Status and future perspectives on V_{cs} and V_{cd}

Marina Artuso
Syracuse University

Motivation: unitarity constraints

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 1-\frac{1}{2}l^2 & l & Al^3\left(r-ih\left(1-\frac{1}{2}l^2\right)\right) \\ -l & 1-\frac{1}{2}l^2-ihA^2l^4 & Al^2\left(1+ihl^2\right) \\ Al^2\left(1-r-ih\right) & -Al^2 & 1 \end{pmatrix}$$

weak eigenstates ↑ $\quad$ ↑ V_{CKM} $\quad$ ↑ mass eigenstates $\quad$ Wolfenstein parameterization

To λ^3 in real part & λ^5 in im. part

- CKM unitary → described by 4 parameters (3 real, 1 imaginary: e.g. A,λ,ρ,η), but each quark mixing is in principle measurable → highly constrained system

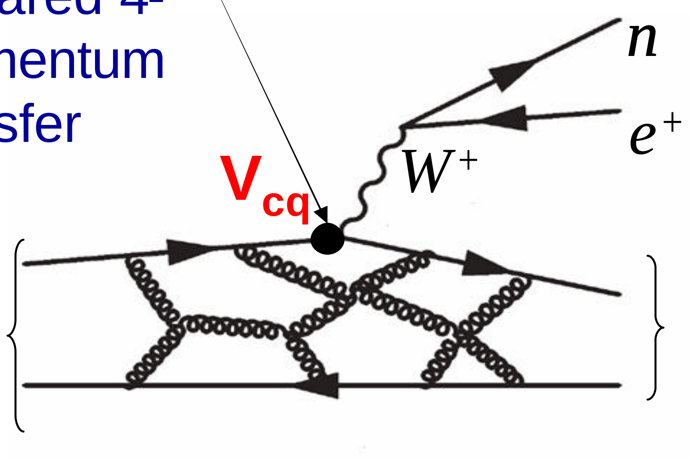
- This talk focuses on unitary test on the second row

V_{cs} and V_{cd} from charm semileptonic decays

In D rest frame

$$q^2 = m_D^2 + m_{K(p)}^2 - 2m_D E_{K(p)}$$

Squared 4-momentum transfer



- Received a lot of attention in recent years because of developments in lattice QCD (see R. Van de Water presentation)
- Pseudoscalar hadronic final states preferred because they are stable to strong decay

•We measure:

$$\frac{d\Gamma\left(D^+ \rightarrow Xen\right)}{dq^2} = \frac{G_F^2}{24p^3} P_X^3 \left| f_+(q^2) \right|^2$$

Theory input

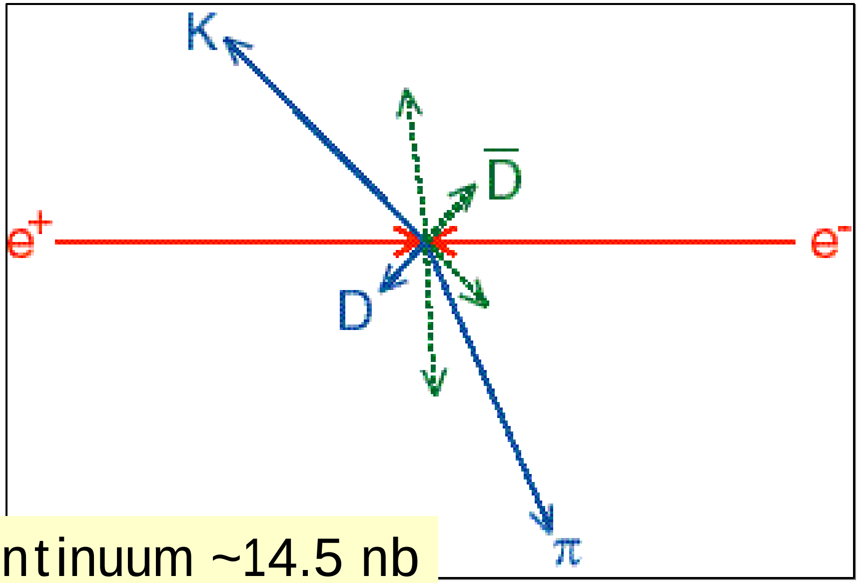
Two approaches

- Assuming V_{cs} and V_{cd} known (Stone's talk)
  - $D\to K(K^*)\ell\nu$, $D\to\pi\ell\nu$ determine form factor shapes & distinguish among models + test lattice QCD predictions (see S. Stone talk, WG2/3 joint session)
    - Note that lattice checks comparing semileptonic ff & f_D can be done independently of knowledge of CKM parameters
- Assuming lattice predictions OK (this talk)
  - measurements of V_{cd} & V_{cs}

