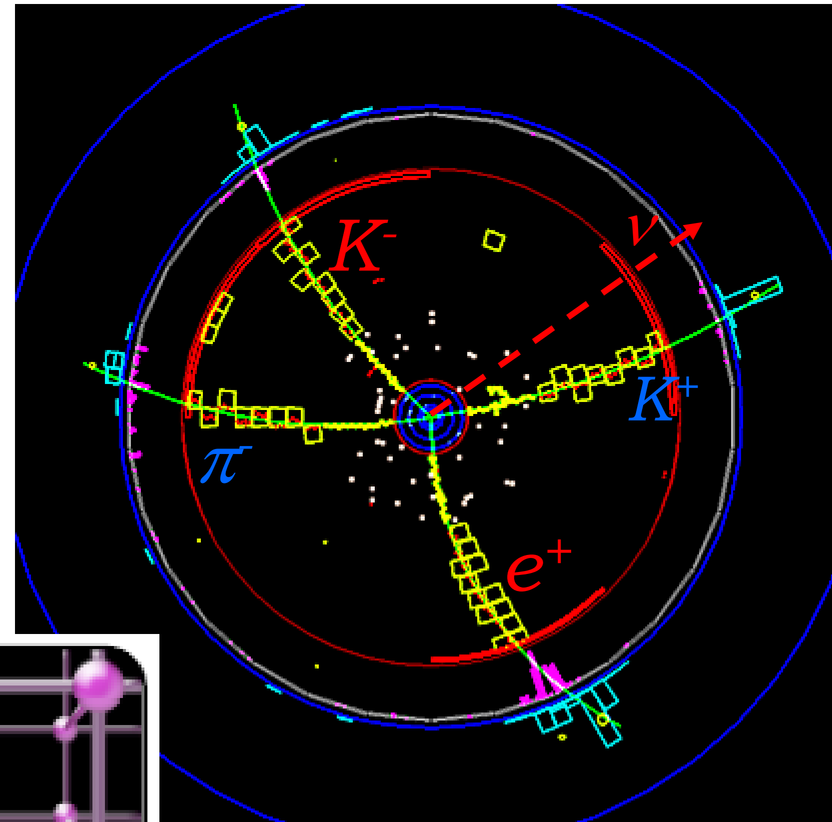
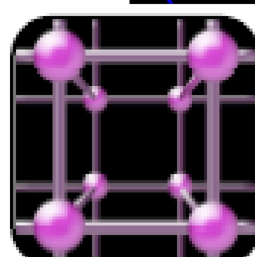
Latest Charm Semileptonic Decay Results from CLEO-c

OUTLINE

CLEO-c in the context of testing the Standard Model with precision quark flavor physics.

- *Decay constants*
- *Form Factors*
- *CKM matrix elements*





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

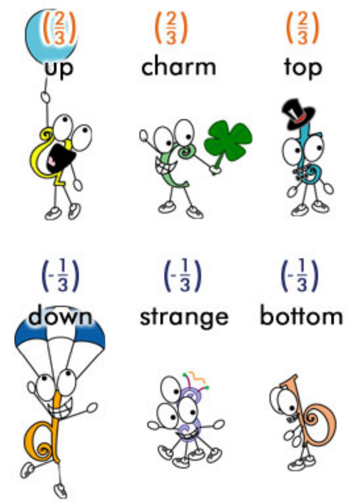
$$\overline{D}^0 \to K^+\pi^-, D^0 \to K^- e^+ \nu$$

Ian Shipsey, Purdue University
CLEO-c Collaboration

Big Questions in Flavor Physics

Dynamics of flavor?

Why generations?
Why a hierarchy of masses & mixings?



Origin of Baryogenesis?

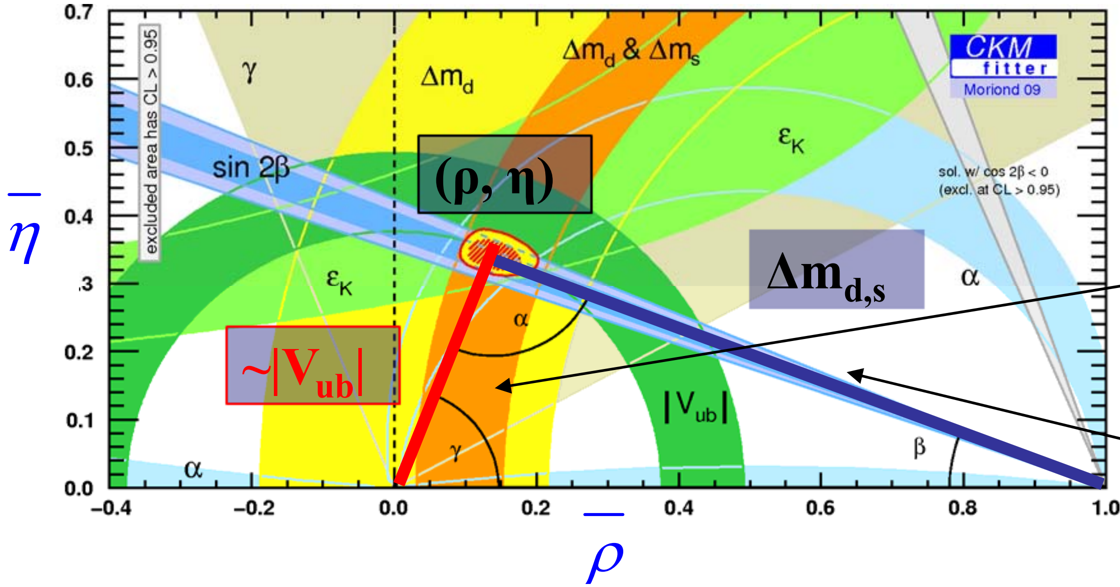
Sakharov's criteria: Baryon number violation
CP violation Non-equilibrium

3 examples: Universe, kaons, beauty but Standard Model CP violation too small, need additional sources of CP violation

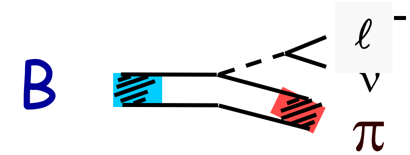
Connection between flavor physics & electroweak symmetry breaking?

Extensions of the Standard Model (ex: SUSY) contain flavor & CP violating couplings that should show up at some level in flavor physics, but *precision* measurements and *precision* theory are required to detect the new physics

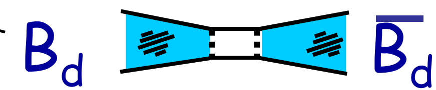
Precision Quark Flavor Physics



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

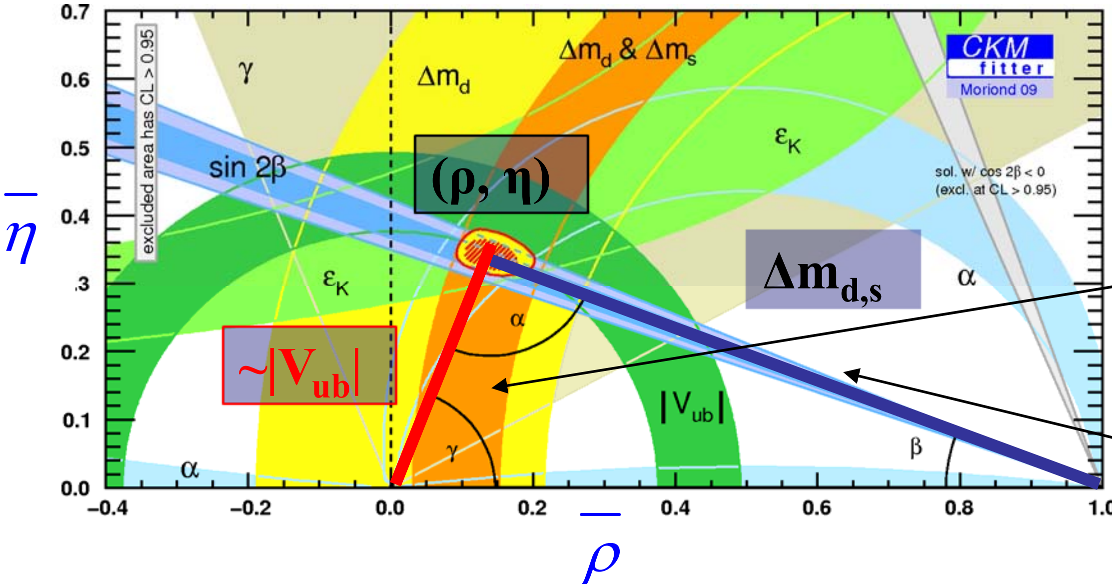


$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$



$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

Precision Quark Flavor Physics



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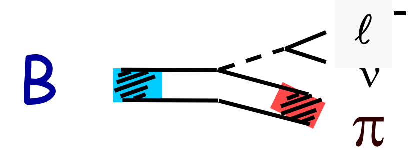

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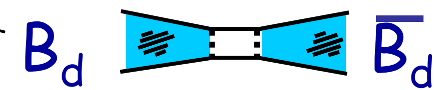
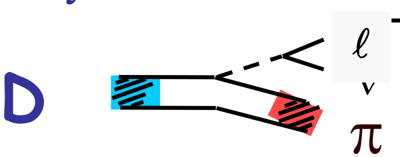
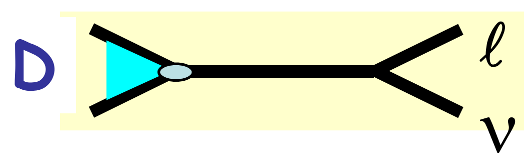


$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

D system- CKM elements known to <1% by unitarity



$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

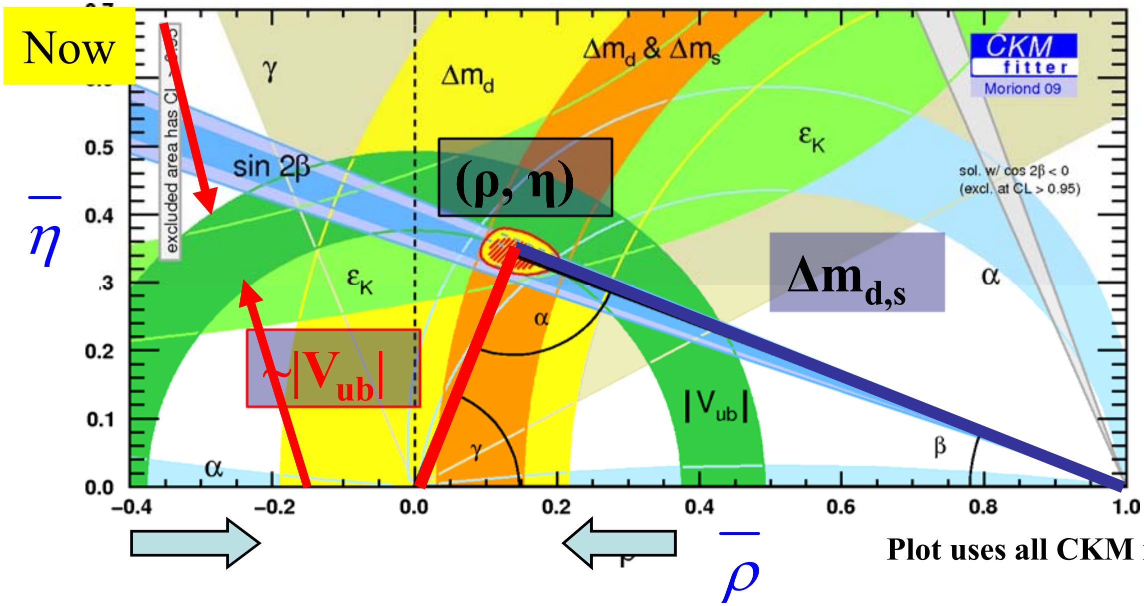


$$\propto \left[f_{D+} \right]^2 |V_{cd}|^2$$

→ *measurements* of *absolute rates* for D semileptonic & leptonic decays yield decay constants & form factors to *test* and hone QCD techniques into a *precision theory* which can be applied to the B system enabling improved determination of the apex (ρ,η)

+ Br(B→ D)~100% *absolute* D hadronic rates normalize B physics important for V_{cb} (scale of triangle) - also normalize D physics

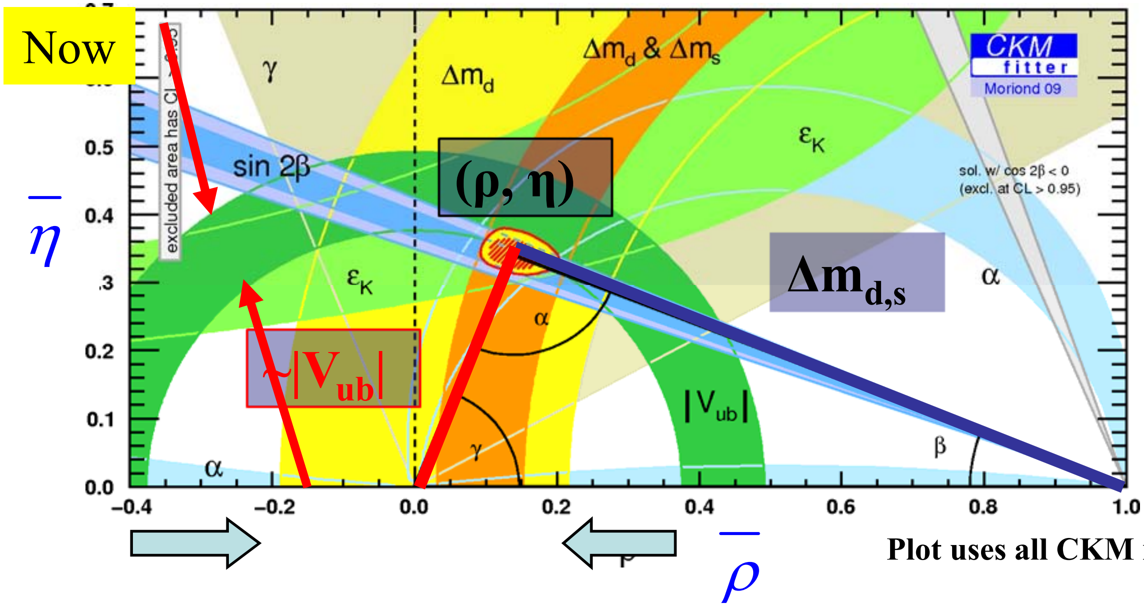
Precision theory + charm = large impact



Plot uses all CKM inputs

Theoretical errors dominate width of bands

Precision theory + charm = large impact



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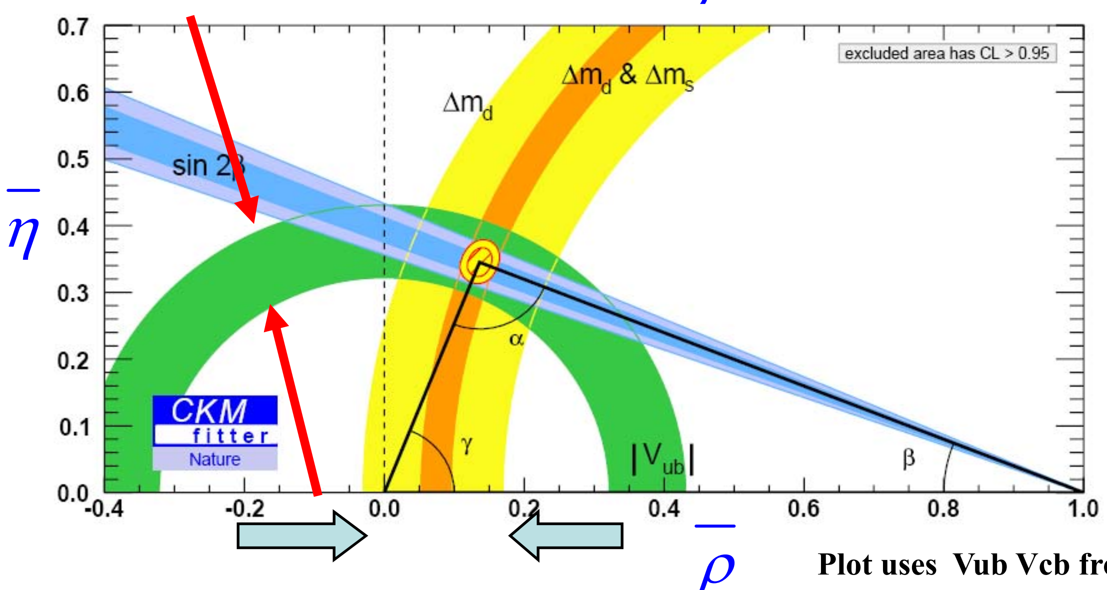


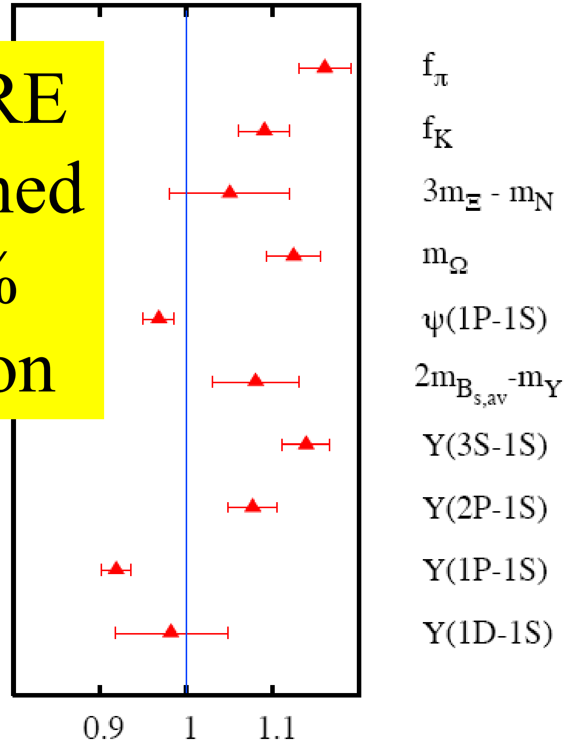
Plot uses Vub Vcb from exclusive decays
no gamma or alpha constraints

Theoretical errors dominate width of bands

Few % precision QCD Calculations tested with few % *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

Precision theory? Lattice QCD

BEFORE
Quenched
10-15%
precision

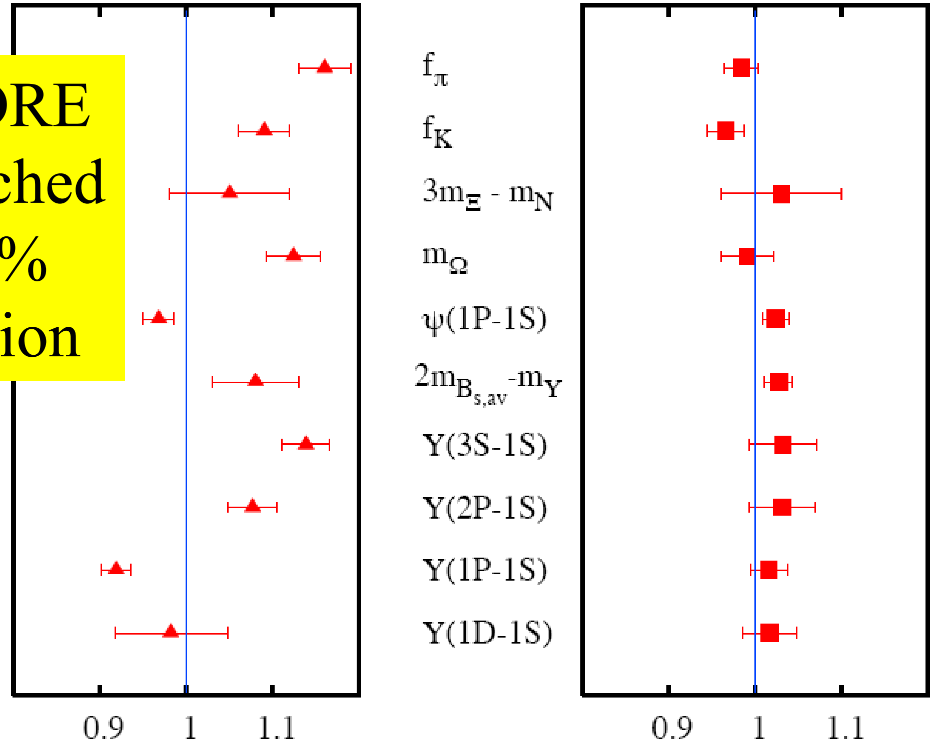


$$\frac{\text{theory-expt}}{\text{expt}}.$$

Precision theory? In 2003 a breakthrough in Lattice QCD

Recent revolutionary progress in algorithms allows inclusion of QCD vacuum polarization. LQCD demonstrated it can reproduce a wide range of mass differences & decay constants. *These were postdictions*

BEFORE Quenched 10-15% precision



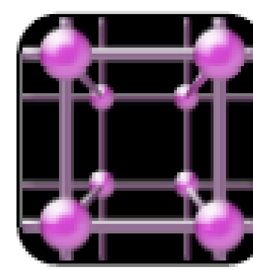
$\frac{\text{theory-expt}}{\text{expt}}$. $\frac{\text{theory-expt}}{\text{expt}}$.

