The Role of Charm in Flavor Physics- Experimental Perspective & Outlook
from charm factory to superflavor factory

OUTLINE

The role of charm in particle physics

Testing the Standard Model with precision quark flavor physics

Searches for Physics Beyond the Standard Model

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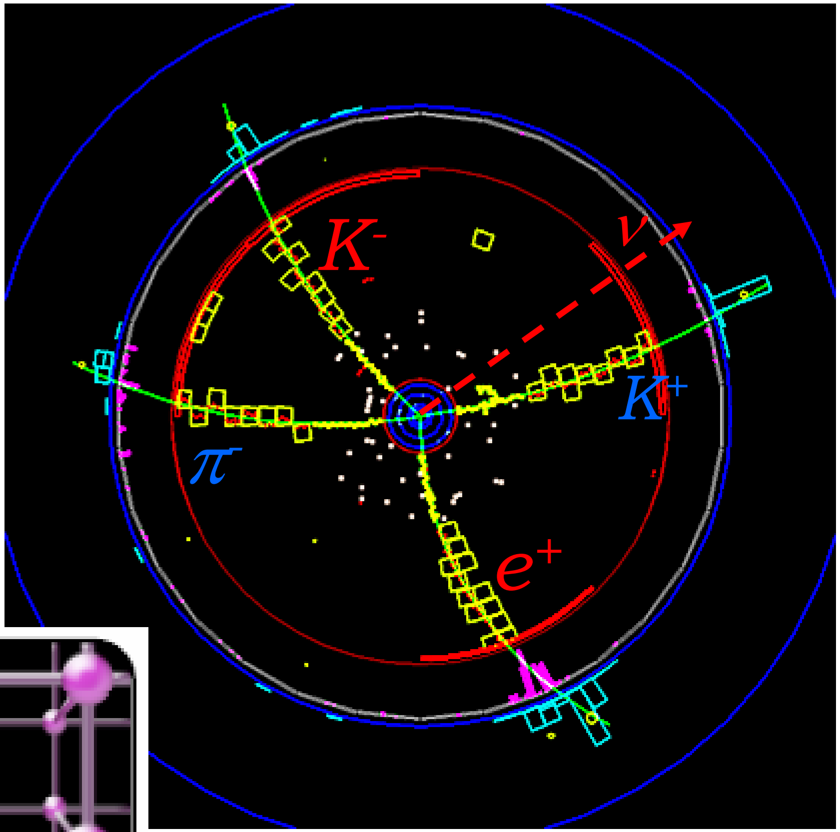
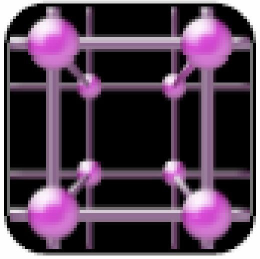
Superflavour factory

Ian Shipsey, Purdue University





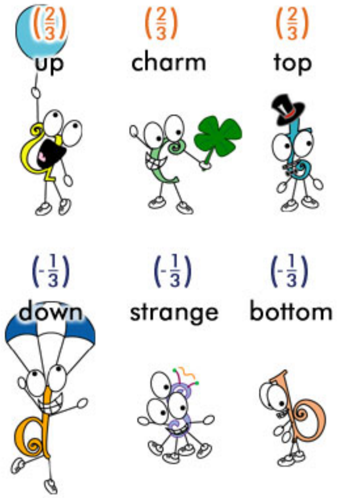
$$\psi(3770) \to D^0 \overline{D^0}$$

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

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 Two Roles

1st Role

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

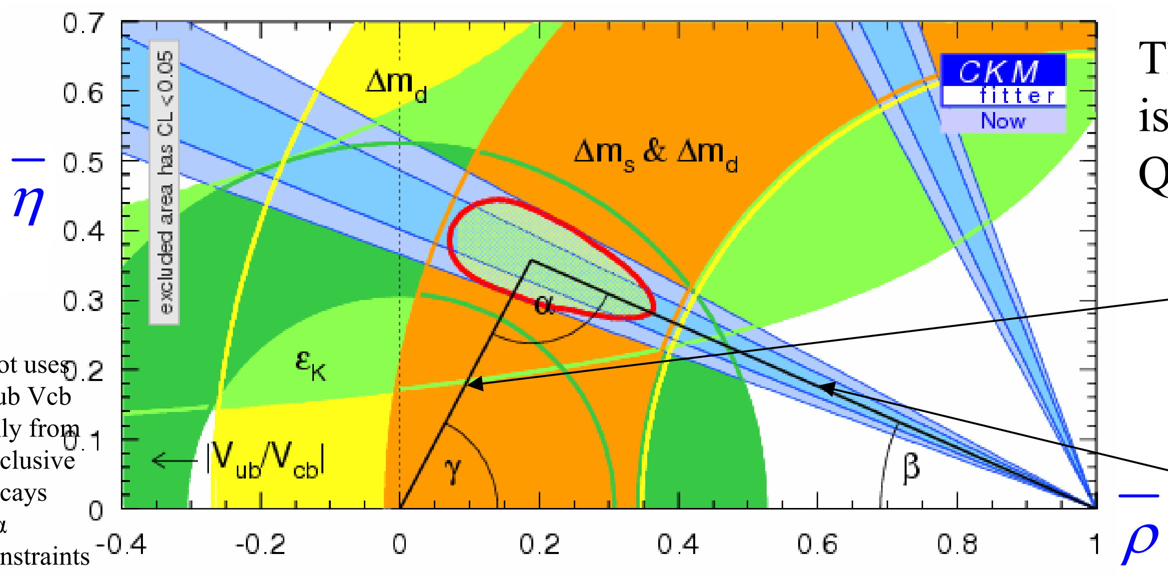
Complete definition of pert. and non-pert. QCD Goal:
Calculate B, D, Υ, ψ to 5% (few years), few % (longer term)

Charm can provide data to test & calibrate non-pert. QCD techniques
such as the lattice (especially true @ charm threshold)➔ *charm factories*

2nd Role

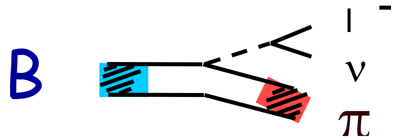
Physics Beyond Standard Model: D CPV, D mix, D rare
charm is a unique probe of the up type quark sector

Precision Quark Flavor Physics: charm's 1st role

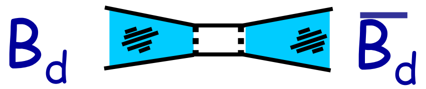


Plot uses Vub Vcb only from exclusive decays
γ,α constraints not shown

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

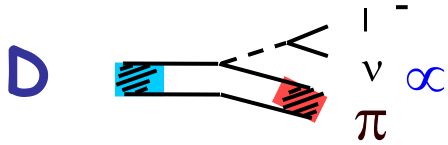


$$\propto \left[f^{B\to\pi}(q) \right]^2 \left| V_{ub} \right|^2$$

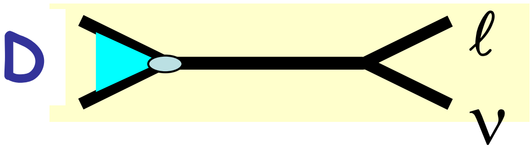


$$\propto \left[f_{Bd} \right]^2 \left| V_{td} \right|^2$$

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



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



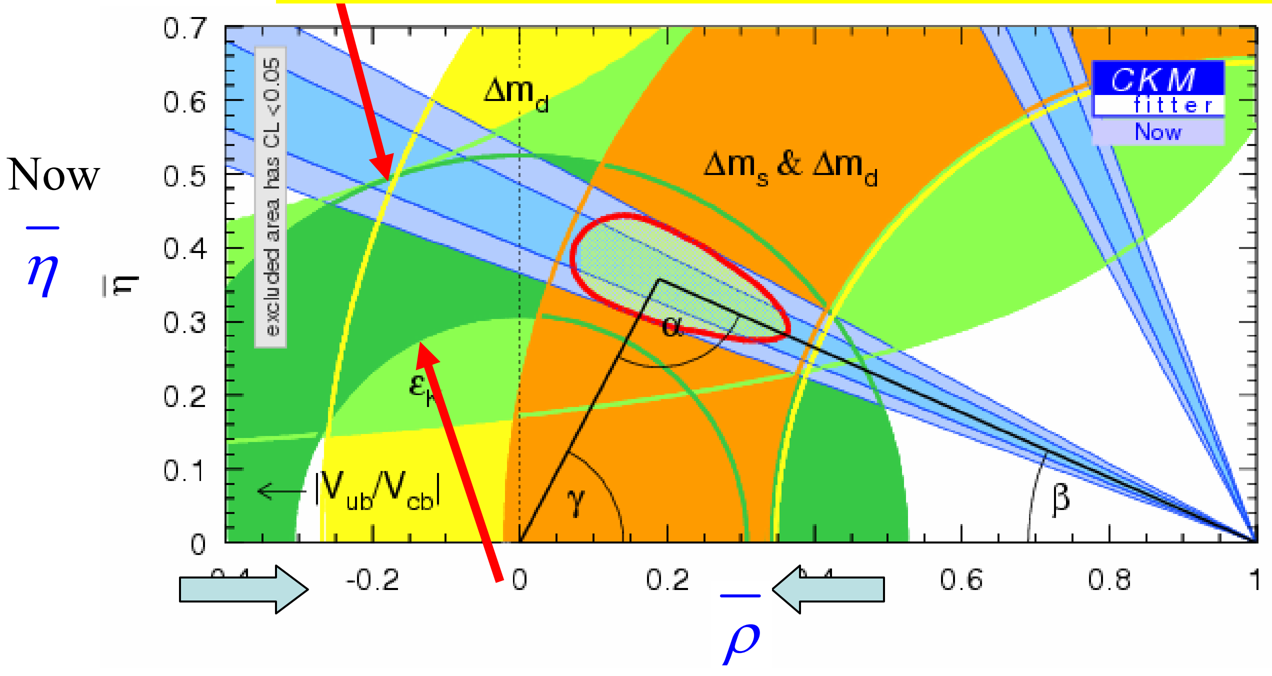
$$\propto \left[f_{D+} \right]^2 \left| V_{cd} \right|^2$$

→*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:D→Kπ important for Vcb (scale of triangle)

Charm's role

Precision theory + charm = large impact



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

+

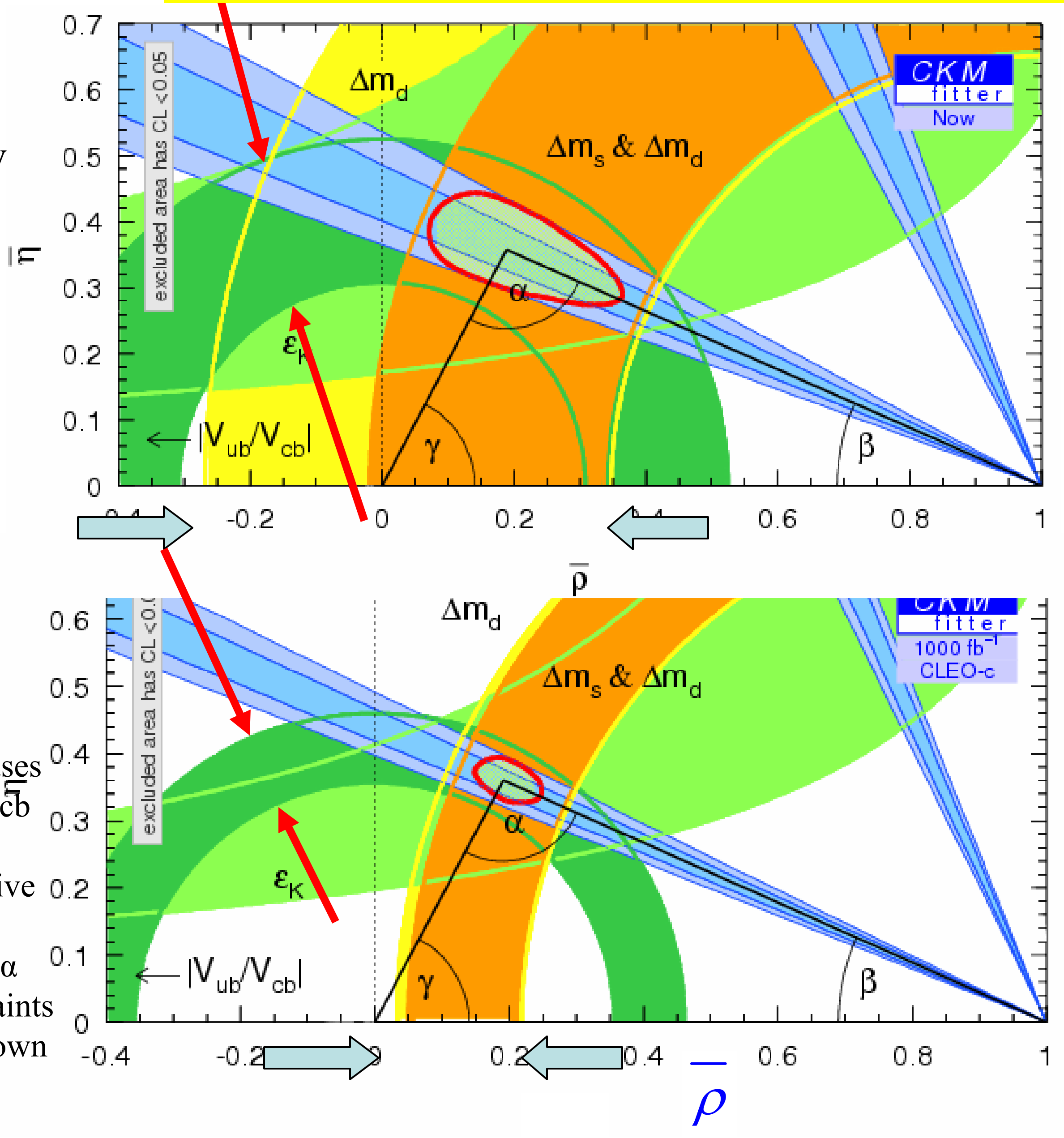
500 fb-1 @ BABAR/Belle

Precision theory + charm = large impact

Now

$\overline{\eta}$

$\overline{\eta}$



Plots uses Vub Vcb from exclusive decays only γ,α constraints not shown

$\overline{\rho}$

Theoretical errors dominate width of bands

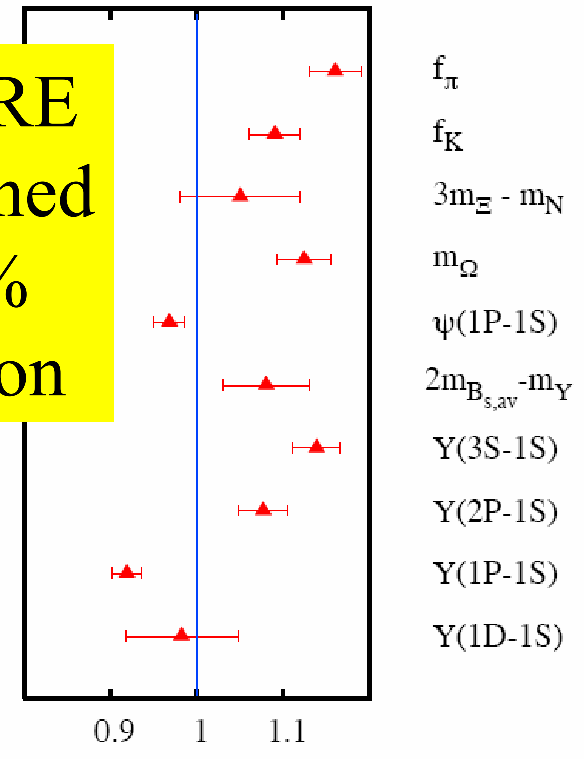
precision QCD calculations tested with few % *precision* charm data at threshold ➔theory errors of a few % on B system decay constants & semileptonic form factors

+

~500 fb-1 @ BABAR/Belle

Precision theory? Lattice QCD

BEFORE
Quenched
10-15%
precision

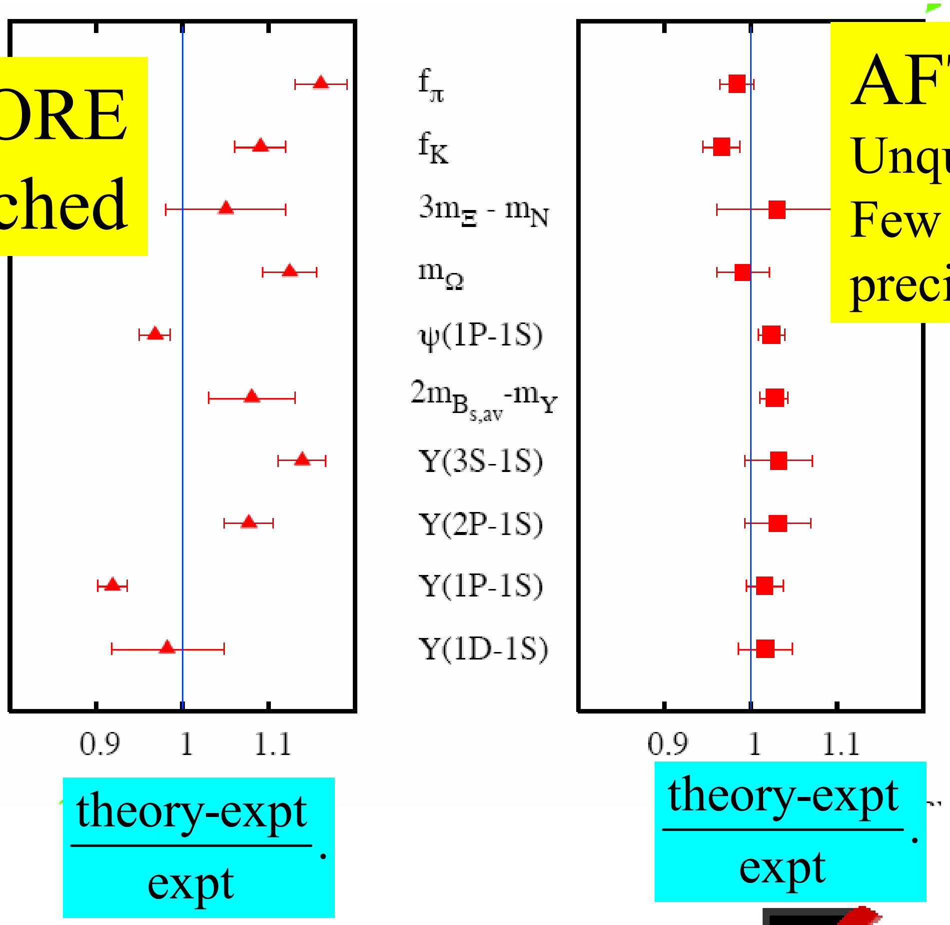


$$\frac{\text{theory-expt}}{\text{expt}}.$$

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

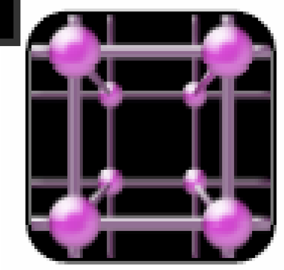
Testable *predictions* are now being made:

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

Charm decay constant f_D ← Harder- first test July 2005

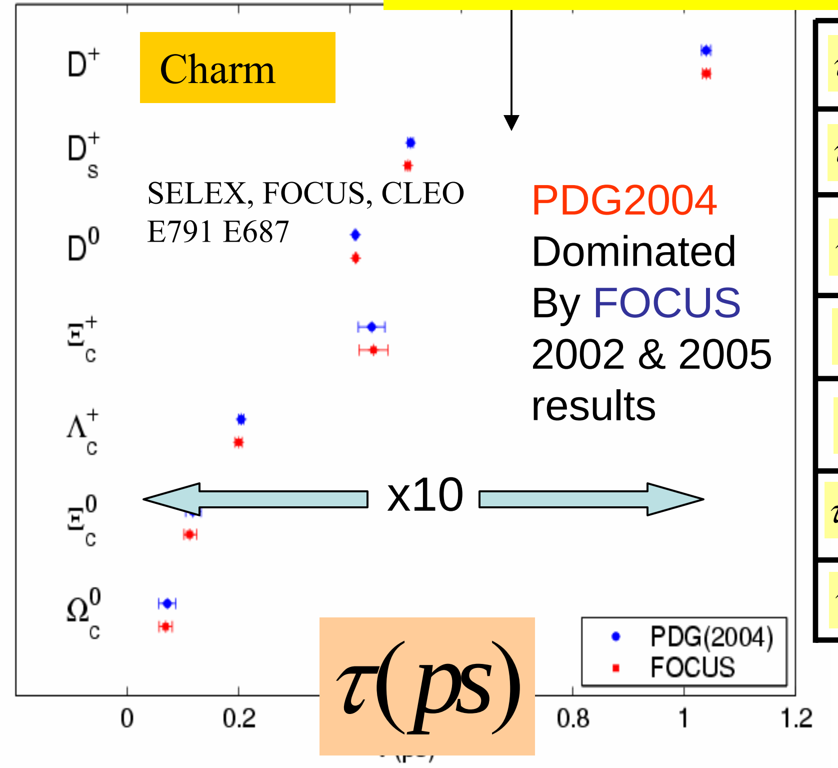
Semileptonic *D/B* form factors ← Hardest- Tests 2005/6

} This talk



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

Precision Experiment? Yes for lifetimes {needed to compare Br(expt) to partial Γ (theory)}

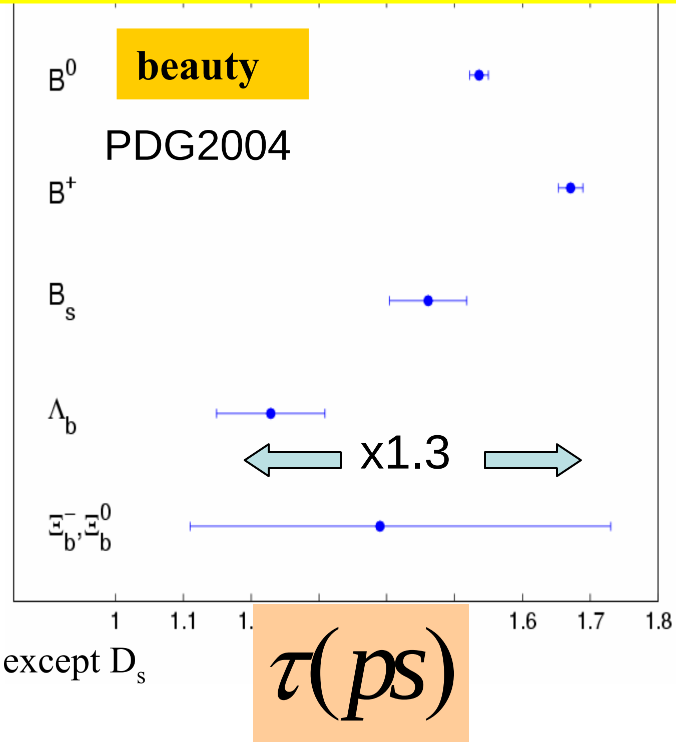


SELEX, FOCUS, CLEO E791 E687

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 ‰, Λ_c 3%, Ξ^0 10%, $\Xi^+{}_c$ 6 %, Ω_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.

