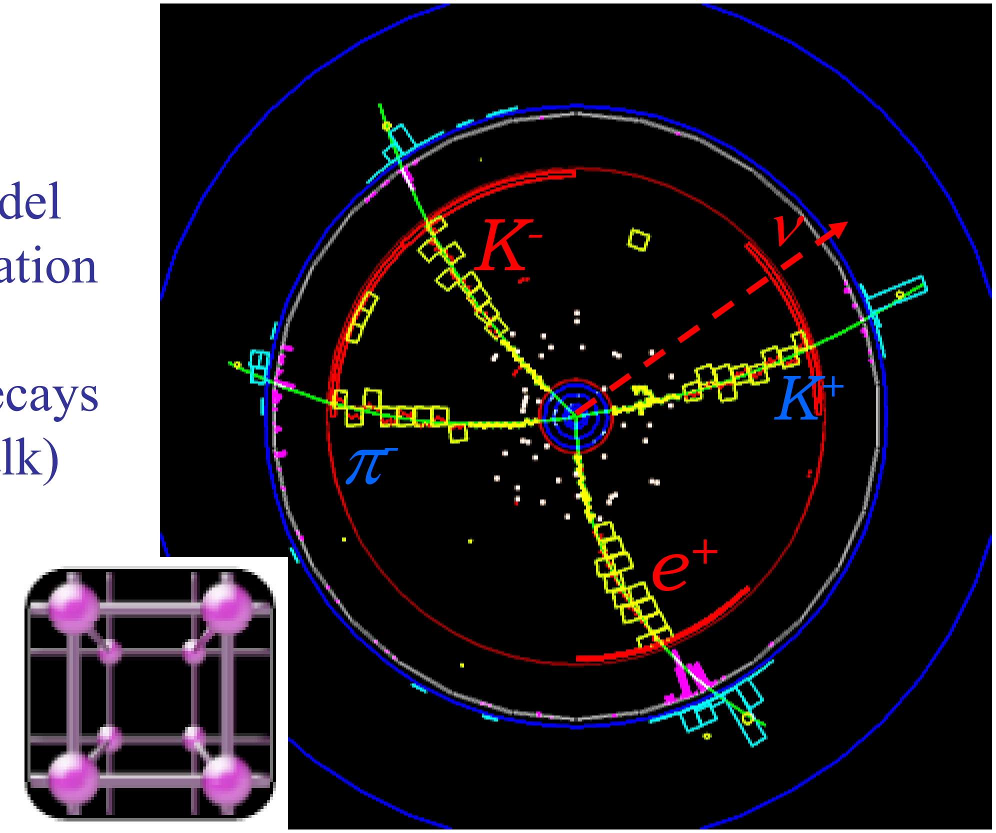
# Recent Results in Charm Flavour Physics: CKM Studies and New Physics Searches with Charm

Two themes:

1) *CKM Physics*
Charm's role in testing the Standard Model description of Quark Mixing & CP Violation
Lifetimes
Hadronic , Leptonic & Semileptonic Decays
(significant progress this year, bulk of talk)

2) *Physics Beyond the Standard Model*
D mixing
D CP Violation
D Rare Decays



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

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

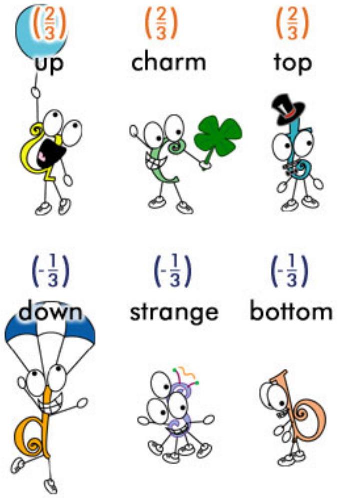
Ian Shipsey, Purdue University

**Frontier Science 2005 , Milano, Sept. 12 – 16, 2005**

# 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

# Charm Physics: The Context

**This Decade**

Flavor physics is in the “$\sin 2\beta$ era’ akin to precision Z.
Over constrain CKM matrix with precision measurements
Discovery potential is limited by systematic errors
from non-pert. QCD

**The Future**

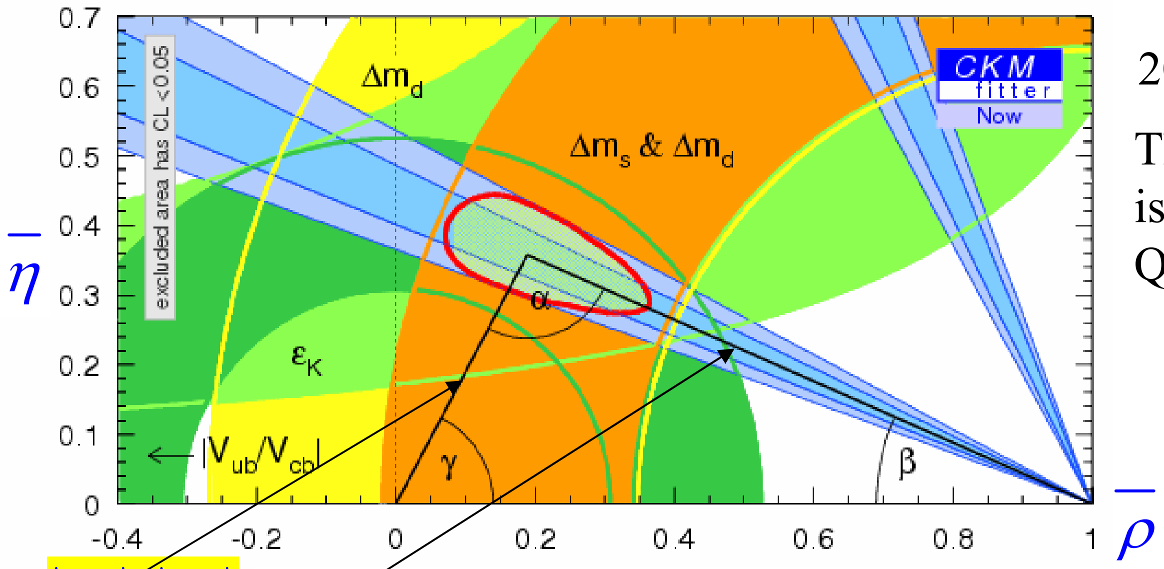
LHC may uncover strongly coupled sectors in the physics
Beyond the Standard Model. The ILC will study them.
Strongly coupled field theories→ an outstanding challenge
to theory. Critical need: reliable theoretical techniques
& detailed data to calibrate them

**The Lattice**

Complete definition of pert. and non-pert. QCD Goal:
Calculate B, D, Y, $\psi$ to 5% in a few years, and a few %
longer term.

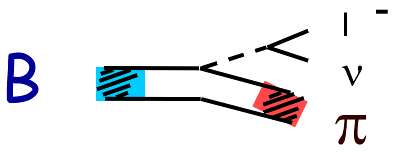
Charm can provide the data to test and calibrate non-pert. QCD
techniques such as the lattice (especially true at charm threshold)

# Precision Quark Flavor Physics: charm's role



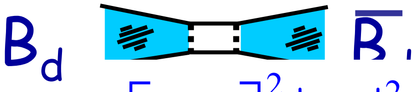
2005

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



$\propto [f(q)]^2 |V_{ub}|^2$

$|V_{ub}|, |V_{cb}|$ From semileptonic decay requires form factors (theory)



$|V_{td}|, |V_{ts}|$ From B mixing requires decay constants (theory)

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

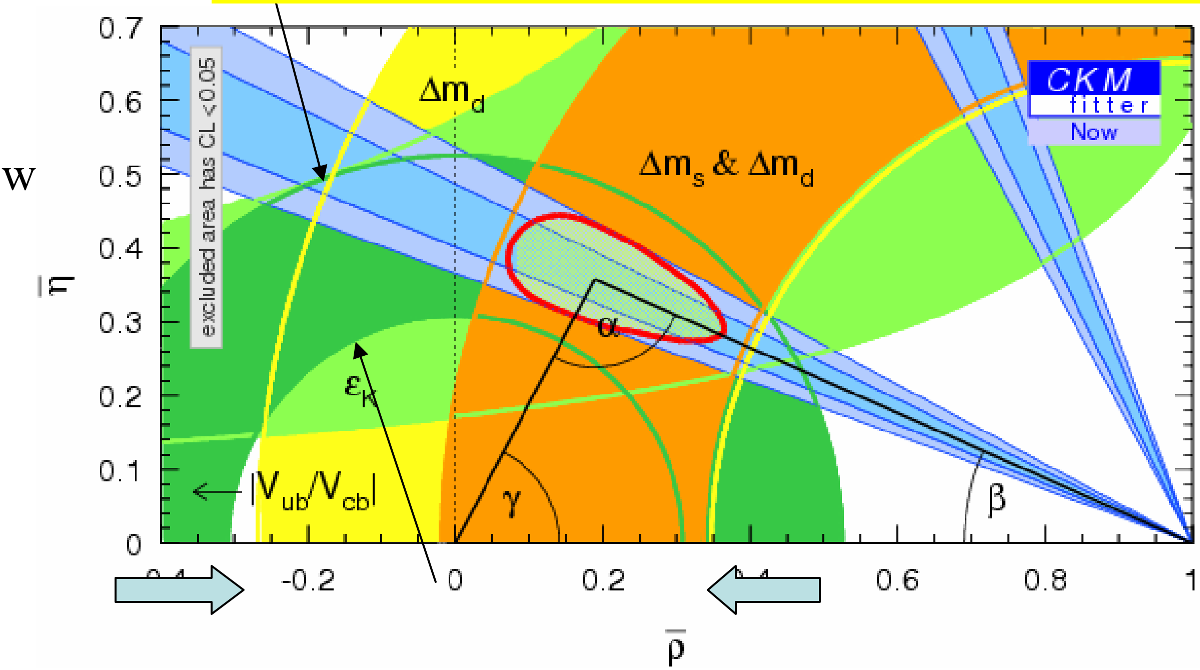
D system- CKM matrix elements are known to a precision of <1% by unitarity

➔Work back from *measurements of absolute rates* for leptonic and semileptonic D decays yielding decay constants and form factors to *test* and hone QCD techniques into *precision theory* which can then be applied to the B system.

In addition as Br(B➔ D)~100% *absolute* D branching ratios normalize B physics.

# Precision theory + charm = large impact

Now



Theoretical errors dominate width of bands

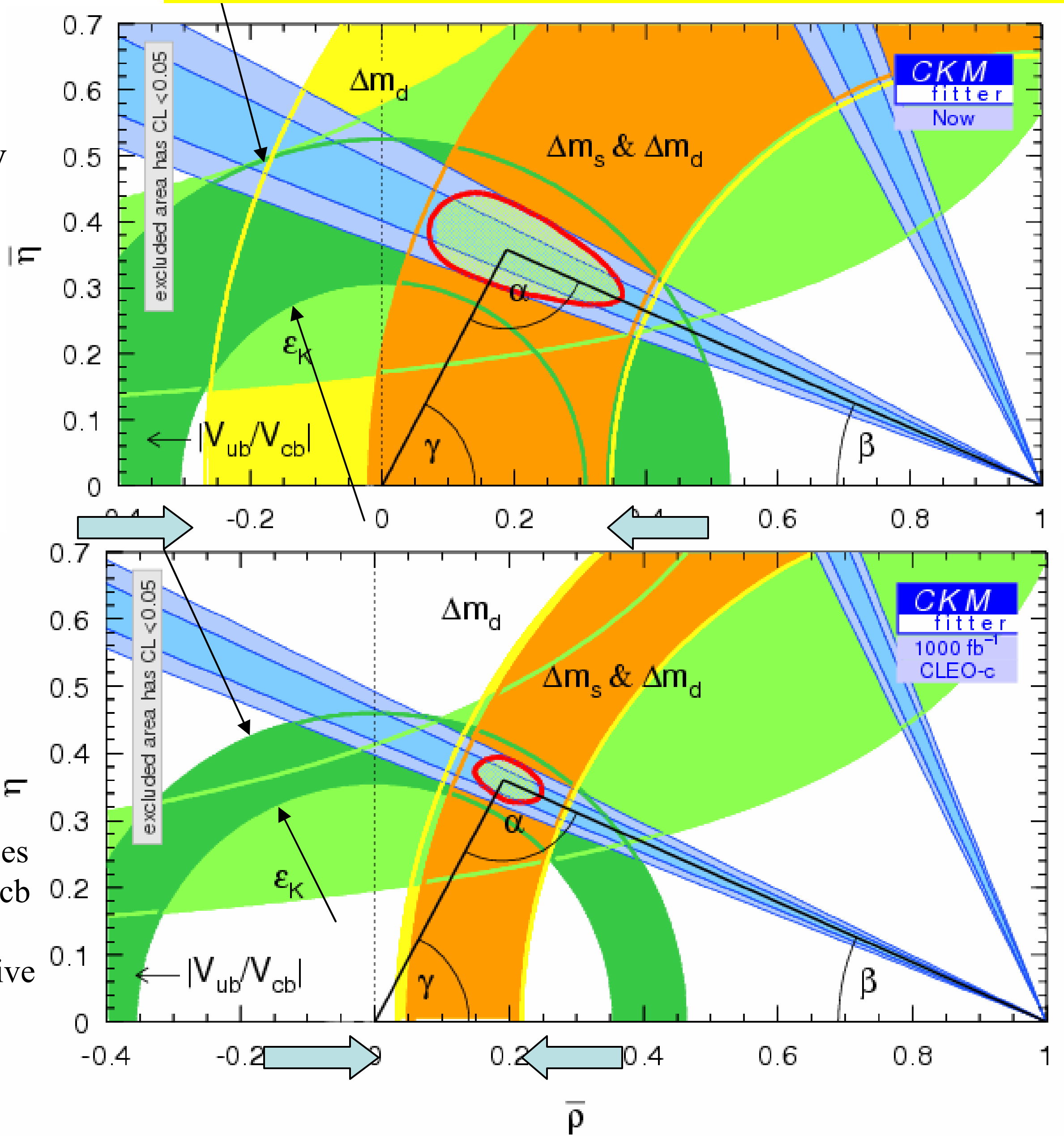
*precision* QCD calculations tested with *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

500 fb-1 @ BABAR/Belle

# Precision theory + charm = large impact

Now



Theoretical errors dominate width of bands

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

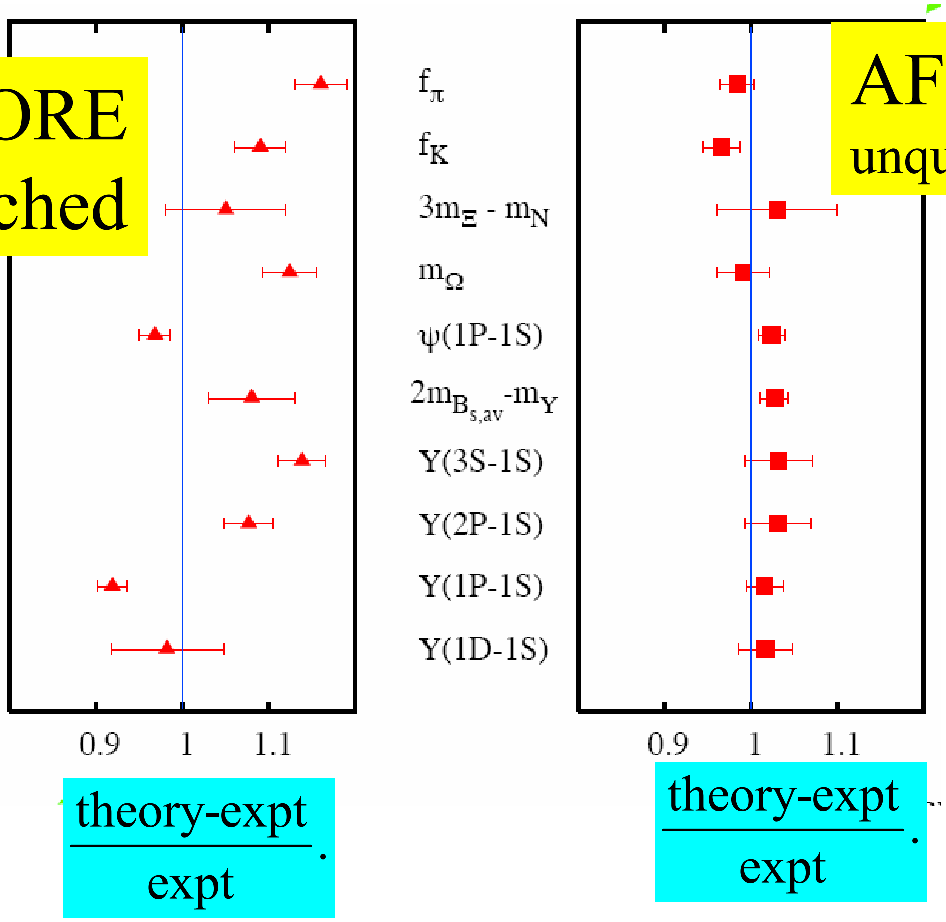
+

500 fb-1 @ BABAR/Belle

Plot uses Vub Vcb from exclusive ecays only

# Precision theory? In 2003 a breakthrough in Lattice QCD

After 30 years of struggle Lattice QCD demonstrated that it can reproduce a wide range of mass differences and decay constants for the first time. These were postdictions.

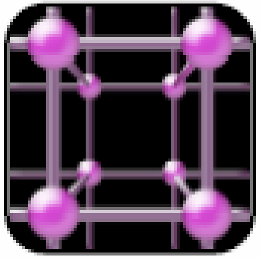


Testable predictions are now being made:

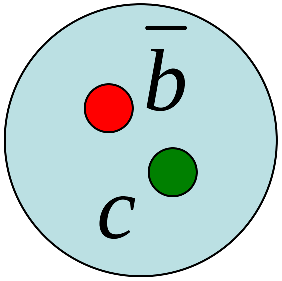
M($B_c$) ← Easier, the 1st prediction Nov. 2004 - a success.

Charm decay constant $f_D$ ← Harder- first test July 2005

Semileptonic D/B form factors ← Hardest- First tests 2005



# Lattice QCD Prediction Mass of the $B_c$

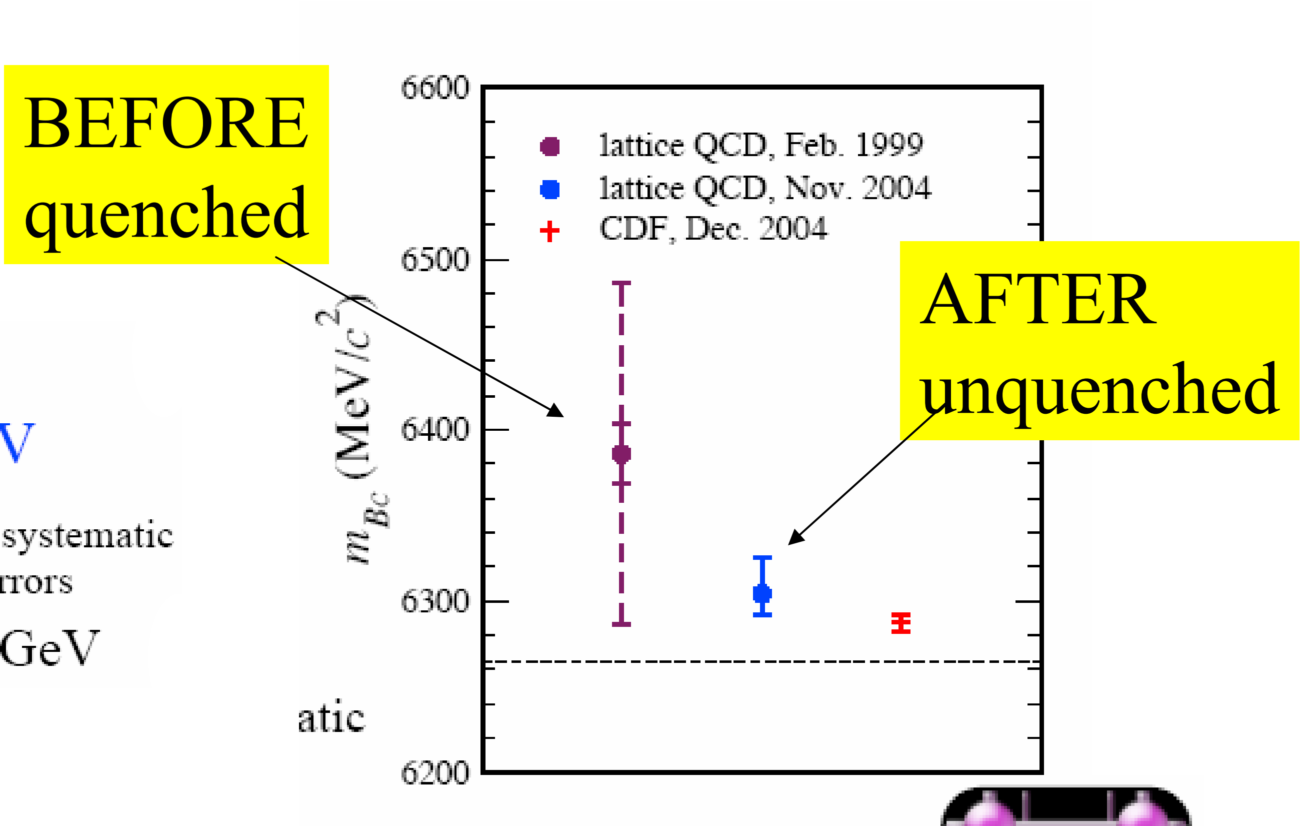


Result:

$$M_{B_c} = 6.304(20)\,\mathrm{GeV}$$

Lattice systematic errors

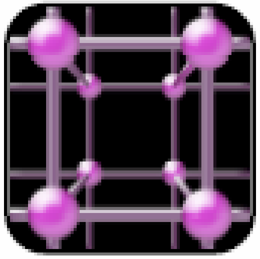
CDF (2005): 6.287(5) GeV



BEFORE quenched

AFTER unquenched

lattice prediction came out just 5 days before
the CDF measurement and agrees to 3 parts in 1,000



HPQCD/FNAL /UKQCD Allison et al, hep-lat/0411027; CDF, Acosta et al, hep-ex/0505076,

# Many Experiments Contribute

Results used in this talk have been obtained by the following Collaborations:

| | Fixed Target | | $e^+e^-$ | | | $p\bar{p}$ |
|---|---|---|---|---|---|---|
| | E791 | FOCUS | LEP | CLEO | BaBar/Belle | CDF |
| Beam | Hadron | Photon | $e^+e^- \to Z^0$ | $e^+e^-$ | | $p\bar{p}$ |
| $K^-\pi^+$ | $\sim 2\times10^4$ | $\sim 2\times10^5$ | $\sim 10^4$ /expt. | $\sim 2\times10^5$ | $\sim$ few $10^6$ | $\sim 10^6$ |
| $\sigma_t$ | ~ 40 fs | ~ 40 fs | ~ 100 fs | ~ 140 fs | ~ 160 fs | ~ 50 fs |

The B Factories and CDF now have the largest charm samples.

In 2003-2005:

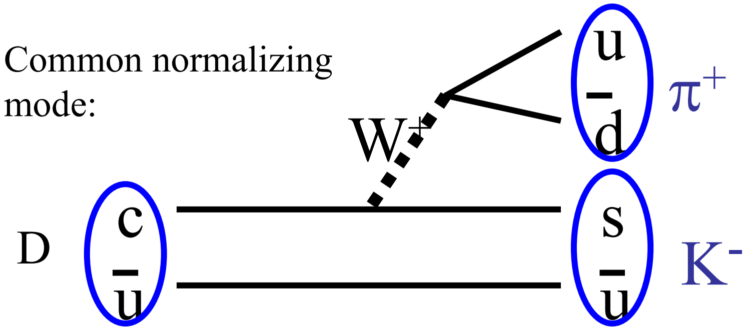
(Pilot run)

| | BESII | CLEO-c |
|---|---|---|
| Beam | $e^+e^- \to \psi(3770)$ | |
| $K^-\pi^+$ | $\sim 2.7\times10^3$ | $\sim 5\times10^4$ |
| $\sigma_t$ | Not applicable | Not applicable |

Note:K-π+ is # reconstructed in published analyses, not total collected.