This dramatic improvement needs validation of predictions. m(Bc) successful.

Charm decay constants f_{D+} & f_{Ds}

Charm semileptonic form factors

Understanding strongly coupled systems is important beyond flavor physics. LHC might discover new strongly interacting physics



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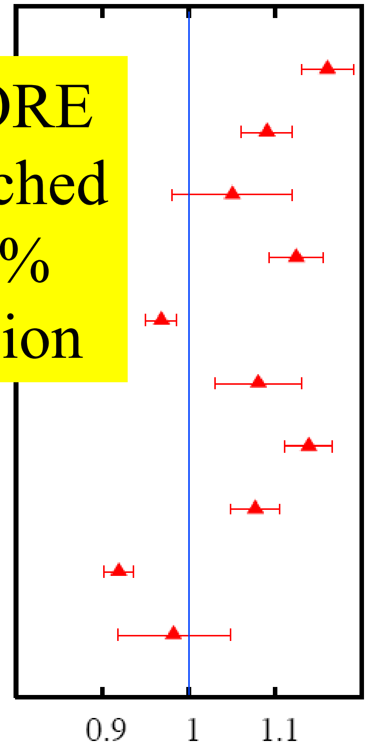

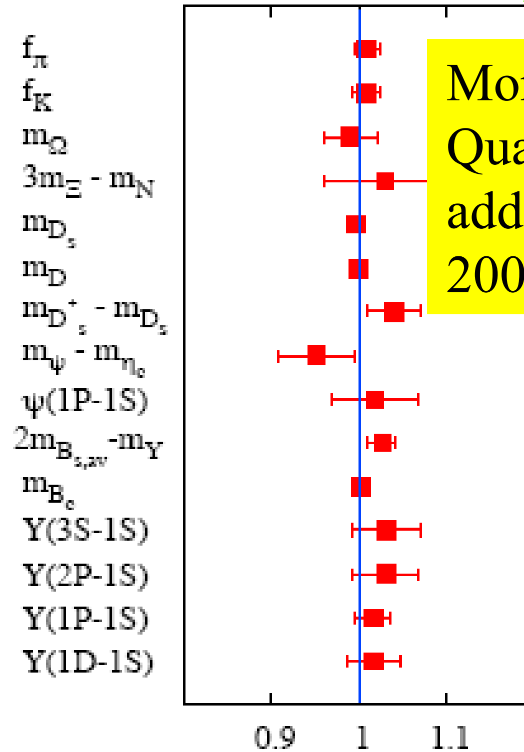

More Quantities added 2007

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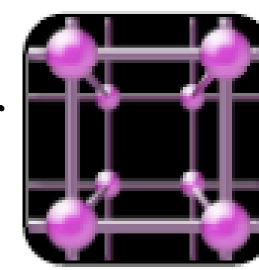


Precision Experiment for charm?

Circa 2004 (pre-CLEO-c)

Key leptonic, semileptonic & hadronic modes:

Experiment : Theory

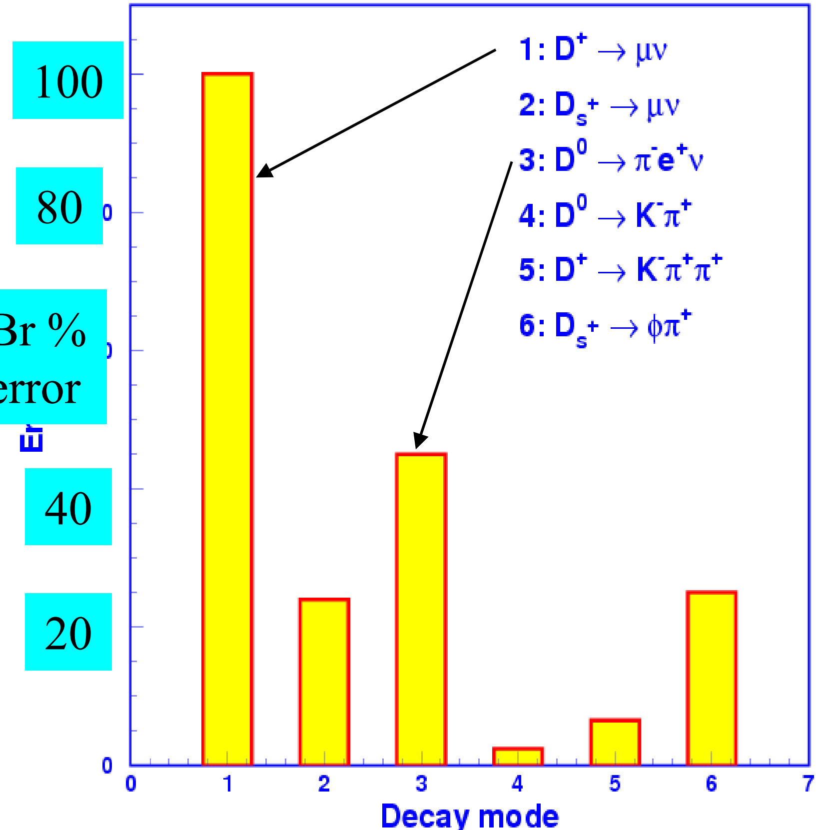
Poorly known

$$\frac{Br}{\tau} = \Gamma$$

Measured very precisely 0.4-0.8%

$$\frac{\delta B}{B}(D \rightarrow \pi e^{+}\upsilon) = 45\%$$

$$\frac{\delta B}{B}(D^{+} \rightarrow \mu^{+}\upsilon) = 100\%$$



Before CLEO-c precise measurements of charm decay constants and form factors did not exist, because at Tevatron/FT/ B factories:

$$Br(D \rightarrow X) = \frac{\text{\#X Observed}}{\text{efficiency x \#D's produced}}$$

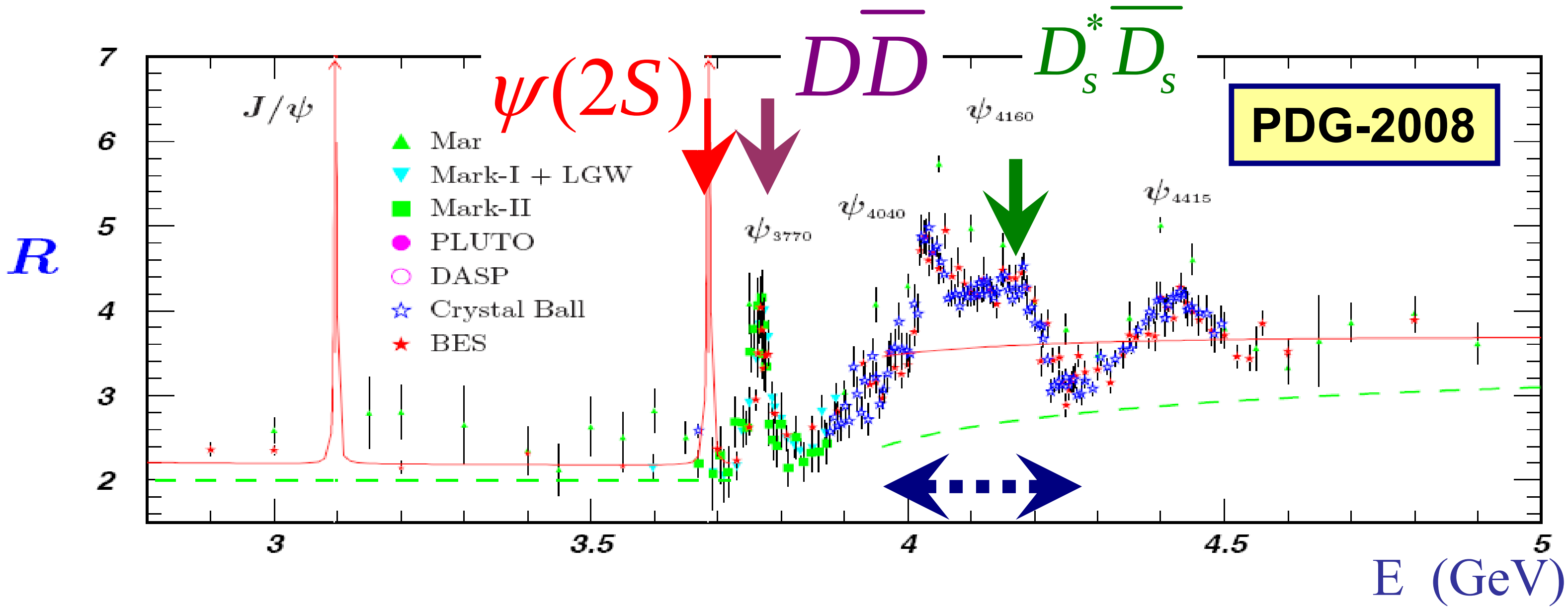
Backgrounds are large.

#D’s produced is usually not well known.

CLEO-c: World's largest data sets at charm threshold

CLEO-c: Oct. 2003 – March 2008, **CESR (10GeV) → CESR-c at 4GeV**

CLEO III detector → CLEO-c

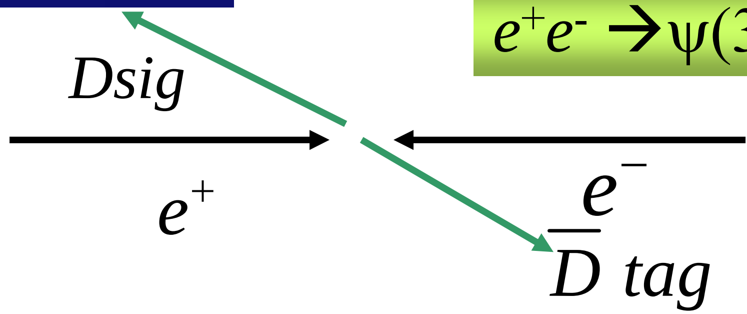


$\sqrt{s}$ (MeV)	Ldt (pb^{-1})			
3686	54	$N(\psi(2S)) \approx 27M$		
3773	818	$\psi(3770) \to D\overline{D} \approx 5\times10^6 D\overline{D}$	⟸	X86 MARK III X25 BES II
4170	600	$D_{(s)}^{(*)}\overline{D_{(s)}^{(*)}} \approx 6\times10^5 D_s^* \overline{D}_s$	⟸	First sample at this energy

$\psi(3770)$ Analysis Strategy

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

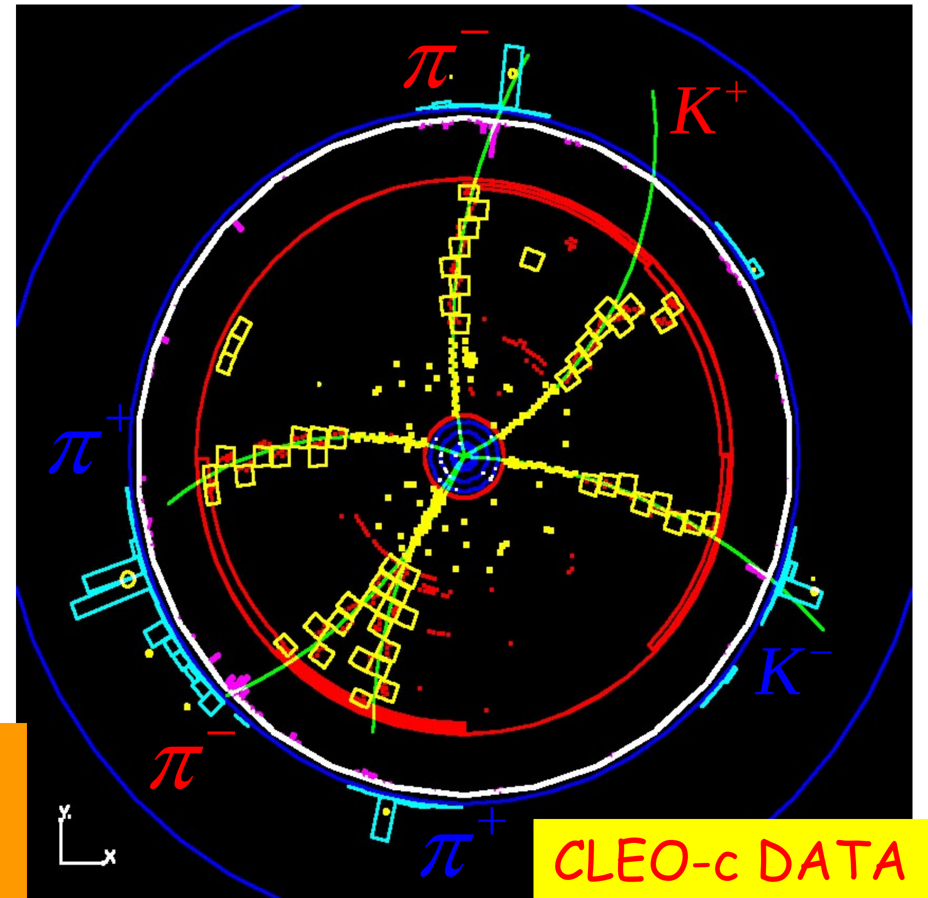
$\psi(3770)$ is to charm what $\Upsilon(4S)$ is to beauty



- Pure DD, no additional particles ($E_D = E_{beam}$).
- σ (DD) = 6.4 nb ($\Upsilon(4S)$->BB ~ 1 nb)
- Low multiplicity ~ 5-6 charged particles/event

➔ high tag efficiency: ~20% of events

Compared to ~0.1% of B's at the $\Upsilon(4S)$



$\psi(3770) \rightarrow D^+ D^-$

$D^+ \rightarrow K^- \pi^+ \pi^+, \;\; D^- \rightarrow K^+ \pi^- \pi^-$

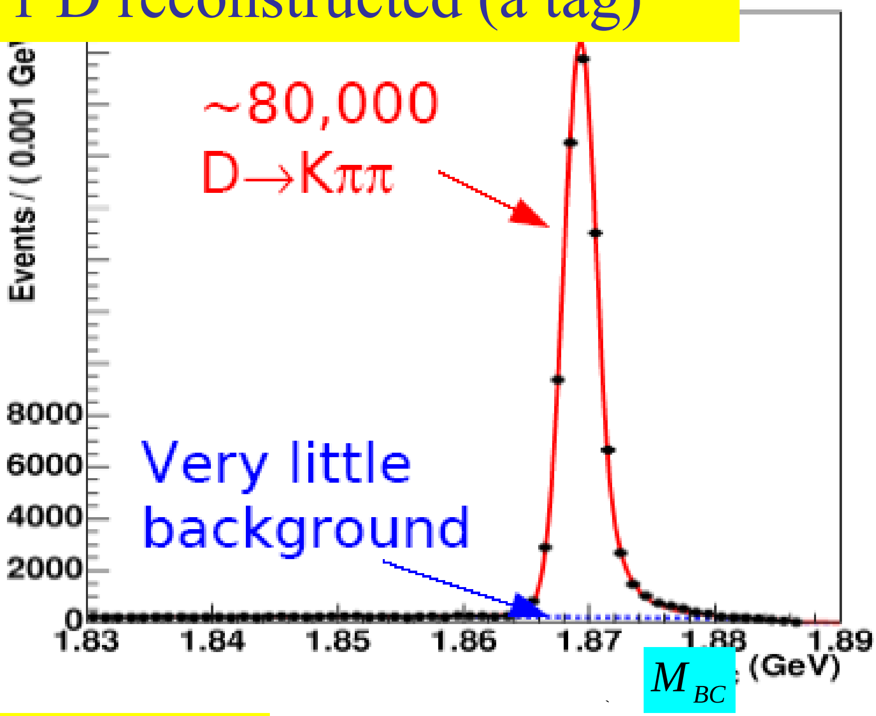
A little luminosity goes a long way:
Tagging ability:
D tags in 800 pb^{-1} @ charm factory
~ # B tags in 1300 fb^{-1} @ $\Upsilon(4S)$