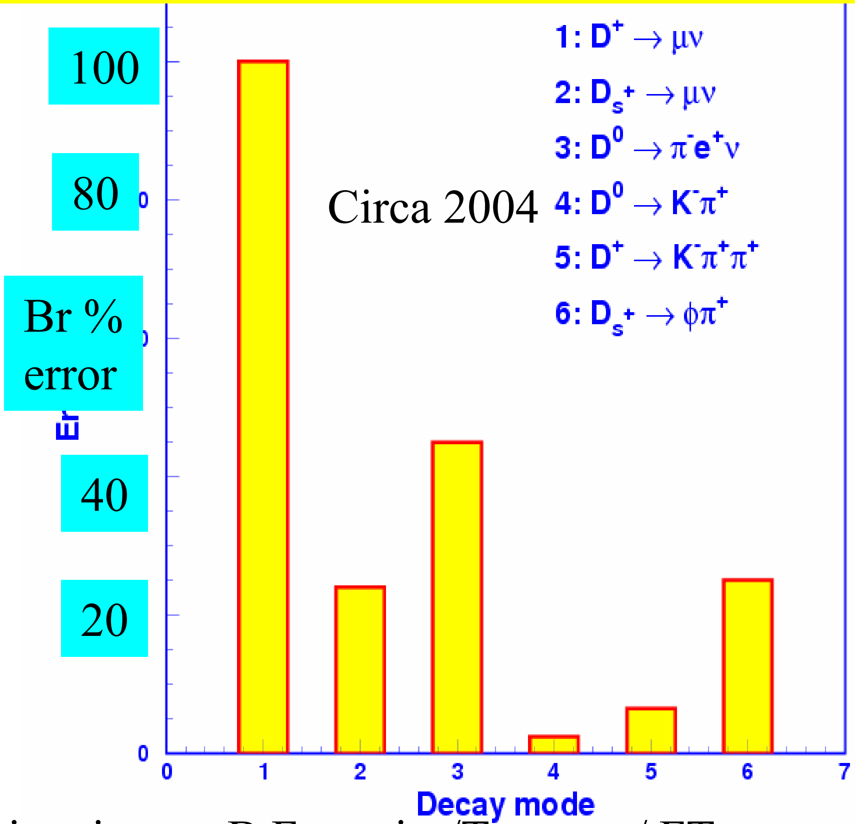
Errors on lifetimes are *not* a limiting factor in the measurement of absolute rates.

Precision Experiment? For Branching Ratios No!
Status of Absolute Charm Branching Ratios in 2004 :

Poorly known → Br

Measured very precisely → τ

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



Circa 2004

And: D^0, D^+ & D_S hadronic 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.*

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

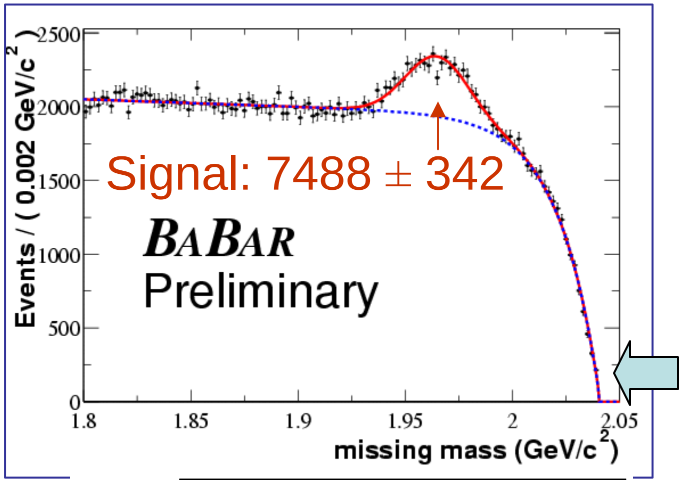
Backgrounds are large. → #X Observed

#D's produced is usually not well known. → #D's produced

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

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

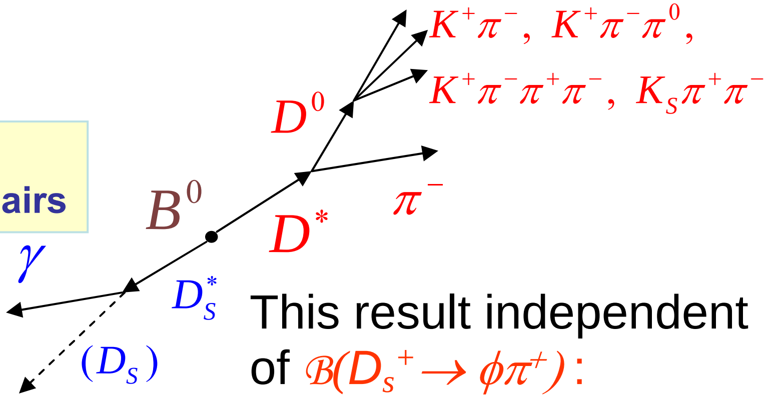
Hep-ex/0502041
PRD 71 091104 (2005)



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

Recoil mass

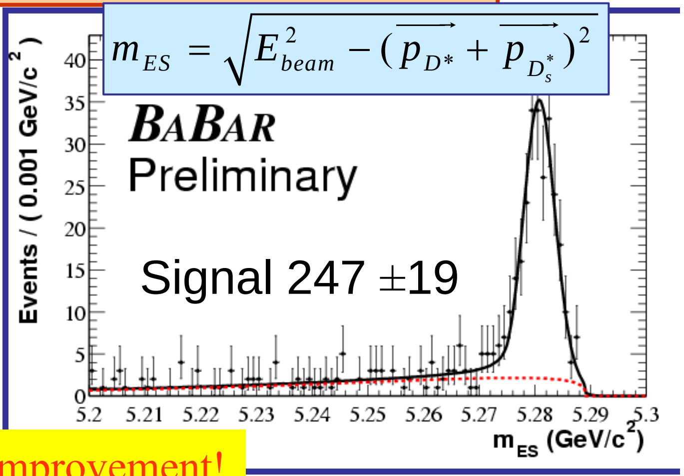
Data sample:
124 million B pairs



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



$$m_{ES} = \sqrt{E_{beam}^2 - (\vec{p}_{D^*} + \vec{p}_{D_s^*})^2}$$

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

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%)

With 500/fb expect systematics limited at ~5%

charm factories:
Now: CESR-c/CLEO-c Status. Datasets & Runplan

Approved for 5 years by NSB 2/03

CESR (10 GeV) → CESR-c (3-4 GeV)

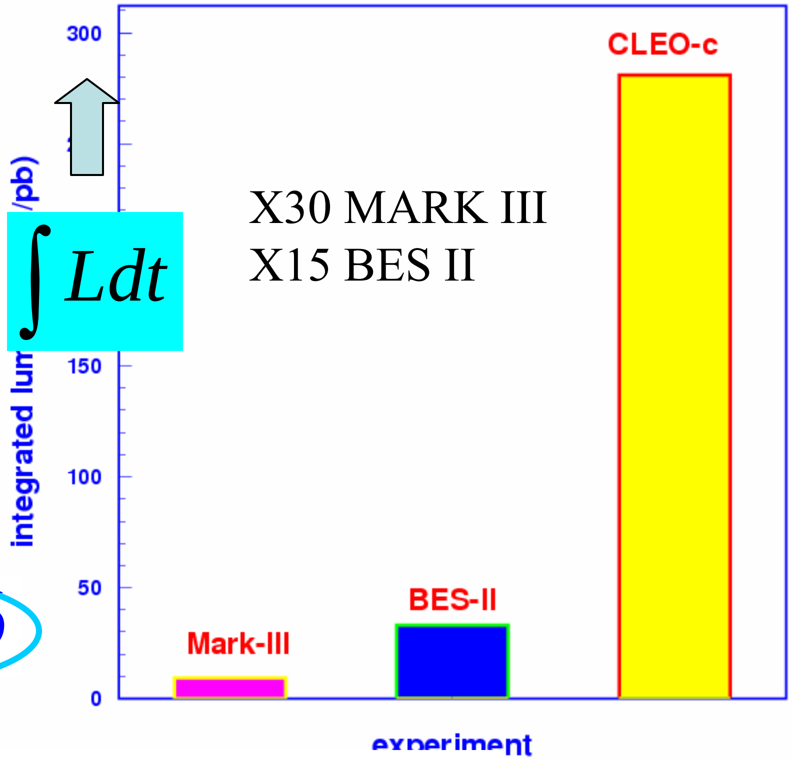
CLEO III → CLEO-c

2 runs $@\psi(3770) \rightarrow D\bar{D}$

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

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

Results from these two datasets in this talk



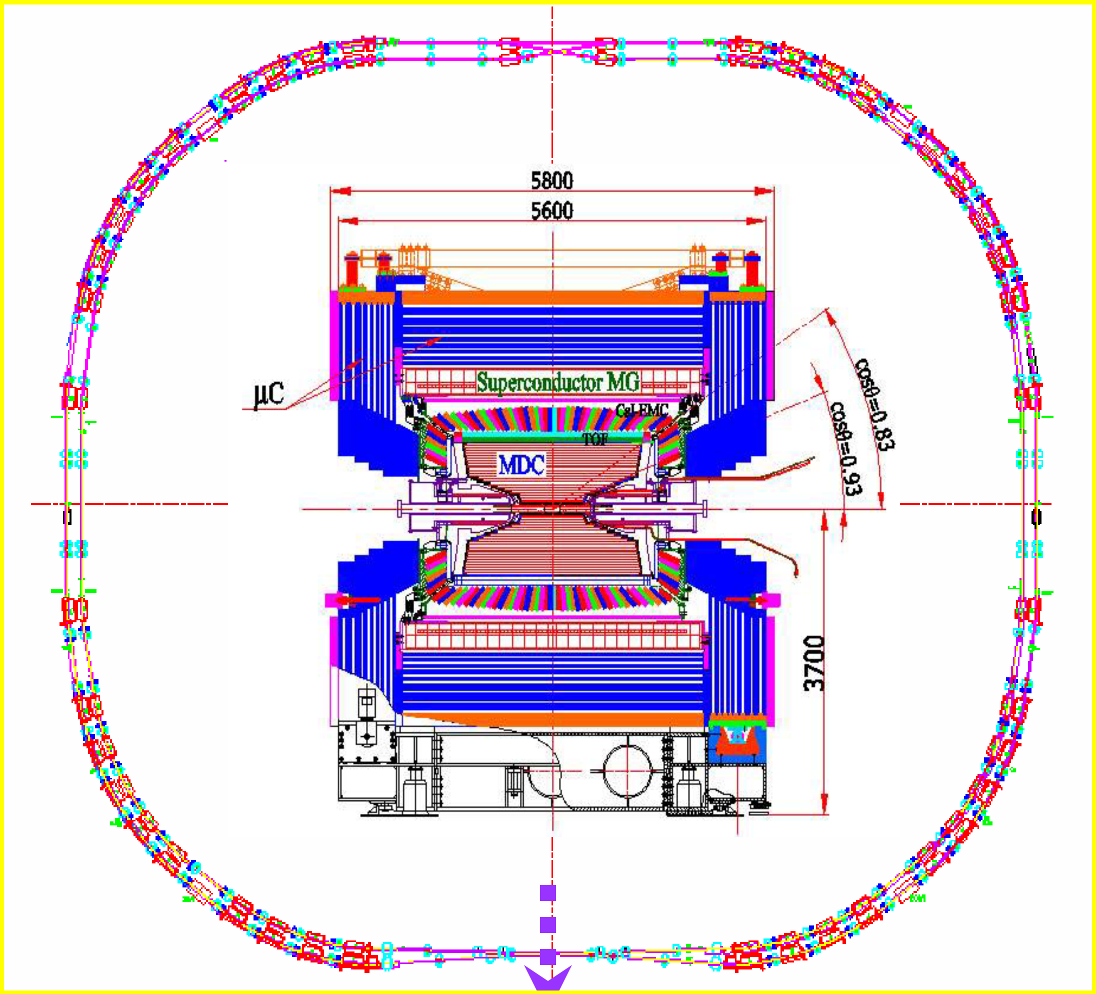
X30 MARK III
X15 BES II

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

⇒ ~750 pb^{-1} @ ~ 4170 MeV above $D_s\bar{D}_s$ threshold (×130 BES)

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

Near Future: BEPCII/BESIII Project



run plan not decided: example 5/fb/yr 15/fb/3yrs

3 yrs @ 3770 25M $D\bar{D}$/yr =75M$D\bar{D}$ ~×15 full CLEO-c

3 yrs @4170 2M $D_s\bar{D}_s$/yr = 6M$D_s\bar{D}_s$ ~×15 full CLEO-c

Design

See talk by Jin Shan @ DIF06

- **Two ring machine**
- **93 bunches each**
- **Luminosity**

X5 CESR-c design

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

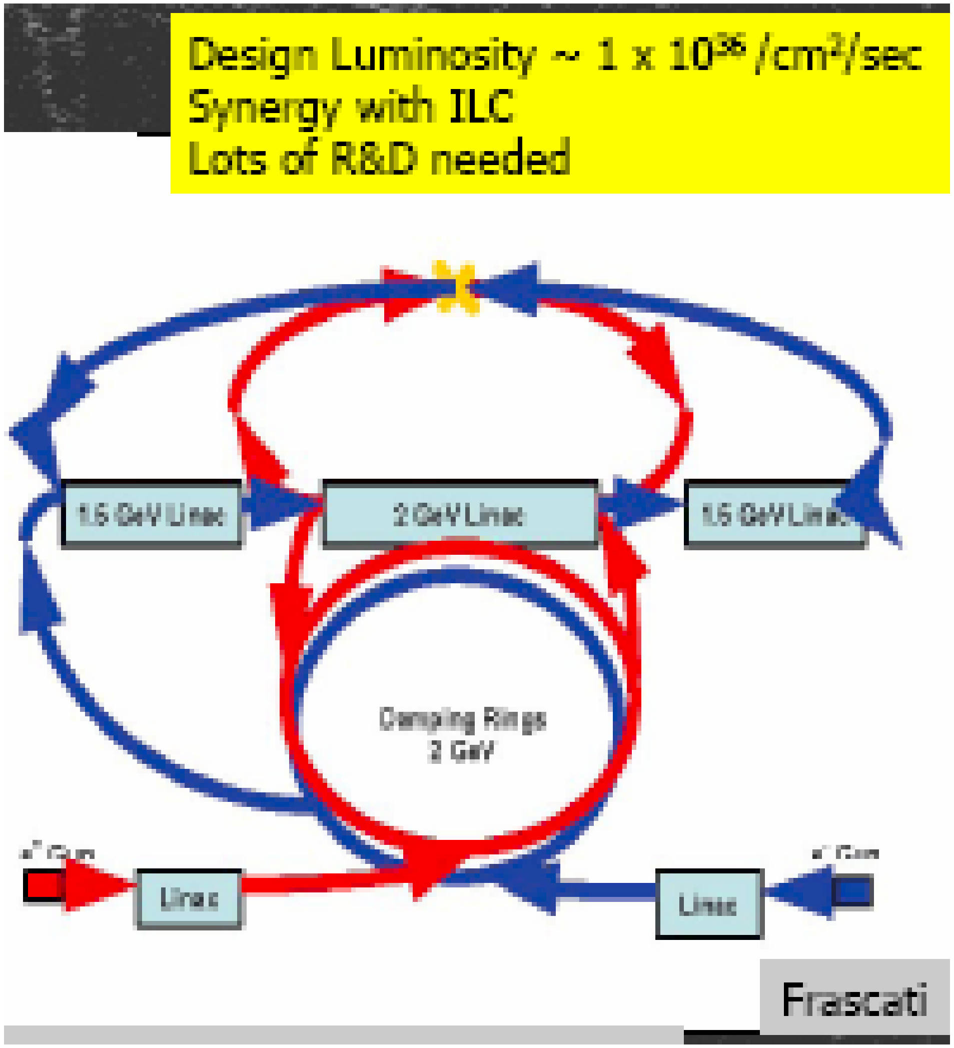
- **Most contracts signed**
- **Linac installed 2005**
- **Ring to be installed 2006**
- **BESIII in place**

and Commissioning 2007

BEPCII/BESIII

data taking beginning of 2007

Super B Factories plans for KEK and Frascati: connection to charm



Design Luminosity ~ 1 x 10^{36} /cm²/sec
Synergy with ILC
Lots of R&D needed

Frascati machine

10^{10} $e^+e^- \rightarrow c\bar{c}$ $/10^7$s

important source of charm

(as is SuperKEK-b)

+ option to

lower energy to ~4GeV

super B factory

→ super flavour factory B/D/τ

L penalty x10 ↓ (guess)

at $1\text{x}10^{35}$ for $10^7 s = 1\,\text{ab}^{-1}$

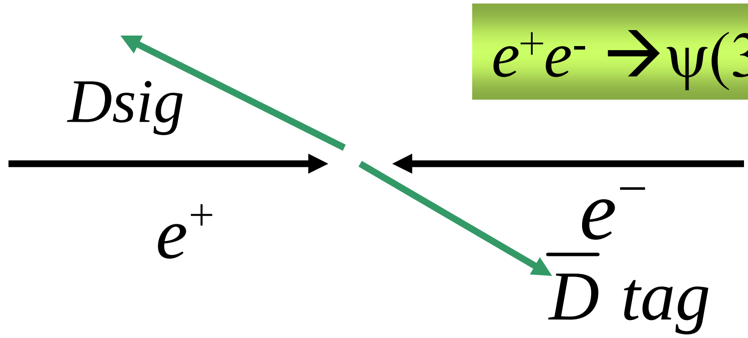
or $6.4 \times 10^9 D\bar{D}/10^7 s @ \psi(3770)$

70 × BEPCII 1,000 xCESR-c

When discussing CLEO-c
will extrapolate to BEPCII/BESIII
and *super flavour*

LHC-b another important source of charm, studies are at an early stage

ψ(3770) Analysis Strategy



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

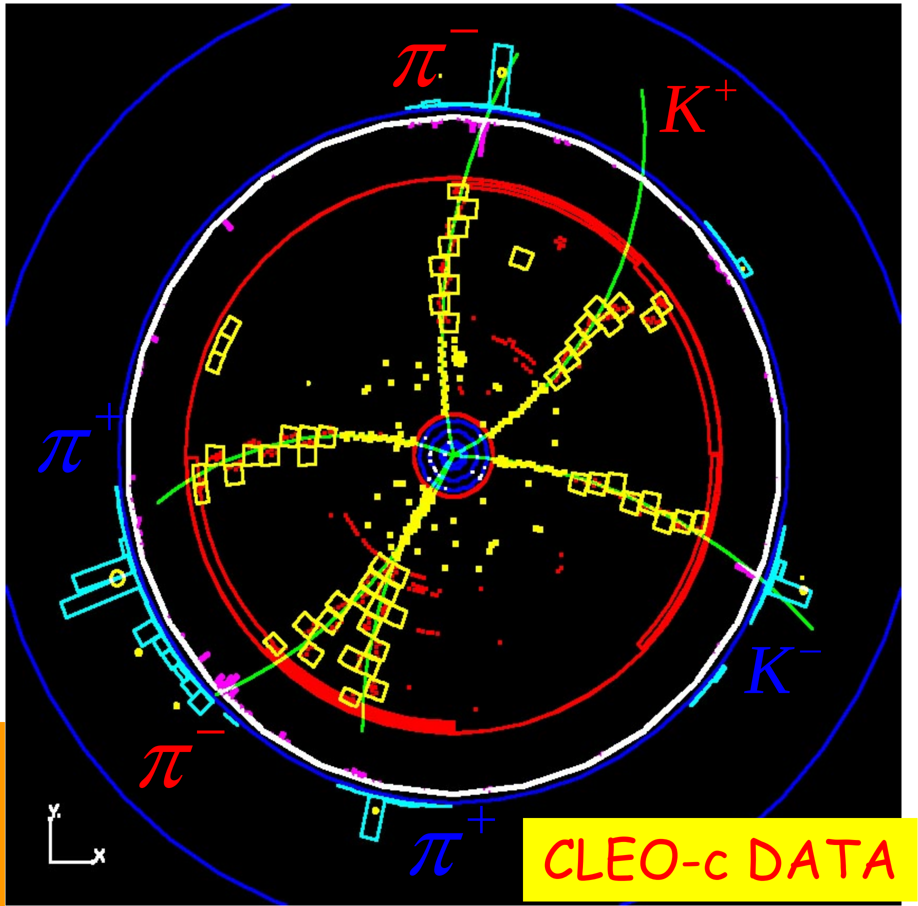
ψ(3770) is to charm what Y(4S) is to beauty

- ❑ 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 ~0.1% of B's at the Y(4S)

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



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

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

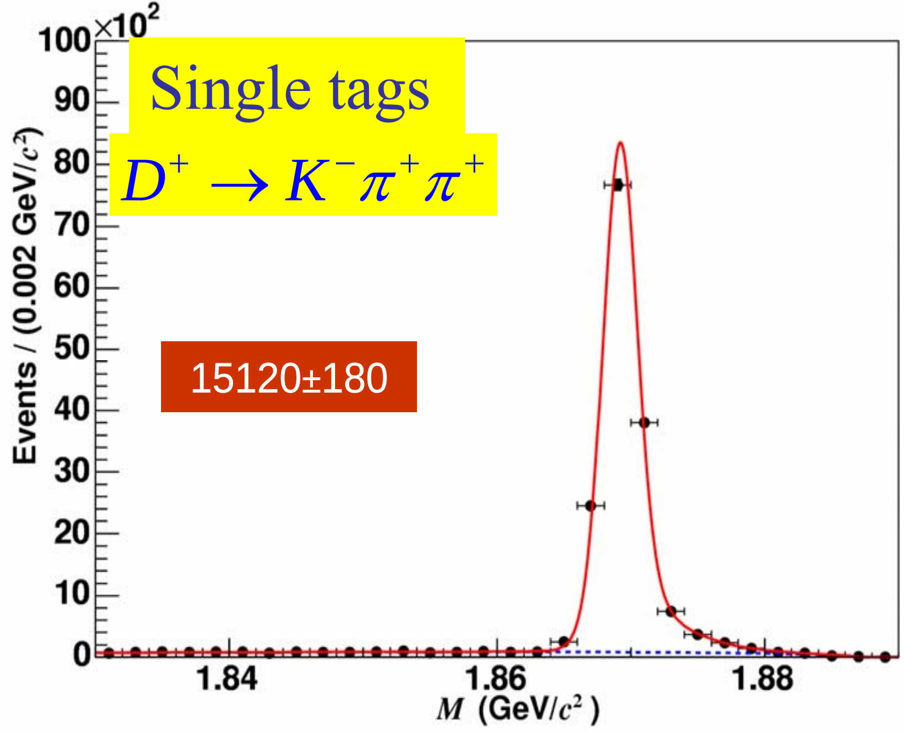
Absolute Charm Branching Ratios at Threshold (CLEO-c)

