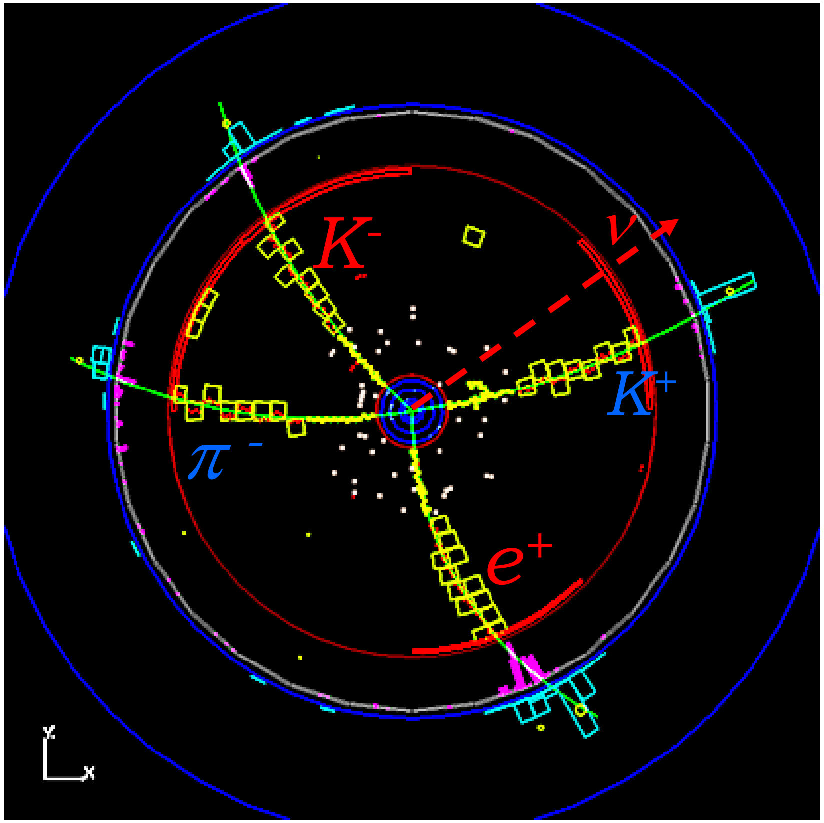
Study of $D \to K/\pi e^+ \nu$ and measurement of V_{cs} and V_{cd} at CLEO-c



- Introduction
- Reconstruction techniques
- Results: branching fractions, form factors, V_{cs} and V_{cd}
- Summary

Bo Xin

Purdue University

CLEO collaboration

Lake Louise Winter Institute, Feb 18 - 23, 2008

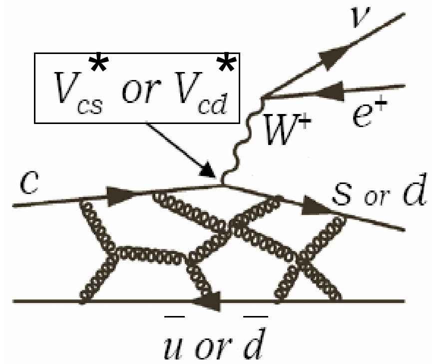
Introduction

- Semileptonic decays are an excellent laboratory to study

Weak Physics

QCD Physics

$$\frac{d\Gamma(D\to K(\pi)e\nu)}{dq^2}=\frac{G_F^2|V_{cs(cd)}|^2 P_{K(\pi)}^3}{24\pi^3}|f_+(q^2)|^2, \text{where } q^2\equiv M^2(e\nu)$$



- Assuming theoretical calculations of form factors, we can extract $|V_{cs}|$ *and* $|V_{cd}|$

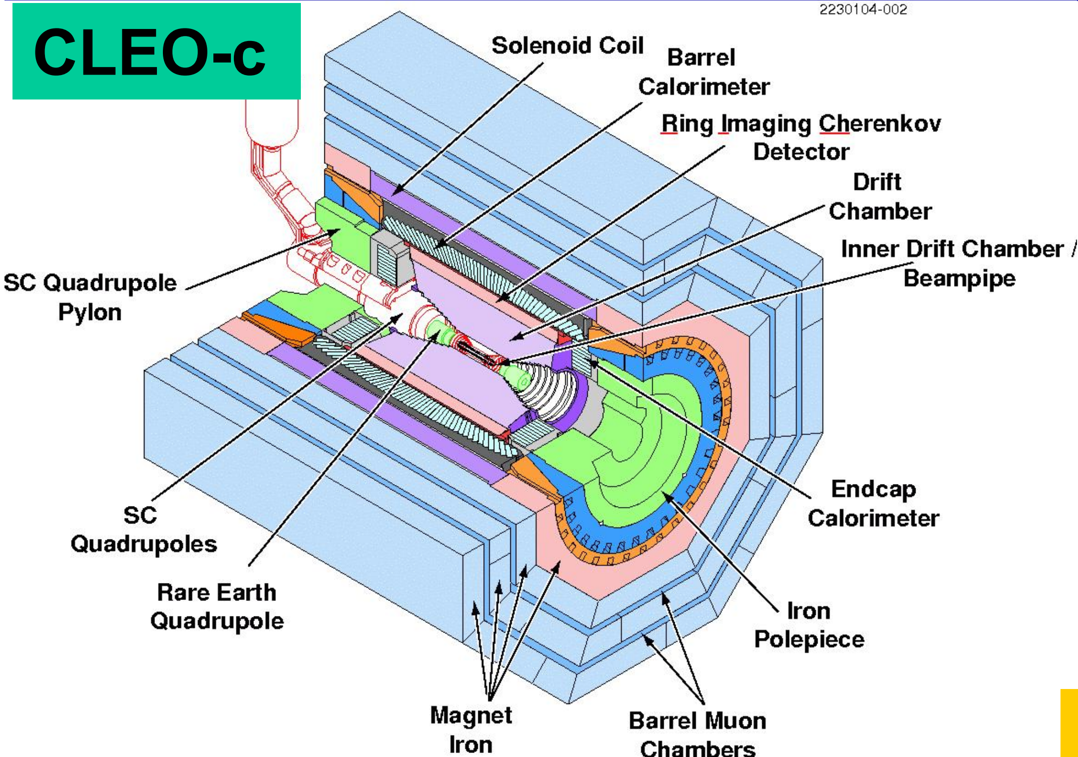
- Since $|V_{cs}|$ *and* $|V_{cd}|$ are tightly constrained by unitarity, we can check theoretical calculations of the form factors

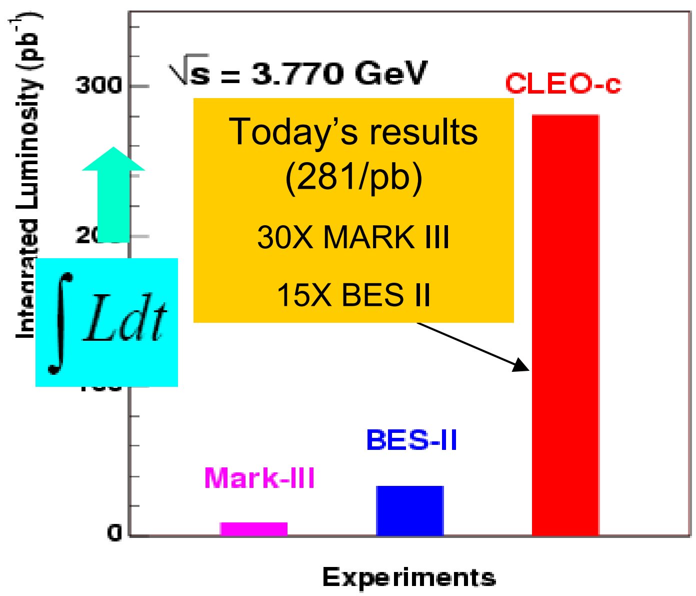
- Tested theory can then be applied to B semileptonic decays to extract $|V_{ub}|$.