Absolute Charm Branching Ratios at Threshold

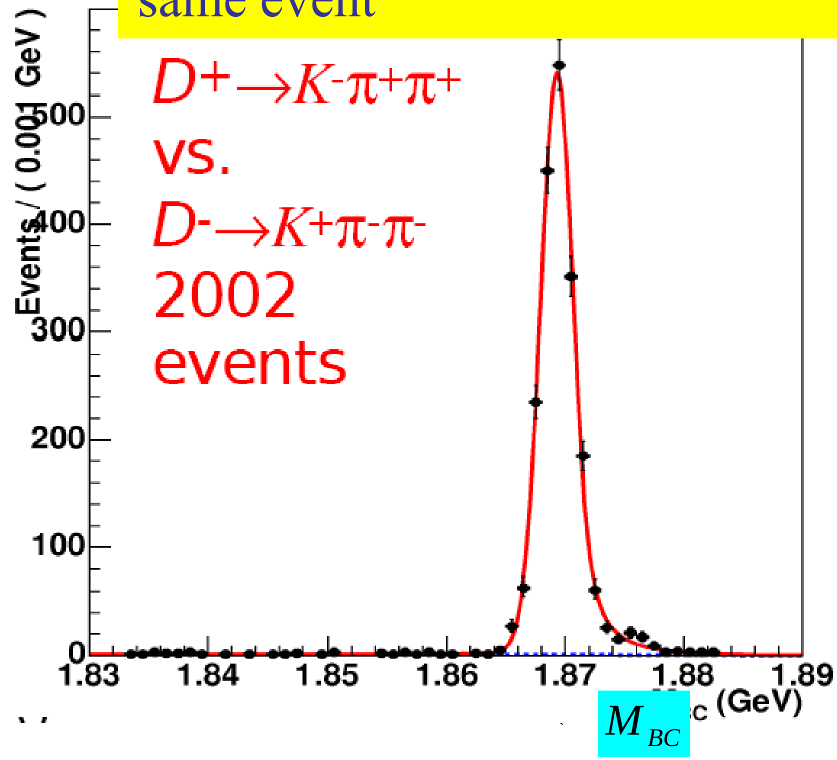
281/pb

$$E_D \Rightarrow E_{beam}: \quad \Delta E = E_D - E_{beam} \qquad M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|^2}$$

1 D reconstructed (a tag)



1D$^+$ & 1D$^-$ reconstructed in same event



Independent of L and cross section

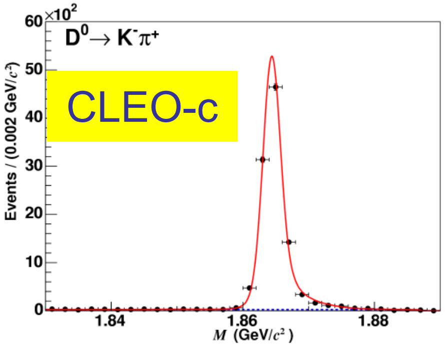
$$B(D^- \to K^+\pi^-\pi^-) = \frac{\#\,(K^+\pi^-\pi^-)\ \text{Observed in tagged events}}{\text{detection efficiency for } (K^+\pi^-\pi^-) \bullet \#\text{D tags}}$$

$B(D^0 \to K^-\pi^+)$

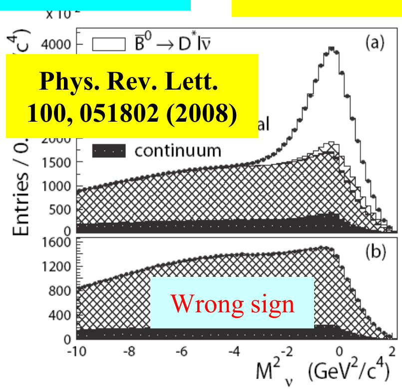
Sets scale of bd triangle

BABAR

CLEO-c

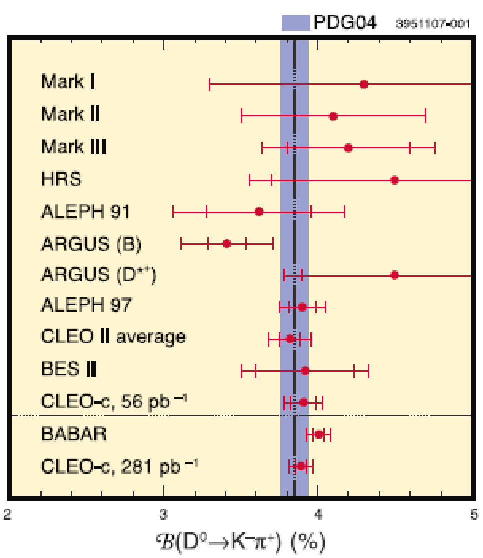


Phys. Rev. Lett. 100, 051802 (2008)



$\mathcal{B}$ (%)	Error(%)	Source
3.80 ±0.09	2.4	PDG04
3.891±0.035 ±0.069	2.0	CLEO-c
4.007 ±0.037 ±0.072	2.0	BABAR

281/pb

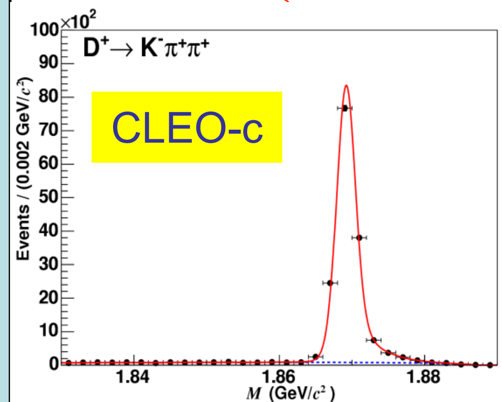


Syst. limited: 2%

CLEO-c & BABAR agree vastly superior S/N at CLEO-c

charm hadronic scale is finally on a SECURE FOUNDATION

$B(D^+ \to K^-\pi^+\pi^+)$



CLEO-c

Previous best:

measure:

$$\frac{B(D^{*+} \to D^0\pi^+)}{B(D^{*+} \to D^+\pi^0)} \quad \frac{B(D^0 \to K^-\pi^+)}{B(D^+ \to K^-\pi^+\pi^+)}$$

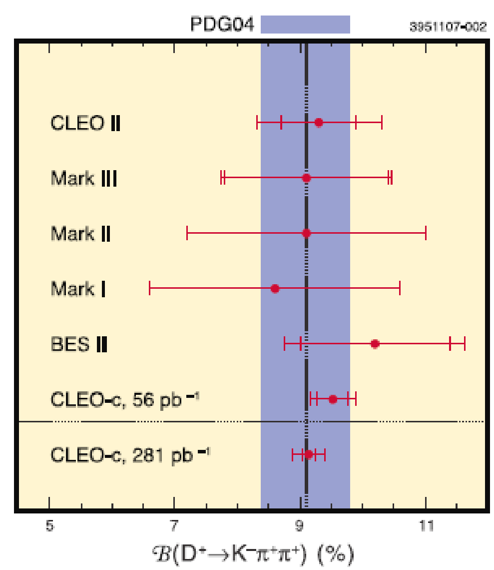
$B(D^+ \to K^-\pi^+\pi^+)$ *dependent on* $B(D^0 \to K^-\pi^+)$

$\mathcal{B}$ (%)	Error(%)	Source
9.3±0.6±0.8	10.8	CLEO
9.1±1.3±0.4	14.9	MKIII
9.1±0.7	7.7	PDG04
9.14 ±0.10±0.17	1.9	CLEO-c

281/pb

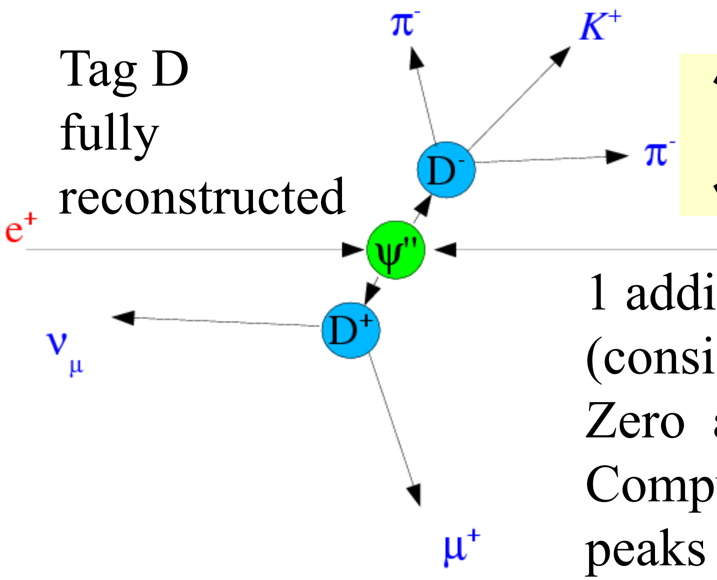
now: $B(D^+ \to K^-\pi^+\pi^+)$ *independently measured*

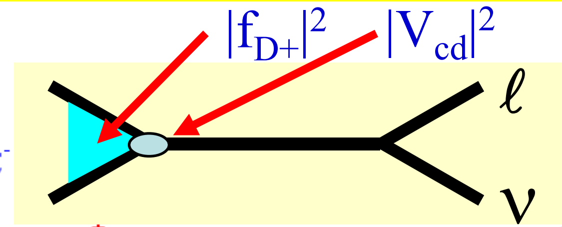
CLEO-c x 3.5 More precise than PDG



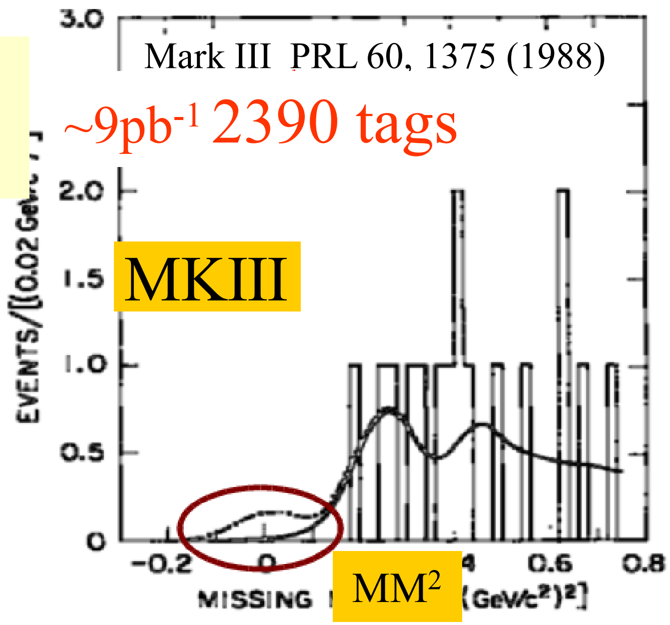
Phys. Rev. D 76, 112001 (2007)

f_{D+} from Absolute $Br(D^+ \to \mu^+\nu)$ at $\psi(3770)$





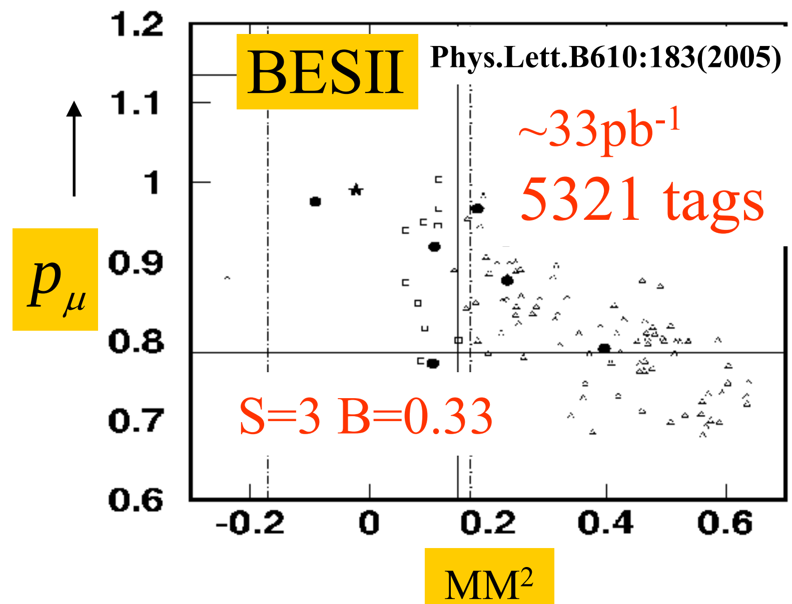
1 additional track
(consistent with a muon)
Zero additional photons
Compute missing mass^2:
peaks at 0 for signal



$$MM^2 = (E_D - E_\mu)^2 - (\vec{P_D} - \vec{P_\mu})^2$$

where $E_D = E_{beam}$, $\vec{P_D} = -\vec{P}_{D\,tag}$

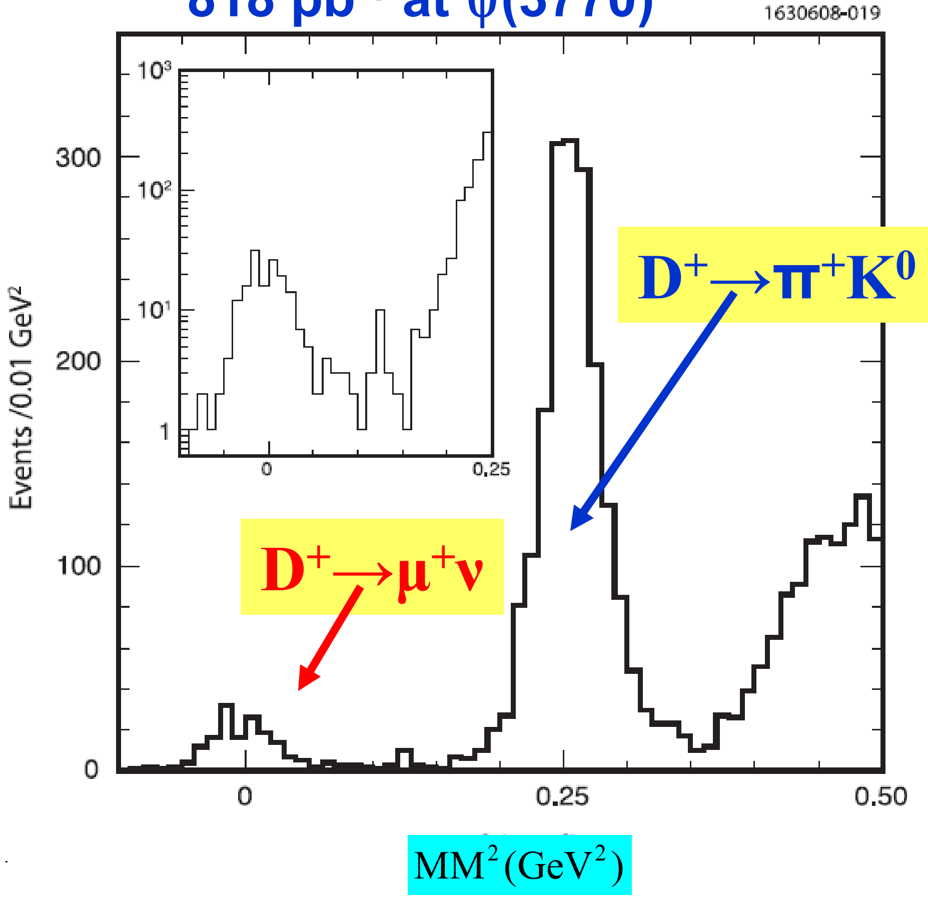
	$B(D^+ \to \mu\nu)\times 10^{-4}$	f_D MeV
MkIII	< 7.2	< 290
BESII	$12.2^{11.1}_{-5.3} \pm 0.11$	$371^{+129}_{-119} \pm 25$



f_{D+} from $D^+ \to \mu^+\nu$

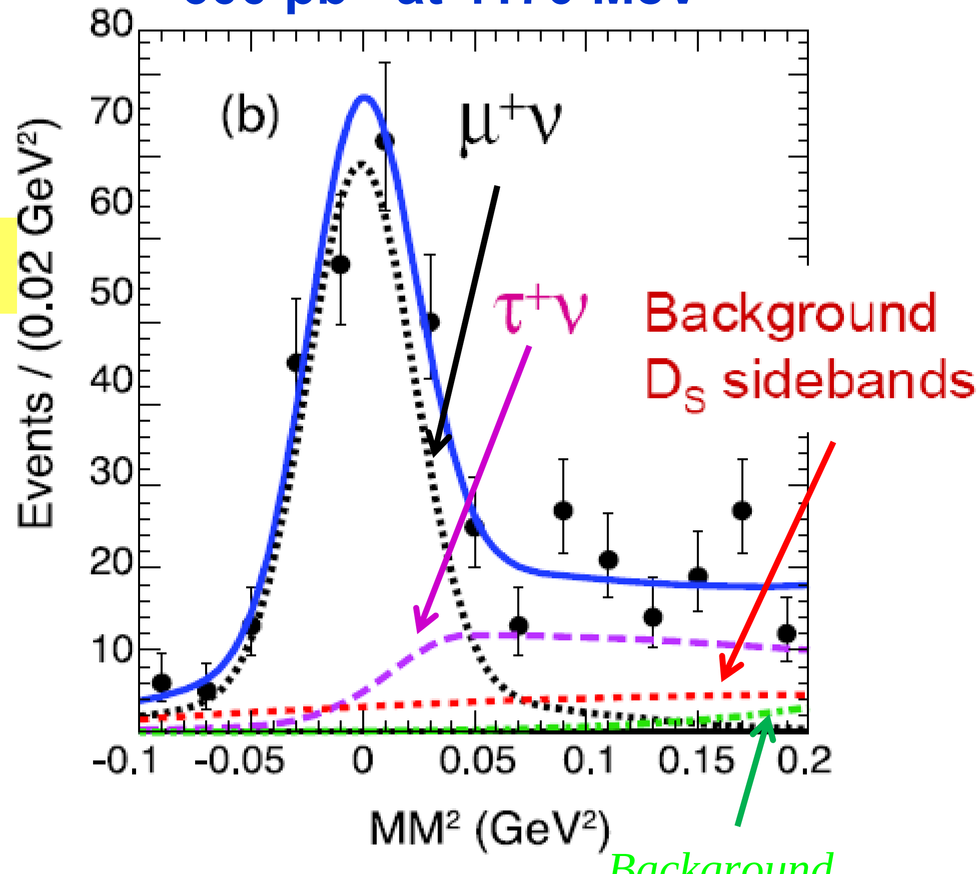
f_{Ds} from $D_s \to \mu^+\nu \;\&\; \tau^+(\pi^+\nu)\nu$

818 pb^{-1} at $\psi(3770)$



PRD 78,052003 (2008)

