# Flavor Physics and the Strange Beauty Clock

**"There is no excellent beauty that hath not some strangeness in the proportion"**
**(Francis Bacon via Murray Gell-Mann)**

Particle clocks- elegant demo of quantum superposition,
long story, 1955-2008

**Bs is third (of four) known "clocks"**
Culmination of ~20 year search at CERN, SLAC, Fermilab
Demanding measurement – 3000 GHz (± 0.7 %)

Glimpse into electroweak flavor physics
$2^{nd}$ order weak FCNC ($10^{-2}$ eV)
invitation to "new physics"

Particle clocks (K0, B0, Bs) tell time
and also direction of time (CP violation)

Today- survey meson mixing, some history,
flavor physics and CP.

Chicago Tribune

# METRO

WEST

TUESDAY
SEPTEMBER 26, 2006

# Quite a catch for Fermilab

2nd major Tevatron discovery after top quark

Like top, only possible at Tevatron

Top and strange beauty mixing strongly linked

Orbach- recommended!

*'This remarkable tour de force details with exquisite precision how the antiworld is tied to our everyday realm.'*

—Raymond Orbach, undersecretary for science with the U.S. Department of Energy

## Lab findings being called a triumph

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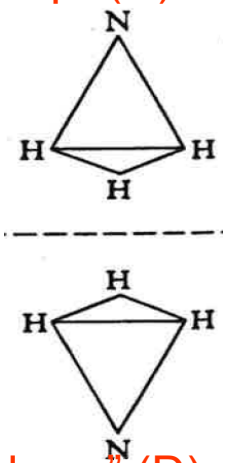
# Mixing in quantum mechanics- $NH_3$ Maser inversion lines

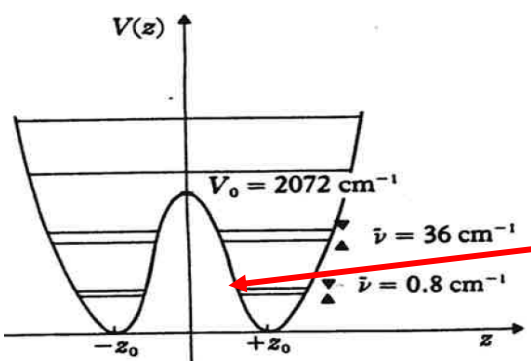
"up" (U)




"down" (D)

- Degenerate "up" and "down" levels "U", "D"
- Barrier penetration allows U to jump over to D
- => Non-degenerate mixed eigenstates U ± D

$$\begin{bmatrix} E & \delta\nu \\ \delta\nu & E \end{bmatrix}\Psi = \lambda\Psi \qquad \begin{aligned} \Psi^{+} &= U + D \sim e^{i(E+\delta\nu)t} \\ \Psi^{-} &= U - D \sim e^{i(E-\delta\nu)t} \end{aligned}$$




D ⟷ U

- Eigenstates $\psi^+$ and $\psi^-$ are $45^0$ admixtures of U, D
- $\psi^+$ and $\psi^-$ propagate with different phases, $\pm\delta v$
- U= $\psi^+ + \psi^-$ oscillates to D= $\psi^+ - \psi^-$ as $\cos(\delta v\, t)$
- NH3 maser frequency $\delta v$ = 23 G Hz
- Separation of (heavy) $\psi^+$ state by Stark effect=>maser

Analogous to separation of heavy from light meson eigenstates via lifetime.

# Meson Clocks- particle-antiparticle mixing

Analogous to NH3 inversion lines, start with exactly degenerate neutral meson- antimeson states (equal mass and width)

Added complexity from decay width:

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

Eigenstates are ~$45^0$ admixtures of (meson ± antimeson) with mass and width splittings $\Delta M \sim 2|M_{12}|$, $\Delta\Gamma \sim 2|\Gamma_{12}|$

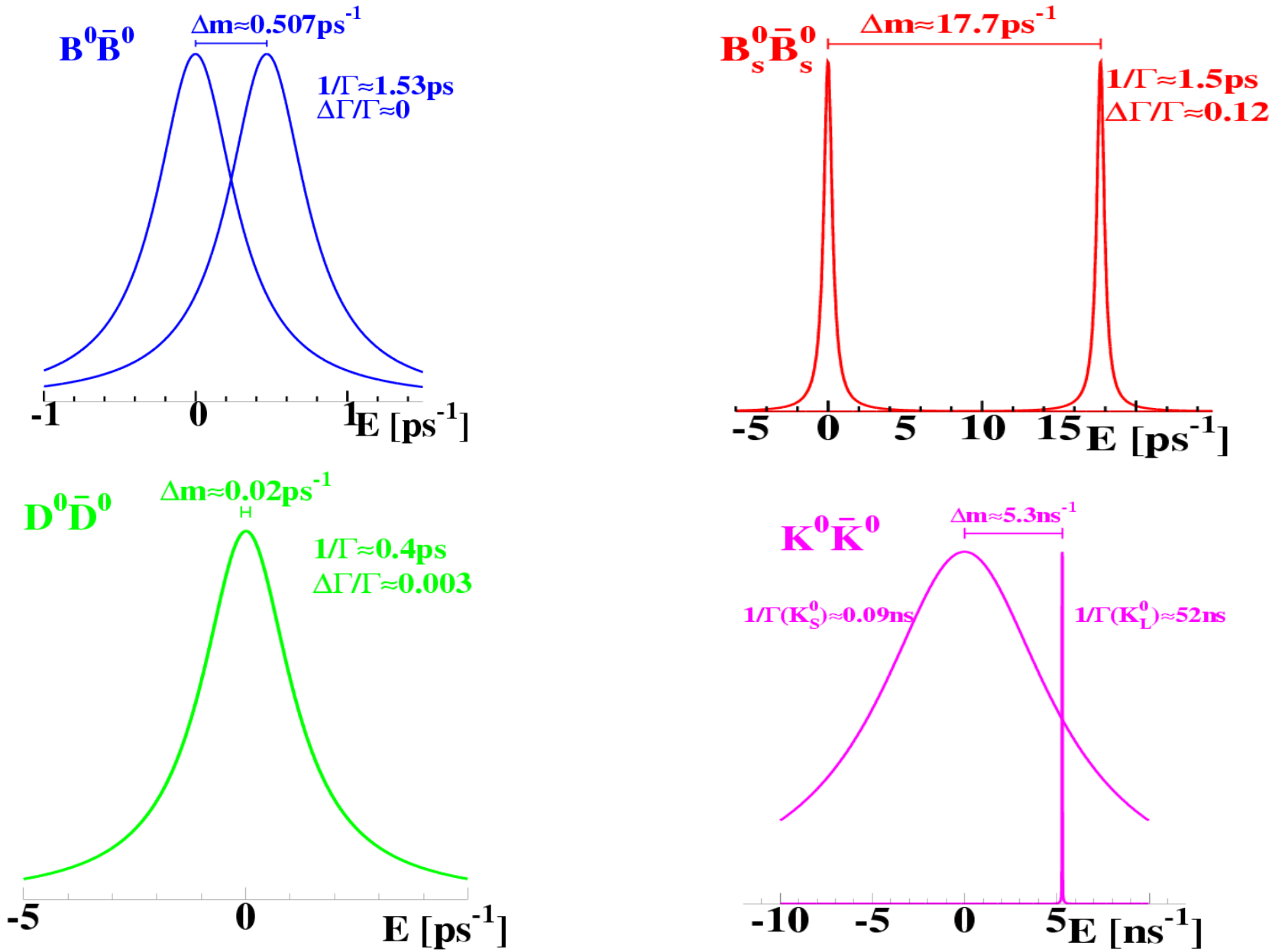
Exactly four systems:

$K^0 - \overline{K}^0$ (1958)
$B^0 - \overline{B}^0$ (1987), UA1, ARGUS
$B_s^0 - \overline{B}_s^0$ (2006), Tevatron
$D^0 - \overline{D}^0$ (2007), BaBaR, Belle, CDF

B factories have $B^0$ and charm

Hadron colliders have $B_s$ as well

# Neutral Mesons



# Early days of flavor

## The "new" (strange) particles: much confusion

(1) "theta-tau" puzzle: charged K's decay to even and odd parity final states (2pions, 3 pions) "impossible" ?????

(2) Strong production but weak (long-lived) decays ?????

(3) Isospin: K-mesons "must" behave like pions, e.g.

$$(\pi^- \ \pi^0 \ \pi^+) \sim\sim (K^- \ K^0 \ K^+) \text{ ?????}$$

Hmm, why does $K^0$ decay weakly (to $\pi+ \ \pi-$), unlike $\pi^0$ ??

# Break-through, Gell-Mann and Pais (1954)

(1) Regroup kaons as doublets:

$$\begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \begin{pmatrix} \overline{K}^0 \\ K^- \end{pmatrix}$$

$K^0 = C\,\overline{K}^0$, distinct particle-antiparticle (opposite strangeness)

(2) Eigenstates are $45^0$ admixtures

$K_S = K0 + \overline{K0}$ even C, decays to 2 pions (= the observed "$\theta^0$" )
$K_L = K0 - \overline{K0}$ odd C, decays to 3 pions with longer life (prediction)

(3) Expect mass and width splitting and expect oscillations between K0 and $\overline{K0}$ with frequency given by $\Delta m$.

(4) Great leap forward, sets paradigm for 50 years of flavor physics:
-Flavor- antiflavor pair production in strong and neutral EWK ($\gamma$-Z)
-Meson mixing repeated for $K^0$, $D^0$, $B^0$, $B_s^0$
-Flavor (u, d, s, c, b, t) changed only by EWK CC ($W^{\pm}$)

# Experimental confirmation of Gell-Mann Pais idea

**K0 mixing 1957-1958 (Baldo-Ceolin et al., plus others..)**

**produce $K^0$ via K+ beam, observe subsequent interactions consistent with anti-$K^0$/ K- interactions**

**Second long-lived state (KL) 1957 (Lande, Lederman, Chinowsky)**

"It is by no means certain that, if the complex phenomena concerning the neutral K mesons were known without the benefit of the Gell-Mann-Pais theory, we could even today correctly interpret the behavior of these particles. That their theory, published in 1955, actually preceded most of the experimental evidence known at present, is one of the most astonishing and gratifying successes in the history of the elementary particles..."

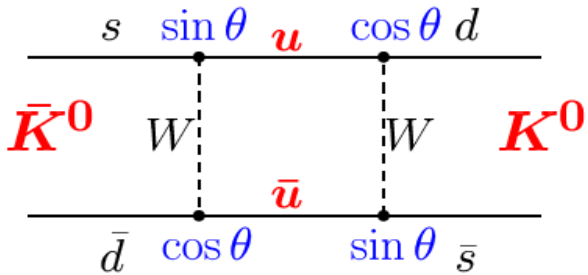
(**Good et al., 1961**)

"This is one of the greatest achievements of theoretical physics. It is not based on an elegant mathematical hocus-pocus such as the general theory of relativity, yet the predictions are just as important as, say, the prediction of positrons. Especially interesting is the fact that we have taken the principle of superposition to its ultimately logical conclusion. Bohm thought the principles of quantum mechanics were temporary and would fail to explain new phenomena. But it works. It does not prove it right but for my money the principle of superposition is here to stay!"

(**Feynman, 1961**)

# $\Delta M(K^0)$ Theory vs Experiment

$M_{12} =$



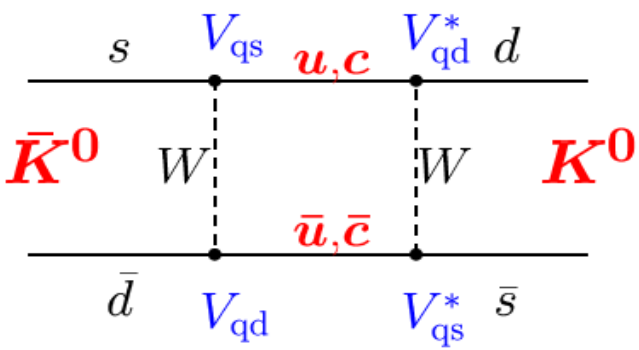

$+ \sum_f \frac{A(K^0 \to f) A^*(\bar{K}^0 \to f]}{M(K^0) - E_f}$

**π π intermediate states**

$$\Delta M = 2|M_{12}| \simeq \frac{4M_W^2 \cos^2\theta_C}{3\pi m_\mu^2} \Gamma(K^+ \to \mu^+ \nu_\mu)$$

$$\Delta M \simeq (5.3ns^{-1})_{exp} \times \frac{M_W^2}{(1.5)^2}$$

**"GIM" mechanism- add charm quark to loop**




$$V = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_c \end{pmatrix}$$

$$\Delta M \simeq (5.3ns^{-1})_{exp} \times \frac{m_c^2 - m_u^2}{(1.5)^2}$$

- **ΔM(K) predicted both existence and mass of charm**

- **But, <u>Experimental Meson Spectroscopy</u> April 1974**

  **"There are just three possibilities:**

  **1. Charm is not found, and I eat my hat**

  **2. Charm is found by hadron spectroscopers, and we celebrate**

  **3. Charm is found by outlanders, and you eat your hat." (Glashow's talk)**

  **"We conclude that if charmed particles are produced in pp collisions (in bubble chamber)either their mean lives must lie below the expected range or their masses must exceed 4 GeV." (Ferbel's reply)**

- **November 1974, accidental discovery of J/ψ by outlanders at SLAC and BNL, charm quark is long-lived, mass~ 1.5 GeV**

# CP Violation

Aside: Gell-Mann used C-conjugation only. Since P-violation (cf theta-tau puzzle) is established, the relevant symmetry for EWK interactions is now **CP**

**Christensen et al. (1964): CP violation in decay of long-lived eigenstate**

**Either CP is violated in the decay K0->π π, or eigenstates are not CP pure**

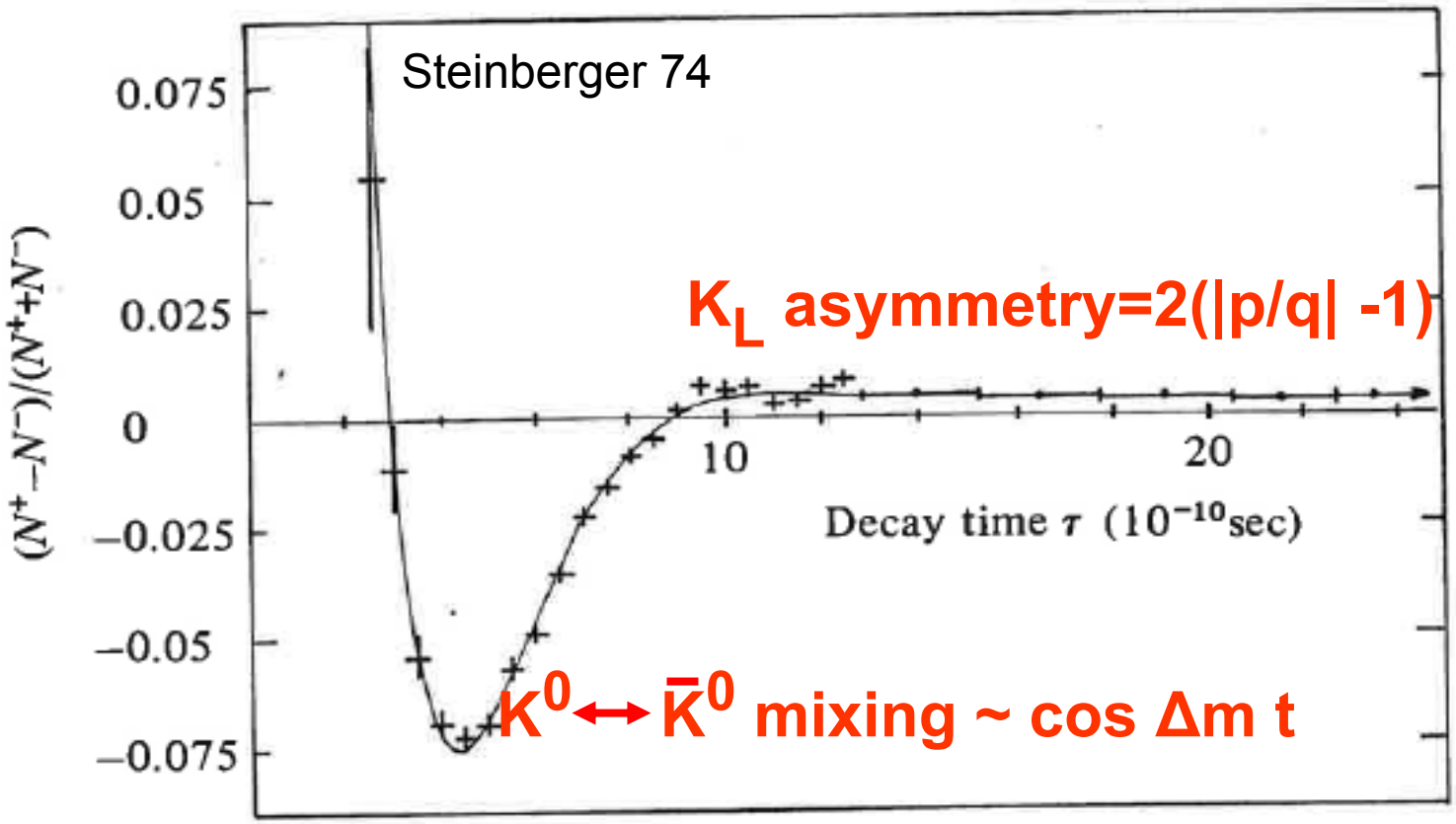
$$K_S = K^0 + \overline{K}^0 \rightarrow \pi\pi \text{ (CP conserving)}$$
$$K_L = K^0 - \overline{K}^0 \rightarrow \pi\pi \text{ (CP violating)}$$

$$K_S = pK^0 + q\overline{K}^0$$
$$K_L = pK^0 - q\overline{K}^0, \quad |p/q| > 1 \text{ implies lepton asymmetry}$$
$$K^0 \rightarrow \mu^+, \overline{K}^0 \rightarrow \mu^-$$