Exceptionally low background charm samples were obtained at BESII & CLEO-c ideal for measuring absolute charm branching ratios.

Common normalizing mode:



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

# Charm Hadron Lifetimes

Lifetime needed to compare Br(expt) to partial Γ (theory)

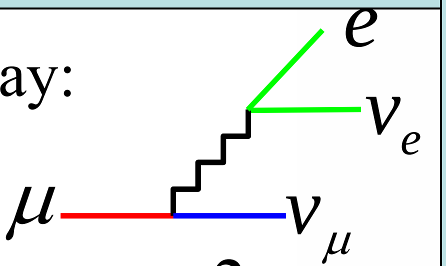
Interpreted within O.P.E.

$$\Gamma(H_c) = \Gamma_{spect} + O(1/m_c^2) + \Gamma_{PI,WA,WS}(H_c) + O(1/m_c^4)$$

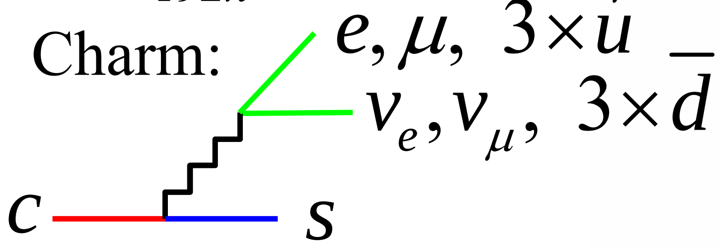
Spectator effects (PI.WA,WS) are $O(1/m_c^3)$ these differentiate between species

Muon decay:

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3}$$



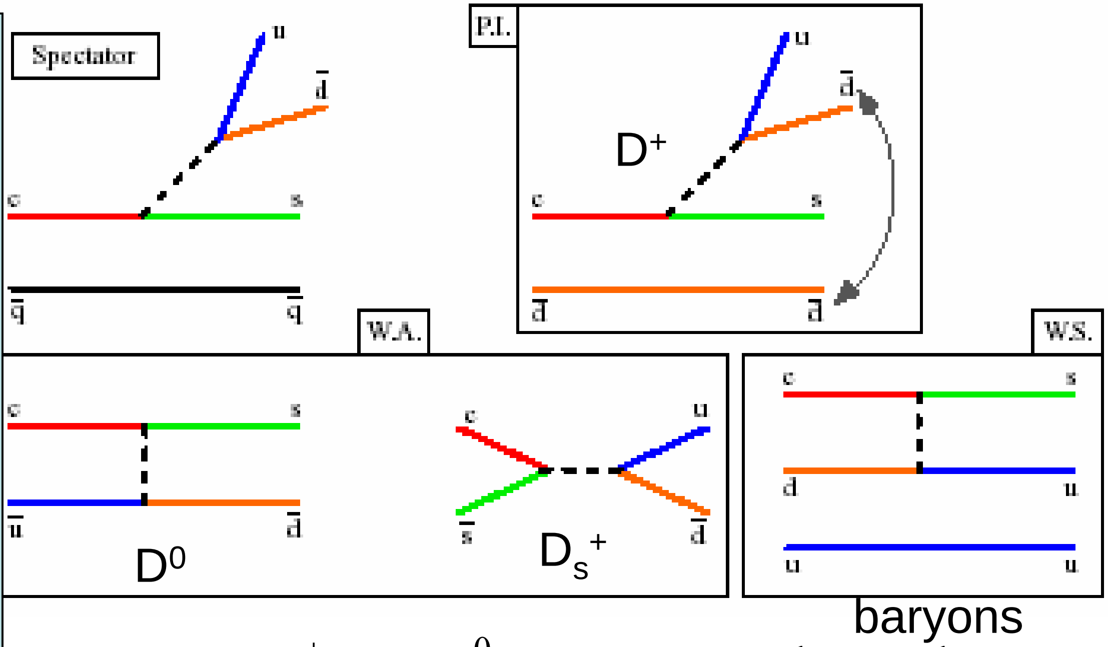
Charm:



$$\Gamma_{charm} = (2+3)\Gamma_\mu \quad e, \mu \quad 3\times(ud)$$

$$\Gamma_{charm} = \frac{G_F^2 m_c^5}{192\pi^3}|V_{cs}|^2 \Rightarrow \tau_{charm} = 700\ fs$$

$\tau(D^+)$ ~1,000 fs $\tau(D^0)$ ~400 fs.



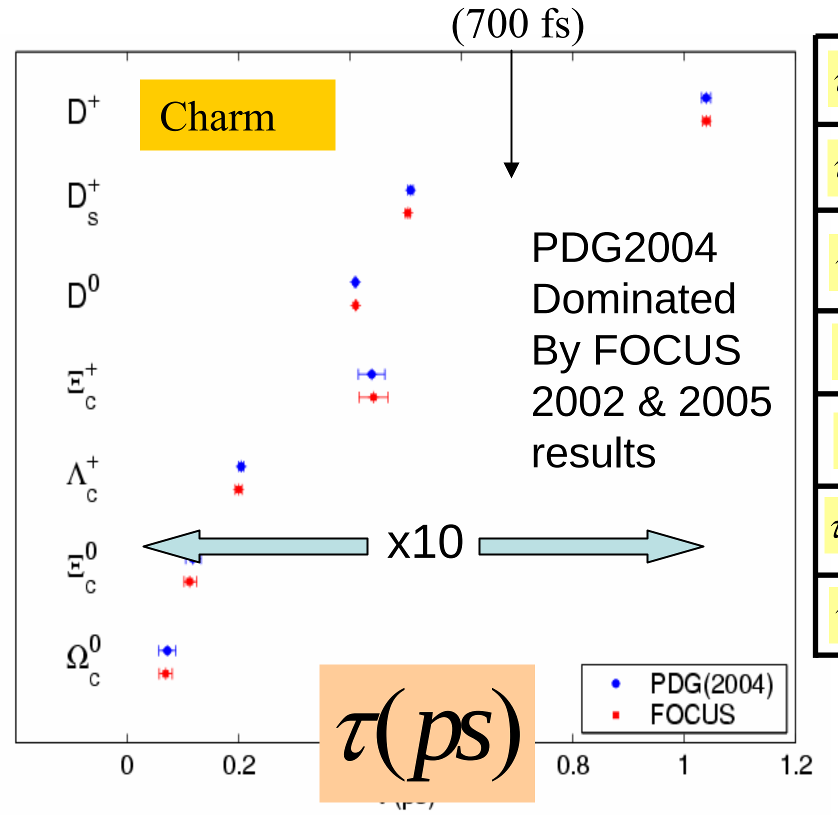
Expect: $\tau D^+ > \tau D^0 \sim \tau D_S > \tau$ charm baryons

Data is consistent with this

Gross features of lifetime hierarchy can be explained

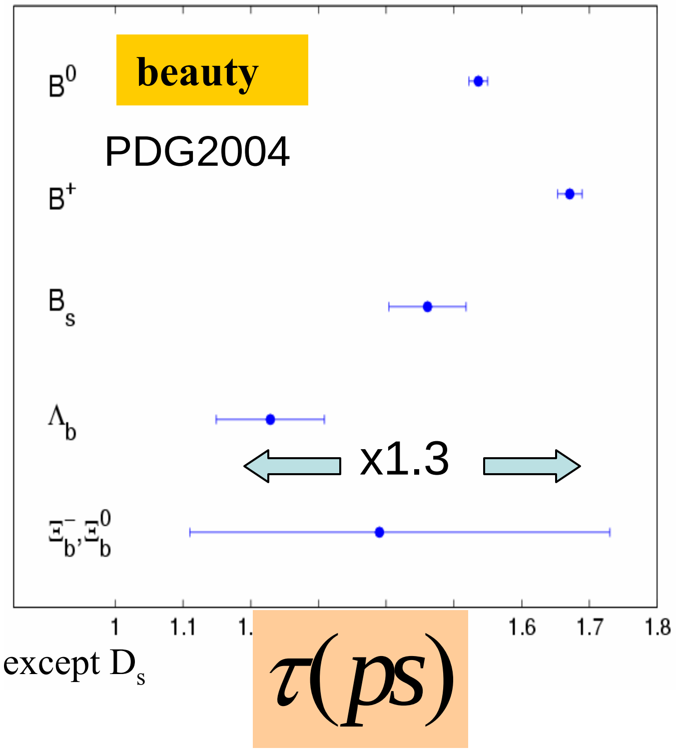
SELEX, FOCUS, CLEO
E791 E687

Expect: $\tau D^+ > \tau D^0 \sim \tau D_S > \tau$ charm baryons
Data is consistent with this



PDG2004
Dominated
By FOCUS
2002 & 2005
results

| | |
|---|---|
| $\tau(D^+)$ | $1040 \pm 7\ fs$ |
| $\tau(D_s)$ | $501 \pm 6\ fs$ |
| $\tau(D^0)$ | $410.3 \pm 1.5\ fs$ |
| $\tau(\Xi^+{}_c)$ | $442 \pm 26\ fs$ |
| $\tau(\Lambda_c)$ | $200 \pm 6\ fs$ |
| $\tau(\Xi^0{}_c)$ | $112^{+13}_{-10}\ fs$ |
| $\tau(\Omega_c)$ | $69 \pm 12\ fs$ |



Lifetimes are PDG2004 except $D_s$
which is a PDG2004
+ FOCUS 2005.

$D^+$ 7 ‰, $D^0$ 4 ‰, $D_s$ 8 ‰, $\Lambda_c$ 3%, $\Xi^0$ 10%, $\Xi^+{}_c$ 6 %, $\Omega_c$ 17%
some lifetimes known as precisely as kaon lifetimes.

$$\frac{\tau(D^+)}{\tau(D^0)} \approx 2.5 \qquad \frac{\tau(B^+)}{\tau(B^0)} \approx 1.1$$

PDG2004

Charm quarks more influenced by hadronic environment than beauty quarks.

Errors on lifetimes are *not* a limiting factor in the measurement of absolute rates.

# Status of Absolute Charm Branching Ratios in 2004 : (no progress for many years but lots since 2004)

Poorly known → $Br$

Measured very precisely → $\tau$

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

decay constants

form factors

Key hadronic charm decay modes used to normalize B physics

Circa 2004

| | Mode | PDG04 (%) | Error (%) |
|---|---|---|---|
| $D^+$ | $\mu\nu$ | $0.08^{+0.17}_{-0.05}$ | 100 |
| $D_s^+$ | $\mu\nu$ | $0.60 \pm 0.14$ | 24 |
| $D^0$ | $\pi^- e^+ \nu$ | $0.39^{+0.23}_{-0.11} \pm .04$ | 45 |
| $D^o$ | $K^-\pi^+$ | $3.80 \pm 0.09$ | 2.4 |
| $D^+$ | $K^-\pi^+\pi^+$ | $9.2 \pm 0.6$ | 6.5 |
| $D_s^+$ | $\phi\pi^+$ | $3.6 \pm 0.9$ | 25 |
| $\Lambda_c$ | $pK^-\pi^+$ | $5.0 \pm 1.3$ | 26 |
| $J/\psi$ | $\mu^+\mu^-$ | $5.88 \pm 0.10$ | 1.7 |

Charm produced at B Factories/Tevatron or at dedicated FT experiments allows relative rate measurements but absolute rate measurements are hard because backgrounds are sizeable & *because # D's produced is not well known.*

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

Backgrounds are large.

#D's produced is not well known.

# Importance of precision *absolute* charm hadronic branching ratios

ALEPH, DELPHI,
L3,OPAL.BABAR/BELLE,
ARGUS/CLEO/CDF

**Vcb Zero recoil in B → D*$l^+\nu$ & B → D$l^+\nu$**

needs absolute B(D→Kπ)

$$\frac{d\Gamma}{dq^2}(B\to D^*\ell\nu)\propto F(q^2)^2|V_{cb}|^2$$

$$F(q^2=q^2_{\max})=0.91\pm0.04$$

$$|V_{cb}|=(41.3\pm1.0_{\exp}\pm1.8_{theo})\times10^{-3}$$

(World Average Summer 2005)

**Lattice & sum rule**

As B Factory data sets grow,
& calculation of F improve

dB(D→Kπ)/dB(D→Kπ)
➔ $dV_{cb}/V_{cb}=1.2\%$

becomes significant

---

Test models of B decay ex: HQET & factorization:

Understanding charm content of B decay ($n_c$)

Precision Z →bb and Z →cc ($R_b$ & $R_c$)

At LHC/LC H → bb H → cc

Now: several key charm branching ratios have errors between 7-26%

# Status of B($D^o \to K^-\pi^+$) in 2004

>12 previous measurements

| $\mathcal{B}$ (%) | Error(%) | Source |
|---|---|---|
| 3.82±0.07±0.1 | 3.6 | CLEO |
| 3.82±0.09±0.1 | 3.8 | ALEPH |
| 3.80 ±0.09 | 2.4 | PDG |

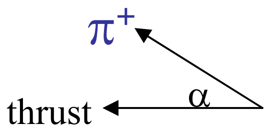
CLEO & ALEPH

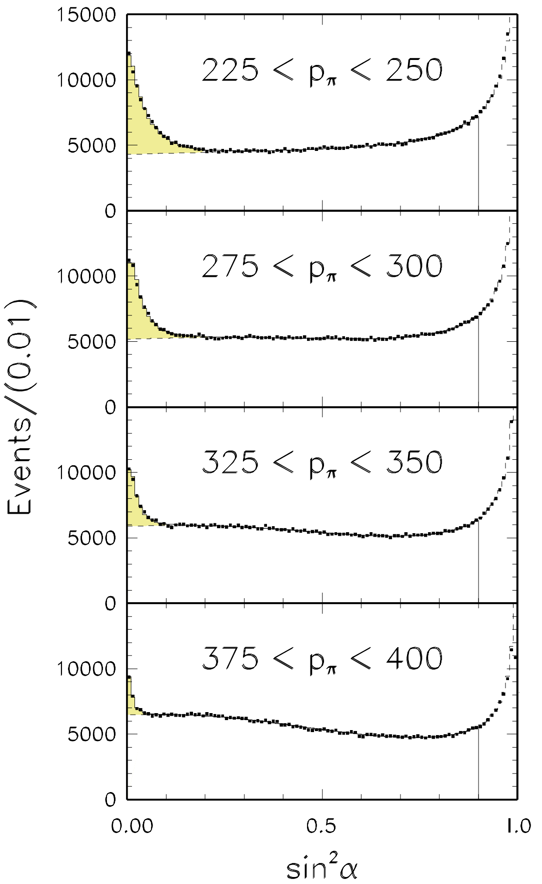
$D^{*+} \to \pi^+ D^o$, $D^o \to K^-\pi^+$

compare to:

$D^{*+} \to \pi^+ D^o$, $D^o \to$ unobserved

(Q~6MeV)





# Status of B($D^+ \to K^-\pi^+\pi^+$) in 2004

Measure:

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

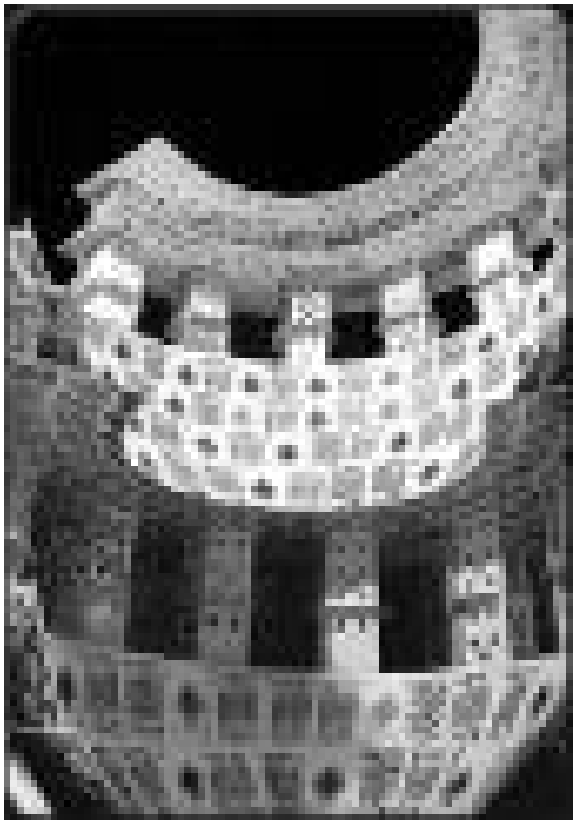
Assume isospin

(a bootstrap method it can never yield a measurement of B($D^+ \to K^-\pi^+\pi^+$) more accurate than B($D^o \to K^-\pi^+$) error was 7.7%

# Status of B($D_S^+ \to \phi\pi^+$) in 2004

B($D^+ \to \phi\pi^+$), which had a 25 % error also bootstraps on B($D^o \to K^-\pi^+$).

# Recall: the D hadronic scale sets the B hadronic scale because B→ D ~100%, *All* D hadronic BRs based on D→Kpi a high bkgd measurement. This is potentially a "house of cards"



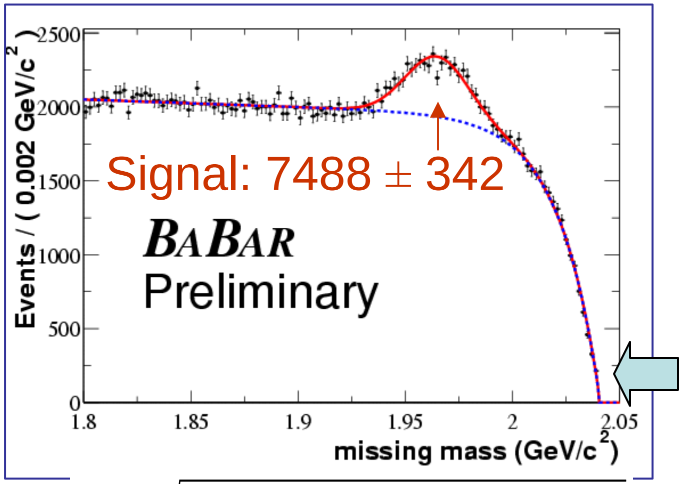
Can we do better? Yes.

FrontierScience 2005

# New Measurement of $B(D_s^+ \rightarrow \phi\, \pi^+)$

## 1: $B^0 \rightarrow D_s^{*+} D^{*-}$: *partial* reconstruction

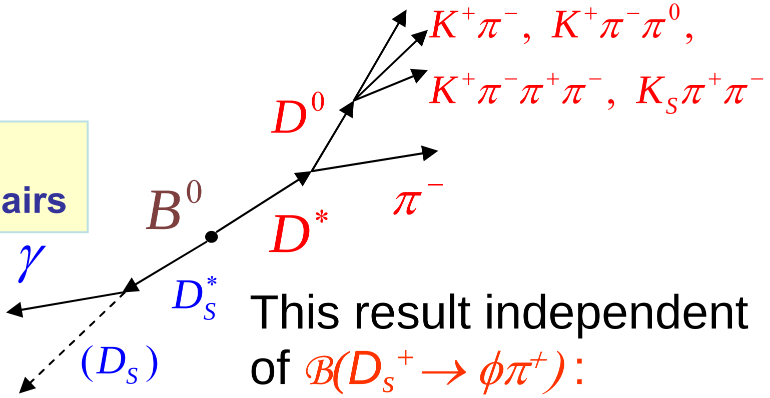
**Hep-ex/0502041**
**PRD 71 091104 (2005)**



$$m_{miss} = \sqrt{(E_{beam} - E_{D^*} - E_\gamma)^2 - (p_B + p_{D^*} + p_\gamma)^2}$$

**Data sample:**
**124 million B pairs**

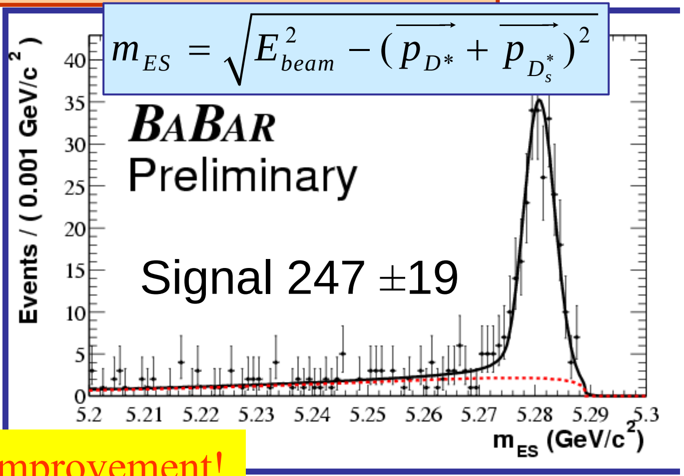
Recoil mass



This result independent of $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+)$:

$\mathcal{B}(B^0 \rightarrow D_s^{*+} D^{*-}) = (1.88 \pm 0.09_{(stat)} \pm 0.17_{(syst)})\%$

## 2: $B^0 \rightarrow D_s^{*+} D^{*-}$: *full* reconstruction



$\mathcal{B}(B^0 \rightarrow D_s^{*+} D^{*-}) \times \mathcal{B}(D_s^+ \rightarrow \phi\, \pi^+) = (8.81 \pm 0.86_{(stat)}) \times 10^{-4}$

Divide by (2) by (1)

13% total error (7.5%) syst

$\mathcal{B}(D_s^+ \rightarrow \phi\, \pi^+) = (4.81 \pm 0.52_{(stat)} \pm 0.38_{(syst)})\%$

BIG improvement!

