Weak Decays/CKM/CP violation

- Experimental summary(highlights) -

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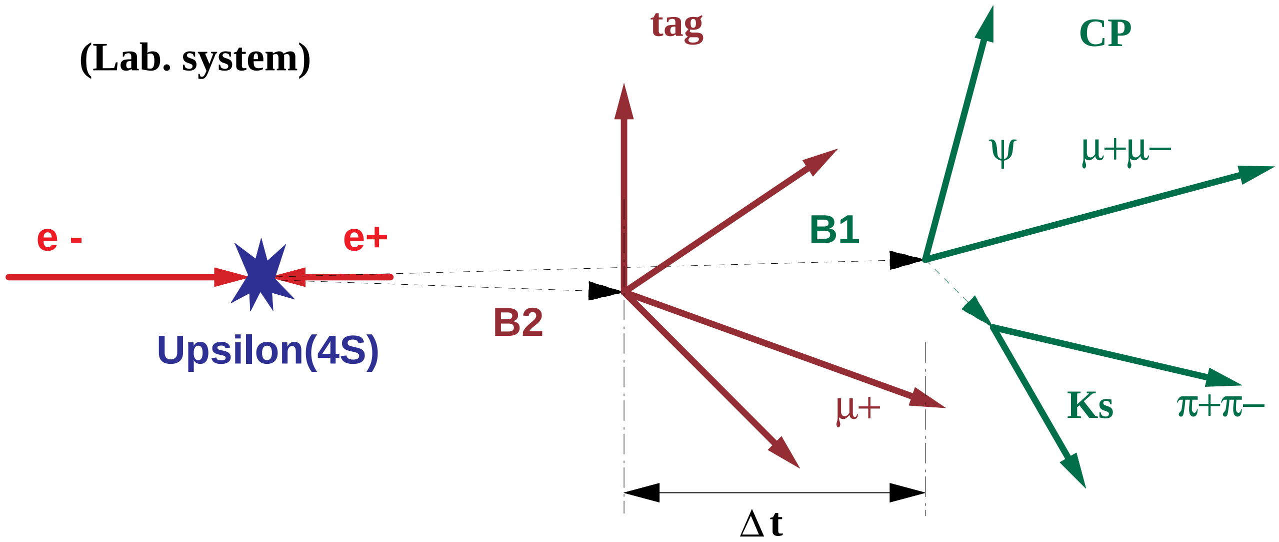
Observation of CP violation in $B \to f_{CP}$(e.g. $J/\Psi K_S$)