**Lepton asymmetry (3.2 $10^{-3}$= |p/q|-1) reveals excess of matter over antimatter in both eigenstates, explains $K_L$->π π**

**30 years until $10^{-6}$ CPV seen in direct decay amplitude (ε'/ε).**

# Lepton asymmetry in K0 mixing

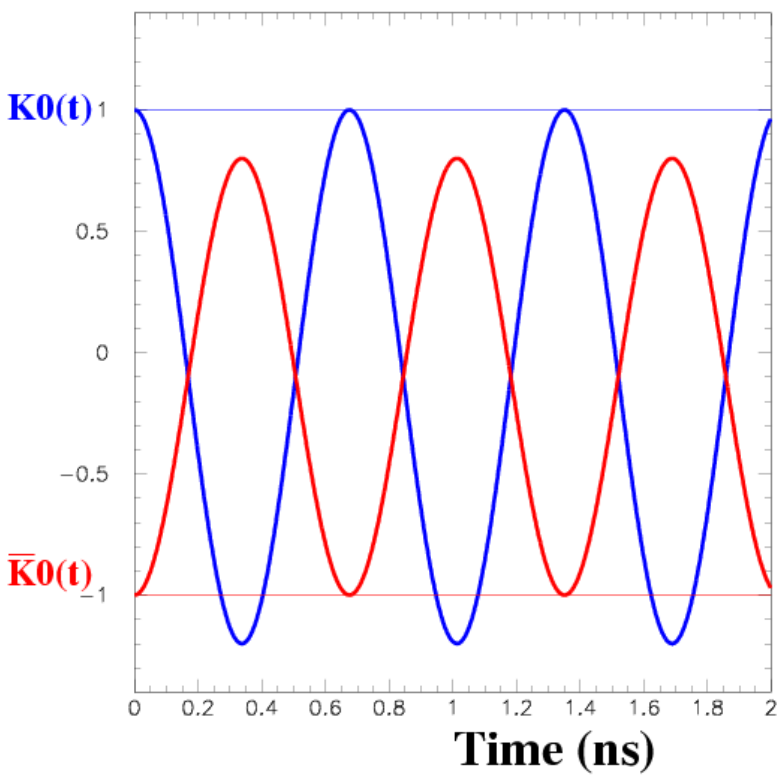


# Interesting consequences of |p/q|> 1

**Oscillation amplitude is different for**

$K^0 \to \bar{K}^0 = |p/q|^2 [1 - \cos \Delta m t]$
$\bar{K}^0 \to K^0 = |q/p|^2 [1 - \cos \Delta m t]$

**=>Manifest violation of time reversal invariance**




**This is same effect as lepton asymmetry in KL decay**

Beautifully confirmed by CPLEAR experiment using tagged $K^0, \bar{K}^0$ in $\bar{p}p \to K^0 K^- \pi^+, \bar{K}^0 K^+ \pi^-$

**In B0, Bs systems expect tiny effect**

$|p/q|-1 = \mathrm{Im}\Gamma_{12}/M_{12} = 2\mathrm{Re}\varepsilon \sim 0,$

where both

$\Delta\Gamma/\Delta M \ll 1$ and $\arg(\Gamma_{12}/M_{12}) \sim 0$

# Interpretation of CPV

Superweak, milliweak, millistrong, dirt in carburetor?

Why such a tiny effect?

"The precise value of the magnitude of ε is not a matter of crucial theoretical importance, since there is no model in which one would anyhow know how to compute this quantity accurately- indeed, in most models a CP-violating parameter is introduced phenomenologically, to be adjusted to requirements."

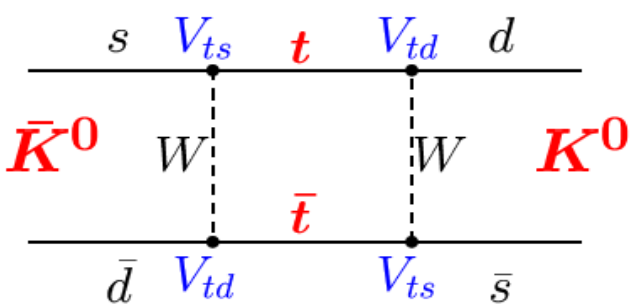
S.B. Treiman, 1968

M. Kobayashi and T. Maskawa 1973,

"An interesting feature of the 6-quark model is that CP…"

Charm is not enough, add third family:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$




$\Rightarrow$ **Kaon mixing predicts charm,**

$\Rightarrow$ **CPV in mixing predicts top and beauty**

# Cabibbo, Kobayashi, and Maskawa

" Kobayashi and Maskawa had known about Niu's strange event and interpreted it as the charm particle. They had no resistance going from a model with 4 quarks to one with 6 quarks. Taking the view that field theory had something to do with nature Weinberg's model written in terms of quarks was taken very seriously. The fact that CP violation must be introduced within this framework came naturally to them." (Sanda,Leonfest 1997)

CKM

# Role of flavor- Kobayashi Maskawa model

Recall QCD gluons and EWK neutral γ/Z do not care about flavor except through (hyper) charge

Only $W^{\pm}$ CC changes flavor- a residual of EWK symmetry breaking and charged Higgs.

Flavor dependence is encoded in the Yukawa couplings of the three families of quarks with the Higgs ($H^0$, $H^+$) doublet.

Mass eigenstates are labelled by the usual "flavors" u, d, s, c, b, t with masses given by

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$H^0$ Yukawa couplings- $m_t : m_c : m_u \sim 1 : 1/150 : 1/150^2$

$m_b : m_s : m_d \sim 1 : 1/25 : 1/25^2$

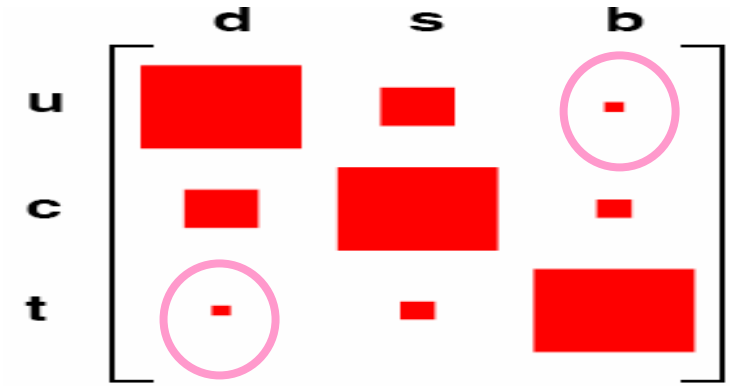
$H^+$ Yukawa couplings relate "family" eigenstates to mass eigenstates via unitary rotations that differ for up and down type quarks.

$$\begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} = M_u \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = M_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V_{CKM} = M_u M_d^{\dagger}$ encodes "mismatch between up and down family membership

# Role of flavor

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




Relative sizes of V(up->down)

**CKM rotation of mass-flavor states**

In principle each |Vud| corresponds to CC semileptonic decay A(u->d l $\nu$)

Unitary 3X3 $V_{CKM}$ defined by one complex phase that encodes CPV, plus 3 Cabibbo angles

In our $V_{ckm}$, complex phase is large only in V(td) and V(ub)

u->d, c->s, t->b ~1

u->s, c->d ~1/5 (=sin$\theta_c$)

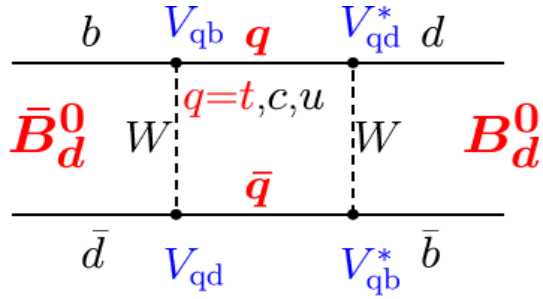
c->b, t->c ~1/20

t->d, u->b ~1/100

CPV in this $V_{ckm}$ is tiny, 3 $10^{-4}$ of maximal, does not explain baryon to photon ratio (Huet+Sather 95)

# Role of flavor- unitarity triangle

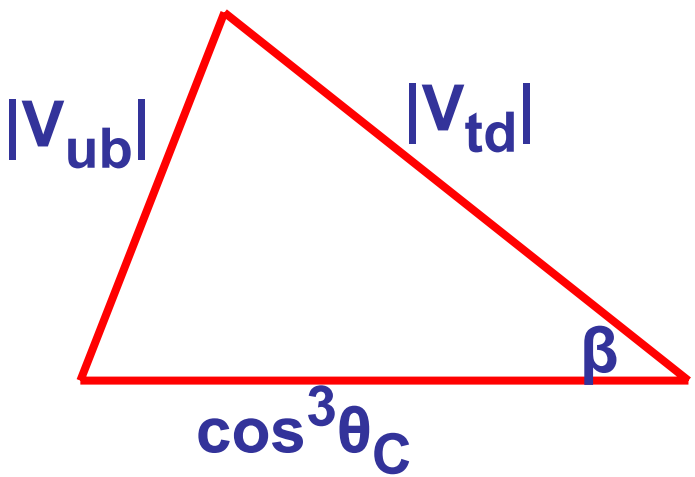
$M_{12}(B^0)=$




$$M_{12}(B_d) \propto m_t^2 m_{B_d} |V_{td}|^2 f_{B_d}^2 e^{2i\beta}$$

$M_{12} \sim (m_t^2 - m_{u,c}^2)$ by CKM unitarity

$2\beta = \arg(V^2_{td}) = \arg(M_{12}) = \arg(p/q) \sim 45^o$




In KM model, the phase β is the same as in the tiny CPV top loop contribution to $p/q(K^0)$

Is it? Test via unitarity triangle $V^\dagger_{ckm} V_{ckm} = 1$

Note: $V_{td}$ and $V_{ts}$ are the only $V_{ij}$ that cannot be measured with semileptonic decays, but only via $M_{12}$

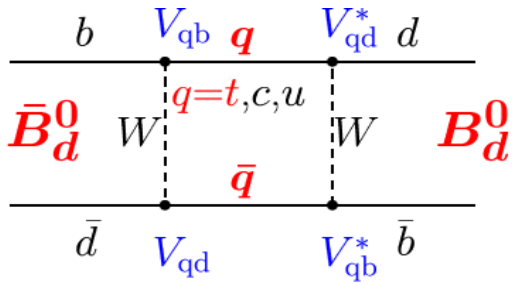
$\Rightarrow$ Precision measurement of $|V_{td}|e^{i\beta}$

Big problem: QCD corrections in $M_{12}$ from $f_B$ decay constant (B->μν) and vacuum insertion bag parameters carry large theoretical uncertainties.

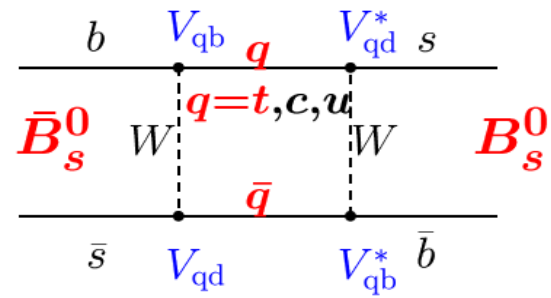
QCD uncertainties affect $|M_{12}|$ (not β)

# Precision determination of $V_{td}$

$M_{12}(B^0)=$




$M_{12}(B_s)=$



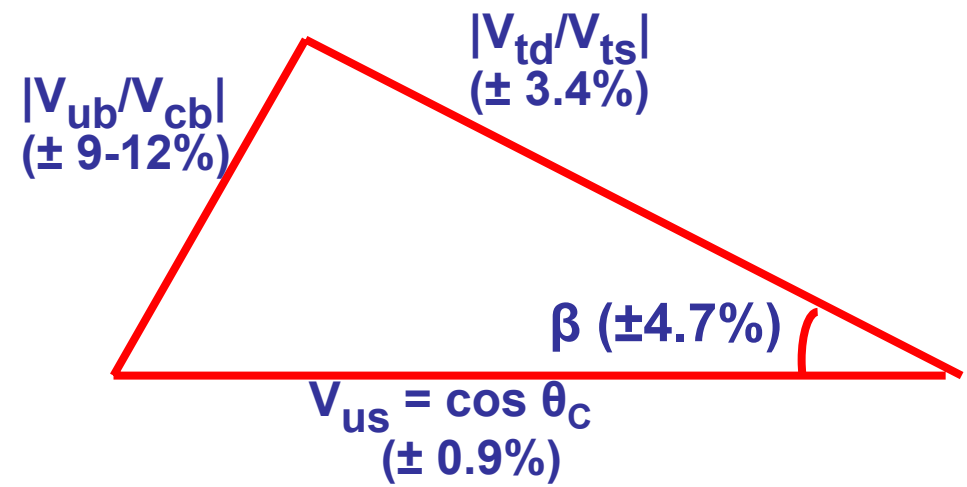

$$M_{12}(B_d) \propto m_t^2 m_{B_d} |V_{td}|^2 f_{B_d}^2 e^{2i\beta}$$
$$M_{12}(B_s) \propto m_t^2 m_{B_s} |V_{ts}|^2 f_{B_s}^2 e^{2i\beta_s}$$

**SU3 QCD symmetry: interchange of s and d spectator quarks gives ~same QCD corrections - s and d quarks are light on the b-quark mass scale.**

**=> Strong interaction uncertainties in $f_B^2$ largely cancel in the ratio**

$$\frac{\Delta m_d}{\Delta m_s} = \xi^2 \frac{m_{B_d}}{m_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

