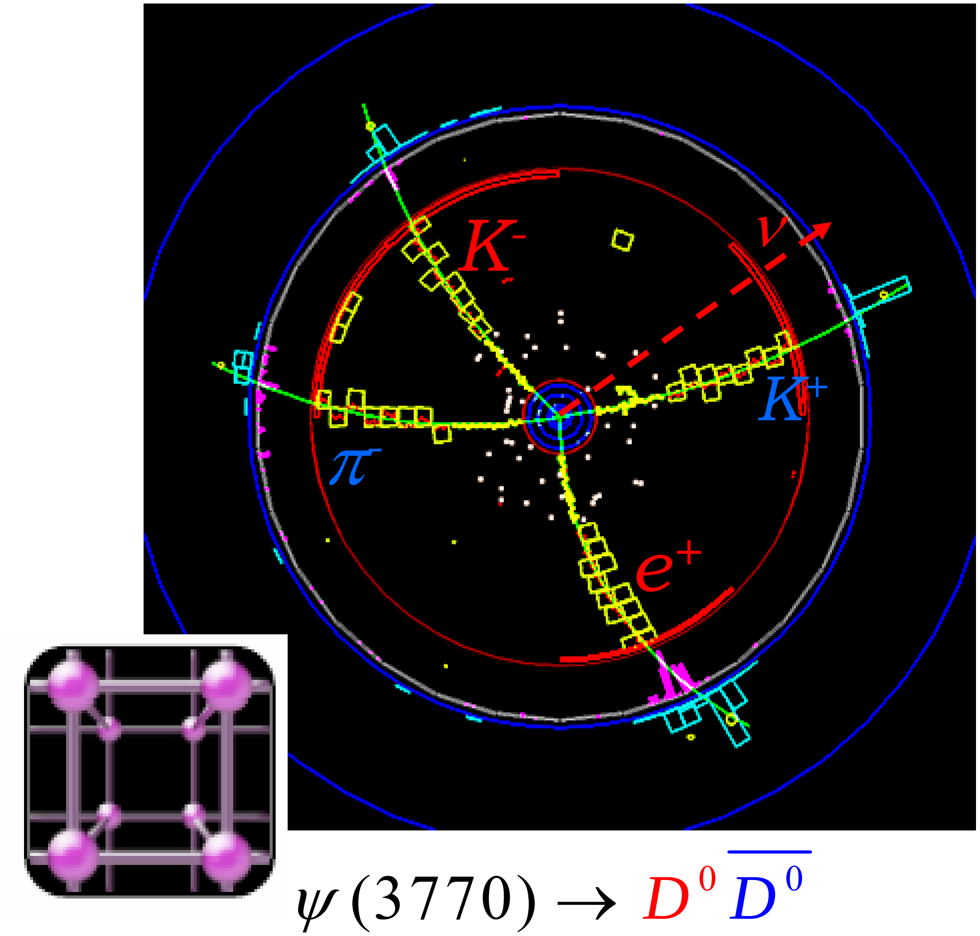
CLEO-c Results and Prospects

OUTLINE

The role of charm in particle physics

Testing the Standard Model with precision quark flavor physics

Searches for Physics Beyond the Standard Model



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

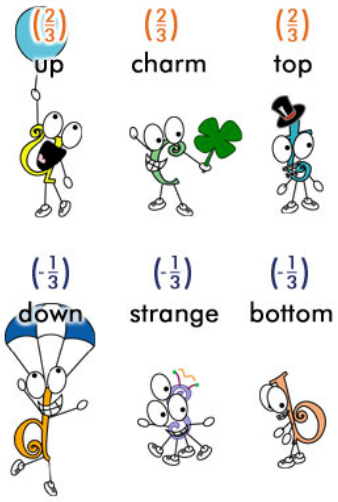
$$\overline{D^0} \rightarrow K^+\pi^-, D^0 \rightarrow K^-e^+\nu$$

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

Charm: The Context

This Decade

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

The Future

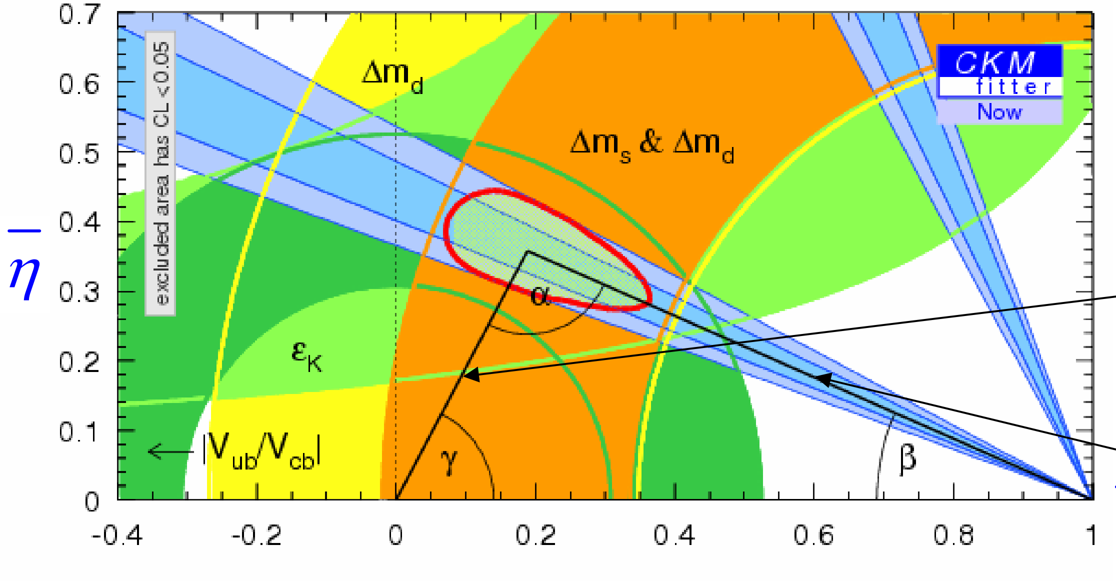
LHC may uncover strongly coupled sectors in the physics Beyond the Standard Model. The ILC will study them. Strongly coupled field theories→ an outstanding challenge to theory. Critical need: reliable theoretical techniques & detailed data to calibrate them

The Lattice

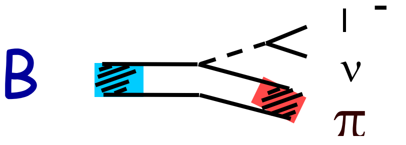
Complete definition of pert. and non-pert. QCD Goal: Calculate B, D, Y, ψ to 5% in a few years, and a few % longer term.

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

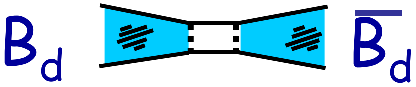
Precision Quark Flavor Physics: charm's role



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

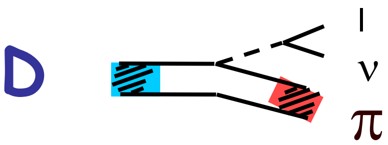


$$\propto \left[f^{B\to\pi}(q) \right]^2 \left| V_{ub} \right|^2$$

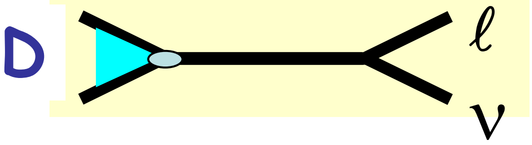


$$\propto \left[f_{Bd} \right]^2 \left| V_{td} \right|^2$$

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



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



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

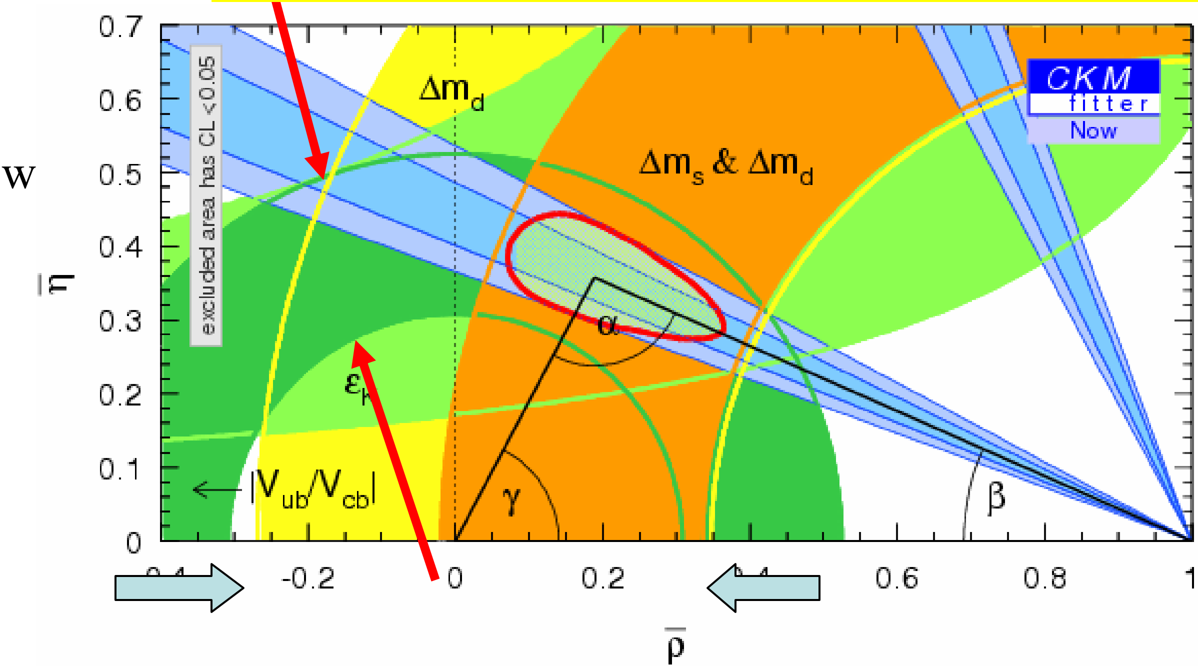
→*measurements* of *absolute rates* for D leptonic & semileptonic decays yield decay constants & form factors to *test* and hone QCD techniques into *precision theory* which can then be applied to the B system.

+ Br(B→ D)~100% *absolute* D hadronic rates normalize B physics:B→DK important for Vcb (scale of triangle)

Charm's role

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

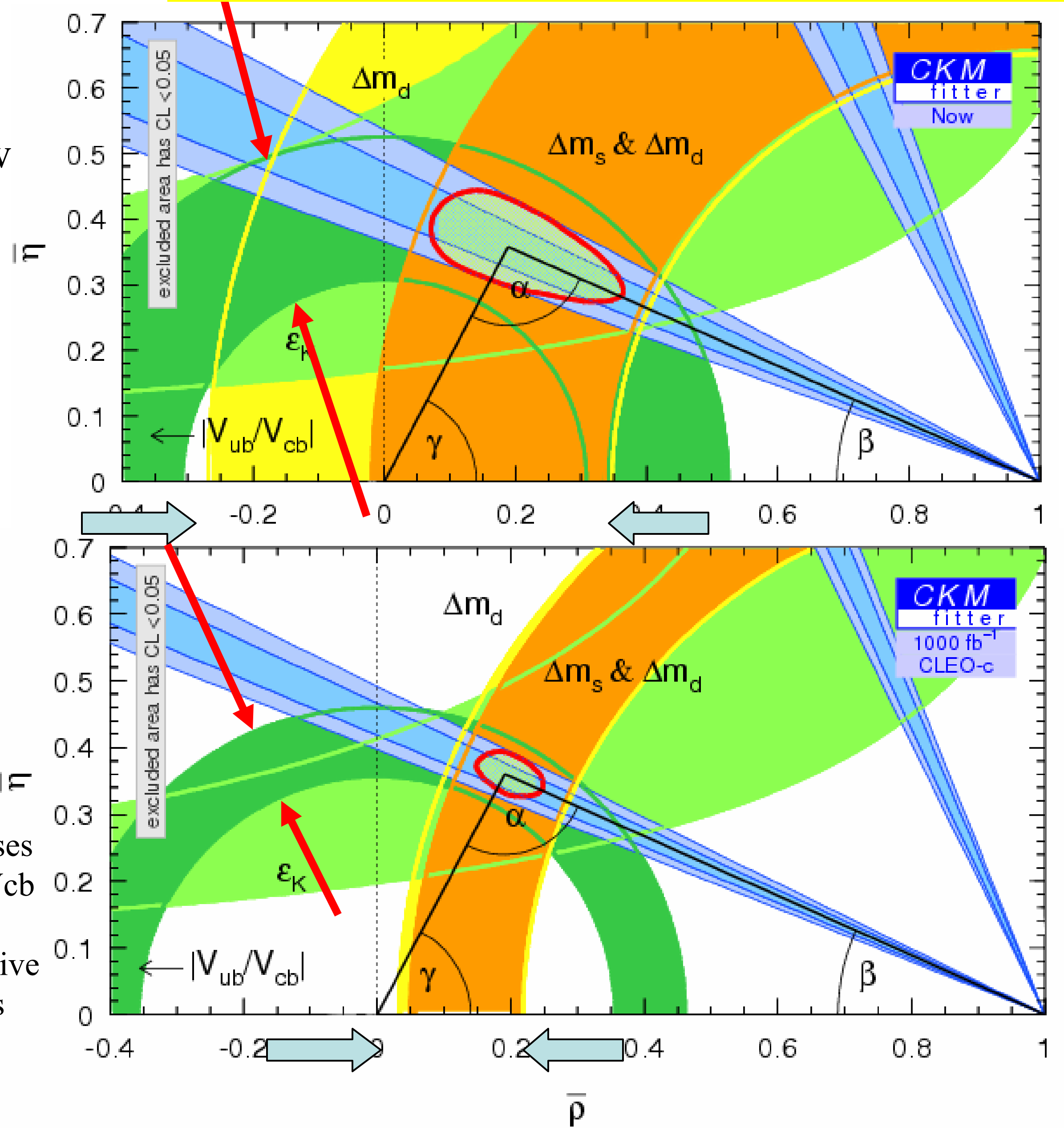
\+

500 fb-1 @ BABAR/Belle

Plot uses Vub Vcb from exclusive decays only

Precision theory + charm = large impact

Now



Plot uses Vub Vcb from exclusive decays only

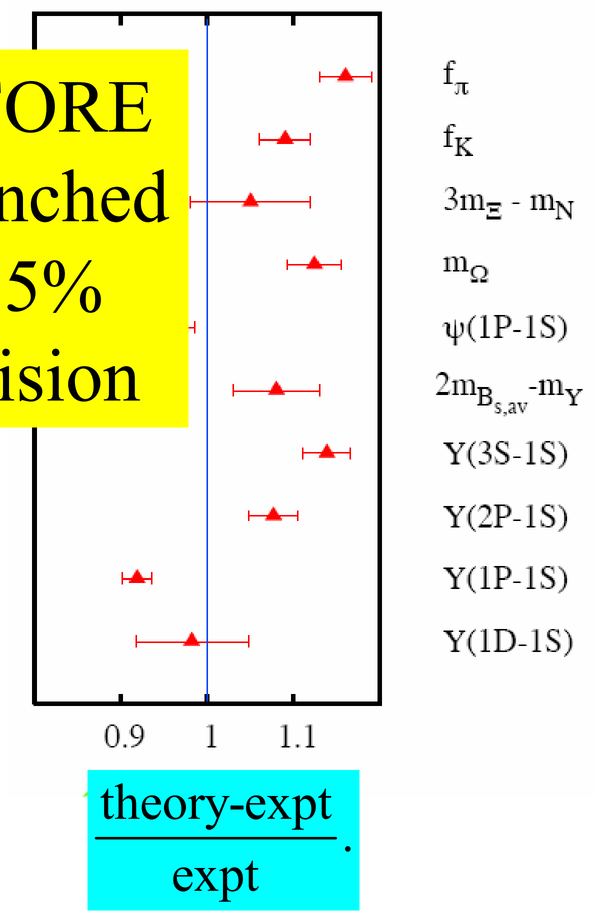
Theoretical errors dominate width of bands

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

Precision theory? Lattice QCD

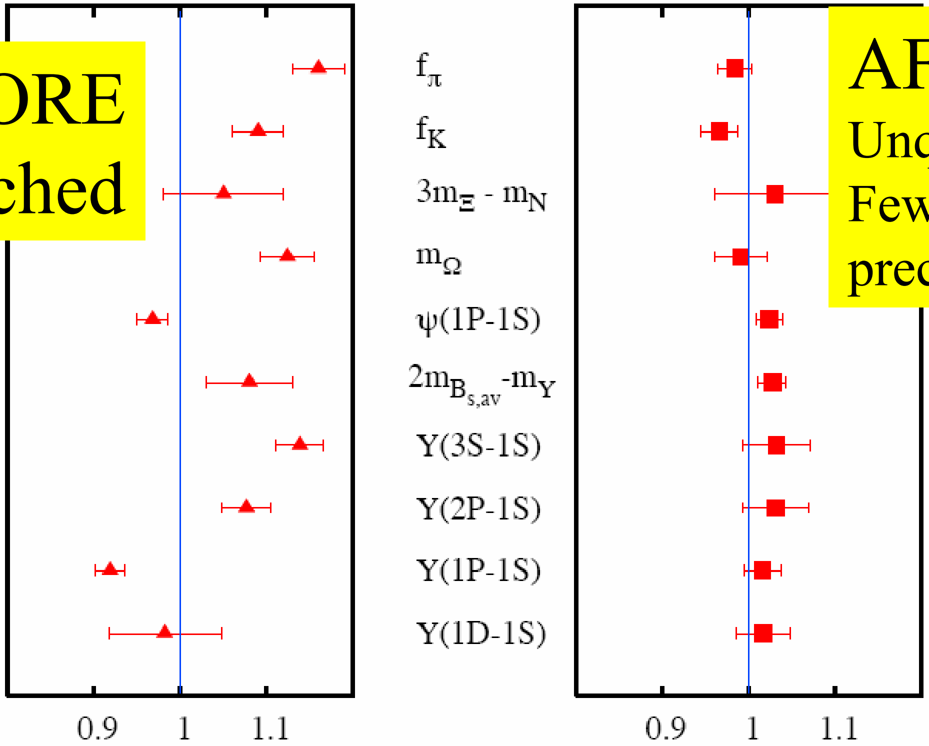


BEFORE
Quenched
10-15%
precision

Precision theory? In 2003 a breakthrough in Lattice QCD

LQCD demonstrated that it can reproduce a wide range of mass differences and decay constants in unquenched calculations. *These were postdictions.*

BEFORE quenched



AFTER
Unquenched
Few %
precision

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

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

Testable *predictions* are now being made:

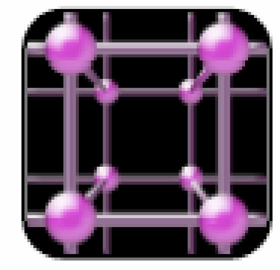
M(B_c) ← Easier, the 1st prediction Nov. 2004 ✓

Charm decay constant f_D ← Harder- first test July 2005

Semileptonic *D/B* form factors ← Hardest- Tests 2005/6

See talk by Howard Trottier

} This talk



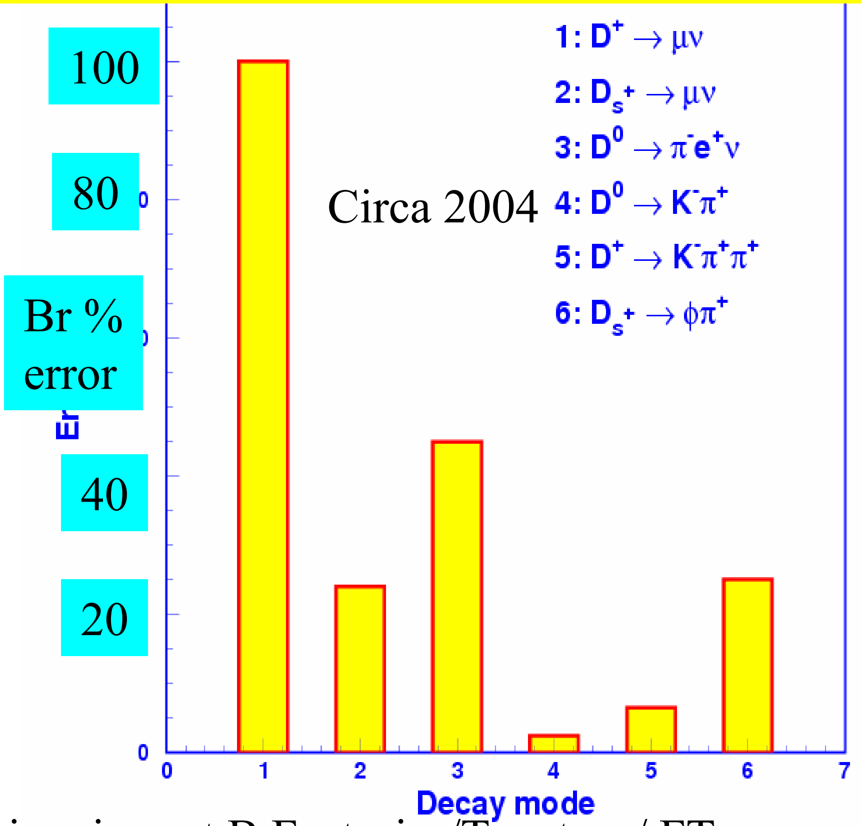
Precision Experiment?
Status of Absolute Charm Branching Ratios in 2004 :

Poorly known → Br

Measured very precisely → τ

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

And: D^0, D^+ & D_S branching ratios used to normalise B & B_S physics are not independent, they are all bootstrapped on a high background measurement of $D^0 \to K^-\pi^+$



Charm absolute rate measurements are not precise since at B Factories/Tevatron/ FT backgrounds are sizeable and, crucially, *because # D's produced is usually not well known.*

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

Backgrounds are large.

