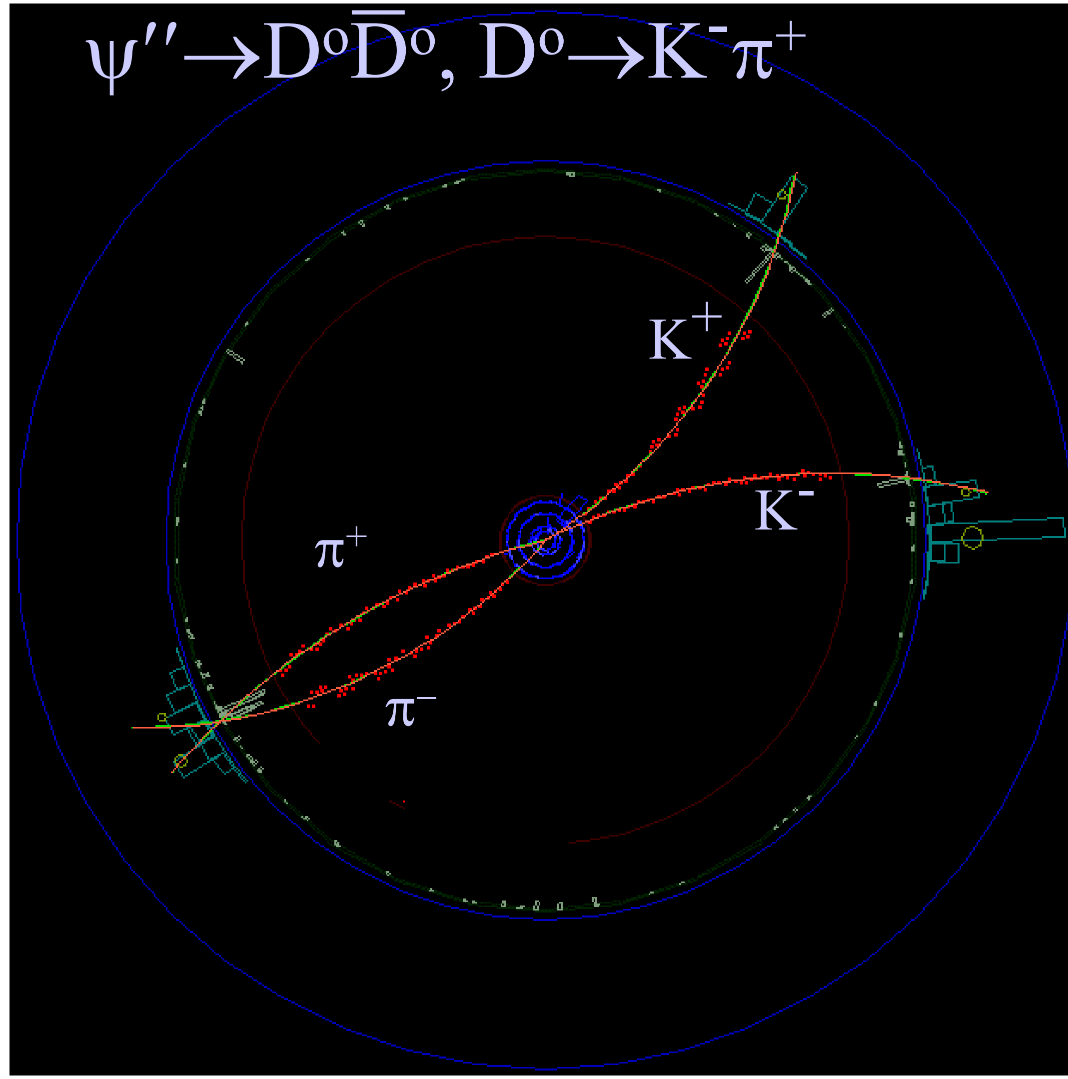
CKM Studies and New Physics Searches with Charm

Two themes:

1) Why Charm Physics allows B Physics to reach its full potential

2) Charm physics as a probe of physics beyond the Standard Model



Ian Shipsey,

Purdue University

- I am completely deaf
- I communicate by lip reading
- BUT lip reading obeys an inverse square law, and the audience is too far away
- Please write down your questions
- Pass them up to me
- I will read out your question before answering it

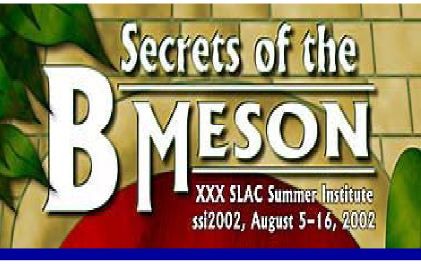
Outline of the Lectures

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

Lecture 2

  - Semileptonic Decays and CKM matrix elements
  - Tests of Unitarity
  - Spectroscopy
- Charm as a Probe of New Physics:
  - Mixing
  - CP Violation & Rare Decays
- Summary & Outlook



Charm Physics:
What do we need to measure?

•flavor physics: overcome the non pert. QCD roadblock

Precision charm lifetimes ← exist

• precision charm abs. branching ratio measurements ← do not exist

Leptonic decays : decay constants

Semileptonic decays: Vcs,Vcd,unitarity form factors

Abs D hadronic Br's normalize B physics

Tests QCD techniques in c sector, apply to b sector → Improved Vub, Vcb, Vtd & Vts

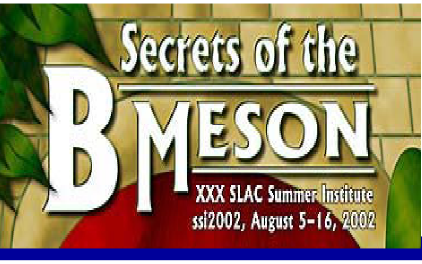
• •strong coupling in Physics beyond the Standard Model

•precise measurements of quarkonia spectroscopy & decay provide essential data to calibrate theory. ← Important Input for the lattice

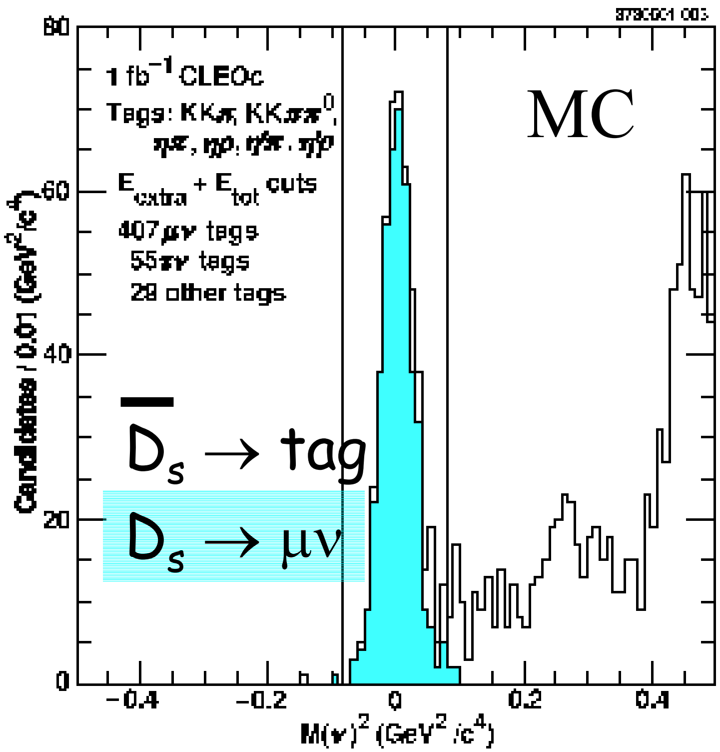
•Physics beyond the Standard Model:

•D-mixing, CPV, rare decays. + measure strong phases

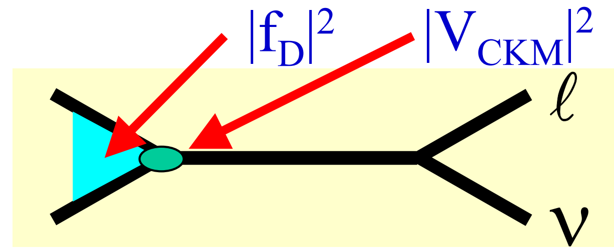
Charm physics builds the tools to enable this decade's flavor physics and the next decade's new physics.



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



- Measure absolute $Br(D_s \to \mu\nu)$
- Fully reconstruct one D (tag)
- Require one additional charged track and no additional photons



- Compute MM^2
- Peaks at zero for $D_s^+ \to \mu^+\nu$ decay.

Expect resolution of $\sim M_{\pi^0}$

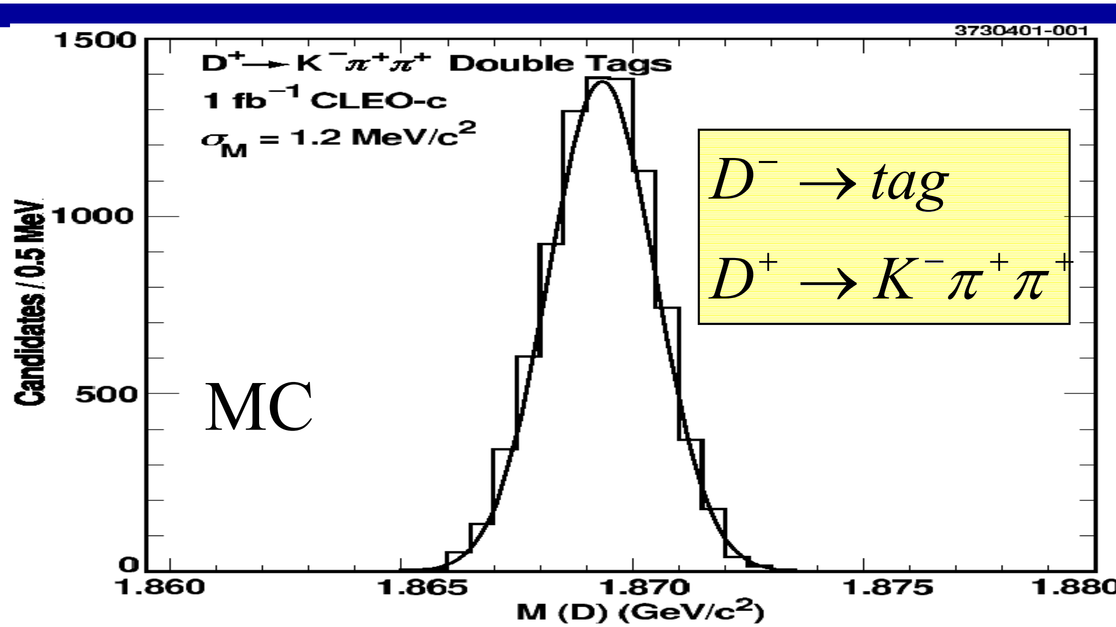
Vcs, (Vcd) known from unitarity to 0.1% (1.1%)

	Reaction	Energy(MeV)	L fb^{-1}	PDG	CLEO-c
f_{Ds}	$D_s^+ \to \mu\nu$	4140	3	17%	1.9%
f_{Ds}	$D_s^+ \to \tau\nu$	4140	3	33%	1.6%
f_{D+}	$D^+ \to \mu\nu$	3770	3	UL	2.3%

Absolute Branching Ratios

~ Zero background in hadronic tag modes

Measure absolute
Br (D→ X) with double tags
Br = # of X/# of D tags

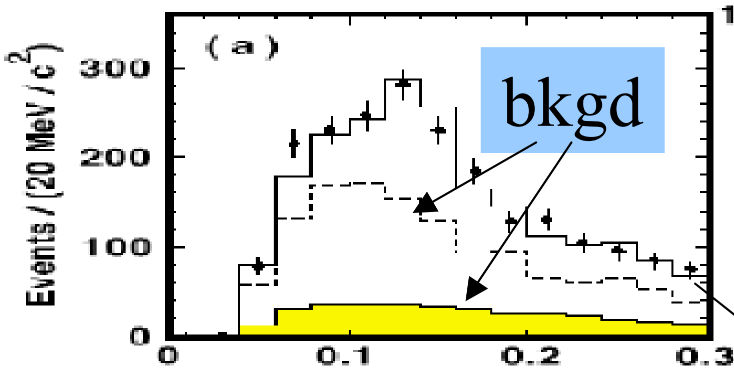


Decay	$\sqrt{s}$	L fb^{-1}	Double tags	PDG (δB/B %)	CLEOc (δB/B %)
$D^0 \to K^-\pi^+$	3770	3	53,000	2.4	0.6
$D^+ \to K^-\pi^+\pi^+$	3770	3	60,000	7.2	0.7
$D_s \to \phi\pi$	4140	3	6,000	25	1.9

CLEO-c potential: set the absolute scale for all heavy quark measurements

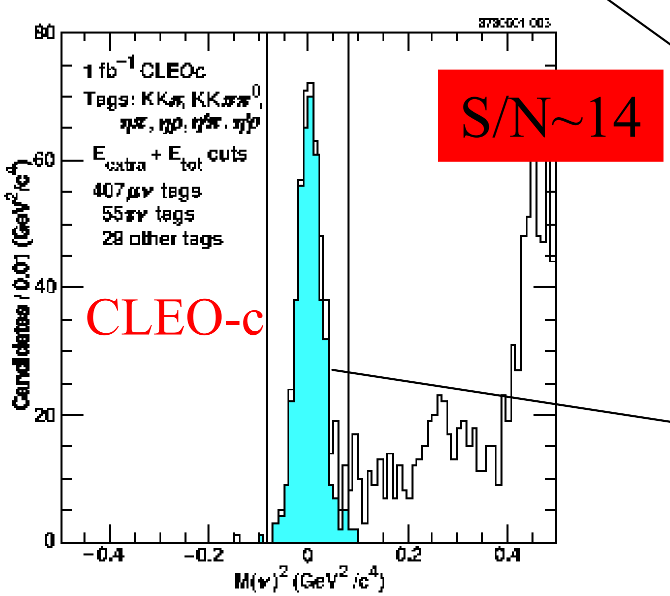
Compare B factories & CLEO-C

CLEO: $f\,D_S : D_S^* \to D_S\,\gamma\; D_S \to \mu\nu$



$\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$ GeV/c

B Factory CLEO technique with improvements



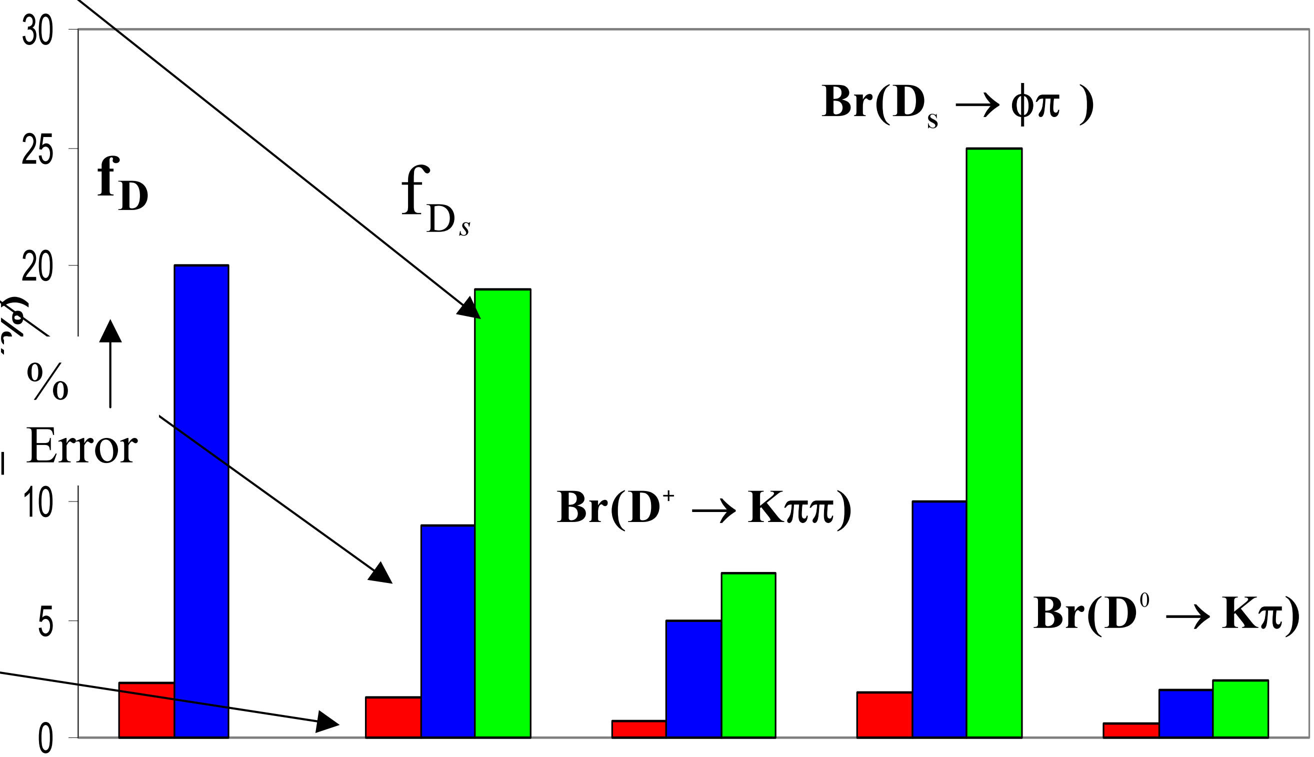
CLEO-c 3 fb^{-1}

Statistics limited

BFactory 400 fb^{-1}

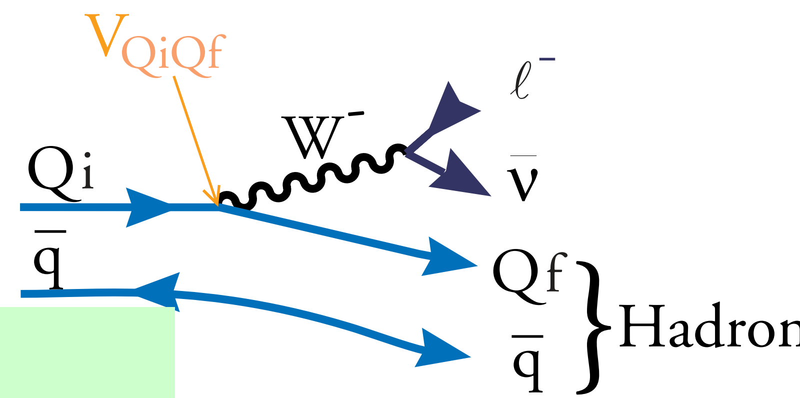
Systematics & Background limited

PDG



Semileptonic Decays: formalism

Best way to determine magnitudes of CKM elements, in principle, is to use semileptonic decays



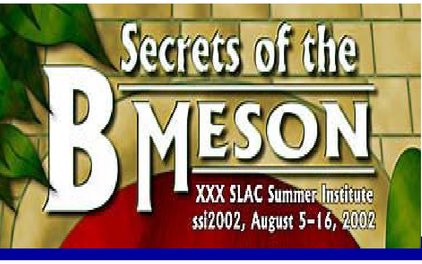
Nuclear β decay → V_{ud}, K→πeν→ V_{us}
D →Keν → V_{cs} b →clν→ V_{cb} b →ulν→V_{ub}

•Kinematics: $q^2 = \left(p_D^\mu - p_{hadron}^\mu\right)^2 = m_D^2 + m_P^2 - 2E_P m_D$

•Weak current is understood. The work is in the hadronic matrix element expressed in terms of form-factors. for D→Pseudoscalar ℓ^+ ν

$$\left\langle P(P_P)\middle|J_\mu\middle|D(P_D)\right\rangle = f_+(q^2)(P_D+P_P)_\mu + f_-(q^2)(P_D-P_P)_\mu$$

•For ℓ = e, contribution of $f_-(q^2)$→0, only way to get information on f_- is to use ℓ = μ, (for D decays)



Uses of Semileptonic Decay

Contraction with the leptonic current gives

$$\frac{d\Gamma(D \to P\ell\nu)}{dq^2} = \frac{|V_{cq}|^2 P_P^3}{24\pi^3} |f_+(q^2)|^2$$

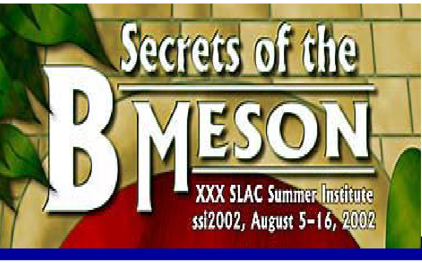
Note: For PS→V there are three form factors

Quark models, HQET, and LGT have all been invoked to calculate form factor absolute normalizations. Until recently these calculations have been done mostly at $q^2 = q^2_{max}$. (i..e w=1, just like F in V_{cb} in $B \to D^* l\nu$)

To find V_{cs} & V_{cd} Need models for f at one fixed q^2 point.

For PS→PS decays the data is mostly at $q^2 = 0$. There is a need to interpolate. To do this models predict (or make educated guesses) about the shapes of the form factors as a function of q^2.

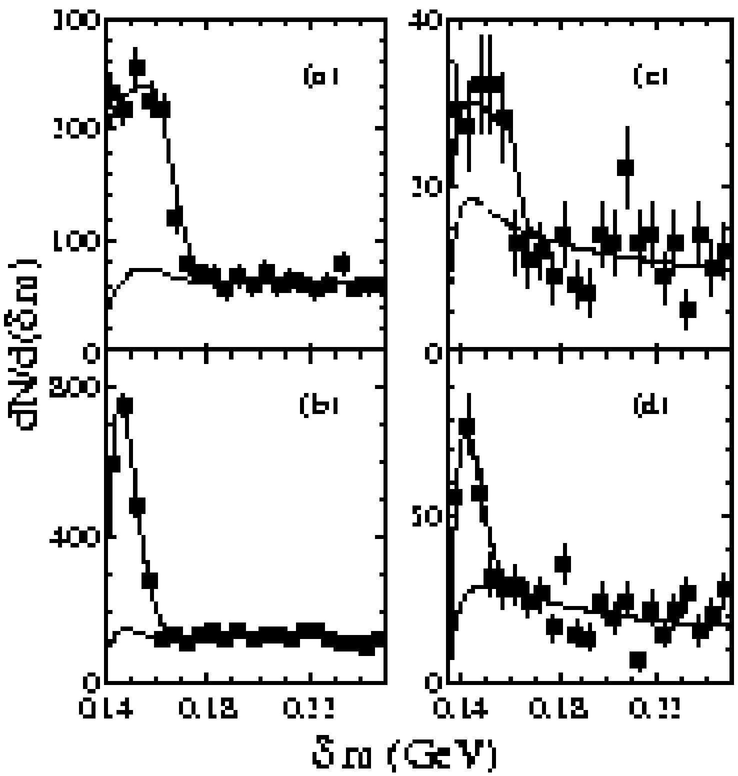
More recently the lattice has calculated rates as a function of q^2, and charm semileptonic decays provide a powerful test of the lattice predictions. Once validated, the lattice predictions can be used with confidence in the extraction of CKM matrix elements in other D and B semileptonic decays .