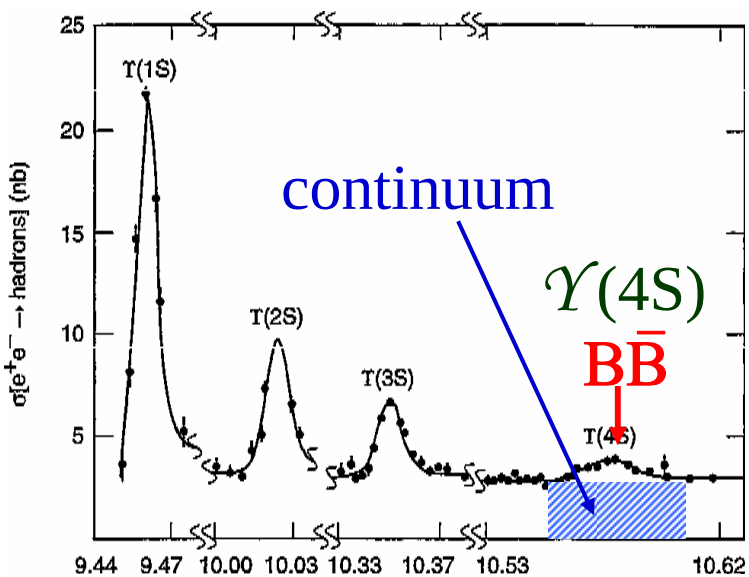
**$\xi$ = 1.21±0.04 lattice QCD**




**Uncertainties achieved are as of 2007 with Bs mixing and 900M B factory events**

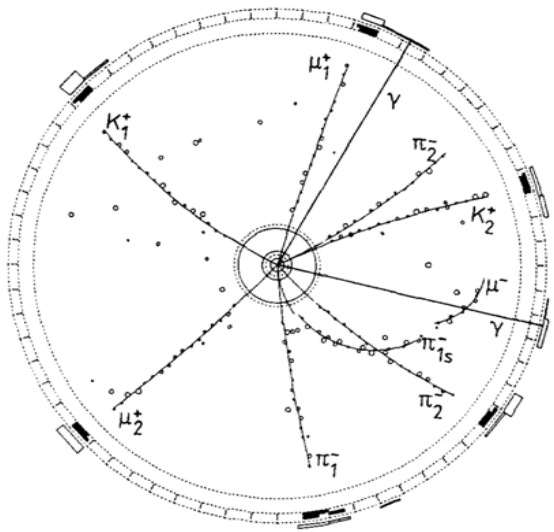
# B0 Mixing ($\Delta M_d$)

- Like-sign muon pairs(UA1 1987) => $B^0$ and $B_s$ mixing
- First clear observation from ARGUS running on U(4S) 1987 (20th anniversary party Nov. 2007)
  - Time average mixing $e^+e^- \to B^0\bar{B}^0 \to B^0B^0 \to l^\pm\, l^\pm\, X$
  - $\sim\int dt\, \cos(\Delta M\, t)e^{-\Gamma t}$ where "t"=t2- t1 (Bose stats)

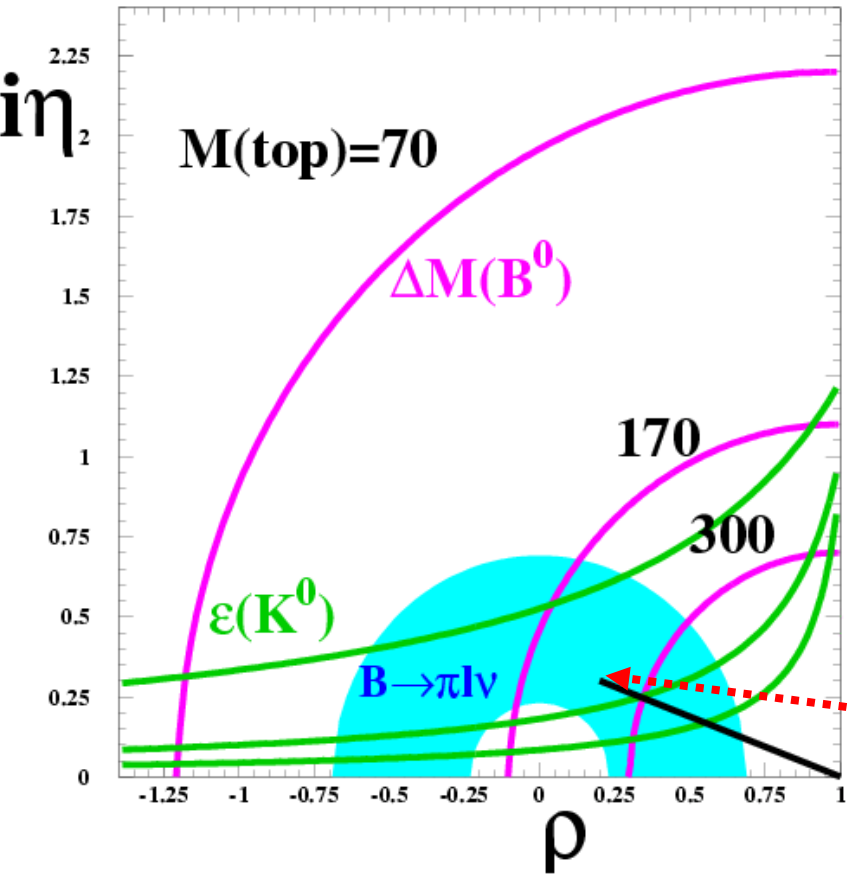



**Search and Discovery 1987-**

"Neutral B mesons show surprisingly large flavor mixing"



# Rosner, Yuan, Kim (1990): Role of (unknown) Top mass




**Reconstruct CKM triangle**

**Input= Re$\varepsilon$(K), b->ul$\nu$, $\Delta M(B^0)$ from time average CLEO/ARGUS measurements**

**Large theoretical uncertainties, but clear evidence that Mtop is larger than $M_W$**

**Current determination from all sources with $M_{top}$=170 GeV**

**=> B0 mixing shows that top mass much larger than expected**

# Mixing asymmetries for $B^0$ and $B_s$ mesons

- At former symmetric (4S) B factories, $B^0\,\overline{B}^0$ are produced at rest
  - No time measurement (require asymmetric PEP2, KEKB)
  - $B^0\overline{B}^0$ pairs evolve coherently (Bose statistics, P wave)

- At Tevatron and former Z factories (LEP, SLC) b-$\overline{b}$ production
  - b, $\overline{b}$ -> 40% $B^0$, 40% $B^+$, 10% Bs, 10% $\Lambda_b$, with b and $\overline{b}$ uncorrelated
  - In absence of $B^0$/Bs mixing, observed B hadron pairs=opposite flavor

- $|p/q| \sim 1$, lifetime difference $\Delta\Gamma/\Gamma<1\%$ ($B^0$), ~15% (Bs) (cf 200% $K^0$)
  - Sets up the basic asymmetries:

**Mixing asymmetry, flavor specific final state ($D^+\mu^-\nu$, $D^+\pi^-$ etc)**

$$B^0(t) = (1+\cos\Delta mt)|B^0> +(1-\cos\Delta mt)|\overline{B}^0>$$
$$\overline{B}^0(t) = (1+\cos\Delta mt)|\overline{B}^0> +(1-\cos\Delta mt)|\overline{B}^0>$$

$$\boxed{\frac{(B^0\to l^+X)-(\overline{B}^0\to l^-X)}{(B^0\to l^+X)+(\overline{B}^0\to l^-X)} = \cos\Delta mt}$$

**CPV asymmetry,"f" = CP self conjugate ($J/\psi\, K^0$, $J/\psi\, \varphi$, $\pi^+\pi^-$)**

$$|B^0\to f(t)>= 1+\sin 2\beta\sin\Delta mt$$
$$|\overline{B}^0\to f(t)>= 1-\sin 2\beta\sin\Delta mt$$

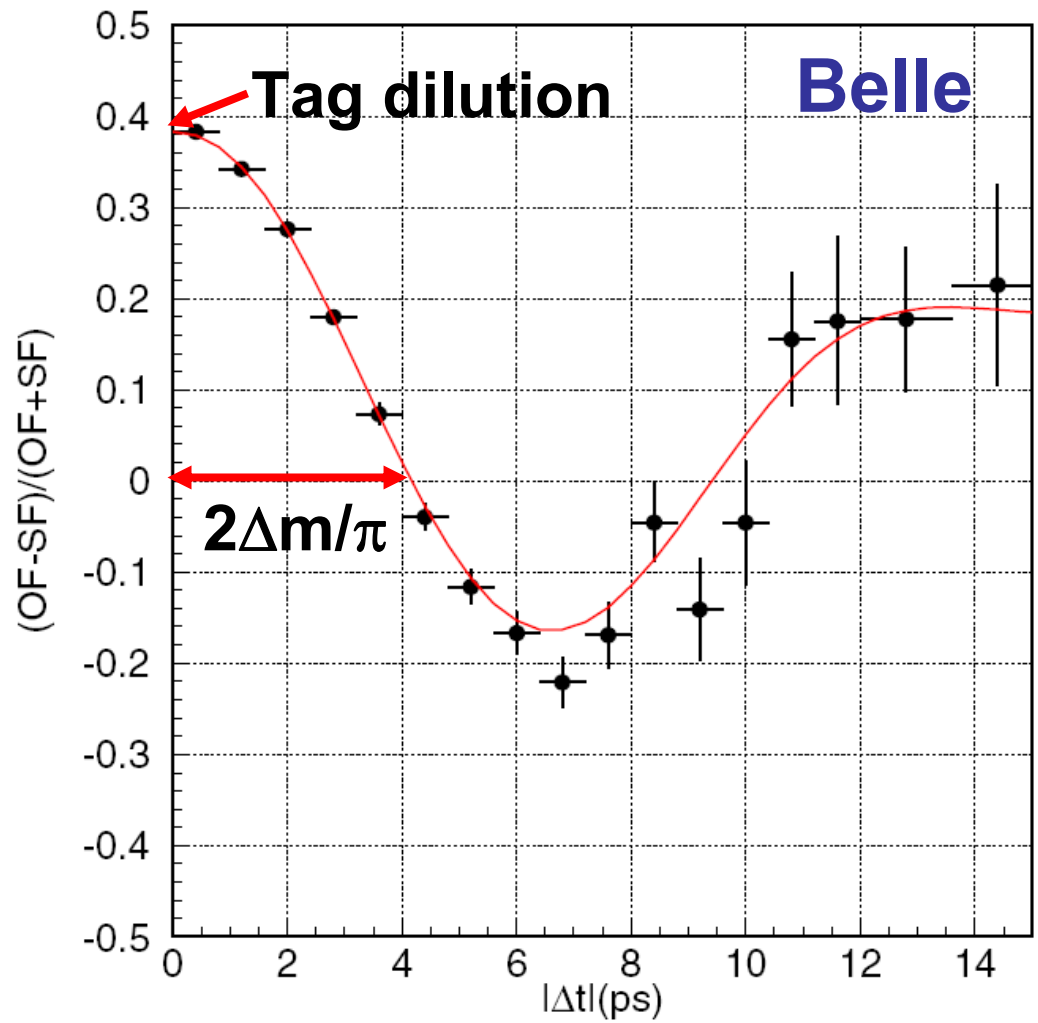
$$\boxed{\frac{(B^0\to f)-(\overline{B}^0\to f)}{(B^0\to f)+(\overline{B}^0\to f}) = \sin 2\beta\sin\Delta mt}$$

# B0 Mixing- Time Dependent $\Delta M(B^0)$

1. Identify $B^0$ at birth =>"flavor tagging"
2. Identify $B^0$, $\overline{B}^0$ at death
3. Asymmetry given by

   $B^0 - \overline{B}^0 = D \cos\Delta mt$

1. Tag dilution "D" defined D=RS -WS. Here tag is given by flavor of the "other" $B^0$. D=0 for "phase of the moon" tag (RS=WS)
2. "Away side tags" from the "other $B^0$" include lepton and $K^+$ signatures.
3. Calibrate D from t=0 asymmetry



# Time Dependent $B^0$ Mixing

- "Away side tags" at Tevatron and LEP/SLD:
  - Second b-jet has opposite flavor
  - Use lepton and kaon charge in opposite jet, also simply the overall jet charge (from 40% $B^+$ fraction)

- Tag dilution D Calibrated from t=0 $B^0$ asymmetry
  - Opposite side tags are the same for $B^0$, $B^+$, $B_s$ signals

- Figure of merit= $\varepsilon D^2$ where $\varepsilon$= tag efficiency
  - N= sample size means $N\varepsilon D^2$= effective sample size.
    - At CDF, $\varepsilon D^2$=0.018 for away side tags (cf 0.30 at PEP/KEK)
    - => 1000 signal events are equivalent to 18 events in mixing measurement.

# B0 mixing- "same side tags"

## Basic idea:

In $D^0$ mixing one tags flavor of $D^0$ using production $D^{*+} \to D^0 \pi^+$

tag $B^0$ flavor using $B^{**+} \to B^0\pi^+$ (also $B^{**0} \to B^+ \pi^-$ to calibrate) (ALEPH)

Use quark fragmentation (CDF Run I, Rosner, Dunietz, LeCompte)

$\bar{b} \to B^+ \pi^-$ , $B^0 \pi^+$ (+ remnants) (note opposite charge correlation)

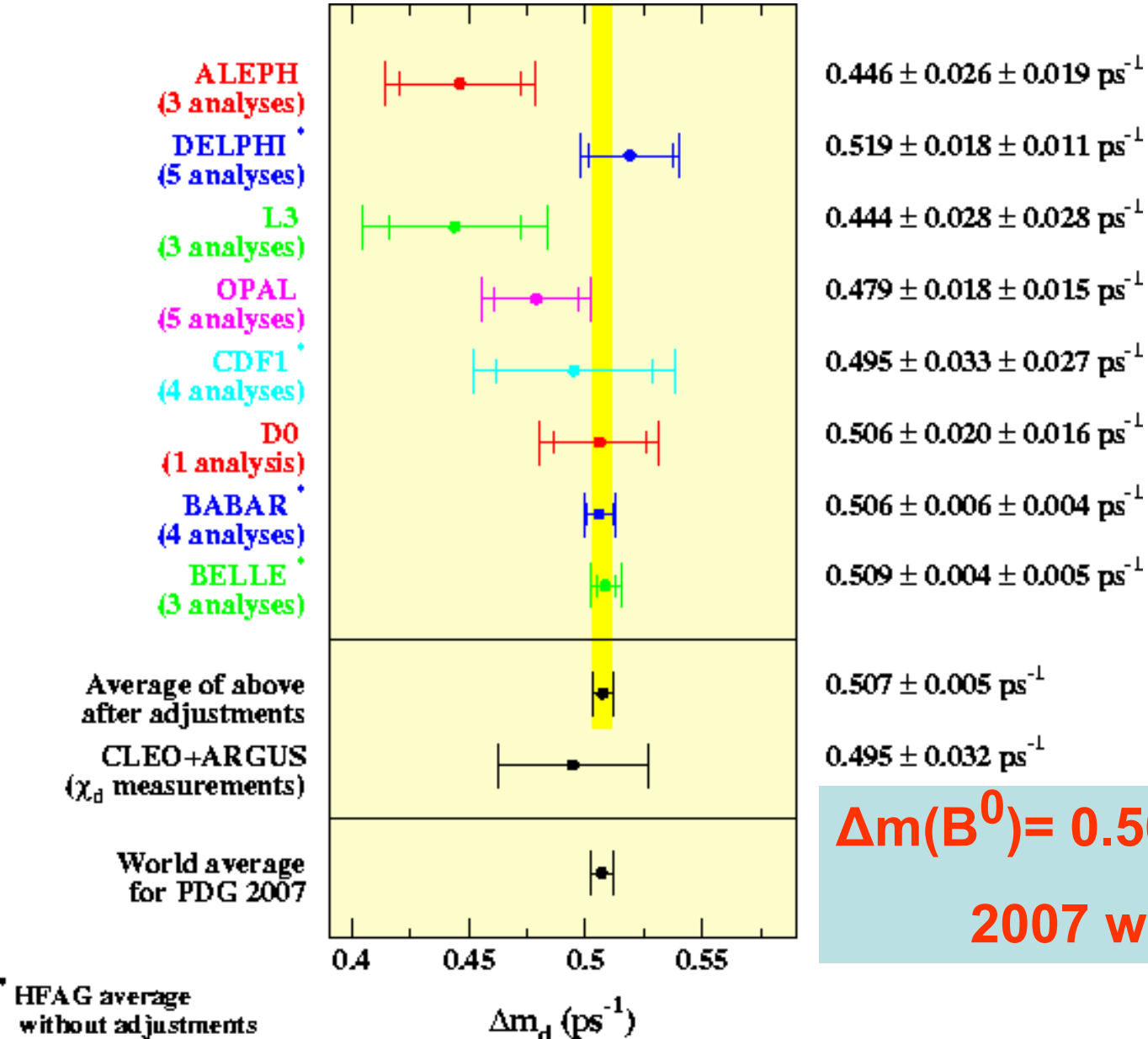
$\bar{b} \to B^+ K^-$ , $B^0 K^-$, $B_s K^+$ (+ remnants)