#D's produced is usually not well known.

CESR-c/CLEO-c Status. Datasets & Runplan

CESR (10 GeV)
→ CESR-c (3-4GeV)

Approved for 5 years by NSB 2/03

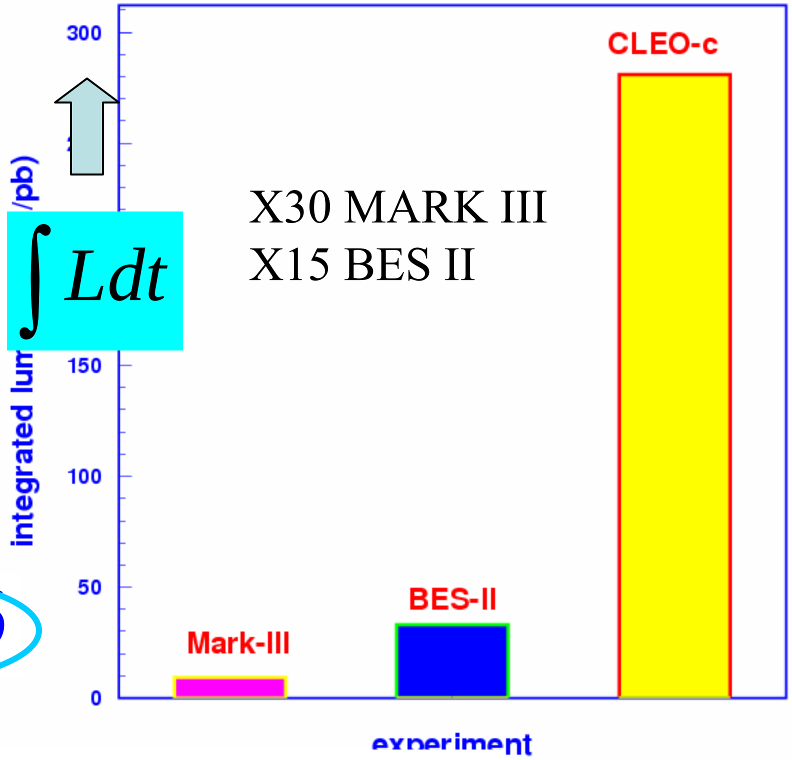
CESR → CESR-c

Results from these two datasets today

2 runs $@\psi(3770) \to D\overrightarrow{D}$

9/03-3/04 56pb^{-1} $360,000\, D\overline{D}$

9/04-4/05 225pb^{-1}.Total 281 pb^{-1} $1.8\times10^6\, D\overline{D}$



$\int Ldt$

X30 MARK III
X15 BES II

next 2.2 years: $\Rightarrow$ ~750 pb^{-1} $@\ \psi(3770)$ (×3 current)

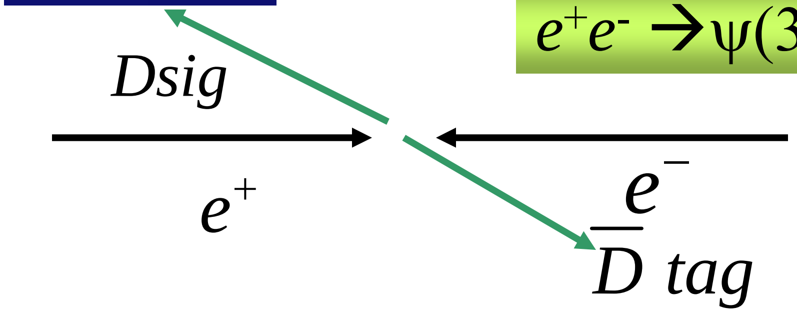
$\Rightarrow$ ~750 pb^{-1} $@\sim$ 4170 MeV above $D_s\overline{D_s}$ threshold (×130 BES)

$\Rightarrow$ some $\psi(2S)$ running, + time for the unanticipated

ψ(3770) Analysis Strategy

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

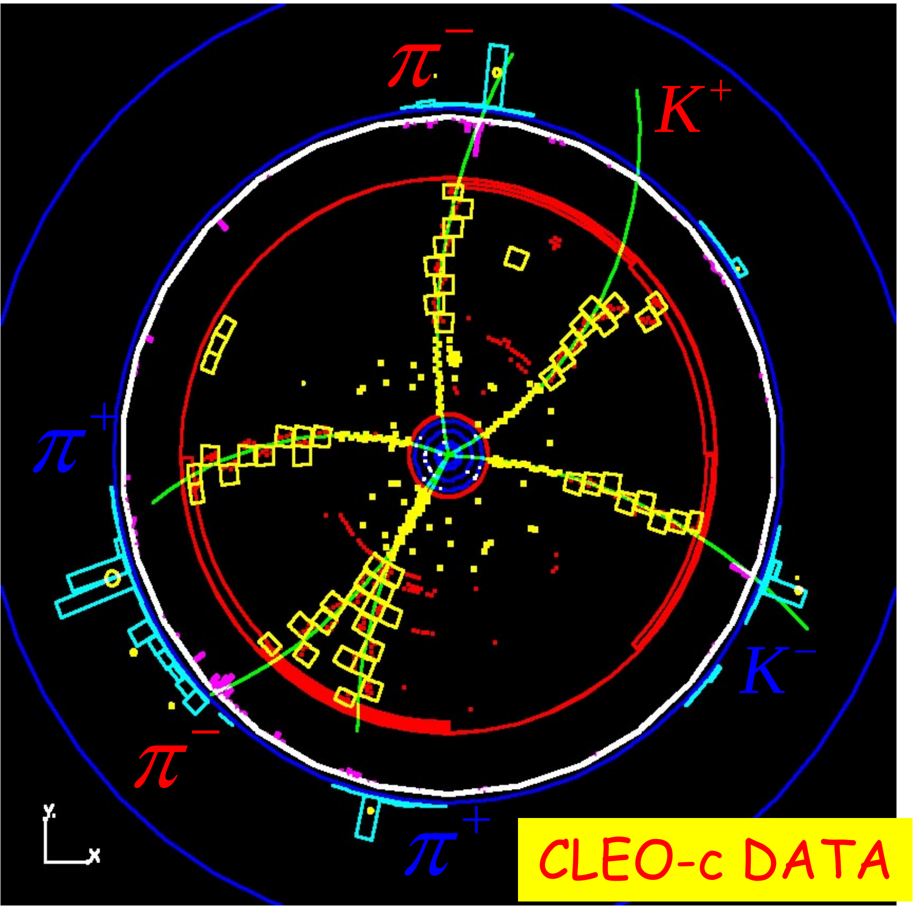
ψ(3770) is to charm what Y(4S) is to beauty



- 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 tagging efficiency: ~22% of D's

Compared to <1% of B's at the Y(4S)



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

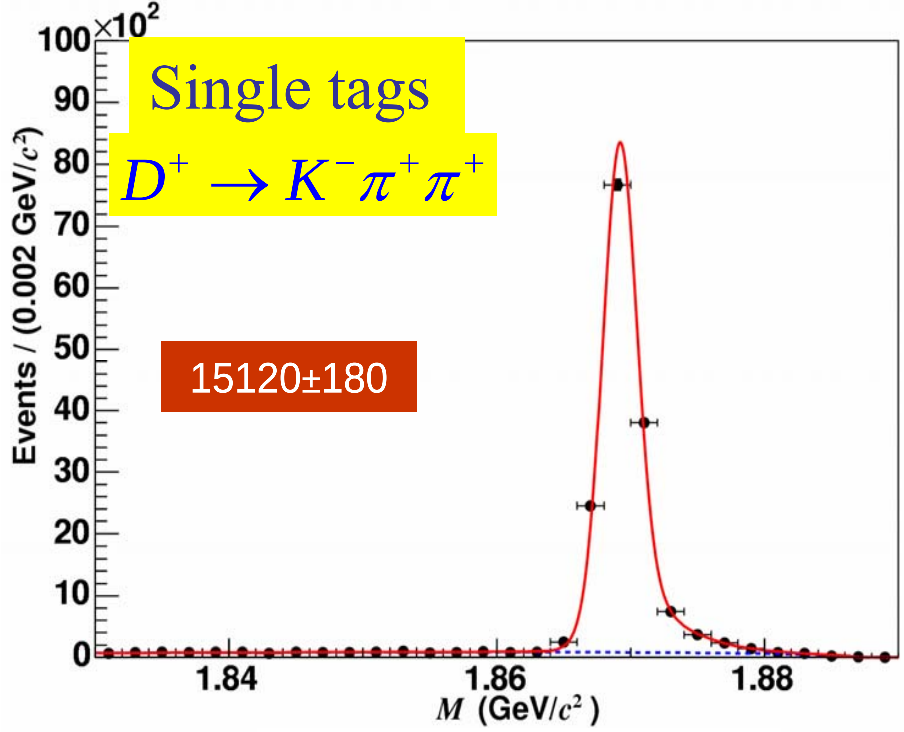
$D^+ \to K^-\pi^+\pi^+,\ D^- \to K^+\pi^-\pi^-$

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

Absolute Charm Branching Ratios at Threshold

- Kinematics analogous to $\Upsilon(4S) \rightarrow BB$: identify *D* using

$$E_D \Rightarrow E_{beam} : \begin{array}{l} \Delta E = E_{beam} - E_D \\ M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2} \end{array}$$

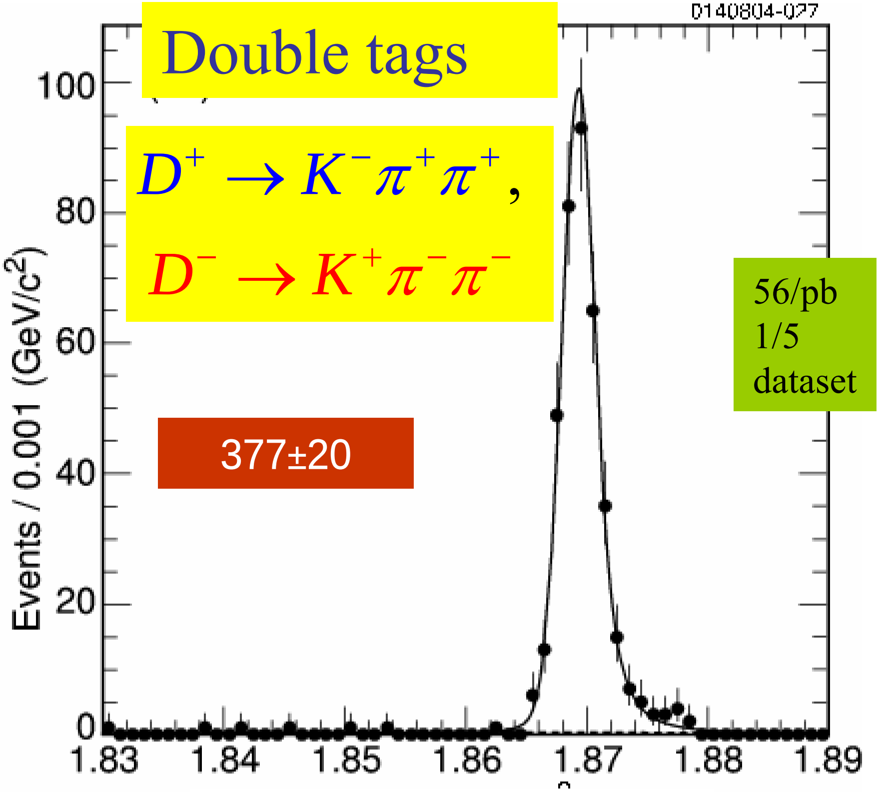


Single tags

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

15120±180

D candidate mass (GeV)



Double tags

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

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

377±20

56/pb
1/5
dataset

D candidate mass (GeV)

Independent of L and cross section

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

Comparison with PDG 2004 $D^o \rightarrow K^-\pi^+$

THEN:

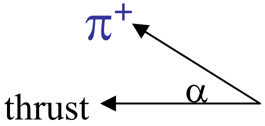
CLEO & ALEPH

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

compare to:

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

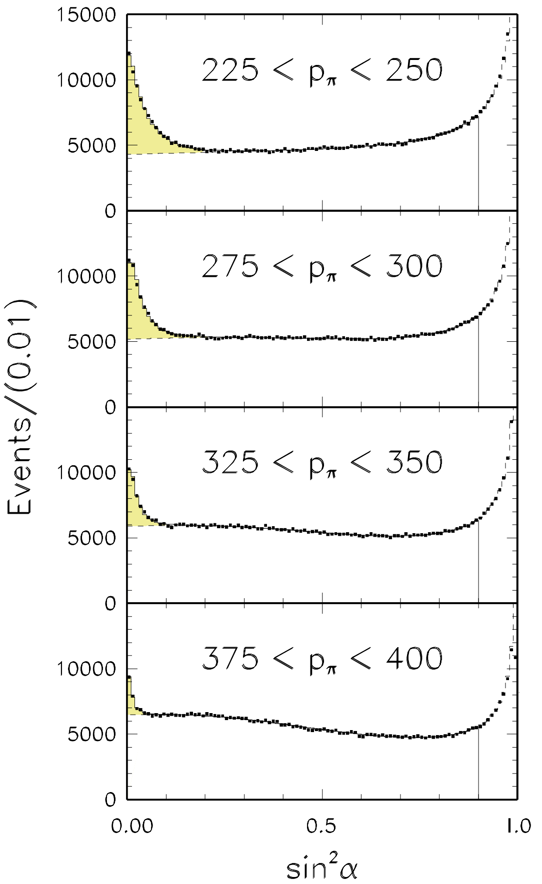
(Q~6MeV)



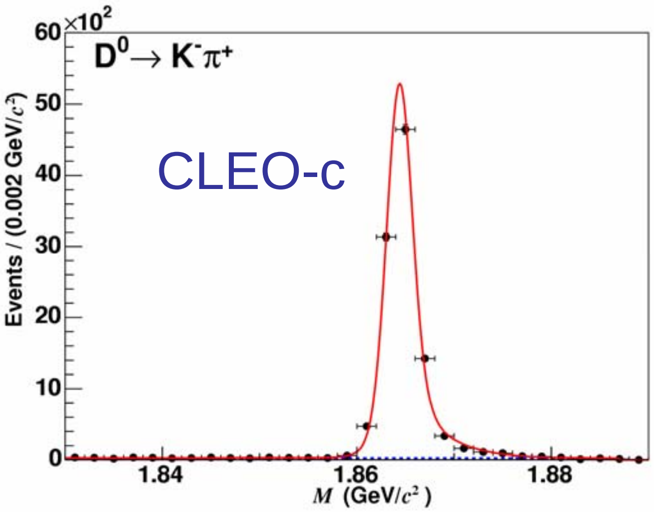
Three best measurements:

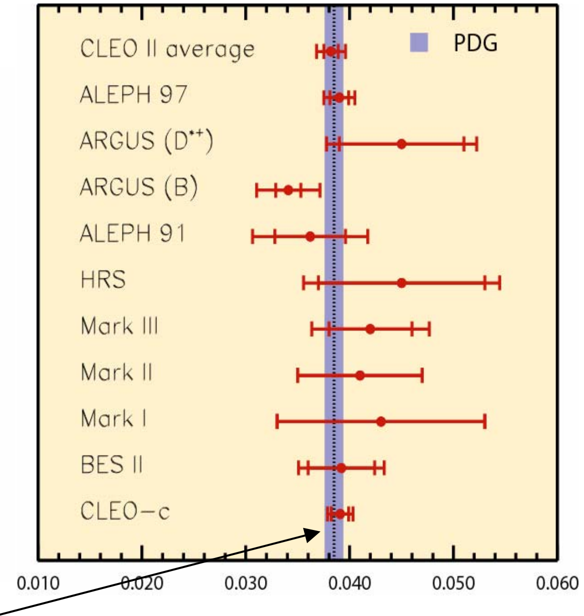
$\mathcal{B}$ (%)	Error(%)	Source
3.82±0.07±0.12	3.6	CLEO
3.90±0.09±0.12	3.8	ALEPH
3.80 ±0.09	2.4	PDG
3.91±0.08 ±0.09	3.1	CLEO-c

CLEO-c as precise as any previous measurement



NOW:





CLEO-c
(not in PDG average)

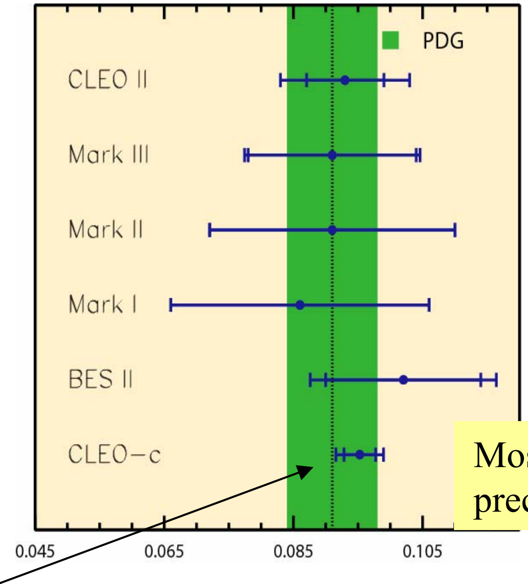
$B(D^+\to K^-\pi^+\pi^+)$

Three best measurements:

$\mathcal{B}$ (%)	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

THEN:

Method (CLEO) Bootstrap: Measure:

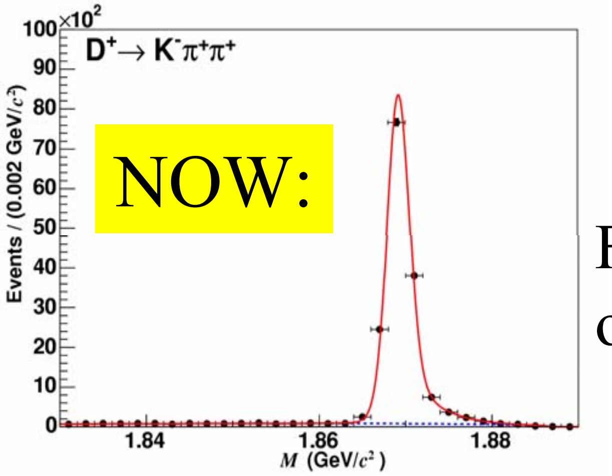


Most precise

CLEO-c (not in PDG average)