- Gold-plated modes are $P \to P$ semileptonic transitions as they are the simplest modes for both theory and experiment:
  - Cabibbo favored : $D^0 \to K^- e^+ \nu$, $D^+ \to \overline{K}^0 e^+ \nu$
  - Cabibbo suppressed : $D^0 \to \pi^- e^+ \nu$, $D^+ \to \pi^0 e^+ \nu$

The CLEO-c detector and data sample

CLEO-c





$\Delta p/p$ = 0.6% at 800 MeV/c

$\Delta E/E$ = 2% at 1 GeV,

5% at 100 MeV

93% coverage (charged and neutral)

Excellent electron and particle ID

CLEO has world's largest data set at 3.770 GeV

- Advantages at $\psi(3770)$
  - **Pure $D\bar{D}$, no additional particles**
  - **Low multiplicity**
  - **High tagging efficiency**

Analysis Technique (tagged)

- Candidate events are selected by reconstructing a D, called a tag, in several hadronic modes
- Then we reconstruct the semileptonic decay in the system recoiling from the tag.
- Two key variables in the reconstruction of a tag:

$$M_{bc} = \sqrt{E_{beam}^2/c^4 - \left|\vec{p}_D\right|^2/c^2}$$

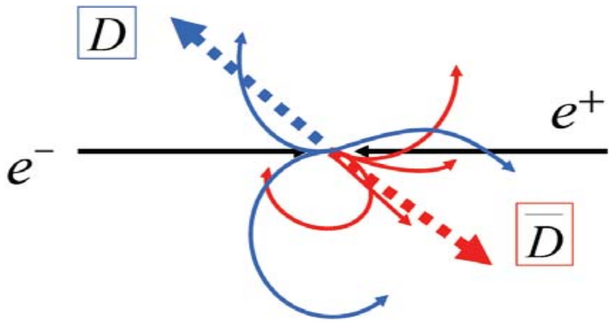
$$\Delta E = E_D - E_{beam}$$

- For semileptonic D : $U = E_{miss} - |\vec{P}_{miss}|$
- The absolute branching fraction is

$$B^{semilep} = \frac{N_U^{semilep}/\varepsilon_{signal}}{N_{M_{bc}}^{tag}/\varepsilon_{tag}} = \frac{N_U^{semilep}}{<\varepsilon_{semilep}> N_{M_{bc}}^{tag}}$$

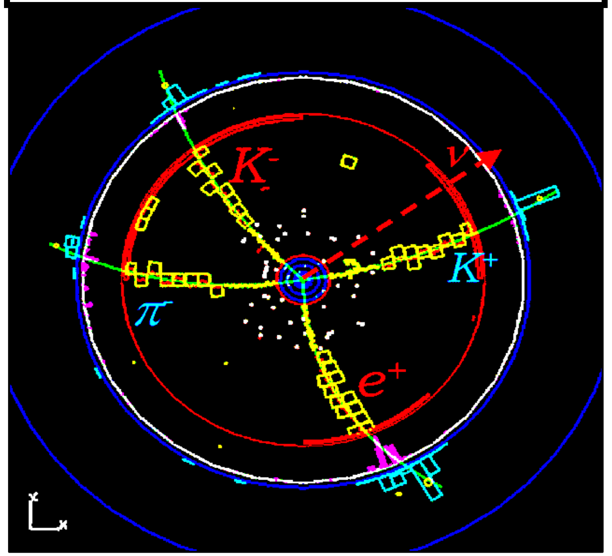
from fits to U

from fits to M_{bc}



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

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



Tagging creates a single D beam of known 4-momentum

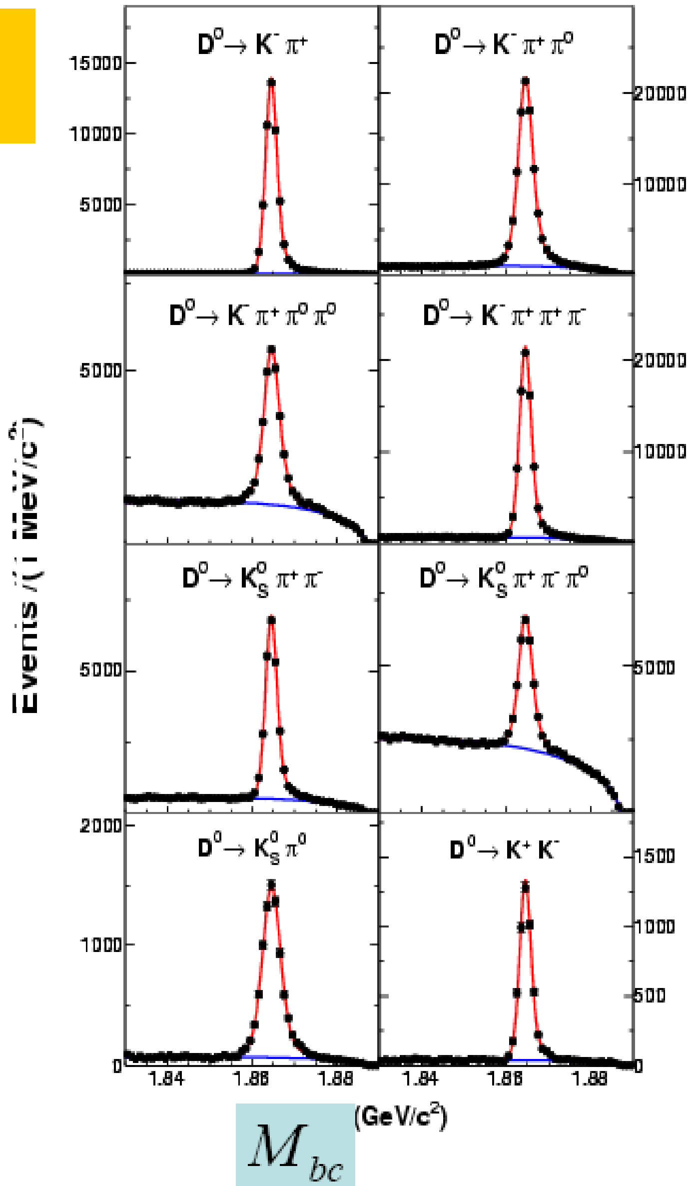
D tagging at CLEO-c (281/pb of Data)

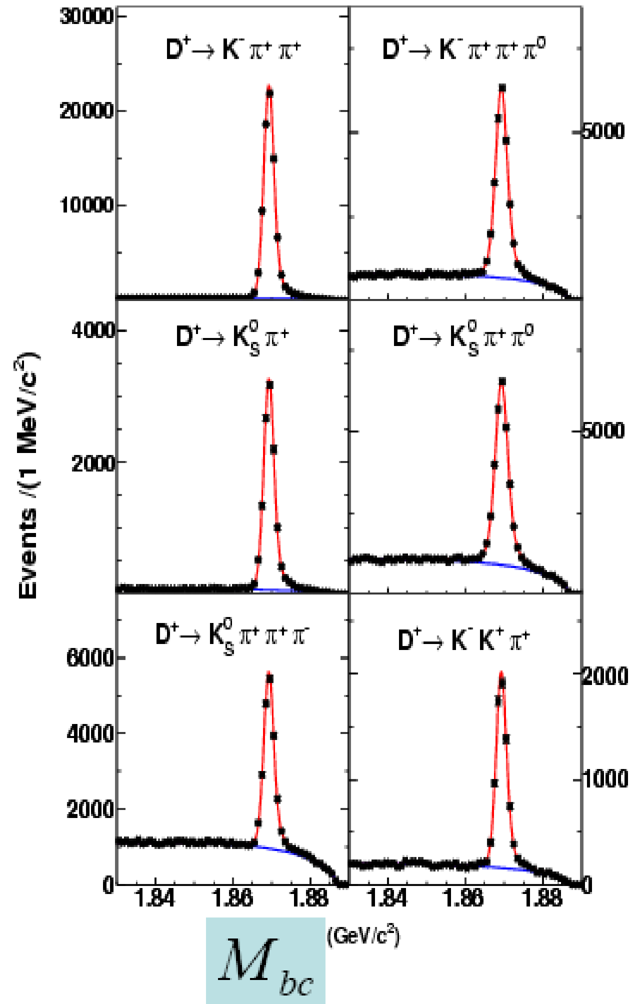
World's largest data set at 3.770 GeV

Pure $D\overline{D}$, zero additional particles, ~5-6 charged particles per event

