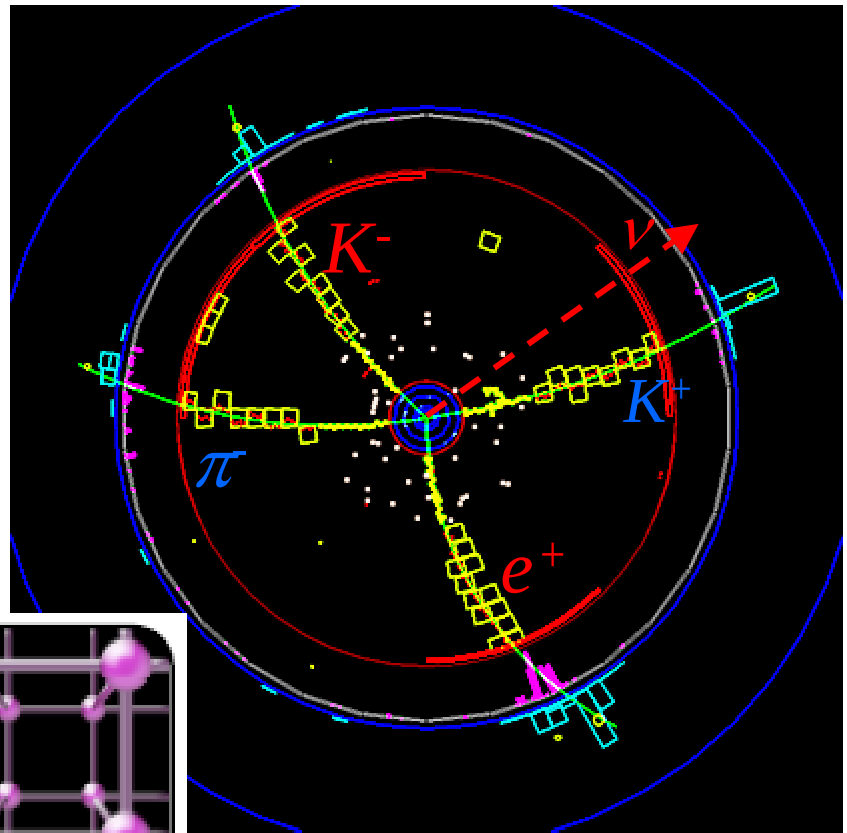
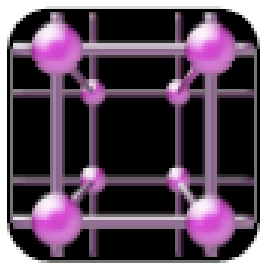
CKM Studies and New Physics Searches with Charm

Two themes:

1) Why Charm Physics allows B physics to reach its full Potential

2) Charm physics as a probe of New physics Beyond the Standard Model





Ian Shipsey, Purdue University

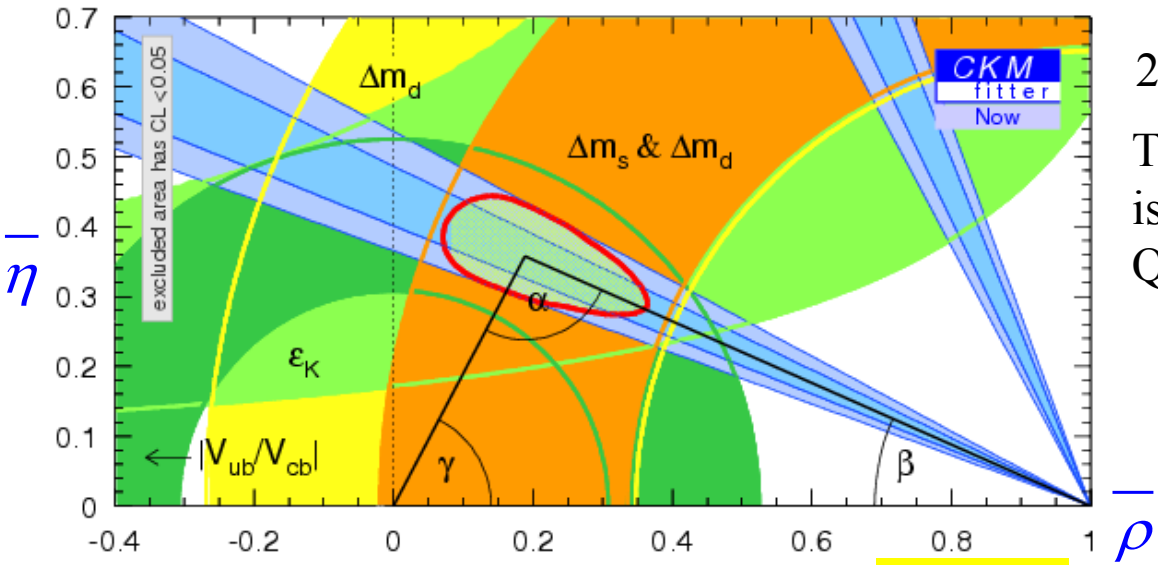
Lecture 2

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

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

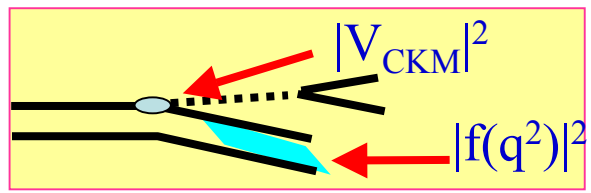
Topical Seminar on the Frontiers of Particle Physics (Beijing)
Aug. 13 – 17, 2005

Precision Quark Flavor Physics: charm's role



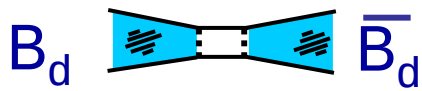
2005

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



Form factors in semileptonic (β) decay $|V_{ub}|, |V_{cb}|$

Decay constants in B mixing $|V_{td}|, |V_{ts}|$



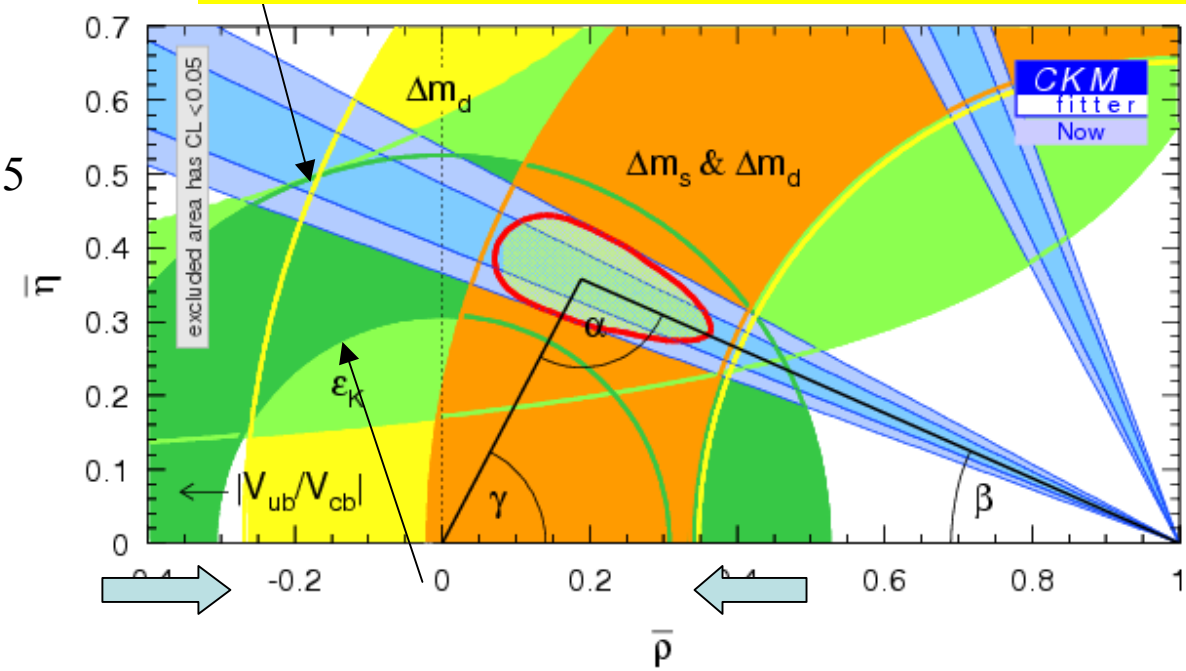
D system- CKM matrix elements are tightly constrained to <1% by unitarity

➔Work back from *measurements* of *absolute rates* for leptonic and semileptonic D decays yielding decay constants and form factors to *test* QCD techniques.that can then be applied to the B system. + determinations of Vcs Vcd

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

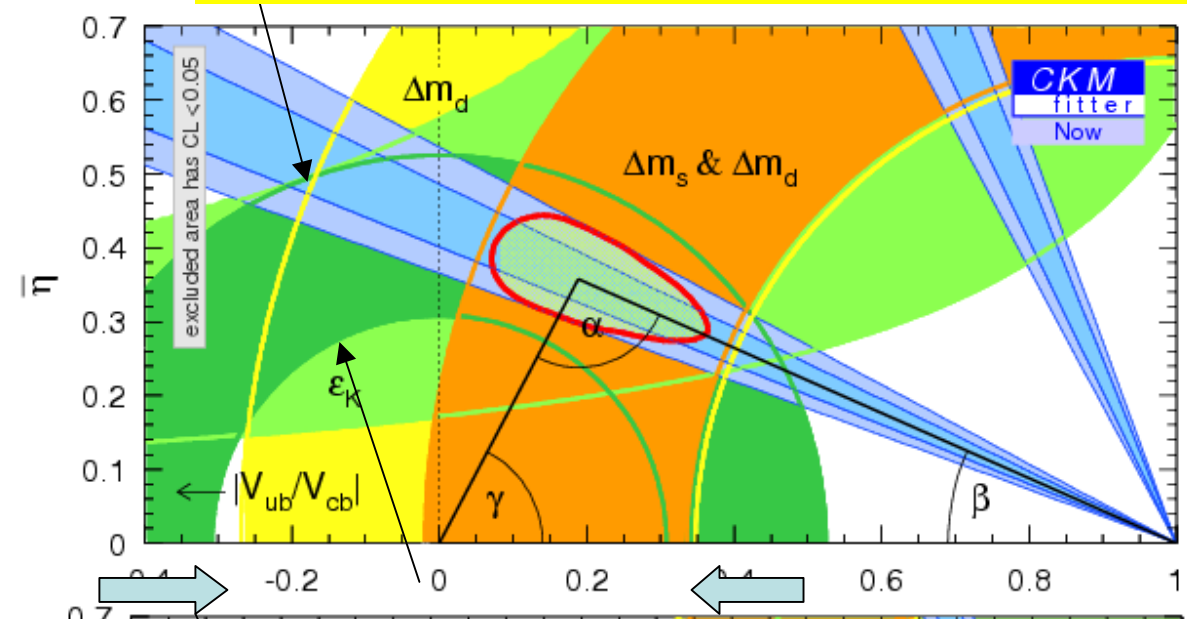
Precision theory + charm = large impact

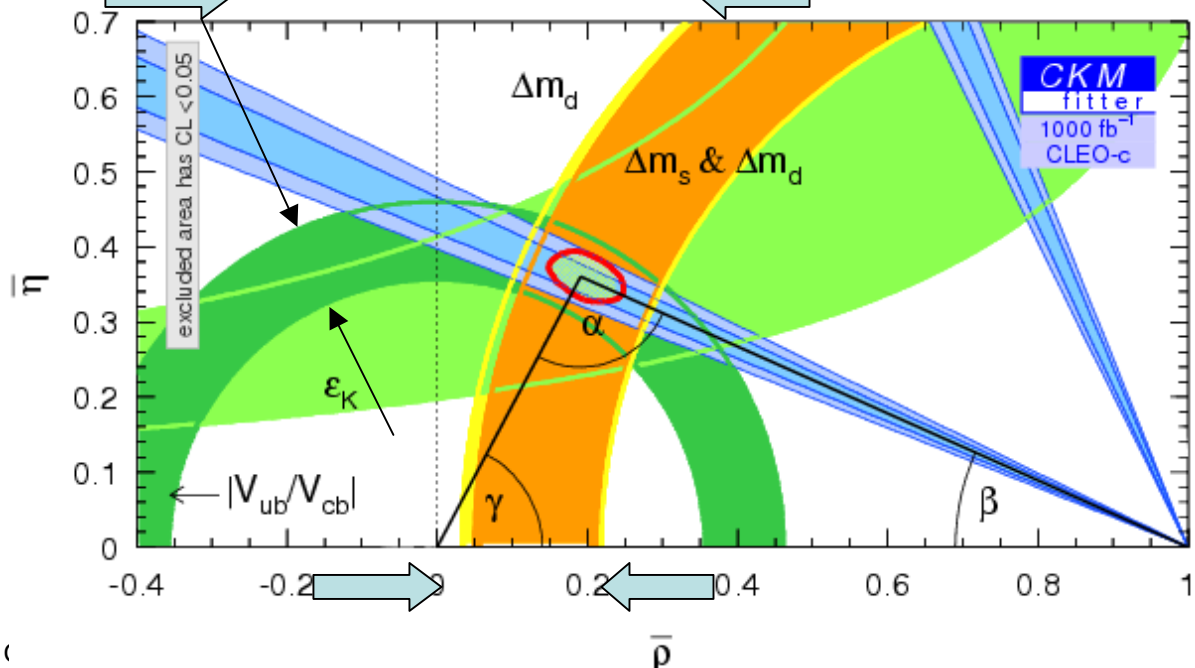
2005



Theoretical errors dominate width of bands

Precision theory + charm = large impact





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

Outline of the Lectures

Lecture 1

Overview: How Charm Physics Helps B Physics
→ Precision Quark Flavor Physics

Experiments That Contribute To Charm Physics

Precision CKM Physics:
- Lifetimes
- Hadronic Decays
- Leptonic Decays and Decay constants
- Semileptonic Decays and CKM matrix elements
- Tests of Unitarity

Lecture 2

Charm as a Probe of New Physics:
- Mixing
- CP Violation & Rare Decays

Summary & Outlook

Reviews for Lecture 2

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

Specific to lecture 2:

D0D0 Mixing and Rare Charm Decays

G. Burdman and I. Shipsey

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

arXivhep-ph/0310076

From the last lecture

Question: what could the additional semileptonic decay modes be?

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

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

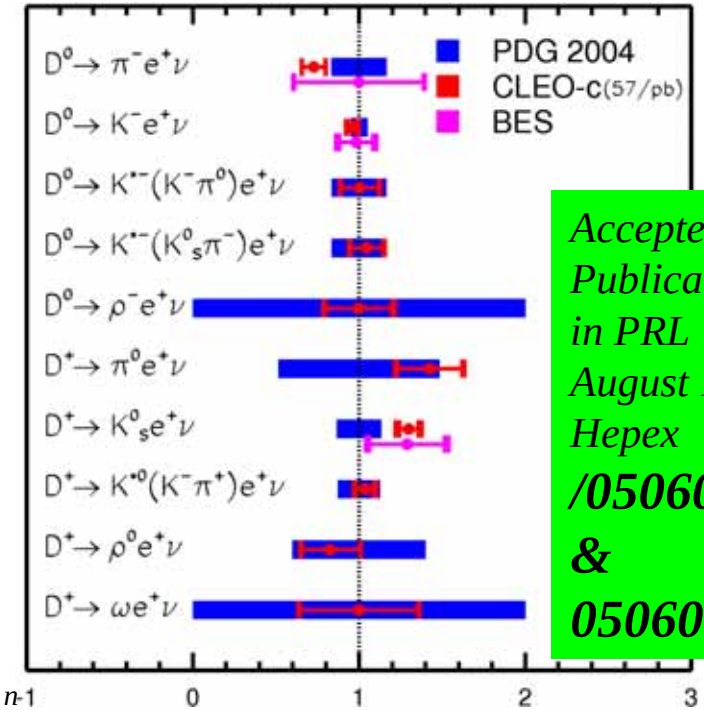
$$B(D^+ \to Xe\nu) = (16.19 \pm 0.20 \pm 0.36)\%$$

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

PreliminaResults

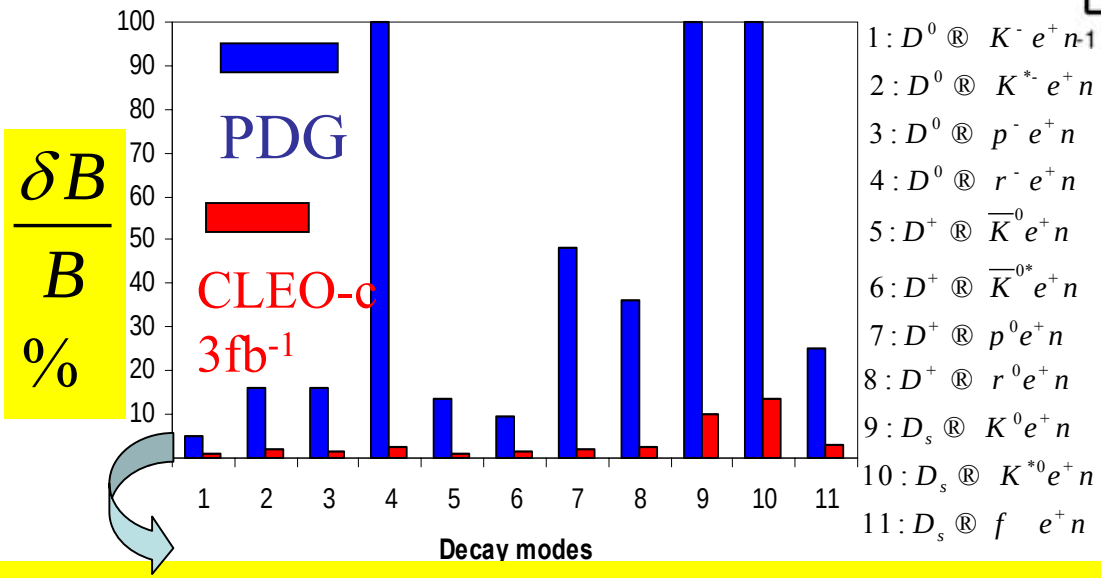
Similar analysis by BES II

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



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

Normalized to PDG



CLEO-c already all modes more precise than PDG.

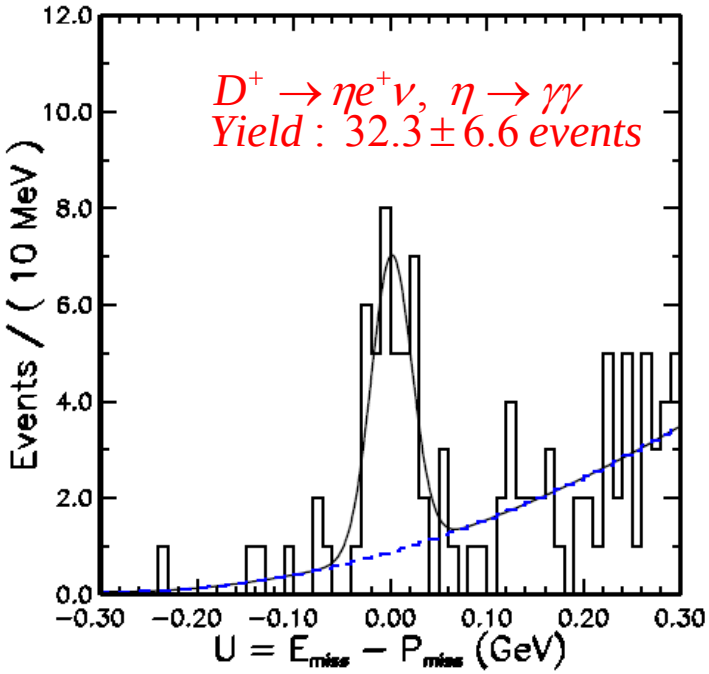
55.8/pb will update by 11/05

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

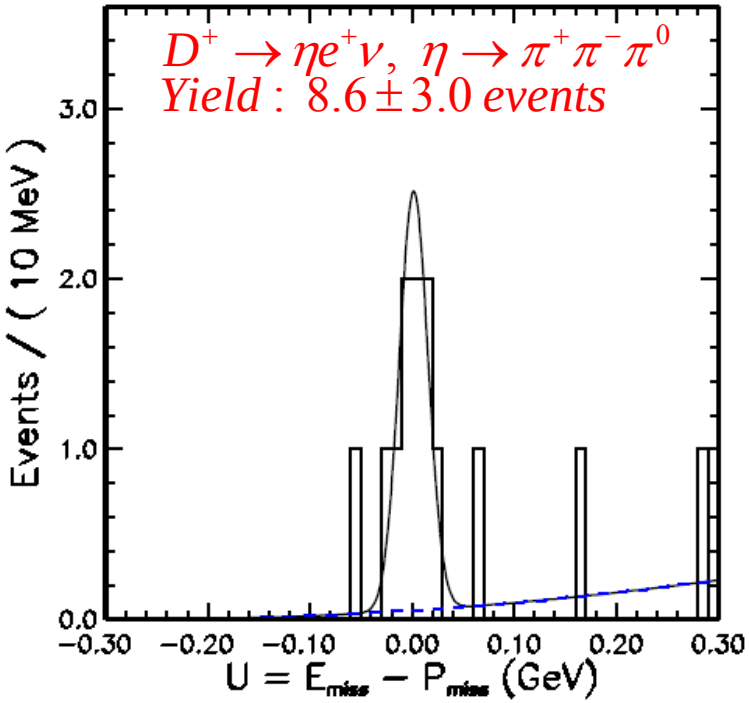
Answer: anything with a d or s valence quark to couple to charm. Examples: excited K*, additional pions, eta, etaprime etc.