Assume isospin

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



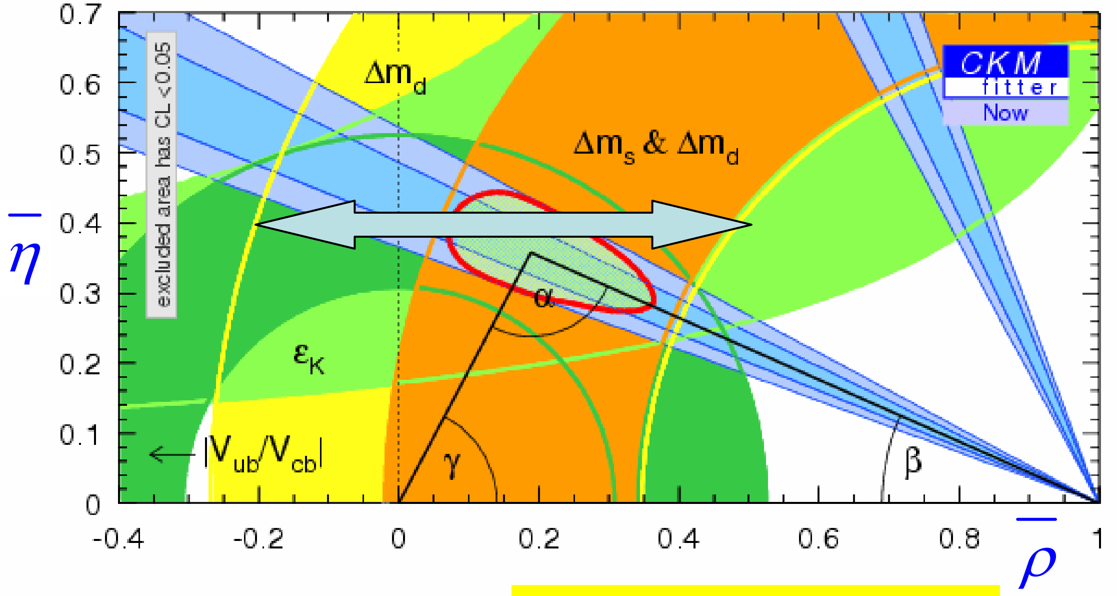
NOW:

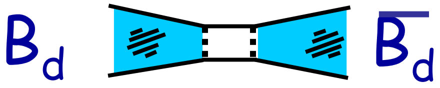
NOW: A SECURE FOUNDATION the charm hadronic scale we have been using for last 10 years is approximately correct & is finally on a secure foundation

Future outlook

Decay	$\delta B/B(\%)$		
	PDG	$CLEO\,c$	
		$56\,pb^1$	$750\,pb^{-1}$
$D^0\to K^-\pi^+$	2.4	3.1	$0.6(stat)(1.1)sys$
$D^+\to K^-\pi^+\pi^+$	7.7	3.9	$0.7(stat)(1.2)sys$
$D_S^+\to\phi\pi$	12.5% $(BABAR)$	−−	$4.0(stat)$

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





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

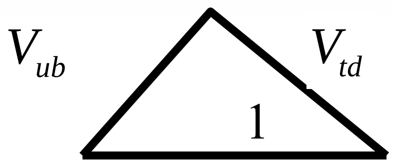
1.0%
(expt)
HFAG 2005

~15% (LQCD)
hep-lat/0409040

~16%

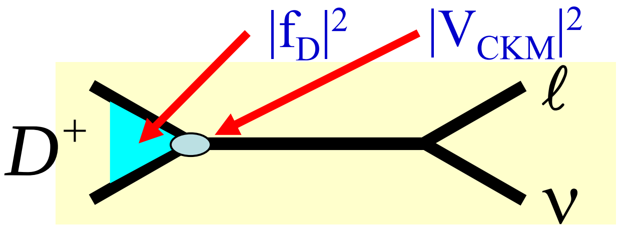
if f_{Bd} was known to 3%

$|V_{td}||V_{tb}|$ 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%

$$\frac{\delta f_{D_s}}{f_{D_s}} \sim 100\%$$

PDG04

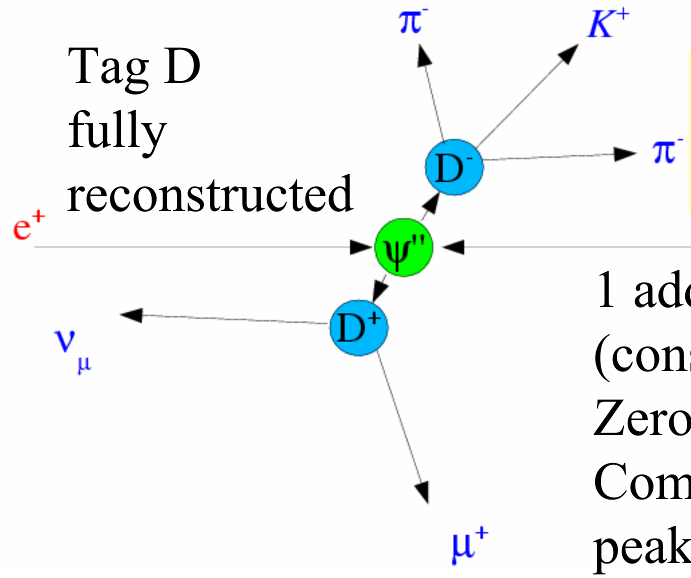
Lattice predicts f_B/f_D with a small errror

If a precision measurement of f_D existed (it does not)

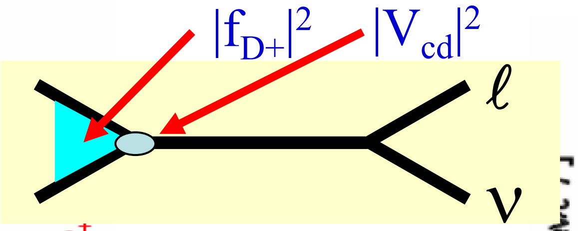
→Precision Lattice estimate of f_B → precision determination of V_{td}

Similarly f_D/f_{Ds} checks f_B/f_{Bs} → precise $|V_{td}|/|V_{ts}|$ once B_s mixing seen

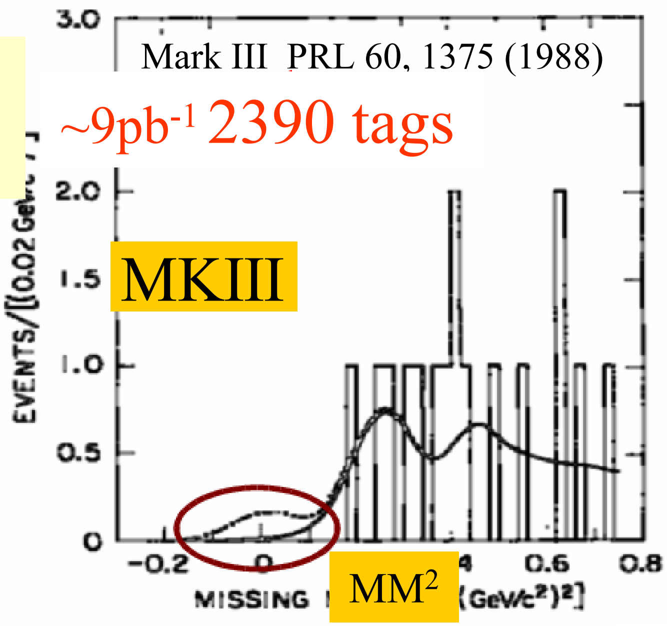
f_{D+} from Absolute Br($D^+ \to \mu^+\nu$) at $\psi(3770)$



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

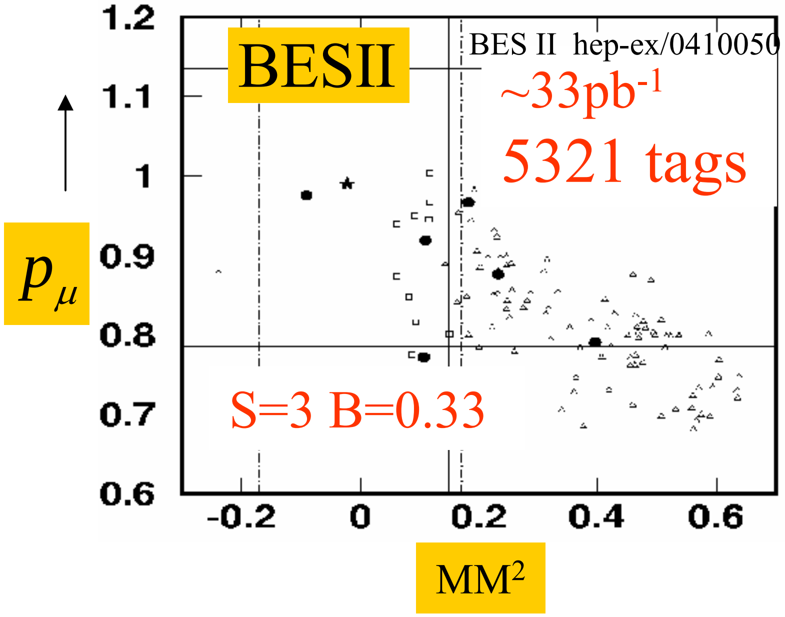
MKIII

MM^2

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

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

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



BESII

BES II hep-ex/0410050

~33pb^{-1}

5321 tags

S=3 B=0.33

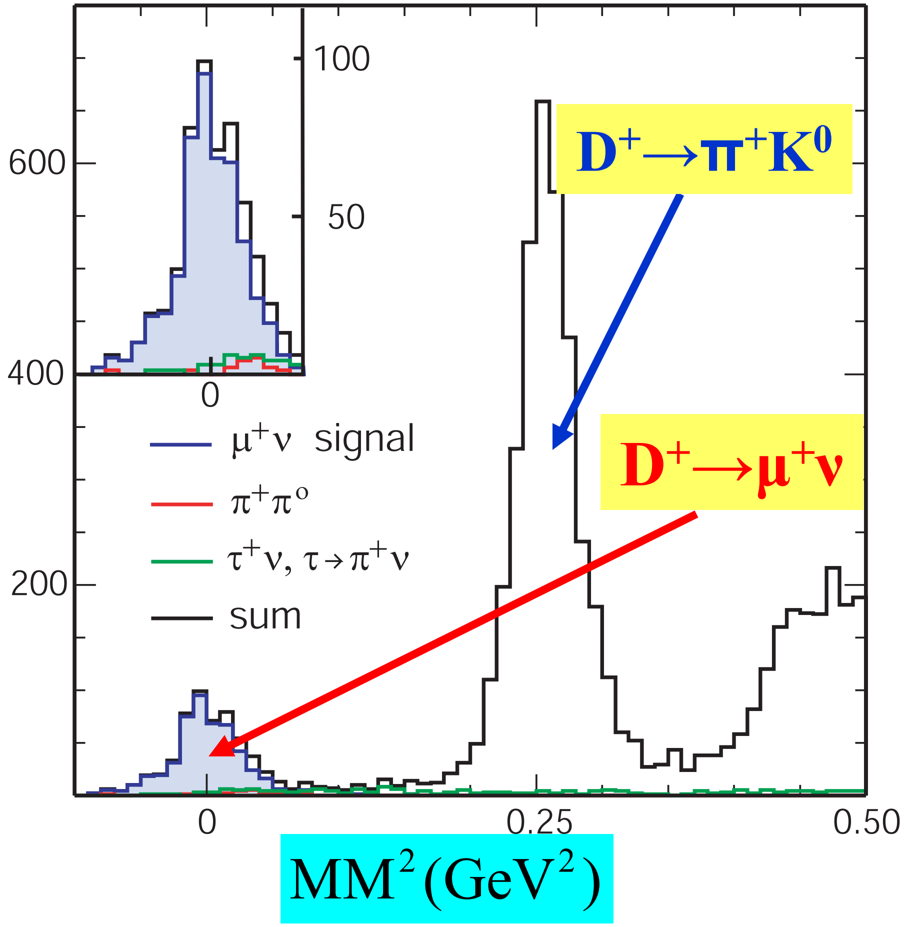
MM^2

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

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

$$\delta MM^2 \sim M^2_{\pi 0}$$

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

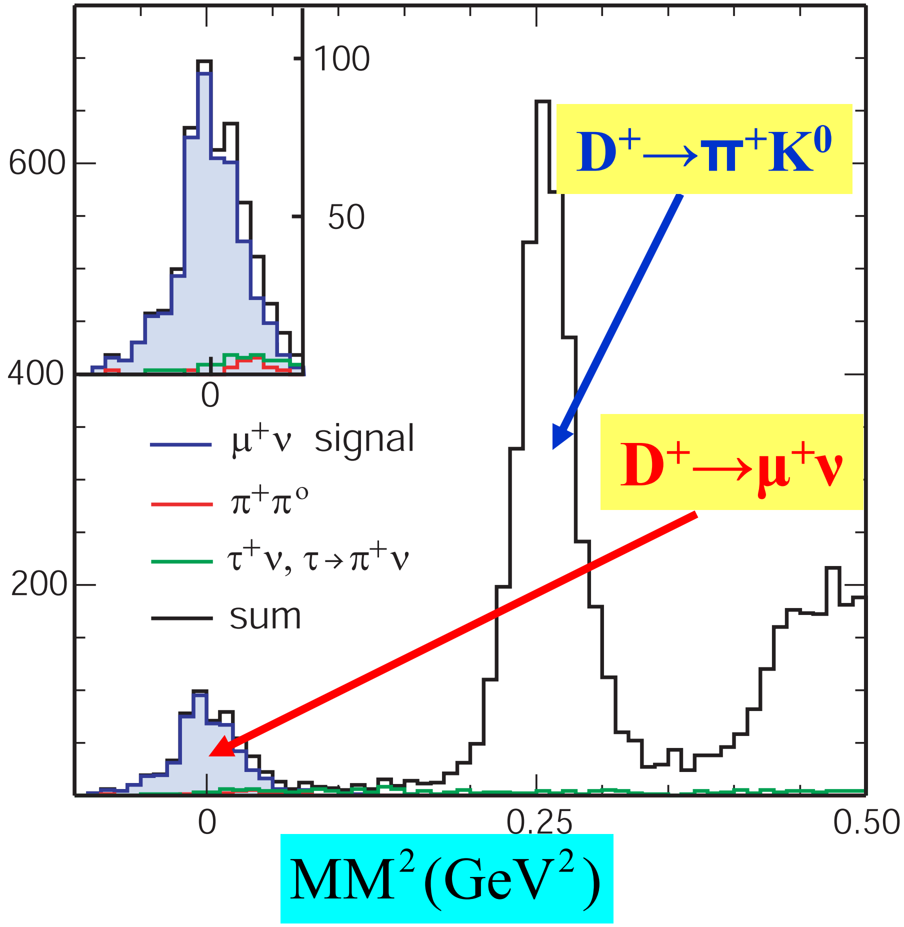


f_{D+} from Absolute Br($D^+ \to \mu^+\nu$)

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

$$\delta MM^2 \sim M^2_{\pi 0}$$

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



CLEO analysis was to be unveiled
at LP05
2 days before LP05
1st full unquenched lattice calc.
a prediction

$$f_{D^+} = (201 \pm 3 \pm 17)\ \text{MeV}$$

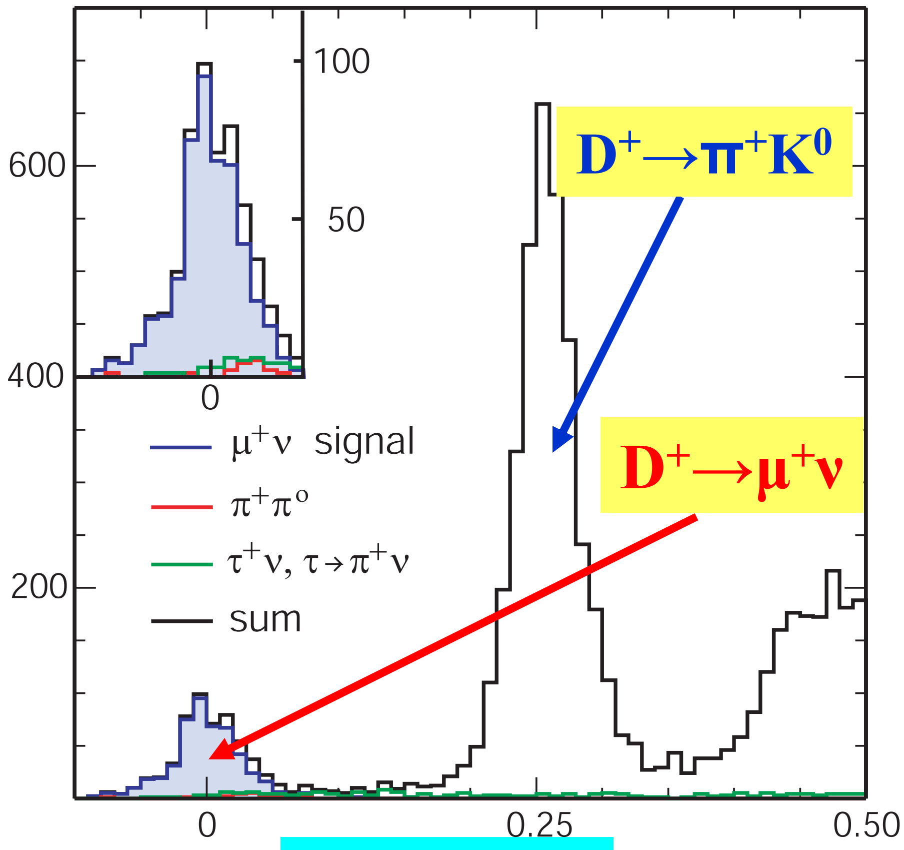
f_{D+} from Absolute Br($D^+ \to \mu^+\nu$)

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

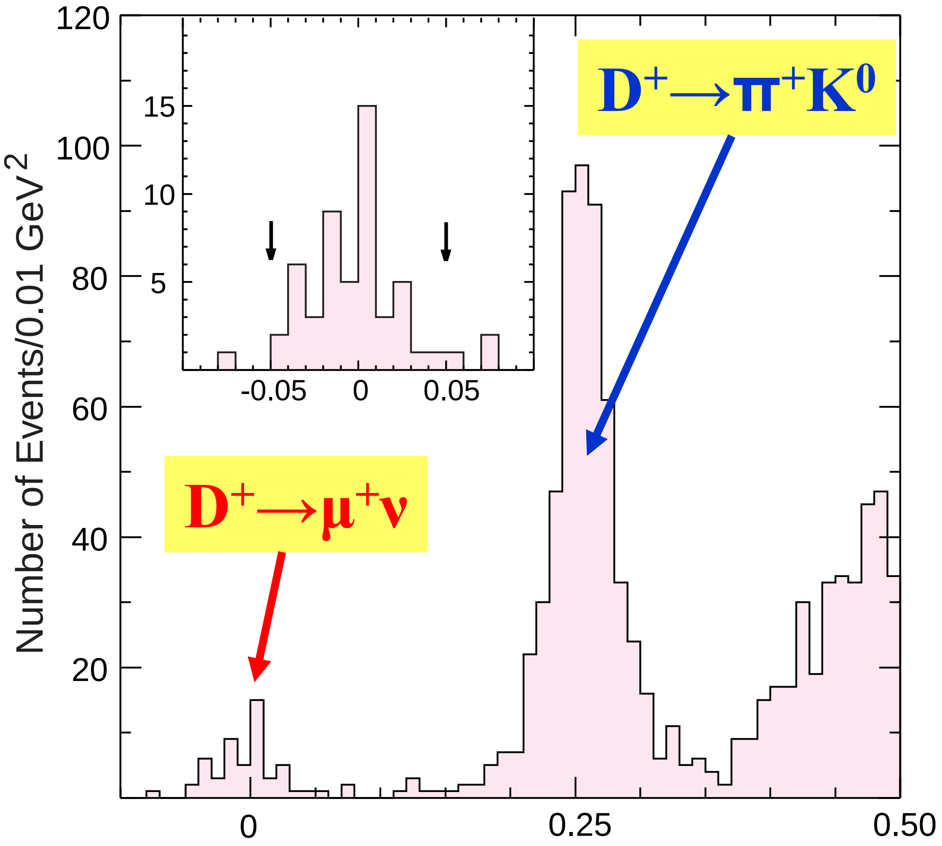
281 pb^{-1} at $\psi(3770)$

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

50 signal events



$MM^2(GeV^2)$



$MM^2(GeV^2)$

$$\delta MM^2 \sim M_{\pi 0}^2$$

f_{D+} from Br($D^+ \rightarrow \mu^+\nu$) & theory comparison

Tags 158,354

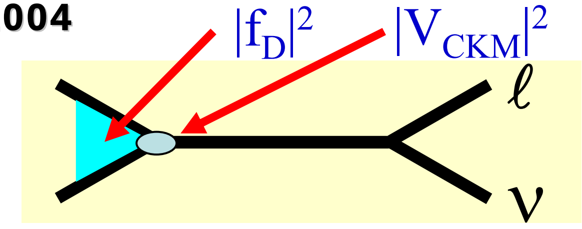
Signal 50 events ε=69.9%

Bkgd $2.81 \pm 0.30^{+0.84}_{-0.22}$ events

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

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

PRD 70, 112004



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

V_{cd} (known to <1%) unitarity

τ_{D+} well-measured (0.3%)

f_{D+} from $Br(D^+ \to \mu^+\nu)$ & theory comparison

Tags 158,354

Signal 50 events ε=69.9%

Bkgd $2.81 \pm 0.30^{+0.84}_{-0.22}$ events

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

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

1st full unquenched lattice calc.(201±3±17) MeV
a prediction (2 days before LP03)

