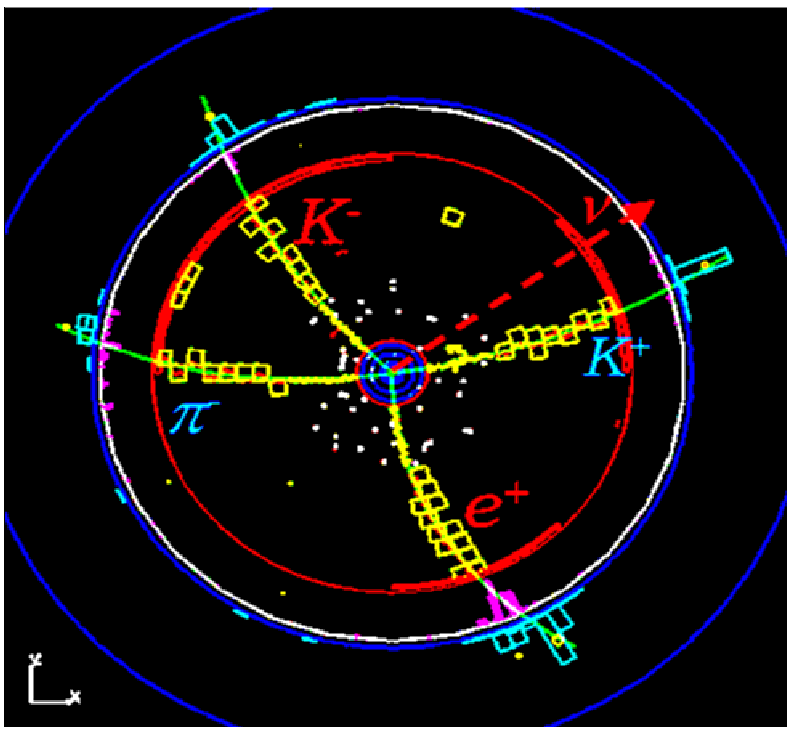
Charm Semileptonic Decays at CLEO-c

charm



Bo Xin
Purdue University
For the CLEO Collaboration

CKM 2010 @ WARWICK
Sep 06 - 10, 2010

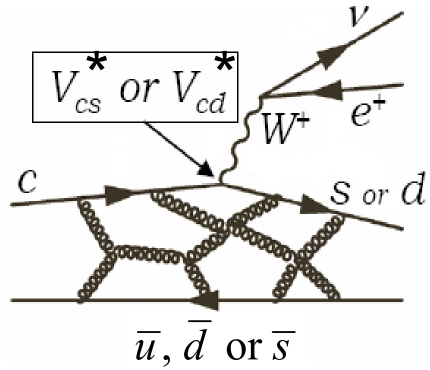
Importance of Charm Semileptonic Decays

- Golden P→P transitions:

Weak Physics

QCD Physics

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



  - Option (a):

    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 $|V_{ub}|$.

  - Option (b):

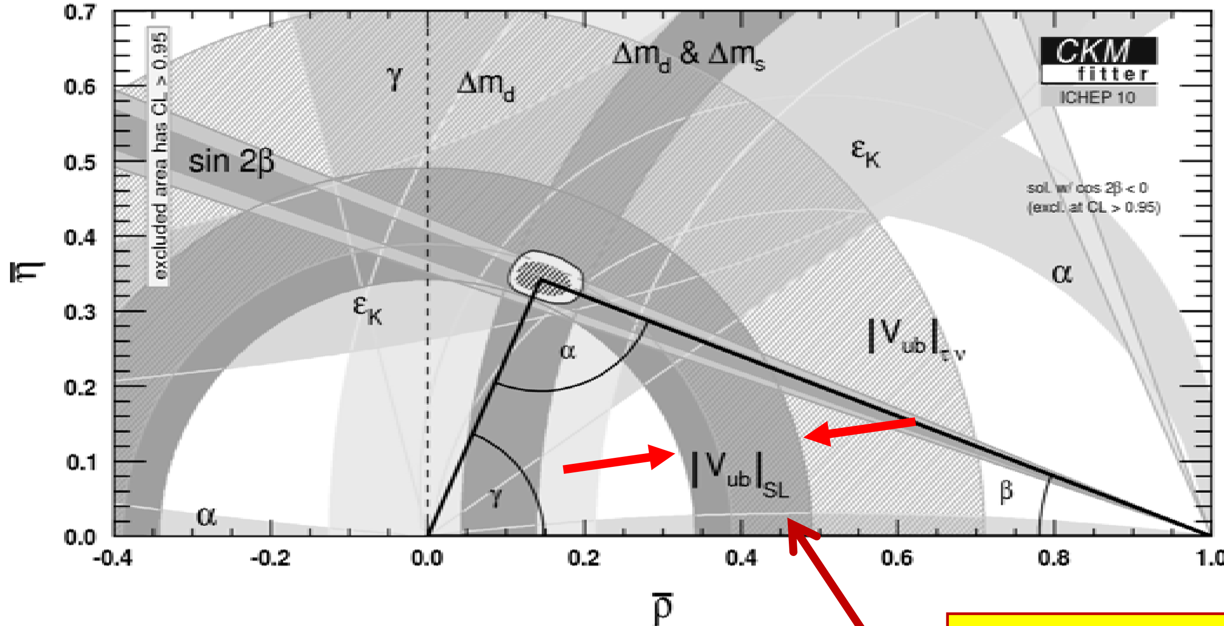
    Assuming theoretical calculations of form factors, we can extract $|V_{cs}|$ *and* $|V_{cd}|$

- New modes: to gain a complete understanding of charm semileptonic decays

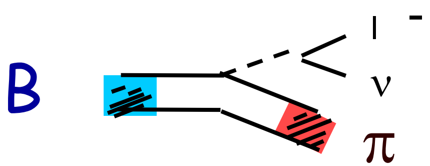
- P→V transitions: 3 hadronic form factors are needed.

  No unquenched LQCD calculation exists.

Theory + Experiment = Precision Flavor Physics



One of the most important goals of B physics

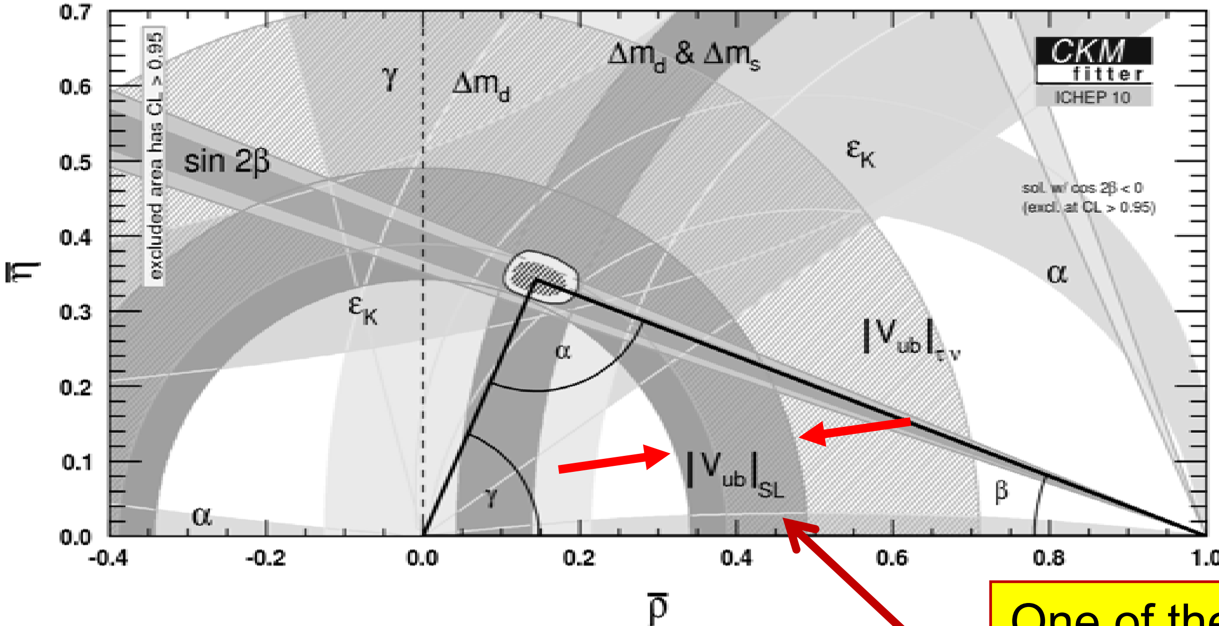


$$rate \propto [f^{B\to\pi}(q^2)]^2 \; |V_{ub}|^2$$

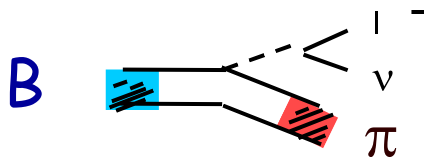
Suffer from large theory uncertainty

The discovery potential of B physics is limited by systematic errors from QCD:

Theory + Experiment = Precision Flavor Physics

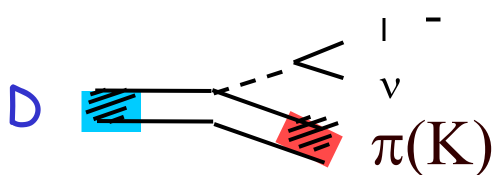


One of the most important goals of B physics



$$rate \propto [f^{B\to\pi}(q^2)]^2 \; |V_{ub}|^2$$

Calibration of the QCD calculation



$$rate \propto [f^{D\to\pi(K)}(q^2)]^2 \, |V_{cd(s)}|^2$$

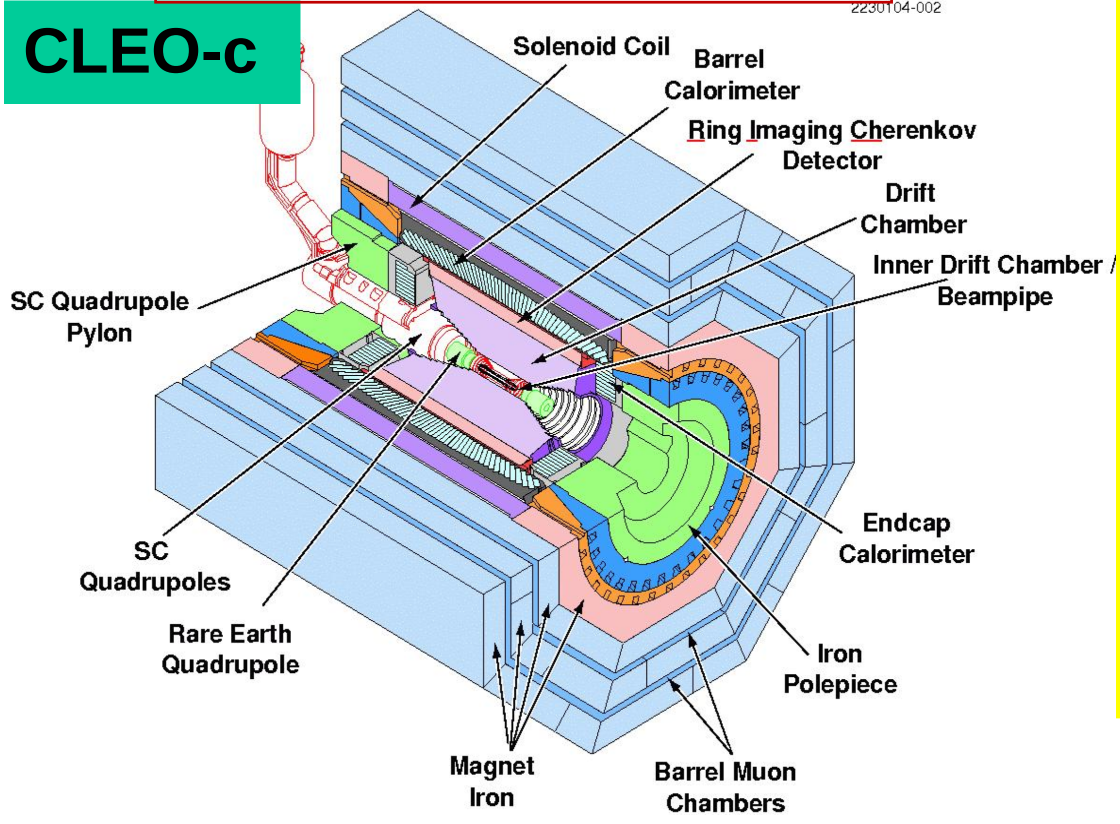
Tightly constrained by CKM unitarity

Precisely measured

The CLEO-c detector

CLEO III – SVX + ZD – 0.5 T

CLEO-c



General purpose symmetric detector

$\Delta p/p$ = 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

Muons do not have enough energy to reach the muon chambers; mostly use electrons to do semileptonic decays

- 818 pb^{-1}@3.770GeV (~5x10^6 $D\bar{D}$ events)
- 600 pb^{-1}@4.170GeV (~6x10^5 $D_s^* D_s$ events)

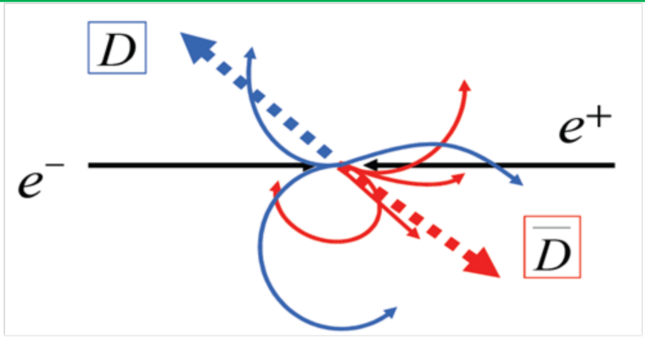
Low multiplicity

D tagging with high efficiency

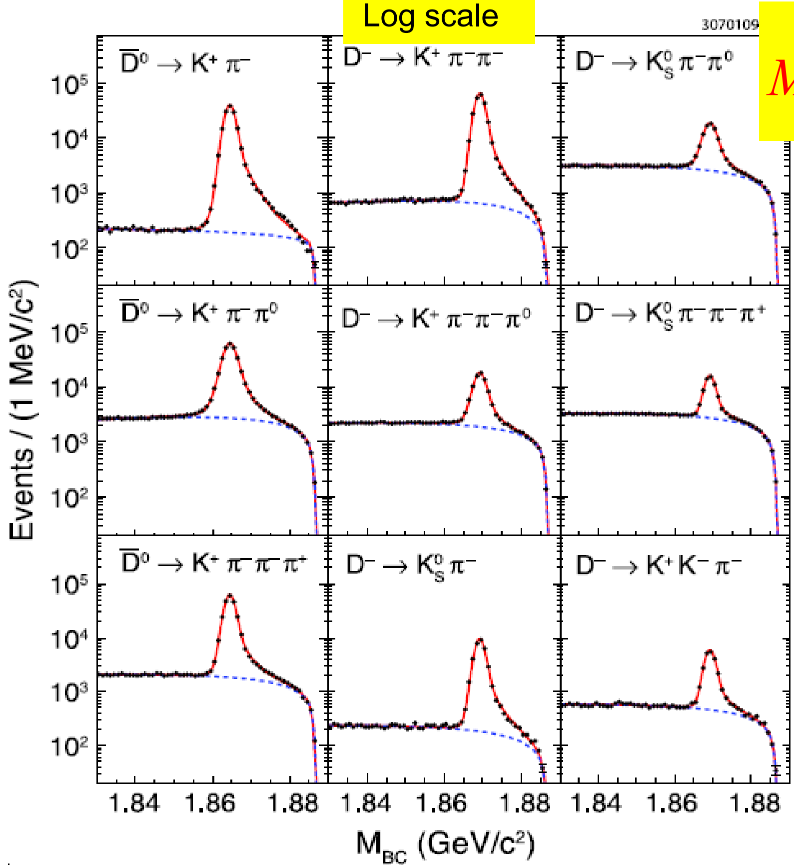
→ CLEAN-c

Analysis Technique at 3770 MeV (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



Log scale



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

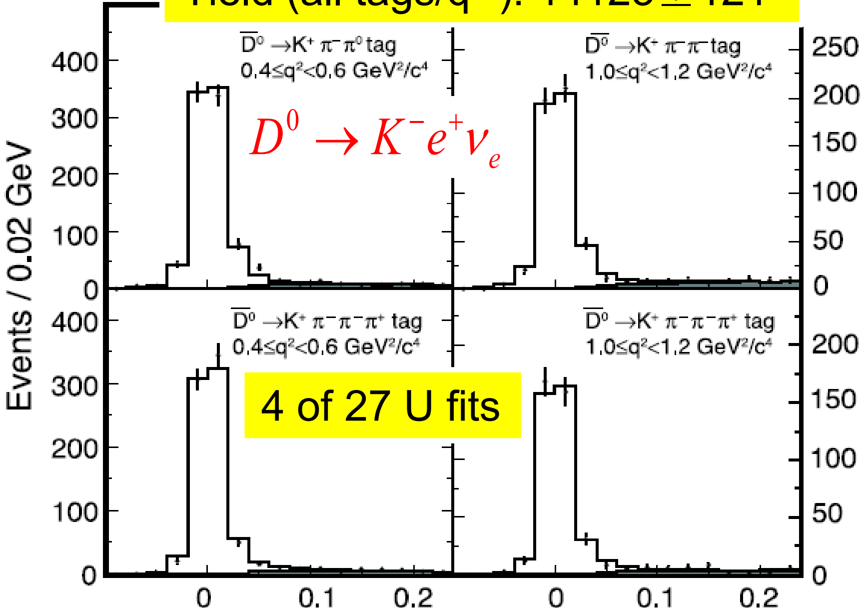
Pure DD,
zero additional particles,
~5-6 charged particles per event

~6.6x 10^5 D^0 and
~4.8 x 10^5 D^+ tags
reconstructed from
~5.4 x 10^6 DD events

We tag
~20% of the events, compared to
~0.1% of B's at the Y(4S)

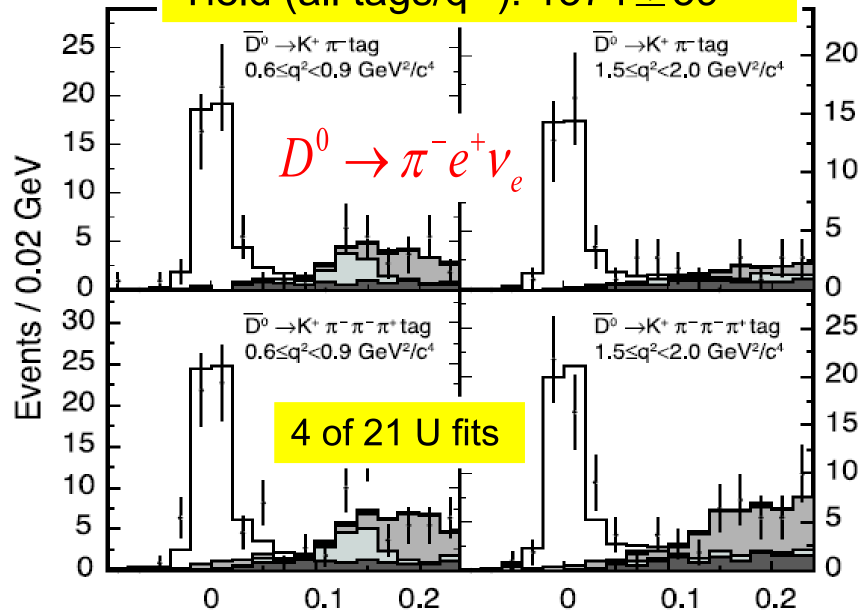
Fits to the U Distributions for $D \to K^- e \nu$