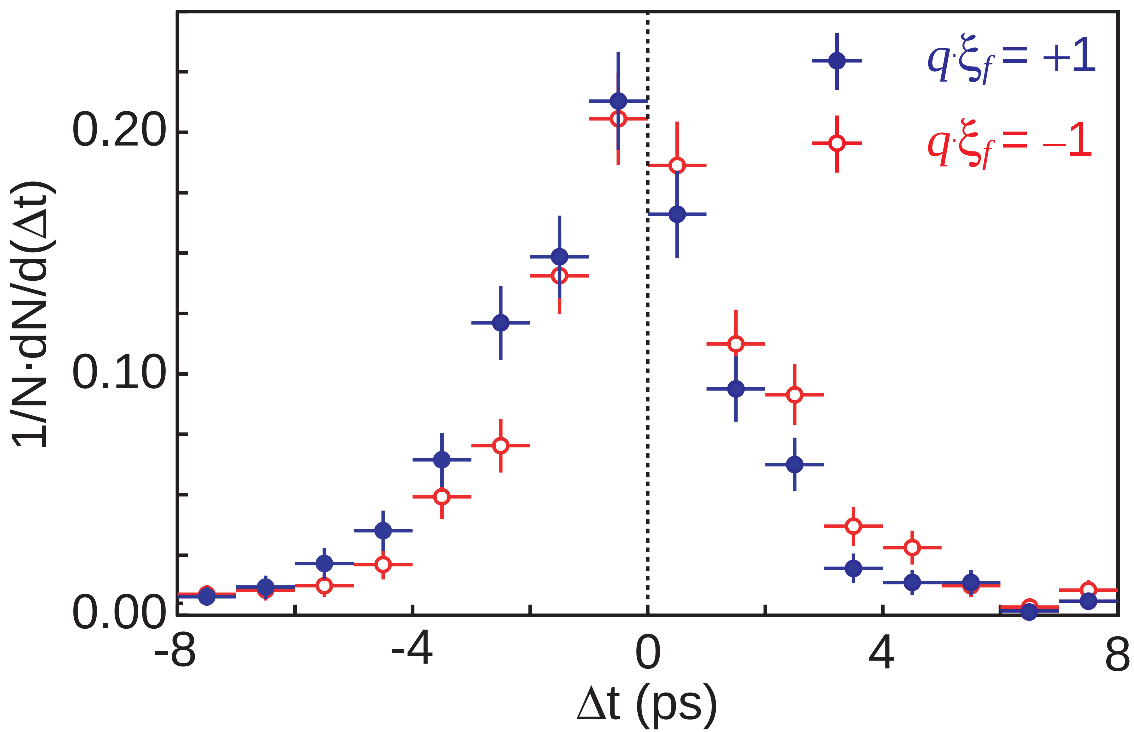
It is found that,

If the tag side is B^0 ($\bar{B}^0$), the $J/\Psi K_S$ side tends to decay later (earlier) than the tag side.

$\xrightarrow{CP}$ If the tag side is $\bar{B}^0$ (B^0), the $J/\Psi K_S$ side tends to decay later (earlier) than the tag side: Not seen.

$\to$ CPV!

$q = +1$ **Tag side is** B^0
$q = -1$ **Tag side is** $\bar{B}^0$, ξ_f : CP eigenvalue



Decay modes

	Babar	Belle
$CP-$	$\Psi K_S, \chi_{c1} K_S$	$\Psi^{(\prime)} K_S, \chi_{c1} K_S, \eta_c K_S$
$CP+$	ΨK_L	ΨK_L
CP mix	ΨK^{*0}	ΨK^{*0}

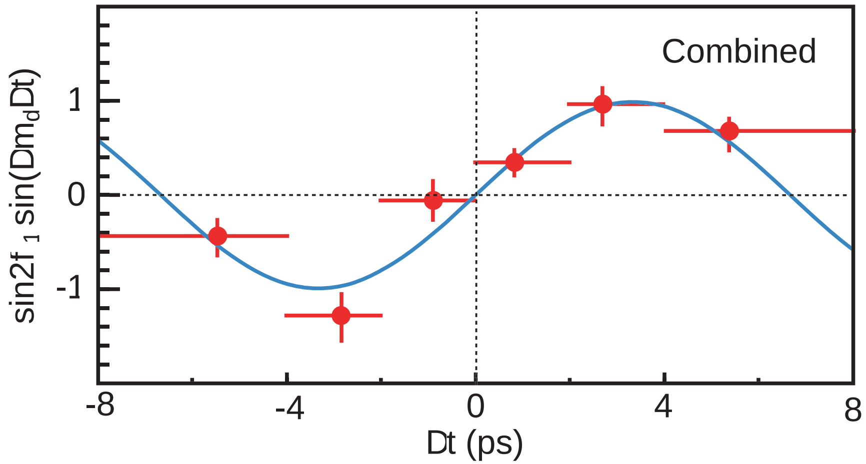
Time-dependent asymmetry

$$A(\Delta t) \equiv \frac{\Gamma_{B^0 \mathrm{tag}}(\Delta t) - \Gamma_{\bar{B}^0 \mathrm{tag}}(\Delta t)}{\Gamma_{B^0 \mathrm{tag}}(\Delta t) + \Gamma_{\bar{B}^0 \mathrm{tag}}(\Delta t)} = -\lambda \sin \Delta m \Delta t,$$

$$\lambda = \mathrm{Im} \frac{q A_{\bar{B}^0 \to f}}{p A_{B^0 \to f}} = \xi_f \sin 2(\phi_1/\beta)$$

(sign convention: $\Delta m = m_1 - m_2 > 0$, $B_1 = pB^0 + q\bar{B}^0$)

