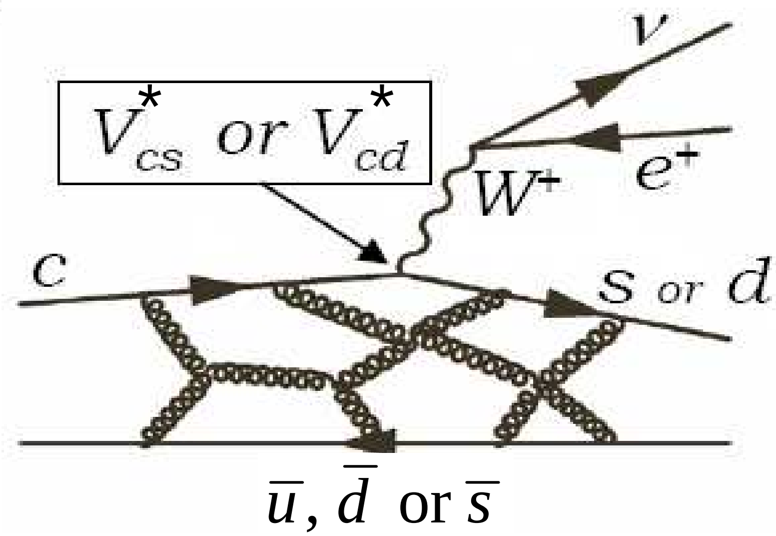
Semileptonic Decays with CLEO-c

charm

Beauty 2009
07-11 September 2009



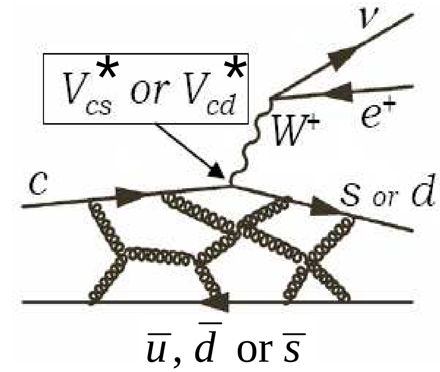
- Introduction
- Analysis techniques
- *D* and D_s Semileptonic:
  Branching fractions
  Semileptonic form factors
  CKM ($|V_{cs}|$, $|V_{cd}|$ and more)
- Summary and prospects

Presented by Patrick Spradlin
University of Oxford
On behalf of the CLEO collaboration

Slides kindly provided by Bo Xin and Ian Shipsey

Importance of Charm Semileptonic Decays

- Golden P→P transitions:



Weak Physics

QCD Physics

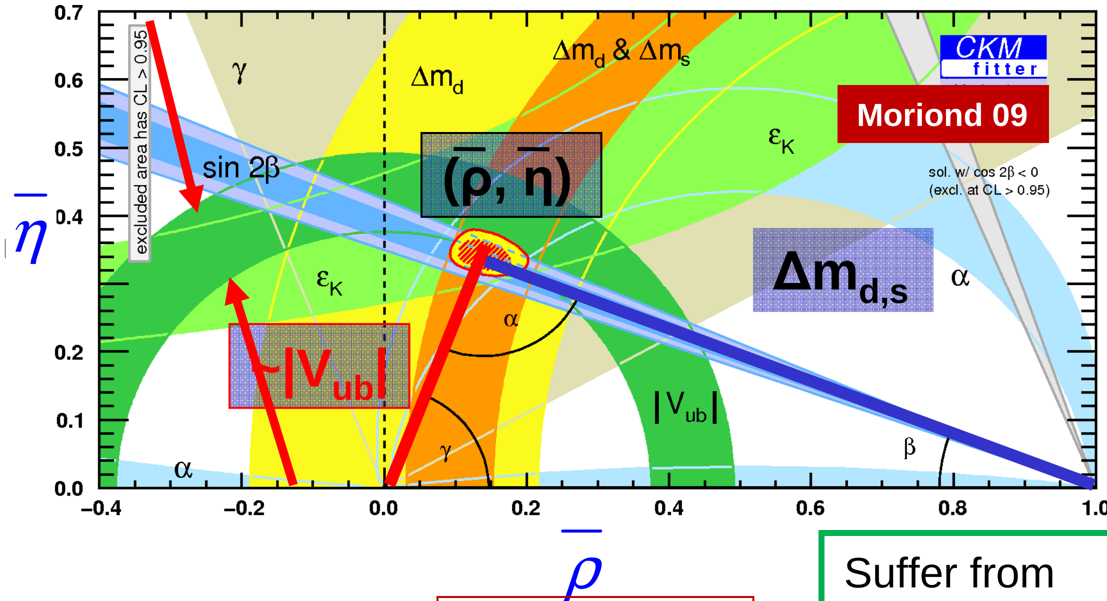
$$\frac{d\Gamma(D\rightarrow K(\pi)e\nu)}{dq^2}=\frac{G_F^2\left|V_{cs(cd)}\right|^2 P_{K(\pi)}^3}{24\pi^3}\left|f_+(q^2)\right|^2, where \quad q^2\equiv M_{e\nu}^2$$

  - ✓ 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 $|V_{ub}|$.

- 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



The discovery potential of B physics is limited by systematic errors from QCD (PDG-08):

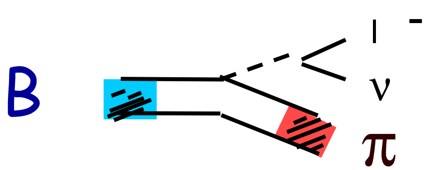
$$|V_{ub}| = (3.62 \pm 0.22 \pm^{+0.63}_{-0.41}) \times 10^{-3}$$

$$\pm \exp \pm \text{LQCD}$$

One of the most important goals of B physics

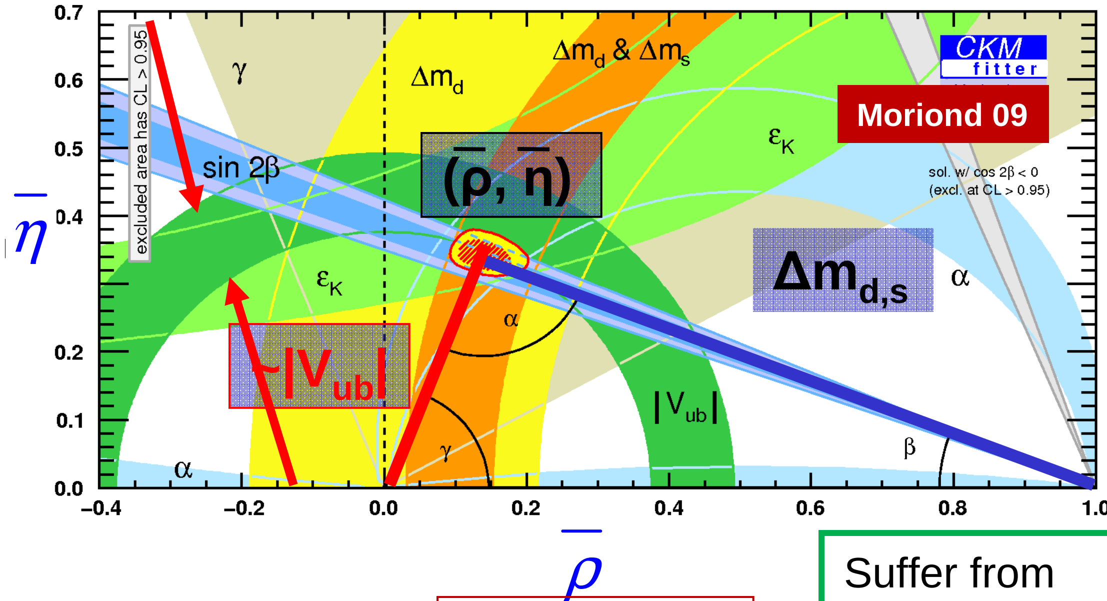
Measured experimentally

Suffer from large theory uncertainty



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

Theory + Experiment = Precision Flavor Physics



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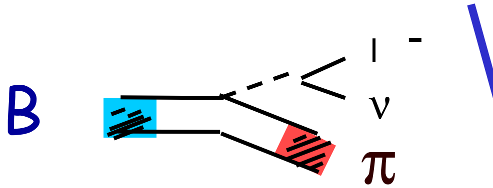
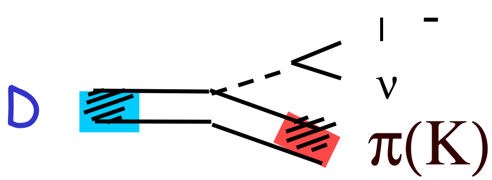