**Having verified that this works well (Run I CDF mixing and CPV sin2β measurements), CDF built a TOF system for π-K separation.**

**"SST" increases $\varepsilon D^2$ from 1.8% to ~6%=>X3 statistics improvement, critical for Bs mixing (next). Calibration of D is tricky, based on comparison of π and K correlations with $B^0$ and $B^+$.**

**But it actually works !!!**

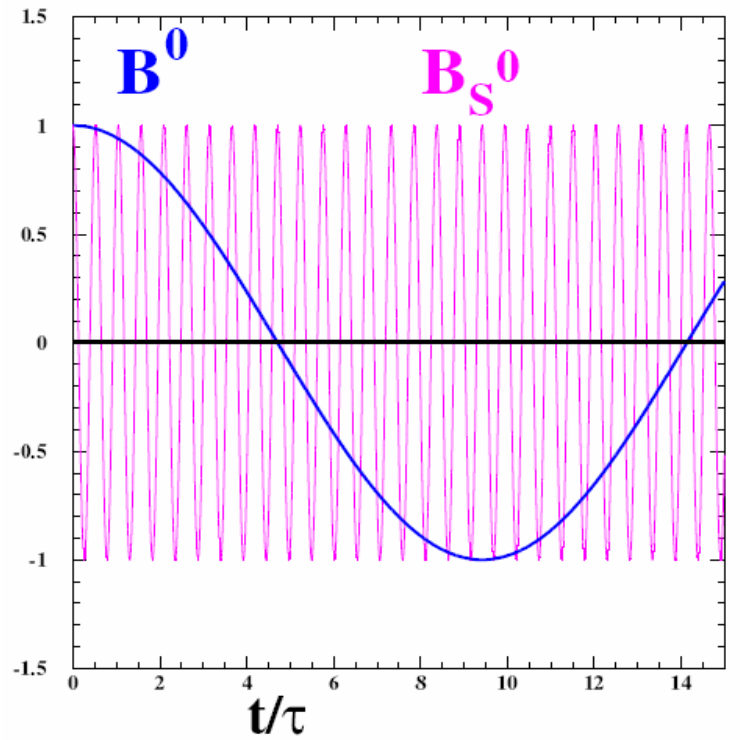
# Combined B0 mixing from all experiments




**$\Delta m(B^0)$= 0.507±0.005 ps$^{-1}$**

**2007 world average**

# Measurement of strange beauty oscillation




- Flavor tagging borrowed from $B^0$
- Time resolution is critical!
- "Amplitude scan" (next}

$$D \cos \Delta m t \rightarrow D e^{-(\sigma_t \Delta m)^2/2} \cos \Delta m t$$

Time resolution $\sigma_t$ intrinsically ~ 80 fs for fully reconstructed $B_s \rightarrow D_s^- \pi^+$ ($3\pi$)

**Effect of time resolution:**

Poorer for $B_s \rightarrow D_s^- l^+ \nu$ where neutrino carries off ~20% of momentum

(proper time ~t m/p )

# Strange beauty mixing

Amplitude scan is essentially a Fourier transform from time to frequency

Start with tagged data sample and fix Δm in steps, like sweeping an NMR scan

At each fixed Δm value fit amplitude "A" of asymmetry:

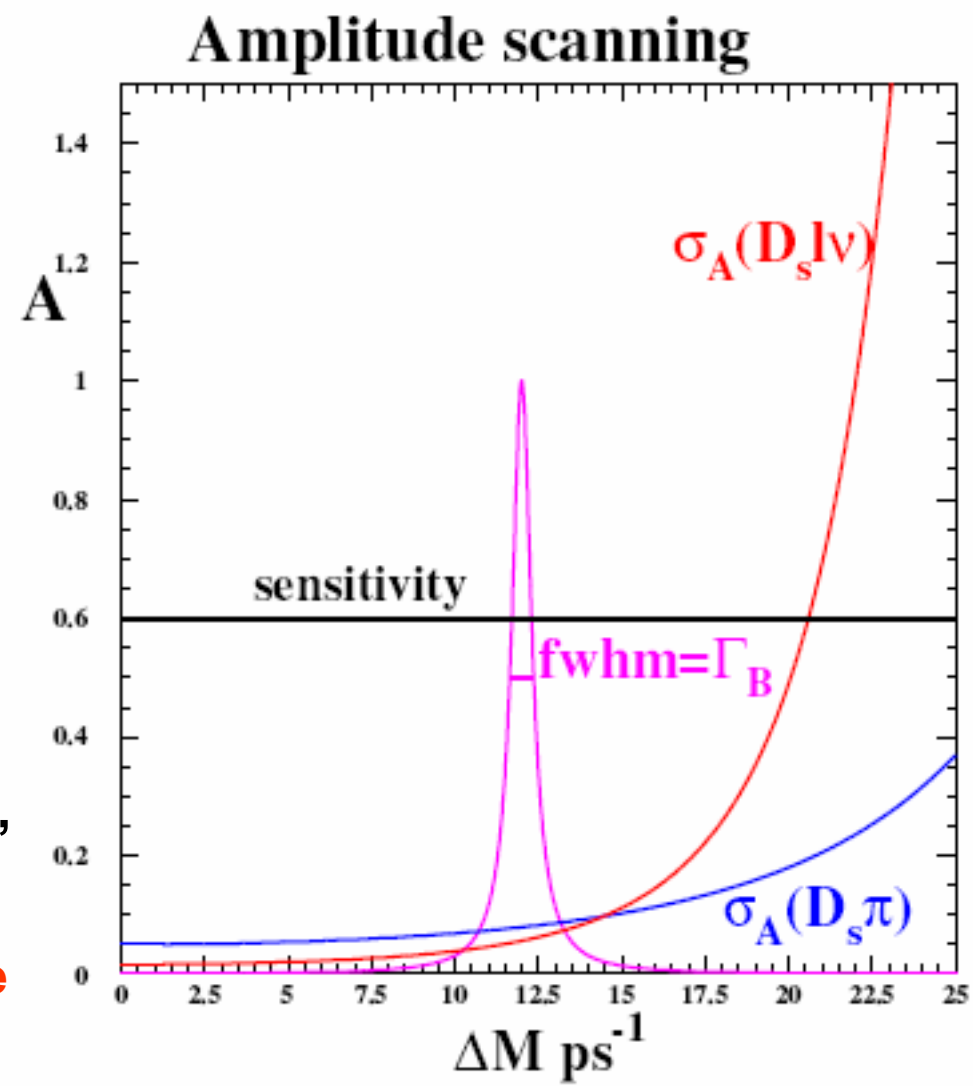
$$ADe^{-(\sigma_t \Delta m)^2/2} \cos \Delta m t$$

True signal is Lorentzian with FWHM = $\Gamma(B_s)$ and peak A=1

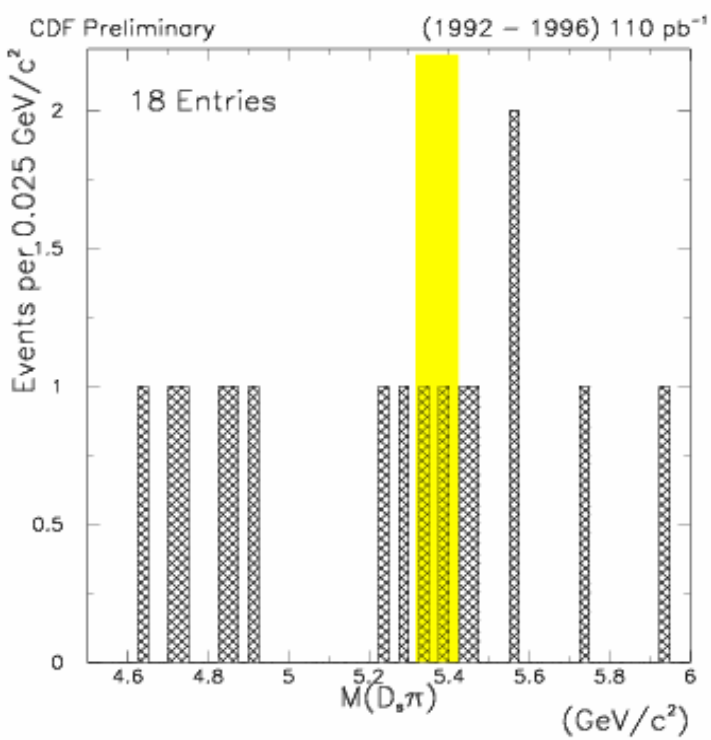
Uncertainty $\sigma(\Delta m/\Gamma) = \sigma(A)/\sqrt{2}$ =>for a 5σ observation, σ(A)=1/5, uncertainty on Δm = 0.095 $ps^{-1}$

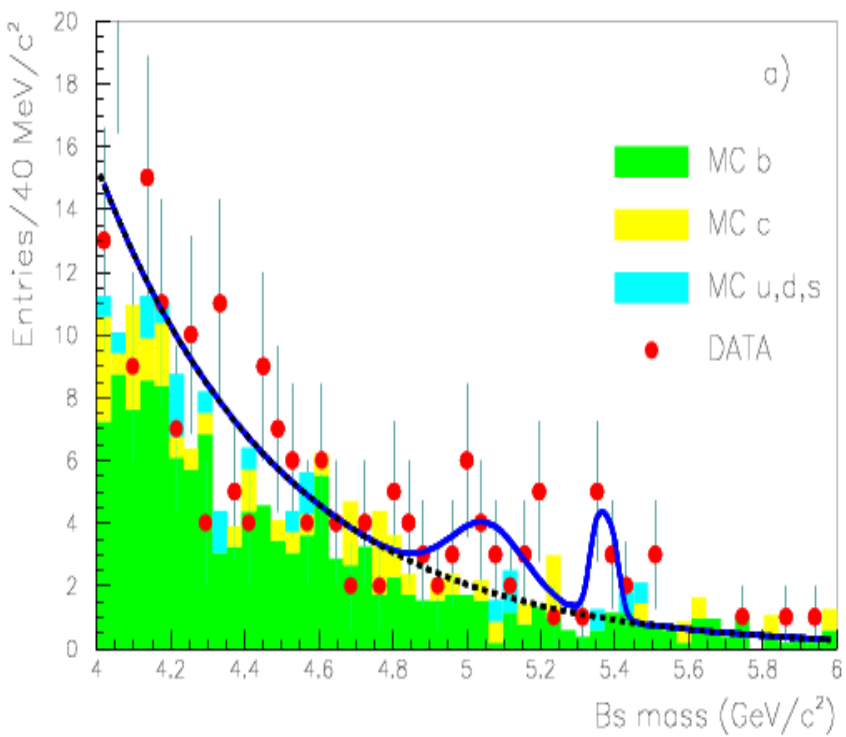
No signal=> 95% C.L. limits set where observed A+1.645 σ(A) = 1.

"Sensitivity" set by σ(A)=1/1.645



# Attempts to use fully reconstructed Bs decays




**CDF Run I, 110 pb-1**

**Search for Bs->Ds π opposite to b->lepton**

**DELPHI LEP I (Z-> b $\bar{b}$)**

**Search for Bs->Ds + X (6 modes)**

# CDF event samples for $B_s$ Mixing

Useful flavor specific final states include: $B_s \to D_s\, l\, \nu$, $B_s \to D_s^- \pi^+(3\pi)^+$

Beauty and charm particles are produced copiously at the Collider, but at low momentum, along with lots of junk. Their only redeeming signature is lepton decays and long lifetimes.

At a B factory this is no problem, 20% of events are B's and physics rates at $10^{34}$ luminosity are ~50 Hz.

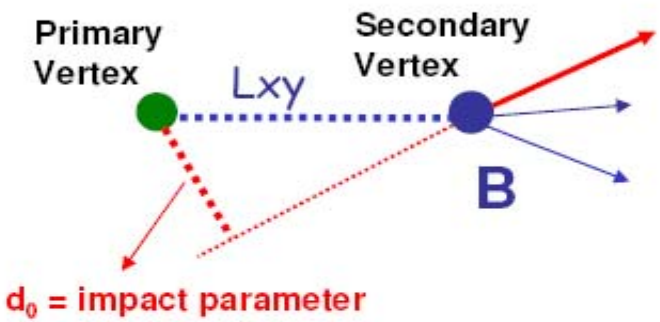
At the Tevatron, input rate at $10^{32}$ luminosity ~ 10 MHz, triggering is the key to the kingdom.

CDF has extremely sophisticated trigger for heavy flavor- we reconstruct charged particle tracks in real time at 10MHz, passing along 30 KHz for hardware selection of long lifetime events, with ~100 Hz saved for analysis. For example, we can give you (one of ~400 trigger configurations) $D_s \to \pi^{\pm}$ ($\varphi \to K^+K^-$) in real time hardware.

This done without compromise to top, Higgs, or SUSY triggers! Trigger menu varied continuously through a store to match luminosity

