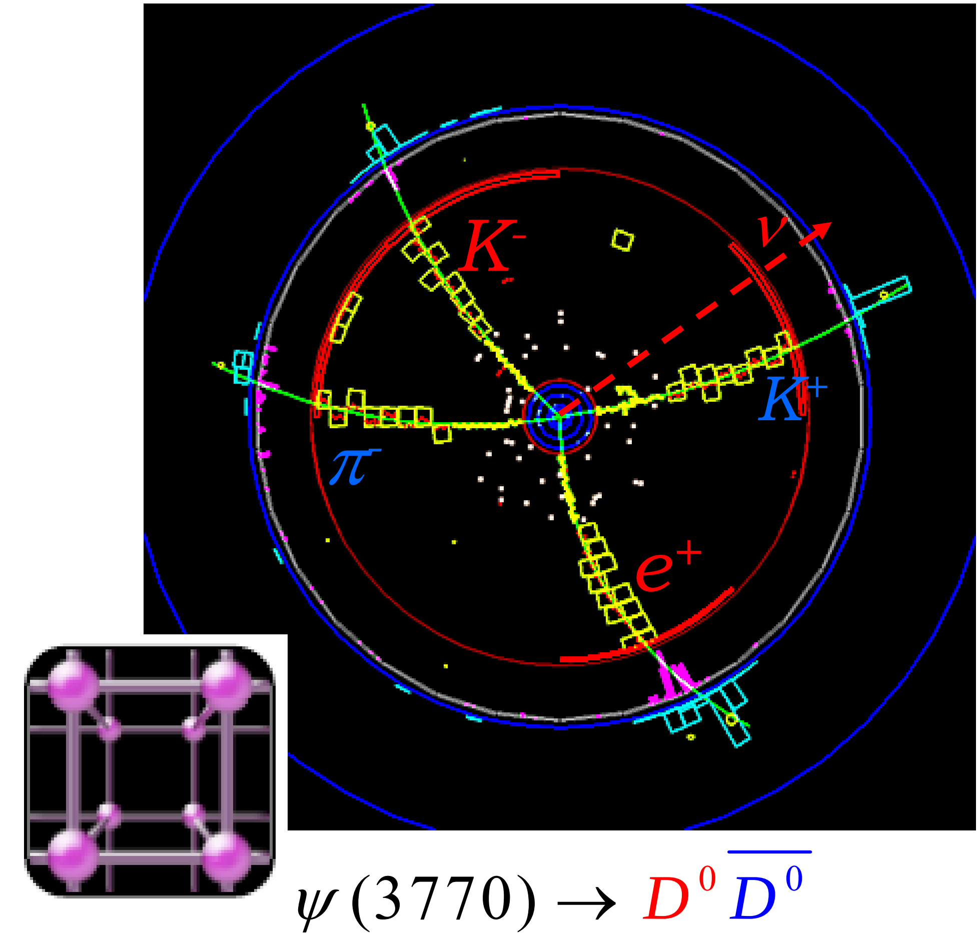
Latest CLEO-c Results

OUTLINE

The role of charm in particle physics

Testing the Standard Model with precision quark flavor physics

Direct Searches for Physics Beyond the Standard Model



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

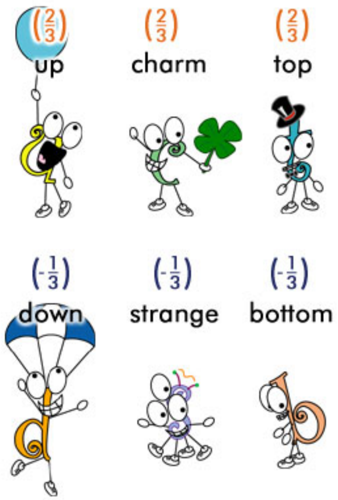
$$\overline{D^0} \to K^+\pi^-, D^0 \to K^- e^+ \nu$$

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

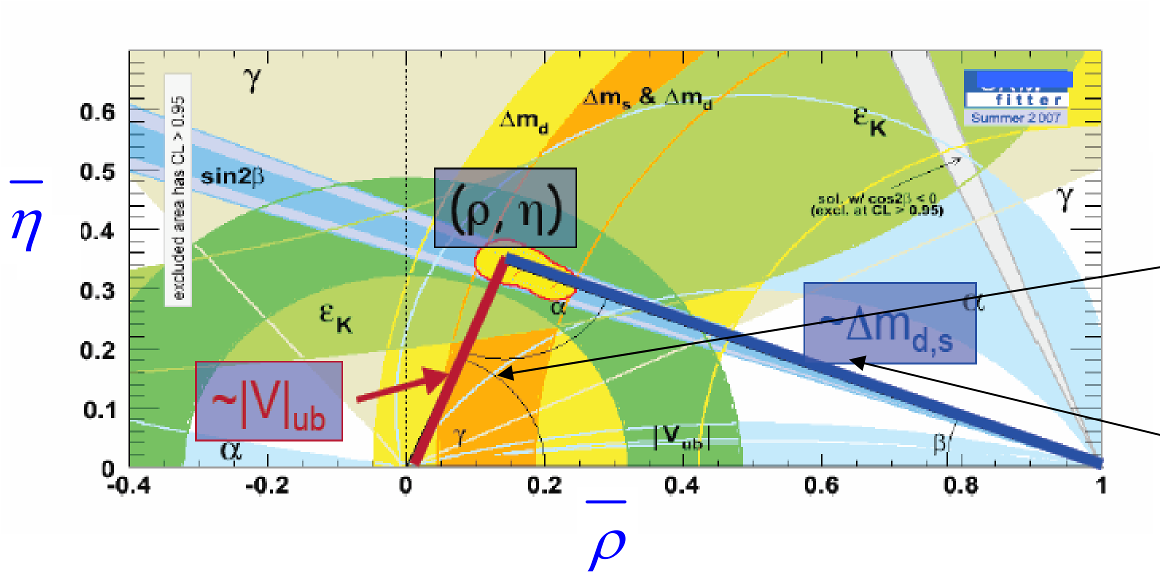
3 examples: Universe, kaons, beauty but Standard Model CP violation too small, need additional sources of CP violation

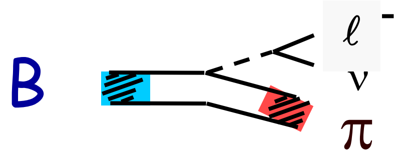
Connection between flavor physics & electroweak symmetry breaking?

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

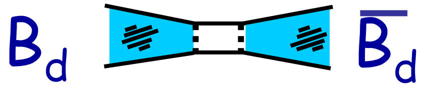
Precision Quark Flavor Physics

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



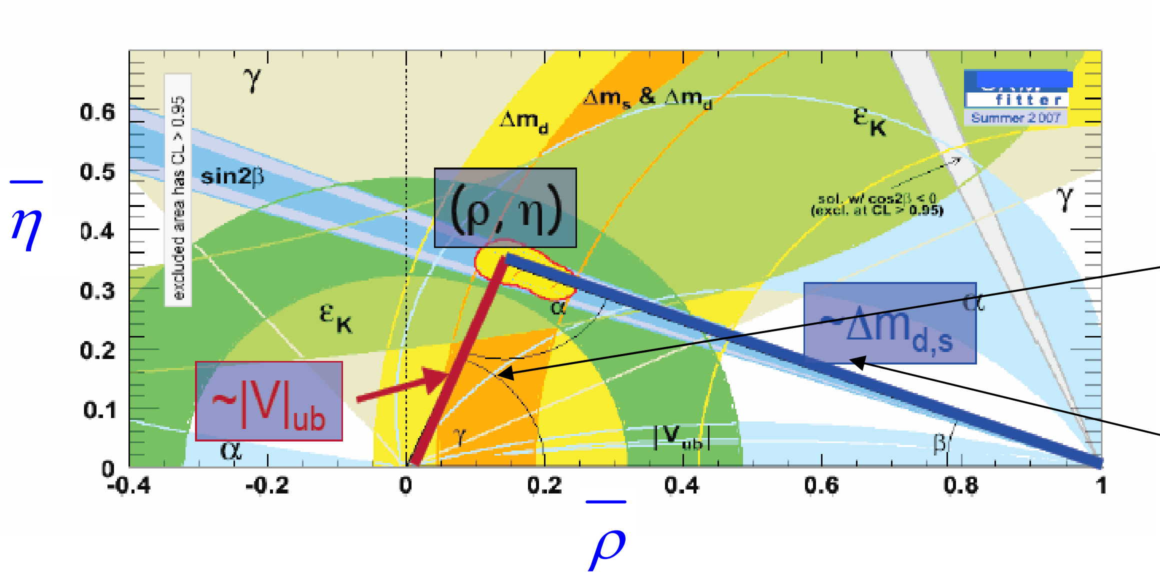


$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$

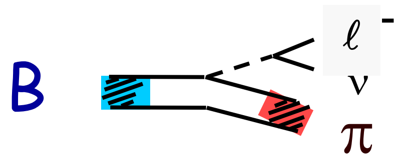


$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

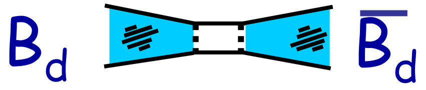
Precision Quark Flavor Physics



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

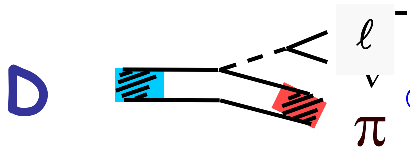


$$\propto \left[f^{B\to\pi}(q) \right]^2 \left| V_{ub} \right|^2$$

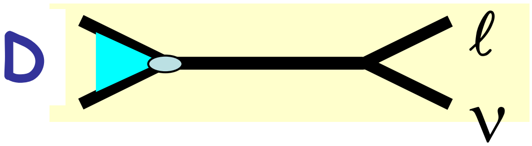


$$\propto \left[f_{Bd} \right]^2 \left| V_{td} \right|^2$$

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



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

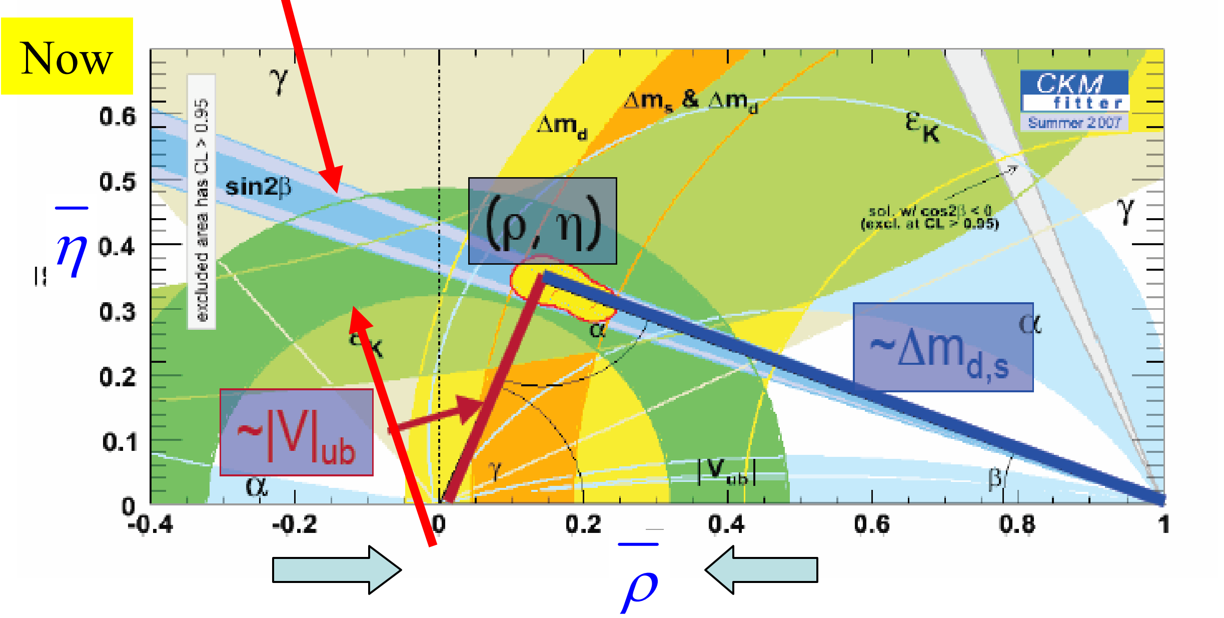


$$\propto \left[f_{D+} \right]^2 \left| V_{cd} \right|^2$$

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

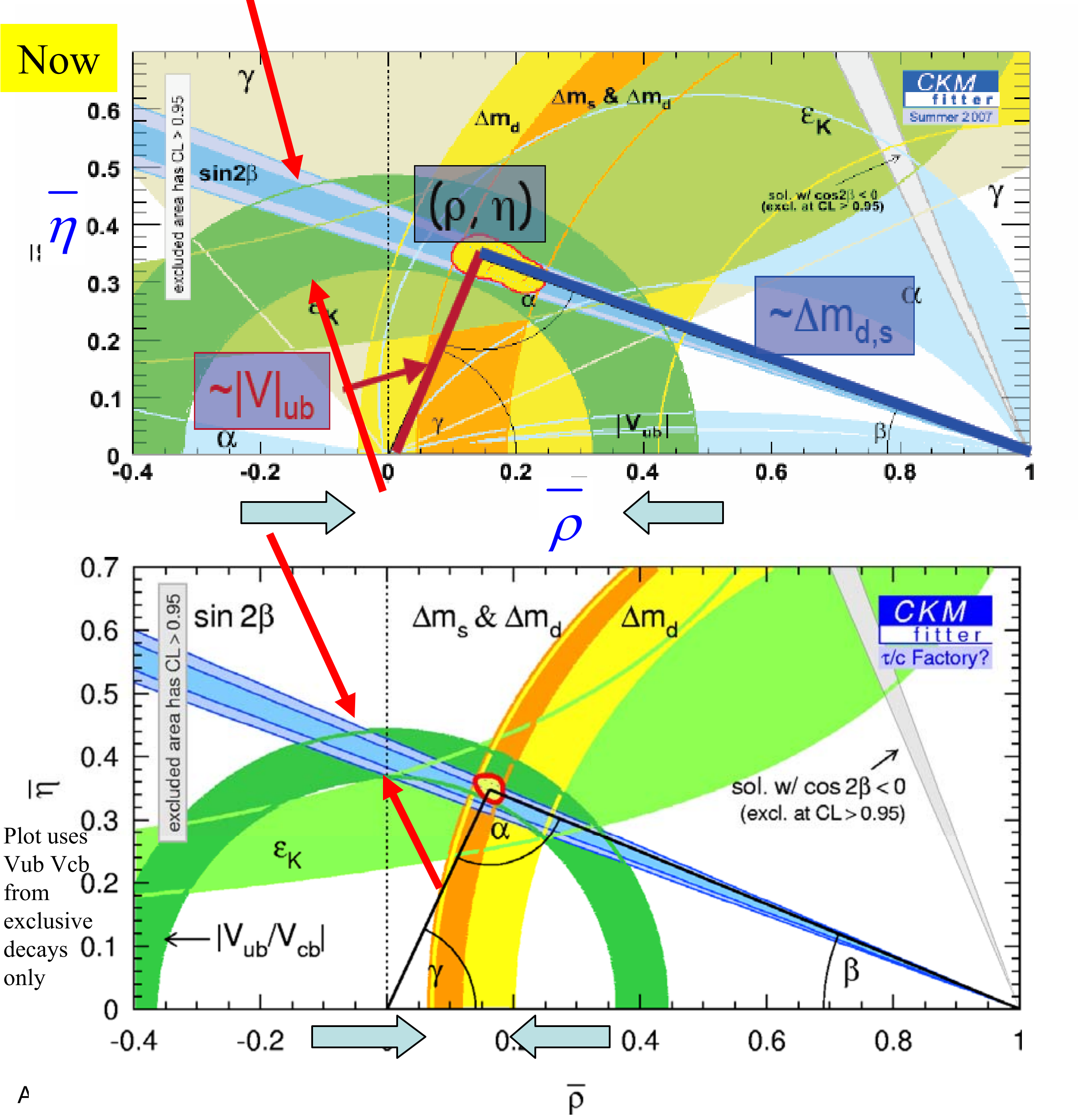
+ Br(B→ D)~100% *absolute* D hadronic rates normalize B physics important for V_{cb} (scale of triangle) - also normalize D physics

Precision theory + charm = large impact



Theoretical errors dominate width of bands

Precision theory + charm = large impact



Now

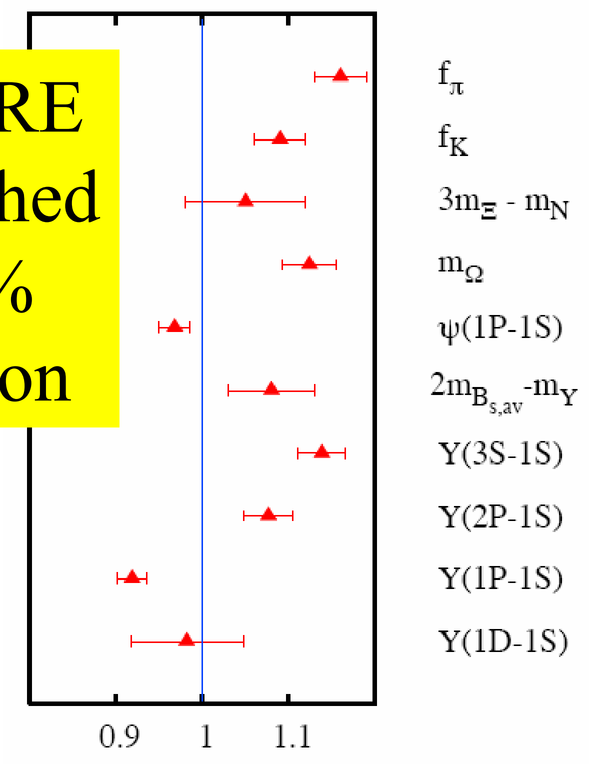
Plot uses Vub Vcb from exclusive decays only