~3.1x 10^5 D^0 and ~1.6 x 10^5 D^+ tags reconstructed from ~1.8 x 10^6 $D\overline{D}$ events

We tag ~25% of the events, compared to ~0.1% of B's at the Y(4S)





$$M_{bc} = \sqrt{E_{beam}^2/c^4 - \left|\vec{p}_D\right|^2/c^2}$$

Reconstruction of Semileptonic Decays (tagged)

$$E_{miss} = E_{beam} - E_{K(\pi)} - E_e$$

$$\vec{p}_{miss} = -\vec{p}_{tag} - \vec{p}_{K(\pi)} - \vec{p}_e$$

$$U = E_{miss} - |\vec{p}_{miss}|$$

$$E_W = E_{beam} - E_{K(\pi)}$$

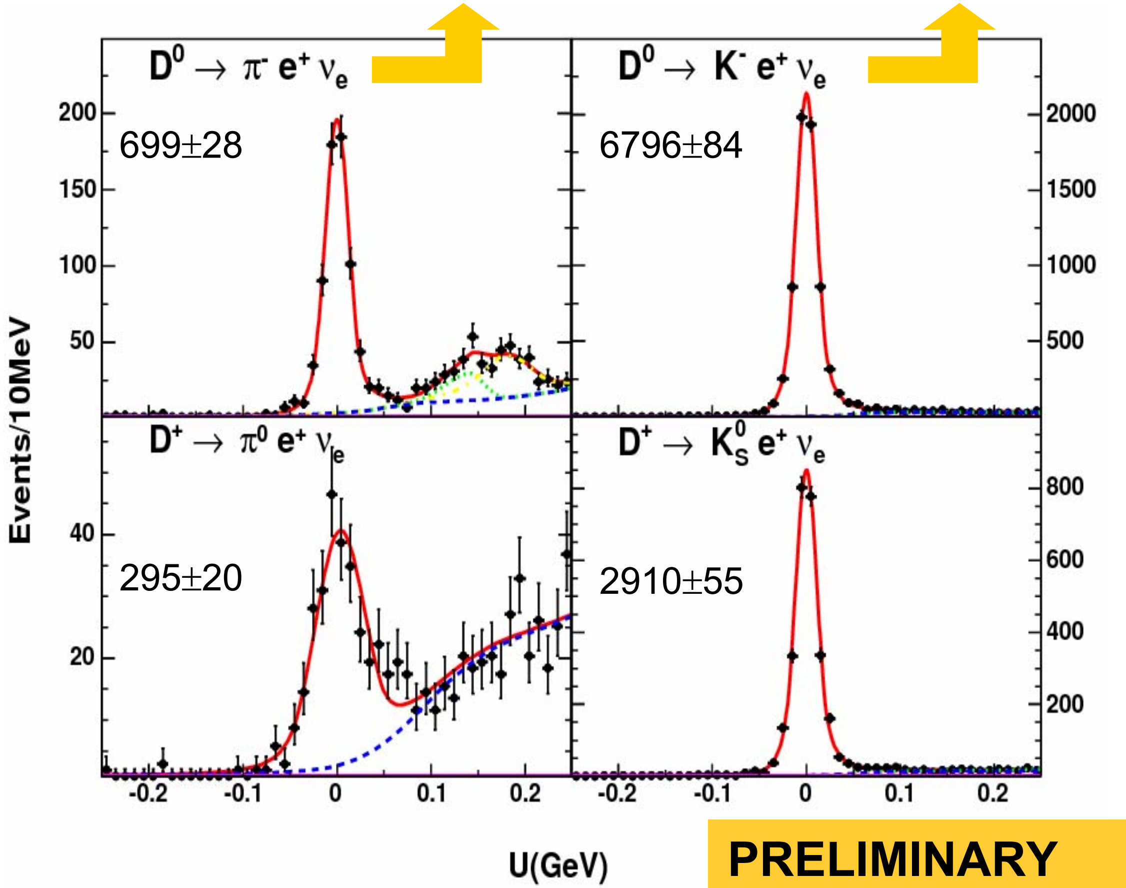
$$\vec{p}_W = -\vec{p}_{tag} - \vec{p}_{K(\pi)}$$

$$q^2 = E_W^2 - |\vec{p}_W|^2$$

- Extract yields from U distributions and measure branching fractions with multiple tag modes separately and combined
- Study form factors and CKM matrix elements using efficiency-corrected decay rate distributions

S/N ~ 40/1,
Compared to Belle
282/fb = 1000xCLEO-c
~220 signal events,
S/N ~ 4/1

S/N ~ 300/1,
Compared to Belle
282/fb = 1000xCLEO-c
~2700 signal events,
S/N ~ 20/1



Neutrino Reconstruction (Untagged)

$$p_{miss} = (E_{miss}, \vec{p}_{miss}) = p_{total} - \Sigma p_{charge} - \Sigma p_{neutral}$$

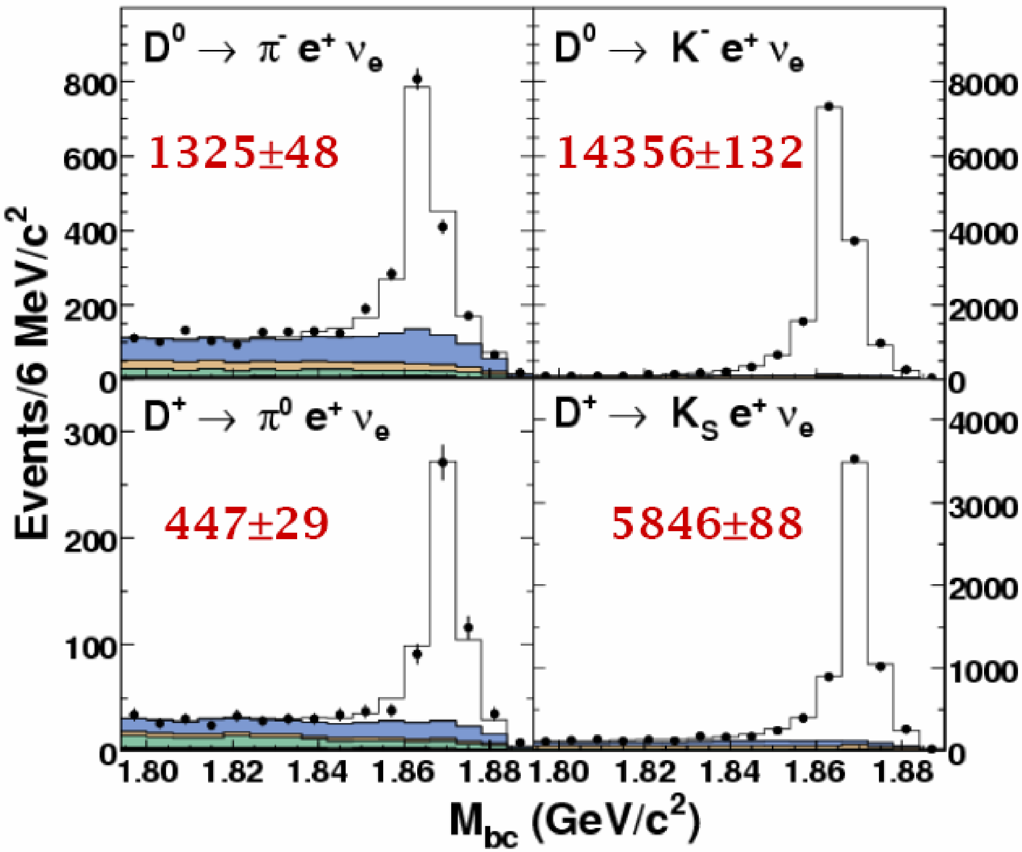
$$\Delta E = E_{K(\pi)} + E_e + |\vec{p}_{miss}| - E_{beam}$$