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

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

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

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

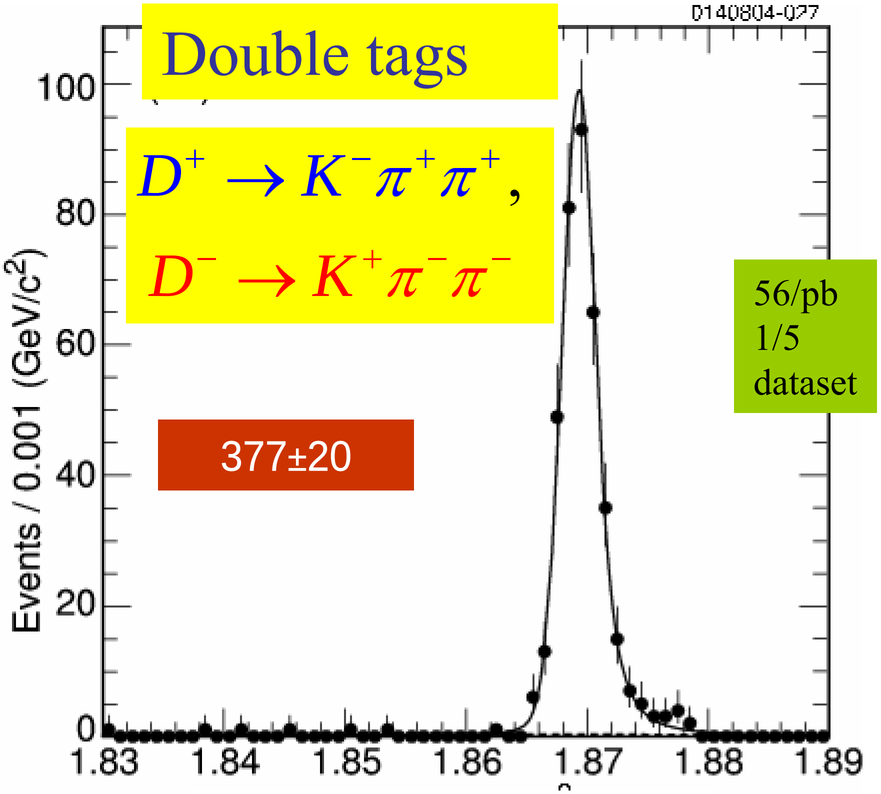


Single tags

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

15120±180

D candidate mass (GeV)



Double tags

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

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

377±20

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

THEN:

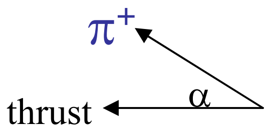
CLEO & ALEPH

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

compare to:

$D^{*+} \to \pi^+ D^0$, $D^0 \to$ unobserved

(Q~6MeV)

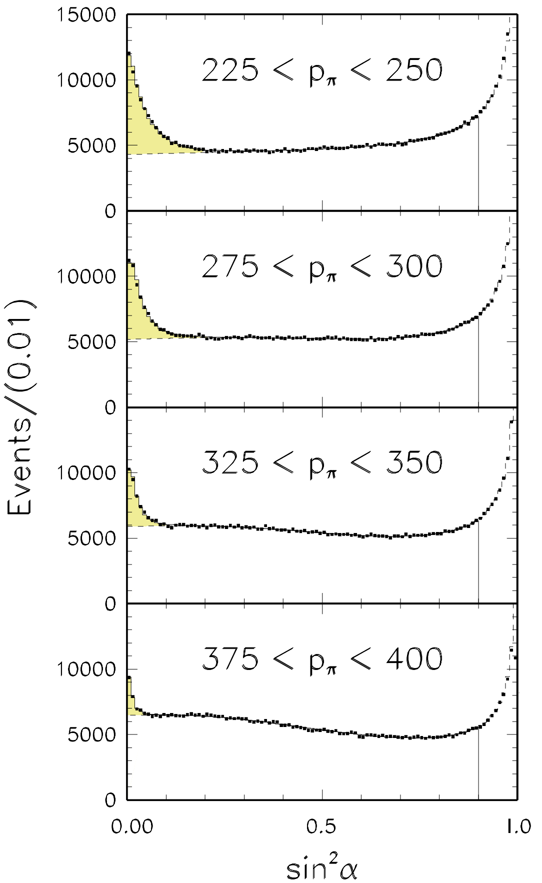


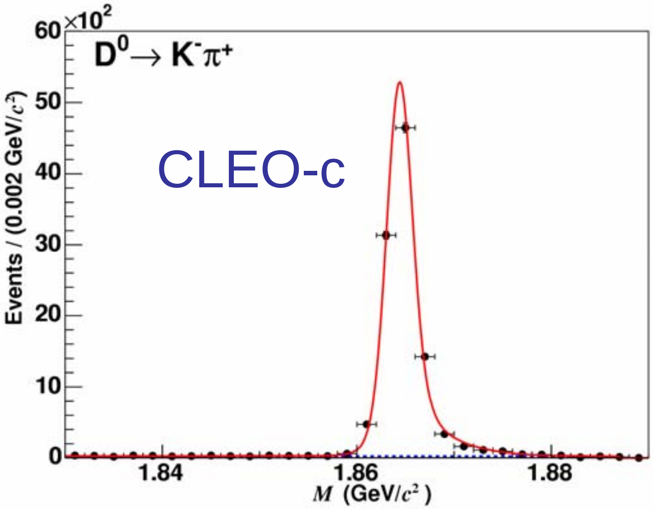
Three best measurements:

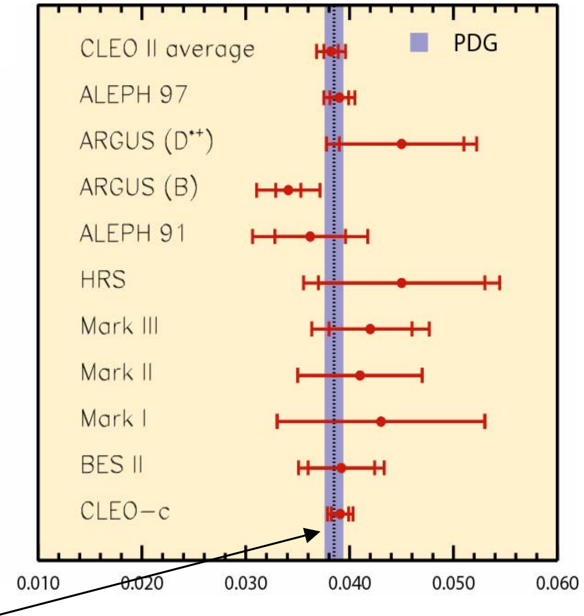
$\mathcal{B}$ (%)	Error(%)	Source
3.82±0.07±0.12	3.6	CLEO
3.90±0.09±0.12	3.8	ALEPH
3.80 ±0.09	2.4	PDG
3.91±0.08 ±0.09	3.1	CLEO-c

CLEO-c as precise as any previous measurement

NOW:





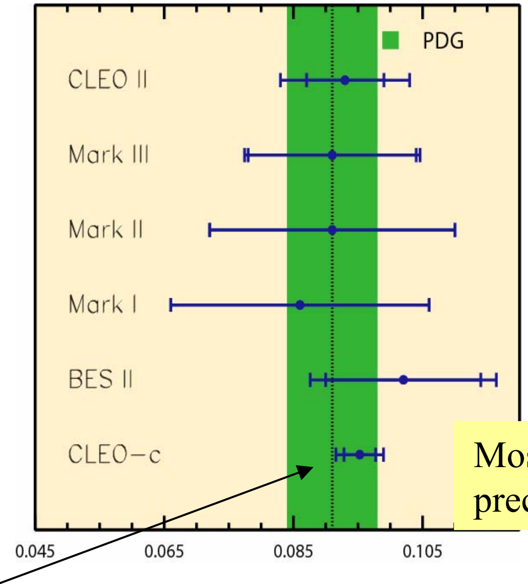


CLEO-c
(not in PDG average)

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

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



Most precise

CLEO-c (not in PDG average)

THEN:

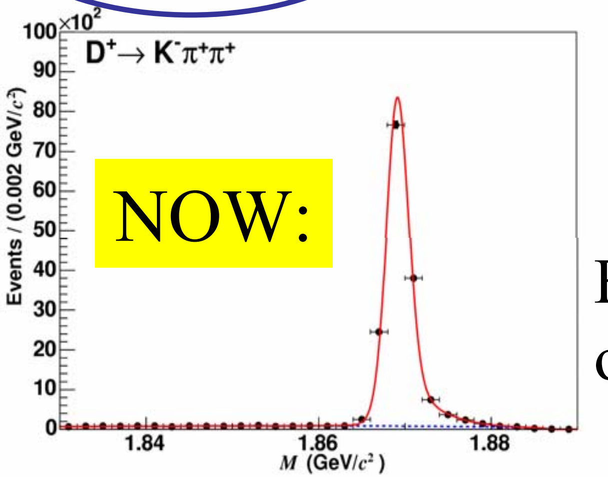
Method (CLEO) Bootstrap: Measure:

← Assume isospin

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

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

NOW:

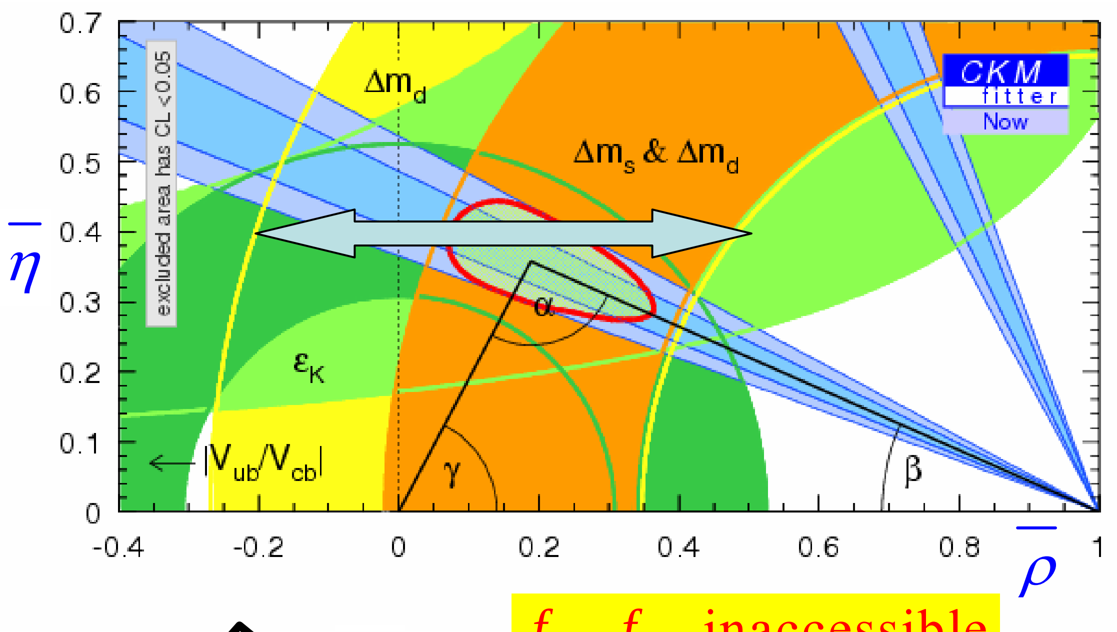


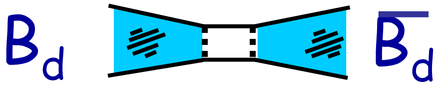
Future outlook

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*)

Refinements from BESIII especially Ds No SM motivation to go beyond ~1% precision

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





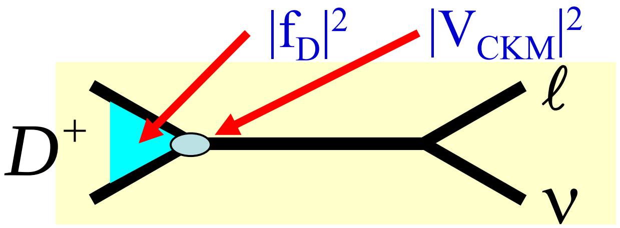
$$rate = (const.)\left[f_{Bd} \right]^2 |V_{td}|^2 |V_{tb}|^2$$

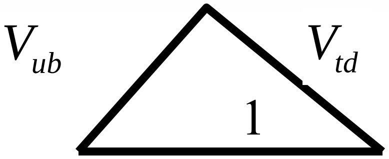
1.0% (expt) HFAG 2005

~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

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

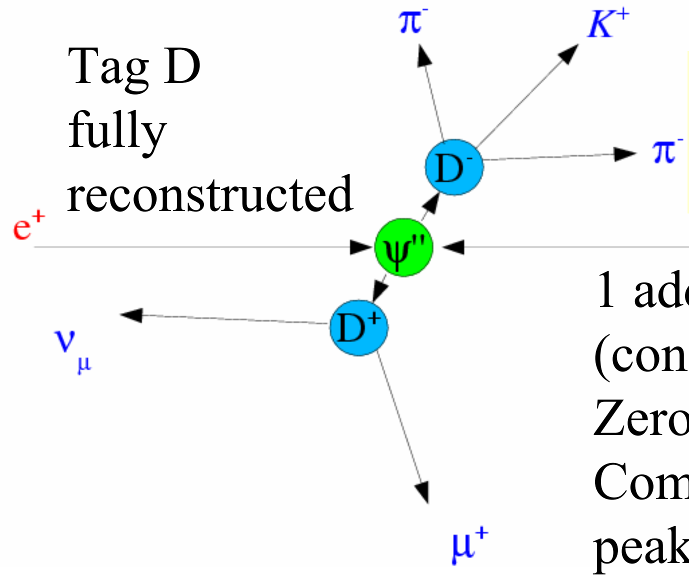
$|V_{cd}|$ known from unitarity to 1%

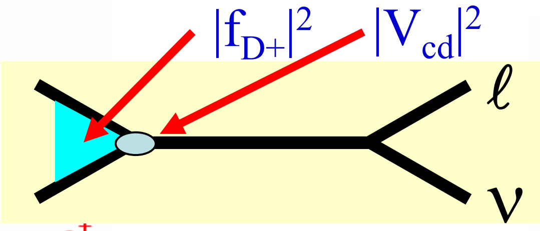
$$\frac{\delta f_{D_c}}{f_{D_c}} \sim 100\%$$

PDG04

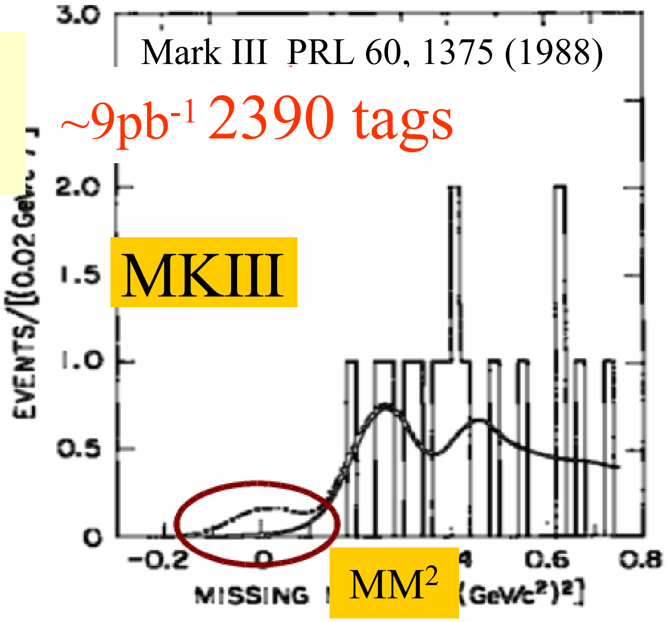
Lattice predicts f_B/f_D with a small errror
If a precision measurement of f_D existed (it does not)
→Precision Lattice estimate of f_B → precision determination of V_{td}
Similarly f_D/f_{Ds} checks f_B/f_{Bs} → precise $|V_{td}|/|V_{ts}|$ once B_s mixing seen

f_{D+} from Absolute Br($D^+ \rightarrow \mu^+\nu$) @ψ(3770) CLEO-c


Tag D fully reconstructed



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

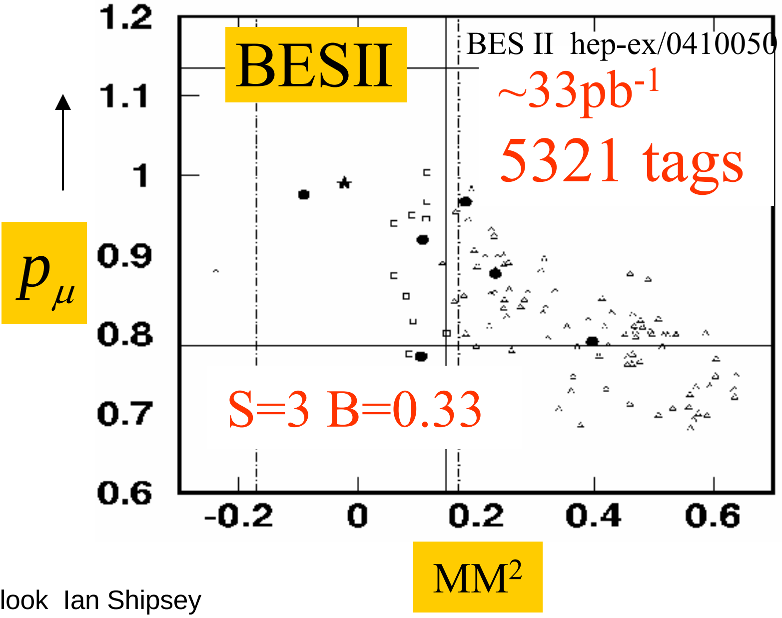

Mark III PRL 60, 1375 (1988)

~9pb^{-1} 2390 tags

MKIII

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

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


BES II hep-ex/0410050

BESII

~33pb^{-1}

5321 tags

S=3 B=0.33

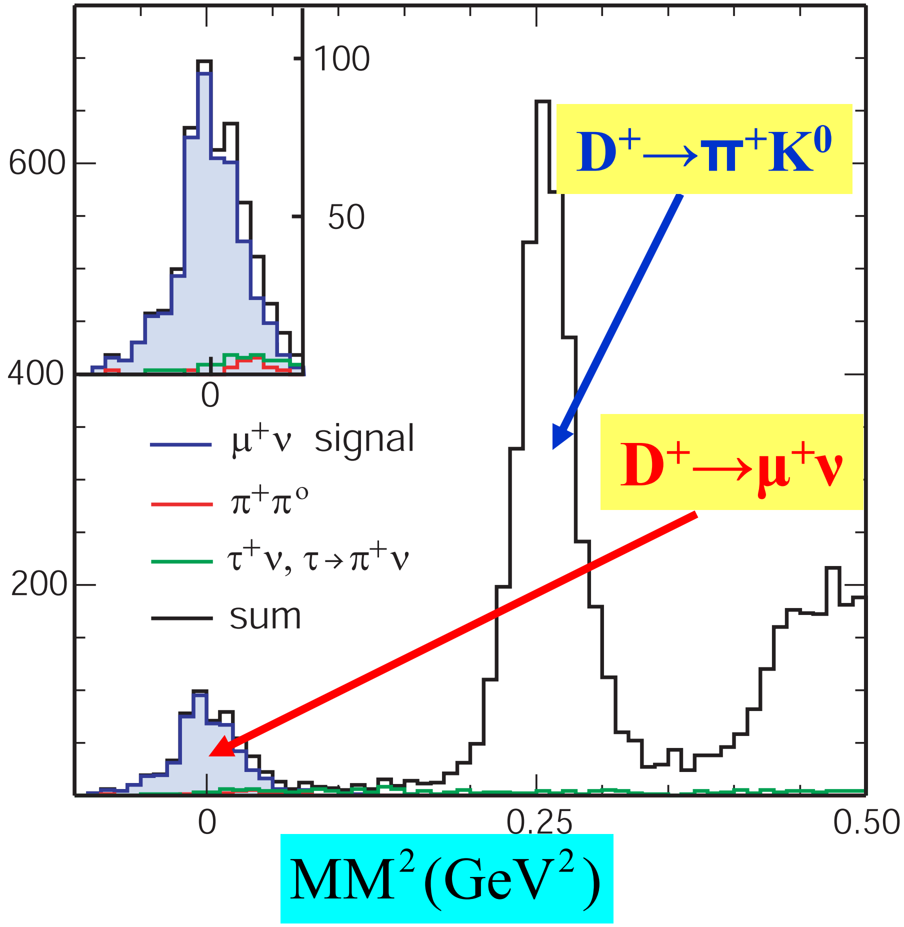
	$B(D^+ \rightarrow \mu\nu)\times 10^{-4}$	f_D MeV
MkIII	< 7.2	< 290
BESII	$12.2^{11.1}_{-53} \pm 0.11$	$371^{+129}_{-119} \pm 25$

$f_{D+}$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

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

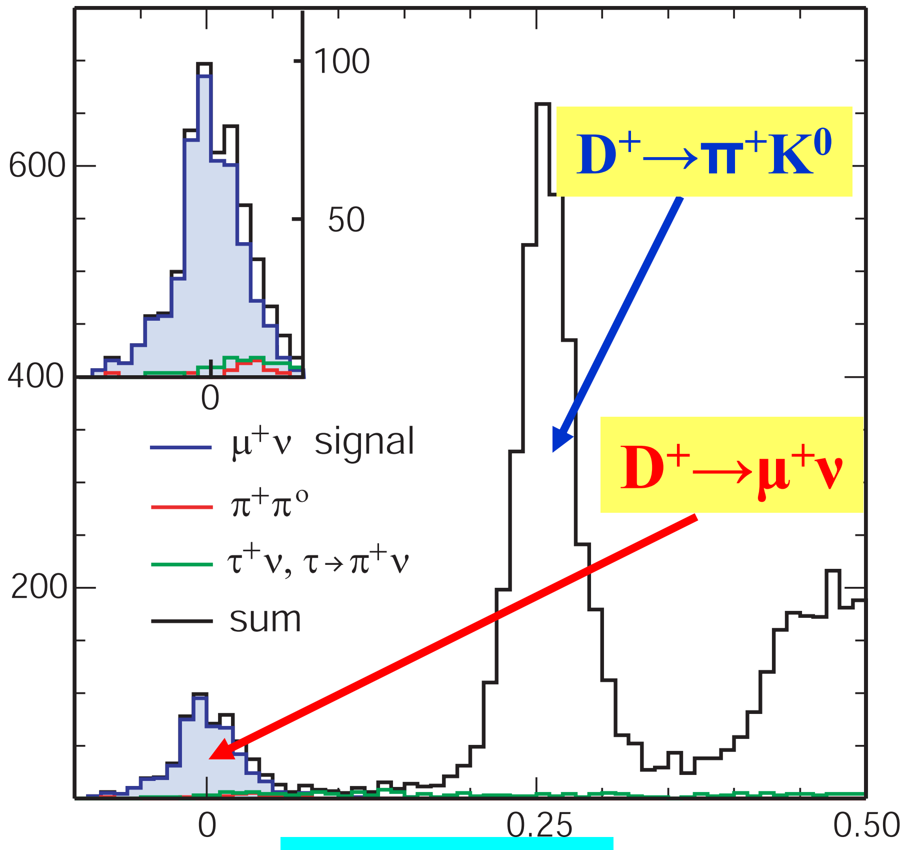
f_{D+} from Absolute $Br(D^+ \to \mu^+\nu)$

