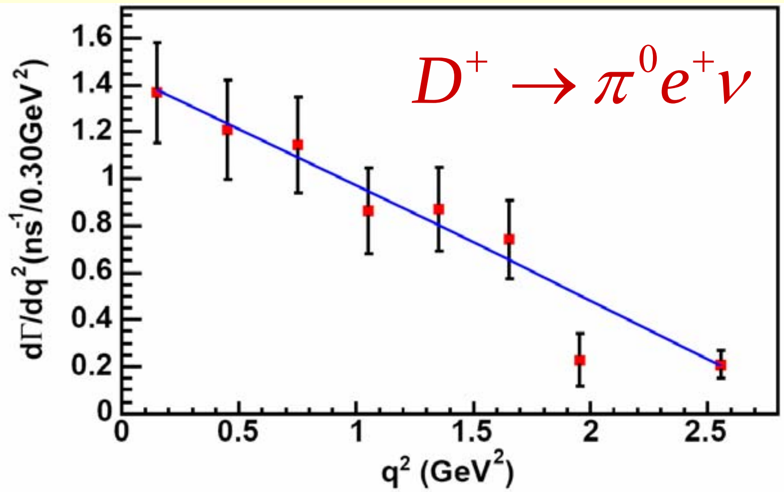
CLEO preliminary

Form factor fit plots









3 FF parameterizations:

Simple Pole Model

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

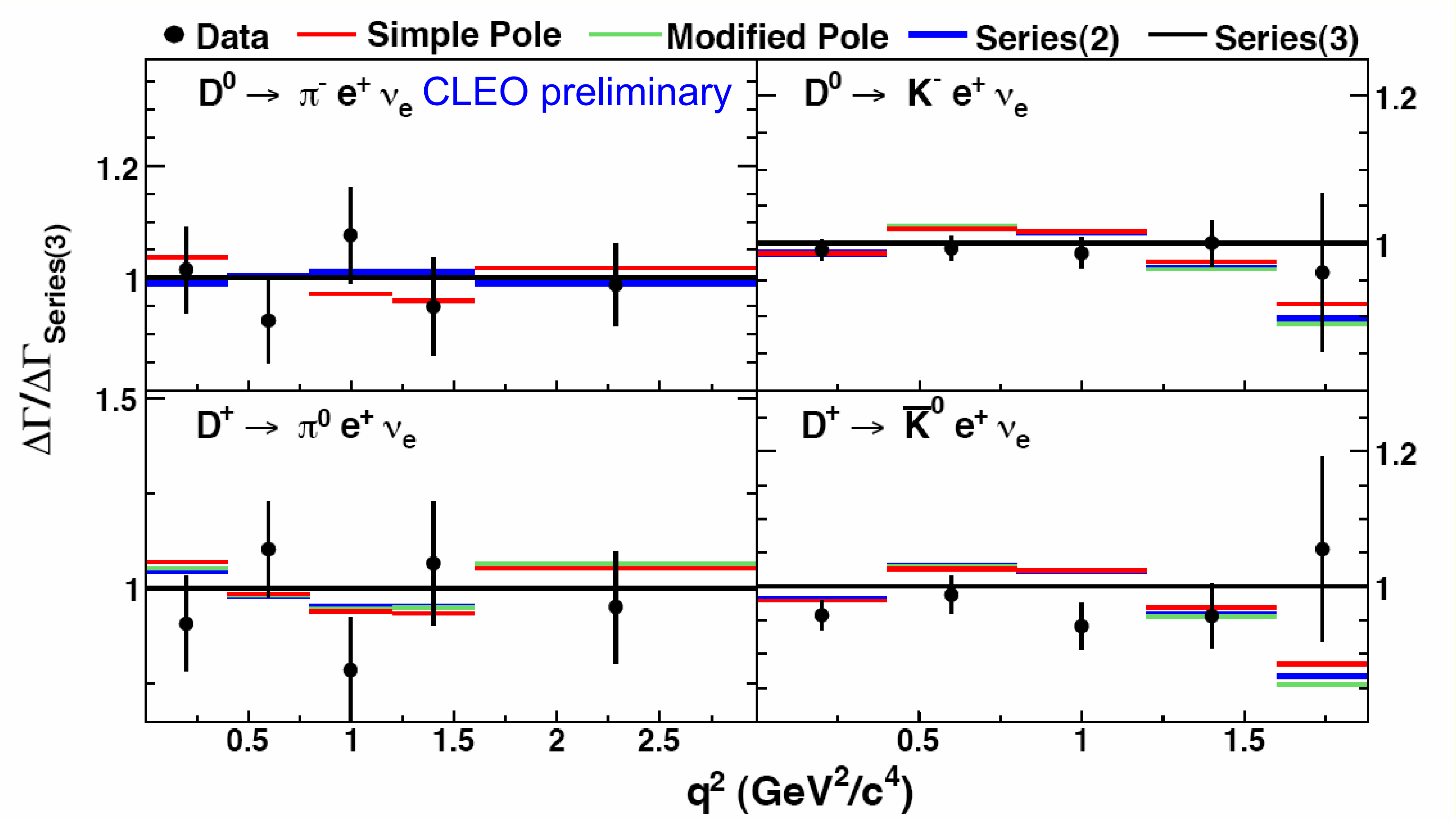
Modified Pole Model

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

+ Hill series expansion (Phys. Lett. B 633, 61 (2006)))

Tagged Modified Pole (BK) Model shown:

$D \to \pi/Ke\nu$: Which Form Factor Parameterization?