$$rate \propto [f^{B\to\pi}(q^2)]^2 \, |V_{ub}|^2$$

HQS



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

Tightly constrained by CKM unitarity

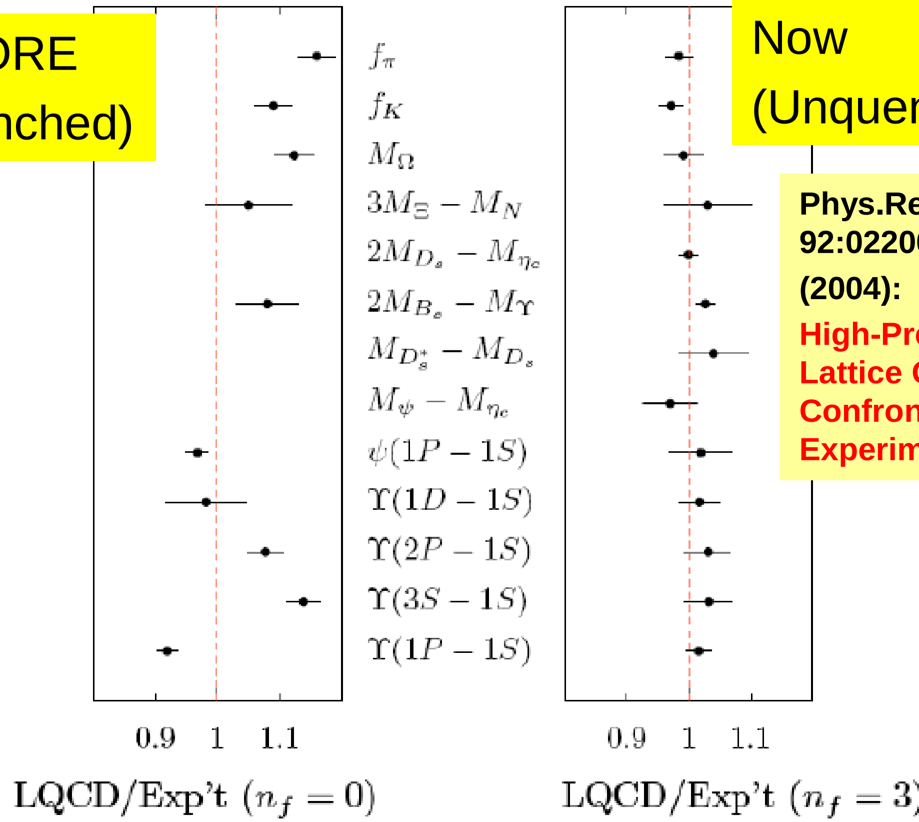
Theory: A Breakthrough in Lattice QCD

- Revolutionary progress (2003) in algorithms allows inclusion of QCD vacuum polarization.
- LQCD demonstrated it can reproduce a wide range of mass differences and decay constants.

These were postdictions

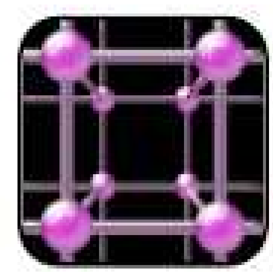
BEFORE (Quenched)

Now (Unquenched)



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

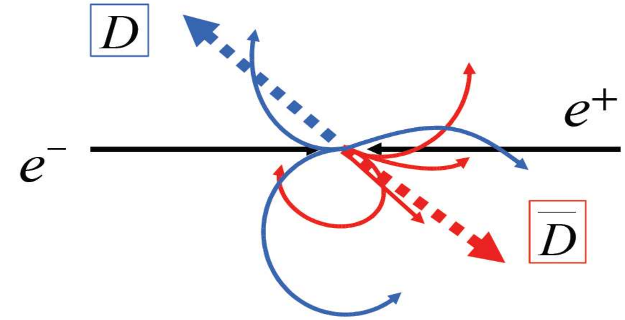
- This dramatic improvement needs validation
- *Charm* decay constants f_{D+} & f_{Ds}
- *Charm* semileptonic Form factors



Tagged Analysis Technique at 3770 MeV

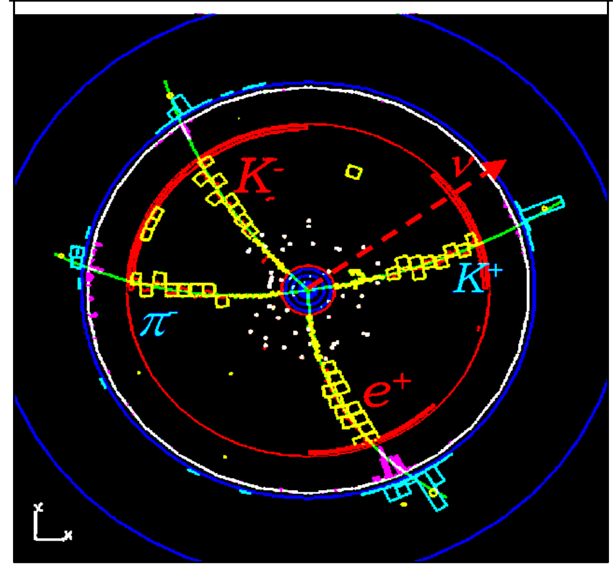
- Candidate events are selected by reconstructing a D, called a tag, in several hadronic modes
- Then we reconstruct the semileptonic decay in the system recoiling from the tag
- Two key variables in the reconstruction of a tag: $\Delta E = E_D - E_{beam}$

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



$e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$

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



Tagging creates a single D beam of known 4-momentum

- For semileptonic *D* : $U = E_{miss} - |\vec{P}_{miss}|$

U peaks at zero for real semileptonic decays

An absolute measurement, independent of the integrated luminosity and number of D mesons in the data sample

D Tagging at 3770 MeV

World's largest data set at 3.770 GeV

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

818 pb^{-1} @3770 (full data set)

