Semileptonic Results from CLEO

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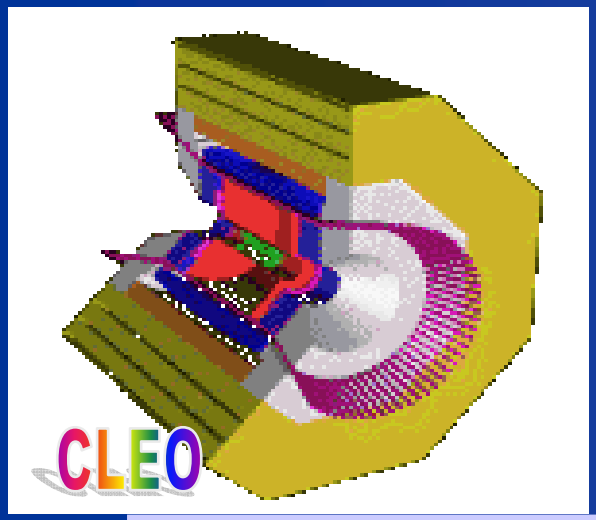
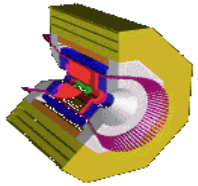
(CLEO Collaboration)

ICHEP06, Moscow, July. 26 – Aug 2, 2006





CLEO Semileptonic Results

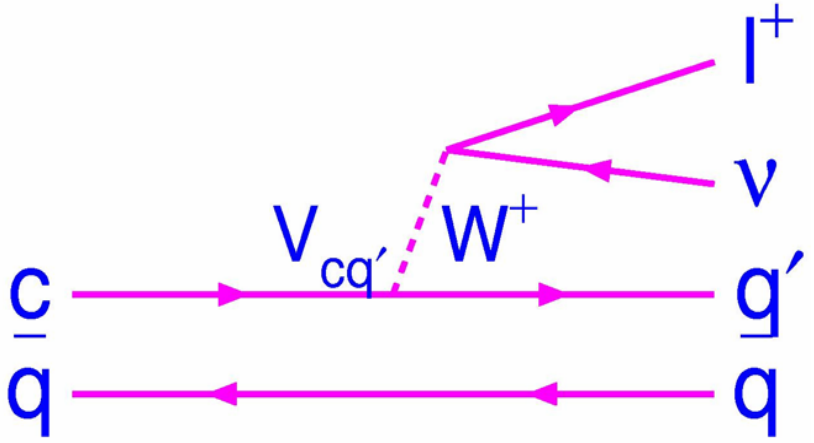
CLEO-c data: 281 pb^{-1} at ψ(3770)

- D^0/D^+ inclusive semileptonic decays
- First Observation of $D^+ \to \eta e^+ \nu$, $D^0 \to K^- \pi^+ \pi^- e^+ \nu$
- Form Factors & Vcs, Vcd from $D^0/D^+ \to K/\pi e^+ \nu$
- First measurement of Form Factors in $D \to \rho e^+ \nu$
- Form Factors in $D^+ \to K^- \pi^+ e^+ \nu$
- Exclusive semileptonic $b \to u$

CLEO Y(4S) data

Why Semileptonic D Decay?

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



$D^0 \to Xe^+\nu$ and $D^+ \to Xe^+\nu$:

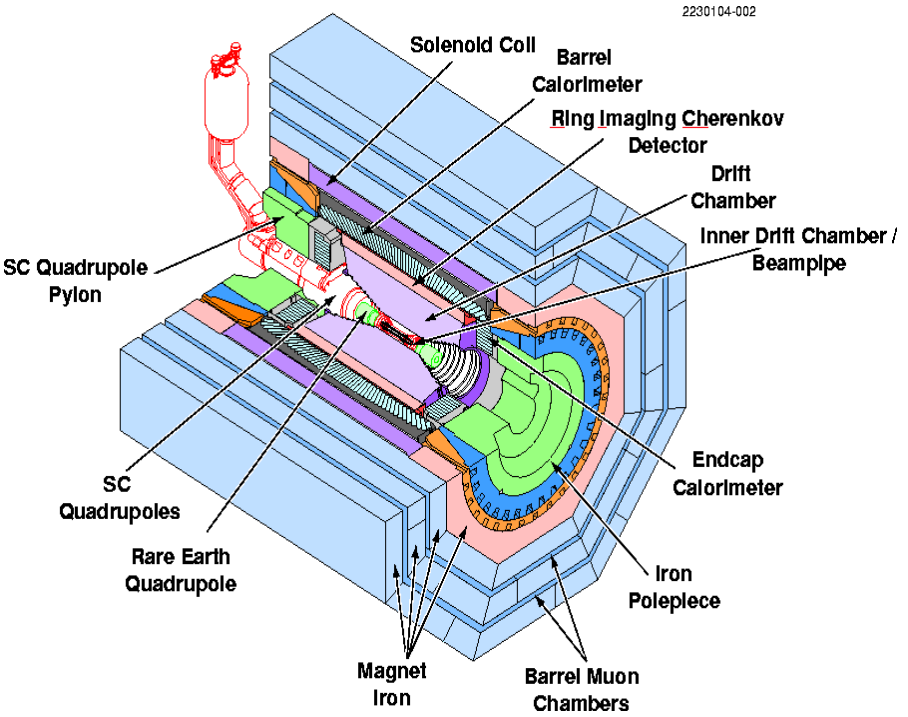
- **Inclusive semileptonic BR and spectrum**

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

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

- **Form Factors, V_{cd}, V_{cs} and V_{ub}**

CESR and CLEO-c



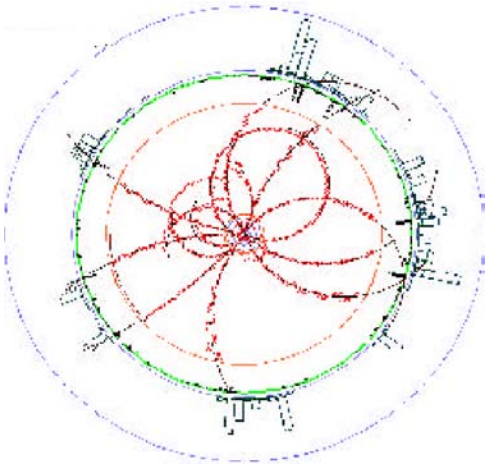
Tracking: Drift Chambers

Electron ID: CsI Cal.

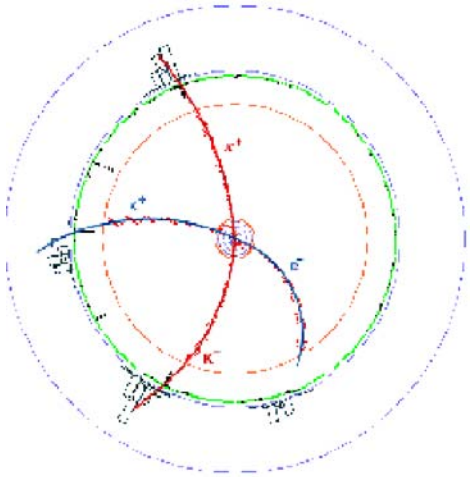
Hadron ID: RICH

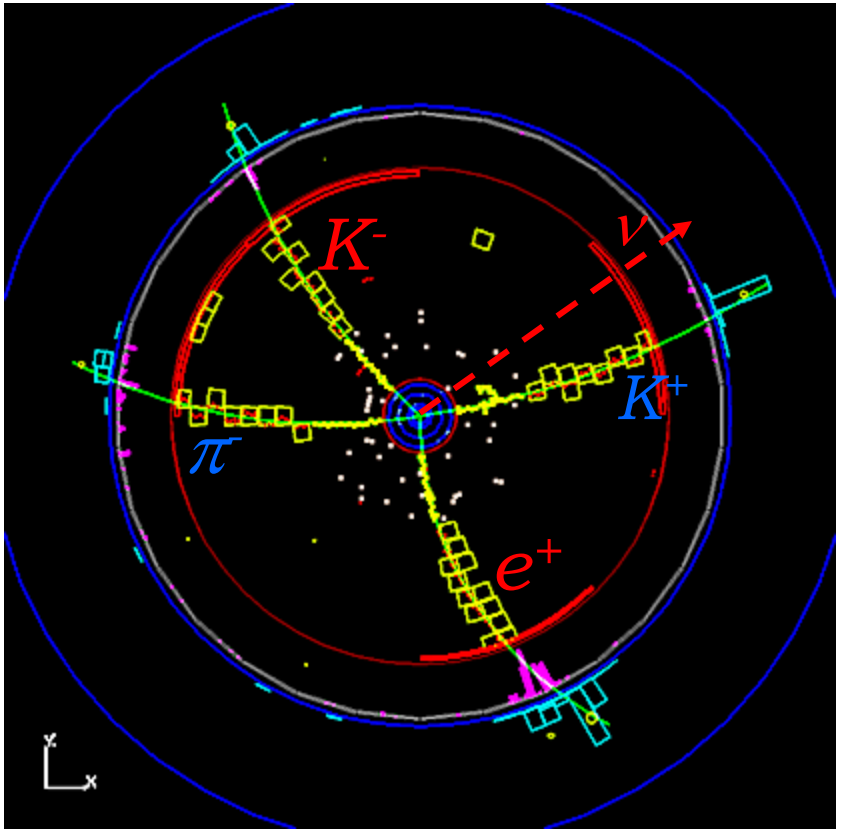
Charm at Ψ(3770) vs ~ϒ(4S)

~ϒ(4S)



Ψ(3770)





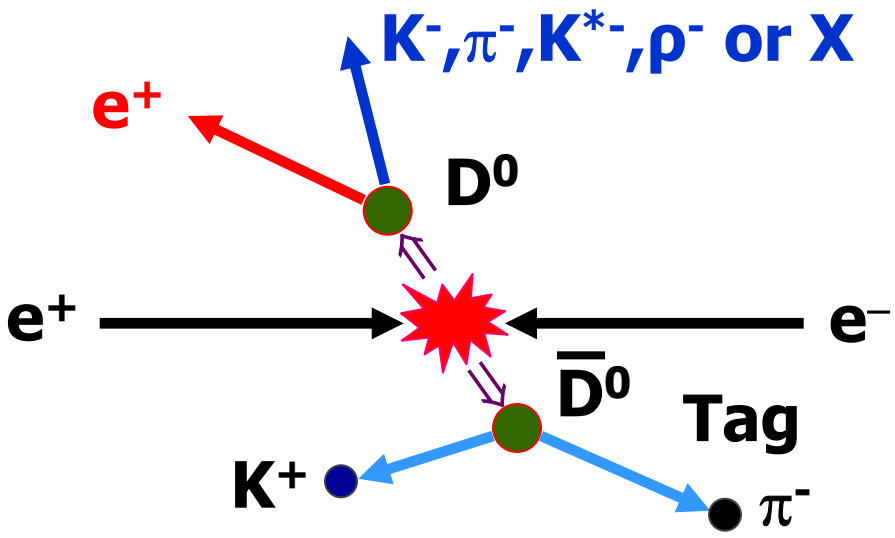
- Large Cross-Section
- Low Multiplicity
- NO Fragmentation
- Kinematics Variables: →
- "Background Free"