Example of an additional mode

First Observation



Preliminary



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

We find significant yields for $D^+ \to \eta\, e^+ \nu$ with η reconstructed

In $\gamma\gamma$ and $\pi^+\pi^-\pi^0$, *the* relative yields are consistent with expectation

This is the first time these plots have been shown outside CLEO

Charm As a Probe of Physics Beyond the Standard Model

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

The existence of multiple fermion generations appears to 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 $\leq 10^{-6}$

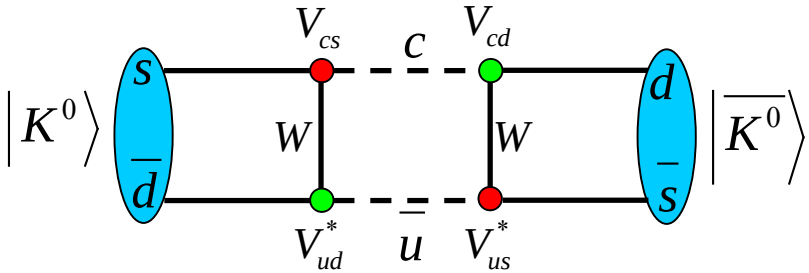
$D^0 - \bar{D}^0$ mixing $\leq 10^{-2}$

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:

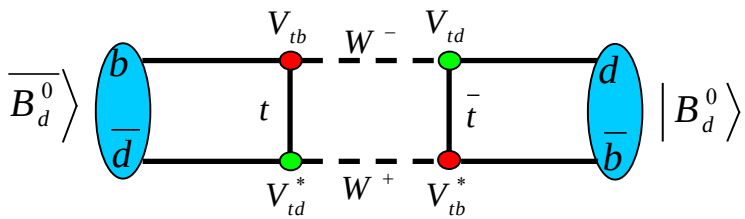


CKM factors $\propto \Theta_c^2$
same order as τ_{kaon}
i.e.s → u

Mixing rate ≈1

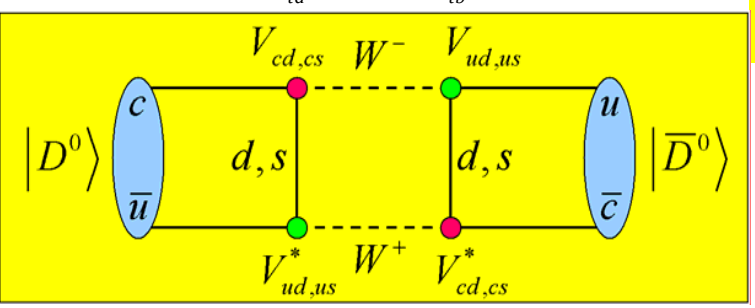
Mixing rate (1958) used to bound c quark mass → discovery(1974).

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}~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

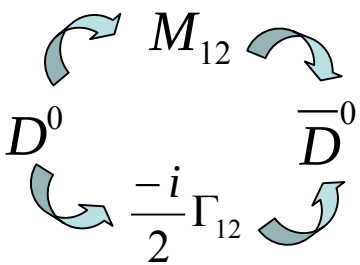
SM mixing small $\propto \Theta_c^2$ x [SU(3) breaking]^2<O(10^{-3})

Some Formalism

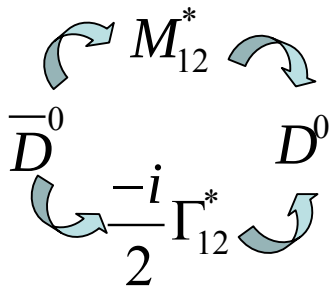
O. Schneider &
David Asner RPP
2002

Time evolution of D^0 or D^0 is determined by Schrodinger's Equation

$$\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} = \left| M - \frac{i}{2}\Gamma \right| \begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} \qquad a(t)\,|\,D^0> + b(t)\,|\,\overline{D}^0>$$



$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$



- Diagonalizing H gives mass eigenstates as linear combinations of D^0 and $\overline{D}^0$.
- Γ_{12} describes $D^0 \to f \to \overline{D}^0$ via on-shell intermediate states.
- M_{12} describes $D^0 \to f \to \overline{D}^0$ via off-shell intermediate states.
- CP violation in mixing can arise from interference between on-shell and off-shell amplitudes. This leads to $\Gamma(D^0 \to \overline{D}^0) \neq \Gamma(\overline{D}^0 \to D^0)$
- Note in the *Bd* system Γ_{12} is very small; mixing is dominated by $\Delta M = 2M_{12}$.

Switching to x and y

O. Schneider &
David Asner RPP
2002

$$a(t)\,|\,D^0> + b(t)\,|\,\bar{D}^0>$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} a \\ b \end{pmatrix} = \left[\left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & M_{12} - \frac{i}{2}\Gamma_{12}^* \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & 0 \end{pmatrix}\right]\begin{pmatrix} a \\ b \end{pmatrix}$$

$\frac{1}{\tau_{D^0}}$ C.P.T assumed

$K^0 - \bar{K}^0 : |M_{12}| : |\Gamma_{12}|$

$B^0 - \bar{B}^0 : |M_{12}| \,?\, |\Gamma_{12}|$

$D^0 - \bar{D}^0 :$ to be determined

$$CPV : \left|M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right| \neq \left|M_{12} - \frac{i}{2}\Gamma_{12}\right|$$

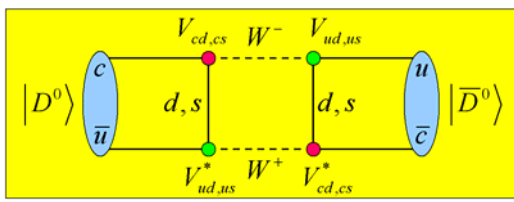
But initially assume conservation here

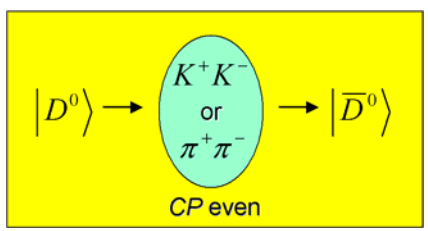
$$\frac{1}{2}\begin{pmatrix} 0 & -ix - y \\ -ix - y & 0 \end{pmatrix}$$

- **Measure time in units of** τD^0

$$D^0 \xleftrightarrow{-\frac{i}{2}x} \bar{D}^0$$ **shifts energy of CP eigenstates** $x = \frac{2M_{12}}{\Gamma}$

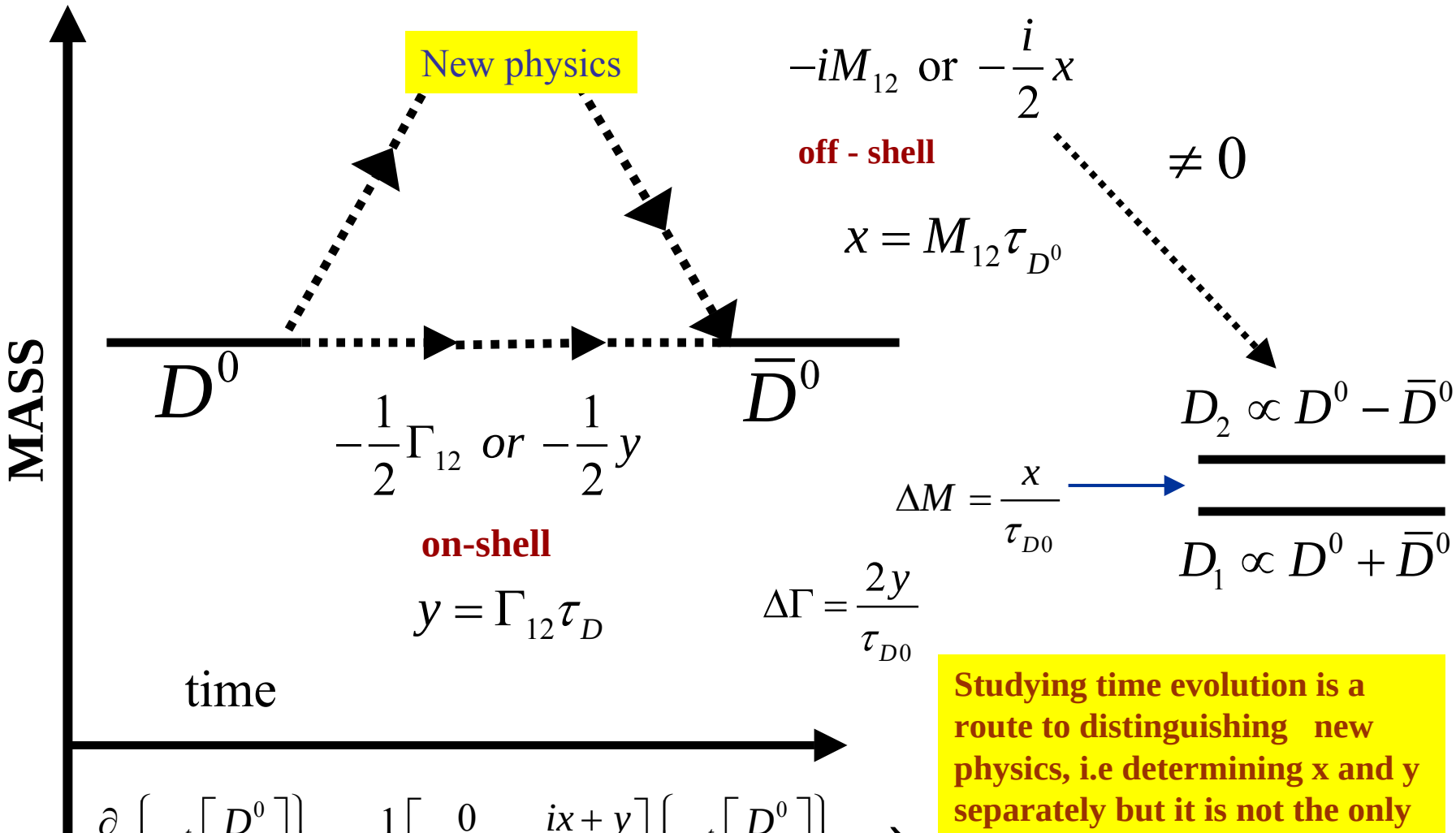
$$D^0 \xleftrightarrow{-\frac{y}{2}} \bar{D}^0$$ **shifts lifetimes of CP eigenstates** $y = \frac{\Gamma_{12}}{\Gamma}$





New Physics Alters x not y

Assume:
CP Conserved



$$\frac{\partial}{\partial t}\left\{e^{-t}\begin{bmatrix} D^0 \\ D^0 \end{bmatrix}\right\} = -\frac{1}{2}\begin{bmatrix} 0 & ix+y \\ ix+y & 0 \end{bmatrix}\left\{e^{-t}\begin{bmatrix} D^0 \\ D^0 \end{bmatrix}\right\} \Longrightarrow$$

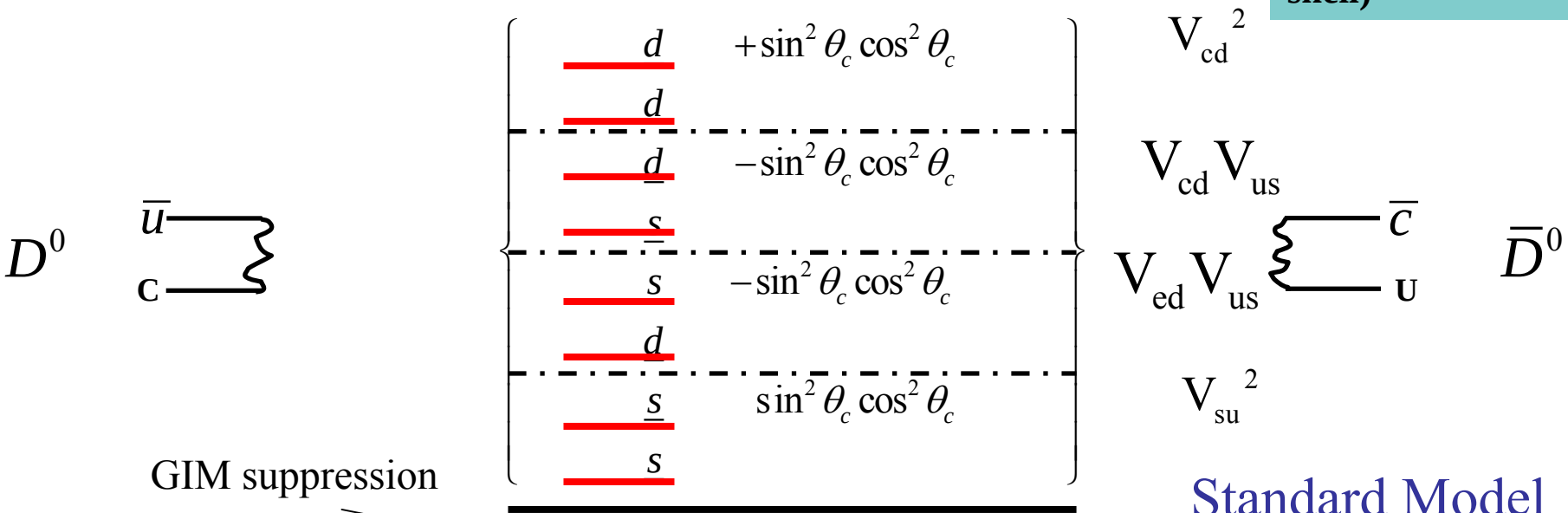
Studying time evolution is a route to distinguishing new physics, i.e determining x and y separately but it is not the only way to achieve this.

x in the Standard Model

$$D^0 \xrightarrow{-\frac{i}{2}xt} \bar{D}^0 \qquad x : \sum_n \frac{\langle \bar{D}^0 | H_{\not{0}} | n \rangle \langle n | H_{\not{0}} | D^0 \rangle}{m_{D^0} - E_n}$$

n=index of intermediate state

(states are off mass shell)



GIM suppression

Sum ; 0 when $m_s = m_d$

(ignore b quark contribution suppressed by $V_{cb} V_{ub}$)

In SU(3) limit x = 0

Standard Model Estimate: $x \le 10^{-3}$

But large range

- **Because x is very small, x is a window for new physics**

y in the Standard Model

$$D^0 \xrightarrow{-y\frac{1}{2}} \bar{D}^0$$

$$y : \Sigma \quad \underset{\propto \sqrt{BR}}{A(\bar{D}^0 \to \text{Common State})} \quad \underset{\propto \sqrt{BR}}{A(D^0 \to \text{Common State})}$$

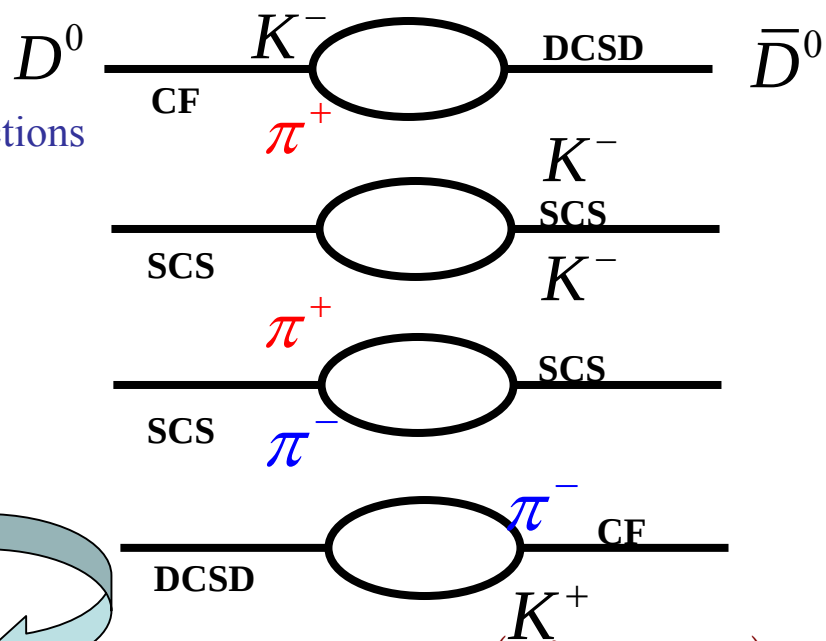
- **In principle, a precision experimental determination O(1%) of all branching ratios, and phases, "measures" y to 1%**

Common States

$$E_n = M_{D^0}$$

$$\boxed{y \le 10^{-3}}$$

- **Simple example only K and π intermediate states**



$-\sin^2\theta_C \cos^2\theta_C$

$\sin^2\theta_C \cos^2\theta_C$

$\sin^2\theta_C \cos^2\theta_C$

$-\sin^2\theta_C \cos^2\theta_C$

Short Distance predictions Span wide range But major sources of SU(3) breaking exist $m_K \neq m_\pi \neq m_\eta$ $f_K \neq f_\pi$ and relative phases between DCSD and CF amplitudes

Work by Falk, Grossman, Ligeti, Nir, Petrov indicate y~ 1% possible (see later)

Hadronic Problem : $\dfrac{\Gamma\left(D^0 \to K^+K^-\right)}{\Gamma\left(D^0 \to \pi^+\pi\right)}$; 3.0 ± 0.2

Approximate cancellation

- **Probably not a window for new physics**

More on x,y in SM

In fact the diagrams for y may also be the best way to think about x as well.

Both x and y are generated by s, d contributions The same diagram generates both the real part (x) and the imaginary part (y)

Same thing happens in B mixing (the c quark contribution takes place for both x and y) but for B's the real part (x) is dominated by top. If $m_{top} \sim m_{charm}$ then B and D mixing would be analogs.

example

for y $D \to 4\pi$ is cancelled $D \to 4K$ in the SU(3) limit but 4K is kinematically forbidden so it cannot contribute to y

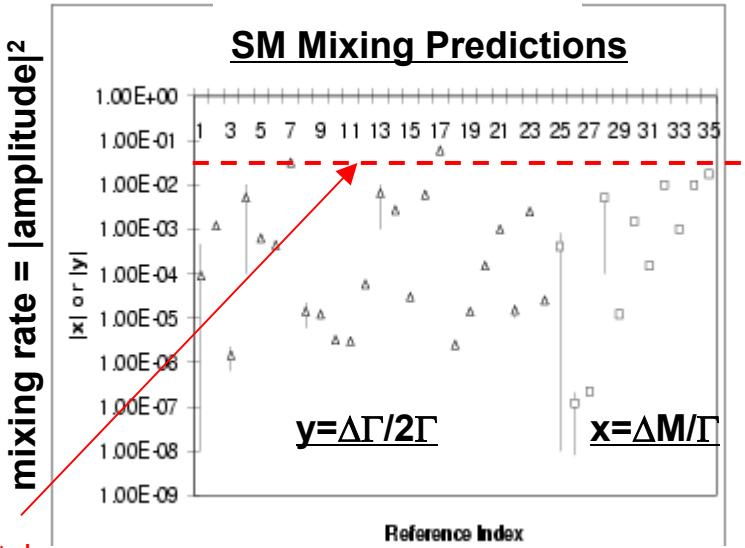
$\to$ For y SU(3) cancelation is broken by phase space.