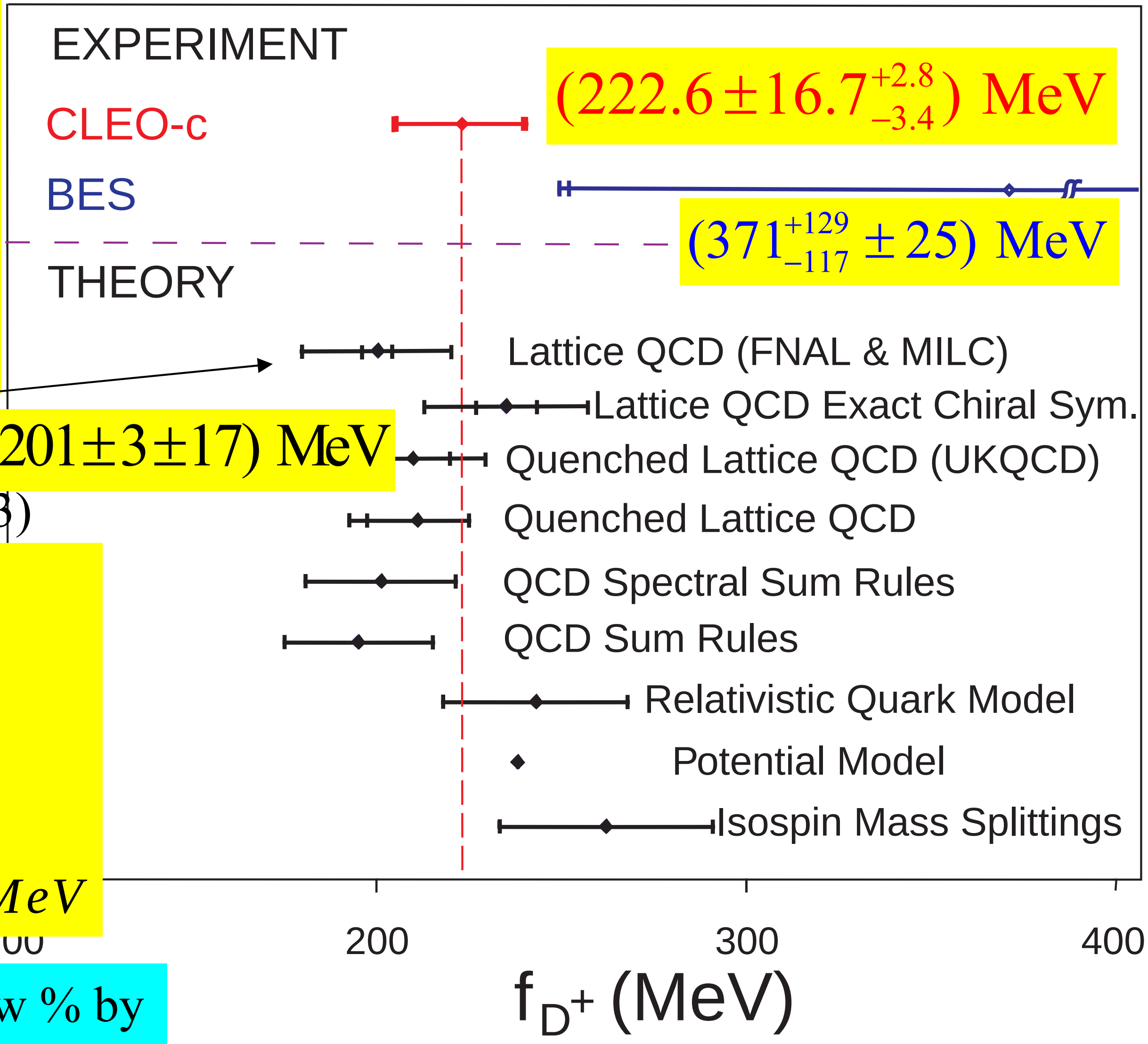
Expt/LQCD consistent

Now: CLEO-c error 8%

LQCD error 8%

with 0.75fb^{-1} : f_{D+} to 4.5%

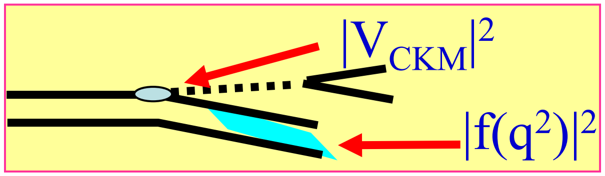
f_{Ds} to ~4.5% @ $\sqrt{s} \sim 4170 MeV$



Need LQCD predictions to few % by 2007 f_{D+} & f_{Ds} (see Trottier talk for important development)

f_B / f_D for V_{td} from B mixing

Importance of *Absolute* Charm Semileptonic Decay Rates



1 Charm semileptonic decays determine Vcs and Vcd

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

2 *Test theoretical calculations of form factors* $|V_{cd}|$ known from unitarity to 1%

3 Input to Vub from exclusive semileptonic B 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

$BABAR / Belle / CLEO$

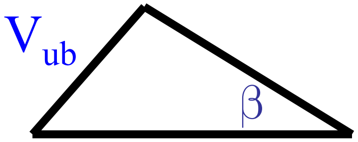
(World Average BF Summer 2005)

Expt. 4%

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

form factor

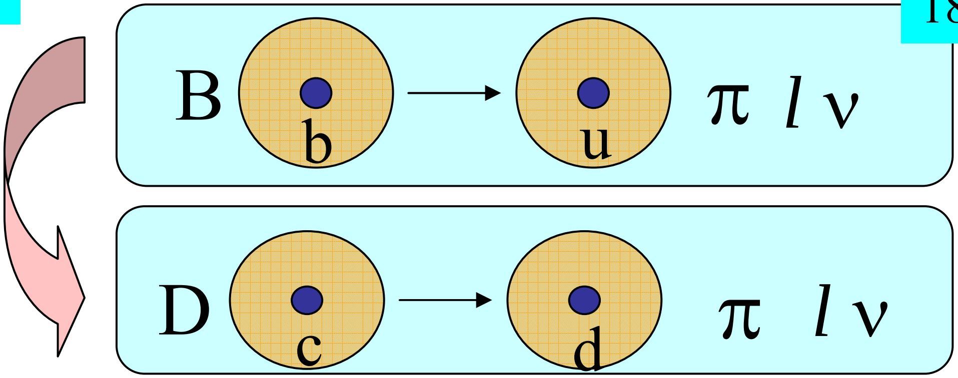
Typical Theory Error 18% hep-lat/0409116



HQS

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

PDG04



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

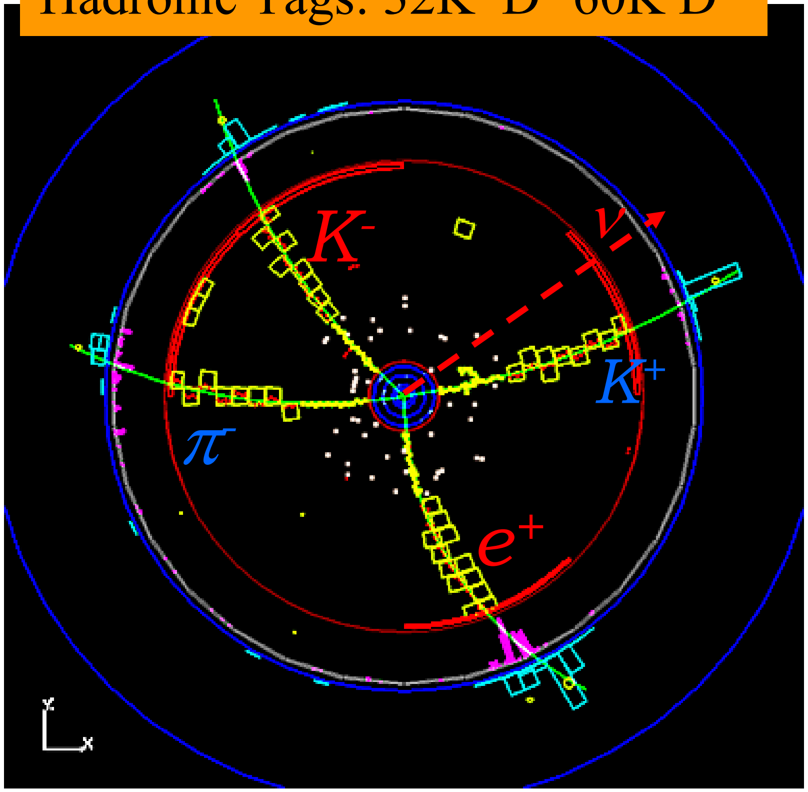
2) BaBar/Belle can extract V_{ub} using *tested* LQCD calc. of B→π form factor.

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

Absolute Branching Ratios of Semileptonic Decays at ψ(3770) 56pb^{-1}

Hepex
/0506053
&0506052
PRL 95
181802
(2005)
PRL 95
181801
(2005)

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



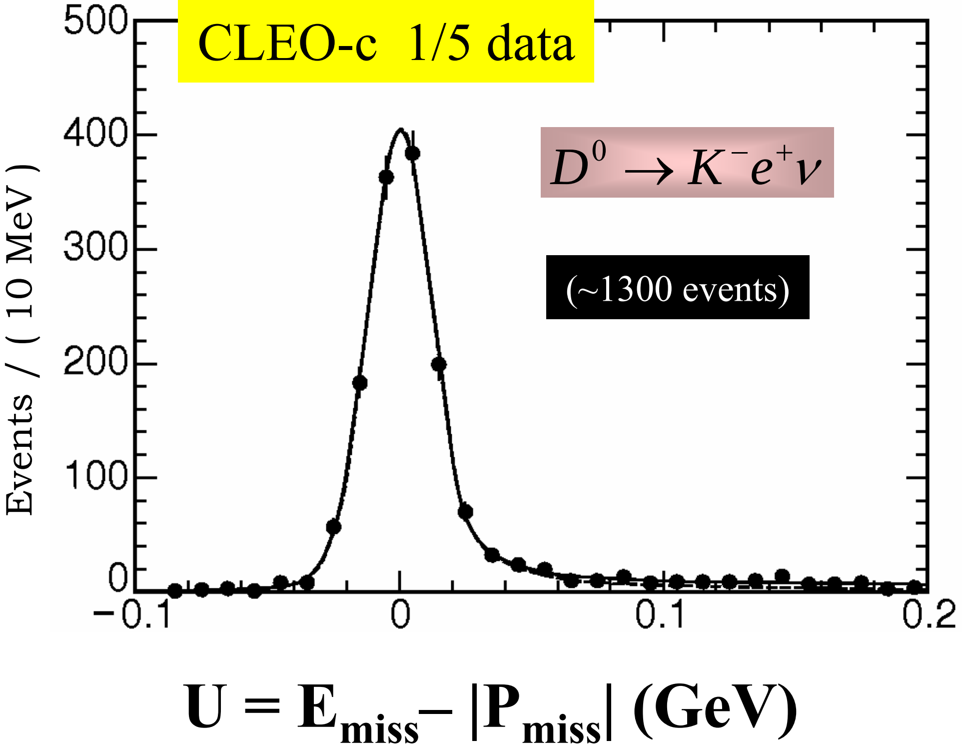
$$\psi(3770) \rightarrow D^0 \overline{D^0}$$

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

Tagging creates a single D beam of known 4-momentum

Semileptonic decays are reconstructed with *no* kinematic ambiguity

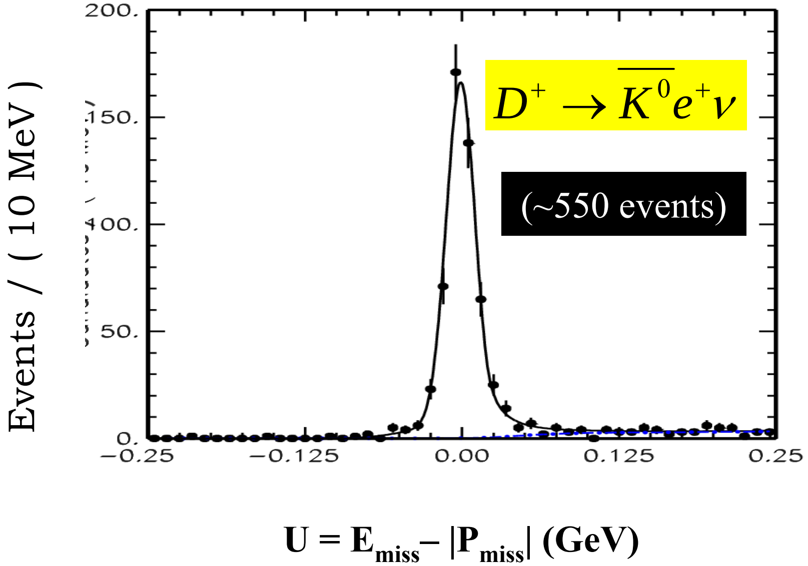
$$U \equiv E_{miss} - |\vec{p}_{miss}| = 0$$



More Cabibbo allowed modes

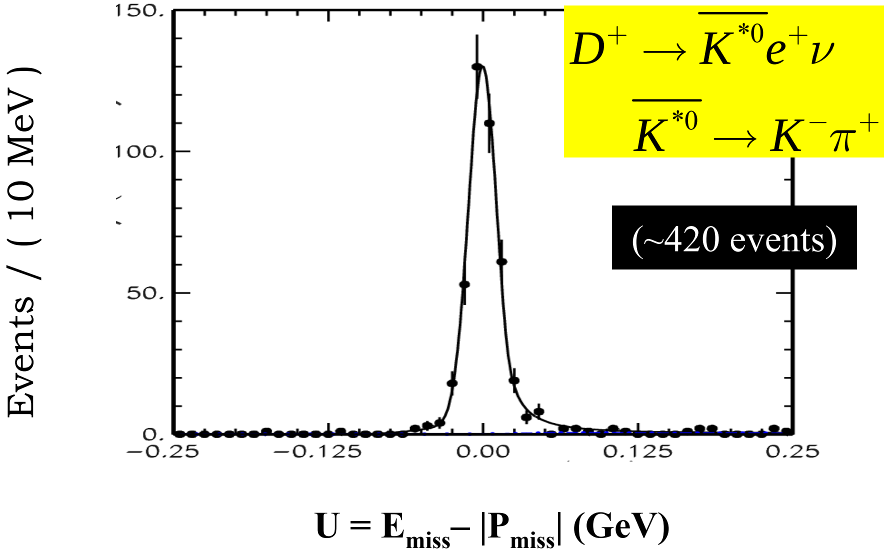
$c \rightarrow s$ Cabibbo Favored

56 pb^{-1} Data



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

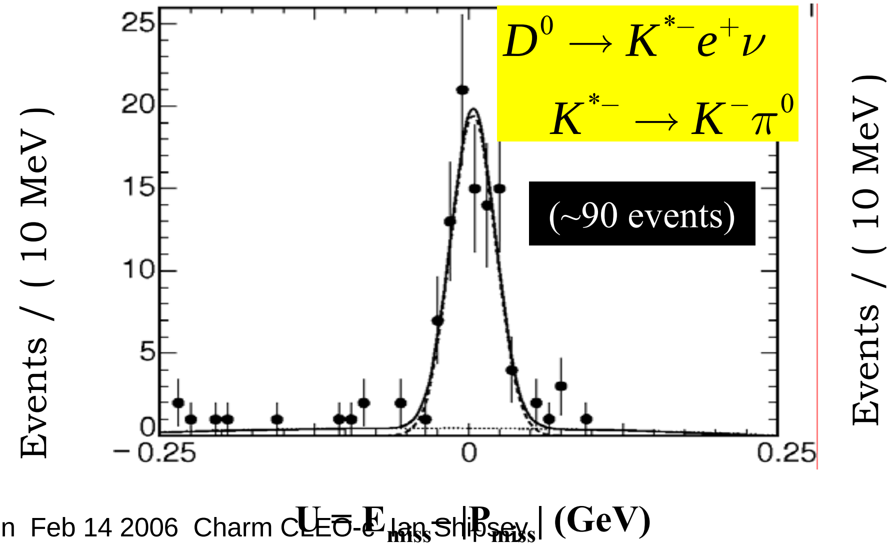
(~550 events)



$D^+ \rightarrow \overline{K^{*0}} e^+ \nu$

$\overline{K^{*0}} \rightarrow K^- \pi^+$

(~420 events)



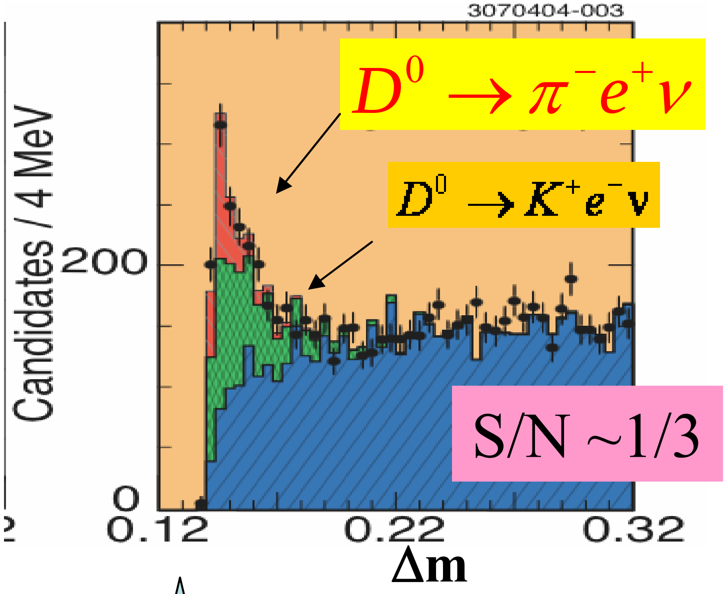
$D^0 \rightarrow K^{*-} e^+ \nu$

$K^{*-} \rightarrow K^- \pi^0$

(~90 events)