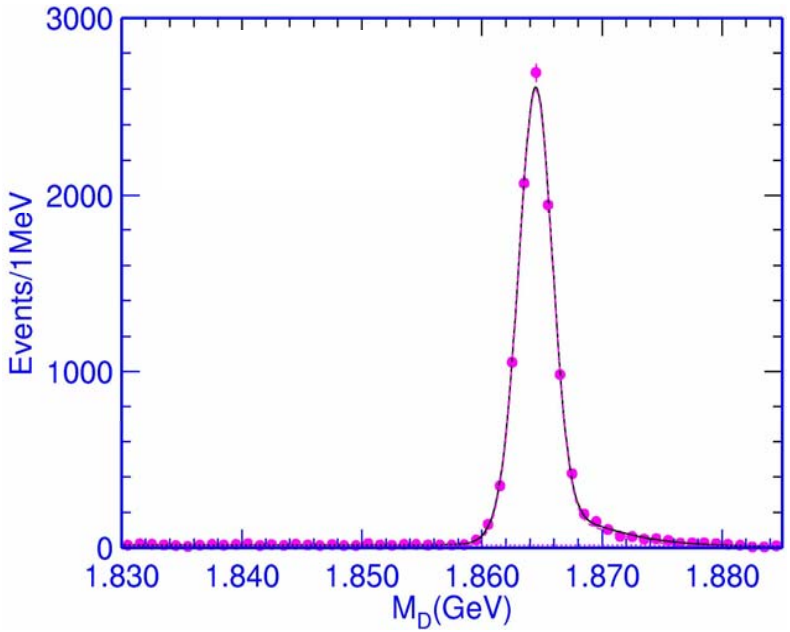
$$M_D \equiv \sqrt{E_b^2 - |p_D|^2}$$

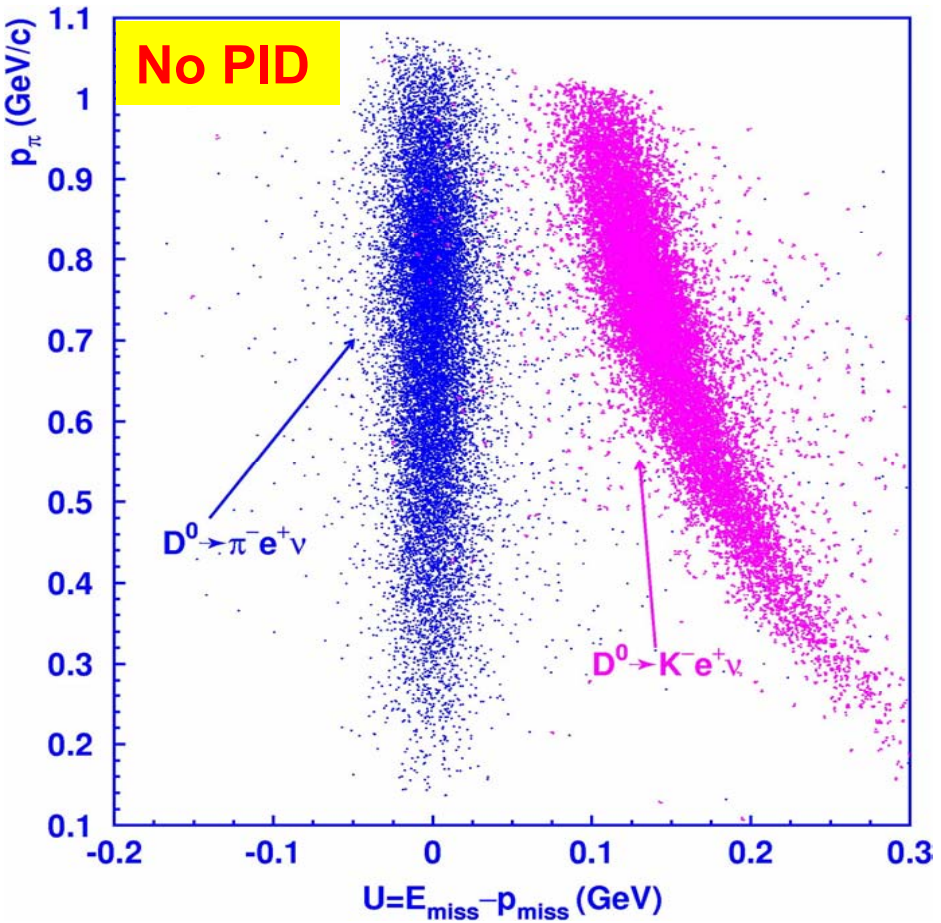
$\Delta E = E_b - E_D$

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

Unique Kinematics at Ψ(3770)

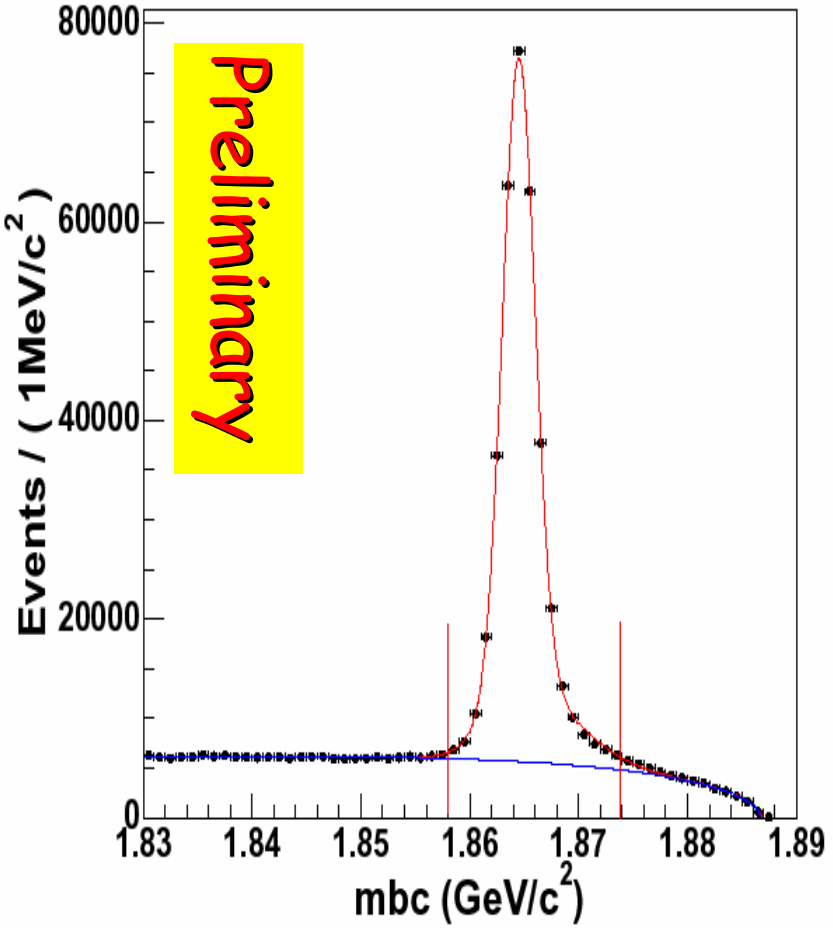


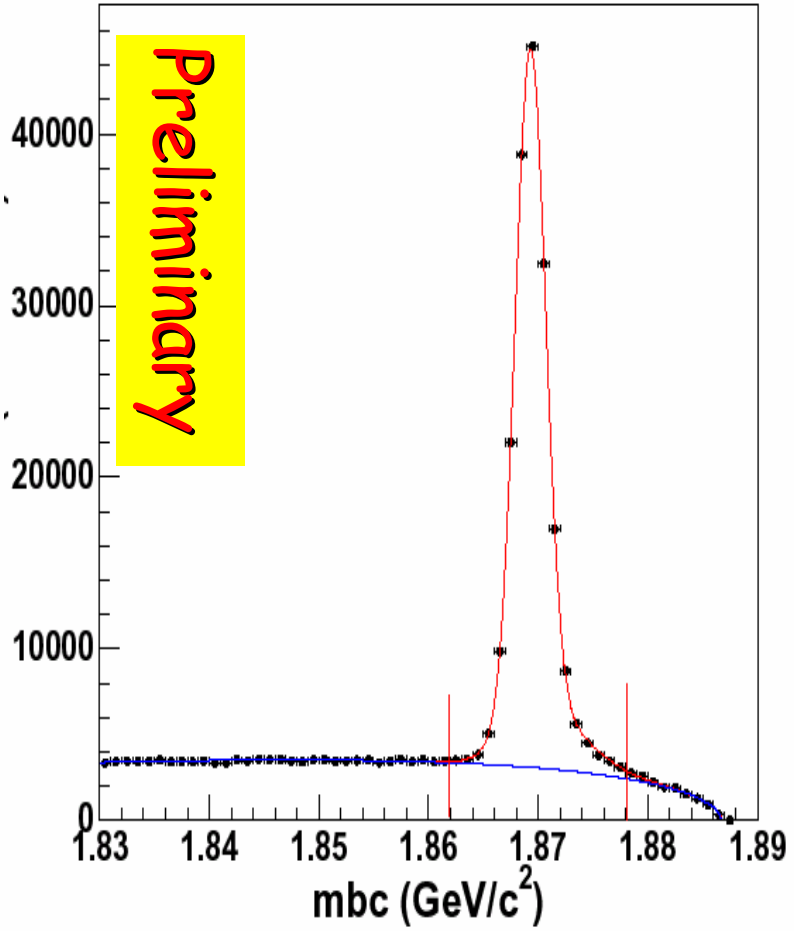




$D^0 \to \pi^- e^+ \nu$

Fully Reconstructed D^0/D^+ (Tag)





From 281 pb^{-1} at $\Psi(3770)$

All D^0 tags
~308K fully reconstructed

All D^+ tags
~163K fully reconstructed

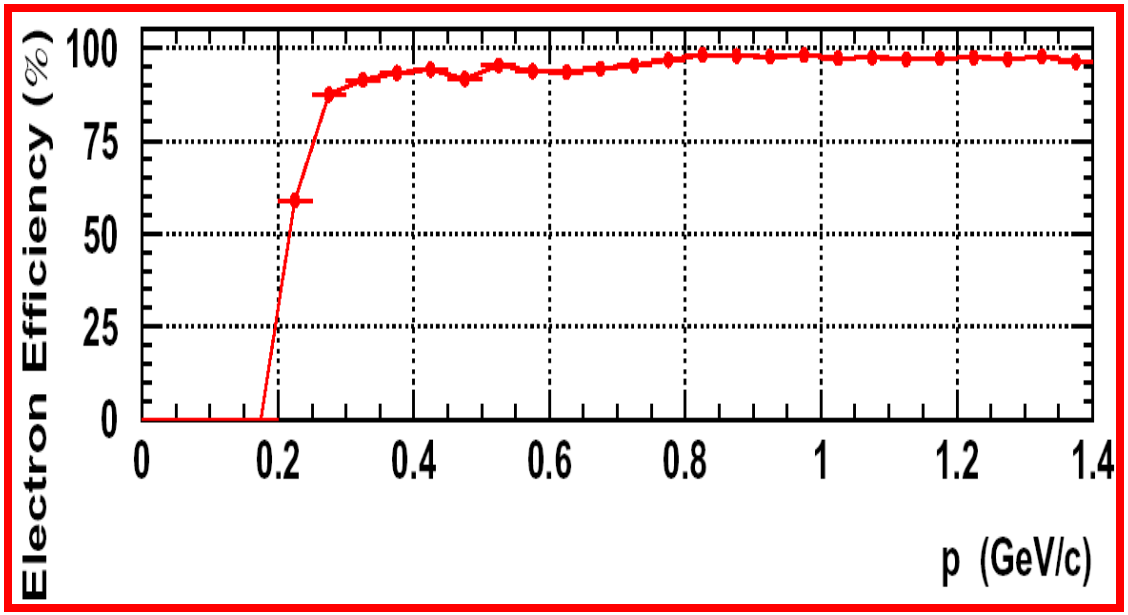
Inclusive Semileptonic Decays

Motivation

→BR(D→Xlν) to compare with sum of exclusive BRs.
→Precision measurement of lepton momentum spectrum.
→Compare $\Gamma_{sl}(D^0)/\Gamma_{sl}(D^+)$
→Test HQT with $\Gamma_{sl}(D^0)/\Gamma_{sl}(D_s)$

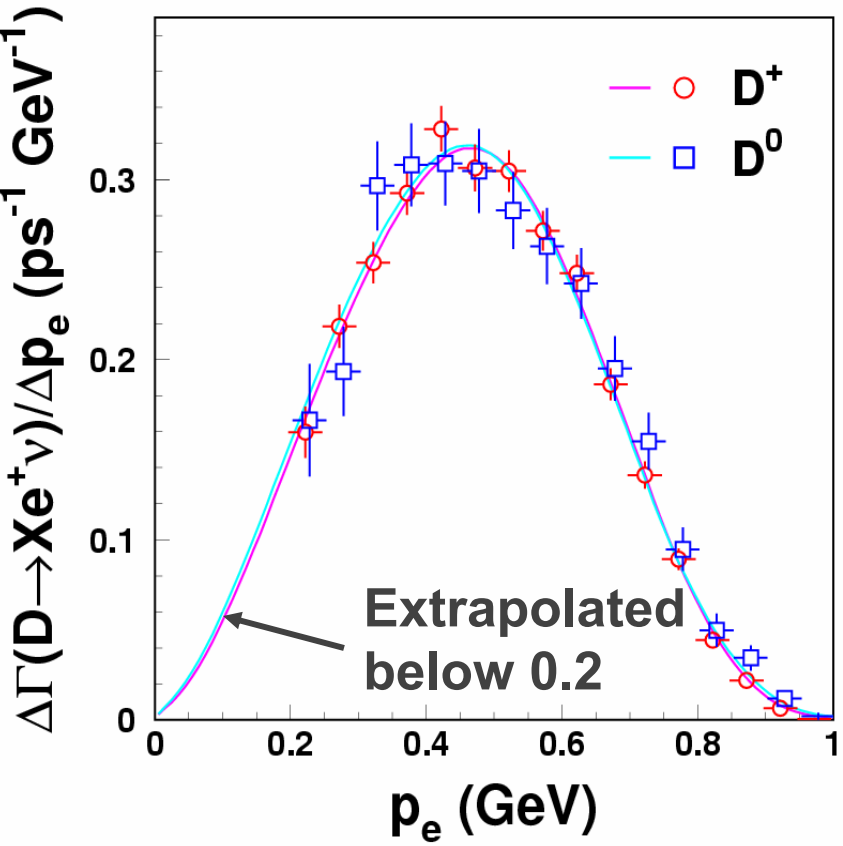
Technique

→D-Tag
→Electron ID
→Gold DTags only
  •$K^-\pi^+$ and $K^-\pi^+\pi^+$
→Charge correlation



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 .