For x both $D \to 4\pi$ & $D \to 4K$ can contribute. For x there is more effective SU(3) cancellation than in y. Nobody knows how big the size of this effect. It is feasible that y>x (SM)

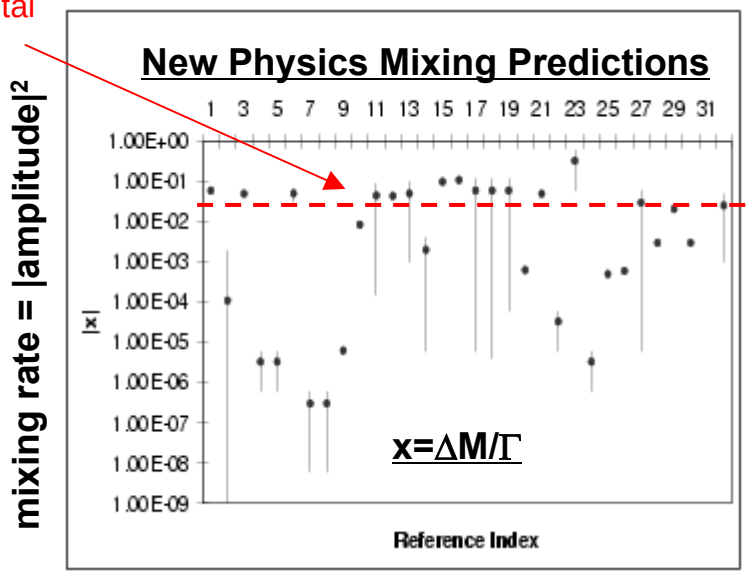
New physics Signatures:

: New physics will enhance *x* but not *y we can consider y as a SM background. CP* violation in mixing would be a smoking gun for new physics

Theoretical "Guidance"

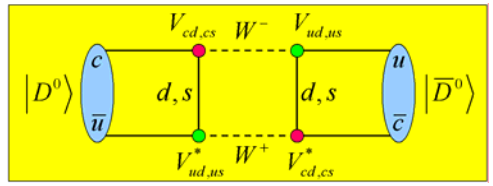


current experimental sensitivity



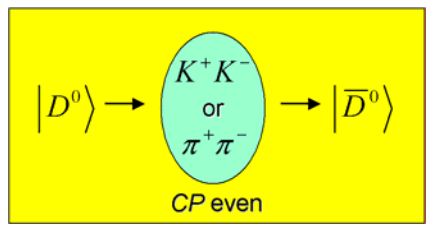
(A. Petrov, hep/ph 0311371)

x mixing: Channel for New Physics.



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

y (long-range) mixing: SM background.



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

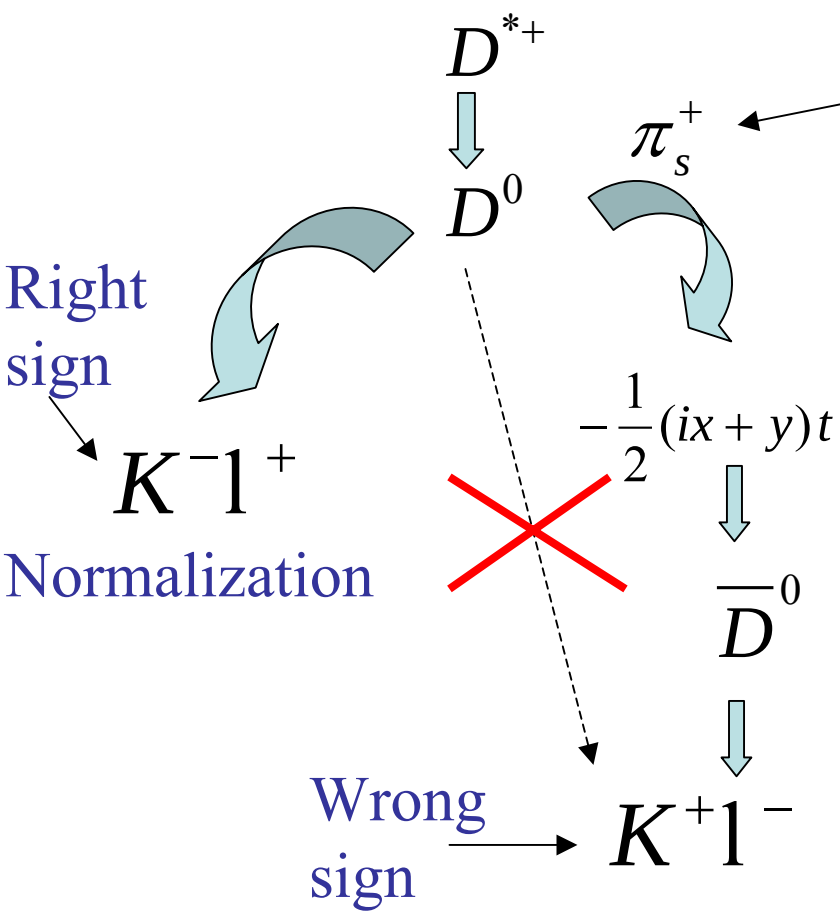
New physics will enhance *x* but not *y*.

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

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

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

$D^0\bar{D}^0$ Mixing x, y, semileptonic Theoretically Cleanest



- Charge of the "soft pion" tags whether the initial state was D^0 or D^0.
- Cabibbo favored decay: $D^0 \rightarrow K^- l^+ \upsilon$ (7%) gives "right-sign" charge correlation
- Mixing is a source of "wrong-sign" decays: $D^0 \rightarrow \bar{D}^0 \rightarrow K^+ l^+ \upsilon$
- As there is only one diagram there is no direct decay route for a $D^0 \rightarrow K^+ l^+ \upsilon$
- This is what "clean" means, the wrong sign pair is unambiguously a mixing signature

$$\text{time distribution} \propto \frac{1}{4}([x^2+y^2]\ \ t^2)\ \ e^{-t}$$

$$\text{but} \quad x^2+y^2 << x \text{ or } y$$

Theoretically clean usually means experimentally challenging

$m(\pi_s K^+ l^-) - m(K^+ l^-) \rightarrow$ Missing ν

Measurement of y_{CP} from $D^0 \to K^+K^-$ & $D^0 \to \pi^+\pi^-$

y can be determined by measuring the lifetime difference between D^0 decays to *CP*-even and *CP*-odd final states:

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_{CP^+} - \Gamma_{CP^-}}{\Gamma_{CP^+} + \Gamma_{CP^-}}$$

Experimentally, it is easier to measure the lifetime difference of a *CP*-even decay relative to the non-*CP* final state $D^0 \to K^-$ $\square^+$ (assumes no *CP* violation):

In the limit of no CP violation $\Gamma_+ = \Gamma + \delta, \Gamma_- = \Gamma - \delta$

$$y_{cp} = \frac{\Gamma + \delta - (\Gamma + \delta)}{2\Gamma} = \frac{\delta}{\Gamma} = \frac{\Gamma + \delta}{\Gamma} - 1 = \frac{\tau_{mixed}}{\tau_+} - 1$$

K^-K^+ (or $\pi^+\pi^-$)	pure *CP*	D_+		
$K^-\pi^+$	50%	D_+	50%	D_-

$$y_{CP} = \frac{\tau\left(D^0 \to K^-\pi^+\right)}{\tau\left(D^0 \to K^-K^+\right)} - 1$$

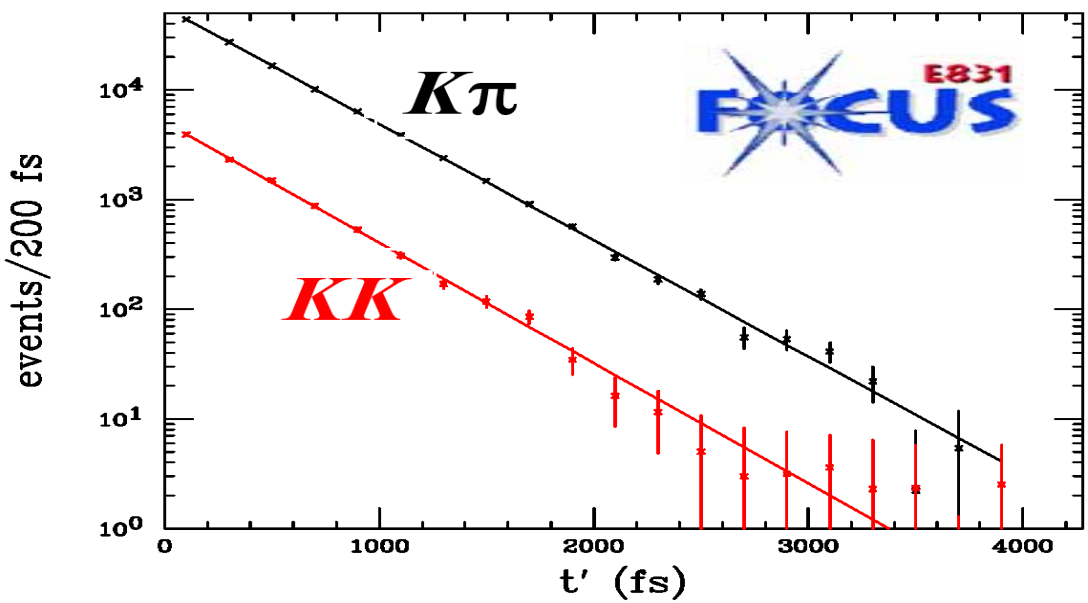
Measurement of y

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_{CP^+} - \Gamma_{CP^-}}{\Gamma_{CP^+} + \Gamma_{CP^-}}$$

Easier, measure *CP*-even decay relative to $D^0 \to K^-\pi^+$: (1/2 CP even ½ CP odd)

$$y_{CP} = \frac{\tau\left(D^0 \to K^-\pi^+\right)}{\tau\left(D^0 \to K^-K^+\right)} - 1$$

Early FOCUS measurem with non zero y_{CP}:



$$y = (3.4 \pm 1.4 \pm 0.7)\%$$

Status of y (summer 2005)

D^0 and $\overline{D^0}$ have diferent lifetimes to CP even final states if CPV is present

More recent analyses allow for CP violation, by comparing charge conjugate states rather than combining them

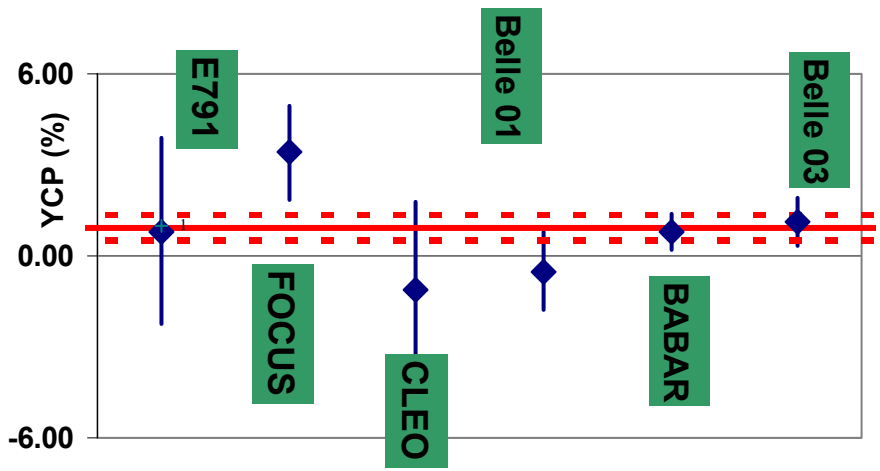
No evidence for CPV is found.

$$\begin{cases} \tau\left(D^0 \to K^-K^+\right) & \tau\left(\overline{D^0} \to K^-K^+\right) \\ \tau\left(D^0 \to \pi^-\pi^+\right) & \tau\left(\overline{D^0} \to \pi^-\pi^+\right) \end{cases}$$

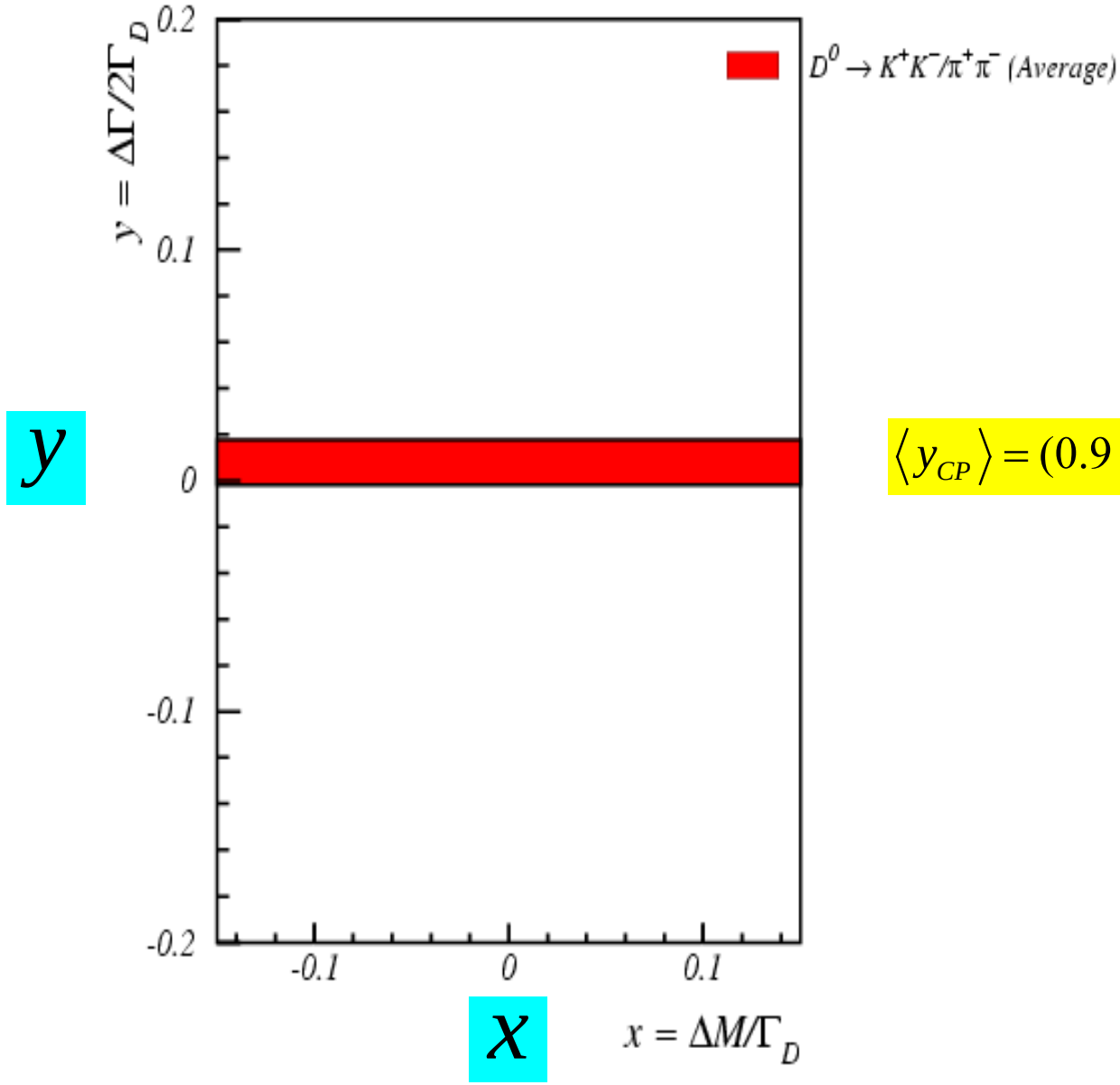
The observables become: $Y = y\cos\phi, \quad \Delta Y = x\sin\phi$

I take ϕ=0 in the average:

	y_{CP}
E791	$(0.8 \pm 2.9 \pm 1.0)\%$
FOCUS	$(3.4 \pm 1.4 \pm 0.7)\%$
CLEO	$(-1.1 \pm 2.5 \pm 1.4)\%$
Belle 01	$(-0.5 \pm 1.0 \pm 0.8)\%$
BABAR	$(0.8 \pm 0.4\ ^{+0.5}_{-0.4})\%$
Belle 03	$(1.15 \pm 0.69 \pm 0.38)\%$



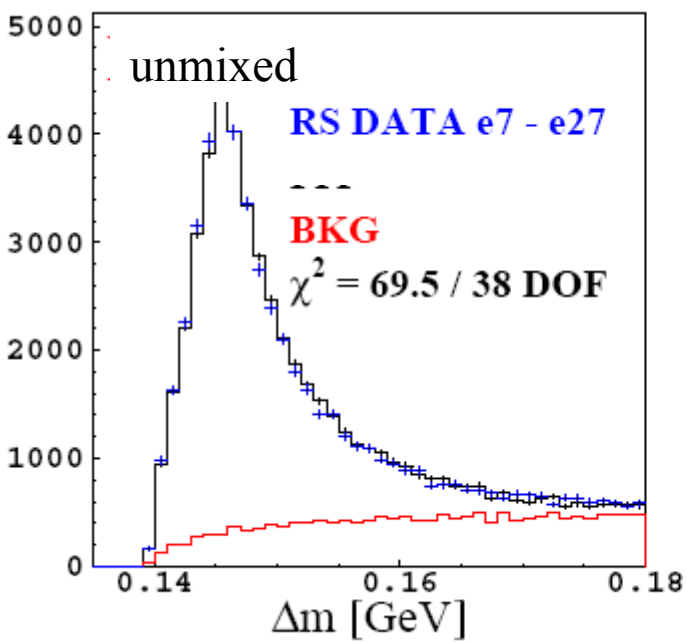
$$\langle y_{CP} \rangle = (0.9 \pm 0.4)\%$$

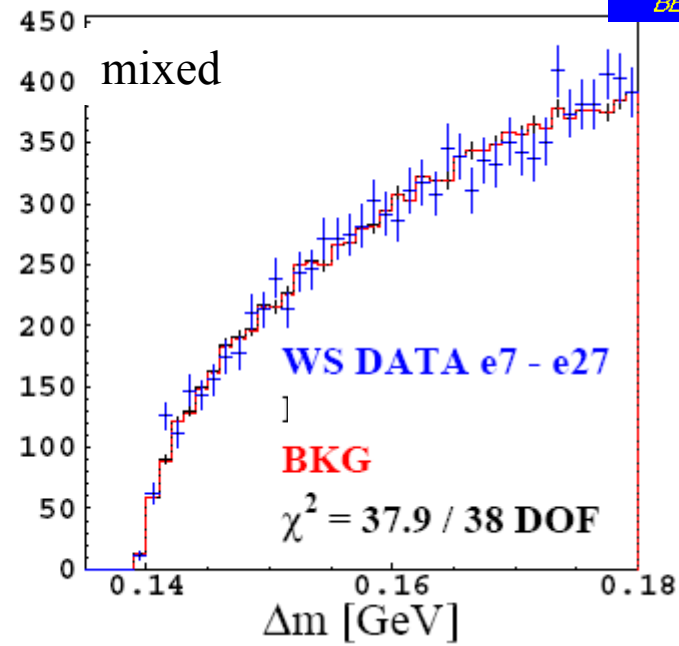


$$\langle y_{CP} \rangle = (0.9 \pm 0.4)\%$$

Search for D Mixing in Semileptonic Decays

Counting analysis





$$\Delta m = m(\pi_s K^+ l^-) - m(K^+ l^-)$$

$$N_{unmix} = 40198 \pm 329 \qquad N_{mix} = 19 \pm 67$$

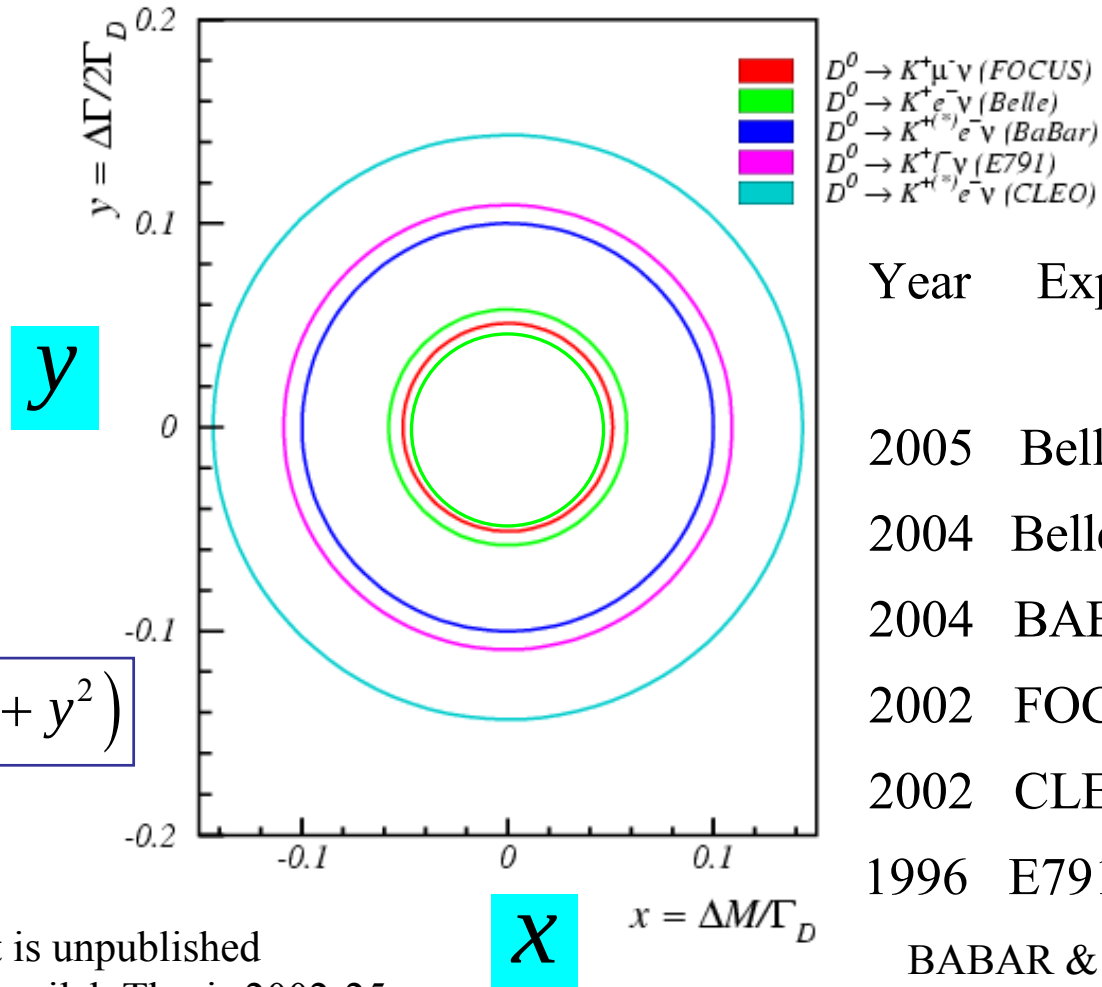
$$R_{mix} = \frac{N_{unmix}}{N_{mix}} \bullet \frac{\varepsilon_{unmix}}{\varepsilon_{mix}} = (0.20 \pm 0.70) \times 10^{-3} \text{(stat)}$$

$$R_{mix} < 1.4 \times 10^{-3} \text{ at 90\% CL (stat + sys)} \qquad \text{(ICHEP, 2004)}$$