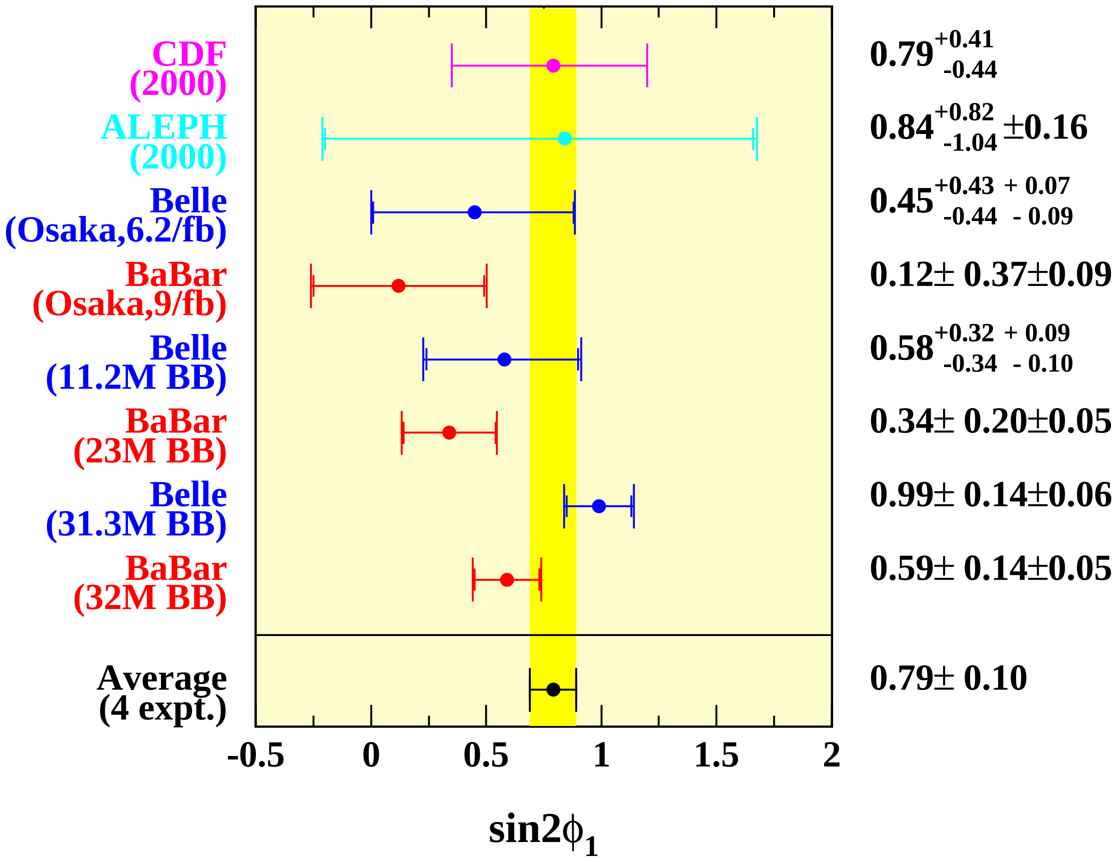
Plot $-\xi_f A(t)$ (all modes)



$$\lambda = \xi_f \sin 2(\phi_1/\beta)$$

	Babar	Belle
$CP-$	-0.56 ± 0.15	-0.84 ± 0.17
$CP+$	0.70 ± 0.34	1.31 ± 0.23
$\sin 2(\phi_1/\beta)$	$0.59 \pm 0.14 \pm 0.05$	$0.99 \pm 0.14 \pm 0.06$

- $CP+$ and $CP-$ final states have opposite asymmetries.
- Babar and Belle consistent at 1.9σ.