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

Cabibbo suppressed modes



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

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

S/N ~1/3

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

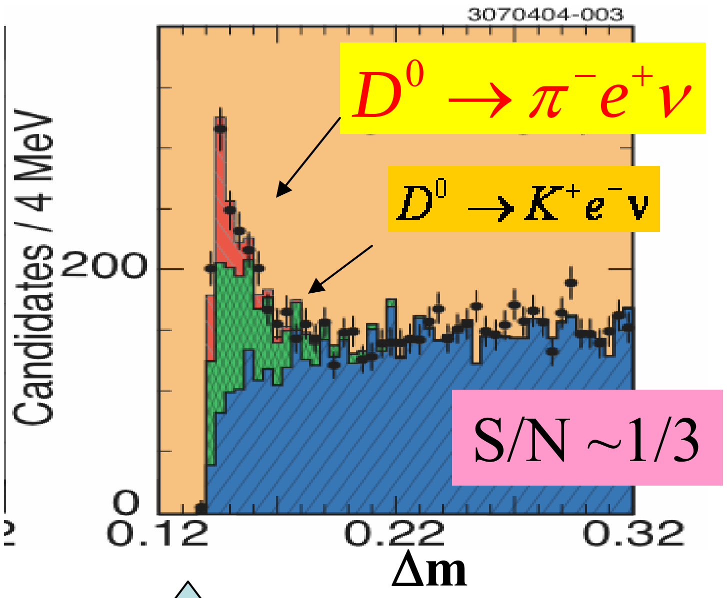
$D^0 \to \pi^+ \ell^- \nu$

$observable:$

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

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

Cabibbo suppressed modes

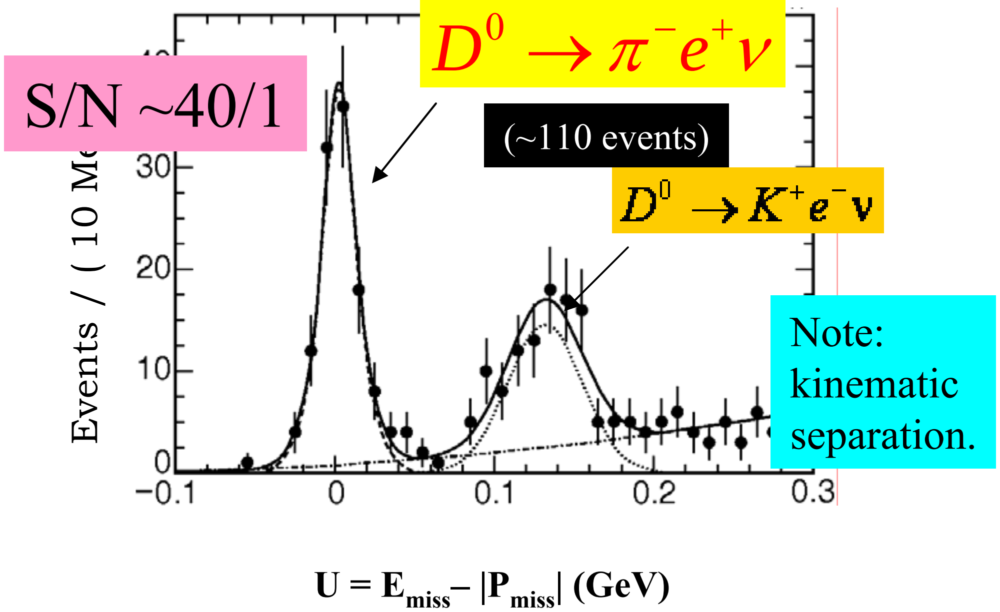


$D^0 \to \pi^- e^+ \nu$

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

S/N ~1/3

56 pb^{-1} Data



S/N ~40/1

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

(~110 events)

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

Note: kinematic separation.

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

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

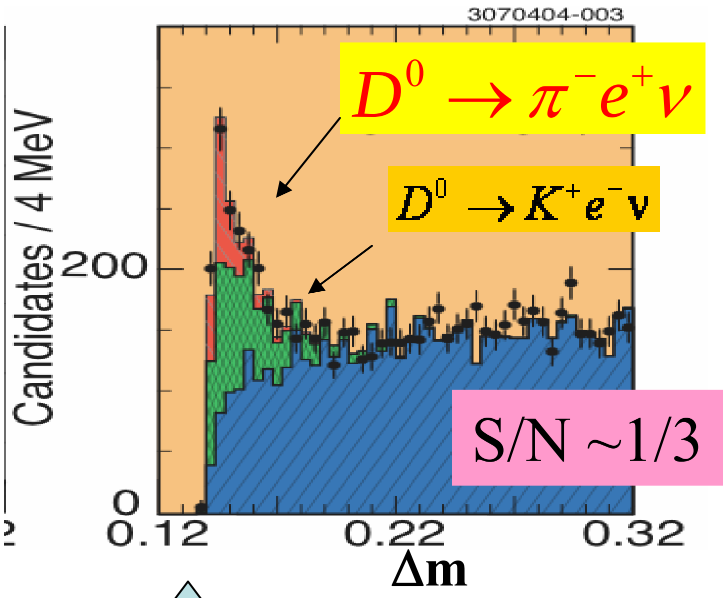
observable :

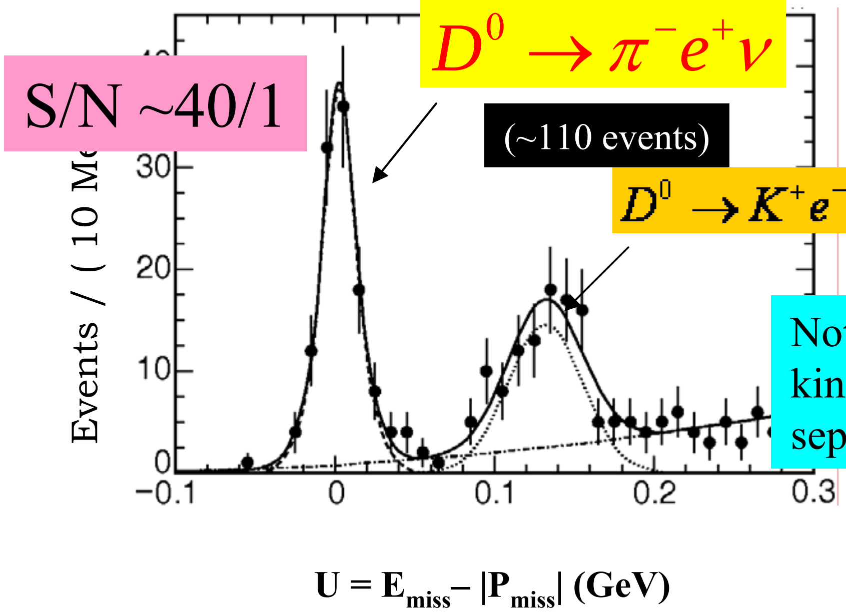
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

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

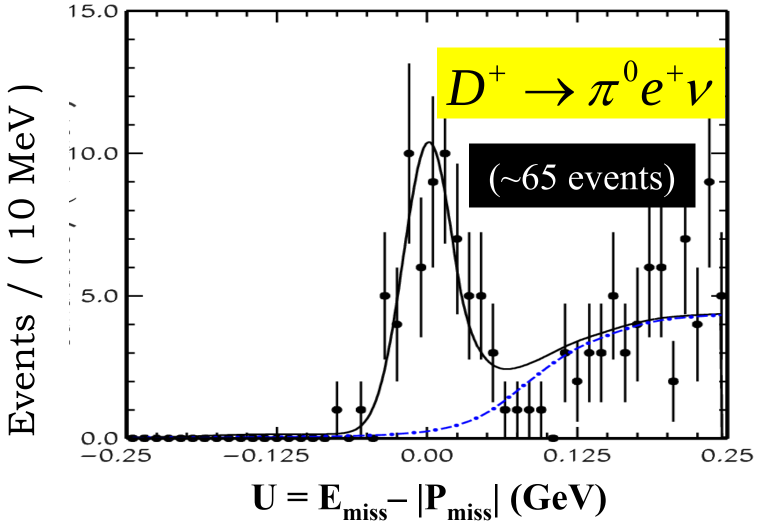
Cabibbo suppressed modes

56 pb^{-1} Data





Note: kinematic separation.



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

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

observable:

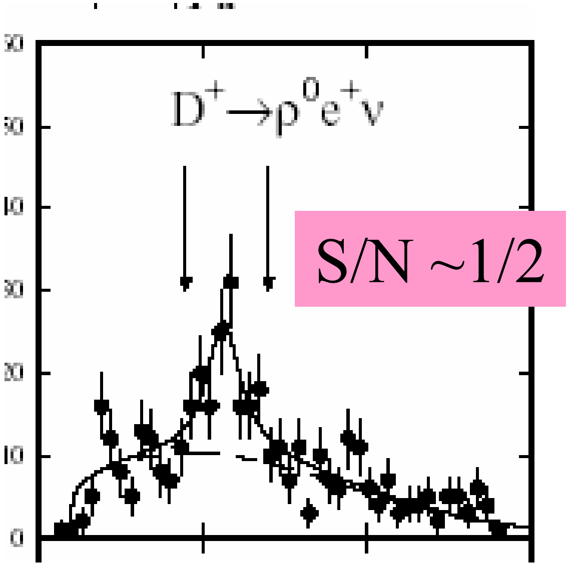
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

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

More Cabibbo supressed modes

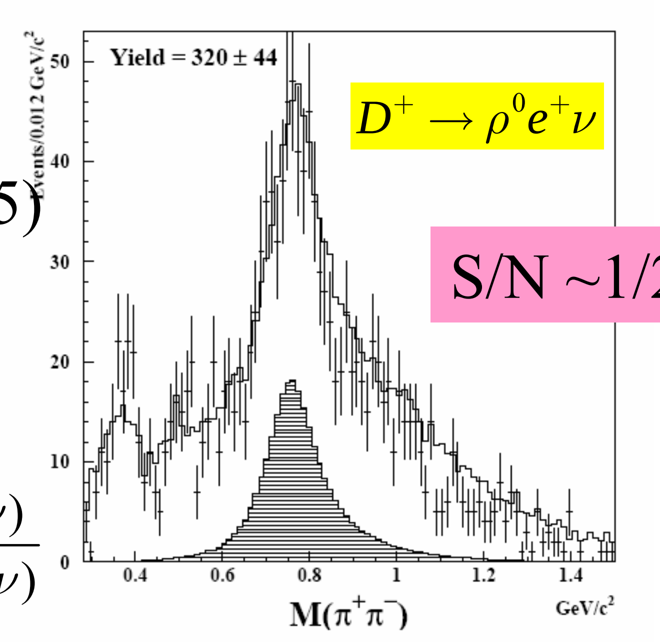
Only measurements
untl now

E791
PLB 397
325
(1997)



S/N ~1/2

FOCUS
Hep-ex
/0511022
(Nov 2005)



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

S/N ~1/2

Relative
Rate:

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

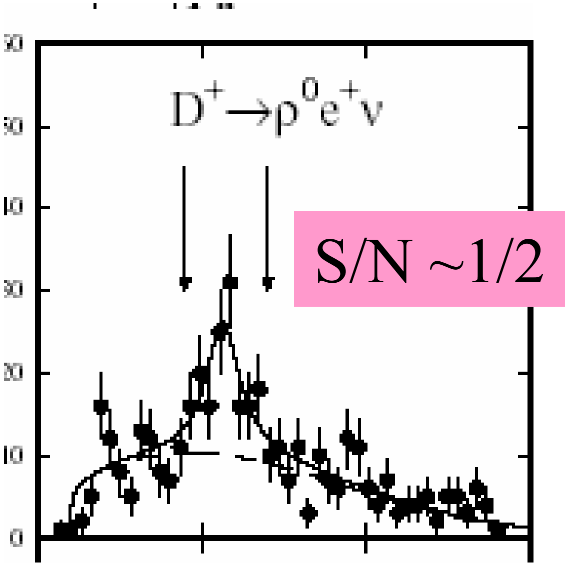
More Cabibbo supressed modes

56 pb^{-1} Data

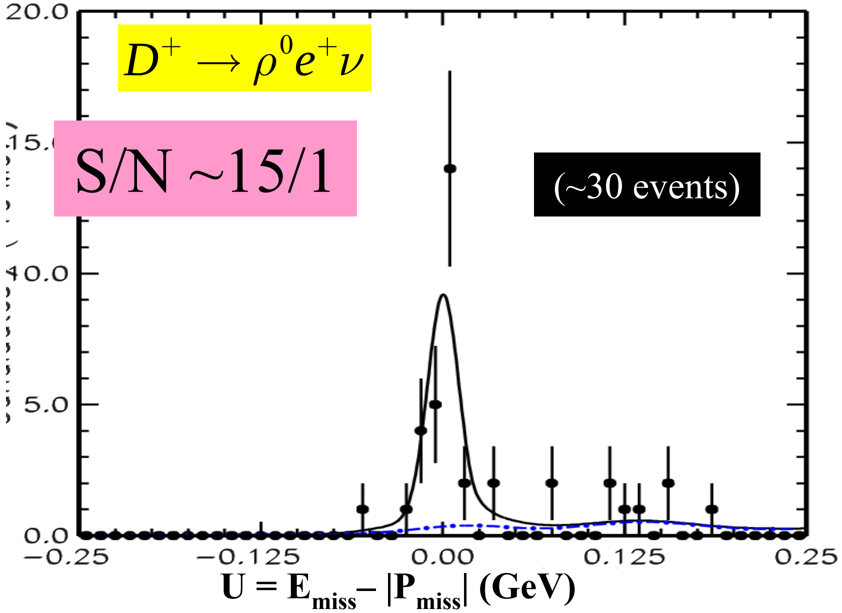
Only measurements untl now

E791

PLB 397 325 (1997)



S/N ~1/2

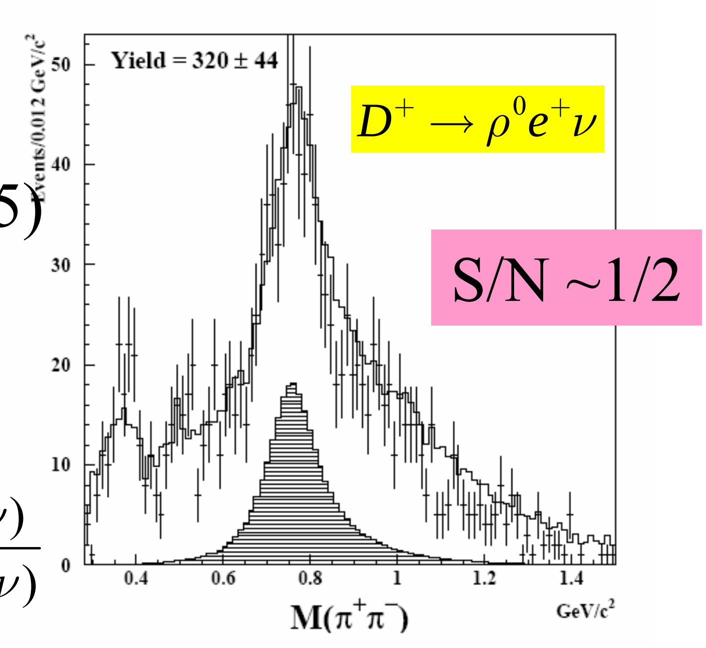


S/N ~15/1

(~30 events)

FOCUS

Hep-ex /0511022 (Nov 2005)



S/N ~1/2

Relative Rate:

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

More Cabibbo supressed modes

56 pb^{-1} Data

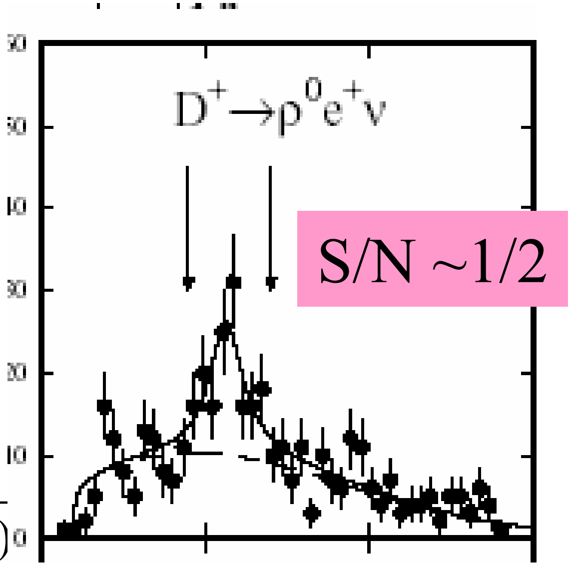
Only measurement
untl now

E791

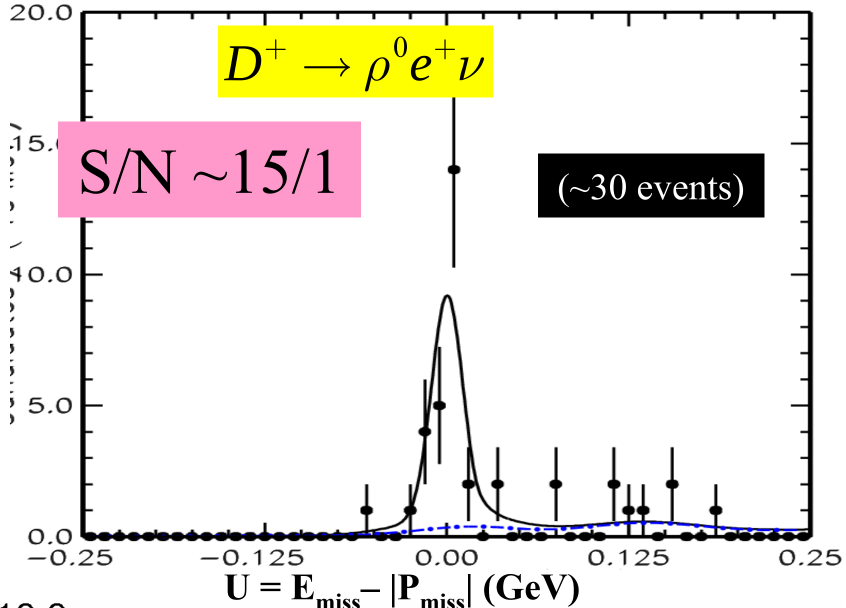
PLB 397
325
(1997)

Relative rate:

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



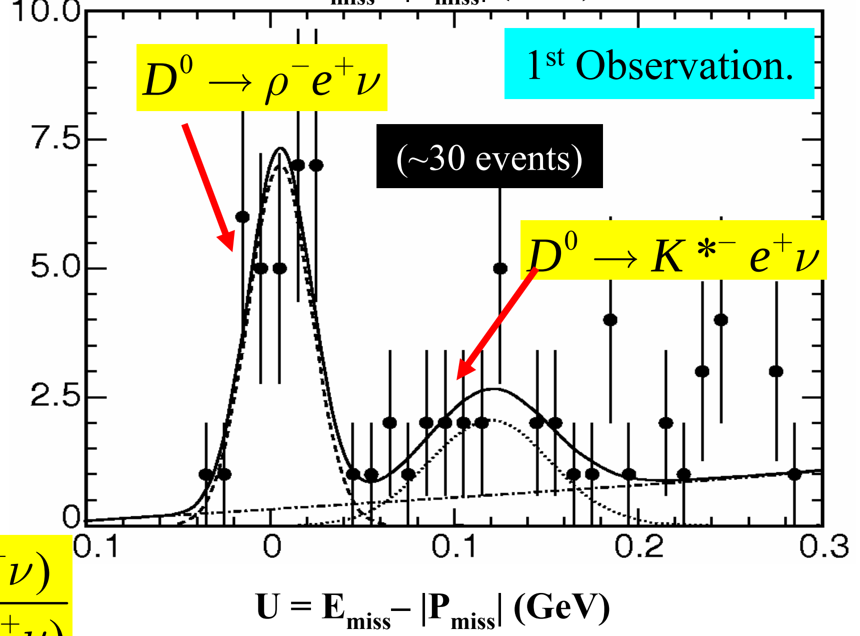
S/N ~1/2



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

S/N ~15/1

(~30 events)



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

1st Observation.