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

$$\Gamma(D^0 \to Xe^+\nu_e) = 0.1574 \pm 0.0041 \pm 0.0032 \text{ ps}^{-1}$$
$$\Gamma(D^+ \to Xe^+\nu_e) = 0.1551 \pm 0.0020 \pm 0.0031 \text{ ps}^{-1}$$

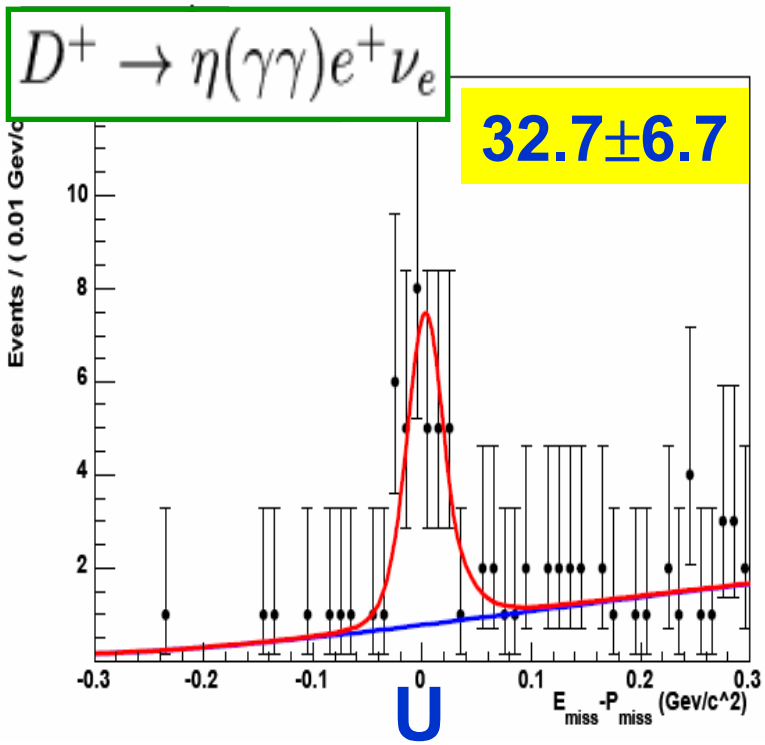
Consistent with isospin symmetry

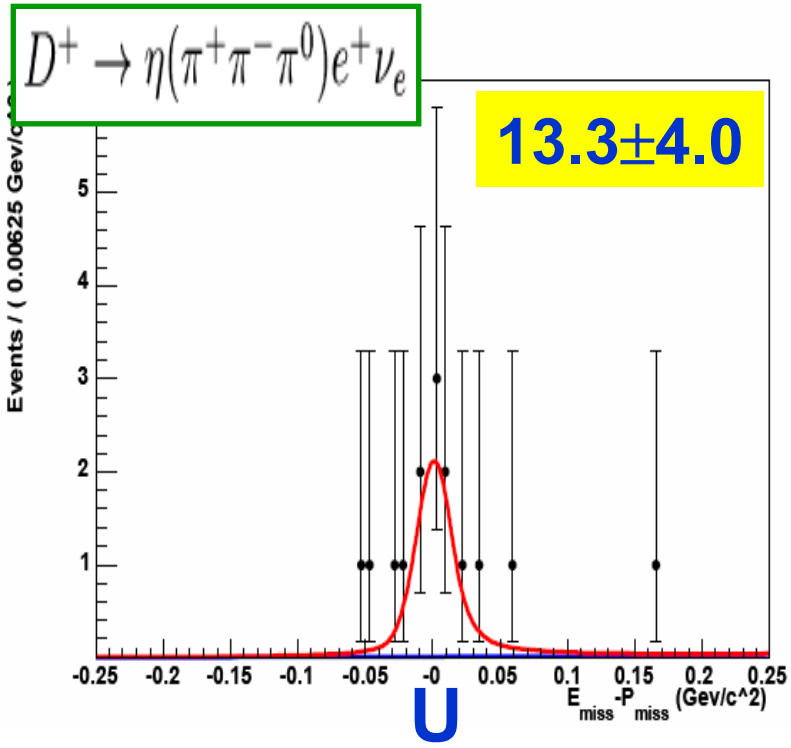
CLEO-c 281pb^{-1}

hep-ex/0604044

Submitted to PRL

First observation of $D^+ \to \eta e^+ \nu$





Preliminary

CLEO-c 281 pb^{-1} Preliminary

$$\mathrm{B}(D^+ \to \eta e^+ \nu) = (1.29 \pm 0.19 \pm 0.07) \times 10^{-3}$$

$$\mathrm{B}(D^+ \to \eta' e^+ \nu)_{combined} < 3 \times 10^{-4} (90\% C.L.)$$

$$\mathrm{B}(D^+ \to \phi e^+ \nu) < 2 \times 10^{-4} (90\% C.L.)$$

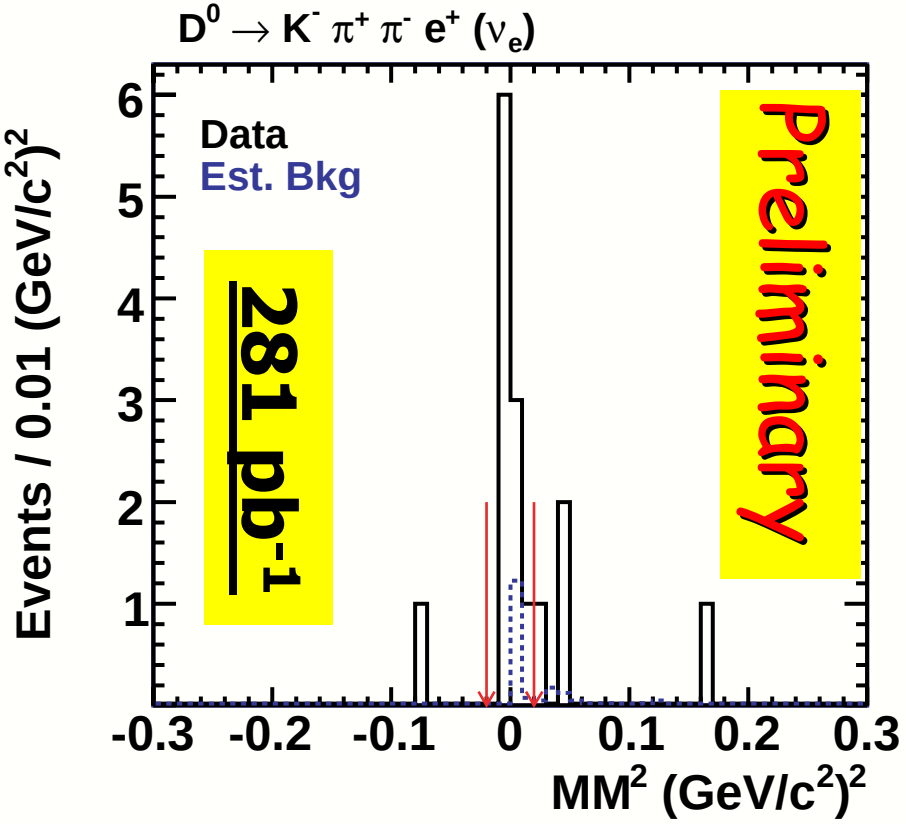
PDG (2004)

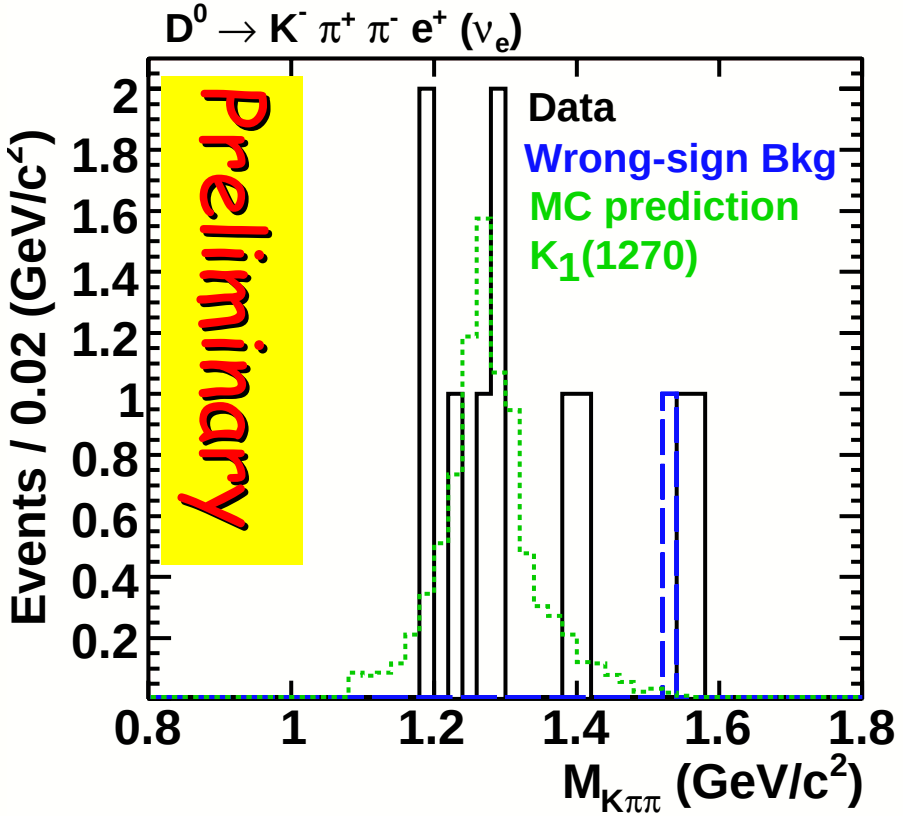
$$\mathrm{B}(D^+ \to \eta l^+ \nu) < 5 \times 10^{-3} (90\% C.L.)$$

$$\mathrm{B}(D^+ \to \eta' \mu^+ \nu) < 1.1\% (90\% C.L.)$$

$$\mathrm{B}(D^+ \to \phi e^+ \nu) < 2.09\% (90\% C.L.)$$

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





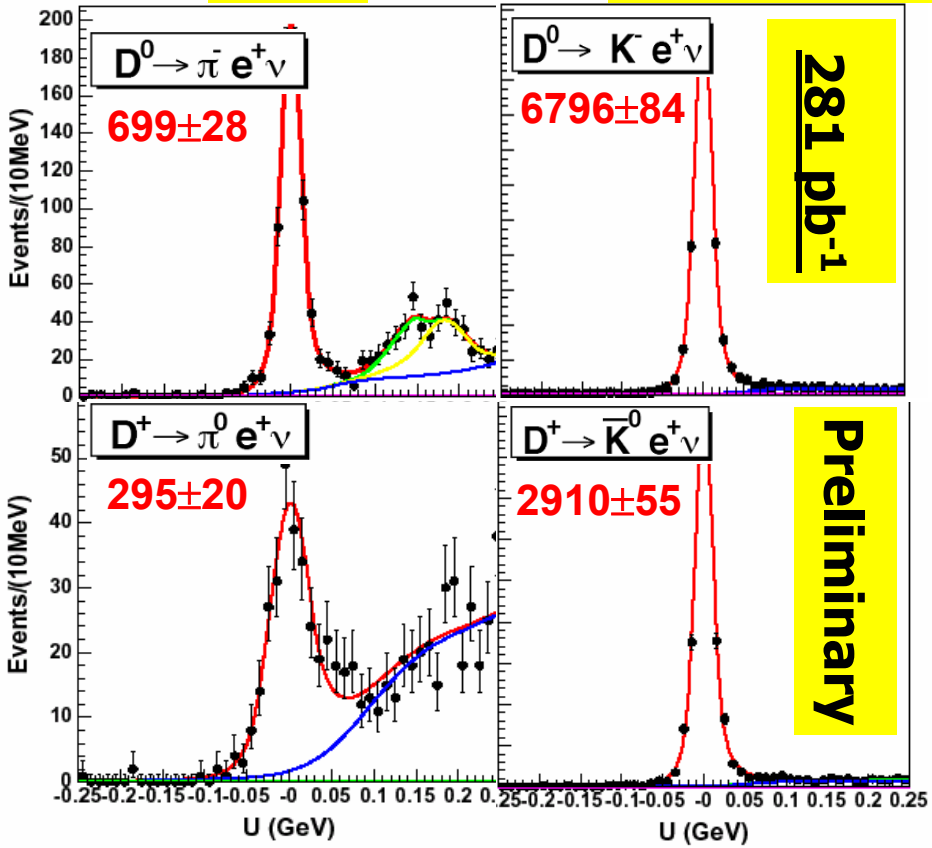
$B(D^o \to K^-\pi^+\pi^-e^+\nu) = (2.9^{+1.5}_{-1.1} \pm 0.5) \times 10^{-4}$