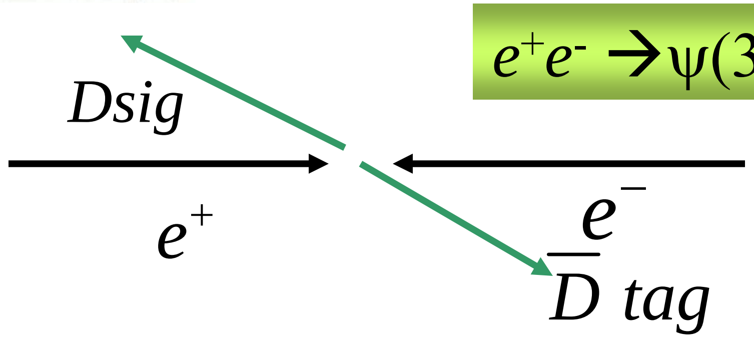
$\mathcal{B}(D_s^+ \rightarrow \phi\, \pi^+) = (3.6 \pm 0.9)\%$ **(PDG)**

(25%)

# ψ(3770) CLEO-c/BESII (+BESIII in 2007)

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

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

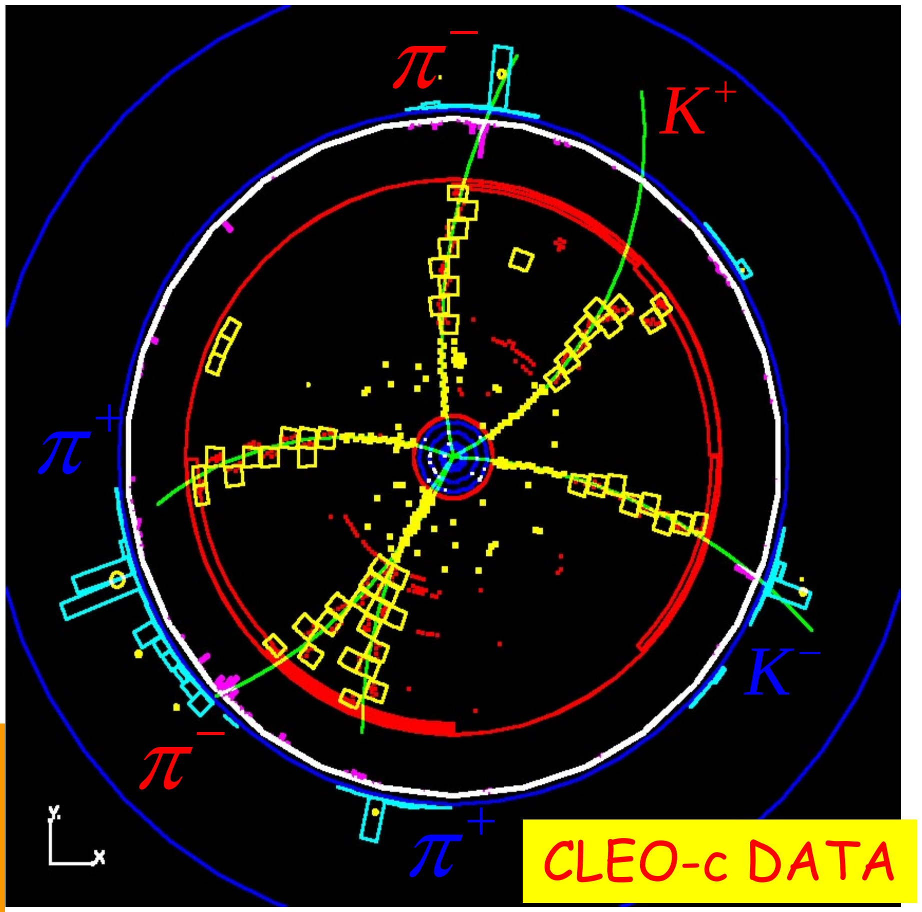


- ☐ Pure DD, no additional particles ($E_D = E_{beam}$).
- ☐ σ (DD) = 6.5 nb (Y(4S)->BB ~ 1 nb)
- ☐ Low multiplicity ~ 5-6 charged particles/event
- ☐ Pure $J^{PC} = 1^{--}$ (mixing, CP, strong phase)

- analyses strategy fully reconstruct 1D “the tag”, analyze 2nd D (the signal) to extract exclusive or inclusive properties

➔ high tagging efficiency: ~22% of D’s

Compared to <1% of B’s at the Y(4S)



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

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

A little luminosity goes a long way:
# events in 100 pb$^{-1}$ @ charm factory with 2D’s reconstructed =
# events in 500 fb$^{-1}$ @ Y(4S) with 2B’s reconstructed

FrontierScience 2005

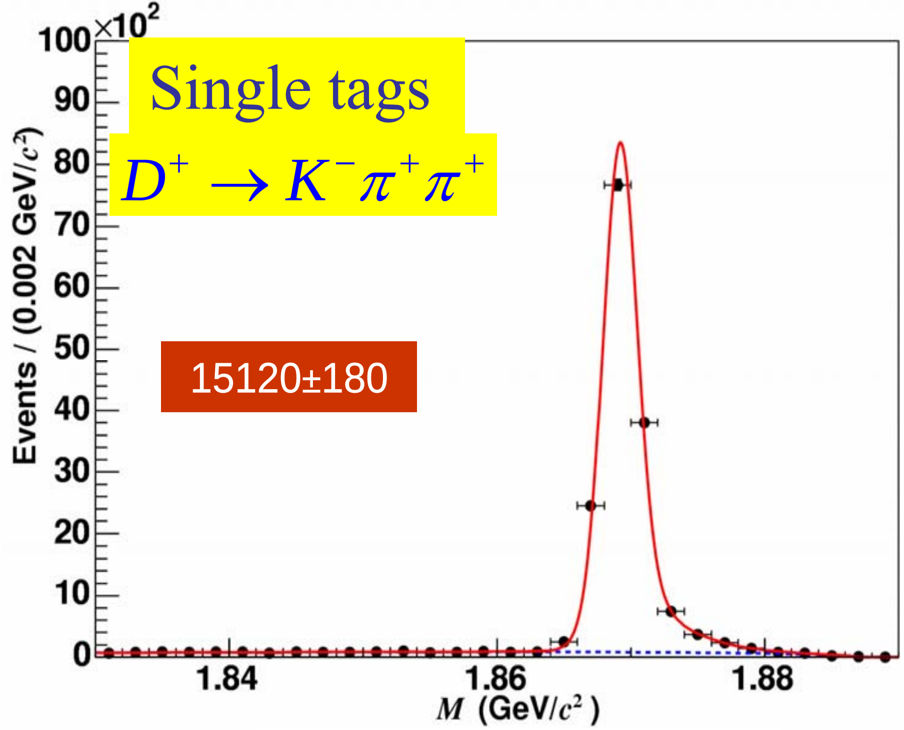
# *Absolute* Charm Branching Ratios at Threshold

- Kinematics analogous to Υ(4S)→*BB*: identify *D* with

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

- $\sigma(M_{BC}) \sim 1.3$ MeV, x2 with $\pi^0$
- $\sigma(\Delta E) \sim 7$—$10$ MeV, x2 with $\pi^0$

$$E_D \Rightarrow E_{beam} : \times 10 \downarrow \delta M_{bc} / M_{bc}$$

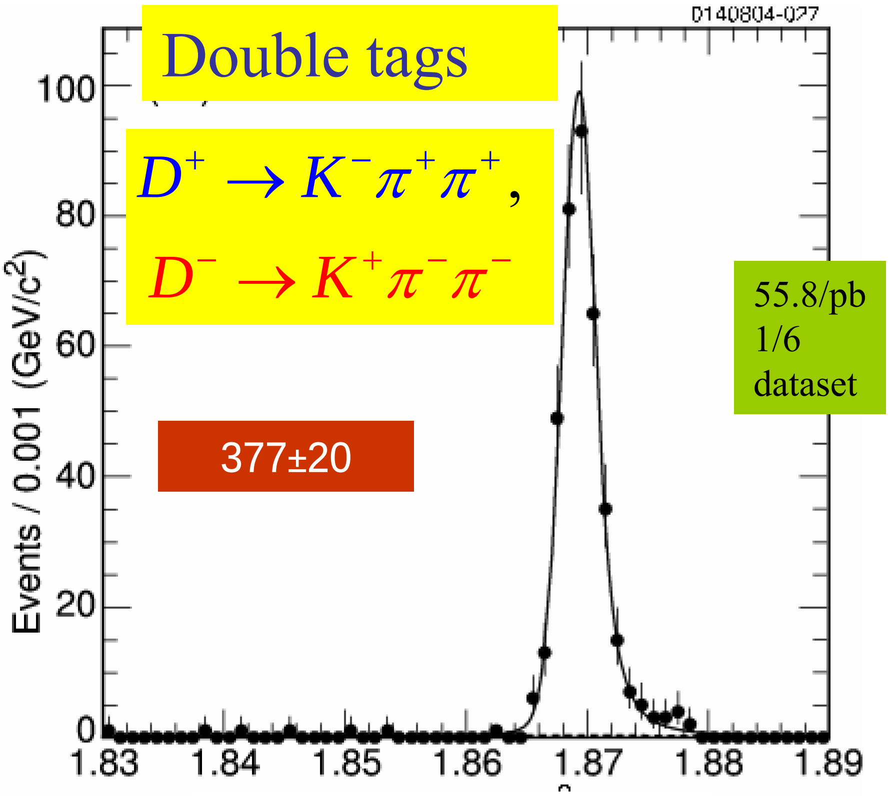


Single tags

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

15120±180

D candidate mass (GeV)



Double tags

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

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

377±20

55.8/pb
1/6
dataset

D candidate mass (GeV)

**Independent of L and cross section**

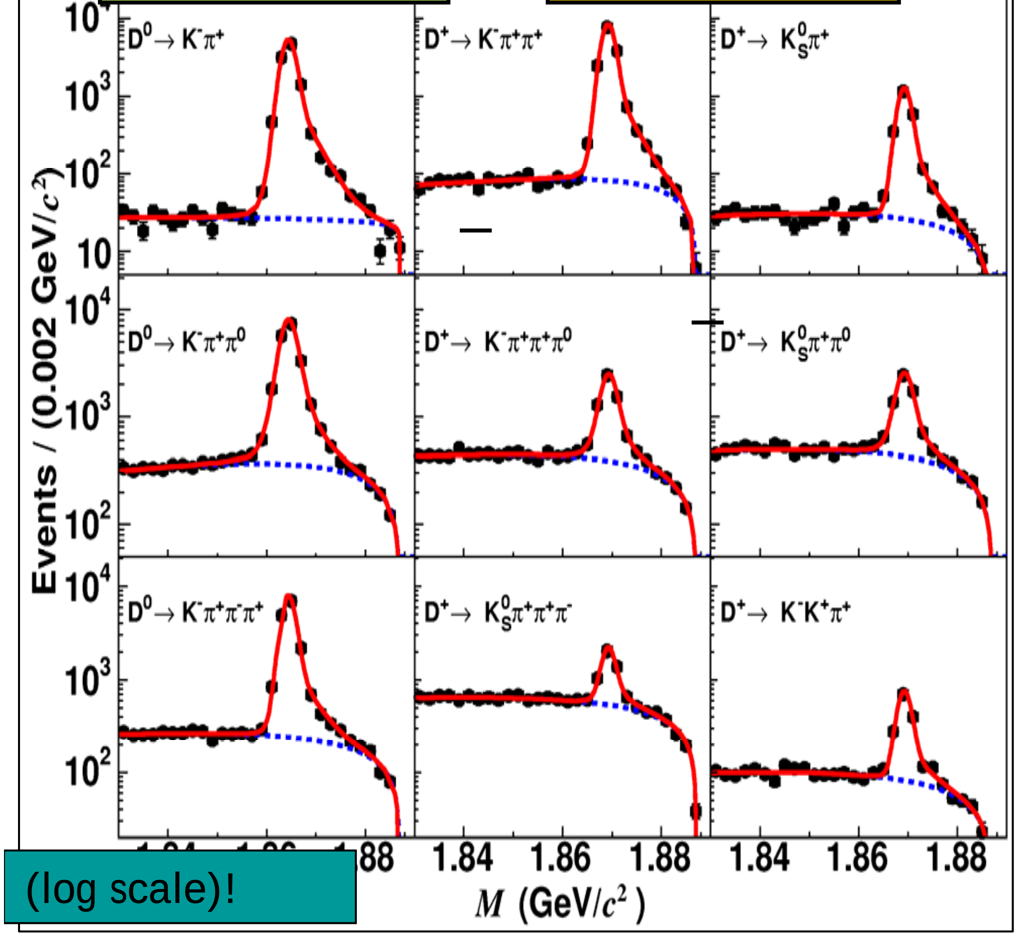
$$B(D^- \rightarrow K^+\pi^-\pi^-) = \frac{\#\,(K^+\pi^-\pi^-)\,\text{Observed in tagged events}}{\text{detection efficiency for }(K^+\pi^-\pi^-)\;\bullet\;\#\text{D tags}}$$

**Single tags** $N_i = N_{D\bar{D}} B_i \varepsilon_i$

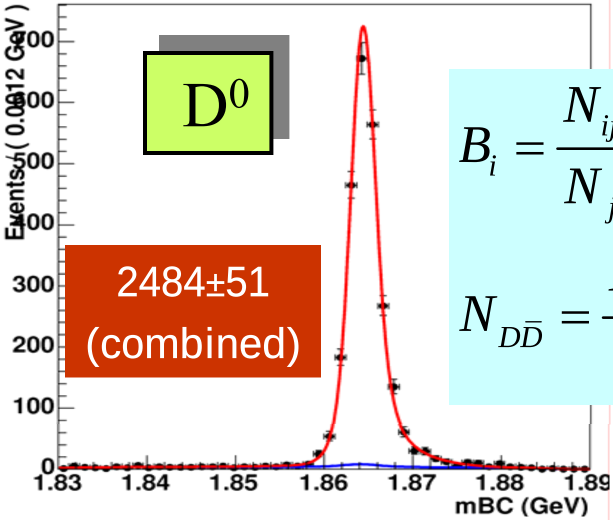
**Double tags** $N_{ij} = N_{D\bar{D}} B_i B_j \varepsilon_{ij}$

**3 $D^0$ Modes**

**6 $D^+$ Modes**



(log scale)!

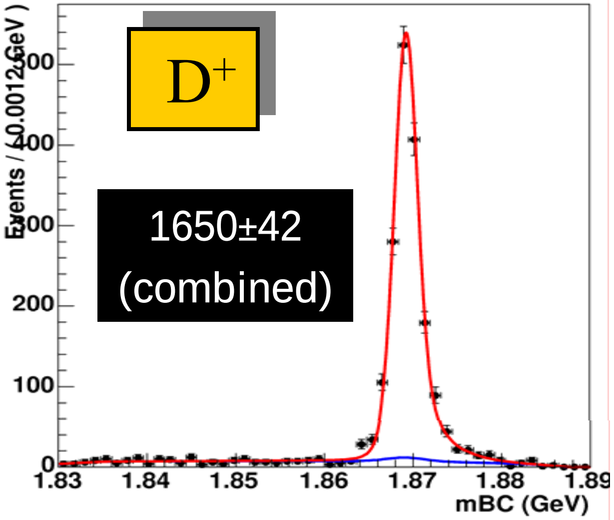


**$D^0$**

2484±51 (combined)

$$B_i = \frac{N_{ij}}{N_j}\frac{\varepsilon_j}{\varepsilon_{ij}}$$

$$N_{D\bar{D}} = \frac{N_i N_j}{N_{ij}}\frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$



**$D^+$**

1650±42 (combined)

55.8/pb
1/6
dataset

Signal shape: ψ(3770) line shape, ISR, beam energy spread & momentum resolution, Bgkd: ARGUS

Global fit (pioneered by Mark III) to single and double tag yields with $\chi^2$ minimization technique to extract $N_{DD}$ & 9 $B_i$'s

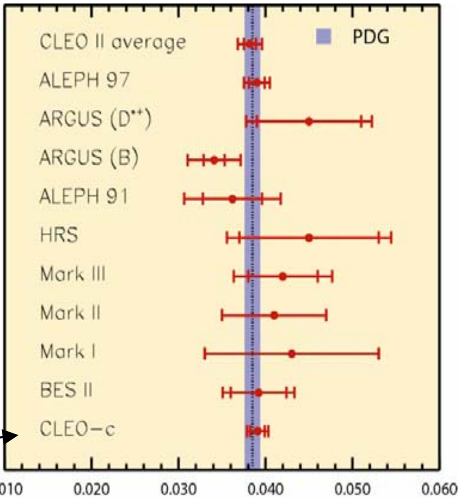
# $B(D^o \rightarrow K^-\pi^+)$

| $\mathcal{B}$ (%) | Error(%) | Source |
|---|---|---|
| 3.82±0.07±0.1 | 3.6 | CLEO |
| 3.82±0.09±0.1 | 3.8 | ALEPH |
| 3.80 ±0.09 | 2.4 | PDG |
| 3.91±0.08 ±0.09 | 3.1 | CLEO-c |

# $B(D^+ \rightarrow K^-\pi^+\pi^+)$

| $\mathcal{B}$ (%) | 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 | PDG |
| 9.52 ±0.25±0.27 | 3.9 | CLEO-c |

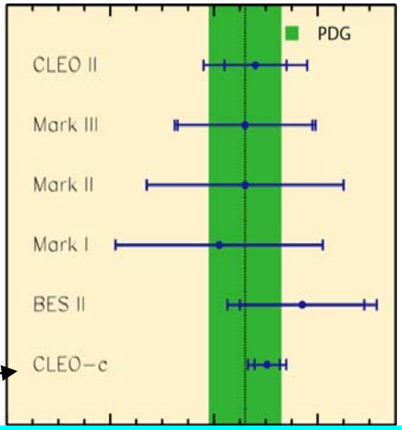
9 BRs are measured only 2 key modes shown here



Most precise

55.8/pb 1/6 dataset in hand 1/fb soon

Most precise



*Accepted for publication in PRL*
***hep-ex/ 0504003***

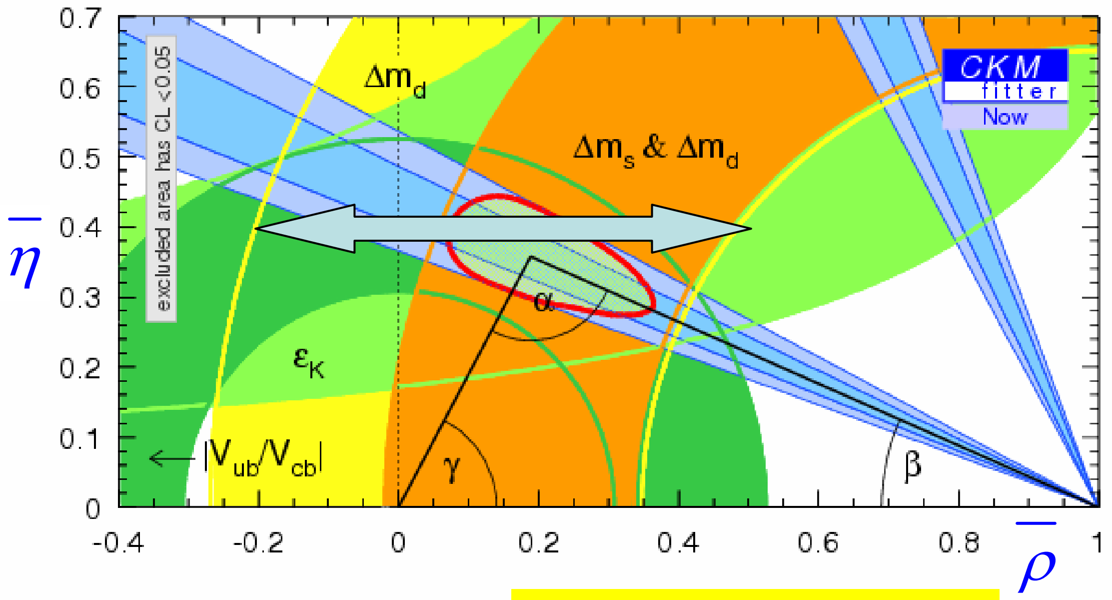
See Ecklund Radcorr, UCSD 3/05

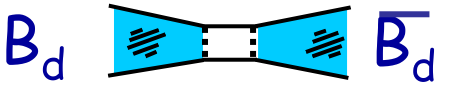
| Decay | $\delta B / B(\%)$ | | |
|---|---|---|---|
| | $PDG$ | $CLEO\,2005$ | $1\,fb^{-1}$ |
| $D^0 \rightarrow K^-\pi^+$ | 2.4 | 3.1 | $0.5(stat)(1.3)sys$ |
| $D^+ \rightarrow K^-\pi^+\pi^+$ | 7.7 | 3.9 | $0.6(stat)(1.5)sys$ |
| $D_S^+ \rightarrow \phi\pi$ | 12.5% ($BABAR$) | −− | 3.2 |

*Conclusion: the charm hadronic scale we have been using for last 10 years is approximately correct & is finally on a secure foundation*

*CLEO-c & BES III set absolute scale for all heavy quark measurements*

# Importance of measuring *absolute* charm leptonic branching ratios: $f_D$ & $f_{Ds}$ → $V_{td}$ & $V_{ts}$





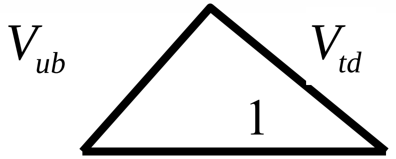
$$rate = (const.)\left[ f_{Bd} \right]^2 |V_{td}|^2 |V_{tb}|^2$$

1.0%
(expt)
Winter 2005

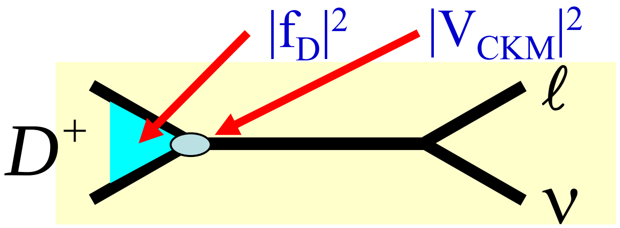
~15% (LQCD)
hep-lat/0409040

~16%

if $f_{Bd}$ was known to 3%
$|V_{td}||V_{tb}|$ would be known to ~5%



$f_{Bd}$ $f_{Bs}$ inaccessible
$f_{D+}$ $f_{Ds}$ accessible



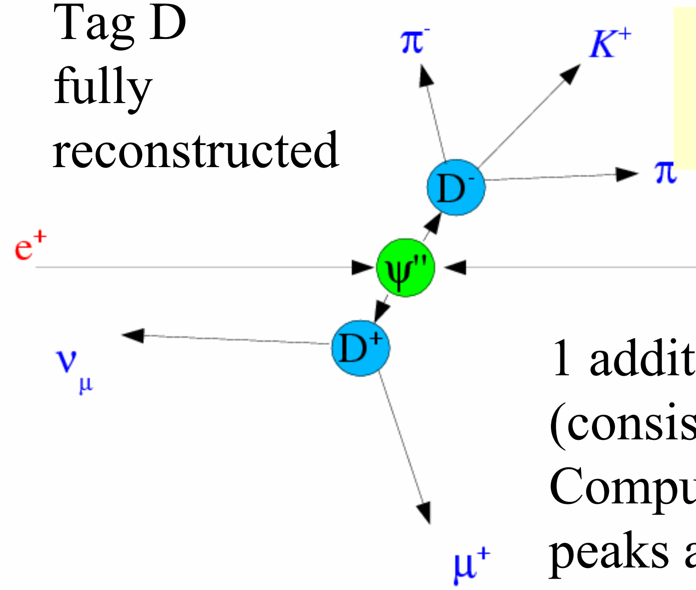
$$B(D^+ \to \mu\nu)/\tau_{D^+} = (const.)\, f_{D^+}^2 |V_{cd}|^2$$

$|V_{cd}|$ known from unitarity to 1%

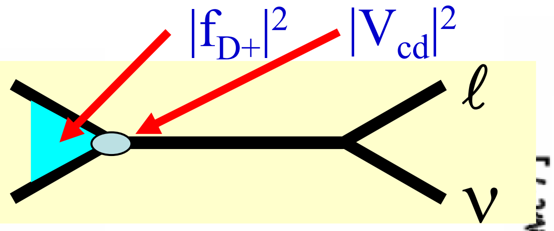
$$\frac{\delta f_{D_c}}{f_{D_c}} \sim 100\%$$
PDG04

Lattice predicts $f_B/f_D$ with a small errror
If a precision measurement of $f_D$ existed (it does not)
→Precision Lattice estimate of $f_B$ → precision determination of $V_{td}$
Similarly $f_D/f_{Ds}$ checks $f_B/f_{Bs}$ → precise $|V_{td}|/|V_{ts}|$ once $B_s$ mixing seen