(~30 events)

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

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

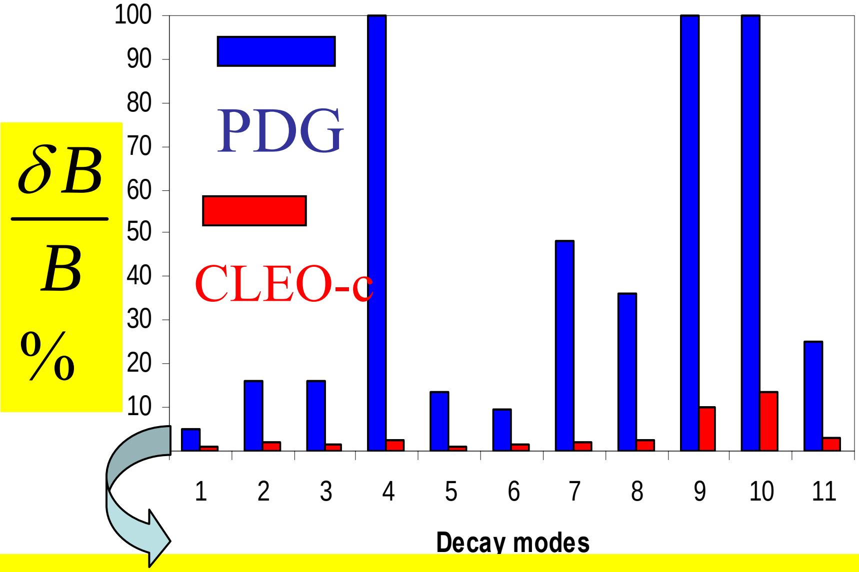
$$\frac{\Gamma(B \to \rho\, e^+ \nu)}{\Gamma(B \to K^* \ell\ell)} / \frac{\Gamma(D \to \rho e^+ \nu)}{\Gamma(D \to K e^+ \nu)}$$

Results

PRL 95 181802 (2005)
PRL 95 181801 (2005)

(Similar analysis but less precise from BES II)

Full data set dB/B to 1% for Kev syst. limited, and 2% for pi e v stat. limited



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

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

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

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

5 : $D^+ \to \overline{K}^0 e^+ \nu$

6 : $D^+ \to \overline{K}^{0*} e^+ \nu$

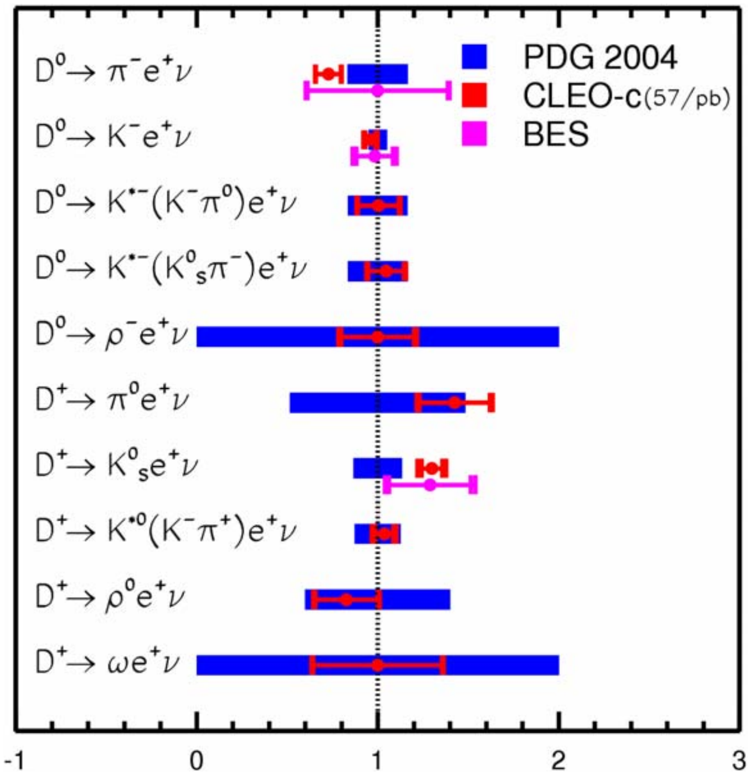
7 : $D^+ \to \pi^0 e^+ \nu$

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

9 : $D_s \to K^0 e^+ \nu$

10 : $D_s \to K^{*0} e^+ \nu$

11 : $D_s \to \phi \;\; e^+ \nu$

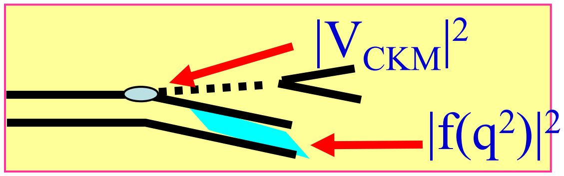


Normalized to PDG

CLEO-c already all modes more precise than PDG.

significant improvements in the precision with which each absolute charm semileptonic branching ratio is known

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

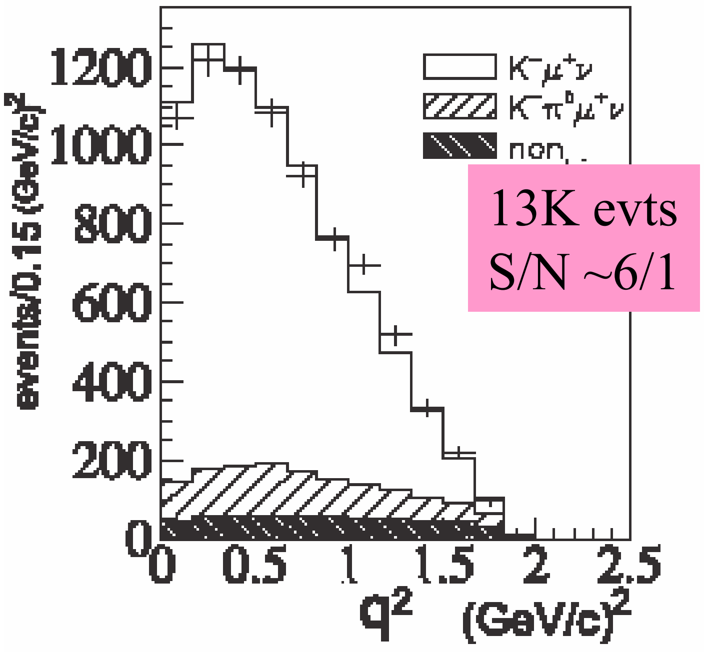


$Tag \quad with \ D^{*+} \to D^0 \pi_s$

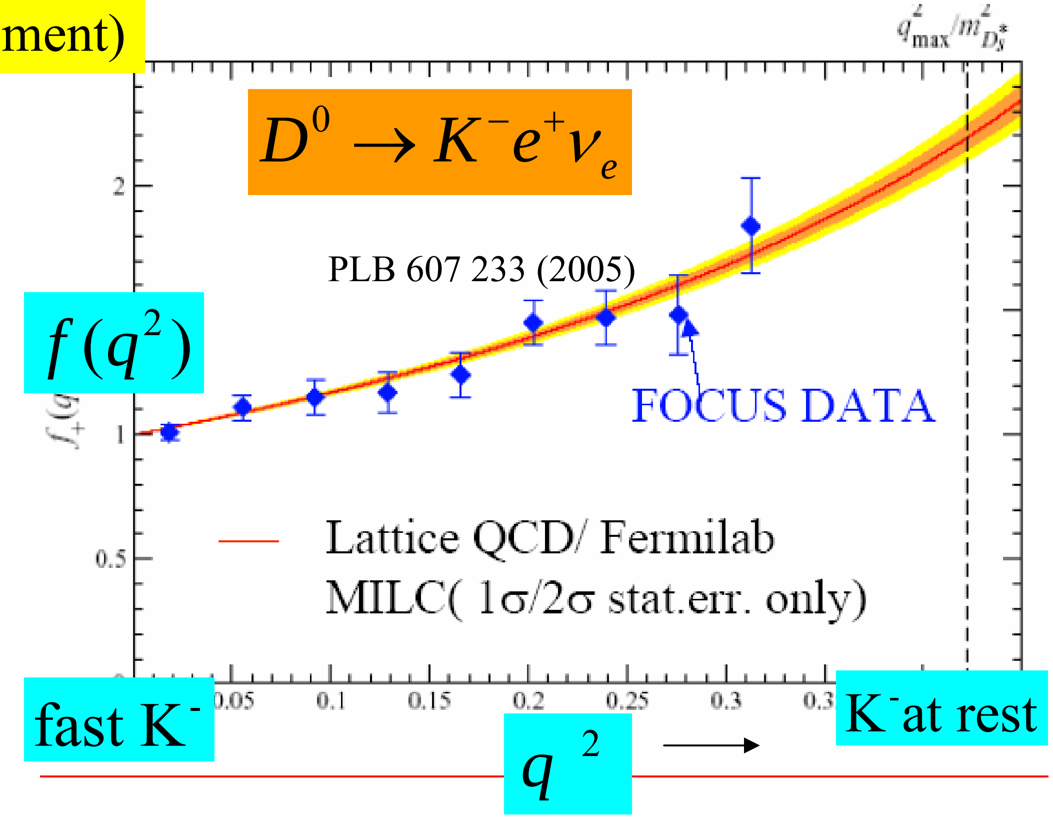
$D^0 \to K^+ \ell^- \nu$

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

FOCUS all data
(best measurement)



13K evts
S/N ~6/1



Impressive work by FOCUS.

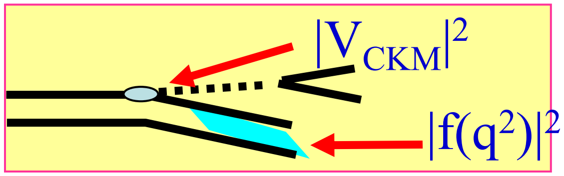
LQCD : shape ~ correct:

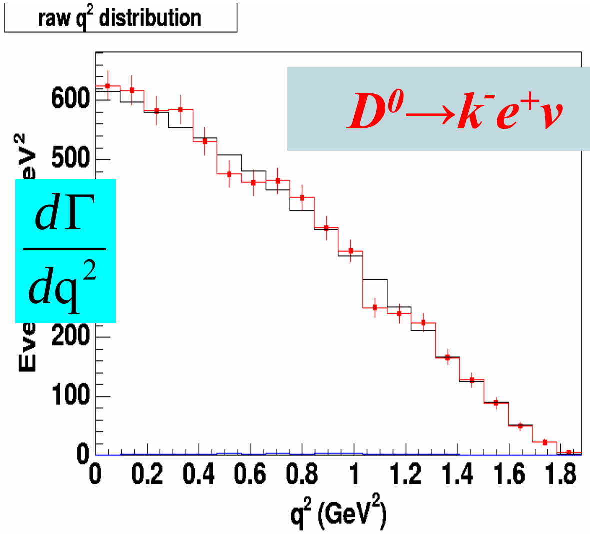
$$f_+(x) = f_+(0)\left(\frac{1}{(1-q^2/m^2_{D_s^*})}\frac{1}{(1-\alpha q^2/m^2_{D_s^*})}\right)$$

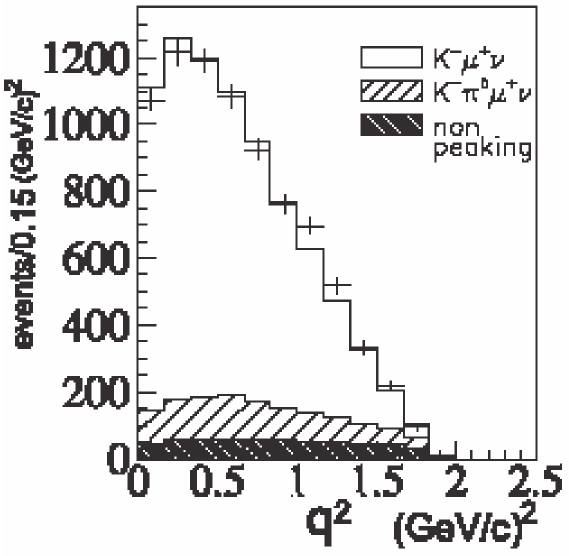
The form factor $\frac{d\Gamma}{dq^2} \propto |V_{cs}|^2 |f_+^{D\to K}(q^2)|^2$

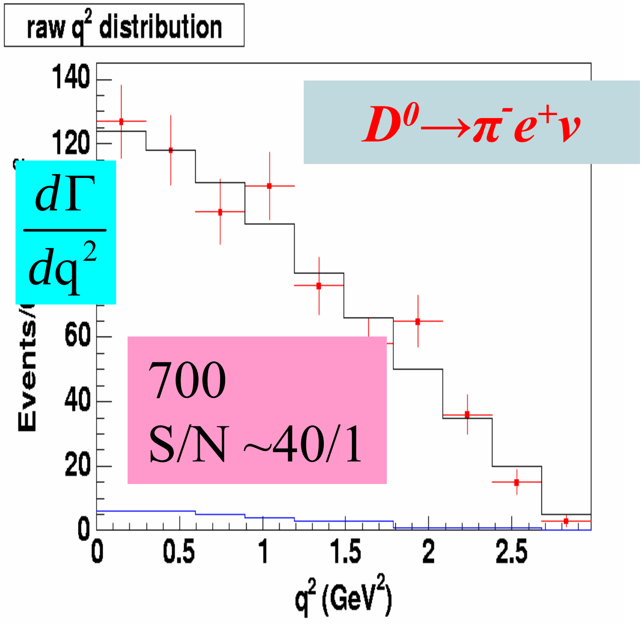
CLEO-c (preliminary)

FOCUS all

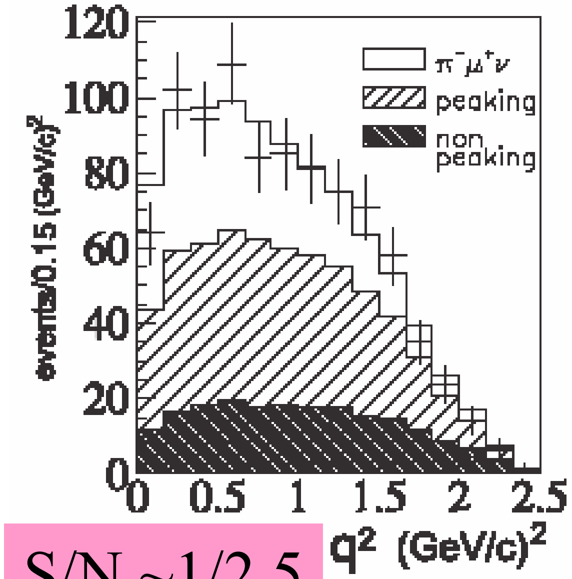








700
S/N ~40/1



S/N ~1/2.5

CLEO-c 7.2 K evts (280/pb)
S/N >300/1

FOCUS 13K evts
S/N ~6/1

CLEO-c: threshold advantage
1) Low background crucial for π final state
2) neutrino direction known

$\frac{\delta q^2}{q^2} \sim 0.1\ \text{GeV}^2$ FOCUS

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

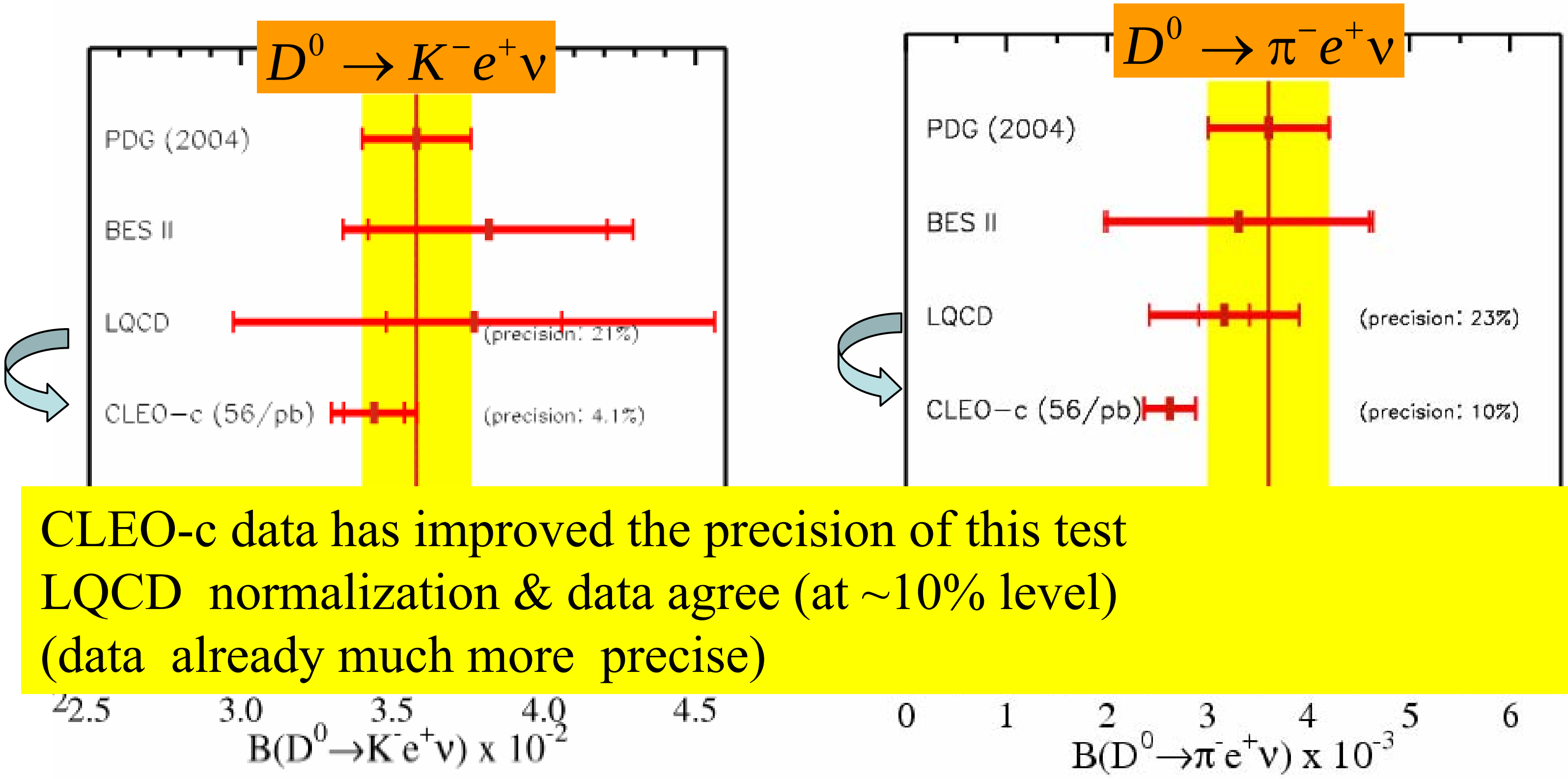
CLEO-c shape results soon.
D→Kev: precision>LQCD
D→pi ev: X3 more precise than previous expt

Lattice comparison: the form factor normalization

Lattice shape: agreed with data, predicted branching fraction tests normalization

$$f_+^{D\to K}(q^2) = f_+(0)\left(\frac{1}{(1-q^2/m^2_{D_s^*})}\,\frac{1}{(1-\alpha q^2/m^2_{D_s^*})}\right)$$

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



(for lattice use PDG Vcs, Vcd)

CLEO-c data has improved the precision of this test
LQCD normalization & data agree (at ~10% level)
(data already much more precise)

Early look: V_{cs} & V_{cd} with CLEO-c data

(My estimates not official CLEO-c)

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

Expt

LQCD

LQCD errors (10%) dominate.

Expt. errors
Vcs ~2%
Vcd~4%

Vcs=0.957±0.017(expt.)±0.093(th.)
Vcd=0.213 ± 0.008(expt) ± 0.021(th.)

Vcs=0.9745±0.0008 (unitarity)
Vcd=0.2238±0.0029 (unitarity)

Agrees with unitarity

The most precise Vcs and Vcd to date using semileptonic decays, but not yet competitive with:

V_{cs} (W→cs, LEP) = 0.976±0.014
V_{cd}(νN) = 0.224±0.012
Currently the CLEO-c data checks lattice calculations

More Lattice checks: f_D & semileptonic form factors

A quantity independent of Vcd allows a CKM independent lattice check:

Experiment

$$R_{\ell s\ell} = \sqrt{\frac{\Gamma(D^+ \to \mu\nu)}{\Gamma(D \to \pi\ell\nu)}} = \frac{f_{D^+}}{f_+^{D\to\pi}(0)}$$

Lattice

(My estimate):

$$R_{\ell s\ell}^{th} = 0.22 \pm 0.03$$

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

~10% uncertainty

Theory & data consistent @ the 28% CL:

With 0.75fb^{-1} @ ψ(3770) R_{lsl}^{exp} ~5% uncertainty

Ultimate precision?