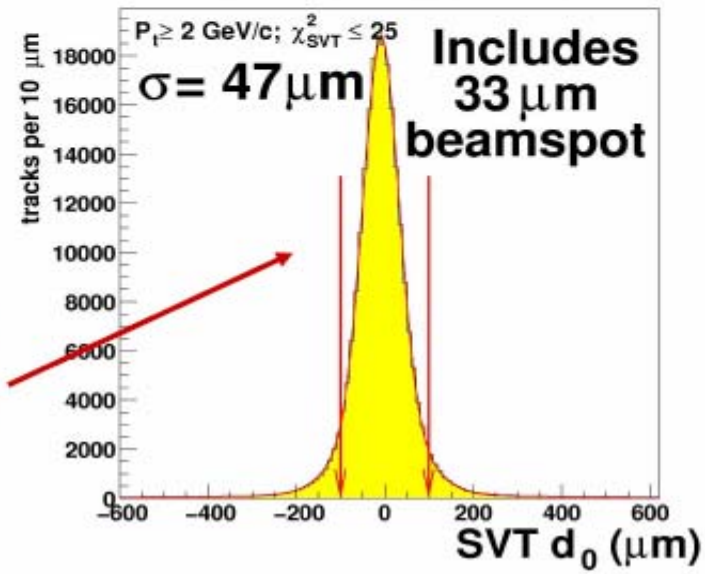
# Triggering On Displaced Tracks

- trigger $B_s \rightarrow D_s^- \pi$, $B_s \rightarrow D_s^- l^+$

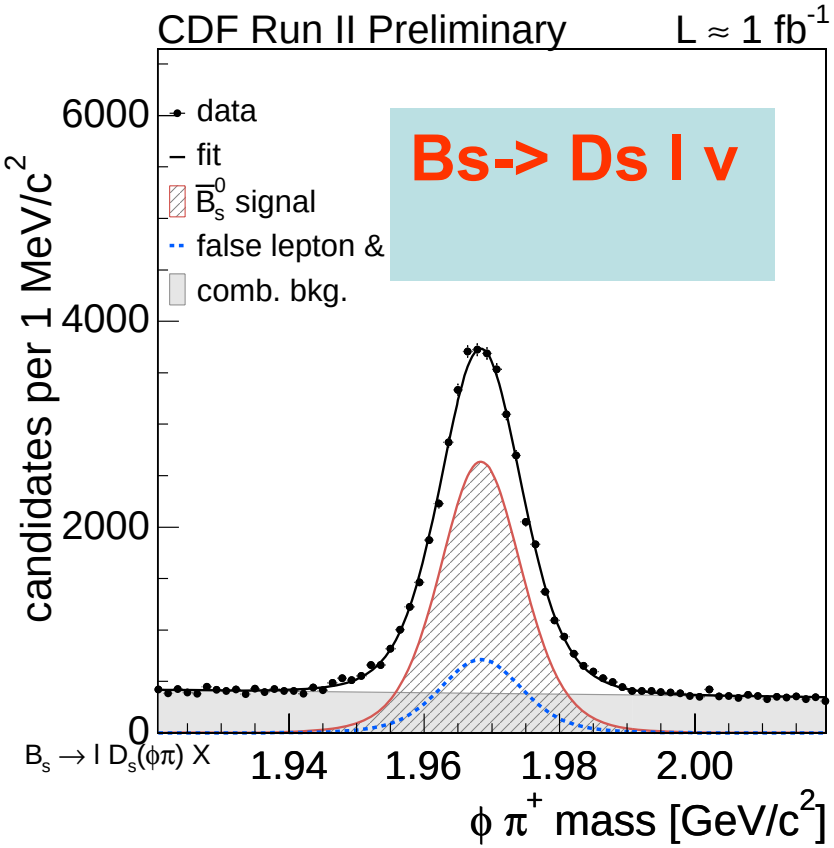


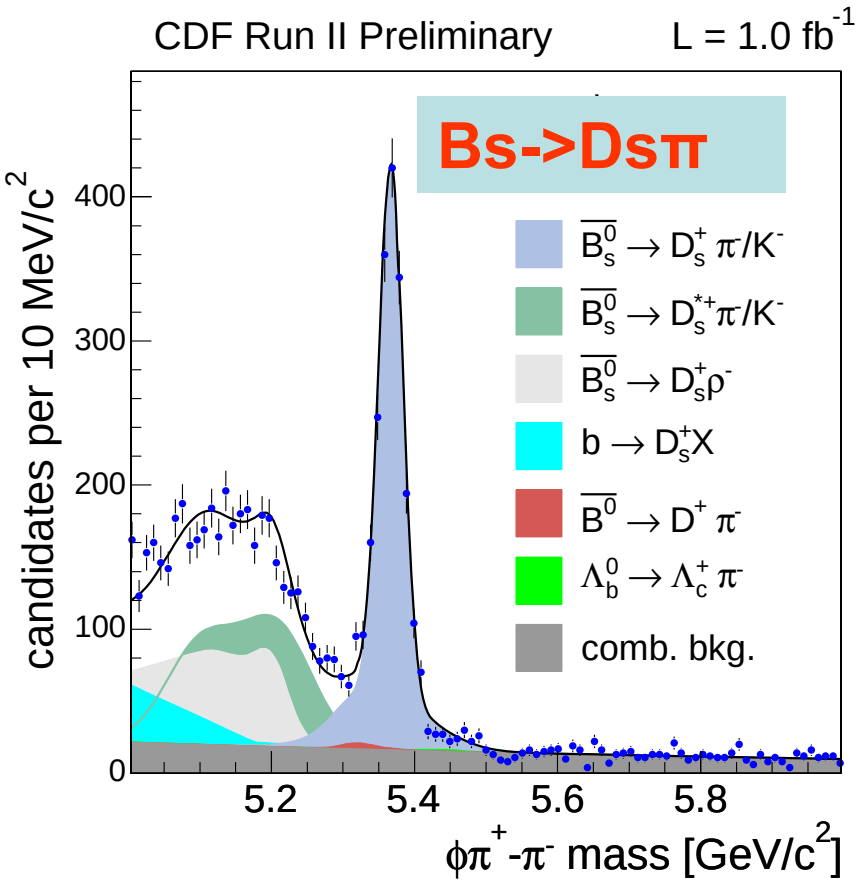
- trigger extracts 20 TB /sec
- "unusual" trigger requirement:
  - two displaced tracks:

  ($p_T$ > 2 GeV/c, 120 μm<|$d_0$|<1mm)
- requires precision tracking in SVX



# Bs event samples from silicon vertex trigger



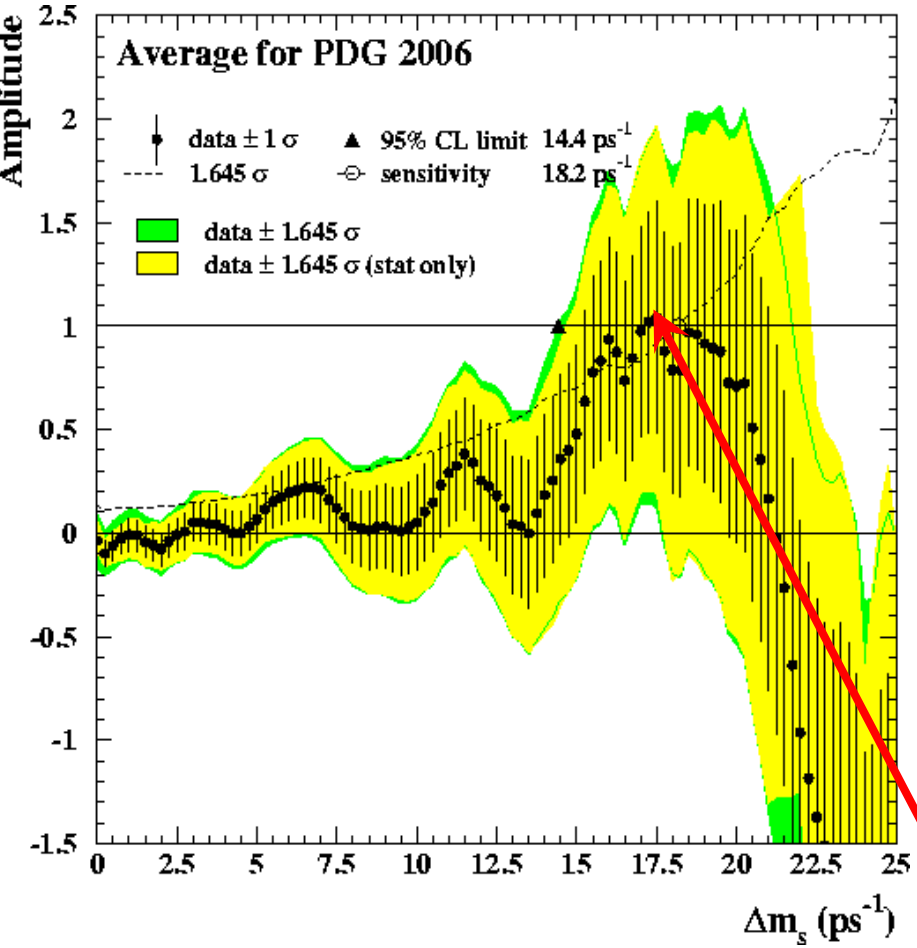

**62000 Semileptonic(1000 pb$^{-1}$)**

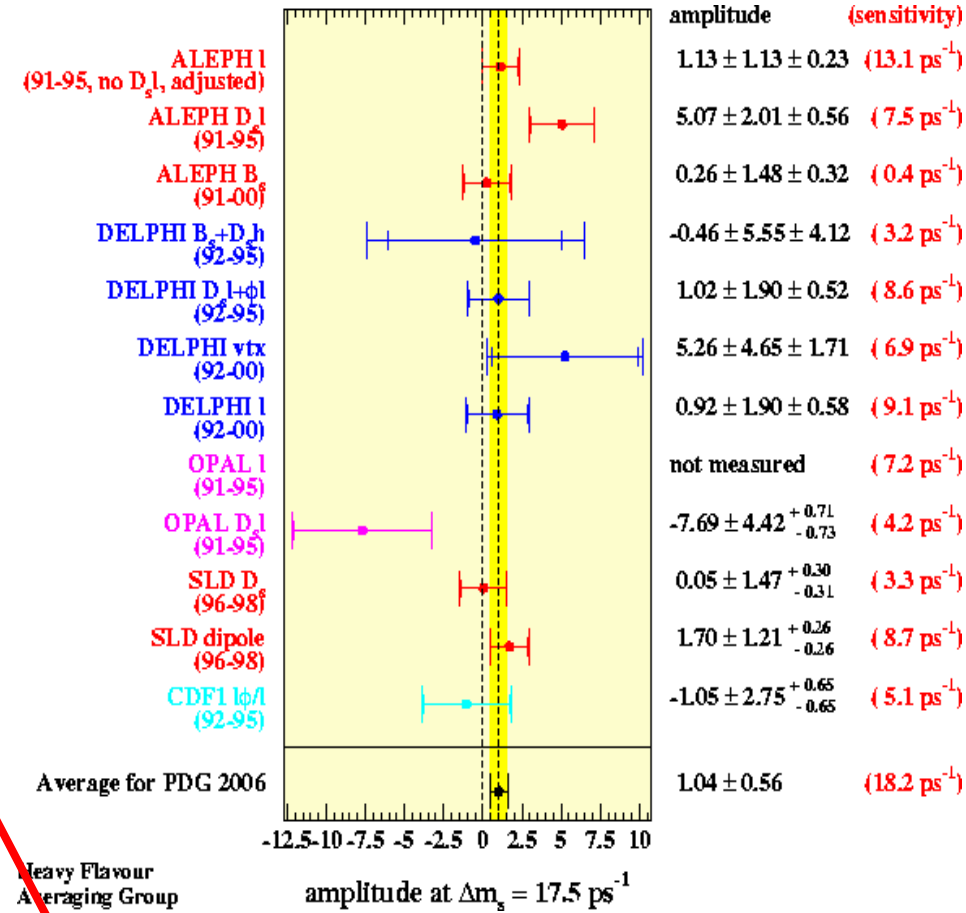
**Run I 220 total (100 pb$^{-1}$)**

**8700 hadronic 1000 pb$^{-1}$**

**Run I ~2 total (100 pb$^{-1}$)**

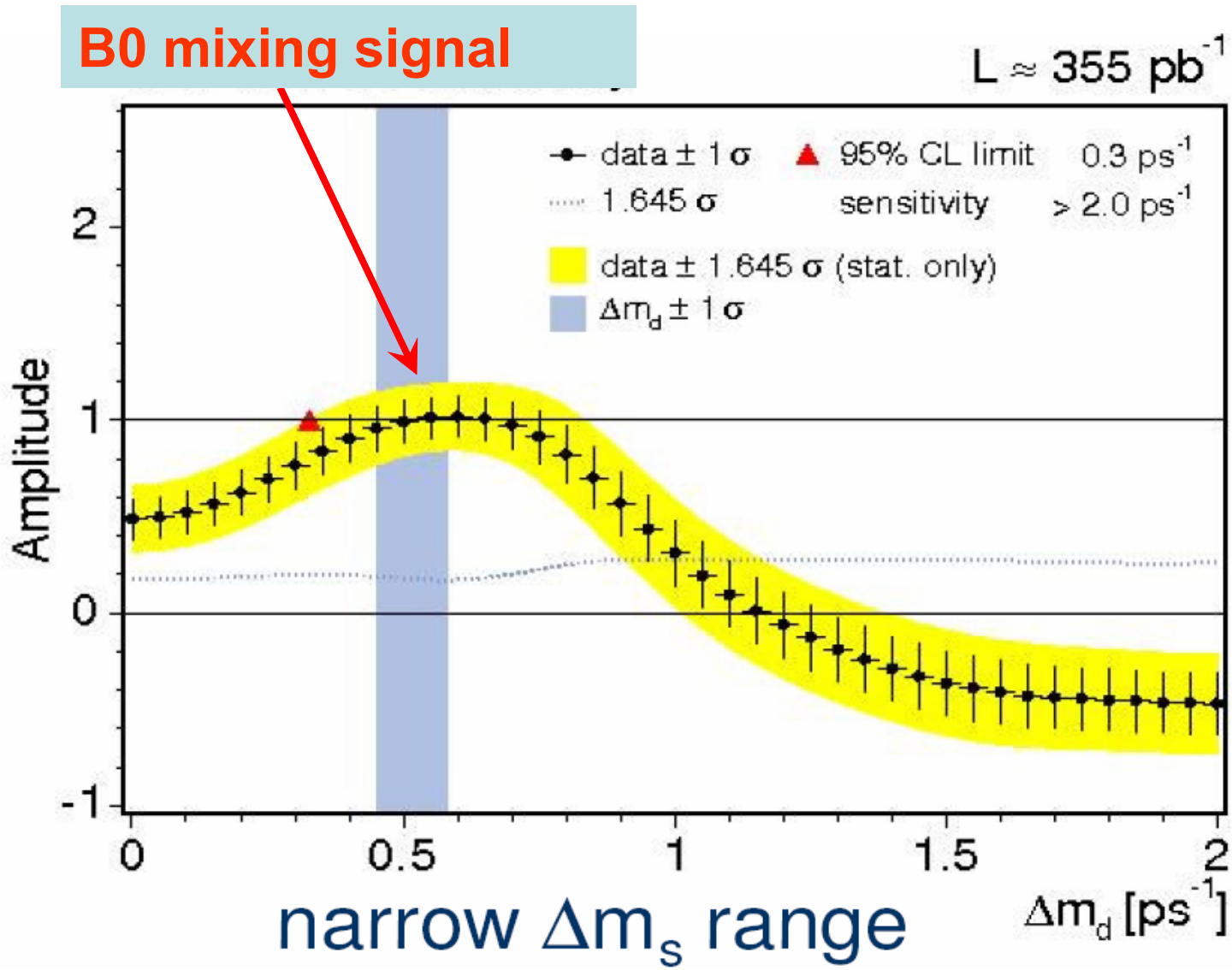
# Combined Bs scan results as of 2006



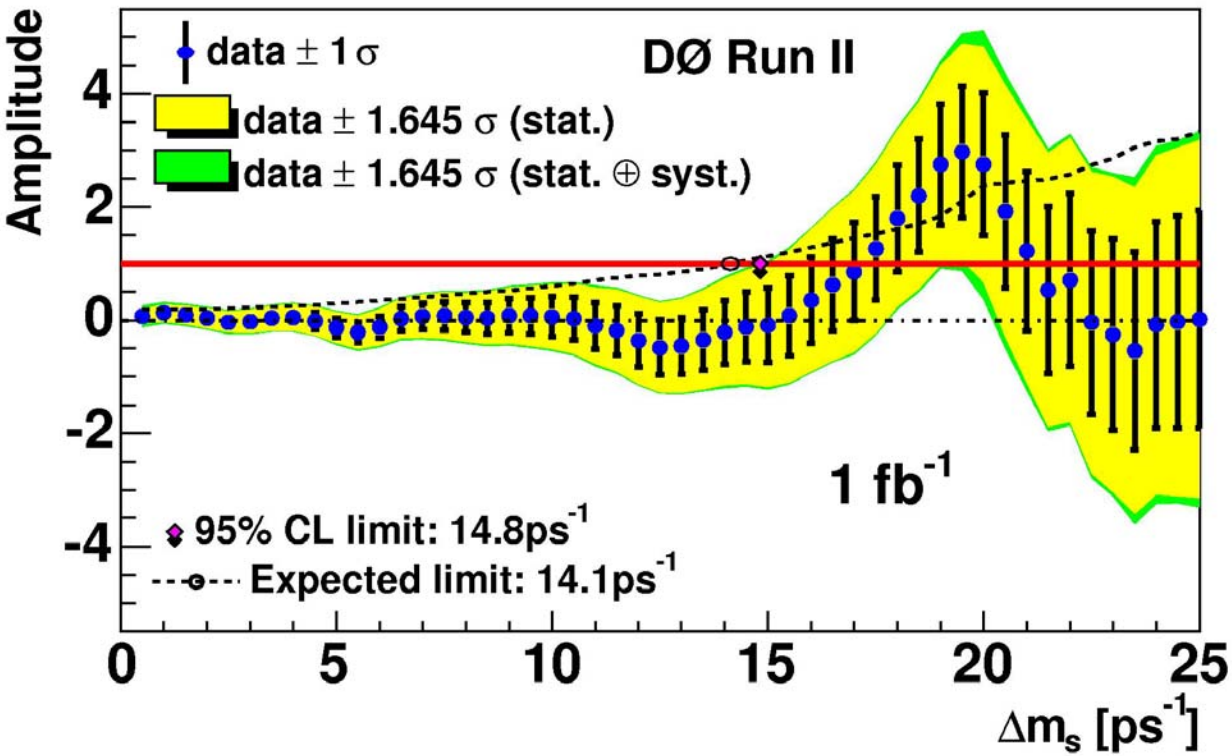




**A=1.04 ± 0.56 at Δm= 17.5 $ps^{-1}$**

# Test of scan method on CDF $B^0 \rightarrow D^0\pi^+$ sample



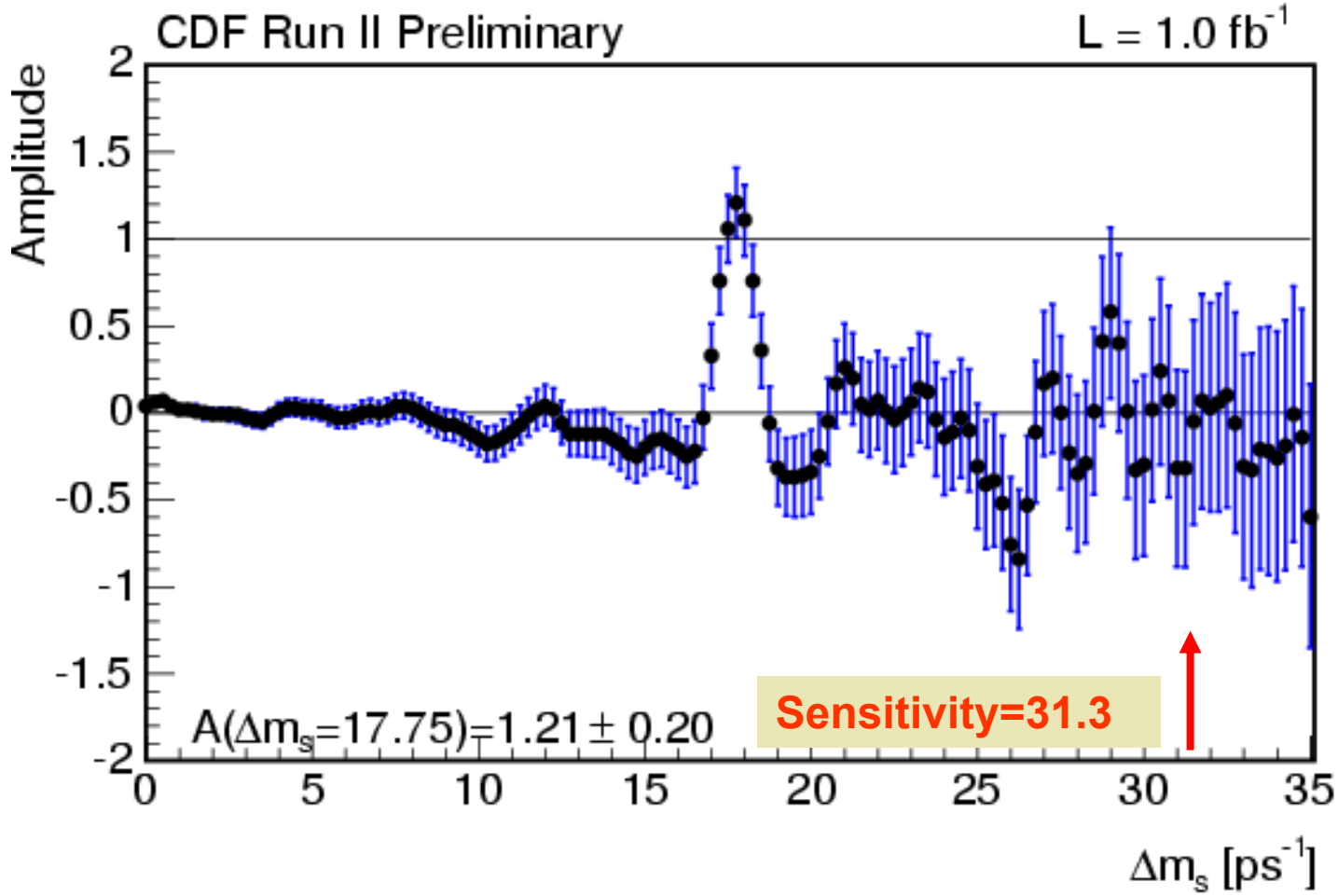
# Moriond winter conference, March 12, 2006



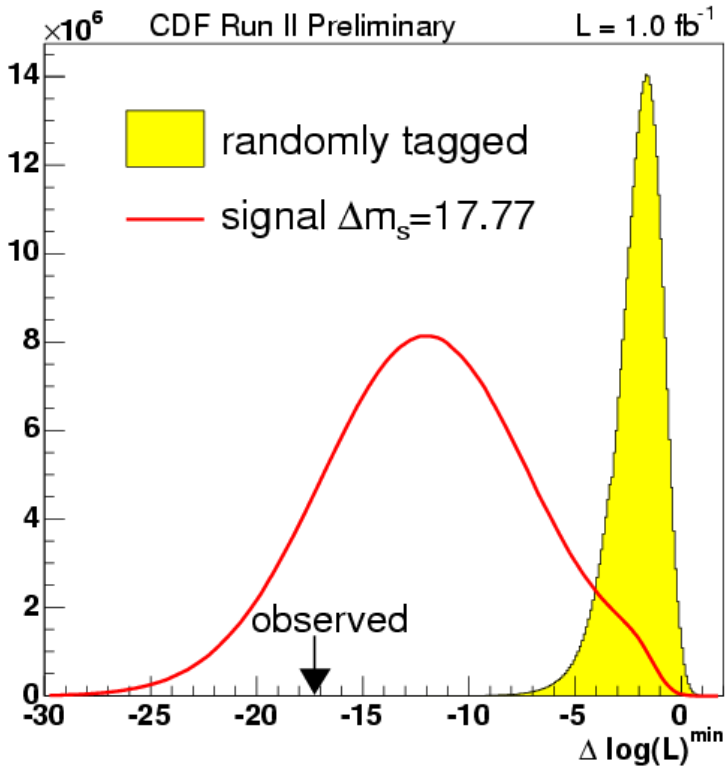

**"Surprise" result from D0 based on $B_s$->$D_s$ l ν**

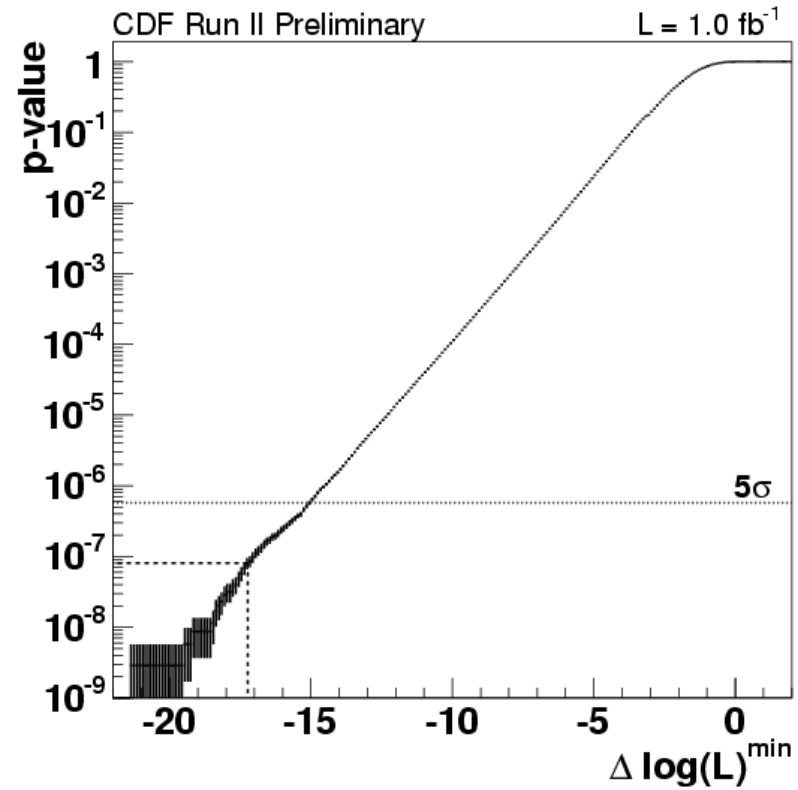
**17< Δms <21 ps-1 (90% CL)**
**actual sensitivity = 14.1 ps-1**
**Amplitude~3 (luck!)**