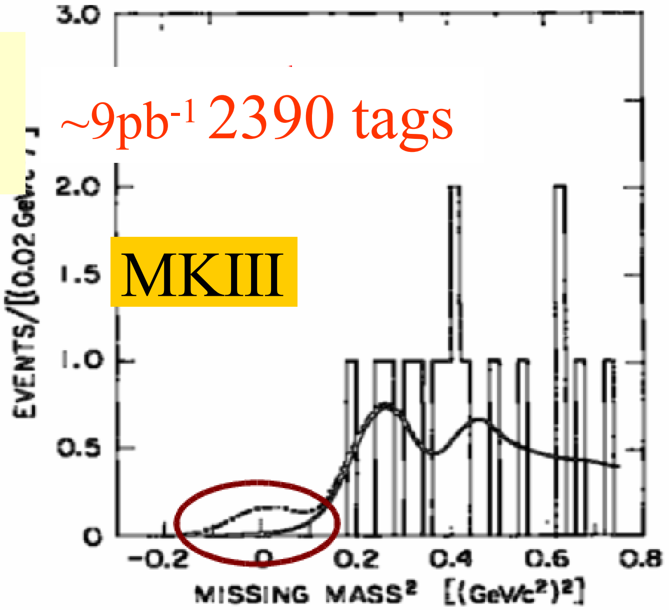
# $f_{D+}$ from Absolute Br($D^+ \rightarrow \mu^+\nu$) at $\psi(3770)$



Tag D fully reconstructed



1 additional track (consistent with a muon)
Compute missing mass²:
peaks at 0 for signal

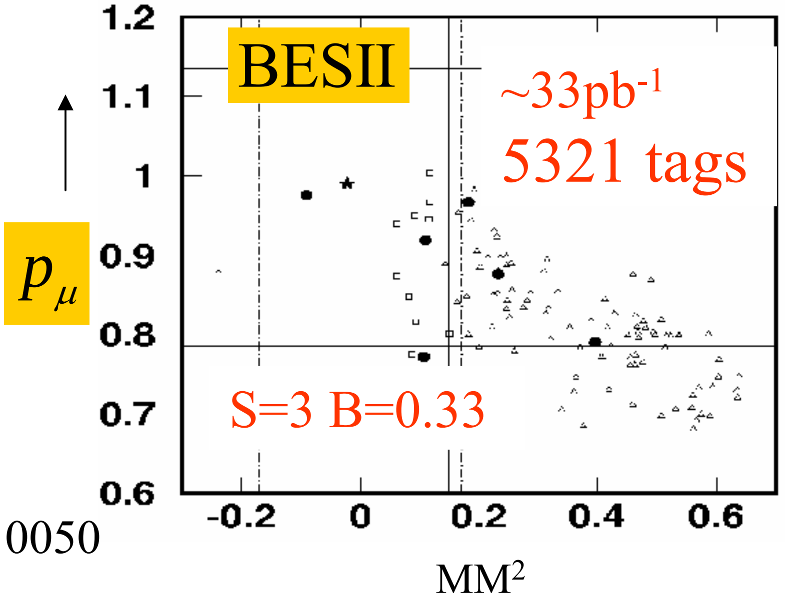


~9pb$^{-1}$ 2390 tags

MKIII

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P_{Dtag^+}} - \overrightarrow{P_\mu})^2$$

| | $B(D^+ \rightarrow \mu\nu) \times 10^{-4}$ | $f_D$ MeV |
|---|---|---|
| MkIII | $< 7.2$ | $< 290$ |
| BESII | $12.2^{11.1}_{-53} \pm 0.11$ | $371^{+129}_{-119} \pm 25$ |



BESII

~33pb$^{-1}$
5321 tags

S=3 B=0.33

Mark III PRL 60, 1375 (1988) BES II hep-ex/0410050

CLEO-c planned to announce a precision measurement of $f_D$ at Lepton Photon

Two days before Lepton Photon the long awaited unquenched lattice prediction was released

Fermilab-MILC-HPQCD Collaborations
Hep-lat/0506030

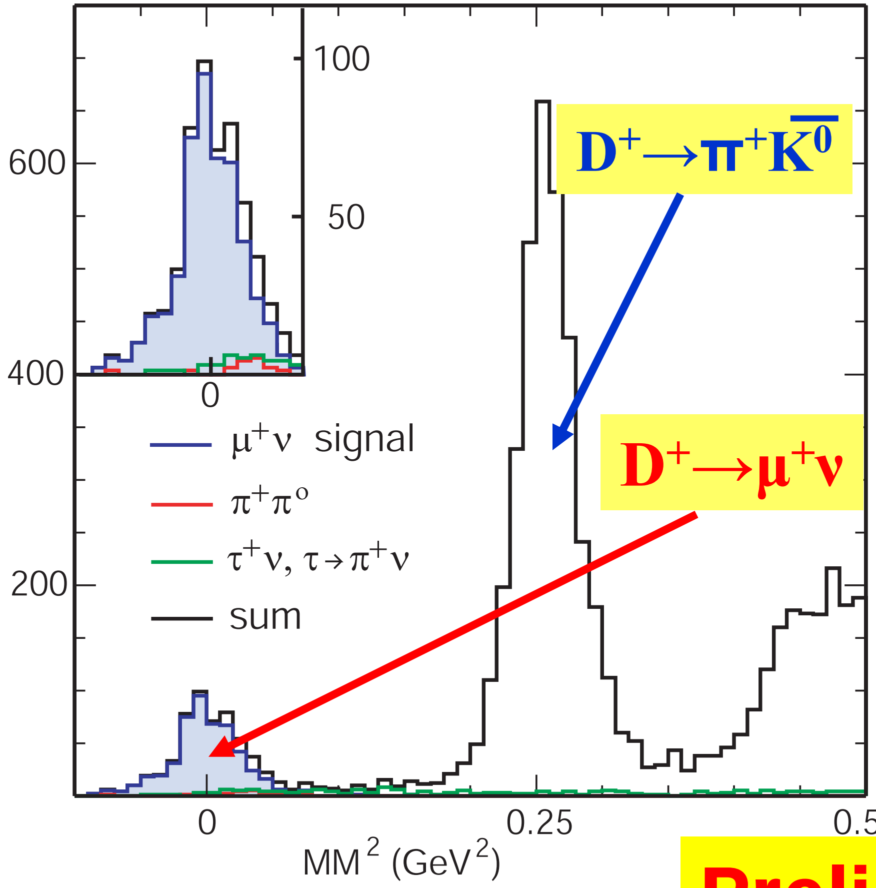
$$(201 \pm 3 \pm 17)\mathrm{MeV}$$

# $D^+ \to \mu^+\nu$ from CLEO-c Data

- **MC Expectations from 1.7 $fb^{-1}$, 6 x data**

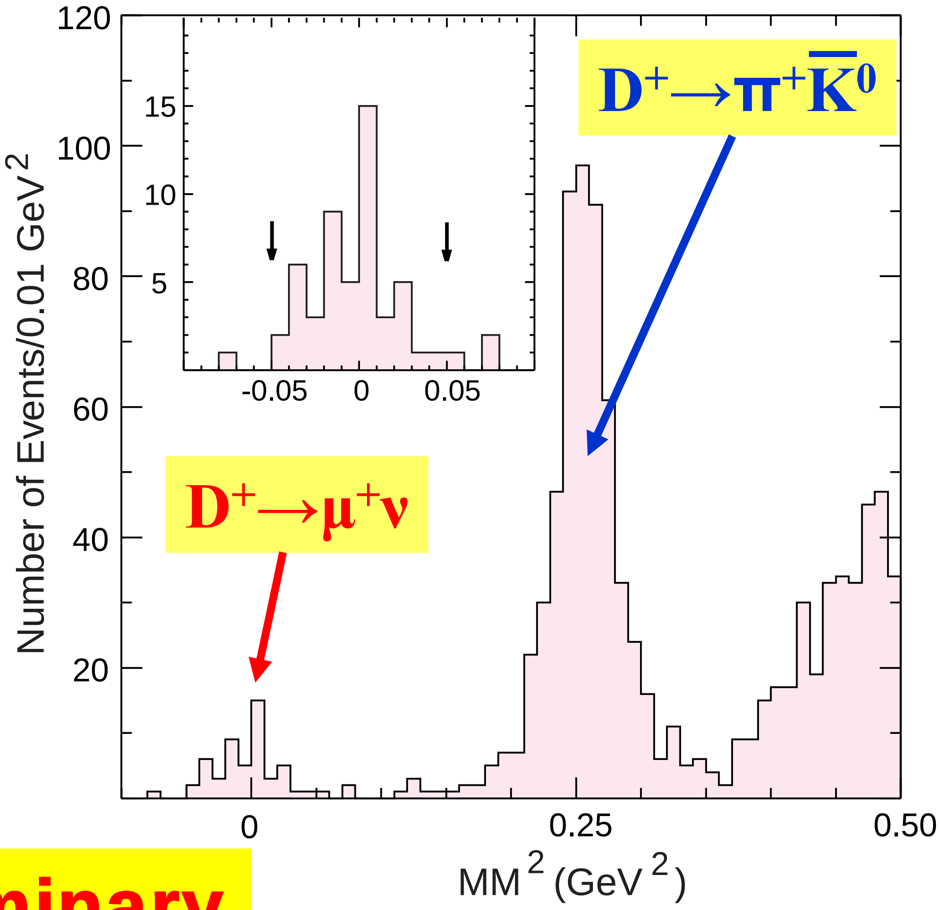
**281 $pb^{-1}$ at $\psi(3770)$**

**50 signal events**



**$D^+ \to \pi^+\overline{K}^0$**

**$D^+ \to \mu^+\nu$**

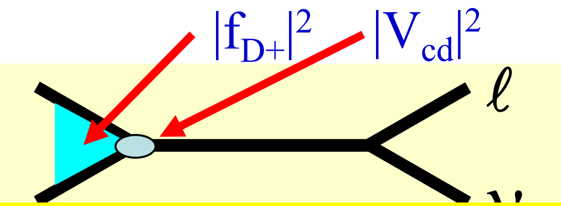


**$D^+ \to \pi^+\overline{K}^0$**

**$D^+ \to \mu^+\nu$**

**Preliminary**

# Extraction of the decay constant



$$B(D^+ \to \mu\nu)/\tau_{D^+} = (const.)\, f_{D^+}^2\, |V_{cd}|^2$$

**Backgrounds**

| Mode | $\mathcal{B}$(%) | # Events |
|---|---|---|
| $\pi^+\pi^0$ | 0.13±0.02 | 1.40±0.18 |
| $K^0\pi^+$ | 2.77±0.18 | 0.44±0.44 |
| $\tau^+\nu$ ($\tau \to \pi^+\nu$) | 2.64*$\mathcal{B}(D^+ \to \mu^+\nu)$ | 1.08 ±0.15 |
| $\pi^0\mu^+\nu$ | 0.25 ±0.15 | negligible |
| Continuum | - | 0 |
| $D^oD^o$ +<br>other $D^+D^-$ | - | 0 |
| Total | - | 2.92±0.50 |

$V_{cd} = V_{us} = 0.225 \pm 0.0023$

(KTeV)

$\tau(D^+) = 1.040 \pm 0.007$ ps (PDG)

Efficiencies & BKG well understood: from data

**$\mathrm{Br}(D^+ \to \mu^+\nu) =$**
$$(4.45 \pm 0.67^{+0.29}_{-0.36}) \times 10^{-4}$$

$$f_{D^+} = (223 \pm 16^{+7}_{-9})\ \mathrm{MeV}$$

Also limit suppressed electron mode

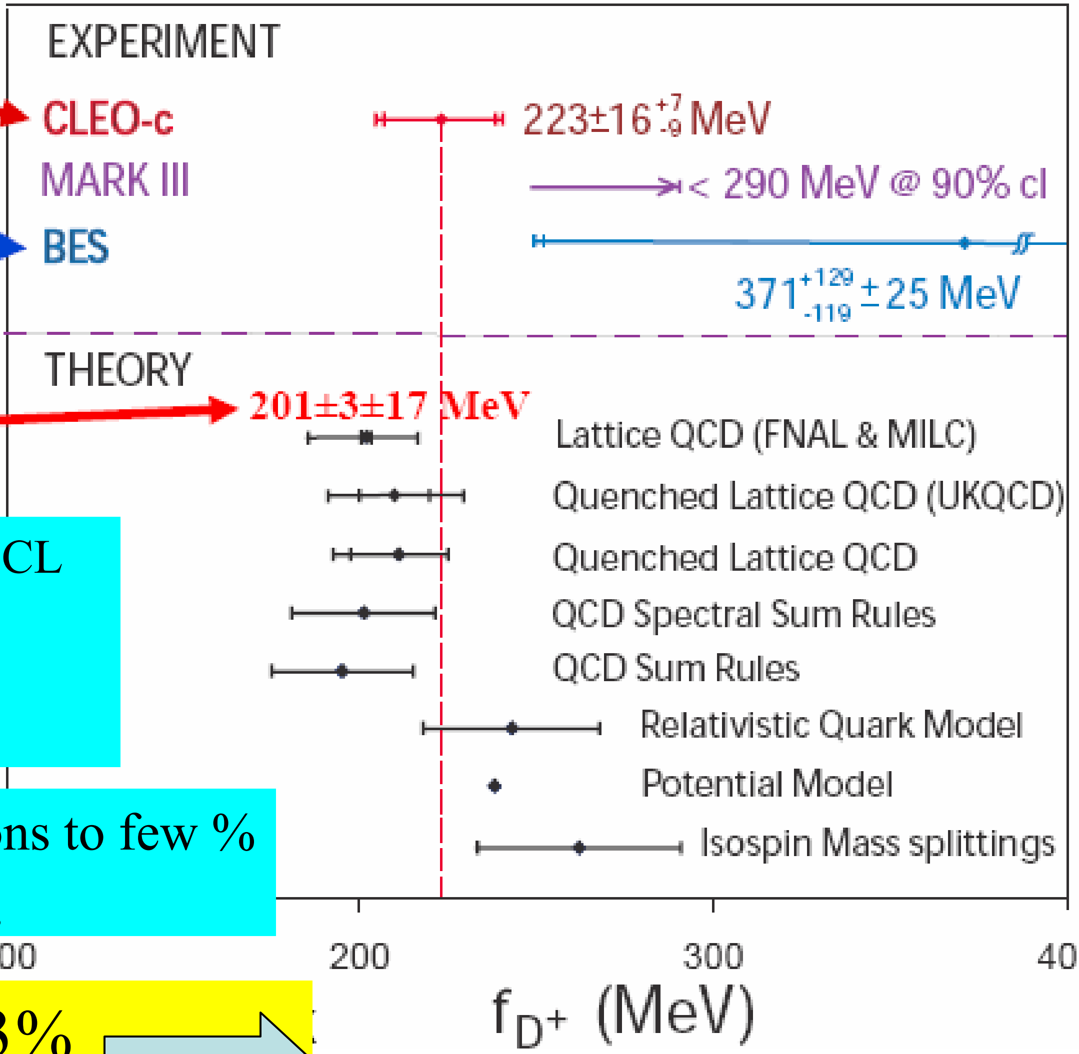
**$\mathrm{Br}(D^+ \to e^+\nu)$**
**$< 2.4 \times 10^{-5}$ @ 90% C.L.**

# Comparison to the lattice

**This measurement**

**BES measurement (2.67±1.74 evts)**

**Fermilab-MILC-HPQCD (hep-lat0506030)**



Expt/LQCD consistent at 45% CL
Now: LQCD error ~8%
CLEO-c error 8%
CLEO <5% within a year

Need latest LQCD predictions to few % by summer 2006 $f_{D+}$ & $f_{Ds}$

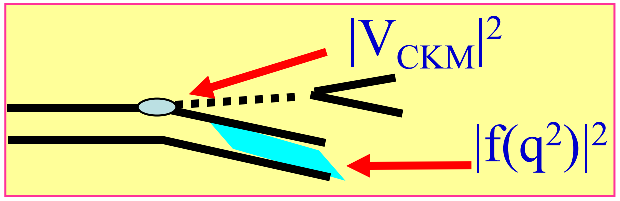
with $3\,\mathrm{fb}^{-1}$ : $f_{D+}$ to 2.3%
$f_{Ds}$ to 1.9% @ $\sqrt{s} \sim 4140\,MeV$

$f_B / f_D$ for $V_{td}$ from B mixing

BES III may make the definitive measurements

# Importance of *Absolute* Charm Semileptonic Decay Rates

When Vub is determined from exclusive semileptonic (β) decay $\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2|f_+^{B\to\pi}(q^2)|^2$



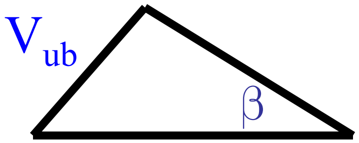
$Br(B\to\pi l\nu)$ 8% precision

$BABAR/Belle/CLEO$

(World Average Summer 2005)

$$|V_{ub}| = (3.76 \pm 0.16^{+0.87}_{-0.51})10^{-3}$$

form factor

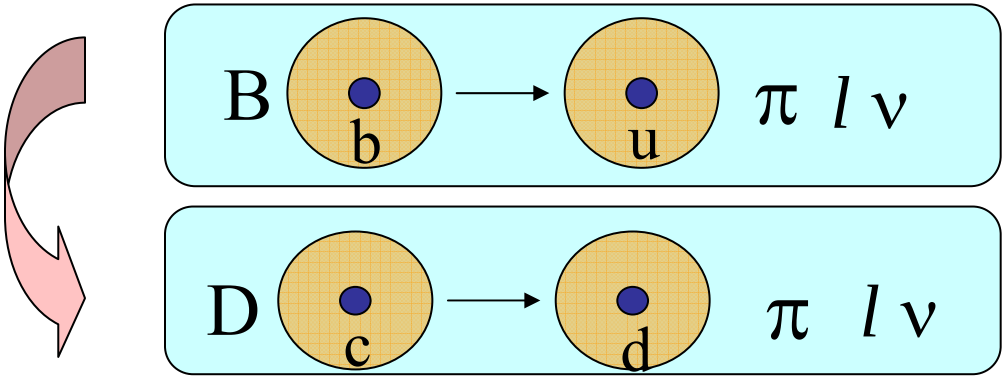


Expt. Error 4%

Theory Error 18%

Charm semileptonic decays test form factor predictions $\frac{d\Gamma}{dq^2} \propto |V_{cd}|^2|f_+^{D\to\pi}(q^2)|^2$

$|V_{cd}|$ known from unitarity to 1%



$\frac{\delta B}{B}\sim 45\%$

PDG04

HQS

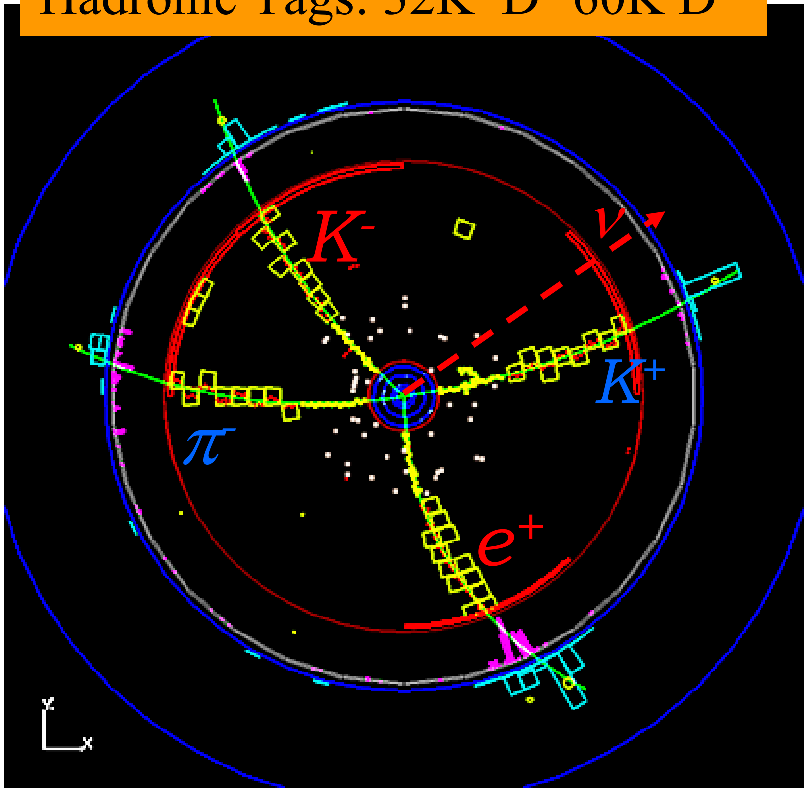
1) Measure D→π form factor in D→πlν. *Tests* LQCD D→π form factor calculation.

2) BaBar/Belle can extract $V_{ub}$ using *tested* LQCD calc. of B→π form factor.

3) Needs precise absolute Br(D →πlν) & high quality dΓ (D →πlν)/dEπ neither exist.