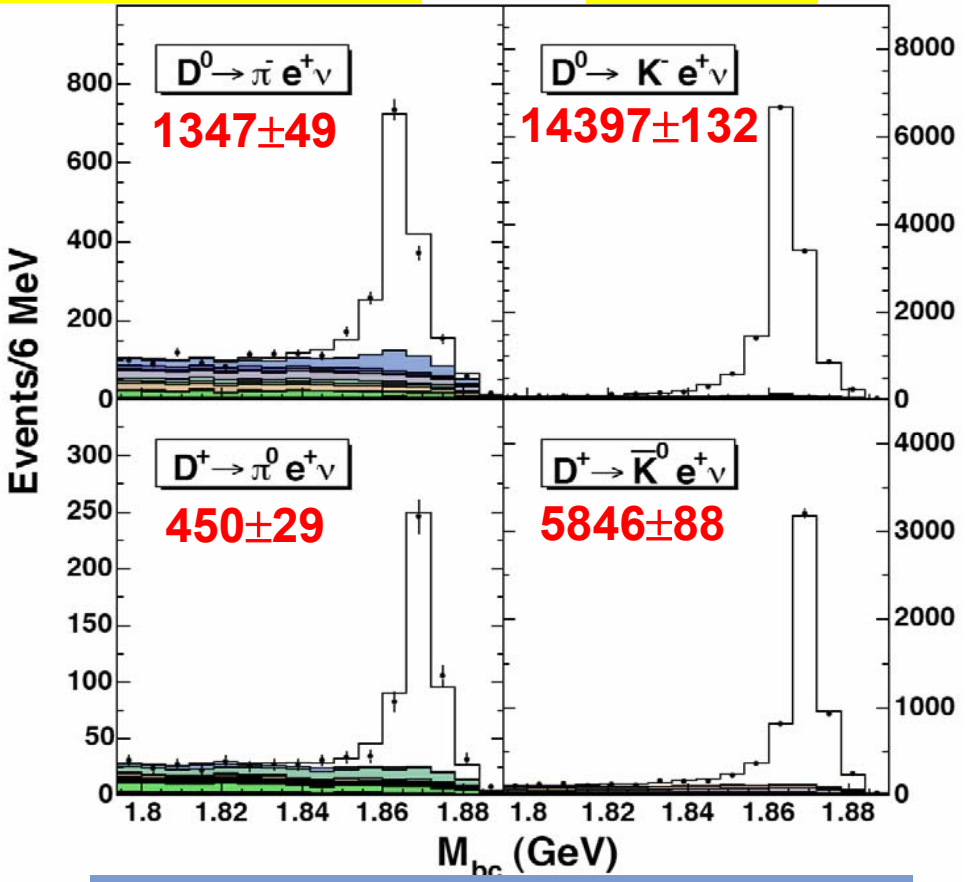
$B(D^o \to K_1(1270)e^+\nu) * B(K_1(1270) \to K^-\pi^+\pi^-) = (2.2^{+1.4}_{-1.0} \pm 0.2) \times 10^{-4}$

Consistent with ISGW2 prediction

$D^0/D^+ \to K/\pi e\nu$ Tag & Untag

Tag | **40% common samples!** | **Untag**





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

E_{miss} and P_{miss} are missing energy and momentum of the event

$$\Delta E = E_{K(\pi)} + E_e + |\mathbf{p}_{miss}| - E_{beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_{K(\pi)} + \mathbf{p}_e + \varsigma \mathbf{p}_{miss})^2}$$

D→K/πeν BFs (Tag/Untag)

40% common samples, do NOT average them!

D Decay	Tag	Br. Frac. (%)	Untag	PDG (%)
$D^0 \to K^- e^+ \nu$	3.58±0.05±0.05		3.56±0.03±0.11	3.62±0.16
$D^0 \to \pi^- e^+ \nu$	0.309±0.012±0.006		0.301±0.011±0.010	0.311±0.030
$D^+ \to \bar{K}^0 e^+ \nu$	8.86±0.17±0.20		8.75±0.13±0.30	7.2±0.8
$D^+ \to \pi^0 e^+ \nu$	0.397±0.027±0.028		0.383±0.025±0.016	0.38±0.19

281 pb-1

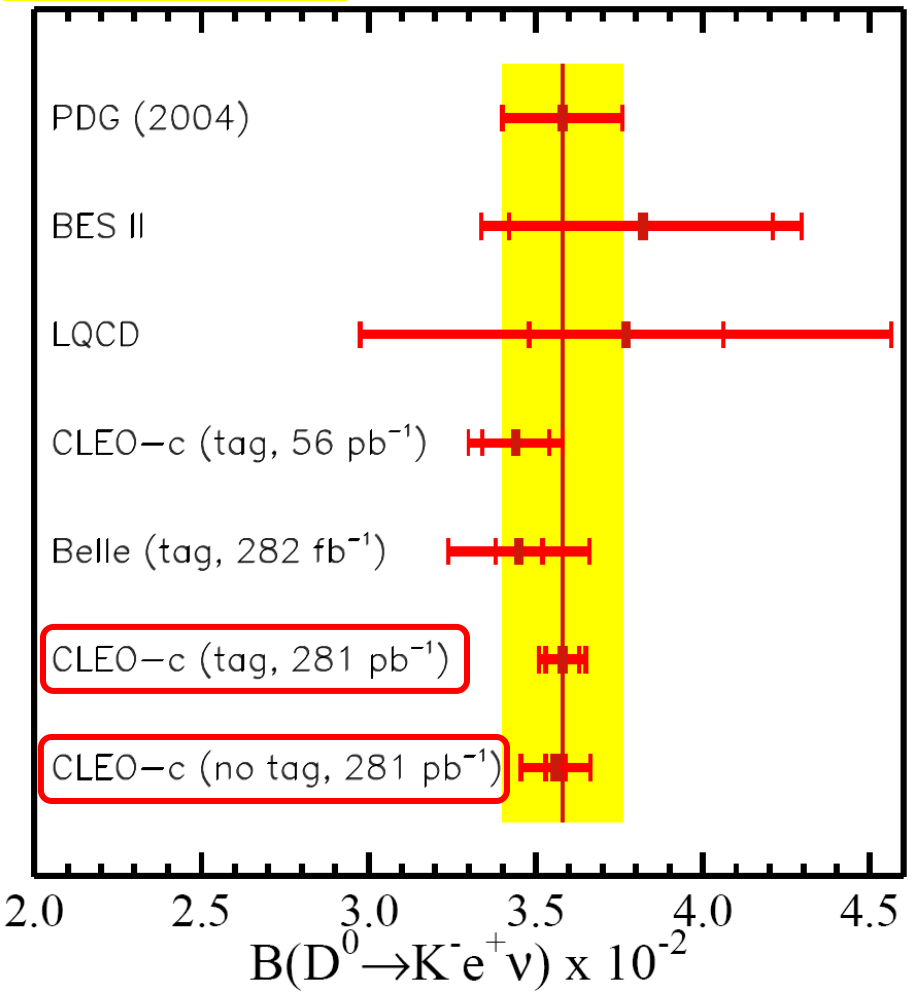
Ratio	Measured (%)	PDG (%)	Ratio	Measured
$\frac{D^0 \to \pi^- e^+ \nu}{D^0 \to K^- e^+ \nu}$	8.5±0.3±0.1	8.6±0.7	$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D^+ \to \pi^0 e^+ \nu)}$	1.95±0.15±0.14 1.99±0.15±0.10
$\frac{D^+ \to \pi^0 e^+ \nu}{D^+ \to \bar{K}^0 e^+ \nu}$	4.4±0.3±0.1	4.6±1.4±1.7	$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu)}$	1.02±0.02±0.02 1.03±0.02±0.04

Preliminary

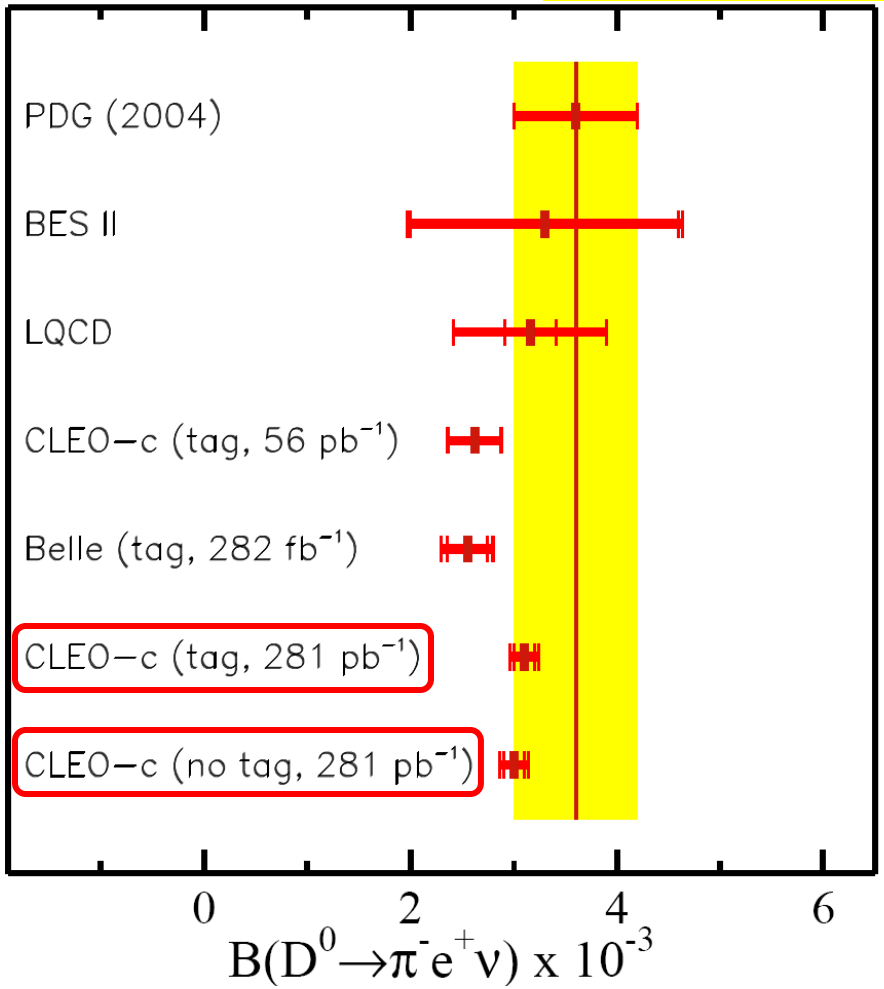
Comparison with LQCD/other exp.