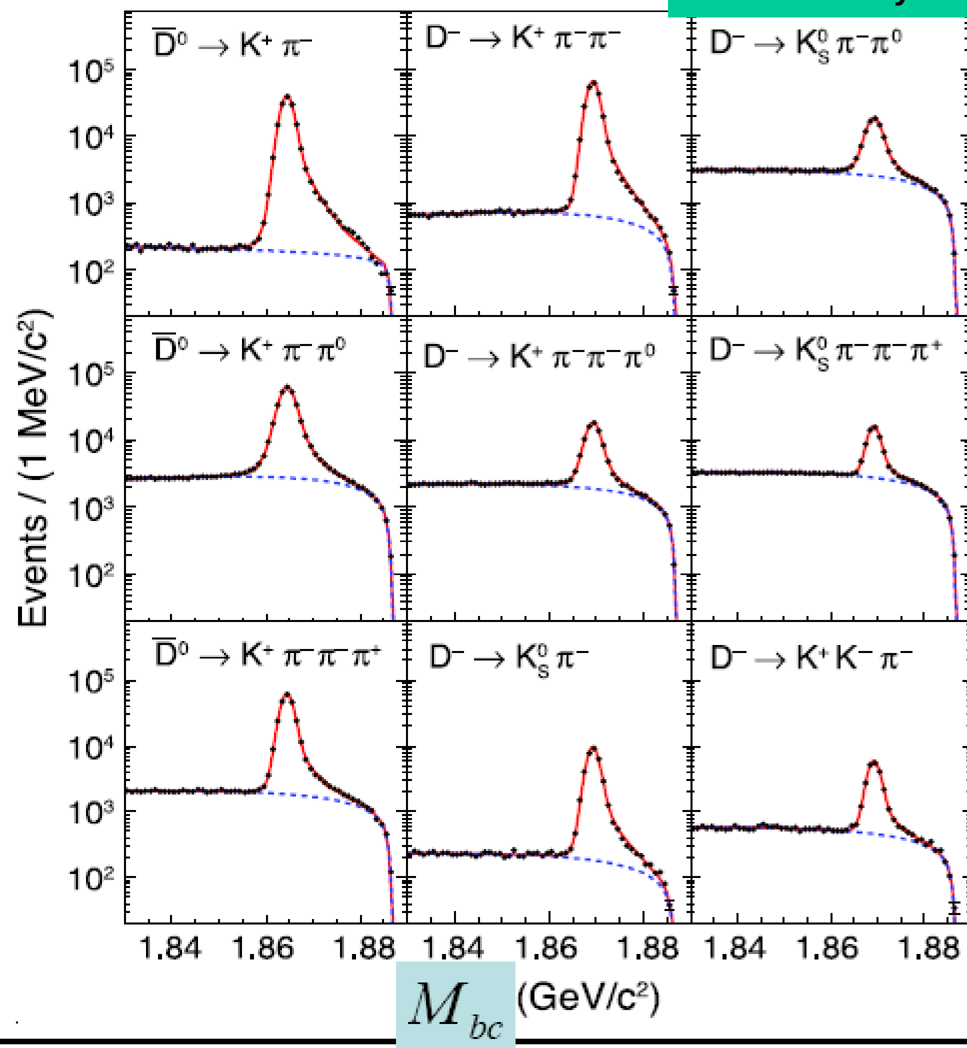
From the 818 pb^{-1}

D→K/πeν analysis

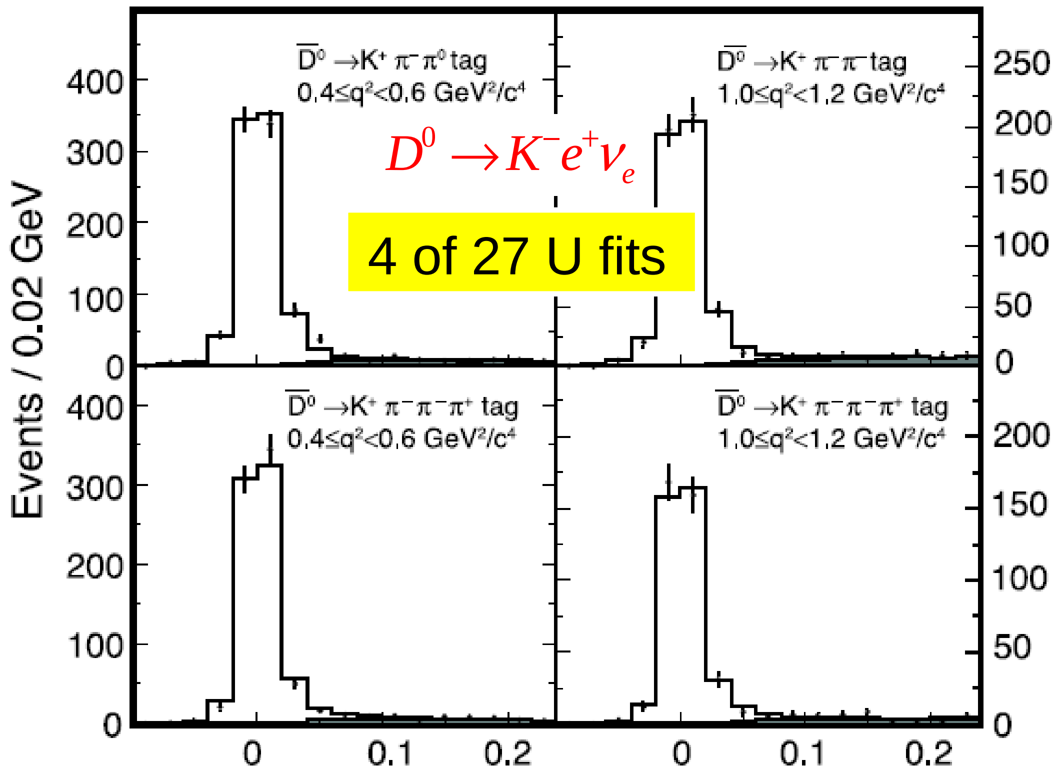
Pure $D\bar{D}$,
zero additional particles,
~5-6 charged particles per event

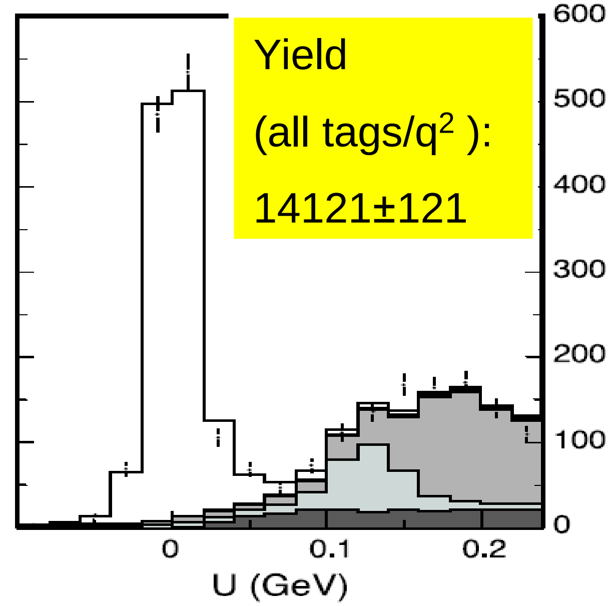
~6.6x 10^5 D^0 and ~4.8 x 10^5 D^+ tags reconstructed from ~5.4 x 10^6 DD events

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



Fits to the U Distributions for D→K⁻eν





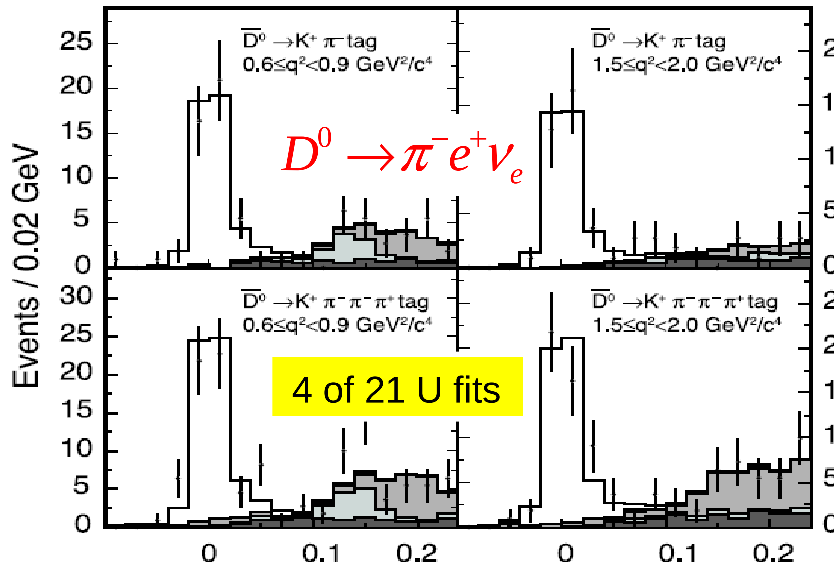
$U = E_{miss} - c|\vec{P}_{miss}|$ (GeV)

Comparisons with B factories follow

S/N	~300/1
Signal events	~14000
U resolution	~10 MeV
q^2 resolution	~0.008 GeV^2/c^4

- 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
- Background shapes are taken from MC with all $D\overline{D}$ and non-$D\overline{D}$ decays

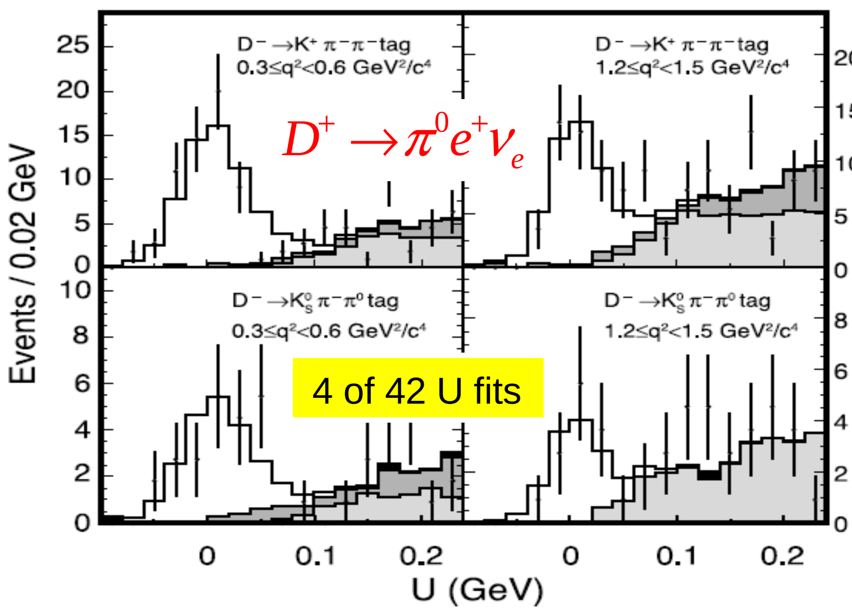
Fits to the U Distributions for $D \to \pi^- / \pi^0 / \bar{K}^0 e\nu$