Yield (all tags/q^2): 14123±121



$U = E_{miss} - c\,|\vec{P}_{miss}|$

Yield (all tags/q^2): 1374±39



$U = E_{miss} - c\,|\vec{P}_{miss}|$

The D+ modes, which B factories have not been able to do, have smaller signals but similar S/N and resolutions. (not shown here)

818 pb^{-1} @3770

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

S/N	~300/1
Signal events	~14000
U resolution	~10 MeV
q^2 resolution	~0.008 GeV²/c⁴

Compared to B factories:

Far fewer D mesons produced,

but far better resolutions

- We perform binned likelihood fits to U distributions in each q^2 bin and tag mode
- Signal shapes are taken from signal MC, smeared with double Gaussians

Form Factor Parameterizations

In general: $$f_+(q^2) = \frac{f_+(0)}{1-\lambda}\frac{1}{\left(1-q^2/m_{pole}^2\right)} + \frac{1}{\pi}\int_{(m_D+m_P)^2}^{\infty}\frac{\mathrm{Im}(f_+(t))}{t-q^2-i\varepsilon}dt$$

Models

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

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

$m_{pole} = m(D^*_{(s)})$

(Allows for additional poles)

Model independent

Series Expansion

form factors can be written as: $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$$

accounts for D_S^* pole → $P(q^2)$

ensure a_K's good behaviour → $\phi(q^2)$

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

$$t_\pm \equiv \left(M_D \pm m_{K,\pi}\right)^2,$$

t_0: arbitrary q^2 value that maps to z=0

z is small and converges quickly, linear or quadratic is sufficient to describe the data

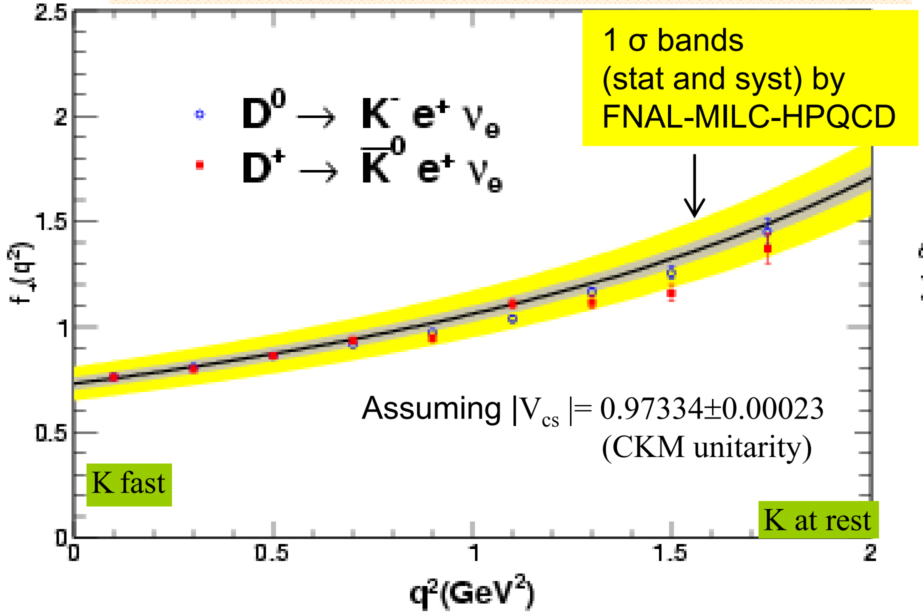
Measure a_0, $r_1 = a_1/a_0$, and $r_2=a_2/a_0$

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

Form Factors: Test of LQCD

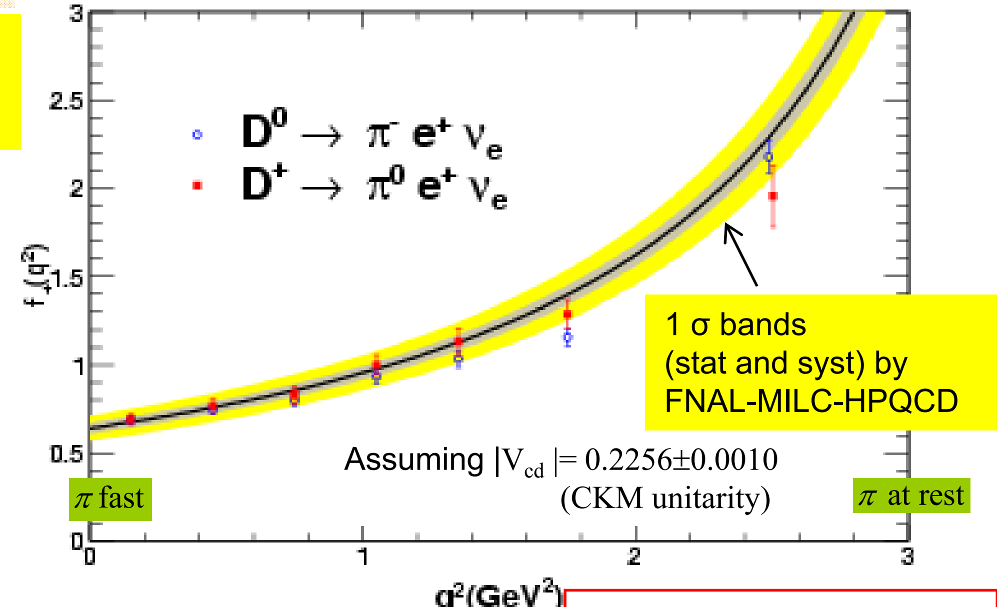
Form factor measures probability hadron will be formed

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



Modified pole model used to compare with LQCD

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



818 pb^{-1} @3770

CLEO-c prefers slightly smaller value for shape parameter α

CLEO-c results consistent with LQCD, but more precise.

Agreement is better at low q^2 than high q^2.

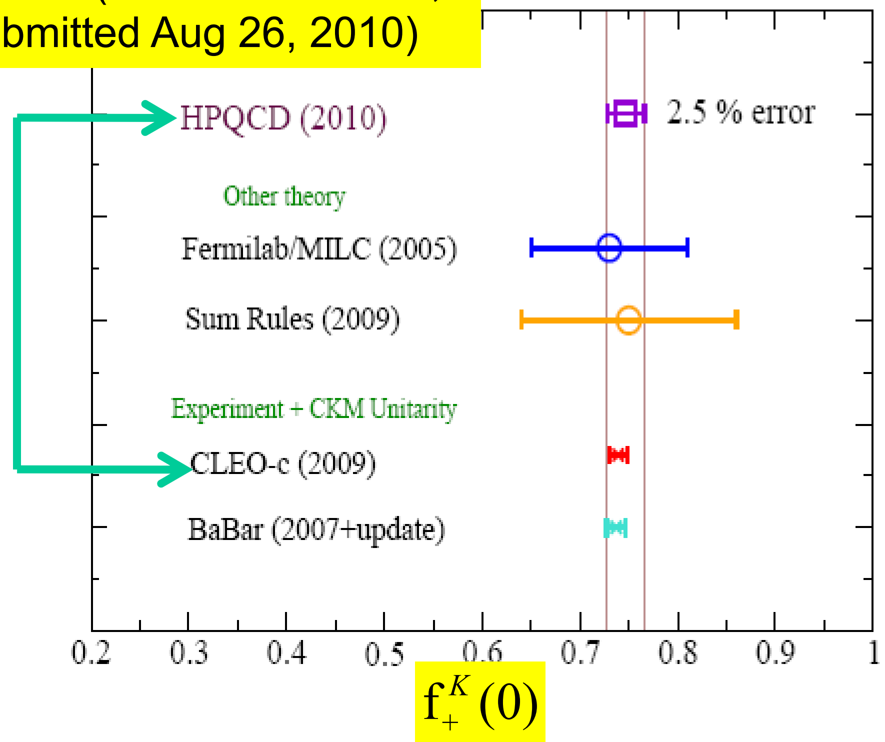
CLEO: PRD80, 032005(2009)
(CLEO 500th paper)

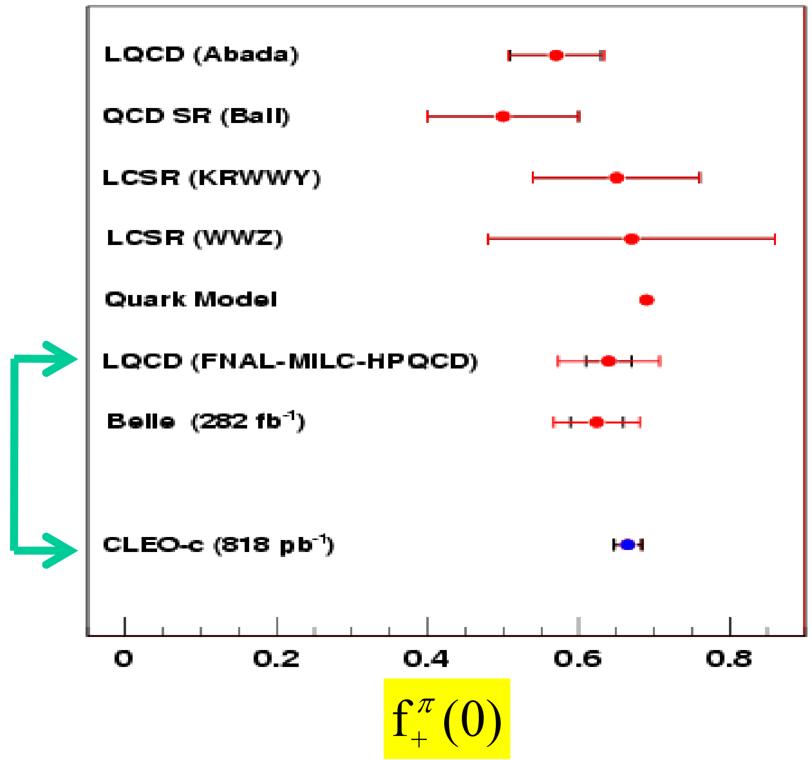
LQCD: PRL94,011601(2005)
PRD80, 034026(2009)

New HPQCD D→Kev form factor results (arXiv: 1008.4562, submitted Aug 26, 2010) have NOT been included in this comparison

Form Factors: Test of LQCD

New D→Kev form factor results (arXiv: 1008.4562, submitted Aug 26, 2010)





The LQCD uncertainty on $f_+^K(0)$ was 10% (in 2005), now 2.5%!