CLEO-c 281 pb^{-1} Preliminary

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



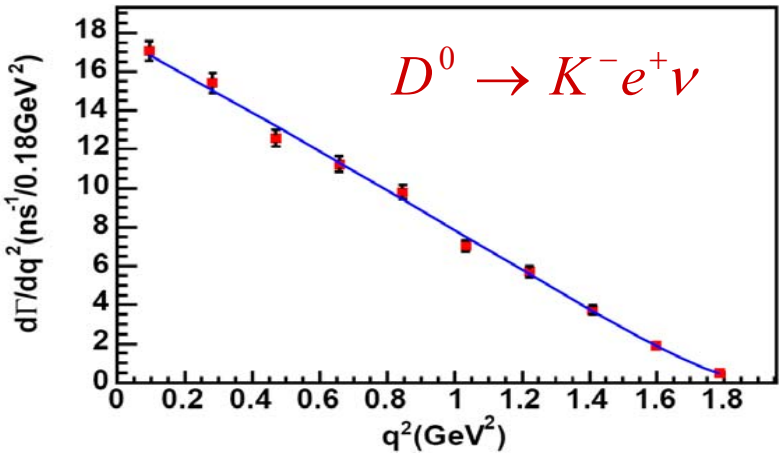
$D^0 \to \pi^- e^+ \nu$

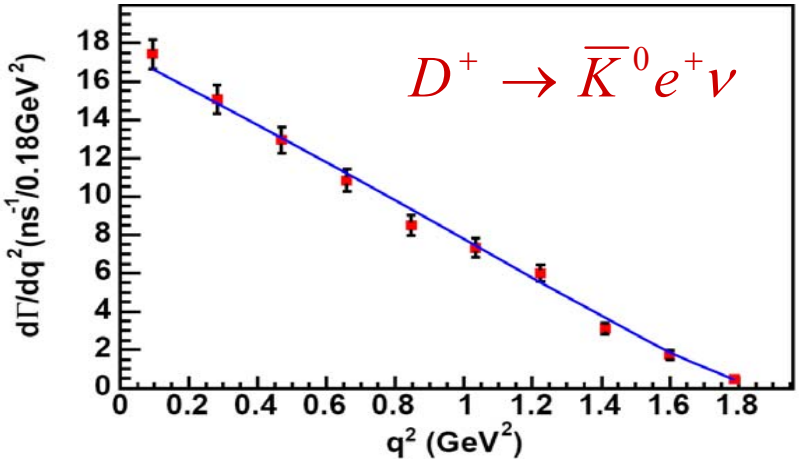


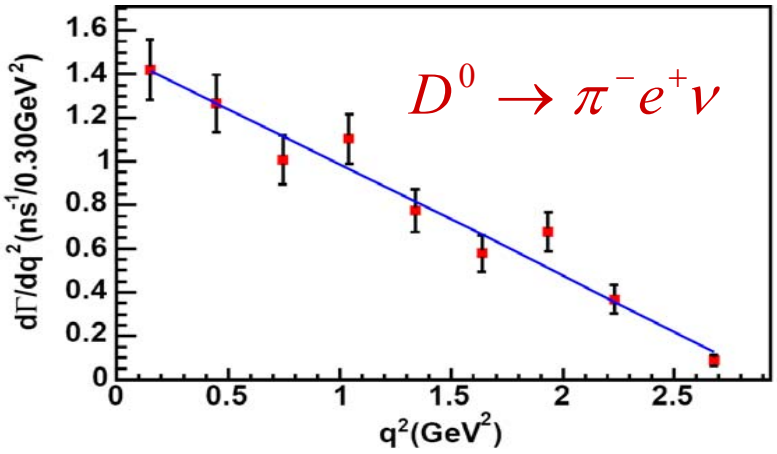
Form Factor Fit (Tag)

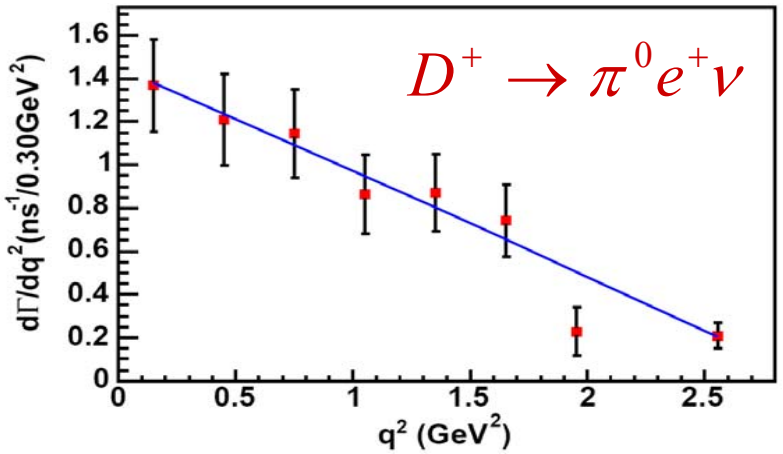
Preliminary

281 pb^{-1} at $\Psi(3770)$









Simple Pole Model

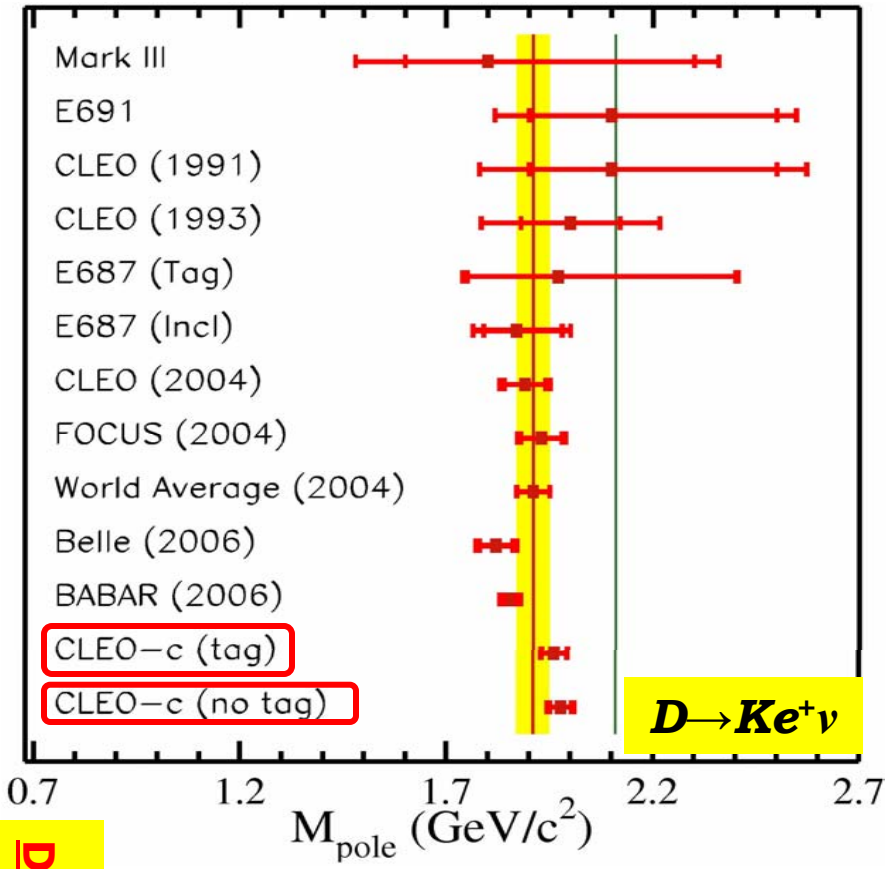
$$f^+(q^2) = \frac{f^+(0)}{\left(1 - q^2/m^2_{pole}\right)}$$

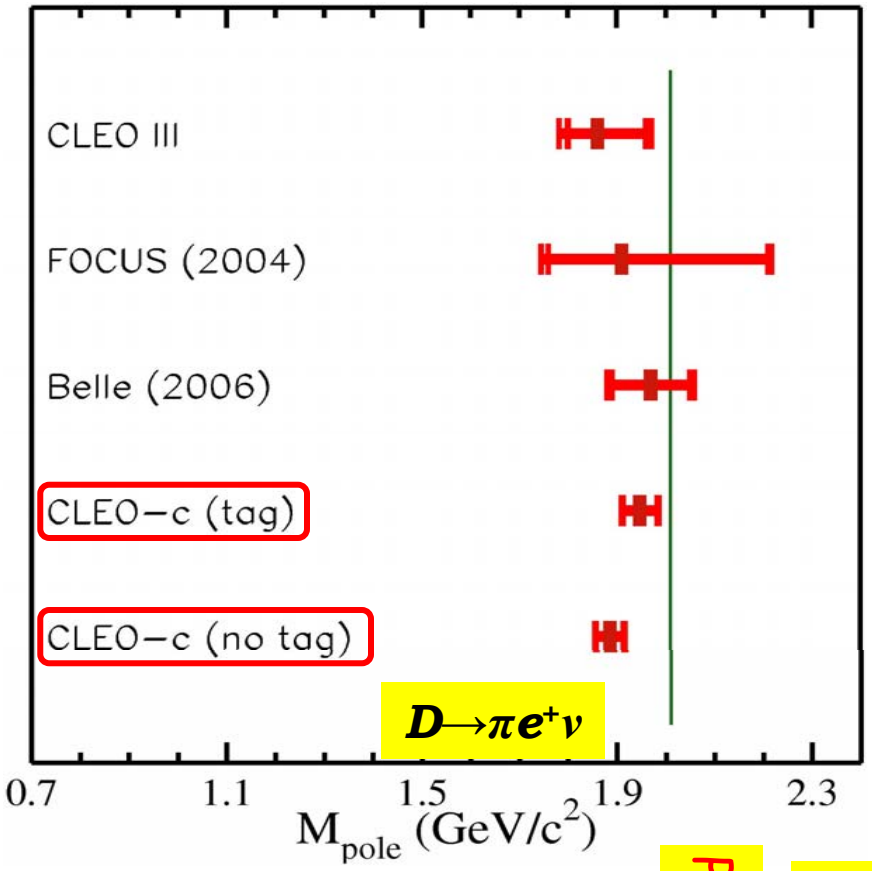
Modified Pole Model

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

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

Form Factors (Tag/Untag)





Don't average!

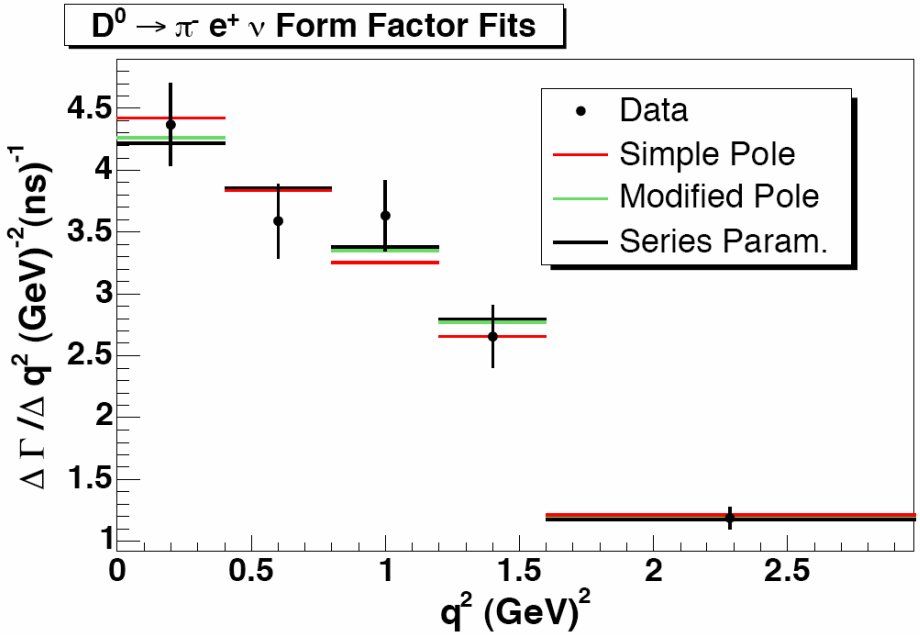
Decay Mode	Mpole (Tag)	Mpole (Untag)
D → Keν (av. D^0 & D^+)	1.96±0.03±0.01	1.98±0.03±0.02
D → πeν (av. D^0 & D^+)	1.95±0.04±0.02	1.88±0.03±0.02

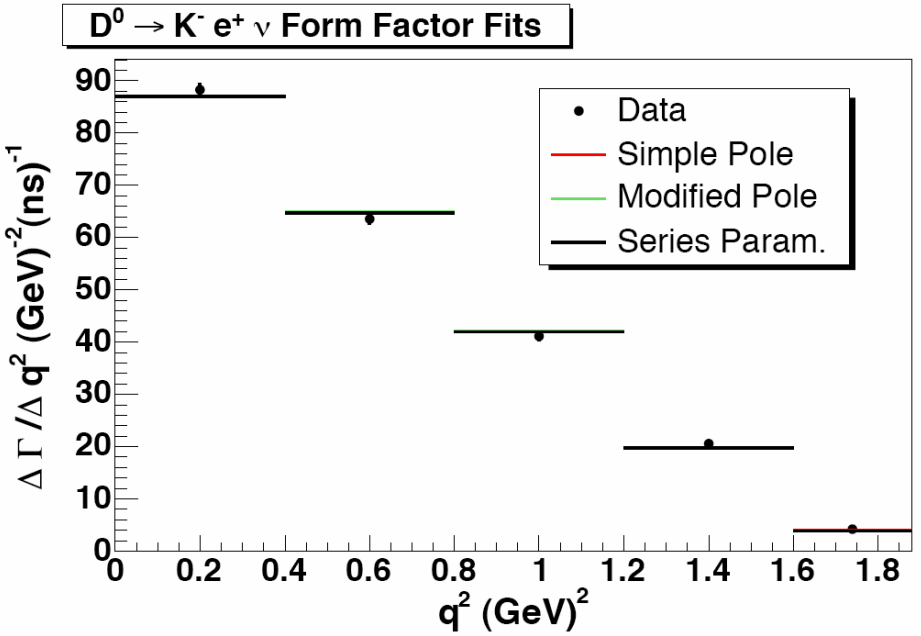
Preliminary

281 pb^{-1}

Form Factor Fits (untag)