Experimental methods

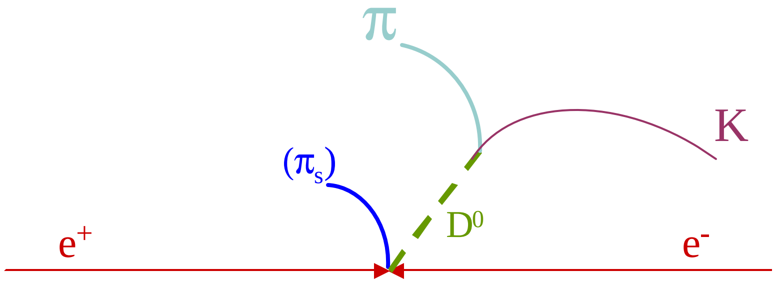
- $D\bar{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
  - Unique event properties
    - ➢ Only $D\bar{D}$ not $D\bar{D}x$ produced
  - Large cross sections:

$\sigma(D^0\bar{D}^0)$ = 3.72±0.09 nb
$\sigma(D^+D^-)$ = 2.82±0.09 nb
} World Ave



Continuum ~14.5 nb

  - Ease of B measurements using "double tags"
- B-factories (e^+e^-) + fixed target & collider experiments at hadron machines
  - D displaced vertex
  - $D^{*+} \rightarrow \pi^+ D^0$ tag



Theoretical Tools

- Lattice QCD
  - Theory (unquenched QCD), still has moderate systematic errors; however theoretical accuracy can be improved in a controlled fashion.
- QCD Sum Rules
  1. **Equating phenomenological and theoretical spectral functions;**
  2. **Determination of theoretical spectral functions by calculating two or three-point correlators in perturbative QCD, including corrections from the OPE**

  Many parameters, difficult to improve their accuracy in a systematic fashion.

- Phenomenological models
  - Important contributions to our understanding of charm decays
  - No way to improve these predictions in any systematic way

Lattice results for $D \to K(\pi)\, e\, \nu_e$ semileptonic decays

- two form factors are needed to describe the vector current matrix element $\langle P|V_\mu|D\rangle$: $f_+(q^2)$ and $f_0(q^2)$, (only $f_+(q^2)$ needed if m_l negligible)
- Lattice QCD calculates both f_+ and f_0, since they can be fit simultaneously imposing the constraint $f_+(0)= f_0(0)$
- Fermilab-MILC-HPQCD reported results using 2+1 flavors of improved staggered quark to implement non-quenched f.f. calculation
- Dominant systematic error from heavy quark discretization (7% of the overall 10% uncertainty)

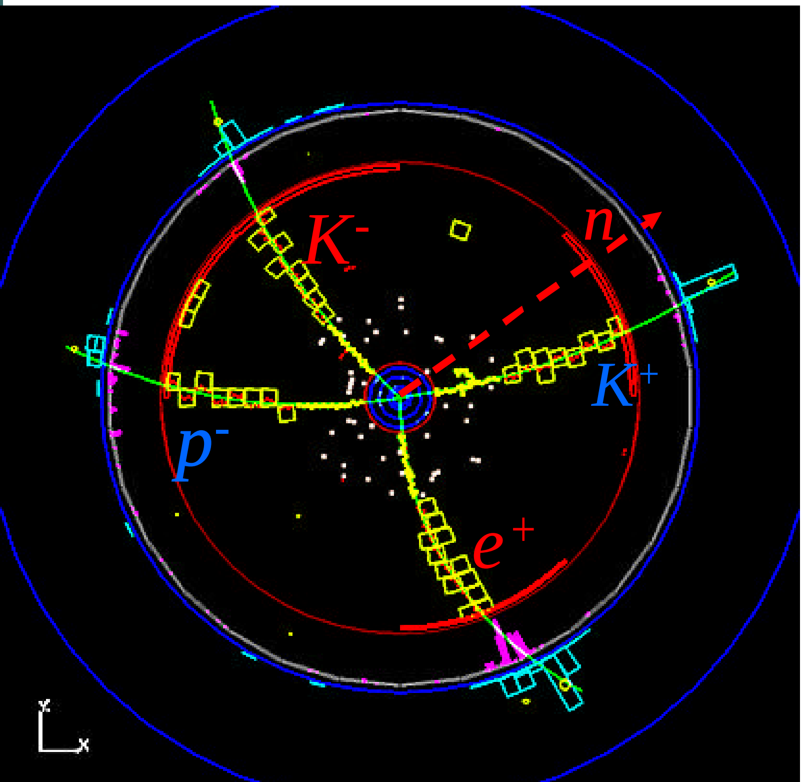
A snapshot of theoretical predictions

- Other predictions are available from quenched lattice QCD calculations, QCD sum rules and form factor models

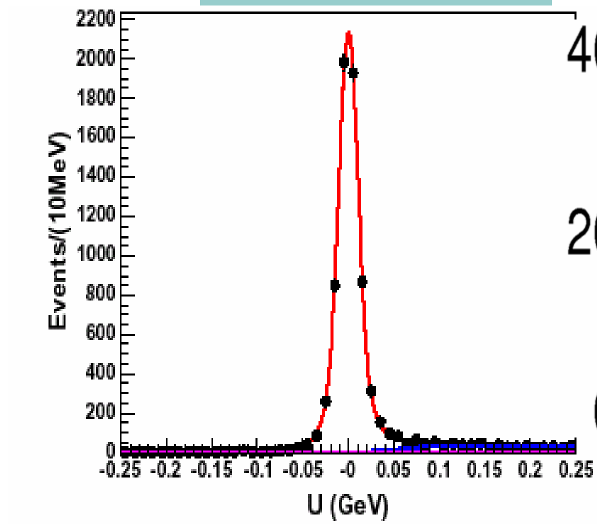
	$f_+(0)[D\to K]$	$f_+(0)[D\to \pi]$	Ref.
N_f=2+1	0.73(3)(7)	0.64(3)(6)	Aubin et al., PRL94, 011601 (2005)
N_f=0	0.71(8)	0.62(7)	Average reported in hep-ph/0512039
QCD sum rules	0.79(14)(8)	0.61(11)	Khodjamirian, hep-ph/0306253 with updated inputs