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



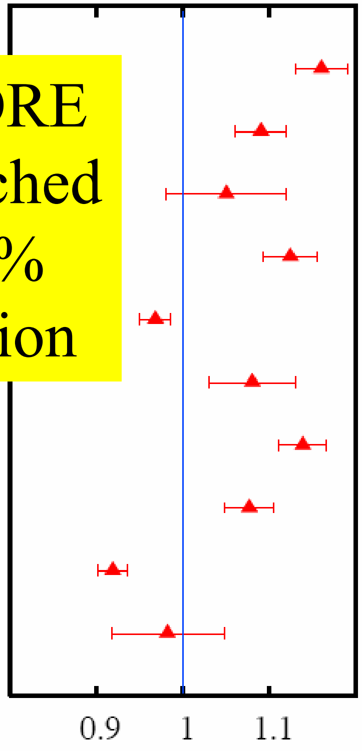
BEFORE
Quenched
10-15%
precision

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

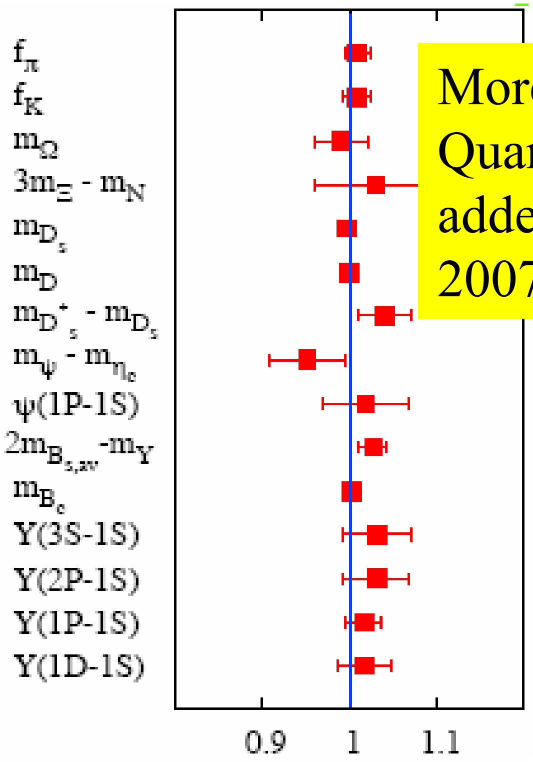
Precision theory? In 2003 a breakthrough in Lattice QCD

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



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



More
Quantities
added
2007

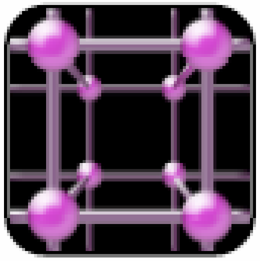
$\frac{\text{theory-expt}}{\text{expt}}$.

This dramatic improvement needs validation

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



Precision Experiment for charm?

Circa 2004 (pre-CLEO-c)

Experiment : Theory

Poorly known

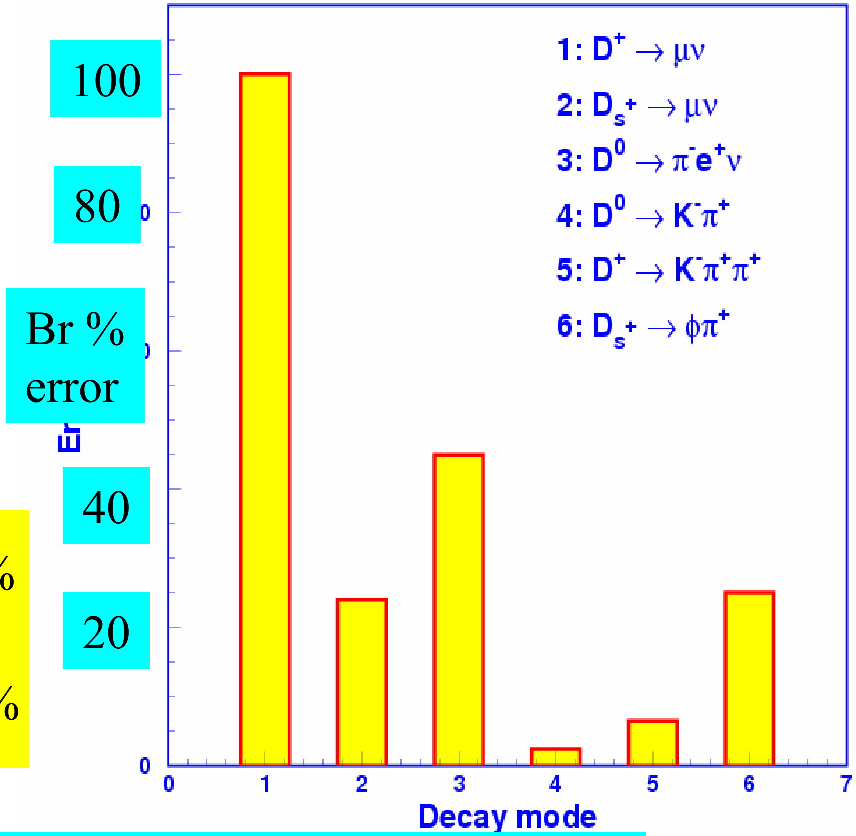
$$\frac{Br}{\tau} = \Gamma$$

Measured very precisely 0.4-0.8%

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

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

Key leptonic, semileptonic & hadronic modes:



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

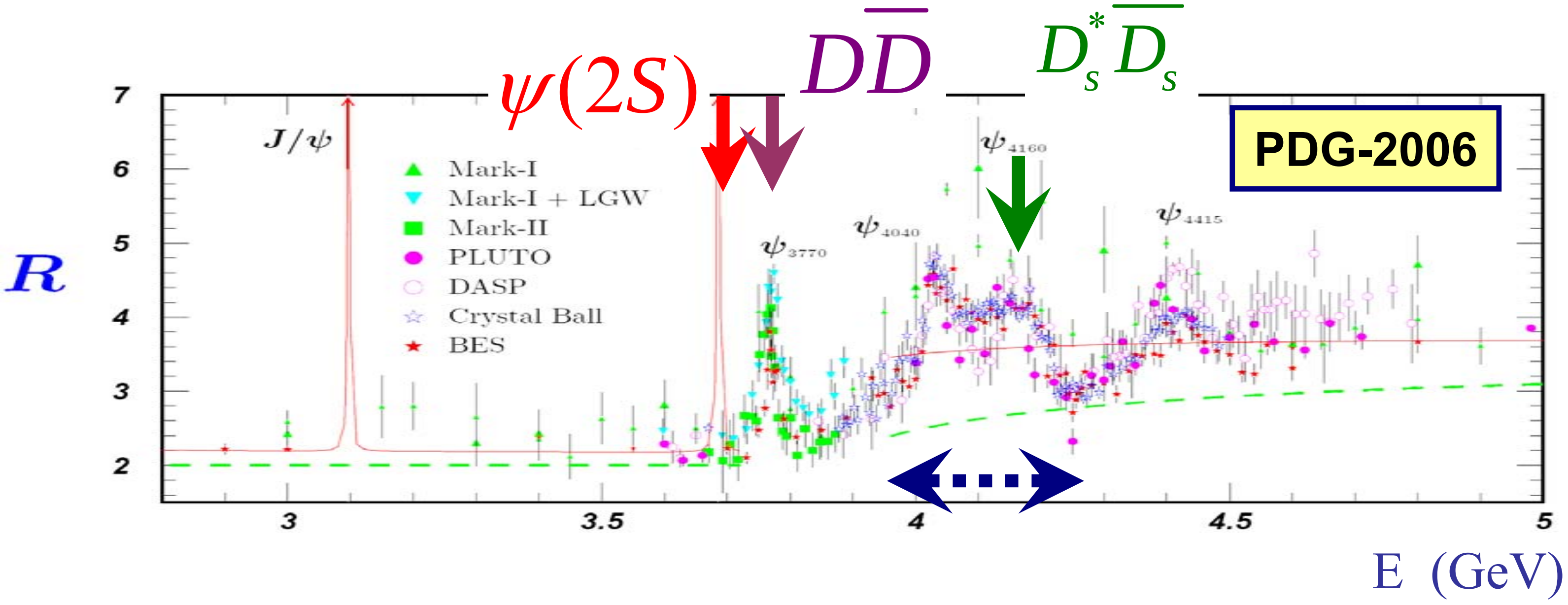
$$Br(D \to X) = \frac{\text{\#X Observed}}{\text{efficiency x \#D's produced}}$$

Backgrounds are large.

#D's produced is usually not well known.

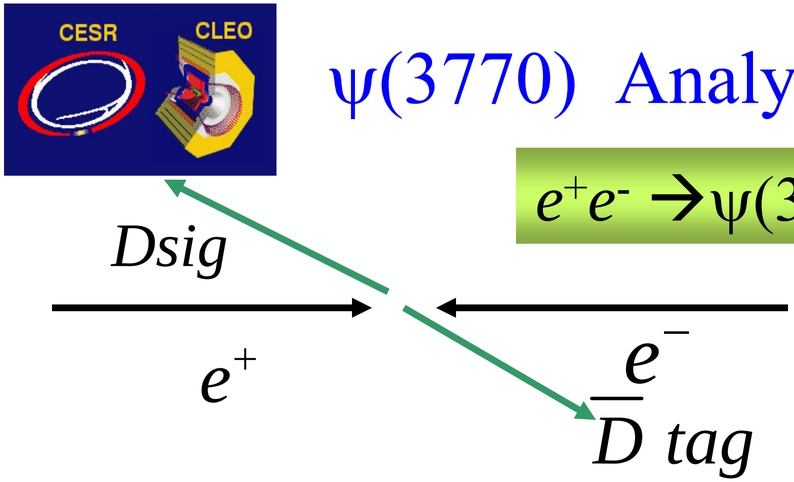
CLEO-c: World's largest data sets at charm threshold

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	800	$\psi(3770) \rightarrow \mathrm{D\overline{D}} \approx 5.1\times10^6\, D\overline{D}$	← X84 MARK III X42 BES II
4170	314	$D_{(s)}^{(*)}\overline{D_{(s)}^{(*)}} \approx 3\times10^5\, D_s^* \overline{D_s}$	← Expect to collect x2 by end of running

ψ(3770) Analysis Strategy



Dsig

e^+

e^-

$\bar{D}$ tag

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

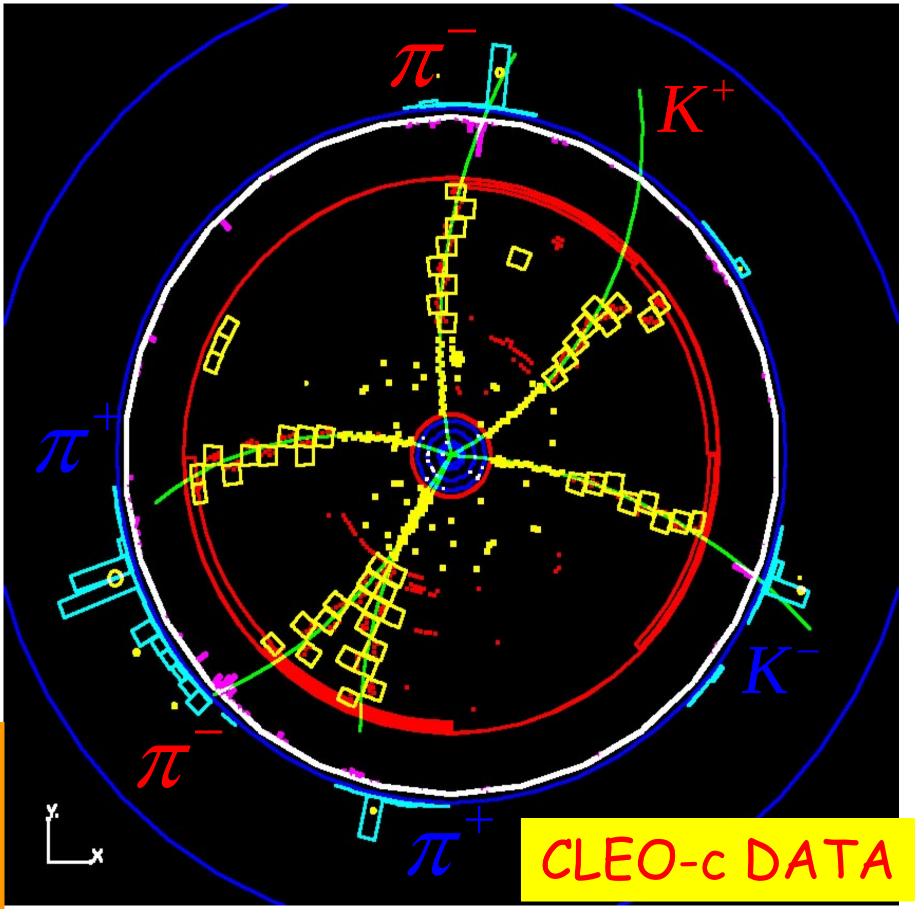
ψ(3770) is to charm what Y(4S) is to beauty

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

➔ high tag efficiency: ~25% of events

Compared to ~0.1% of B's at the Y(4S)

A little luminosity goes a long way:
Tagging ability:
D tags in 300 pb^{-1} @ charm factory
~ # B tags in 500 fb^{-1} @ Y(4S)



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

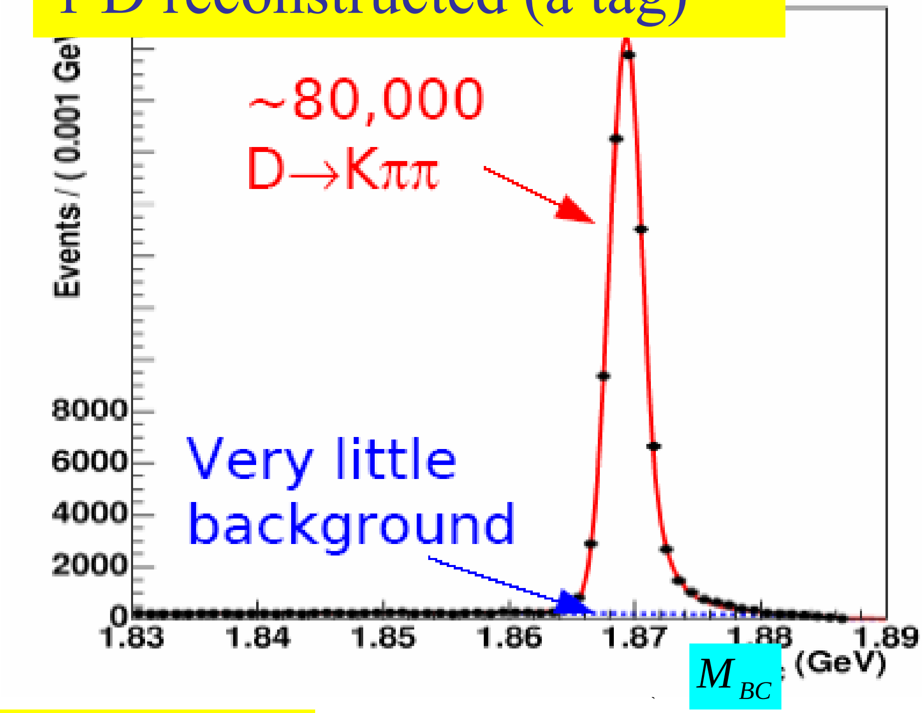
$D^+ \rightarrow K^-\pi^+\pi^+,\ D^- \rightarrow K^+\pi^-\pi^-$