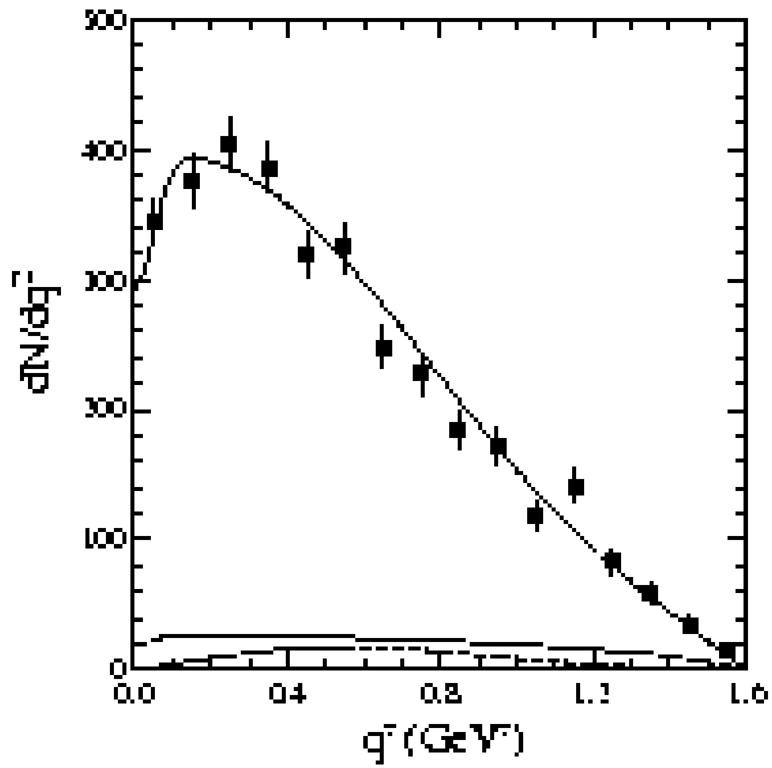
Current Status of D semileptonic decays

- Absolute Br's poorly known dB/B- 5% - 73% because no running at the ψ(3770).
- Vcs $f_+(0)$ measured for D→Klν: 0.79±0.01±0.04 (CLEO)
- Shape of $f_+(q^2)$, given by $f_+(0)/(1-q^2/m_p)^2$ measured for D→Klν: m_p=2.00±0.12±0.18 GeV

$$D^{*+} \to D^0 \pi_s,$$
$$D^0 \to K^- \ell^+ \nu$$



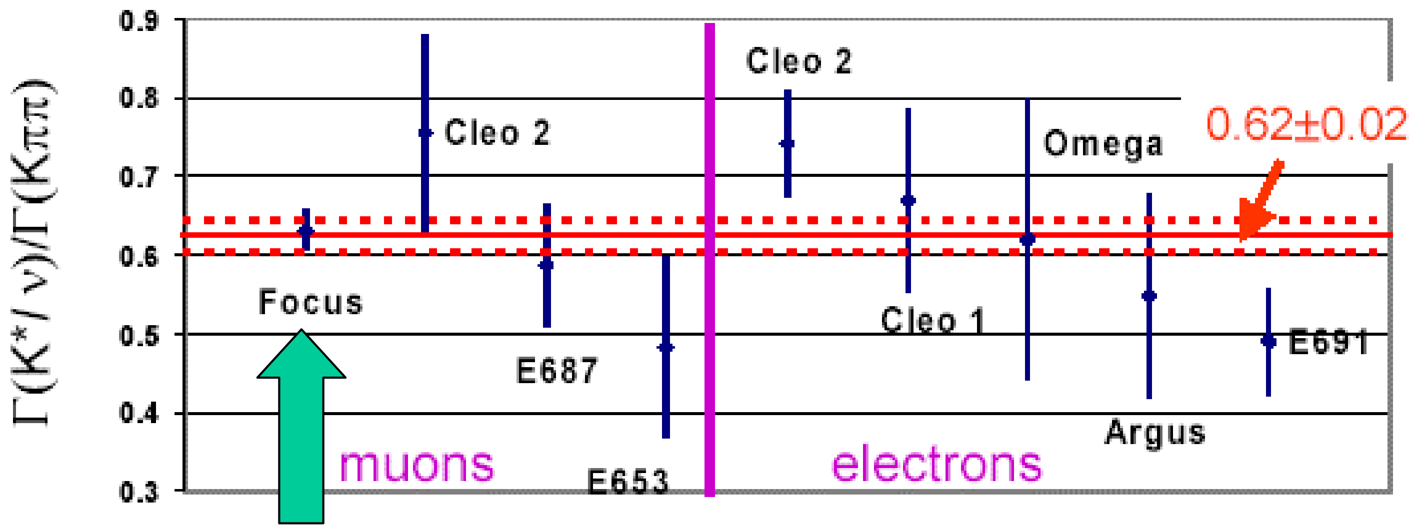
$$\Delta m = m(\pi_s K \ell) - m(K \ell)$$



PS→V Relative BR $\Gamma(D^+ \to \overline{K^{*0}}\mu^+\nu)$

$$\frac{\Gamma(D^+ \to \overline{K^{*0}}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.01(stat) \pm 0.021(sys)$$

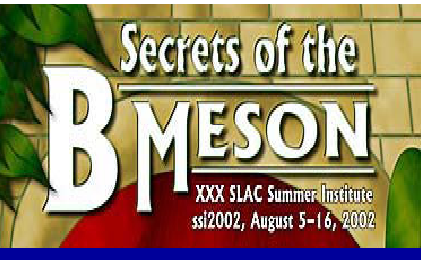
3.9% relative error



All values consistent with their average value with a CL of 19%

Significant improvement in 2002

Precision measurements but they are relative not absolute



$\Gamma(D^+ \to \overline{K^{*0}} \mu^+ \nu)$ Form Factor Ratios

The vector and axial form factors are generally parametrized by a pole dominance form

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$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

$M_A = 2.5\ GeV/c^2$
$M_V = 2.1\ GeV/c^2$
Nominal spectroscopic pole masses

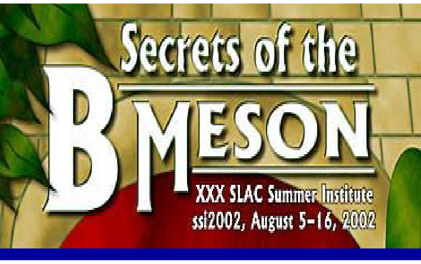
Decay intensity Parametrized by $r_v \equiv V(0)/A_1(0) \quad r_2 \equiv A_2(0)/A_1(0)$

New FOCUS Results much more precise Than previous work: →

$\delta r_v / r_v$=4..6%
$\delta r_2 / r_2$ =9.2%

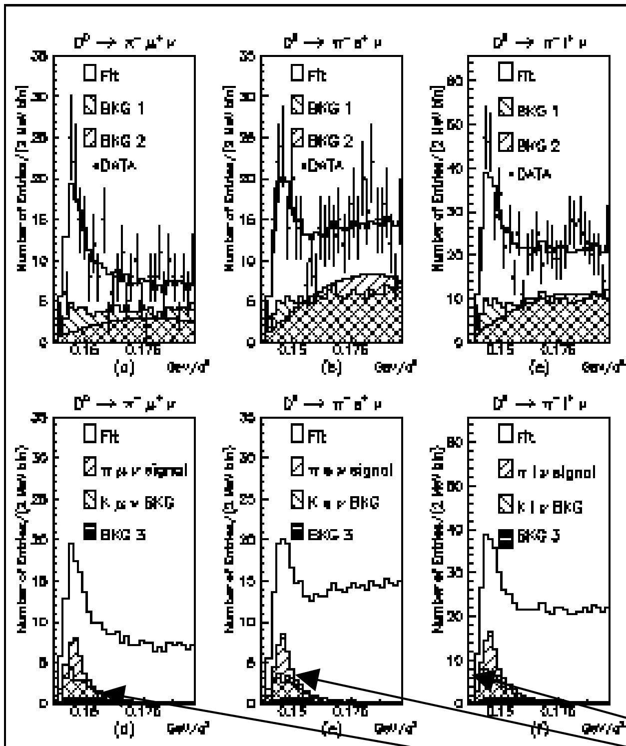
Group	r_v	r_2
FOCUS	$1.504 \pm 0.057 \pm 0.039$	$0.875 \pm 0.049 \pm 0.064$
BEATRICE	$1.45 \pm 0.23 \pm 0.07$	$1.00 \pm 0.15 \pm 0.03$
E791(e)	$1.90 \pm 0.11 \pm 0.09$	$0.71 \pm 0.08 \pm 0.09$
E791(μ)	$1.84 \pm 0.11 \pm 0.09$	$0.75 \pm 0.08 \pm 0.09$
E687	$1.74 \pm 0.27 \pm 0.28$	$0.78 \pm 0.18 \pm 0.11$
E653	$2.00 \pm 0.33 \pm 0.16$	$0.82 \pm 0.22 \pm 0.11$
E691	$2.0 \pm 0.6 \pm 0.3$	$0.0 \pm 0.5 \pm 0.2$

Beautiful measurements. Ratios of form factors are known precisely known
absolute magnitudes of the form factors cannot be measured with these experiments



Cabbibo suppressed semileptonic decays

The form factors governing D→πlν D→ρlν and B→πlν B→ρlν are related by HQS.



D→πlν

E687

D→ρlν:

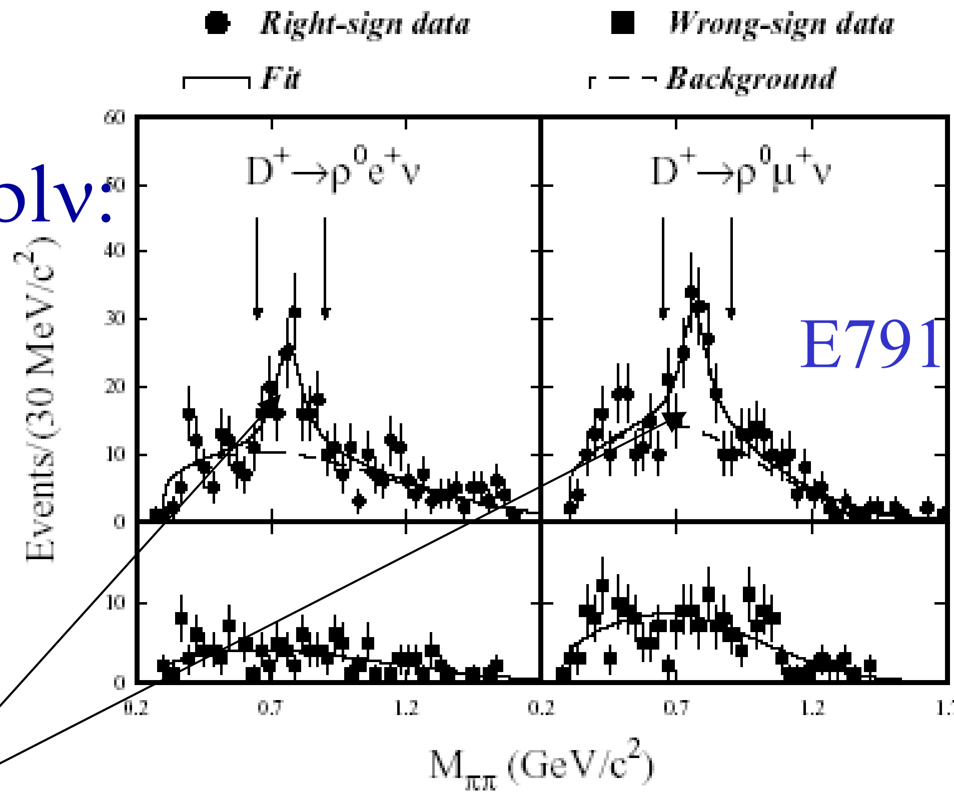
Composition of E687 $\pi\ell\nu$

$M_{D^*} - M_D$ histogram

BKG1 = mis-id

BKG2 = random $\bar{\pi}$

BKG3 = $K^*\ell\nu$



signal

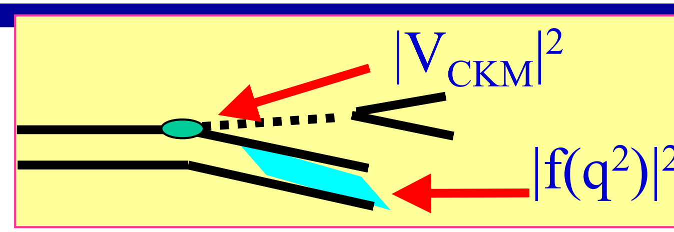
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

Expect the BABAR, Belle and CLEO to improve on this

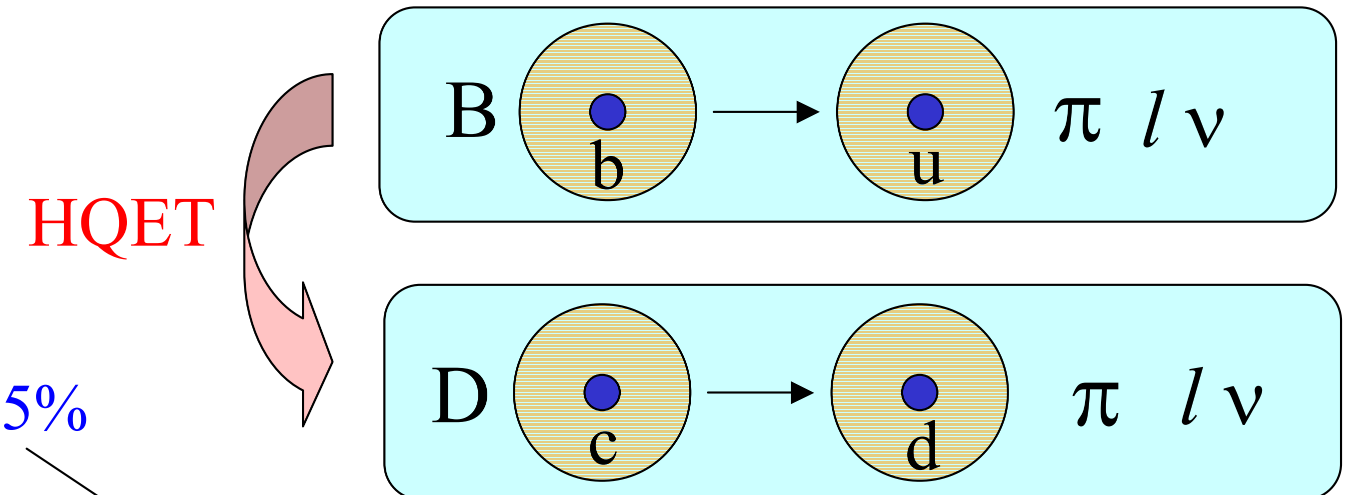
These modes are difficult to observe as their rates are low, and due to Cabbibo allowed semileptonic decay backgrounds. No absolute rates, only relative rates to ~20% accuracy

Importance of absolute charm semileptonic decay rates.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 p_K^3 |f_+(q^2)|^2$$

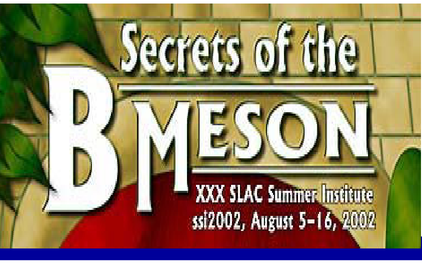


I. Absolute magnitude & shape of form factors are a stringent test of theory.
II. Absolute charm semileptonic rate gives direct measurements of V_{cd} and V_{cs}.
III Key input to precise Vub vital CKM cross check of sin2β

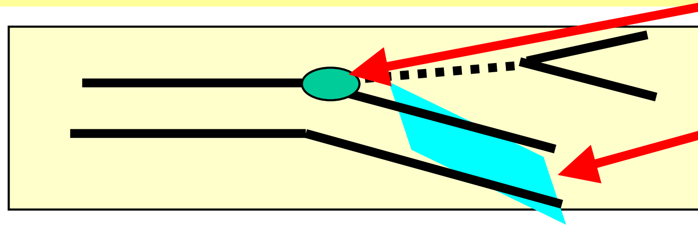


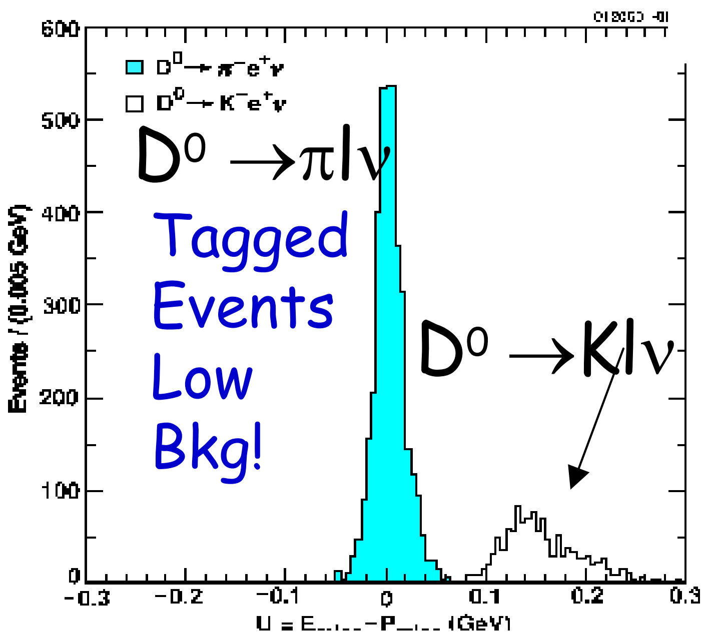
$$\frac{\delta B}{B} \sim 25\%$$

1) Measure D→π form factor in D→πlν. Calibrate LQCD uncertainties .
2) Extract V_{ub} at BaBar/Belle using *calibrated* LQCD calc. of B→π form factor.
3) But: need absolute Br(D →πlν) and high quality dΓ (D →πlν)/dEπ neither exist
The program in charm semileptonic decay studies does not provide this…

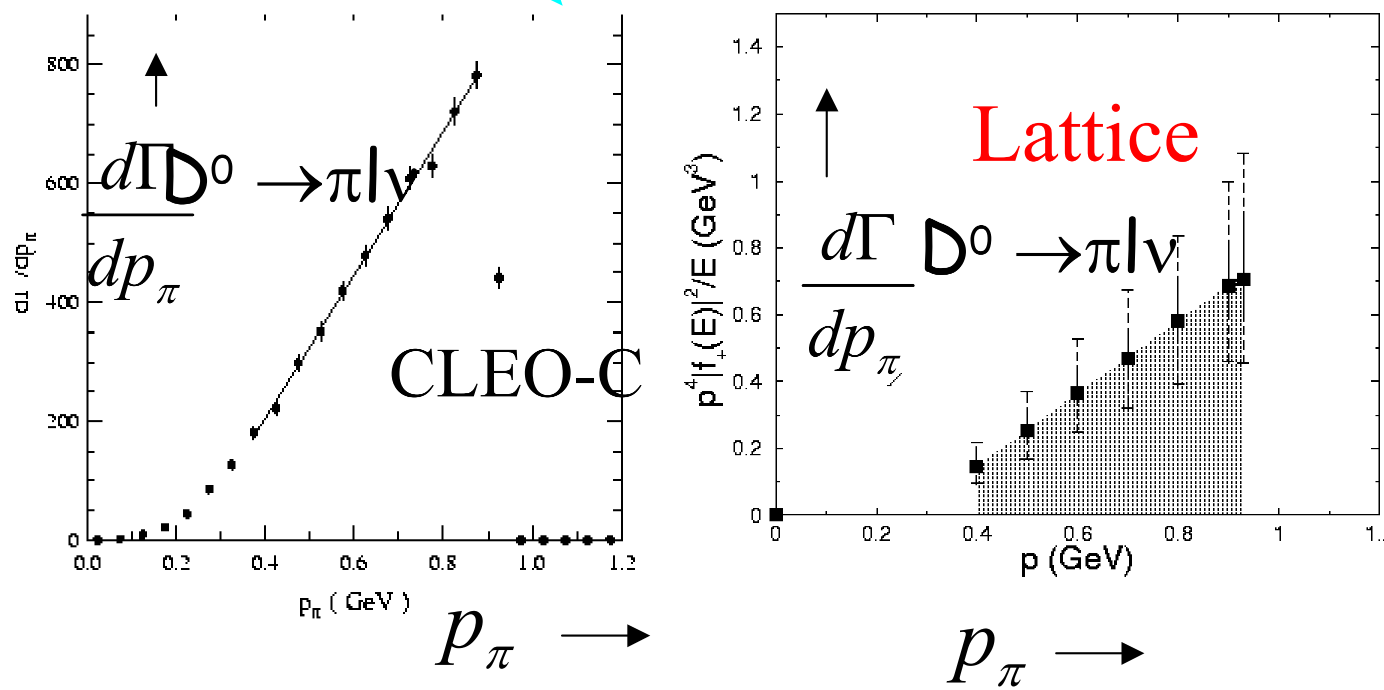


Semileptonic Decays $|V_{CKM}|^2 \, |f(q^2)|^2$



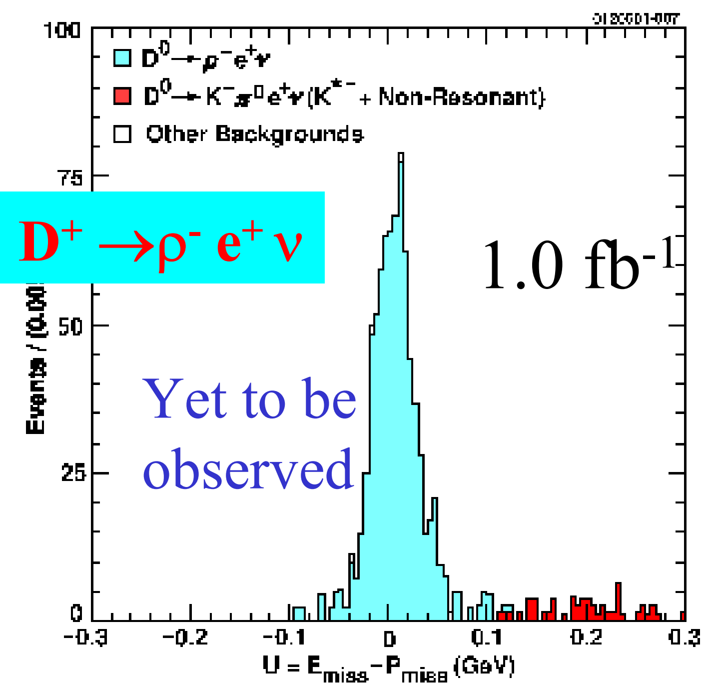


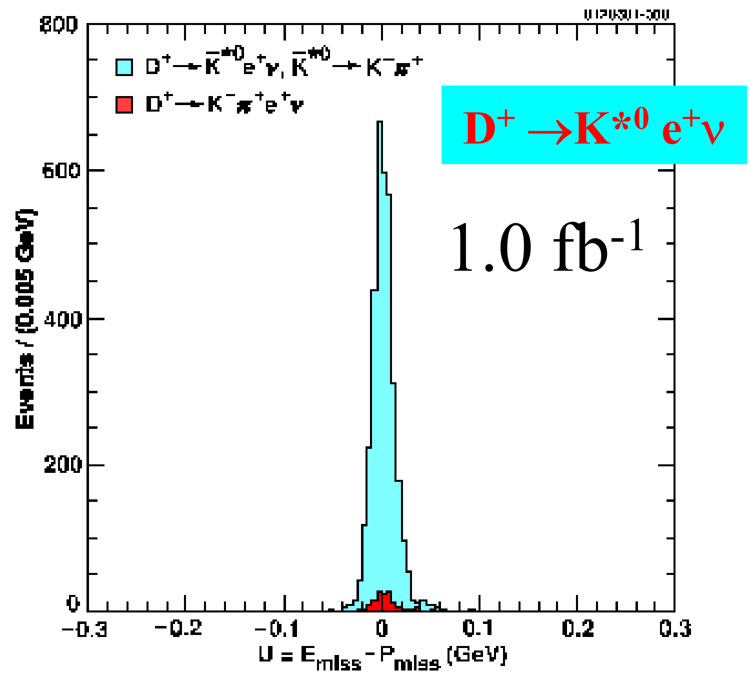
$U = E_{miss} - P_{miss}$



Assume 3 generation unitarity: for the first time measure complete set of charm PS → PS & PS → V absolute form factor magnitudes and slopes to a few% with ~zero bkgd in one experiment. Stringent test of theory!

Pseudoscalar to Vector transitions





$D \to \rho \ell \nu$

HQS

$B \to \rho \ell \nu$

$D \to K^* \ell \nu$

HQS & $SU(3)$

$B \to \rho \ell \nu$

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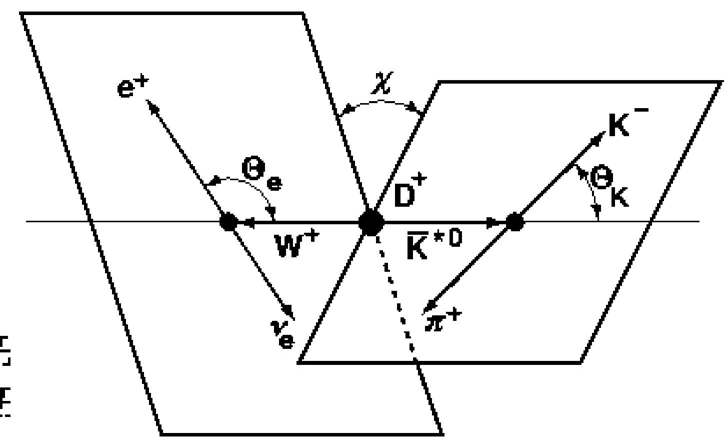
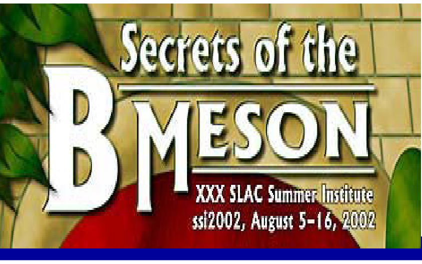
The four-fold joint angular decay distribution for D→K*/ρlν:

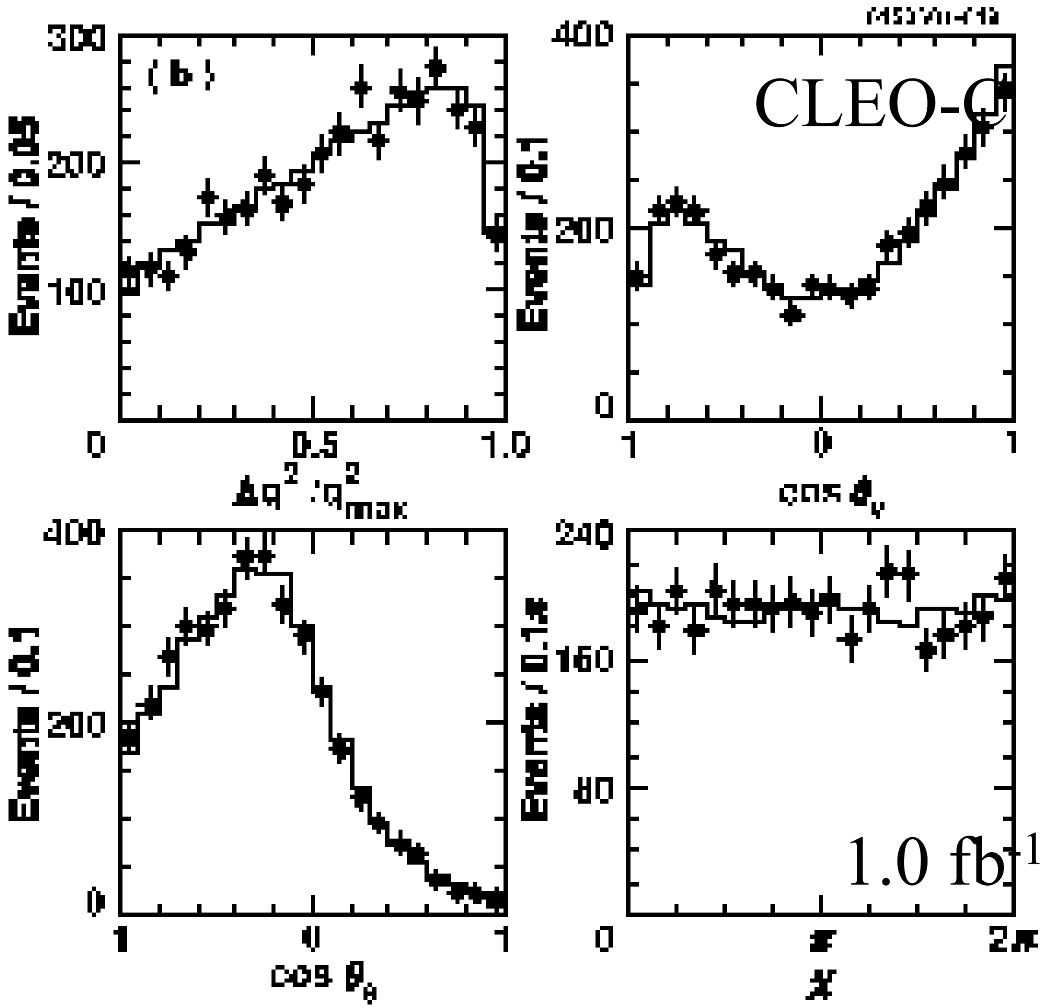
$$\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_\ell d\chi} = \frac{3G_F^2}{8(4\pi)^4}|V_{cs}|^2$$
$$\times \frac{p_K \cdot q^2}{M_D^2}[(1+\cos\theta_\ell)^2 \sin^2\theta_K |H_+(q^2)|^2$$
$$+(1-\cos\theta_\ell)^2 \sin^2\theta_K |H_-(q^2)|^2$$
$$-4\sin^2\theta_\ell \cos^2\theta_K |H_0-(q^2)|^2$$
$$+4\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_K\cos\theta_K\cos\chi H_+(q^2)E$$
$$-4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_K\cos\theta_K\cos\chi H_-(q^2)E$$
$$-2\sin^2\theta_\ell\sin^2\theta_K\cos 2\chi H_+(q^2)H_-(q^2)]$$
$$\times B(K^* \to K\pi).$$



Note: figure also applies to D→ρlν.