$$p'_{miss} = \zeta p_{miss}$$

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

$$q^2 = (p_e + p'_{miss})^2$$

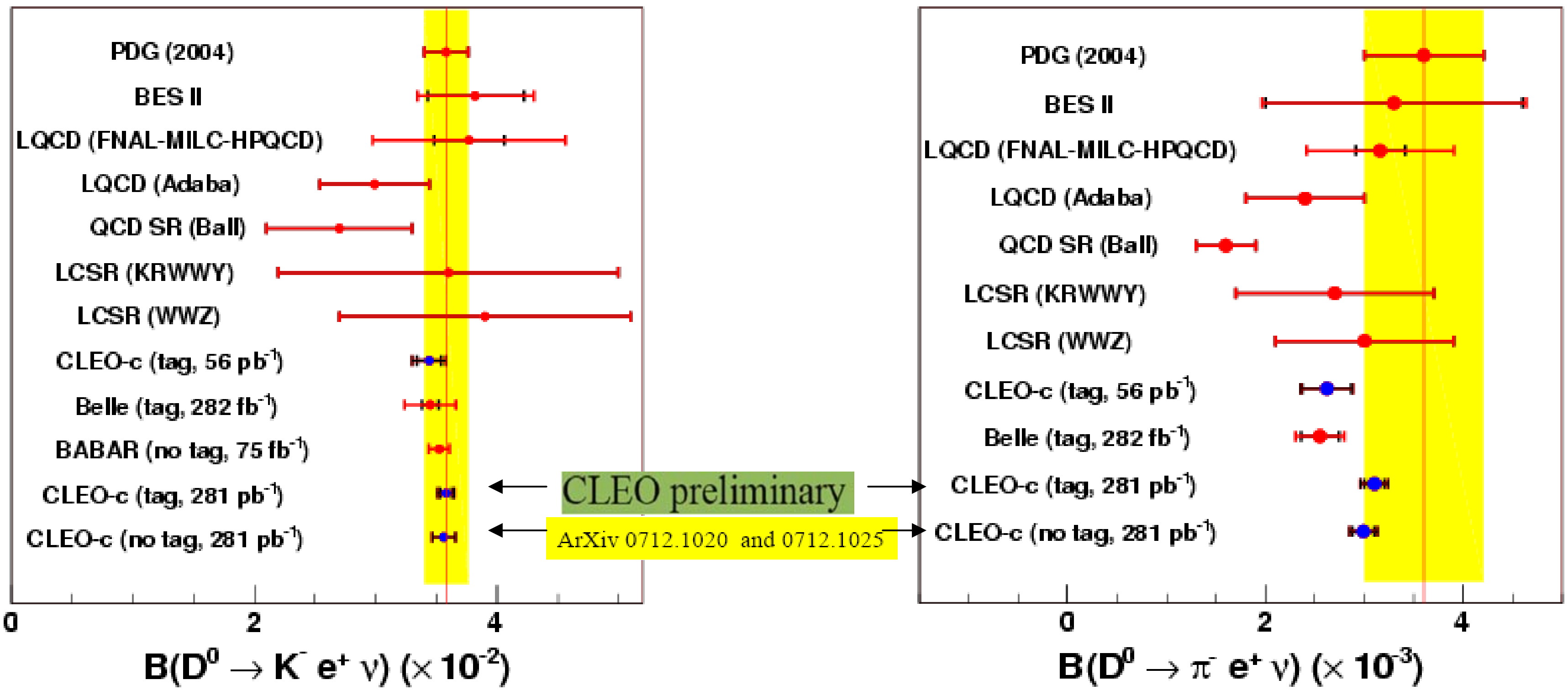
ArXiv 0712.1020 and 0712.1025



Larger signal yields, also larger backgrounds

- Hermeticity and excellent resolution of the CLEO-c detector
- Simultaneously fit M_{bc} distributions of the 4 signal modes in 5 q^2 bins to extract d(BF)/dq^2 and integrate to get branching fractions.

$D\to K/\pi e^+\nu$ Branching fractions



CLEO-c Tagged/untagged consistent,
40% overlap, DO NOT AVERAGE

CLEO-c most precise!
Theoretical precision lags experiment

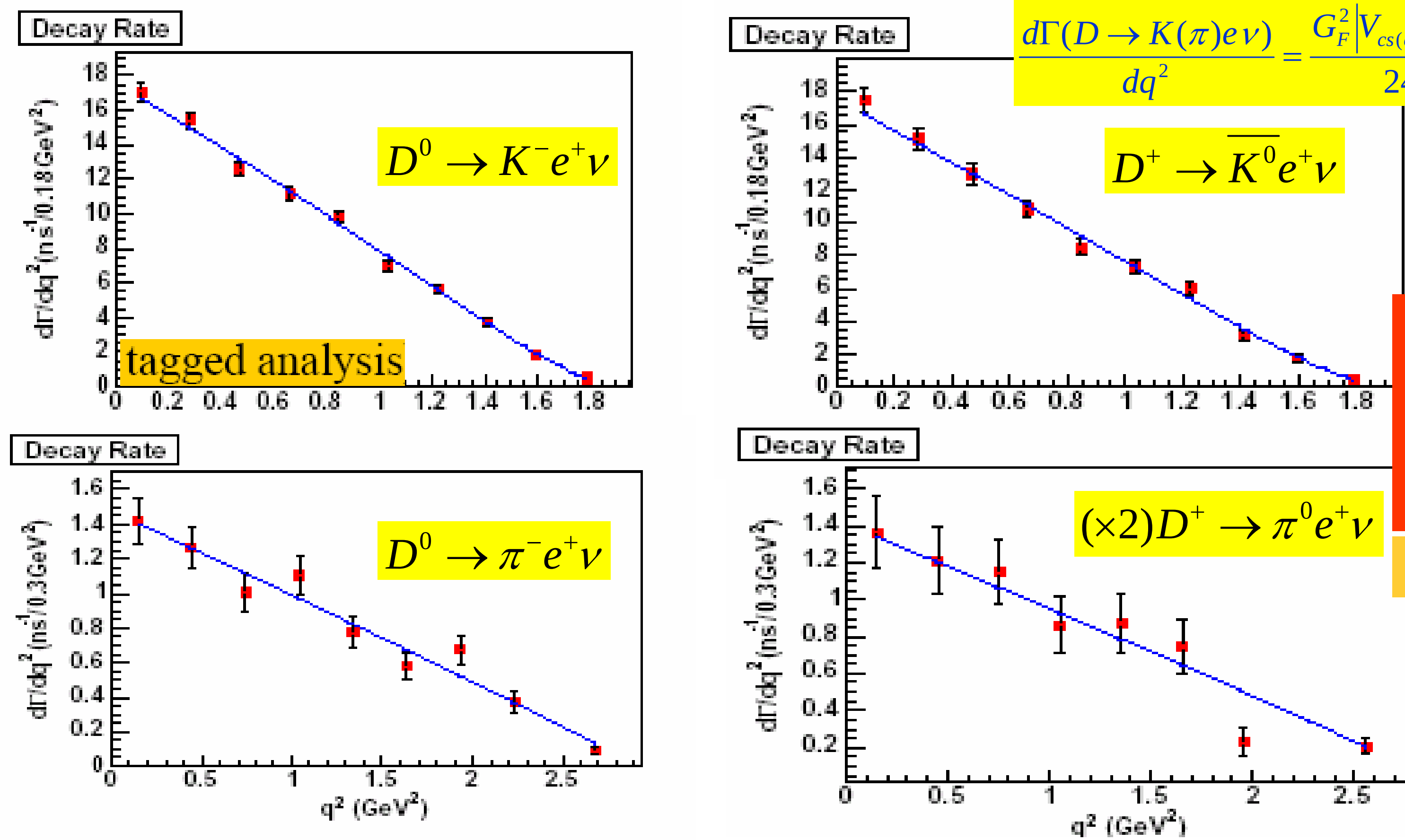
Isospin Invariance: (from tagged analysis)

$$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)} = 1.024 \pm 0.024(stat)$$

$$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{2\Gamma(D^+ \to \pi^0 e^+ \nu)} = 0.975 \pm 0.075(\mathrm{stat})$$