# Absolute Branching Ratios of Semileptonic Decays at ψ(3770)

Hadronic Tags: 32K $D^+$ 60K $D^0$



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

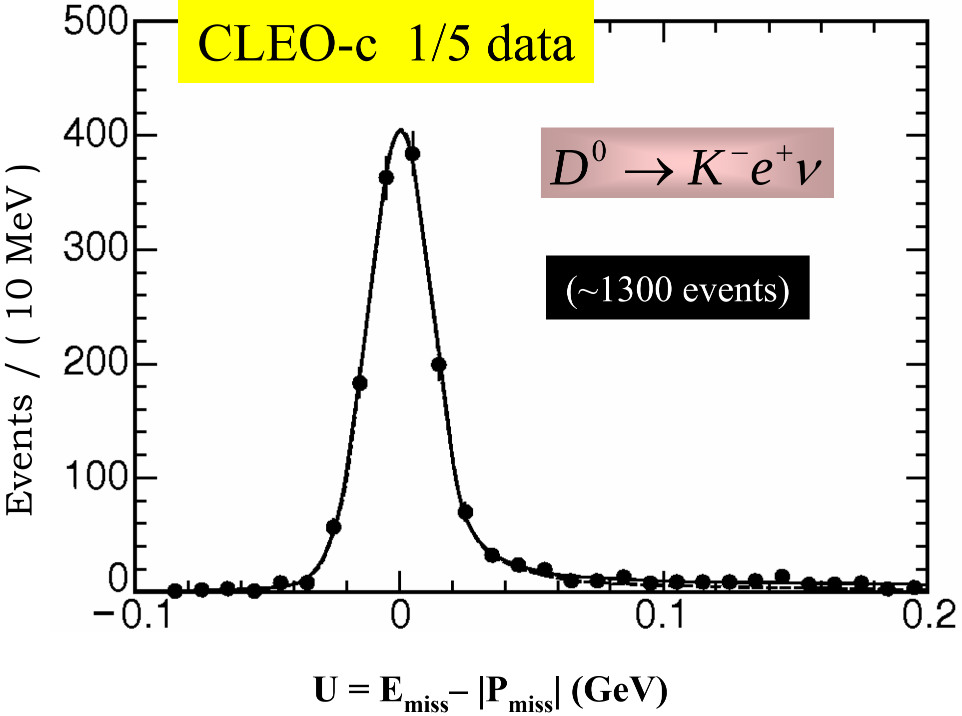
$$\overline{D^0} \rightarrow K^+\pi^-, D^0 \rightarrow K^-e^+\nu$$

Tagging creates a single D beam of known 4-momentum

Semileptonic decays are reconstructed with *no* kinematic ambiguity

ss

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



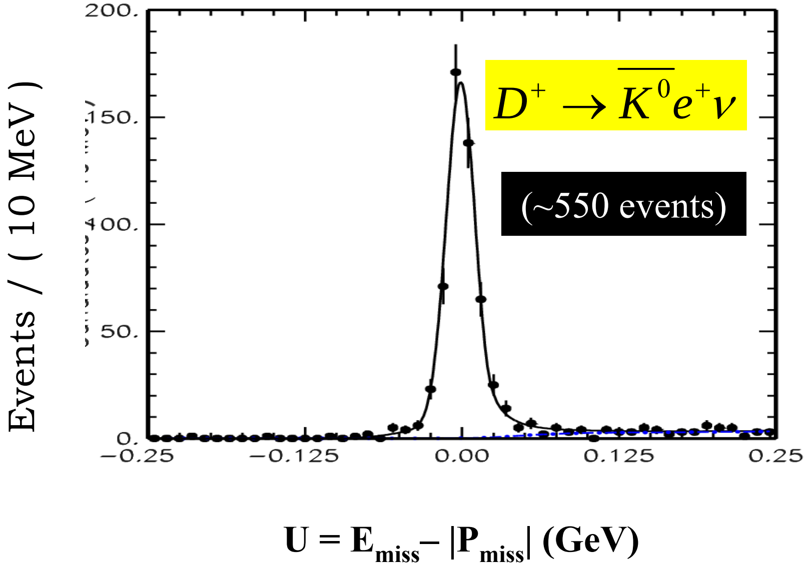
$D^+$ results are new, $D^0$ update ICHEP04

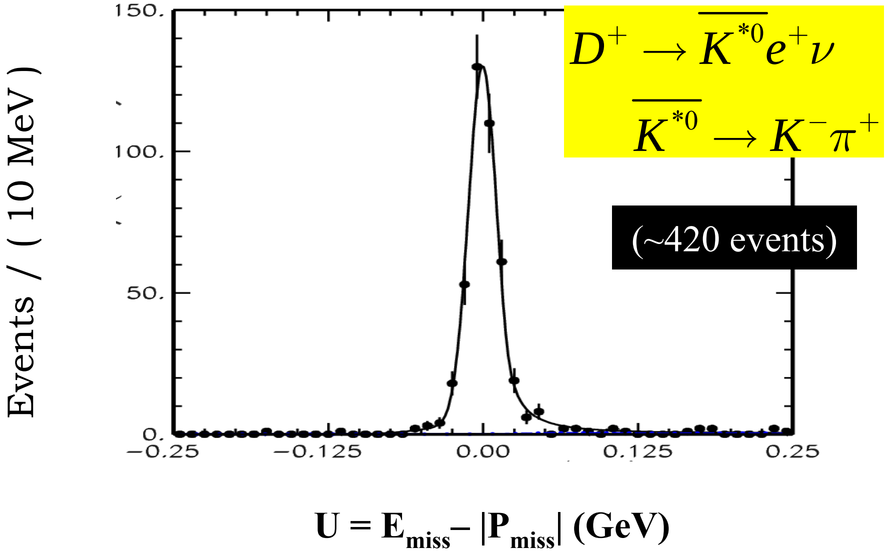
*Accepted for Publication in PRL August 12 2005 Hepex* ***/0506053 & 0506052***

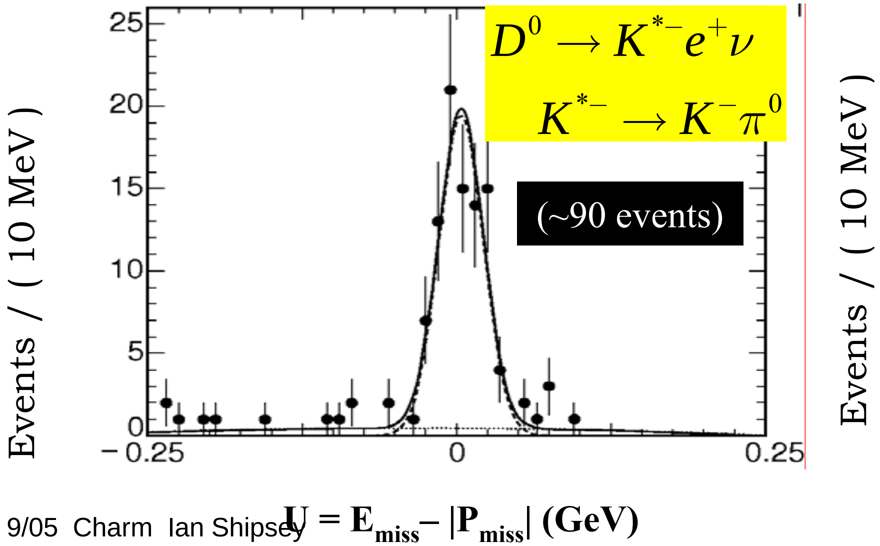
# More Cabibbo allowed modes

$c \rightarrow s$ Cabibbo Favored

57 pb$^{-1}$ Data



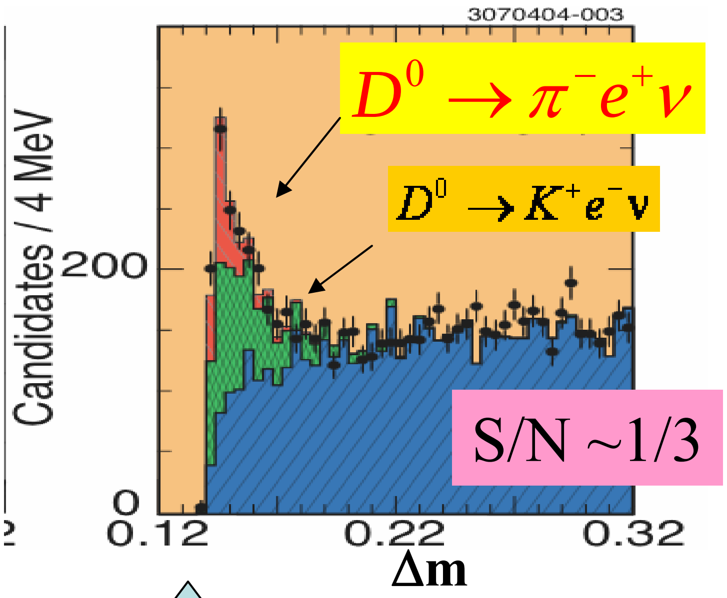




Historically Cabibbo allowed modes: provide a significant background to Cabibbo suppressed modes, making the latter particularly challenging…..

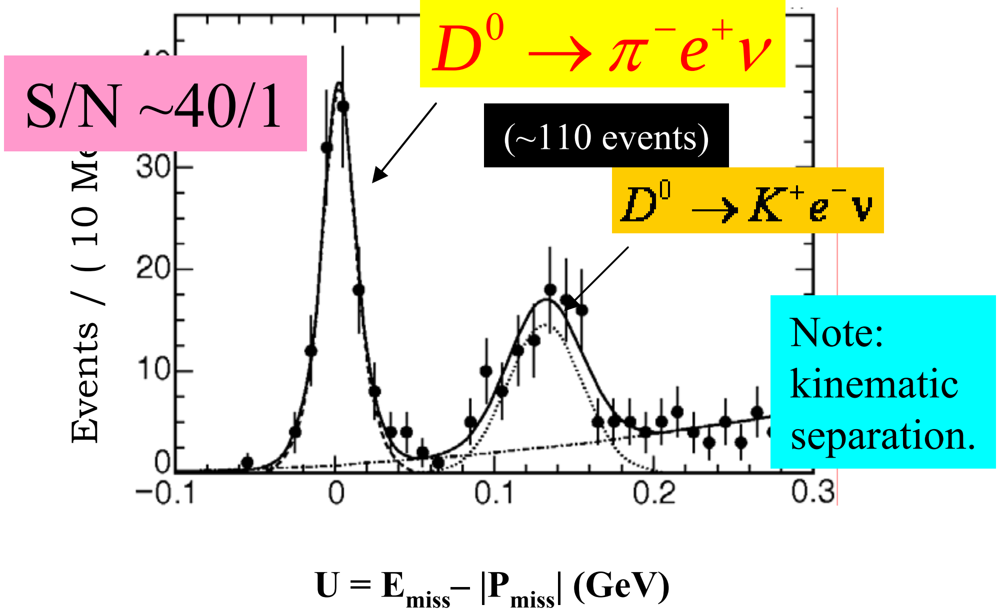
# Cabibbo suppressed modes

57 pb$^{-1}$ Data


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

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

S/N ~1/3


S/N ~40/1

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

(~110 events)

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

Note: kinematic separation.

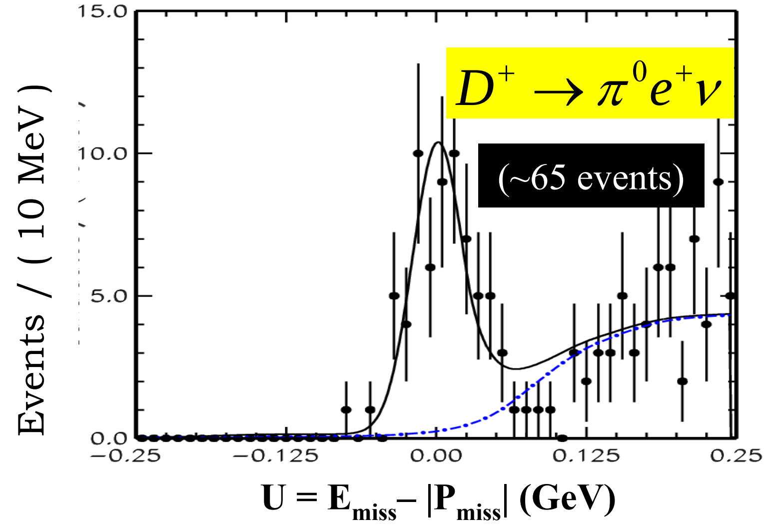
Tag with $D^{*+} \to D^0 \pi_s$

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

observable:

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

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


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

(~65 events)

# More Cabibbo supressed modes

57 pb$^{-1}$ Data

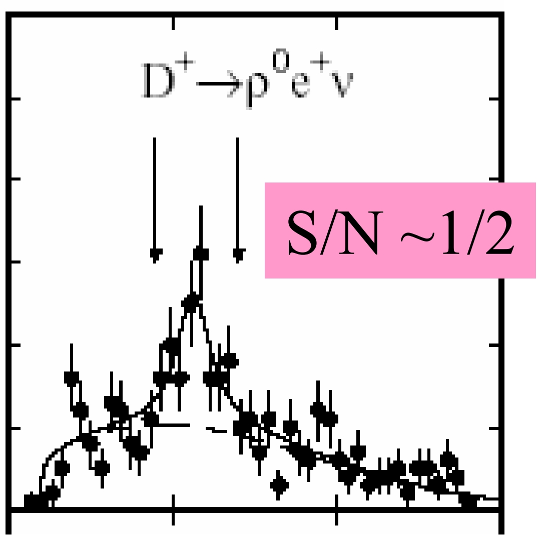
Only measurement untl now

**E791**

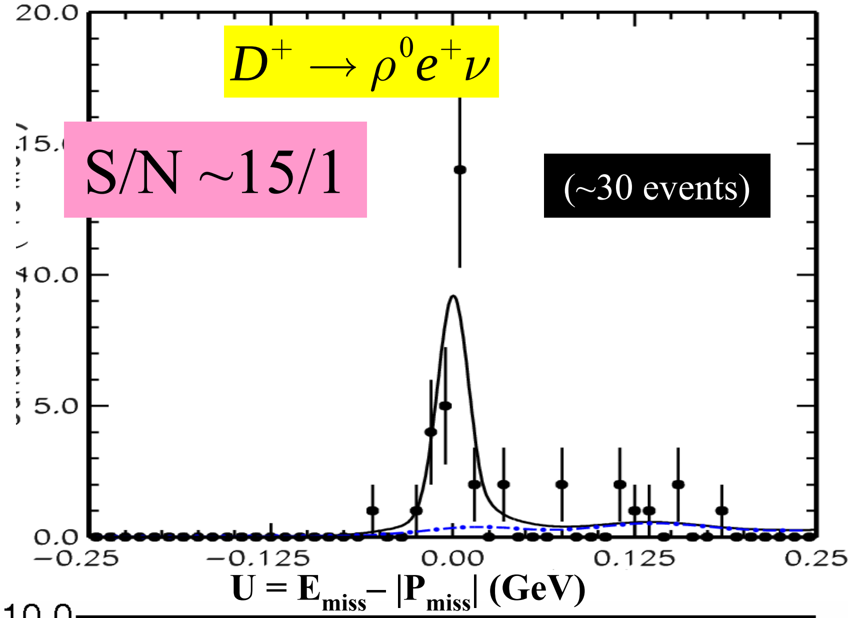
PLB 397 325 (1997)

Relative rate:

$$\frac{\Gamma(D^+ \to \rho^0 e^+ \nu)}{\Gamma(D^+ \to K^{*0} e^+ \nu)}$$



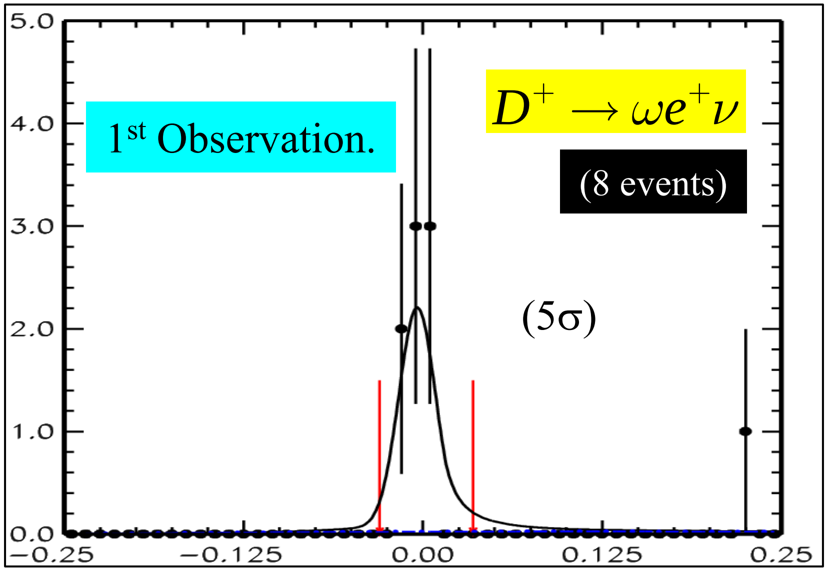
S/N ~1/2



$D^+ \to \rho^0 e^+ \nu$

S/N ~15/1

(~30 events)

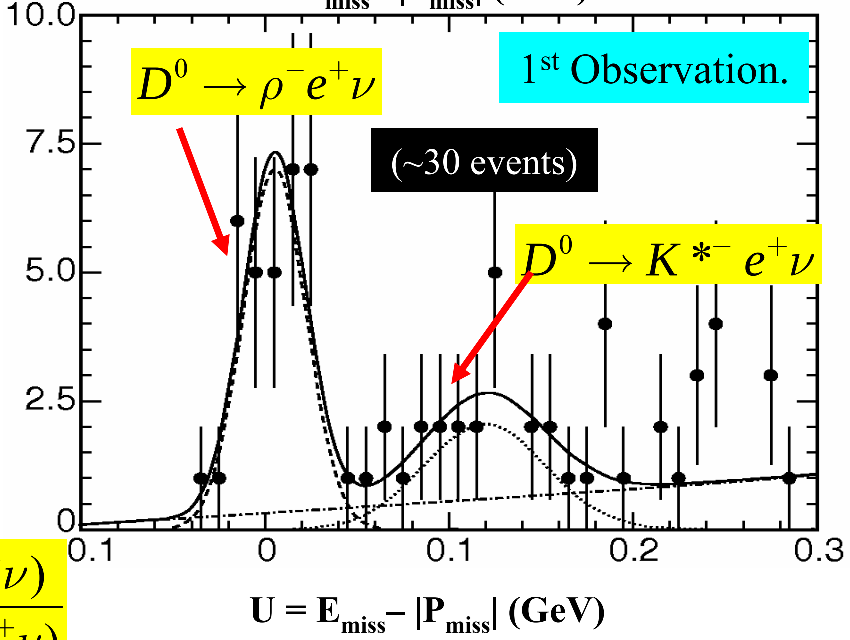


1st Observation.

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

(8 events)

(5σ)



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

1st Observation.

(~30 events)

$D^0 \to K^{*-} e^+ \nu$

Useful for Grinstein's Double ratio Vub$^2$/ Vcb$^2$

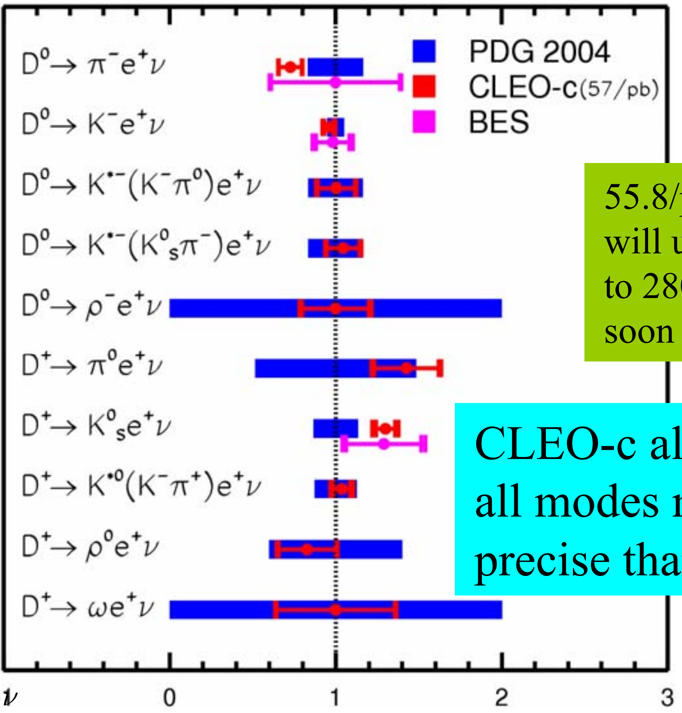
$$\frac{\Gamma(B \to \rho\, e^+ \nu)}{\Gamma(B \to K^* \ell\ell)} \Big/ \frac{\Gamma(D \to \rho e^+ \nu)}{\Gamma(D \to K e^+ \nu)}$$

FrontierScience 2005

# Preliminary Results

Similar analysis by BES II

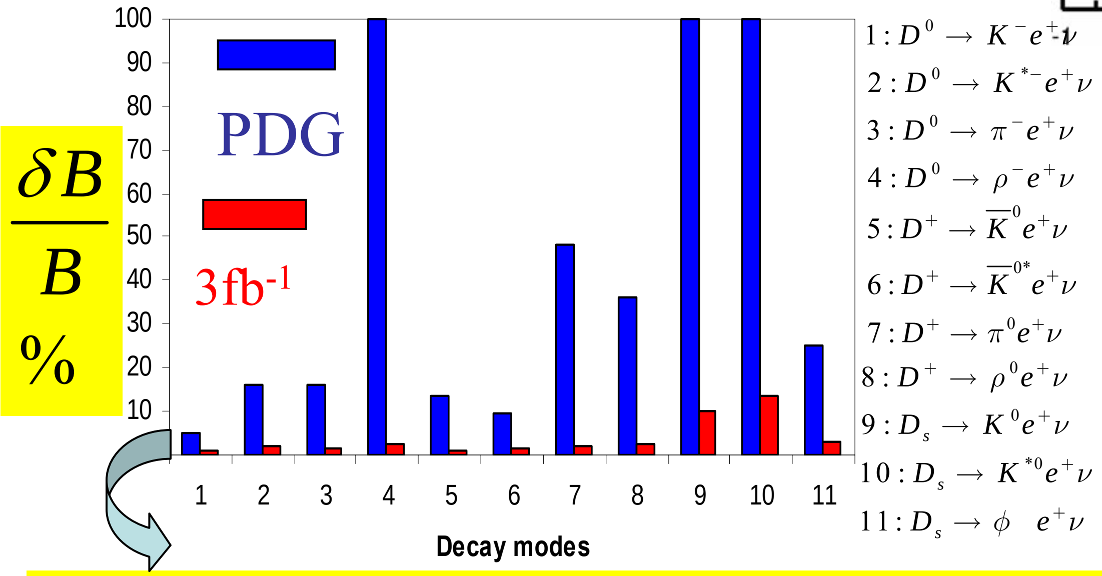
| | Decay Mode | $\mathcal{B}$ (%) (CLEO-c/(57/pb)) | $\mathcal{B}$ (%) (PDG-04) |
|---|---|---|---|
| 1. | $D^0 \to \pi^- e^+ \nu$ | $0.26 \pm 0.03 \pm 0.01$ | $0.36 \pm 0.06$ |
| 2. | $D^0 \to K^- e^+ \nu$ | $3.44 \pm 0.10 \pm 0.10$ | $3.58 \pm 0.18$ |
| 3. | $D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$ | $2.16 \pm 0.24 \pm 0.11$ | $2.15 \pm 0.35$ |
| 4. | $D^0 \to K^{*-}(K^0_S \pi^-) e^+ \nu$ | $2.25 \pm 0.21 \pm 0.11$ | $2.15 \pm 0.35$ |
| 5. | $D^0 \to \rho^- e^+ \nu$ | $0.19 \pm 0.04 \pm 0.02$ | — |
| 6. | $D^+ \to \pi^0 e^+ \nu$ | $0.44 \pm 0.06 \pm 0.03$ | $0.31 \pm 0.15$ |
| 7. | $D^+ \to \bar{K}^0 e^+ \nu$ | $8.71 \pm 0.38 \pm 0.37$ | $6.7 \pm 0.9$ |
| 8. | $D^+ \to \bar{K}^{*0}(K^- \pi^+) e^+ \nu$ | $5.70 \pm 0.28 \pm 0.25$ | $5.5 \pm 0.7$ |
| 9. | $D^+ \to \rho^0 (\pi^+ \pi^-) e^+ \nu$ | $0.21 \pm 0.04 \pm 0.02$ | $0.25 \pm 0.10$ |
| 10. | $D^+ \to \omega (\pi^+ \pi^- \pi^0) e^+ \nu$ | $0.17 \pm 0.06 \pm 0.01$ | — |



Normalized to PDG

55.8/pb will update to 280/pb soon

CLEO-c already all modes more precise than PDG.