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

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

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

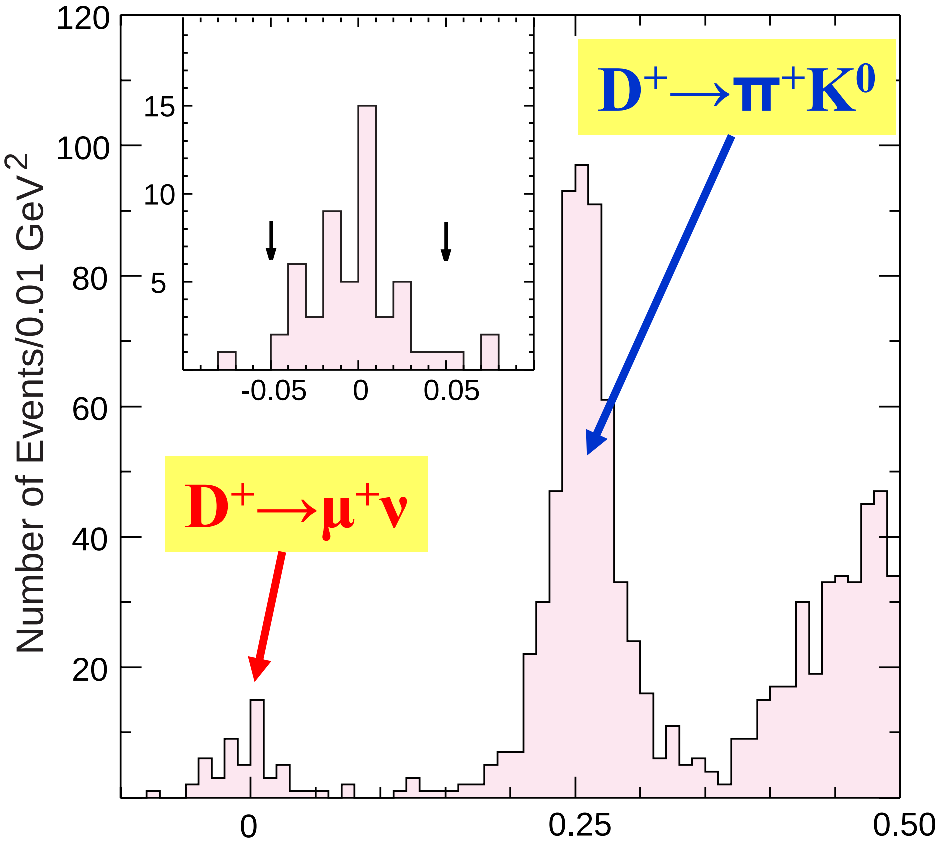
50 signal events



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

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

$MM^2 (GeV^2)$



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

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

$MM^2 (GeV^2)$

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

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

Tags 158,354

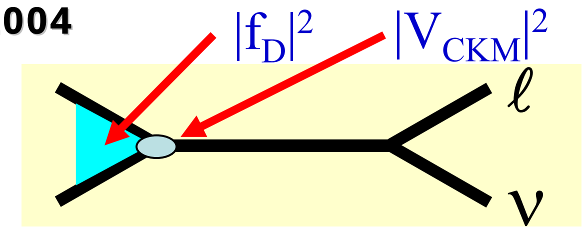
Signal 50 events ε=69.9%

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

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

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

PRD 70, 112004



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

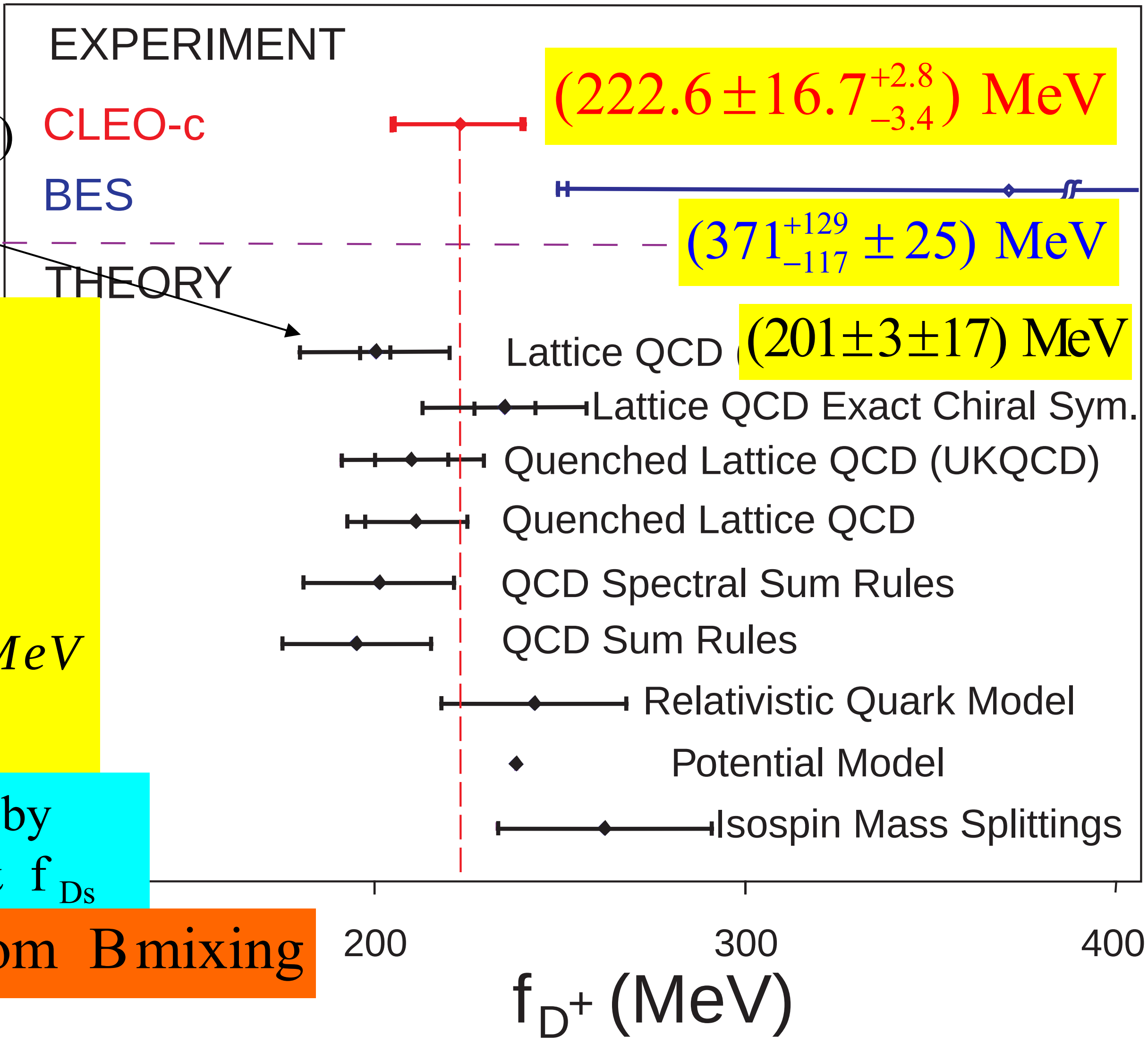
V_{cd} (known to <1%) unitarity

τ_{D+} well-measured (0.3%)

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

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

1st full unquenched lattice calc.
a prediction (2 days before LP03)



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

$(371^{+129}_{-117} \pm 25)$ MeV

$(201 \pm 3 \pm 17)$ MeV

Expt/LQCD consistent
Now: CLEO-c error 8%
LQCD error 8%
with $0.75 fb^{-1}$: f_{D+} to 4.5%
f_{Ds} to ~4.5% @ $\sqrt{s} \sim 4170 MeV$
BESIII several % f_{D+} & f_{Ds}

Need LQCD predictions to 5% by
2007 and a few % ~2009 f_{D+} & f_{Ds}

f_B / f_D for V_{td} from B mixing

No SM motivation to go beyond precision achievable by LQCD ~few %

Compare sensitivity existing B factories to charm factories

full data set
CLEO-c
$0.75\ fb^{-1}$
BESIII
$15\ fb^{-1}$

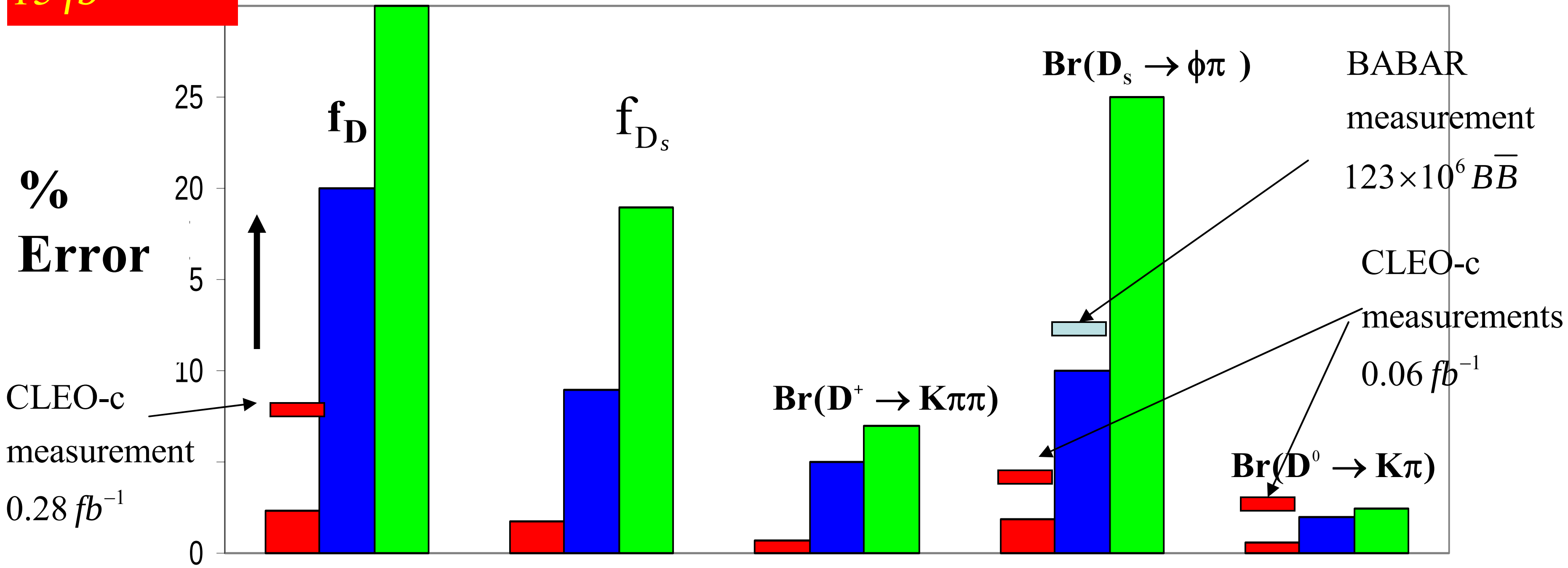
Charm factory
3 fb^{-1}

Statistics limited

BFactory
400 fb^{-1}

Systematics & Background limited

PDG04



BABAR measurement $123 \times 10^6\ B\overline{B}$

CLEO-c measurements $0.06\ fb^{-1}$

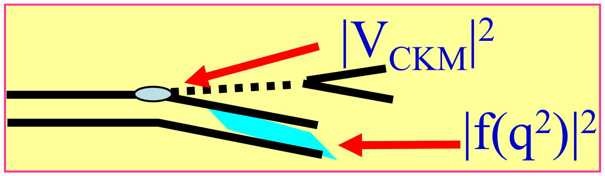
CLEO-c measurement $0.28\ fb^{-1}$

Plot made for CLEO-c Yellow Book in 2001 For charms's role in precision flavor physics the the conclusion that 3/fb at a charm factory is sufficient seems to be about right

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

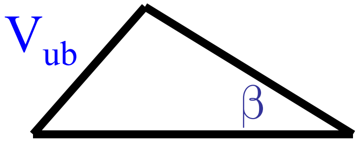
BABAR / Belle / CLEO

(World Average BF Summer 2005)

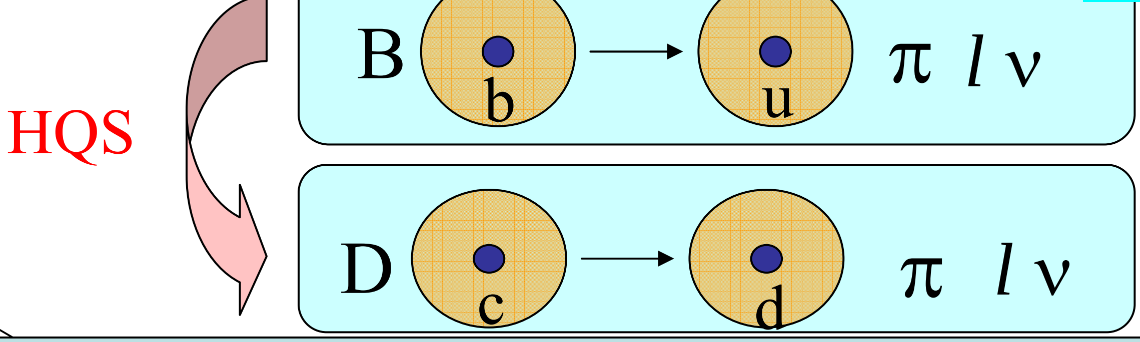
Expt. 4%

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

form factor



Typical Theory Error 18% hep-lat/0409116



$\frac{\delta B}{B} \sim 45\%$ PDG04

---

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

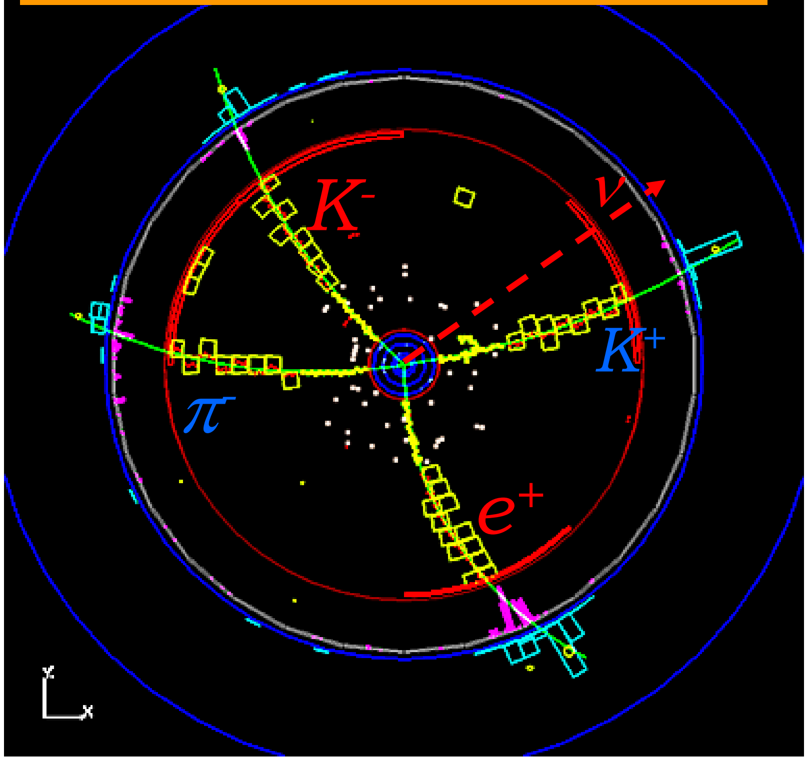
2) BaBar/Belle can extract V_{ub} using *tested* LQCD calc. of B→π form factor.

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

Absolute Branching Ratios of Semileptonic Decays at ψ(3770) CLEO-c

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

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



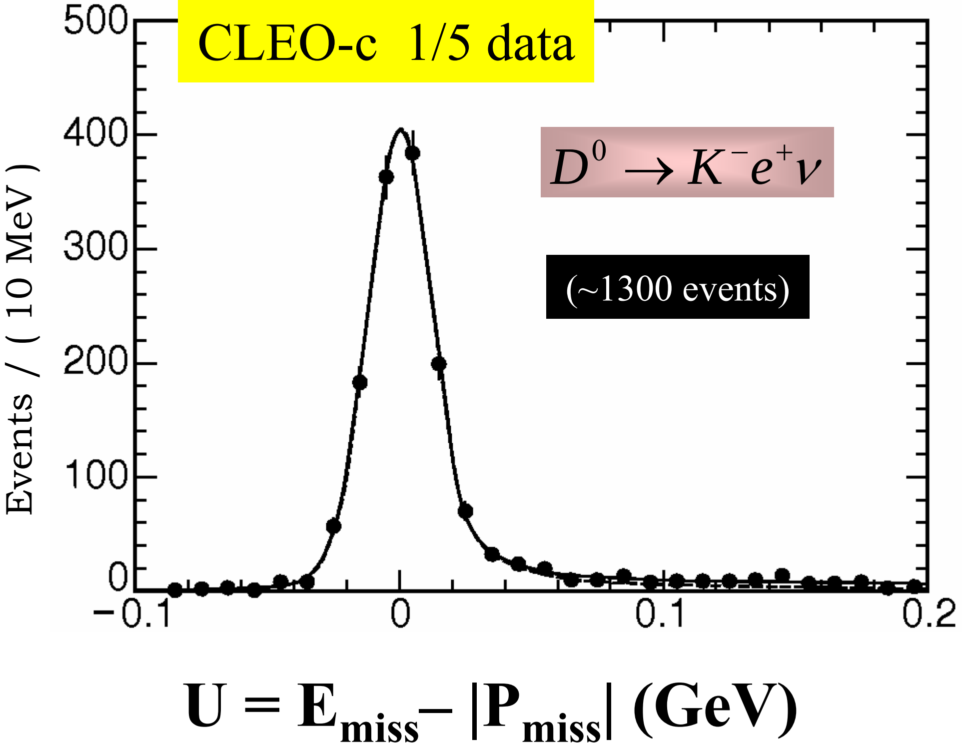
$$\psi(3770) \rightarrow D^0 \overline{D^0}$$

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

Tagging creates a single D beam of known 4-momentum

Semileptonic decays are reconstructed with *no* kinematic ambiguity

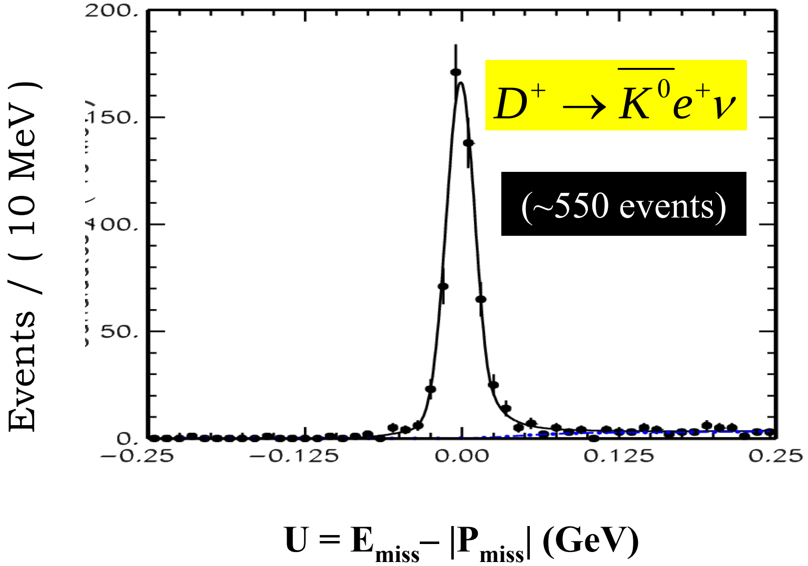
$$U \equiv E_{miss} - |\vec{p}_{miss}| = 0$$

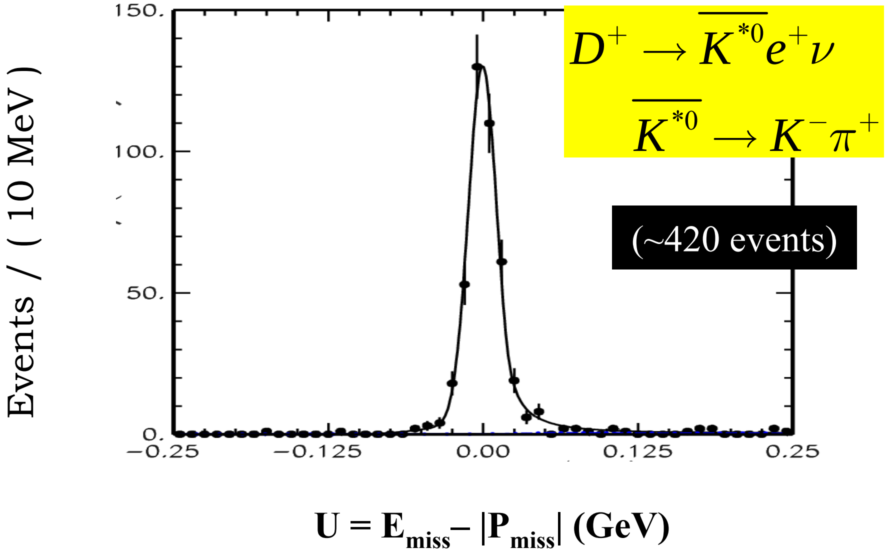


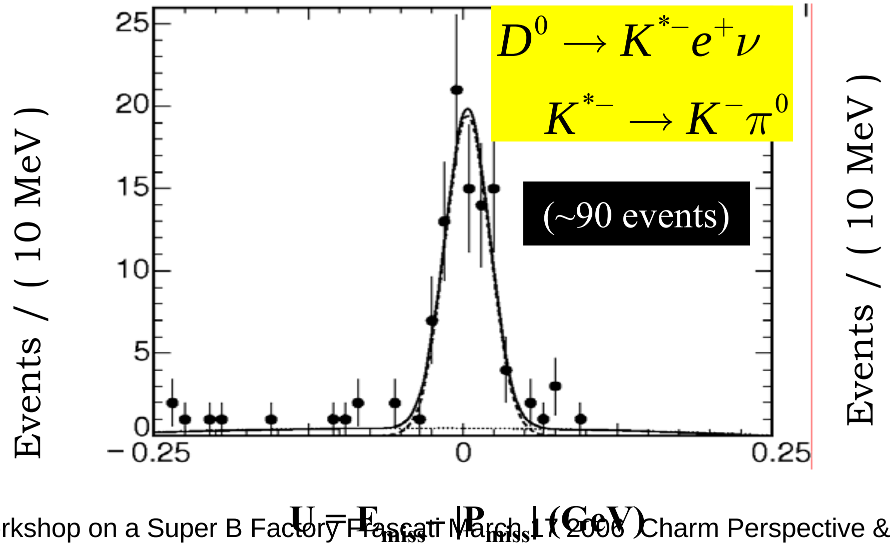
More Cabibbo allowed modes

c→*s* Cabibbo Favored

56 pb^{-1} Data



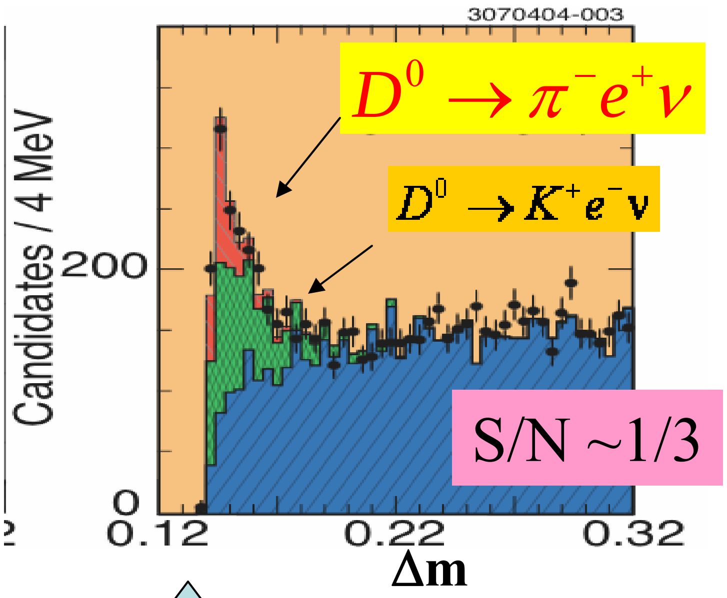




Historically Cabibbo allowed modes: provide a significant background to Cabibbo suppressed modes, making the latter particularly challenging…..