600 pb^{-1} at 4170 MeV



Background

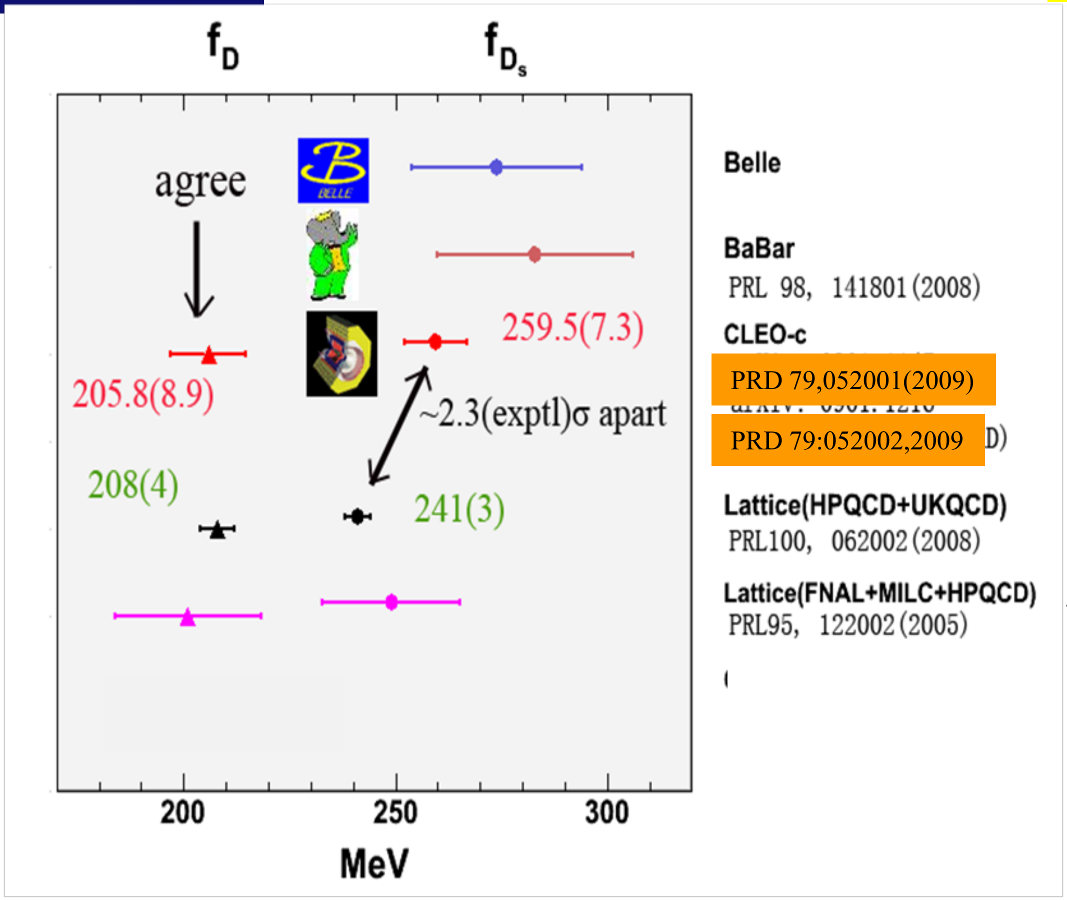
$D_s \to 3\pi \,/\, K^0\pi \;\; / \eta\pi$

PRD 79,052001(2009)

f_{Ds} Method 2: $D_s \to \tau^+\nu, \tau^+ \to e^+\nu\nu$

PRD 79:052002,2009

Comparison to LQCD



CLEO f_D consistent with calculations (4% test of lattice)

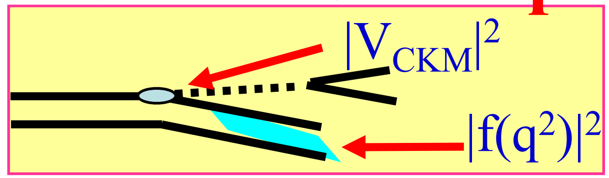
CLEO f_{Ds} (and Belle & BABAR) higher than most theoretical expectations

CLEO f_{Ds} is ~2.3σ above the most recent & precise LQCD calculations

Ds leptonic decay width could be modified by new physics example: Dobrescu and Kronfeld arXiv:0803.0512

The difference between experiment HPQCD+UKQCD could be due to new physics, unlikely statistical fluctuations in experiment or lattice calculations or systematic uncertainties which are not understood in the lattice calculation or experiment. *BES III measurements are eagerly awaited.*

Importance of Charm Semileptonic Decays

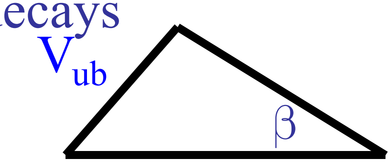


$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to(K)\pi}(q^2)|^2$$

1 Assuming theoretical form factors $\Rightarrow V_{cs}$ and V_{cd}

2 Assuming V_{cs} and V_{cd} known, we can check theoretical calculations of the form factors

3 *Potentially* useful input to Vub from exclusive B semileptonic decays



$Br(B \to \pi l \nu) \sim 6\%$ precision

BABAR/Belle/CLEO(HFAG)

(summer 2008)

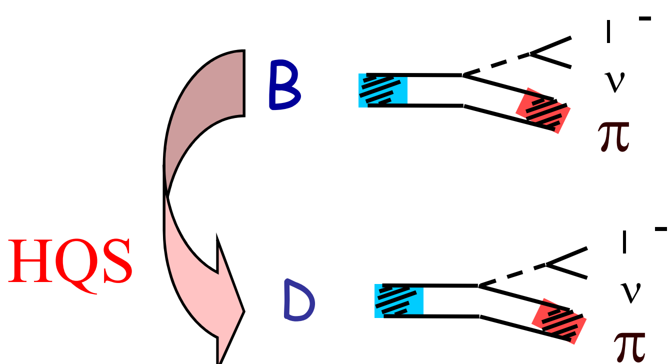
$$|V_{ub}| = (3.62 \pm 0.22 \pm ^{+0.63}_{-0.41}) \times 10^{-3}$$

$$\pm \exp \pm \mathrm{LQCD}$$

Expt. 5%

$q^2 > 16\,GeV^2$

~11- 17% e.g. HPQCD &FNAL



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

$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

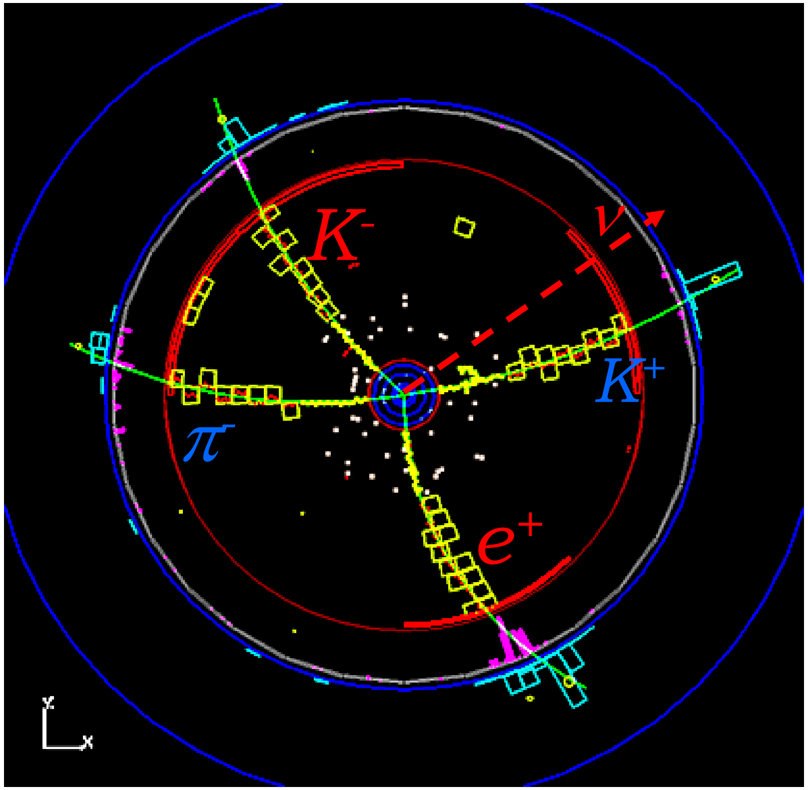
Related at same invariant 4 velocity

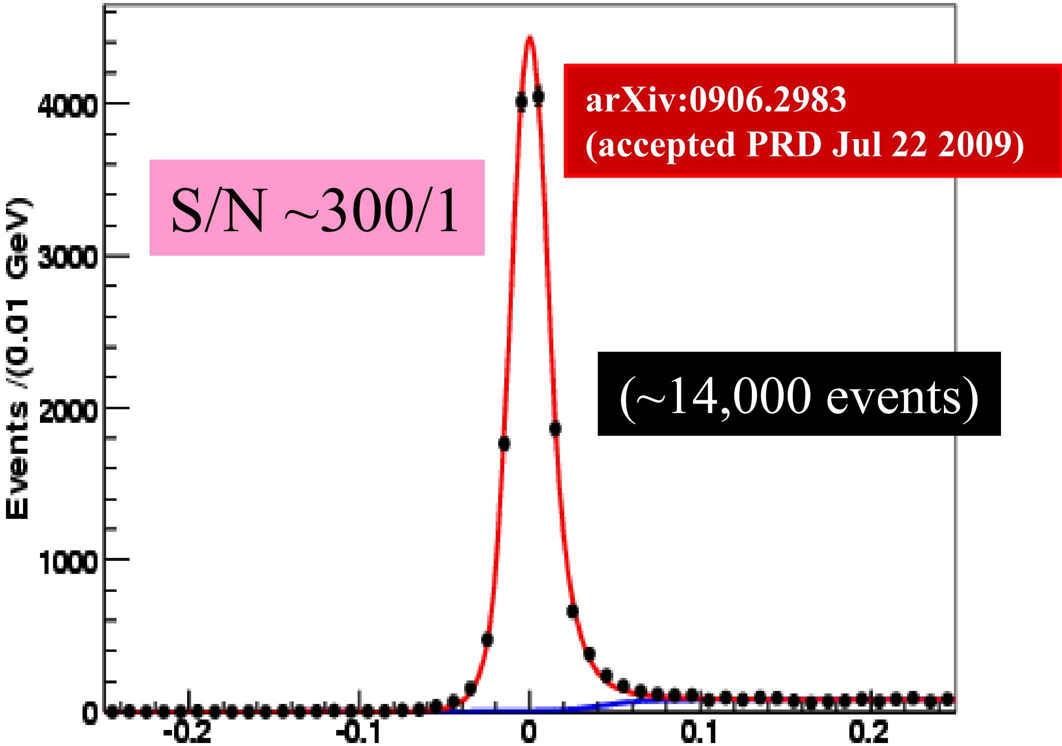
Absolute Semileptonic Branching Fractions

The neutrino direction is determined to 1°

no kinematics ambiguity

$$U \equiv E_{miss} - |\vec{p}_{miss}| = 0$$





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

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

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

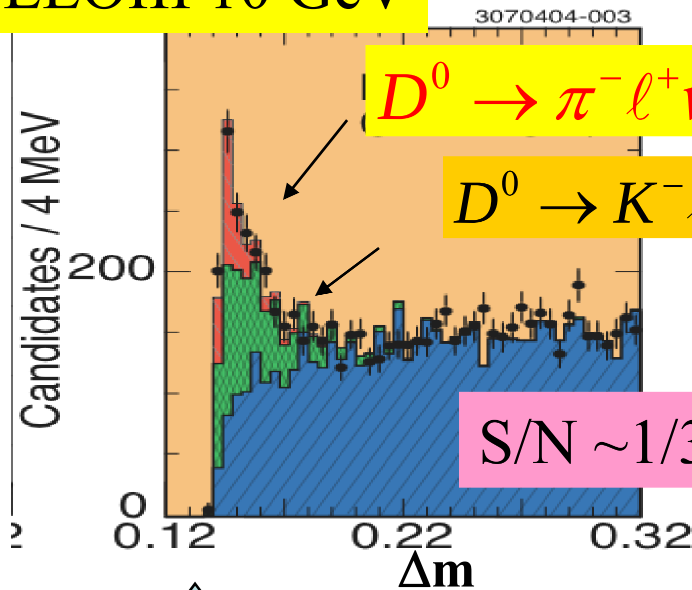
Tagging creates a single D beam of known 4-momentum

$$\mathcal{B}(D \to Ke\nu) = \frac{N(D \to Ke\nu)}{\text{Efficiency} \times N_{\text{tags}}}$$

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

arXiv:0906.2983
(accepted PRD Jul 22 2009)

CLEOIII 10 GeV



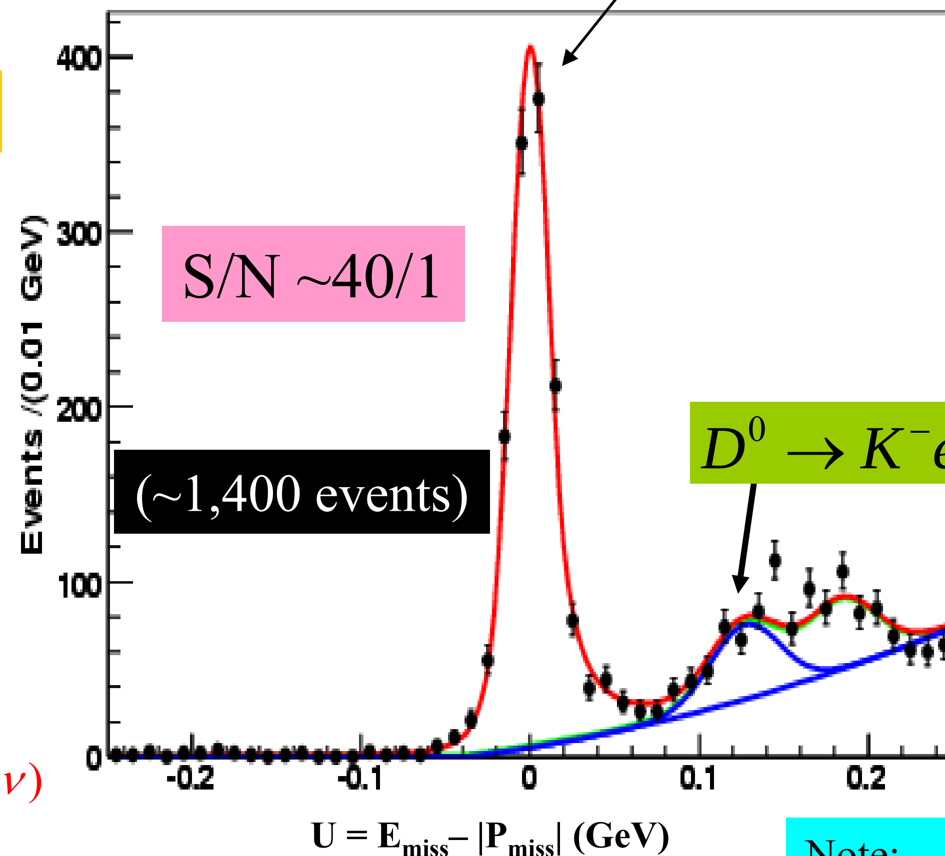
$D^0 \to \pi^- \ell^+ \nu$

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

S/N ~1/3

CLEO-c

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



S/N ~40/1

(~1,400 events)

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

$Tag \quad with \; D^{*+} \to D^0 \pi_s$

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

$observable:$

$\Delta m = m(\pi_s \pi \ell \nu) - m(\pi \ell \nu)$

Compare to:
state of the
art measurement
at 10 GeV (CLEO III)
PRL 94, 11802 (2004)

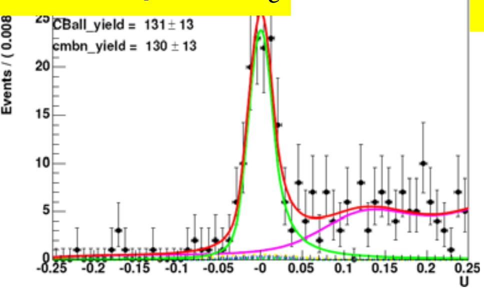
Note:
kinematic
separation.