In a new analysis (2005) Belle fit the WS time dependence $t^2 e^{-t}$

$$R_{mix} < 1.0 \times 10^{-3} \text{ at 90\% CL (stat + sys)}$$

D Mixing Semileptonic Summary



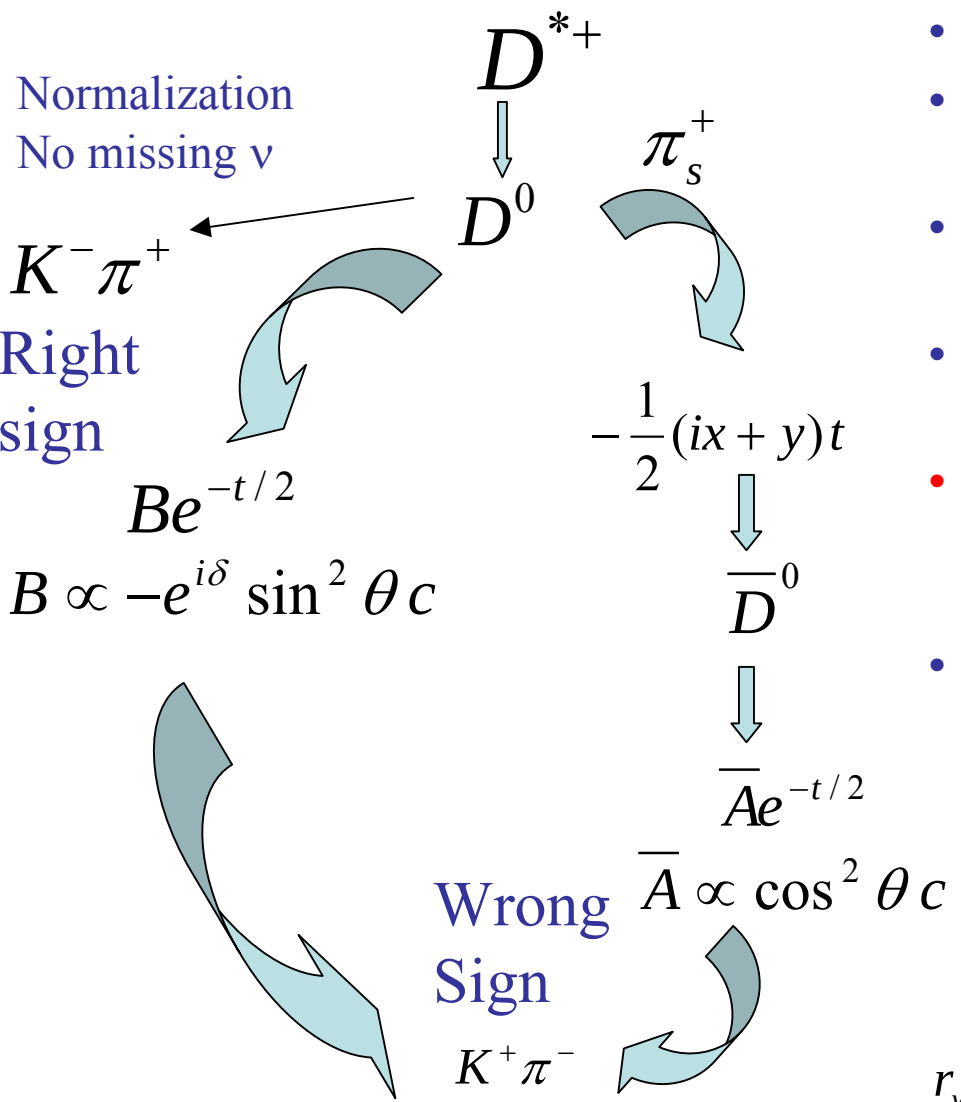
$$R_{mix} \equiv \tfrac{1}{2}\left(x^2 + y^2\right)$$

Year	Expt.	R_{mix} 90% C.L.
2005	Belle	$<1.0\times10^{-3}$
2004	Belle	$<1.4\times10^{-3}$
2004	BABAR	$<4.2\times10^{-3}$
2002	FOCUS	$<1.31\times10^{-3}$
2002	CLEO	$<8.6\times10^{-3}$
1996	E791	$<5.0\times10^{-3}$

FOCUS result is unpublished
M. Hosack Fermilab Thesis 2002-25.

BABAR & Belle are adding more data and expect to publish improved upper limits soon.

$D^0\bar{D}^0$ Mixing II from hadronic decays



- Production: $e^+e^- \rightarrow cc$; $c \rightarrow D^{*+} \rightarrow D^0\pi^+_s$.
- Charge of the "soft pion" tags whether the initial state was D^0 or D^0 (as before)
- Cabibbo favored decay: $D^0 \rightarrow K^-\pi^+$ (4%) gives "right-sign" charge correlation
- Mixing is a potential source of wrong-sign decays: $D^0 \rightarrow D^0 \rightarrow K^+\pi^-$
- Doubly Cabibbo suppressed decay $D^0 \rightarrow K^+\pi^-$ also gives wrong-sign ($\pi_s^+ K^+$) charge correlation with strong phase δ
- Use time dependence to distinguish:

$$rws(t) = \left(\left[\frac{B}{\bar{A}} - \frac{1}{2}(ix+y)t\right]e^{-t/2}\right)^2$$

$$R_D = \left|B/\bar{A}\right|^2$$

$$\left[R_D + \sqrt{R_D}(y\cos\delta - x\sin\delta)t + \frac{1}{4}(x^2+y^2)t^2\right]e^{-t}$$

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

The Wrong Sign Rate

PRL 94 071801 (2005)

$90\ fb^{-1}$

Observables:

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

$D^{*+} \to D^0\pi^+$ 3σ cut on Q

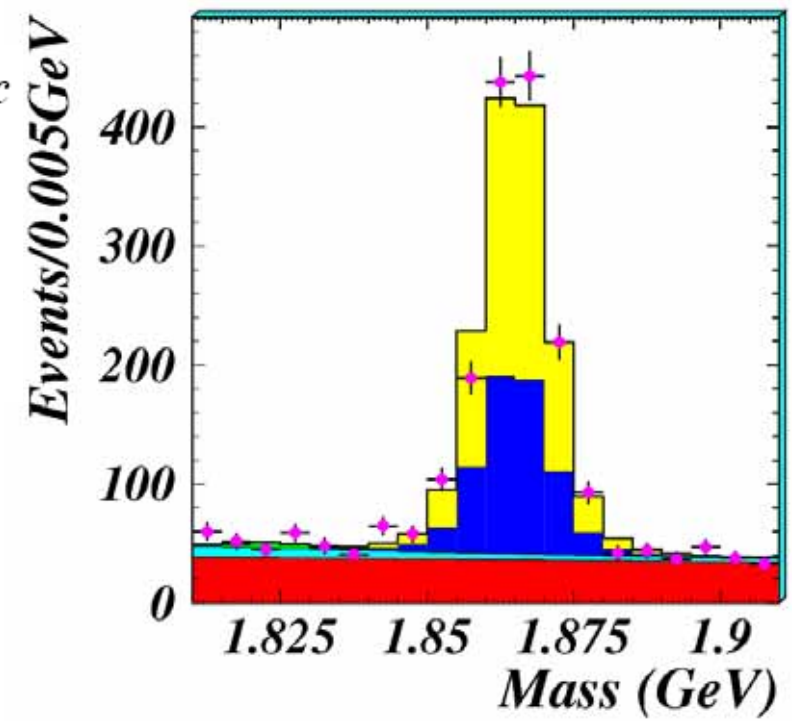
Right sign : $D^0 \to K^-\pi^+$ $228K$

Wrong sign

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

845 ± 40

S/B~1



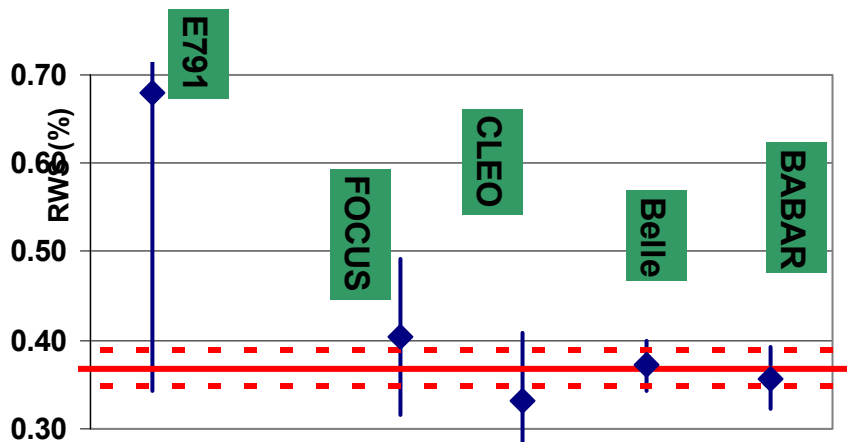
x2 statistics of previous measurements.

$$R_{WS} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (0.371 \pm 0.0$$

$$B(D^0 \to K^+\pi^-) \sim 1.4 \times 10^{-4}$$

The Wrong Sign Rate

	$K^-\pi^+$	$K^+\pi^-$	R_{ws} [%]	A_D [%]
E791 (66)	5.6K	not quoted	$0.68^{+0.34}_{-0.33} \pm 0.07$	–
ALEPH (67)	1038	19	$1.84 \pm 0.59 \pm 0.07$	–
FOCUS (68)	37K	150	$0.404 \pm 0.085 \pm 0.025$	–
CLEO (61)	13.5K	45	$0.332^{+0.063}_{-0.065} \pm 0.040$	$-2^{+19}_{-20} \pm 1$
Belle (63)	83K	845	0.371 ± 0.018	-8.0 ± 7.7
BaBar (62)	120K	430	$0.357 \pm 0.022 \pm 0.027$	$9.5 \pm 6.1 \pm 8.3$
Average			0.368 ± 0.021	

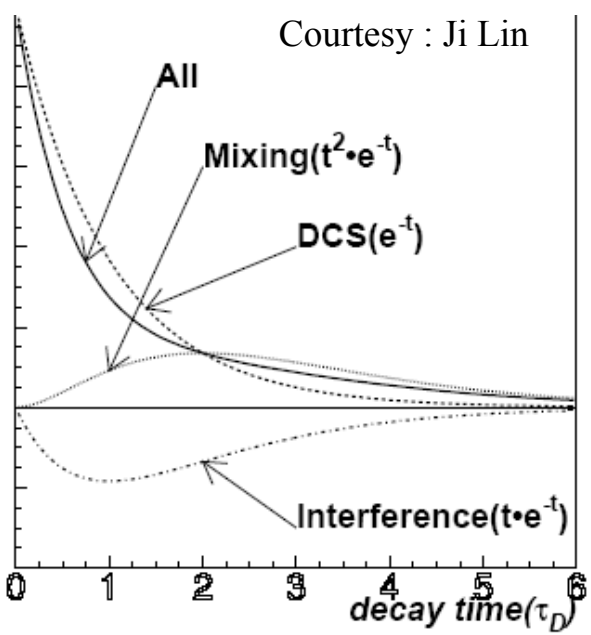


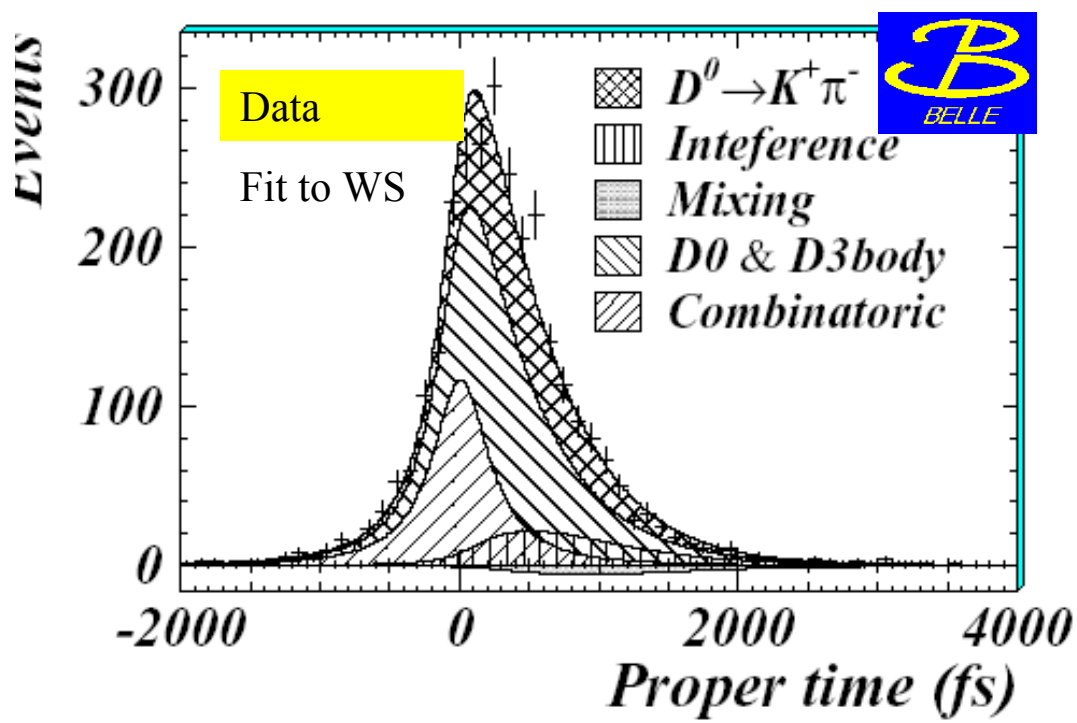
$$\langle R_{WS} \rangle = (0.368 \pm 0.021)\%$$

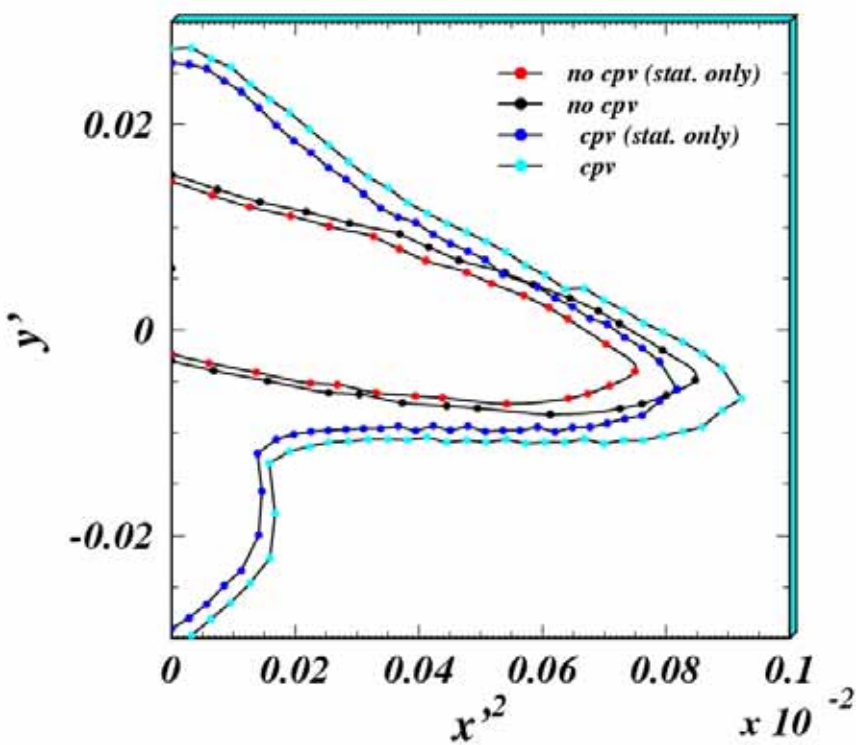
$$r_{ws}(t) = (R_D + \sqrt{R_D}\, y' t + \frac{1}{4}[x'^2 + y'^2]t^2)e^{-t}$$

DCSD interference mix

Simulation







This is a substantial improvement on previous results.

Fit case	Parameter	95% C.L. interval ($\times 10^{-3}$)
CPV (decay)	A_D	$-250 < A_D < 110$
CPV (Mixing)	A_M	$-991 < A_M < 1000$
	x'^2	$x'^2 < 0.89$
	y'	$-30 < y' < 27$
no CPV	x'^2	$x'^2 < 0.81$
	y'	$-8.2 < y' < 16$
	R_D	$2.7 < R_D < 4.0$

Mixing Summary

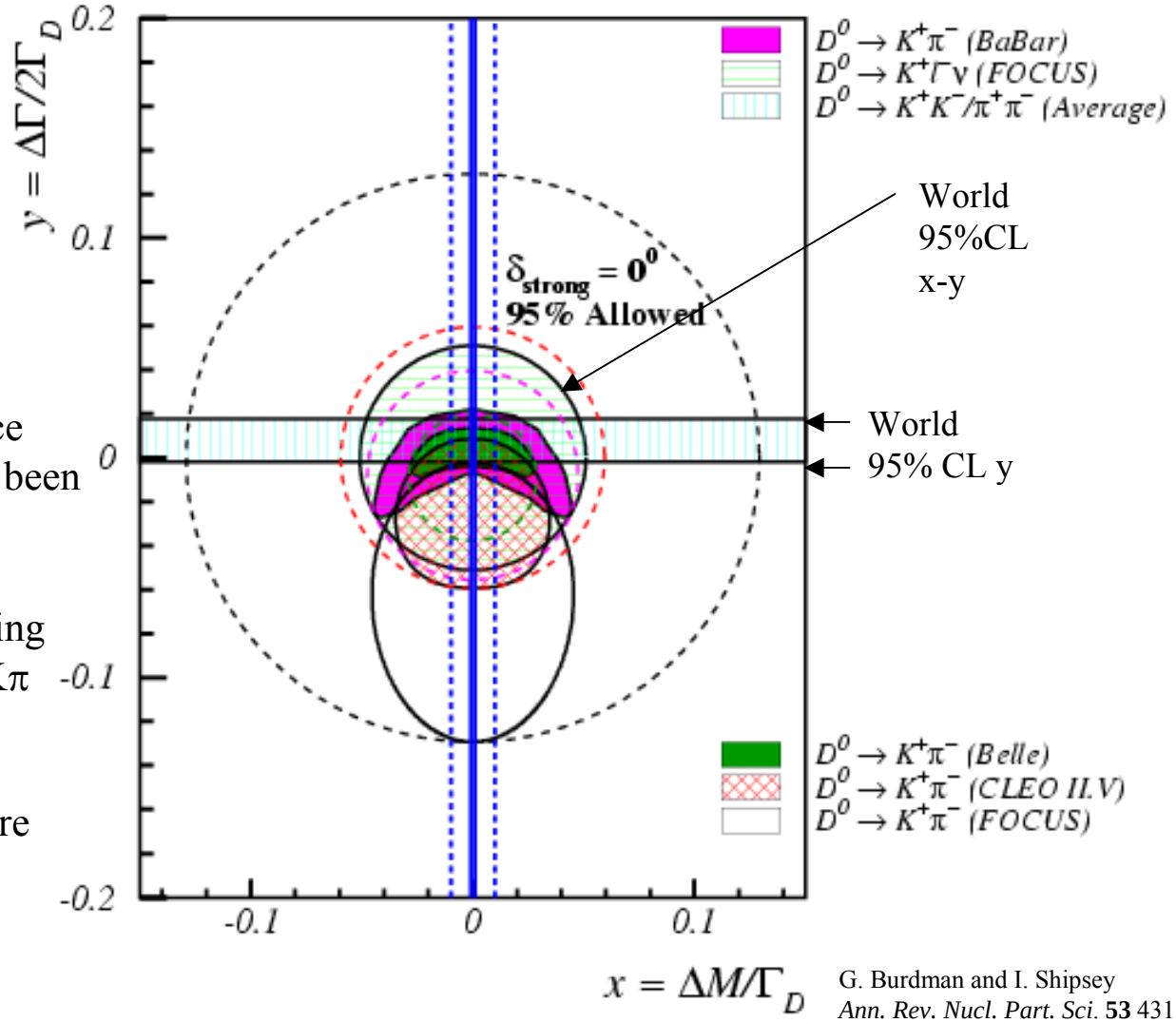
Combining all results:

CP conservation is assumed.