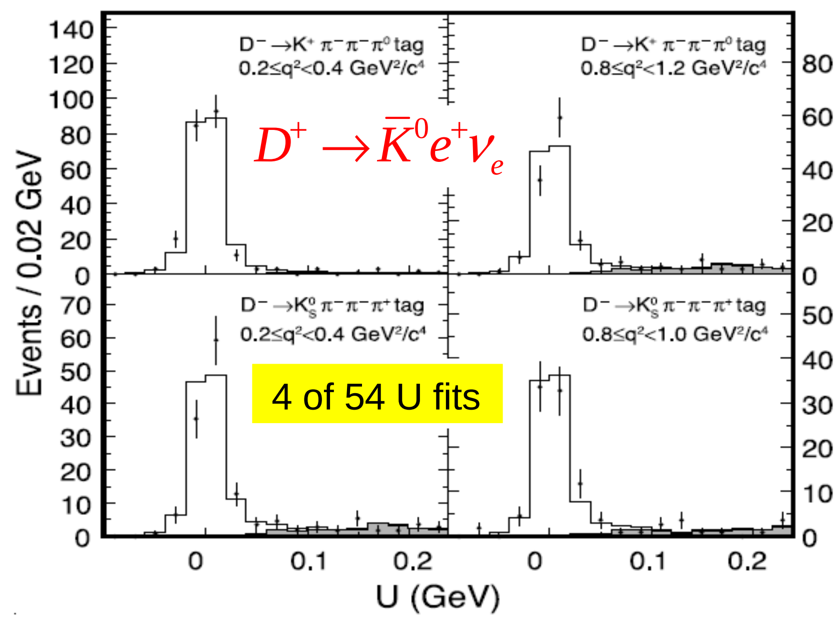


$D^0 \to \pi^- e^+ \nu_e$

S/N	~40/1
Signal events	~1400
U resolution	~10 MeV
q^2 resolution	~0.008 GeV^2/c^4

Comparisons with B factories on the next two slides





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 → $\phi(q^2)$

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

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

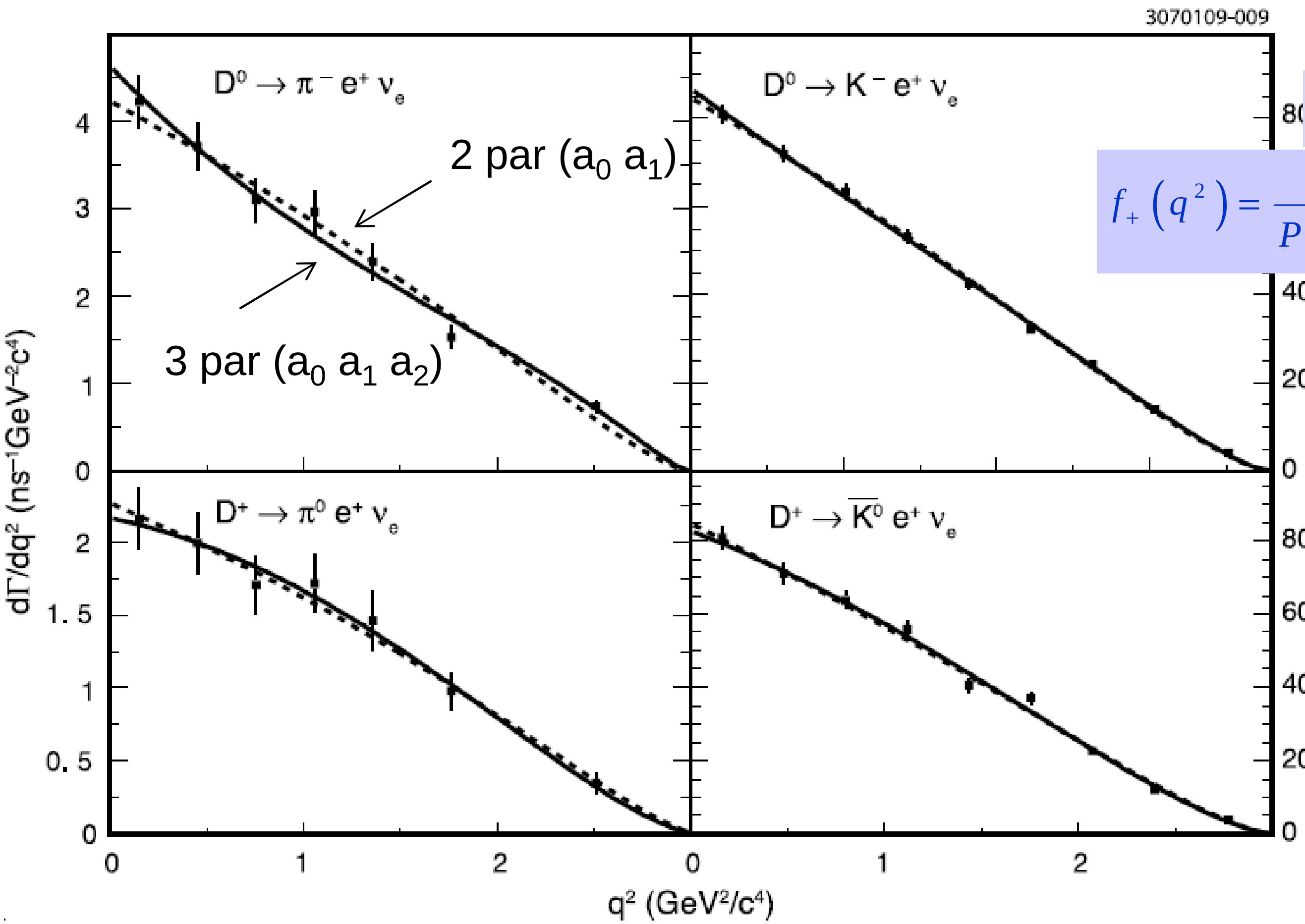
z is small and converges quickly, linear or quadratic is sufficient to describe the data

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

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

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

PRD 80, 032005 (2009)