Only other high statistics measurement is from Belle
282/fb (x350 CLEO-c) 222± 17 events S/N 4/1

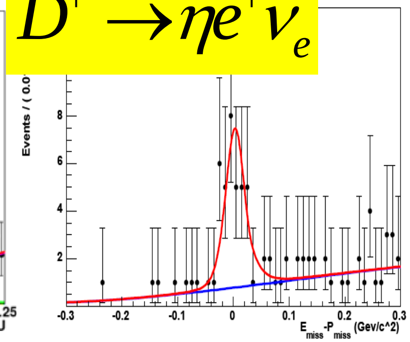
CLEO-c semileptonic tagging analysis technique: big impact

1^{st} Observations:

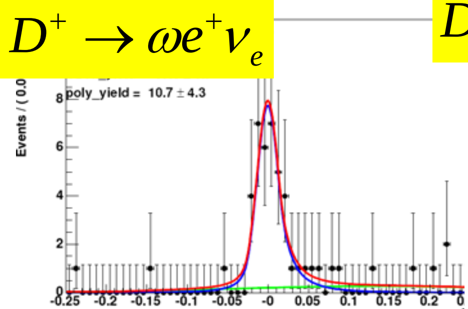
$D^0 \to \rho^- e^+ \nu_e$



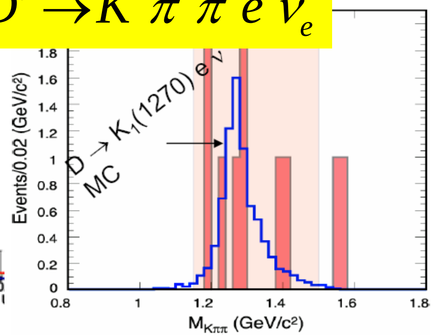
$D^+ \to \eta e^+ \nu_e$



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



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



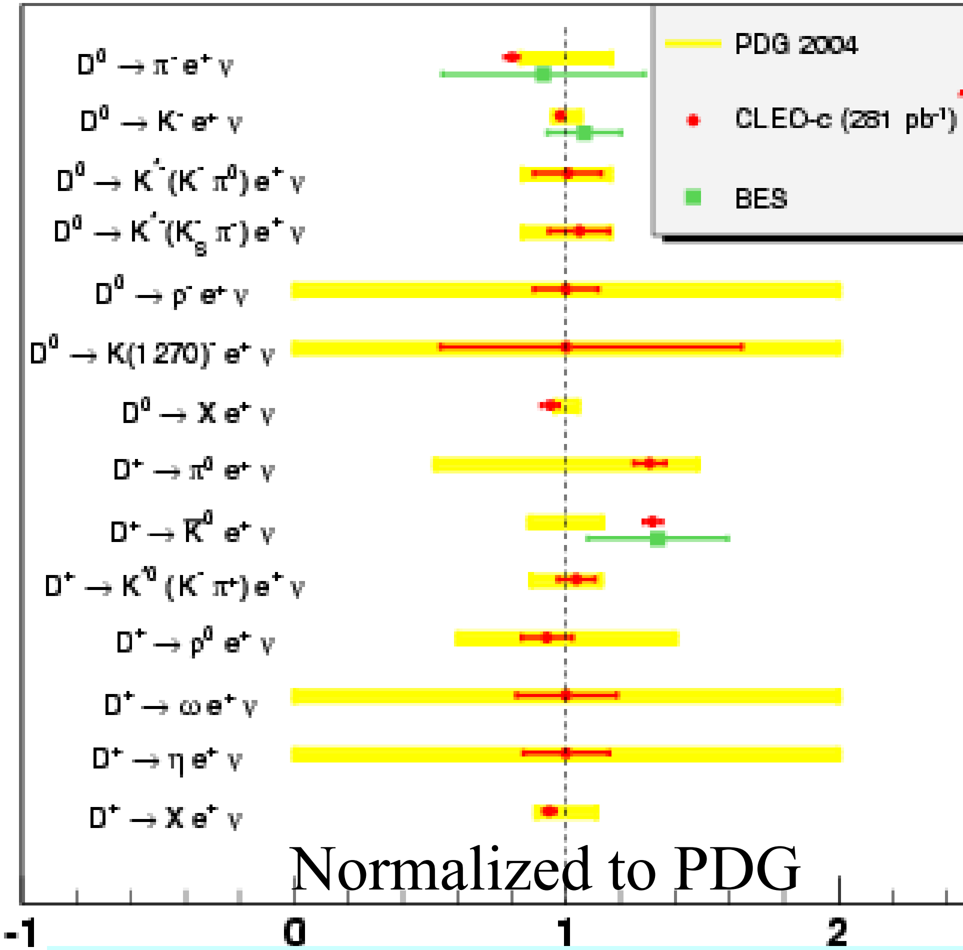
$+ \quad D^+ / D^0 \to X e^+ \nu_e$

$D \to K^* e^+ \nu_e$ form factors

Note: use PDG2004, as PDG2006 & PDG2008 are dominated by CLEO-c measurements

PRL. 97, 251801 (2006);
arXiv:0906.2983(accepted PRD);
PRL, 100, 251802(2008);
PRD, 77, 112005(2008);
PRD. 74, 052001(2006);
PRL, 102, 081801(2009);
PRL. 99, 191801 (2007);

Precision Measurements:



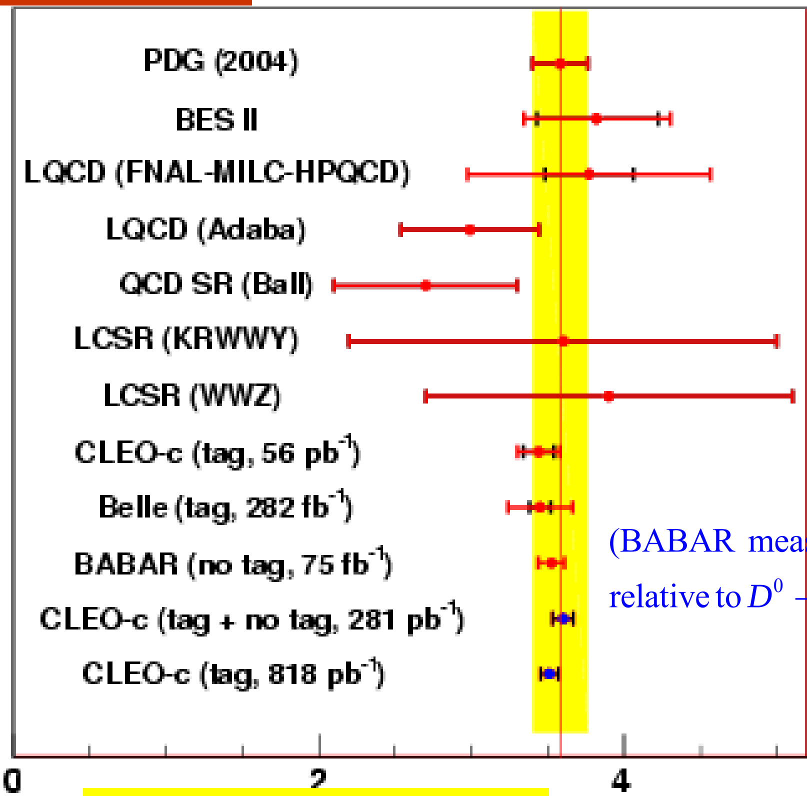
* $D \to K^* e^+ \nu$ branching fractions are for 56/pb

$D \to \pi^- / K^- / \pi^0 / \bar{K}^0 e^+ \nu$ branching fractions are for 818/pb

CLEO's measurements most precise for ALL modes; *4 modes* observed for the first time

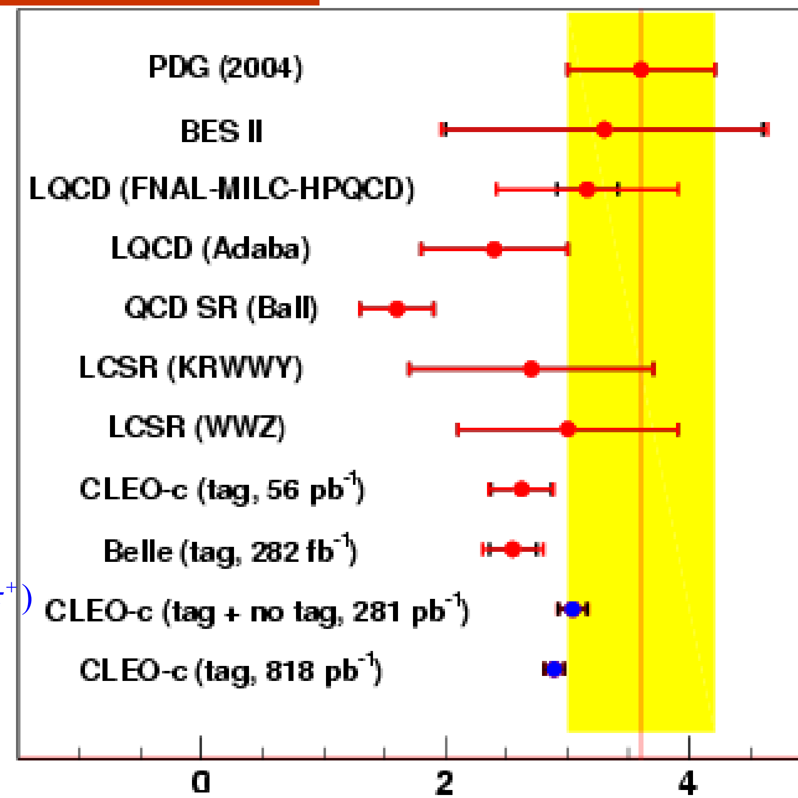
$D \to K, \pi e \nu$ Branching Fractions

$D \to K e^+ \nu$



(BABAR measures relative to $D^0 \to K^-\pi^+$)

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



$B(D^0 \to K^- e^+ \nu)$
$3.50(3)(4)\,\%$
(CLEO-c 818 pb^{-1})

$\sigma(B(Ke\nu))/B(Ke\nu) \sim 1.4\%$
$\sigma(B(\pi e\nu))/B(\pi e\nu) \sim 3.0\%$

$B(D^0 \to \pi^- e^+ \nu)$
$0.288(8)(3)\%$

arXiv:0906.2983
(accepted PRD Jul 22 2009)

Precision measurements from BABAR/Belle/CLEO-c.
CLEO-c most precise. Theoretical precision lags experiment.

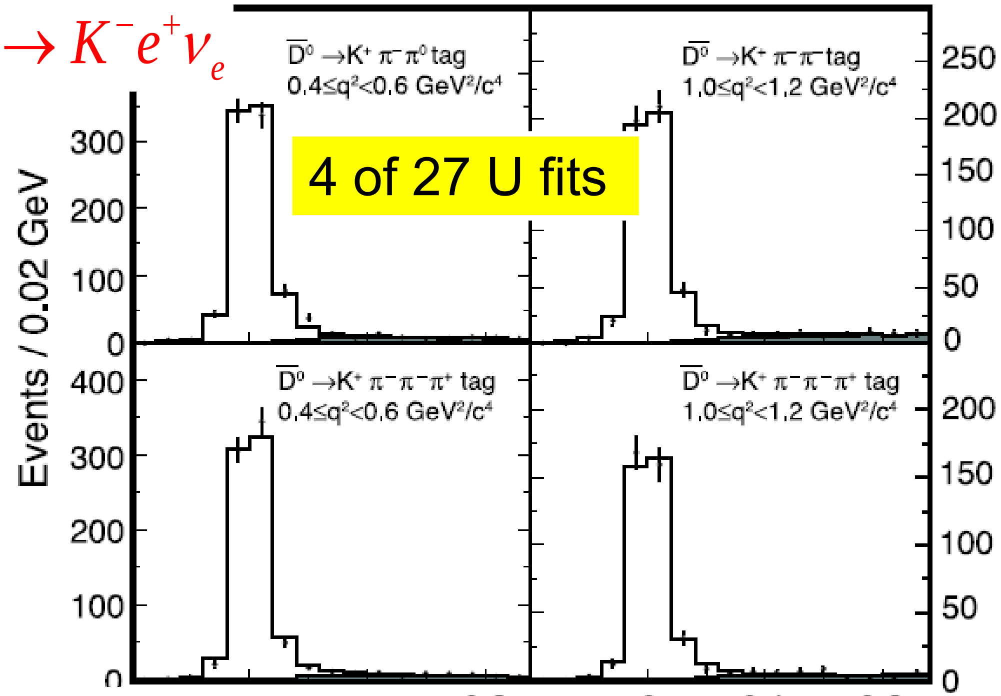
Measuring the form factor in $D \to K/\pi e\nu$

$$\frac{d\Gamma(D \to Ke\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} P_K^3 \left|f_+(q^2)\right|^2 \left|V_{cs}\right|^2$$

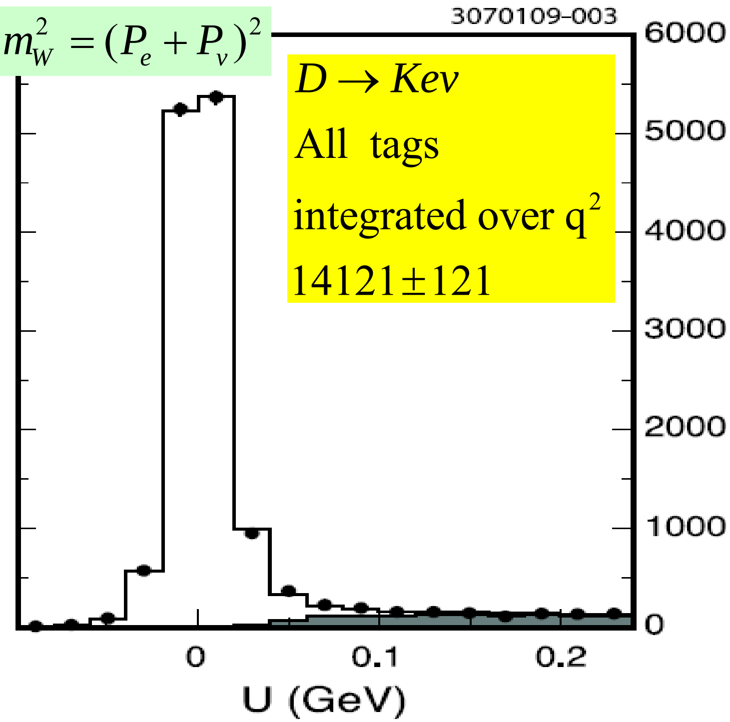
Form factor $\to$ probability hadron forms as a function of q^2

$$q^2 = m_W^2 = (P_e + P_\nu)^2$$

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



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



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 each 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

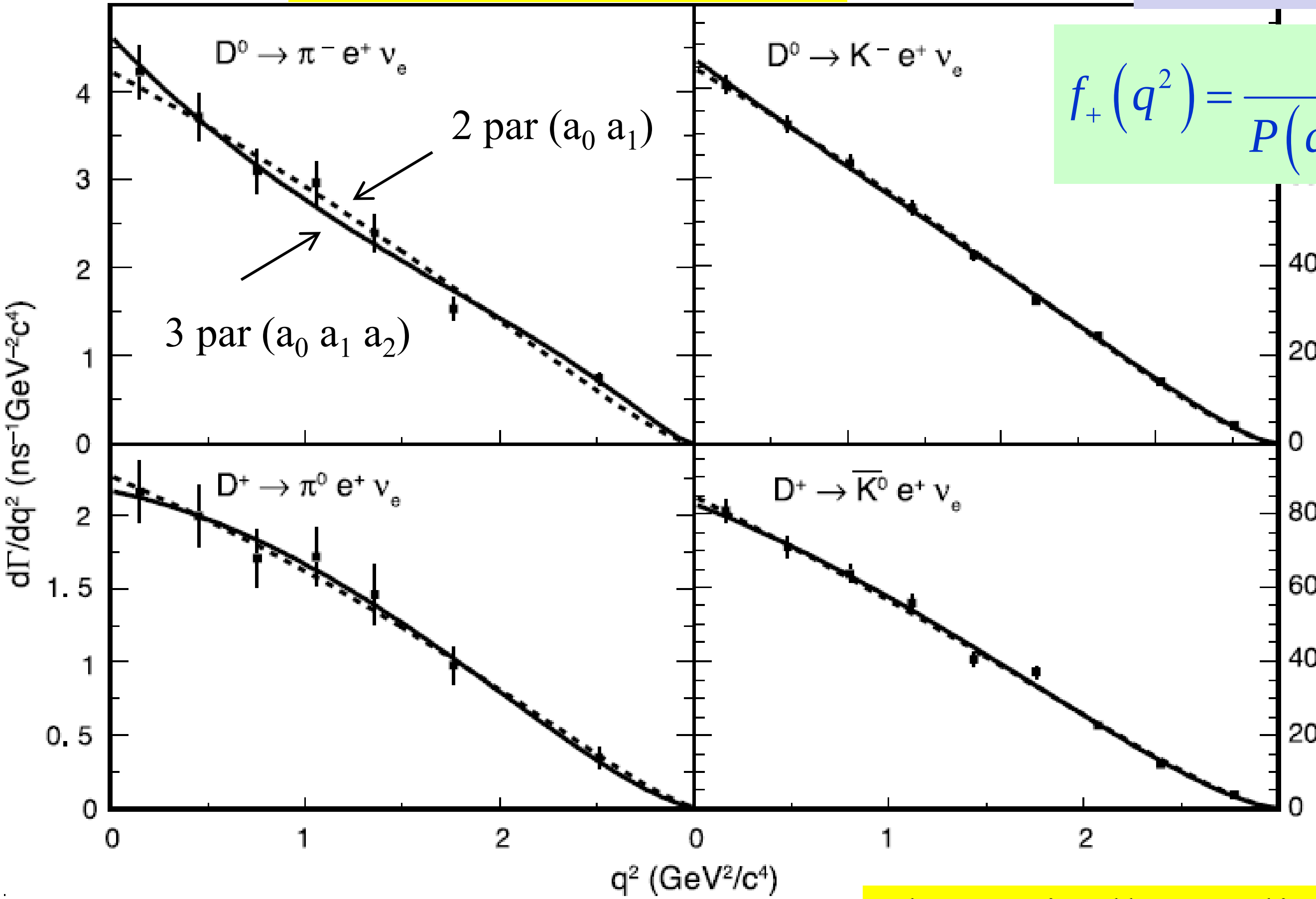
arXiv:0906.2983 (accepted PRD Jul 22 2009)

$D \to K/\pi e^+ \nu$: Fits to the $d\Gamma/dq^2$ Distributions

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K/\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cx} \right|^2$$

Fit to Becher-Hill Series

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



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

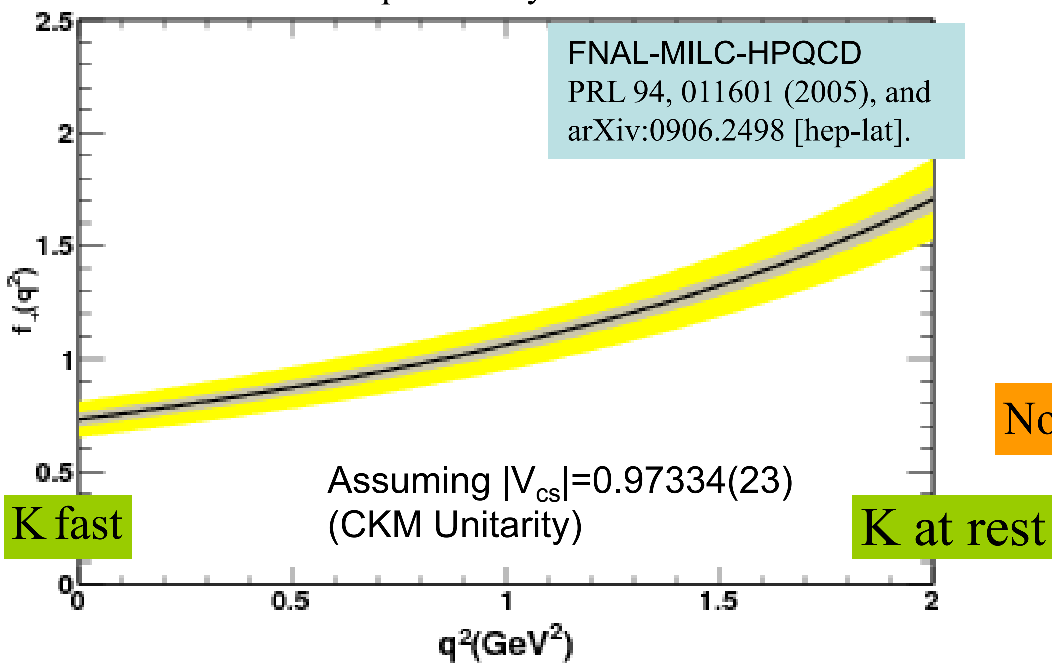
Theoretically predicted decay rates

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

$D \to Ke^{+}\nu$ Form Factor: test of LQCD

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

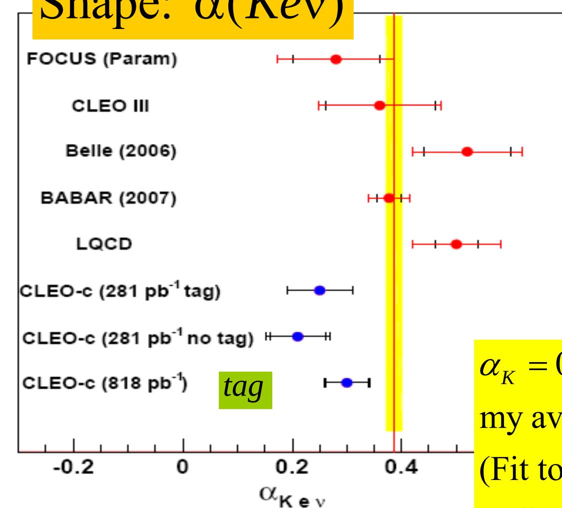
Form factor measures probability hadron will be formed