## CDF combined result (April 2006, revised September 2006)



# Significance tests



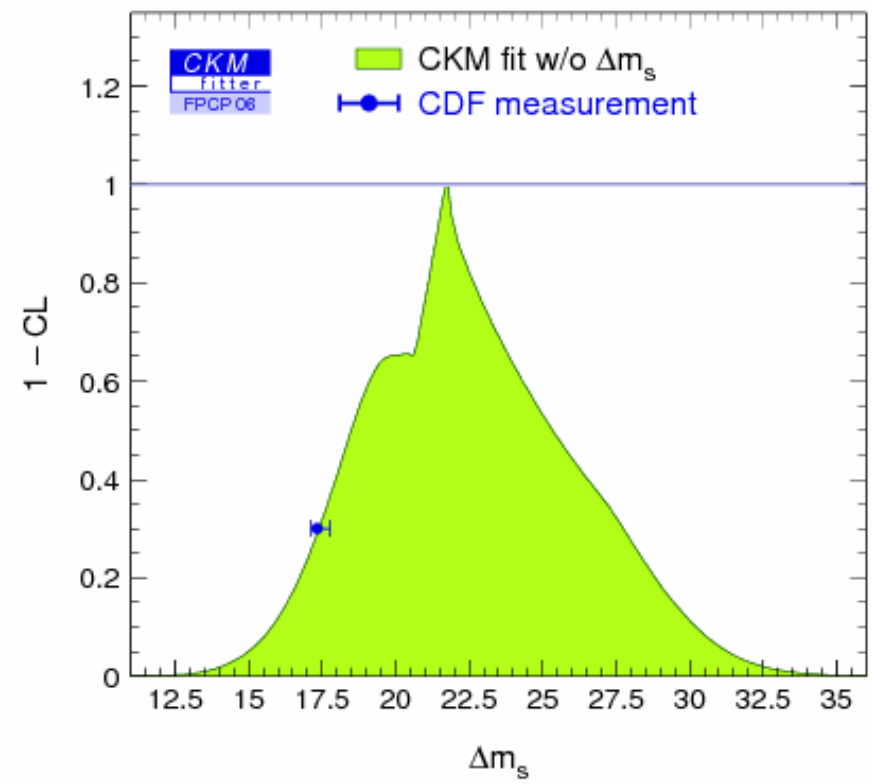



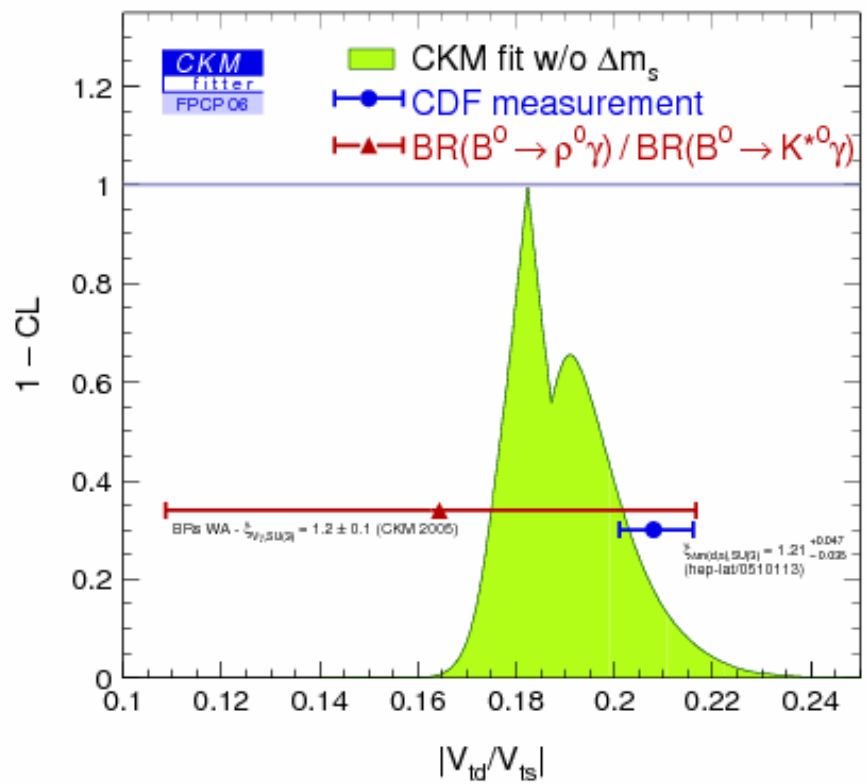

**Define a statistical variable ΔIn *L*= largest signal seen in a scan**

**Randomize the flavor tags in the data sample and repeat the scan 350M times**

**28/350M such scans have signal as large as data => 5.4 σ significance**

# Impact on flavor physics

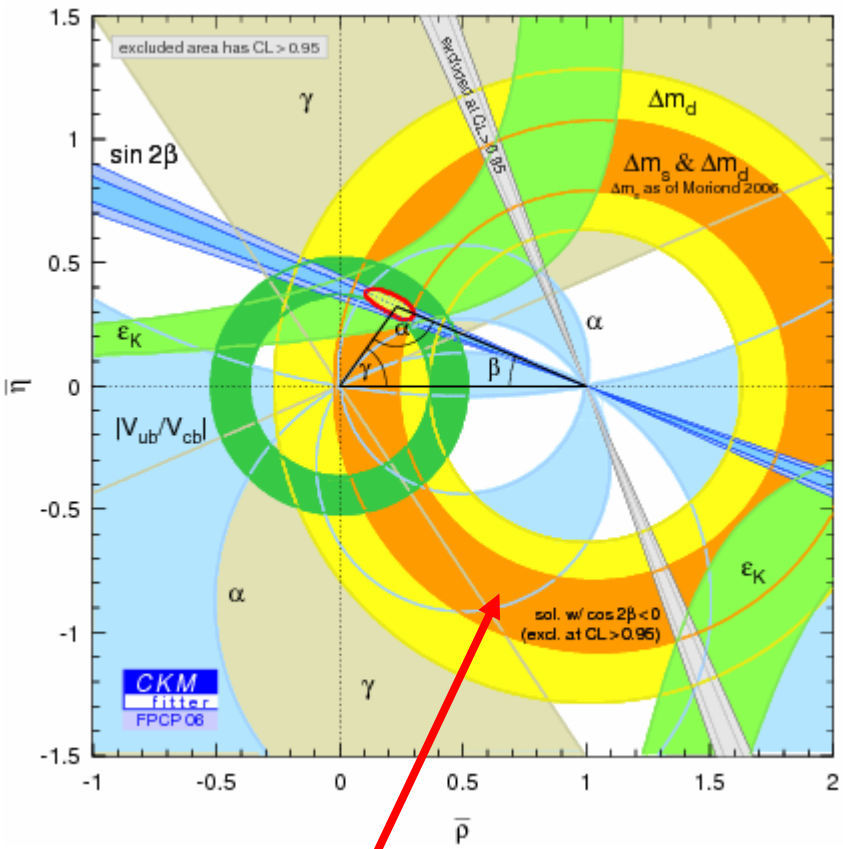


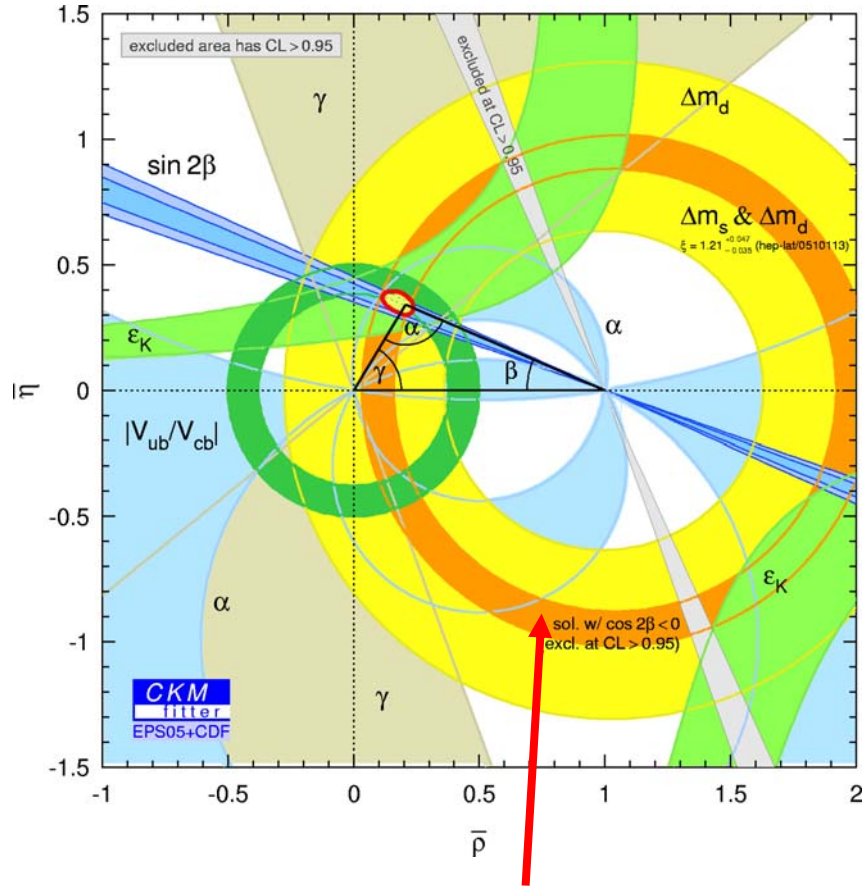




**(1) Δms measurement compared with range allowed by all other CKM inputs.**

**(2) $|V_{td}/V_{ts}|$ ratio compared with allowed CKM range and with radiative decay measurement**

# Impact on flavor physics




**CKM triangle 2006 without $\Delta m_s$**

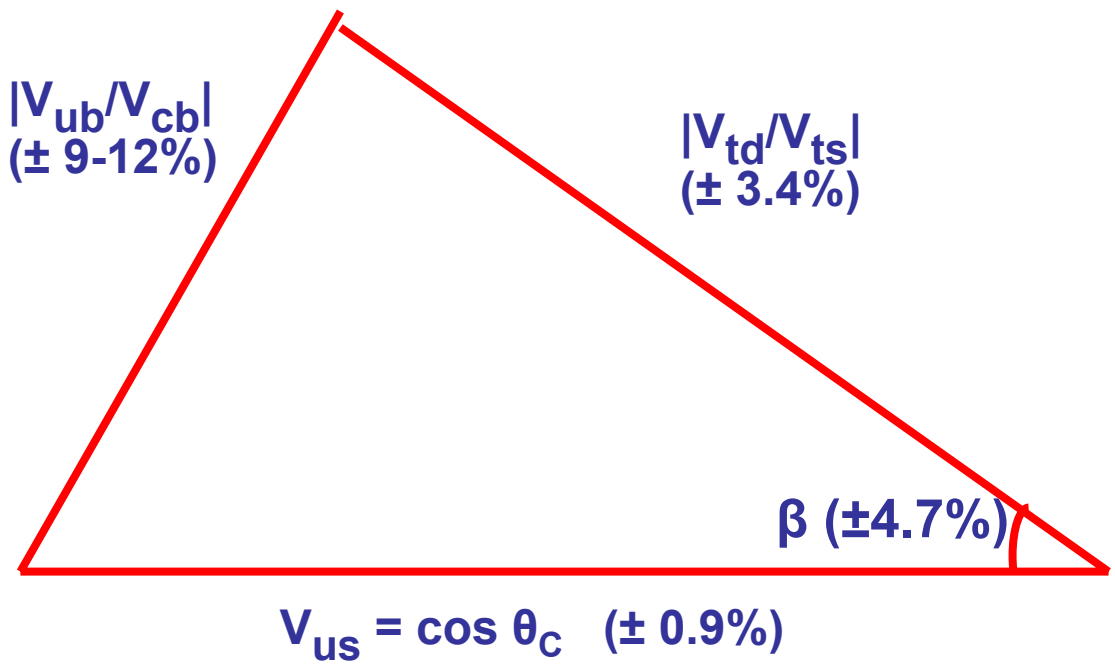
**Plus CDF measurement**

# Precision determination of CKM triangle (2007)

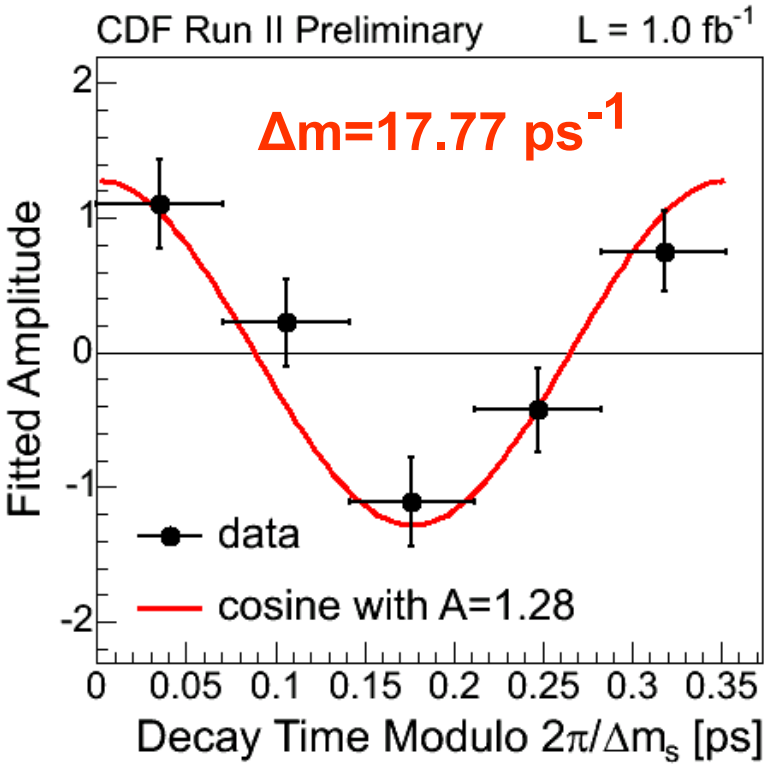
$\Delta ms = 17.77 \pm 0.12\ ps^{-1}$ (CDF)

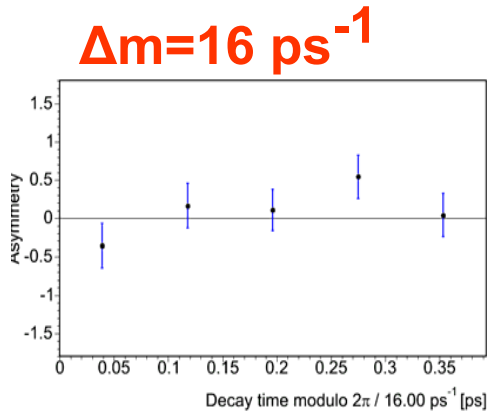
$|Vtd/Vts| = 0.2060 \pm 0.0007\ (\Delta m_s) \pm 0.0071\ (\sigma\xi + \Delta m_d)$

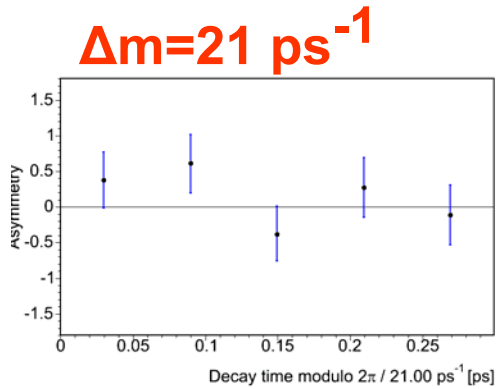
$\sin 2\beta = 0.678 \pm 0.026$ (Belle and BaBaR)



# Convert from frequency back to time domain




**Precision $\Delta m$ => lock into frequency for time-dependent measurements:**

**CPV tests:** $A = [(B_s \rightarrow f_{CP}) - (\overline{B}_s \rightarrow f_{CP})] = \sin 2\beta_S \sin(17.77\ t)$

$\sin 2\beta_S \sim \int A(t) \sin(17.77\ t)\, dt$ **Fourier projection**

# Search for CPV in $B_s$ $\bar{B}_s$ mixing with $B_s$->J/ψ φ

Analogous to CP asymmetry in $B^0$->J/ψ $K_S$, J/ψ $K_L$ decay to CP conjugate final state "f"

$$\frac{(B^0 \to f) - (\overline{B}^0 \to f)}{(B^0 \to f) + (\overline{B}^0 \to f}) = \sin 2\beta \sin \Delta m t$$

More complicated, J/ψ φ final state has S and D (CP +) and P (CP -)

In effect $|S|^2$, $|D|^2$, S*D, $|P|^2$, S*P, and D*P (6 density matrix elements)

Assuming CP conservation, expect Γ(CP +) < Γ(CP -) (further complication)

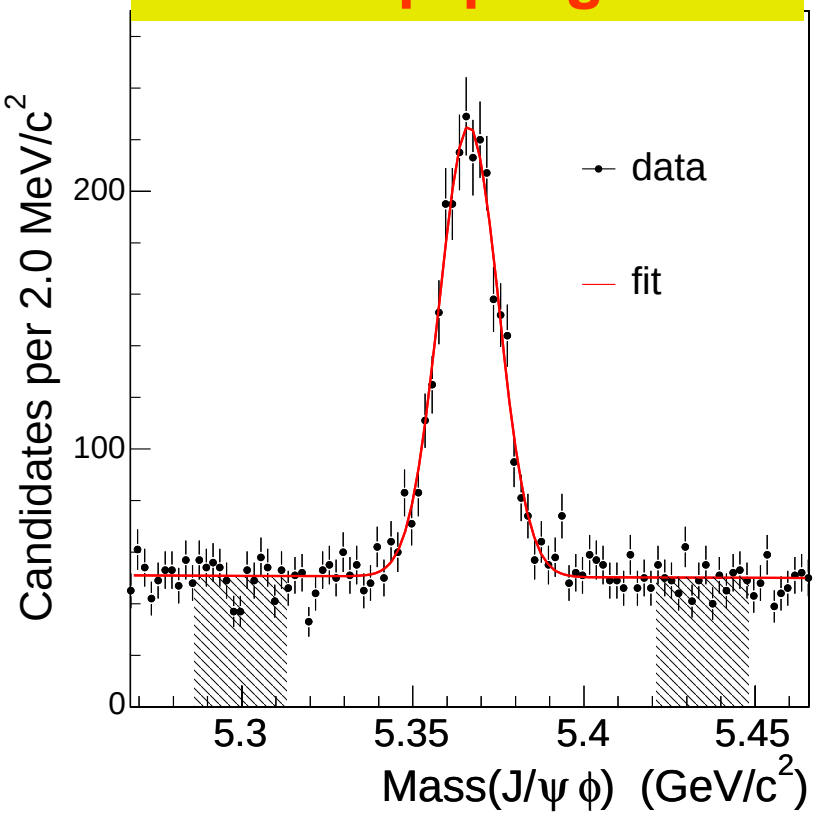
ΔΓ/Γ = 15 ± 6 % (theory) 13.7 ± 7.7% (CDF/D0 Run II)
allows statistical separation of eigenstates In principle

CPV sin $2\beta_s$ in Bs mixing is tiny in CKM paradigm=> nonzero sin 2βs implies new physics contributions to $M_{12}$ (Bs)

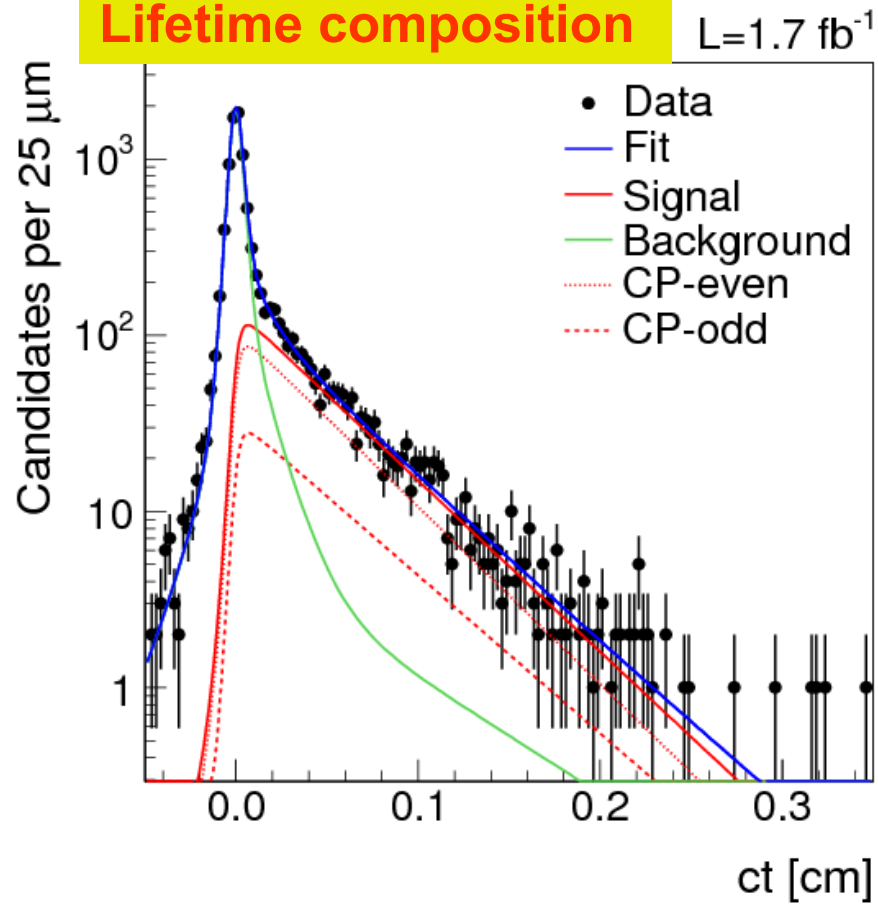
Any S-P, D-P interference must be opposite sign for Bs and $\overline{Bs}$, otherwise =>CPV in untagged sample $B_s$->J/ψ φ complicated but rich……

# Search for CPV in Bs -> Jψ φ

**2500 J/ψ φ signal**




**Lifetime composition**

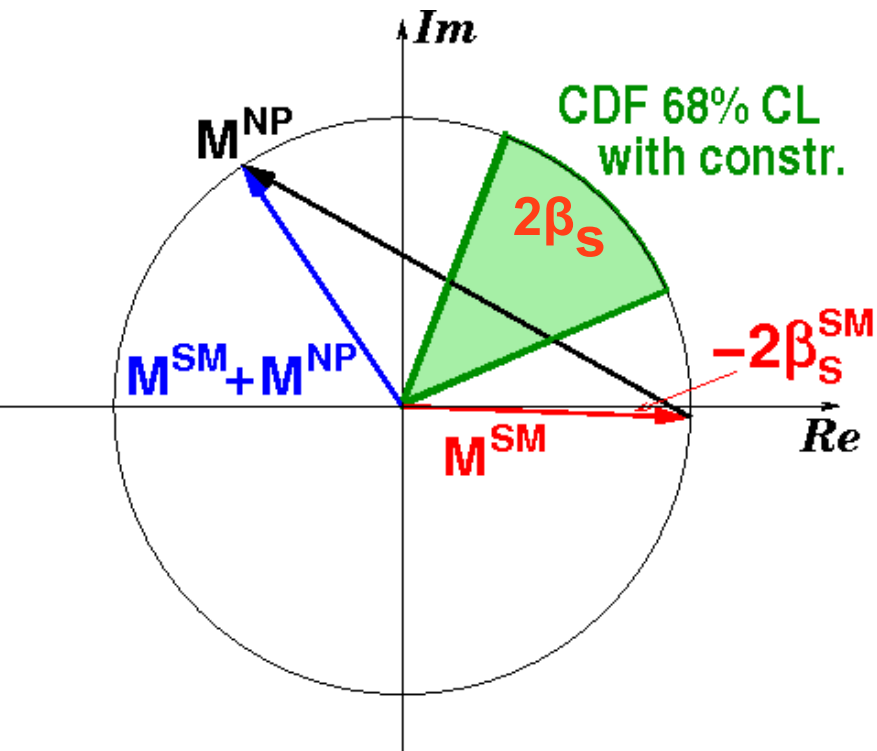



**CDF made a very respectable measurement of sin 2β with 400 $B^0$->J/ψ$K_S$ events in Run I**

# Search for CPV in Bs -> Jψ φ

CDF and D0 have both reported on ΔΓ and searched for flavor-averaged CPV effects: ~ S*P, D*P (CP-even*CP-odd) interference in either long or short lived eigenstates.