No statistically significant evidence for mixing has yet been found.

CDF expect a mixing result using D➔ Kπ soon.

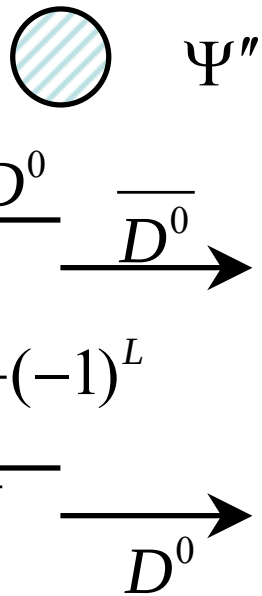
Important to measure δ can be done at a charm factory.



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

Unique opportunities at Threshold

$$\Psi'' \to D^0\overline{D^0},\ D^+D^-$$



$$\left|D^0\overline{D}^0\right\rangle_L = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle + (-1)^L\left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

Angular momentum (L=1 for ψ(3770))

CLEO-c/BES III Charm Mixing

Mixing: $\psi(3770) \rightarrow DD(C = -1)$

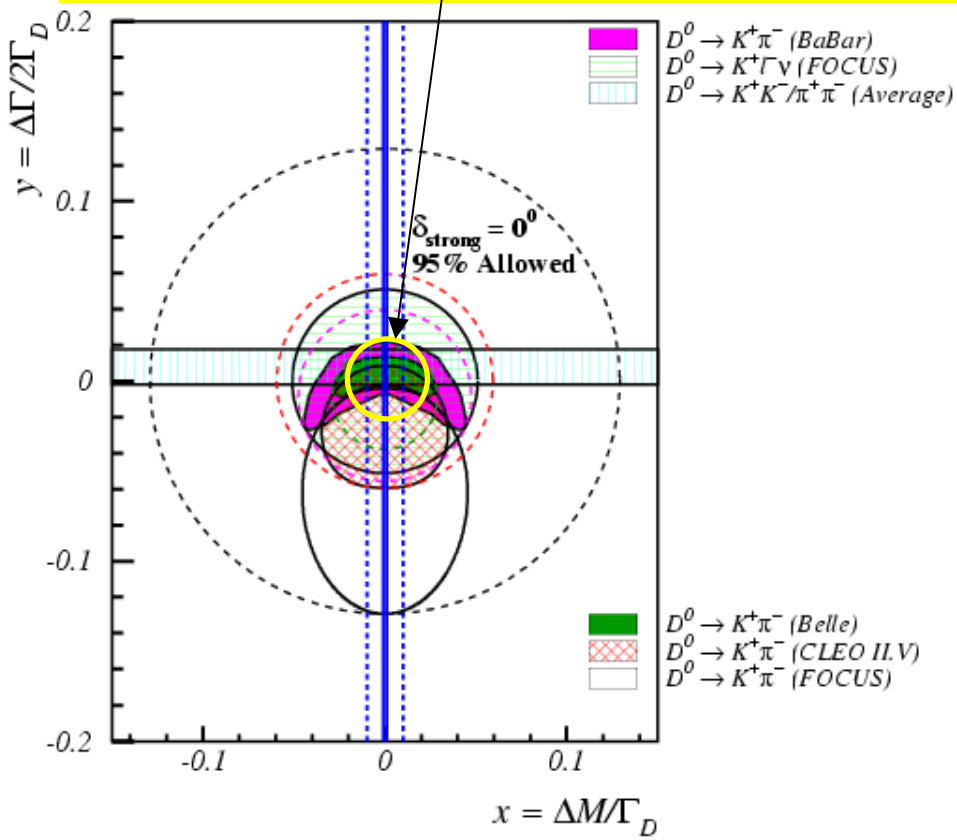
Coherence simplifies study DCSD interfere away so not a background

Unmixed: $D^0 \rightarrow K^-\pi^+$ $D^0 \rightarrow K^+\pi^-$

mixing: $D^0 \rightarrow K^-\pi^+$ $D^0 \rightarrow D^0 \rightarrow K^-\pi^+$

Can add lepton final states (Klv Klv)

Sensitivity: ~10^{-4} (CLEO-c) ~2×10^{-5} (BES III) current limit: 10^{-3}



CPV in D Decays

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

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

$$\Gamma\left(D^0 \xrightarrow{\overline{D}^0} f \;\&\; D^0 \xrightarrow{} f\right) \neq \Gamma\left(\overline{D}^0 \xrightarrow{D^0} f \;\&\; \overline{D}^0 \xrightarrow{} f\right)$$

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

Time dependent since mixing is involved

Direct CPV:

Experiment concentrates on this

$$\Gamma\left(D \xrightarrow{A_1 e^{i\delta_1}} f \;\&\; D \xrightarrow{A_2 e^{i\delta_2}} f\right) \neq \Gamma\left(\overline{D} \xrightarrow{A_1^* e^{i\delta_1}} \bar{f} \;\&\; \overline{D} \xrightarrow{A_2^* e^{i\delta_2}} \bar{f}\right)$$

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

2 weak amplitudes with phase difference

strong phase-shift

Direct CP Violation

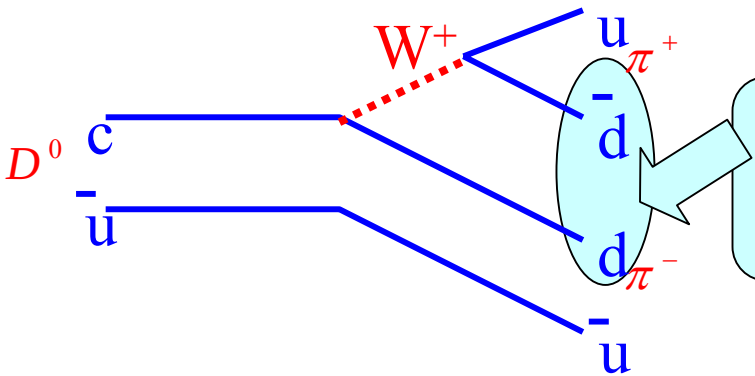
$$Acp \approx \frac{\mathrm{Im}\left[V_{cd}V_{ud}^{*}V_{cs}V_{us}^{*}\right]}{\lambda^{2}}\sin\delta_{PT}\frac{P}{T}\ ;\ \ A^{2}\eta\lambda^{4}\sin\delta_{PT}\frac{P}{T}\leq 10^{-3}$$

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

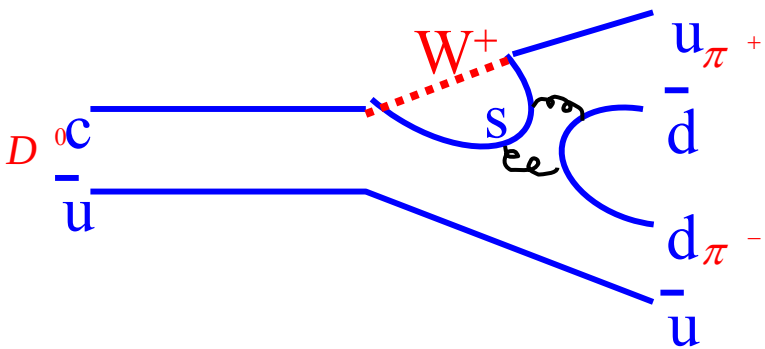
1) Consider $D^0 \rightarrow \pi^+\pi^-$

(same for K^+K^- $\{K^+K^-\pi^+,\ \phi\pi^+, K^*K\}$ $K^+K^-\pi^0$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, 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

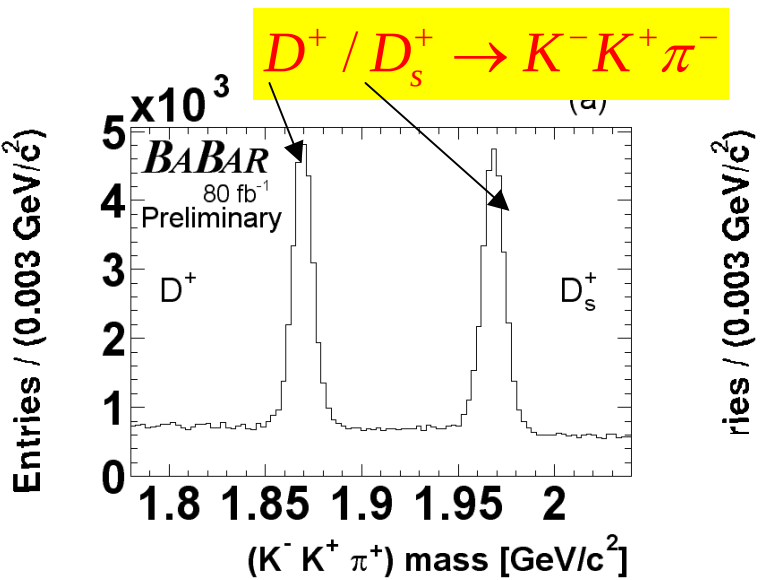
$\Delta I = \frac{1}{2}$

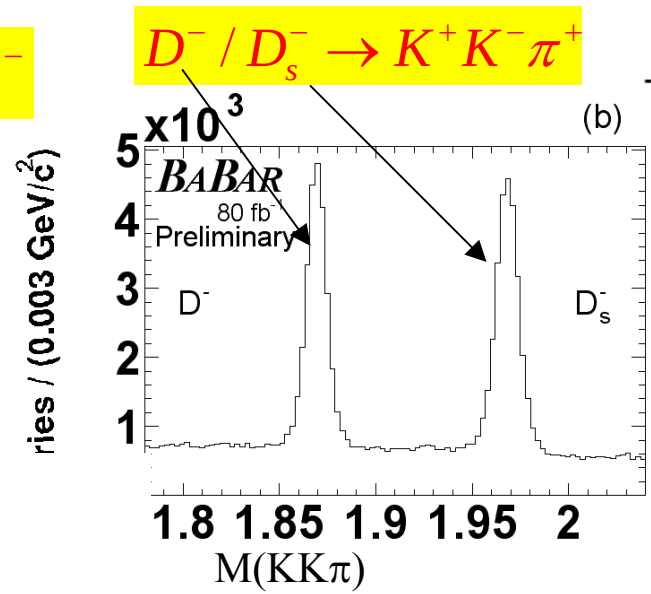
Search for Direct CP Violation in $D^+ \to K^-K^+\pi^-$

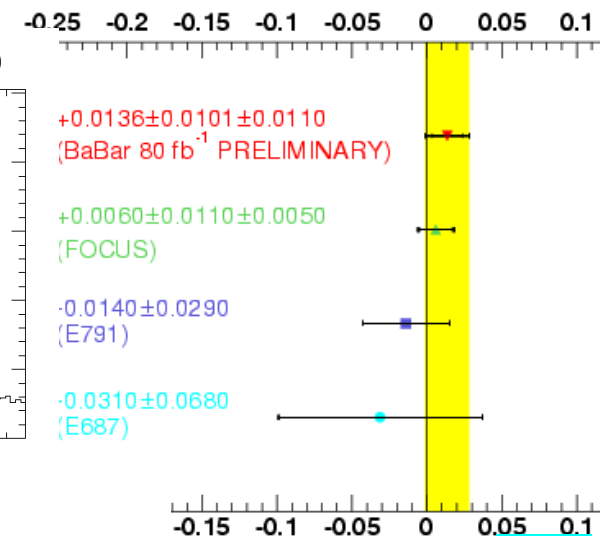
79.9 fb^{-1}

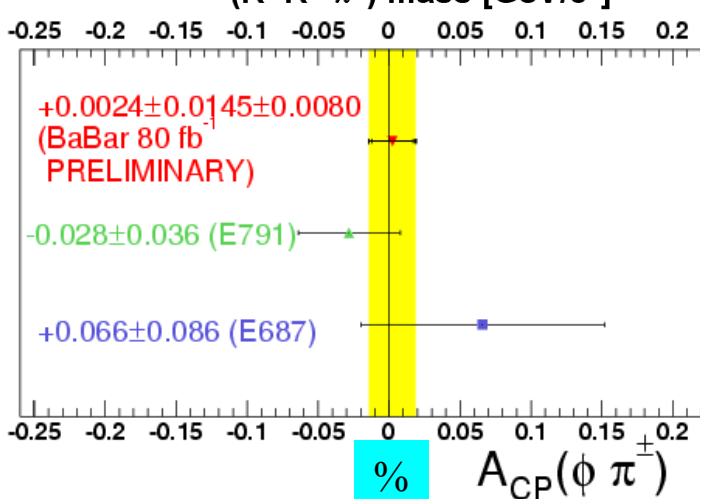
Three A_{CP} measurements: (1) KKπ (2) $\phi\,\pi$, (3) K^*K ~43,000 events relative to $D_s^+ \to KK\pi$ as control [Cabibbo favored hence no CP].

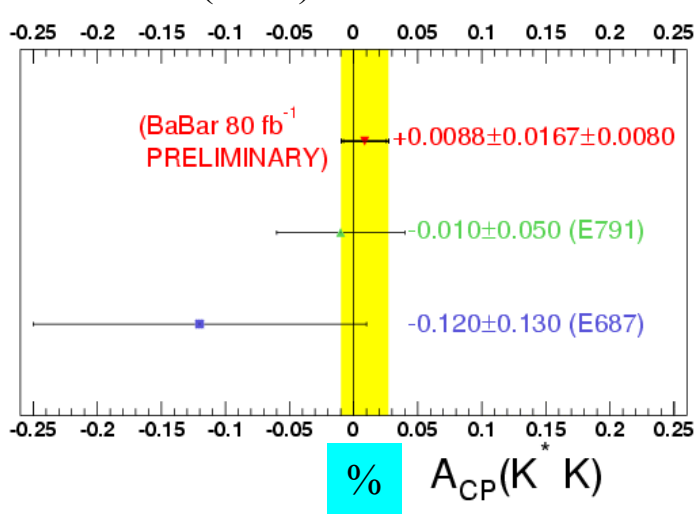
$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}$$











For $\phi\pi$ & K^*K significant improvement over previous measurements.

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

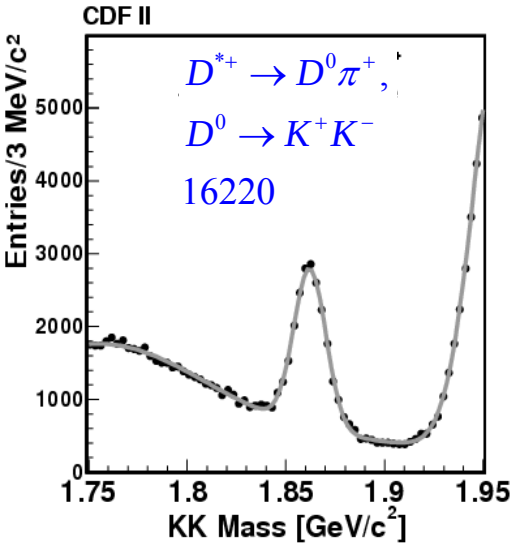
PRL 94 122001 (2005)

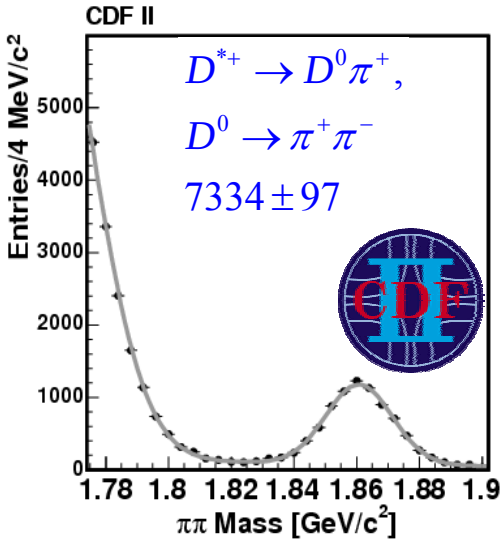
D* to tag D^0 flavor. Measure relative to $D^0 \to K\pi$ 123pb^{-1}
Cabibbo allowed mode (Acp=0) as control).

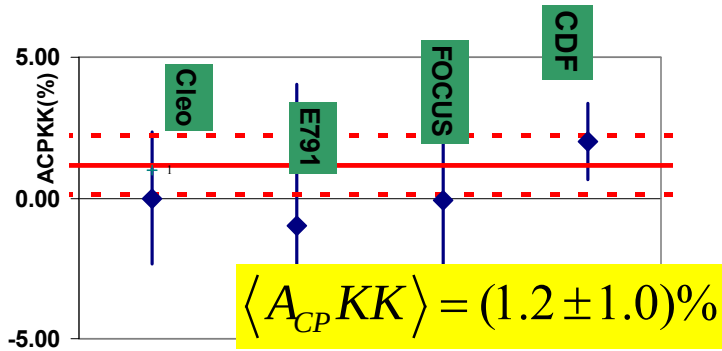
Time integrated
Most recent (& precise) result.