CLEO-c 281 pb^{-1} Preliminary Results:





To be submitted to PRL & PRD

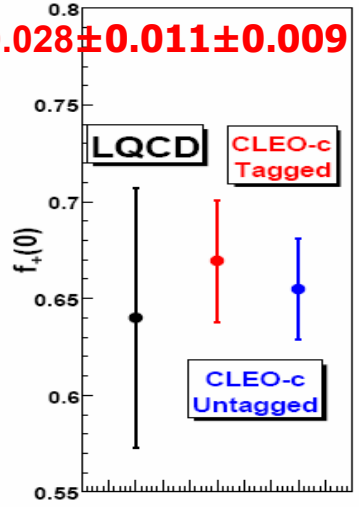
Decay Mode	$\lvert V_{cx}\rvert$ ± (stat) ± (syst) ± (theory)	PDG Value
D → πeν (av. D^0 & D^+)	0.229±0.007±0.005±0.024	0.224 ± 0.012
D → Keν (av. D^0 & D^+)	0.996±0.008±0.015±0.104	0.976 ± 0.014

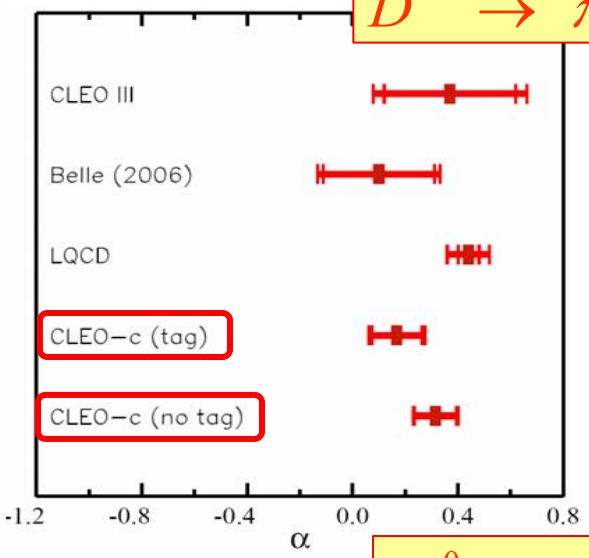
Form Factors and Test of LQCD

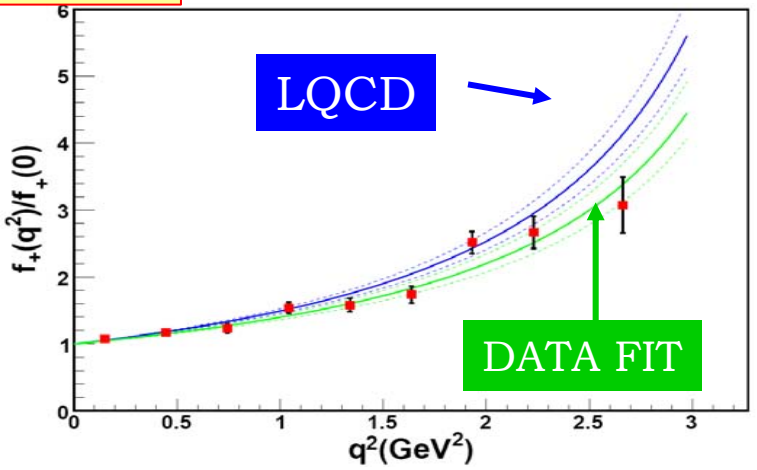
281 pb-1 Preliminary

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

0.670±0.028±0.011±0.009

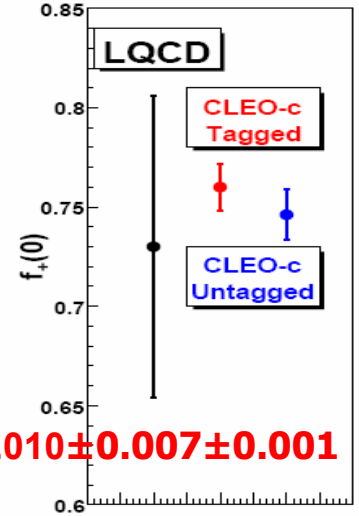


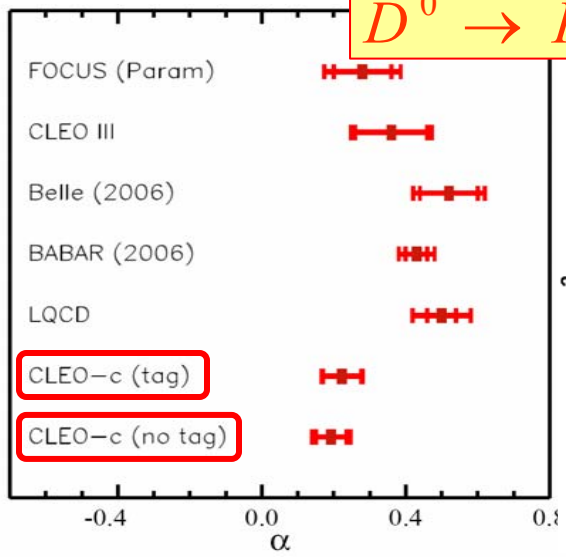


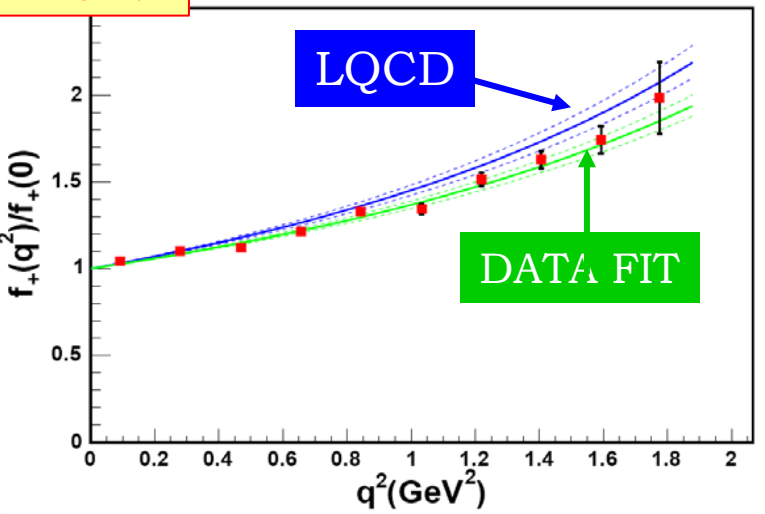


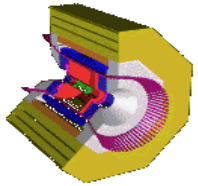
$D^0 \to K^- e^+ \nu$

0.760±0.010±0.007±0.001









V_{cs} and V_{cd} Results

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

Decay Mode	$\|V_{cx}\|$ ± (stat) ± (syst) ± (theory)	PDG Value
D → πeν (tag)	0.234 ± 0.010 ± 0.004 ± 0.024	
D → πeν (untag)	0.229 ± 0.007 ± 0.005 ± 0.024	0.224 ± 0.012
D → Keν (tag)	1.014 ± 0.013 ± 0.009 ± 0.106	
D → Keν (untag)	0.996 ± 0.008 ± 0.015 ± 0.104	0.976 ± 0.014

Preliminary

Tag/Untag: 40% of comment sample. **DO NOT AVERAGE!!!**

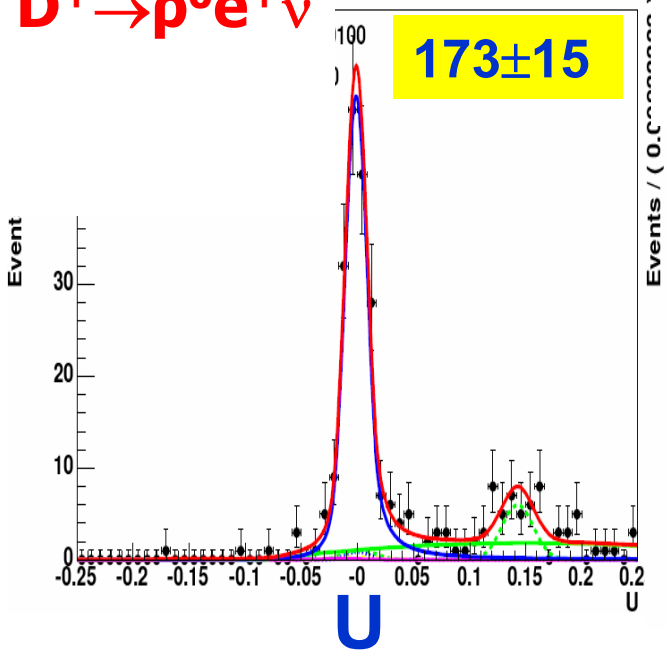
Expt. uncertainties Vcs <2% Vcd~4% LQCD uncertainty 10%

Since Vcs (W→ cs LEP) and Vcd (νN) are well measured, good agreement between PDG and CLEO-c results is primarily a check of the LQCD value for $f_+(0)$. Nevertheless, the most precise & robust Vcs & Vcd determinations using semileptonic decays to date.

Exclusive D → peν Results

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

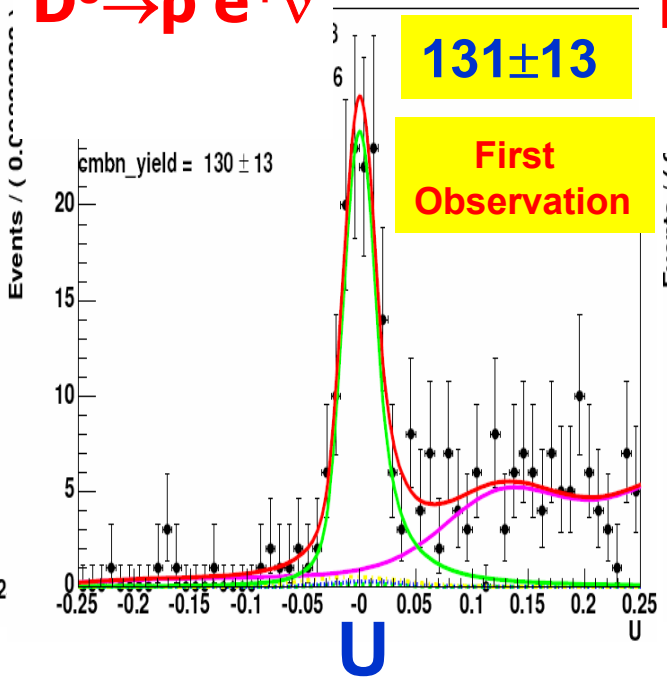
173±15



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

131±13

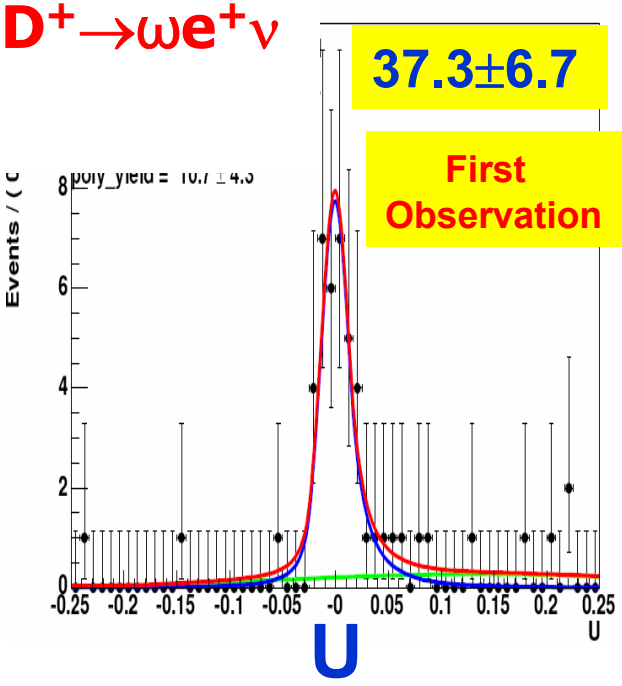
First Observation



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

37.3±6.7

First Observation



CLEO-c 281 pb^{-1} Preliminary Results:

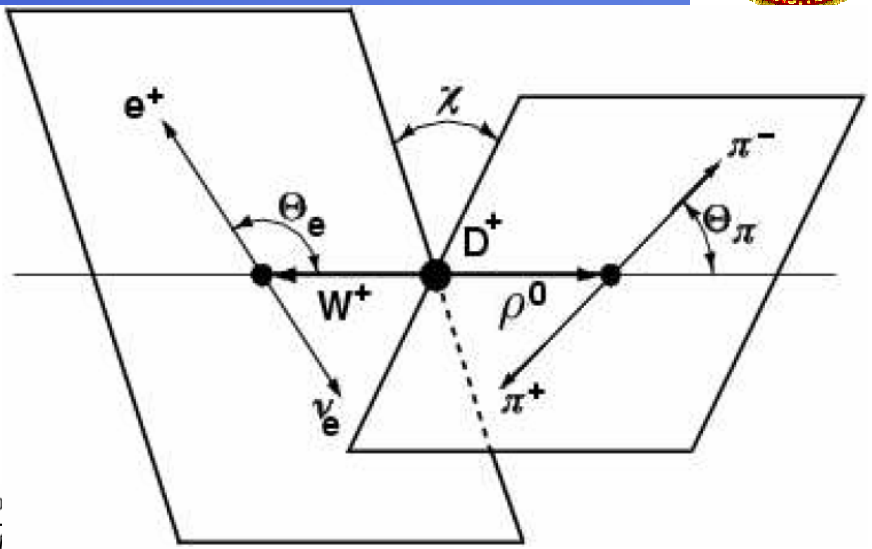
$B(D^0 \to \rho^- e^+ \nu) = (0.156 \pm 0.016 \pm 0.009)\%$
$B(D^+ \to \rho^0 e^+ \nu) = (0.232 \pm 0.020 \pm 0.012)\%$
$B(D^+ \to \omega e^+ \nu) = (0.149 \pm 0.027 \pm 0.005)\%$

$$\frac{\Gamma\left(D^0 \to \rho^- e \nu\right)}{2 \cdot \Gamma\left(D^+ \to \rho^0 e \nu\right)} = 0.85 \pm 0.11$$

kinematics & Decay Rate

- Five kinematic variables describe the decay rate:

$$q^2, \cos\theta_e, \cos\theta_\pi, \chi, m(\pi\pi)$$



- We fit to the decay rate

$$\frac{d\Gamma}{dq^2 d\cos\theta_\pi d\cos\theta_e d\chi} = \mathcal{B}(\rho^0 \to \pi\pi)\frac{3G_F^2}{8(4\pi)^4}|V_{cs}|^2\frac{p_{\rho^0}}{M_D}$$
$$\{(1+\cos\theta_e)^2\sin^2\theta_\pi |H_+(q^2)|^2$$
$$+(1-\cos\theta_e)^2\sin^2\theta_\pi |H_-(q^2)|^2$$
$$+4\sin^2\theta_e\cos^2\theta_\pi |H_0(q^2)|^2$$
$$+4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_+(q^2)H_0(q^2)$$
$$-4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_-(q^2)H_0(q^2)$$
$$-2\sin^2\theta_e\sin^2\theta_\pi\cos 2\chi H_+(q^2)H_-(q^2)\}$$

- Dependence on the form factors enters through H_+, H_- and H_0.

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

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

Exclusive D → peν Results

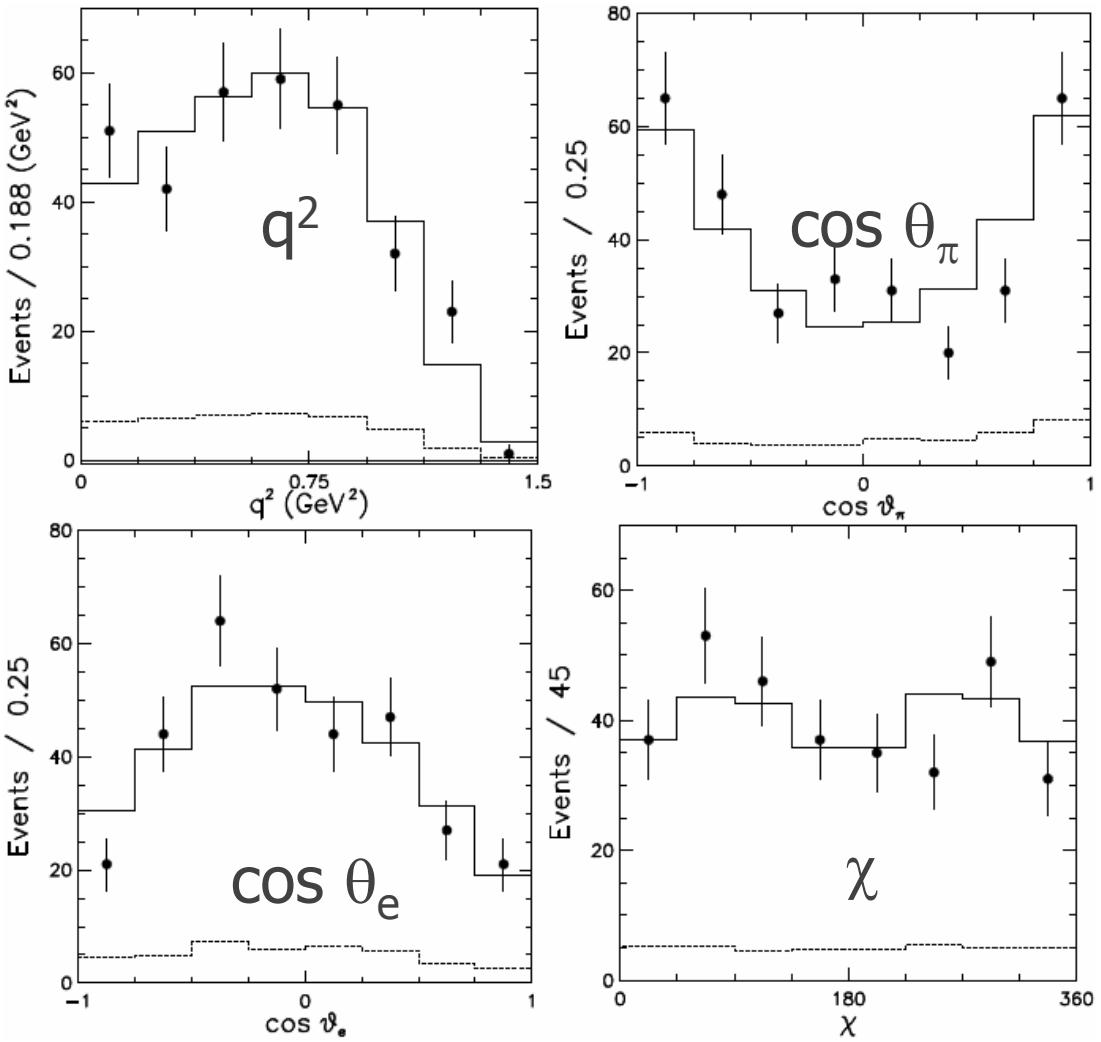
Preliminary Results:

CLEO-c 281 pb^{-1}:

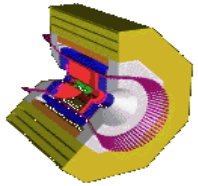
$R_v = 1.40 \pm 0.25 \pm 0.03$

$R_2 = 0.57 \pm 0.18 \pm 0.06$

First measurement



Line is projection for fitted R_V, R_2



Exclusive Semileptonic b→u

Important for Vub, but challenges:

- **Large b → c backgrounds**
- **Missing neutrino**

$$B \longrightarrow X_u \ell \nu \qquad X_u = \pi^{\pm}, \pi^0, \eta, \rho^{\pm}, \rho^0, \omega, \eta' \qquad \ell = \mu, e$$

Neutrino Reconstruction: $p_\nu = p_{\text{beam}} - p_{\text{visible}}$

Signature: peaks in

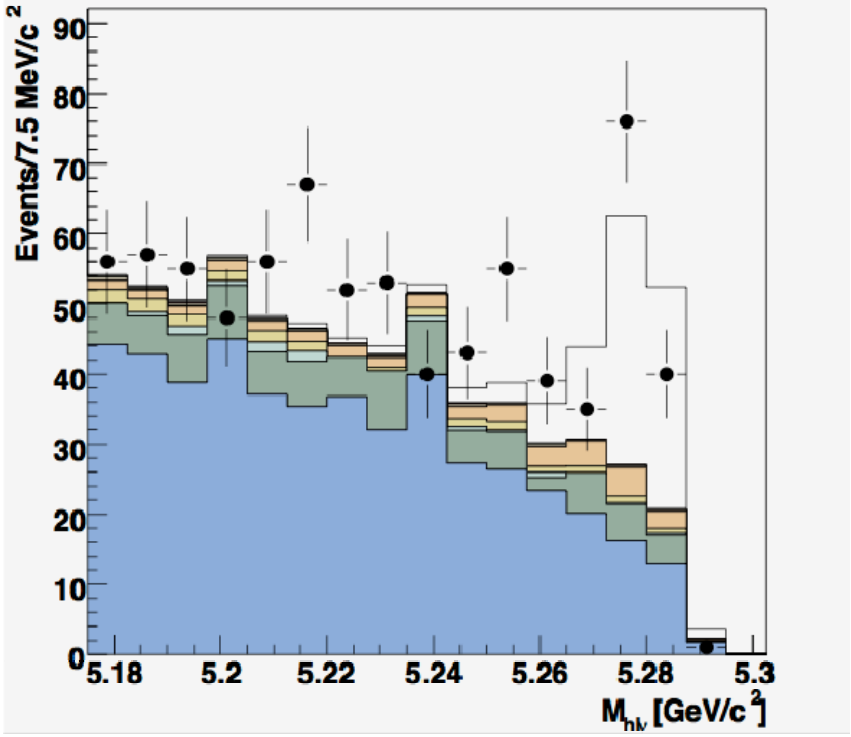
$$\Delta E = (E_{X_u} + E_\ell + E_\nu) - E_{\text{beam}}$$

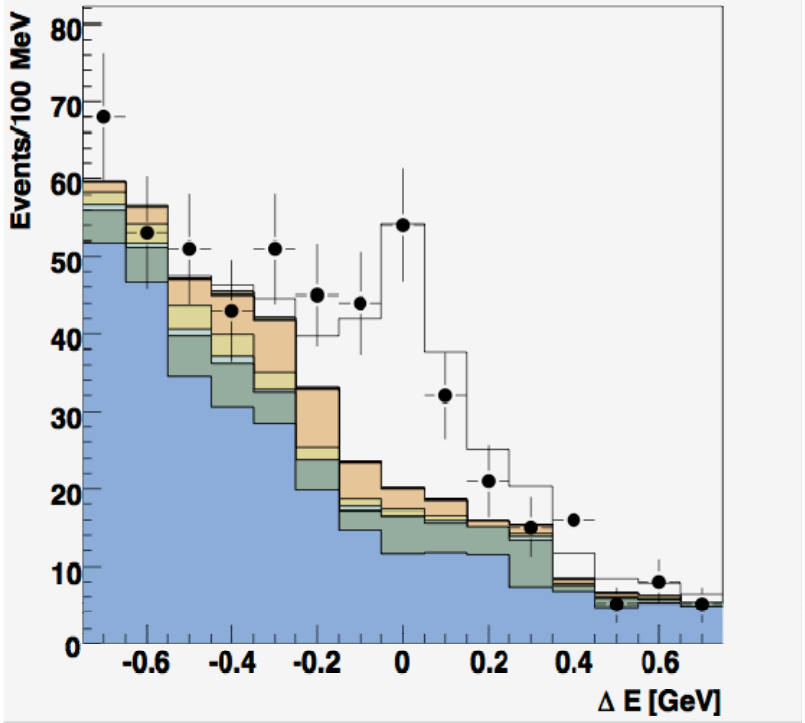
$$M_{X_u \ell \nu} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{X_u} + \vec{p}_\ell + \vec{p}_\nu|^2}$$

CLEO data at Y(4S): CLEO II, II.V and III

- **15.8×10^6 BB events (60% more data)**
- **Supersedes PRD68, 072003 (lower lepton Pt)**

Exclusive Semileptonic B → $\pi l \nu$





Supersedes PRD68, 072003

Preliminary

15.8x10⁶ BB evts

CLEO II, II.V, III

CLEO Preliminary

q^2 Bin [GeV²]	Branching Fraction [x10⁻⁴] (errors: stat., syst., theo.)
$q^2 < 2$	0.13 ± 0.07 ± 0.02 ± 0.00
$2 < q^2 < 8$	0.27 ± 0.08 ± 0.03 ± 0.00
$8 < q^2 < 16$	0.56 ± 0.09 ± 0.06 ± 0.01
$q^2 > 16$	0.40 ± 0.08 ± 0.05 ± 0.02
Total	**1.37 ± 0.16 ± 0.13 ± 0.02**