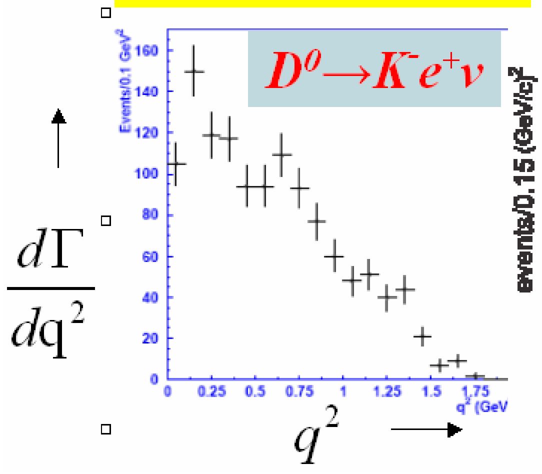
*Accepted for Publication in PRL August 12 2005 Hepex* ***/0506053 & 0506052***

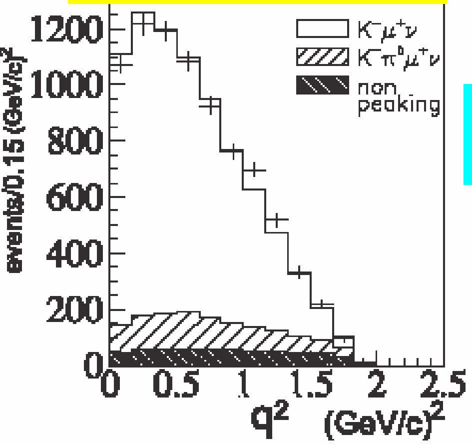
Full CLEO-c data set (later BESIII) will make *significant* improvements in the precision with which each absolute charm semileptonic branching ratio is known

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

CLEO-c 1/5 data

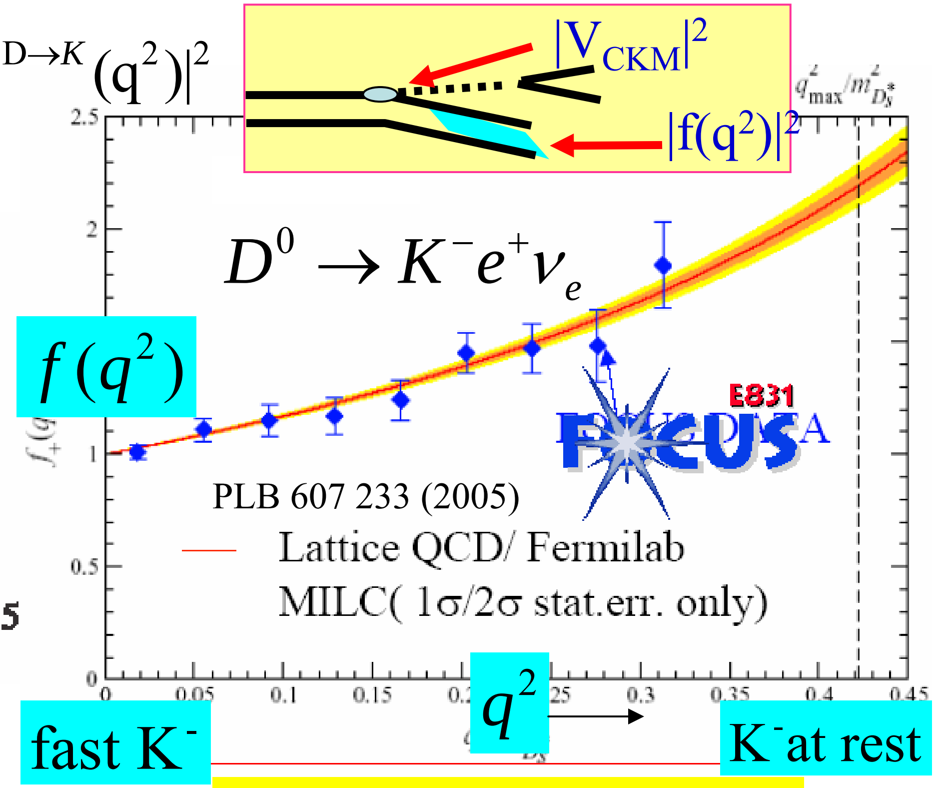
FOCUS all data





6.5K evts (280/pb)
S/N >300/1

13K evts
S/N ~6/1

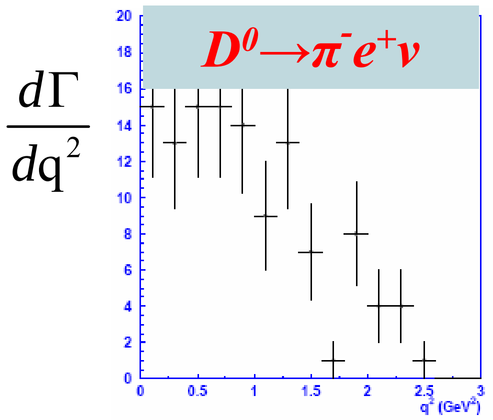


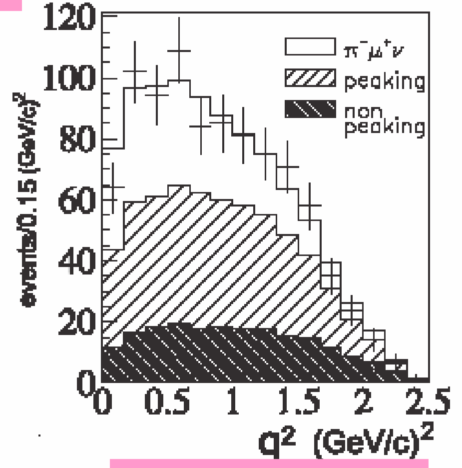
LQCD : shape correct:

Impressive work by FOCUS. Result form CLEO-c soon. The threshold advantage

1) Low background crucial for π final state

2) neutrino direction known





S/N ~40/1

S/N ~1/2.5

$\frac{\delta q^2}{q^2} \sim 0.4\,\text{GeV}^2$ B Factory

$\sim 0.1\ \text{GeV}^2$ FOCUS

$\sim 0.025\ \text{GeV}^2$ CLEO-c

# Lattice comparison: the form factor normalization

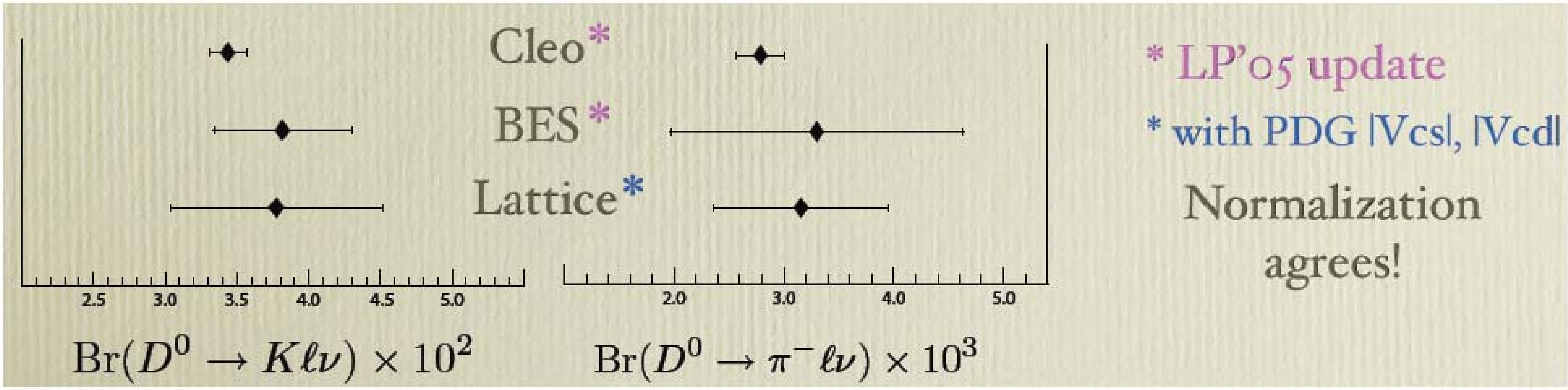
Lattice predicted shape: agreed with data

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

Lattice predicts absolute magnitude of form factor too

$$\Gamma(D \to Ke\nu) \propto |V_{cs}|^2 \int |f_+^{D\to k}(q^2)|^2 dq^2$$

Under the assumption that the lattice shape and data shape differ by a negligible amount for both K and π ⇒we can use absolute branching fraction measurements to validate the normalization



* LP’05 update

* with PDG |Vcs|, |Vcd|

Normalization agrees!

Total lattice Br agrees with experiment for PDG: Vcs, Vcd

LQCD : normalization agrees with data (at ~10% level)!

# Early look at $V_{cs}$ and $V_{cd}$ with CLEO-c data

Artuso estimate at LP03 not official CLEO-c

Assuming the shape and normalization of the form factors are OK

Expt

LQCD

$$\sqrt{\frac{\Gamma(D \to K e \nu)}{(const.)\int |f_+^{D\to k}(q^2)|^2 dq^2}} = |V_{cs}|$$

Expt. errors
Vcs ~2%
Vcd~4%

LQCD errors dominate expt.

Vcs=0.953±0.017(expt.)±0.067(th.)

Vcd=0.214 ± 0.009(expt) ± 0.016(th.)

Using isospin averaged widths

i.e. combining D0 and D+ uses only 57/pb

**Result is theory limited**

The total error using semileptonic charm decay to determine CKM

| | CLEO-c | PDG |
|---|---|---|
| Vcs | 7 % | 16% |
| Vcd | 8.5% | -- |

Expect 1fb$^{-1}$ at $\psi(3770)$ (soon) and LQCD to few % within 1-2 years

# Lattice comparison $f_D$ and semileptonic form factors

- We can use a quantity independent of $V_{cd}$ to do a CKM independent lattice check:

Experiment

$$R_{\ell sl} \equiv \sqrt{\frac{\Gamma(D^+ \to \mu\upsilon)}{\Gamma(D \to \pi\ell\upsilon)}} \propto \frac{f_D}{f_+^{\pi}(0)}$$

Lattice

- I obtain:

$$R_{\ell sl}^{th} = 0.22 \pm 0.02$$

$$R_{\ell sl}^{\exp} = 0.25 \pm 0.02$$

~10% uncertainty

- Theory and data consistent at ~30% C.L.

Artuso LP03

With 1fb$^{-1}$ @ ψ(3770) $R_{lsl}^{exp}$ ~3% uncertainty

With 1fb$^{-1}$ @ 4140 $\Gamma(D_s \to l\nu) / \Gamma(D_s \to \eta l\nu)$ independent of Vcs $R_{lsl}^{exp}$ ~ 3% uncertainty

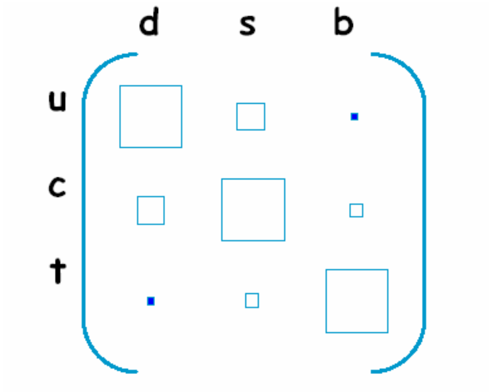
$D \to Ke^+\upsilon$ δVcs /Vcs = 1.6% (now ~7%*) $D \to \pi\ e^+\upsilon$ δVcd /Vcd = 1.7% (now: 5.4%)

*Then Tested* lattice to calc. B→πlv is available for precise exclusive Vub

* 3 flavor unquenched LQCD + D→Kev (last sldie) (note W decays at LEP in hadronic to leptonic 1.3%)

# Unitarity Tests Using Charm

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



$uc^{*}=0$

- $2^{nd}$ row: $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$ ??
  CLEO-c/BESII : test to few% (if theory $D \to K/\pi l\nu$ good to few %)
  & $1^{st}$ column: $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$ ?? with similar precision to $1^{st}$ row
  ($1\,\mathrm{fb}^{-1}$)

- $uc^{*}$ △

Compare ratio of long sides to 1.3%

# Charm As a Probe of Physics Beyond the Standard Model

Can we find violations of the Standard Model at low energies?
Example β Decay ➔ missing energy
➔ W (100 GeV mass scale) from experiments at the MeV mass scale.

The existence of multiple fermion generations may originate at high mass scales ➔ can only be studied indirectly.

CP violation, mixing and rare decays ➔ may investigate the physics at these new scales through intermediate particles entering loops.

Why charm? in the charm sector the SM contributions to these effects are small ➔ large window to search for new physics

CP asymmetry $\leq 10^{-3}$

Rare decays $\leq 10^{-6}$

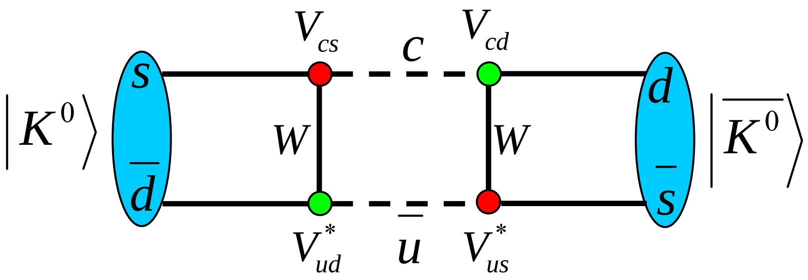
$D^0$ - $\bar{D}^0$ mixing $\leq 10^{-2}$

charm is the *unique* probe of the up-type quark sector (down quarks in the loop).

High statistics instead of High Energy

# D Mixing

Mixing has been fertile ground for discoveries:

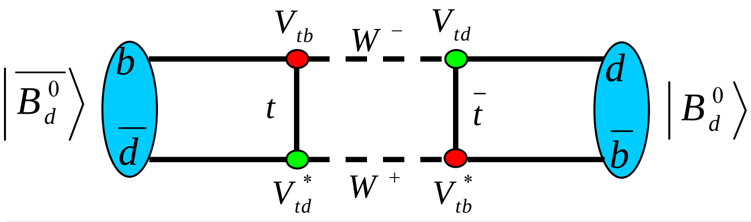


CKM factors $\propto \Theta_c^2$ same order as $\tau_{kaon}$ i.e.s → u

**Mixing rate ≈1**

Mixing rate (1958) used to bound c quark mass → discovery(1974).

CPV part of transition , $\varepsilon_K$ (1964), was a crucial clue top quark existed → discovery (1994).



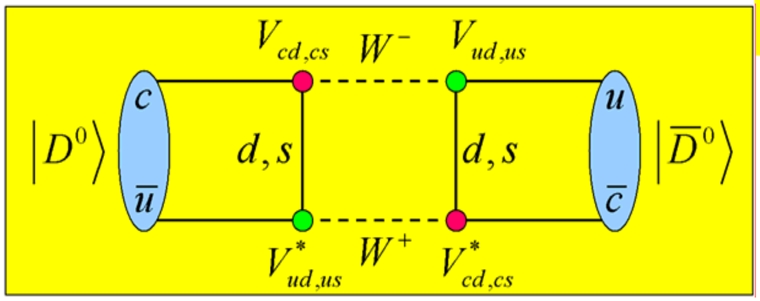
dominated by top $\propto (m_t^2 - m_{c,u}^2))/m_W^2$ → Large

B lifetime Cabibbo suppressed $\propto V_{cb}^2$

Mixing also Cabibbo suppressed ($V_{td}^2$)

Mixing rate → early indication m $_{top}$ large

**Mixing rate ≈1**



CKM factors $\propto \Theta_c^2 \sim 0.05$

(b-quark $\propto V_{ub}V_{cb}$ negligible)

But $\tau_D$ not Cabbibo suppressed ($V_{cs}$~1)

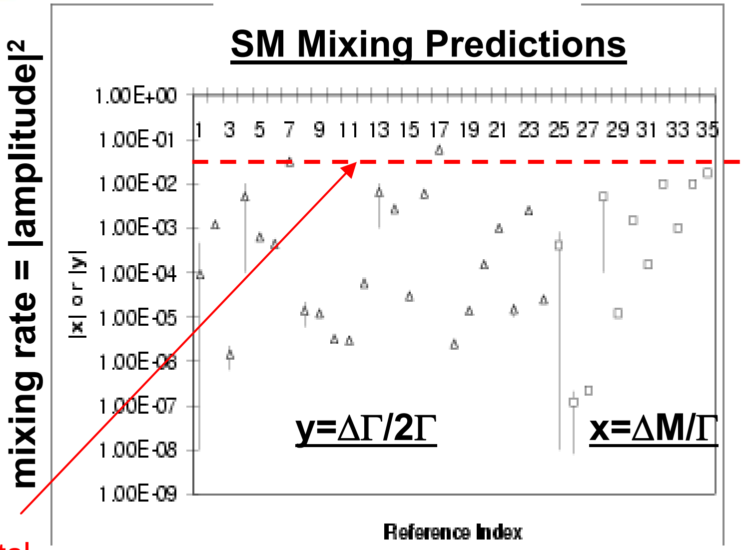
**Mixing rate ≈0.05**

Additional suppression: Mixing $\propto (m_s^2 - m_d^2)/ m_W^2 = 0$ SU(3) limit.

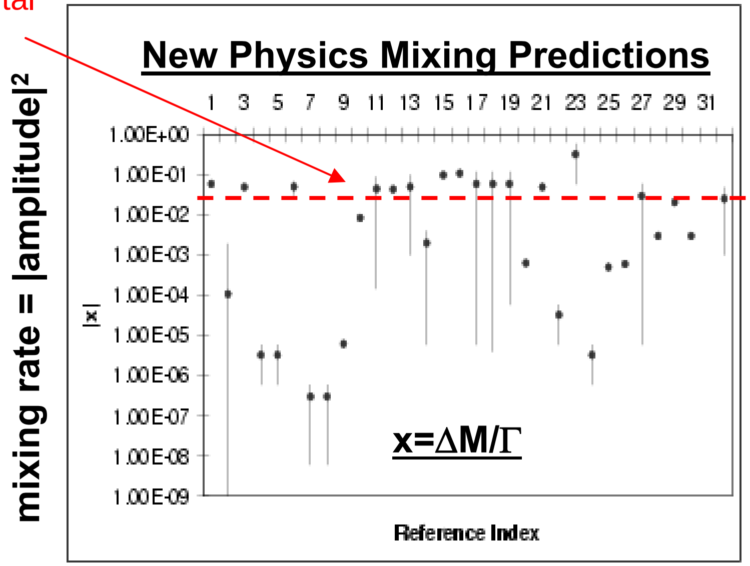
SM mixing small $\propto \Theta_c^2$ x [SU(3) breaking]$^2$<O($10^{-3}$)

$10^{-2}$ possible

# Theoretical “Guidance”

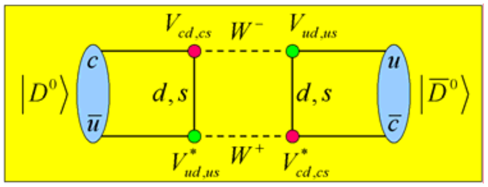


current experimental sensitivity



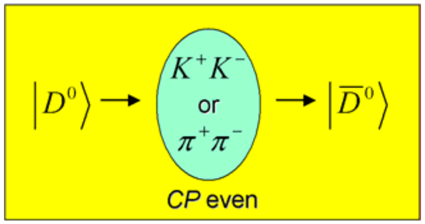
**(A. Petrov, hep/ph 0311371)**

*x* mixing: Channel for New Physics.



$$x = \frac{\Delta M}{\Gamma}$$

*y* (long-range) mixing: SM background.



$$y = \frac{\Delta\Gamma}{2\Gamma}$$

New physics will enhance *x* but not *y*.

$$\boxed{R_{\text{mix}} \equiv \tfrac{1}{2}\left(x^2 + y^2\right)}$$

SM mixing predictions ~ bounded by box diagram rate & expt. sensitivity. New Physics predictions span same large range ➔ mixing is not a clear indication of New Physics.

No CP-violating effects expected in SM. CP violation in mixing would therefore be an unambiguous signal of New Physics.

# $D^0$-$D^{0bar}$ Mixing Limits Summer 2005

No sign of D mixing yet

$\langle y \rangle = (0.9 \pm 0.4)\%$

**Mixing parameters:**

$x = \Delta m / \Gamma \qquad y = \Delta\Gamma / 2\Gamma$

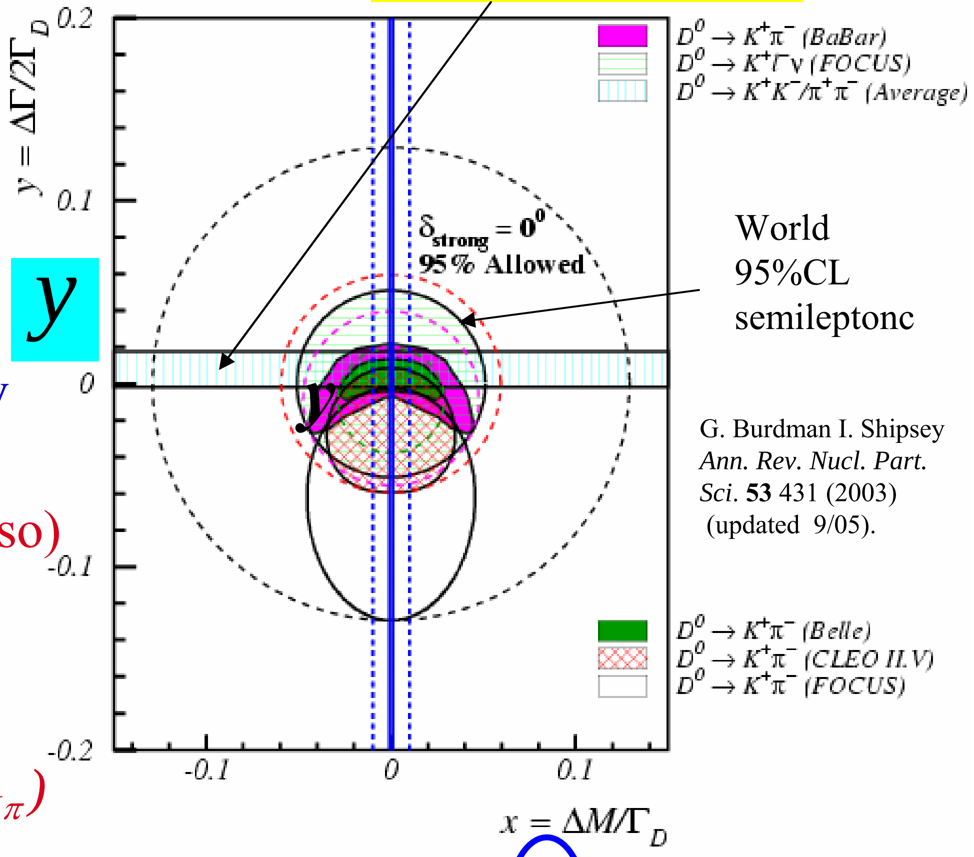
*CP*-eigenstate lifetimes (e.g., $K^+K^-$, $\pi^+\pi^-$)
(compare to $K^+\pi^- \Rightarrow \Gamma_{AVE}$) measures *y*
***(torquoise band)***

Next two: tag flavor at birth with D*

Semileptonic: unambiguous flavor @decay
wrong sign measures $r_M \sim (x^2 + y^2)/2$
***(black circle)*** (can do time-dep. analysis also)

Wrong-sign $K^+\pi^-$ time dependence
$R_D$ DCSD rate ( see below )
*x', y'* time-dep't ***(bananas/ellipses)***
(primes: *x*, *y* are rotated by strong phase $\delta_{K\pi}$)

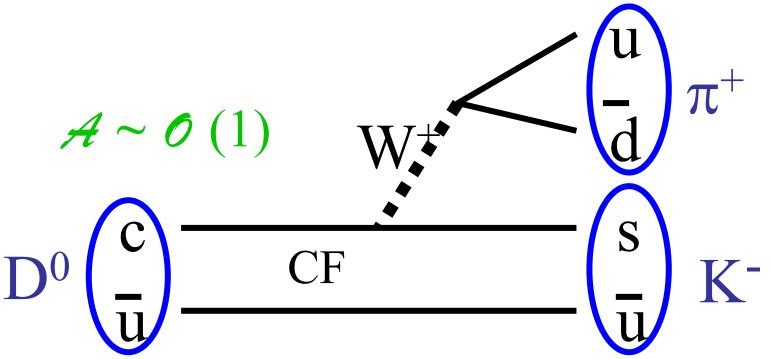
*y*



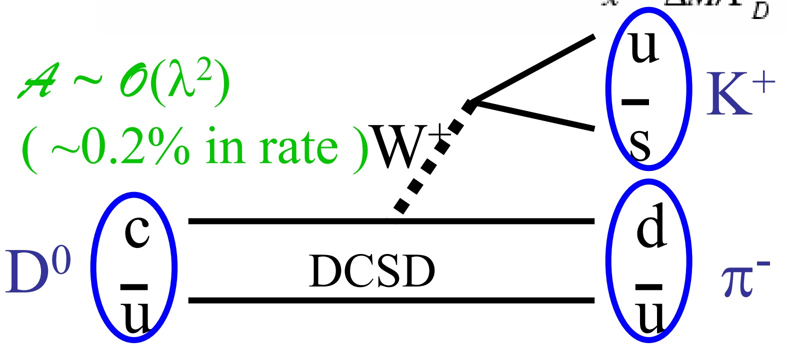
World
95%CL
semileptonc

G. Burdman I. Shipsey
*Ann. Rev. Nucl. Part. Sci.* **53** 431 (2003)
(updated 9/05).

$\mathcal{A} \sim \mathcal{O}\,(1)$

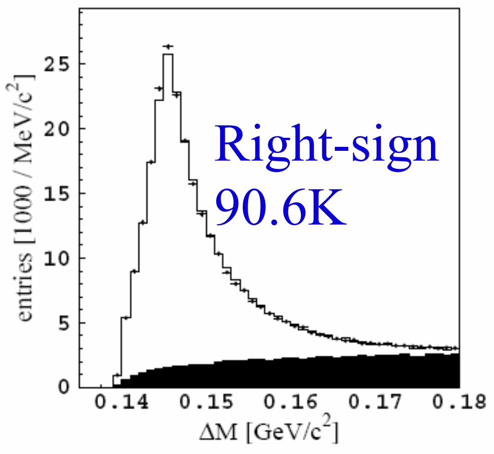


$\mathcal{A} \sim \mathcal{O}(\lambda^2)$
( ~0.2% in rate )