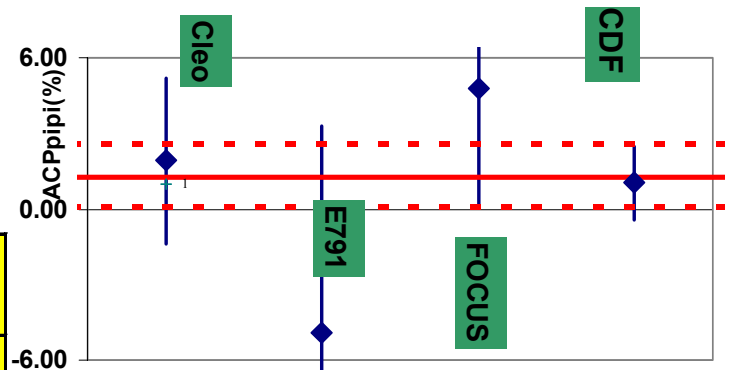
$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}$$

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









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

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

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

CP Eigenstates at ψ(3770)

At the ψ"(3770)

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

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

Suppose 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

$$(\pi^+\pi^-)(K_s^0\pi^0)(-1)^1$$

$$+ \quad - \quad - \quad = CP+$$

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

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

•Sensitivity (two body final states)

• $A_{cp} < 0.01$ (CLEO-c)

• $<2 \times 10^{-3}$ (BESIII)

•CP tagging allows searches for CPV in multi body decays using Dalitz plots. These searches are sensitive to amplitudes, rather than rates

More on CP Eigenstates at $\psi(3770)$

- In BFac/Tevatron: searches for D mixing, large DCSD rate interferes with signal with an unknown phase δ

$$y' = y\cos\delta - x\sin\delta$$
$$x' = x\cos\delta + y\sin\delta$$

(CLEO-c /BESIII can measure δ by using CP tagging

- CP eigenstate tag X flavor mode

$$K^+K^- \leftarrow D_{CP} \leftarrow \psi(3770) \rightarrow D_{CP} \rightarrow K^-\pi^+ \; (-1)^l$$

$$+ \qquad - \qquad - \qquad = CP+$$

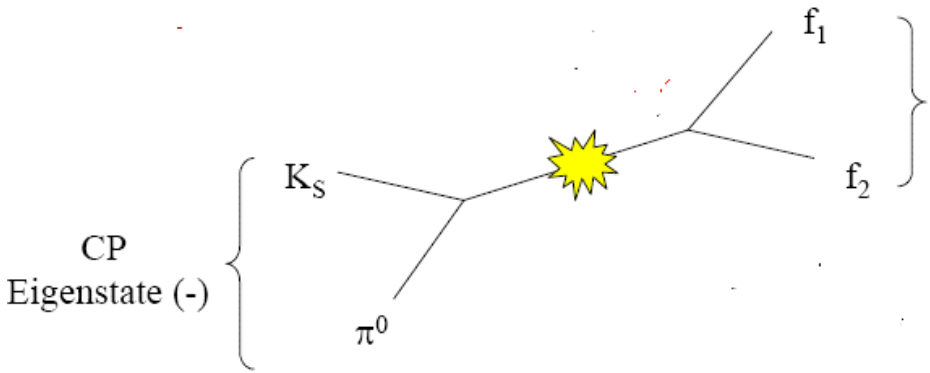
(same phase is important in ADS method of determining phi3/gamma)

Measurement of Strong Phase

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

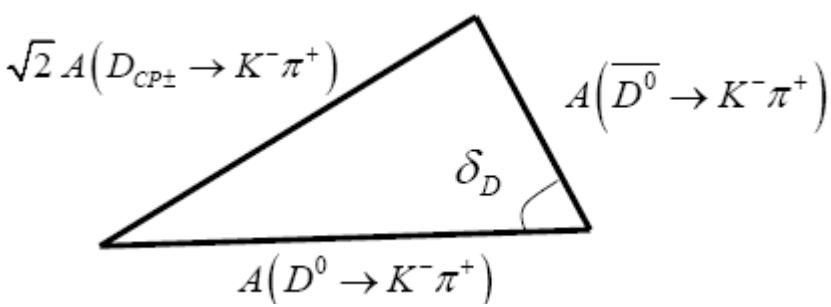
$$\left|D_{CP\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0\right\rangle \pm \left|\overline{D^0}\right\rangle\right]$$

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



Flavor mode

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



In the limit of CP-invariance

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

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

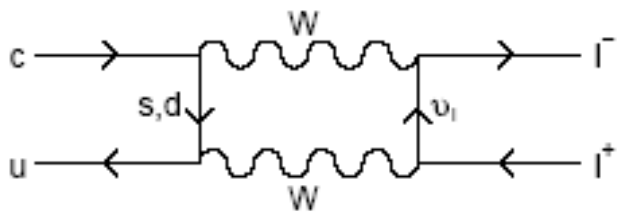
$-\cos\delta_D \sim \pm 10\%$

Rare Charm Decays

FCNC modes are suppressed by the GIM mechanism:

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

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



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

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

R-parity violating SUSY:

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

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

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

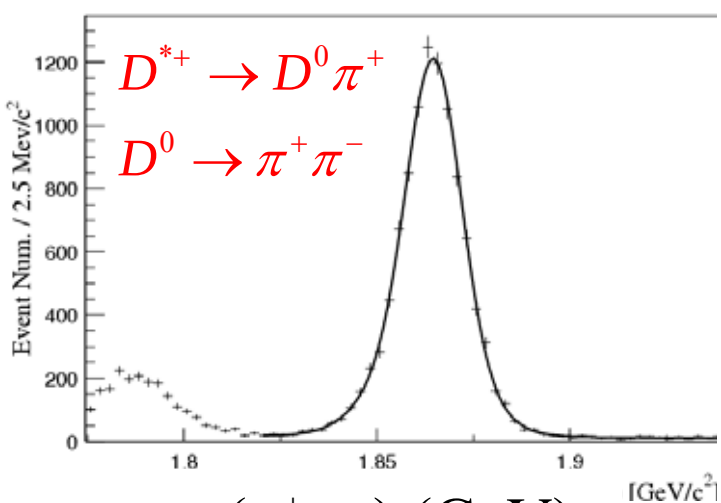
(Burdman et al., Phys. Rev. D66, 014009).

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

PRL 93 101801 (2005)

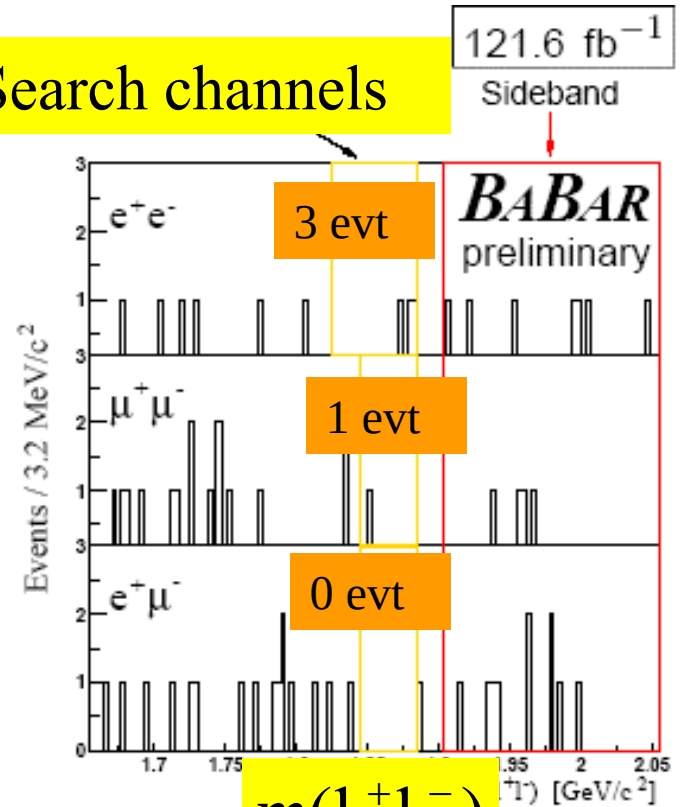
121.6 fb^{-1}

Normalizing mode:



mass(π^+,π^-) (GeV)

Search channels

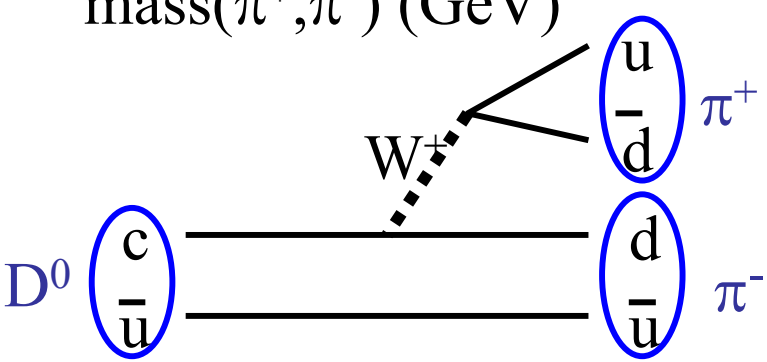


$m(l^+l^-)$

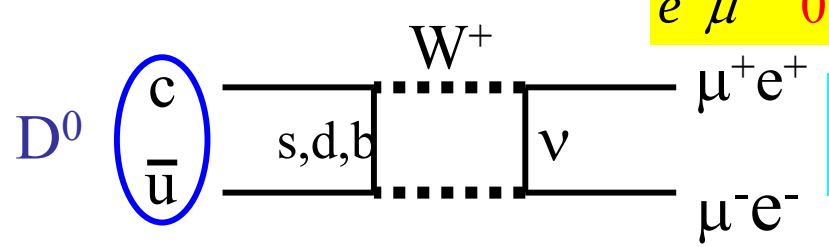
121.6 fb^{-1}

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
$e^m\mu^\pm$	0.81	8.1



standard model rate ~ 10^{-3}



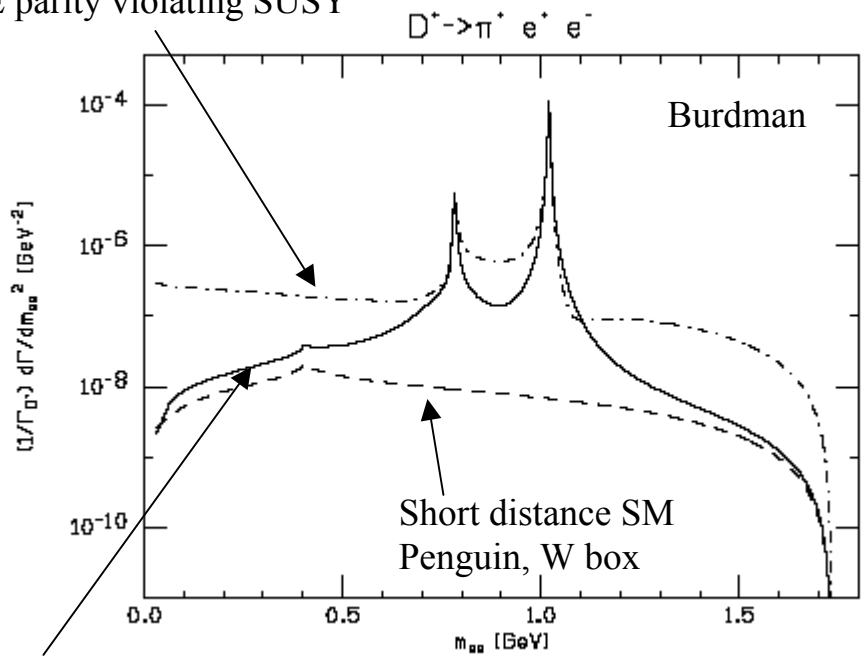
standard model rate ~ 10^{-13} (10^{-23})

Big Improvement!

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

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

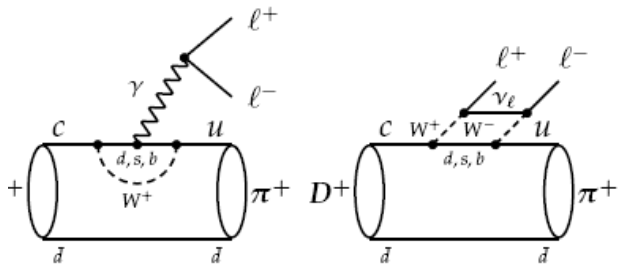
E parity violating SUSY



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

In the SM

B ($D^+ \Rightarrow \pi^+e^+e^-$) ~ 2 x 10^{-6}



R-parity violating SUSY:

B ($D^+ \Rightarrow \pi^+e^+e^-$) ~ 2.4 x 10^{-6}

Increase in rate is small but significant at low dilepton mass

Current experimental limit CLEO II:

B ($D^+ \Rightarrow \pi^+e^+e^-$) ~ 4.5 x 10^{-5} ar 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 search at the Y(4S)

281pb^{-1} at ψ(3770)

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

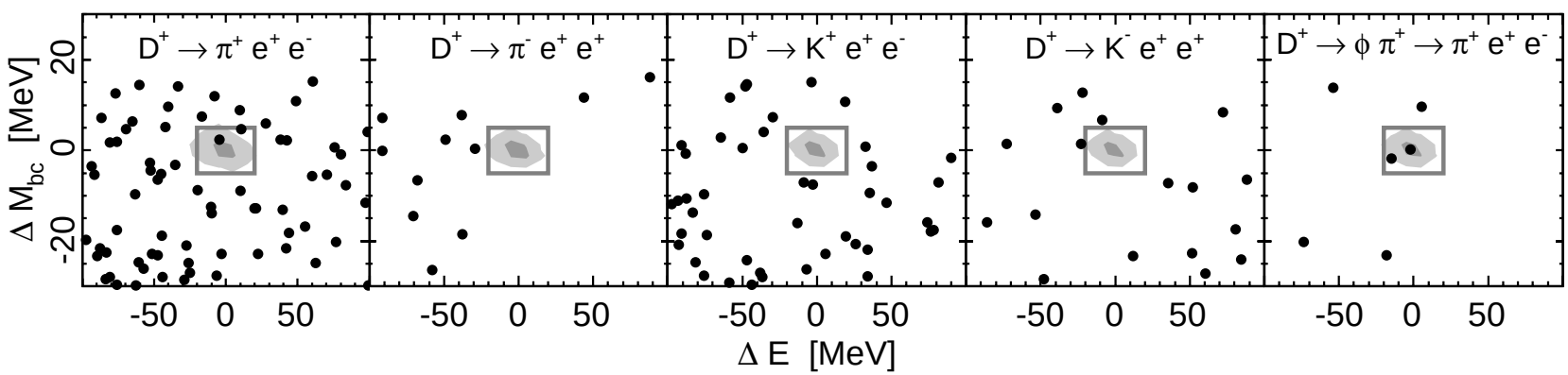
(signal box is ± 20MeV) (resolution is 6 MeV)

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

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

Multiple candidates are resolved by taking the best |ΔMbc|

$\pi^+e^+e^-$ $\pi^-e^+e^+$ $K^+e^+e^-$ $K^-e^+e^+$ $D^+ \Rightarrow \phi\pi^+ \Rightarrow \pi^+e^+e^-$



Mbc vs. ΔE plots

Panel 1: $\pi^+e^+e^-$ (& limit) has $\phi \Rightarrow e^+e^-$ removed

Results:

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

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

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

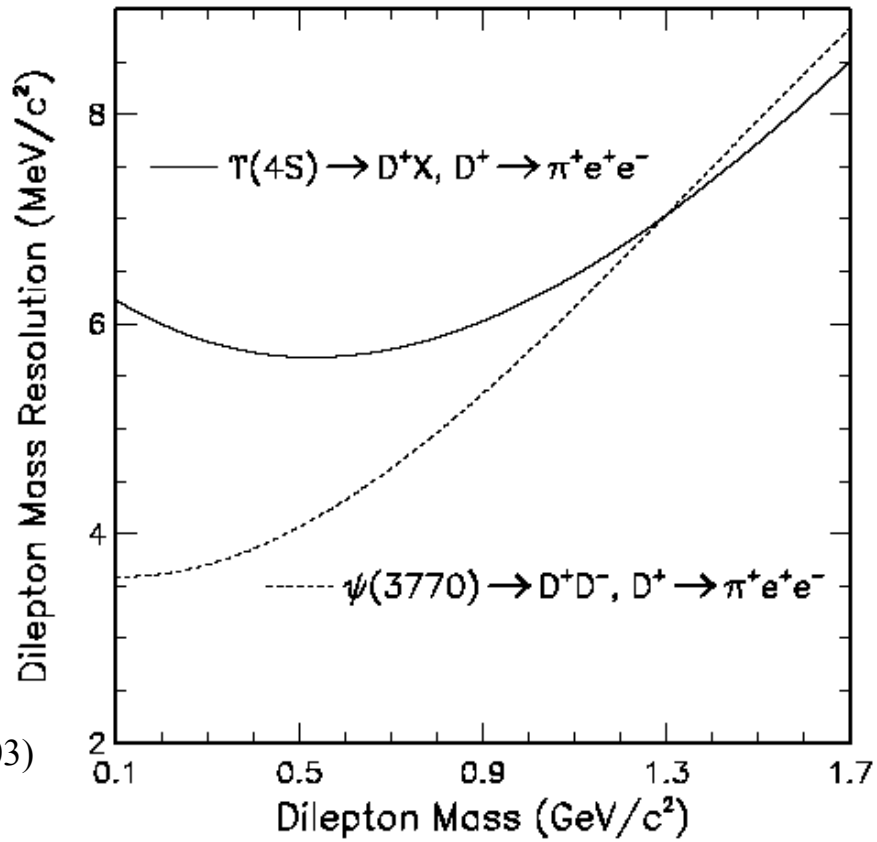
$B\,(D^+ \Rightarrow K^-e^+e^+) \;<\; 4.5 \times 10^{-6}$ (90% CL)

Forbidden in SM

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

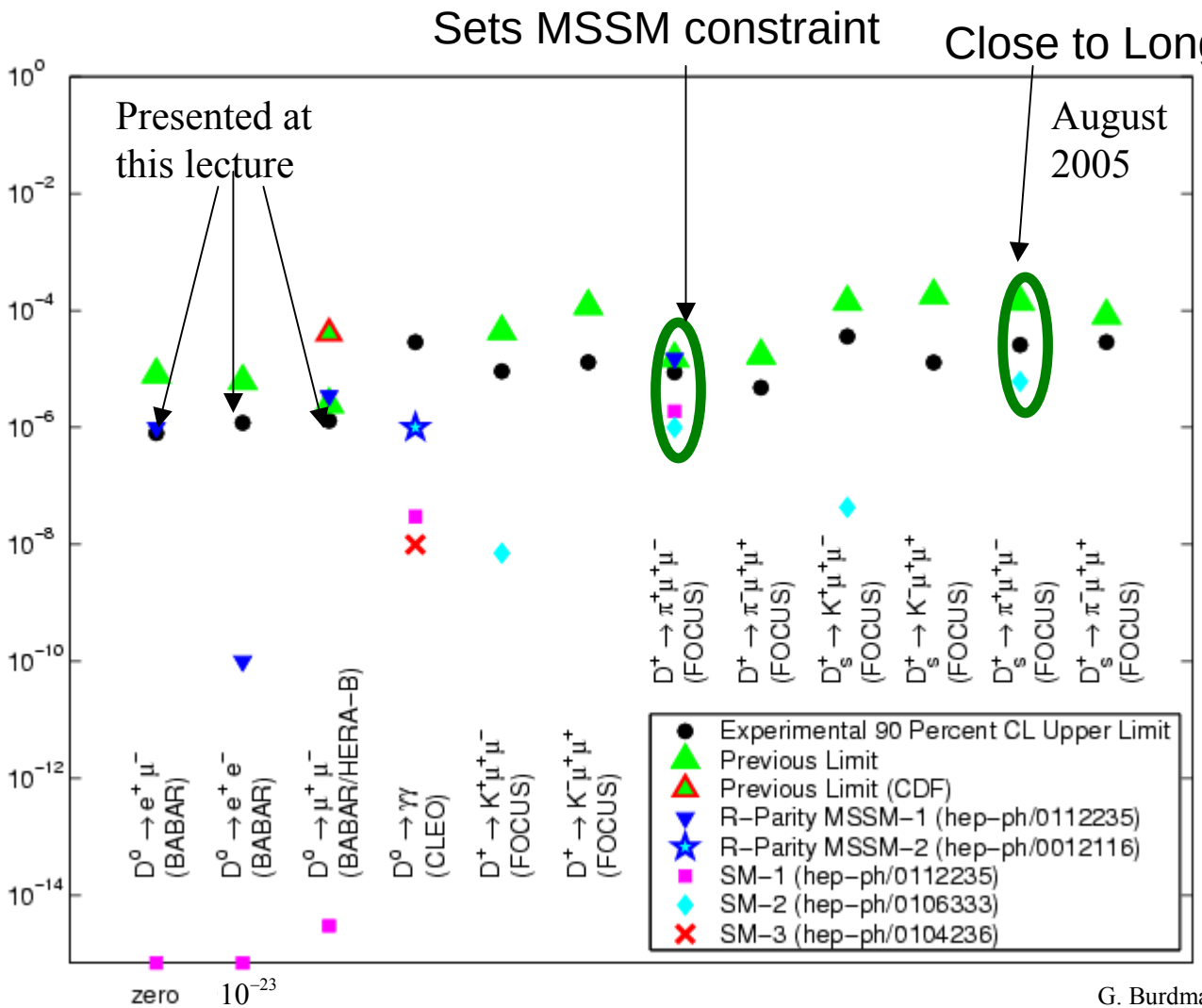
With 1/fb signal may show up

More likely observation of these modes and studies of the dilepton mass (20 MeV mass resolution adequate) will be the province of BES III and Super B factories (~100 event samples)



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

Rare Decay Summary



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

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

Still plenty of room for New Physics.