Full data set

$$D \to Ke^+\upsilon \quad \frac{\delta Vcs}{Vcs} = 0.8\% \oplus \frac{\delta Theory}{Theory}$$

(Now 1.3%)

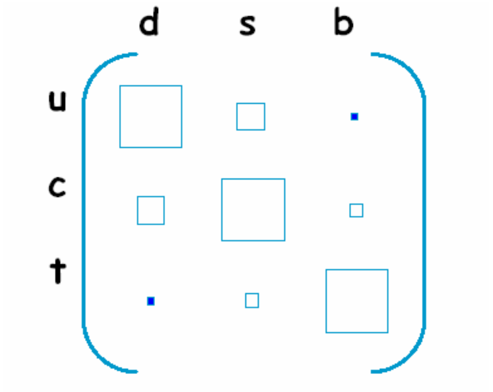
$$D \to \pi e^+\upsilon \quad \frac{\delta Vcd}{Vcd} = 1.6\% \oplus \frac{\delta Theory}{Theory}$$

(Now 5.4%)

Tested lattice for Vub determination at B factories

Unitarity Tests Using Charm

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

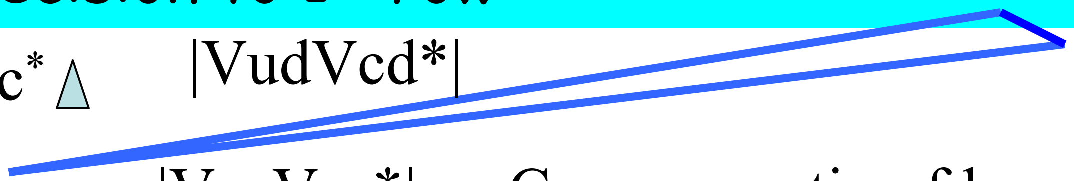


$uc^{*}=0$

- 2nd row: $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$??
  CLEO-c now: $|1- \{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^{2\}} = 0.037 \pm 0.181$
  CLEO-c/BESIII: test to few% (if theory D →K/πlν good to few %)
  & 1st column: $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$?? with similar precision to 1st row

  ($750 pb^{-1}$)

- uc^{*} Δ



Compare ratio of long sides to few %

Charm: Physics Beyond the Standard Model

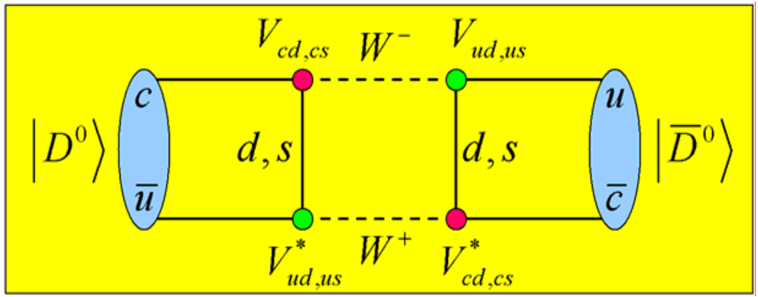
Can we find violations of the Standard Model at low energies?
Natural β Decay ➔ missing energy ➔ W (100 GeV) from experiments @ MeV scale.

CPV, mixing, rare decays ➔ sensitive to new physics at high mass scales through intermediate particles entering loops.

Why charm? D CPV/mix/rare small in SM ➔ low bkgd search for new physics

D^o-D^o Mixing

May proceed by:



CKM suppressed
Mix $\propto\Theta_c^2 \sim 0.05$
τ_D (V_{cs}~1)

- **d-type quarks in the loop ➔ D^o- D^o mixing *small*** compared to systems involving u-type quarks in the box diagram because those loops include 1 dominant heavy quark **(top):** example B^o (20%)
- New physics in loops implies x $\equiv\Delta M/\Gamma >>$ y $\equiv\Delta\Gamma/2\Gamma$;
- but long range effects complicate predictions x<0.1% y<1%

Smallness of Vbc and Vub limits b quark contribution ➔ D mixing is a 2 generation phenomenon ➔ no CPV in mixing, if seen →New Physics

D^0-D^{0bar} Mixing Limits Winter 2006

No sign of D mixing yet

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

Mixing paramters $x = \Delta m / \Gamma \quad y = \Delta\Gamma / 2\Gamma$

y CP eigentstate lifetimes $(K^- K^+, \pi^- \pi^+)$

Semileptonic unambiguous

unmix mix

$D^0 \to X \ell^- \nu \quad D^0 \to \overline{D^0} \to X \ell^+ \nu$

$\propto \frac{x^2 + y^2}{2} = R_{mix}$

wrong sign K π ambiguous

unmix mix

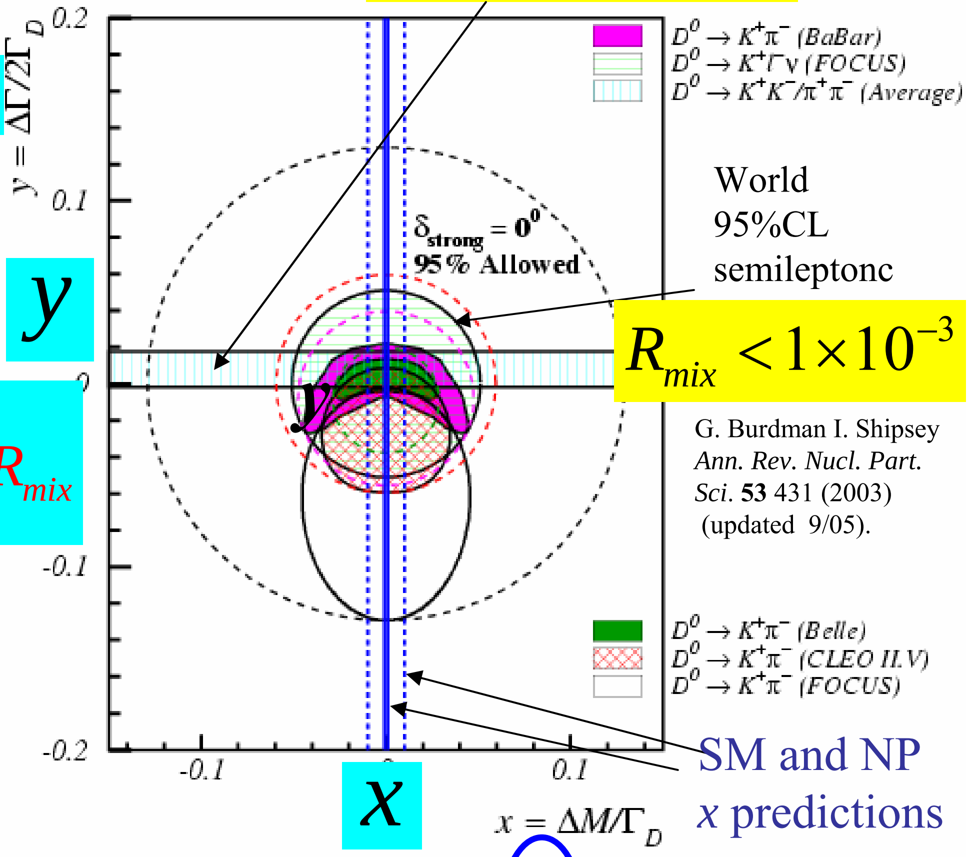
$D^0 \to K^- \pi^+ \quad D^0 \to \overline{D^0} \to K^+ \pi^-$

$\propto x^2 + y$

if CF/DCS

phase $\delta_{K\pi}$

known



y

x

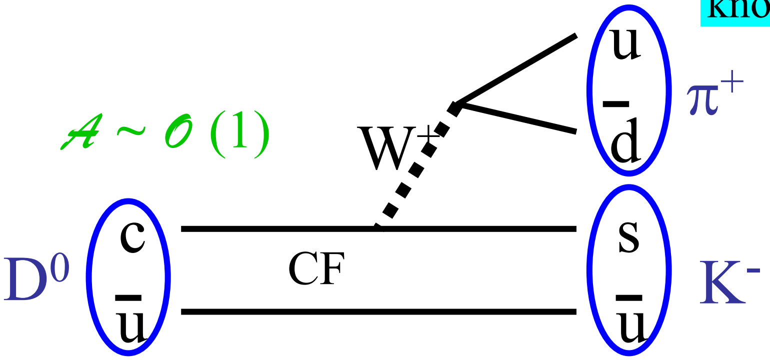
World
95%CL
semileptonc

$R_{mix} < 1 \times 10^{-3}$

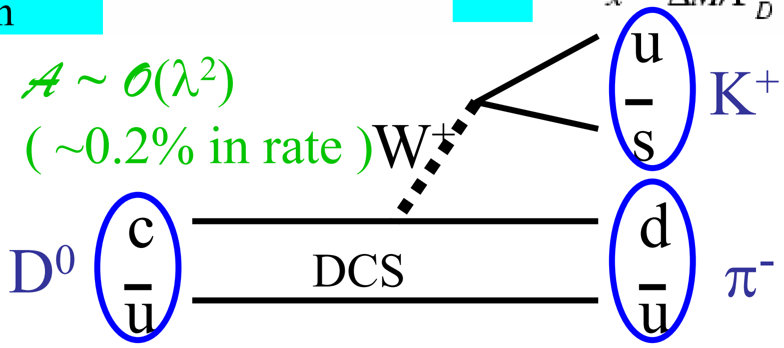
G. Burdman I. Shipsey
Ann. Rev. Nucl. Part. Sci. **53** 431 (2003)
(updated 9/05).

SM and NP
x predictions

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



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

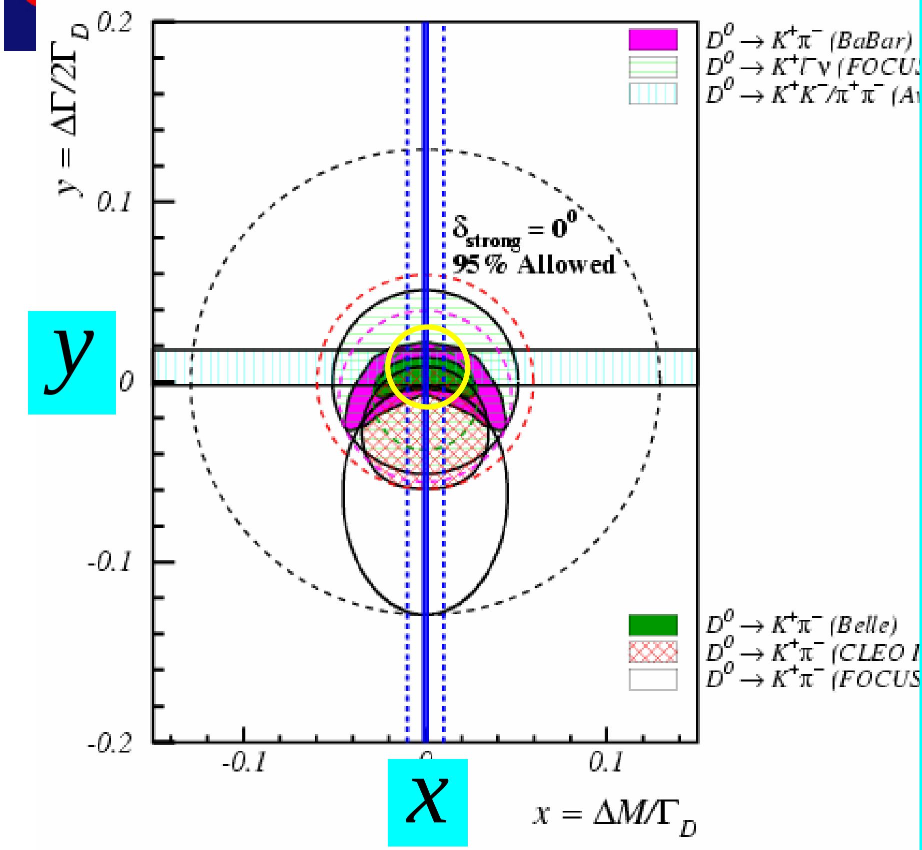


Mimics

$D^0 \to \overline{D^0}$

$\to K^+ \pi^-$

CLEO-c mixing (+ input to ϕ_3 /γ)



Mixing: $\psi(3770) \to D\overline{D}$ (C=-1)

Coherence simplifies study no DCSD

unmixed: $D^0 \to K^-\pi^+$ $\overline{D^0} \to K^+\pi^-$

mixed: $D^0 \to K^-\pi^+$ $\overline{D^0} \to D^0 \to K^-\pi^+$

can combine with $(K\ell\nu, K\ell\nu)$

Sensitivity 750/pb:

$R_{mix} < 1.4\times10^{-4}$ $now\ R_{mix} < 10^{-3}$

$(x < 1.7\%\ )$ $(x < 4\%\ )$

other techniques exist to determine x, y

(linear) sensitivty comparable to other expts.

different systematics (time independent)

- Mixing: BFac/Tevatron: $K^-\pi^+$ limited by unknown phase δ. CLEO-c can measure δ
- CP eigenstate tag X flavor mode

$K^+K^- \leftarrow D_{CP} \leftarrow \psi(3770) \to D_{CP} \to K^-\pi^+$ Δcosδ ±0.2

δ aids determination of γ [i.e. arg(Vub)] in B→DK @ BFact.

CP Violation at $\psi(3770)$

CP violation 3 types (1) mixing, (2) decay amplitude (direct) or interference between (1) & (2) But small D mixing ➔ best bet direct CP violation (A_{CP} ~0.001 SM, larger NP). Many limits from CDF/FOCUS/CLEOII/BABAR/BELLE A_{CP} <~1%)

@ 3770
Unique search strategy
Complementary to other expts.

$$e^+e^- \to \psi(3770) \to D^0D^0 \quad J^{PC} = 1^{--} \text{ i.e. CP+}$$

$$\mathrm{CP}(f_1\, f_2) = \underbrace{\mathrm{CP}(f_1)\ \mathrm{CP}(f_2)}_{-}\ \underbrace{(-1)^l}_{-\ (\text{since } l = 1)} = \mathrm{CP}+$$

CP conserving

$$\underset{+}{(\pi^+\pi^-)}\underset{+}{(\pi^+\pi^-)} \quad \underset{-}{(-1)^l} = CP-$$

CP violating

Sensitivity (two body final states)

- A_{cp} < 0.02 (CLEO-c full data set)
- <2 x10^{-3} (BESIII)

Limits and Eventual observation depends crucially on Ldt

Rare Charm Decays

FCNC in kaons → charm, B mixing → heavy top , FCNC in charm→ ??
Large suppression & difficult to predict in SM

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

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

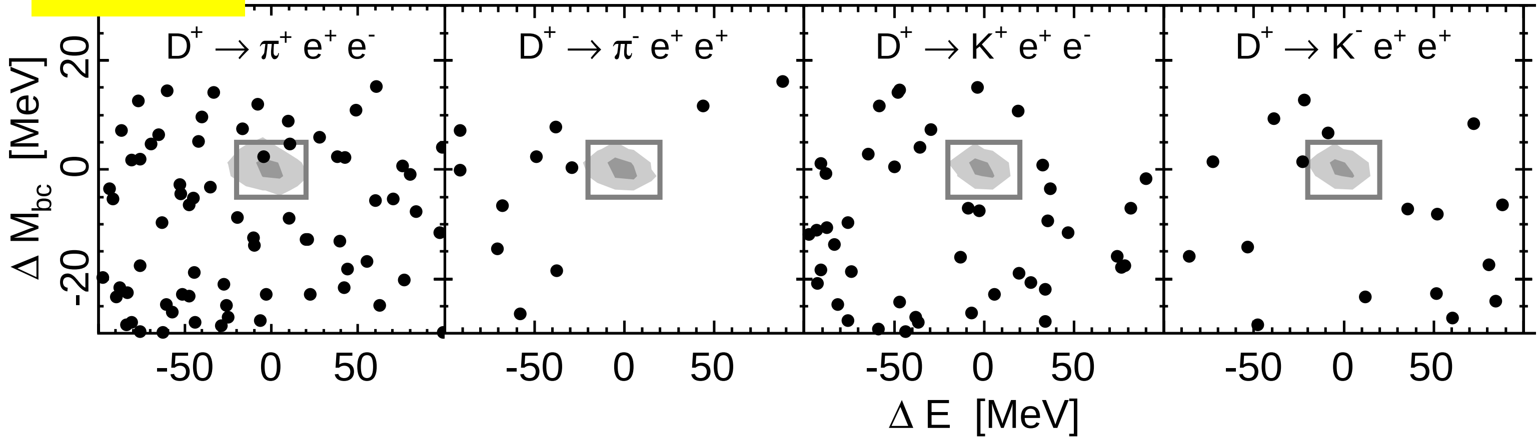
R-parity violating SUSY: $\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-) \sim 2.4 \times 10^{-6}$

Increase in rate small, but significant at low dilepton mass

Best limit CLEO II: $\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-) \sim 4.5 \times 10^{-5}$ ar 90%CL

CLEO-c

$$\Delta E = E_D - E_{beam} \qquad \Delta M_{bc} = \sqrt{(E^2_{beam} - p^2_D)} - M_D$$



No signal seen Results @90%CL Order of magnitude improvement

$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-) < 7.4 \times 10^{-6}$ $\mathcal{B}(D^+ \Rightarrow \pi^-e^+e^+) < 3.6 \times 10^{-6}$

$\mathcal{B}(D^+ \Rightarrow K^+e^+e^-) < 6.2 \times 10^{-6}$ $\mathcal{B}(D^+ \Rightarrow K^-e^+e^+) < 4.5 \times 10^{-6}$

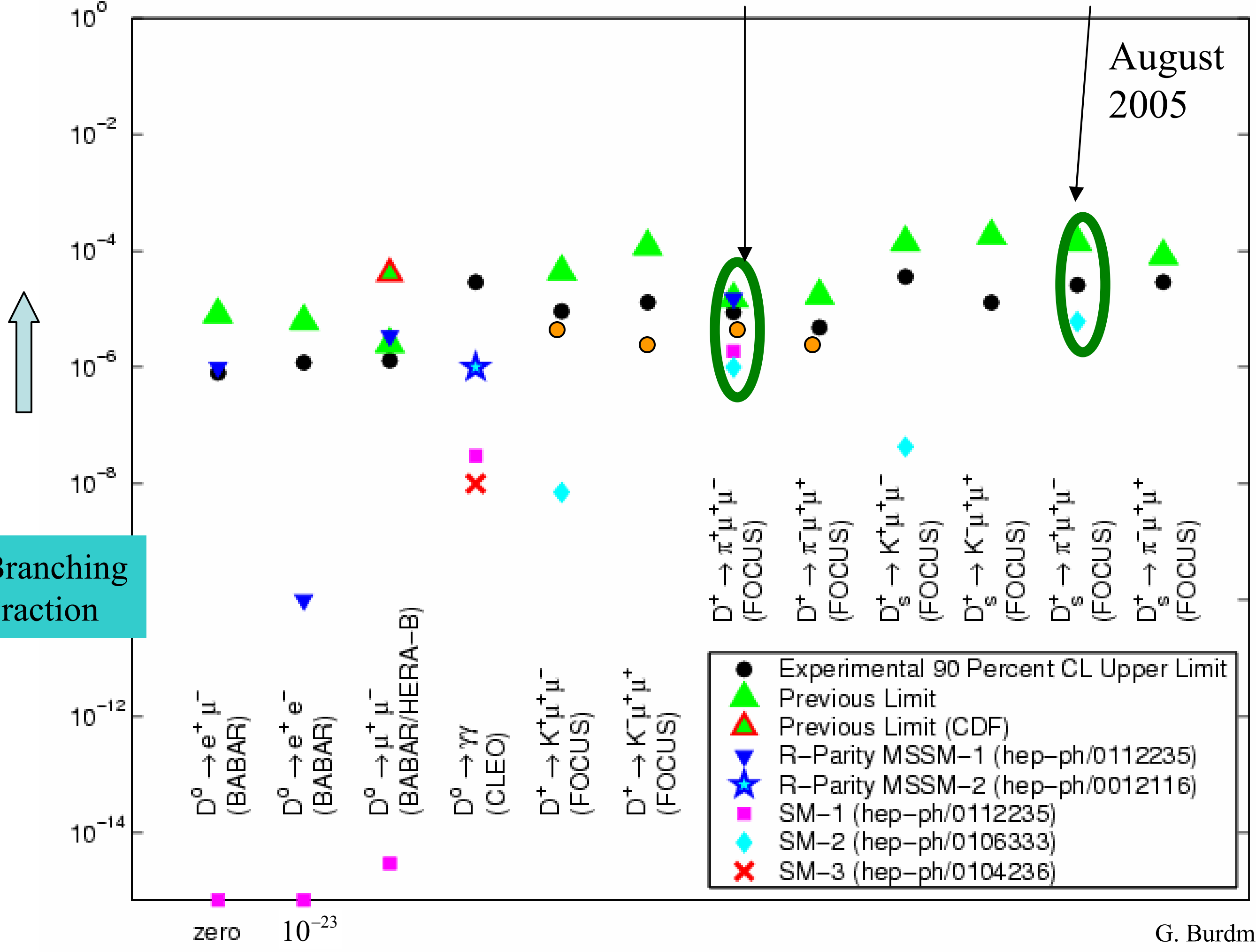
~x4 above SM rates

Rare Decay Summary

- CLEO-c (from last slide), modes with electrons and muons now at similar sensitivity