Absolute Charm Branching Ratios at Threshold

281/pb

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

1 D reconstructed (a tag)

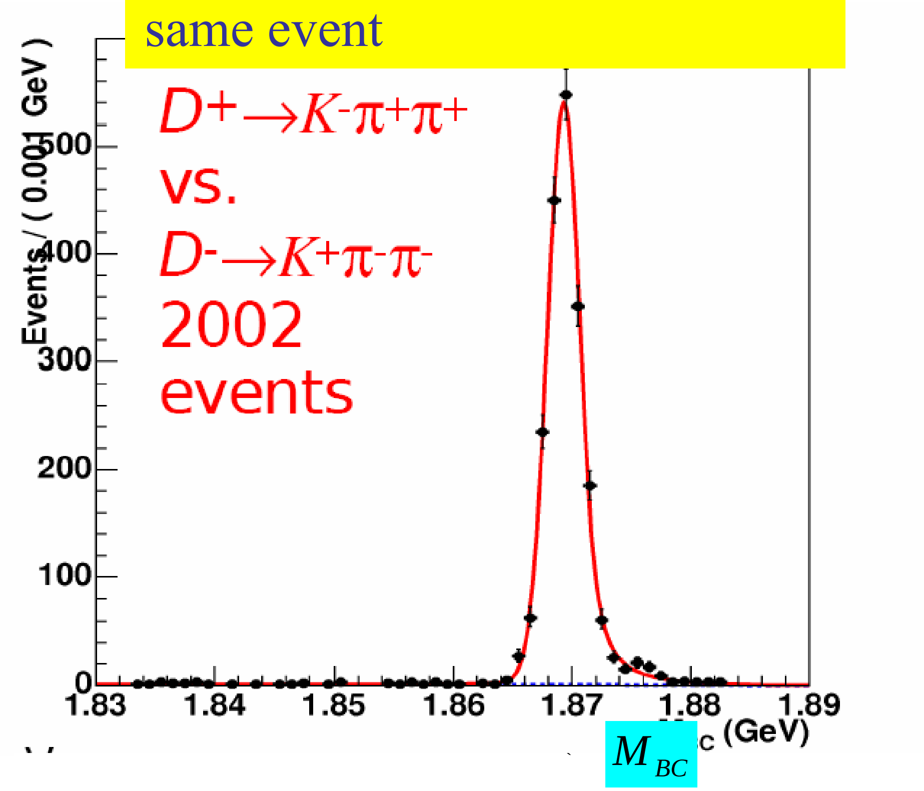


~80,000 D→Kππ

Very little background

M_{BC}

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



$D^+ \to K^-\pi^+\pi^+$
vs.
$D^- \to K^+\pi^-\pi^-$
2002 events

M_{BC}

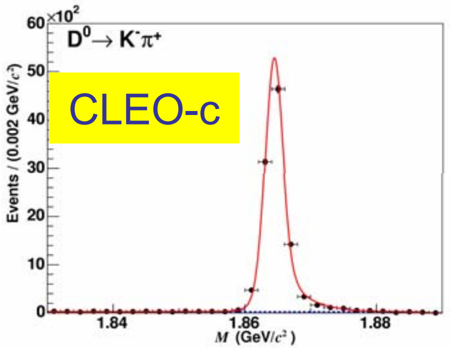
Independent of L and cross section

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

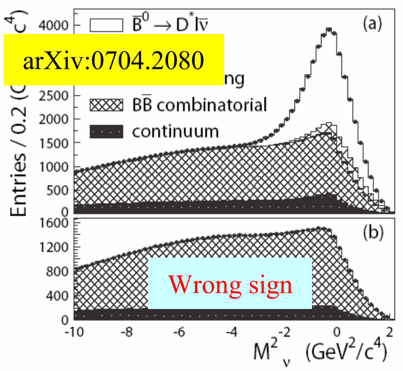
$B(D^0 \to K^-\pi^+)$

Sets scale of bd triangle

BABAR



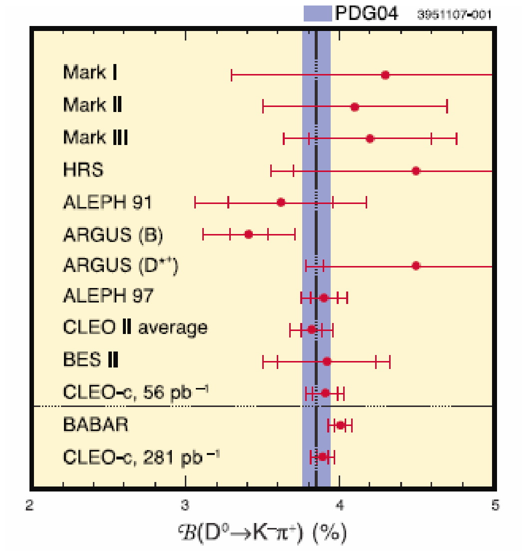
CLEO-c



arXiv:0704.2080

Wrong sign

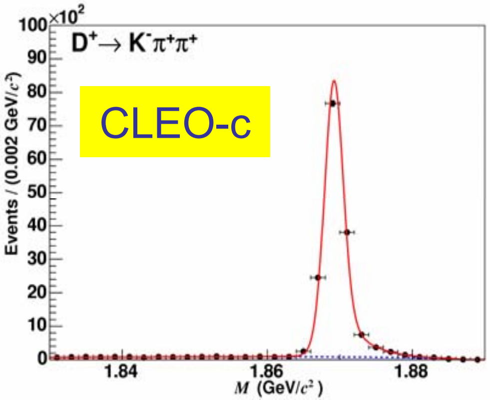
$\mathcal{B}$ (%)	Error(%)	Source
3.80 ±0.09	2.4	PDG04
3.891±0.035 ±0.069	2.0	CLEO-c
4.007 ±0.037 ±0.070	2.0	BABAR



Syst. limited: 2%

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

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



CLEO-c

Previous best:

measure:

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

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

dependent on

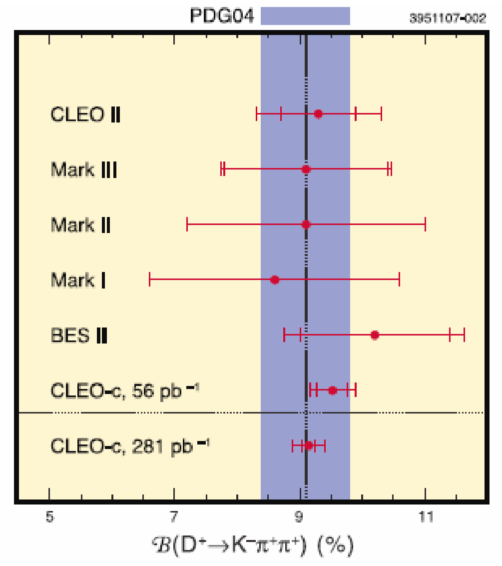
$B(D^0 \to K^-\pi^+)$

$\mathcal{B}$ (%)	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

now: $B(D^+ \to K^-\pi^+\pi$

independently measure

CLEO-c x 3.5 More precise than PDG



charm hadronic scale is finally on a SECURE FOUNDATION

Phys. Rev. D 76, 112001 (2007)

D_s Hadronic BRs

NEW

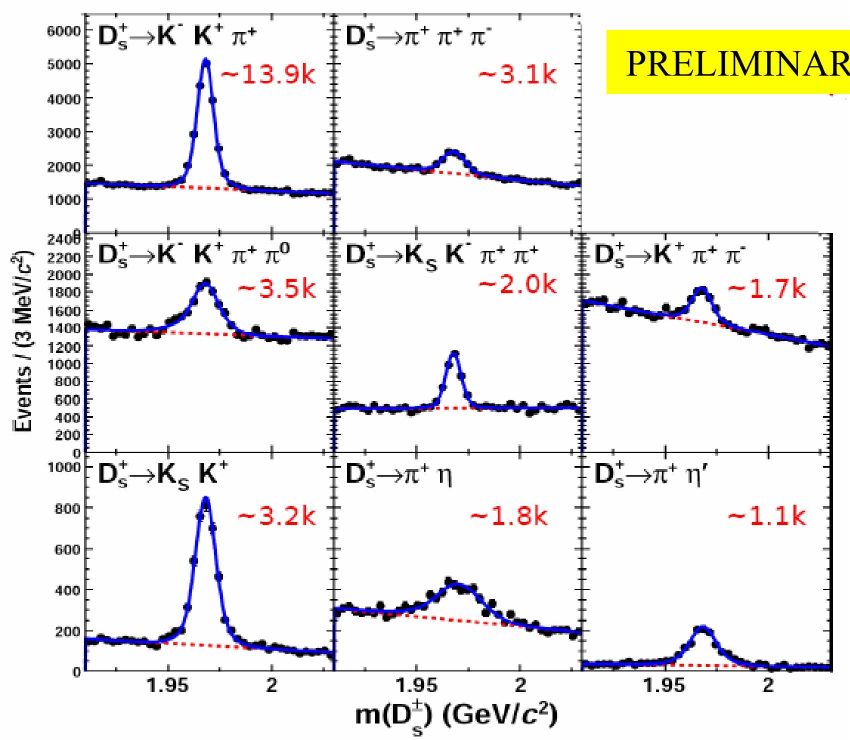
D_s hadronic BFs serve to nomalize many processes in D_s & B_s physics

This is the 1st high statistics study @ threshold arXiv:0801.0680 (4 Jan 2008)

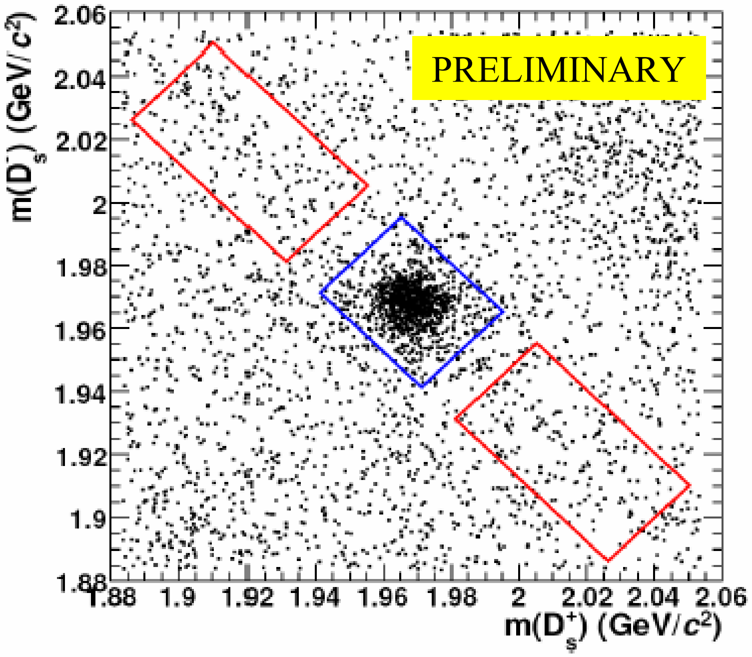
E_{cm}=4170 MeV. 298/pb. Optimal energy for D_sD_s*production. Analysis technique same as for DDbar at 3770.

8 D_s single tag modes

~1000 double tags (all modes) (~3.5% stat.)



PRELIMINARY



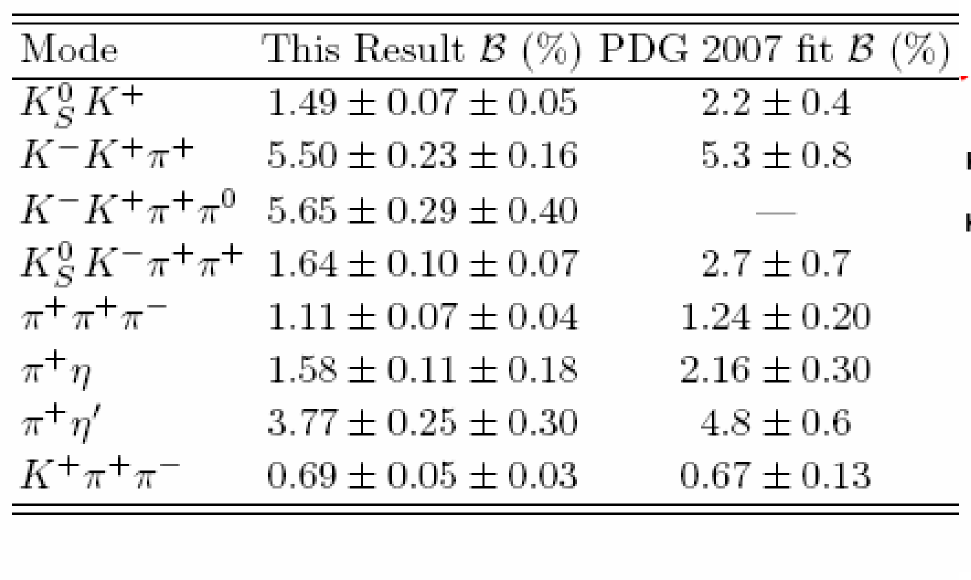
PRELIMINARY

Absolute D_s hadronic $\mathcal{B}$'s

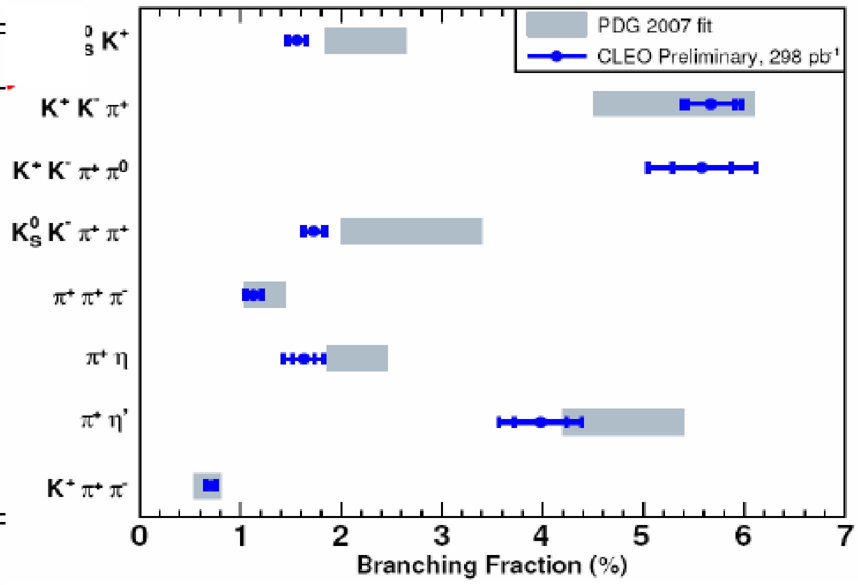
arXiv:0801.0680 (4 Jan 2008)

Errors already << PDG

CLEO-c, 4170MeV, 298pb^{-1}

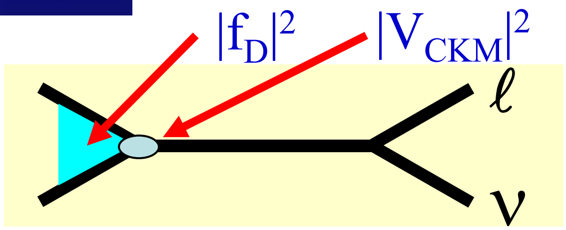


Mode	This Result $\mathcal{B}$ (%)	PDG 2007 fit $\mathcal{B}$ (%)
$K_S^0 K^+$	$1.49 \pm 0.07 \pm 0.05$	2.2 ± 0.4
$K^- K^+ \pi^+$	$5.50 \pm 0.23 \pm 0.16$	5.3 ± 0.8
$K^- K^+ \pi^+ \pi^0$	$5.65 \pm 0.29 \pm 0.40$	—
$K_S^0 K^- \pi^+ \pi^+$	$1.64 \pm 0.10 \pm 0.07$	2.7 ± 0.7
$\pi^+ \pi^+ \pi^-$	$1.11 \pm 0.07 \pm 0.04$	1.24 ± 0.20
$\pi^+ \eta$	$1.58 \pm 0.11 \pm 0.18$	2.16 ± 0.30
$\pi^+ \eta'$	$3.77 \pm 0.25 \pm 0.30$	4.8 ± 0.6
$K^+ \pi^+ \pi^-$	$0.69 \pm 0.05 \pm 0.03$	0.67 ± 0.13



$K^+K^+\pi^+$ in good agreement with PDG
We do not quote $B(D_s \rightarrow \varphi\pi^+)$
Requires amplitude analysis
Results soon

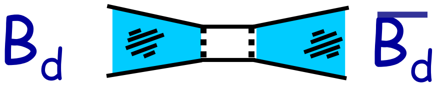
Importance of *absolute* charm leptonic branching ratios 1



$$\Gamma(D_q^+ \to \ell \nu) = \tfrac{1}{8\pi} G_F^2 M_{D_q^+} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D+}^2}\right) \boxed{f_{D+}^2} |V_{cq}|^2$$

1 Check lattice calculations of decay constants

2 Improve constraints from B mixing

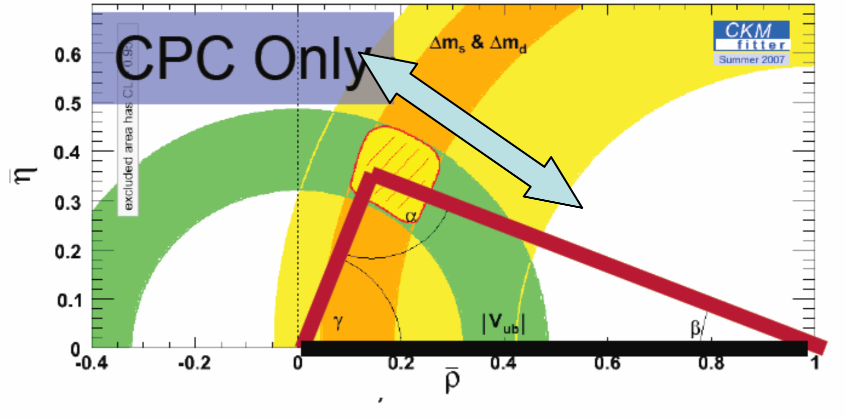


$$rate = (const.)\left[f_{Bd}\right]^2 |V_{td}|^2 |V_{tb}|^2$$

0.8% (expt) HFAG

~10% (HPQCD) PRL95 212001 (2005)

~ 12%



if f_{Bd} to 3% → $|V_{td}||V_{tb}|$ to ~5%

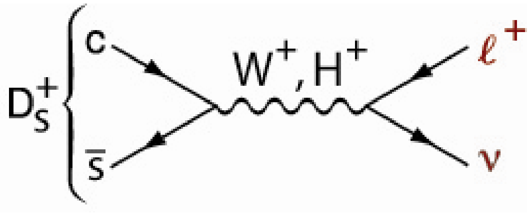
$B \to \tau\nu \propto f_{B+} V_{ub}$ but rate low & V_{ub} not well known

$f_{D\ \text{CLEO-c}}$ and $(f_B/f_D)_{\text{lattice}}$ → f_B
(And f_D/f_{Ds} CLEO-c checks f_B/f_{Bs})lattice

precise $|V_{td}|$

important for $|V_{td}|/|V_{ts}|$

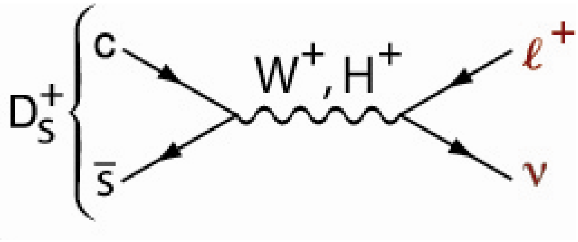
3 Sensitive to new physics



In 2HDM effect is largest for Ds

Importance of *absolute* charm leptonic branching ratios 2

A new charged Gauge Boson



SM Ratio of leptonic decays could be modified (e.g.)

$$\frac{\Gamma(P^+ \to \tau^+\nu)}{\Gamma(P^+ \to \mu^+\nu)} = m_\tau^2\left(1-\frac{m_\tau^2}{M_P^2}\right)^2 \Big/ m_\mu^2\left(1-\frac{m_\mu^2}{M_P^2}\right)^2$$

(If $H^\pm$ couples to M^2 no effect)

Hewett [hep-ph/9505246]
Hou, PRD 48, 2342 (1993).