CLEO-c results – tagged analysis

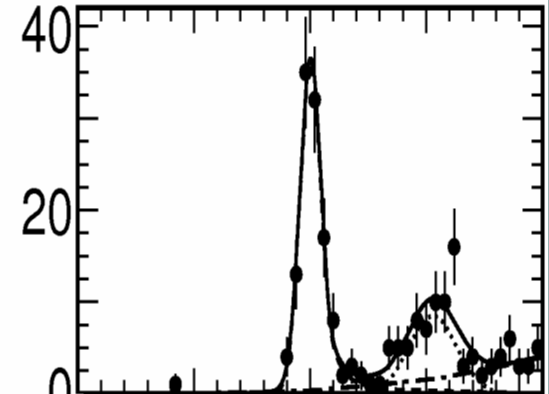
281 pb^{-1} ~310K D^+ ~160K D^0



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



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



Signal events:
U = E_{miss} – $|P_{miss}|$ = 0

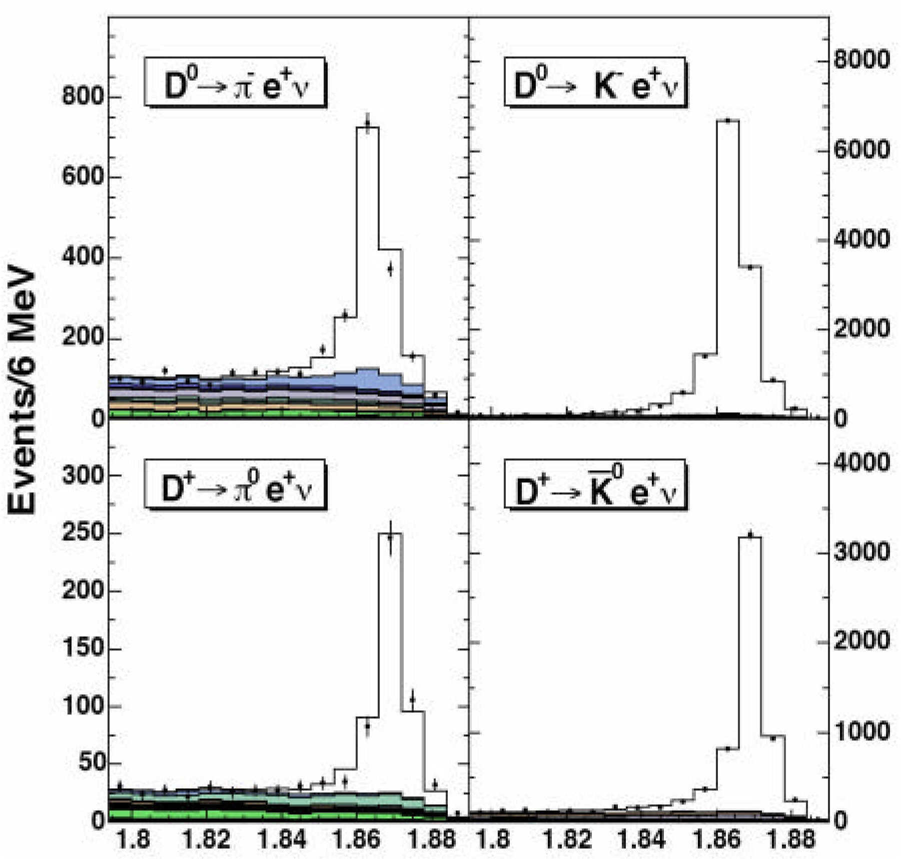
$\psi(3770) \to \bar{D}^0 D^0$

$\bar{D}^0 \to K^+ \pi^-$ ← Tag allows to determine signal D^0 momentum