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

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

Summary

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

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

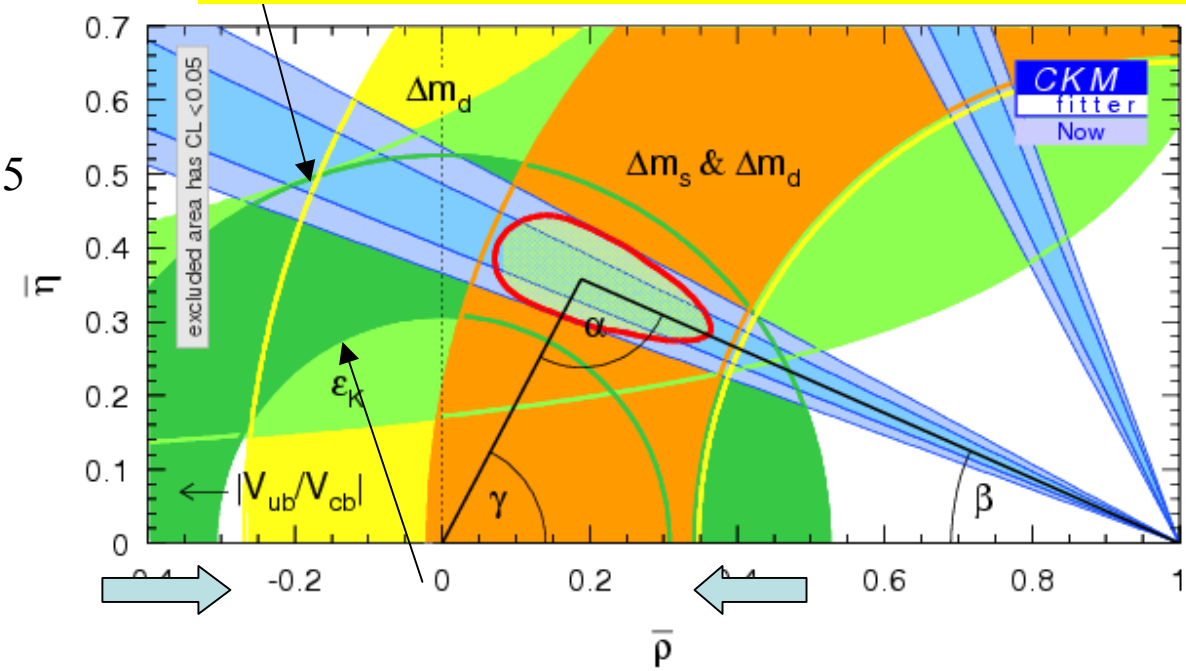
The precision with which the charm decay constant f_{D+} is known has already improved from 100% to ~8%. And the $D \rightarrow K$ semileptonoc form factor has be checekd to 10%. A reduction in errors for decay constants and form factors to the few % level is promised.

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

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

Precision theory + charm = large impact

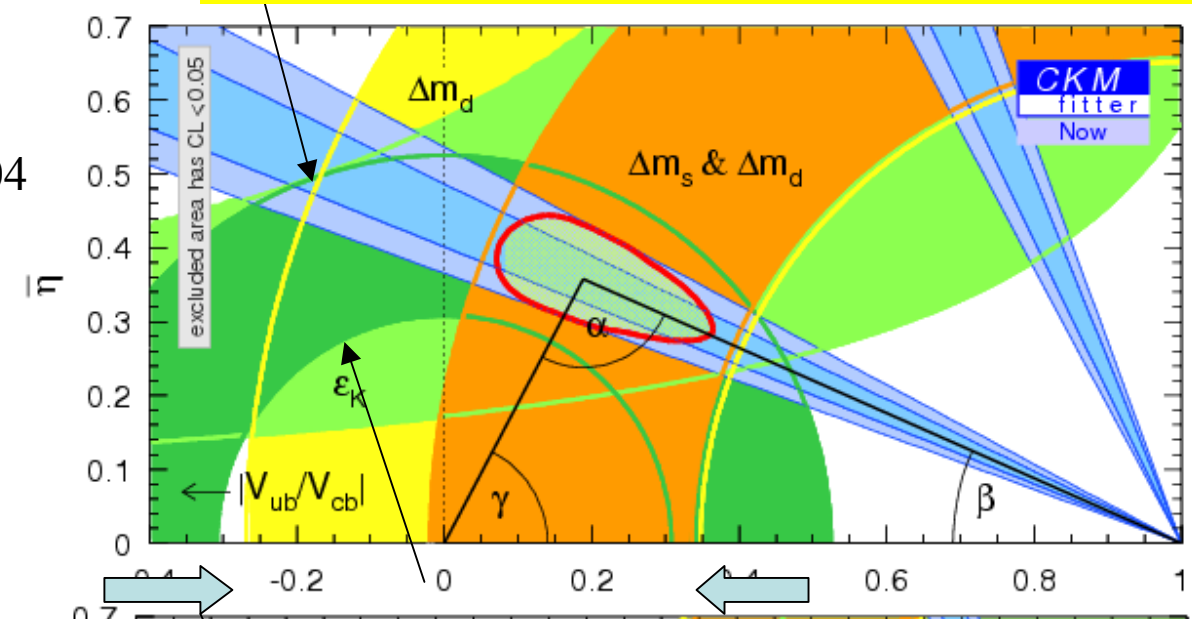
2005

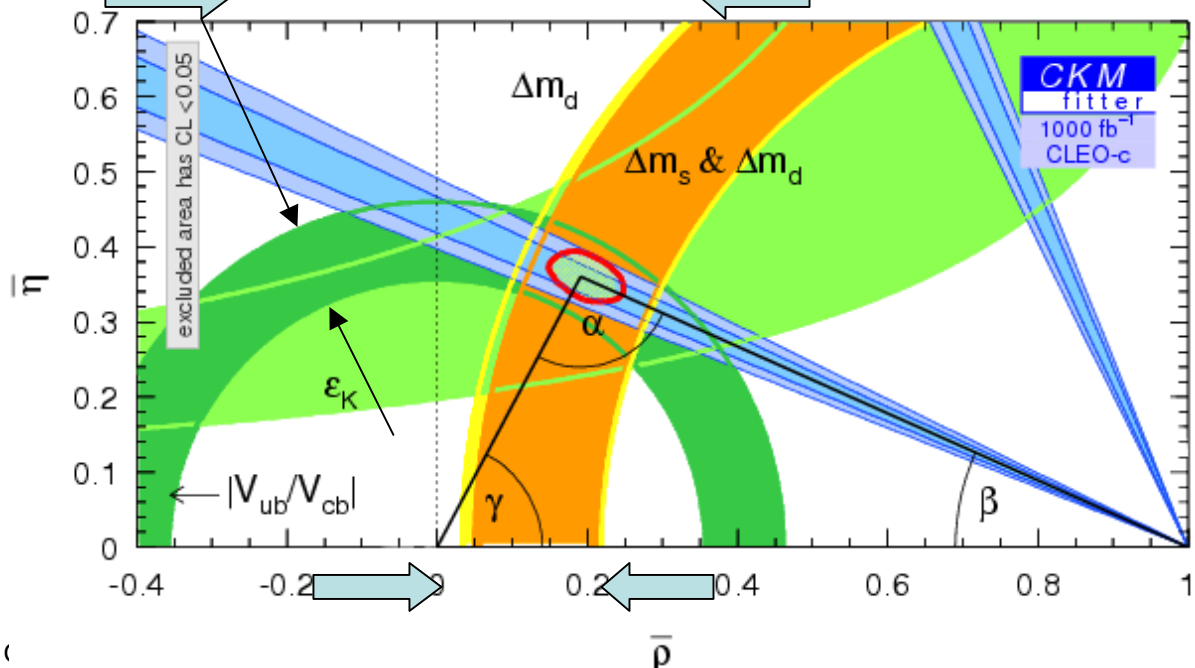


Theoretical errors dominate width of bands

Precision theory + charm = large impact

2004

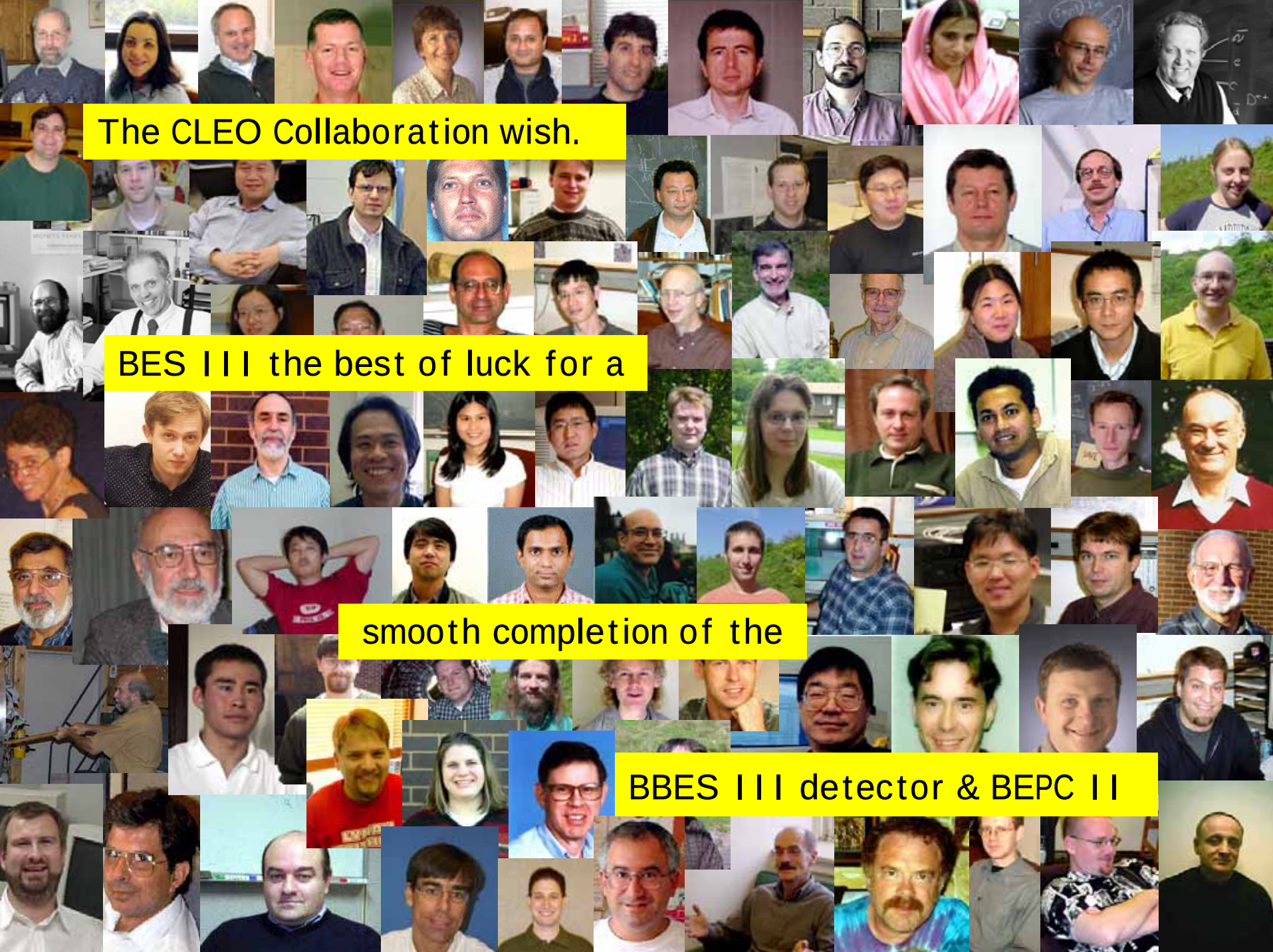




precision QCD calculations tested with *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

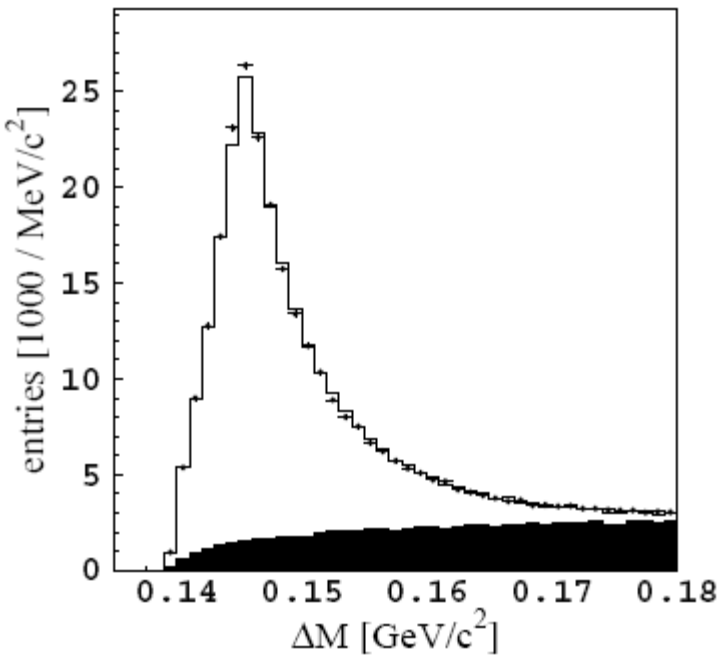
500 fb-1 @ BABAR/Belle


The CLEO Collaboration wish.
BES III the best of luck for a
smooth completion of the
BBES III detector & BEPC II

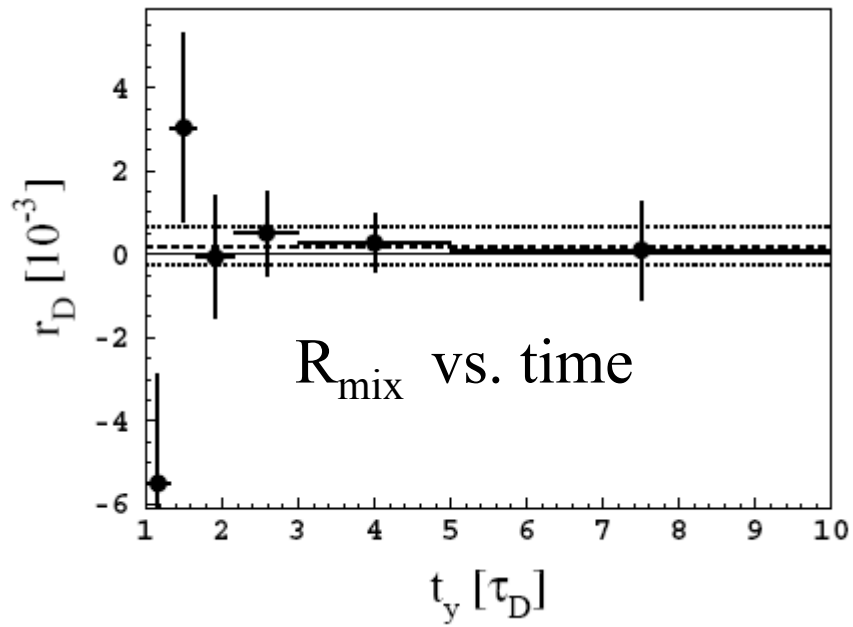
Additional Slides

Search for D Mixing in Semileptonic Decays

unmixed



mixed



$$\Delta m = m(D^*) - (D^0)$$

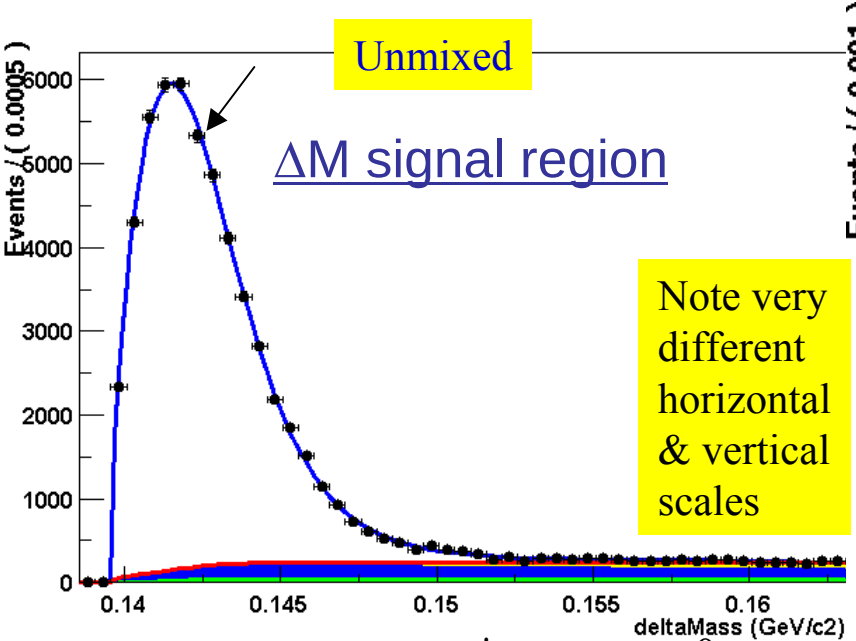
$$R_{mix} < 1.0 \times 10^{-3} \text{ at } 90\% \text{ CL (stat + sys)}$$

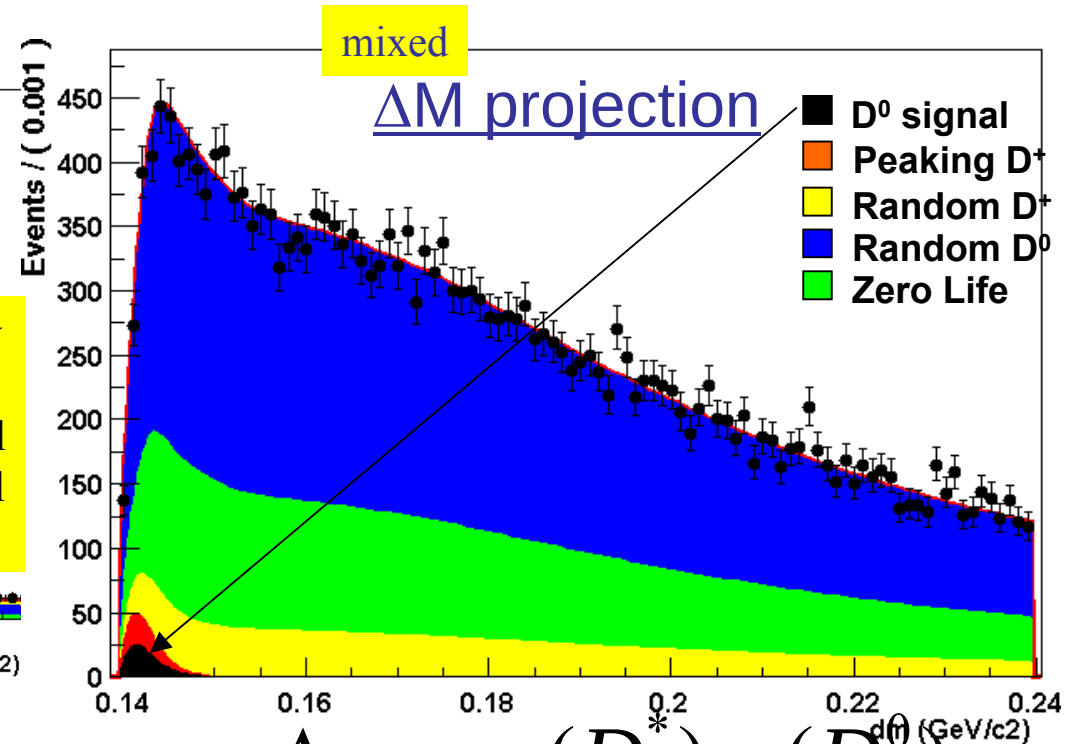
New best measurement

Search for D Mixing in Semileptonic Decays

ICHEP ABS11-0629

- Unbinned extended maximum likelihood fit to transverse **lifetime** and **ΔM** = M(D*)-M(D^0) with 15 floated parameters D→K and K* e ν continuum events 80fb^{-1} ON 7.1fb^{-1} OFF





$$\Delta m = m(D^*) - (D^0)$$

Unmixed D0 yield: **49620 ± 324 evts** (stat)

$$R_{mix} = N_{mix} / N_{unmix}$$

$$R_{mix} = 0.0023 \pm 0.0012(\text{stat}) \pm 0.0004(\text{syst})$$

$$R_{mix} < 0.0042 (90\% \text{ C.L.})$$

$$\Delta m = m(D^*) - (D^0)$$

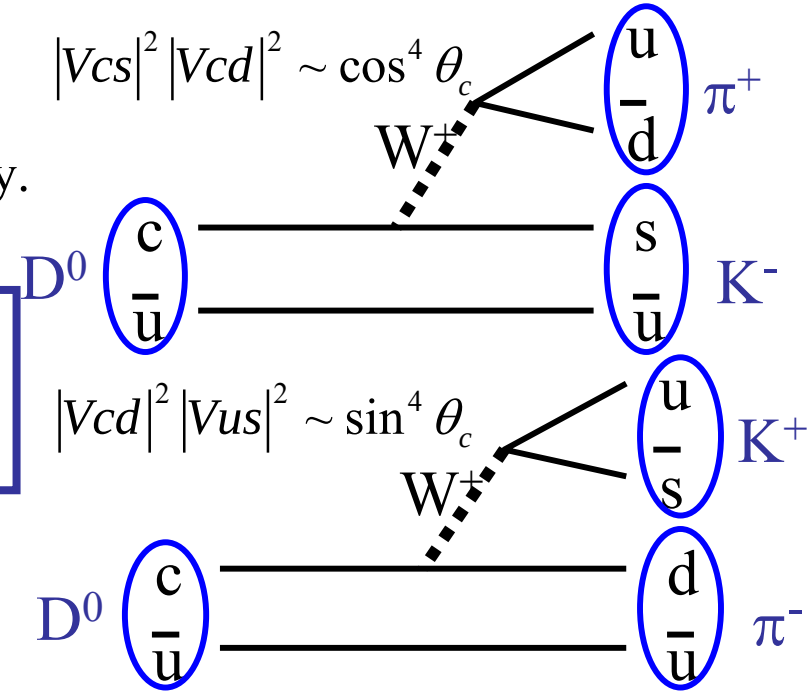
- **N(mix): 114 ± 61**

(~5% probability of getting a larger result for R_{mix}=0)

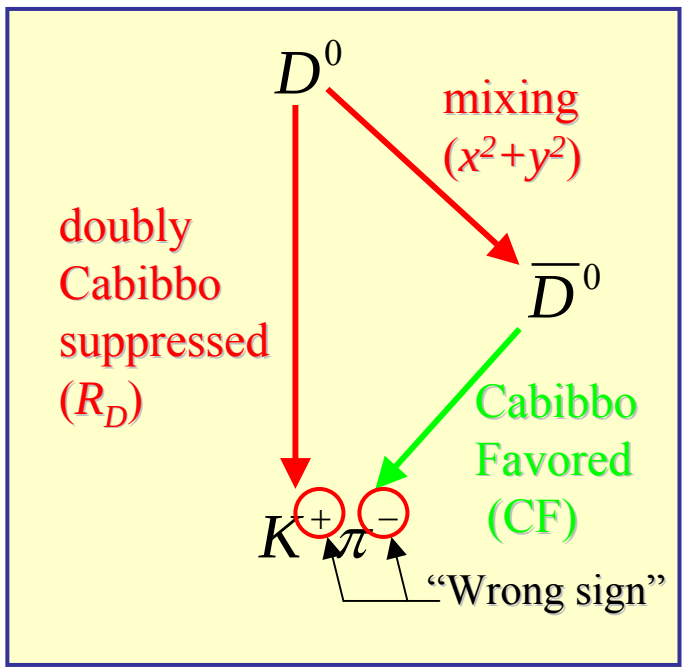
Search for D Mixing in D→Kπ

ICHEP ABS11-0704 PRL 94 071801 (2005)

Sensitive to both x and y, and linear in y.
Best constraints come from this mode.