In 2HDM predict
SM decay width is x by

$$r_q = \left[1 - M_D^2\left(\frac{\tan\beta}{M_{H^\pm}}\right)^2\left(\frac{m_q}{m_c+m_q}\right)\right]^2$$

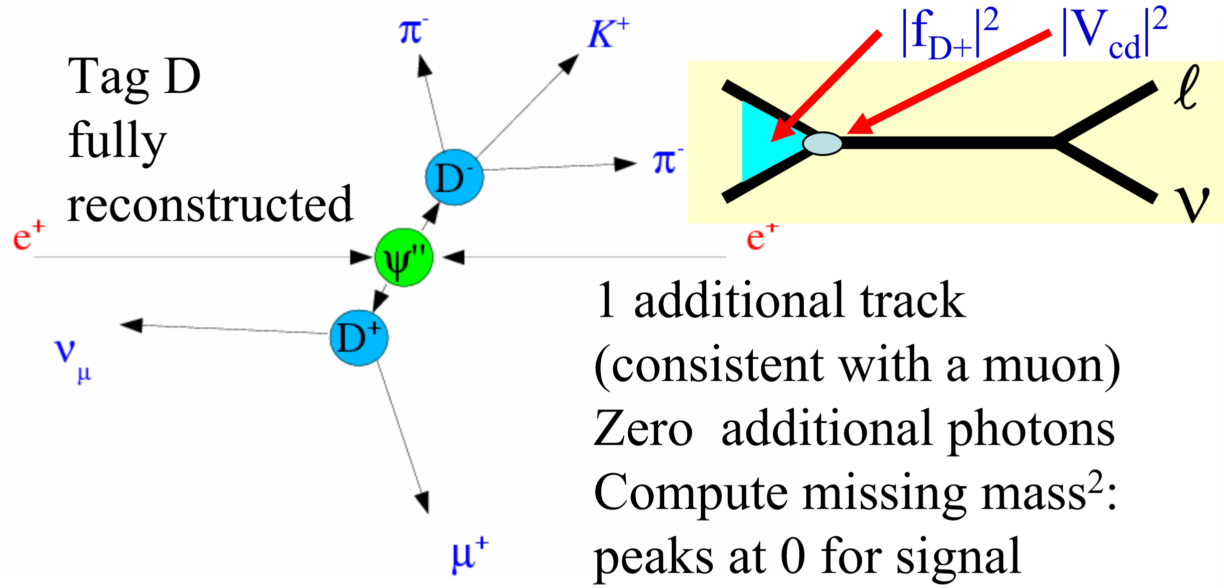
Akeryod [hep-ph/0308260]

Since m_d is ~0, effect can be seen only in D_s

CLEO-c has made absolute measurements of

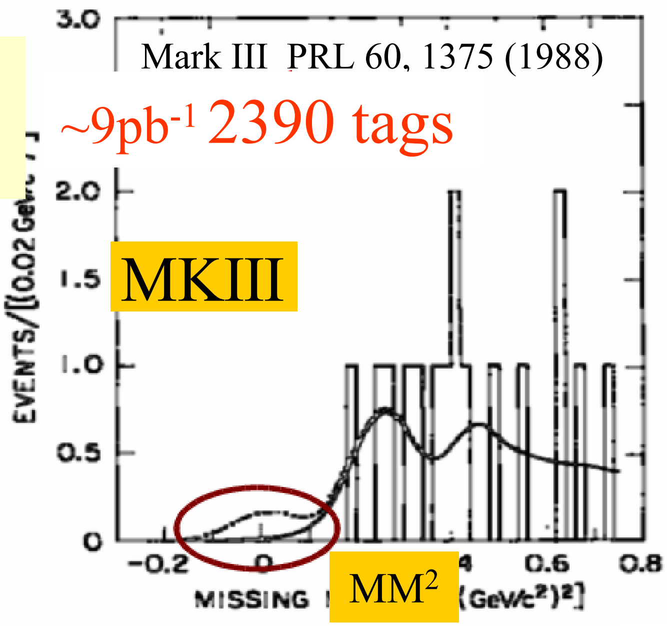
$B(D^+ \to \mu\nu), B(D^+ \to \tau\nu), B(D_s^+ \to \mu\nu), B(D_s^+ \to \tau\nu)$

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



Tag D fully reconstructed

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



Mark III PRL 60, 1375 (1988)

~9pb^{-1} 2390 tags

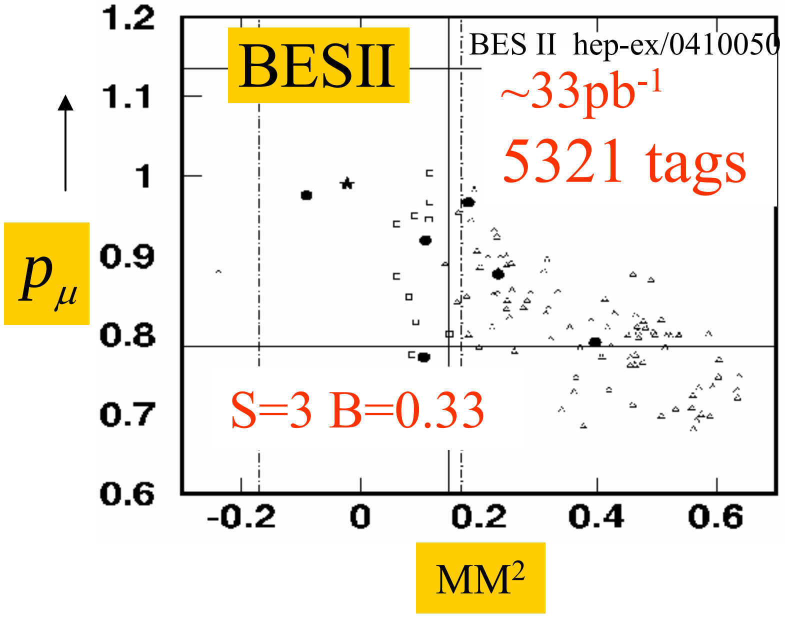
MKIII

MM^2

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

$$\text{where } E_D = E_{beam}, \; \overrightarrow{P_D} = -\overrightarrow{P_{D\,tag}}$$

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



BESII

BES II hep-ex/0410050

~33pb^{-1}

5321 tags

S=3 B=0.33

p_μ

MM^2

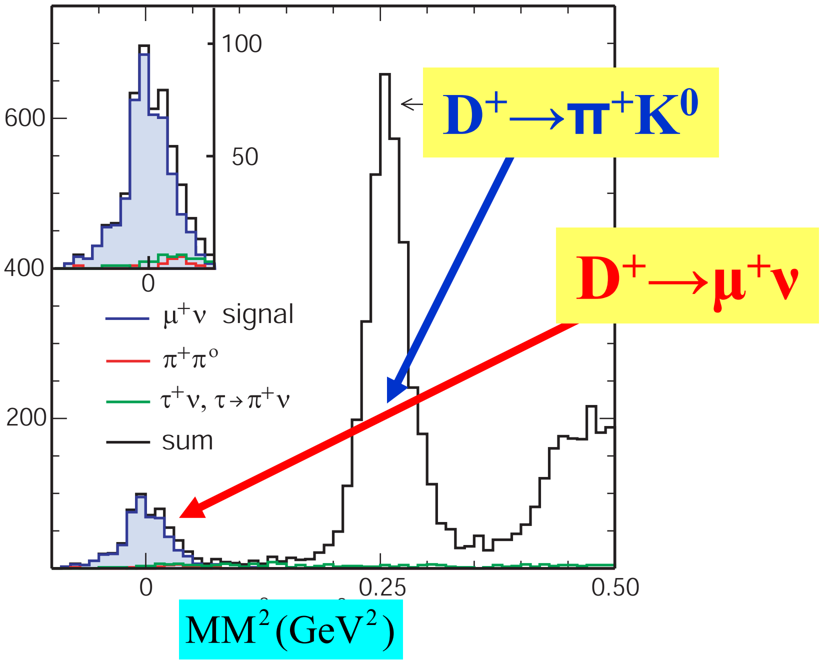
f_{D+} from Absolute $Br(D^+ \rightarrow \mu^+\nu)$

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P}_{D\,tag} - \overrightarrow{P}_\mu)^2$$

MC

6 x

data



$D^+ \rightarrow \pi^+ K^0$

$D^+ \rightarrow \mu^+ \nu$

$MM^2 (GeV^2)$

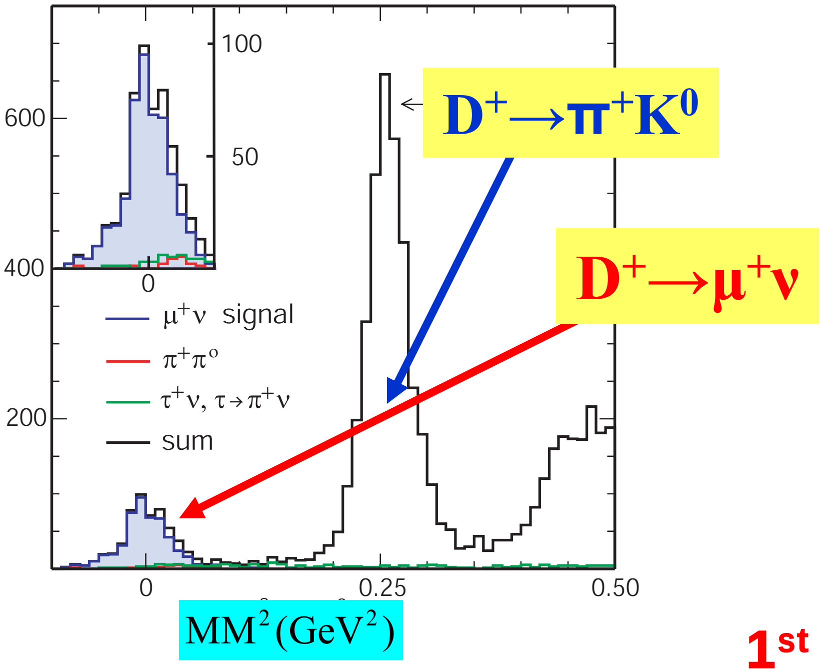
f_{D+} from Absolute Br($D^+ \to \mu^+\nu$)

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P}_{D\,tag} - \overrightarrow{P}_\mu)^2$$

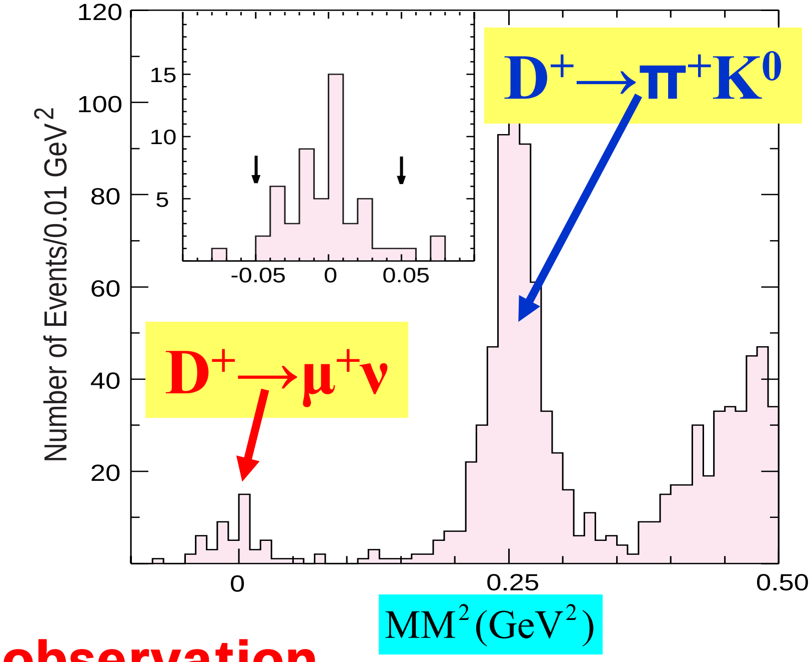
MC

6 x

data



Data 281 pb^{-1} at ψ(3770)



1st observation of $D^+\to\mu^+\nu$

$$B(D^+ \to \mu^+\upsilon) = (4.40 \pm 0.66\,^{+0.09}_{-0.12}) \times 10^{-4}$$

$$f_{D^+} = (222.6 \pm 16.7\,^{+2.8}_{-3.4})\,MeV$$

PRL 95, 251801 (2005)

Mode	Events
Data	50
$D^+ \to \pi^+\pi^0$	1.4
$D^+ \to K_{long}\,\pi^+$	0.33
$D^+ \to \tau^+\nu_\tau$	1.08
Total Bck:	2.81

$f_{D^+} = (201 \pm 3 \pm 17)$ MeV (LQCD) Expt/Theory agree ~ to 10%

$D^+ \to \tau^+\nu, \tau^+ \to \pi^+\nu$

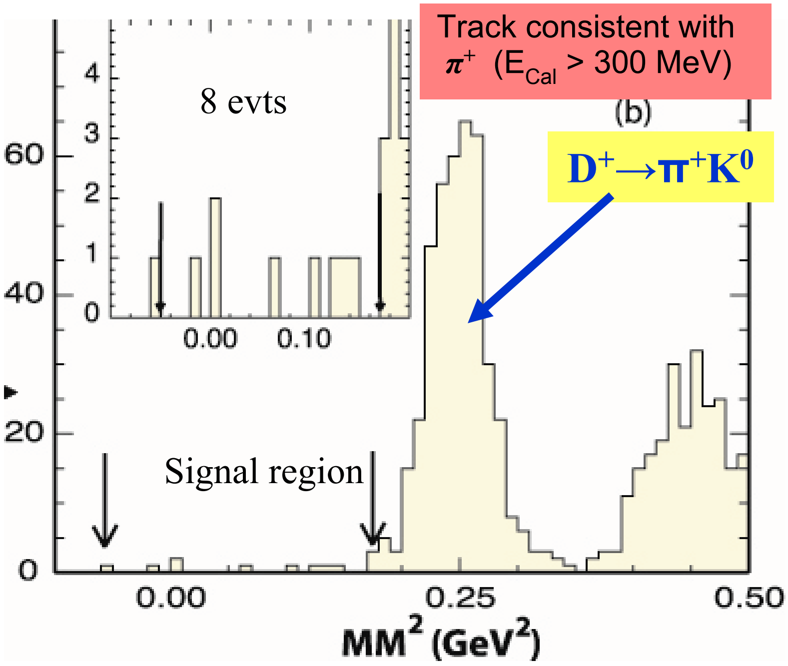
A test of lepton universality

D^- tag + single π track

two ν: larger MM^2 region

event yields consistent with bkgd estimates

$B(D^+ \to \tau^+ \nu_\tau) < 2.1 \times 10^{-3}$



Track consistent with π^+ (E_{Cal} > 300 MeV)

$D^+ \to \pi^+ K^0$

In SM:

$$R = \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = m_\tau^2 \left(1 - \frac{m_\tau^2}{M_{D^+}^2}\right)^2 \Big/ m_\mu^2 \left(1 - \frac{m_\mu^2}{M_{D^+}^2}\right)^2 = 2.65$$

combine with CLEO-c $B(D^+ \to \mu^+\nu)$:

$R_{CLEO} / R_{SM} < 1.8$ at 90% CL

First measurement of R

➔ lepton universality in purely leptonic *D+* decays is satisfied at the level of current experimental precision.

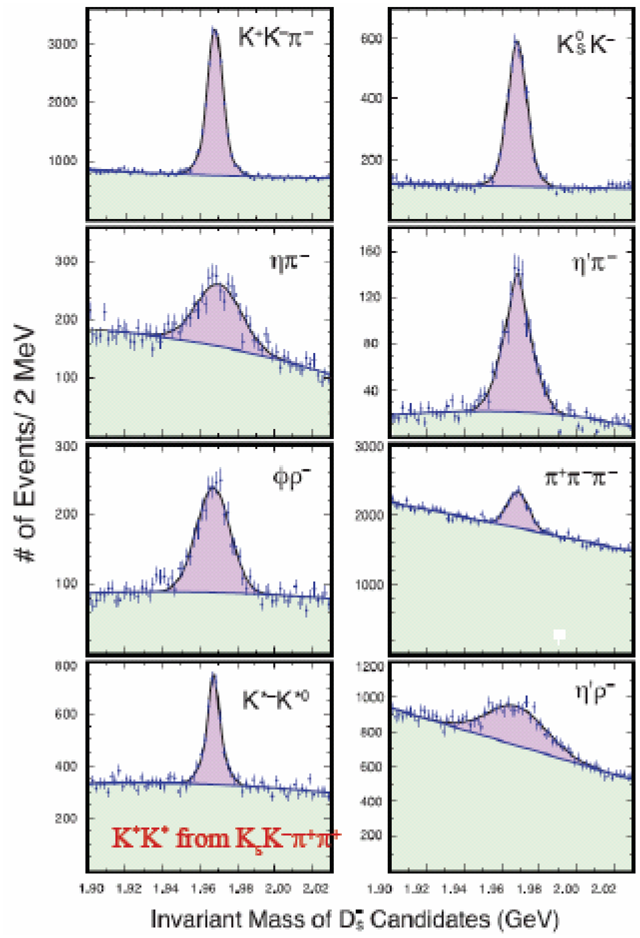
***PRD*73 112005 (2006)**

Method 1: $D_s \to \mu^+\nu, D_s \to \tau^+\nu, \tau^+ \to \pi^+\nu$ & f_{Ds}

D_s (tag) 8 modes

D_s tags 31302±472

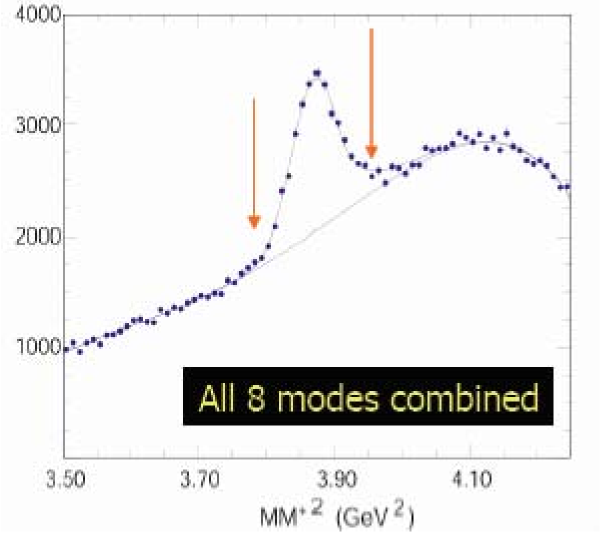
Cabibbo favored decay compensates for smaller cross section @ 4170 MeV



@4170 $D_s D_s^*$, $D_s^* \to D_s\gamma$

Calculate MM² for D_s tag plus photon.