Modified pole model used as example

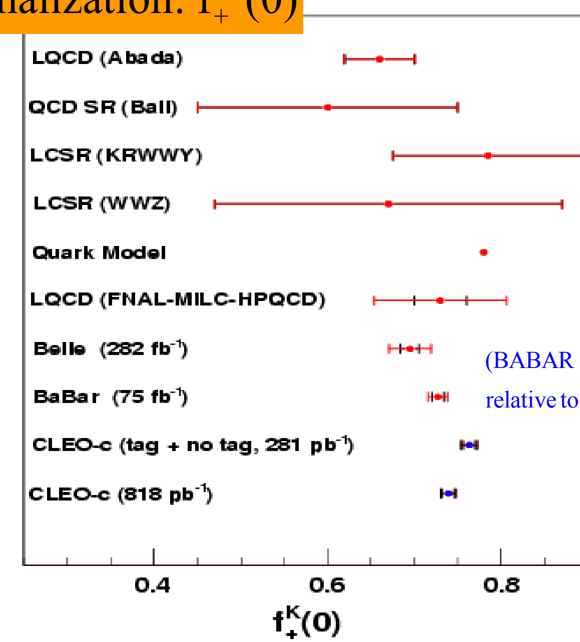
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha\, q^2/m_{pole}^2\right)}$$

Shape: $\alpha(Ke\nu)$



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

Normalization: $f_+^K(0)$

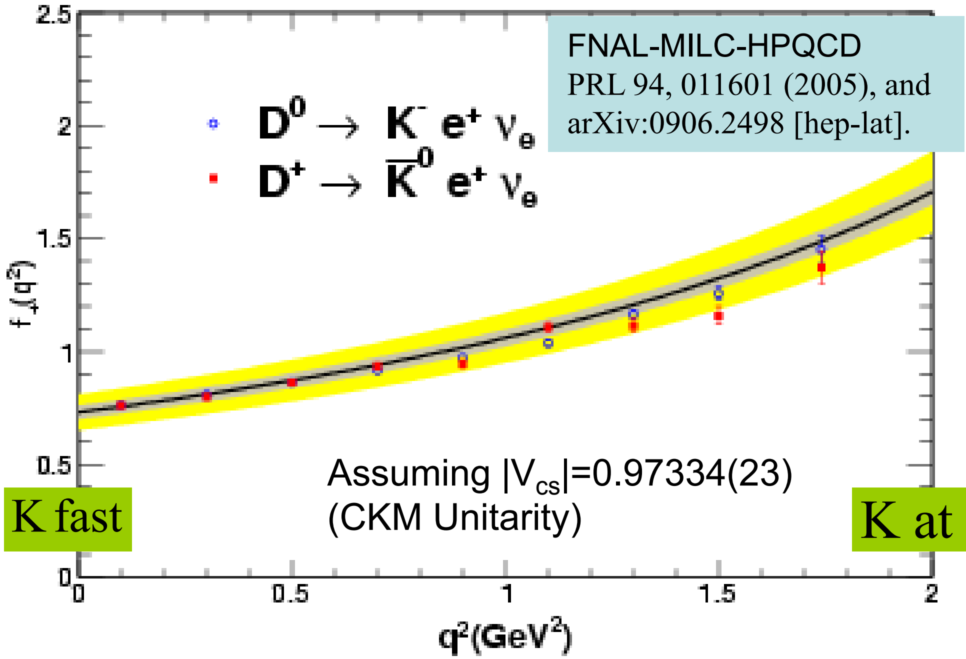


Normalization: experiments (1.2%) consistent with LQCD (10%). *Theoretical precision lags.*
CLEO-c prefers smaller value for shape parameter, α

$D \to K e^+ \nu$ Form Factor: test of LQCD

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

Form factor measures probability hadron will be formed



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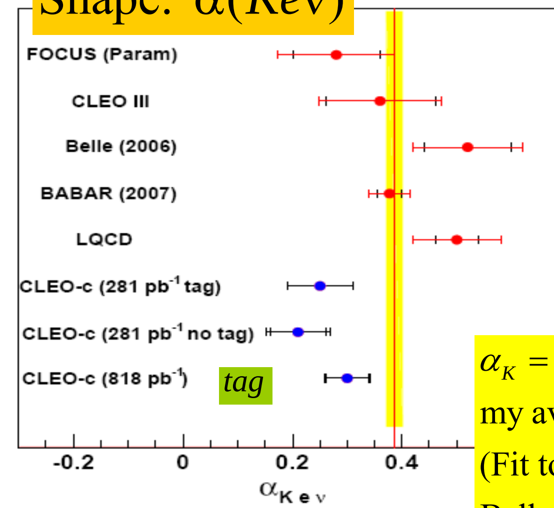

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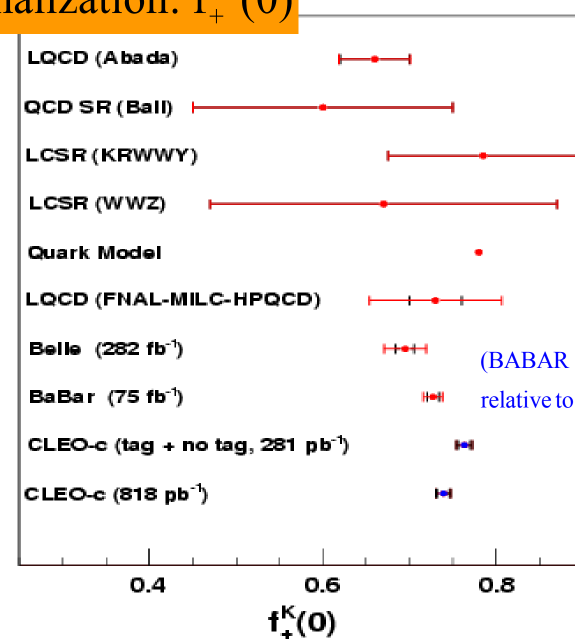
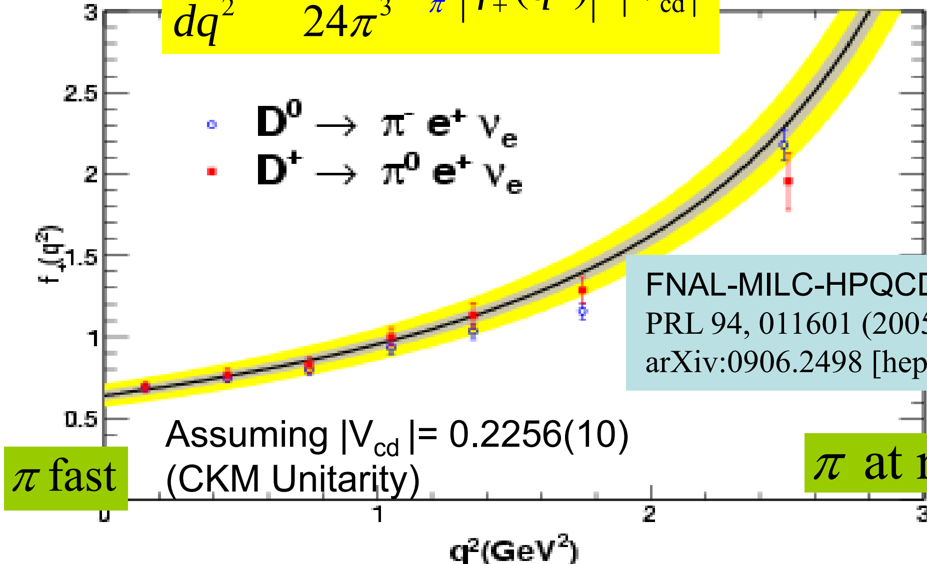


CLEO-c prefers smaller value for shape parameter, α
Normalization: experiments (1.2%) consistent with LQCD (10%). *Theoretical precision lags.*

$D^0 \to \pi^- e^+ \nu$ Form Factor: test of LQCD

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



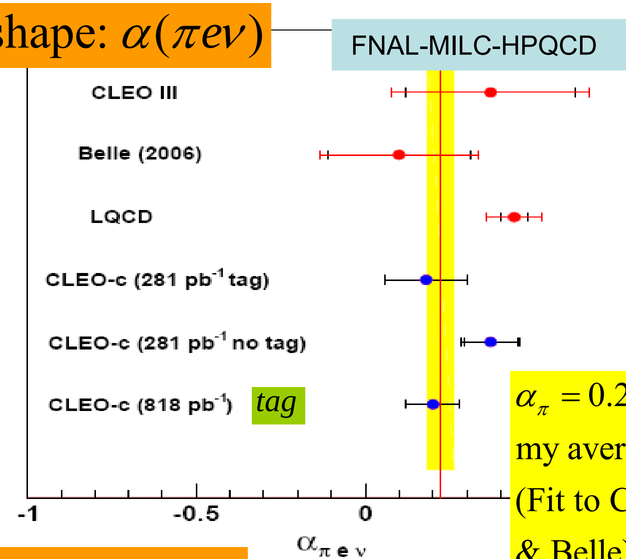
FNAL-MILC-HPQCD
PRL 94, 011601 (2005), and arXiv:0906.2498 [hep-lat].

Assuming $|V_{cd}|$= 0.2256(10) (CKM Unitarity)

π fast

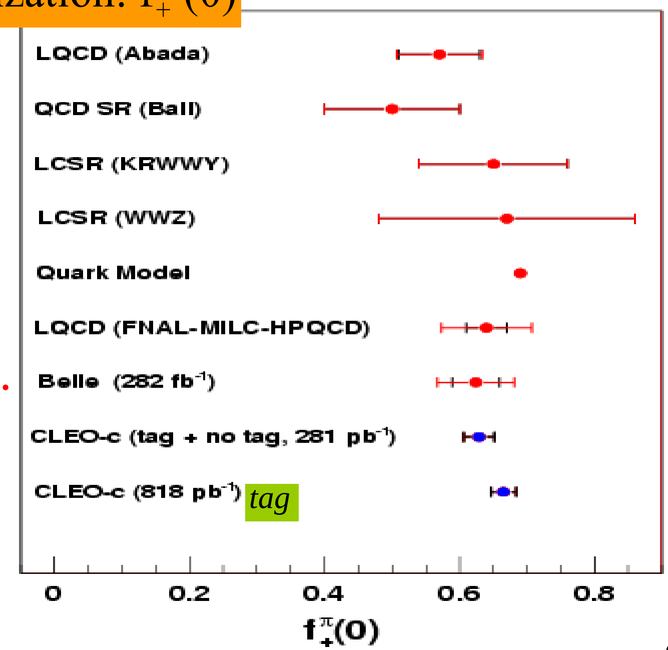
π at rest

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



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

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



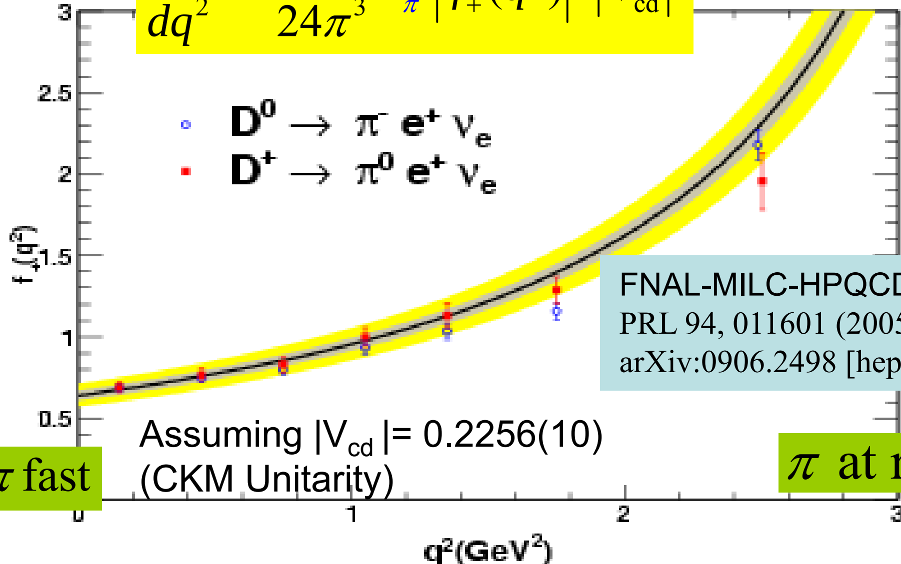
Modified pole model used as example

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

Normalization experiments (2%) consistent with LQCD (10%). CLEO-c is most precise. *Theoretical precision lags.*

$D^0 \rightarrow \pi^- e^+ \nu$ Form Factor: test of LQCD

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



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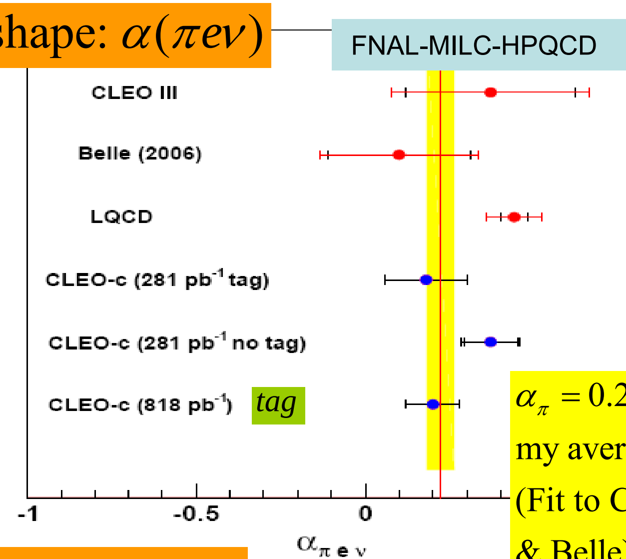

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(Fit to CLEO
& Belle)

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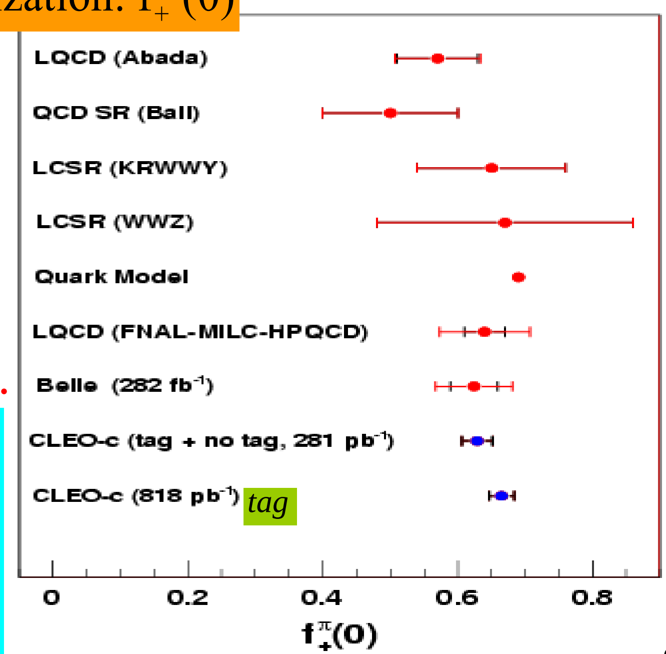

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Normalization experiments (2%) consistent with LQCD (10%). CLEO-c is most precise. *Theoretical precision lags.*

The data determines $|V_{cd}|f_+(q^2)$. To extract $|V_{cd}|$ we fit to $|V_{cd}|f_+(q^2)$ using Becher-Hill z -expansion to determine $|V_{cd}|f_+(0)$ & use $f_+(0)$ from LQCD (FNAL-MILC-HPQCD.) Same for $|V_{cs}|$

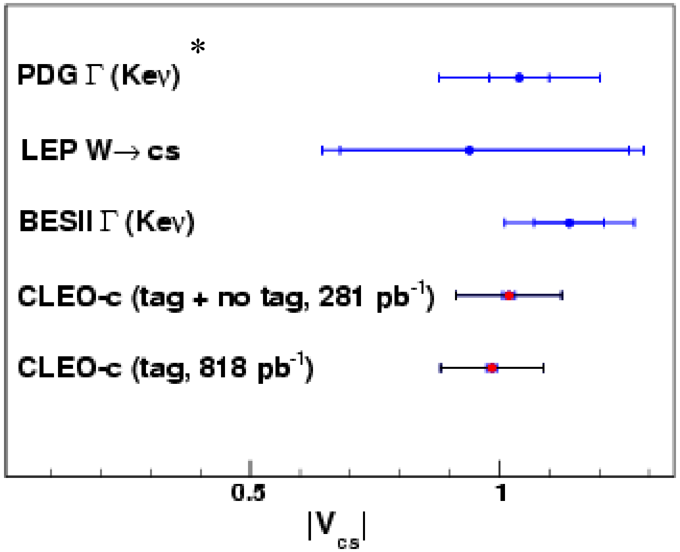
$|V_{cs}|$ & $|V_{cd}|$ Results

arXiv:0906.2983
(accepted PRD Jul 22 2009)

CLEO-c: the most precise *direct* determination of V_{cs}

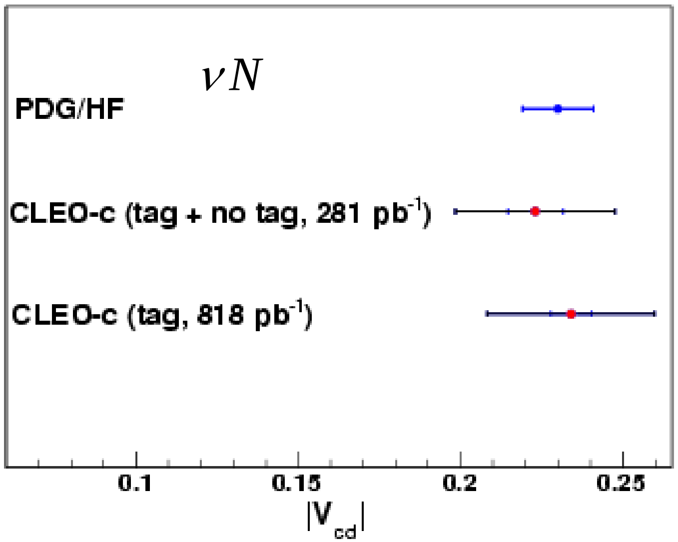
$$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 10\%(\text{theory})$$