OPAL(98):
$3.2^{+1.8}_{-2.0} \pm 0.5$

ALEPH(00):
$0.84^{+0.82}_{-1.04} \pm 0.16$

CDF(02):
$0.91 \pm 0.32 \pm 0.18$

World average: $\sin 2(\phi_1/\beta) = 0.79 \pm 0.10$

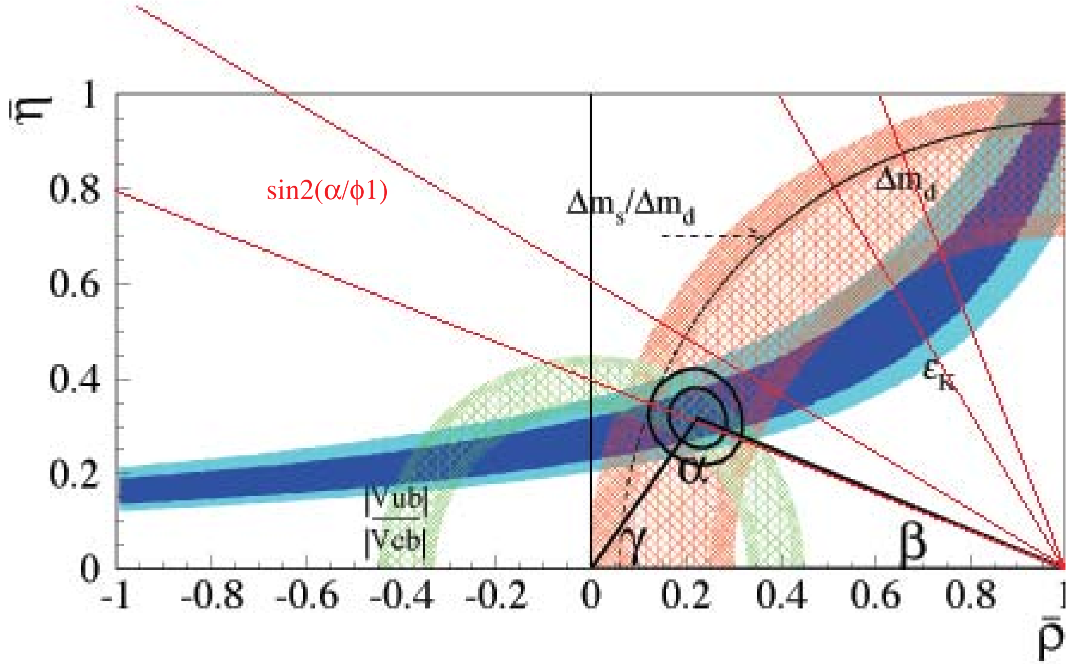
In terms of the unitarity triangle

Pre-Babar/Belle experimental inputs:

1. $|V_{ub}/V_{cb}|$ (by $b \to ue\nu$)
2. B^0-$\bar{B}^0$ mixing $\to |V_{td}|$
3. ϵ_K (from Kaon system)

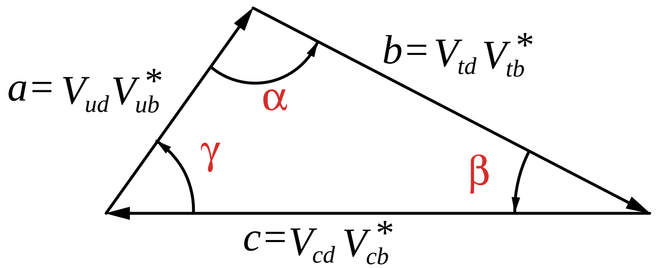
An (agressive) example: Ciuchini et.al.:
3 lines crosses at one point $\to$ already a triumph of SM.

$\sin 2(\phi_1/\beta) = 0.79 \pm 0.10$ falls nicely on top of it.



Measure all 3 angles of the unitarity triangle.

Does the triangle close (is CKM unitary)?



$$\alpha/\phi_2 \equiv \arg\left(\frac{b}{-a}\right),\ \beta/\phi_1 \equiv \arg\left(\frac{c}{-b}\right),\ \gamma/\phi_3 \equiv \arg\left(\frac{a}{-c}\right)$$

$$\alpha+\beta+\gamma = \arg\Big(\overbrace{\frac{b}{-a}\cdot\frac{c}{-b}\cdot\frac{a}{-c}}^{1}\Big) = \pi\ (\mathrm{mod} 2\pi)$$

for any a, b, c (closed triangle or not)

$\rightarrow$ **Important to measure the sides of the triangle.**

($|V_{ub}|, |V_{cb}|, |V_{td}|$)

B Mixing and lifetimes

Angle α/ϕ_2 (BaBar)

$$\Gamma(\Delta t) = Ne^{-\gamma\Delta t}[1 \pm S_{\pi\pi} \sin \Delta m \Delta t \mp C_{\pi\pi} \cos \Delta m \Delta t]$$

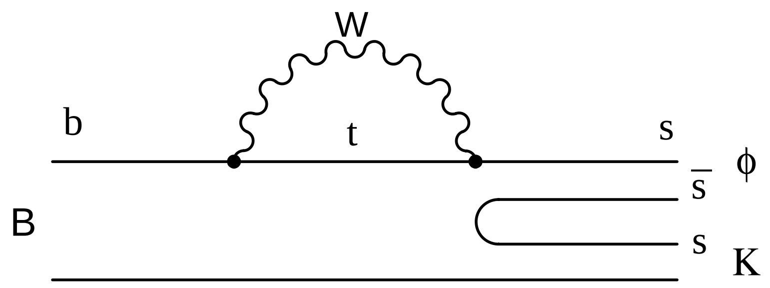
If NO penguin, $S_{\pi\pi} = \sin 2\alpha$, $C_{\pi\pi} = 0$.
(Penguin will be there, but try it anyway for now)

Modes useful for β/ϕ_1

Observable: $\lambda \equiv \dfrac{q\, Amp(\bar{B}^0 \to f)}{p\, Amp(B^0 \to f)}$

$$(B_{H,L} = pB^0 \pm q\bar{B}^0)$$

- $b \to s$ penguin process.
  - $\phi K_S\,(CP-)$: $\mathrm{Im}\lambda \sim \sin 2\phi_1$
    pure penguin (short or long-distance)
    may be modified by new physics in $b \to s$.