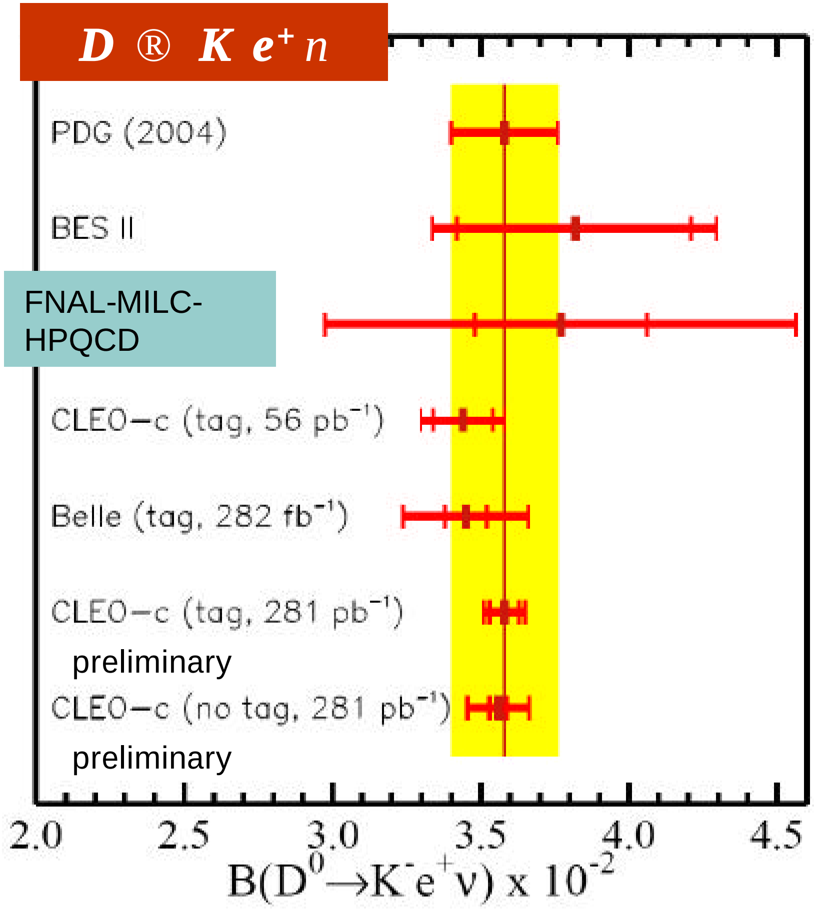
$D^0 \to K^- e^+ \nu_e$ ← Signal semileptonic decay

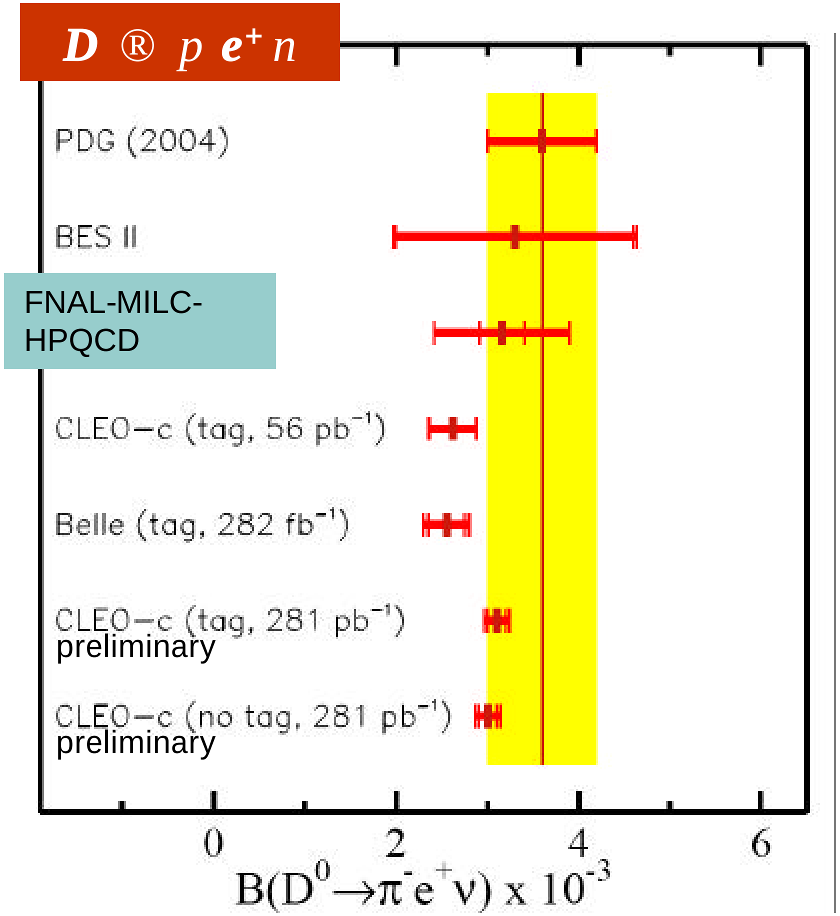
CLEO-c results untagged analysis

- Unspecified other side D decay, collect other showers and tracks
- Use neutrino reconstruction like $B \to \pi/\rho\ l\nu$
- Higher statistical accuracy, worse systematic error
- Samples overlap



D →K, π eν Branching Fractions





FNAL-MILC-HPQCD precision lags experiment.