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

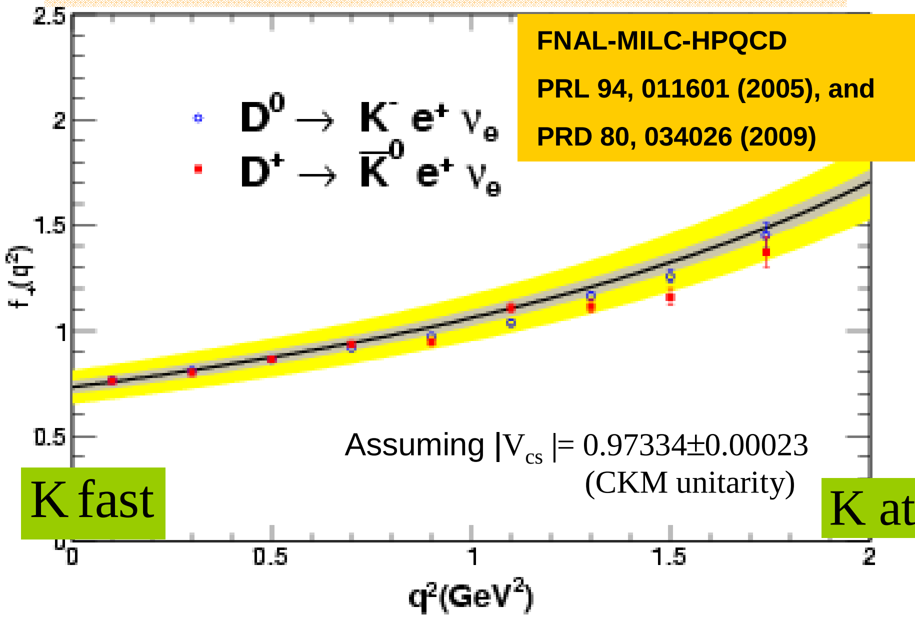
Theoretically predicted decay rates

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

D → K $e^+\nu$ Form Factor: Test of LQCD

Form factor measures probability hadron will be formed

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

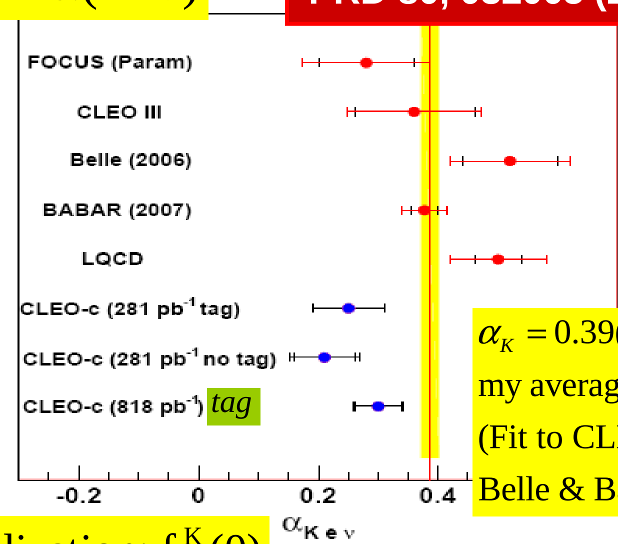


Modified pole model used to compare with LQCD

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

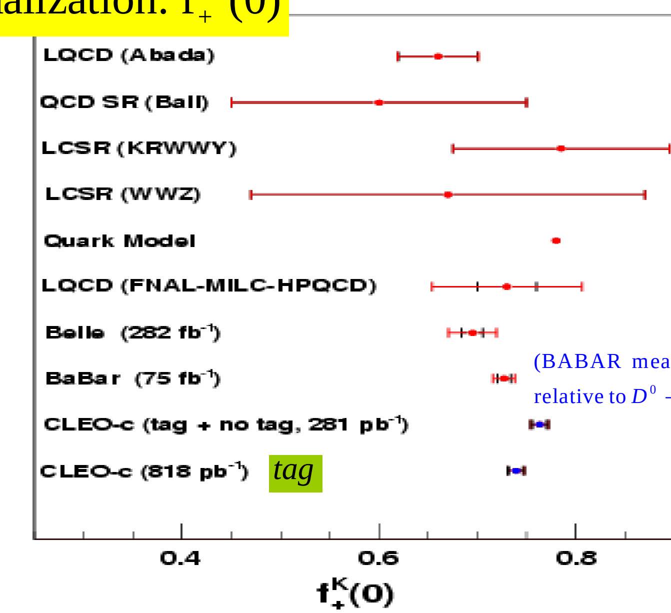
Shape: $\alpha(Ke\nu)$

PRD 80, 032005 (2009)



$\alpha_K = 0.39(2)$
my average
(Fit to CLEO, Belle & BaBar)

Normalization: $f_+^K(0)$



α : CLEO-c prefers smaller value for shape parameter than other experiments

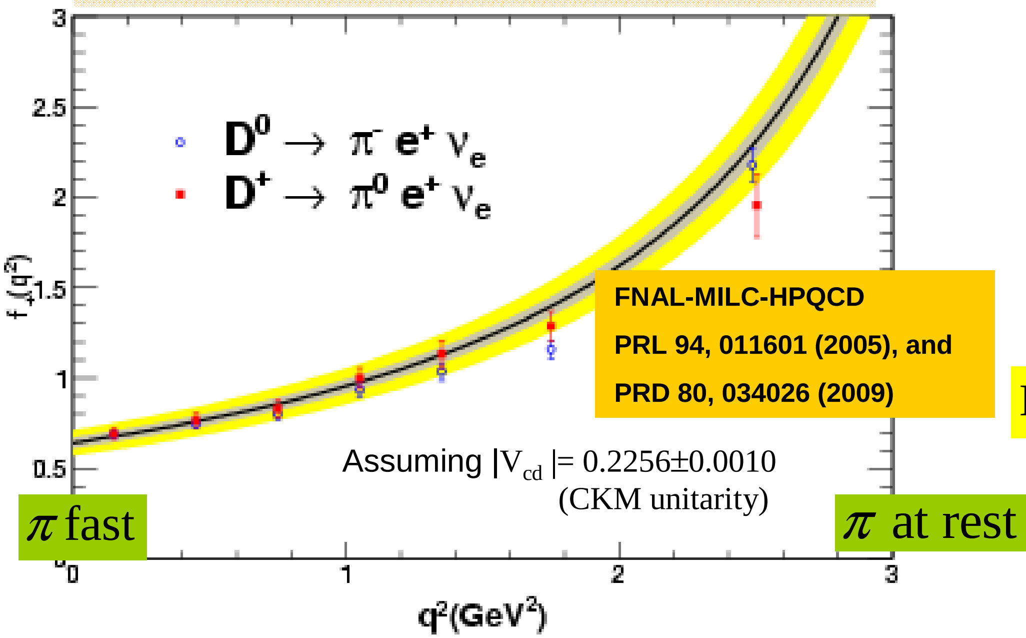
f_+ (0): experiments (1.2%) consistent with LQCD (10%)

CLEO-c is most precise. *Theoretical precision lags.*

D→πe⁺ν Form Factor: Test of LQCD

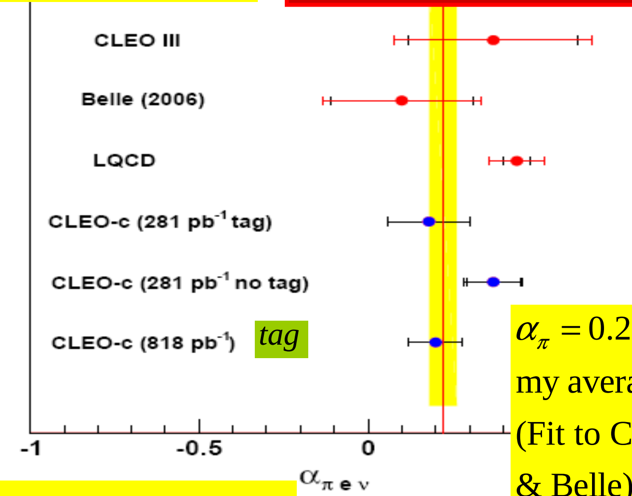
Form factor measures probability hadron will be formed

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



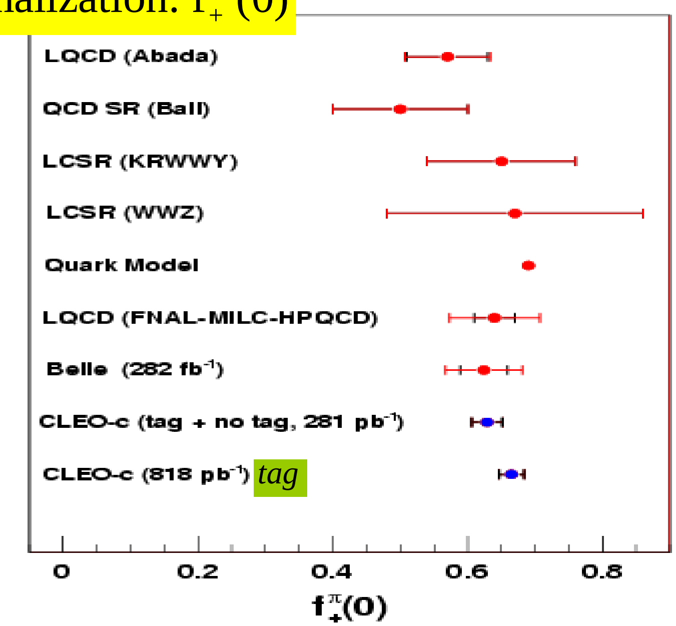
shape: $\alpha(\pi e\nu)$

PRD 80, 032005 (2009)



$\alpha_\pi = 0.22(4)$
my average
(Fit to CLEO & Belle)

Normalization: $f_+^\pi(0)$



Modified pole model used to compare with LQCD

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

α : CLEO-c measurements are compatible with LQCD
f_+ (0): experiments (2.9%) consistent with LQCD (10%).
CLEO-c is most precise. *Theoretical precision lags.*

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

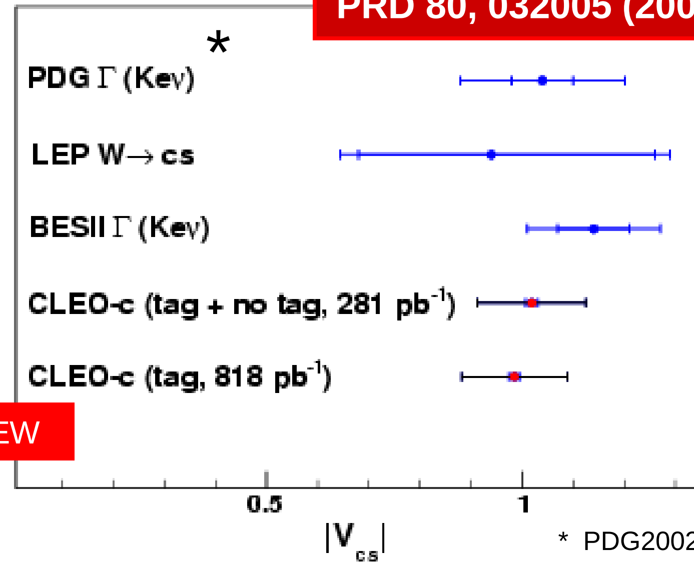
The data determine $|V_{cs(d)}|f_+(0)$.