Cabibbo suppressed modes

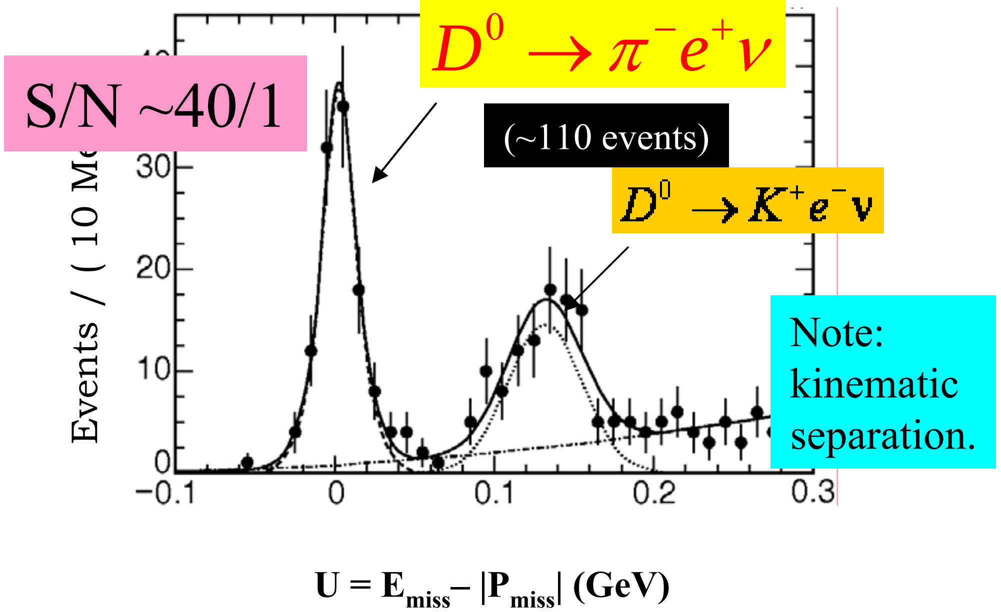
56 pb^{-1} Data



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

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

S/N ~1/3



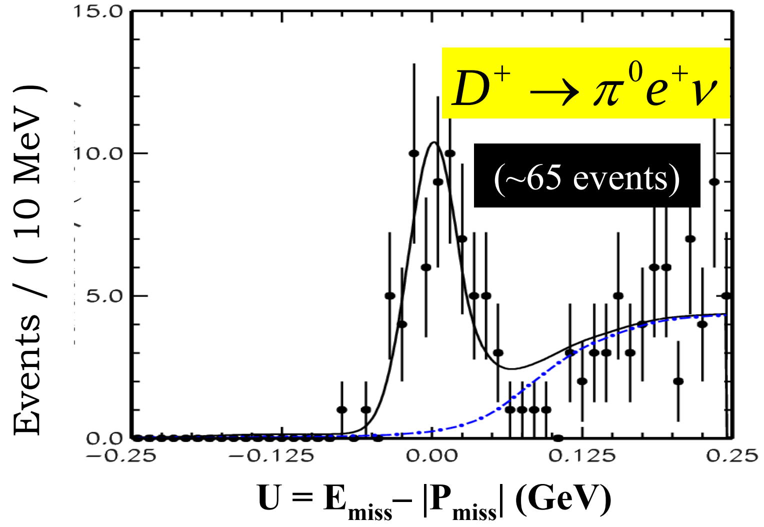
S/N ~40/1

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

(~110 events)

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

Note: kinematic separation.



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

(~65 events)

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

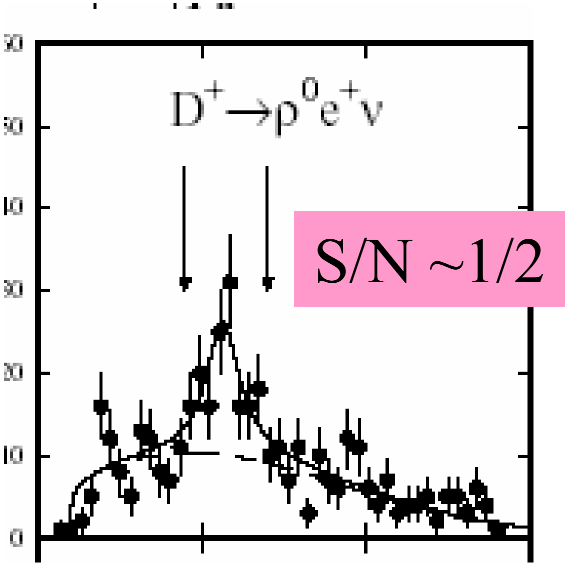
More Cabibbo supressed modes

56 pb^{-1} Data

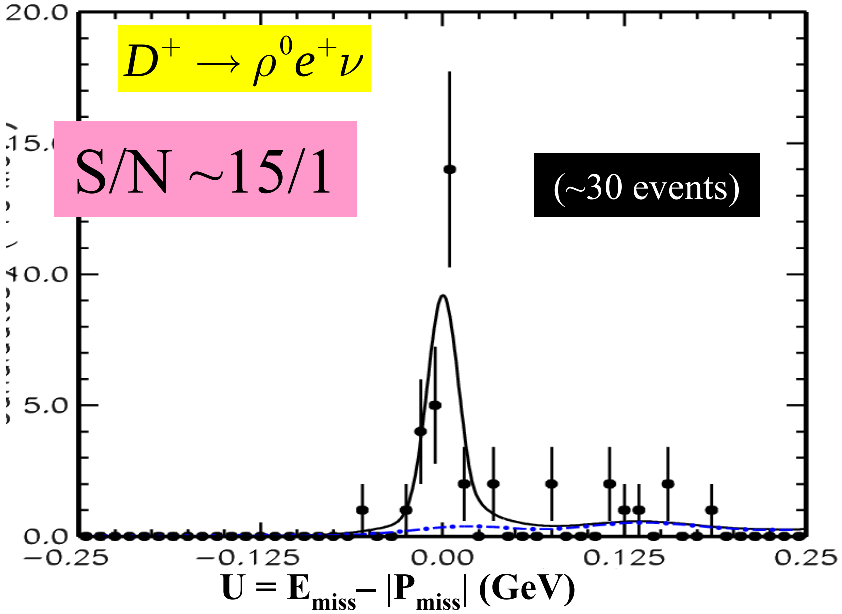
Only measurements untl now

E791

PLB 397 325 (1997)



S/N ~1/2



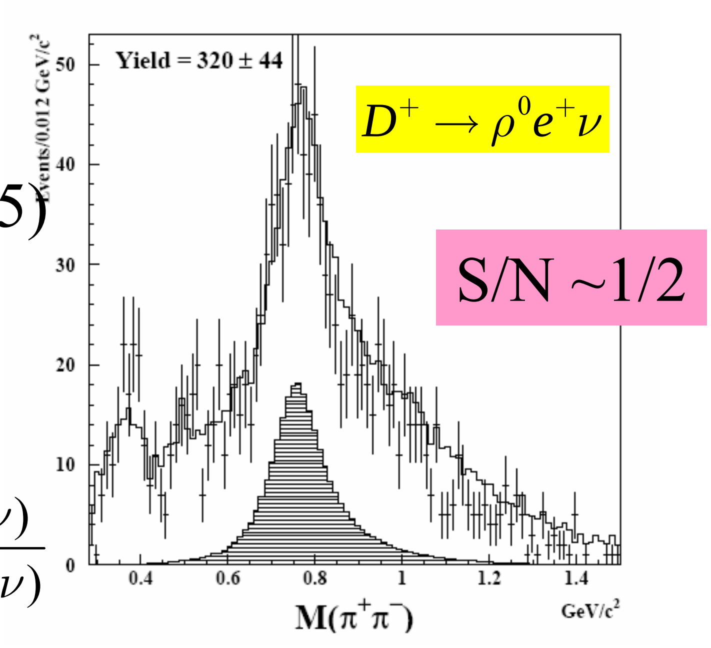
$D^+ \rightarrow \rho^0 e^+ \nu$

S/N ~15/1

(~30 events)

FOCUS

Hep-ex /0511022 (Nov 2005)



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

S/N ~1/2

Relative Rate:

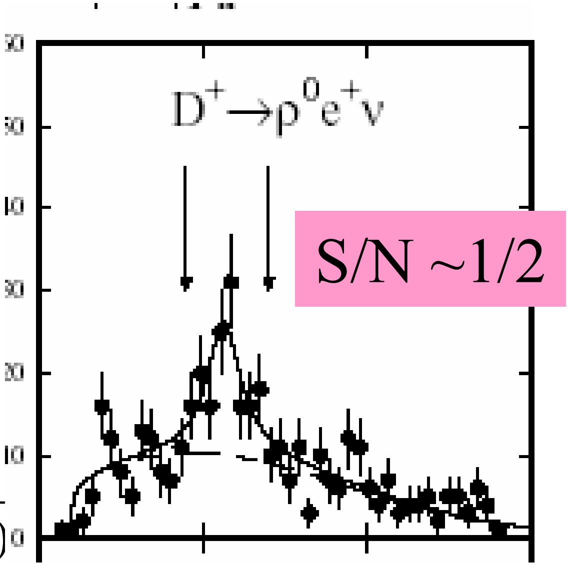
$$\frac{\Gamma(D^+ \rightarrow \rho^0 e^+ \nu)}{\Gamma(D^+ \rightarrow K^{*0} e^+ \nu)}$$

More Cabibbo supressed modes

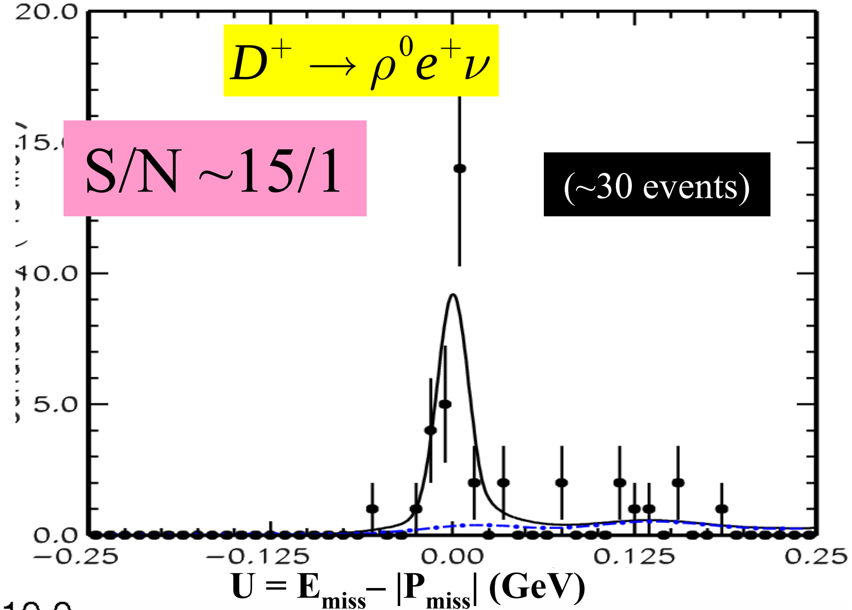
56 pb^{-1} Data

Only measurement untl now
E791
PLB 397
325
(1997)
Relative rate:

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



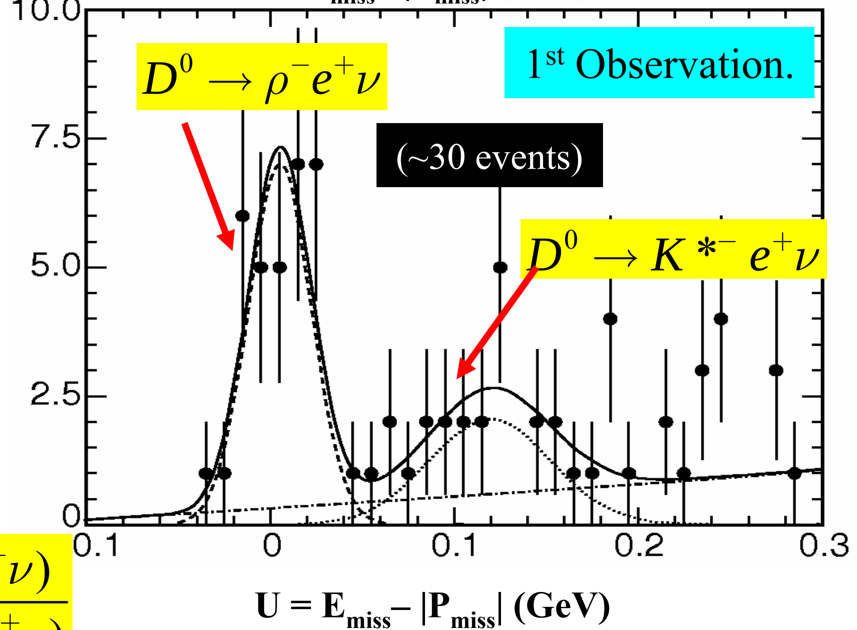
S/N ~1/2



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

S/N ~15/1

(~30 events)



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

1st Observation.

(~30 events)

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

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

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

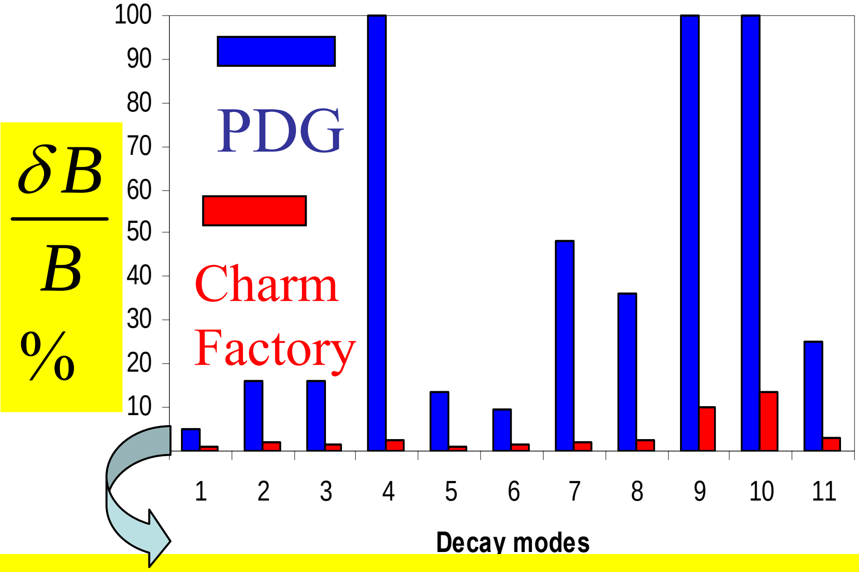
Results

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

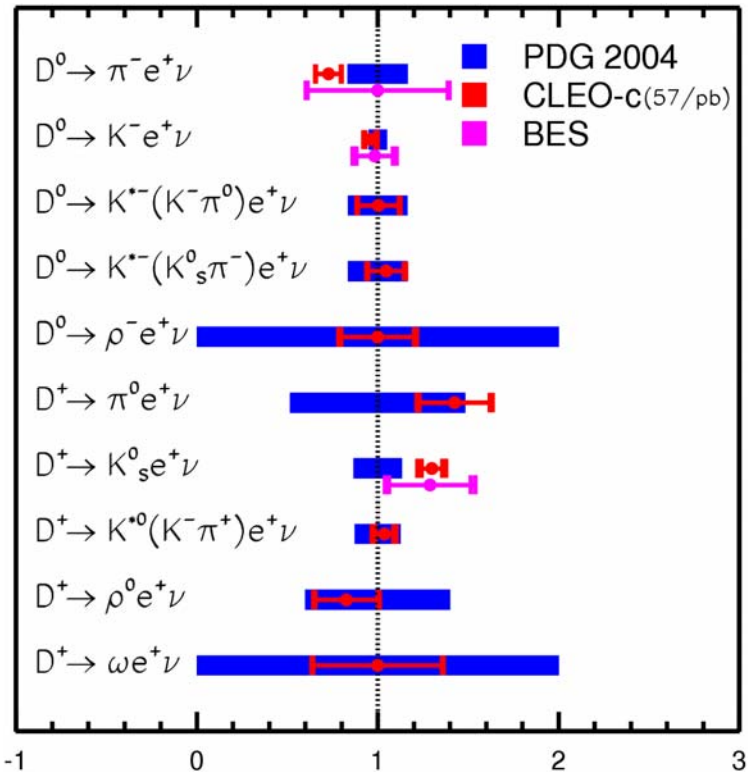
(Similar analysis but less precise from BES II)

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

Projection to 3/fb (BESIII)



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

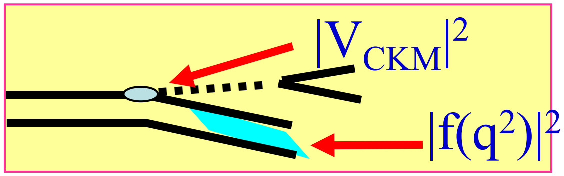


Normalized to PDG

CLEO-c already all modes more precise than PDG.

significant improvements in the precision of each absolute charm semileptonic branching ratio (CLEO-c,/BES III) no SM motivation to measure to better than ~1%

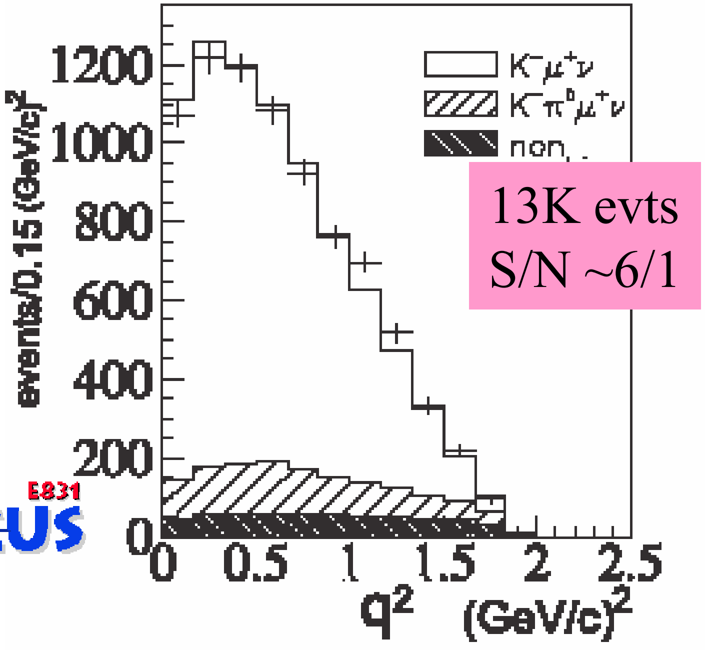
The form factor $\frac{d\Gamma}{dq^2} \propto |V_{cs}|^2 |f_+^{D\to K}(q^2)|^2$



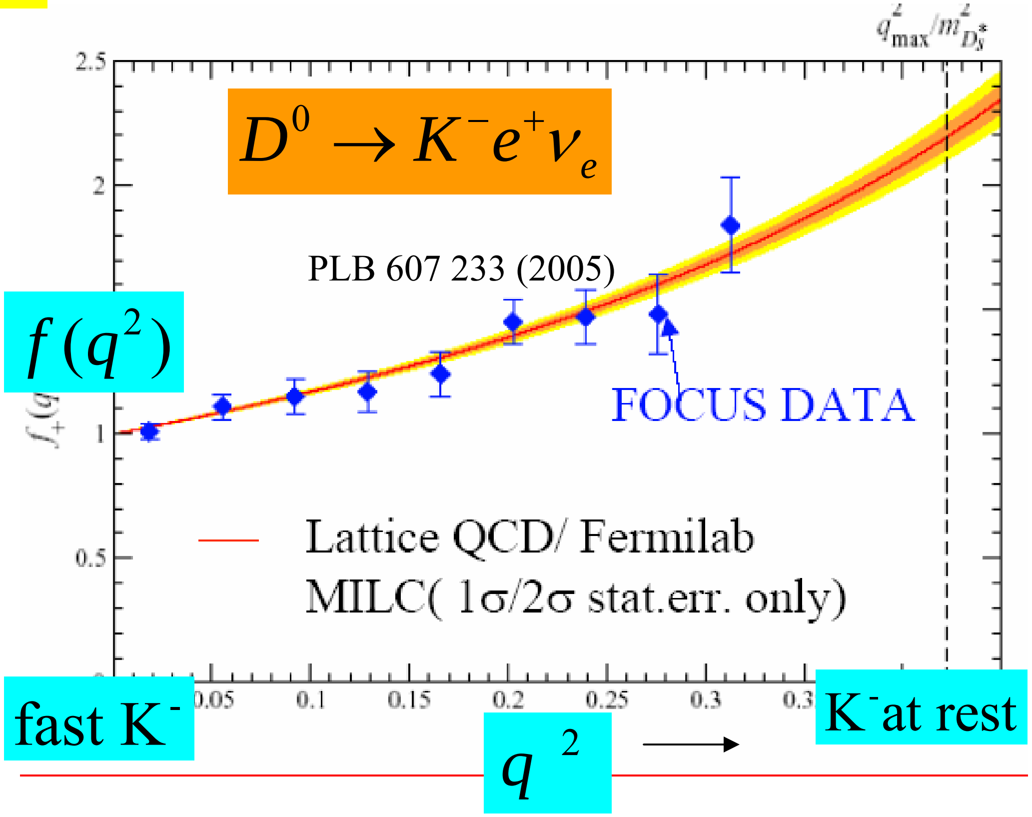
Tag with $D^{*+} \to D^0 \pi_s$ FOCUS all data

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

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



13K evts
S/N ~6/1



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

$f(q^2)$

fast K⁻

q^2 →

K⁻ at rest

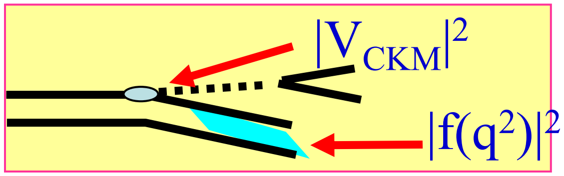
Impressive work by FOCUS.