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



CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.1\%(\text{expt}) \oplus 10\%(\text{theory})$
νN remains most precise determination *(for now)*

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



* PDG2002

Fits use Becher-Hill z-expansion

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

arXiv:0906.2983
(accepted PRD Jul 22 2009)

THEORY UNCERTAINITY REMOVED

CLEO-c: the most precise *direct* determination of V_{cs}

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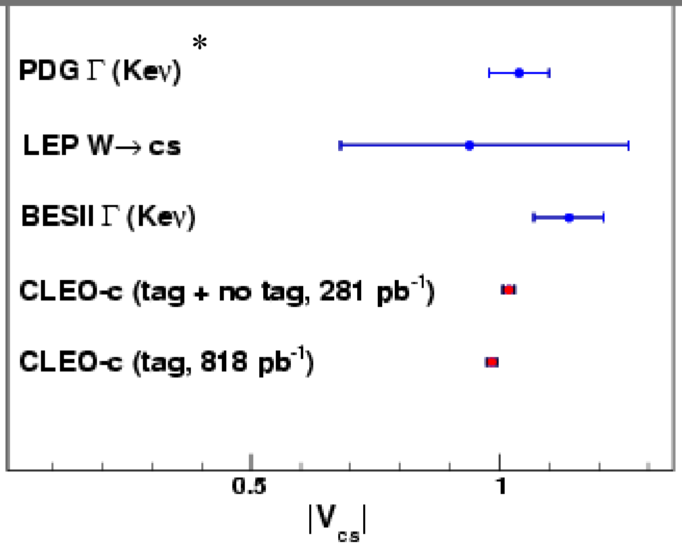

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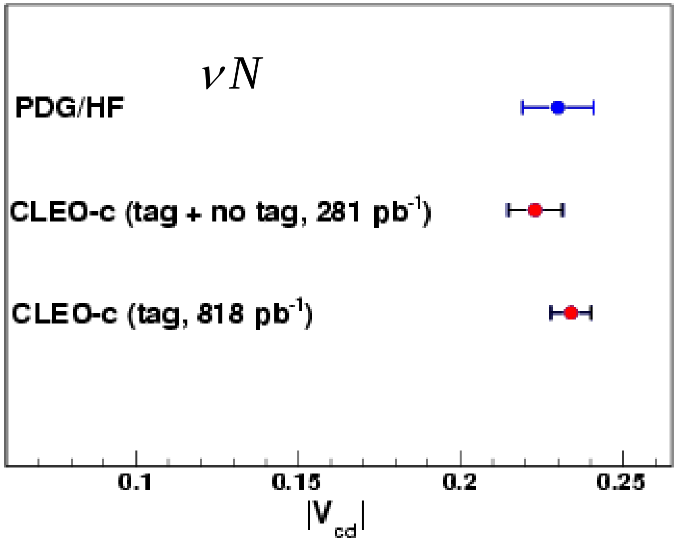


LQCD form factors with improved precision are eagerly awaited

* PDG2002

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

arXiv:0906.2983 (accepted PRD Jul 22 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

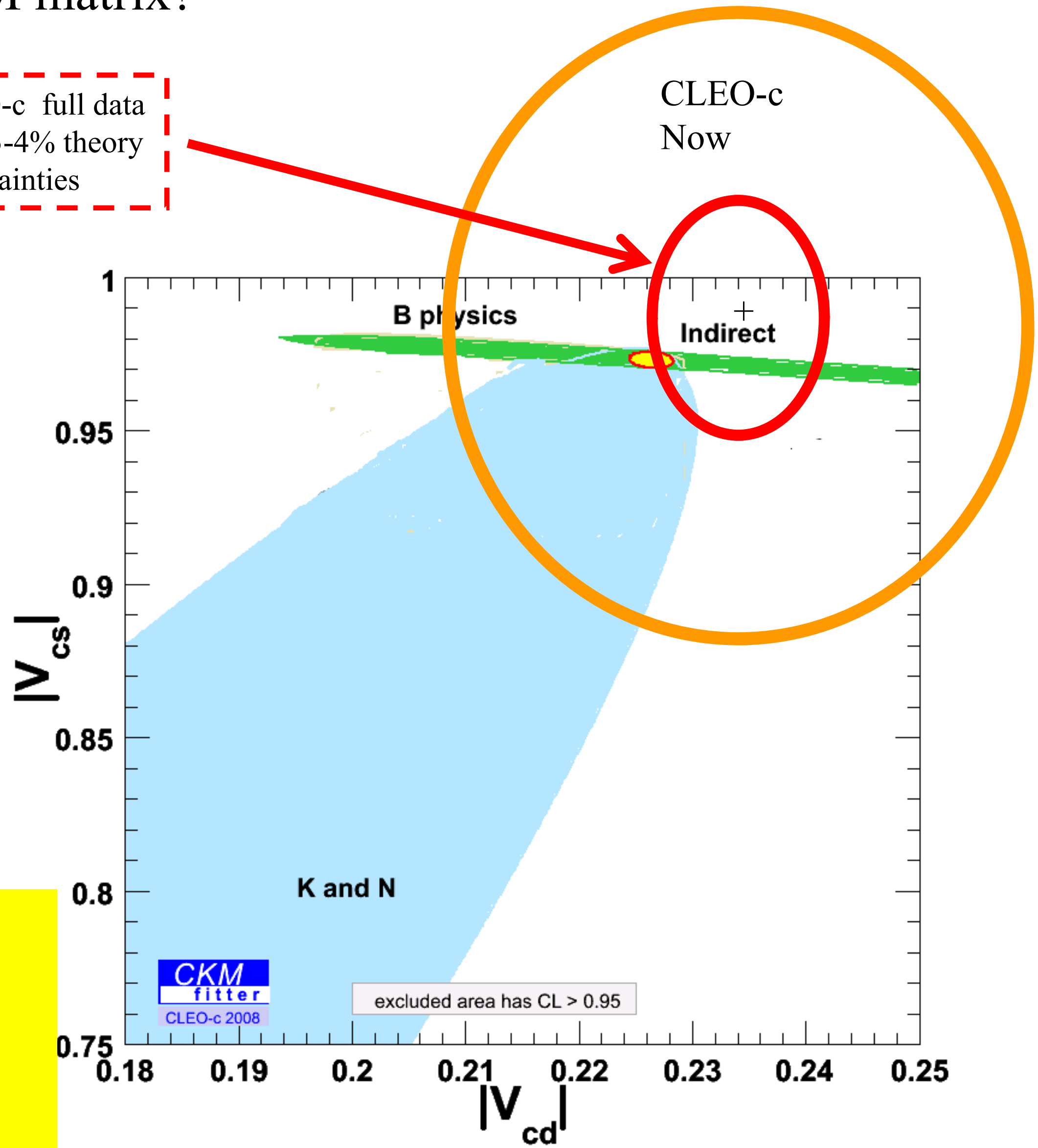
(D semileptonic decays CLEO)

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



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

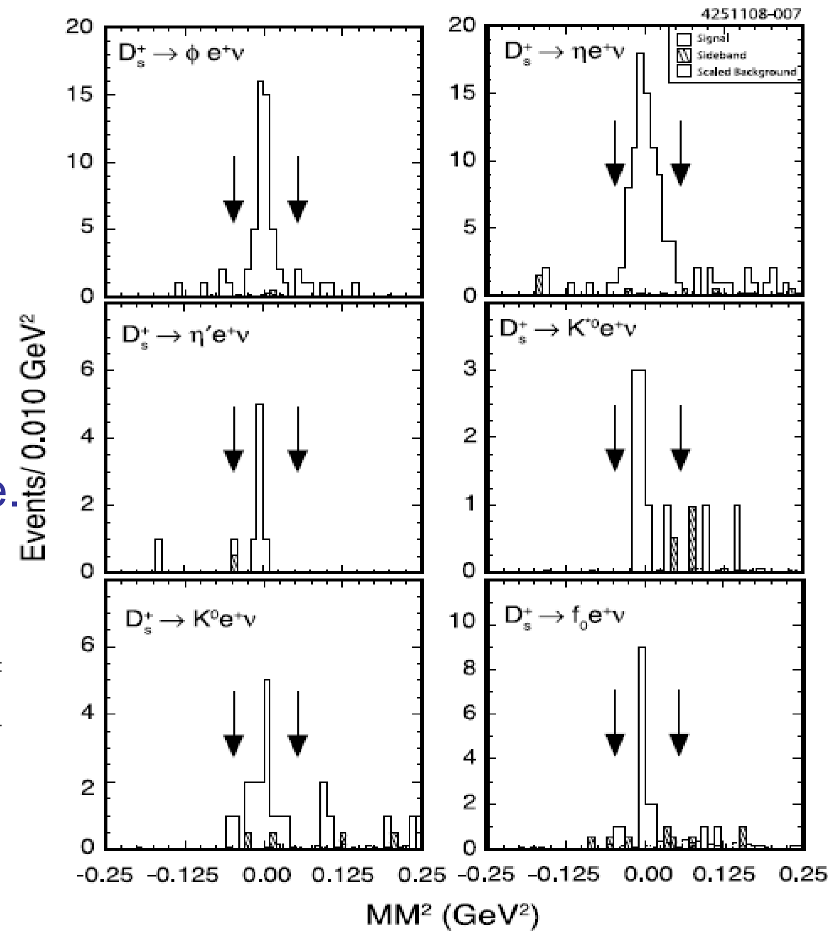
Plots by Sebastien Descortes-Genon & Ian Shipsey

See also talk by Descotres-Genon at joint BABAR-Belle-BESIII-CLEO-c Workshop 11/07, Beijing

Observe 6 Exclusive D_s Semileptonic Decays

- Similar to $D_s \to \mu\nu$ analysis: tag;
  reconstruct visible parts of signal; plot MM^2
- First absolute branching fraction measurements for D_s SL decays
- Total width of these exclusive modes is 16% lower than the D^0/D^+ semileptonic widths.
- Shed light on η-η'-glueball mixing
- Observation of a semileptonic decay including a scalar meson in the final state.

arXiv:0903:0601



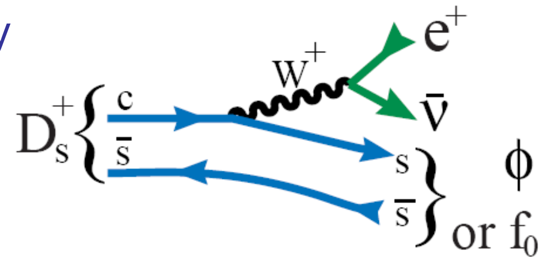
Signal Mode	$\mathcal{B}(\%)$
$D_s^+ \to \phi e^+ \nu_e$	$2.29 \pm 0.37 \pm 0.11$
$D_s^+ \to \eta e^+ \nu_e$	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \to \eta' e^+ \nu_e$	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \to K^0 e^+ \nu_e$	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \to K^{\star 0} e^+ \nu_e$	$0.18 \pm 0.07 \pm 0.01$
$D_s^+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

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

310 pb^{-1} @4170 (Half of full dataset)

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

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



600 pb^{-1} @4170

(CLEO-c full dataset)

arXiv: 0907.3201
(submitted to PRD Jul 18 2009)

- 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:

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

✓ $$B(D_s^+ \to \phi e^+\nu) = (2.36 \pm 0.23 \pm 0.13)\%$$

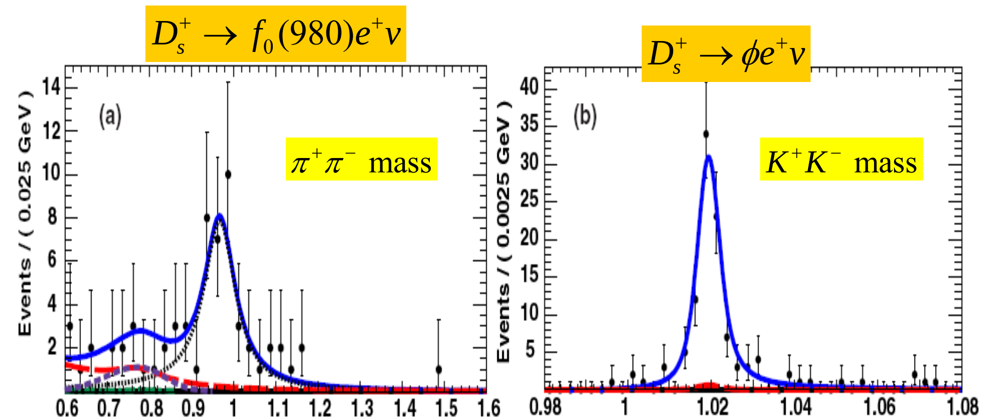
✓ $$\left.\frac{\Gamma(D_s^+ \to f_0(980)e^+\nu,\ f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42 \pm 11)\%$$

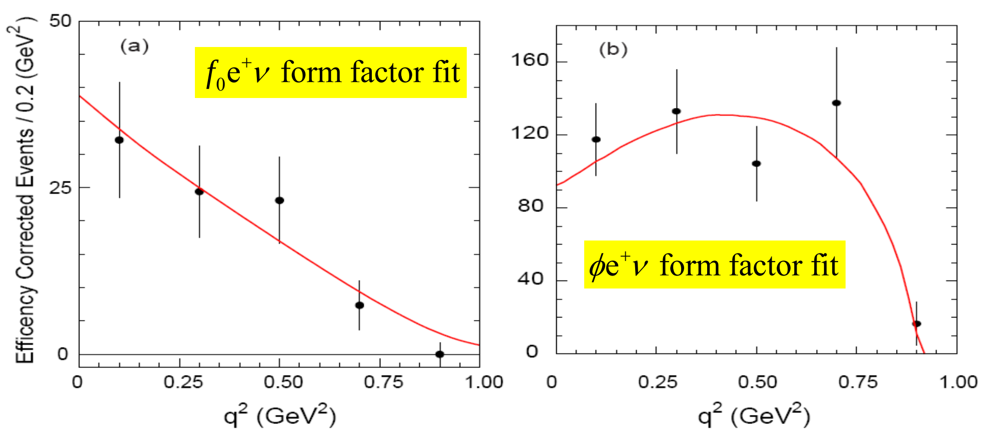
$$\left[\text{Predicted to equal } \frac{\Gamma(B_s \to J/\Psi f_0(980),\ f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\Psi\phi, \phi \to K^+K^-)}\right]$$

(Stone & Zhang)

✓ $M_{f_0(980)} = (977^{+11}_{-9} \pm 1)$ 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

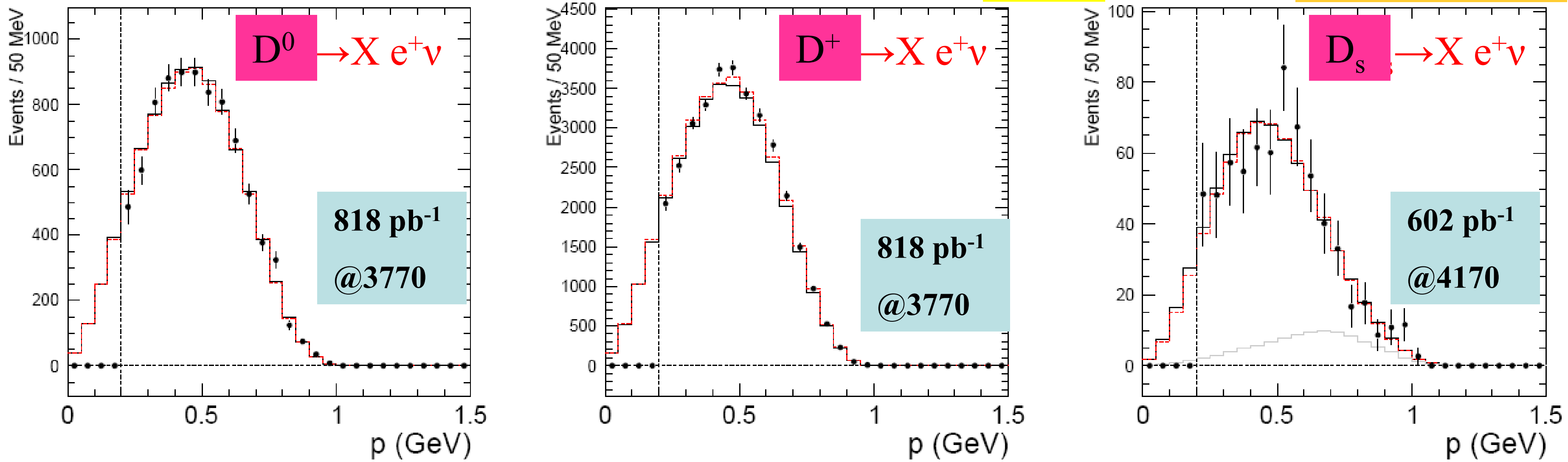




Inclusive Semileptonic Decays of D^0,D^+, and D_s

NEW

PRELIMINARY



	$D^0 \to X e^+\nu$	$D^+ \to X e^+\nu$	$D_s \to X e^+\nu$
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

- 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

Summary of CLEO-c CKM physics motivated measurements

CLEO-c hadronic D^0, D^+ and D_s branching fractions more precise than PDG averages: (for D^0, D^+ 2% precision is syst.limited) CLEO establishes charm hadronic scale

Most precise: $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV consistent with LQCD $\rightarrow$ 1% (2 MeV) full data

Most precise: $f_{Ds} = (259.5 \pm 6.6 \pm 3.1)$ MeV $\sim 2.3\sigma$ higher than LQCD.
To interpret as "prosaic" or "exciting": requires more data (BES III)

Most precise measurement of form factors magnitudes in $D \rightarrow K/\pi e \nu$

Most precise $|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103_{\text{theory}}$