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* $f_+(0)$

PRD 80, 032005 (2009)

CLEO-c: the most precise *direct* determination of $|V_{cs}|$ $\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 10\%(\text{theory})$

$CLEO-c$	$|V_{cs}|$
$(818\ \text{pb}^{-1})$	$0.985 \pm 0.009 \pm 0.006 \pm 0.103$
	stat syst theory

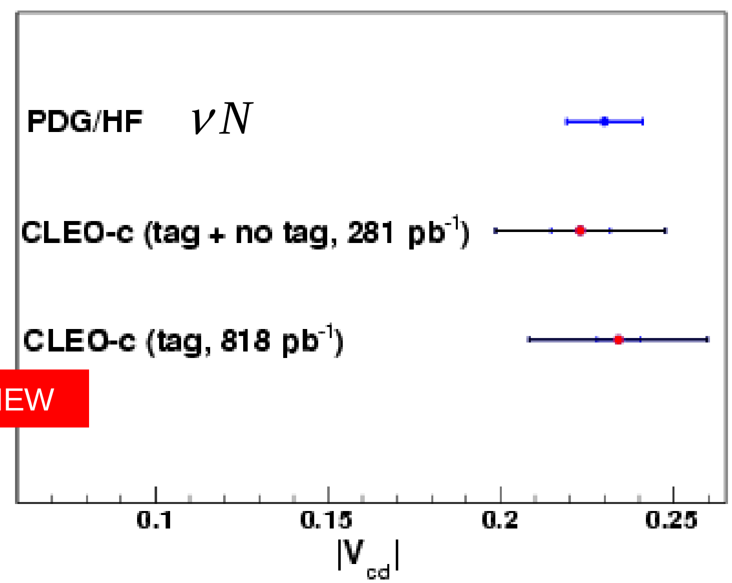


NEW

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



NEW

Unitarity Test: Compatibility of charm & beauty sectors of CKM matrix?

PRD 80, 032005 (2009)

$|V_{cd}|$ & $|V_{cs}|$ indirect

1) K & nucleon

$|V_{ud}| \simeq |V_{cs}|$ & $|V_{cd}| \simeq |V_{us}|$

2) B physics

Indirect= global CKM fit = 1+2

$|V_{cd}|$ & $|V_{cs}|$ direct

(D semileptonic decays CLEO)

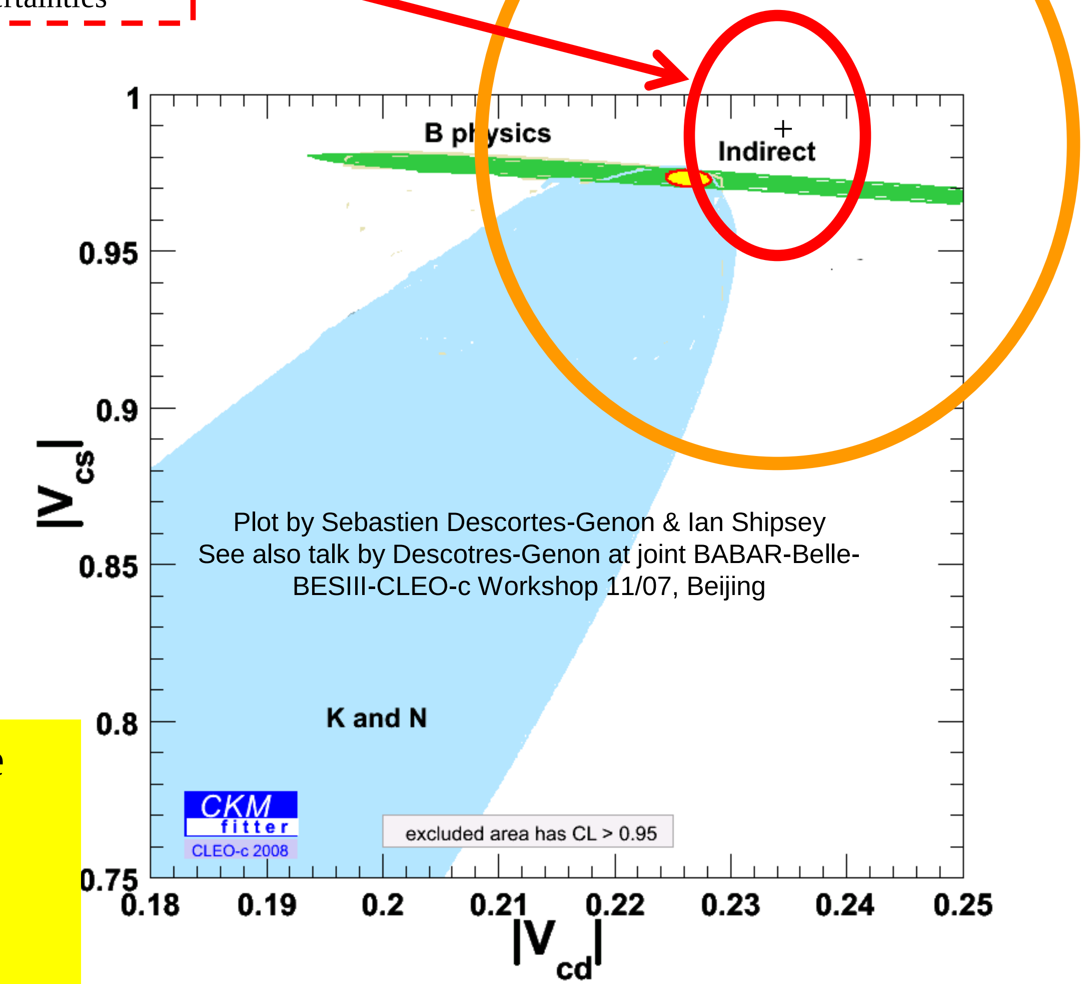
CLEO-c full data set

$\sigma(|V_{cd}|)/|V_{cd}| \sim 3.1\% \oplus \text{theory}$

$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\% \oplus \text{theory}$

CLEO-c full data set + 3-4% theory uncertainties

CLEO-c Now

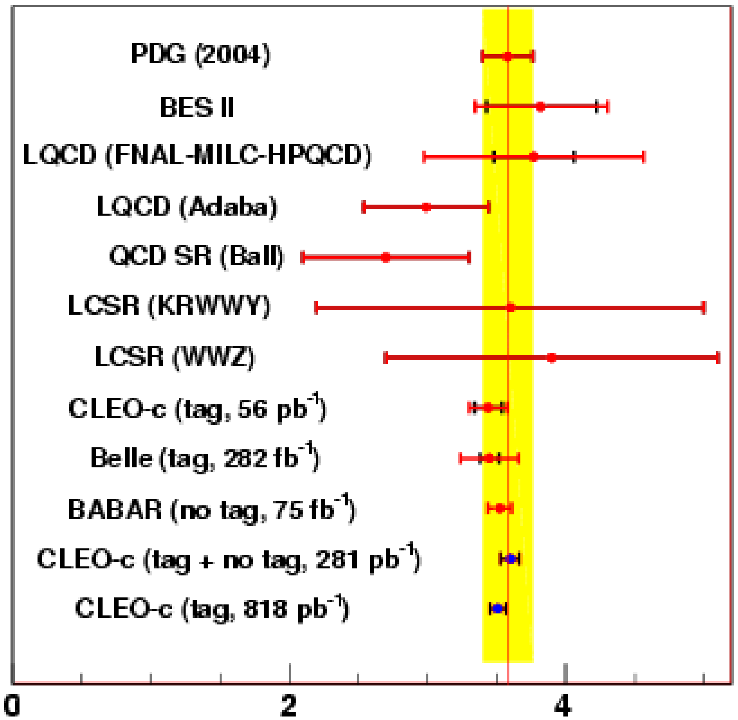


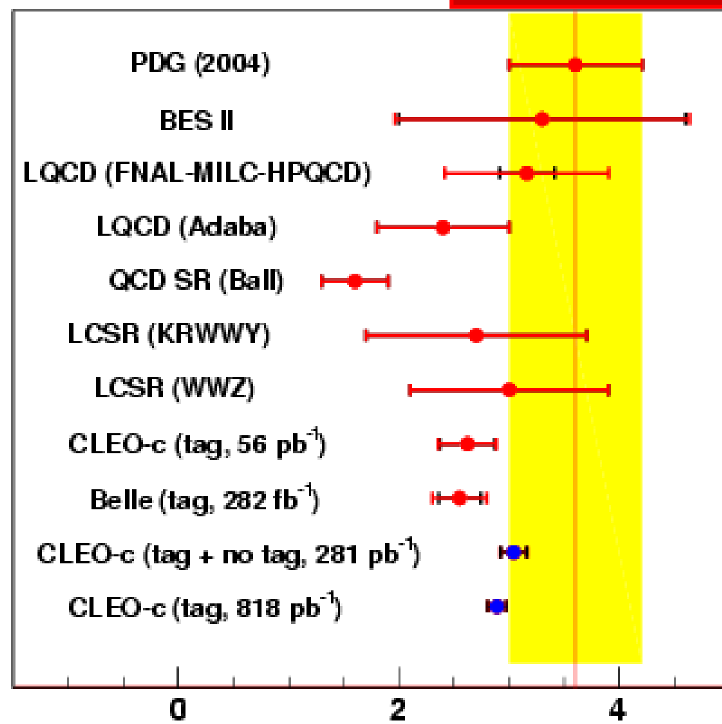
D semileptonic decays with comparable theory and experimental uncertainty may lead to interesting competition between direct and indirect constraints

We eagerly await new precise lattice calculations

D→K/πe⁺ν Branching fractions

PRD 80, 032005 (2009)





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

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

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.