$D^+ \to \bar{K}^{*0} e\nu$ form factor determination at threshold





$r_V = V/A_1 \quad r_2 = A_2/A_1$

CLEO-C 12 K events/3 fb^{-1} S/B~20/1

$$\frac{\delta r_V}{r_V} \approx 2\%(stat) \qquad \frac{\delta r_2}{r_2} \approx 3\%(stat)$$

E791 3K S/B 5/1 (FOCUS 40K S/B 8/1)

$$\frac{\delta r_V}{r_V} \approx 7\% \ (4.6\%) \qquad \frac{\delta r_2}{r_2} \approx 17\% \ (9.2\%)$$

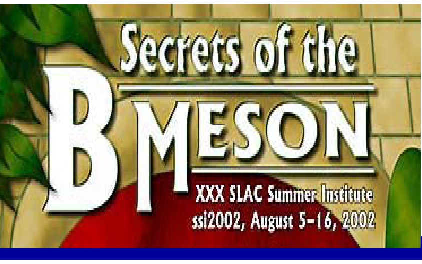
From CLEO-c determined abs Br Lifetime and unitarity:

$$\frac{\delta A_1(0)}{A_1(0)} \approx 1\% \quad \frac{\delta A_2(0)}{A_2(0)} \approx 3\% \quad \frac{\delta V(0)}{V(0)} = 3\%$$

E791 PDG Br, Lifetime & unitarity

$$\frac{\delta A_1(0)}{A_1(0)} \approx 5\% \quad \frac{\delta A_2(0)}{A_2(0)} \approx 15\% \quad \frac{\delta V(0)}{V(0)} = 8\%$$

+ excellent for form factor determination in the Cabibbo suppressed modes $D \to \rho e\nu$



CLEO-c Impact semileptonic dB/B

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

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

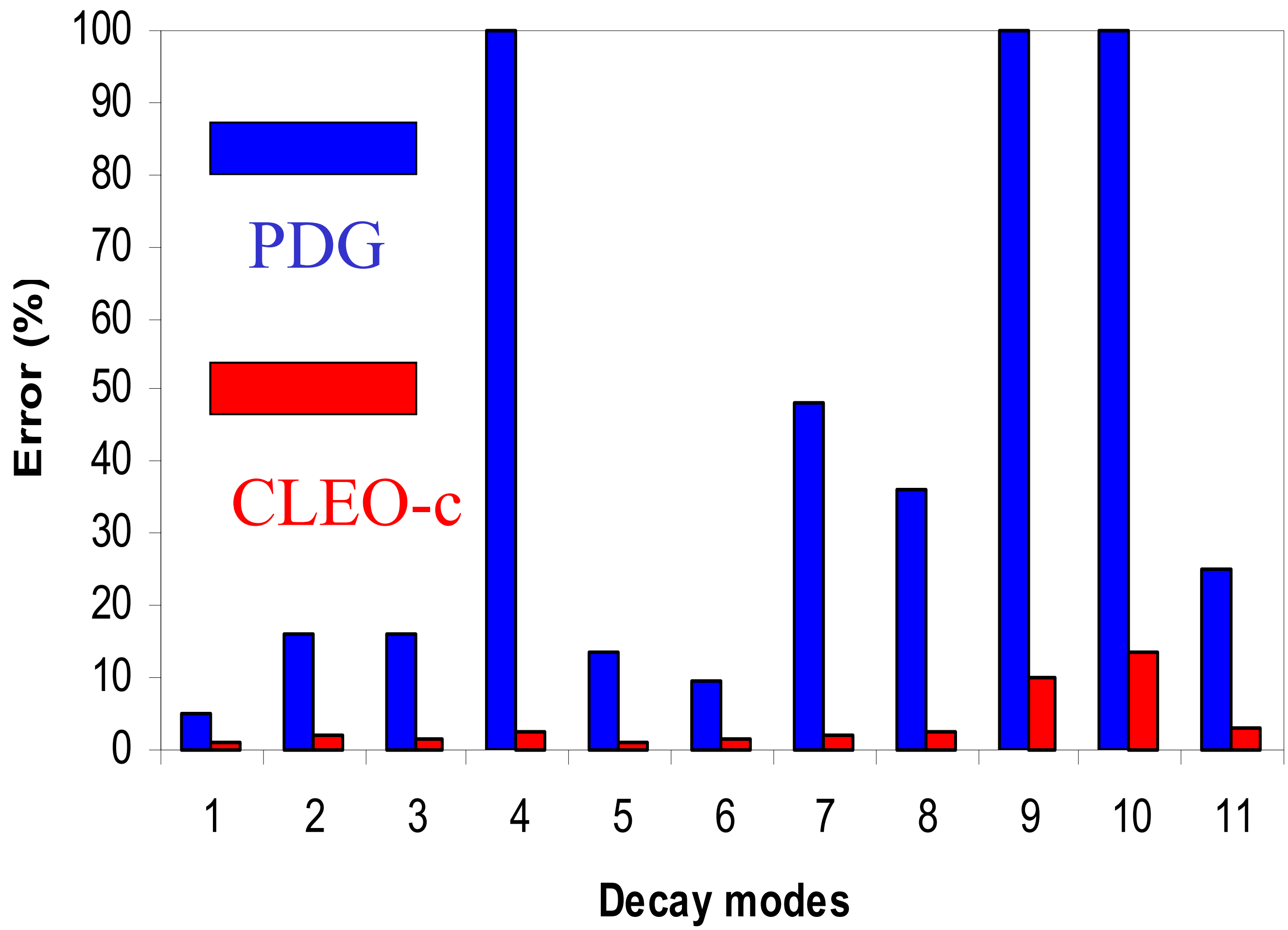
7 : $D^+ \to \pi^0 e^+ \nu$

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

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

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

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



CLEO-c will make significant improvements in the precision with which each absolute charm semileptonic branching ratio is known

Determining Vcs and Vcd

combine semileptonic and leptonic decays eliminating V CKM

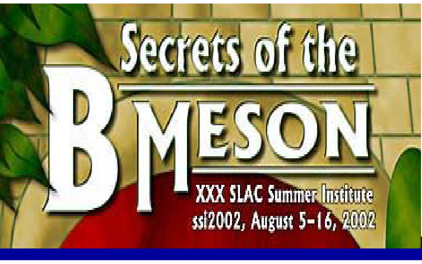
$\Gamma(D^+ \to \pi l \nu) / \Gamma(D^+ \to l \nu)$ independent of Vcd
Test rate predictions at ~4%

$\Gamma(D_s \to \phi l \nu) / \Gamma(D_s \to l \nu)$ independent of Vcs
Test rate predictions at ~ 4.5%

Test amplitudes at 2%
Stringent test of theory!   If theory passes the test.....

I
$D^0 \to K^- e^+ \upsilon$ δVcs /Vcs = 1.6% (now: 11%)
$D^0 \to \pi^- e^+ \upsilon$ δVcd /Vcd = 1.7% (now: 7%)

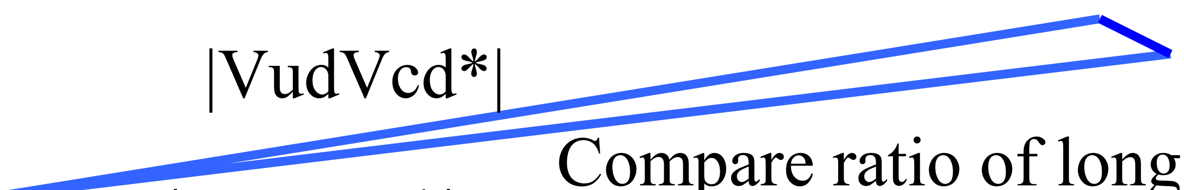
II
Use CLEO-c validated lattice to calc. B semileptonic form factor, then B factories can use $B \to \rho/\pi/\eta/l\nu$ for precise Vub



Unitarity Constraints from threshold running

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

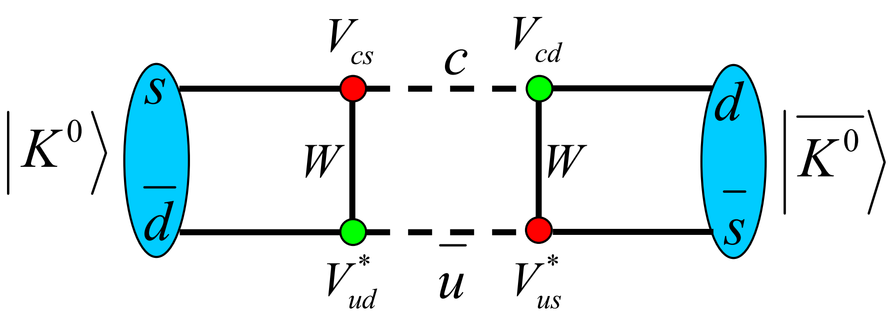
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- $|Vud|^2 + |Vus|^2 + |Vub|^2 = 1$??
  With current values this test fails at ~ 2.7σ (PDG2002)
- $|Vcd|^2 + |Vcs|^2 + |Vcb|^2 = 1$??
  CLEO -c: test to ~3% (if theory D →K/πlν good to few %)
  Also 1st column
- 

  Compare ratio of long sides to 1.3%
  Also major contributions to Vub, Vcb, Vtd, Vts.

Why study 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

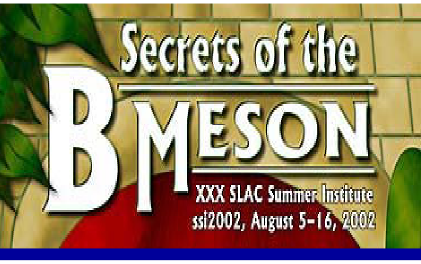
Mixing $\propto (m_c^2 - m_u^2)/m_W^2$
measured rate in 1958 used to bound c quark mass
→ discovery (1974)

$$\Delta\Gamma = \Gamma_- - \Gamma_+ = \Gamma_{K_L^0} - \Gamma_{K_S^0} \approx -\Gamma_{K_S^0} \approx 10^{10}\, s^{-1}$$

$$\Delta M = M_- - M_+ = M_{K_L^0} - M_{K_S^0} = (0.5304 \pm 0.0014) \times 10^{10}\, s^{-1}$$

$$\Delta m / \Delta\Gamma \approx 1/2$$

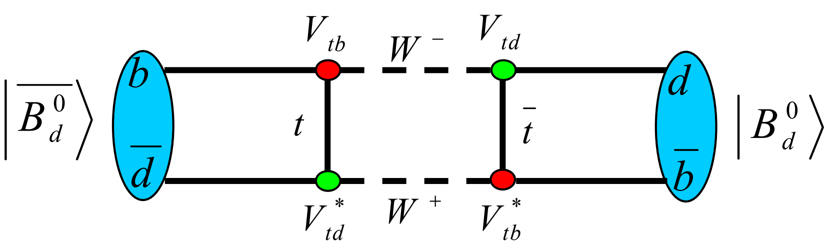
CPV part of transition , ε_K
measured in 1964 was a crucial
clue that the top quark exists (1994)



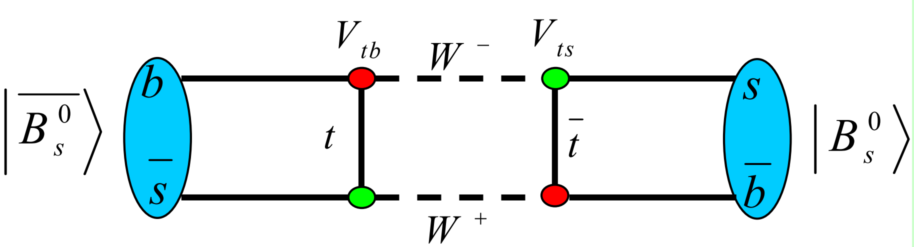
Why study D mixing?

strange → beauty

$$B_d^0 - \overline{B_d^0}$$



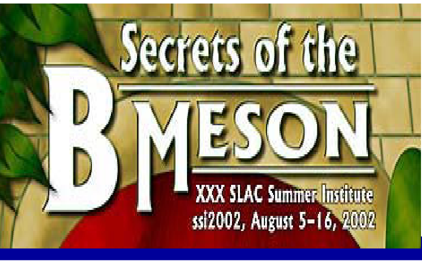
$$B_s^0 - \overline{B_s^0}$$



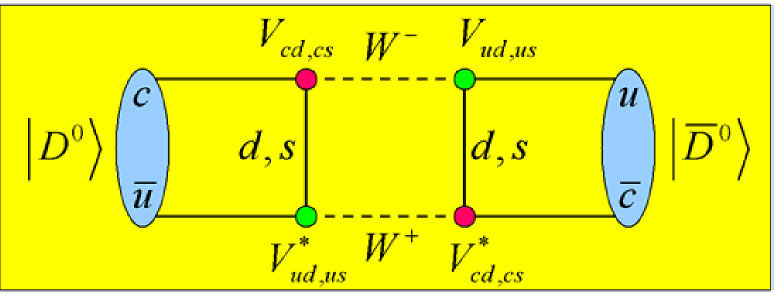
Mixing dominated by top quark
Mixing $\propto (m_t^2 - m_{c,u}^2))/m_W^2$ → Large
B lifetime Cabibbo suppressed $\propto V_{cb}^2$
Mixing rate also Cabibbo suppressed (V_{td}^2)
But large Mixing rate → early indication
m_{top} large
Now: sin2β (in the Standard Model)
Future: once f_B is known ➔ V_{td} (in SM)

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

Mixing $\propto (m_t^2 - m_{c,u}^2) / m_W^2$ → Large
As $V_{ts} >> V_{td}$ B_s mixing >B_d mixing
B lifetime Cabibbo suppressed $\propto V_{cb}^2$
Future: Y(5S) & hadron collider studies
Route to γ & sin2χ.
Once f_{Bs} is known ➔ V_{ts} (in SM)



D mixing



CKM factors $\propto \Theta_c^2 \sim 0.05$
(b-quark contribution $\propto V_{ub} V_{cb}$
can be neglected)
But τ_D not Cabbibo suppressed ($V_{cs} \sim 1$)

Mixing •τ ~ 0.05

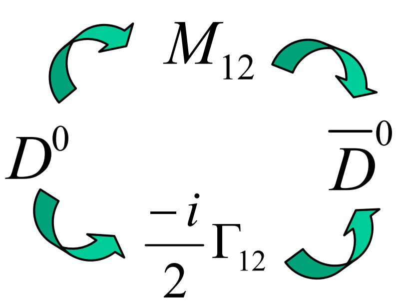
Additional suppression:
Mixing $\propto (m_s^2 - m_d^2)/ m_W^2 = 0$ SU(3) limit

SM mixing very small $\propto \Theta_c^2$ x additional suppression
➔ A window for new physics

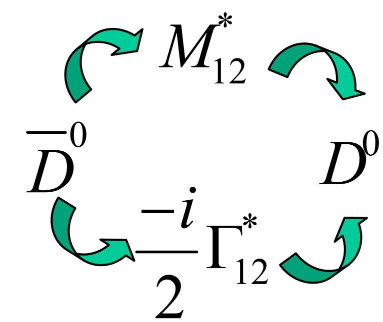
Some Formalism

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 $D^0 \rightarrow f \rightarrow \overline{D}^0$ via on-shell intermediate states.
- M_{12} describes $D^0 \rightarrow f \rightarrow \overline{D}^0$ via off-shell intermediate states.
- CP violation in mixing can arise from interference between on-shell and off-shell amplitudes. This leads to $\Gamma(P^0 \rightarrow \overline{P}^0) \neq \Gamma(\overline{P}^0 \rightarrow P^0)$
- Note in the *B* 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

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

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

Γ ← $\frac{1}{\tau_{D^0}}$

↑ C.P.T assumed

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

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

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

$$CP : \left| M^*_{12} - \frac{i}{2}\Gamma^*_{12} \right| \neq \left| M_{12} - \frac{i}{2}\Gamma_{12} \right|$$

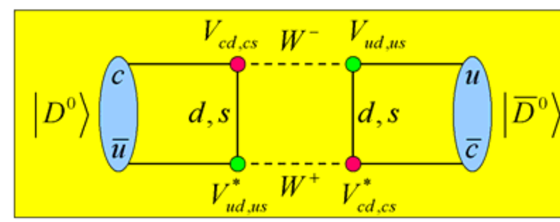
But initially assume conservation here

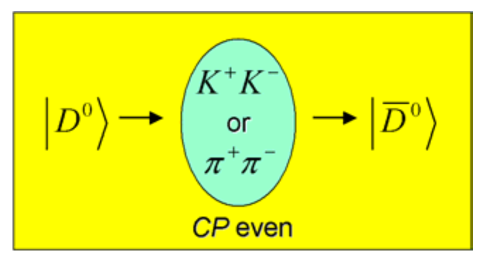
- **Measure time in units of** τD^0

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

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

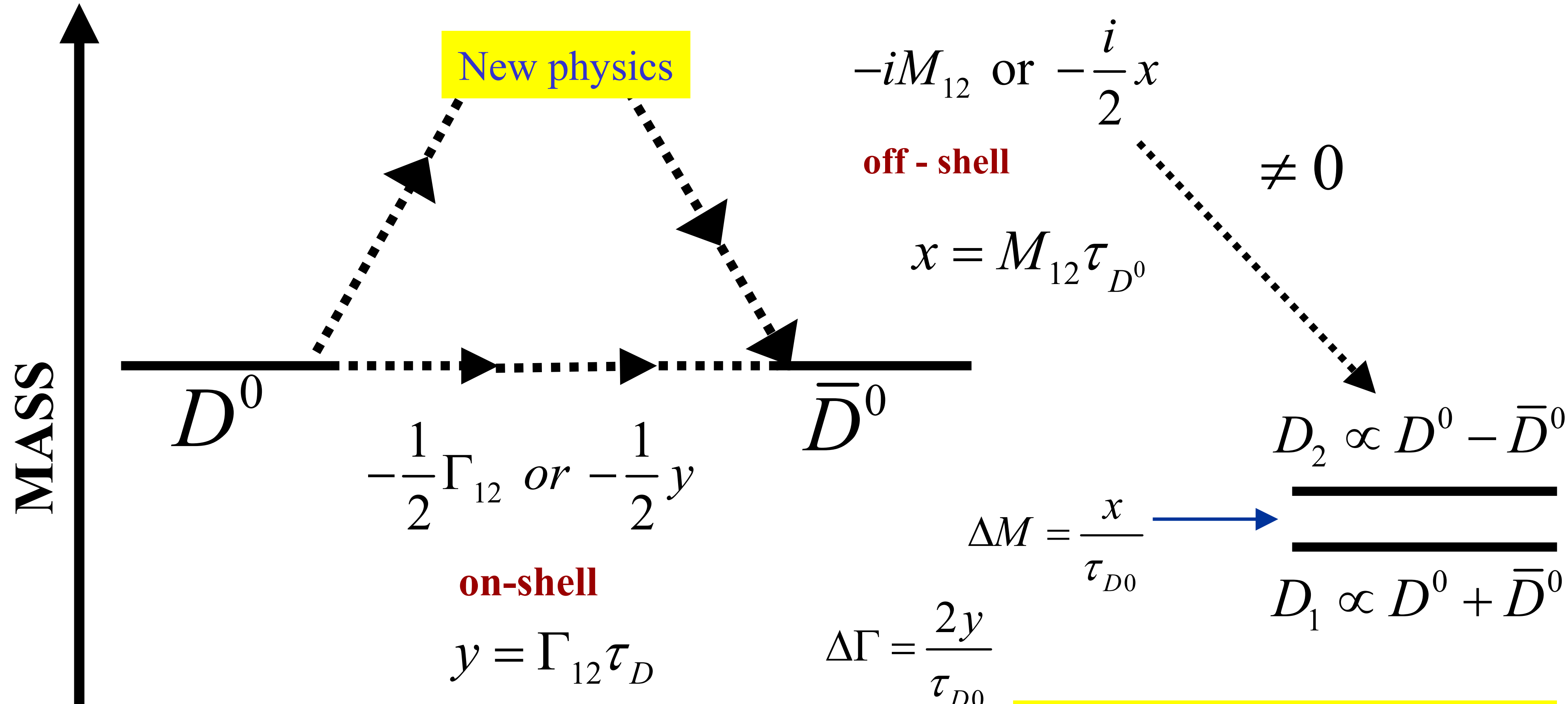
$D^0 \xleftrightarrow{-\frac{y}{2}} \bar{D}^0$ **shifts lifetimes of CP eigenstates** $y = \frac{\Gamma_{12}}{\Gamma}$





New Physics Alters x not y

Assume: CP Conserved



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

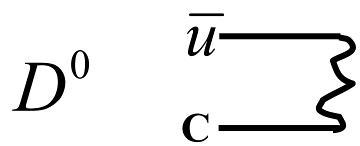
Studying time evolution is a route to distinguishing new physics, i.e determining x and y separately but it is not the only way to achieve this.

x in the Standard Model

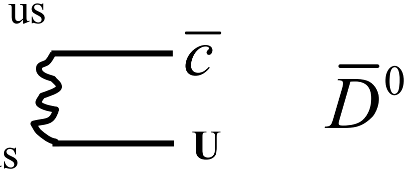
$$D^0 \xrightarrow{-\frac{i}{2}xt} \bar{D}^0 \qquad x \sim \sum_n \frac{\langle \bar{D}^0 | \underset{\sim}{H} | n \rangle \langle n | \underset{\sim}{H} | D^0 \rangle}{m_{D^0} - E_n}$$

n=index of intermediate state

(states are off mass shell)



Intermediate state		
$d\ d$	$+\sin^2\theta_c \cos^2\theta_c$	$V_{cd}^{\ 2}$
$d\ \bar{s}$	$-\sin^2\theta_c \cos^2\theta_c$	$V_{cd} V_{us}$
$s\ \bar{d}$	$-\sin^2\theta_c \cos^2\theta_c$	$V_{ed} V_{us}$
$\bar{s}\ s$	$\sin^2\theta_c \cos^2\theta_c$	$V_{su}^{\ 2}$



Sum $\simeq 0$ when $m_s = m_d$

Standard Model Estimate: $x \leq 10^{-3}$
But large range

(b case suppressed by $V_{cb}V_{ub}$)

In SU(3) limit x = 0

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

y in the Standard Model

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

$$y \sim \sum \underbrace{A(\bar{D}^0 \to \text{Common State})}_{\propto \sqrt{BR}} \; \underbrace{A(D^0 \to \text{Common State})}_{\propto \sqrt{BR}}$$

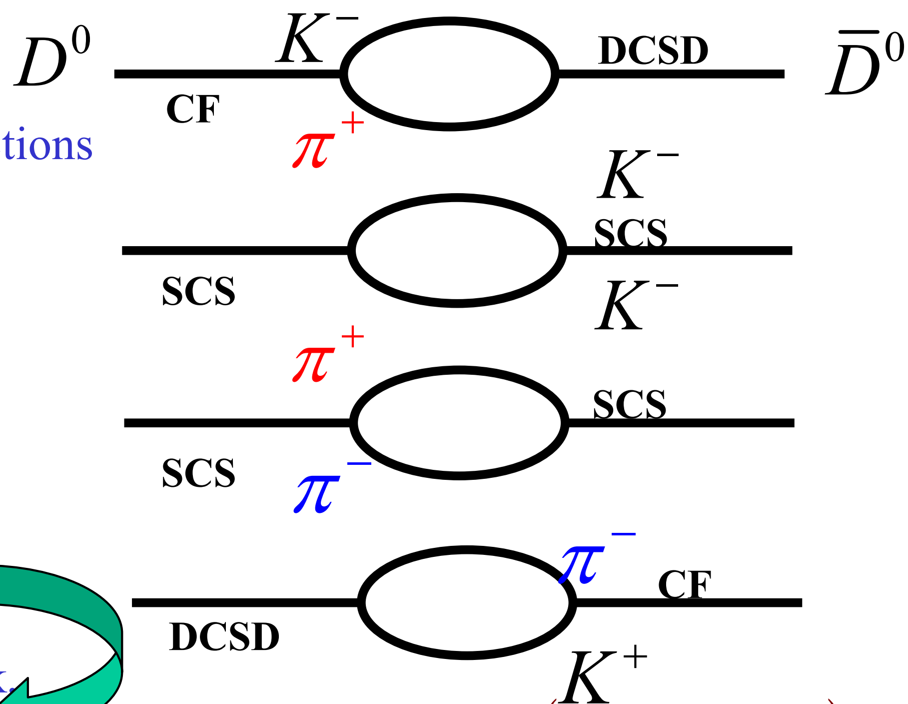
Common States

$E_n = M_{D^0}$

$y \leq 10^{-3}$

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

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



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

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

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

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

Approximate cancellation

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

Hadronic Problem : $\dfrac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} \simeq 3.0 \pm 0.2$

- **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 $B \to 4\pi$ is cancelled $B \to 4K$ 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 $B \to 4\pi$ & $B \to 4K$ can contribute. For x there is more effective SU(3) cancellation than in y. Nobody know s how big the size of this effect by. It is feasible that y>x (SM)

New physics Signatures:

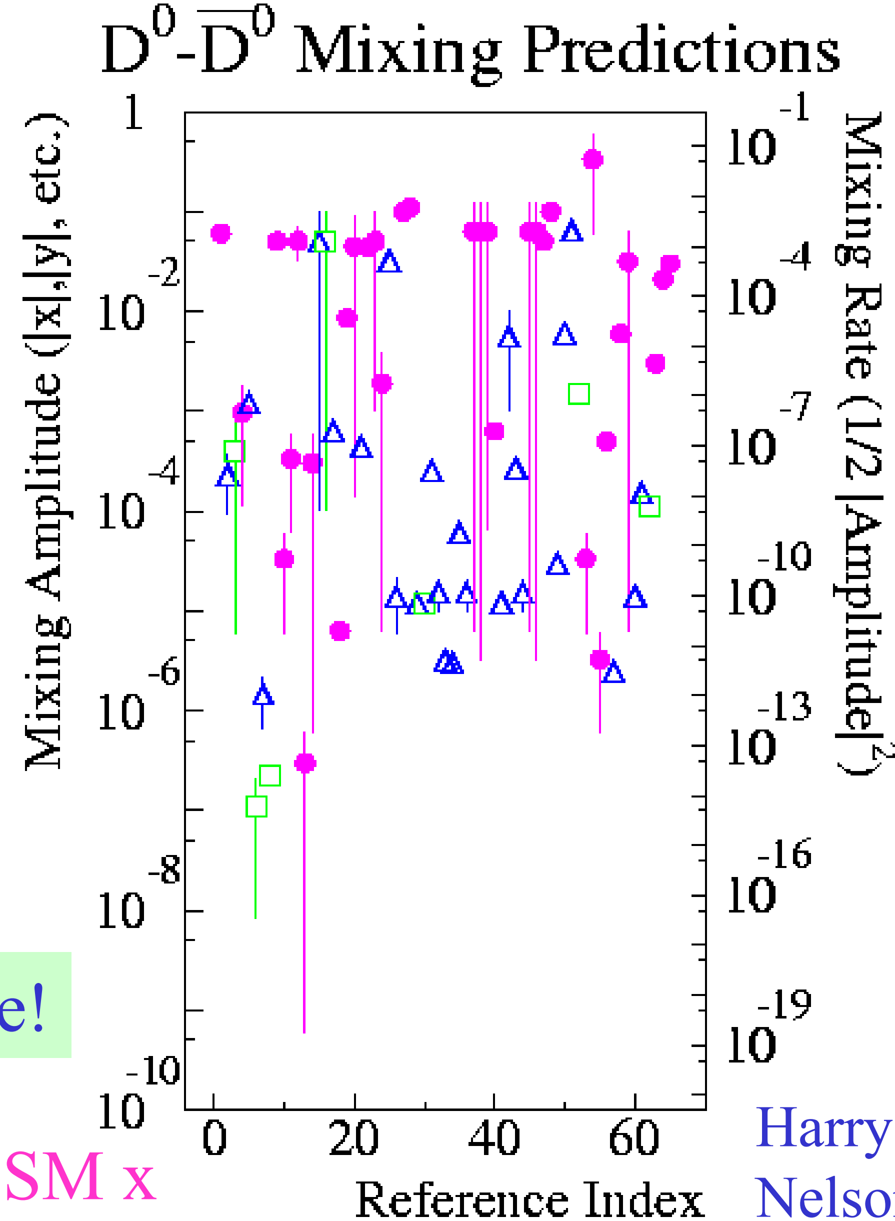
: New physics will enhance *x* but not *y we can consider y* as a *SM background.*
CP violation in mixing would be a smoking gun for new physics