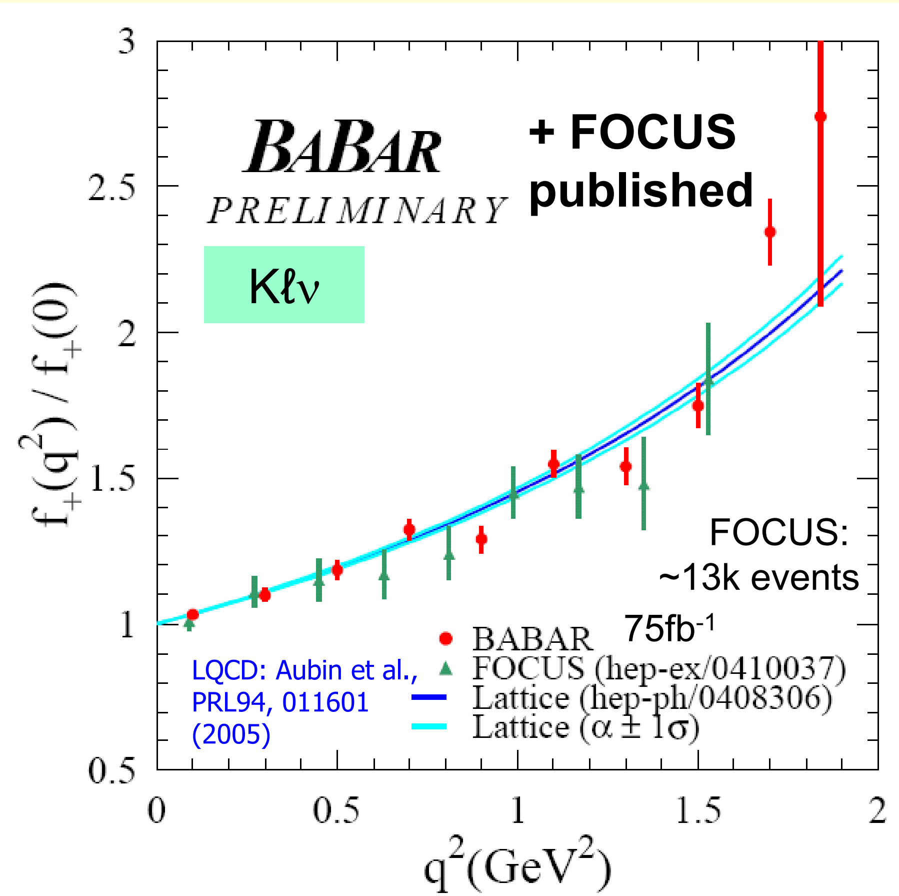


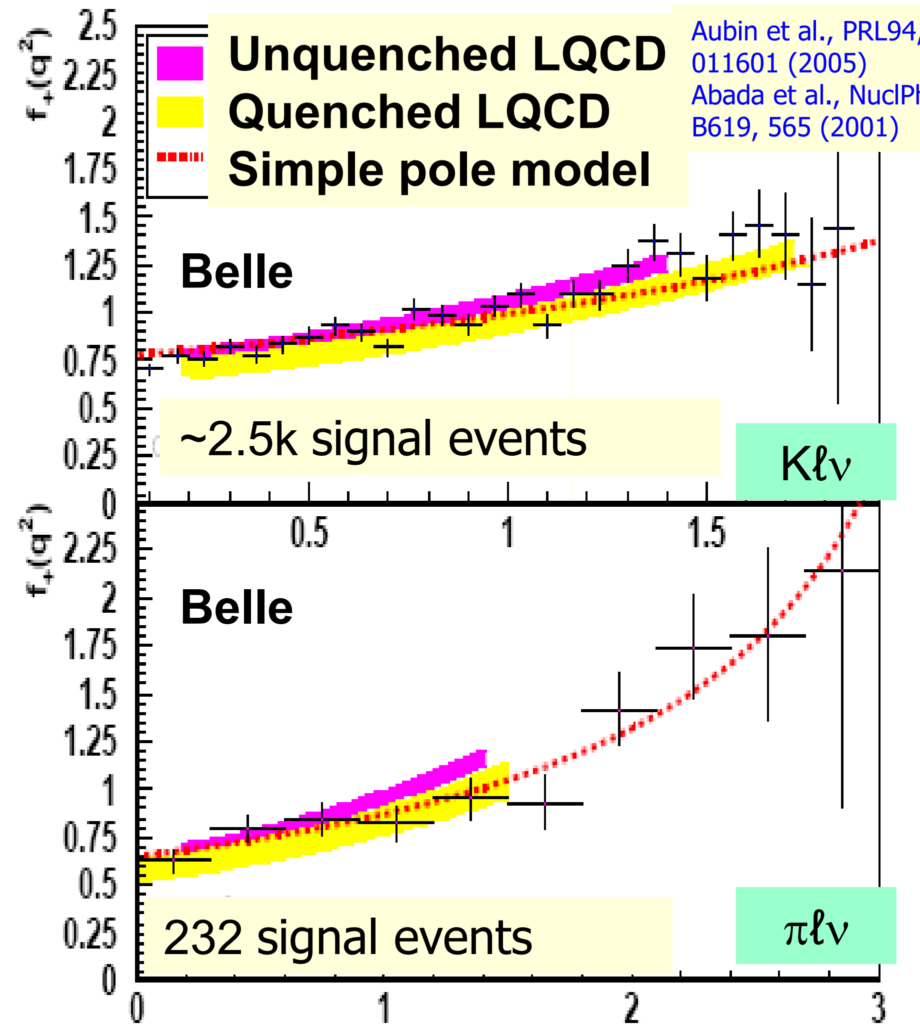
All these models describe the data pretty well (except when forcing pole mass to nominal value in pole model).