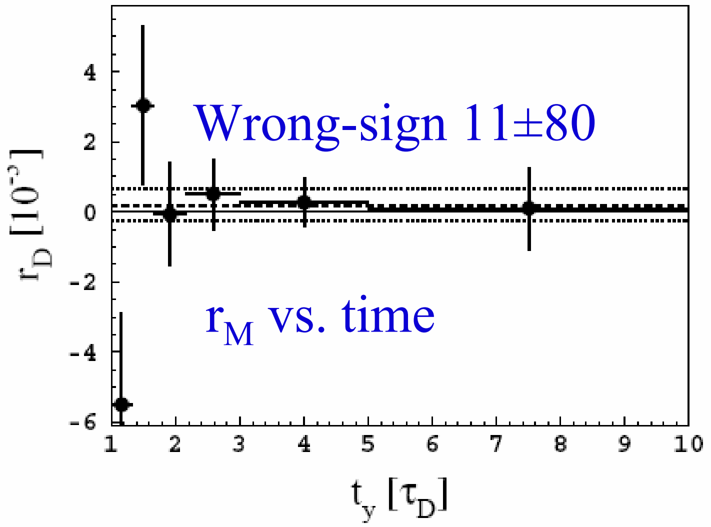
*Mimics*
$D^0 \to \overline{D^0} \to K^+\pi^-$

# New Mixing Results



Right-sign
90.6K

*ΔM(D* - D)*



Wrong-sign 11±80

$r_M$ vs. time

hep-ex/0507020
253 fb$^{-1}$

$D^0 \Rightarrow K^{(*)-}e^+\upsilon$
Tag initial flavor
with $D^{*+} \Rightarrow D^0\pi^+$

Note: FOCUS'02 similar:
$r_M < 0.13\%$

***Result:***

***$r_M < 0.10\%$ (best)***

---

**Tag flavor with *D****

- $M = M(K, \pi)$
- $Q = M(K^+, \pi^-, \pi_{\text{slow}}) - M(K^+, \pi^-)$

PRL 94, 071801
(2005) 90 fb$^{-1}$

Right sign :

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

228*K*

Wrong sign

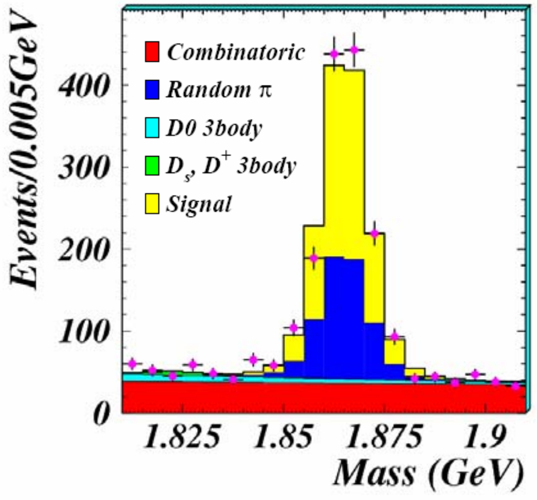
$D^0 \to K^+\pi^-$

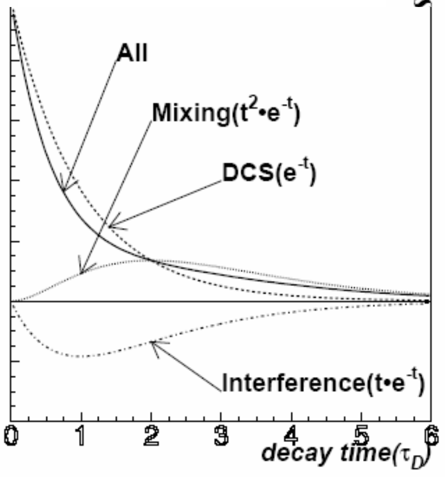
$845 \pm 40$

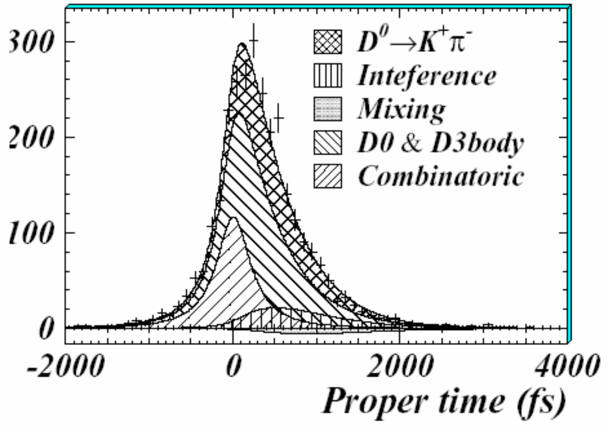
DCSD

+mixing?

Fit to WS $$r_{ws}(t) = (R_D + \sqrt{R_D}\,y't + \frac{1}{4}[x'^2 + y'^2]t^2)e^{-t}$$







***Green contour( new best )***

# Search for Direct CP Violation in $D^0 \to \pi^+\pi^-, K^+K^-$

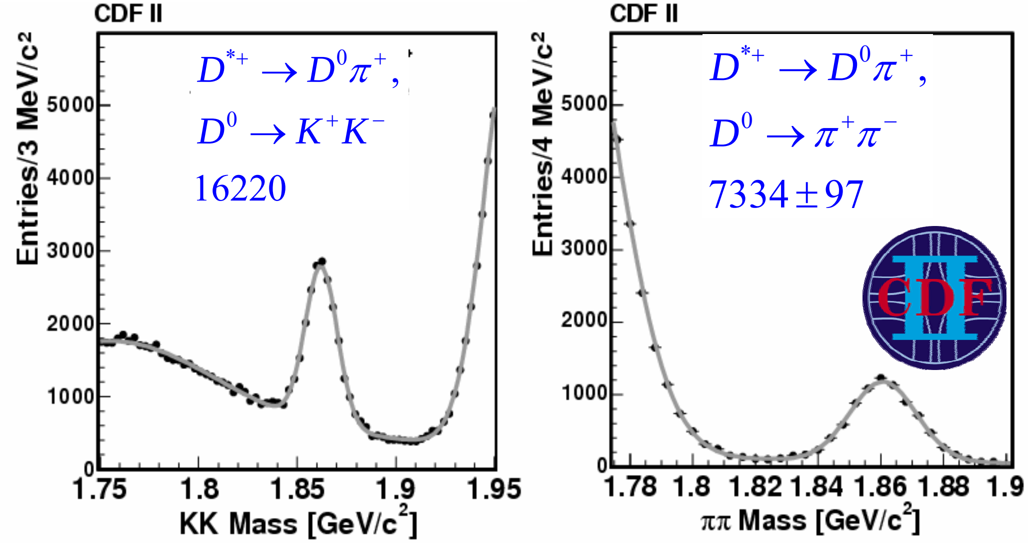
**PRL 94 122001 (2005)**

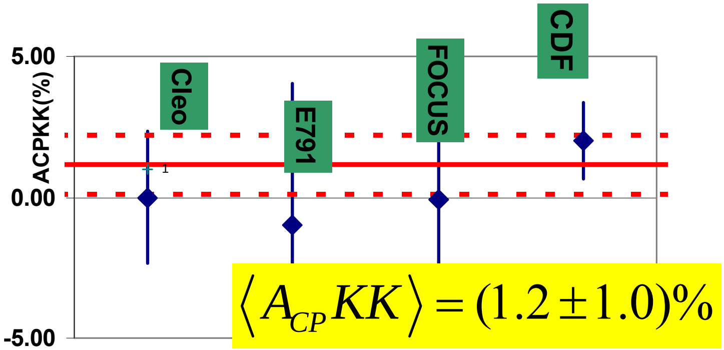
D* to tag $D^0$ flavor. Measure relative to $D^0 \to K\pi$ 123pb$^{-1}$
Cabibbo allowed mode (Acp=0) as control).

Time integrated
Most recent (& precise) result.

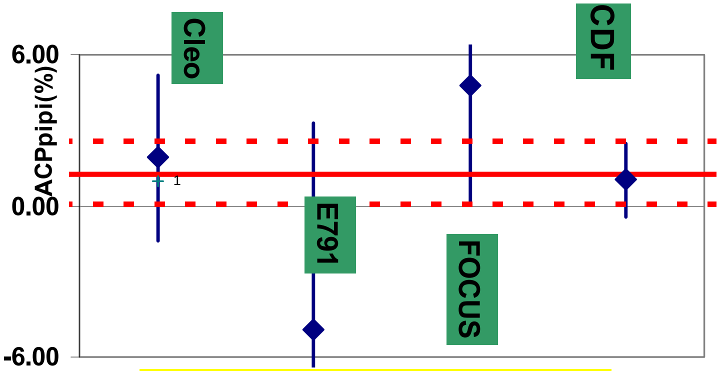
$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}$$

| Mode | $D^0$ | $D^0$ | |
|---|---|---|---|
| KK | 8190 ±140 | 8030 ±140 | |
| ππ | 3660±69 | 3674±68 | |





$\langle A_{CP} KK \rangle = (1.2 \pm 1.0)\%$



$\langle A_{CP} \pi\pi \rangle = (1.3 \pm 1.2)\%$

| | $A_{CP}\, D^0 \to K^+K^-$ | $A_{CP}\, D^0 \to \pi^+\pi^-$ |
|---|---|---|
| CLEO | $(0.0 \pm 2.2 \pm 0.8)\%$ | $(1.9 \pm 3.2 \pm 0.8)\%$ |
| E791 | $(-1.0 \pm 4.9 \pm 1.2)\%$ | $(-4.9 \pm 7.8 \pm 2.5)\%$ |
| FOCUS | $(-0.1 \pm 2.2 \pm 1.5)\%$ | $(4.8 \pm 3.9 \pm 2.5)\%$ |
| CDF | $(2.0 \pm 1.7 \pm 0.6)\%$ | $(1.0 \pm 1.3 \pm 0.6)\%$ |

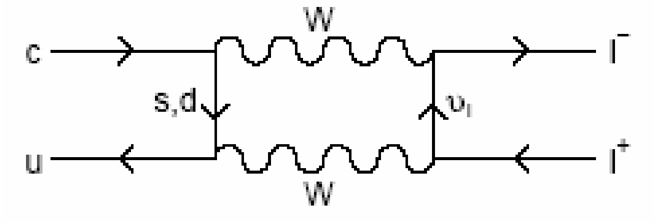
Time dependent measurements can distinguish direct & indirect CPV. CDF plan this. BABAR/Belle (2003) found no evidence for indirect CP at the 1% level.

# Rare Charm Decays

FCNC modes are suppressed by the GIM mechanism:

$D^0 \to e^+e^- \quad (\mathcal{B} \sim 10^{-23})$

$D^0 \to \mu^+\mu^- \quad (\mathcal{B} \sim 3\times10^{-13})$



The lepton flavor violating mode $D^0 \to e^\pm\mu^\mp$ is strictly forbidden.

Beyond the Standard Model, New Physics may enhance these, e.g.,

R-parity violating SUSY:

$\mathcal{B}\left(D^0 \to e^+e^-\right)$ up to $10^{-10}$

$\mathcal{B}\left(D^0 \to \mu^+\mu^-\right)$ up to $10^{-6}$

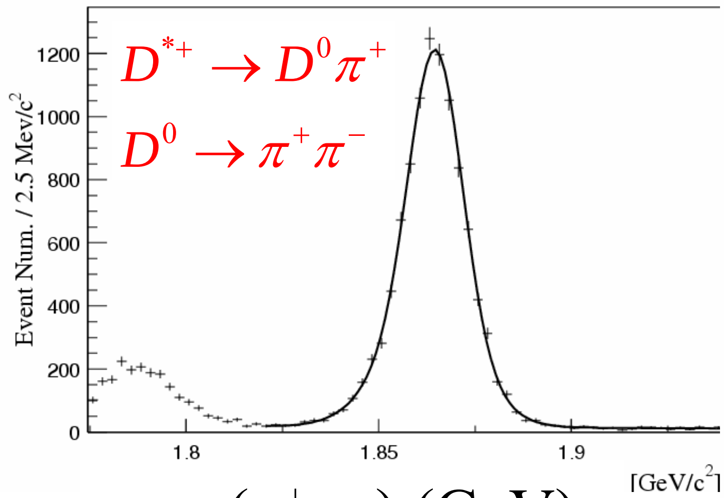
$\mathcal{B}\left(D^0 \to e^\pm\mu^\mp\right)$ up to $10^{-6}$

(Burdman et al., Phys. Rev. D66, 014009).

# Search for $D^0 \to e^+e^-, \mu^+\mu^-, e^\mp\mu^\pm$

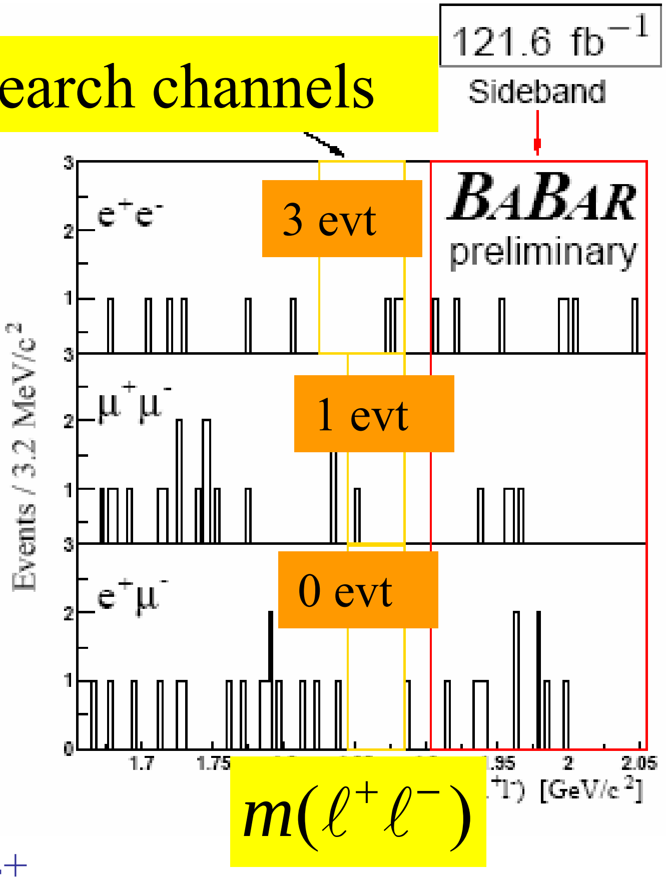
**PRL 93 101801 (2005)**

Normalizing mode:



mass(π+,π-) (GeV)

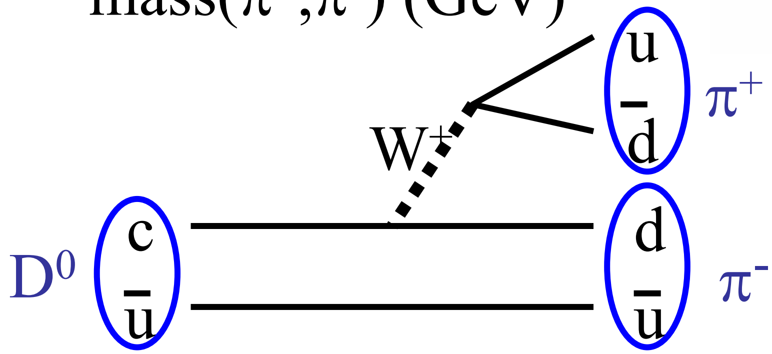
Search channels



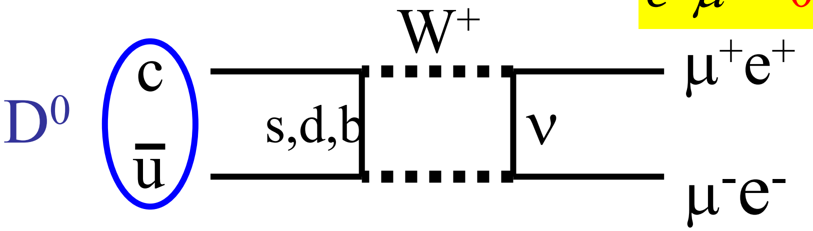
121.6 fb⁻¹

Large backgrounds, only D⁰ final states are tractable in e+e- at 10 GeV so far. Use D*→D⁰π tag. Measure relative to D →π π.

| mode | ULx$10^{-6}$ | prev |
|---|---|---|
| $e^+e^-$ | 1.2 | 6.2 |
| $\mu^+\mu^-$ | 1.3 | 2.0 |
| $e^\mp\mu^\pm$ | 0.81 | 8.1 |



standard model rate ~ $10^{-3}$



standard model rate ~ $10^{-13}$ ($10^{-23}$ )

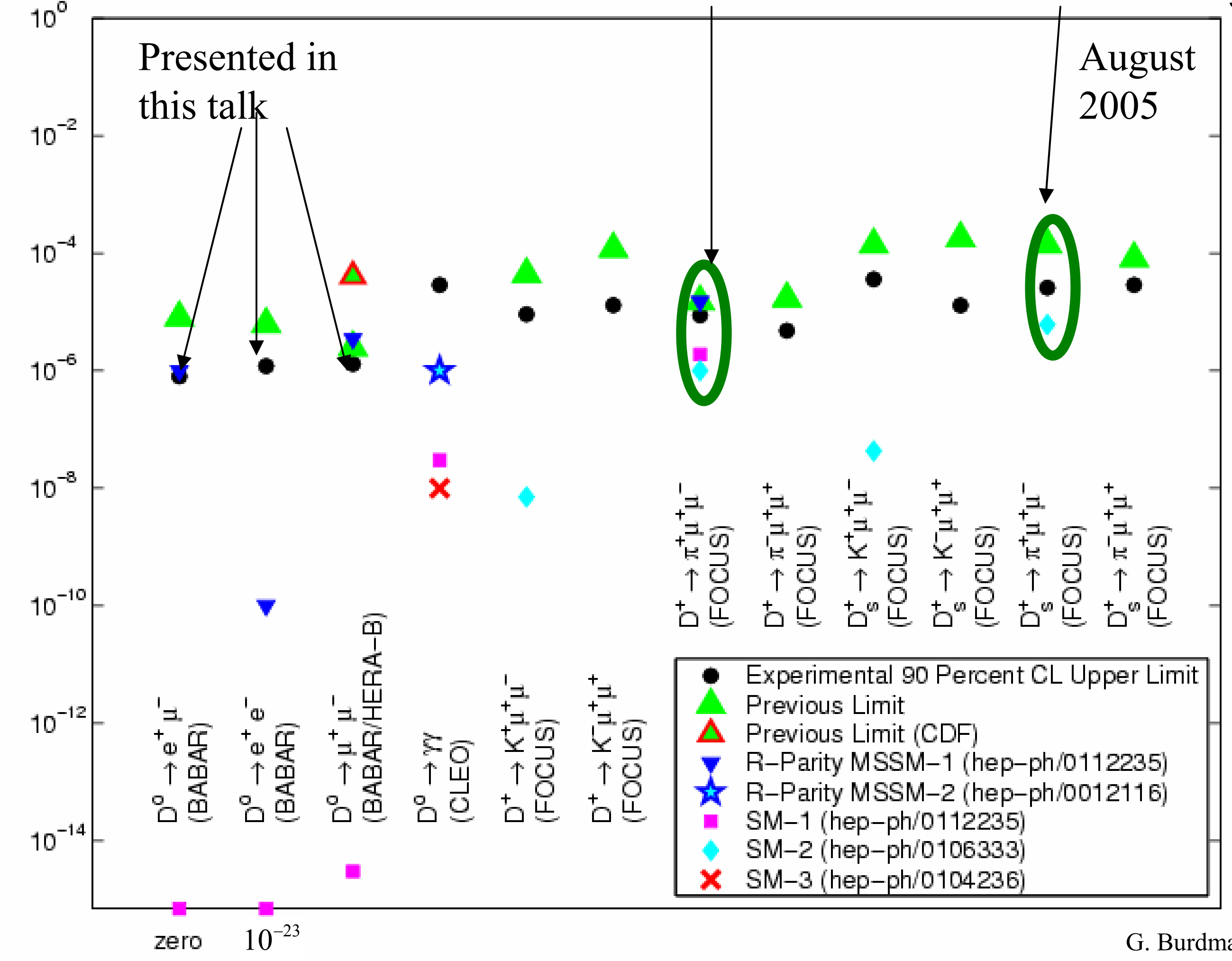
Big Improvement!

$D^0 \to e^\mp\mu^\pm$ forbidden.

# Rare Decay Summary

Sets MSSM constraint

Close to Long Distance Predictions



For $D^+$ all charged final states are well-suited to fixed target and Tevatron CDF/DZero beginning to enter the game

Expt. sensitivity $10^{-5}$-$10^{-6}$ Just beginning to confront models of New Physics in an interesting way.

Still plenty of room for New Physics.

Outlook: bright CDF/D0, B factories, charm factories,

G. Burdman and I. Shipsey
*Ann. Rev. Nucl. Part. Sci.* **53** 431 (2003)
arXivhep-ph/0310076 (updated August 20 2004).

# Summary

New Physics searches in D mixing, D CP violation and in rare decays by BABAR, Belle and CDF have become considerably more sensitive in the past year, however all results are null. CLEO-c and BES III will underatke complementary studies.

In charm's role as a natural testing ground for QCD techniques there has been solid progress. The start of data taking at the $\psi(3770)$ by BESII and CLEO-c (and later BESIII) promises an era of precision absolute charm branching ratios.