Form-Factor Parameterizations

- In general

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

- Modified Pole

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

- Series Expansion

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

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

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

Form factor data and FNAL-MILC-HPQCD predictions

- FNAL-MILC-HPQCD calculation uses modified pole model to fit for form factor from “measured”points [PRL 94, 011601 (2005)]
- FF predictions:
  - $D \to K e \nu$

$f_+(0)=0.73\pm0.03\pm0.07$

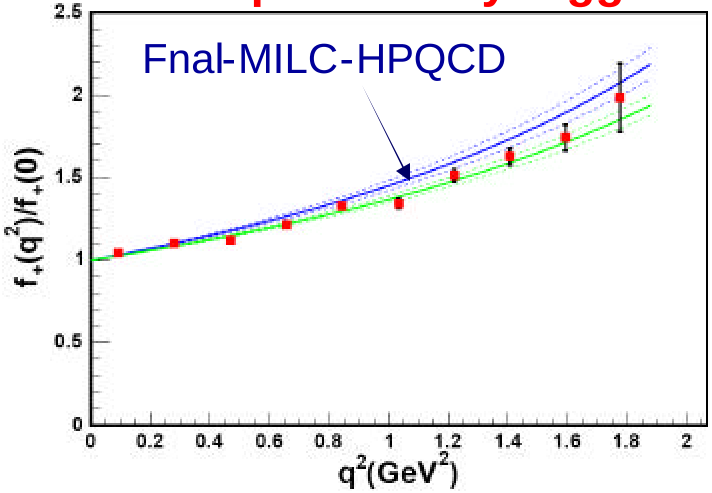
$\alpha=0.50\pm0.04\pm0.07$

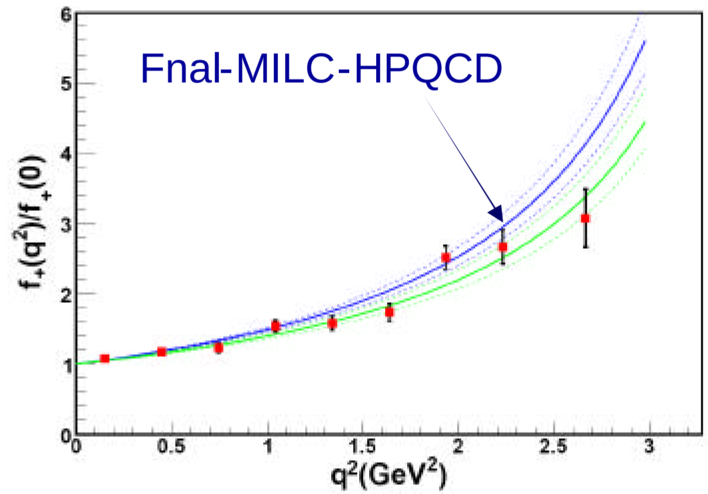
  - $D \to \pi e \nu$

$f_+(0)=0.64\pm0.03\pm0.06$

$\alpha=0.44\pm0.04\pm0.07$

CLEO-c preliminary-tagged