Absolute $d\Gamma/dq^2$ distributions

$$\frac{d\Gamma(D \to K(\pi) e \nu)}{dq^2} = \frac{G_F^2 |V_{cs(cd)}|^2 P_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$



Fit to Simple Pole Model Shown

PRELIMINARY

Simple Pole Model

$$f(q^2) = \frac{f(0)}{(1 - q^2/M_{pole}^2)}$$

Modified Pole (BK) Model

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

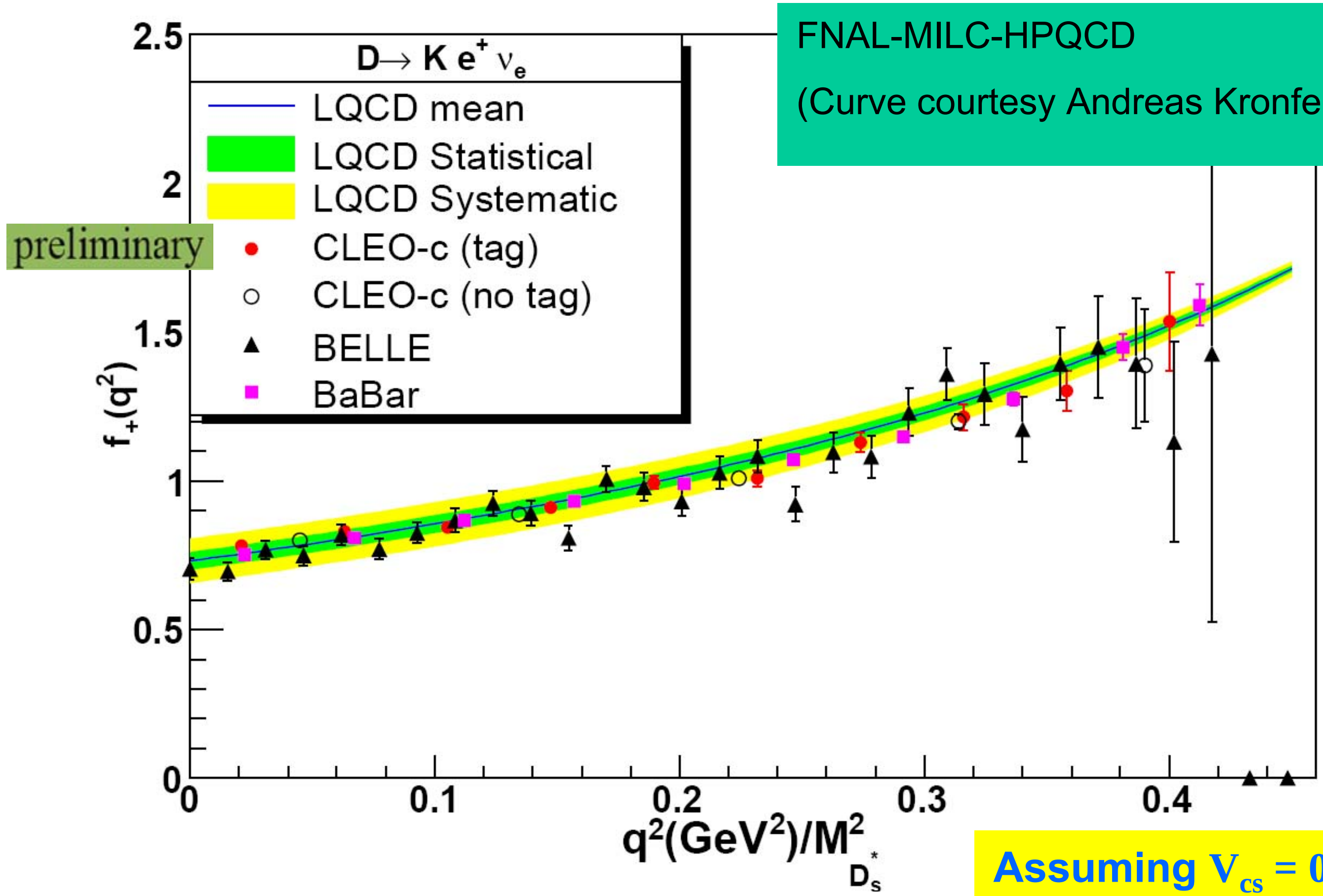
Hill Series parameterization

$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, 0)} \left[\sum_k a_k z^k(q^2, 0) \right]$$

Form factors as a stringent test of LQCD

Removing the kinematic terms reveals the form factor

$$|V_{cs(cd)}||f_+(q^2)| \sim \left[\frac{\Delta\Gamma_i(D\to K(\pi)e\nu)}{\Delta q_i^2} / P^3_{K(\pi)i}\right]^{1/2}$$



FNAL-MILC-HPQCD

(Curve courtesy Andreas Kronfeld)

Modified Pole (BK) Model shown

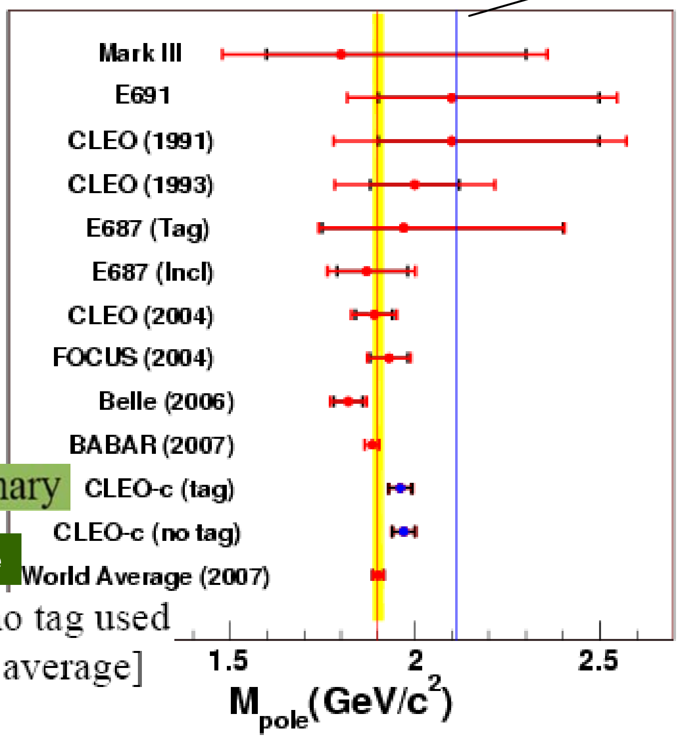
Assuming V_{cs} = 0.9745±0.0008 (CKM unitarity)

Simple Pole Model

$D \to K e^+ \nu$

Spectroscopic pole ($M_{D_s^*}$)

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



preliminary

My average

[CLEO-c no tag used in world average]