Exclusive Semileptonic B → ρ$l\nu$

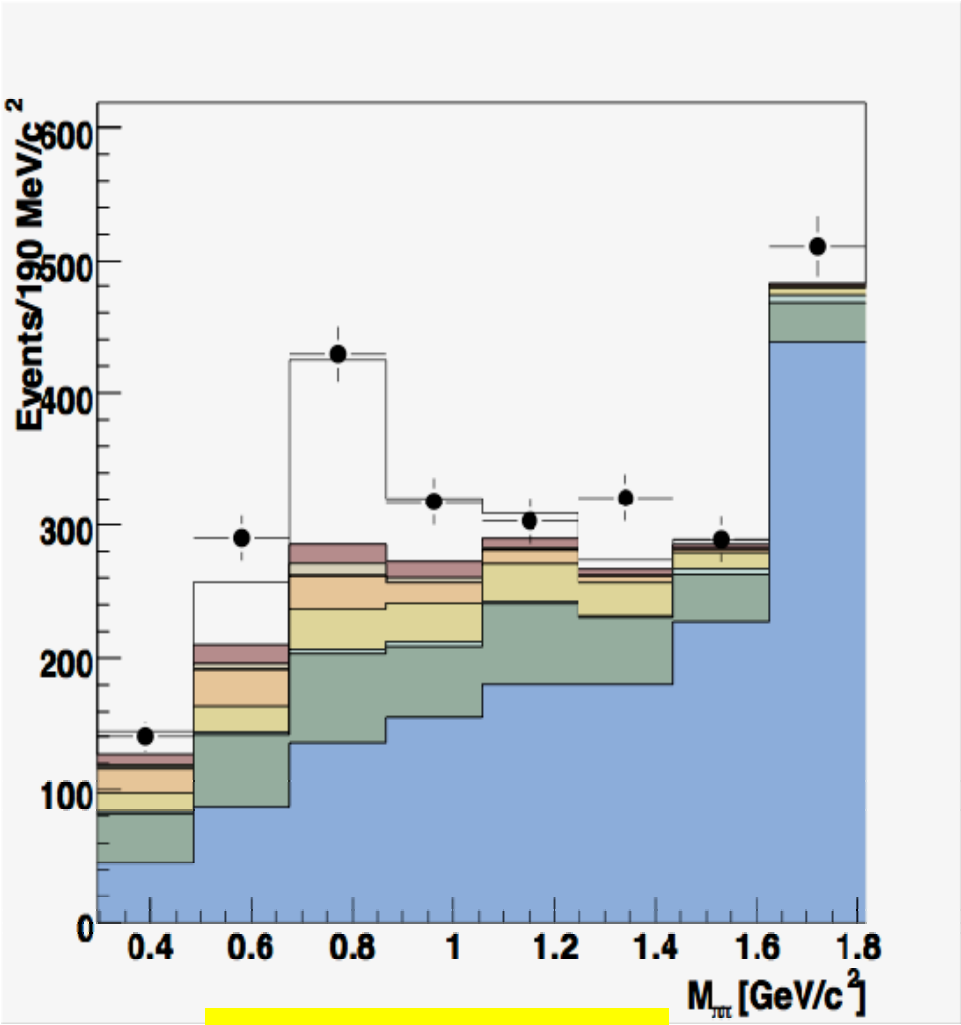
Preliminary Results:

CLEO Y(4S) data

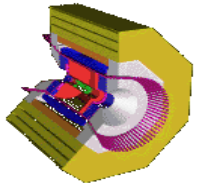
15.8x10^6 BB evts

CLEO Preliminary

q^2 Range [GeV^2]	cos Θ_{wl} Range	Branching Fraction [x10^{-4}] (errors: stat., syst., theo.)
$q^2 < 2$	$-1 < \cos\Theta_{wl} < 1$	0.45 ± 0.20 ± 0.15 ± 0.02
$2 < q^2 < 8$	$-1 < \cos\Theta_{wl} < 1$	0.95 ± 0.20 ± 0.30 ± 0.07
$8 < q^2 < 16$	$0 < \cos\Theta_{wl} < 1$	0.75 ± 0.16 ± 0.12 ± 0.01
$q^2 > 16$	$0 < \cos\Theta_{wl} < 1$	0.35 ± 0.07 ± 0.04 ± 0.01
$q^2 > 8$	$-1 < \cos\Theta_{wl} < 0$	0.43 ± 0.18 ± 0.30 ± 0.04
Total		**2.91 ± 0.38 ± 0.37 ± 0.07**



Mass of ππ



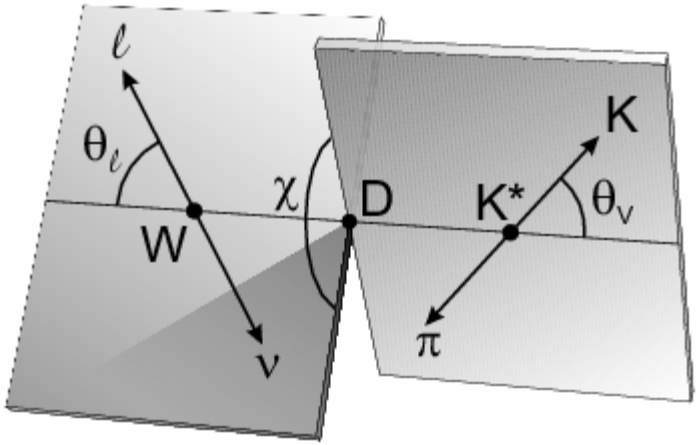
back-up slides

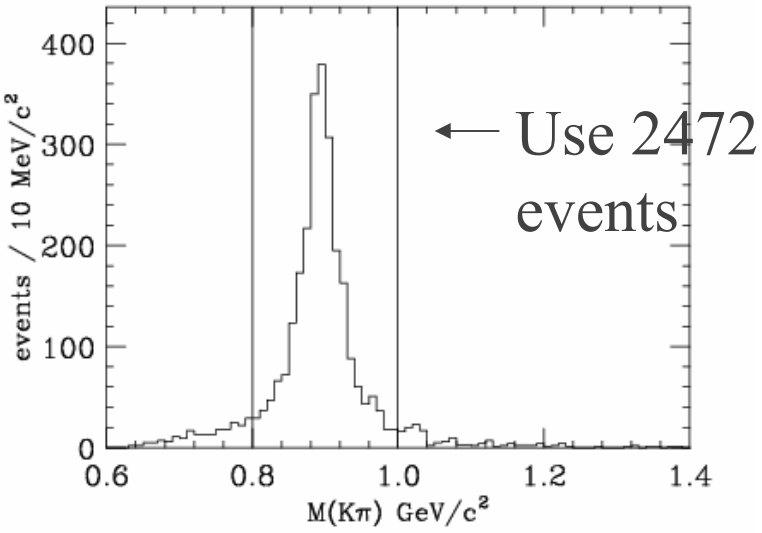
Exclusive $D^+ \to K^-\pi^+e^+\nu$

hep-ex/0606010

Submitted to PRD

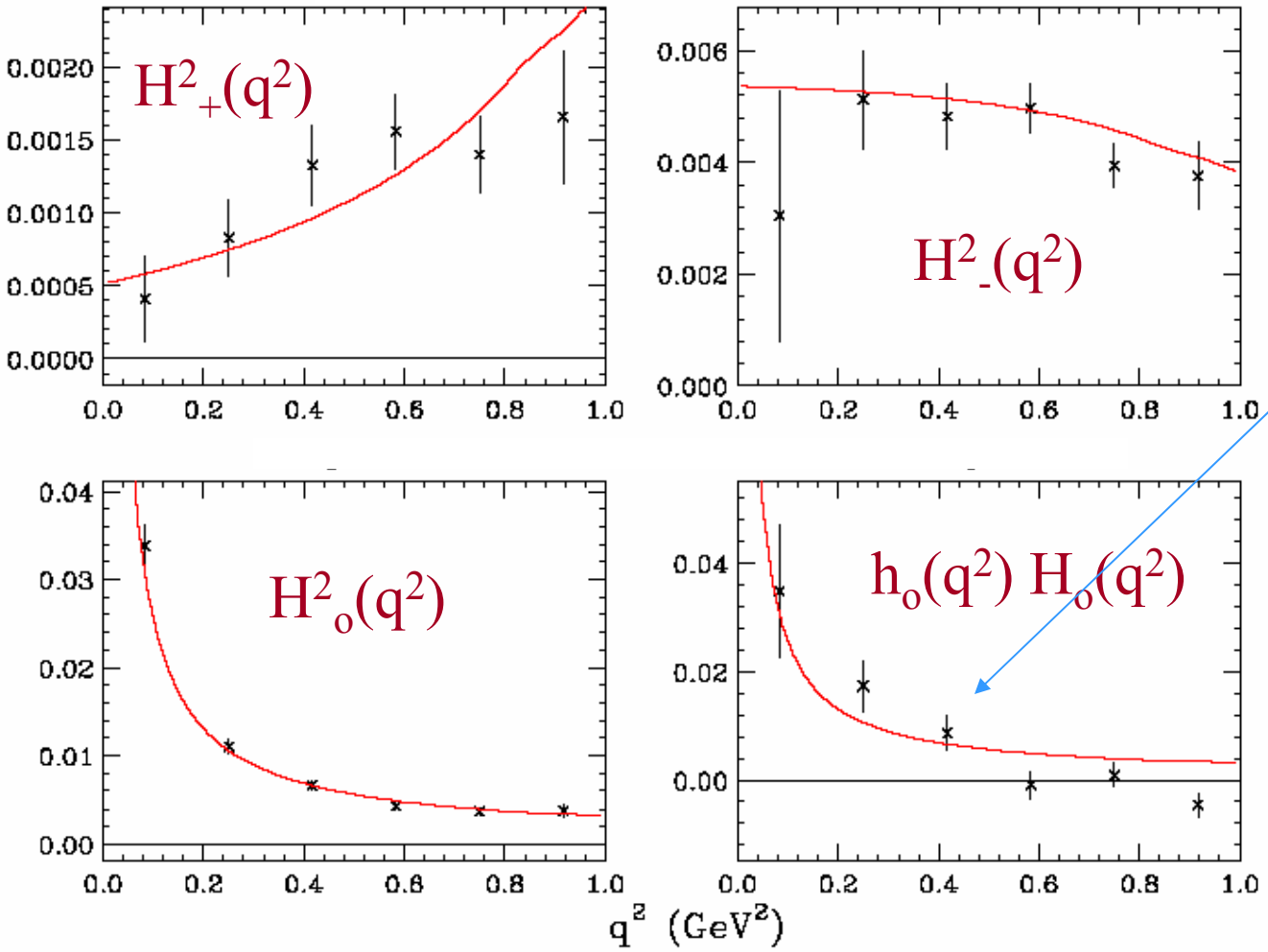
- K-π+ mostly K* with some s-wave (first seen by FOCUS)
- For D→V e+ν, use 3 helicity amplitudes $H_o(q^2)$, $H_+(q^2)$, & $H_-(q^2)$
- Add $h_o(q^2) \bullet H_o(q^2)$ to account for s-wave term
- Use 281 pb^{-1} tagged analysis





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

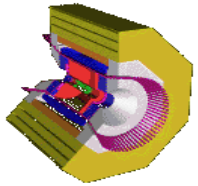
hep-ex/0606010



Significant s-wave amplitude confirmed

No evidence for d or f wave

Submitted to PRD



Neutrino Reconstruction

Neutrino Reconstruction

We use the whole event to reconstruct the event missing four-momentum (P_{miss}). This can be associated with a neutrino if the missing mass is consistent with zero.

$$P_{miss} = P_{event} - \sum P_{charged} - \sum P_{neutral}$$

$$\Delta E = E_{K(\pi)} + E_e + \left|\mathbf{p}_{miss}\right| - E_{beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_{K(\pi)} + \mathbf{p}_e + \beta\mathbf{p}_{miss})^2}$$

β is a correction to the missing momentum

$$E_{K(\pi)} + E_e + \beta\left|\mathbf{p}_{miss}\right| - E_{beam} \equiv 0$$

Form Factors

$$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\frac{1}{1-q^2/m_{pole}^2} + \frac{1}{\pi}\int_{(M_D+m)^2}^{\infty} dq'^2 \frac{\mathrm{Im}(f(q'^2))}{q'^2 - q^2}$$

General dispersion relation -- too complicated…

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

Simple Pole Model

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

Modified Pole Model

$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$$

Series Parameterization

$$t_\pm \equiv \left(M_D \pm m_{\pi(K)}\right)^2, \quad z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

Hill & Becher, Phys. Lett. B 633, 61 (2006)