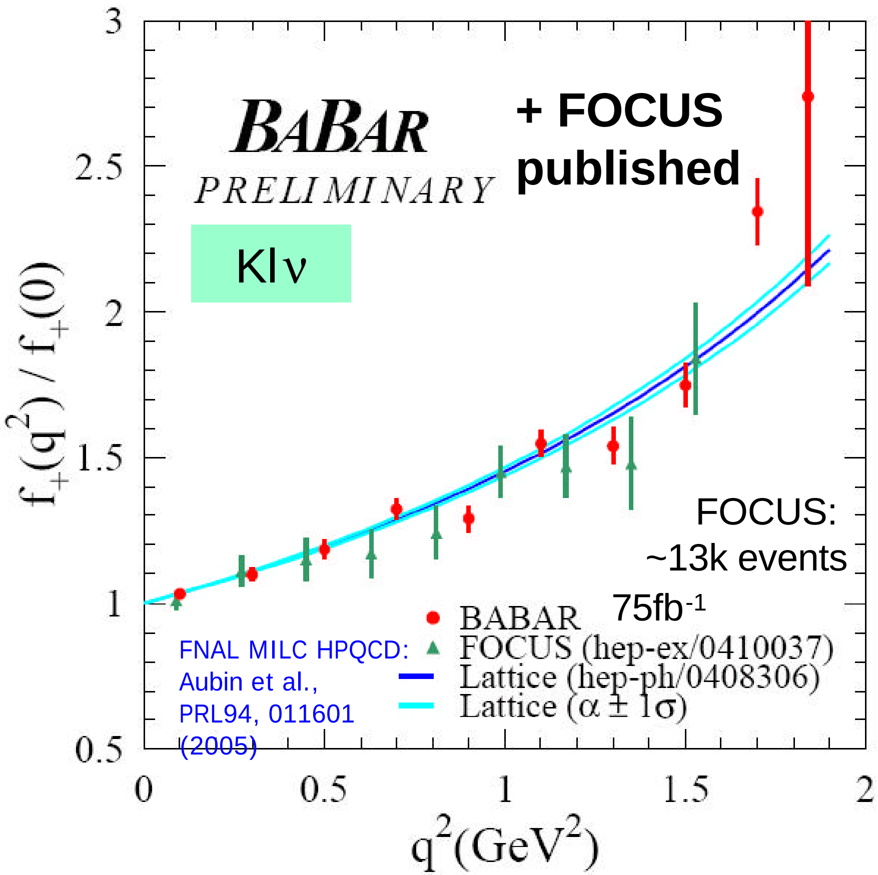


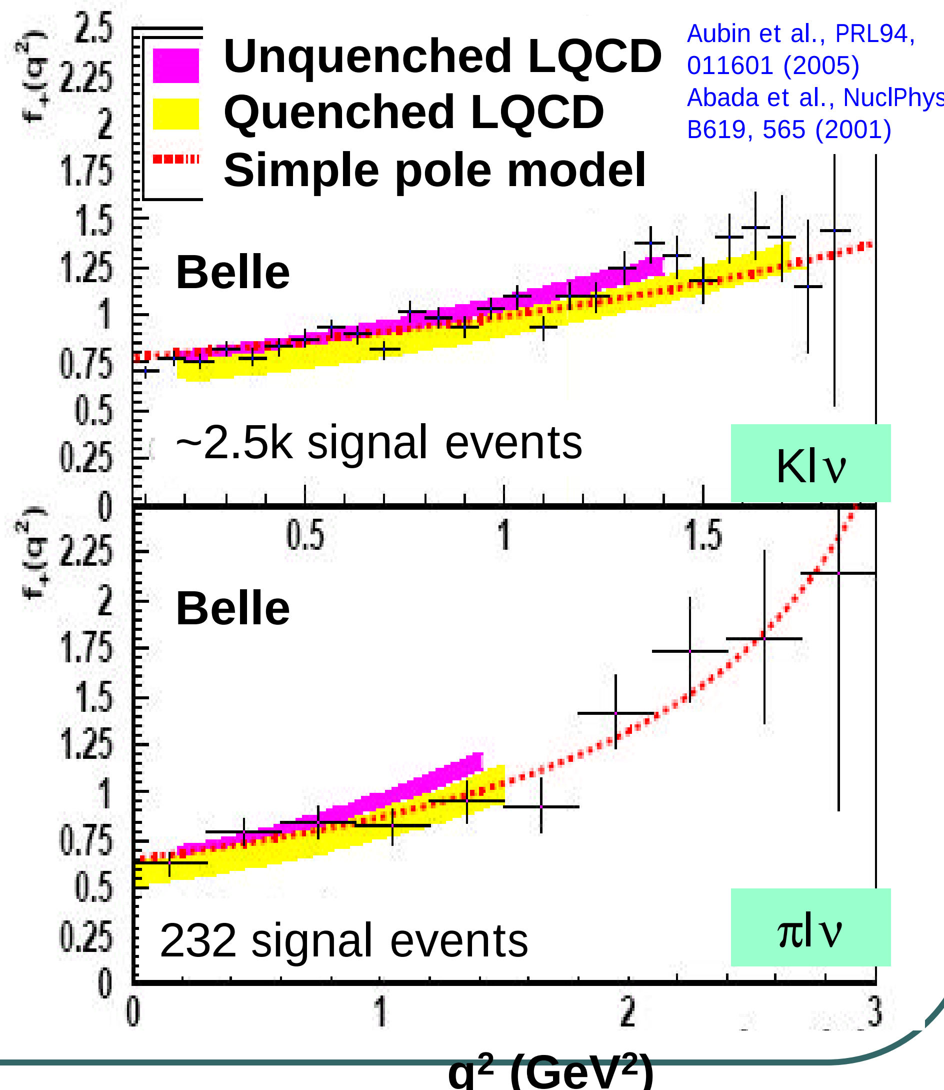


Belle,BaBar,FOCUS
D → K,πl ν
form factors
data

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

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

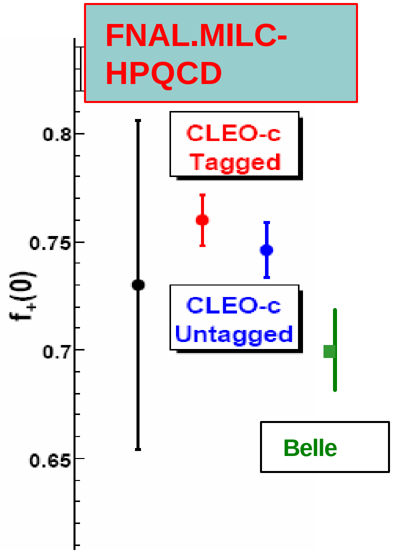




Summary of lattice-experiment comparison

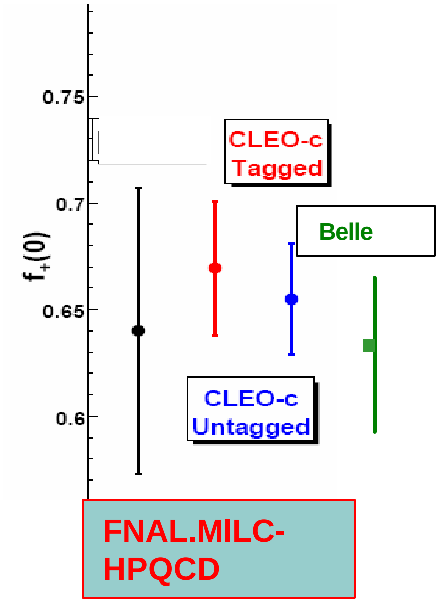
$D^0 \to K^- e^+ \nu_\varepsilon$

Assuming V_{cs}=0.9745



D0 $\to \pi^- e^+ \nu_e$

Assuming V_{cd}=0.2238



Using semileptonic width and form factors

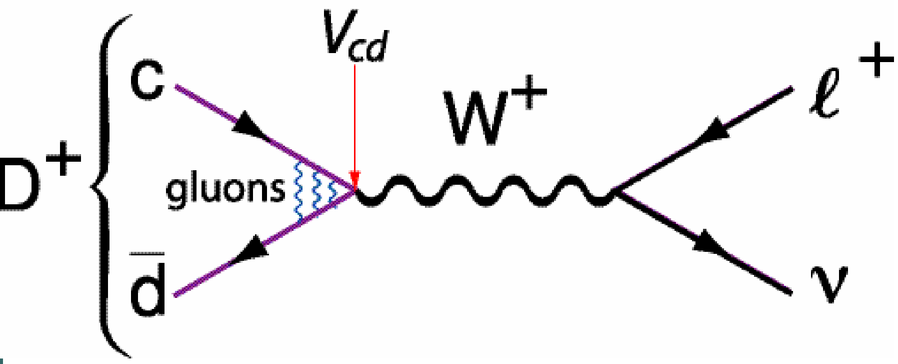
- Using the preliminary CLEO-c semileptonic widths $\Gamma(D\to Ke\nu_e)$ =(8.7±0.16) x10^{-2} ps^{-1} and $\Gamma(D\to\pi e\nu_e)$= (0.76 ±0.03)x10^{-2} ps^{-1} and FNAL-MILC-HRQCD $\Gamma(D\to Ke\nu_e)/|V_{cs}|^2$ and $\Gamma(D\to\pi e\nu_e)/|V_{cd}|^2$
  - V_{cs}=0.966 ± 0.008 [exp] ± 0.093 [th]