- $b \to c\bar{c}d(s)$ **tree process**
  ($b \to c\bar{c}d$**: some penguin with** V_{td}**)**

  - $D^+D^-(CP+)$ **(**$b \to c\bar{c}d$**):** $\mathrm{Im}\lambda \sim \sin 2\phi_1$
  - $D^{*+}D^{*-}$**: (**$b \to c\bar{c}d$**):** $\mathrm{Im}\lambda \sim \sin 2\phi_1$
    CP**-diluted by polarizations (as in** $J/\Psi K_S^*$**).**

  - $D^{*+}D^-$ **(**$b \to c\bar{c}d$**),** $D^{(*)+}D^{(*)-}K_S$ **(**$b \to c\bar{c}s$**):**
    $\mathrm{Im}\lambda \sim r\sin(2\phi_1 + \delta_{\mathrm{strong}})$
    CP**-diluted.**
    In general, $r \equiv |Amp(\bar{B}^0 \to f)/Amp(B^0 \to f)| \neq 1$**,**
    and the strong phase δ_S **does not cancel out.**

Partial Reconstruction of $D^{*+}D^{-}$ (Belle)

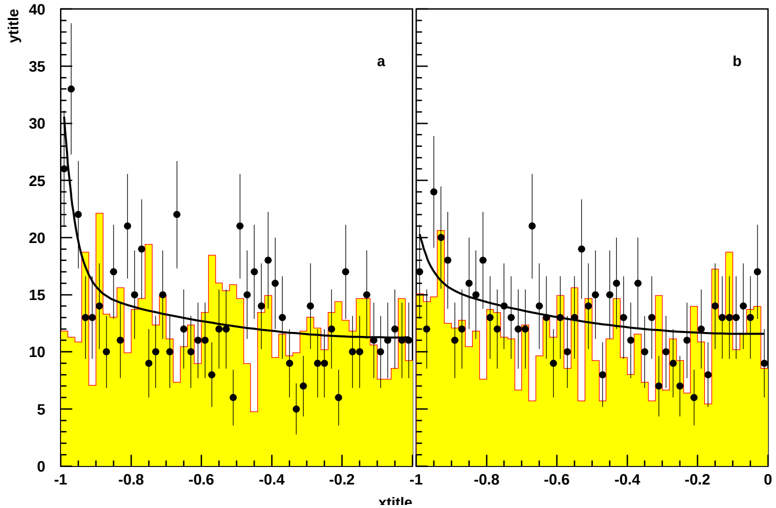
$B^0 \rightarrow D^{*+}D^{-}$, $D^{*+} \rightarrow D^0\pi^+_{slow}$
D^- and $\pi+_{slow}$ back-to-back

No reconstruction of D^0.

θ: helicity angle of D^{*+} decay.
(expect $\cos^2\theta$)
Require $\cos\theta$ is 'physical'
Plot $\cos\theta_{D^- - \pi^+_{slow}}$

Two samples:
w/ and w/o lepton tag.

Lepton-tag



$0.5 < |\cos\theta| < 1.05$ $\quad |\cos\theta| < 0.5$

$$Br(B^0 \rightarrow D^{*+}D^{-}) + Br(B^0 \rightarrow D^{*-}D^{+}) = (1.84 \pm 0.43^{+0.68}_{-0.63}) \times 10^{-3}$$