Non-standard model mixing

Several classes of model exist
Higgs Doublet
Flavor Changing Neutral Currents
SUSY
Fourth Generation Quarks
Iso(singlet quarks)

Non-standard model DD mixing rate depends on the chosen model of new physics

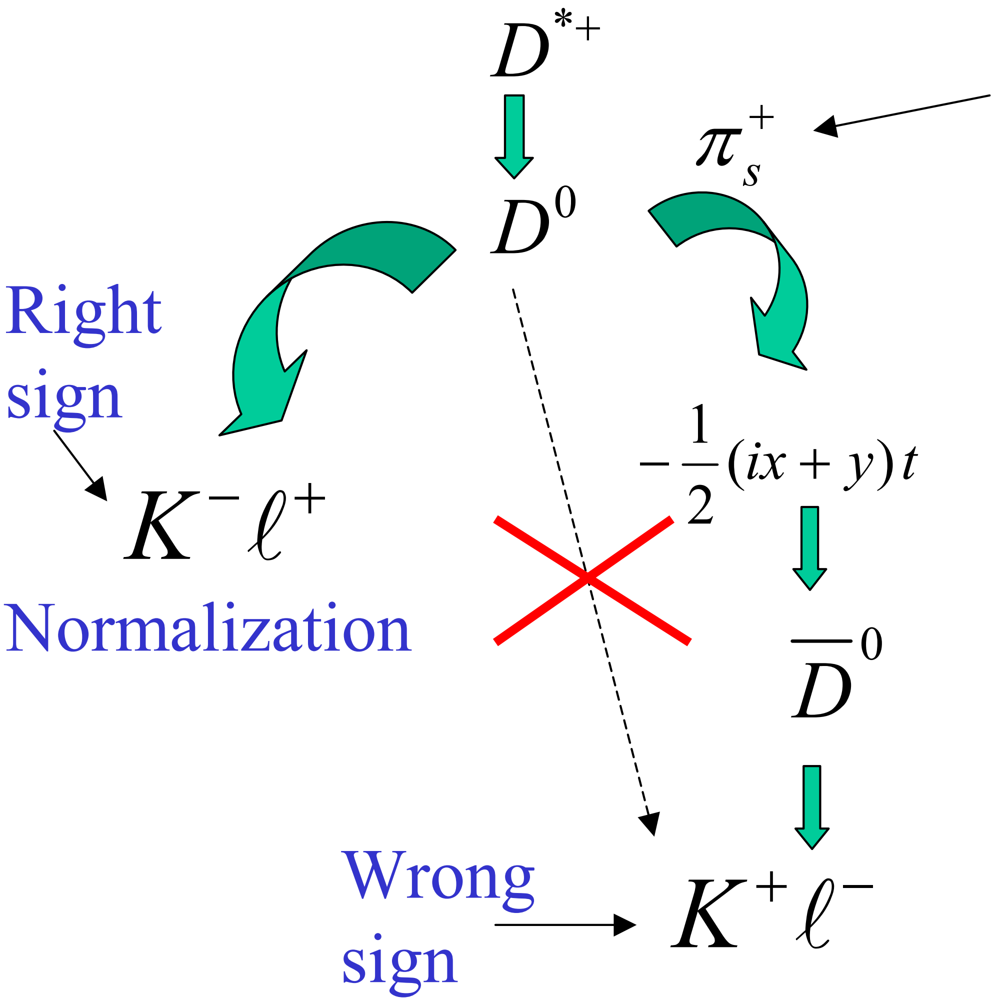
Predictions span orders of magnitude!



△ SM x □ SM y ○ non-SM x

Harry Nelson

$D^0\overline{D}^0$ Mixing Measurements I Theoretically Cleanest



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

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

but $x^2 + y^2 << x$ or y

Theoretically clean usually means experimentally challenging

$m(\pi_s K^+ \ell^-) - m(K^+ \ell^-) \to$ Missing ν

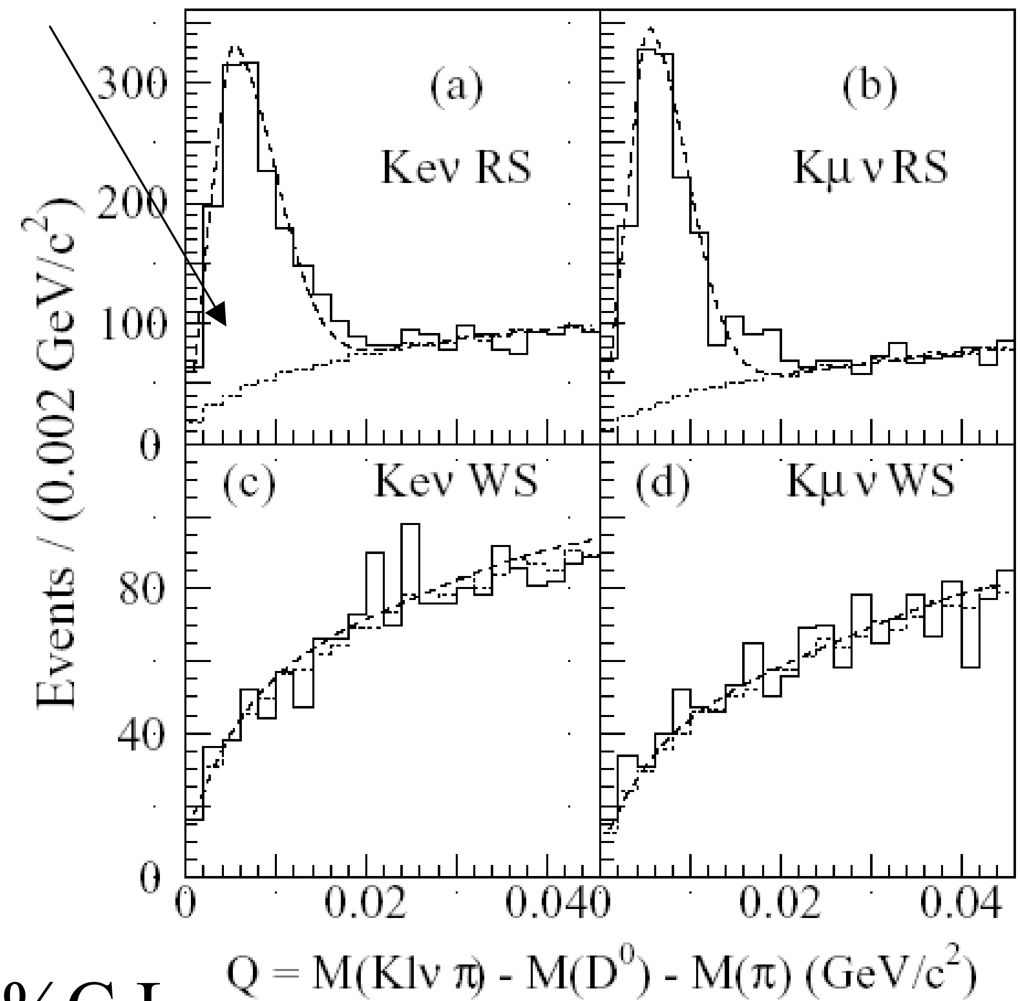
$D^0 D^0$ Mixing Measurements E791 Semileptonics

Width : → Missing ν

E791 (fixed target πPt)

(after t requirement)

The $t^2 e^{-t}$ particularly suits fixed target experiments, but x and y not separated



$$R_{\text{mix}} = \tfrac{1}{2}\left(x^2 + y^2\right) < 0.5\% \text{ at } 90\%\text{C.L.}$$

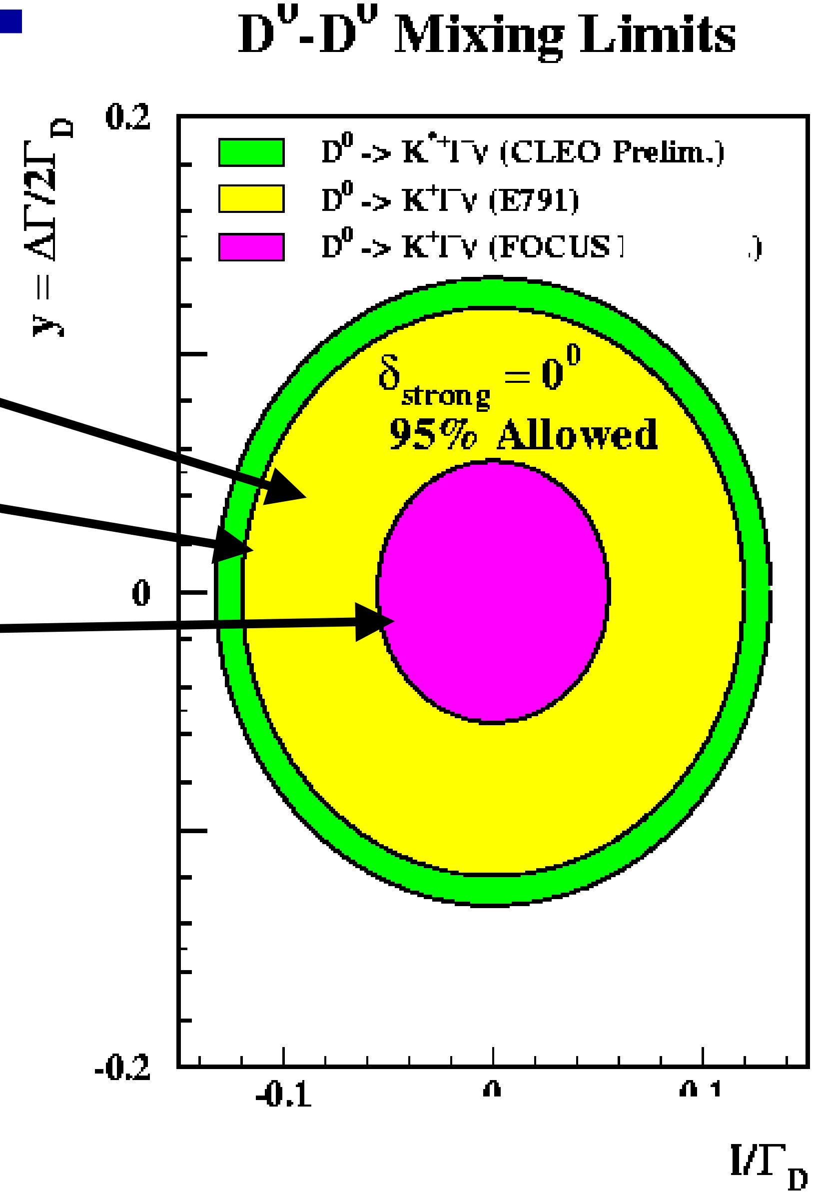
Measurements of the Mixing Rate Using Wrong Sign Semileptonic D^0 Decays

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

- Measurements from
  - E791 (D^0->$Kl\nu$): $< 0.5\%$ at 90%C.L.
  - CLEO (D^0->$K^*l\nu$):

$R = (0.00 \pm 0.31 \pm 0.32)\%$, or 0.87% @90%CL

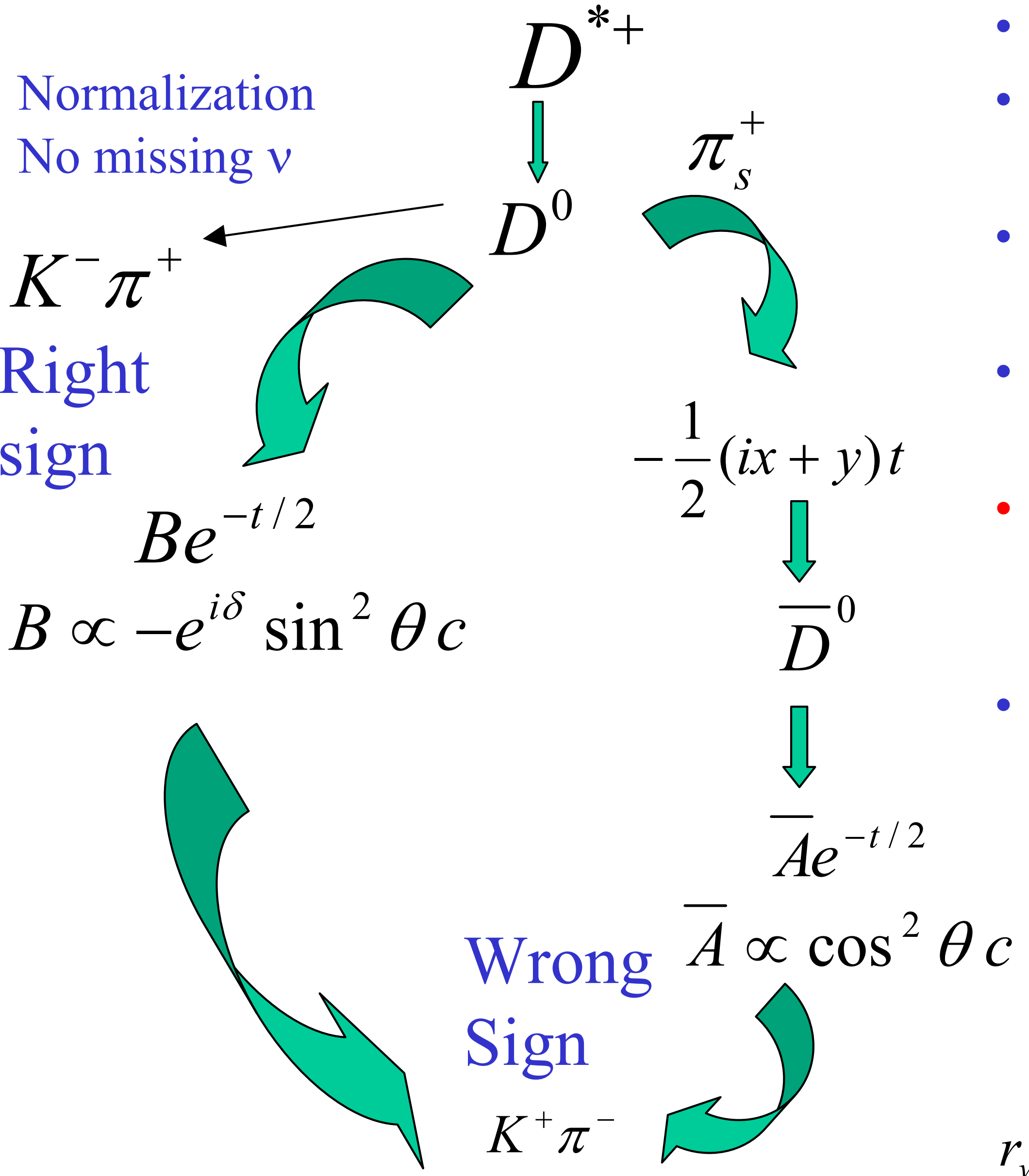
- FOCUS (ICHEP02) R<0.12% @90%CL (best)
- B factories will have results soon
- Accessible to future experiments
  - Hadron machines
    - Lepton helps triggering
  - CLEO-c
    - Opposite side tag



•Will need separate measurement of y if that turns out to be larger or comparable to x

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

CLEO



- 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 ($\pi_s^+{}_sK^+$) charge correlation with strong phase δ
- Use time dependence to distinguish:

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

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

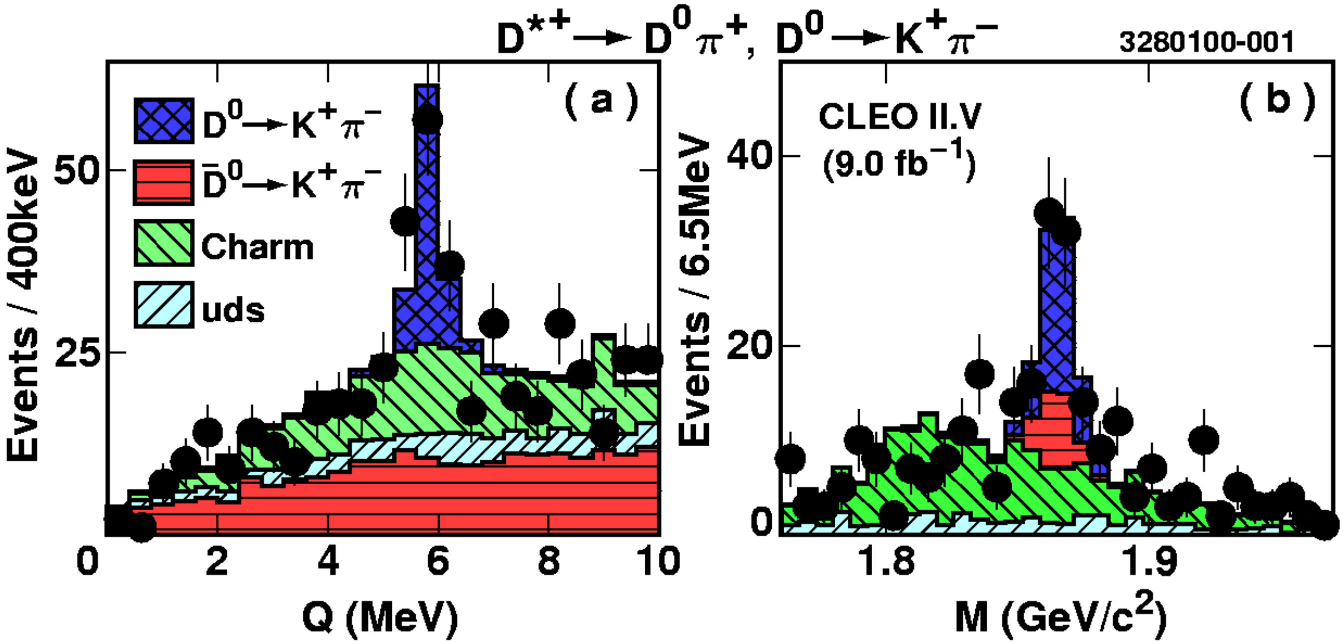
$$\left[R_D + \sqrt{R_D}(y\cos\delta - x\sin\delta)t + \frac{1}{4}(x^2+y^2)t^2 \right] e^{-t}$$

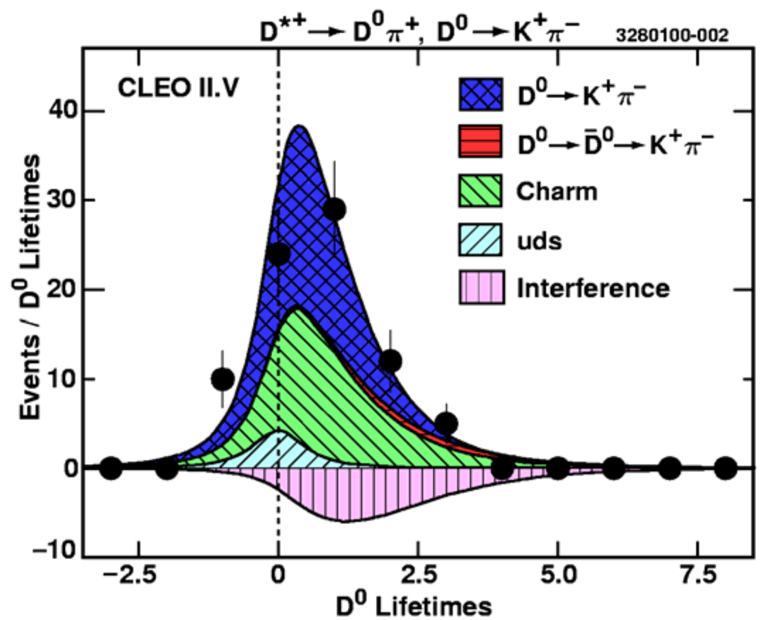
$$r_{ws}(t) = (R_D + \sqrt{R_D}\, y' t + \frac{1}{4}[x'^2 + y'^2]t^2)\, e^{-t}$$

x, y and R_D from $D^0 \to K^+\pi^-$

CLEO

- Currently, best constraints come from this mode if assumptions about strong phase are made
- Unknown strong phase difference weakens these constraints

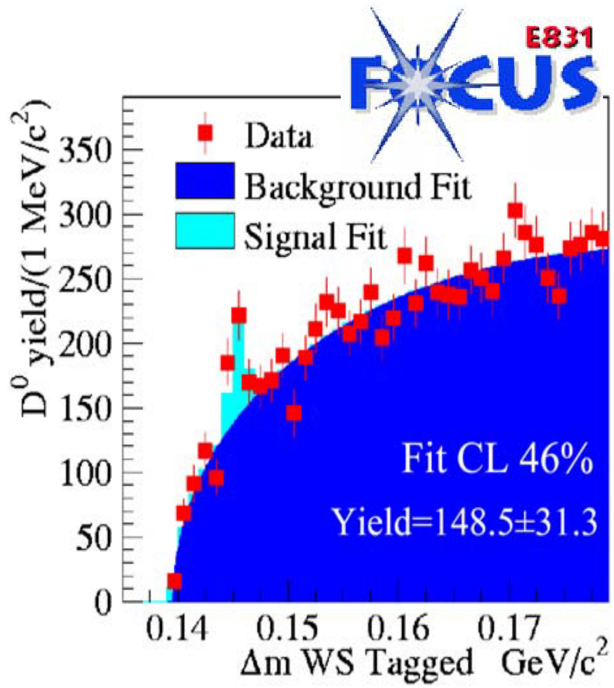




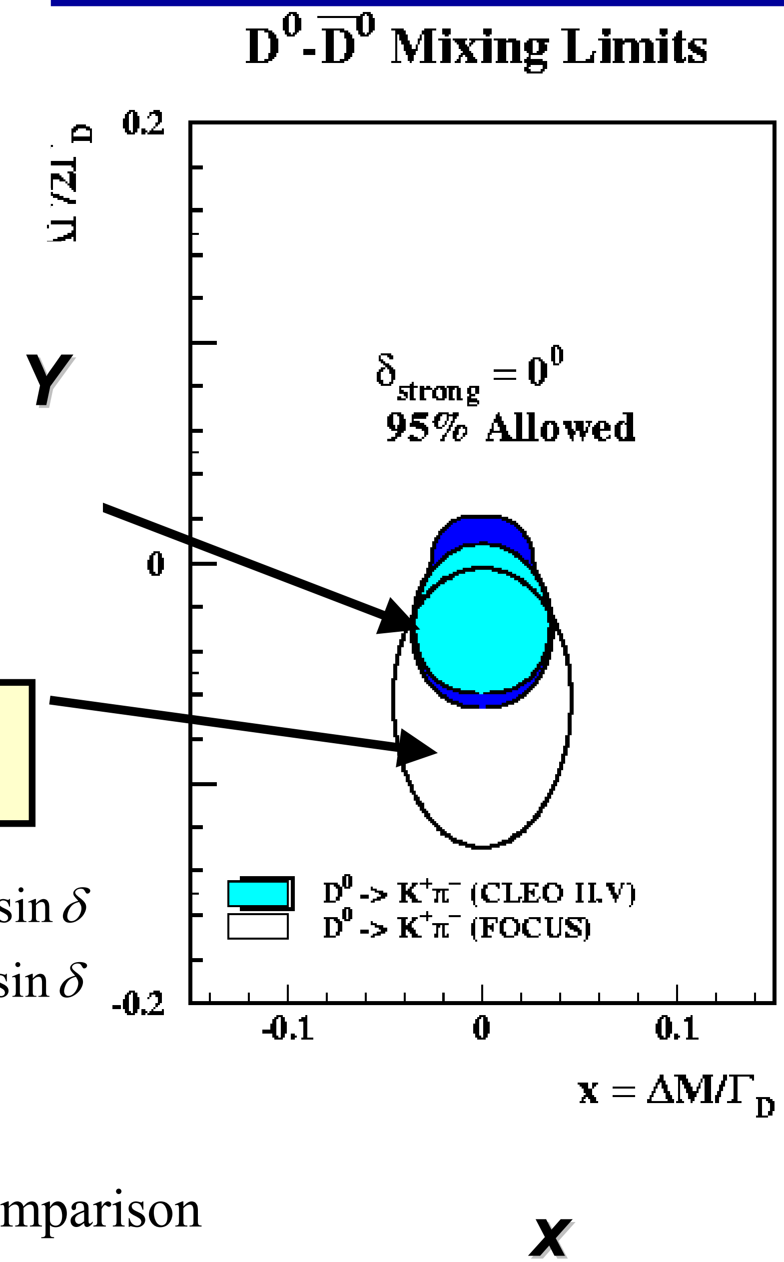
$$N_{WS} = 44.8^{+9.7}_{-8.7}$$
$$N_{RS} = 13527 \pm 116$$

$$\left.\begin{array}{c} |x'| < 2.8\% \\ -5.2\% < y' < 0.2\% \\ 0.24\% < R_D < 0.69\% \end{array}\right\} @95\% \text{ C.L.}$$

x, y, and R_D from $D^0 \to K^+\pi^-$



$$N_{WS} = 148.5 \pm 31.3$$
$$N_{RS} = 36760 \pm 195$$

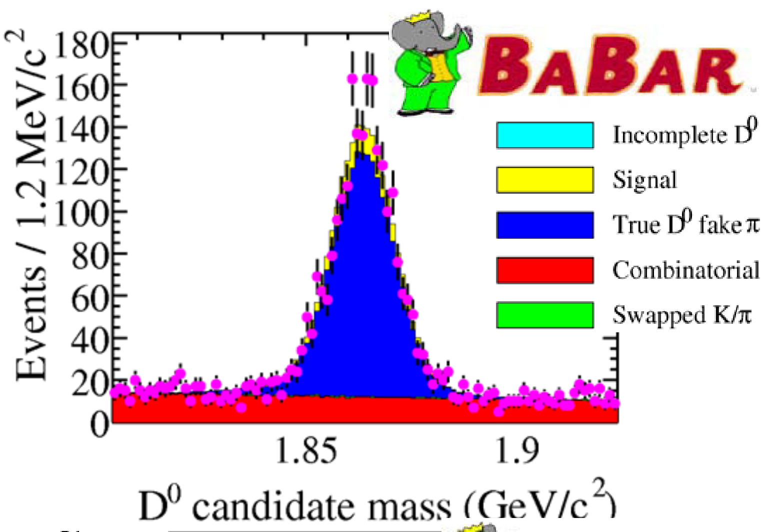


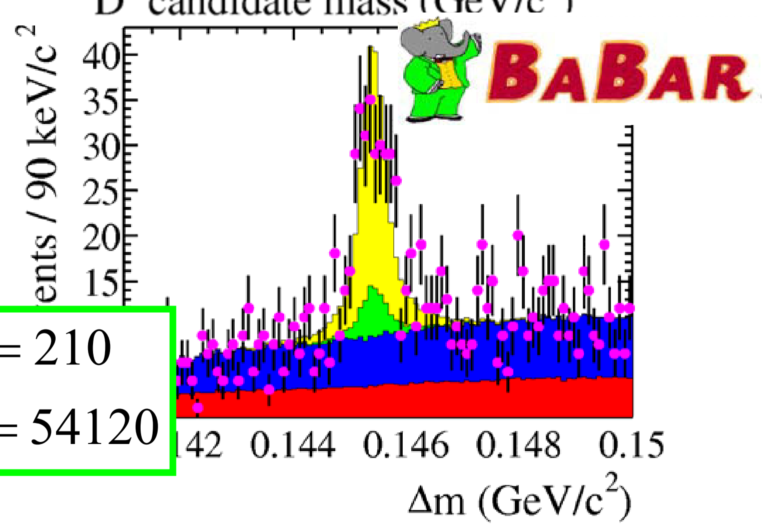
$$\left.\begin{array}{c} |x'| < 3.9\% \\ -12.4\% < y' < -0.6\% \\ 0.43\% < R_D < 1.73\% \end{array}\right\} @ 95\%\ \text{C.L.}$$