Belle,BaBar,FOCUS $D \to K,\pi\ell\nu$ form factors

BELLE: PRL 97, 061804 (2006) [hep-ex/0604049]
BaBar: hep-ex/0607077
FOCUS: PLB607, 233 (2005) [hep-ex/0410037]

Belle, 282fb^{-1}, fully reconstructed events, excellent q^2 resolution





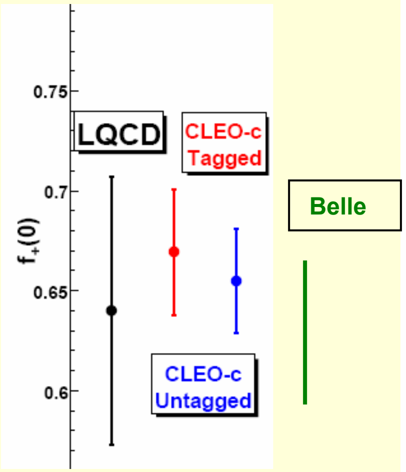
q^2 (GeV^2)

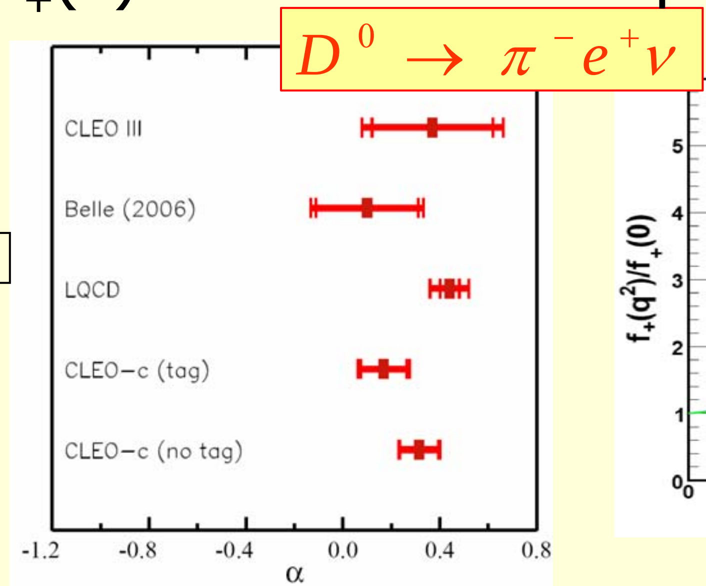
Form Factors as a Stringent Test of LQCD