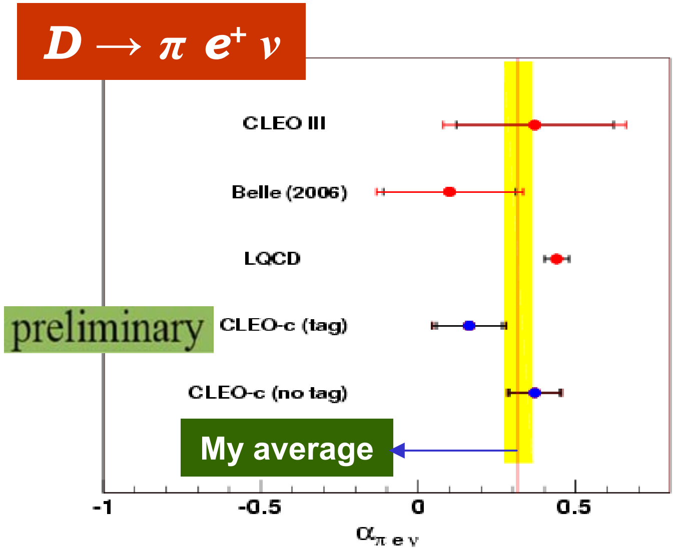
- CLEO-c tagged and untagged results are consistent
- Most of the recent precise measurements are NOT consistent with the spectroscopic pole (~14σ discrepancy between the average and the spectroscopic pole)
- Simple pole model is NOT supported by experiments

similar situation for $D \to \pi e \nu$
but limited statistics → more data

CLEO-c has 1st measurements of M_{pole} for D^+
important consistency check!

Modified Pole (BK) Model

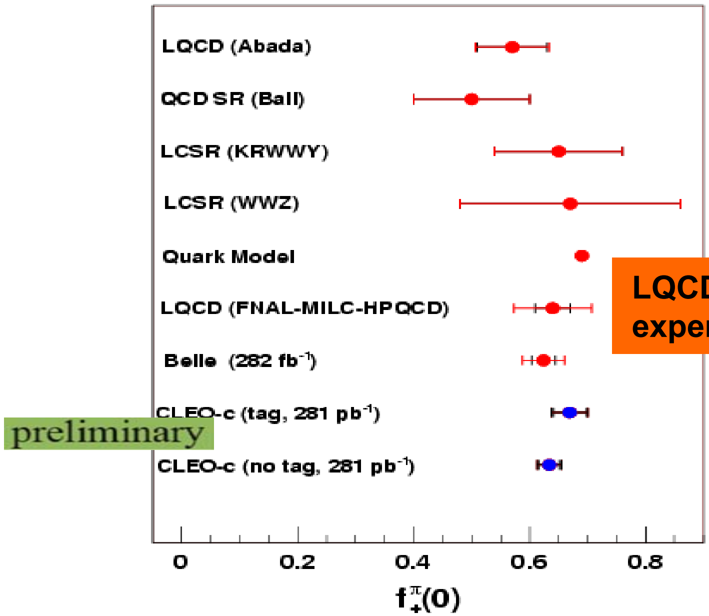
$$f^+(q^2) = \frac{f^+(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha q^2/m_{pole}^2\right)}$$



- CLEO-c tagged and untagged results are consistent

- Experimental data are compatible with LQCD, but NOT with the physical picture of the modified pole model, which gives α = 1.75 (>10σ discrepancy between the average and the physical value)

- Modified pole model is NOT supported by experiments



LQCD precision(10%) lags experiments (4%)

Similar situation for *$D \to K e^+ \nu$:*

CLEO-c α values > 27σ away from BK physical value, LQCD precision (10%) lags experiments (2%) !

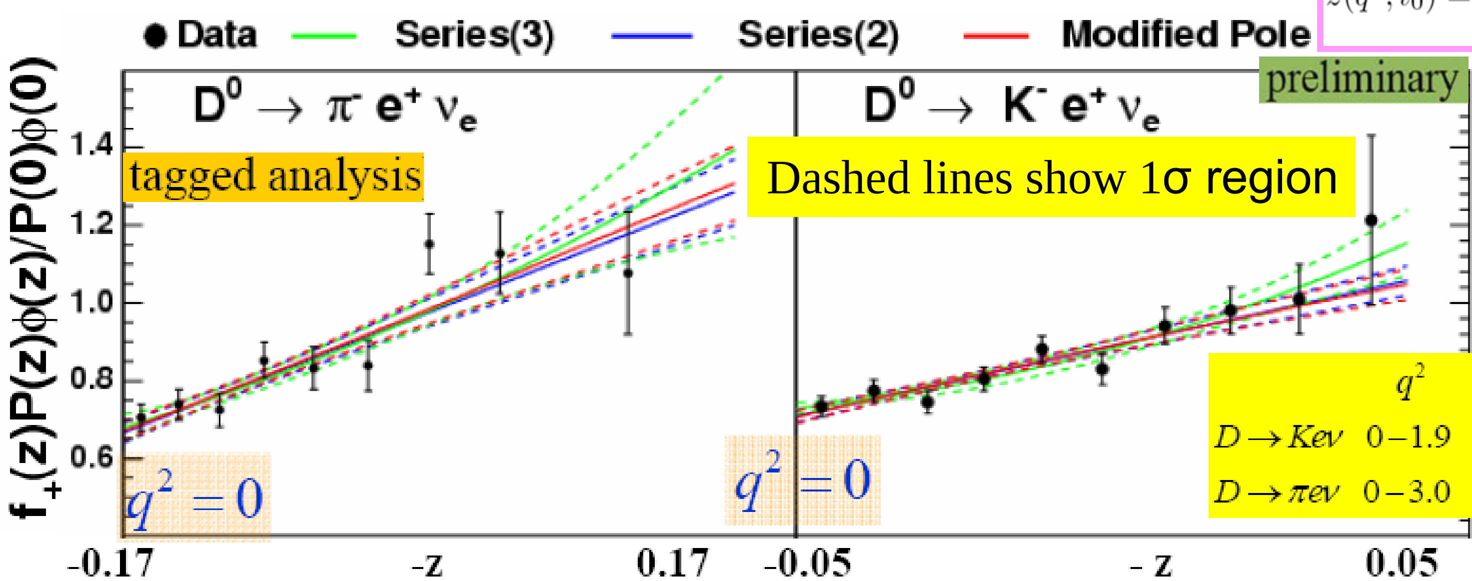
Becher-Hill series parameterization

*Advantages include: model independent,

*shape variable "physically meaningful" slope at $q^2=0$

$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,0)}\left[\sum_k a_k z^k(q^2,0)\right]$$

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$



	q^2	z
$D \to Ke\nu$	$0-1.9$	$-0.05-+0.05$
$D \to \pi e\nu$	$0-3.0$	$-0.165-+0.165$

- Both linear "series(2)" and quadratic "series(3)" parameterization describes data well
- Quadratic term a_2 not well-determined with current statistics
- As data does not support physical basis for the pole & modified pole models, the model independent Becher-Hill series parameterization is used for $|V_{cx}|$.