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

set $\delta = 0$ for comparison

R_{WS} from $D^0 \to K^+\pi^-$



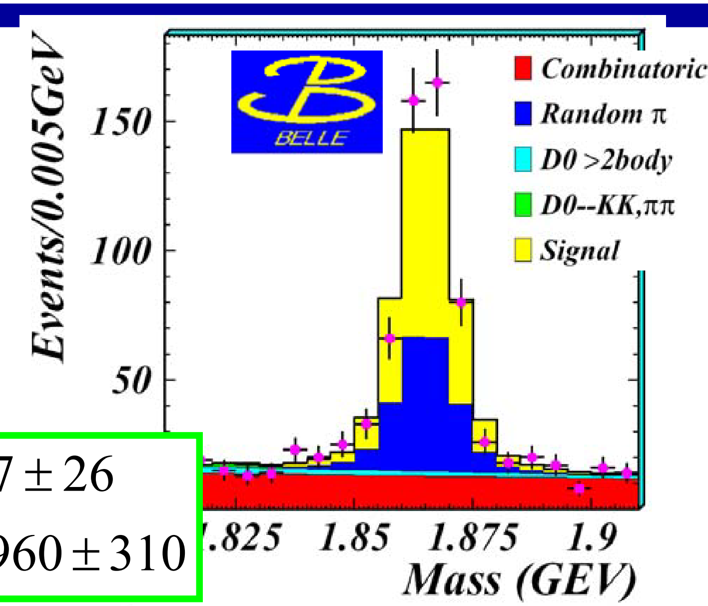


$N_{WS} = 210$

$N_{RS} = 54120$

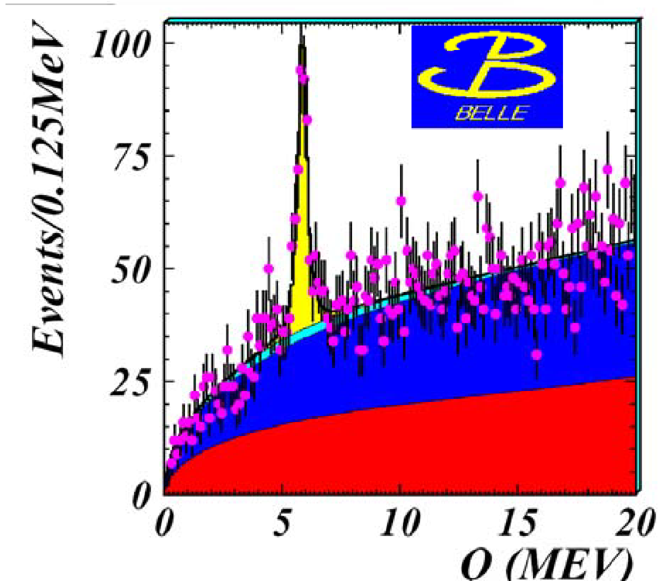
$R_{WS} = (0.38 \pm 0.04 \pm 0.02)\%$

$R_{WS} \equiv \frac{\Gamma(WS)}{\Gamma(RS)}$

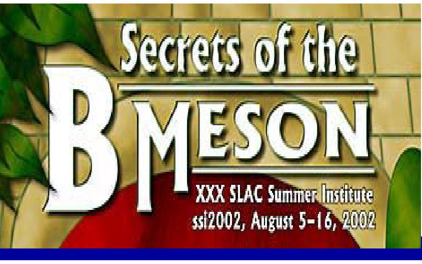


$N_{WS} = 317 \pm 26$

$N_{RS} = 82960 \pm 310$



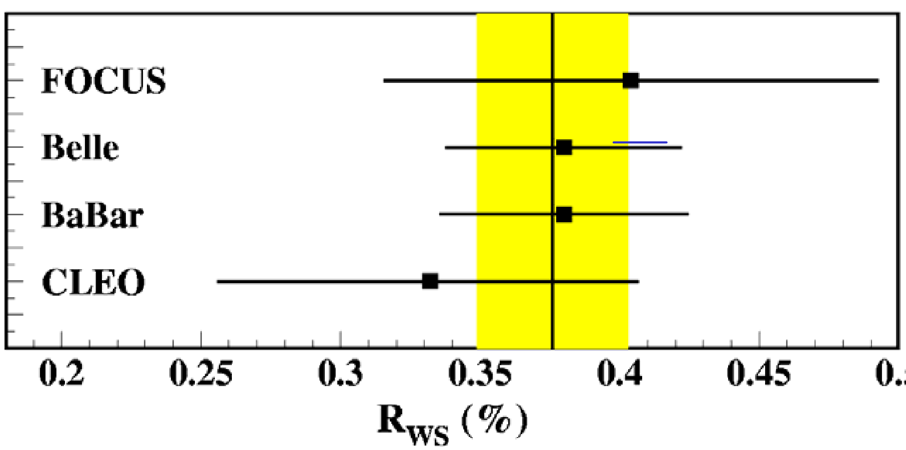
$R_{WS} = (0.38 \pm 0.03 \pm \sim 0.03)\%$



Measurements of the Wrong Sign Rate R_{WS}

- Belle and BaBar
  - Significant improvements in R_{WS}
  - x' and y' proper time fits soon!
- Information in multi-body modes not yet fully exploited
  - *x*, *y*, *CP* violation

R_{WS} in $D^0 \to K^+\pi^-$



$$R_{WS}\left(D^0 \to K^+\pi^-\right) = (0.38 \pm 0.03)\%$$

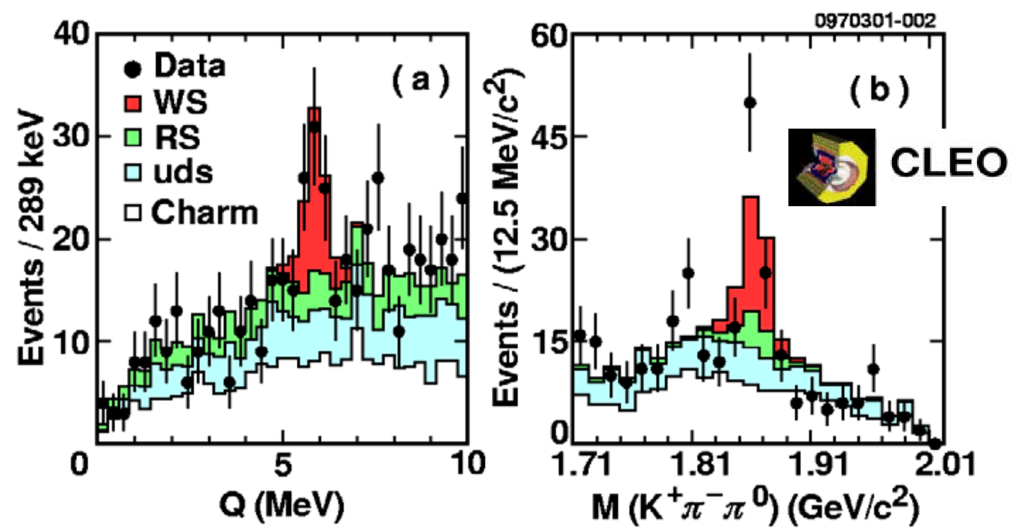
R_{WS} in multi-body hadronic modes

CLEO

$$R_{WS}\left(D^0 \to K^+\pi^-\pi^0\right) = \left(0.43^{+0.11}_{-0.10} \pm 0.07\right)\%$$

$$R_{WS}\left(D^0 \to K^+\pi^-\pi^+\pi^-\right) = \left(0.41^{+0.12}_{-0.11} \pm 0.04\right)\%$$

- Situation more complicated
- Time dependent Dalitz plot fits of RS and WS required to get limits on *x*, *y*, *CPV*
- Need lots of statistics, Advantagess
- Fit is to amplitudes I.e linear in x and y



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

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 $D^0 \to K^- \pi^+$ (assumes no *CP* violation):

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

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

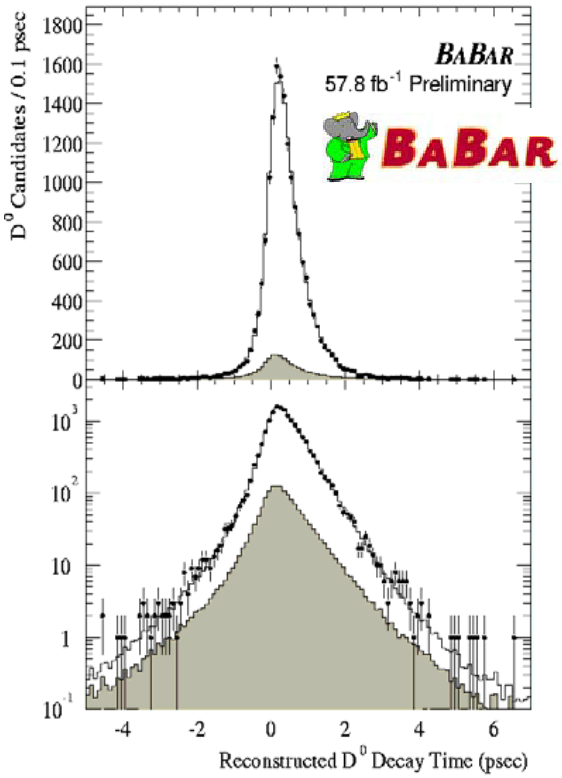
K^-K^+ (or $\pi^+\pi^-$) pure *CP* D_+

$K^-\pi^+$ 50% D_+ 50% D_-

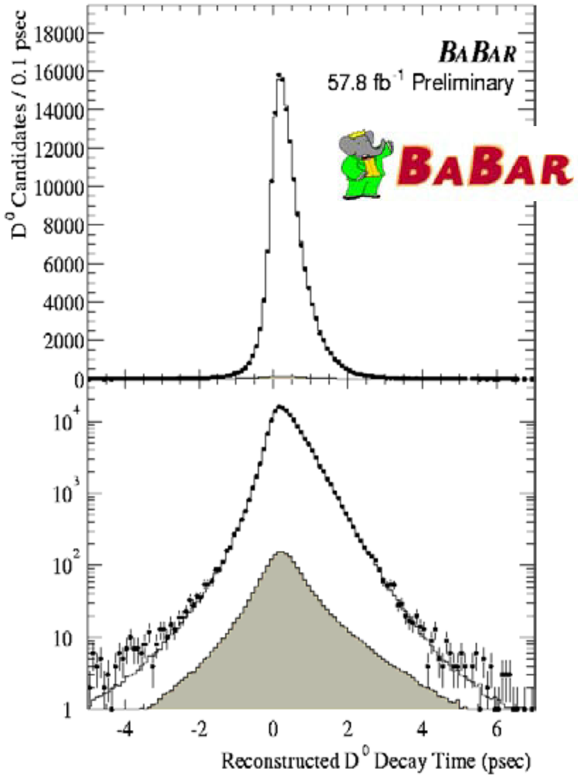
$$y_{CP} = \frac{\tau\left(D^0 \to K^-\pi^+\right)}{\tau\left(D^0 \to K^-K^+\right)} - 1$$

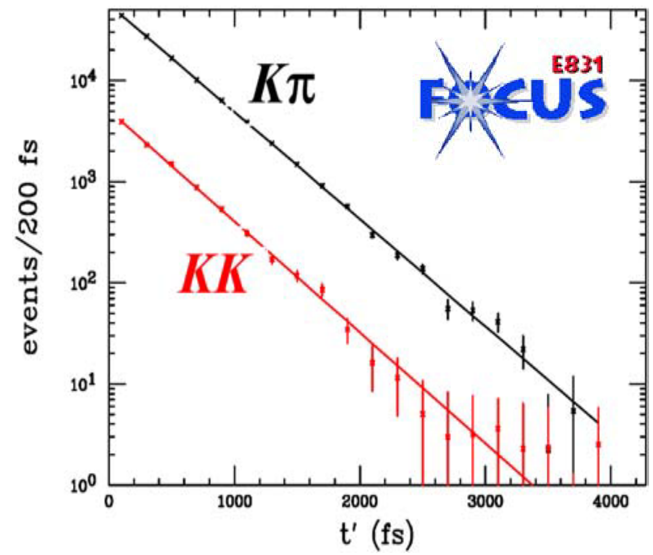
Measurement of y_{CP} from $D^0 \to K^+K^-$ & $D^0 \to \pi^+\pi^-$

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



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





Many systematic errors cancel in the ratio

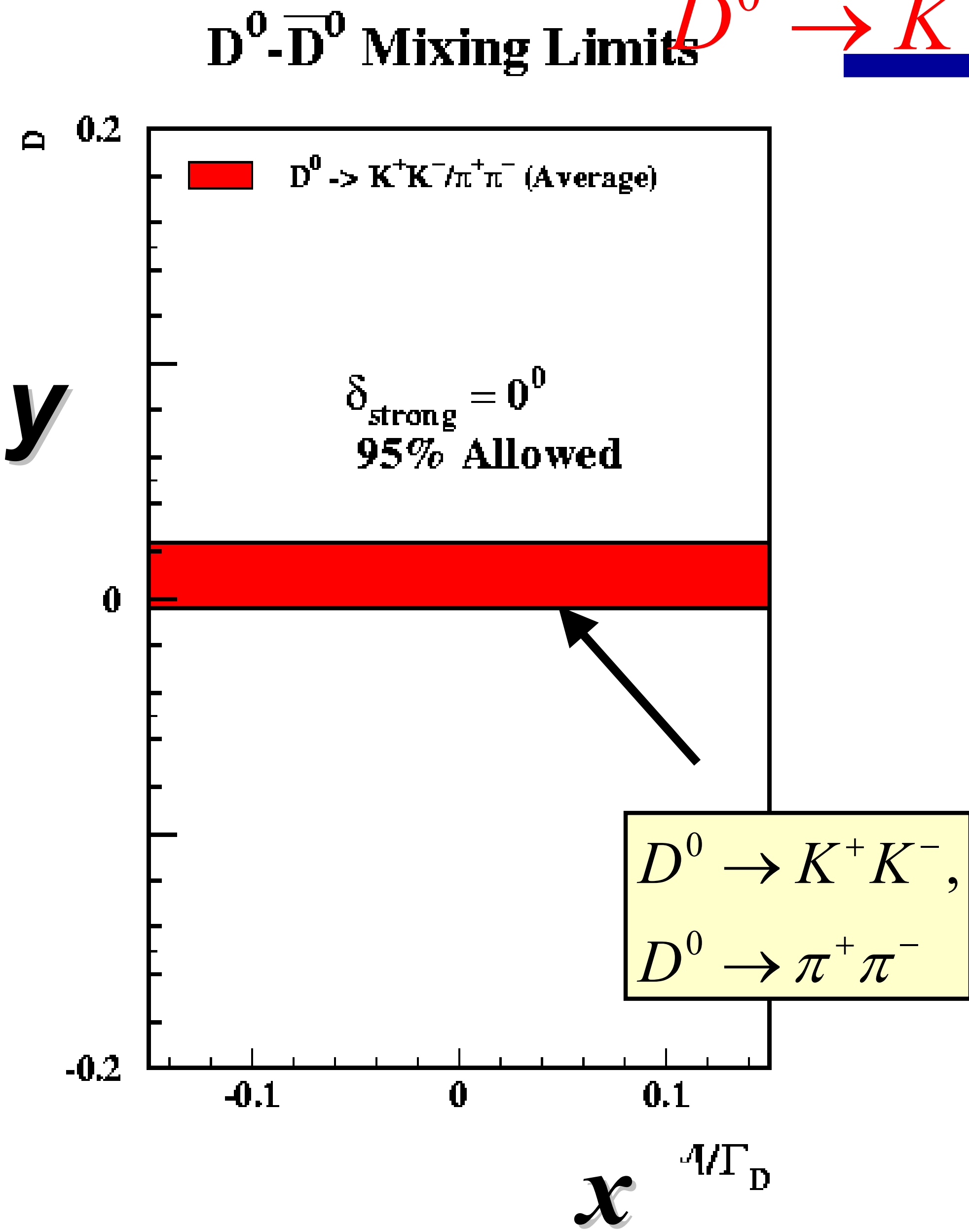
Technique, resolution, and systematics are quite different at fixed target experiments (FOCUS, E791) and e^+e^- (Belle BaBar, CLEO)

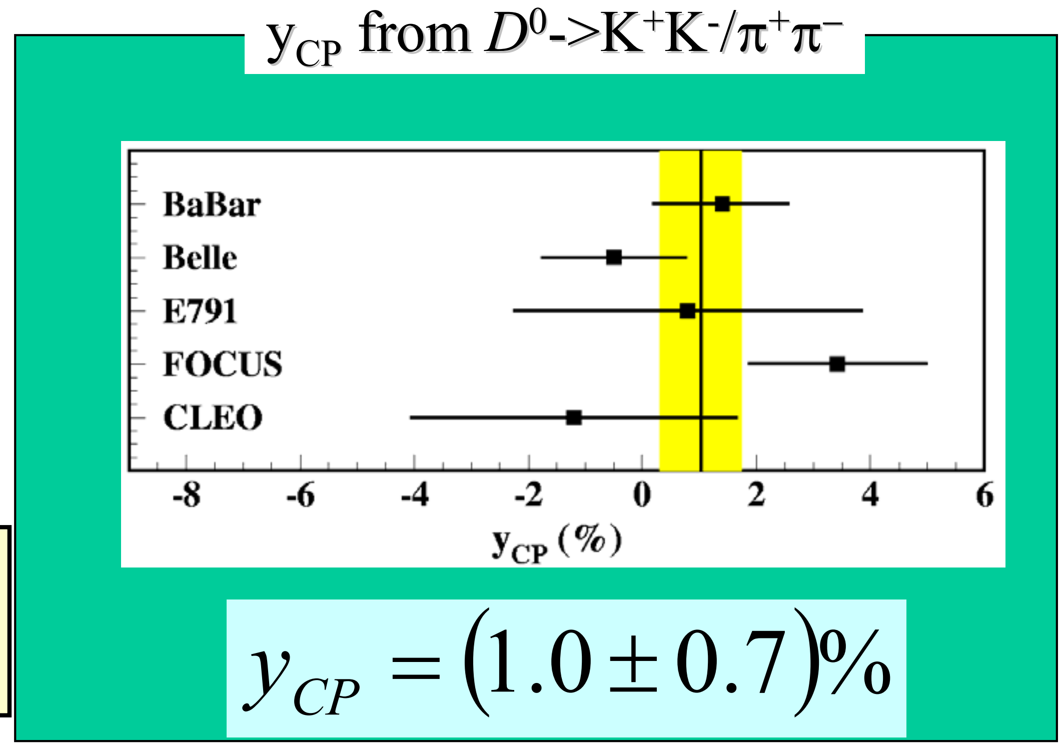
These were some of the first *D* mixing results to come out of the *B* factories…..

$e^+e^- : \sigma_t \approx 160$ fs

F.T. $: \sigma_t \approx 40$ fs

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

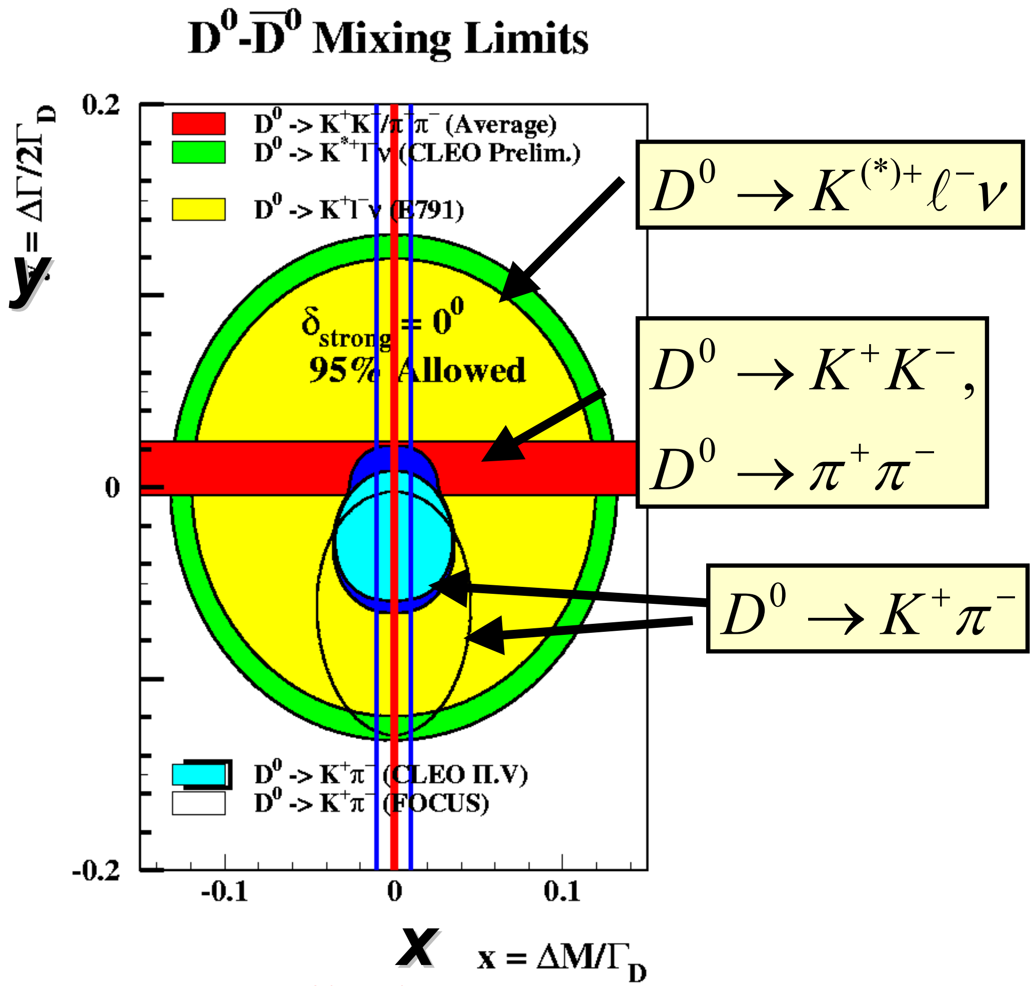




$$y_{CP} = (1.0 \pm 0.7)\%$$

Current Status of D^0-$\overline{D}^0$ Mixing

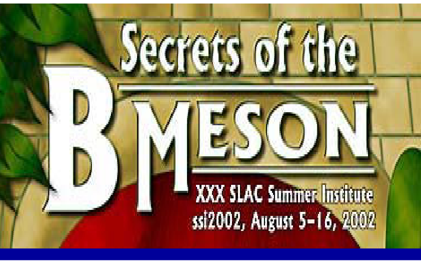
y_{CP} is appears high relative
to the limits on x and y form hadronic
The unknown strong phase difference
could be the cause.



- Current measurements cutting into range of some non-SM predictions
- Much room for improvement before we hit SM background

"Typical" upper SM predictions

"Typical" non-SM predictions (many higher and lower, however)



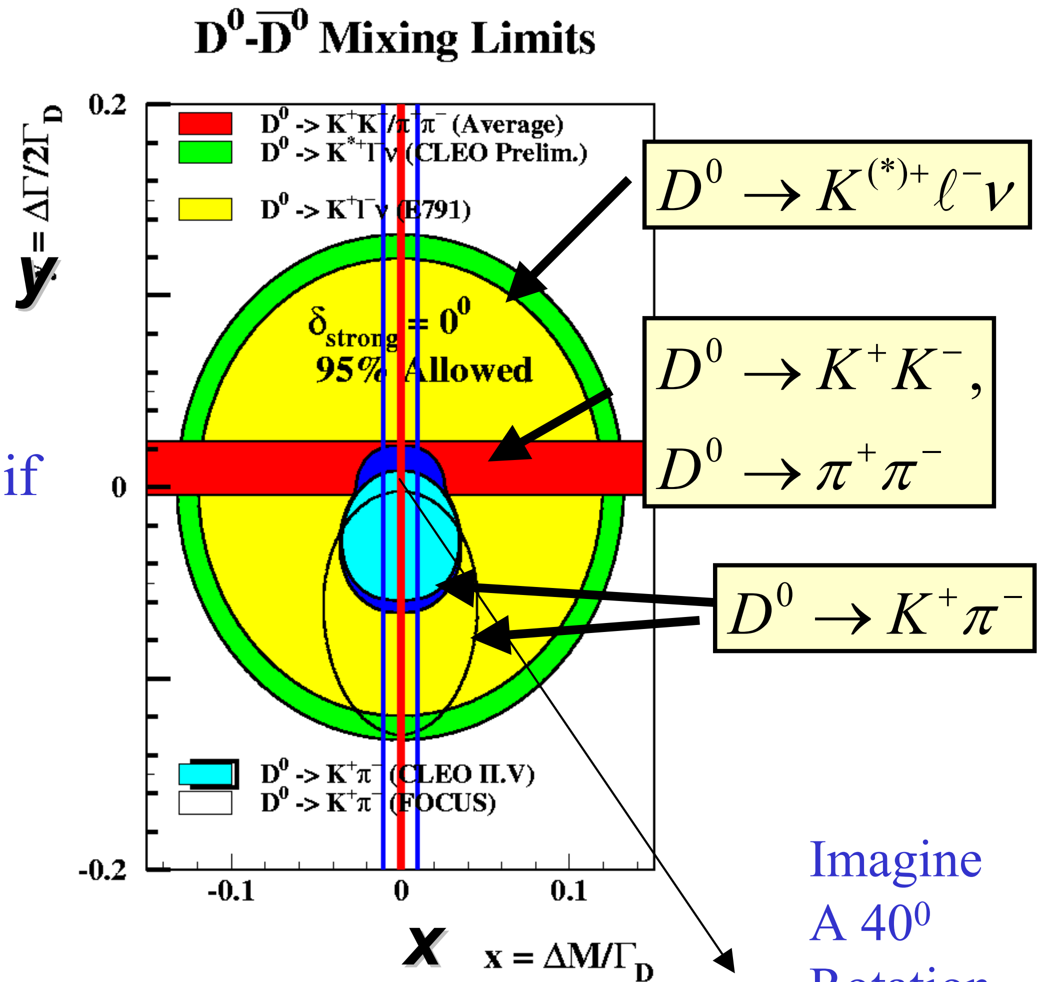
Current Status of D^0-$\bar{D}^0$ Mixing

y_{CP} is appears high relative
to the limits on x and y form hadronic
The unknown strong phase difference
could be the cause.