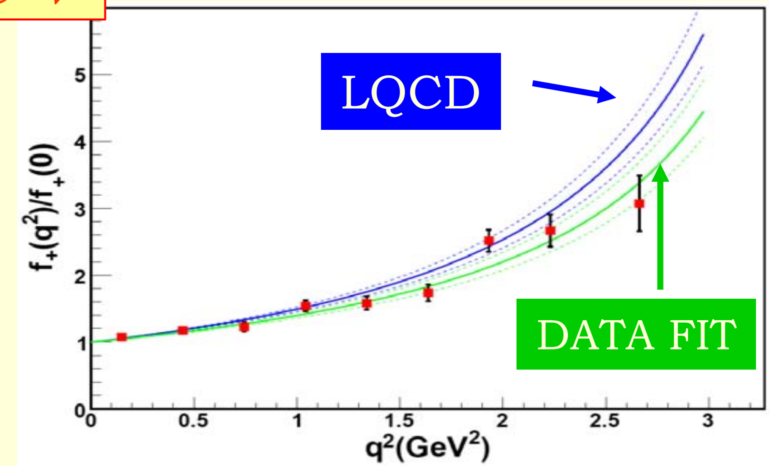
Normalization $f_+(0)$

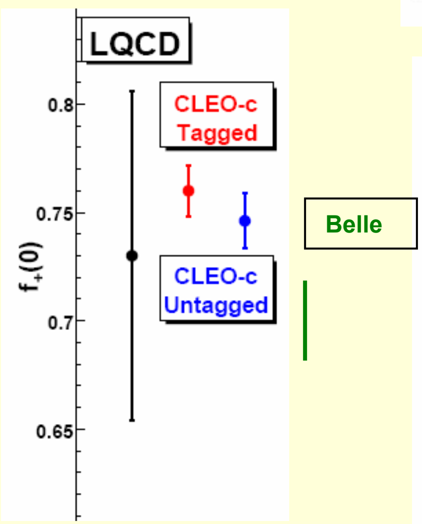
Shape; α

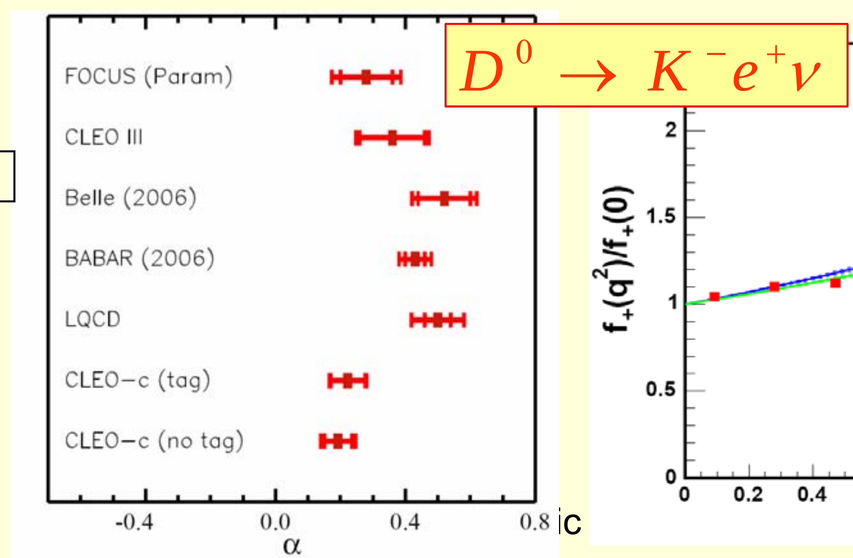
LQCD: PRL94,011601(2005)
Belle: PRL 97, 061804 (2006)
CLEO: preliminary

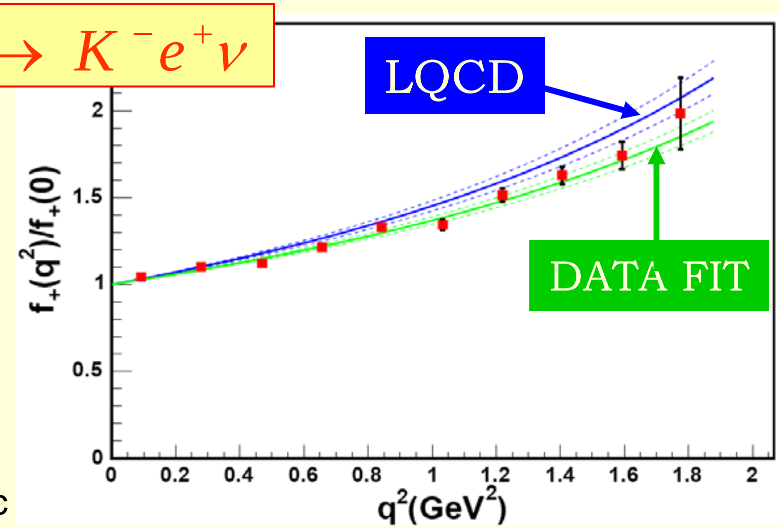












H. Mahlke, Cornell, HQL06

CLEO preliminary

V_{cs} and V_{cd} Precision

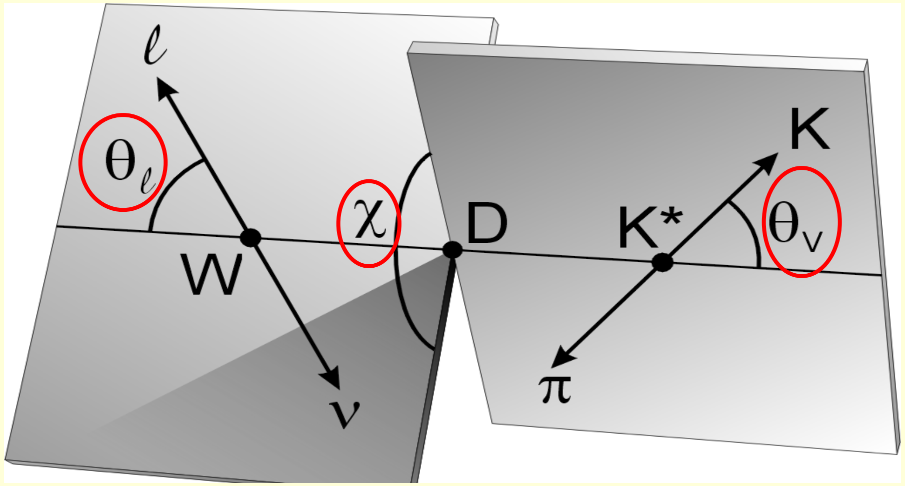
Experimental $|V_{cx}|f_+(0)$ from fits $\oplus$ $f_+(0)$ from unquenched LQCD
$\Rightarrow$ $|V_{cs}|$ and $|V_{cd}|$: PRL 94, 011601 (2005)

Decay Mode	$\|V_{cx}\|$ ± (*stat*) ± (*syst*) ± (*theory*)	*PDG/HF Value*
$D \to \pi e \nu$ *(tagged)*	0.234 ± 0.010 ± 0.004 ± 0.024	
$D \to \pi e \nu$ *(untagged)*	0.229 ± 0.007 ± 0.005 ± 0.024	0.224 ± 0.012
$D \to K e \nu$ *(tagged)*	1.014 ± 0.013 ± 0.009 ± 0.106	
$D \to K e \nu$ *(untagged)*	0.996 ± 0.008 ± 0.015 ± 0.104	0.976 ± 0.014

Tagged and untagged consistent.
40% of events are common to both analyses: DO NOT AVERAGE!
Uncertainties: experiment: V_{cs} <2%, V_{cd}~4% / LQCD $f_+(0)$ prediction: 10%

V_{cs} (W→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→Vector l ν Decay



"Traditional Method":
Rewrite $\mathbf{H_{\pm}(q^2), H_0(q^2)}$ as functions of $\mathbf{A_1(q^2), A_2(q^2), V(q^2)}$, spectroscopic pole dominance:

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_{Ai}^2} \quad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

M_V=2.1GeV
M_{A1}=M_{A2}=2.5GeV

R_V=V(0)/A_1(0)
R_2=A_2(0)/A_1(0)

Assume shape, end up with only two shape parameters.