The same LQCD technique can be used for D→π to further reduce the theory uncertainty on $f_+^\pi(0)$.

CLEO-c results consistent with LQCD, but more precise. $f_+^K(0)$: 1% vs 3%, $f_+^\pi(0)$: 3% vs. 10%

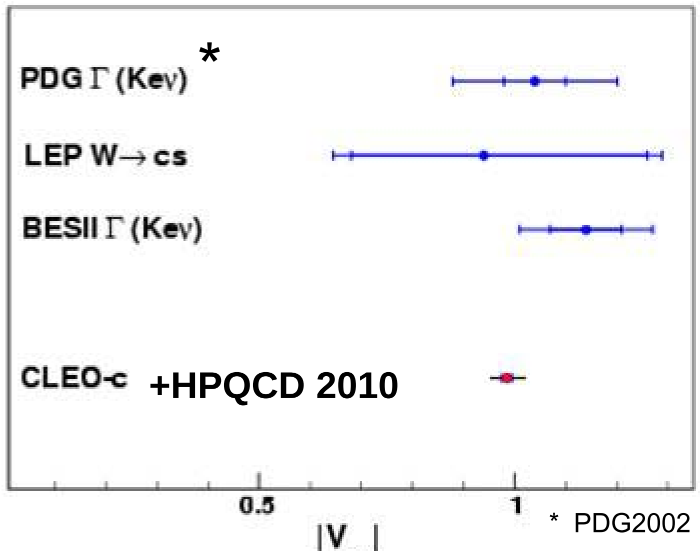
$|V_{cs}|$ and $|V_{cd}|$ Results

The data determine $|V_{cs(d)}|f_+(0)$.

To extract $|V_{cs(d)}|$, we combine the measured $|V_{cs(d)}|f_+(0)$ values using the Becher-Hill parameterization with (FNAL-MILC-HPQCD) for $f_+(0)$

CLEO-c: the most precise *direct* determination of $|V_{cs}|$ $\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 2.5\%(\text{theory})$

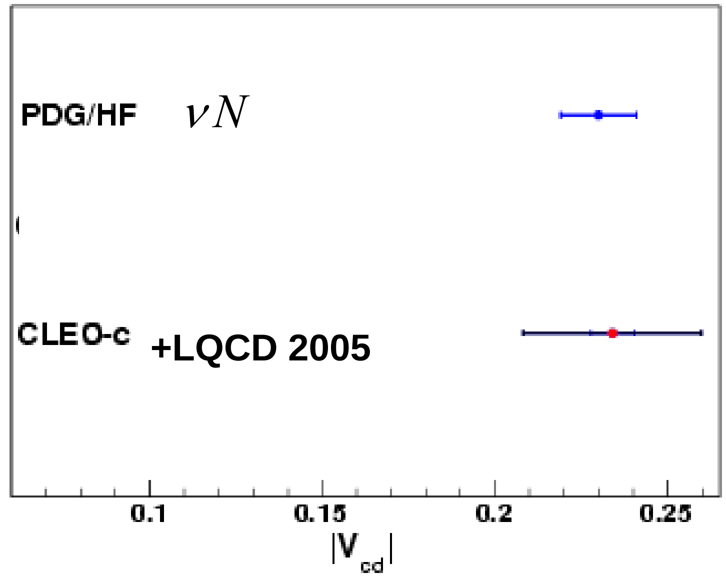
$CLEO-c$	$\|V_{cs}\|$
$(818\ \text{pb}^{-1})$	$0.963 \pm 0.009 \pm 0.006 \pm 0.024$
	stat syst theory



CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.1\%(\text{expt}) \oplus 10\%(\text{theory})$

νN remains most precise determination

$CLEO-c$	$\|V_{cd}\|$
$(818\ \text{pb}^{-1})$	$0.234 \pm 0.007 \pm 0.002 \pm 0.025$
	stat syst theory



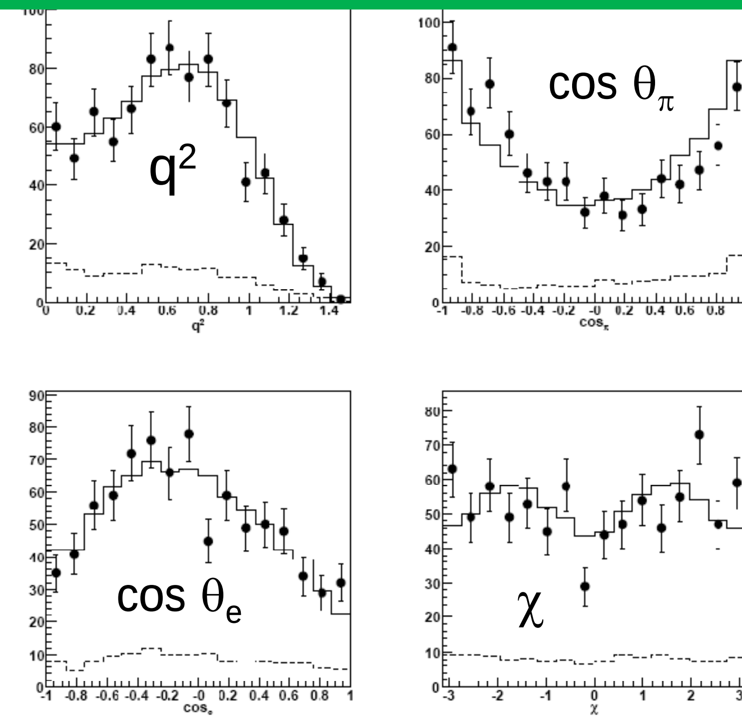
D→ρeν Branching Fraction and Form Factors

Interest: 1st measurement of FF in Cabibbo suppressed charm P→ V decays +

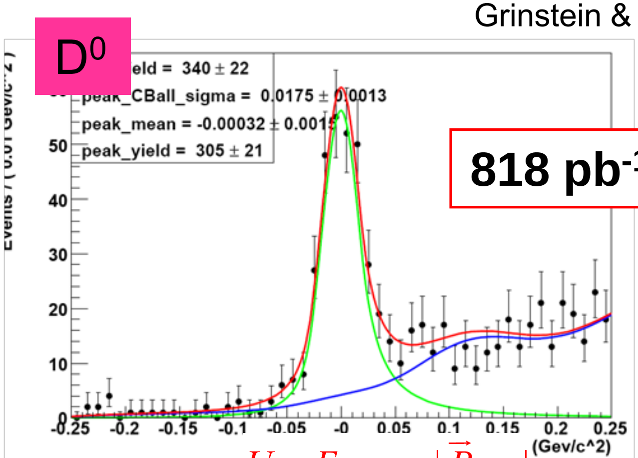
$$\frac{d\Gamma(B\to\rho e\nu)/dq^2}{d\Gamma(B\to K^*\ell^+\ell^-)/dq^2} \propto \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

Need $D\to K^* e\nu$, $D\to\rho e\nu$ FF

Grinstein & Pirjol [hep-ph/0404250]

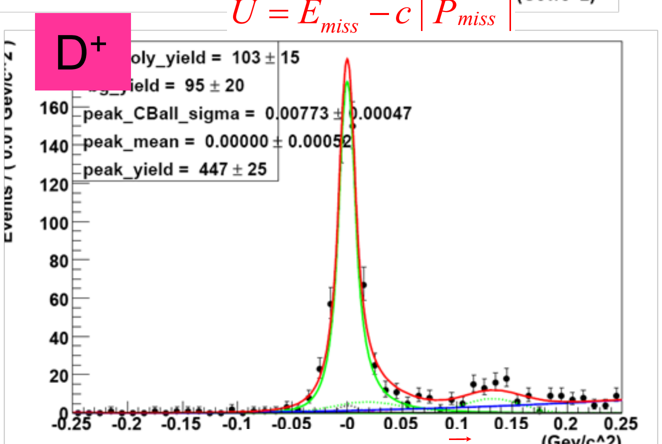


Line is projection for fitted R_V, R_2



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

818 pb⁻¹ @3770



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

$B(D^0\to\rho^- e^+\nu) = (1.77\pm0.11\pm0.10)\times10^{-3}$

$B(D^+\to\rho^0 e^+\nu) = (2.17\pm0.13\pm0.11)\times10^{-3}$

Consistent Isospin invariance:

$$\frac{\Gamma(D^0\to\rho^- e^+\nu_e)}{2\Gamma(D^+\to\rho^0 e^+\nu_e)} = 1.03\pm0.08$$

First presentation at this conference

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

$R_V = 1.48\pm0.15\pm0.03$

$R_2 = 0.83\pm0.11\pm0.04$

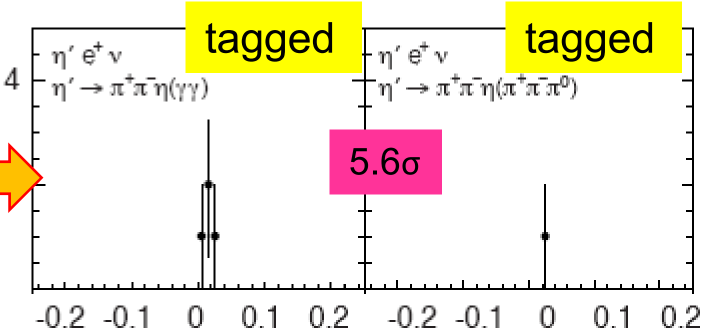
PRELIMINARY

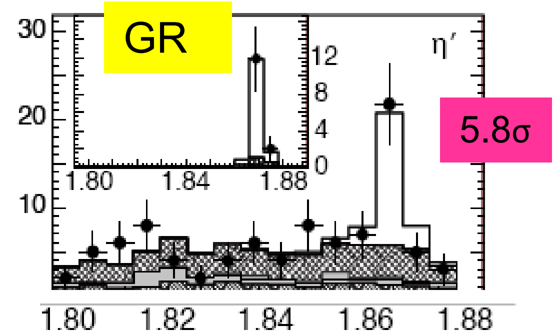
Observation of D→η'eν & D→ηeν Form Factor

Two different analysis techniques for D→η'eν and ηeν **PRELIMINARY**

- Tagged: reconstruction a D tag and look at E_{miss} & P_{miss} on the other side of the event
- Generic Reconstruction (GR):
  - find signal (η/η'+e), then attempt to form a hadronic decay mode on the opposite side by looking for $\pi^{\pm}$, $K^{\pm}$, π^0, η, and K^0_s.
  - Beam constrained mass is then calculated using neutrino 4-momentum as inferred from the missing 4-momentum of the event.