What if δ=40°, the estimated
maximum of Falk, Nir & Petrov (99)?
Y_{CP} and K π would be more consistent if
δ=90⁰. Bergman, Grossman etal (00).

My opinion: the errors are
too large to draw any strong
Conclusion at this time.

- Current measurements cutting into range of some non-SM predictions
- Much room for improvement before we hit SM background



“Typical” upper SM predictions

“Typical” non-SM predictions (many higher and lower, however)

Imagine
A 40⁰
Rotation
Of the Kπ
ellipses

The Future
of these techniques

Babar, Belle the heavyweights

by 2005 ~500 1/fb

B Factory Kπ x $\propto$ $L^{-1/4}$

can do better with Dalitz analysis

Each experiment,

Scaling from CLEO

$$\left.\begin{array}{l} |x'| \lesssim 0.9\% \\ |y'| \lesssim 0.6\% \\ |y| \lesssim 1.0\% \end{array}\right\}$$

$D^0 - \bar{D}^0$ **surpasses** $K^0 - \bar{K}^0$ **generic** **FCNC constraints**

$$\Delta M \bullet \tau \propto f_M^2 M \bullet \tau$$

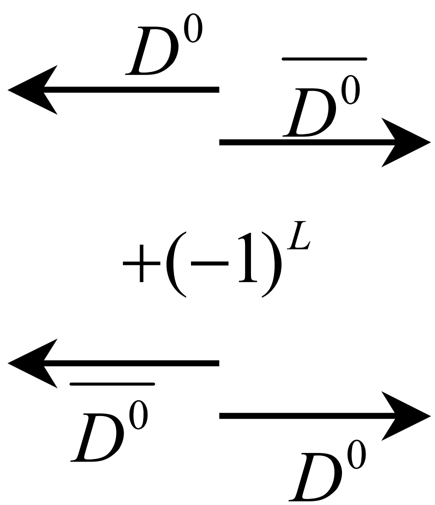
$K^0 \to \bar{K}^0$	$\equiv 1$
$D^0 \to \bar{D}^0$	$\simeq 0.03$

Because standard model present and big backgrond in kaon decay

Unique opportunities at Threshold

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

$\Psi'' \to L = 1$



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

Angular momentum (L=1 for ψ(3770))

Special Opportunities to measure mixing by exploitmg Quantum Coherence at the Ψ’’

#1

$$\Psi'' \to D^0\bar{D}^0 \to (K^-\pi^+)(K^-\pi^+)$$

$$\therefore\ L = 1$$

J=1

p-wave

is sensitive to mixing, and insensitive to Doubly Cabibbo suppressed decays

K^- π^+ t_1 t_2 K^- π^+

$a_1 =$ D^0 A (CF) **x** $\bar{D}^0$ $\left(\bar{B} - \frac{1}{2}(ix+y)t_2 \cdot A\right)$ (DCSD, mix, CF)

Indistinguishable from…..

$a_2 =$ $\bar{D}^0$ $\left(\bar{B} - \frac{1}{2}(ix+y)t_1 \cdot A\right)$ **x** D^0 A

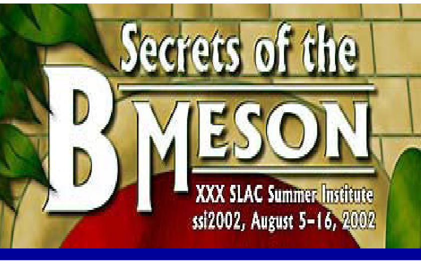
H.Yamamoto (thesis) I.Bigi
A.I .Sanda
Z.Z.Xing
D. Attwood.
A Petrov

Add amplitudes, $(-1)^L = -1$ relative sign

$$|a_1 - a_2|^2 = |A\bar{B} - \bar{B}A + \frac{1}{2}(ix+y)A^2(t_1 - t_2)|^2 = \frac{1}{4}A^4(x^2+y^2)(t_1-t_2)^2|$$

Interferes away!

(no time information)



Time integrated mixing at the ψ(3770)

normalizing by $\Gamma(D^0\overline{D^0}) \to (K^-\pi^+)(K^+\pi^-)$

implies for the time integrated rate

$$R\left[\frac{(K^-\pi^+)(K^-\pi^+)}{(K^-\pi^+)(K^+\pi^-)}\right] = 1/2(x^2+y^2)$$

(in the limit of CP conservation)

same for the semileptonic rate

$$R\left[\frac{(K^-\ell^+)(K^-\ell^+)}{(K^-\ell^+)(K^+\ell^-)}\right] = 1/2(x^2+y^2)$$

	#Right Signs
$(K^-\pi^+)(K^+\pi^-)$	10,000
$(K^-\ell^+x)(K^+\ell^-x)$	40,000
	50,000

$$\sqrt{\frac{1}{2}(x^2+y^2)} < \sqrt{\left(\frac{2.3}{50,000}\right)} < 1.0\%$$

Since, Ψ″ likely background free… The above is limited by statistics, measurements at 10 GeV or hadron machines have entirely different systematics errors

note: at 3770 $x \propto L^{-1/2}$, B Factory $K\pi$ $x \propto L^{-1/4}$

B-factory my estimate X< 0.8%

With 500 fb so 3770 with 3fb close

BESIII X3 smaller error

Aside: **if it were possible**

To obtain 500 fb^{-1} at Ψ″:

$$\sqrt{\frac{1}{2}(x^2+y^2)} < \sqrt{\frac{2.3}{50,000\times\frac{500}{3}}} < 0.08\%$$

(Unique sensitivity)

CP Eigenstates at $\psi(3770)$

At the $\psi''(3770)$

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

$J^{PC} = 1^{--}$ 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 :

$$CP(f_1 f_2) = CP(f_1)\,CP(f_2)\,(-1)^l = CP+$$

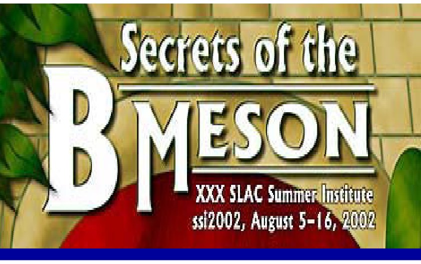
$$\underbrace{CP(f_1)\,CP(f_2)}_{-}\;\underbrace{(-1)^l}_{-\ (\text{since } l=1)}$$

•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

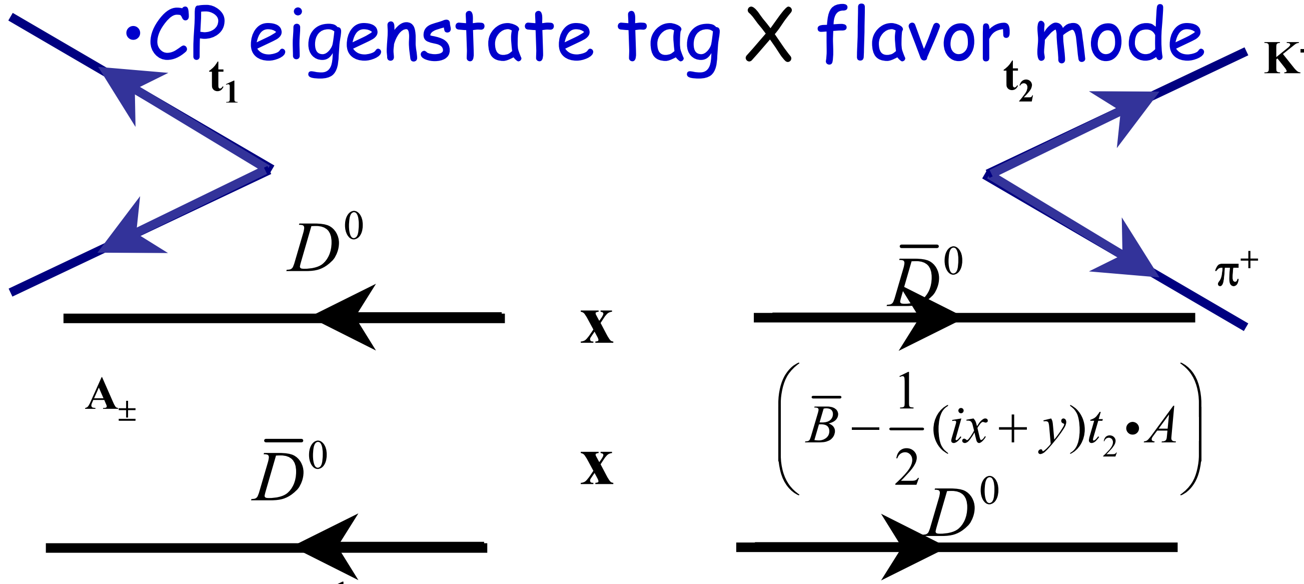
$$\underset{+}{K^+K^-} \leftarrow D_{CP} \leftarrow \psi(3770) \to \underset{-}{D_{CP}} \to K^-\pi^+\ \underset{-}{(-1)^l} = CP+$$



Measuring the DCSD/CF phase δ at $\Psi(3770) \to D^0\overline{D}^0 (f_\pm)(K^-\pi^+)$

#2

•CP eigenstate tag X flavor mode



examples

+ K^+K^-

- $K_S\pi^\varepsilon$

$a_1 =$ $A_\pm$ x $\left(\overline{B} - \frac{1}{2}(ix+y)t_2 \bullet A\right)$

$a_2 =$ $\pm A_\pm (1 \mp \frac{1}{2}(ix+y)t_1) \times A \times (-1)^1$

$$|a_1 + a_2| \propto |1 \mp (\frac{\overline{B}}{A} + \frac{1}{2}(ix+y)(t_1 - t_2))|^2$$

$$-\sqrt{R_D}e^{-i\delta}$$

$$\int dt \cong 1 \pm 2\sqrt{R_D}\cos\delta$$

Measures strong phase diff. CF/DCSD $\Delta\cos\delta$ ~0.05. Crucial input for B factories Needed for γ in $B \to DK$

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

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

J. Silva and A. Soffer Phys. Rev. D61: 112001, 2000, (hep-ph/9912242)

Gronau Grossmann J.Rosner (hep-ph/0103110).

$\Psi \rightarrow D^0 \bar{D}^0 (f_\pm)(K^- \pi^+)$

$\int dt \cong \; | \; \pm 2\sqrt{R_D}\cos\delta$

$$A = \frac{(K^-\pi^+)f_+ - (K^-\pi^+)f_-}{(K^-\pi^+)f_+ + (K^-\pi^+)f_-} = 2\sqrt{R_D}\cos\delta$$

Expect 32,000

$K^-\pi^+ f_-$

A is expected to be small

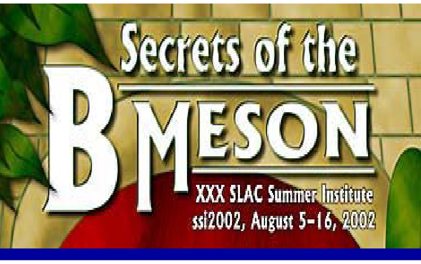
$\Delta\cos\delta \simeq \frac{1}{2\sqrt{R_D}\sqrt{N}}$

$\Delta\cos\delta \simeq \pm 0.05$

BESIII X3 smaller

Error (0.006 500 fb^{-1})

CP(+1) eigenstates			
Channel	B.F.(x10^3)	#(3fb^{-1} ψ(3770))	#(3fb^{-1} γD^{0}D^0)
K^-K^+	4.1	110,000	9,400
$\pi^-\pi^+$	1.6	36,000	3,000
$\rho^o\pi^o$	15.0	54,200	4,600
CP(-1) eigenstates			
$K_s\eta$	3.5	61,600	5,300
$K_s\rho^o$	6.0	98,400	8,400
$K_s\pi^o$	10.6	176,000	15,000
$K_s\eta'$	10.0	141,000	12,000
$K_s\phi$	4.3	39,100	3,300



Experimental constraints on y at Threshold

1. Time-dependent analyses are not possible, Are time dependent Analyses possible?

Semileptonic: quadratic in x,y: not so sensitive wanted: ***linear*** **in x or y**

2. Recalll: (quantum-mechanically) entangled initial state

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

angular momentum (L=1 for ψ(3770))

… so one can measure decay rates for CP-tagged decays

The semi-leptonic width of a meson should be independent of the CP quantum number since it is flavor specific. So the semi-leptonic branching ratio in CP tagged events is inversely proportional to the total width of that meson. Since we know whether the D is CP even or CP odd we can extract y

- CP eigenstate tag X flavor mode

$K^+K^- \leftarrow D_+ \leftarrow \psi(3770) \rightarrow D_- \rightarrow X\,l\nu$

$K_s^0\,\pi^0 \leftarrow D_- \leftarrow \psi(3770) \rightarrow D_+ \rightarrow X\,l\nu$

D. Atwood, A.A. Petrov, hep-ph/0207165

Experimental constraints on y at Threshold

$$\left[\frac{Br(D_+ \to X\ell\nu)}{Br(D_- \to X\ell\nu)} - \frac{Br(D_- \to X\ell\nu)}{Br(D_+ \to X\ell\nu)}\right] = 4y$$

$in\, 3\, fb^{-1}$	$\#tags$	$CP = +$	$CP = -$
		$\sim 800K$	$\sim 200K$
	$\#tag + \ell$	$9.8K$	$39.2K$

$$for\ \ y = 0.75\%, \delta y = 0.4\%$$

$$at\ \ BEPCII\ \ \delta y = 0.13\%$$

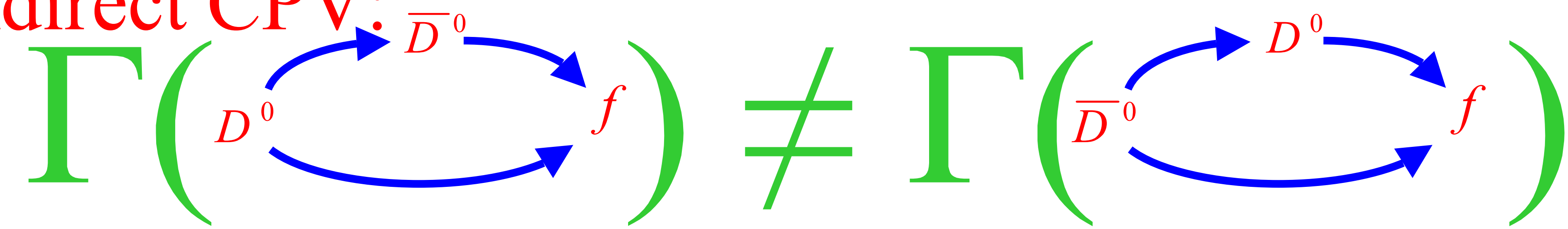
Expect background free systematics entirely different to lifetime measurements

once y is obtained x can be obtained from $\sqrt{1/2(x^2 + y^2)}$

Secrets of the B MESON — XXX SLAC Summer Institute ssi2002, August 5-16, 2002

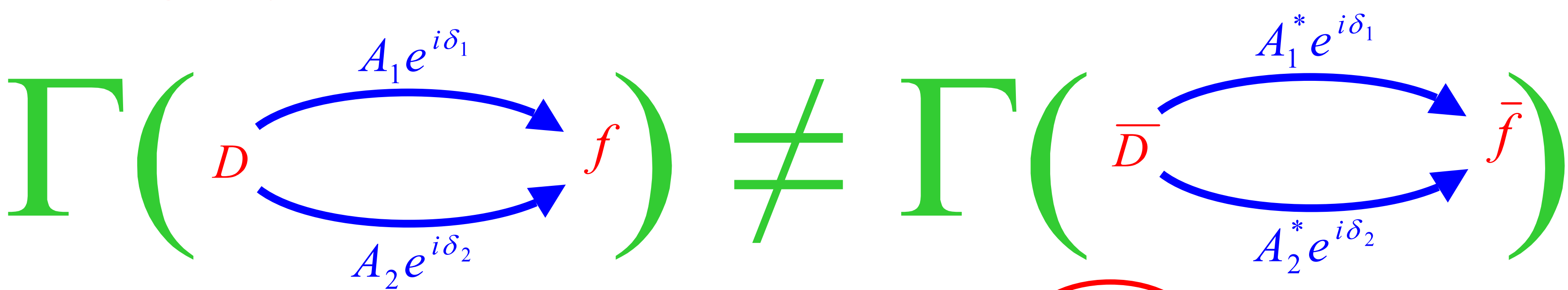
CPV in D Decays

Indirect CPV:



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

Direct CPV:



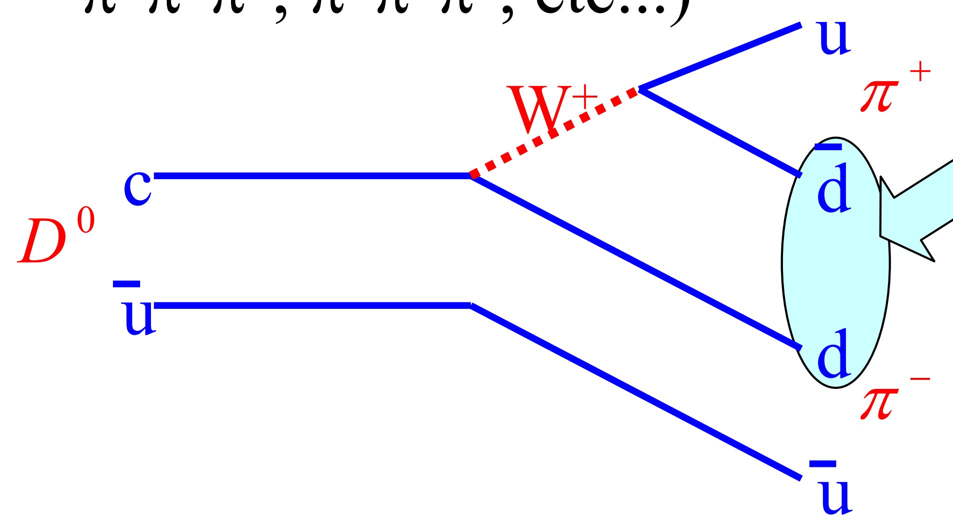
$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2 Im A_1 A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 Re A_1 A_2^* \cos(\delta_1 - \delta_2)} < 10^{-3}$$

2 different amplitudes **strong phase-shift**

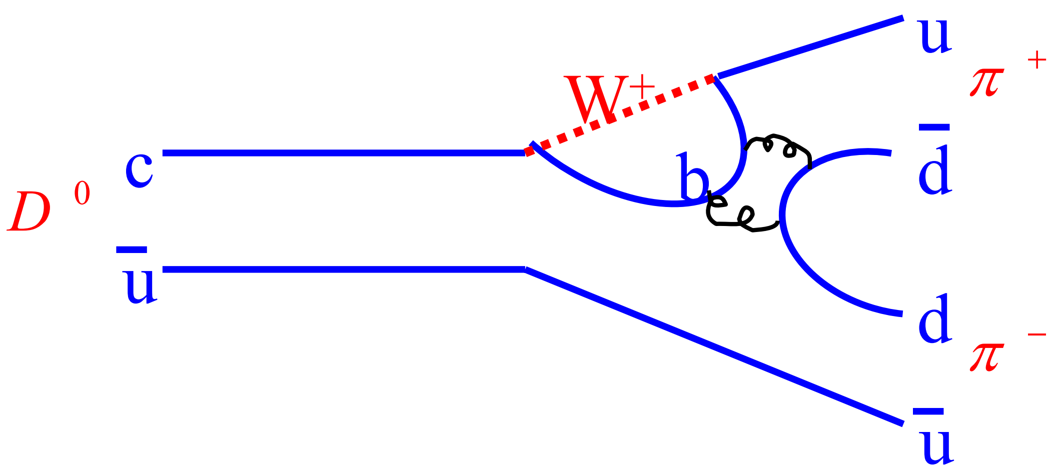
We have the ingredients:

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

(same for K^+K^-, $K^+K^-\pi^+$, $K^+K^-\pi^0$, $\phi\pi^+$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, etc...)



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

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

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

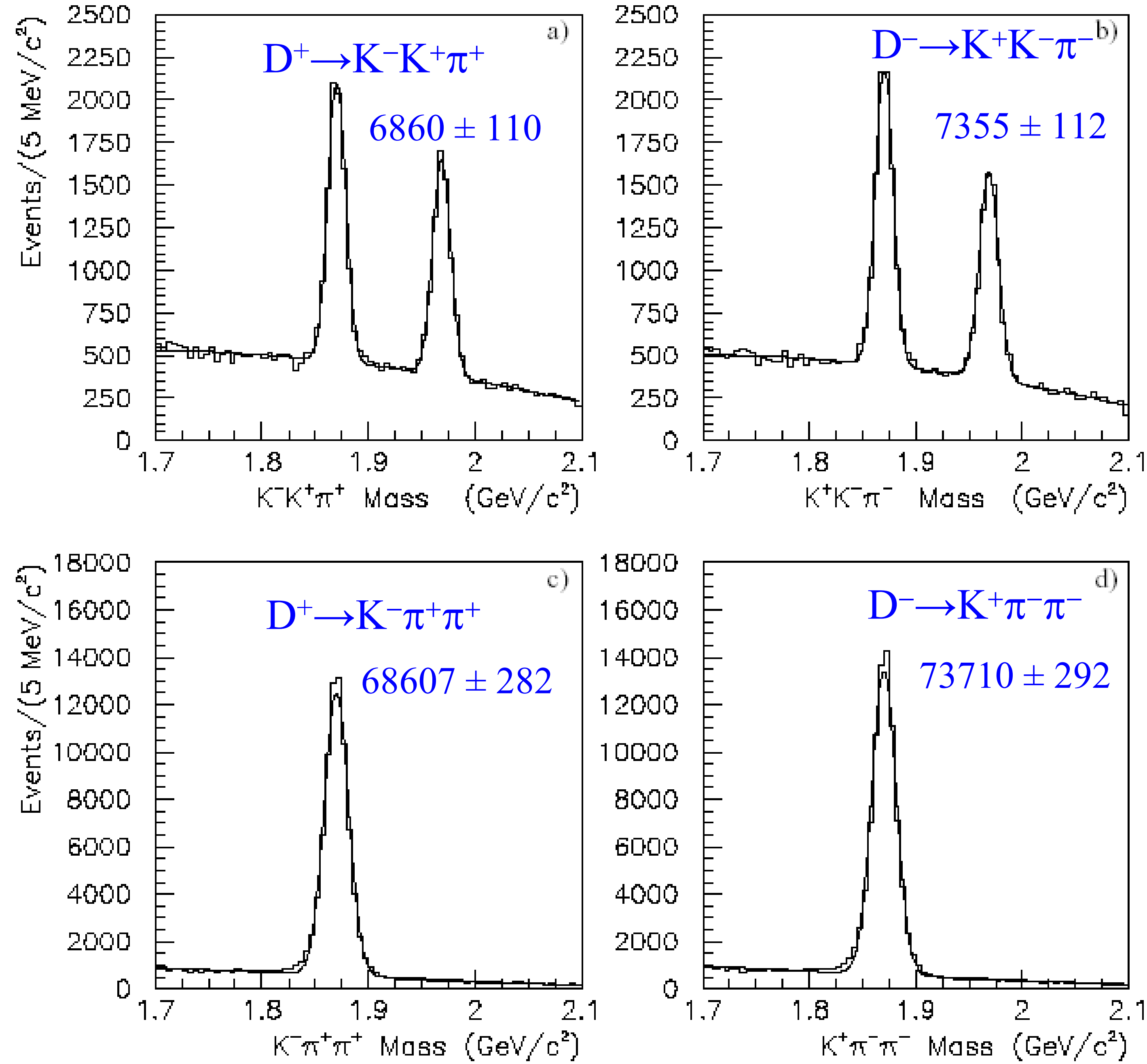
different strong phases are likely

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

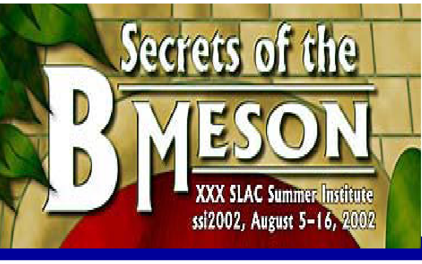
Expect $A_{CP} < 10^{-3}$ in most cases

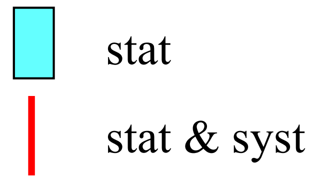
matter

anti-matter



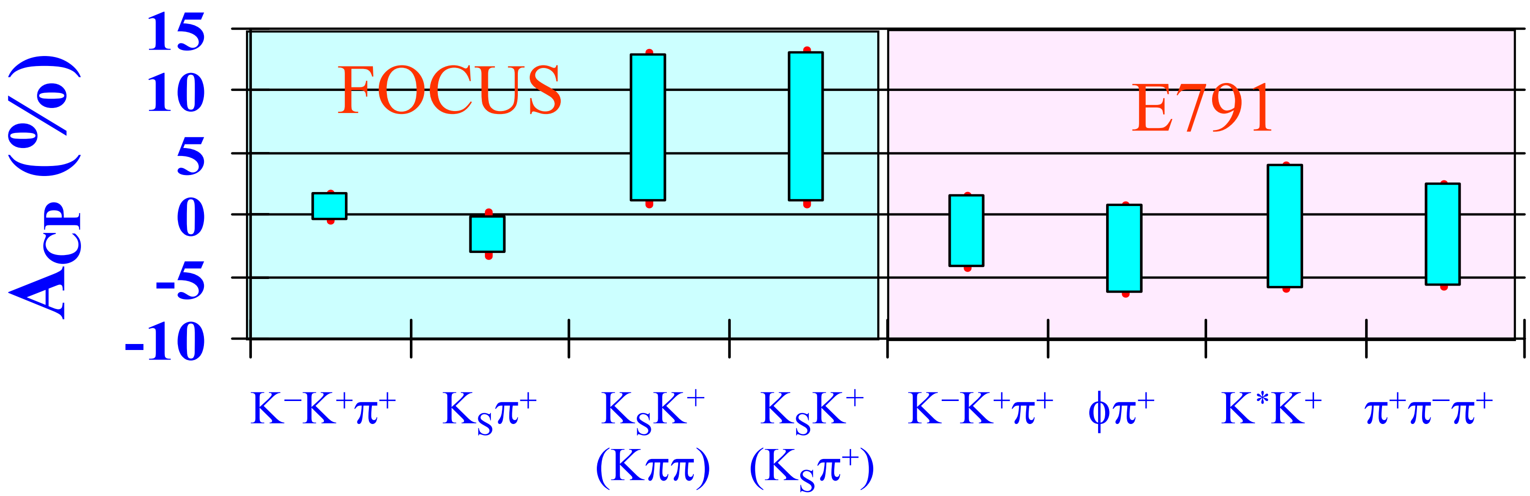
Cabbibo allowed (Acp=0) mode used to take into account matter-anti-matter production asymmetry