  - V_{cd}=0.225 ± 0.004 [exp] ± 0.022 [th]
- Relies on correct shape and normalization of the form factors

CLEO-c untagged form factor analysis

Combine measured $|Vcx|f_+(0)$ with FNAL-MILC-HPQCD value for $f_+(0)$PRL **94**, 011601 (2005)

Decay Mode	$\lvert V_{cx}\rvert$ c (*stat*) ± (*sys*) ± (*theory*)	PDG06 Value
$D^0 \rightarrow K^{\pm}en$	1.006 ± 0.007 ± 0.013 ± 0.103	0.957 ± 0.017 ± 0.093 (charm exclusive sl width, smaller data sample)
$D^0 \rightarrow p^{\pm}en$	0.221 ± 0.013 ± 0.004 ± 0.028	0.230 ± 0.011 ($\nu-\bar{\nu}$ interactions, later)
$D^{\pm} \rightarrow K^0en$	0.984 ± 0.042 ± 0.017 ± 0.101	0.957 ± 0.017 ± 0.093
$D^{\pm} \rightarrow p^0en$	0.235 ± 0.016 ± 0.006 ± 0.029	0.230 ± 0.011

A check on the theory



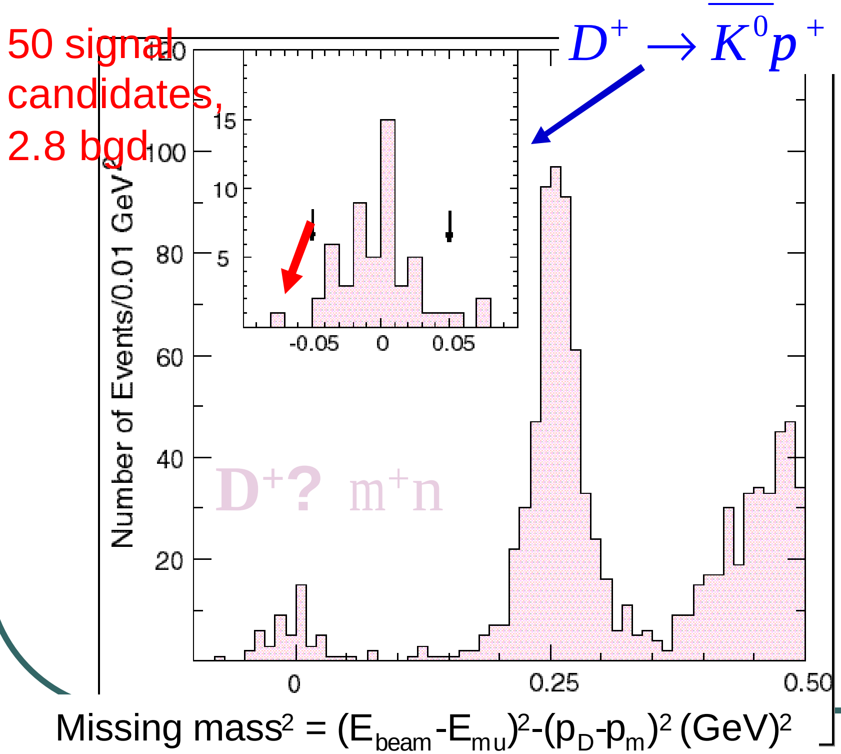
CLEO-c results based on 281 pb^{-1} (tagged)