LQCD : shape ~ correct:

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

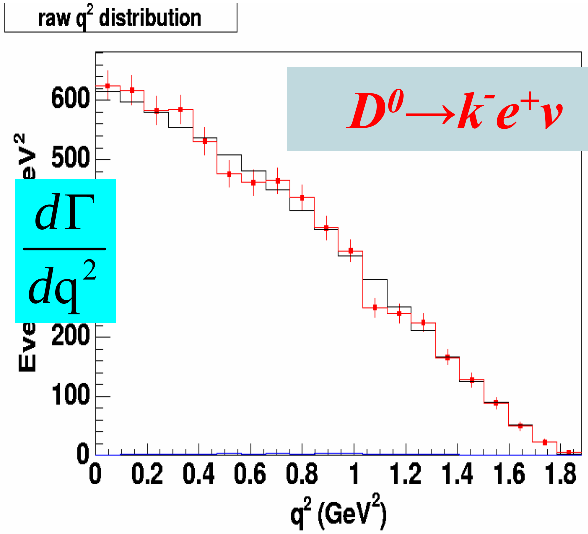
New analysis from Belle 282/fb where 2D's in the event are reconstructed yields results consistent with and slightly more precise than FOCUS

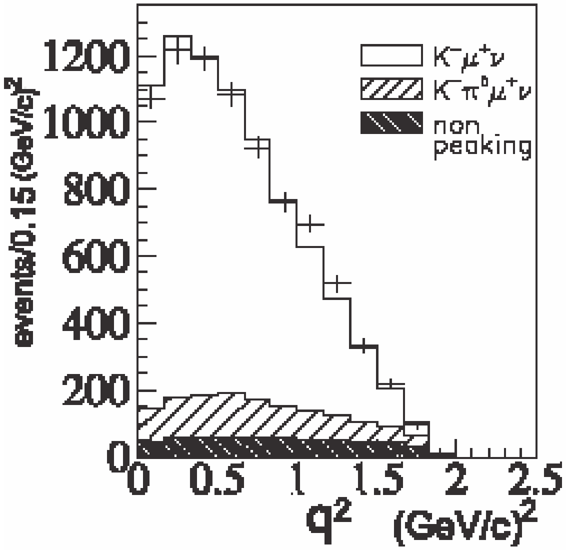
The form factor $\frac{d\Gamma}{dq^2} \propto |V_{cs}|^2 |f_+^{D\to K}(q^2)|^2$

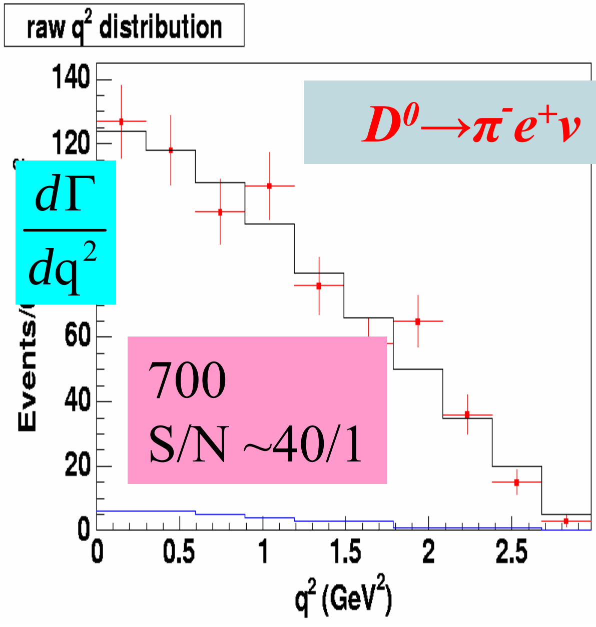


CLEO-c (preliminary)

FOCUS all

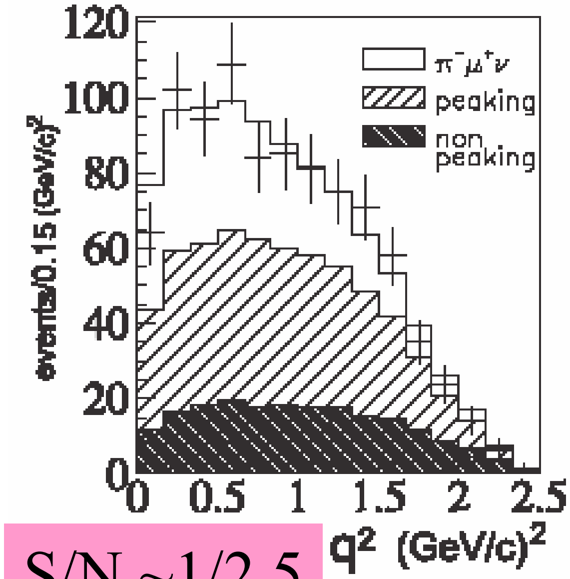






700

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

Charm threshold advantage
1) Low background crucial for π final state
2) neutrino direction known

$\frac{\delta q^2}{q^2} \sim 0.1\ \text{GeV}^2\,(\sigma)$ FOCUS

$\sim 0.01\ \text{GeV}^2\ (\sigma)$ CLEO-c

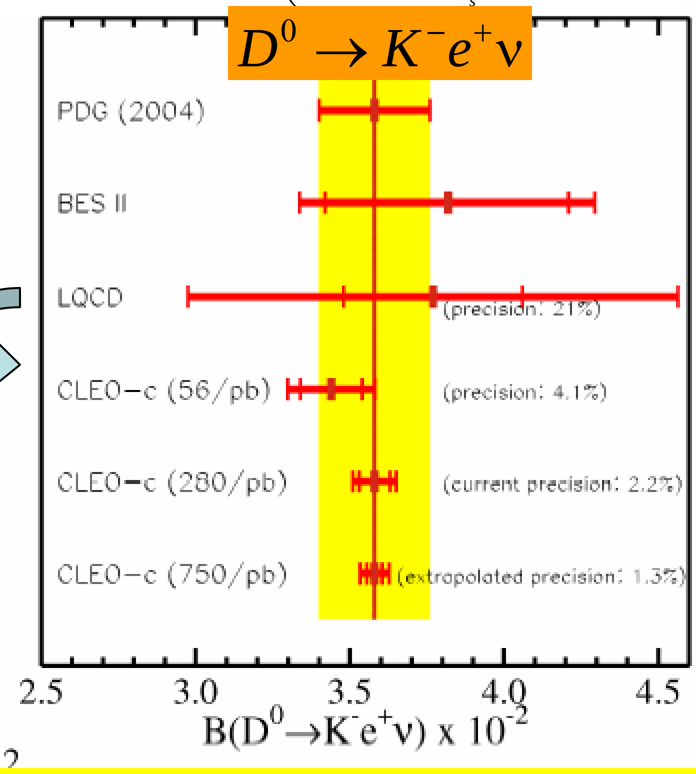
CLEO-c results in April
D→Kev: precision>LQCD
D→pi ev: X3 more precise than previous expt. A few/fb sufficient to match ultimate LQCD precision

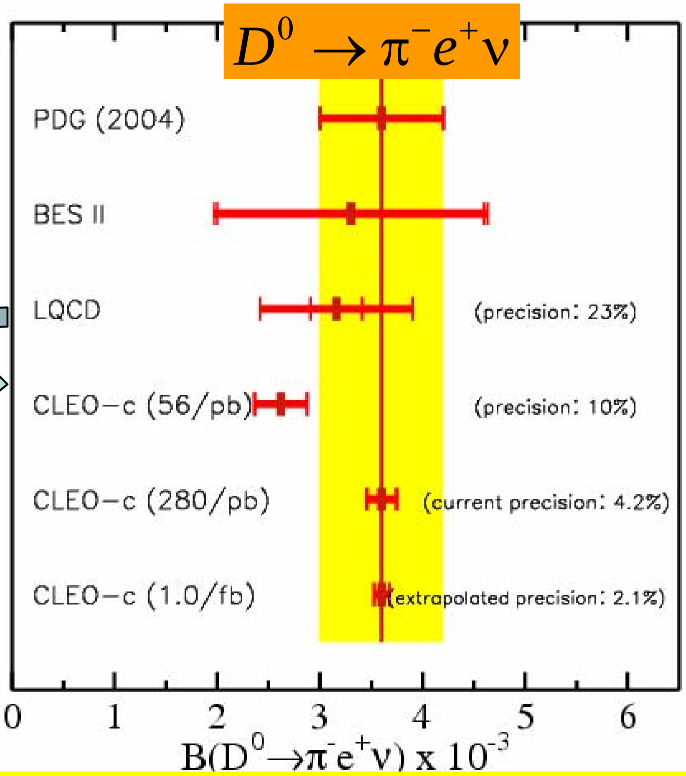
Lattice comparison: the form factor normalization

Lattice shape: agreed with data, lattice predicted branching fraction tests normalization (need absolute branching fractions to test this- easiest at charm factories)

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

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





(for lattice use PDG Vcs, Vcd)

Belle results (not shown) Comparable precision to CLEO-c 56/pb

CLEO-c data has improved the precision of this test, LQCD normalization & data agree (at ~10% level) (data already much more precise, expect another X2 improvement in April)

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

(My estimates not
official CLEO-c)

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

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, i.e. Vcd=Vus)

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):

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

$$R^{\exp}_{\ell s \ell} = 0.25 \pm 0.02 \longleftarrow \sim 10\% \text{ uncertainty}$$

Theory & data consistent errors large

0.75fb^{-1} @ $\psi(3770)$ R_{lsl}^{exp} ~5% uncertainty, (3 fb^{-1} several % @ BESIII)

If theory passes the test $R_{lsl}^{exp} = R_{lsl}^{th}$ Ultimate VCKM precision?

0.75 fb^{-1}

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

(Now 1.3%)

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

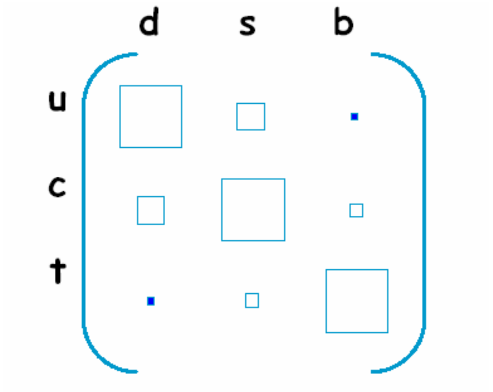
(Now 5.4%)

for VCKM with 0.75fb^{-1} precision of data will challenge theory & with few fb^{-1} precision sufficient to match conceivable improvements in theory

Tested lattice for Vub determination at B factories

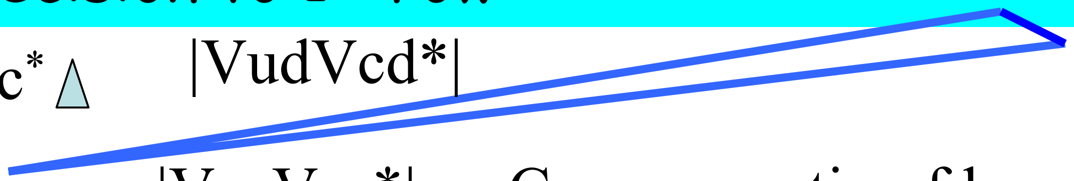
Unitarity Tests Using Charm

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



$uc^{*}=0$

- 2nd row: $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$??
  CLEO-c now: $|1-\{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2\} = 0.037\pm0.181$
  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
  (750pb^{-1})
- uc^{*} △



$|V_{ud}V_{cd}^{*}|$

$|V_{ub}V_{cb}^{*}|$

$|V_{us}V_{cs}^{*}|$

Compare ratio of long sides to few %

Charm As a Probe of 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.

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 $\leq 10^{-6}$

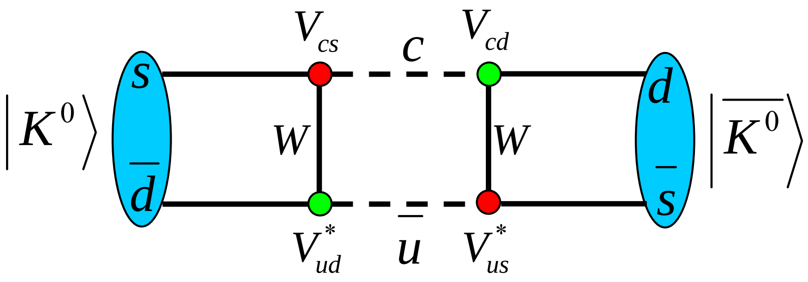
D^0 - $\bar{D}^0$ mixing $\leq 10^{-2}$

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:

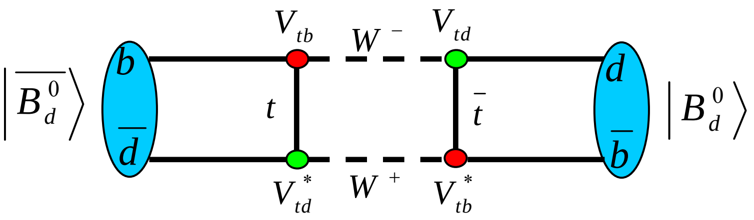


CKM factors $\propto \Theta_c^2$
same order as τ_{kaon}
i.e.s → u

Mixing rate ≈1

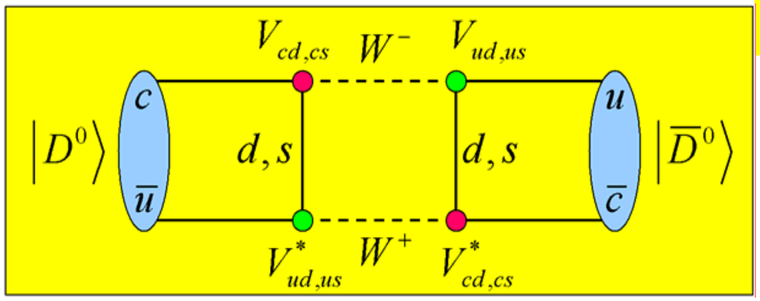
Mixing rate (1958) used to bound c quark mass → discovery(1974).

CPV part of transition , ε_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 τ_D not Cabbibo suppressed $(V_{cs}\sim 1)$

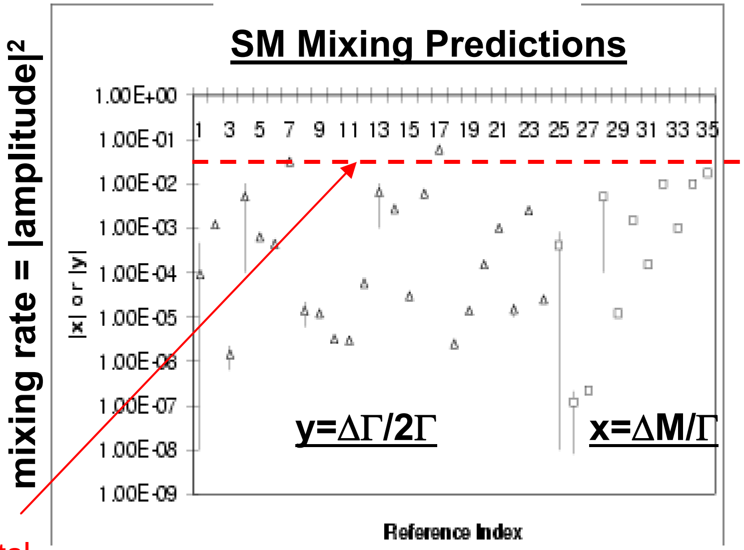
Mixing rate ≈0.05

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

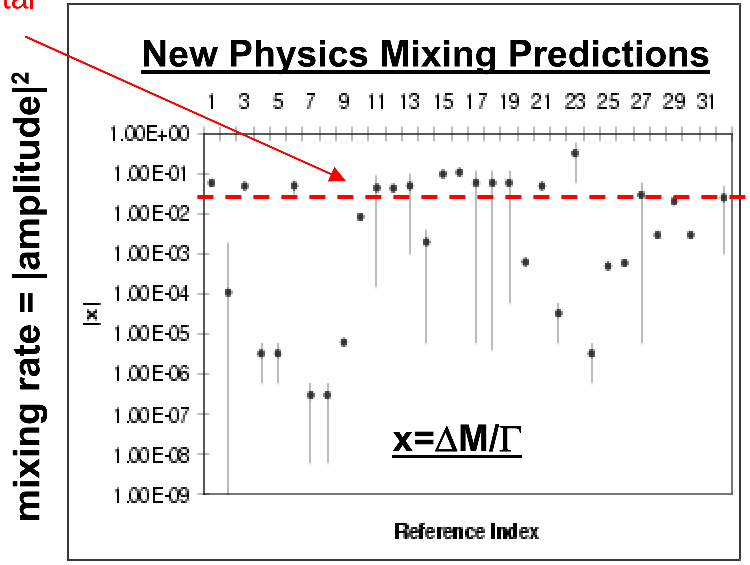
10^{-2} possible

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

Theoretical “Guidance”

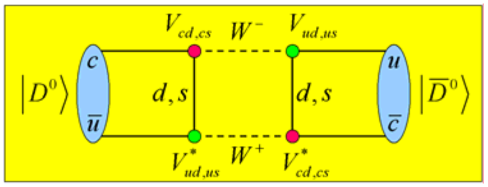


current experimental sensitivity



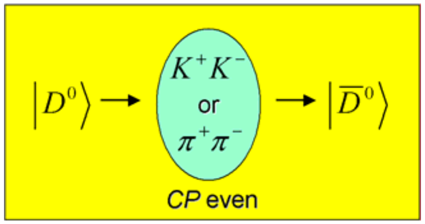
(A. Petrov, hep/ph 0311371)

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 evidence for NP.unless x>>y

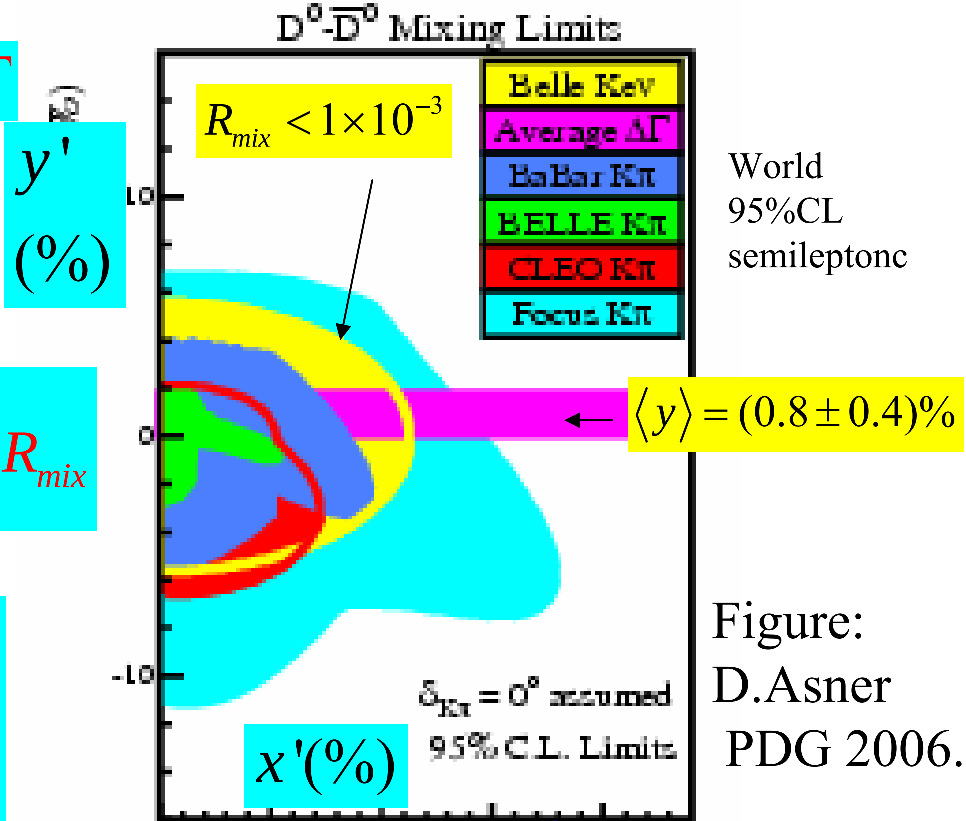
Smallness of Vbc & Vub limits b quark contribution ➔ D mixing is a 2 generation phenomenon ➔ no CPV in mixing, if seen →New Physics

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

No sign of D mixing yet

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

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



World
95%CL
semileptonc

Figure:
D.Asner
PDG 2006.

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

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

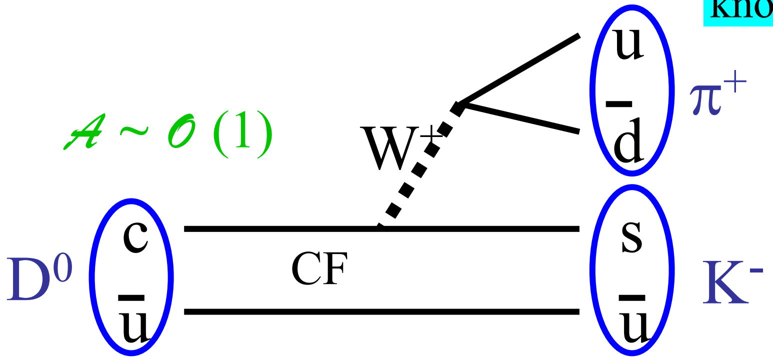
$\propto x^2 + y$

if CF/DCS

phase $\delta_{K\pi}$

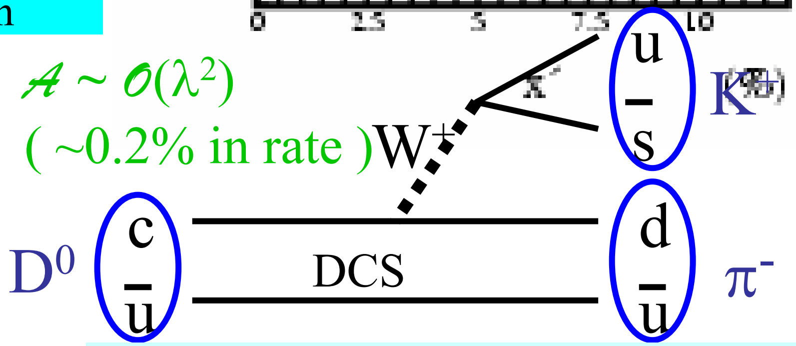
known

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



$\mathcal{A} \sim \mathcal{O}(\lambda^2)$

(~0.2% in rate)



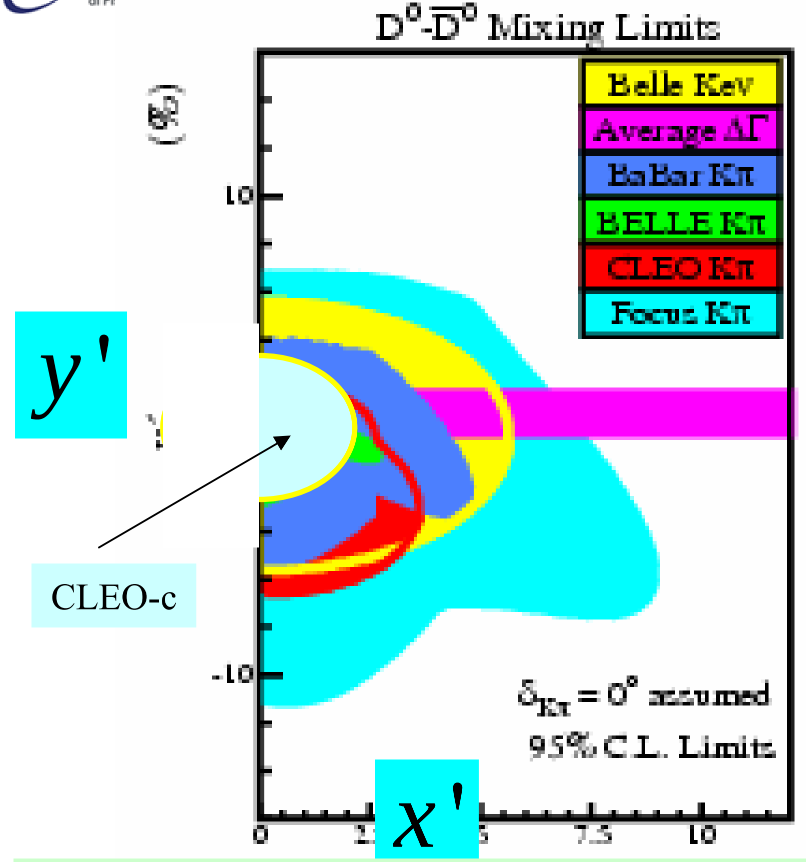
Mimics

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

$\to K^+\pi^-$

See talks by Milind Purohit and Alan Schwartz

Charm factory mixing (+ input to ϕ_3 /γ)



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

Coherence simplifies study no DCSD

simplest approach

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

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

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

750/pb: $R_{mix} < 1.4\times10^{-4}$ $(x < 1.7\%)$

$now\, R_{mix} < 10^{-3}$ $(x < 4\%)$

→ comparable sensitivity to other expts.

different systematics (time independent)

TQCA @ BESIII 10/fb $\psi(3770)$ & 4160:

preliminary: x<0.9% y<0.6% (stat. only)

TQCA 1/ab @ superflavour @$\psi(3770)$

x~1×10^{-3}! cf $x <$ ~1% @ 10 GeV/10/ab

(Purohit DIF06) + D(t) → $K^0\pi^+\pi^-$Dalitz

greater sensitivity. $x <$ ~.4% LHCb (Nakada DIF06) → careful evaluation needed, so far

superflavour @3770 looks very attractive

A more sophisticated approach

The Quantum Correlated Analysis

(TQCA) fits single/double CP/flavor

tag yields @$\psi(3770)$ &4160

$\propto B_i\ x^2$, y, & strong phases δ.