"right-sign" (RS) => Cabibbo-favored decays
"wrong-sign" (WS) => Mixing or doubly Cabibbo-suppressed decays.



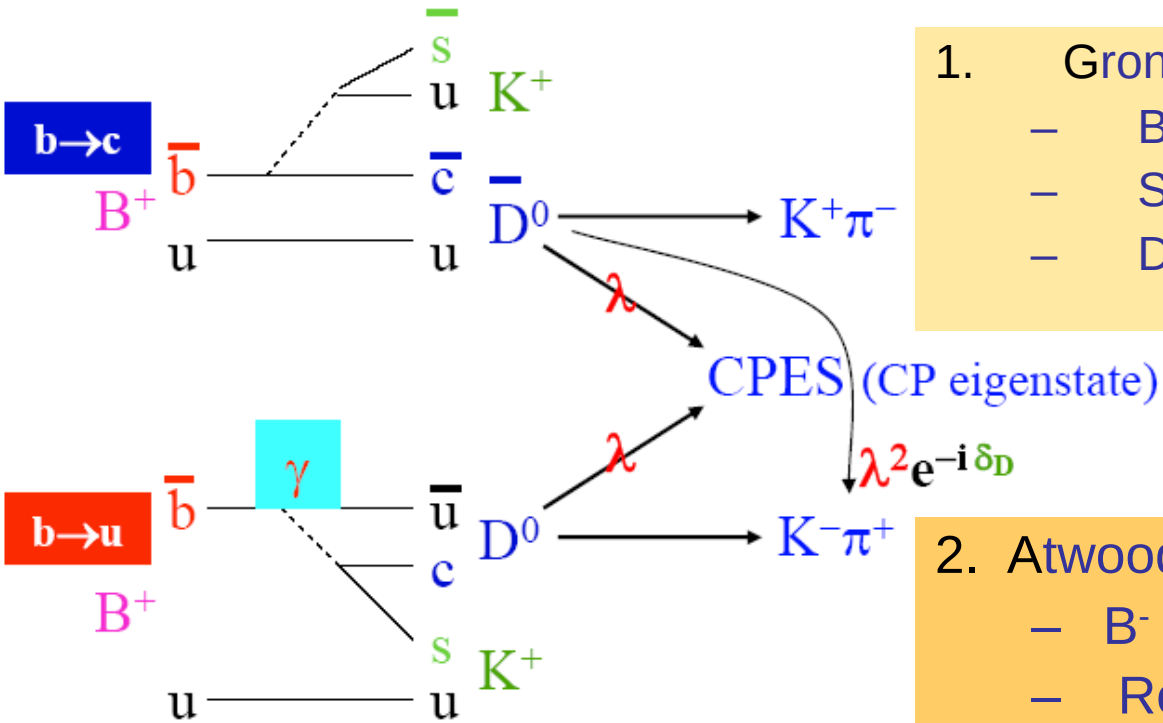
CP Violating effects are measured by fitting D^0 and $\overline{D}^0$ separately.

Need to fit proper decay time in order to distinguish mixing (both *x* and *y*) from doubly Cabibbo-suppressed (DCS) decays:

$$r(t) = \left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y' t}_{\text{interference}} + \underbrace{\tfrac{1}{4}\left(x'^2 + y'^2\right) t^2}_{\text{mixing}} \right) e^{-t}$$

Complication: phase difference, $\delta_{K\pi}$, between CF and DCS amplitudes can lead to observable quantities *x'* and *y'*, related to *x* and *y* by a rotation.

CLEO-c 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

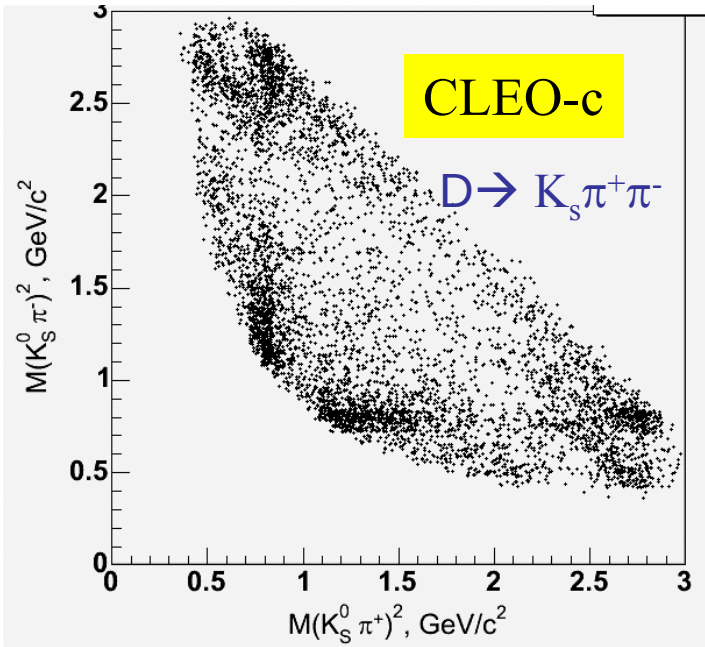
2. Atwood-Dunietz-Soni Method
   - $B^- \to D K^-$
   - Requires very large Ldt
   - CLEO-c measure r_D & $\cos \delta_D$

3. Dalitz plot Method
   - $B^- \to DK^-$, $D \to K_s\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K_sK^+K^-$
   - limited by uncertainty due to Dalitz plot model
   - CLEO-c quantum correlated D's reduce model dependence

See talks by Asner, Fleischer, Grossman, Petrov WG-5

CLEO-c Probes of New Physics (+ input to ϕ_3 /γ)

2. Dalitz plot Method
   - $B^- \rightarrow DK^-$, $D \rightarrow K_s\pi^+\pi^-$
   - limited by uncertainty due to Dalitz plot model currently $10\text{-}11^0$
   - CLEO-c CP tagged D's reduce Dalitz plot model dependence, compare CP+←DD→ $K_s\pi^+\pi^-$, CP-←DD→ $K_s\pi^+\pi^-$, & untagged D→ $K_s\pi^+\pi^-$, Extrapolation of Belle study CLEO-c 285 pb^{-1}/6fb^{-1} (3770 + DsDs) reduce model error to ~7^0, ~1^0

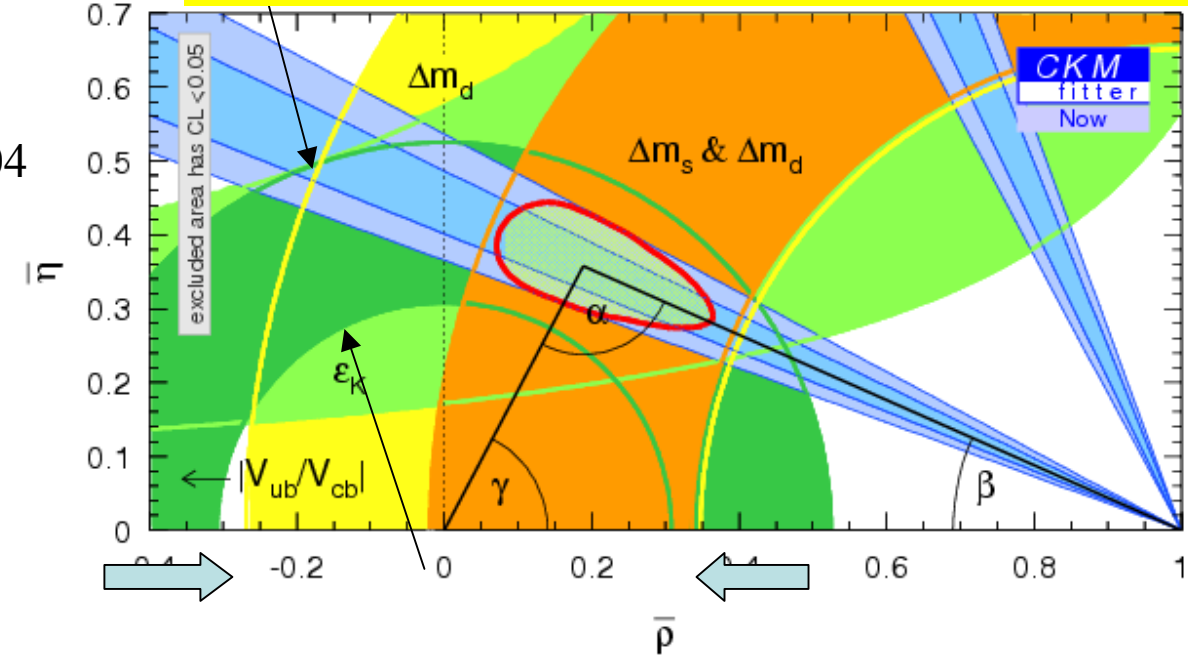


- CP violating asymmetries
  - Unique:L=1,C=-1 CP tag one side, opposite side same CP
  - CP=±1 ← $\psi(3770)$ → CP=±1 = CPV Sensitivity (two body final states) $A_{cp} < 0.01$
  - CP tagging allows many searches for CPV in Dalitz plots sensitive to amplitudes

Rare charm decays. Sensitivity: 10^{-6}

Today: the potential of quark flavor physics to discover new physics is limited by theory errors

2004



Theoretical errors dominate width of bands

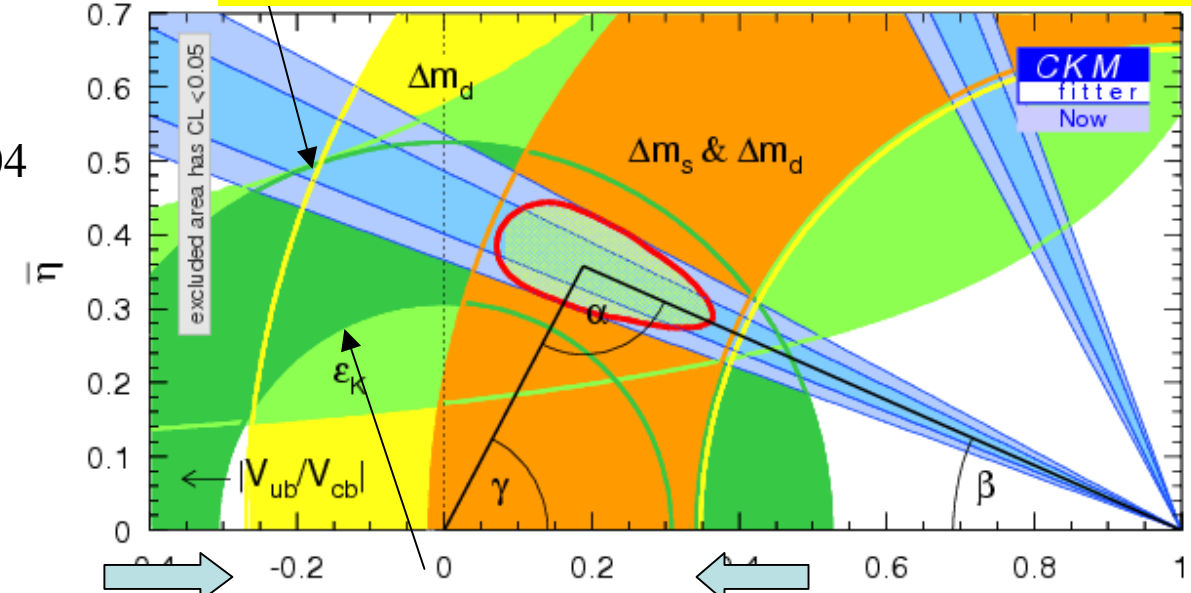
precision QCD calculations tested with *precision* charm data from CLEO-c
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

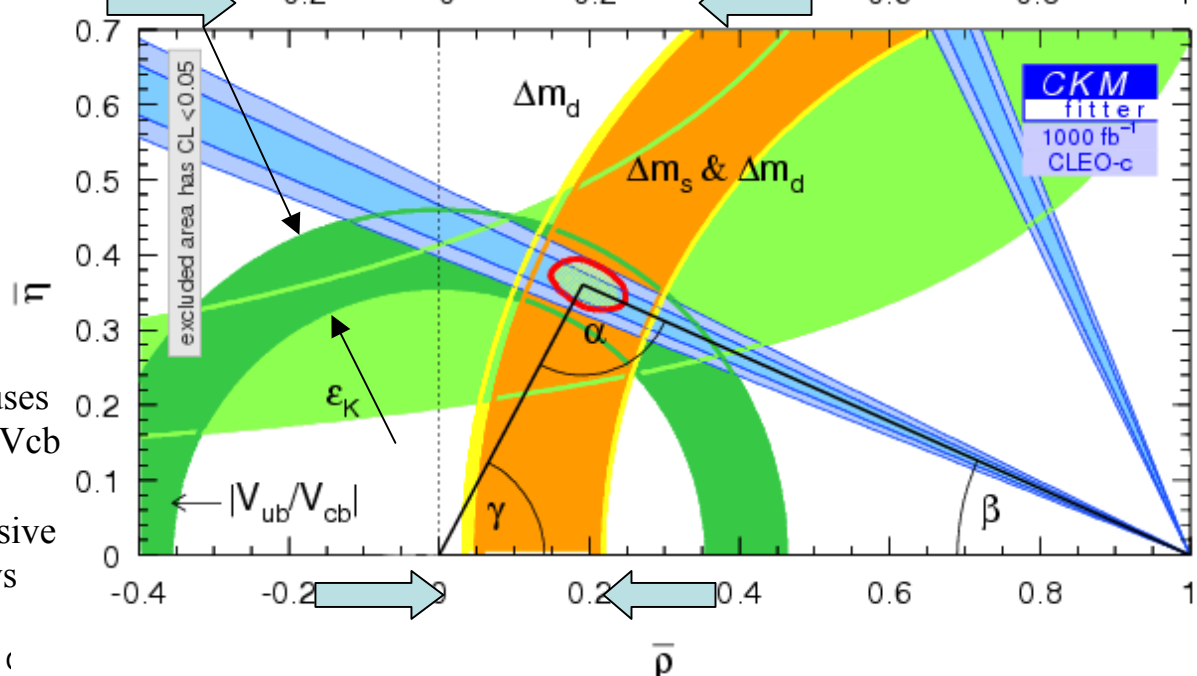
500 fb-1 @ BABAR/Belle

Precision theory + charm = dramatic increase in the potential of quark flavor physics to discover new physics

2004



Theoretical errors dominate width of bands



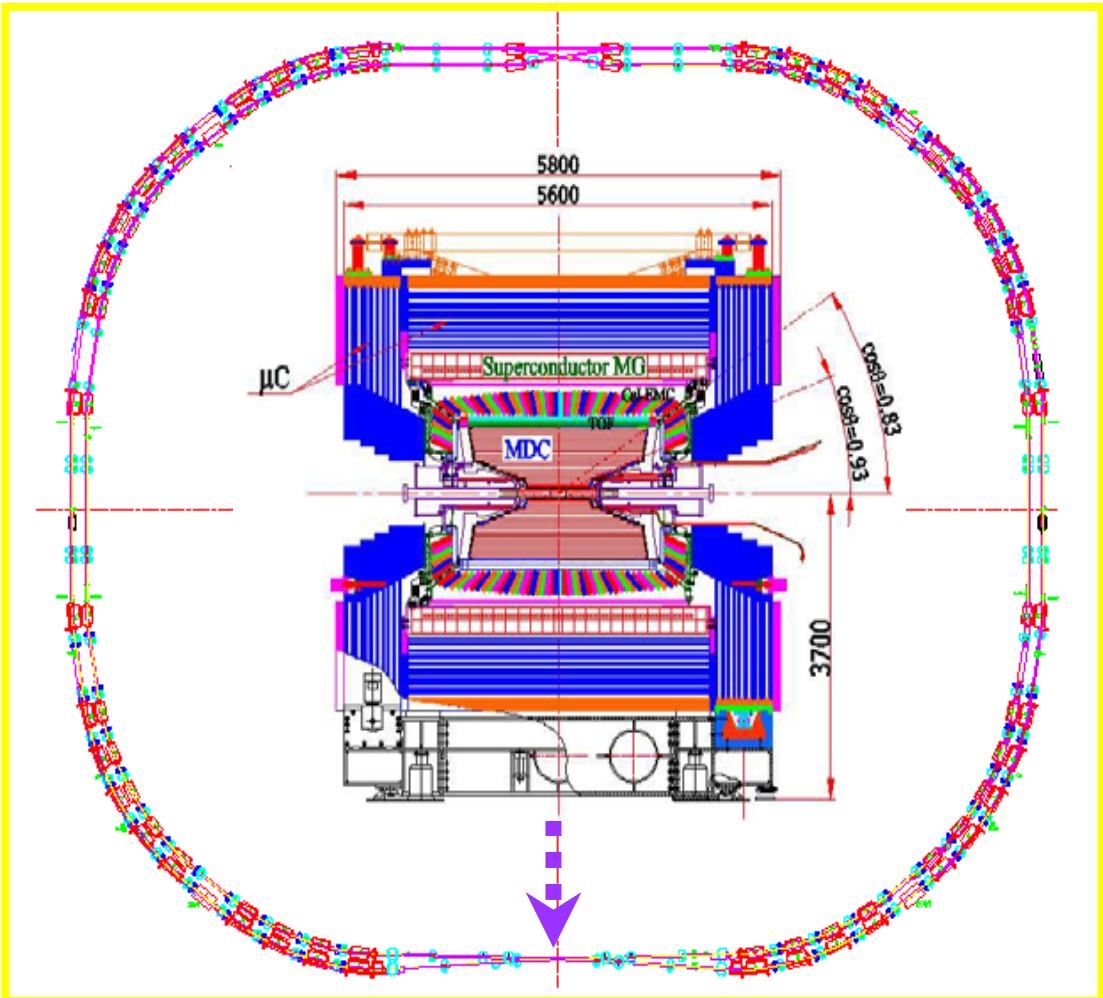
precision QCD calculations tested with *precision* charm data from CLEO-c
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

500 fb-1 @ BABAR/Belle

Plot uses Vub, Vcb from exclusive decays only

BEPCII/BESIII Project



Design

- Two ring machine
- 93 bunches each
- Luminosity

  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