Peaks at D_s mass.
N(tag+γ)=18645±426



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

We search simultaneously for $D_s \to \mu\nu$ & $D_s \to \tau\nu$

* For the signal: require one additional track and no unassociated extra energy

* Calculate missing mass (next slide)

$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$

PRL 99 071802 (2007)
PRD 76 072002 (2007)

Three cases depending on particle type:

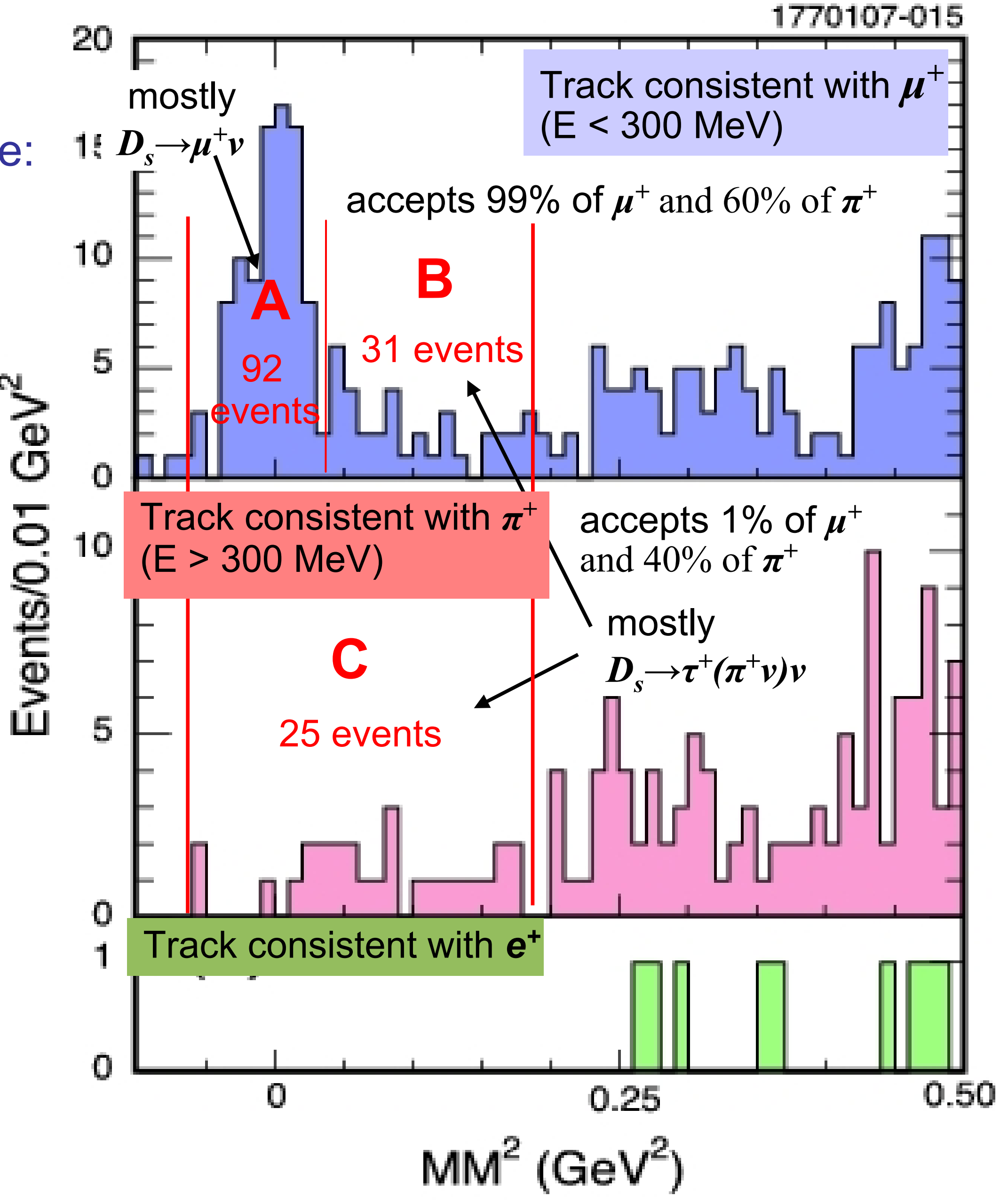
A $B(D_s \to \mu^+\nu)$
92 events (3.5 bkgd)
$B(D_s \to \mu^+\nu)$ = **(0.597 ± 0.067 ± 0.039)%**

B+C $B(D_s \to \tau^+\nu)$:
31+25 = 56 events (3.6+5= 8.6 bkgd)
$B(D_s \to \tau^+\nu)$ = **(8.0 ± 1.3 ± 0.4)%**

A+B+C: By summing both cases and using SM τ/μ ratio
$B^{eff}(D_s \to \mu^+\nu)$ = ***(0.638 ± 0.059 ± 0.033)%***

f_{D_s} = (274 ± 13 ± 7) MeV

$B(D_s \to e^+\nu)$ **< 1.3x10^{-4}**



Track consistent with μ^+ (E < 300 MeV)

mostly $D_s \to \mu^+\nu$

accepts 99% of μ^+ and 60% of π^+

92 events

31 events

Track consistent with π^+ (E > 300 MeV)

accepts 1% of μ^+ and 40% of π^+

mostly $D_s \to \tau^+(\pi^+\nu)\nu$

25 events

Track consistent with e^+

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

NEW

300/pb @4170 MeV

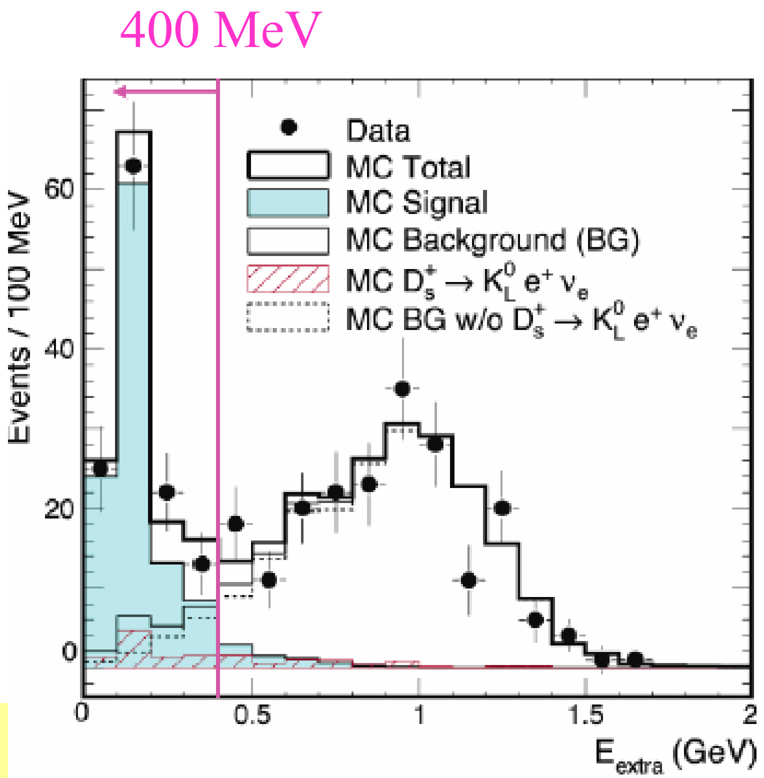
Require D_s tag

Require 1 electron and no other tracks

Primary bkgd semileptonic ($D_s \to X e \nu$).

Suppress X by requiring low amount of extra energy in calorimeter. Shown on right.

Signal region E_{cc}(extra)< .4 GeV.
Backgrounds from scaled MC.



Results:

$B(D_s \to \tau^+\nu)$ **= (6.17 ± 0.71 ± 0.36)%**
[PDG06: $B(D_s \to \tau^+\nu)$ = (6.4 ± 1.5)%]
f_{Ds} = (273 ± 16 ± 8) MeV

arXiv:0712.1175

(Submitted to PRL Dec 12 2007)

This is the most precise determination of $B(D_s \to \tau^+\nu)$

f_{Ds} & f_{Ds}/f_{D^+}

Combining method 1 $D_s \to \mu\nu$ & $D_s \to \tau\nu, \tau \to \pi\nu$

& method 2 $D_s \to \tau\nu, \tau \to e\nu$

weighted average: $f_{Ds} = (274 \pm 10 \pm 5)$ MeV

(syst. uncertainties are mostly uncorrelated between methods)

combine with $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV (CLEO)

$$f_{Ds}/f_{D^+} = 1.23 \pm 0.10 \pm 0.03$$

$$R = \frac{\Gamma(\mathrm{D_s^+} \to \tau^+\nu)}{\Gamma(\mathrm{D_s^+} \to \mu^+\nu)} = 11.0 \pm 1.4 \pm 0.6$$

compared to:

$$R = \frac{\Gamma(\mathrm{D_s^+} \to \tau^+\nu)}{\Gamma(\mathrm{D_s^+} \to \mu^+\nu)} = 9.72 \quad \text{(Standard Model)}$$

➔ lepton universality in purely leptonic D_s decays is satisfied at the level of current experimental precision.

Comparison with theory

CLEO f_D consistent with calculations

CLEO f_{Ds} higher than most calculations indicating an absence of the suppression expected for a H+

Our f_{Ds} is ~3σ above the most recent & precise LQCD calculation (HPQCD).

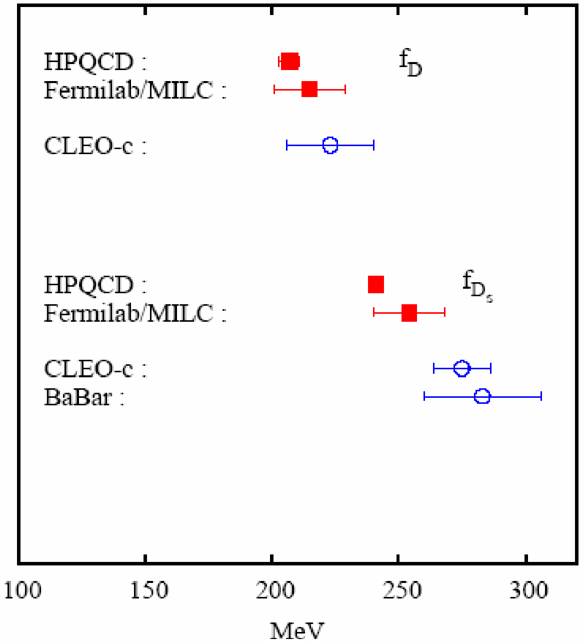
This discrepancy needs to be studied.

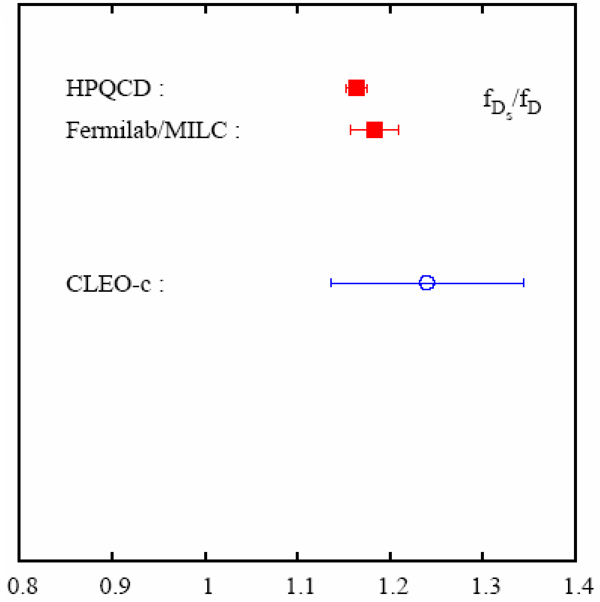
1) ***HPQCD is checking against Γee for J/ψ & φ***
2) ***Radiative corrections are not made to LQCD results. Expected magnitude a few % . Needs to be investigated with high priority.***

If all checks hold up, it is evidence for new physics that interferes constructively with the SM

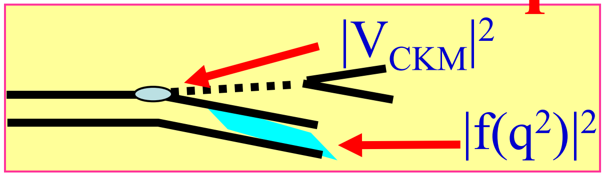
Comparing measured f_{Ds}/f_{D+} with HPQCD
mH+>2.2 GeV tanβ @90% CL

Using HPQCD f_{Ds}/f_{D+} find:
|Vcd /Vcs|=0.217±0.019 (exp)±0.002(theory)





Importance of Charm Semileptonic Decays

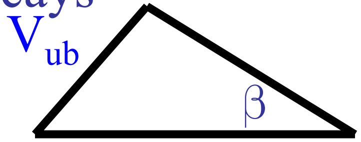


$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to(K)\pi}(q^2)|^2$$

1 Assuming th ff⇒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



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

BABAR / Belle / CLEO

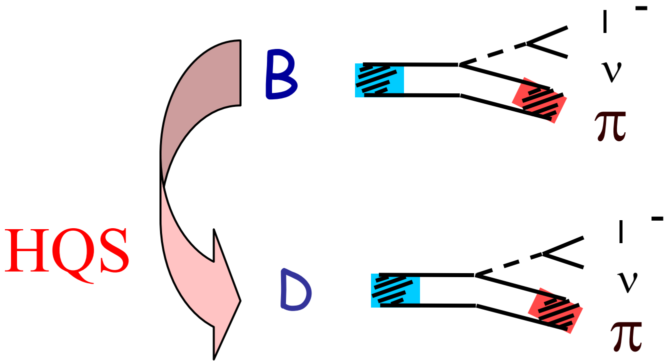
(HFAG (2007)

$$|V_{ub}| = (3.17 \pm 0.10 \pm^{+0.74}_{-0.44}) \times 10^{-3}$$

± exp ± LQCD

Expt. 3%

~16% HPQCD
hep-lat/0601021



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

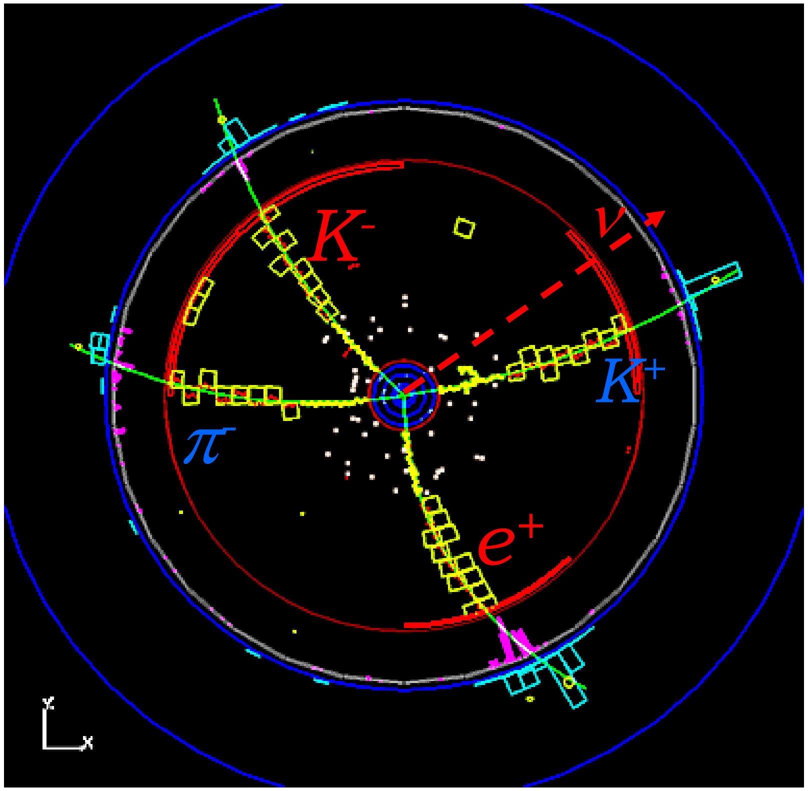
$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