Sets MSSM constraint

Close to Long Distance Predictions



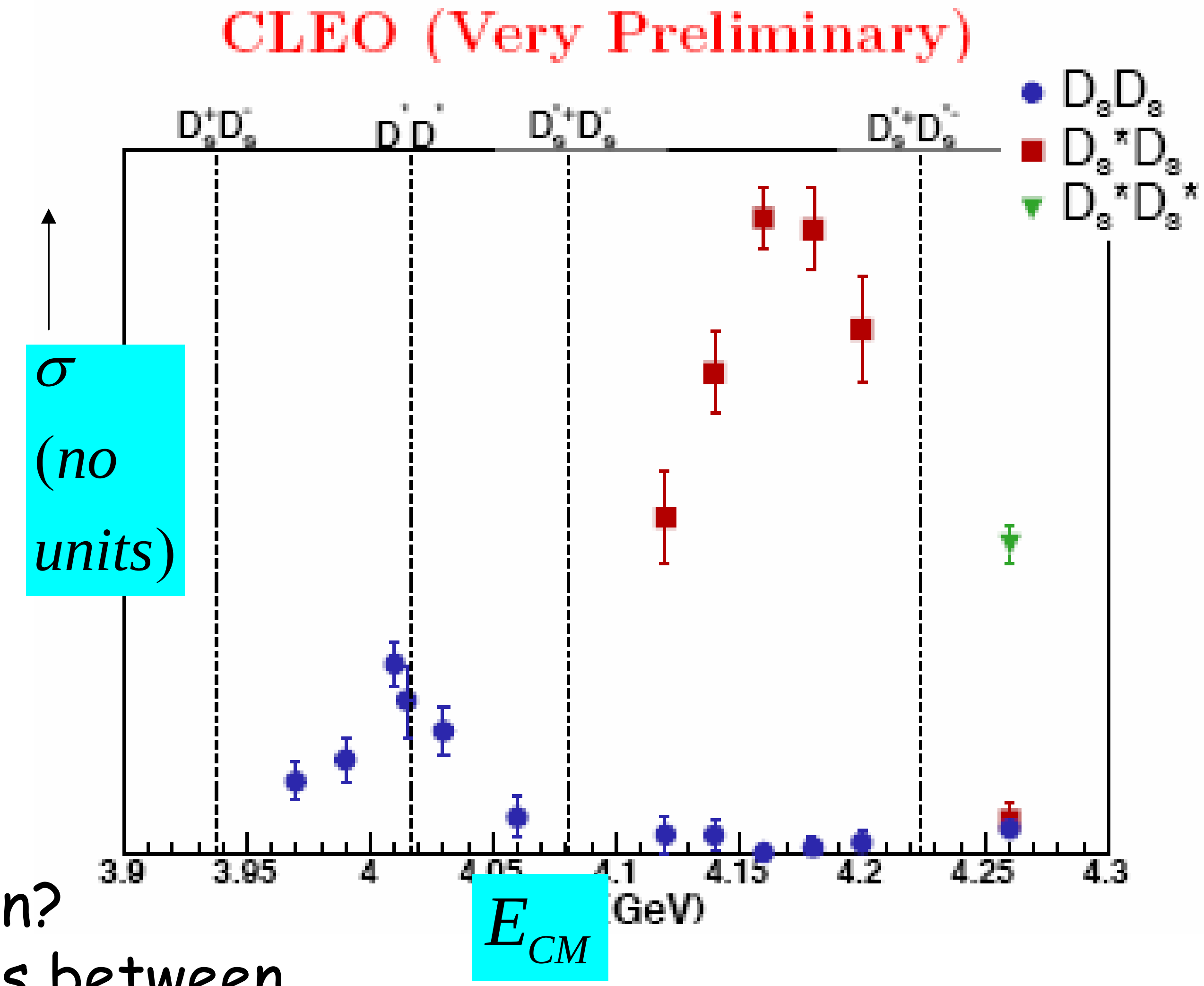
August 2005

Branching Fraction

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

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

Next from CLEO the D_S



Physics Program

f_{Ds} / f_D

$B(D_S \to \phi\pi)$

$\Gamma_{SL}(D_S)$ & shape

What energy to run?
Take 12 data points between 3970MeV and 4260 MeV

Maximum @ 4170 MeV

σ measurements ready by APS

1^{st} Announcement: Confirmation of the Y(4260)

BABAR Discovery Y(4260) in $e^+e^- \to \gamma\pi^+\pi^- J/\psi(ISR)$ & $B \to K\ \pi^+\pi^- J/\psi$

Y(4260) $\to \pi^+\pi^- J/\psi$

many different interpretations

BABAR ISR $\to J^{PC} = 1^{--} \to$ CESR

CLEO: data @ E_{CM} = 4260 MeV (D_S scan)

Observe Y(4260) $\to \pi^+\pi^- J/\psi$

First confirmation of BABAR

Observe Y(4260) $\to \pi^0\pi^0 J/\psi$

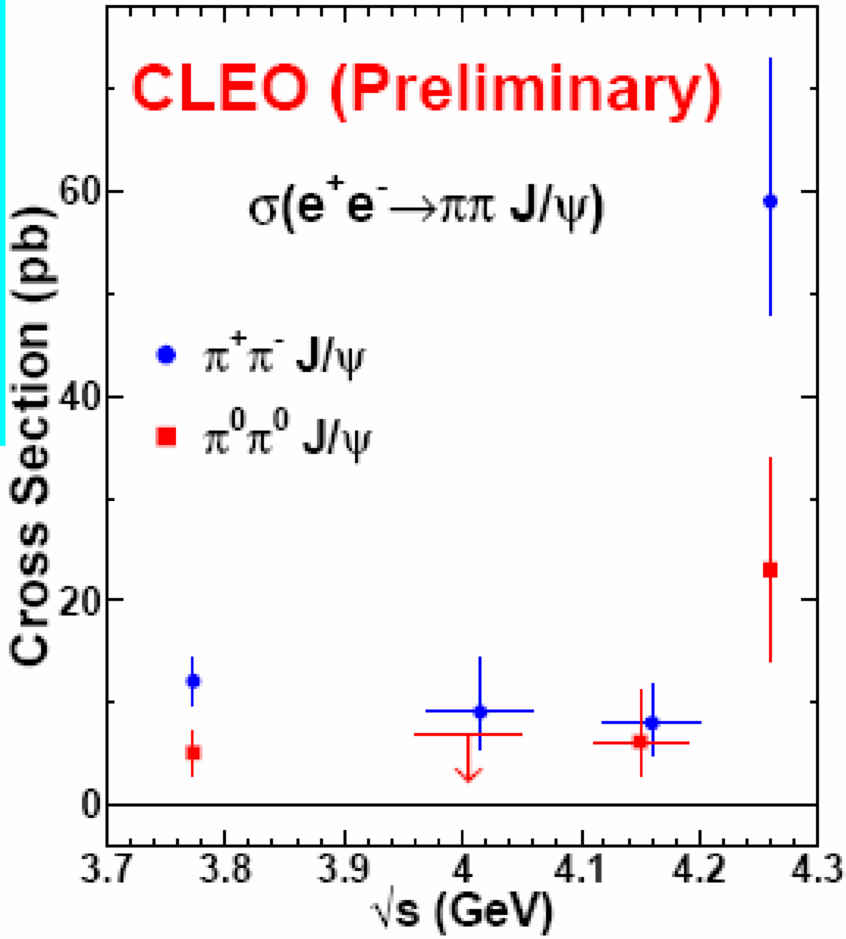
First Observation

$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ much smaller

@ $\psi(4160)$ $\psi(4040)$

Eliminates some interpretations

disfavors others. Results in ~1 week



Summary

New Physics searches in D mix, D CPV & D rare are just beginning at CLEO-c Searches at BABAR,/Belle /CDF/D0/FOCUS have become considerably more sensitive.
All results are null. As Ldt rises CLEO-c (& BES III) will become significant players.

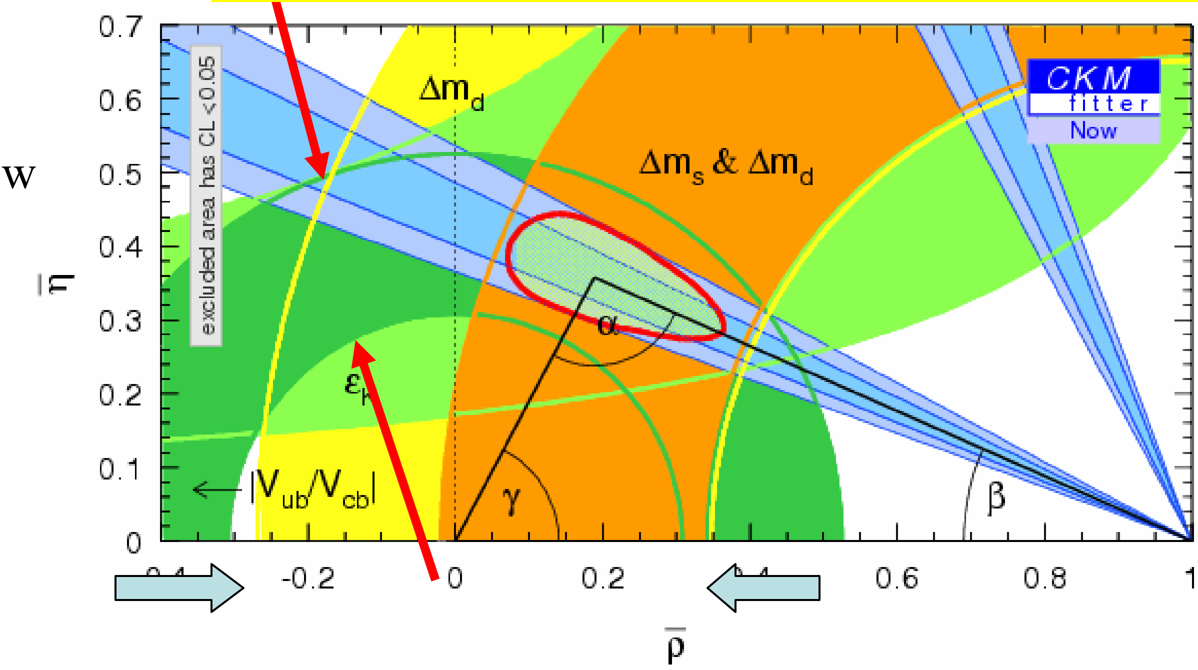
In charm's role as a natural testing ground for QCD techniques there has been solid progress. The precision with which the charm decay constant f_{D+} is known has already improved from 100% to ~8%. And the D→K semileptonic form factor has be checked to 10%. A reduction in errors for decay constants and form factors to at five - few % level is promised.

This comes at a fortuitous time, recent breakthroughs in precision lattice QCD need detailed data to test against. Charm is providing 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 improved precision in 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

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

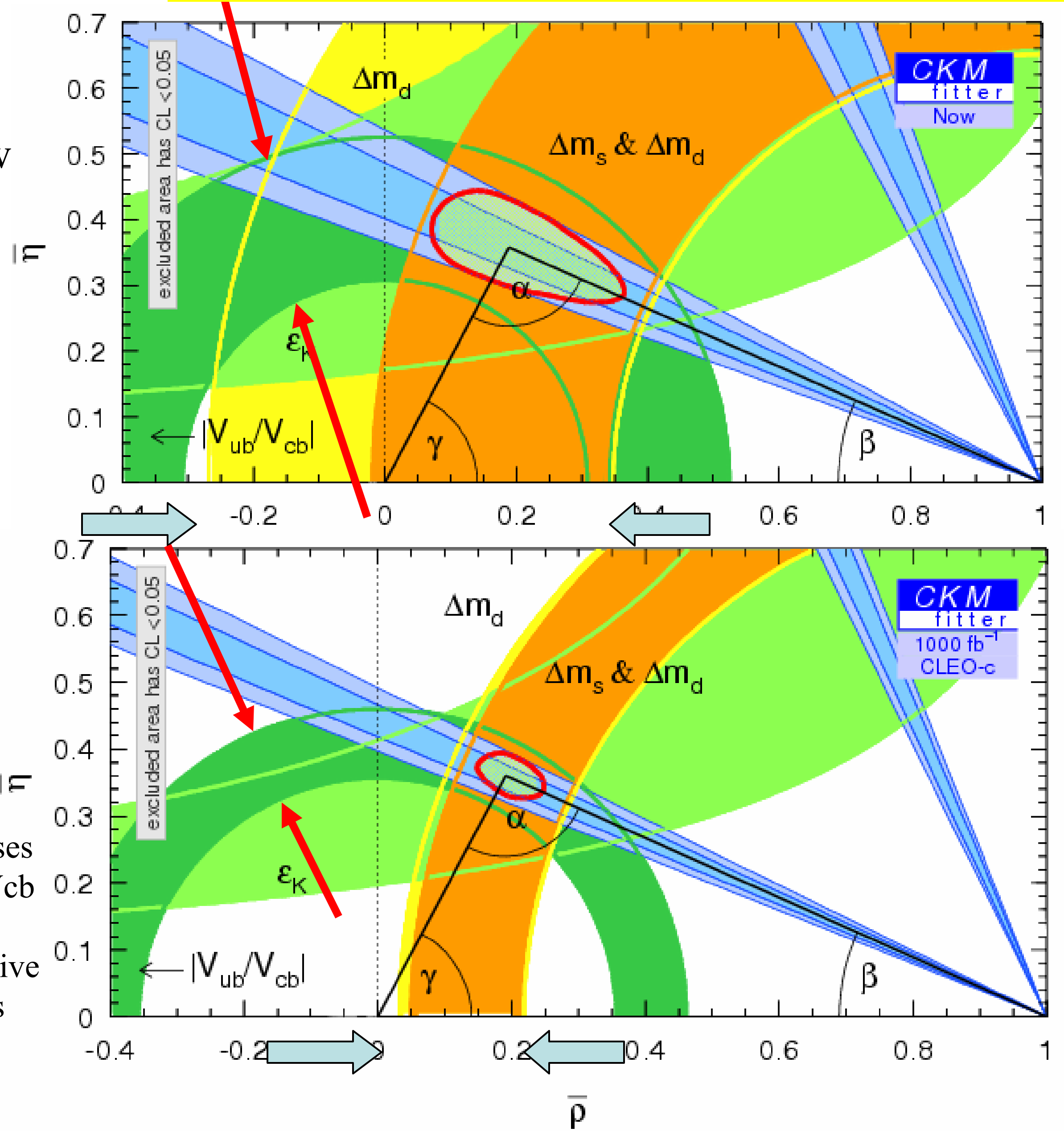
+

500 fb-1 @ BABAR/Belle

Plot uses
Vub Vcb
from
exclusive
decays
only

Precision theory + charm = large impact

Now



Plot uses Vub Vcb from exclusive decays only

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

+

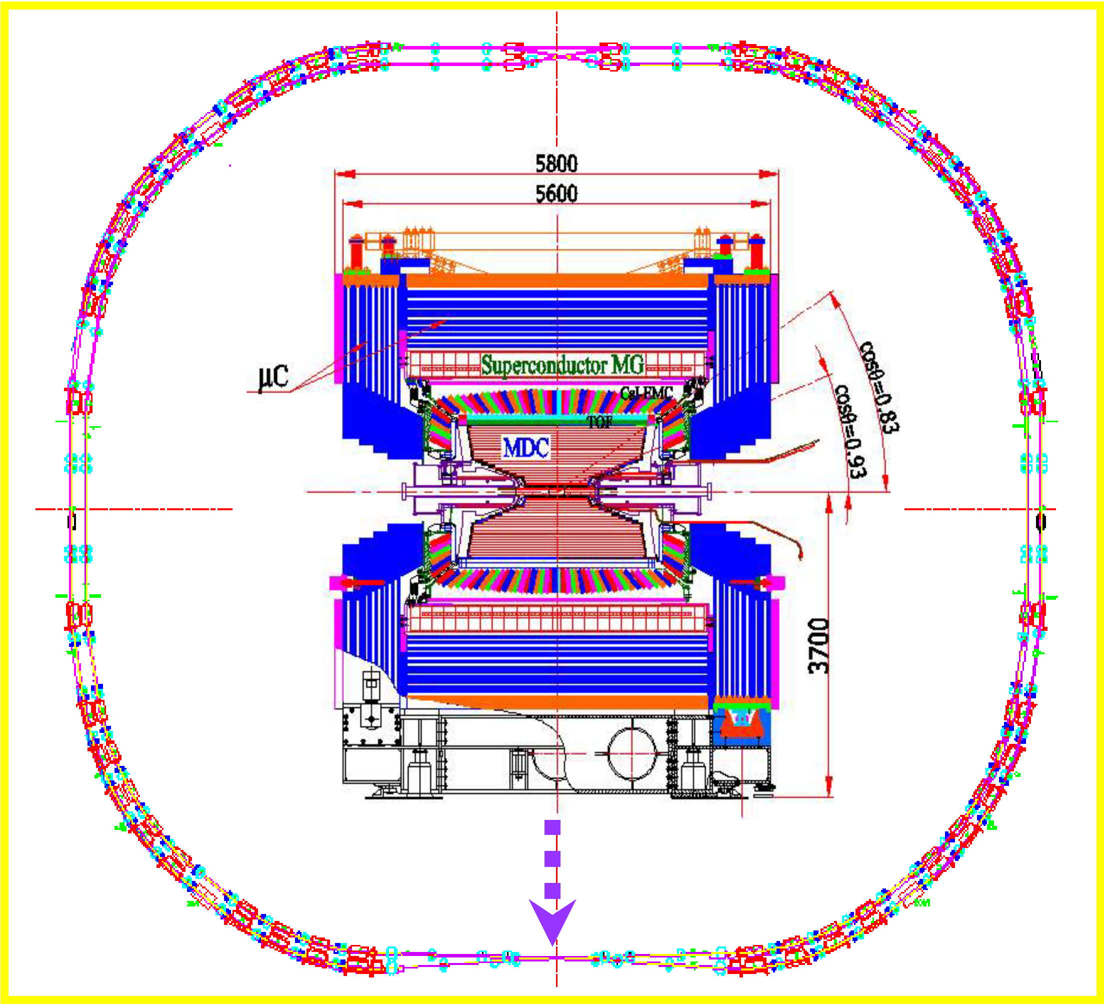
500 fb-1 @ BABAR/Belle

Acknowledgement:

The CLEO Collaboration

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