CLEO-c sensitivty x<2.7% y<1.3%

Dif06
Asner

CP Eigenstates @ ψ(3770) & strong phases

At the ψ”(3770)

$$e^+e^- \to \psi'' \to D^0\bar{D}^0$$

$J^{PC} = 1^{--}$ i.e. CP+

A D^0 is observed to decay to a CP eigenstate f_1 which is CP even:
Then in the limit of CP conservation, the state recoiling against the tag has a definite CP as well and it must be of opposite sign :

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

- Example
  Two CP eigenstates of opposite sign

$$\underset{+}{(\pi^+\pi^-)}\underset{-}{(K_s^0\pi^0)}\underset{-}{(-1)^\ell} = CP+$$

- CP eigenstate tag X flavor mode

$$\underset{+}{K^+K^- \leftarrow D_{CP}} \leftarrow \psi(3770) \to \underset{-}{D_{CP}} \to K^-\pi^+\ \underset{-}{(-1)^l} = CP+$$

Charm factories measure δ by using CP tagging (δ needed to interpret mixing in Kπ at B Factories/Tevatron)

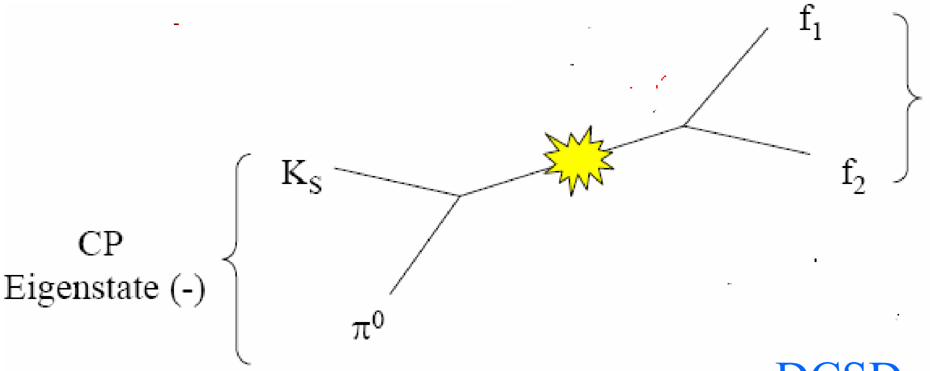
Basic Measurement of a Strong Phase

- If CP violation in charm is neglected: mass eigenstates = CP eigenstates

$$\left|D_{CP\,\pm}\right\rangle=\frac{1}{\sqrt{2}}\left[\left|D^{0}\right\rangle\pm\left|\overline{D^{0}}\right\rangle\right]$$

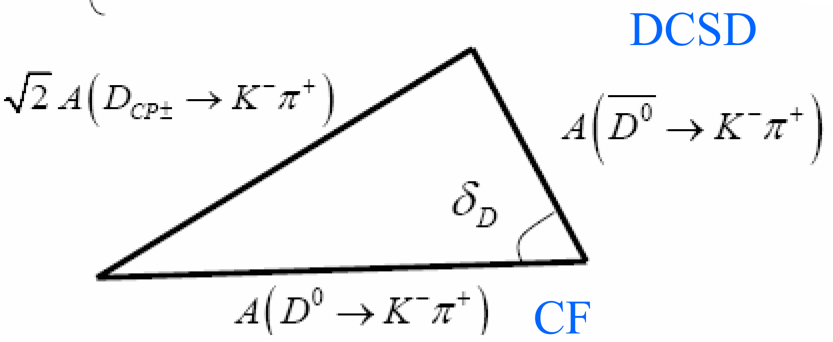
$$\sqrt{2}\,A\left(D_{CP\pm}\to K^{-}\pi^{+}\right)=A\left(D^{0}\to K^{-}\pi^{+}\right)\pm A\left(\overline{D^{0}}\to K^{-}\pi^{+}\right)$$

CF DCSD



Flavor mode

$$D_{CP\,(+)}\to f_1 f_2$$



In the limit of CP-invariance

$$A\left(D^{0}\to K^{+}\pi^{-}\right)=A\left(\overline{D^{0}}\to K^{-}\pi^{+}\right)$$

Currently cos δ_D unknown

Method limited CP tag statistics

Extend method TQCA with 0.75/fb @ 3770 & 4160

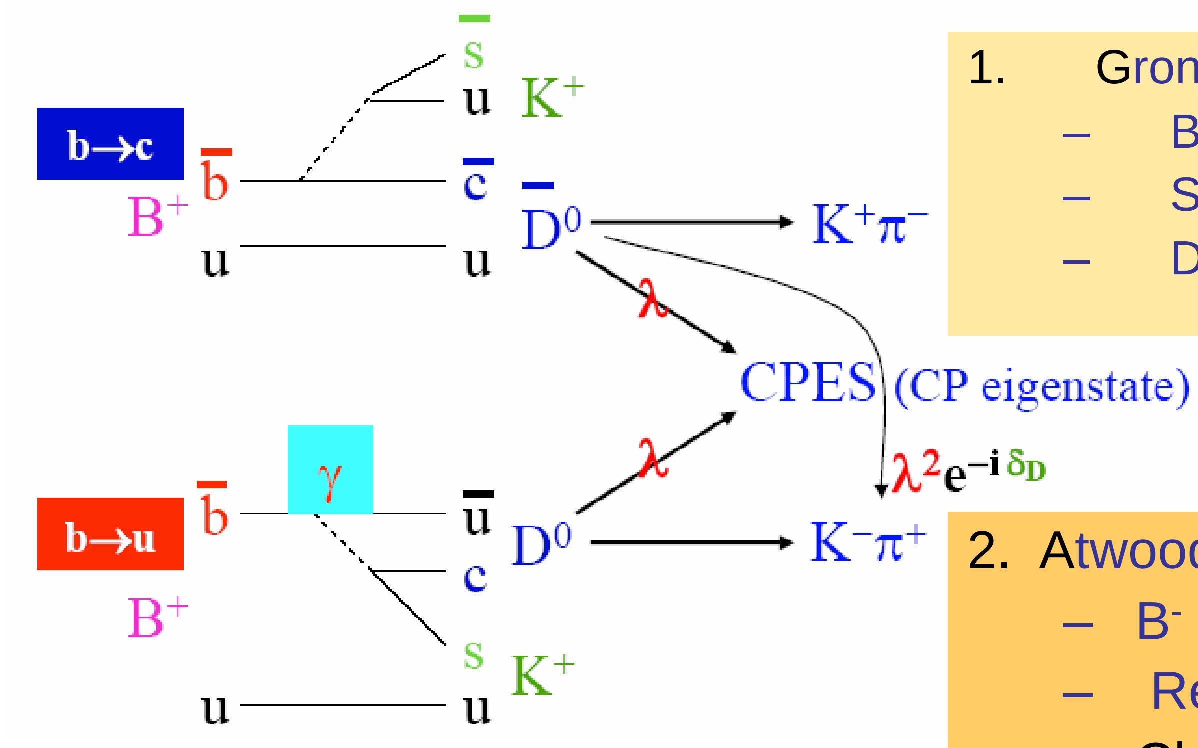
cos δ_D ~ ±0.13 BESIII 10/fb

@3770 & 4160 cos δ_D ~ ±0.05

$$\boxed{\cos\delta_D=\frac{Br\left(D_{CP+}\to K^{-}\pi^{+}\right)-Br\left(D_{CP-}\to K^{-}\pi^{+}\right)}{2\sqrt{r_D}\,Br\left(D^{0}\to K^{-}\pi^{+}\right)}}$$

as r_D is well measured $r_D=(3.74\pm0.18)\times10^{-3}$

Charm Factory INPUTS TO CKM ANGLE ϕ_3 /γ



1. Gronau-London-Wyler Method
   - $B^- \to D_{CP} K^-$
   - Statistics Limited so far
   - D mixing parameters can alter γ

2. Atwood-Dunietz-Soni Method
   - $B^- \to D K^-$
   - Requires very large Ldt
   - Charm factory measures cos δ_D

3. Dalitz plot Method
   - $B^- \to DK^-$, $D \to K_s\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K_sK^+K^-$

Charm Factory INPUTS TO CKM ANGLE ϕ_3 /γ

3. Dalitz plot Method

- $B^- \to DK^-$, $D \to K_s\pi^+\pi^-$

currently most accessible method experimentally.

Model uncertainty can be reduced by analyzing CP tagged Dalitz plots at CLEO-c

Belle PRD70 072003 (2004)

$$\phi_3 = (68 \pm 14 \pm 13 \pm \boxed{11})^o$$

BaBar hep-ex/0507101

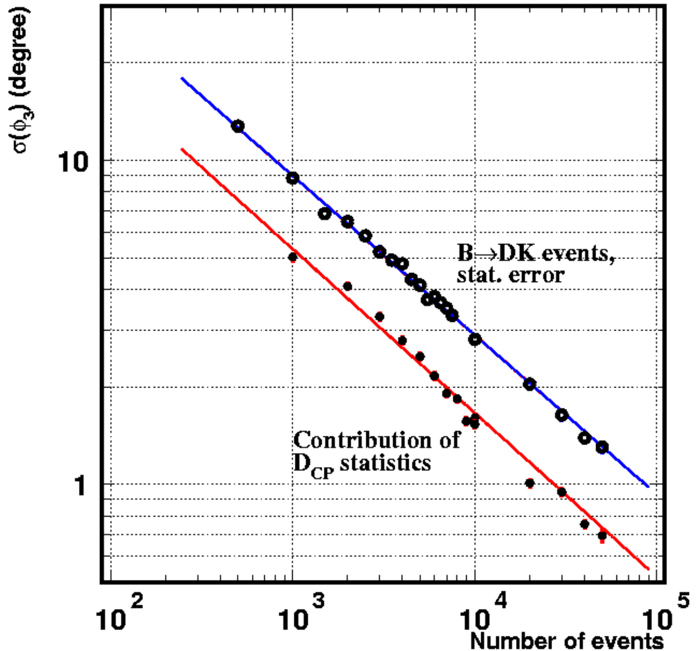
$$\gamma = (67 \pm 28 \pm 13 \pm \boxed{11})^o$$

D Decay Model Systematic Uncertainty

- Toy MC from Belle (Bondar hep-ph/05/10246) estimates statistical error on γ/ϕ_3 vs statistics in D Dalitz plot from B+→DK+,
  - 1 ab^{-1}/B-factory ±6° stat,
  - 10 ab^{-1}/B-factory ±2° stat
- And the number of CP tagged D's.
  - 750 pb^{-1} ⇒ 6° systematic
  - Need 10/fb at charm factory BES III to obtain error ±2° systematic error (sufficient)
  - CLEO-c Statistics (281 pb^{-1}) consistent with this prediction

Sys. Error on γ/ϕ_3

Stat. Error on γ/ϕ_3



of $B^+ \to DK^+$, $D \to K_S\pi^+\pi^-$

of CP tagged $D \to K_S\pi^+\pi^-$

CPV in D Decays

I’ll ignore CP violation in mixing (as it is negligible).

CPV via interference between mixing & decay (D^0 only)

$$\Gamma\left(\begin{tikzcd} & \bar{D}^0 \arrow[dr, bend left] & \\ D^0 \arrow[ur, bend left] \arrow[rr, bend right] & & f \end{tikzcd}\right) \neq \Gamma\left(\begin{tikzcd} & D^0 \arrow[dr, bend left] & \\ \bar{D}^0 \arrow[ur, bend left] \arrow[rr, bend right] & & f \end{tikzcd}\right)$$

Very small in charm since mixing is suppressed
(i.e. good hunting ground for New Physics).

Time dependent since mixing is involved

Direct CPV:

Concentrate on this

$$\Gamma\left(\begin{tikzcd} D \arrow[r, bend left, "A_1 e^{i\delta_1}"] \arrow[r, bend right, "A_2 e^{i\delta_2}"'] & f \end{tikzcd}\right) \neq \Gamma\left(\begin{tikzcd} \bar{D} \arrow[r, bend left, "A_1^* e^{i\delta_1}"] \arrow[r, bend right, "A_2^* e^{i\delta_2}"'] & \bar{f} \end{tikzcd}\right)$$

$$A_{CP} = \frac{\Gamma(f)-\Gamma(\bar{f})}{\Gamma(f)+\Gamma(\bar{f})} = \frac{2 Im A_1 A_2^* sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 Re A_1 A_2^* cos(\delta_1 - \delta_2)} < 10^{-3}$$

2 weak amplitudes with phase difference

strong phase-shift

Direct CP Violation

$$Acp \approx \frac{\mathrm{Im}\left[V_{cd}V_{ud}^{*}V_{cs}V_{us}^{*}\right]}{\lambda^{2}}\sin\delta_{PT}\frac{P}{T} \simeq A^{2}\eta\lambda^{4}\sin\delta_{PT}\frac{P}{T} \le 10^{-3}$$

In Standard Model Direct CPV only for Singly Cabibbo suppressed decays.

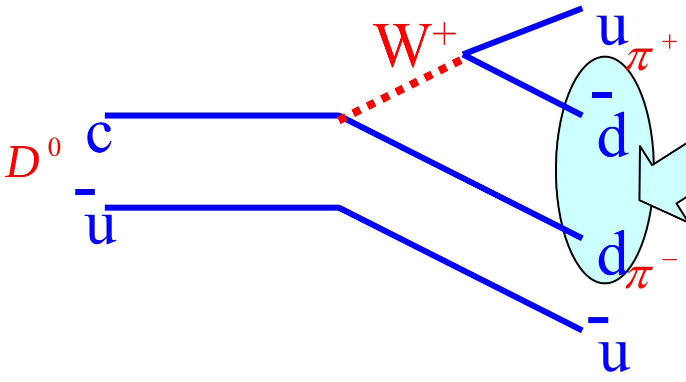
1) Consider $D^0 \to \pi^+\pi^-$

(same for K^+K^- $\left\{K^+K^-\pi^+, \phi\pi^+, K^*K\right\}$ $K^+K^-\pi^0$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, etc...)

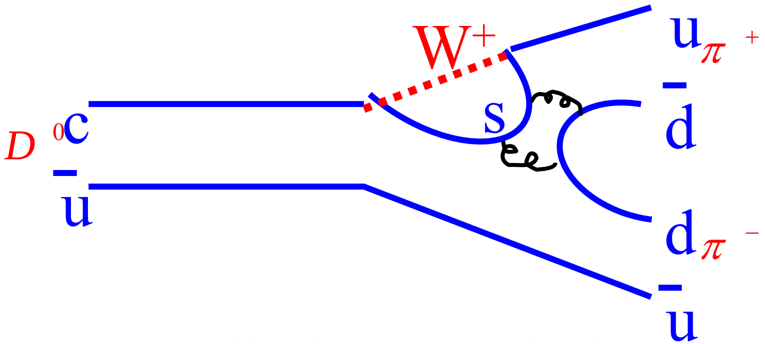
Standard Model Contribution $A_{CP} \sim 10^{-3}$

New Physics up to ~1%

If CP~1% observed:is it NP or hadronic enhancement of SM? Strategy: analyze many channels to elucidate source of CPV.



Since this decay is Singly Cabibbo Suppressed…



…we can modify it's topology in a simple way to get a penguin.

$V_{cd}^{*}V_{ud}$

↑

different weak phases

↓

$V_{cs}^{*}V_{us}$

$\Delta I = \frac{1}{2}, \frac{3}{2}$

↑

different strong phases are likely

↓

$\Delta I = \frac{1}{2}$

Current limits ~1% in best cases

CP Violation at ψ(3770)

@ 3770
Unique search strategy
Complementary to other expts.

$e^+e^- \to \psi'' \to D^0D^0$ $J^{PC} = 1^{--}$ i.e. CP+

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

CP conserving

- CP violating asymmetries can be measured by searching for events with two CP odd or two CP even final states ex:

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

CP violating

K-K+ $A_{cp} < 0.08$ (CLEO-c) , $< 4 \times 10^{-3}$ (BESIII), 6×10^{-5} (superflavour/10^7s)
(1.4×10^{-4} (stat) LHCb/yr)

2nd method D (flavor) D (CP)

- $A_{cp} < 0.025$ (CLEO-c) , $< 6 \times 10^{-3}$ (BESIII), 7×10^{-4} (superflavour)

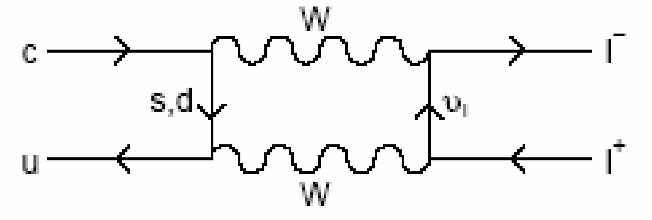
Many other strategies exist to search for CP violation
Ex: CP tagged Dalitz plots. are particularly interesting as they are sensitive to amplitudes, rather than rates

Rare Charm Decays

The absence of FCNC in kaons lead to the prediction of charm,
Large B mixing (a FCNC process) was evidence for heavy top
FCNC in charm have so far been less informative, & less studied
Short distance charm FCNC are much more highly suppressed by the GIM mechanism than down type quarks due to the large mass difference between up type quarks

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

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



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}

Best limits are from BABAR

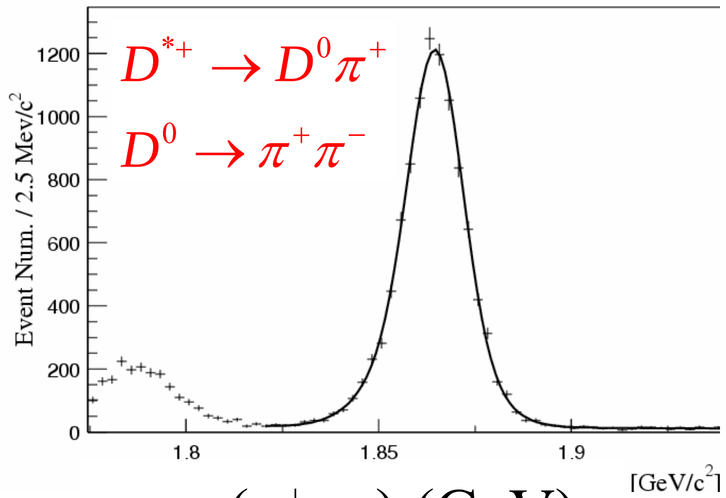
(Burdman et al., Phys. Rev. D66, 014009).

Search for $D^0 \rightarrow e^+e^-, \mu^+\mu^-, e^\mp\mu^\pm$ @ BABAR

PRL 93 101801 (2005)

Normalizing mode:

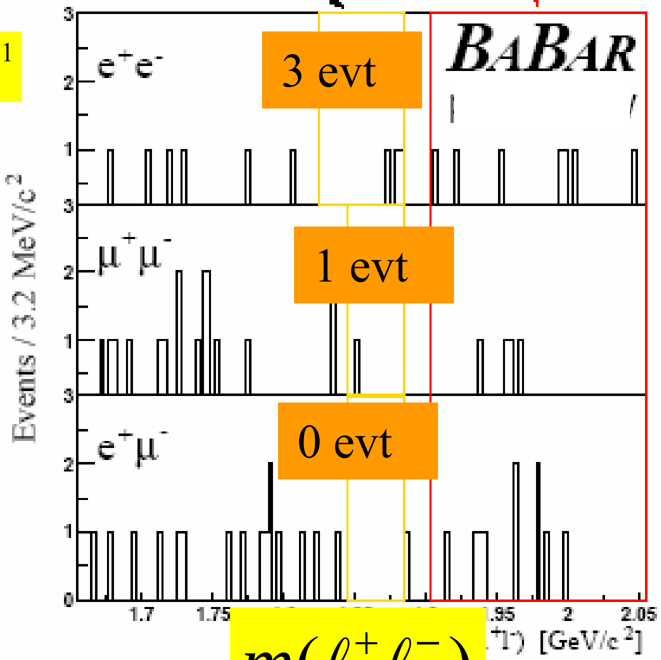
121.6 fb^{-1}



mass(π^+,π^-) (GeV)

Search channels

121.6 fb^{-1}
Sideband

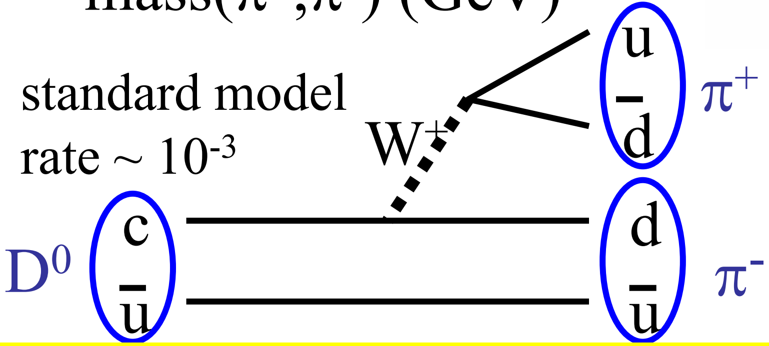


$m(\ell^+\ell^-)$

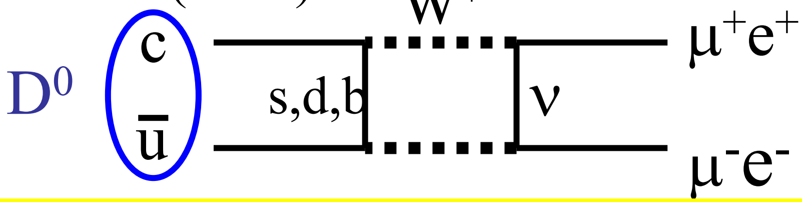
Large backgrounds, only D^0 final states are tractable in e+e- at 10 GeV so far.
Use D*→D^{0}π tag.
Measure relative to D →π π.

mode	ULx10^{-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}



SM rate ~ 10^{-13} (10^{-23})



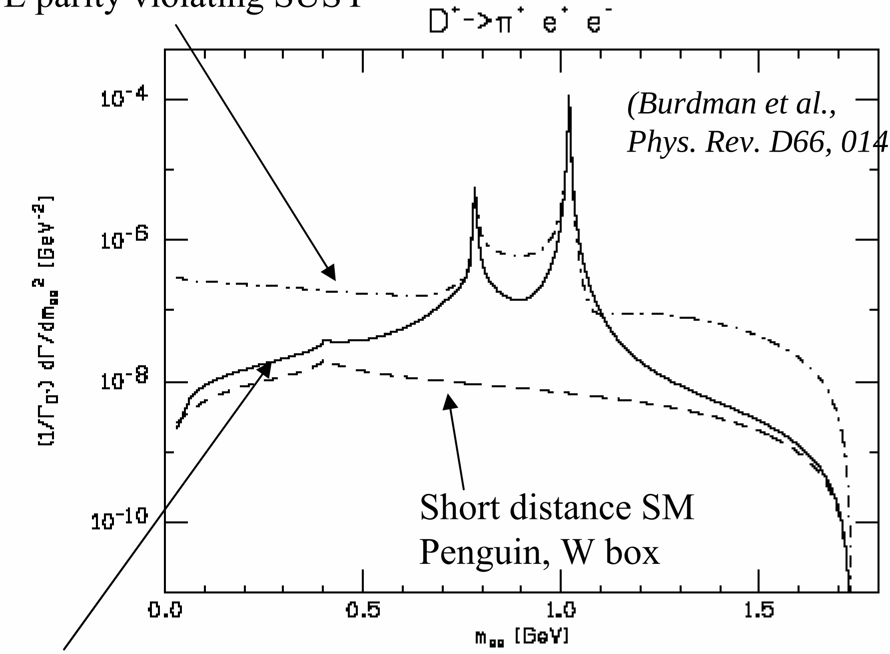
Big Improvement!