$D^{\pm}$ A_{CP} Summary

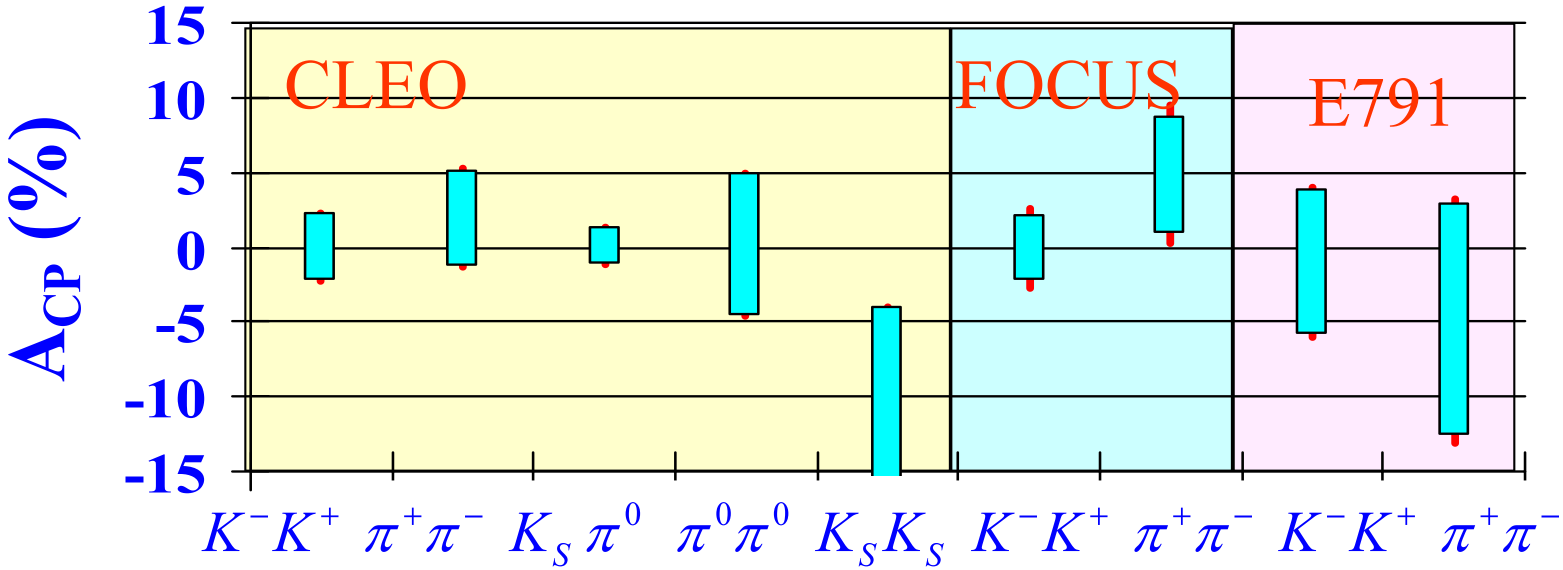
Self tagging no D* tag needed



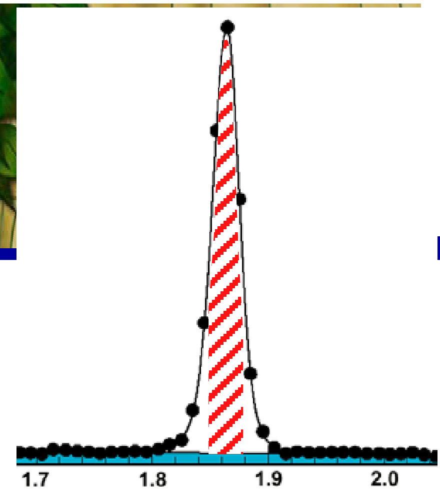
* All analyses statistics limited.
* None are background free.

D^0 A_{CP} Summary

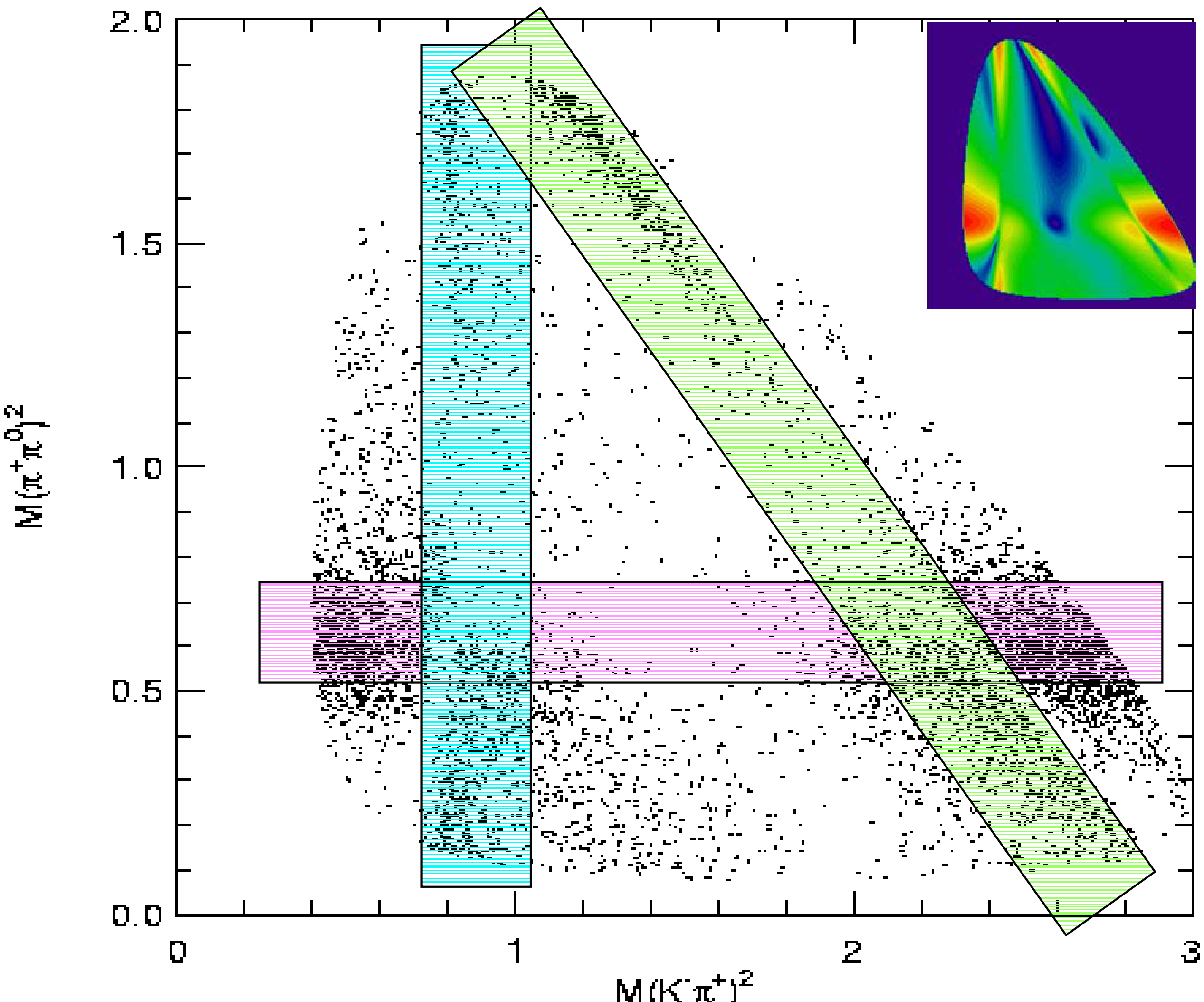
Use D^* decays to tag D^0 flavor

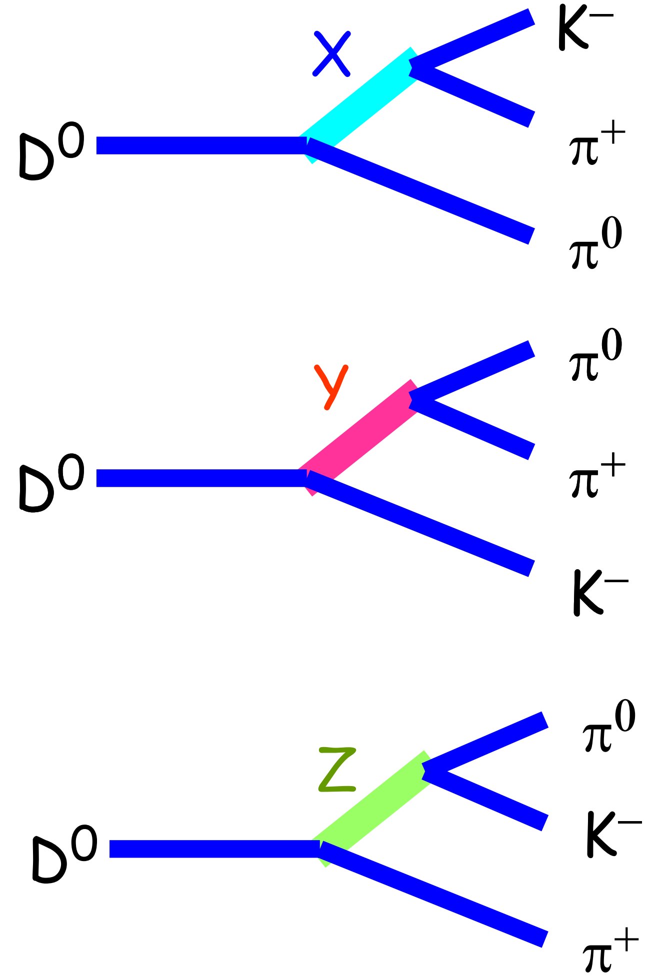


$D^0 \to K^- \pi^+ \pi^0$



- Look for CPV in Dalitz Plots:





CPV at the $\psi(3770) \rightarrow D^o \bar{D}^o \rightarrow f_+ f_+$ or $f_- f_-$

$(f_+ = K^+K^-, \pi^+\pi^-, K_s\eta..)$

•Recall if two decays are observed with the same CP in a single background free event → CP violation in the D system is established 3fb^{-1}

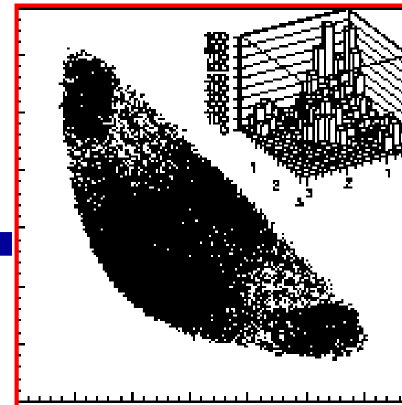
CP eigenstate 1	CP eigenstate 2	# for 100% CPV
K^+K^-	K^+K^-	174
K^+K^-	$K_s\pi^0$	171
K^+K^-	$\rho^0\pi^0$	183
$K_s\pi^0$	$K_s\pi^0$	136

CLEO-c estimates

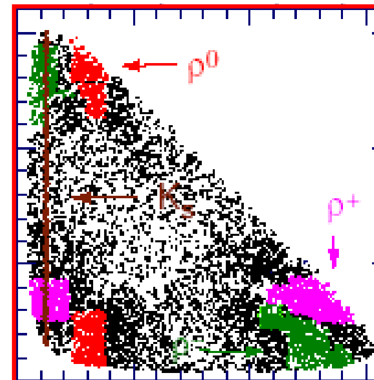
statistics can be increased x3-4 using a MM technique. This technique is very different to the method at 10 GeV and at hadron machines. sensitivity is at the ~1% level (X3 better at BEPCII)

CPV Outlook

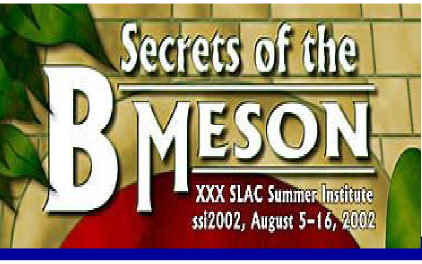
- E791 and FOCUS
  - Working on A_{CP} analyses (for example Dalitz plots).
- CLEO-c..
  - ~30 million DD events (and new A_{CP} search modes).
- B Factories
  ~by 2005 100 times the integrated luminosity that CLEO has at the Y(4S) Improve on present CLEO limits by at least a factor of 10.
- Hadron Machines
  - CDF & D0 are getting into the game.
  - BTeV could have 10^9 reconstructed charm events.
- BESIII



E791 $K^-\pi^+\pi^+$



CLEO $\pi^-\pi^+\pi^0$



Rare Decays

•Rare and decays, Standard Model estimates:

$$Br(D^0 \to X l^+ l^-) \sim 1\times10^{-9} (S.D.:10^{-8})$$

$$Br(D^0 \to X \nu\bar{\nu}) \sim 2\times10^{-15} (S.D.:10^{-15})$$

$$Br(D^+ \to \pi \nu\bar{\nu}) \sim 8\times10^{-16} (S.D.:10^{-16})$$

…background-free tests of New Physics!

Some very difficult to do anywhere except at the (3770) in tagged events. Sensitivity at the 10^{-6} level
A wide range of modes were looked at by CLEO-c
Conclusion was that B Factories with 500 fb and CLEO-c will be complementary. Hadron machines have statistical advantages in certain final states.

Probing QCD

→ Verify tools for strongly coupled theories

→ Quantify accuracy for application to flavor physics

- ψ and Υ Spectroscopy
  - Masses, spin fine structure — Confinement, Relativistic corrections
- Leptonic widths for S-states. — Wave function; Tech: $f_{B,K}\sqrt{B_K}\ f_{D\{s\}}$
  - EM transition matrix elements — Form factors
    - Υ resonances winter '01-summer'02 ~ 4 fb^{-1} total

Rich calibration and testing ground for theoretical techniques → apply to flavor physics

J/Ψ running 2005 10^9 J/Ψ x 20 BES II

- Uncover new forms of matter – gauge particles as constituents
  - Glueballs G=|gg⟩ Hybrids H=|g$q\bar{q}$⟩

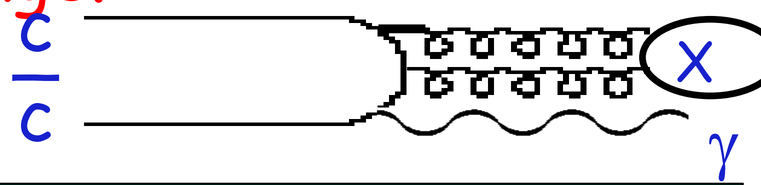
Study fundamental states of the theory

The current lack of strong evidence for these states is a fundamental issue in **QCD.** Requires detailed understanding of ordinary hadron spectrum in 1.5-2.5 GeV mass range.

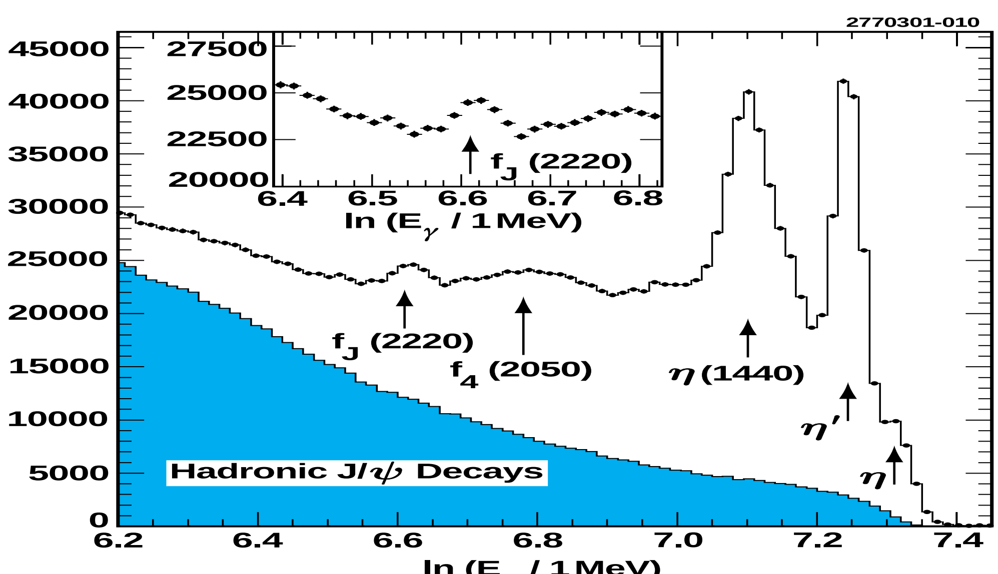
Gluonic Matter

- Gluons carry color charge: *should bind!*

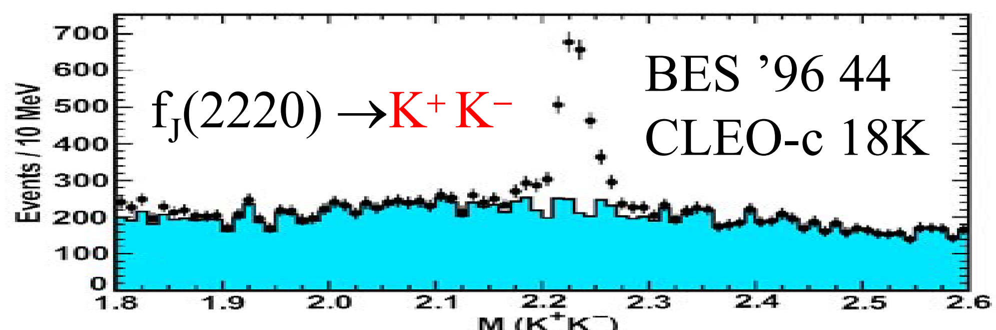
  - But, like Jim Morrison, glueballs have been sighted too many times without confirmation....
- CLEO-c 1st high statistics experiment with modern 4π detector covering 1.5-2.5 GeV mass range.
- Radiative ψ decays:ideal glue factory:
  - (60 M $J/\Psi \to \gamma X$)



Example: $f_J(2220)$ Inclusive γ



Exclusive:



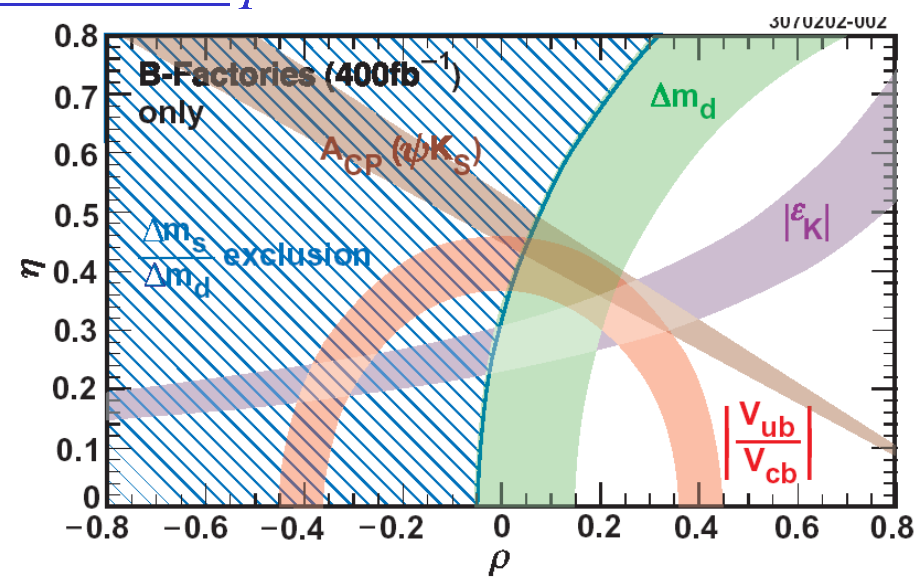
corroborating checks:

Anti-search in $\gamma\gamma$: /Search in $\Upsilon(1S)$

Note: with more data BESII no longer see evidence of $f_j(2220)$

CLEO-c: Helping the B Factories & Tevatron Experiments

- *Crucial Validation of Lattice QCD:* Lattice QCD will be able to calculate with accuracies of 1-2%. *The CLEO-c decay constant and semileptonic data will provide a "golden," & timely test.* *QCD & charmonium data provide additional benchmarks*. (E2 Snowmass WG)



B Factories only ~2005

Imagine a world Where we have theoretical mastery of non-perturbative QCD at the 2% level

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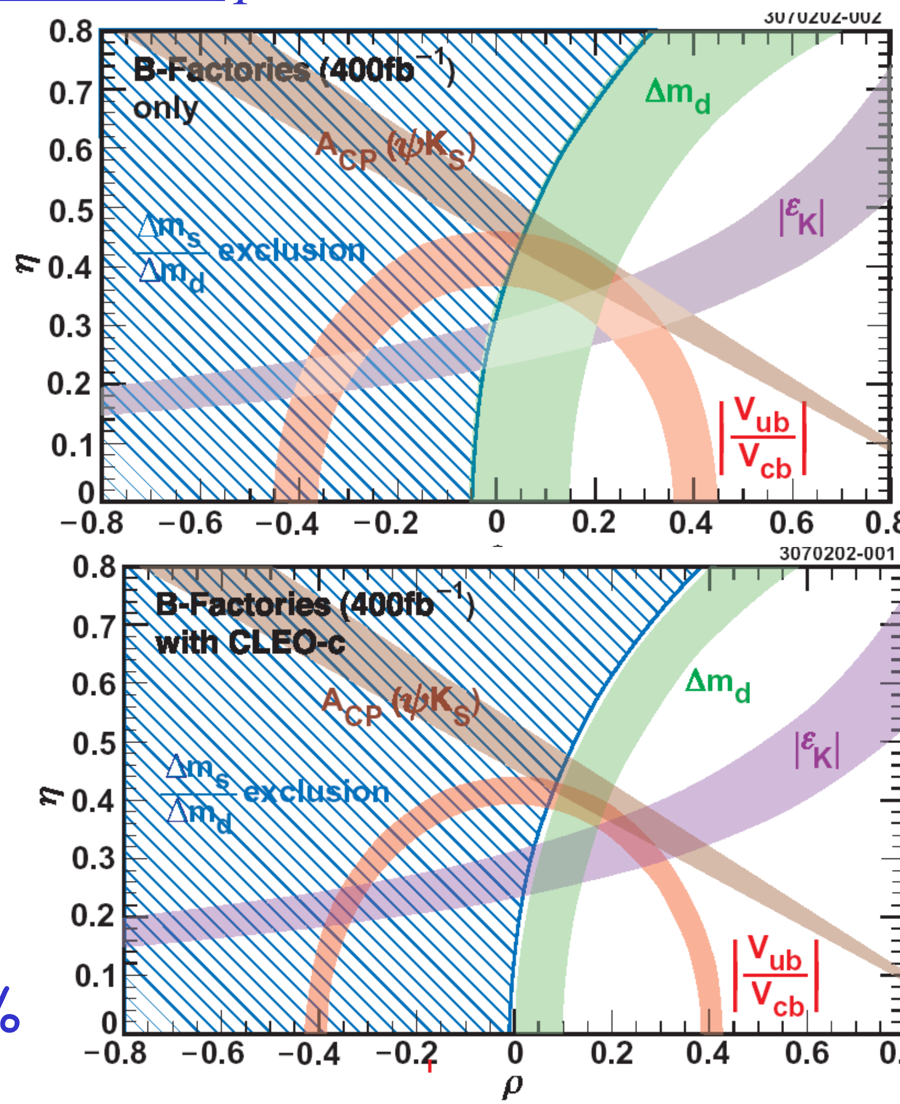
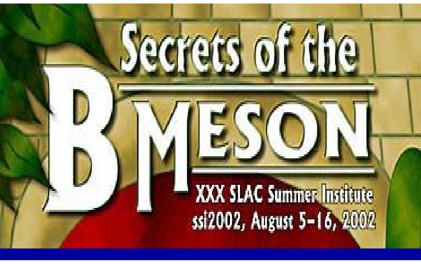
Imagine a world Where we have theoretical mastery of non-perturbative QCD at the 2% level

Theory errors = 2%





CLEO-c: Helping the B Factories & Tevatron Experiments CLEO-c

- Knowledge of absolute charm branching fractions is now contributing significant errors to measurements involving b's. CLEO-c can also resolve this problem in a timely fashion
- Improved Knowledge of CKM elements, which is now not very good.

	Vcd	Vcs	Vcb	Vub	Vtd	Vts
PDG	7%	11%	5%	25%	36%	39%
CLEO-c data and LQCD / B Factory/Tevartron Data & CLEO-c Lattice Validation	1.7%	1.6%	3%	5%	5%	5%

PDG

CLEO-c data and **LQCD**

PDG

B Factory/Tevartron Data & CLEO-c Lattice Validation

(Snowmass E2 WG)

Additional topics At Threshold

- Ψ' spectroscopy (10^{8} decays) $\eta'_c h_c$....
- $\tau^+\tau^-$ at threshold (0.25 fb^{-1})
  - measure m_τ to ± 0.1 MeV
  - heavy lepton, exotics searches
- $\Lambda_c\Lambda_c$ at threshold (1 fb^{-1})
  - calibrate absolute $BR(\Lambda_c \to pK\pi)$
- $R=\sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$
  - spot checks

The Charm Program: Summary

- Powerful physics case
- 1Precision flavor physics – *finally*
- 2 Nonperturbative QCD – *finally*
  3 Probe for New Physics

Direct: Vcs Vcd &
tests QCD techniques
aids BABAR/Belle/
CDF/D0/BTeV/LHC-b
with Vub,Vcb,Vtd,Vts

- 1 and 2 can only be done at threshold CLEO-c is a logical choice now
- Unique: not duplicated elsewhere
- Highest performance detector to run @ charm threshold
- Flexible, high-luminosity accelerator
- Experienced collaboration

- Optimal timing
  - LQCD maturing
  - allows Flavor physics to reach
  - its full potential this decade
  - Beyond the SM in next decade

The most comprehensive
& in depth study of
non-perturbative QCD yet
proposed in particle physics

Probes of charm for new physics

Threshold machines and those operating at Υ(4S) are complimentary

CLEO-c is statistics limited

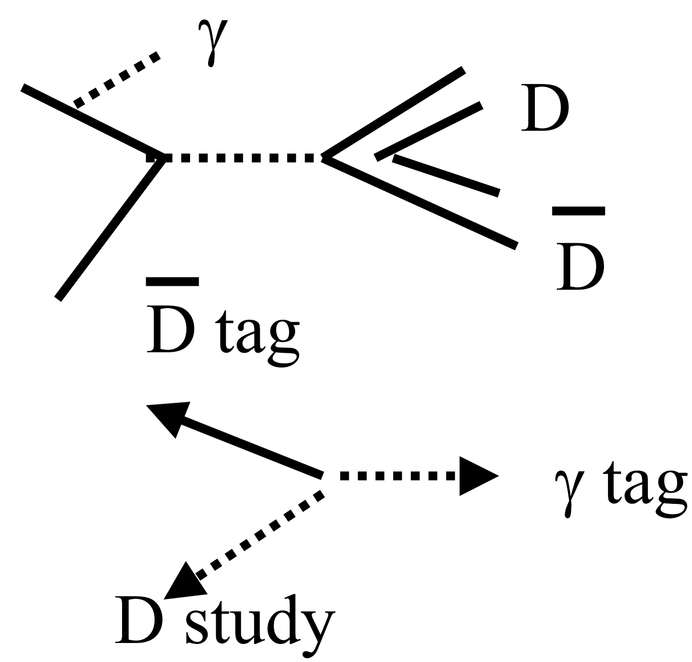
Υ(4S) and hadron machines have very important role to play and will extend the new physics reach considerably

If BESIII is a detector with the same capabilities as BaBar/Belle/CLEO and a luminosity of a few 10^{33} is reached it is a natural next step at the charm threshold

Additional Material

ISR Charm Events at B Factories

Initial State Radiation photon reduces $\sqrt{s}$



Measurement	#events BaBar/Belle 500 fb^{-1}	CLEOc 3fb^{-1}
$D_s^+ \to \mu\nu$	330	1,221
$D^+ \to \mu\nu$	50	672
$D^+ \to K^- \pi^+\pi^+$	6,750	60,000
$D_s^+ \to \phi\pi$	221	6,000

ISR projections made by BaBar show ISR technique is not statistically competitive with CLEO-c. Systematic errors are also much larger.