Observation of D→η'eν



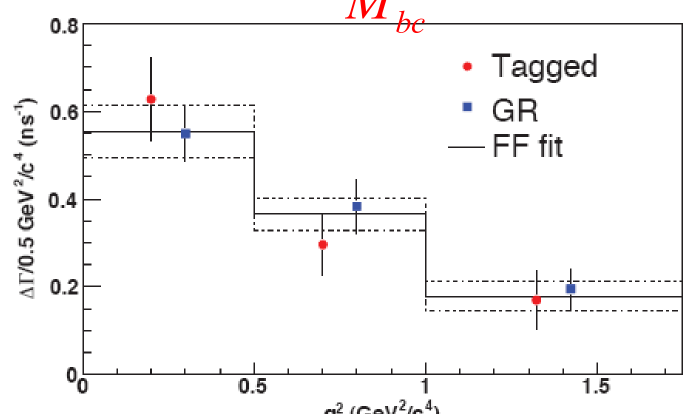


$$U = E_{miss} - c\,|\vec{P}_{miss}|$$

$$M_{bc}$$

$$B(D^+ \to \eta' e^+ \nu) = (2.16 \pm 0.53 \pm 0.05 \pm 0.05) \times 10^{-4}$$

First form factor measurement for D→ηeν



Simultaneous form factor fits to the tagged and GR partial rates using the series expansion

$$B(D^+ \to \eta e^+ \nu) = (11.4 \pm 0.09 \pm 0.04) \times 10^{-4}$$

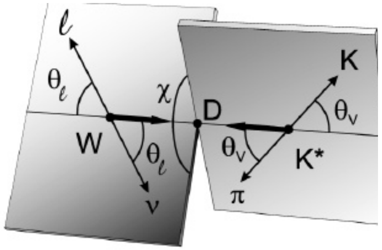
Tagged: $B(D^+ \to \phi e^+ \nu) < 0.9 \times 10^{-4}$ (90% C.L.)

$D^+ \to K^- \pi^+ e^+ \nu$ and $D^+ \to K^- \pi^+ \mu^+ \nu$

- Six hadronic tag modes
- μ/π separation is based on $|m_{K\pi}-m_{K^*}|$ and other cuts including $|E_{miss}-|P_{miss}||<20$MeV

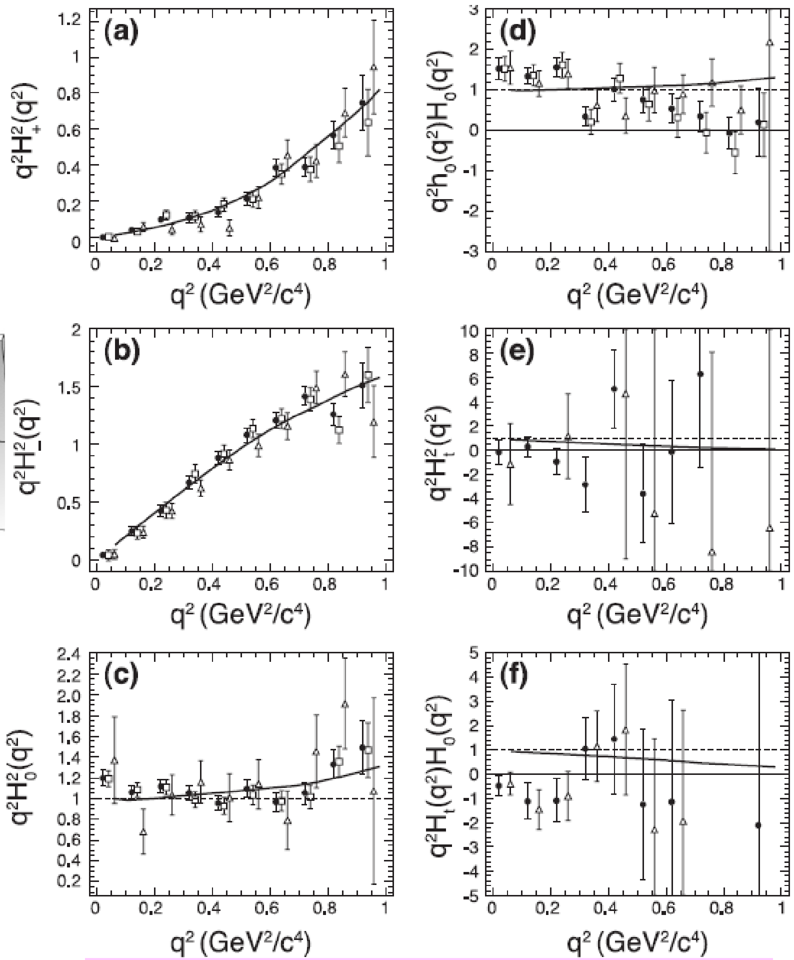
$$B(D^+ \to \bar{K}^{*0} e^+ \nu) = (5.52 \pm 0.07 \pm 0.13)\%$$

$$B(D^+ \to \bar{K}^{*0} \mu^+ \nu) = (5.27 \pm 0.07 \pm 0.14)\%$$



- Five kinematic variables used in a model independent study of the four helicity amplitudes (K* and non-resonant Kπ included)
- Muons enable the study of mass-suppressed helicity form factor $H_t(q^2)$
- Projective weighting technique, first used by FOCUS PLB633, 183(2006)
  - helicity basis form factors are distinguished based on their contributions to the decay angular distribution.
- No evidence for d- or f-wave Kπ component

Six form factor products vs. q^2

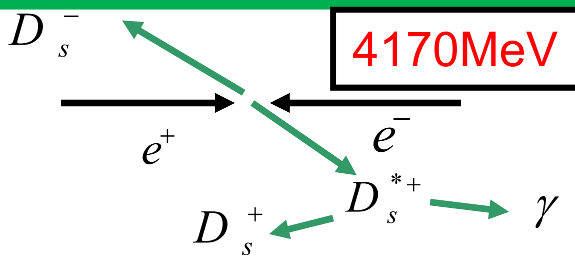


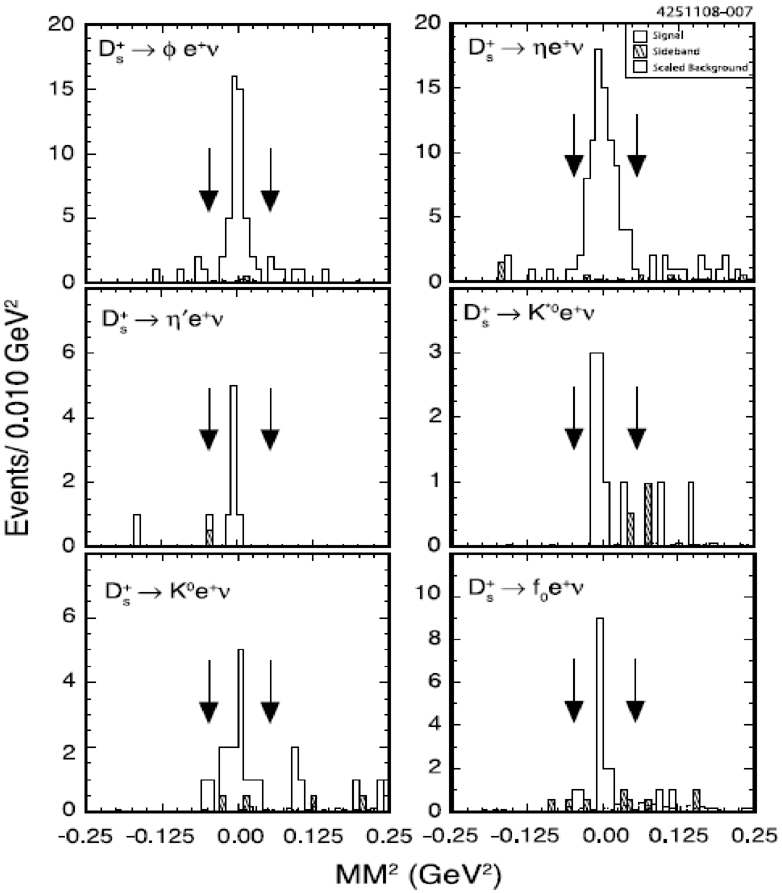
General agreement with the single pole dominance model

PRD 81:112001(2010)

Exclusive D_s Semileptonic Decays

- Reconstruct a D_s tag in several hadronic modes, then study the system against the tag and a well reconstructed γ.
- No other significant D_s semileptonic branching fraction is expected.
- Total width of these exclusive modes is 16% lower than the D^0/D^+ semileptonic widths.
- Direct observation of a semileptonic decay including a scalar meson in the final state.