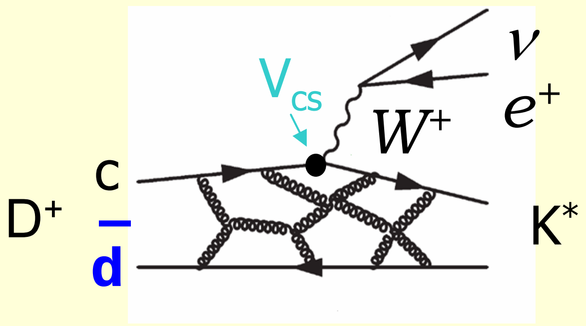
$$\int |A|^2 d\chi = \frac{1}{8} q^2 \left\{ \begin{array}{l} ((1+\cos\theta_l)\sin\theta_V)^2 |H_+(q^2)|^2 |BW|^2 \\ +((1-\cos\theta_l)\sin\theta_V)^2 |H_-(q^2)|^2 |BW|^2 \\ +(2\sin\theta_l\cos\theta_V)^2 |H_0(q^2)|^2 |BW|^2 \\ +8\left(\sin^2\theta_l\cos\theta_V\right) H_0(q^2) h_o(q^2) \mathrm{Re}\left\{A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

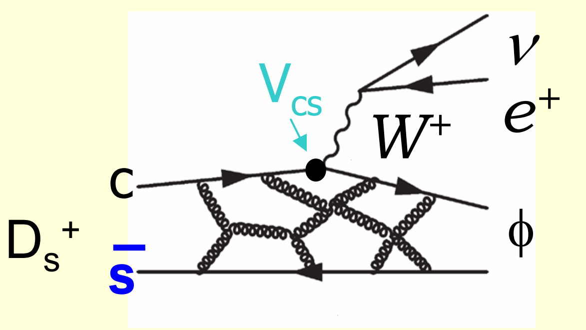
Present in K*ℓν; what about ρℓν? φℓν?

$H_0(q^2)$, $H_+(q^2)$, $H_-(q^2)$ are helicity-basis form factors computable by LQCD
A new factor $\mathbf{h_0}$ (q^2) is needed to describe **s-wave interference piece**.

An earlier controversy

Expect form factor similarity:



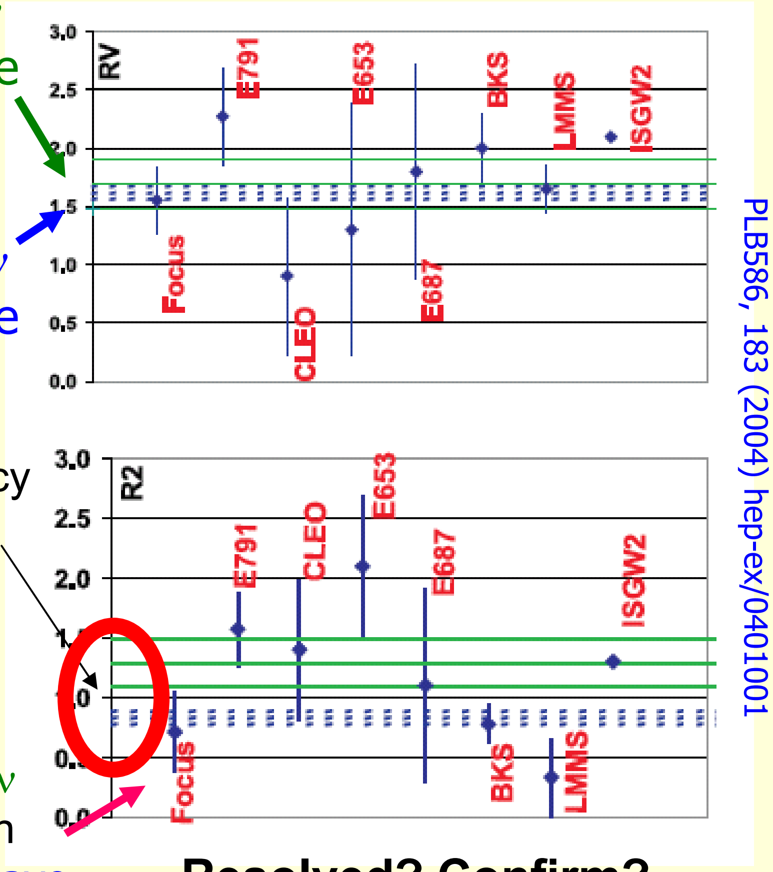


$D_s \to \phi \ell \nu$ world ave

$D \to K^* \ell \nu$ world ave

Discrepancy for R_2:

FOCUS $\phi \ell \nu$ agrees with $K^* \ell \nu$ world ave

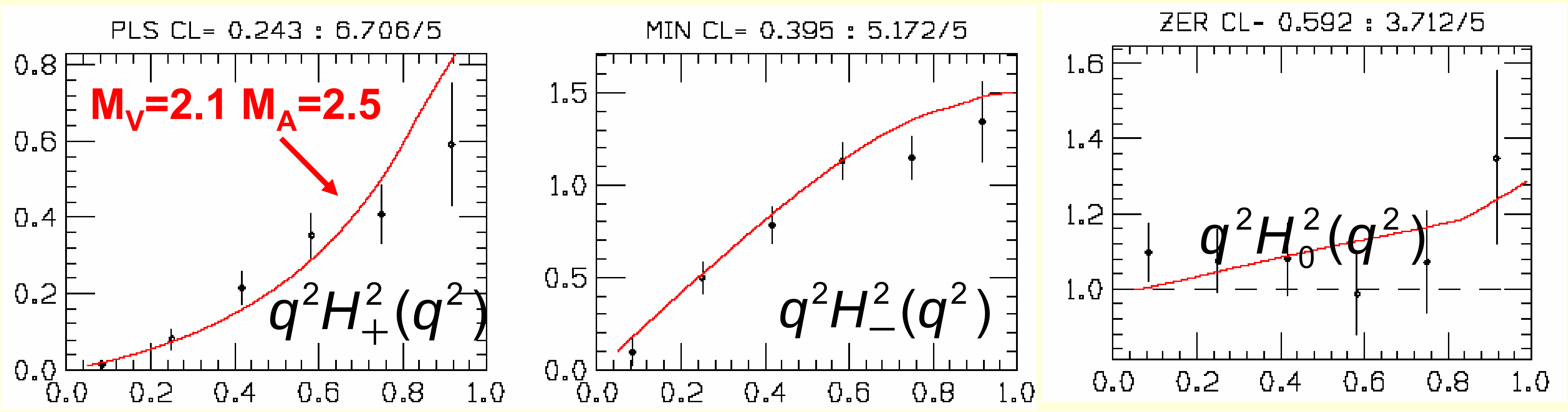


Resolved? Confirm?

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

- data (281 pb^{-1})
- – overlay (not fit)

$H_0(q^2)$, $H_+(q^2)$, $H_-(q^2)$ are **helicity-basis form factors** computable by LQCD
A new factor **h_0** (q^2) is needed to describe **s-wave interference piece**.



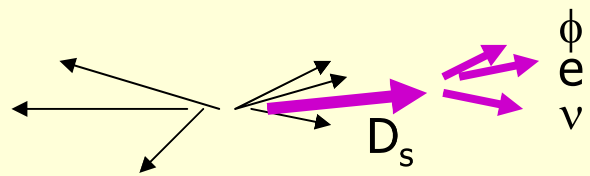
CLEO PRD 74, 052001 (2006)

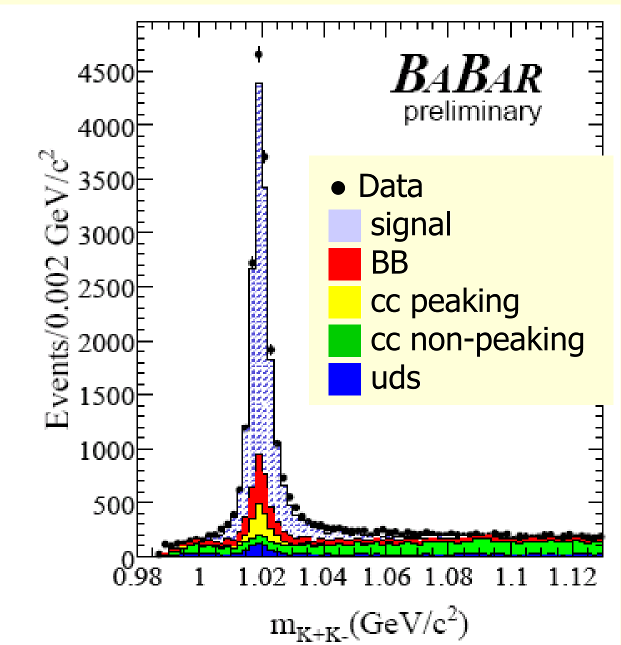
Data fits spectroscopic poles and constant form factors equally well.
No evidence for d- or f-wave contributions.