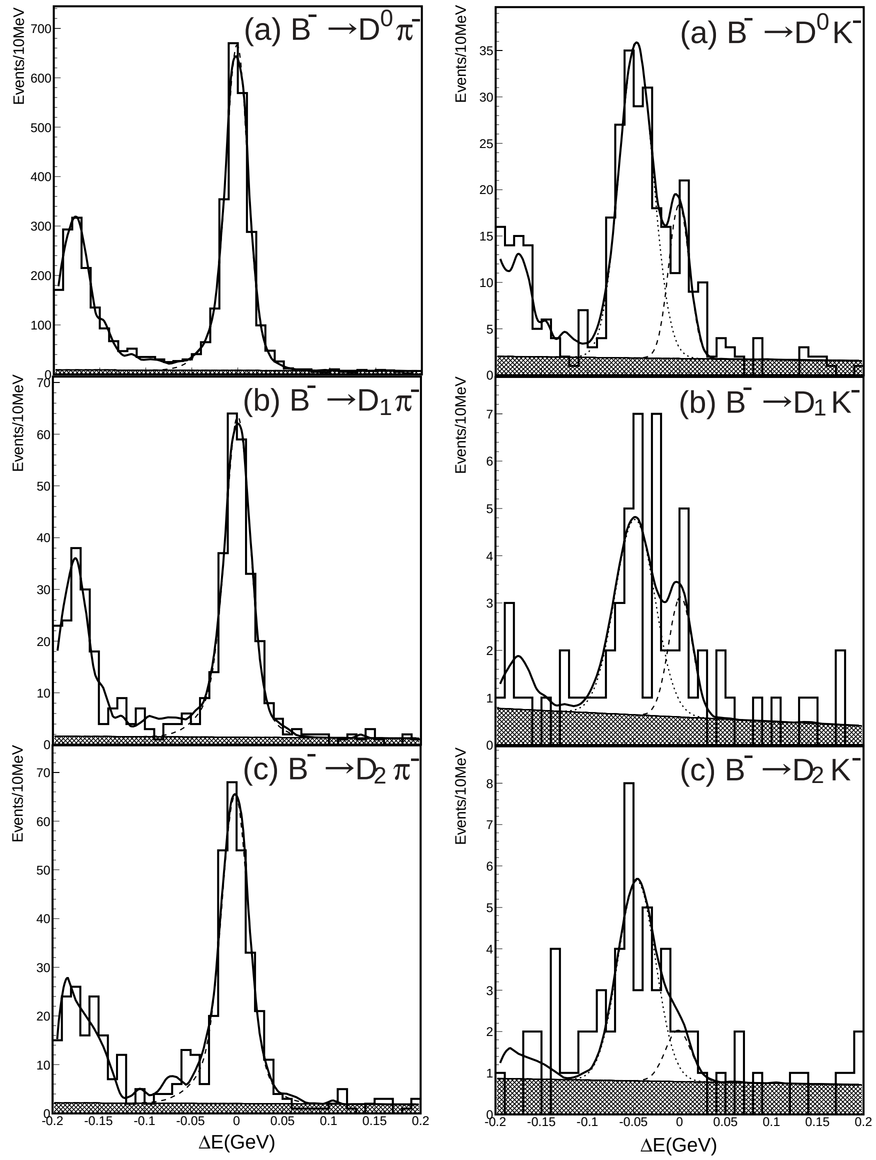
Modes useful for γ/ϕ_3

$B^- \to D_{CP} K^-$ (29.1 fb^{-1}) (Belle)

$D^0 h^-$: assign π mass to h^-.
Signal at $\Delta E = -49$ MeV.

CP $+$:
$K^+K^-, \pi^+\pi^-$

CP $-$:
$K_S\pi^0, K_S\omega, K_S\eta, K_S\eta'$



$B^- \to D_{CP} K^-$

Preliminary

	$CP+$	$CP-$
A_{CP}	$A_1 = 0.29^{+0.29}_{-0.24} \pm 0.05$ $-0.14 < A_1 < 0.79$	$A_2 = -0.22^{+0.26}_{-0.22} \pm 0.04$ $-0.60 < A_2 < 0.21$
R_{CP}	$R_1 = 1.38 \pm 0.38 \pm 0.15$	$R_2 = 1.37 \pm 0.36 \pm 0.12$