BR(D → μν)=$(4.4\pm0.7\pm0.1)\times10^{-4}$

BR(D → eν) <2.4×10^{-5}

BR(D → tν) <3.1×10^{-3}

(more details on Stone's talk)



Ratio $$\frac{\Gamma(D \to mn)}{\Gamma(D \to p\, en)}$$

does not depend upon V_{cd}

Comparison with FNAL-MILC-HPQCD predictions

$$R_{\ell sl} \equiv \sqrt{\frac{\Gamma(D^{+} \to m u)}{\Gamma(D \to p \, \ell u)}} \propto \frac{f_D}{f_{+}^{p}(0)}$$

- .

$$R_{\ell sl}^{th} = 0.212 \pm 0.028$$

$$R_{\ell sl}^{\exp} = 0.236 \pm 0.019$$

Data and theory are consistent within error

W branching ratios and V_{cs}

- LEP-2 performed measurements sensitive to $|V_{cs}|$ from on-shell $W^{\pm}$ decays:

$$\frac{1}{B(W \to \ell \bar{\nu}_{\ell})} = 3[1 + \Sigma_{u,c,d,s,b} |V_{ij}|^2 (1 + \frac{\alpha_s(m_W)}{\pi})$$

$$B(W \to \ell \bar{\nu}_{\ell}) = (10.84 \pm 0.06 \pm 0.07)\%$$

- Using:

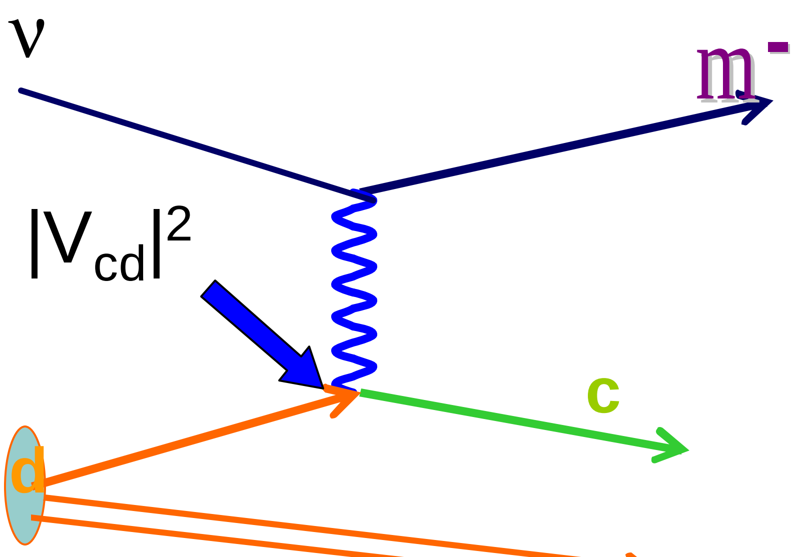
$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2+|V_{cd}|^2+ |V_{cb}|^2=1.0476 \pm 0.0074$

$|V_{cs}| = 0.976 \pm 0.014$

- Error includes contributions from uncertainties on α_s and other CKM parameters, but is dominated by ±0.013 from the measurements of the W branching fractions
- DELPHI tagged $W^+ \to c\bar{s}$ analysis $|V_{cs}| = 0.94^{+0.32}_{-0.26} \pm 0.014$

Neutrino/anti-neutrino interactions and V_{cd}

- Method: $\nu + d \rightarrow c + \mu \propto |V_{cd}|^2 B_\mu$ [average semileptonic branching ratio of charm]



$<|Vcd|^2 B_\mu> = (0.463 \pm 0.034) \times 10^{-2}$

$B_\mu = 0.0873 \pm 0.0052$

[pdg 2006]

$|V_{cd}| = 0.230 \pm 0.011$
(5% accuracy)

Summary

- Best V_{cs} direct determination, using $\Gamma_{exp}(Ke\nu)$ and lattice form factors:

$$|V_{cs}| = 0.966 \pm 0.008_{\exp} \pm 0.093_{th}$$

$$|V_{cs}| = 1.014 \pm 0.013 \pm 0.009 \pm 0.106$$ ← Tagged fit

$$|V_{cs}| = 0.996 \pm 0.008 \pm 0.015 \pm 0.104$$ ← Untagged fit

- Best V_{cd} direct determination from $\nu,\bar{\nu}$ interactions

$$|V_{cd}| = 0.230 \pm 0.011$$

- With these inputs and $|V_{cb}|=(41.6\pm0.6)\times10^{-3}$ [pdg 2006] unitarity constraint on the 2nd row gives:

$$\Delta = 1 - (|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2) = 0.012 \pm 0.18$$

Error dominated by theoretical uncertainty in $|V_{cs}|$

Future prospects

- CLEO-c expects to accumulate 750 pb^{-1} at the $\psi(3770) \rightarrow$ increased statistics will allow to pin down shape of form factors and constrain theoretical calculations
- Further refinements of lattice calculations (now dominating errors) are under way
  - → Goal to determine $|V_{cs}|$ and $|V_{cd}|$ down to a few % accuracy