V_{cs} and V_{cd} Results

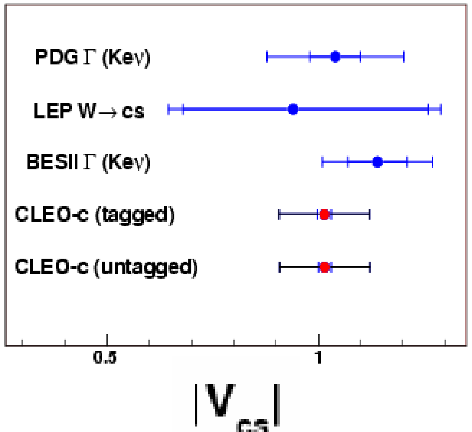
Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$

Expt. uncertainties Vcs <2% Vcd~4% Theory 10%

Decay Mode	$\lvert V_{cx}\rvert$ ± (stat) ± (syst) ± (theory)	PDG
$D \to \pi e \nu$ (tagged) PRELIMINARY	0.234 ± 0.010 ± 0.004 ± 0.024	0.230 ± 0.011 (ν–ν interactions)
$D \to \pi e \nu$ (untagged)	0.217 ± 0.009 ± 0.004 ± 0.023	
$D \to K e \nu$ (tagged) PRELIMINARY	1.014 ± 0.013 ± 0.009 ± 0.106	1.04 ± 0.16 (excl. sl. Width excluding CLEO/BES) $0.94^{+0.32}_{-0.26} \pm 0.13$ W→cs tagged
$D \to K e \nu$ (untagged)	1.015 ± 0.010 ± 0.011 ± 0.106	

Tagged/ untagged consistent, 40% overlap DO NOT AVERAGE

	V_{cs}	Uncertainty (%) exp.	thy.	tot.
PDG Γ(Kev)*	1.04 ± 0.16	6	14.2	15.4
$W \to cs$	$0.94^{+0.32}_{-0.26} \pm 0.14$			31
BESII Γ(Kev)	$1.14 \pm 0.07 \pm 0.11$	6.5	10.4	12.8
CLEO−c (untagged)	$1.015 \pm 0.015 \pm 0.106$	1.5	10.4	10.5



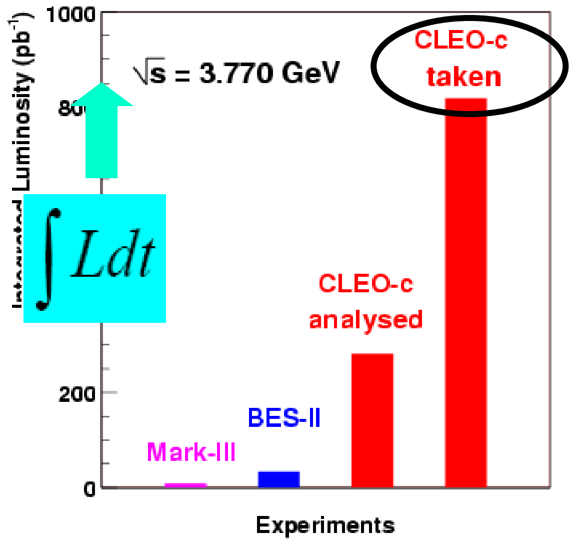
CLEO-c: Best determination of Vcs, and Vcd in good agreement with PDG

Summary

What we have achieved (281/pb)

- Most precise $B(D \to K e^+ \nu)$ *and* $B(D \to \pi e^+ \nu)$.
- Most precise measurements of $f_+(0)$ and shape for $D \to \pi e^+ \nu$.
- Best *direct* measurement of $|V_{cs}|$.
- Most precise determination of $|V_{cd}|$ from semileptonic decays.

What we are going to achieve (818/pb)

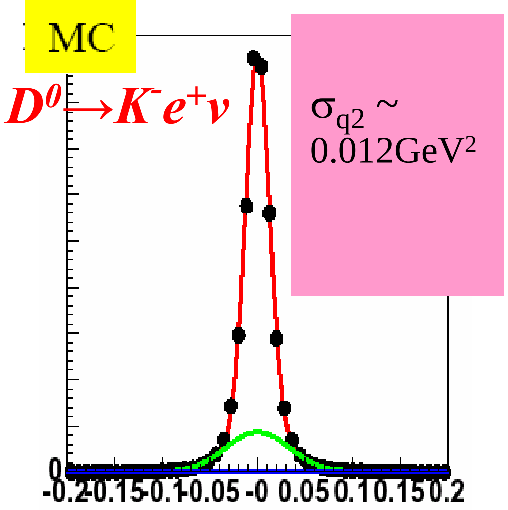


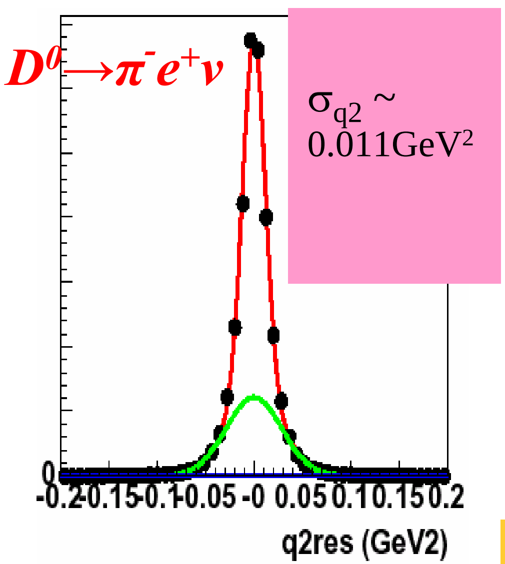
- Statistical uncertainties will be reduced by a factor of $\sqrt{3}$
- Most systematic uncertainties are being reevaluated. Some are expected to be reduced.
- More stringent tests of theory for $D \to K/\pi e^+ \nu$ $f_+(0)$ and shape.
- Reduced uncertainties on $|V_{cs}|$ and $|V_{cd}|$.

We are eagerly awaiting
more precise LQCD calculations of semileptonic form factors.

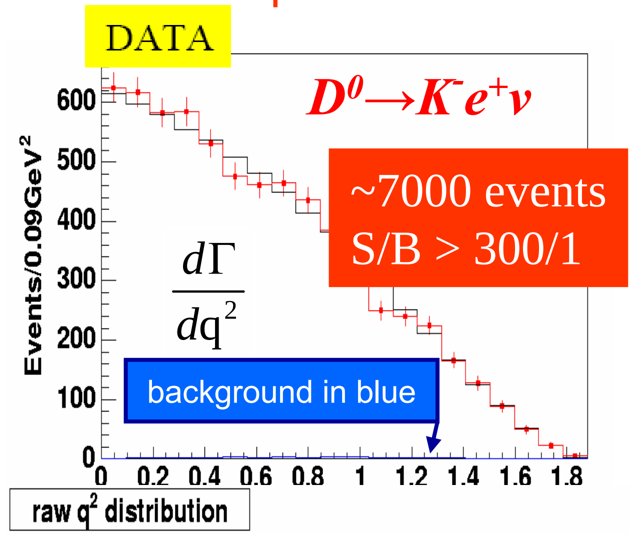
q^2 resolutions and Raw q^2 distributions

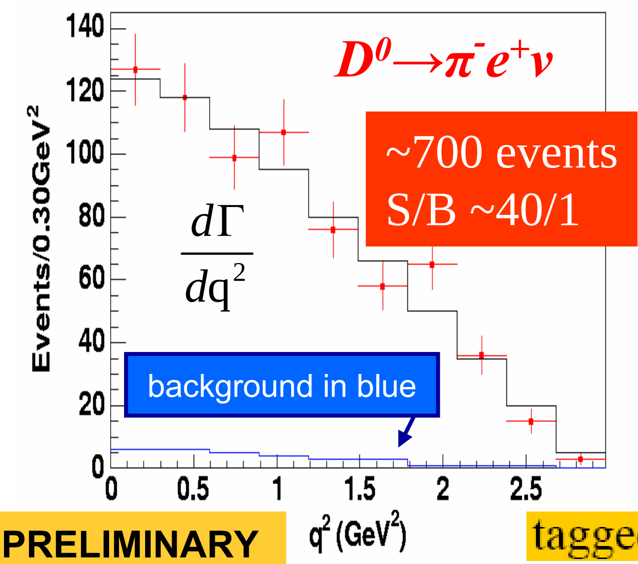
q^2 resolution





Raw q^2 distribution





PRELIMINARY

tagged analysis

CLEOIII(Υ(4S)):
$\delta q^2 \sim 0.4\ GeV^2$
CLEO-c(ψ(3770)):
$\delta q^2 \sim 0.012 GeV^2$