CDF recently performed flavor tagged measurement of the $\sin 2\beta_s \sin\Delta m\, t$ asymmetry, combining all of the six density matrix elements and the lifetime difference between eigenstates



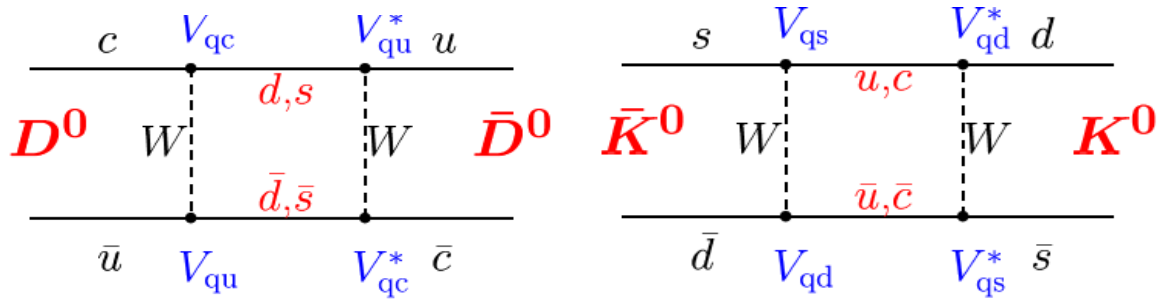

Pure CKM => $M_{12}$, $\Gamma_{12}$, and decay amplitudes are in phase. A NP phase in $M_{12}$ => nonzero $\sin 2\beta_s$ and enhanced $|p/q|-1$ (enhanced lepton asymmetry).

Results are consistent with CKM at 90% CL, $\sin 2\beta_s < 0$ ruled out.

# Charm ($D^0$-$\bar{D}^0$) Mixing

**Box Diagrams**

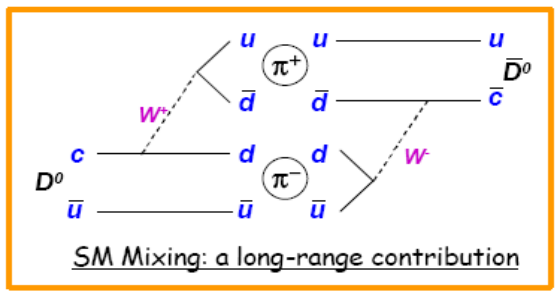
- **Same CKM factors**
- **Different masses**




$\Delta M_K$ **= 5.3 ns$^{-1}$ => $\Delta M_D$~ 0.04 ns$^{-1}$, or $\Delta M_D / \Gamma_D < 10^{-5}$ (undetectable)**

**Expect long-range contributions to dominate**

ππ, Kπ, πK, KK intermediate states plus SU(3) symmetry breaking




$$\Delta\Gamma, \Delta M \sim \sum_f A(D^0 \to f) A^*(\bar{D}^0 \to f)$$

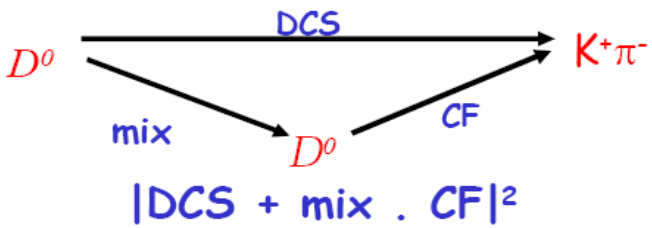
f = ππ, πK,KK

# Charm Mixing

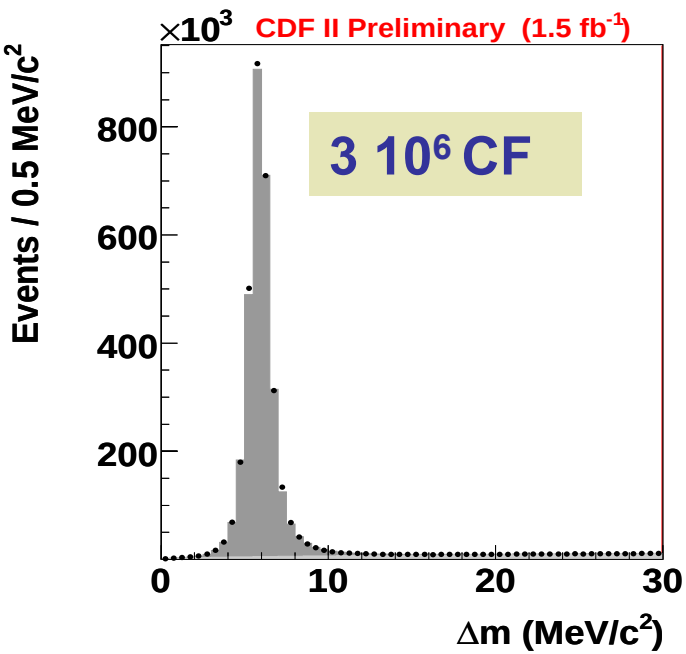
Search for time dependent mixing with flavor tagged $D^{*+} \to D^0\pi^+,\ D^{*-} \to \overline{D}^0\pi^-$

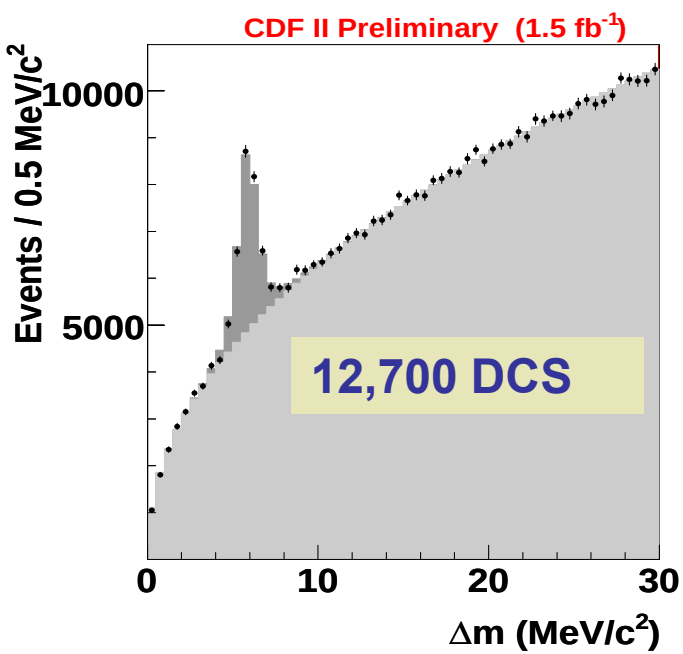
$D^0 \to K^-\pi^+$ (Cabibbo favored "CF", 3.8% )

$D^0 \to K^+\pi^-$ (Cabibbo suppressed "DCS", 0.012%)



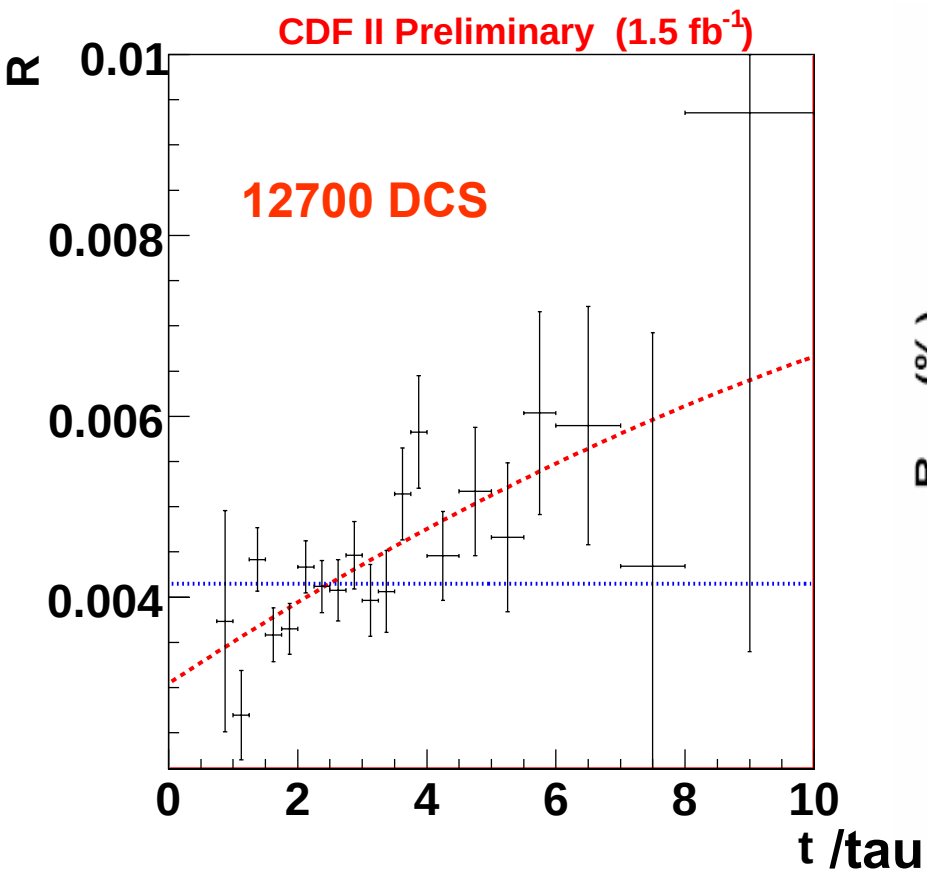

$$Rate\ (D^0 \to K^+\pi^-) = \left|A(CS) + A(CF) \times D^0 \to \overline{D}^0(t)\right|^2$$



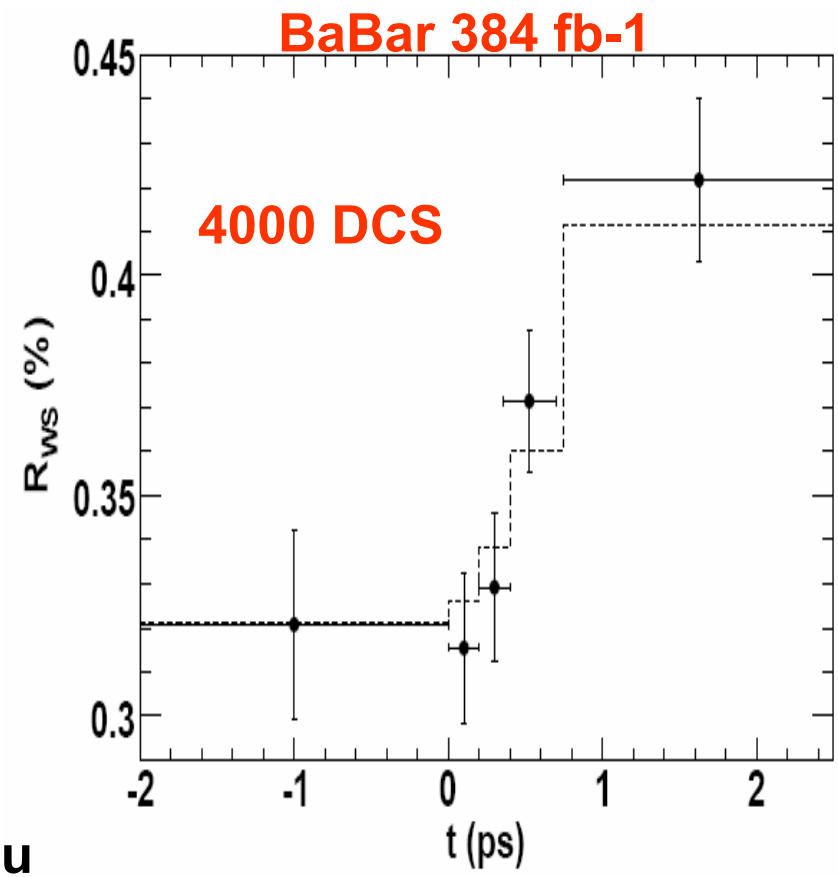



# Evidence for time dependent DCS/CF ratio in D0 Mixing

## $\Delta\Gamma$, $\Delta M$, and strong phase ($A_{DCS}\ A^*_{CF}$) are highly correlated

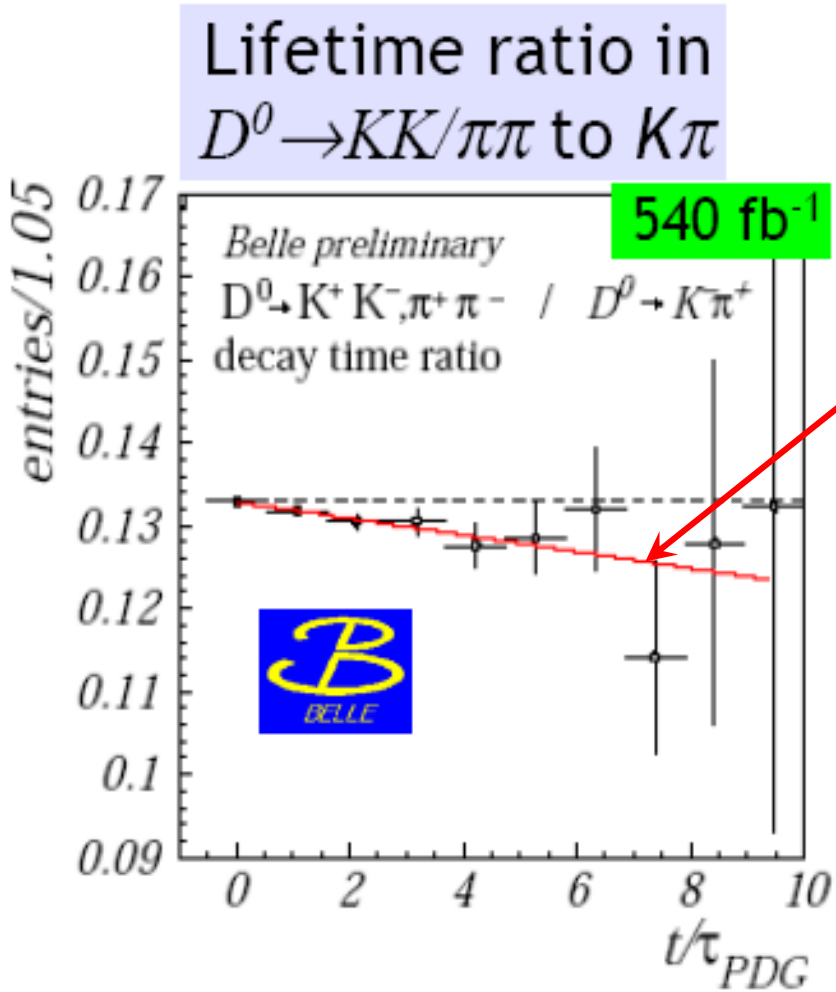



CDF Time dependence= 3.8σ




BaBaR Time dependence=3.9σ

# Further Evidence (Belle)




1.22 M $K^-\pi^+$, 160K $\pi^-\pi^+$/ $K^-K^+$ events

Measure lifetime ratio for CP-even to CP-average = 0.9870±0.0041

$\Delta\Gamma / 2\Gamma = 1.31 \pm 0.41\%$ ($3\sigma$)

Belle also finds from $D^0 \to K_S \pi^+\pi^-$ Dalitz plot analysis (530K) events:

$\Delta\Gamma / 2\Gamma = 0.33 \pm 0.28\%$

$\Delta M / \Gamma = 0.80 \pm 0.34\ \%$

# Conclusions on D0 Mixing

- $\Delta\Gamma / \Gamma$, $\Delta M / \Gamma$ appear to be ~ 0.001 to 0.01, as "predicted" for long-range ($\pi\pi$, KK) intermediate states

  (cf "Dispersive Effects in D-$\bar{D}$ Mixing", J. Donoghue et al 1986)

- Much larger than CKM box diagrams (~$10^{-6}$), which were supposed to invite new loop contributions.

- Getting to this stage just required overwhelming statistics (=> CDF, BaBaR, Belle)

- But, alas, $D^0$ not likely to be a reliable particle clock.

# Wrapup

- Elegant idea of Gell-Mann and Pais leads to 50 years of mixing and CP violation (the physics of flavor)

- $K^0$ mixing predicts existence of charm,
- CPV in $K^0$ mixing predicts third (top, beauty) generation.

- $B^0$ mixing predicts massive (170 GeV) top

- CPV in $B^0$ mixing (sin 2β), together with precision ratio of $B^0$ and $B_s$ mass mixing, nails $V_{td}$ and the CKM triangle (or does it?)
  - Still looking for CPV where it should be zero, $B_s$->J/ψφ

- I read Feynman's monogram about $K^0$ mixing back in 1962, did not then imagine I would end up measuring the next three particle clocks with my CDF collaborators.