310 pb^{-1} @4170

(Half of full dataset)

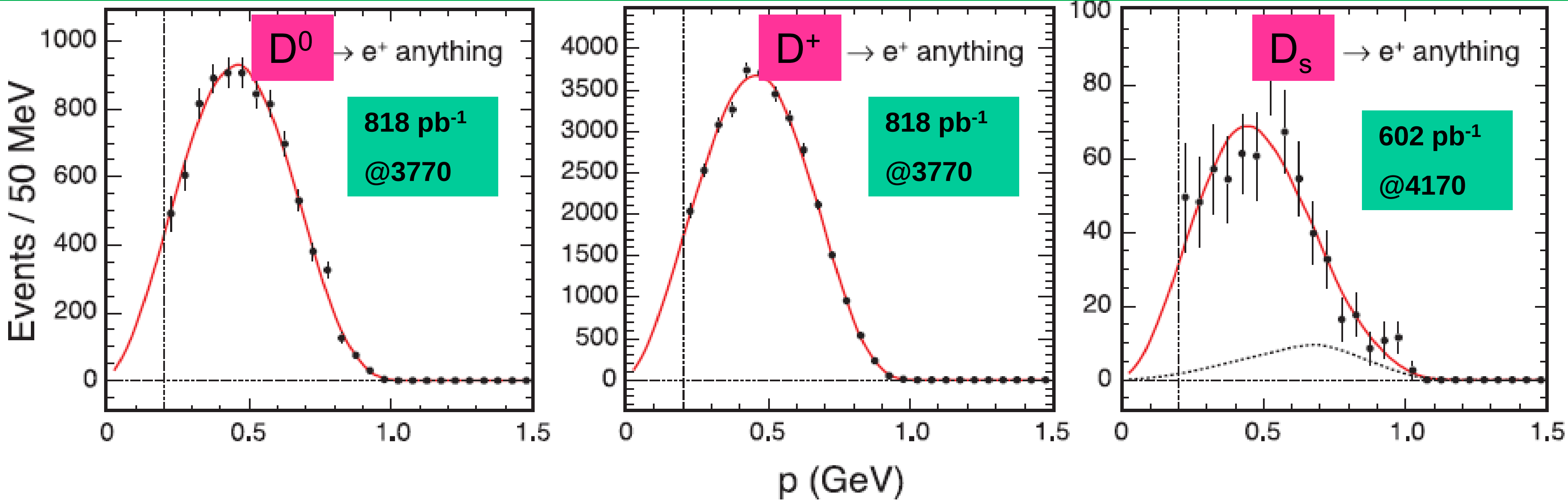
PRD 80:052007(2009)

Signal Mode	$\mathcal{B}(\%)$
$D_s^+ \to \phi e^+ \nu_e$	$2.29 \pm 0.37 \pm 0.11$
$D_s^+ \to \eta e^+ \nu_e$	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \to \eta' e^+ \nu_e$	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \to K^0 e^+ \nu_e$	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \to K^{*0} e^+ \nu_e$	$0.18 \pm 0.07 \pm 0.01$
$D_s^+ \to f_0 e^+ \nu_e$	$0.13 \pm 0.04 \pm 0.01$

$B(D_s^+ \to f_0(980) e^+ \nu) \times B(f_0 \to \pi^+ \pi^-)$ → (last row)

A separate analysis on $D_s^+ \to f_0(980) e^+ \nu$ using full data set (PRD 80:052009(2009)) not shown due to lack of time

Inclusive Semileptonic Decays of D^0, D^+, and D_s



- ❑Cleanest Tagged modes: $D^0 \to K\pi$, $D^- \to K\pi\pi$, $D^-_s \to \phi\pi$
- ❑Unfold true electron using PID efficiency matrix
- ❑Use knowledge about exclusive modes and form factor models to extrapolate below the momentum cutoff (200MeV/c)

$$\Gamma^{SL}_{D^+} / \Gamma^{SL}_{D^0} = 0.99 \pm 0.02 \pm 0.02$$

Isospin symmetry

$$\Gamma^{SL}_{D^+_s} / \Gamma^{SL}_{D^0} = 0.81 \pm 0.05 \pm 0.03$$

Any additional exclusive modes will have small branching ratios

PRD 81:052007(2010)	$D^0 \to X e^+ \nu$	$D^+ \to X e^+ \nu$	$D_s \to X e^+ \nu$
Inclusive $\mathcal{B}$ (%)	6.55±0.10±0.09	16.36±0.11±0.29	6.49±0.40±0.18
Sum of exclusive $\mathcal{B}$ (%)	6.1±0.2±0.2	15.1±0.5±0.5	6.47±0.60

Summary

- Most of CLEO-c Charm semileptonic results have been updated using full data sets.

  - $D \rightarrow Ke^+\nu$, $D \rightarrow \pi e^+\nu$ form factors in general agreement with LQCD.
  - LQCD precision lags.
  - Best direct measurement of $|V_{cs}|$, measured to ±1.1%(experimental) ± 2.5%(theory).

    $|V_{cd}|$ is measured to ±3.1%(experimental) ± 10%(theory).

  - Form factors in many D and D_s modes have been studied.
  - Observations of new semileptonic modes in both D and D_s decays.
  - Measurements of inclusive semileptonic decays.

- The CLEO-c semileptonic program has been highly successful.
- The next D factory, BESIII, will continue to challenge the precisions of QCD calculations.

Theory: A Breakthrough in Lattice QCD

❑Revolutionary progress (2003) in algorithms allows inclusion of QCD vacuum polarization.

(Talk by

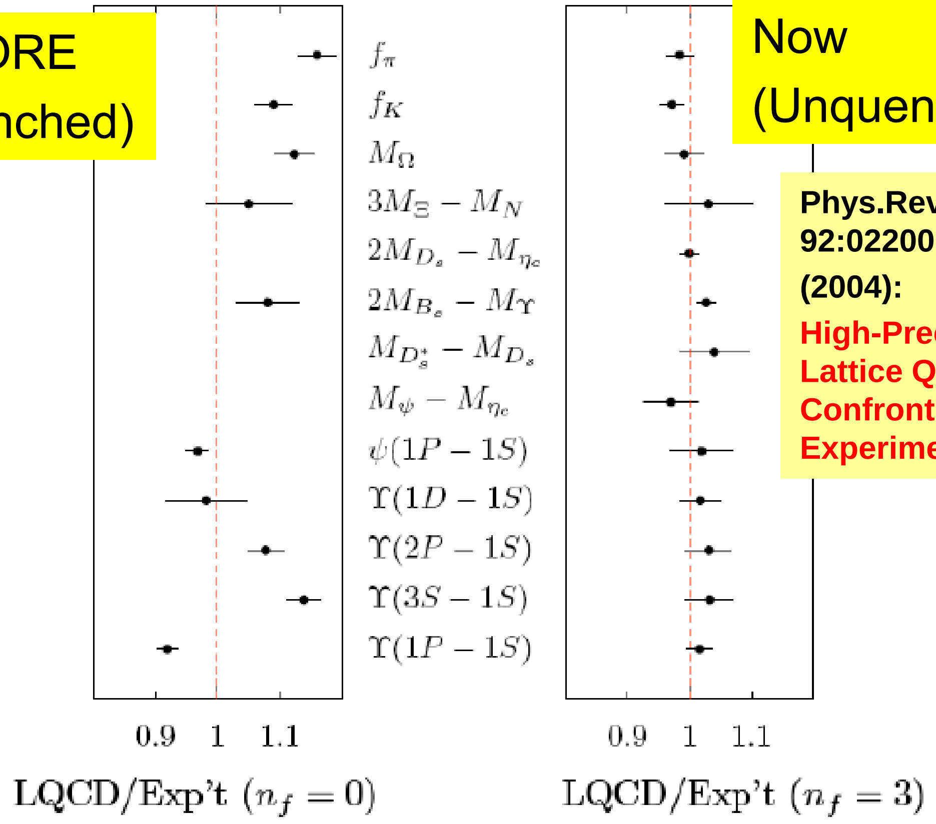
)

❑LQCD demonstrated it can reproduce a wide range of mass differences and decay constants.

These were postdictions

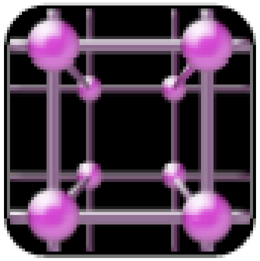
BEFORE (Quenched)

Now (Unquenched)



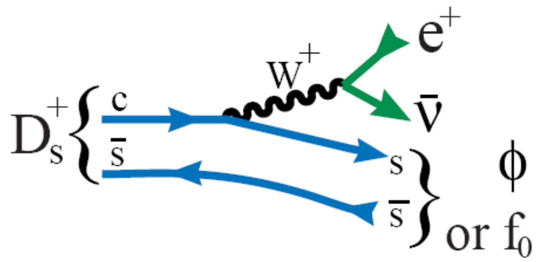
Phys.Rev.Lett. 92:022001 (2004): High-Precision Lattice QCD Confronts Experiment

- This dramatic improvement needs validation
- *Charm* decay constants f_{D+} & f_{Ds} (come to my talk tomorrow)
- *Charm* semileptonic Form factors