Related at
same invariant
4 velocity

Absolute Semileptonic Branching Fractions

The neutrino direction is determined to 1^0

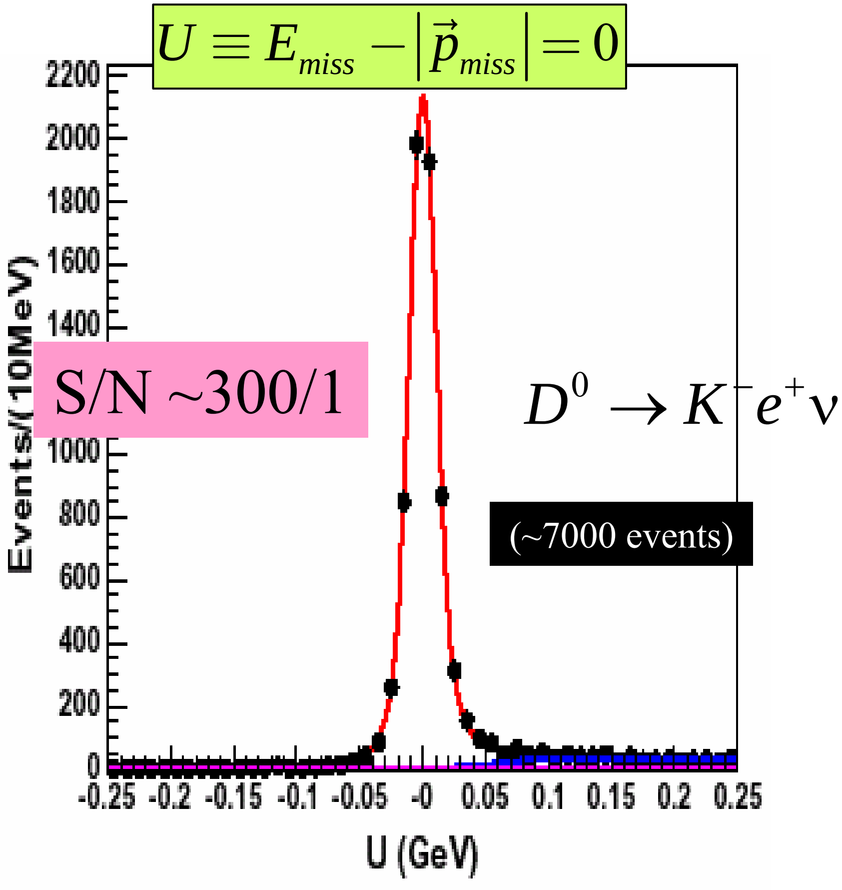
no kinematics ambiguity



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

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

Tagging creates a single D beam of known 4-momentum



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

S/N ~300/1

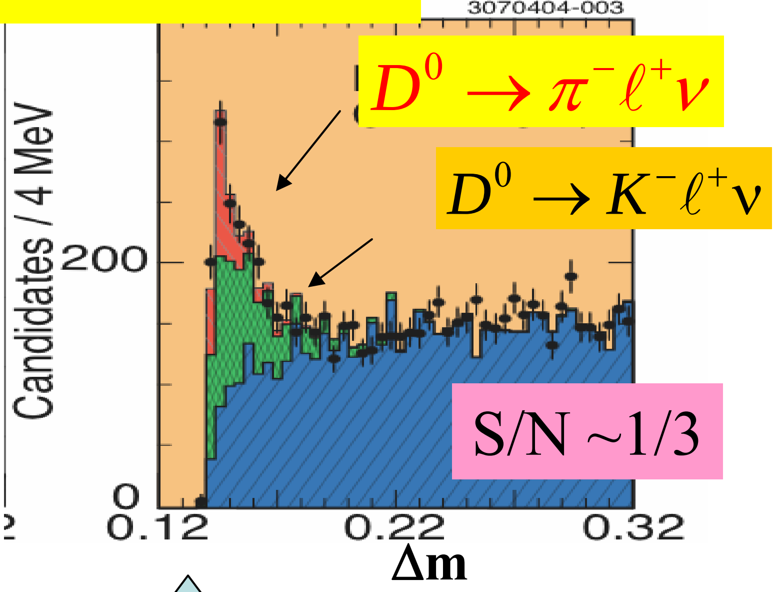
$$D^0 \to K^- e^+ \nu$$

(~7000 events)

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

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

CLEOIII 10 GeV



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

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

S/N ~1/3

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

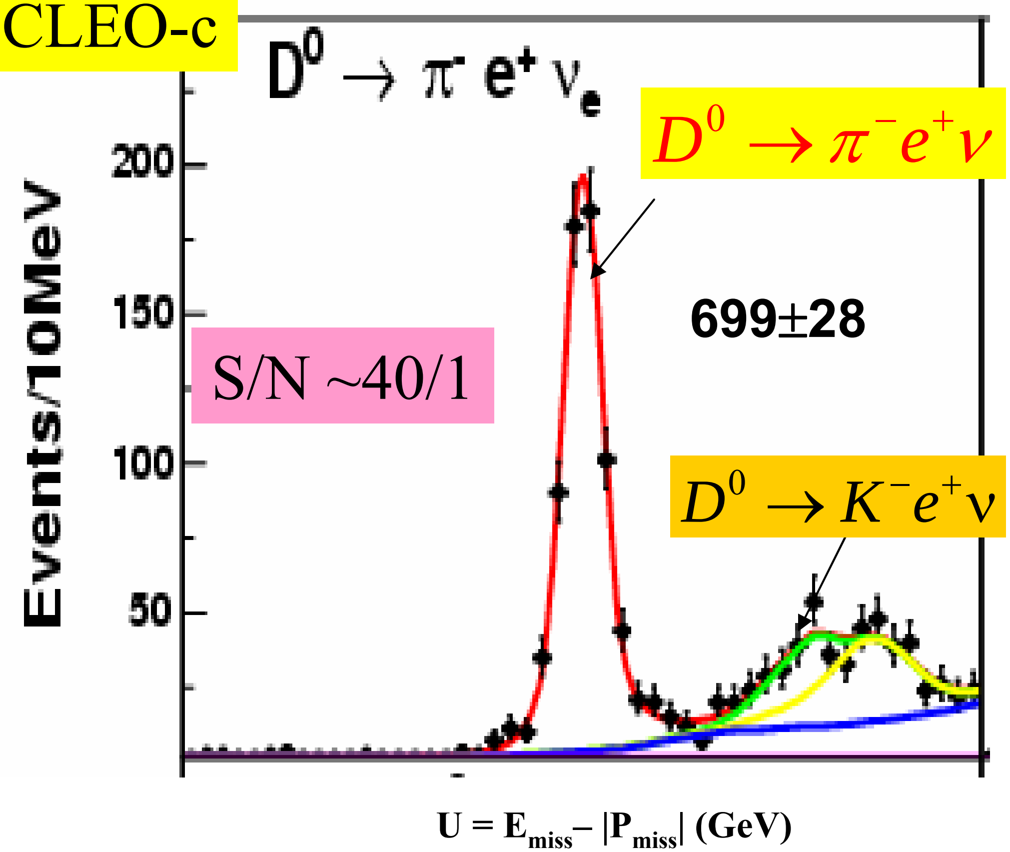
$D^0 \to \pi^- \ell^+ \nu$

$observable:$

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

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

CLEO-c



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

S/N ~40/1

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

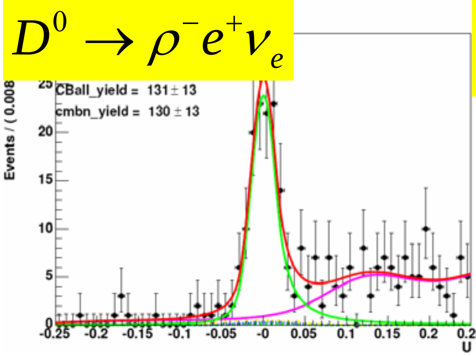
Note:
kinematic
separation.

Only other high statistics measurement is from Belle 282/fb (x1,000 CLEOc) 222± 17 events S/N 4/1

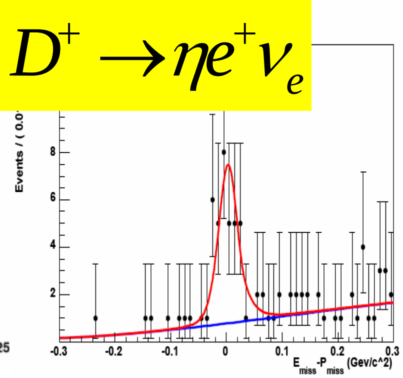
CLEO-c semileptonic tagging analysis technique: big impact

1st Observations:

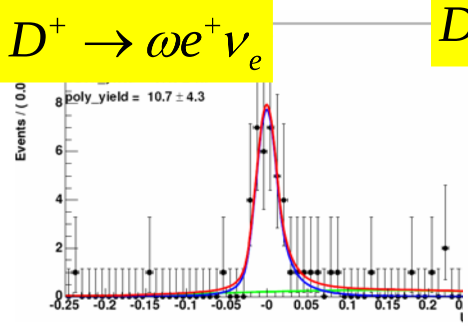
$D^0 \to \rho^- e^+ \nu_e$



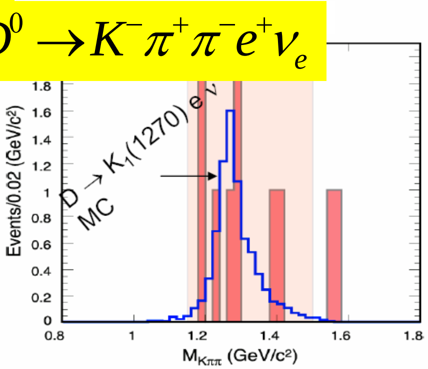
$D^+ \to \eta e^+ \nu_e$



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



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



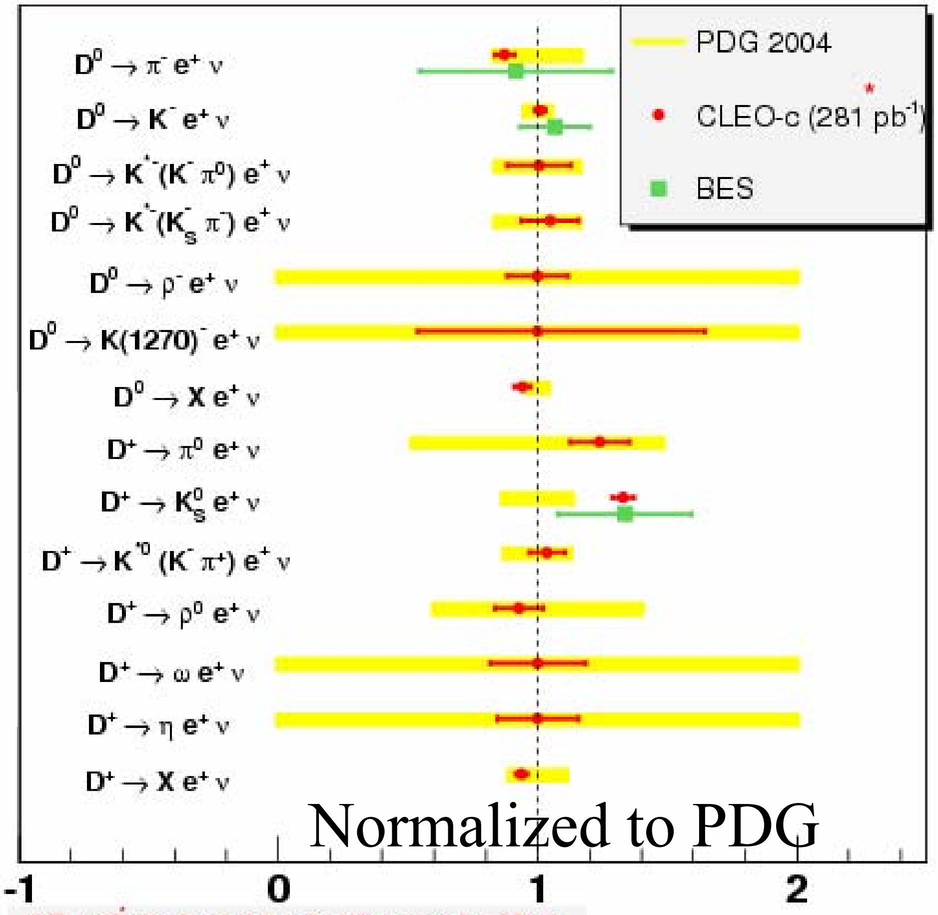
+ $D^+ / D^0 \to X e^+ \nu_e$

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

note: use PDG2004 as PDG2006 is dominated by CLEO-c measurements

PRL 95, 181801 (2005);
PRL 95, 181802 (2005)
PRL. 99, 191801 (2007)

Precision Measurements:



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

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

$D \to K/\pi e^{+}\nu$ without tagging

NEW

Preliminary results FPCP 2006 now superseded

ArXiv 0712.1020 and 0712.1025

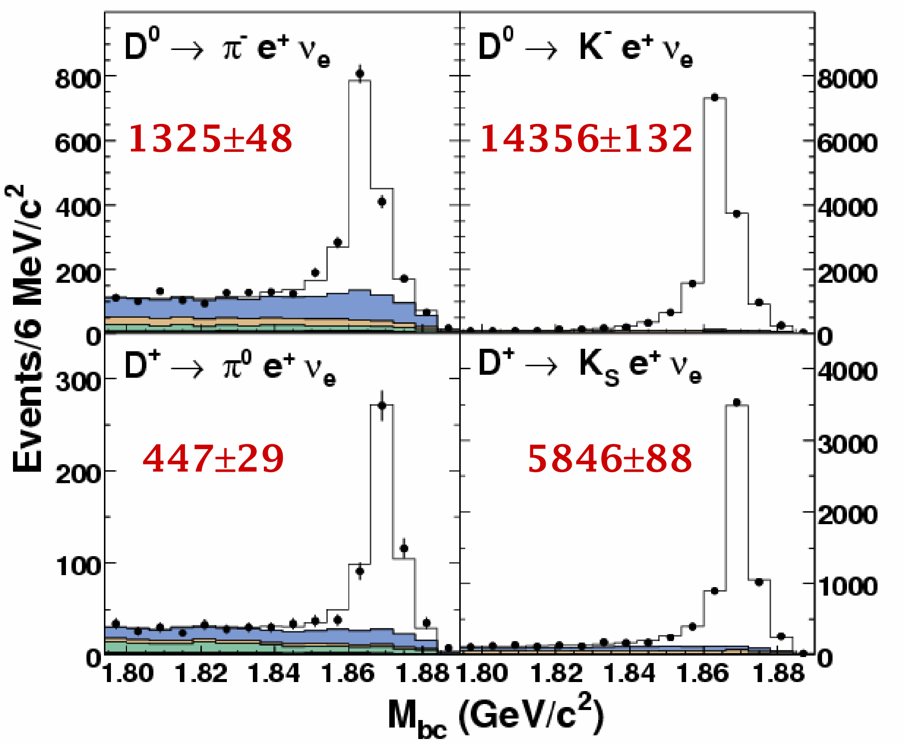
[analogous to neutrino reconstruction @ Υ(4S)]

Uses neutrino reconstruction:
Identify semileptonic decay.

Reconstruct neutrino 4-momentum from all measured energy in the event.

Use K(π), e, and missing 4-momentum and require consistency in energy and beam-energy constrained mass.

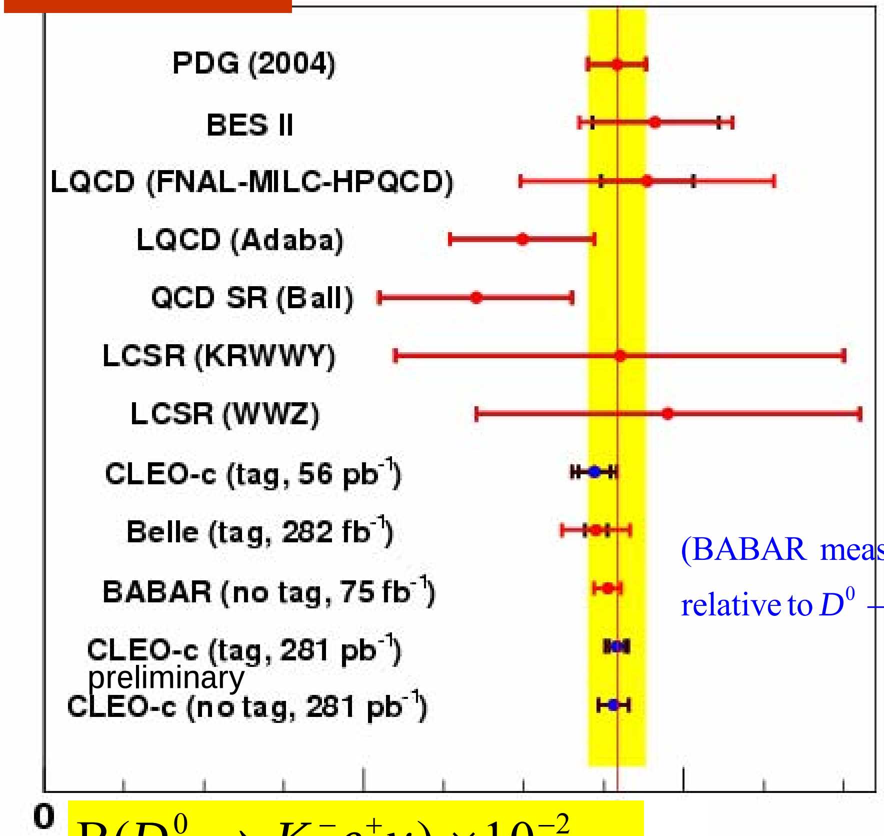
Higher efficiency than tagging but larger backgrounds



M_{bc} distributions fitted simultaneously in 5 q^2 bins to obtain $d(\mathrm{BF})/dq^2$. Integrate to get branching fractions and fit to get form factors

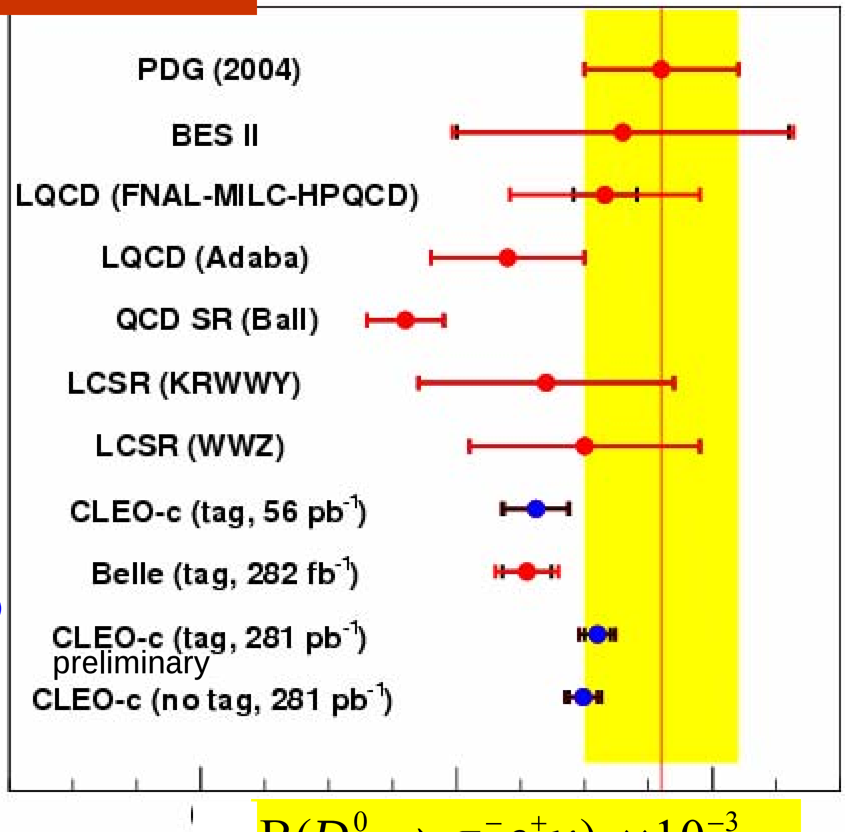
D →K, π eν Branching Fractions

$D \to K e^+ \nu$



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

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



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

3.58(5)(5) (tag) (prelim.)