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

Naive scaling (Bkgd=0) superflavour@10GeV 50/ab $\mu^+\mu^-$ 3 x10^{-9} (10E4>SM)

x2 better superflavour @ψ(3770) 1/ab. (there will be bkgd @10GeV, → ψ(3770) superior)

In charm very difficult to calculate the SM rate for rare decays reliably. one of the most reliable:



E parity violating SUSY

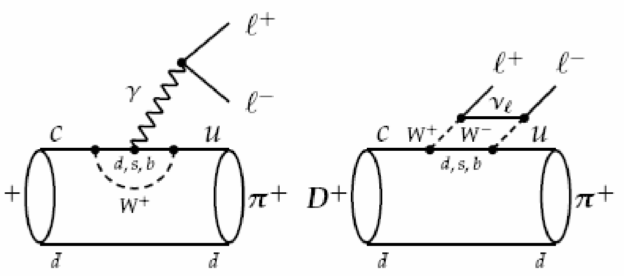
(Burdman et al., Phys. Rev. D66, 014009).

Short distance SM Penguin, W box

Short + long distance SM rho and phi → e+e-

In the SM

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



R-parity violating SUSY:

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

Increase in rate is small but significant at low dilepton mass

Current experimental limit CLEO II:

$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-) \sim 4.5 \times 10^{-5}$ at 90%CL

Goal observe, and one day study dilepton mass

Rare D^+ Decays CLEO-c

This is an untagged analysis, to increase sensitivity and similar to rare B decay searches at the Y(4S)

$\Delta E = E_D - E_{beam}$

(signal box is ± 20MeV) (resolution is 6 MeV)

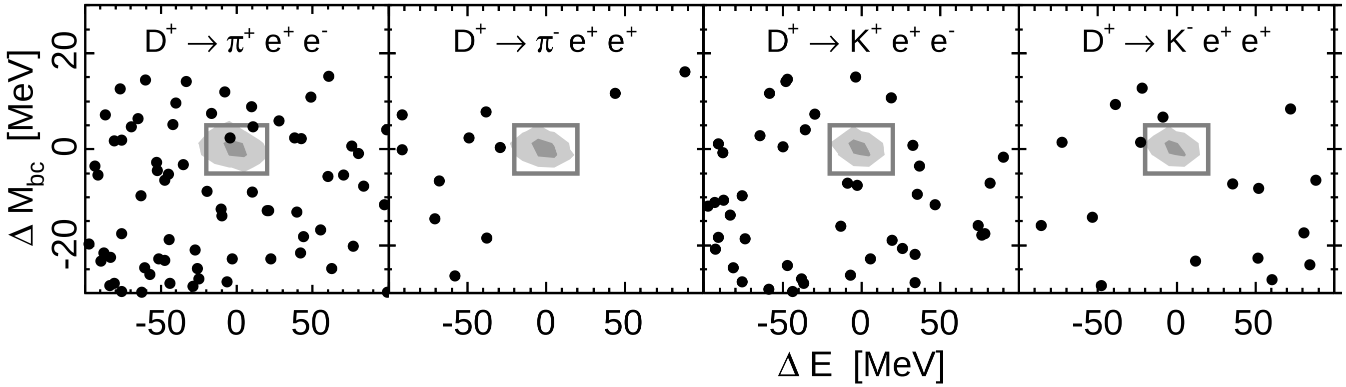
$281 pb^{-1}$ at $\psi(3770)$ ~750,000 D+D-

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

(signal box is ± 5 MeV/c^2) (resolution is 1.5 MeV/c^2)

Multiple candidates are resolved by taking the best |ΔMbc|

$\pi^+e^+e^-$ $\pi^-e^+e^+$ $K^+e^+e^-$ $K^-e^+e^+$



ΔMbc vs. ΔE plots

Results:

$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-) < 7.4 \times 10^{-6}$ (90% CL)

$\mathcal{B}(D^+ \Rightarrow \pi^-e^+e^+) < 3.6 \times 10^{-6}$ (90% CL)

$\mathcal{B}(D^+ \Rightarrow K^+e^+e^-) < 6.2 \times 10^{-6}$ (90% CL)

$\mathcal{B}(D^+ \Rightarrow K^-e^+e^+) < 4.5 \times 10^{-6}$ (90% CL)

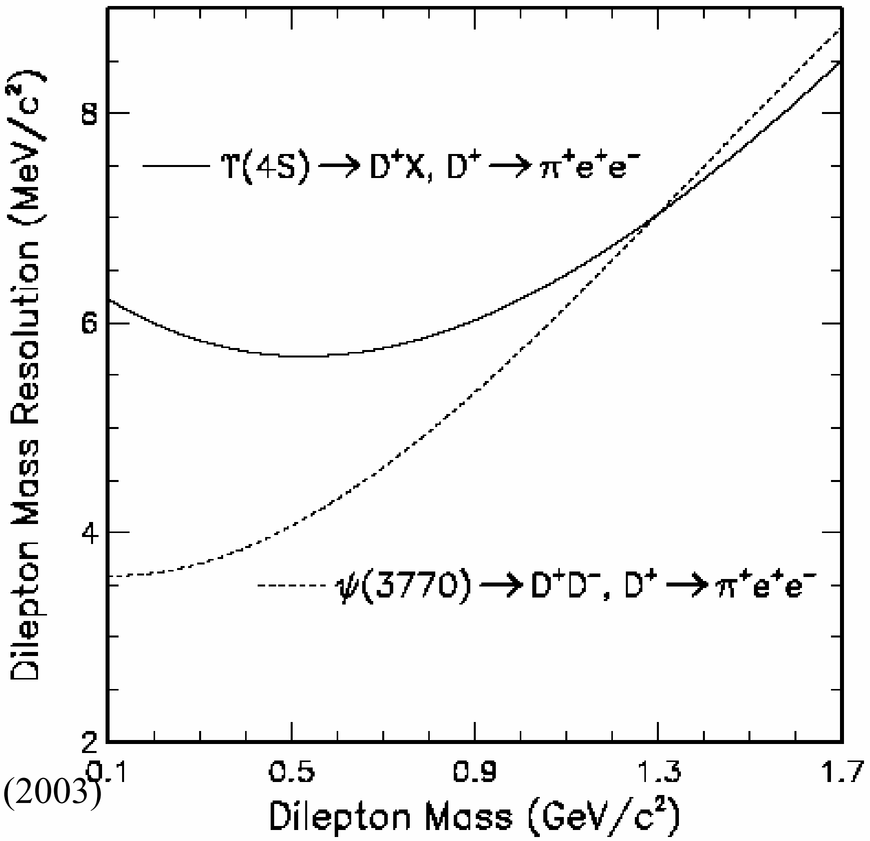
Forbidden in SM

These improve upon previous limits and are ~x4 above SM rates

If $D^+ \Rightarrow \pi^+e^+e^-$ is at SM level expect ~1 event/fb BESIII~`12 evts

Studies of the dilepton mass (20 MeV mass resolution adequate) will be the province of a superflavour facility at ψ(3770) Extrapolate from CLEO-c ($D^+ \Rightarrow \pi^+e^+e^-$ ~800 events (low bkgd) Using $D^* \rightarrow D^0 \Rightarrow \pi^0e^+e^-$ superflavour at 10GeVwill have a similar size sample but much higher background

The CLEO-c limits are comparable to FOCUS limits for the dimuon modes (next slide)



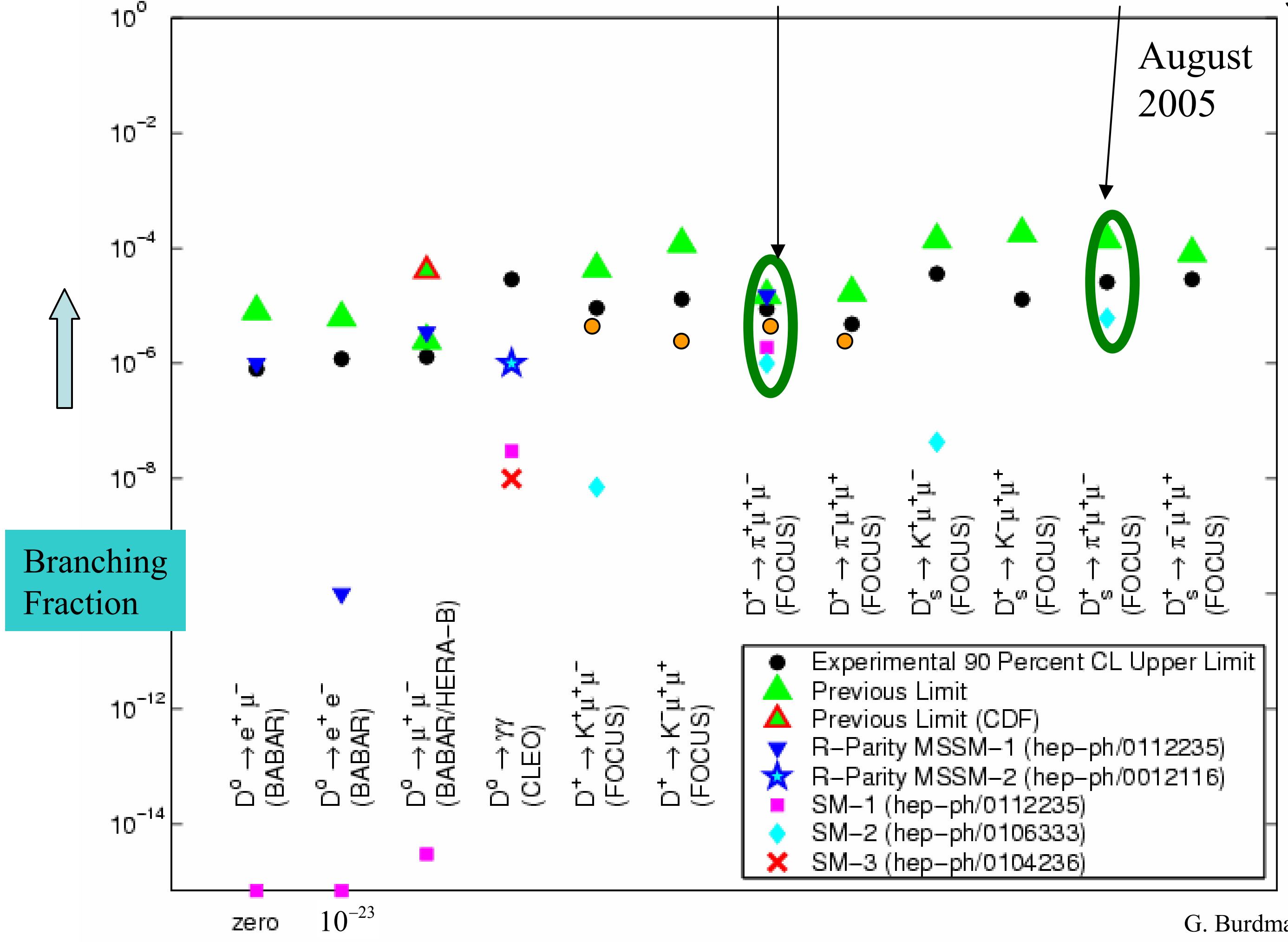
G. Burdman and I. Shipsey
Ann. Rev. Nucl. Part. Sci. **53** 431 (2003)
arXivhep-ph/0310076

Rare Decay Summary

● CLEO-c (from last slide)

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: promising CDF/D0, B factories, *superflavour*

G. Burdman and I. Shipsey
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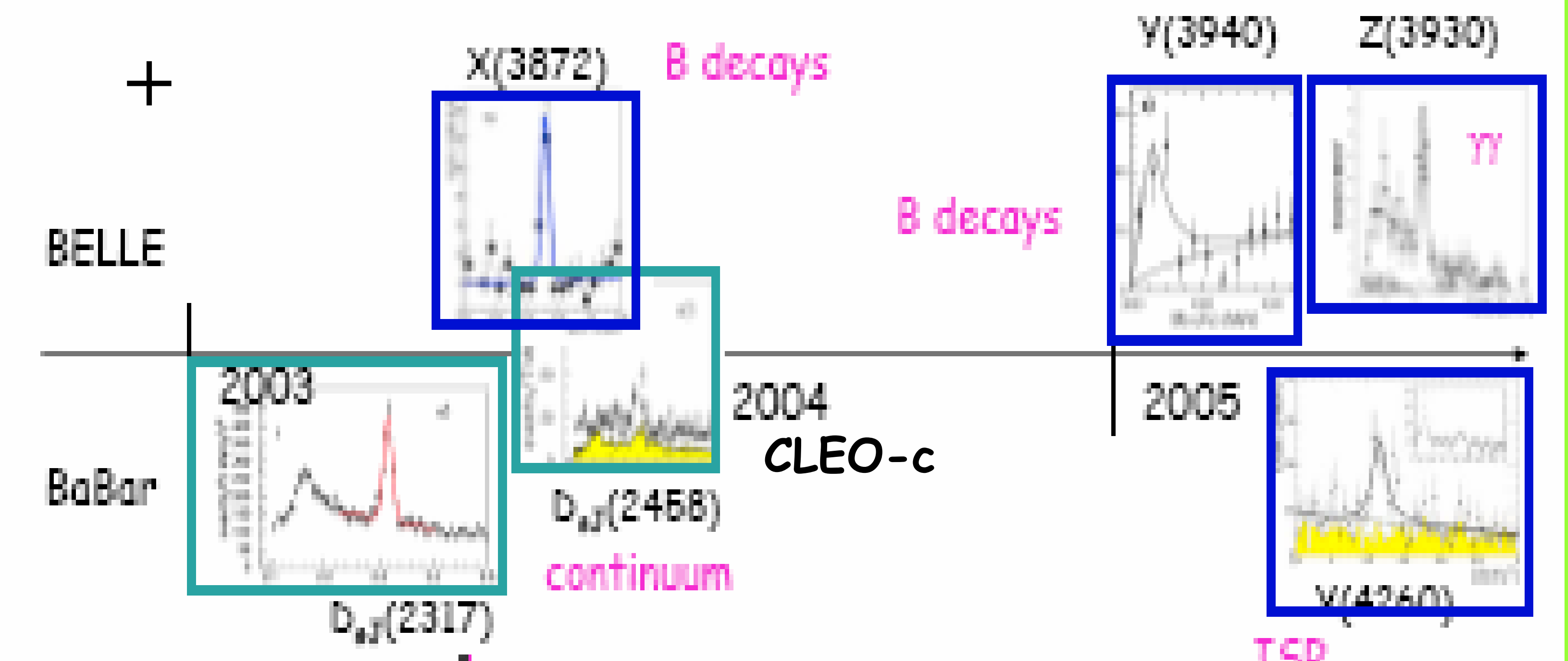
arXivhep-ph/0310076 (updated 12/2005).

Charmonium and new particles

- By 2002 -twenty five years since any new charmonium state observed.
- In the last three years:
  - η'_c and h_c below $D\,\overline{D}$ threshold
  - η''_c and χ'_{c2}



For a nice review by Swanson see hep-ph/0601110

CLEO-c 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) $\to \pi^0\pi^0 J/\psi$

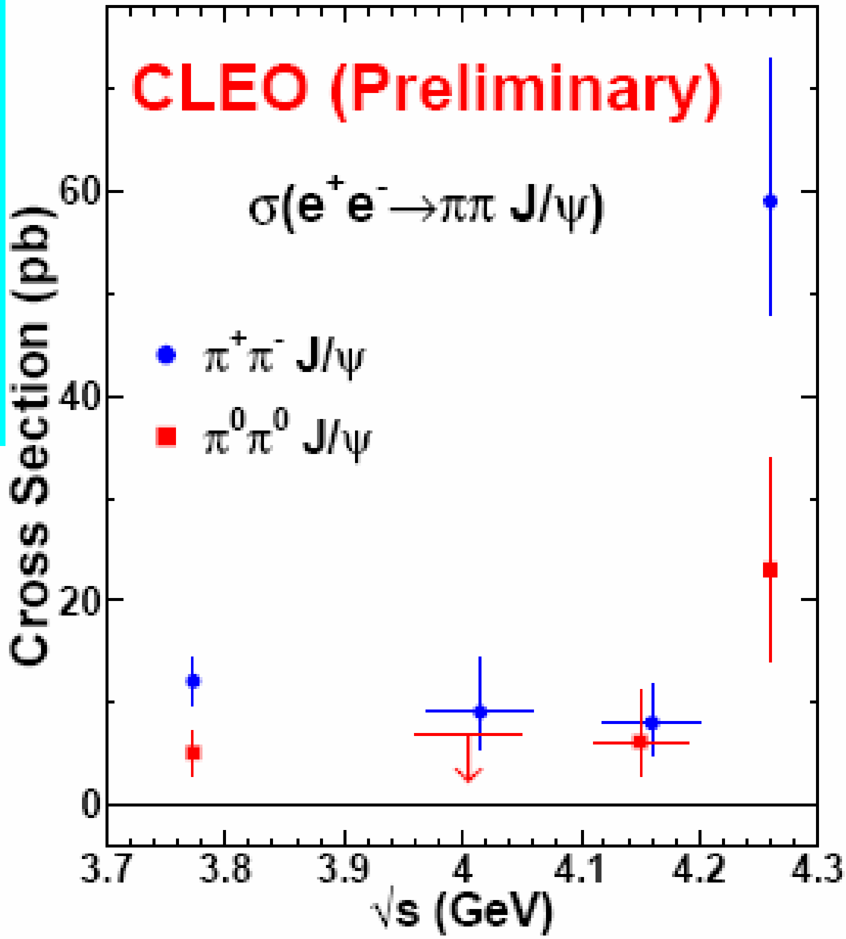
First Observation

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

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

Eliminates some interpretations

disfavors others.



Summary Part 1

Charm within the standard model (precision quark flavor physics)
Goal: is to provide natural testing ground for QCD techniques by measuring charm decay constants and semileptonic form factors to a few %. Impacts B physics
A Charm factory is mandatory for this program.
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 to 5% (CLEO-c) and several % (BES III) & semileptonic form factor to several % (CLEO-c &BESIII) is on schedule and this precision is well matched to the ultimate precision of theory

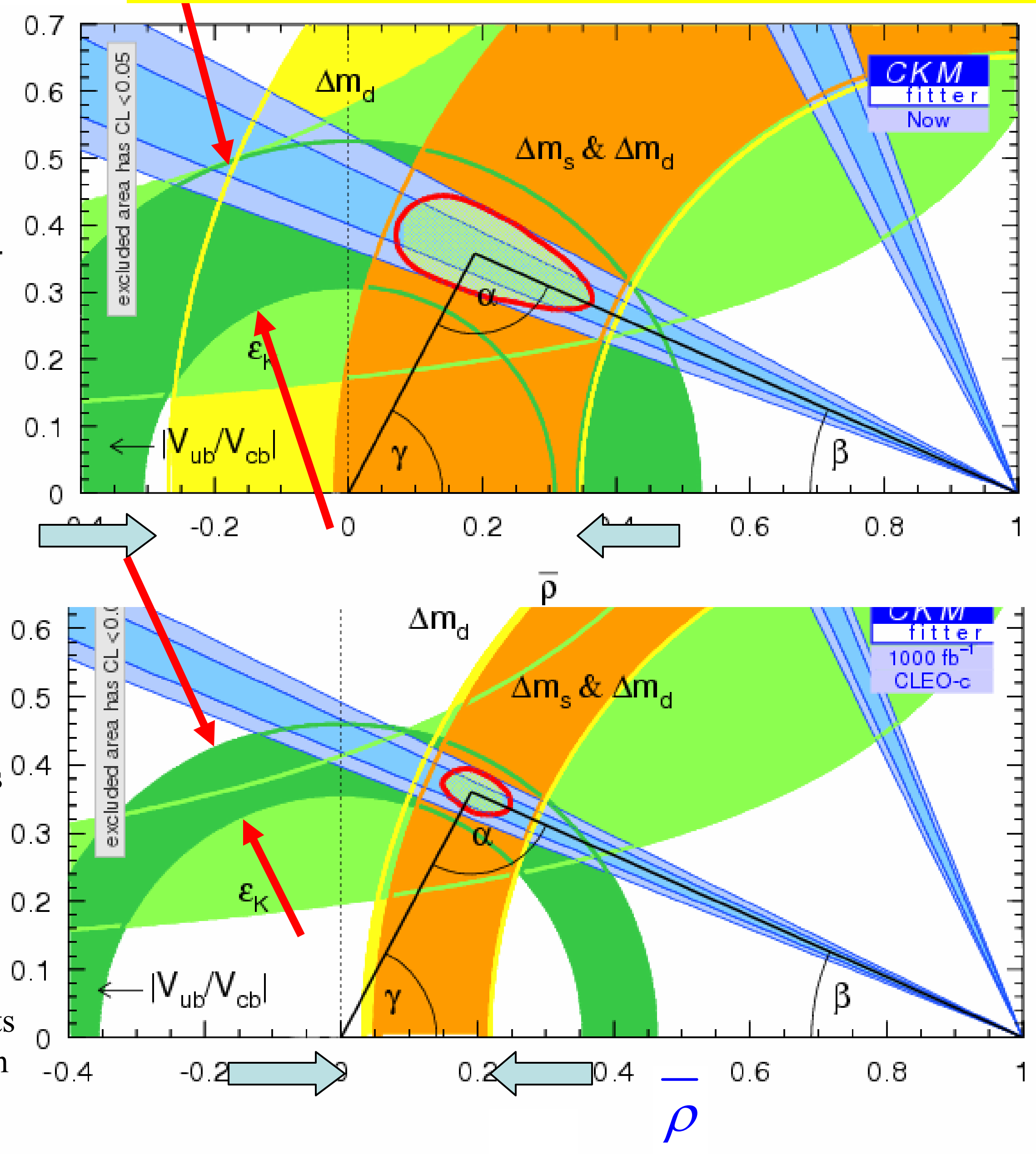
This comes at a fortuitous time, recent breakthroughs in precision lattice QCD need detailed data to test against. Charm is providing that data. If the lattice passes the charm test it can be used with increased confidence by: BABAR/Belle/CDF/D0/ /LHC-b/ATLAS/CMS to achieve improved precision in determinations 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

$\bar{\eta}$



Theoretical errors dominate width of bands

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

$\bar{\eta}$

Plots uses Vub Vcb from exclusive decays only γ,α constraints not shown

+

~500 fb-1 @ BABAR/Belle

$\bar{\rho}$

Summary Part 2

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 (& later BES III) will become significant players

A super B factory is a great idea
A superflavour facility (a B factory with an option to run at 3770 is even better) as it will enable (based on preliminary studies) uniquely powerful searches for, and our best chance for discovery, and subsequent study of, D mixing, DCPV, and D rare decay.

charm is the *unique* probe of the up-type quark sector let's use it!

Recent Reviews (Further Reading)

Covers all of charm:

A Cicerone for the Physics of Charm

S Bianco, F.L. Fabbri, D. Benson & I. Bigi

Nuovo Cimento 26, 1 (2003) hep-ex/0309021

Charm as a probe of physics beyond the SM (a superflavor factory is anticipated in this review and projections given)

D0D0 Mixing and Rare Charm Decays

G. Burdman and I. Shipsey

Ann. Rev. Nucl. Part. Sci. **53** 431 (2003)

arXivhep-ph/0310076

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