A first Look for glue rich states at Υ(1S) CM-energy

- Υ(1S) →γX as a preview of J/Ψ →γX
  - The Υ(1S) is also glue rich but…

$$\frac{\Gamma(\Psi\to\gamma X)_{1-2GeV}}{\Gamma(\Upsilon\to\gamma X)_{1-2GeV}} \sim \frac{\sigma_\Psi}{\sigma_\Upsilon}\left(\frac{q_c}{q_b}\right)^2 \frac{\frac{\Psi\to\gamma X_{1-2GeV}}{\Upsilon\to\gamma X_{1-2GeV}}}{\frac{\Psi\to\gamma X}{\Upsilon\to\gamma X}}$$

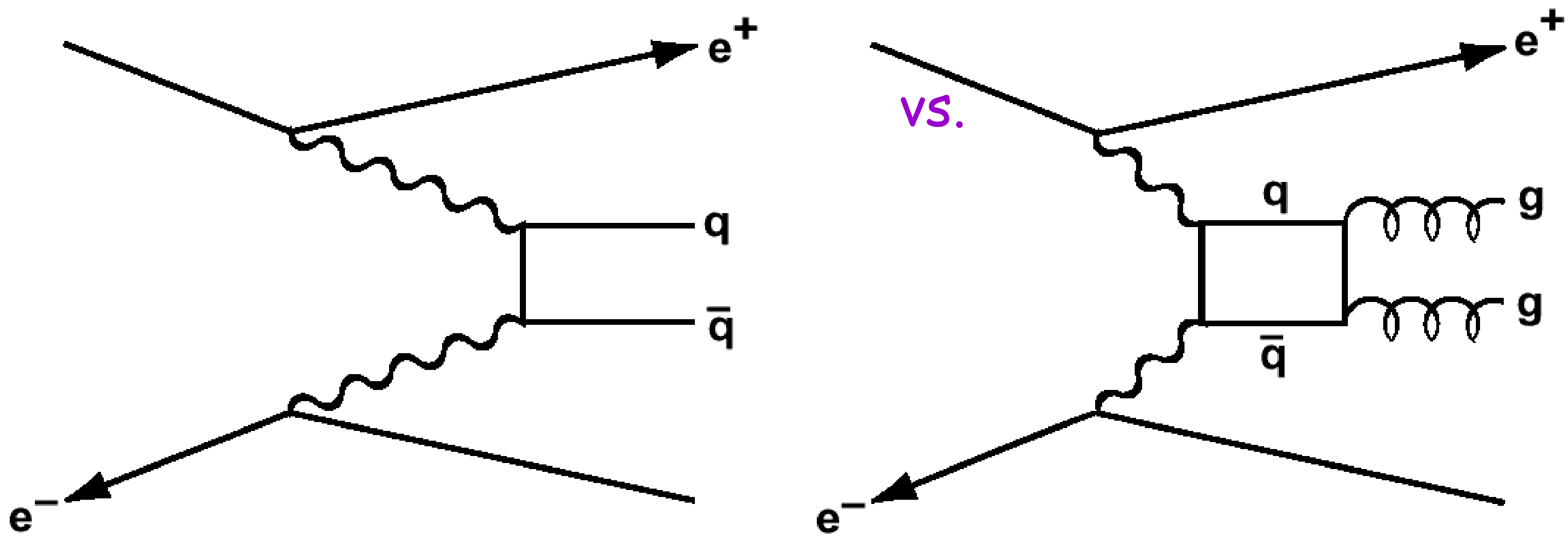
$$\sim 10^2 \bullet 4 \bullet 10 \sim 4000$$

  - No PWA at Υ(1S) but we can show existence of states

A useful check: look at current 2γ data

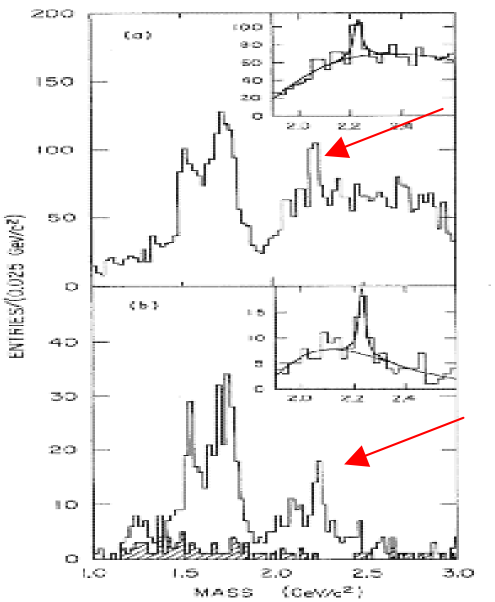
– Anti-search in glue-poor environment

- Eg. $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-X$

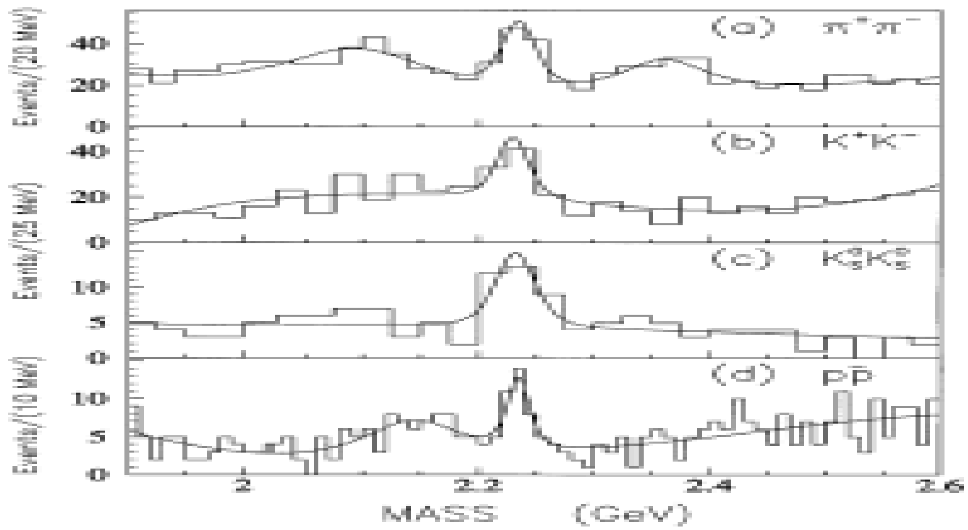


The $f_J(2220)$:A case study

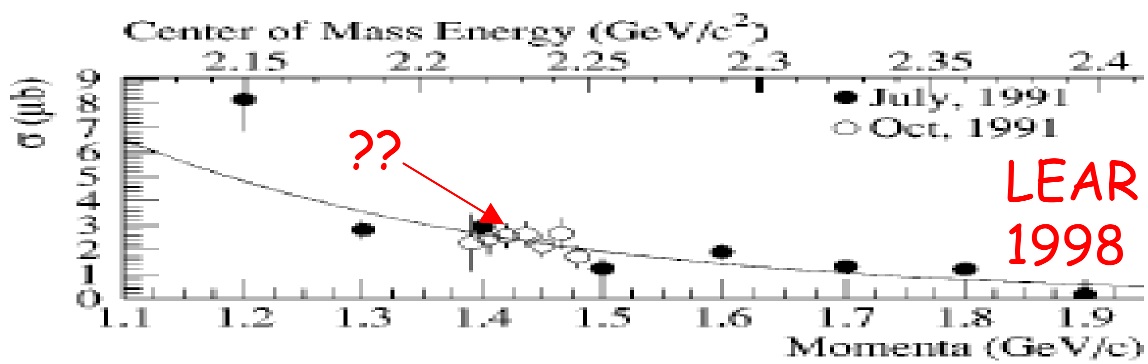
Glueballs are hard to pin down, often small data sets & large bkgds



MARKIII (1986)



BES (1996)

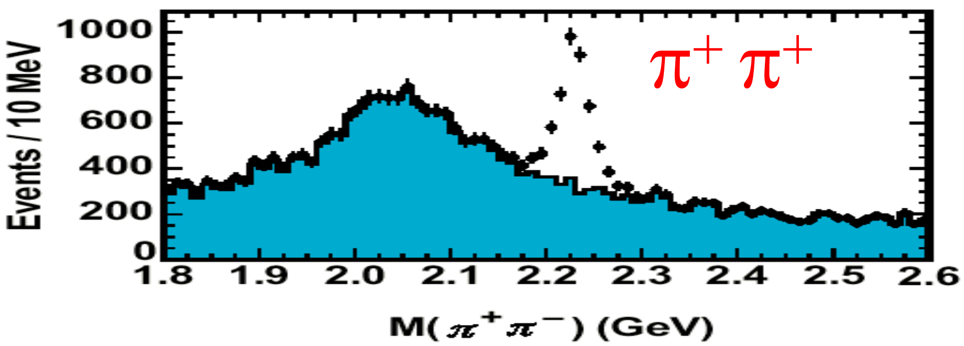


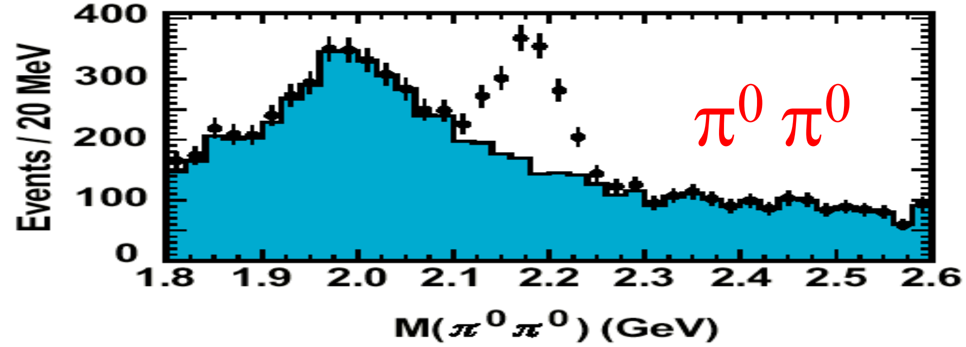
LEAR 1998

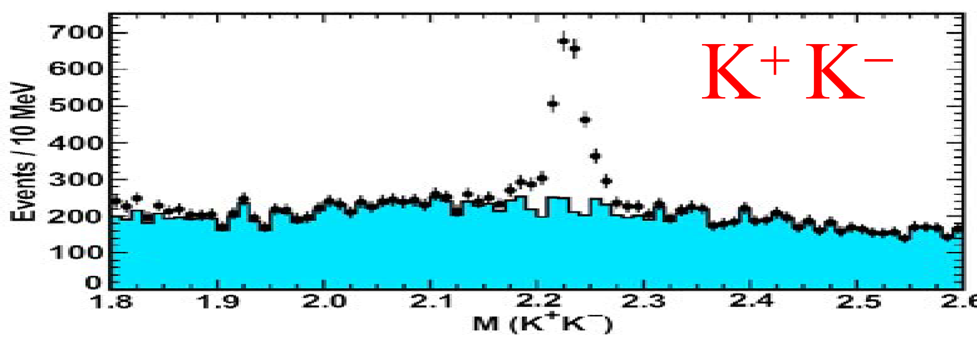
New BES data does not find the $f_J(2220)$! (but not published)

Crystal barrel: $pp \rightarrow K^0{}_s K^0{}_s$

$f_J(2220)$ in CLEO-c?







	BES	CLEO-C
$\pi^+\pi^-$	74	32000
$\pi^0\pi^0$	18	13000
K^+K^-	46	18600
K_SK_S	23	5300
pp	32	8500
$\eta\eta$	–	5000

CLEO-c has *corroborating checks:*

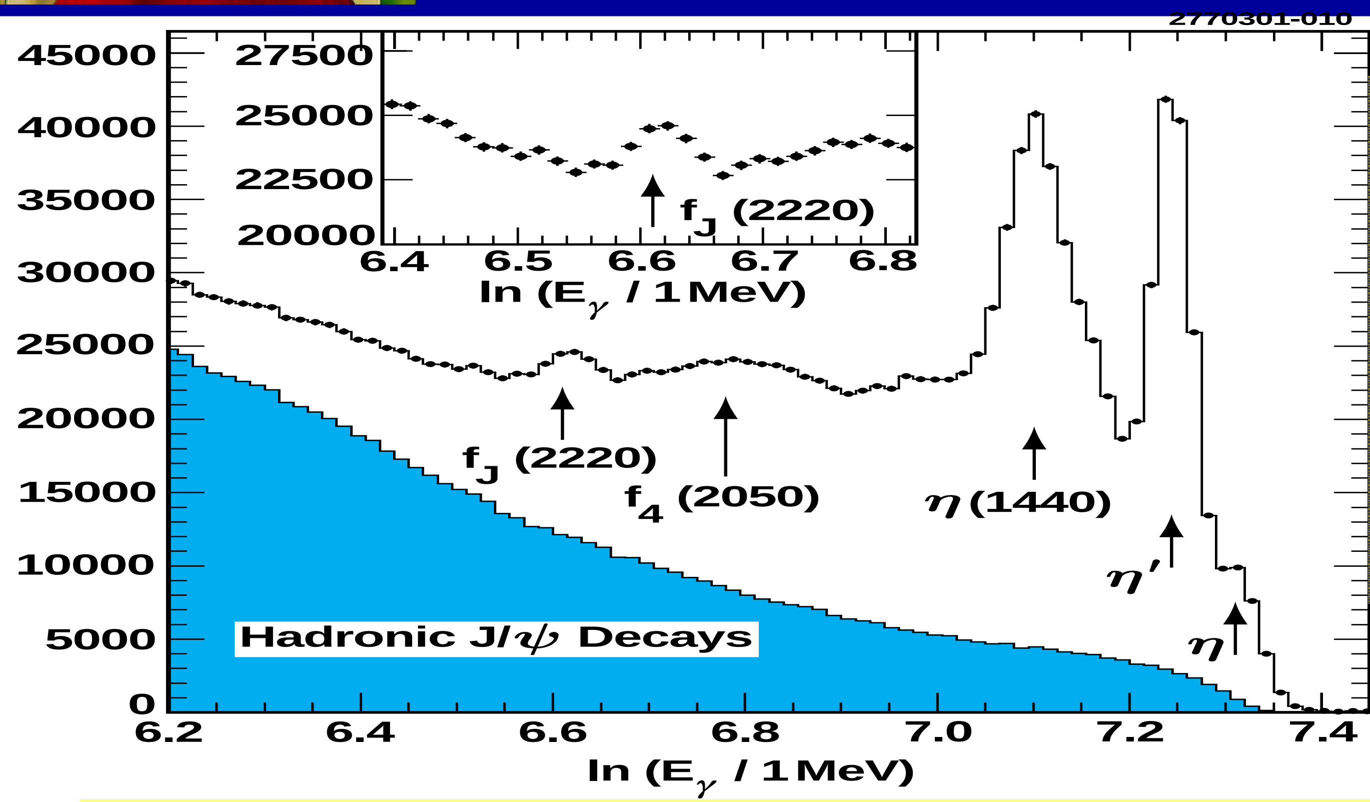
2 Anti-search in Two Photon Data: $\gamma\gamma \to f_J(2220)$:

– CLEO II: $\Gamma_{\gamma\gamma}B(f_J(2220) \to \pi\pi/K_SK_S) < 2.5(1.3)$ eV

– CLEO III: sub-eV sensitivity (new UL to appear ~1 week)

3 – Upsilonium Data: $\Upsilon(1S)$: Tens of events

Inclusive Spectrum $J/\psi \rightarrow \gamma X$



Inclusive photon spectrum a good place to search: monochromatic photons for each state produced

Unique advantages of CLEO-c

+ Huge data set

+Modern 4π detector (Suppress hadronic bkg: $J/\psi \rightarrow \pi^0 X$)

+Extra data sets for corroboration $\gamma\gamma$, $\Upsilon(1S)$:

Lead to Unambiguous determination of J^{PC} & gluonic content

Comparison with Other Expts

China:

BES II is running now.
BES II --> BES III upgrade
BEPC I --> BEPC II upgrade, ~10^{32}
2 ring design at 10^{33} under consideration (workshop 10/01)
} being proposed
Physics after 2006? if approval & construction goes ahead.

BES III complimentary to CLEO-c if new detector is Comparable

Quantity	BES II	CLEO-C
J/psi yield	50M	> 1000M
dE/dx res.	9%	4.9%
K/pi separation up to	600 MeV	1500 MeV
momentum res. (500Mev)	1.3%	0.5%
Photon resolution (100 Mev)	70 MeV	4 MeV
Photon resolution (1000 Mev)	220 MeV	21 MeV
Minimum Photon Energy	80 MeV	30 MeV
Solid angle for Tracking	80%	94%

HALL-D at TJNAL (USA)

γp to produce states with exotic Quantum Numbers
Focus on light states with J^{PC} = 0+-, 1+-, ...
Complementary to CLEO-C focus on heavy states with J^{PC}=0++, 2++, ...
Physics in 2009?

+ HESR at GSI Darmstadt $\bar{p}\,p$ complementary, being proposed: physics in 2007?

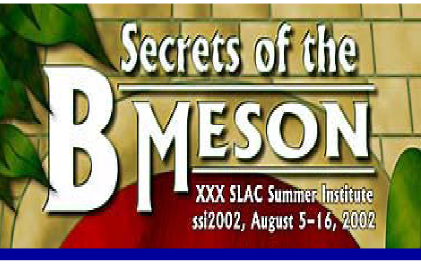
Current Status of exotic QCD bound states

- Experimental
  - Far from clear! Looks messy now due to insufficient statistics
  - List of "glue ball" suspects
    - $\eta(1400)$ region
    - $f_0(1500)$
    - $f_J(1710)$
    - $\xi(2220)$ or $f_J(2220)$
  - Experimental results are contradictory
  - Sorting it out will be challenging!

Run Plan

Resonance	On	Off	Scan	Total	Physics
$\Upsilon(3S)$	1.0	0.1	0.1	1.2	$\Gamma_{ee}\,B_{\mu\mu}$ Triplet D $\eta_b h_b \rightarrow \eta_b \gamma\ \chi_b$
$\Upsilon(2S)$	1.0	0.1	0.1	1.2	$\Gamma_{ee}\,B_{\mu\mu}$
$\Upsilon(1S)$	0.5	0.1	0.1	0.7	$\Gamma_{ee}\,B_{\mu\mu}\,\Gamma_{ee}\,B_{\mu\mu}\,\chi_b$
Total	2.5	0.3	0.3	3.1	

The core run plan is intended to provide as much physics as possible with ~70% of the expected luminosity



Comments on Acp at FOCUS

- Since D^+ and D^- (and similarly D^0 and $\overline{D}^0$) are not produced in equal numbers in FOCUS and E791, these experiments normalize all asymmetries to some known Cabibbo favored mode.

For example: $$A_{CP}(KK\pi) = \frac{\eta(D^+) - \eta(D^-)}{\eta(D^+) + \eta(D^-)}$$

where $$\eta(D^\pm) = \frac{N(D^\pm \to K^\mp K^\pm \pi^\pm)}{N(D^\pm \to K^\mp \pi^\pm \pi^\pm)}$$

- e^+e^- experiments need to worry about, A_{+-}, A_{FB}

Experimental constraints on y at Threshold

1. Time-dependent analyses are not possible, Are time dependent Analyses possible?

Semileptonic: quadratic in x,y: not so sensitive wanted: *linear* in x or y

2. Recalll: (quantum-mechanically) entangled initial state

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

angular momentum (L=1 for ψ(3770))

… so one can measure decay rates for CP-tagged decays

angular momentum

CP quantum number

$$R_\sigma^L = \frac{1}{Br(D^0 \to Xl\nu)} \frac{\Gamma[\psi_L \to (D \to [CP]_\sigma)(D \to Xl\nu)]}{\Gamma[\psi_L \to (D \to [CP]_\sigma)(D \to X)]}$$

… which implies for y

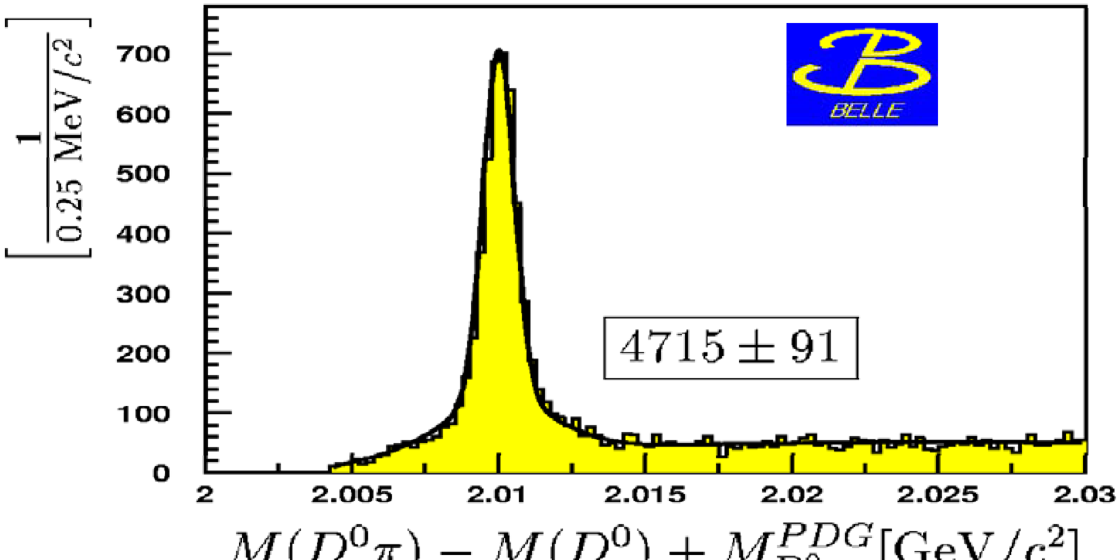
$$y\cos\phi = (-1)^L \sigma \frac{R_\sigma^L - 1}{R_\sigma^L}$$

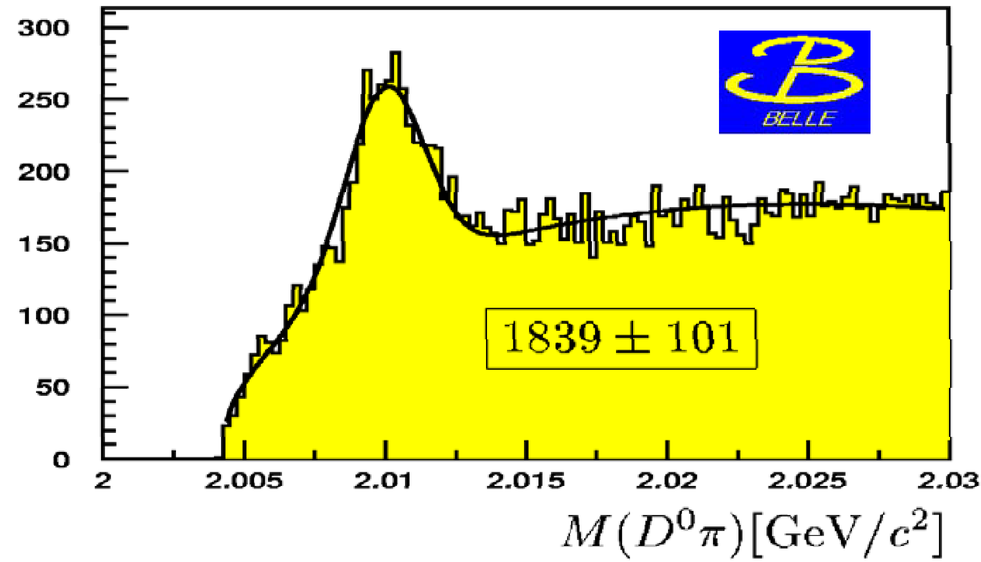
Separately sensitive to y; ϕ=0 in the Standard Model

D. Atwood, A.A. Petrov, hep-ph/0207165

$\delta_{K\pi}$ From $D^0 \to K^0\pi^0$

First measurement!





- Measurement of ratio of $\underline{D}^0$ rates into $K^0{}_L\pi^0$ and $K^0{}_S\pi^0$ can be used to disentangle the CF and DCS amplitudes:
- $K^0{}_L$ content of K^0 and $\overline{K^0}$ is equal
- $K^0{}_L$ content of K^0 and K^0 is opposite in sign to $K^0{}_S$
- Get DCS rate from interference between the two

DCS: $D^0 \to K^0\pi^0$

CF: $D^0 \to \overline{K}^0\pi^0$

$$A = \frac{\Gamma(D^0 \to K^0_S\pi^0) - \Gamma(D^0 \to K^0_L\pi^0)}{\Gamma(D^0 \to K^0_S\pi^0) + \Gamma(D^0 \to K^0_L\pi^0)} = 0.06 \pm 0.05 \pm 0.05$$

Very important measurement!

Uncertainty still too large to limit d_{Kp}, but very intersting with 500 fb^{-1}

Phase ambiguity

What if $\delta = 40°$, the estimated maximum of the model of *Falk, Nir & Petrov (99)*? We see **some overlap...**

CLEO and FOCUS would be more consistent if $\delta > 90°$...

Bergmann, Grossman et al(00).

My opinion: the errors are too large to draw any strong Conclusion at this time.