3.56(3)(9) (notag)

$\sigma(B(Ke\nu))/B(Ke\nu) \sim 2\%$

$\sigma(B(\pi e\nu))/B(\pi e\nu) \sim 4.5\%$

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

0.31(1)(1) (tag) (prelim.)

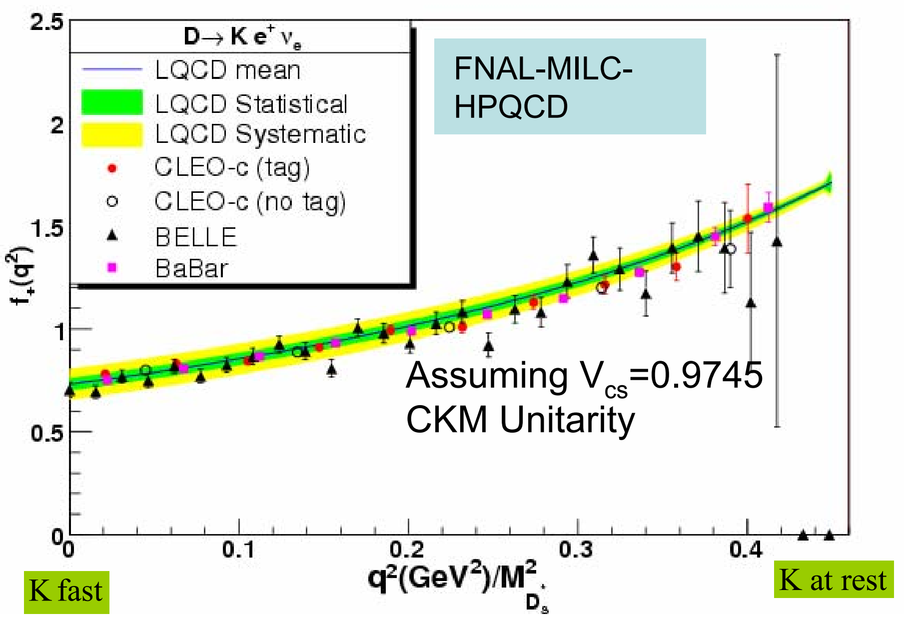
0.30(1)(1) (notag)

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

$D^0 \rightarrow K e^+ \nu$ 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



Assuming V_{cs}=0.9745 CKM Unitarity

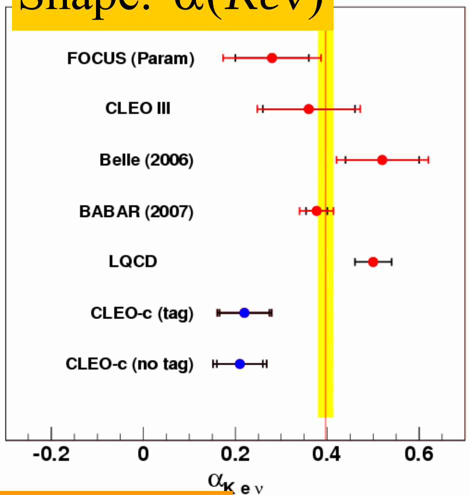
Modified pole model used as example

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

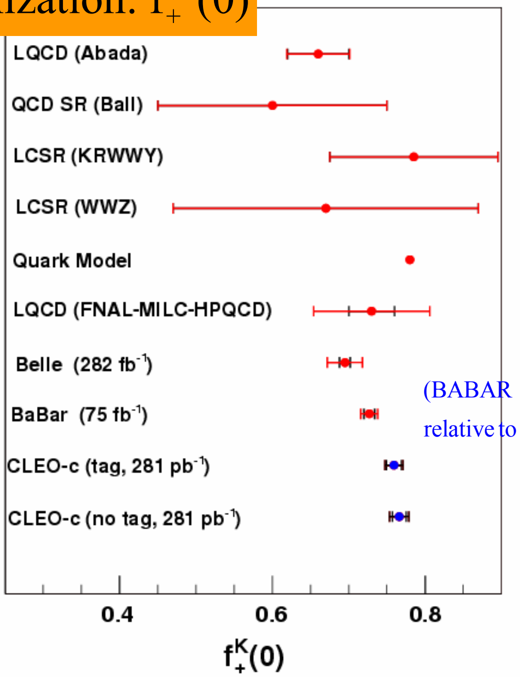
Normalization: experiments (2%) consistent with LQCD (10%). *Theoretical precision lags.*

CLEO-c prefers smaller value for shape parameter, α

Shape: α(Keν)



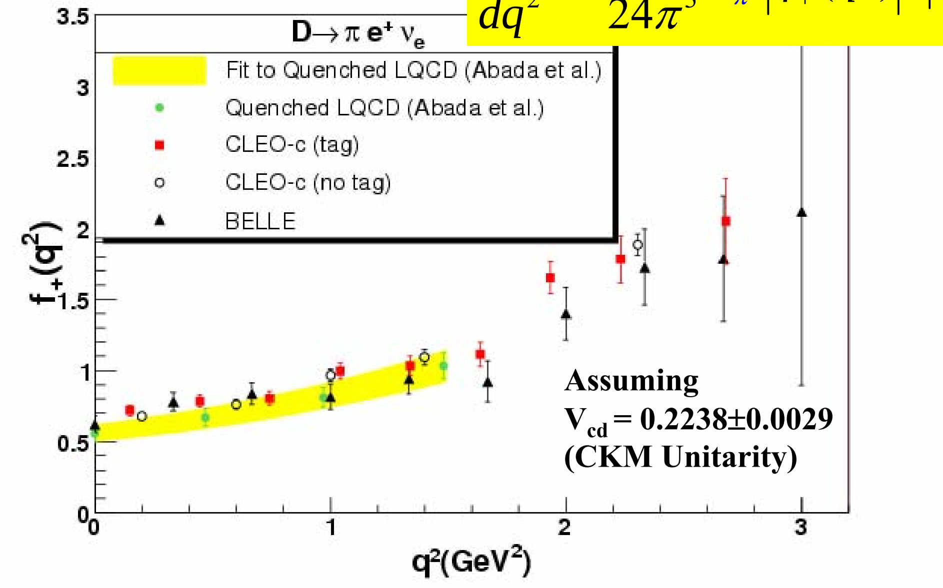
Normalization: $f_+^K(0)$



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

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

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



Assuming
$V_{cd} = 0.2238 \pm 0.0029$
(CKM Unitarity)

Modified pole model used as example

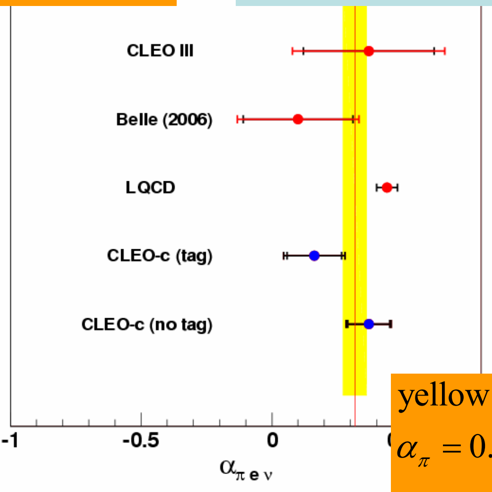
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha\, q^2/m_{pole}^2\right)}$$

Normalization experiments (4%) 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 $|V_{cd}|f_+(q^2)$, determine $|V_{cd}|f_+(0)$ & use $f_+(0)$ from theory (FNAL-MILC-HPQCD.) Same for $|V_{cs}|$

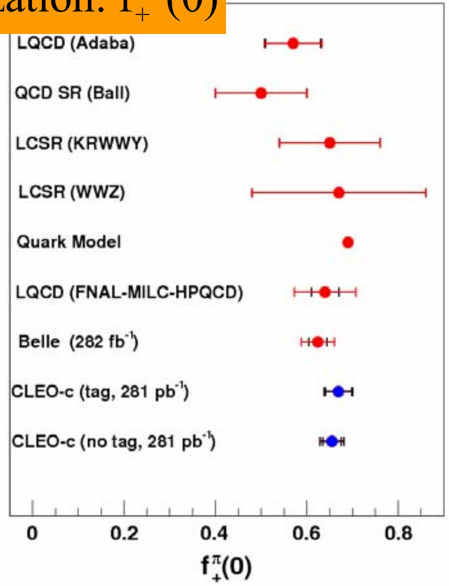
shape: $\alpha(\pi e \nu)$

FNAL-MILC-HPQCD



yellow band
$\alpha_\pi = 0.32(5)$
my avg.

Normalization: $f_+^K(0)$

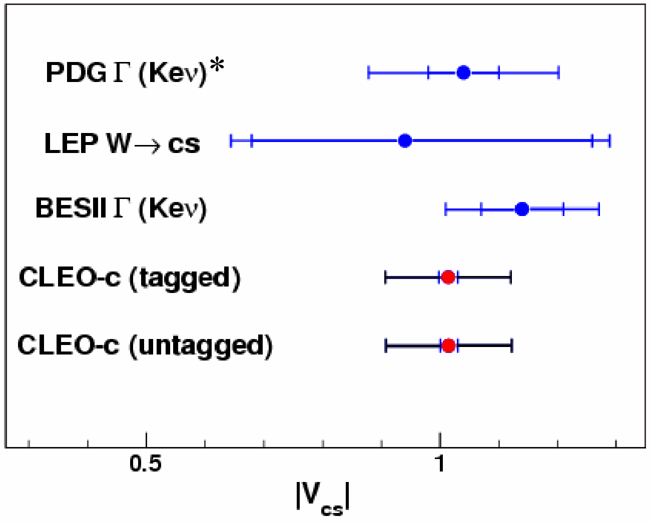


V_{cs} & V_{cd} Results

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

$$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.5\%(\text{expt}) \oplus 10\%(\text{theory})$$

$CLEO-c$	V_{cs}
(tagged prelim)	$1.014 \pm 0.013 \pm 0.009 \pm 0.106$
(untagged final)	$1.015 \pm 0.010 \pm 0.011 \pm 0.106$
	stat syst theory

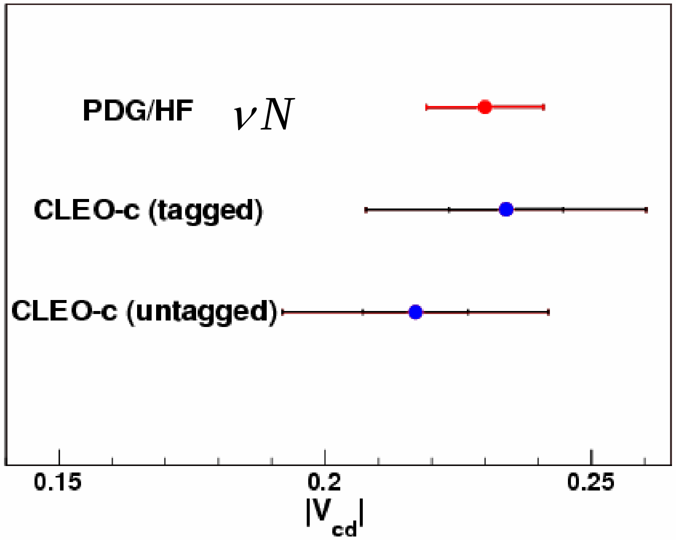


CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 4.5\%(\text{expt}) \oplus 10\%(\text{theory})$

νN remains most precise determination (*for now)*

$CLEO-c$	V_{cd}
(tagged prelim)	$0.234 \pm 0.010 \pm 0.004 \pm 0.024$
(untagged final)	$0.217 \pm 0.009 \pm 0.004 \pm 0.023$
	stat syst theory

Tagged/untagged consistent
40% overlap, DO NOT AVERAGE



We measure $|V_{cx}|f_+(0)$ using Becher-Hill parameterization
& $f_+(0)$ from *FNAL-MILC-HPQCD.*

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

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

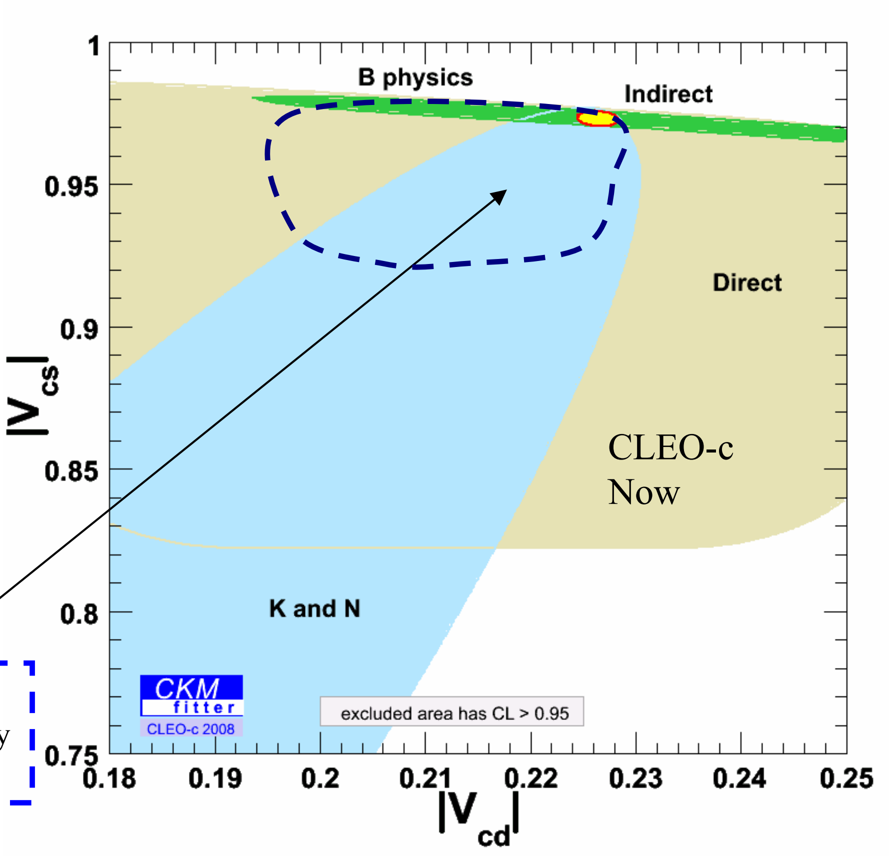
(D semileptonic decays CLEO)

Projections to full data set

$\sigma(|V_{cd}|)/|V_{cd}| \sim 2.5\% \oplus$ theory

$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.0\% \oplus$ theory

CLEO-c full data set + Few % theory uncertainties



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

Plots by Sebastien Descortes-Genon & Ian Shipsey
See also talk by Descotres-Genon at joint BABAR-Belle-BESIII-CLEO-c Workshop 11/07, Beijing

CESR CLEO

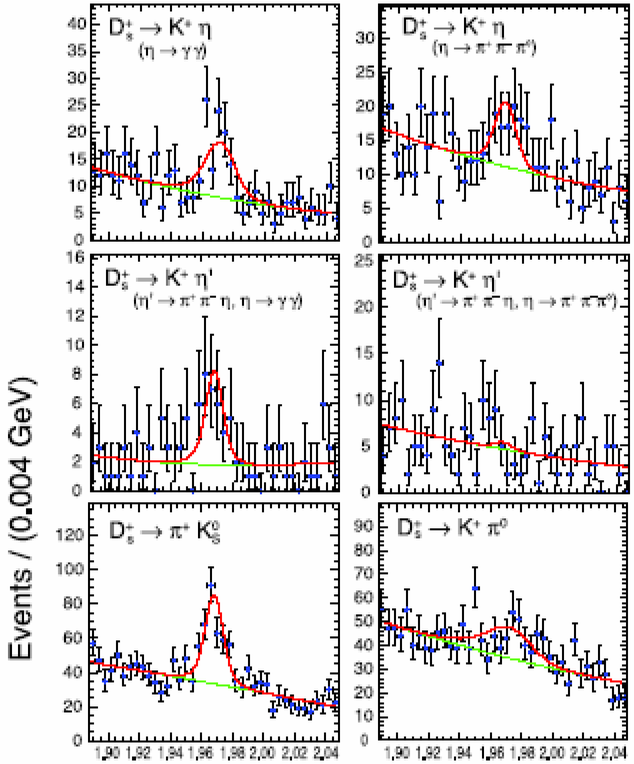
CLEO-c Searches for Direct CP violation in D decays

Many new modes: most promising in SM: Ds Cabibbo suppressed
If CPV seen in Cabibbo allowed or DCSD it would be new physics

Technique: tag & count separately $D \,\&\, \overline{D}$

$D_S \rightarrow PP$

PRL 99 191805 (2007)



arXiv 0801.0680

Mode	$(\mathcal{B}_+ -$ A_{CP} $- \mathcal{B}_-)(\%)$
$\mathcal{A}(D_s^+ \to K^+\eta)$	-20 ± 18
$\mathcal{A}(D_s^+ \to K^+\eta')$	-17 ± 37
$\mathcal{A}(D_s^+ \to \pi^+ K_S^0)$	27 ± 11
$\mathcal{A}(D_s^+ \to K^+\pi^0)$	2 ± 29

1st Observation of the Cabibbo suppressed decays

(Mostly) Cabibbo Allowed:

D_s

Mode	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^+$	$-4.9 \pm 2.1 \pm 0.9$
$K^- K^+ \pi^+$	$+0.3 \pm 1.1 \pm 0.8$
$K^- K^+ \pi^+ \pi^0$	$-5.9 \pm 4.2 \pm 1.2$
$K_S^0 K^- \pi^+ \pi^+$	$-0.7 \pm 3.6 \pm 1.1$
$\pi^+ \pi^+ \pi^-$	$+2.0 \pm 4.6 \pm 0.7$
$\pi^+ \eta$	$-8.2 \pm 5.2 \pm 0.8$
$\pi^+ \eta'$	$-5.5 \pm 3.7 \pm 1.2$
$K^+ \pi^+ \pi^-$	$+11.2 \pm 7.0 \pm 0.9$

Phys. Rev. D 76, 112001 (2007)

$D^0 \,/\, D^+$

Mode	$\mathcal{A}_{CP}$ (%)
$D^0 \to K^-\pi^+$	$-0.4 \pm 0.5 \pm 0.9$
$D^0 \to K^-\pi^+\pi^0$	$0.2 \pm 0.4 \pm 0.8$
$D^0 \to K^-\pi^+\pi^+\pi^-$	$0.7 \pm 0.5 \pm 0.9$
$D^+ \to K^-\pi^+\pi^+$	$-0.5 \pm 0.4 \pm 0.9$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$1.0 \pm 0.9 \pm 0.9$
$D^+ \to K_S^0\pi^+$	$-0.6 \pm 1.0 \pm 0.3$
$D^+ \to K_S^0\pi^+\pi^0$	$0.3 \pm 0.9 \pm 0.3$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$0.1 \pm 1.1 \pm 0.6$
$D^+ \to K^+K^-\pi^+$	$-0.1 \pm 1.5 \pm 0.8$

No statistically significant A_{CP} for any mode. CLEO-c best measurement of all modes except D+→KKpi. δA_{CP} ~1% (best case) for Cabibbo allowed, larger for Cabibbo suppressed.