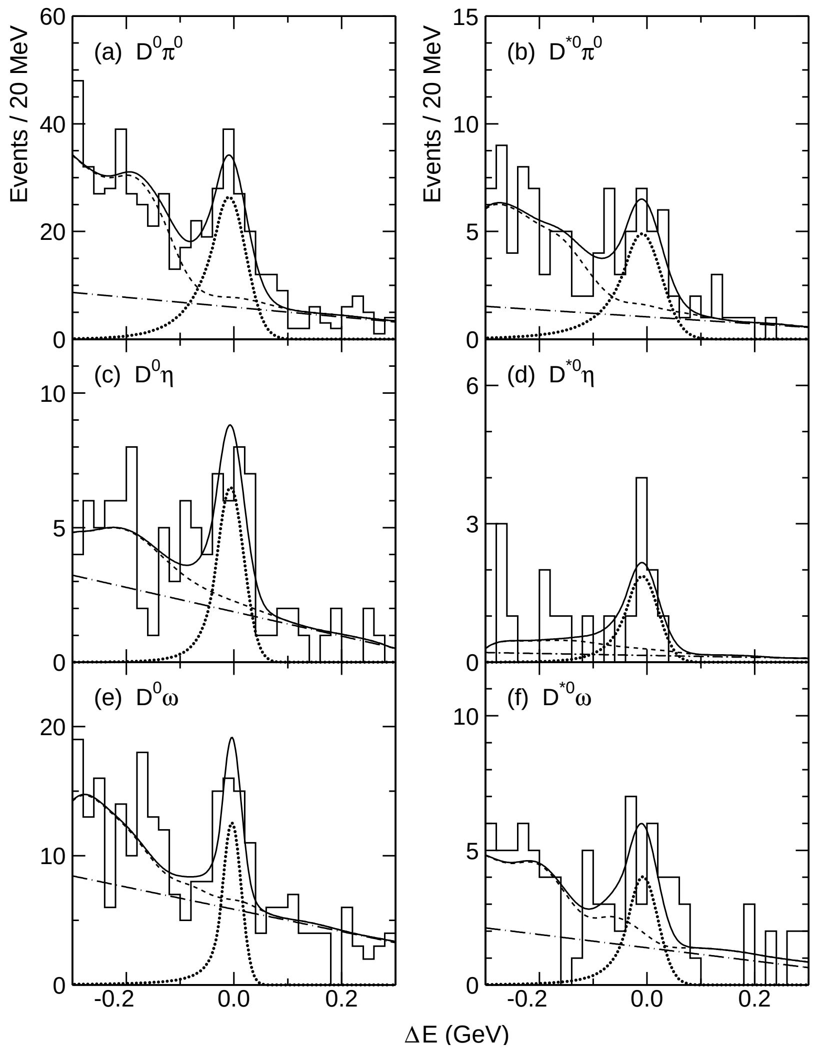
$$R_i \equiv \frac{Br(B^\pm \to D_i K^\pm)/Br(B^\pm \to D_i \pi^\pm)}{Br(B^\pm \to D^0 K^\pm)/Br(B^\pm \to D^0 \pi^\pm)}$$

(Cabibbo suppression factor ratio, D_{CP} vs D^0)

$A_1 \sim -A_2$ expected. Still consistent with no asymmetry.

Color-suppressed $b \to c\bar{u}d$ Modes

$Br(\times 10^{-4})$	Belle	Th.Model
$D^0\pi^0$	$3.1 \pm 0.4 \pm 0.5$	0.7
$D^{*0}\pi^0$	$2.7^{+0.8+0.5}_{-0.7\,0.6}$	1.0
$D^0\eta$	$1.4^{+0.5}_{-0.4} \pm 0.3$	0.5
$D^{*0}\eta$	$2.0^{+0.9}_{-0.8} \pm 0.4$	1.0
$D^0\omega$	$1.8 \pm 0.5^{+0.4}_{-0.3}$	0.7
$D^{*0}\omega$	$3.1^{+1.3}_{-1.1} \pm 0.8$	1.7



Consistently larger than the factorization model.

FSI rescattering from D^+X^-?

$B^+ \to \chi_{c0} K^+$

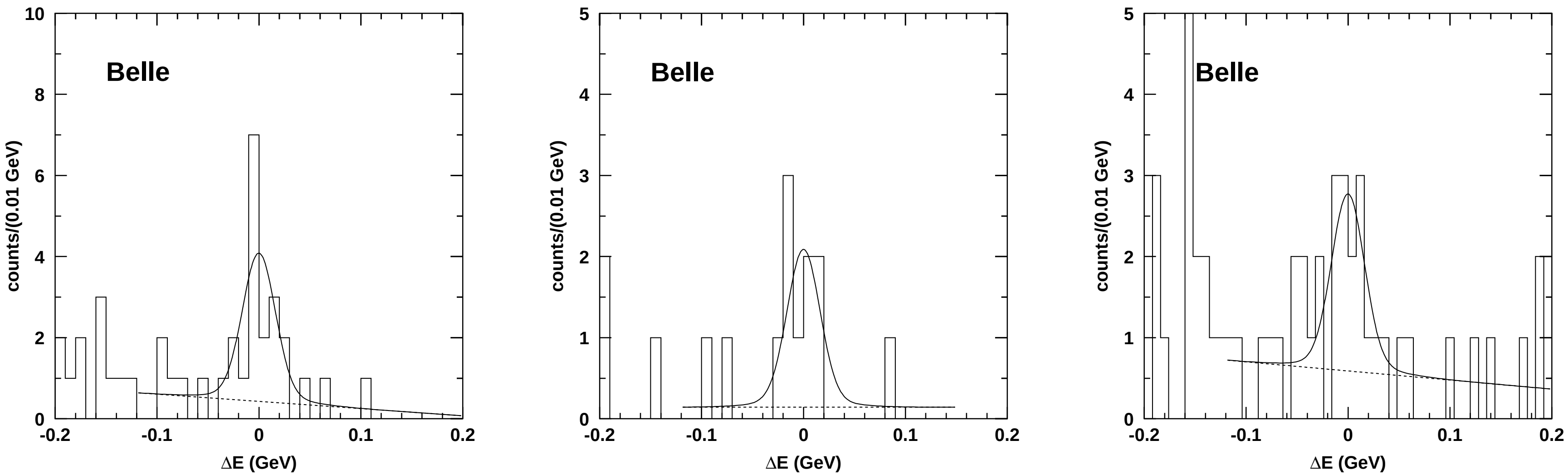
Prohibitted in naive factorization: $\langle \chi_{c0} | (\bar{c}c)^{\mu}_{V-A} | 0 \rangle = 0$