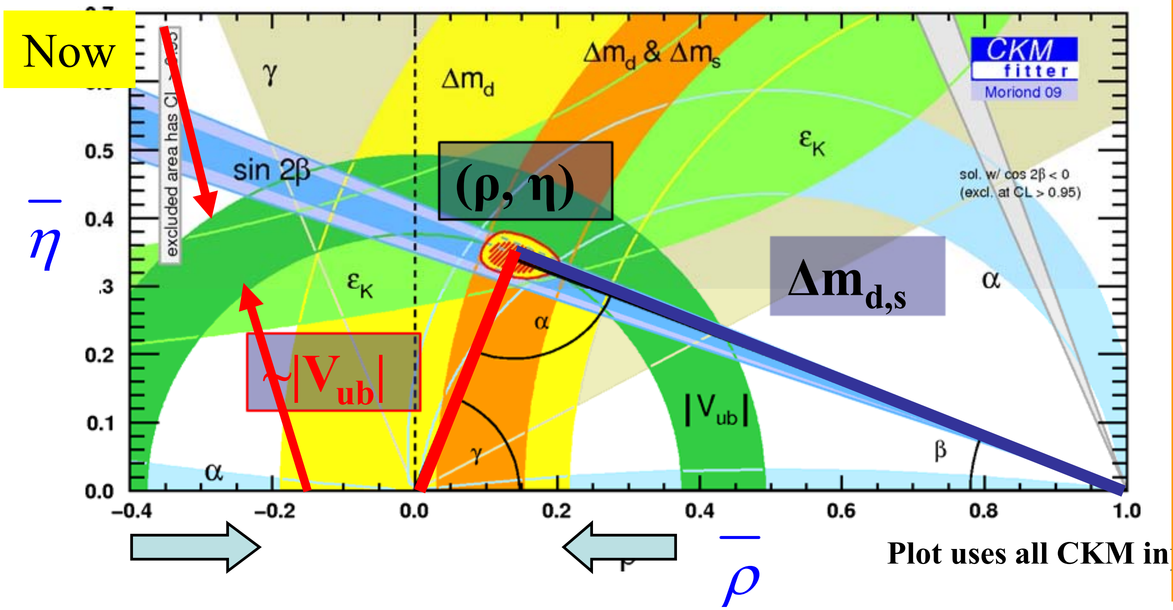
$|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025_{\text{theory}}$

Most precise determination from semileptonic decay

6 exclusive D_s semileptonic decays & measurement of form factor in $D_s \rightarrow f_0(980) e^+ \nu$. $SU(3)$ is broken in $D \rightarrow X e \nu$ decays

~90 CLEO-c papers now pubished or submitted, & many more analyses to come.
Longer term the charm factory mantle passes to BES III

Precision theory + charm = large impact

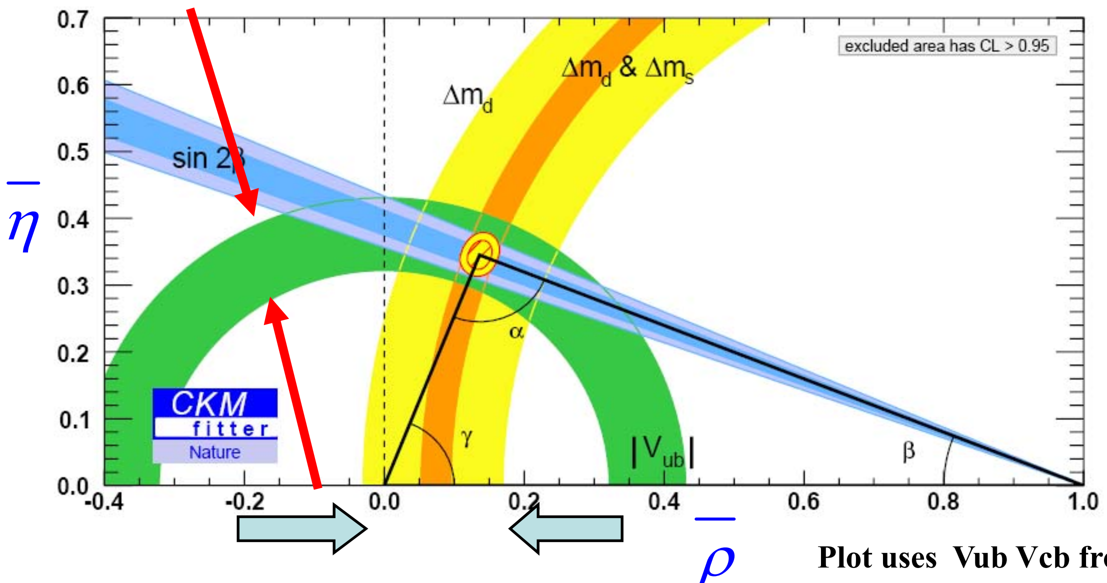


Plot uses all CKM in

* CLEO-c: a major contribution to the goal the lower plot represents
* LQCD has been validated at the 4% level (f_{D+})
* A triumph for theory & experiment!

More precise LQCD form factor calculations needed

more data ➔ BESIII



Few % precision QCD Calculations tested with few % *precision* charm data

➔theory errors of a few % on B system decay constants & semileptonic form factors

Plot uses Vub Vcb from exclusive decays
no gamma or alpha constraints

Additional Material

Semileptonic Decay Form Factors

- Form factors relate to the probability of forming final state at given q^2 .
- Theoretical predictions for form factors are needed to turn the measured rates into $|V_{cx}|$ determinations.
- Theory often calculates this probability at fixed q^2 and uses parameterizations to extrapolate to full q^2 range.
- Theoretical approaches include phenomenological models, QCD sum rules, and LQCD.
- LQCD is systematically improvable and aims for several percent precision (we focus on this)
- Assuming zero lepton mass:

h – pseudoscalar: $$H^{\mu} = f_{+}(q^2)(P_D + P_h)^{\mu}$$

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

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

ensure a_K's good behaviour

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

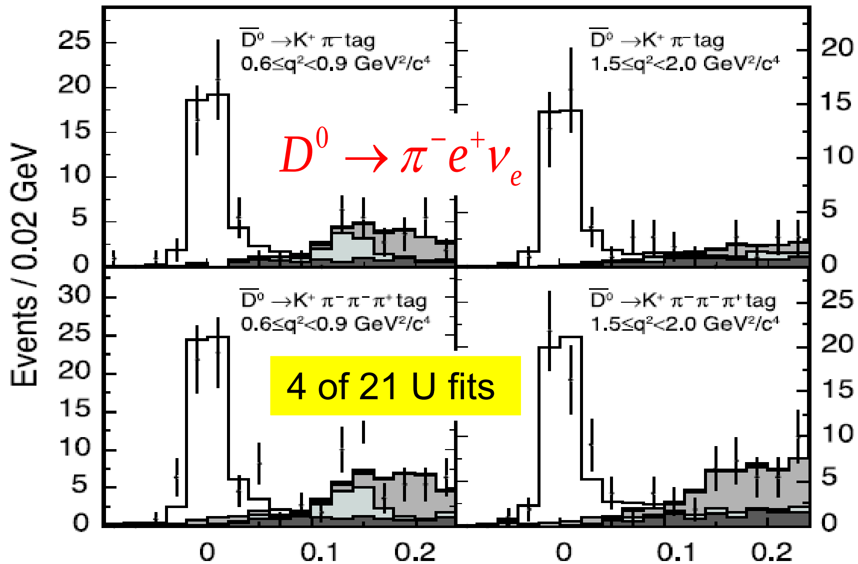
$t_\pm \equiv \left(M_D \pm m_{K,\pi}\right)^2$, t_0: arbitrary q^2 value that maps to z=0

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

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

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

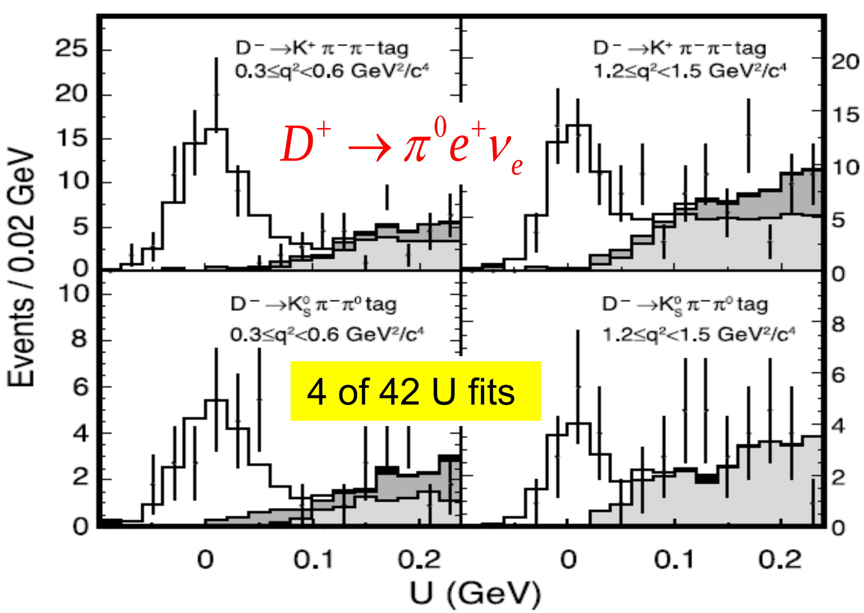
Measuring the form factor in D→K/πeν

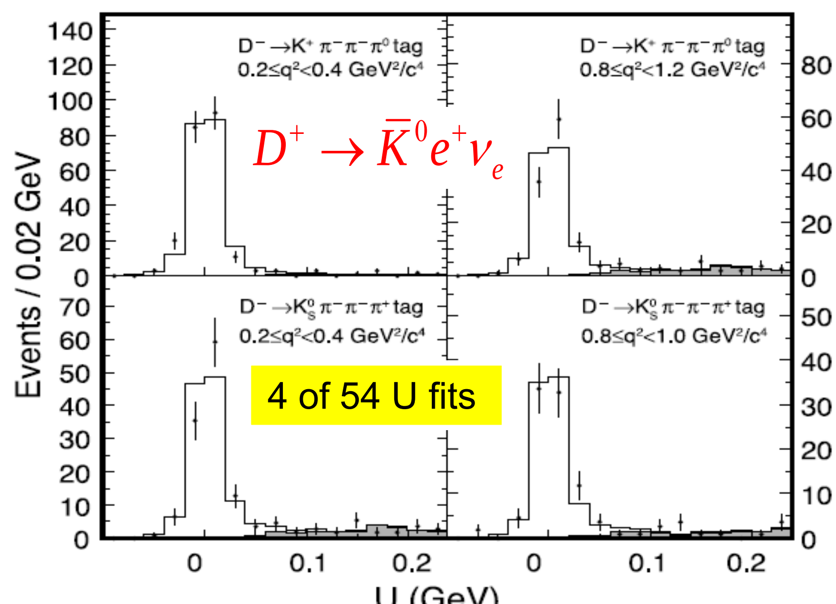


$D^0 \to \pi^- e^+ \nu_e$

S/N	~40/1
Signal events	~1400
U resolution	~10 MeV
q^2 resolution	~0.008 GeV²/c⁴

arXiv:0906.2983
(accepted PRD Jul 22 2009)





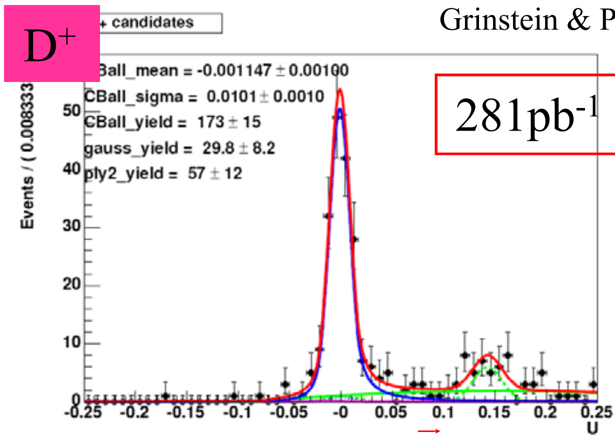
$D \to \rho e \nu$ (tagged, 281/pb)

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

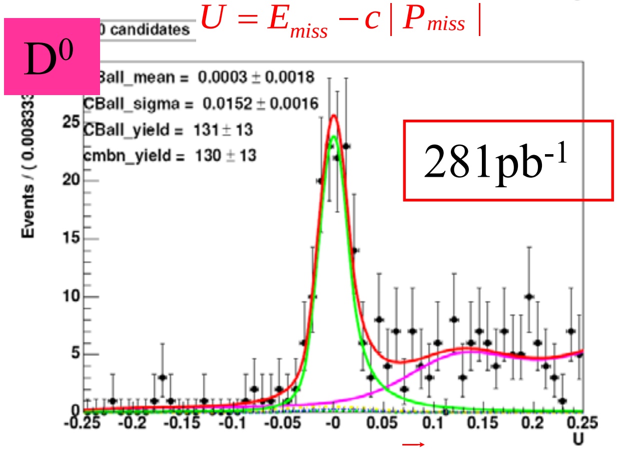
$$\frac{d\Gamma(B \to \rho e \nu)/dq^2}{d\Gamma(B \to K^* \ell^+ \ell^-)/dq^2} \propto \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

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

Grinstein & Pirjol [hep-ph/0404250]

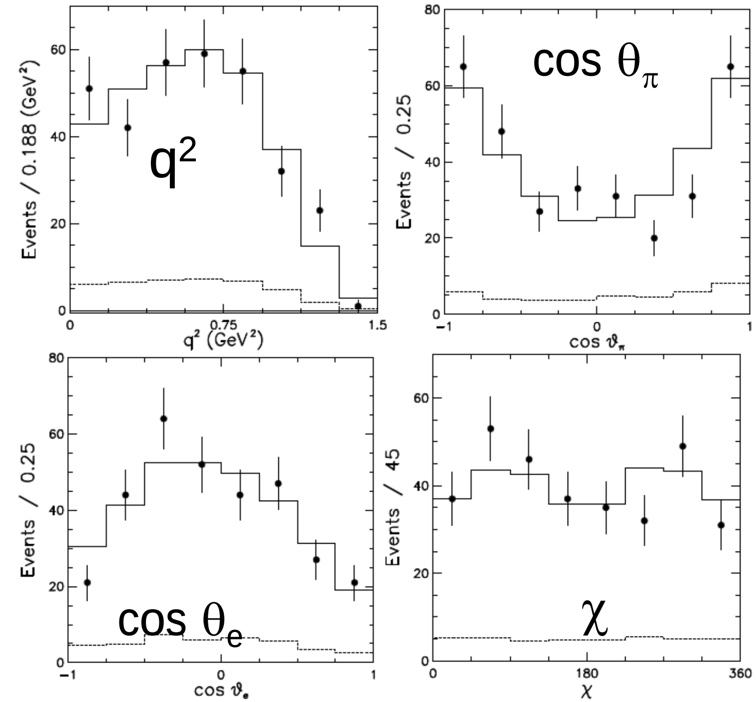


$U = E_{miss} - c\,|\vec{P}_{miss}|$



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

Fixed background shape and signal tails from MC



Line is projection for fitted R_V, R_2

$B(D^0 \to \rho^- e^+ \nu) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$
$B(D^+ \to \rho^0 e^+ \nu) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$
Isospin average:
$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2}\ \mathrm{ps}^{-1}$

Simultaneous fit to $D^+ \to \rho^0 e\nu$, $D^0 \to \rho^- e\nu$
$R_V = 1.40 \pm 0.25 \pm 0.03$
$R_2 = 0.57 \pm 0.18 \pm 0.06$

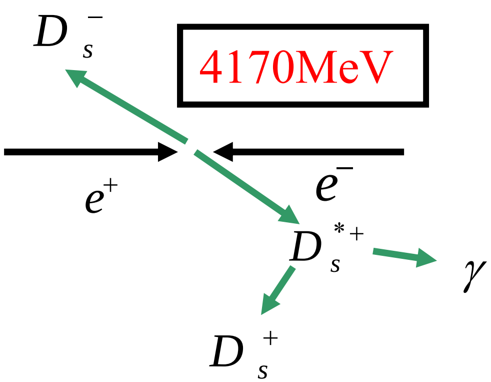
PRELIMINARY

Update to full data set soon

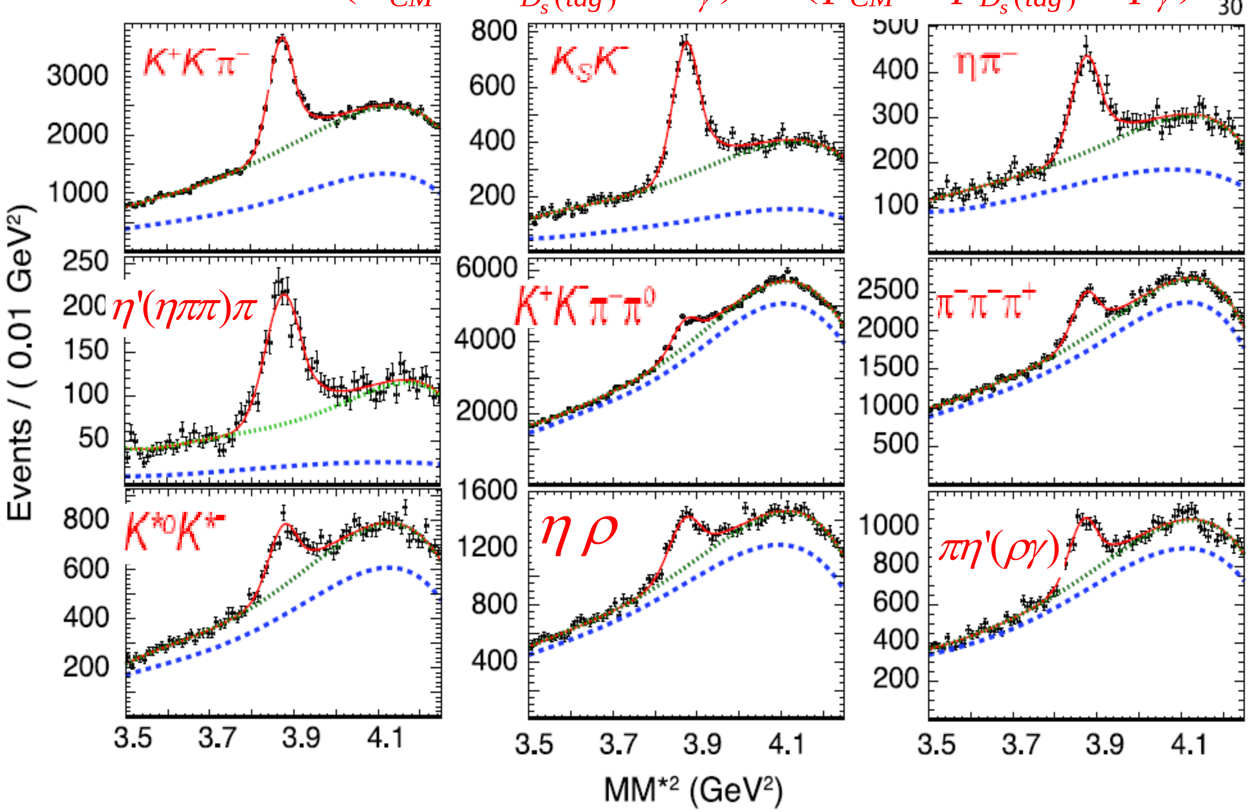
D_s^+ Exclusive Semileptonic Decays

- 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

$e^+e^- \rightarrow D^*_s D_s$



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



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

arXiv: 0907.3201
(submitted to PRD Jul 18 2009)

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