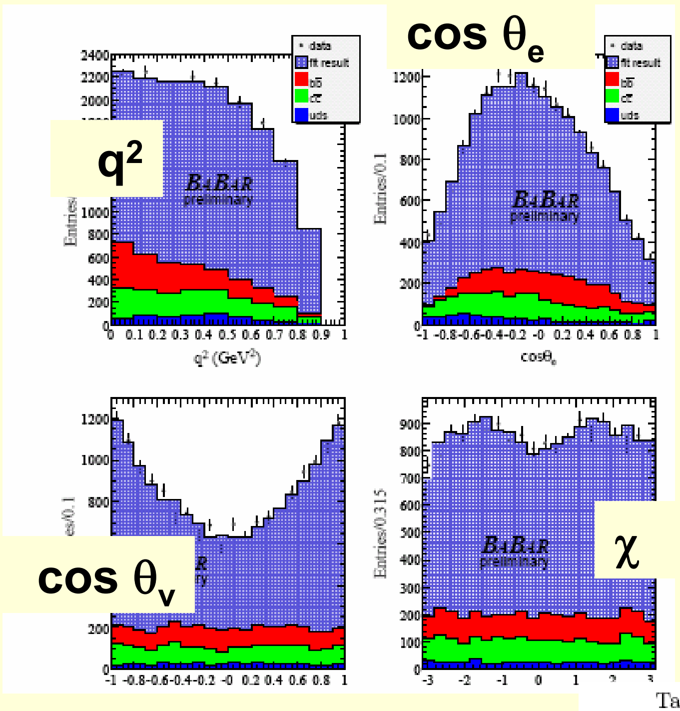
hep-ex/0607085,
ICHEP prelim

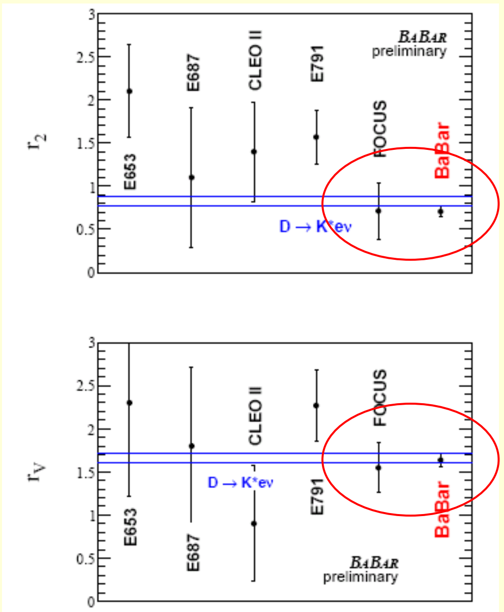
BaBar $D_s \to \phi e \nu$ form factors

$e^+e^- \to cc^{bar}$ from 78.5fb^{-1},
about 13k signal events









Fit in the simple pole model, using m_V=2.1GeV

Table 6: Comparison between $D/D_s^+ \to V e^+ \nu_e$ decays.

Parameter	$D_s^+ \to \phi e^+ \nu_e$ (this analysis)	$D \to K^* e^+ \nu_e$ (average value at FPCP06)
r_V	$1.636 \pm 0.067 \pm 0.038$	1.66 ± 0.06
r_2	$0.705 \pm 0.056 \pm 0.029$	0.827 ± 0.055

Dtagged, 281/pb

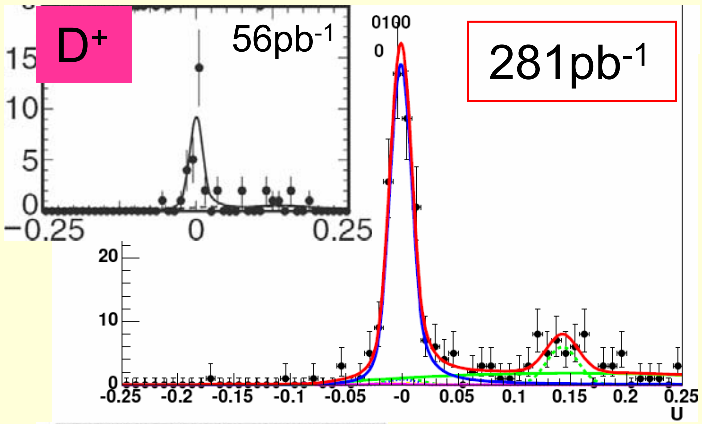
$D \to \rho e \nu$ (BR+FF)

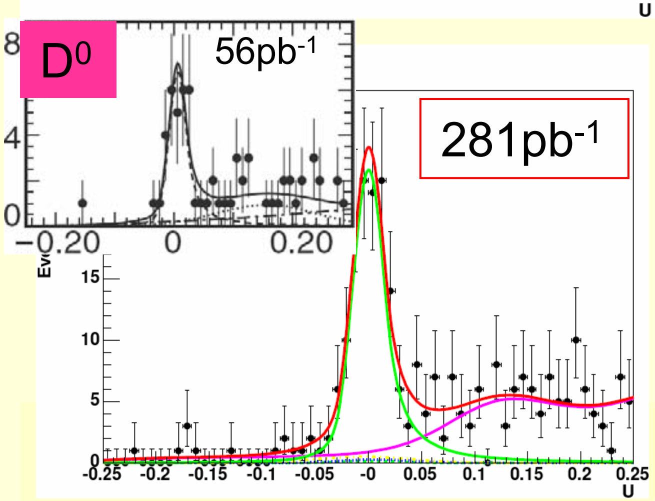
Interest: 1st measurement of FF in Cabibbo-*suppressed* charm PS→ V decay

$$\frac{d\Gamma\left(B \to \rho e^{+} \nu\right)/dq^{2}}{d\Gamma\left(B \to K^{*} ll\right)/dq^{2}} \propto \frac{\left|V_{ub}\right|^{2}}{\left|V_{ts}\right|^{2}}$$