$D \rightarrow X l^+ l^-$

D Rare decays

No FCNC in kaons → charm,
Bmixing → heavy top

How about charm?

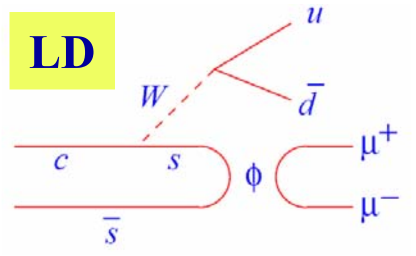
If new particles are to appear

on-shell at LHC

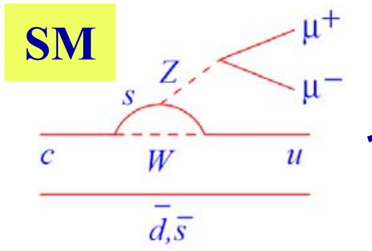
they must appear in virtual loops

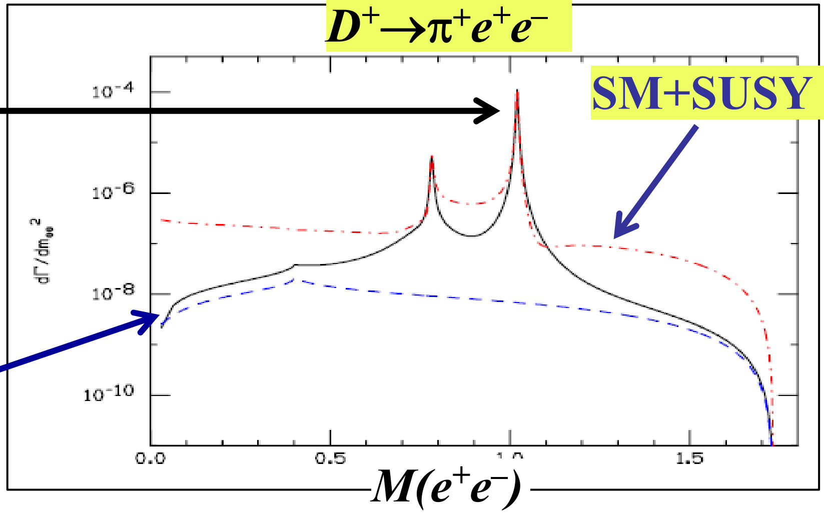
and affect amplitudes

LD



SM

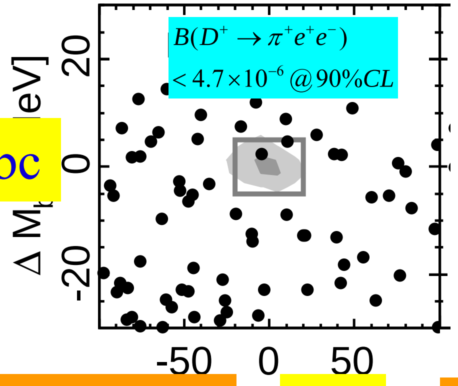




In the SM $\mathcal{B}(D^+ \Rightarrow \pi^+ e^+ e^-) \sim 2 \times 10^{-6}$

R-parity violating SUSY: $\sim 2.4 \times 10^{-6}$

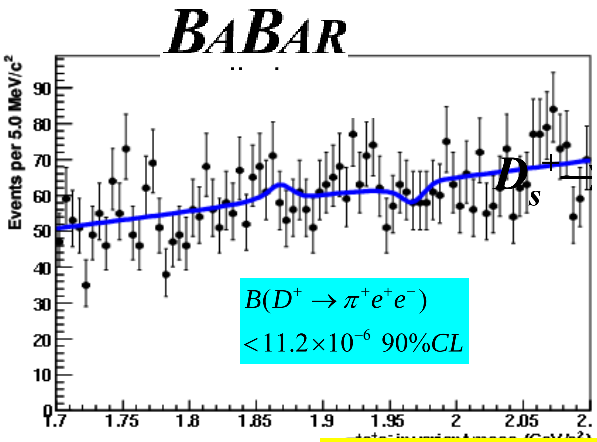
CLEO-c



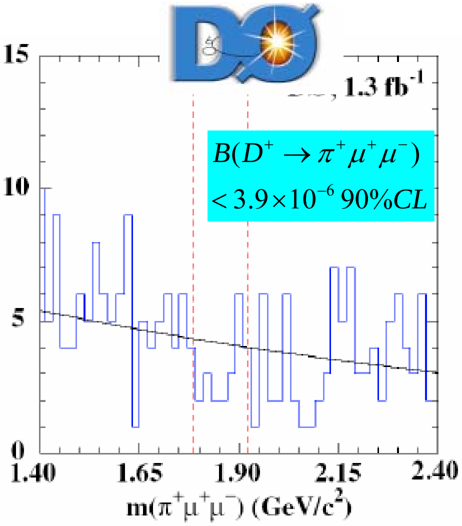
$B(D^+ \rightarrow \pi^+ e^+ e^-)$
$< 4.7 \times 10^{-6}$ @90%CL

ΔMbc

ΔE



$B(D^+ \rightarrow \pi^+ e^+ e^-)$
$< 11.2 \times 10^{-6}$ 90%CL



$B(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$
$< 3.9 \times 10^{-6}$ 90%CL

Statistics limited

Bkgd limited

$M(\pi^+ e^+ e^-)$

Tevatron may glimpse, study @ BES III, super B factories

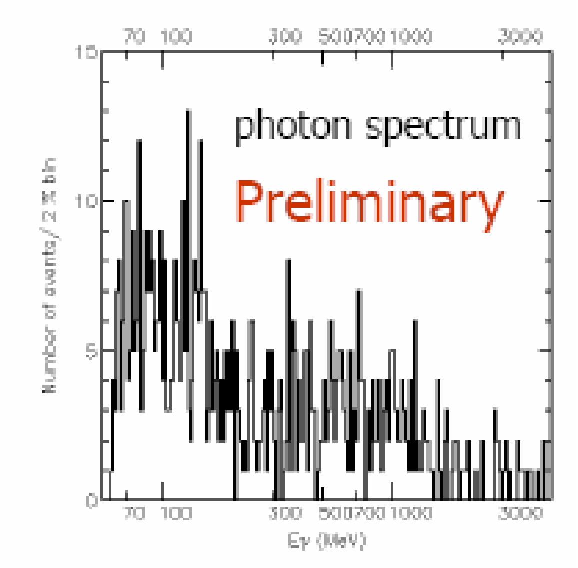
Search for a non-SM-like pseudoscalar Higgs

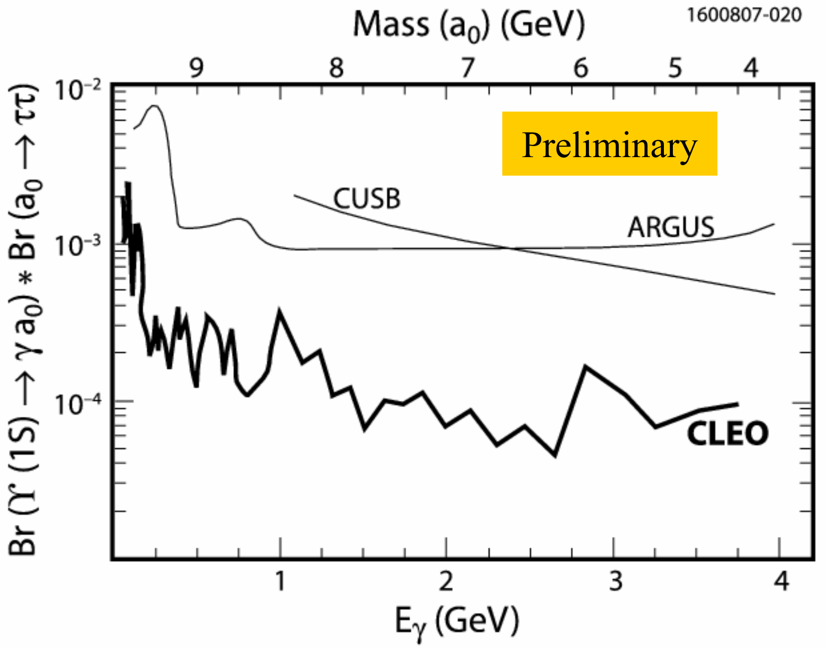
Dermisek, Gunion, McElrath propose adding to the MSSM a non-SM-like pseudoscalar higgs a_0 with $m_{a0} < 2m_b$ [hep-ph/0612031] "NMSSM"

- "natural," avoids fine tuning
- evades the LEP limit $M_h > 100$ GeV since $h \to a_0 a_0$, but $a_0 \not\to bb$ and LEP sought b jets
- $a_0 \to \tau^+\tau^-$ should predominate if $m_{a0} > 2m_\tau$
- Should be visible in $\Upsilon \to \gamma\, a_0$

Experimentally, CLEO seeks monochromatic γ

- Use $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ tag to eliminate $e^+e^- \to \tau\tau\gamma$ background
- Flag presence of τ pair with two 1-prong τ decays (one lepton), missing energy





ULs improved an order of magnitude or more

Rules out many, but not all NMSSM models

Improved $a_0 \to \tau^+\tau^-$ & $a_0 \to \mu^+\mu^-$ (c.f.Hyper-CP) by Spring '08

Summary Slide

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: $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV consistent with LQCD $\rightarrow 3.7\%$ (8 MeV) full data

Most precise: $f_{D_s} = (274 \pm 10 \pm 5)$ MeV 3σ higher than LQCD. To interpret as "prosaic" or "exciting": calculation checks underway & radiative corrections need to be estimated

project: f_{D_s} 2.6%(7MeV) full data set

lepton universality in D, D_s decays is satisfied

most precise $|V_{cs}| = 1.015 \pm 0.010 \pm 0.011 \pm 0.106_{\text{theory}}$

$|V_{cd}| = 0.217 \pm 0.009 \pm 0.004 \pm 0.023_{\text{theory}}$

most precise determination from semileptonic decay

Projections to full data set

$\sigma(|V_{cd}|)/|V_{cd}| \sim 2.5\% \oplus \text{theory}$

$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.0\% \oplus \text{theory}$

Best limits on direct CPV for many D modes

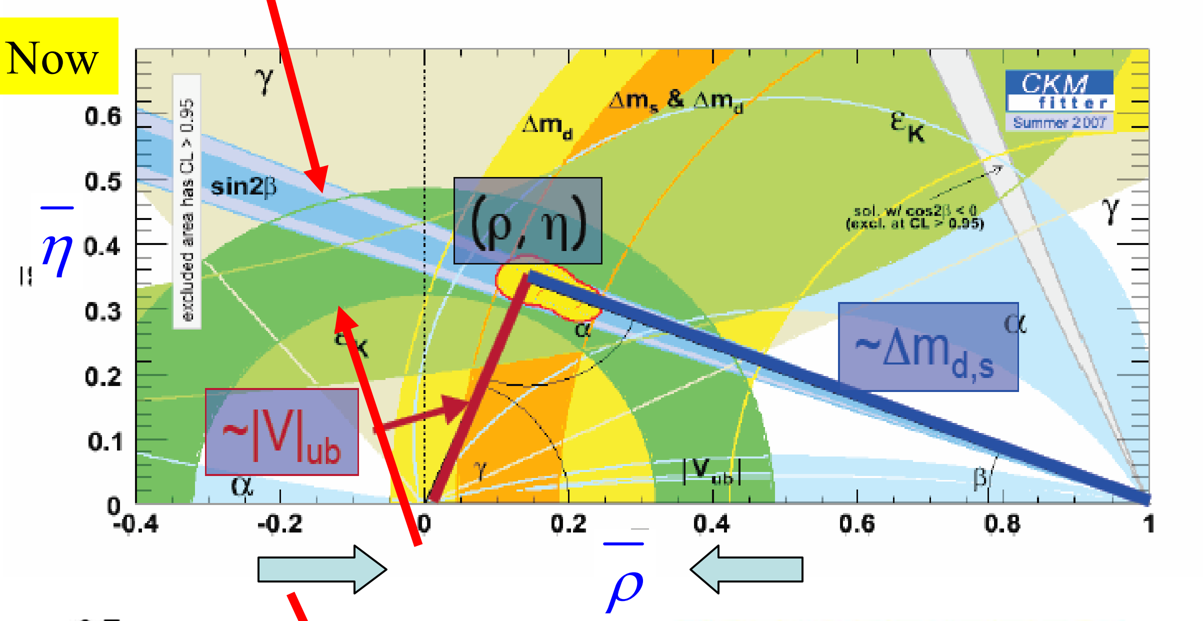
Best limits for a non-SM-like pseudoscalar Higgs

Best limit on $D \rightarrow \pi e^+ e^-$

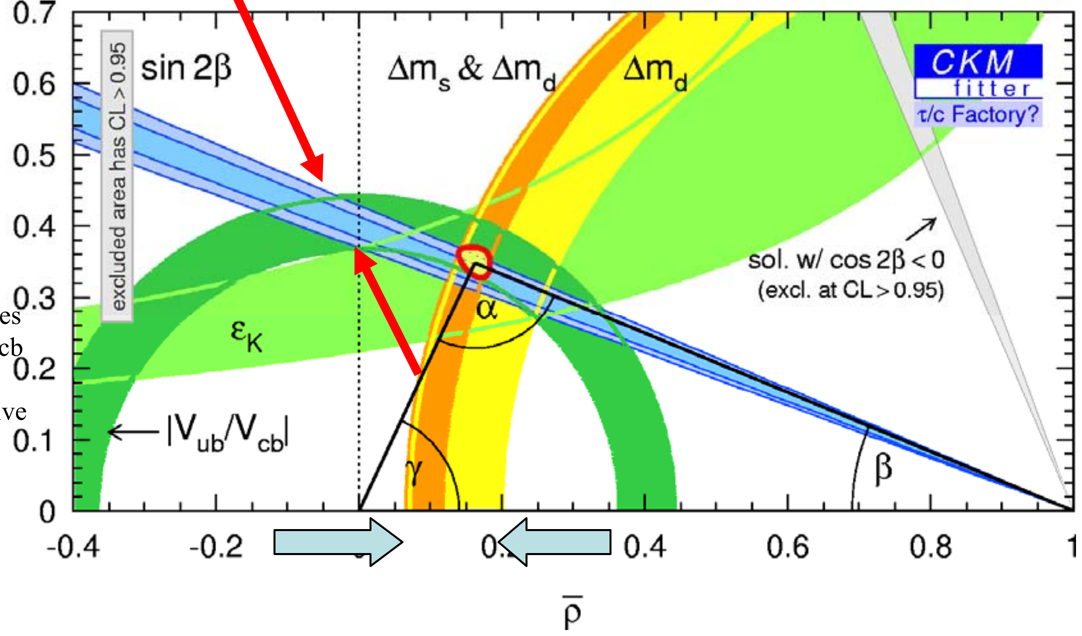
CLEO-c has 800/pb @ 3770 (x3) & 600/pb at 4170 (x2) by 3/31/08
→more stringent tests of theory: fD+, fDs, D→ K/πev f+(0),shape,Vcs & Vcd by summer. Longer term the charm factory mantle passes to BES III.

Precision theory + charm = large impact

Now



Theoretical errors dominate width of bands



Plot uses Vub Vcb from exclusive decays only

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