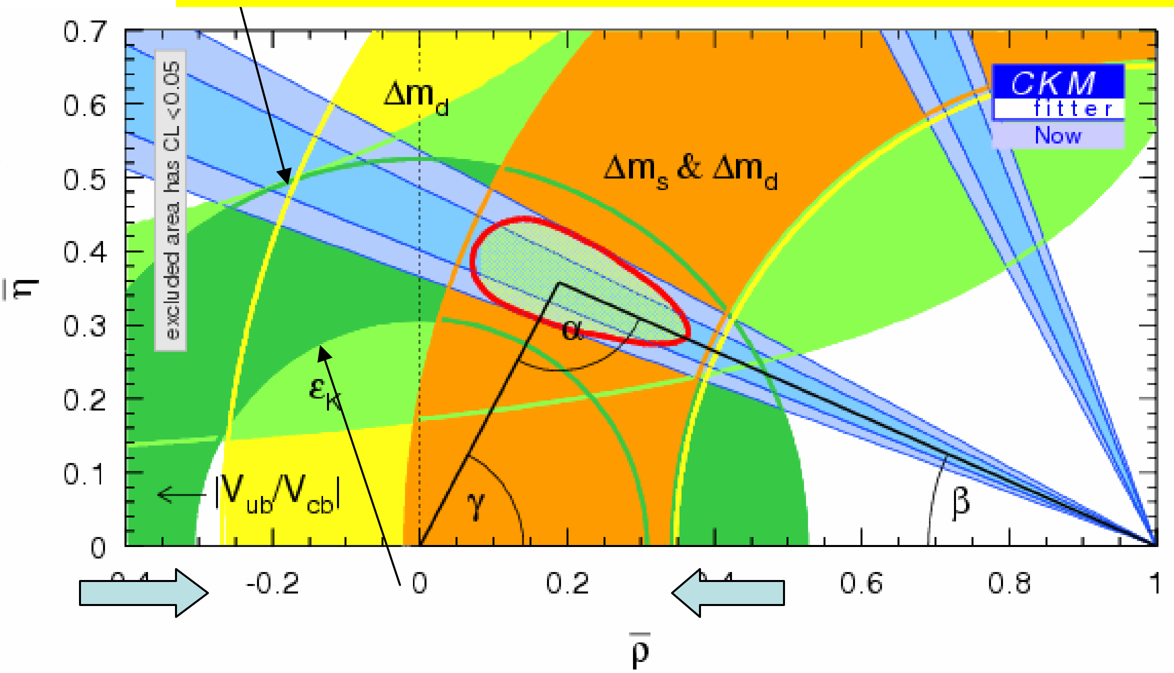
The precision with which the charm decay constant $f_{D+}$ is known has already improved from 100% to ~8%. And the D→K semileptonic form factor has be checked to 10%. A reduction in errors for decay constants and form factors to the few % level is promised.

This comes at a fortuitous time, recent breakthroughs in precision lattice QCD need detailed data to test against. Charm is provide that data. If the lattice passes the charm test it can be used with increased confidence by: BABAR/Belle/CDF/D0//LHC-b/ATLAS/CMS to achieve precision determinations of the CKM matrix elements Vub, Vcb, Vts, and Vtd thereby maximizing the sensitivity of heavy quark flavor physics to physics beyond the Standard Model.

Charm is enabling quark flavor physics to reach its full potential. Or in pictures….

# Precision theory + charm = large impact

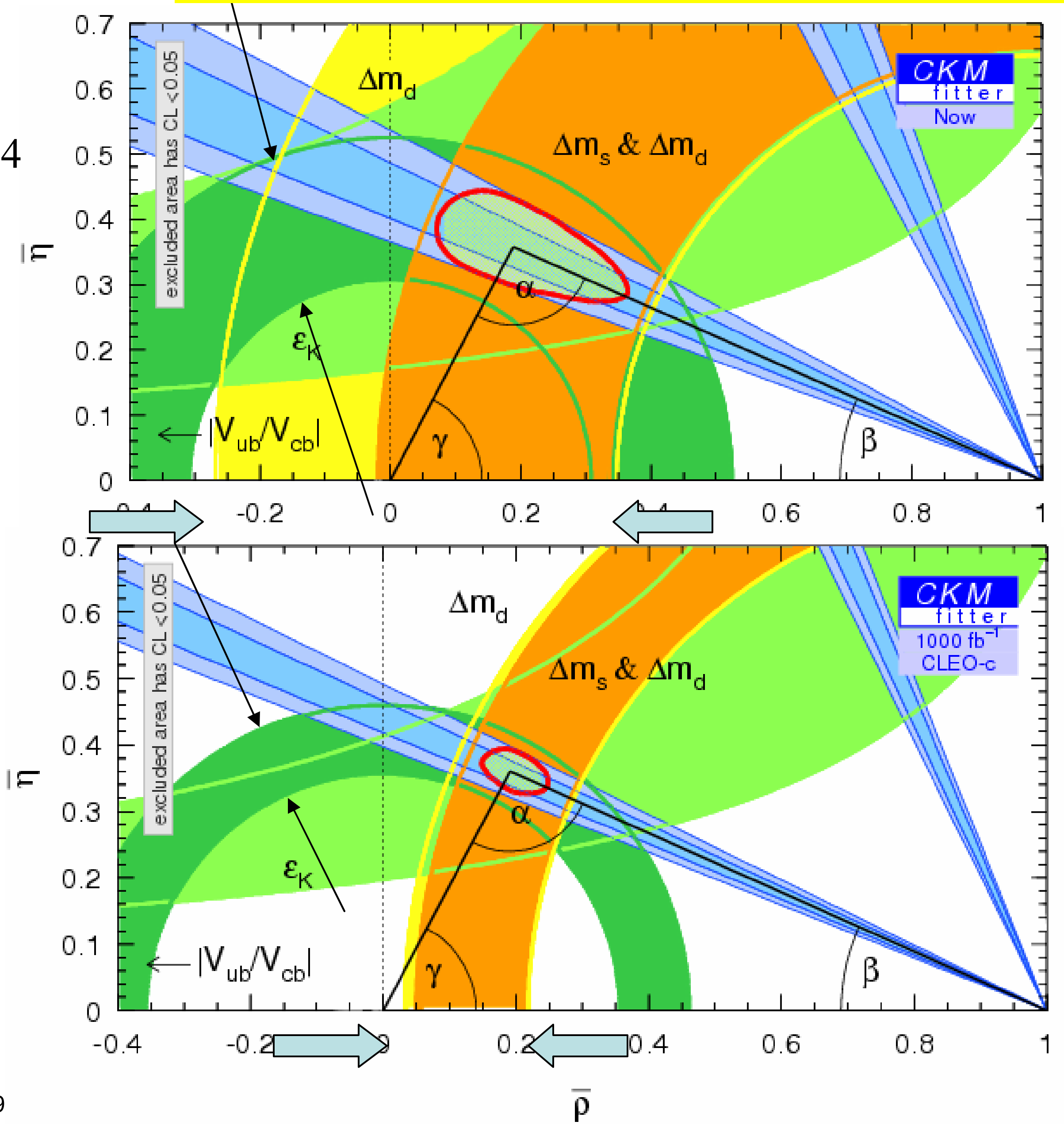
2005



Theoretical errors dominate width of bands

# Precision theory + charm = large impact

2004



*precision* QCD calculations tested with *precision* charm data

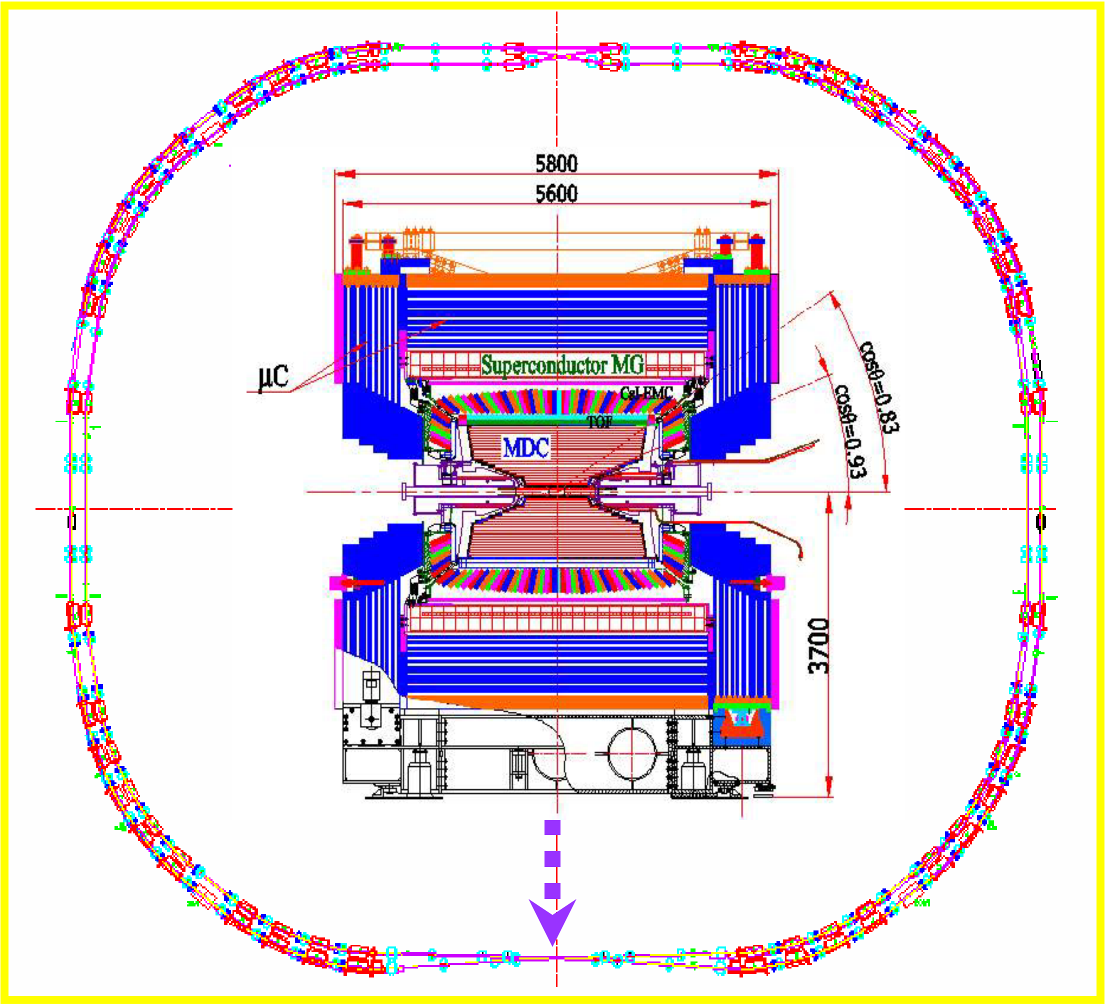
➔theory errors of a few % on B system decay constants & semileptonic form factors

\+

500 fb-1 @ BABAR/Belle

# Additional Slides

# BEPCII/BESIII Project



## Design

- Two ring machine
- 93 bunches each
- Luminosity

X5 CESR-c design
X15 CESR-c current performance

$10^{33}$ cm$^{-2}$ s$^{-1}$ @1.89GeV

6× $10^{32}$ cm$^{-2}$ s$^{-1}$ @1.55GeV

6× $10^{32}$ cm$^{-2}$ s$^{-1}$ @ 2.1GeV

- New BESIII

## Status and Schedule

- Most contracts signed
- Linac installed 2004
- Ring installed 2005
- BESIII in place 2006
- Commissioning BEPCII/BESIII beginning of 2007

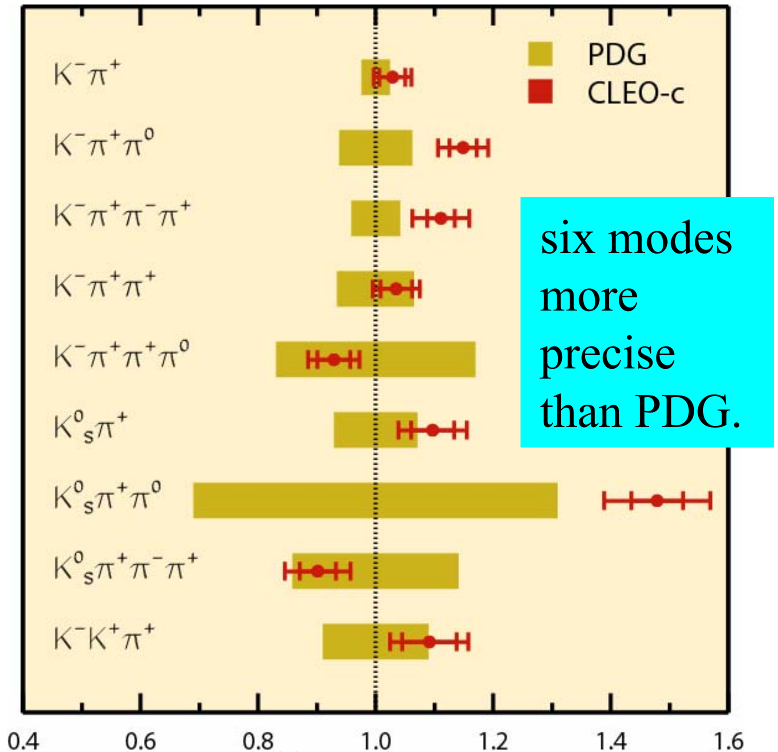
# $D^0$ Modes

| Parameter | Fitted Value (%) |
|---|---|
| $N(D^0\overline{D^0})$ | $(2.006\pm0.038\pm016)\mathrm{x}10^5$ |
| $\mathcal{B}(D^0\to K^-\pi^+)$ | $(3.91\pm0.08\pm0.09)$ % |
| $\mathcal{B}(D^0\to K^-\pi^+\pi^0)$ | $(14.94\pm0.30\pm0.47)$ % |
| $\mathcal{B}(D^0\to K^-\pi^+\pi^+\pi^-)$ | $(8.29\pm0.17\pm0.32)$ % |

# $D^+$ Modes

| Parameter | Fitted Value (%) |
|---|---|
| $N(D^+D^-)$ | $(1.558\pm0.038\pm012)\mathrm{x}10^5$ |
| $\mathcal{B}(D^+\to K^-\pi^+\pi^+)$ | $(9.52\pm0.25\pm0.27)$ % |
| $\mathcal{B}(D^+\to K^-\pi^+\pi^+\pi^0)$ | $(6.04\pm0.18\pm0.22)$ % |
| $\mathcal{B}(D^+\to K_s\pi^+)$ | $(1.55\pm0.05\pm0.06)$ % |
| $\mathcal{B}(D^+\to K_s\pi^+\pi^0)$ | $(7.17\pm0.21\pm0.38)$ % |
| $\mathcal{B}(D^+\to K_s\pi^+\pi^+\pi^-)$ | $(3.20\pm0.11\pm0.16)$ % |
| $\mathcal{B}(D^+\to K^+K^-\pi^+)$ | $(0.97\pm0.04\pm0.04)$ % |

*To be published in PRL*
***hep-ex/ 0504003***



six modes more precise than PDG.

Normalized to PDG

- Stat. errors:
  ~2.0% neutral,
  ~2.5% charged
- σ(systematic)
  ~ σ(statistical).

ε syst. dominates
Many systematics evaluated using data, so will shrink as $\sqrt{\mathcal{L}}$

$$\sigma(DD) = (6.39 \pm 0.10^{+0.17}_{-0.08})\mathrm{nb}$$

55.8/pb will update by 11/05

# From the semileptonic measurements…

Long standing puzzle in D semileptonic decays

Isospin requires $$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)} = 1.0$$

PDG gives $$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)} = 1.4 \pm 0.2$$

CLEO-c & BES II
solve the problem

$$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)} = 1.00 \pm 0.05(stat) \pm 0.04(sys) \text{ CLEO-c}$$

$$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)} = 1.08 \pm 0.22(stat) \pm 0.07(sys) \text{ BES-II}$$

Is anything missing?
sum up all the individual
decay modes

$$\sum B(D^+ \to Xe\nu)_{xcl} = (15.1 \pm 0.5 \pm 0.5)\%$$

$$\sum B(D^0 \to Xe\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\%$$

Compare to inclusive rate
form PDG (not very precise)
room for additional modes

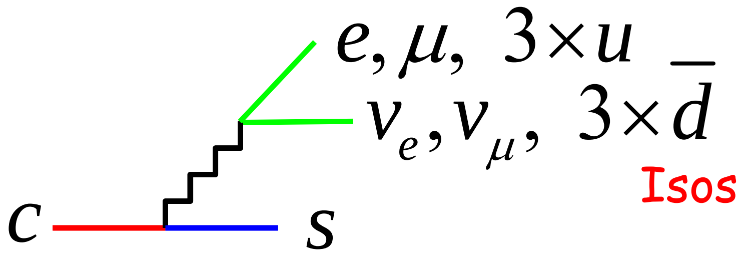
PDG $B(D^+ \to e^+ X) = (17.2 \pm 1.9)\%$ (11%)

PDG $B(D^0 \to e^+ X) = (6.87 \pm 0.28)\%$ (4.1%)

# Inclusive $D^0/D^+$ Absolute Semileptonic Branching Fractions (CLEO-c)

Historically: $B(D\to X\ell\nu)$ important to interpret charm lifetime hierachy

Naïve spectator model:



$$B(D\to e^+X)\sim 20\%$$

But gluon emission enhances hadronic rate

$$B(D\to e^+X)\sim 7\%$$

$$\text{PDG}\ B(D^0\to e^+X)=(6.87\pm0.28)\%$$

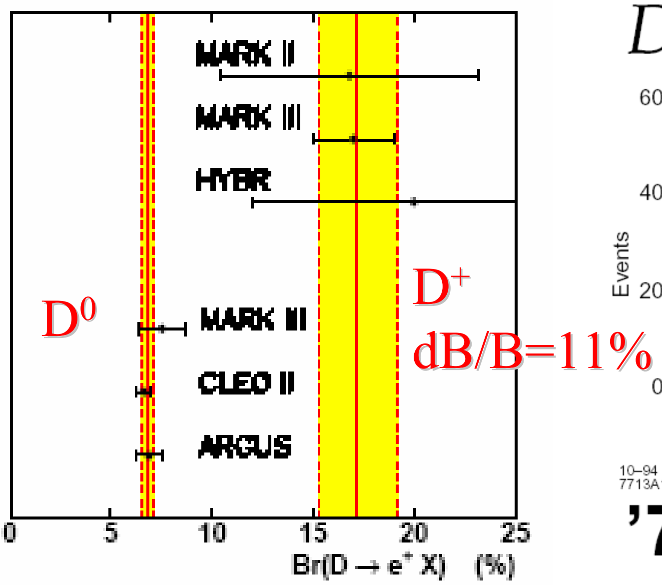
$$\text{PDG}\ B(D^+\to e^+X)=(17.2\pm1.9)\%$$

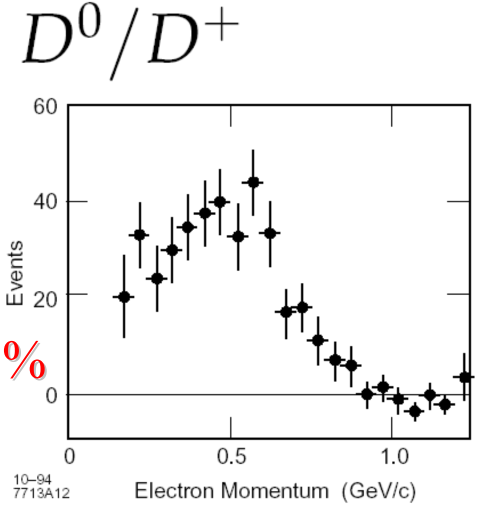
Isospin symmetry requires $\Gamma(D^+\to X\ell\nu)=\Gamma(D^0\to X\ell\nu)$

$$\tau(D^+)/\tau(D^0)=B(D^+\to e^+X)/B(D^0\to e^+X)$$

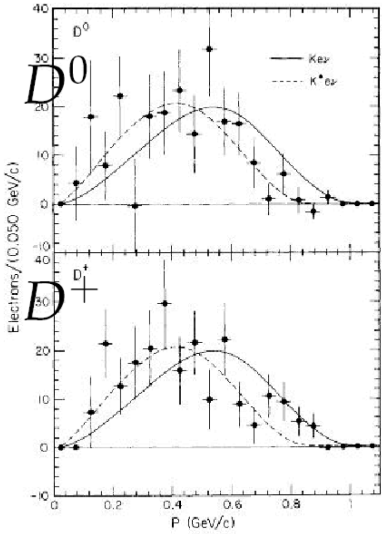
➔ $D^0/D^+$ lifetime difference due to hadronic width (Pauli int. $D^+$)

**Now:** precision measurements of $\Gamma(D\to X\ell\nu)$ and $\Gamma(D_s\to X\ell\nu)$ needed to constrain background to Vub in B inclusive semileptonic decay





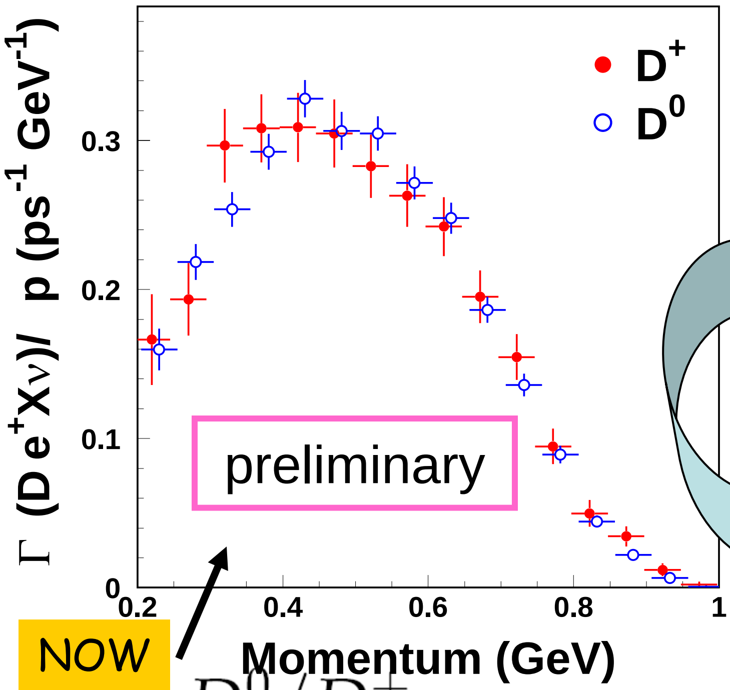
’79 DELCO



’85 MARK III

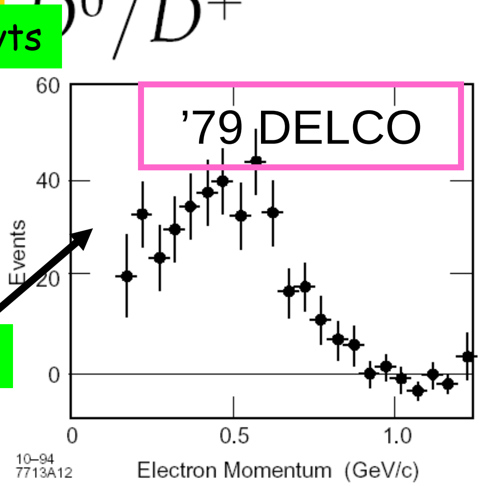
Unfolded background subtracted
efficiency corrected lab
spectrum – no FSR correction

# Corrected Spectra & Results



NOW

10,100evts



THEN

600 evts

Fit low p data to polynomial to extrapolate p=0,
(➔8% has p<200 MeV)

dB/B

$B(D^+ \to Xe\nu) = (16.19 \pm 0.20 \pm 0.36)\%$ (2.5%)

$B(D^0 \to Xe\nu) = (6.45 \pm 0.17 \pm 0.15)\%$ (3.5%)

Sys errors EID 2%, Hadron ID 1% FSR 1% p→0 1%

PDG $B(D^+ \to e^+ X) = (17.2 \pm 1.9)\%$ (11%)

PDG $B(D^0 \to e^+ X) = (6.87 \pm 0.28)\%$ (4.1%)

$\Gamma(D^+ \to e^+ X) = (0.1557 \pm 0.0019 \pm 0.0035)\text{ps}^{-1}$

$\Gamma(D^0 \to e^+ X) = (0.1572 \pm 0.0041 \pm 0.0037)\text{ps}^{-1}$

CLEO-c $B(D^+)/B(D^0) = 2.51 \pm 0.04$

PDG $\tau(D^+)/\tau(D^0) = 2.53 \pm 0.02$

Excellent agreement!

Compare to CLEO-c excl.

$\sum B(D^+ \to Xe\nu)_{xcl} = (15.1 \pm 0.5 \pm 0.5)\%$

$\sum B(D^0 \to Xe\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\%$

Incl & excl. consistent, some room for additional exclusive modes