$D_s^+ \to f_0(980) e^+ \nu$

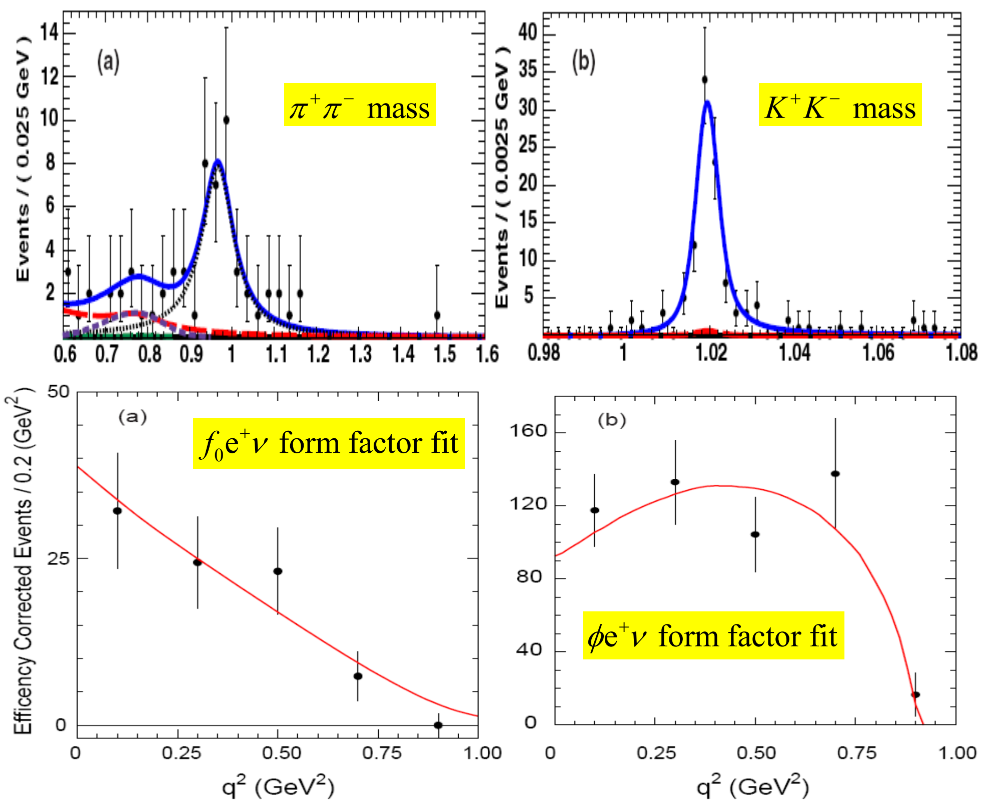
- It is suggested that $B_s \to J/\Psi f_0$ can be an alternative to $B_s \to J/\Psi \Phi$ to measure CP Violation in the B_s system   Stone & Zhang [PRD79, 074024]



600 pb^{-1} @4170
(CLEO-c full dataset)

- D_s semileptonic decays provide a very clean environment to study the properties of the $f_0(980)$ meson

PRD 80:052009(2009)



- Many interesting results:

✓ $$\left.\frac{\Gamma(D_s^+ \to f_0(980) e^+ \nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+ \nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42 \pm 11)\%$$

$$\left[\text{Predicted to equal } \frac{\Gamma(B_s \to J/\Psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\Psi \phi, \phi \to K^+K^-)}\right]$$

✓ $$B(D_s^+ \to f_0(980) e^+ \nu, f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$
$$B(D_s^+ \to \phi e^+ \nu) = (2.36 \pm 0.23 \pm 0.13)\%$$

✓ $M_{f_0(980)} = (977^{+11}_{-9} \pm 1)$ MeV, $\Gamma_{f_0(980)} = (91^{+30}_{-22} \pm 3)$ MeV

✓ Simple pole model $M_{\text{pole}} = (1.7^{+4.5}_{-0.7} \pm 0.2)$ GeV

Backup Slides

In general: $$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\frac{1}{\left(1-q^2/m_{pole}^2\right)} + \sum_{k=1}^{N}\frac{\rho_K}{1-\frac{1}{\gamma_K}\frac{q^2}{m_{pole}^2}}$$

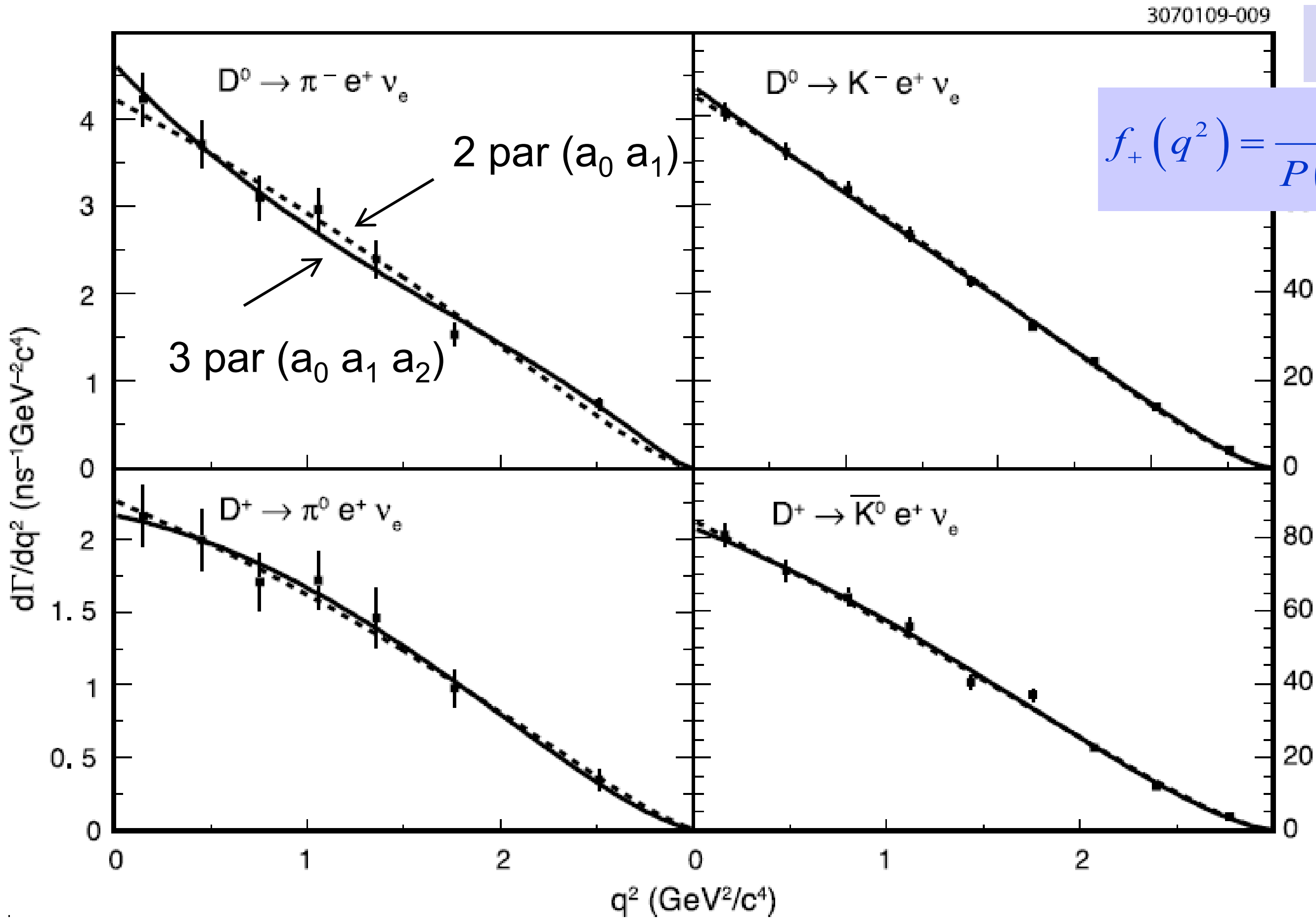
$$\Gamma_i^{measured} = B_i \cdot \Gamma_D = \frac{1}{\tau_D}\frac{\sum_j \varepsilon_{ij}^{-1} N_{tag,SL}^{j}}{N_{tag}}$$

from fits to U

from fits to M_{bc}

Inverse of the efficiency matrix

D→K/πe⁺ν : Fits to the dΓ/dq² Distributions



Fit to Becher-Hill Series

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

Other form factor parameterizations exist, but are only used as functional forms as their physical pictures are not supported by the data

Simultaneous fits to isospin conjugate modes are also performed

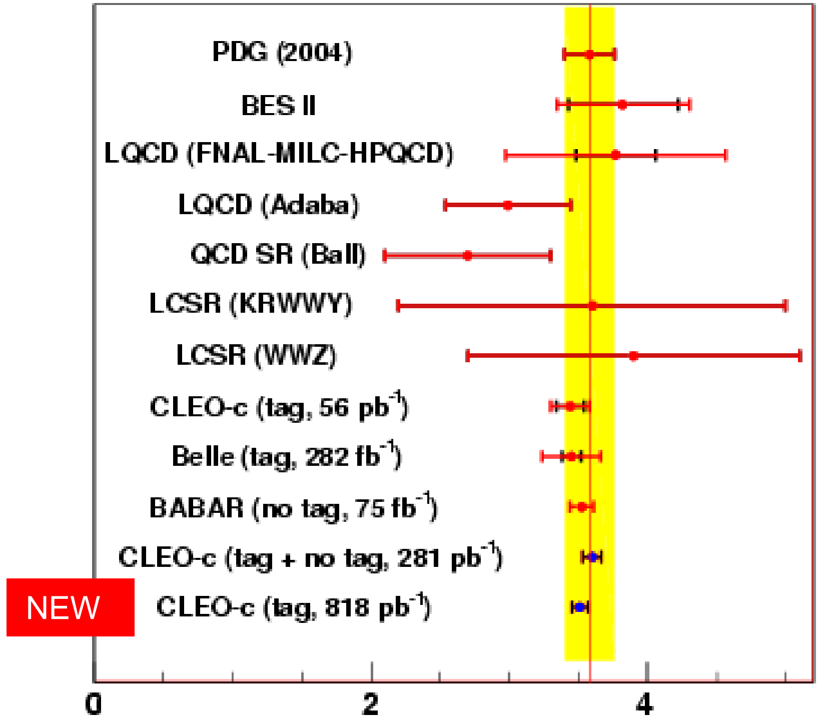
Experimentally measured decay rates $\Gamma_i^{measured}$