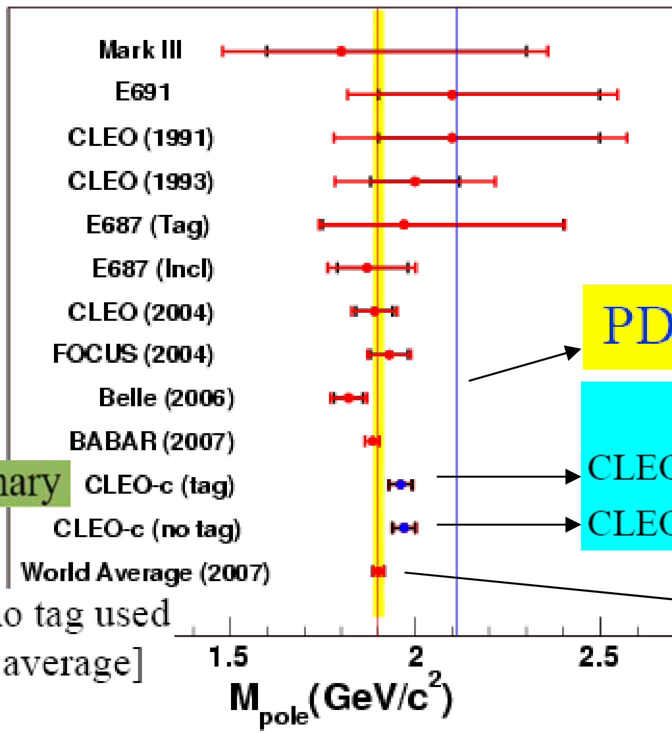
- Excellent q^2 resolution and S/B ratio
- To find the absolute decay rate, need to subtract background and apply efficiency corrections.

Simple Pole Model

$D \to K e^{+} \nu$

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

preliminary



[CLEO-c no tag used in world average]

$\text{PDG}: M(D_s^*) = (2112.0 \pm 0.6)\text{MeV}$

	m_{pole}(GeV)
CLEOc tag	1.96(3)(1)
CLEOc notag	1.97(3)(1)

My average

$< M_{pole} = (1901 \pm 14)\text{MeV} >$

$\sim 14\sigma$ discrepancy

pole model describes $D \to Ke\nu$ but not when the pole mass is the spectrocopic pole $M(D_s^*)$

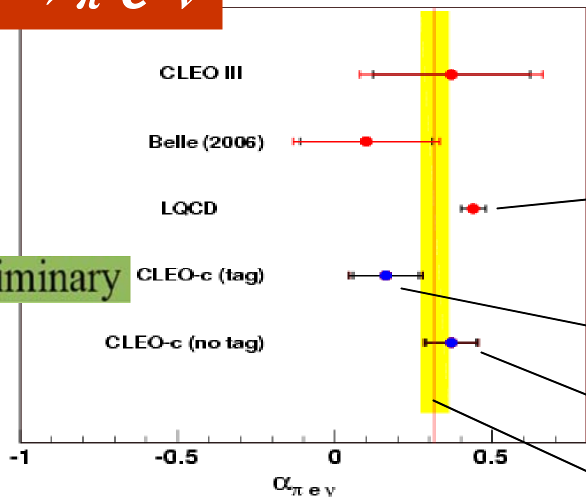
similar situation for $D \to \pi e \nu$ but limited statistics $\to$ more data

CLEO-c has 1st measurements of M_{pole} for D^{+}
Important consistency check!

Modified Pole (BK) Model

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

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



BK parameterization α~1.75

0.44(4)(syst.) LQCD

α_{π}

0.16(10)(5) CLEO tag

0.37(8)(3) CLEO no-tag

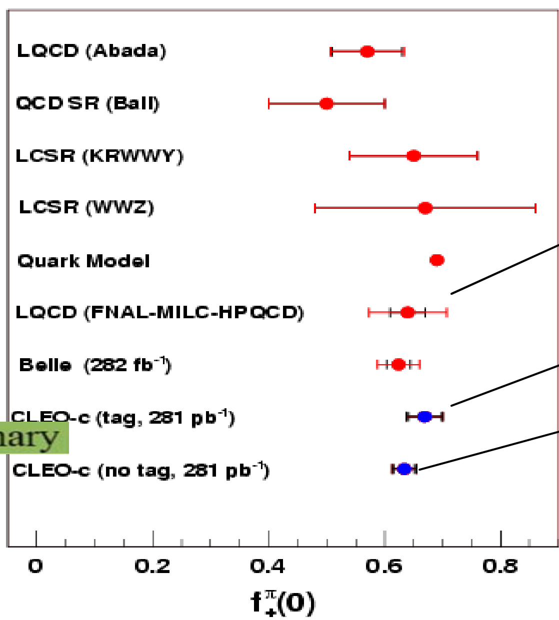
Compatible

0.32(5) **My average**

[CLEO-c no tag used in world average]

CLEO-c values > 10σ away

Physical basis of BK model not supported



0.64(3)(6) (LQCD)

$f_{+}^{\pi}(0)$

0.669(28)(11)(8) (tag)

0.634(18)(9)(8) (notag)

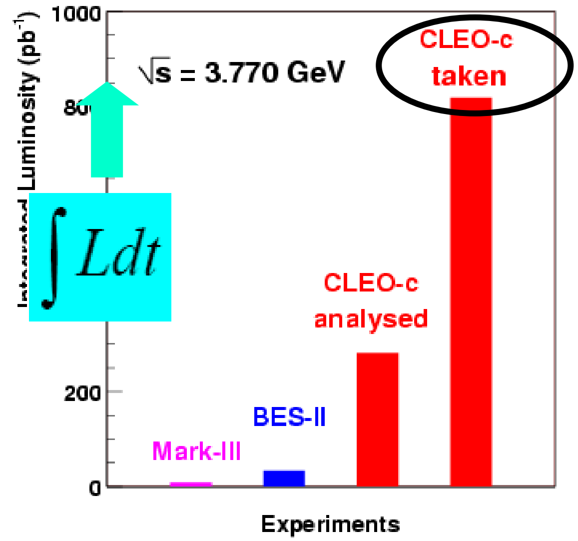
Consistent

LQCD precision(10%) lags experiments (4%)

For $D \rightarrow K\, e^{+}\, \nu$, CLEO-c α values > 27σ away from BK physical value, LQCD precision (10%) lags experiments (2%) !

Projections with 818/pb data

- Statistical uncertainties will be reduced by a factor of $\sqrt{3}$
- Most systematic uncertainties are being reevaluated. some are expected to be reduced.



NOT CLEO-c official (Based on tagged analysis)	281/pb stat.(%)	818/pb stat.(%)	281/pb syst.(%)	818/pb syst.(%)
$B(D \to Ke\nu)$	1.4	0.9	1.5	1.0
$f_+^K(0)V_{cs}$ (linear)	1.1	0.7	0.8	0.5
$f_+^K(0)V_{cs}$ (quad.)	1.6	1.0	0.8	0.5
$B(D \to \pi e\nu)$	4.1	2.7	1.4	1.0
$f_+^\pi(0)V_{cd}$ (linear)	3.7	2.3	0.7	0.4
$f_+^\pi(0)V_{cd}$ (quad.)	5.3	3.5	0.7	0.4

I. Shipsey Aspen 2008 Winter Conference

CKM Unitarity

$$\frac{\delta Vcd}{Vcd} = 0.9\%$$

$$\frac{\delta Vcs}{Vcs} = 2.7\times10^{-4}$$

$$D \to \pi e^+ \upsilon \quad \frac{\delta f_+^\pi(0)}{f_+^\pi(0)} = (2.3-3.5)\%$$

$$D \to K e^+ \upsilon \quad \frac{\delta f_+^\pi(0)}{f_+^\pi(0)} = (0.9-1.2)\%$$

$$D \to \pi e^+ \upsilon \quad \frac{\delta Vcd}{Vcd} = (2.3-3.5)\% \oplus \frac{\delta f_+^\pi(0)}{f_+^\pi(0)}$$

$$D \to K e^+ \upsilon \quad \frac{\delta Vcs}{Vcs} = (0.9-1.2)\% \oplus \frac{\delta f_+^\pi(0)}{f_+^\pi(0)}$$