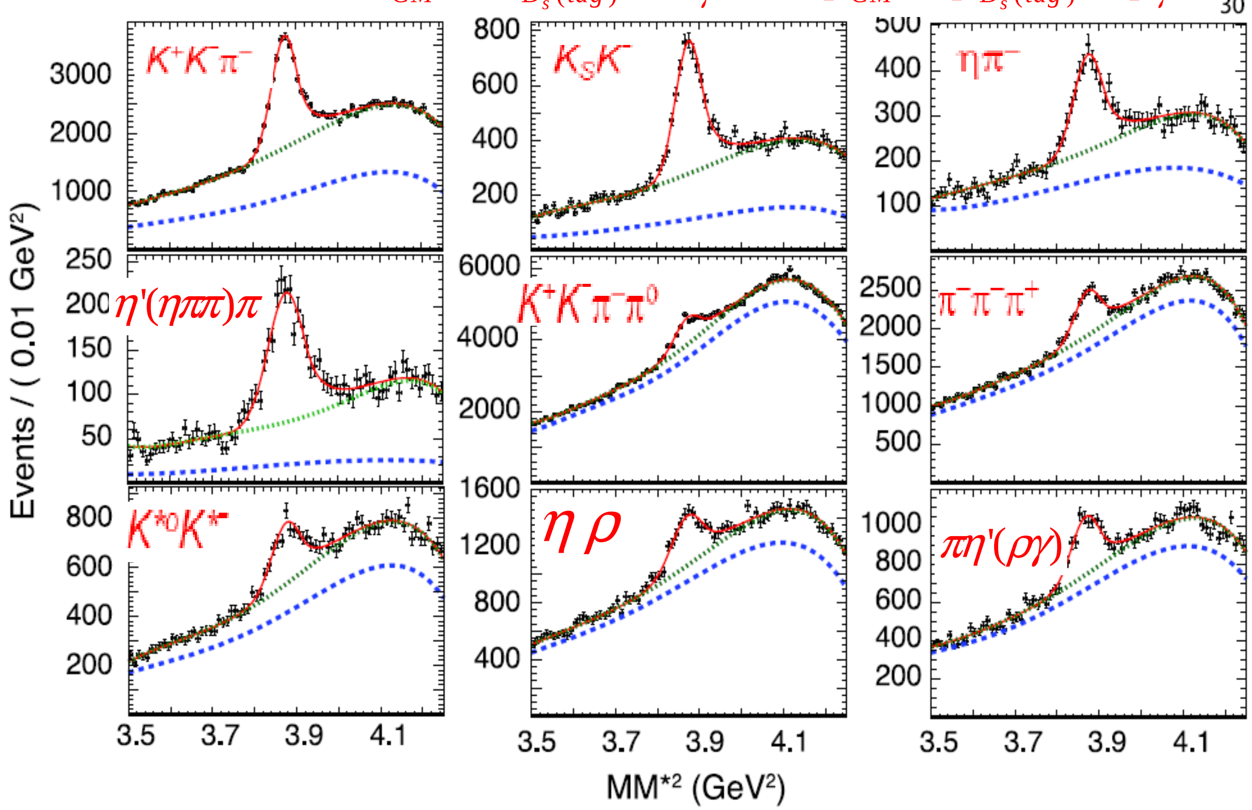
CLEO-c most precise. Theoretical precision lags experiment.

Analysis Technique at 4170 MeV (tagged)

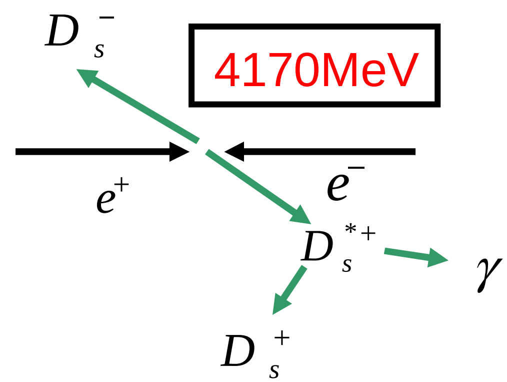
- Candidate events are selected by reconstructing a D_s in several hadronic modes

- The tag is then combined with a well reconstructed γ, The missing mass squared against the γ-tag pair

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



$e^+e^- \to D^*_sD_s$



preliminary

9 D_s tag modes:

N(tag)=70514±963

N(tag+γ)=43859±936

reconstructed from

~5.5 x 10^5 D_s^* D_s events

600 pb^{-1} @4170

(CLEO-c full dataset)

Exclusive D_s Semileptonic Decays

arXiv:0903:0601

- First absolute branching fraction measurements for Ds semileptonic decays
- Total width of these exclusive modes is 16% lower than the D^0/D^+ semileptonic widths.
- Shed light on η-η'-glueball mixing

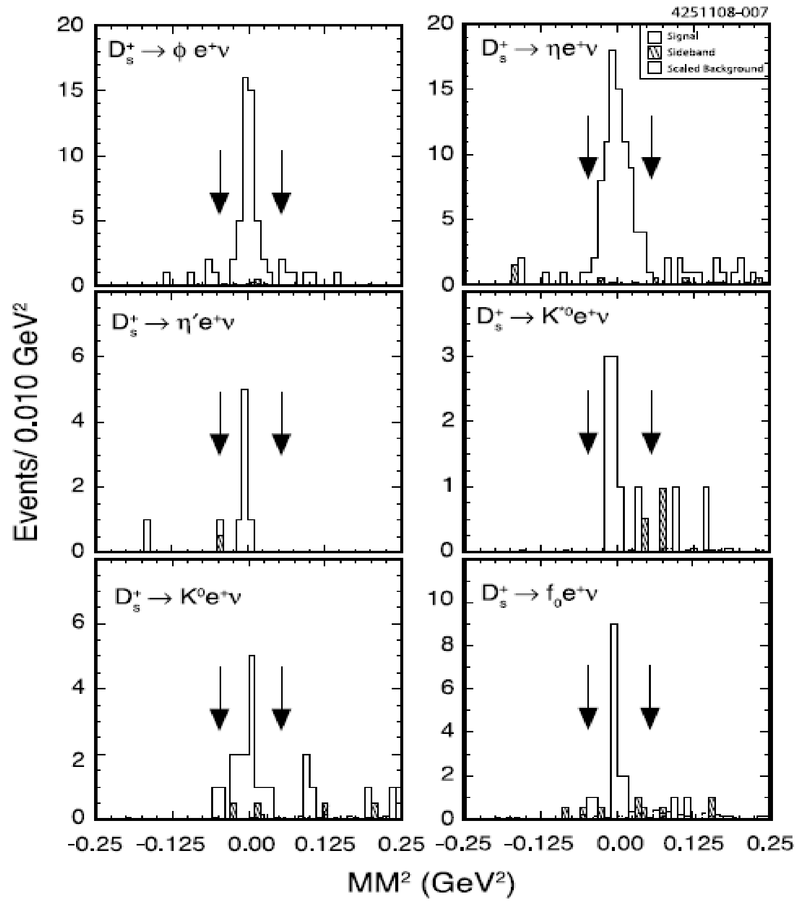
$$MM^2 = (E_{CM} - E_{D_s(tag)} - E_\gamma - E_e - E_{had})^2 - (-\vec{p}_{D_s(tag)} - \vec{p}_\gamma - \vec{p}_e - \vec{p}_{had})^2,$$

in the CM system

310 pb^{-1} @4170

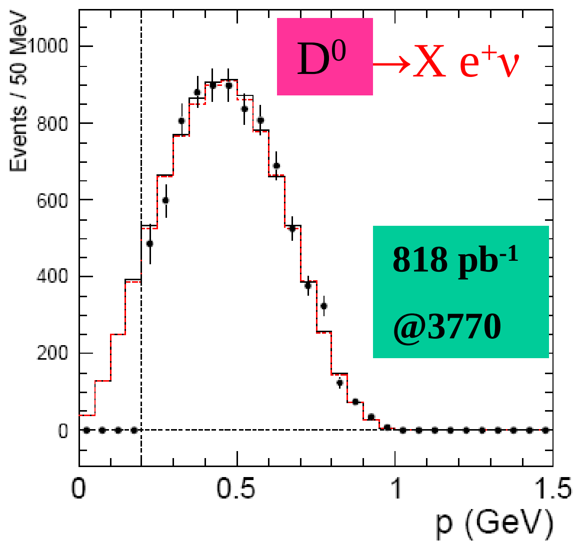
(Half of full dataset)