χ^2

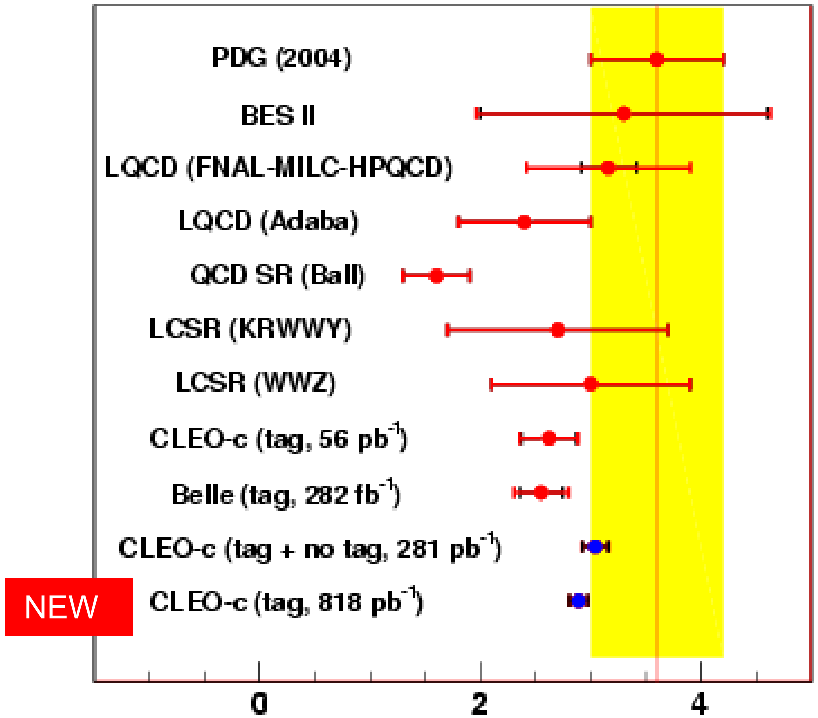
Theoretically predicted decay rates

$$\Gamma_i^{predicted} = \int_i d\Gamma = \frac{G_F^2 |V_{Qq'}|^2}{24\pi^3} \int_i |f_+(q^2)|^2 \; p_{P'}^3 dq^2$$

D→K/πe⁺ν Branching fractions



$B(D^0 \to K^- e^+ \nu) \times 10^{-2}$



$B(D^0 \to \pi^- e^+ \nu) \times 10^{-3}$

3.50(3)(4)%

(CLEO-c 818 pb^{-1})

$\sigma(B(Ke\nu))/B(Ke\nu) \sim 1.4\%$

$\sigma(B(\pi e\nu))/B(\pi e\nu) \sim 3.0\%$

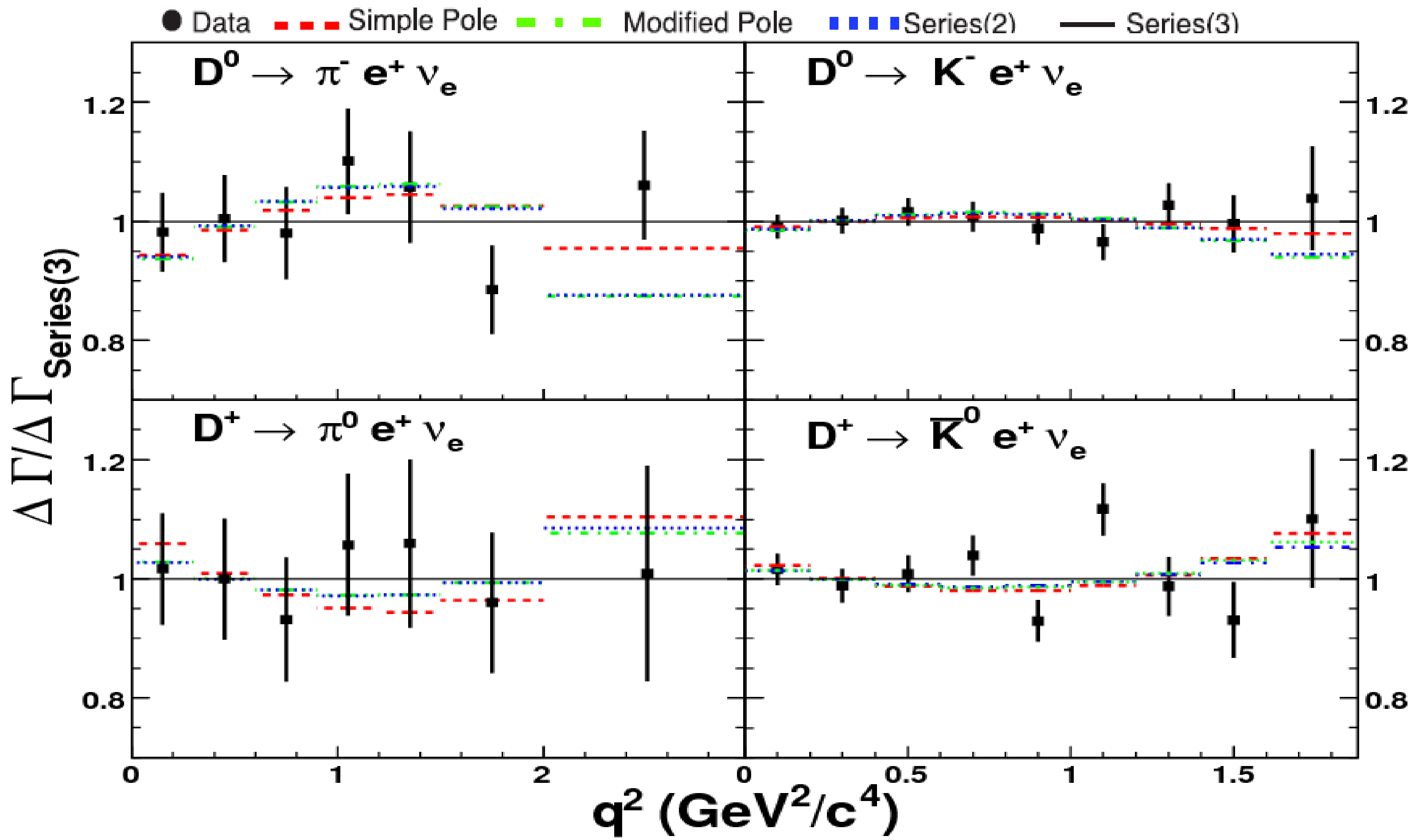
0.288(8)(3)%

(CLEO-c 818 pb^{-1})

Precision measurements from BABAR/Belle/CLEO-c.

CLEO-c most precise. Theoretical precision lags experiment.

D→ P e ν, which parameterization to choose?



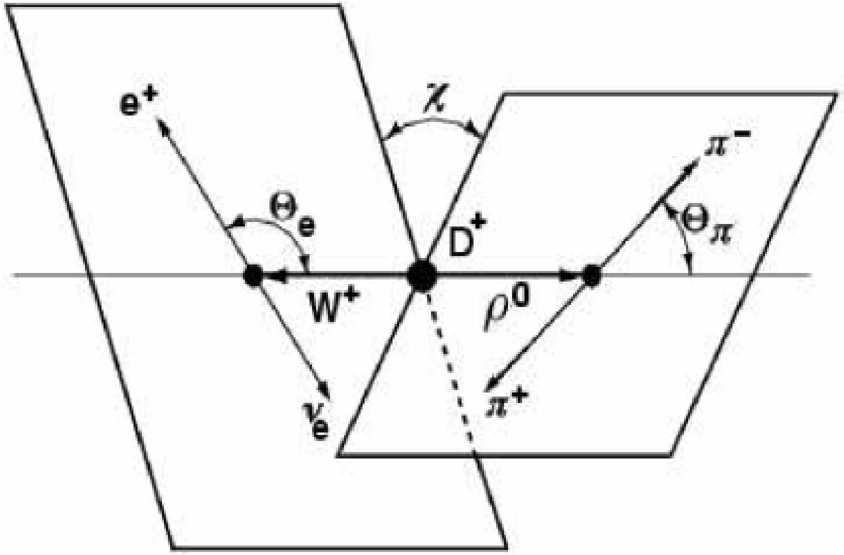
When the shape parameters are not fixed, each parameterization is able to describe the data with a comparable χ^2 probability.

As data do not support the physical basis for the pole & modified pole models, the model independent Becher-Hill series parameterization is used for $|V_{cx}|$.

D → ρeν: Kinematic Variables

- Five kinematic variables describe the decay rate (plot):

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



- The decay rate we make a fit to:

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

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

$D \to \rho e \nu$: Form Factor Ratios R_V and R_2

- The helicity amplitudes are given by

$$H_\pm(q^2, m_{\pi\pi}) = (M_D + m_{\pi\pi})A_1(q^2) \mp 2\frac{M_D P_{\pi\pi}}{M_D + m_{\pi\pi}} V(q^2);$$

$$H_0(q^2, m_{\pi\pi}) = \frac{1}{2m_{\pi\pi}\sqrt{q^2}}\left[(M_D^2 - m_{\pi\pi}^2 - q^2)(M_D + m_{\pi\pi})A_1(q^2) - 4\frac{M_D^2 P_{\pi\pi}^2}{M_D + m_{\pi\pi}} A_2(q^2)\right]$$

- Form factors are parameterized using the simple pole model (*i.e.*, vector dominance):

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

- We make a 4D fit to the decay rate for form factor ratios R_V and R_2:

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

- We make a fit (Fit B) described in *Nucl. Instr. and Meth.* **A328**, 547 (1993): a multidimensional fit to variables modified by experimental acceptance and resolution taking into account correlations among them