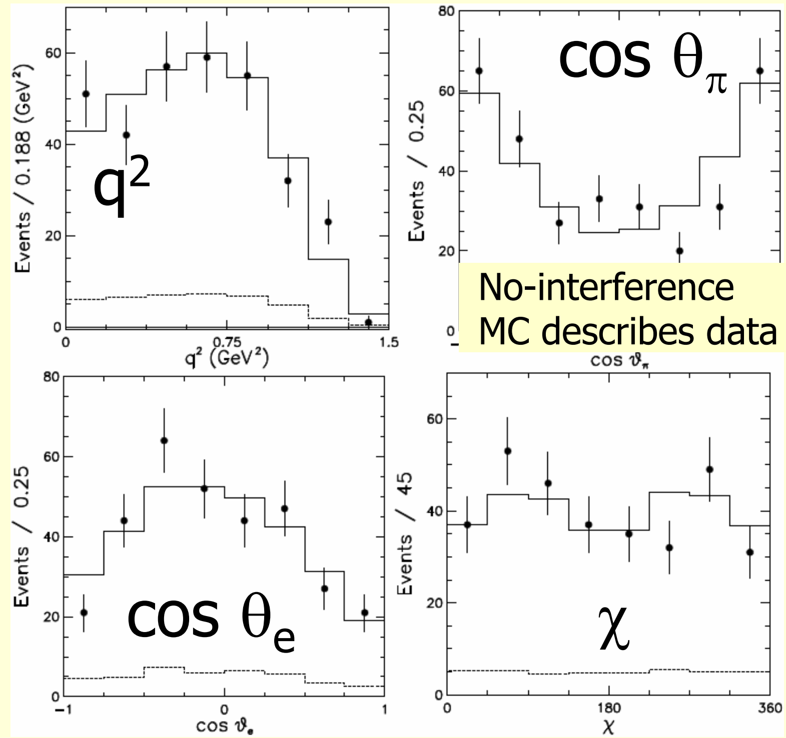
Need $D \to K^{*} e \nu$ and **$D \to \rho e \nu$ FF**

Grinstein & Pirjol [hep-ph/0404250]





Fixed background shape and signal tails from MC



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:

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

this analysis

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

FOCUS PLB 637,32 (2006)

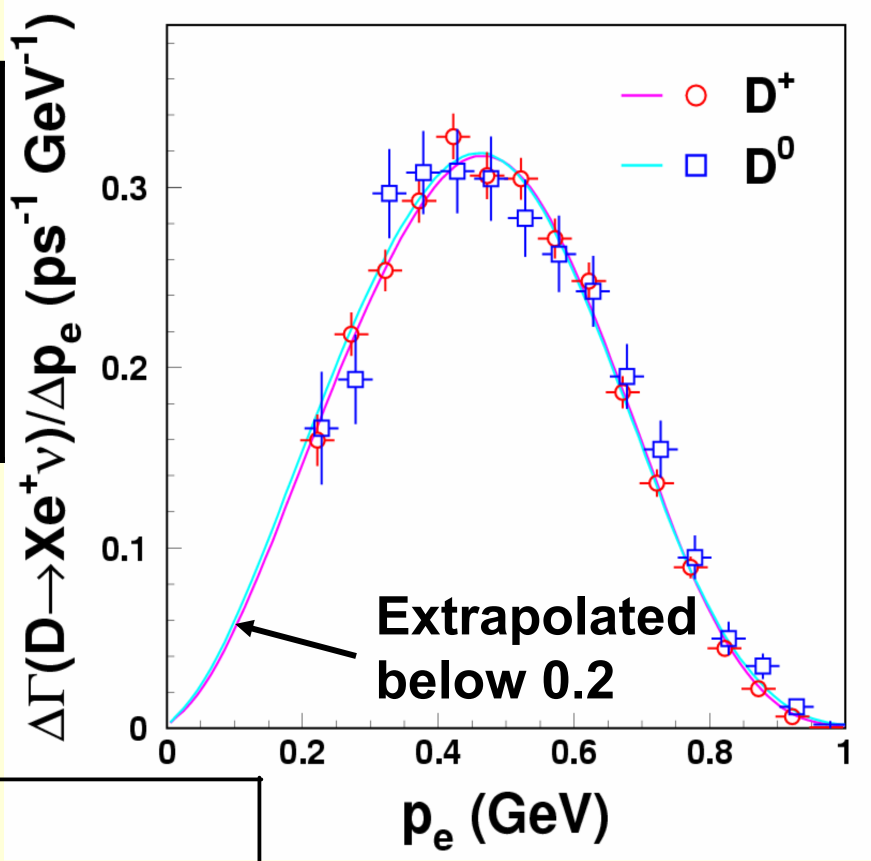
CLEO preliminary

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

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

Inclusive Semileptonic Results

mode	Branching Fraction
$D^0 \to Xe^+\nu$	**$(6.46 \pm 0.17 \pm 0.13)\%$**
$\Sigma_i B_i (D^0 \to Xe^+\nu)$	$(6.1 \pm 0.2 \pm 0.2)\%$
$D^+ \to Xe^+\nu$	**$(16.13 \pm 0.20 \pm 0.33)\%$**
$\Sigma_i B_i (D^+ \to Xe^+\nu)$	$(15.1 \pm 0.5 \pm 0.5)\%$



Consistent with the known exclusive modes saturating the inclusive branching fractions.

$$\frac{\Gamma^{SL}_{D^+}}{\Gamma^{SL}_{D^0}} = \frac{B^{SL}_{D^+}}{B^{SL}_{D^0}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985 \pm 0.028 \pm 0.015$$

Consistent with isospin symmetry

CLEO-c 281pb^{-1}, DTagged

hep-ex/0604044, subm to PRL

Summary

Leptonic and semileptonic charm decays are a very active area of research:

- Insight into QCD phenomena that occur in charm as well as in bottom
- Experimental accuracy provides stringent tests for theoretical tools, to be applied in bottom physics
- A variety of experimental techniques explored, with great success

Conclusions:

1) The race between theory and experiment is still on.
2) It's all connected!

➢ **Leptonic decays:**
theory and experiment are at the same level of precision for f_D and f_{Ds};
most significant improvements:
experiment – statistics,
theory – systematics

➢ **Semileptonic decays:**

- Critical measurements of branching fractions and form factors for pseudoscalar and vector final state hadrons
- Consistency checks
- Much improved precision in normalization and shape