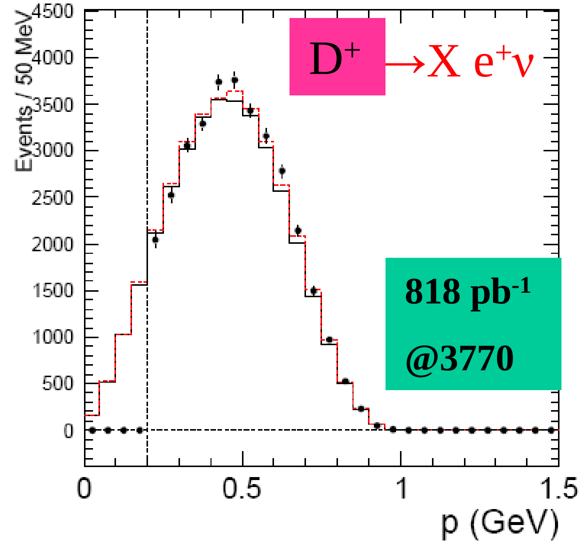
Signal Mode	$\mathcal{B}(\%)$
$D_s^+ \to \phi e^+ \nu_e$	$2.29 \pm 0.37 \pm 0.11$
$D_s^+ \to \eta e^+ \nu_e$	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \to \eta' e^+ \nu_e$	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \to K^0 e^+ \nu_e$	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \to K^{\star 0} e^+ \nu_e$	$0.18 \pm 0.07 \pm 0.01$
$D_s^+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

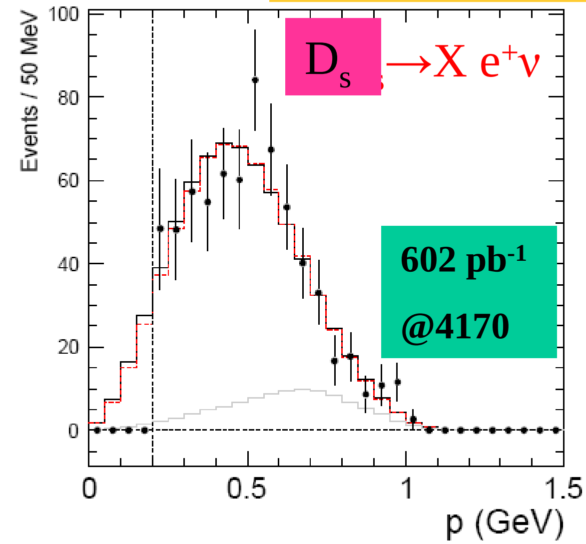


Inclusive Semileptonic Decays of D0,D+, and Ds

PRELIMINARY







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

❑Use knowledge of D semileptonic decay to extrapolate below the momentum cutoff (200MeV/c)

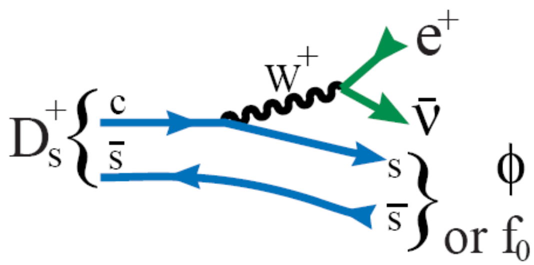
Any additional exclusive modes will have small branching ratios

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

$$\Gamma^{SL}_{D_s^+} / \Gamma^{SL}_{D^0} = 0.81 \pm 0.05 \pm 0.03$$ SU(3) is broken

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

arXiv: 0907.3201 (submitted to PRD)



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
- Implications for quark content of f_0
- 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]
- Many interesting results:

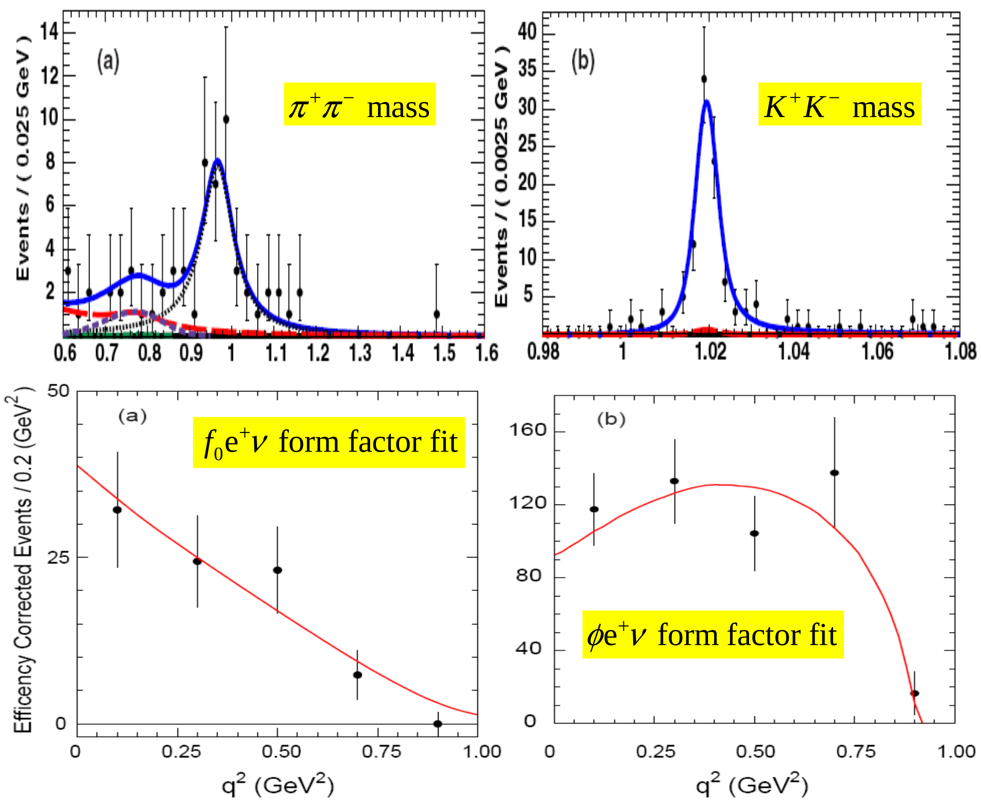
✓ $\mathrm{Br}(D_s^+ \to f_0(980) e^+ \nu,\ f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$
$\mathrm{Br}(D_s^+ \to \phi\, e^+ \nu) = (2.36 \pm 0.23 \pm 0.13)\%$

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

$$\left[\text{Predicted to equal } \frac{\mathrm{Br}\left(B_s \to J/\psi\ f_0\right)\mathrm{Br}\left(f_0 \to \pi^+\pi^-\right)}{\mathrm{Br}\left(B_s \to J/\psi \phi\right)\mathrm{Br}\left(\phi \to K^+K^-\right)} \right]$$

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

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



Summary

- Charm semileptonic decays are an excellent test ground of LQCD.
  - $D \to K e^+ \nu$, $D \to \pi e^+ \nu$ form factors in general agreement with LQCD.
- Measured to better precision than LQCD.
  - CLEO-c measures form factor normalizations for $D \to K e^+ \nu$, $D \to \pi e^+ \nu$ to 3% and 1%, respectively, while LQCD predicts them at 10% level.
- Direct measurements of CKM elements.
  - Best direct measurement of $|V_{cs}|$, measured to ±1.1%(experimental) ± 10%(theory).
  - $|V_{cd}|$ is measured to ±3.1%(experimental) ± 10%(theory).
- Recent measurements of D_s semileptonic measurements with tagged data sets.
  - Measurement of 6 exclusive semileptonic branching fractions.
  - First direct evidence of a semileptonic decay with scalar meson in the final state.
  - Form factor measurement for $D_s \to f_0(980) e^+ \nu$

- Thanks again to Bo Xin and Ian Shipsey