(P and C conservation. Conserved vector current also is relevant.)

$$Br(B^+ \to \chi_{c0} K^+) = (8.0^{+2.7}_{-2.4} \pm 1.0 \pm 1.1[Br]) \times 10^4$$

$$Br(\chi_{c0} K^+)/Br(J/\Psi K^+) = 0.77^{+0.27}_{-0.23} \pm 0.11$$

$\chi_{c0} \to \pi^+\pi^-$ $\qquad$ $\chi_{c0} \to K^+K^-$ $\qquad$ $\chi_{c0} \to K^{*0}K^+\pi^-$



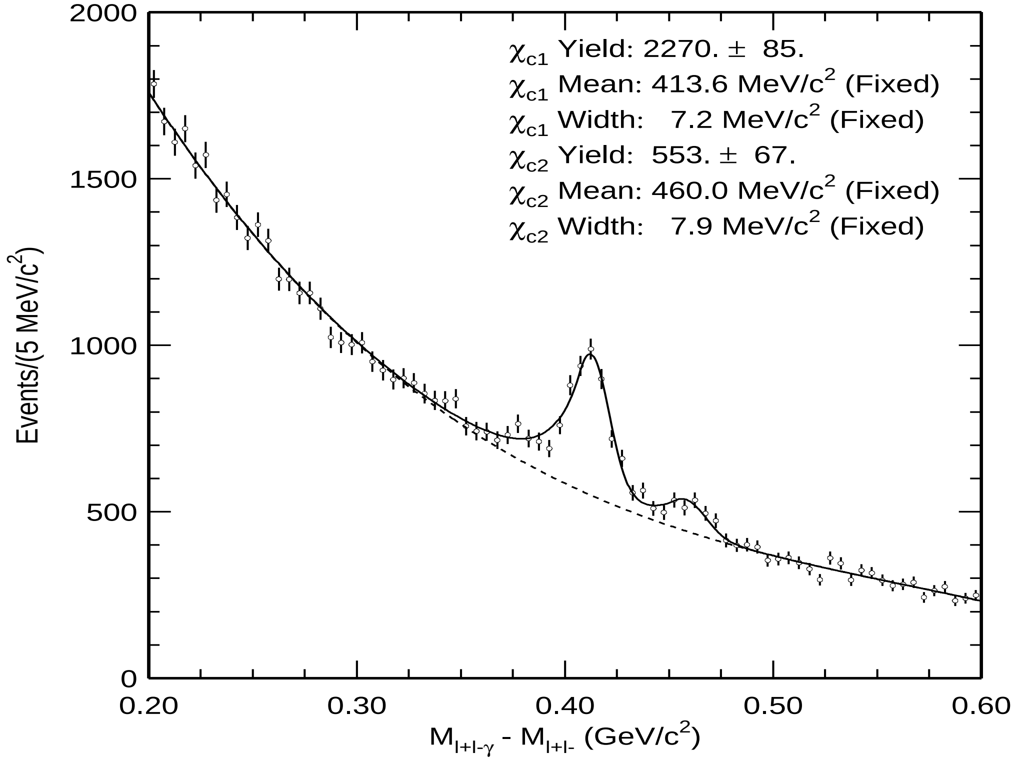
Inclusive χ_{c2} Productions

Prohibitted in naive factorization:

$$\langle \chi_{c2} | (\bar{c}c)^{\mu}_{V-A} | 0 \rangle = 0$$

$$\chi_{c1,2} \to J/\Psi\gamma, \; J/\Psi \to \ell^+\ell^-$$

$$Br(B \to \chi_{c2}X) = (1.22 \pm 0.24 \pm 0.25) \times 10^{-2}$$
$$Br(B \to \chi_{c1}X) = (3.14 \pm 0.16 \pm 0.29) \times 10^{-2}$$



$B^+ \to p\bar{p}K^+$

Baryon production in charmless modes.

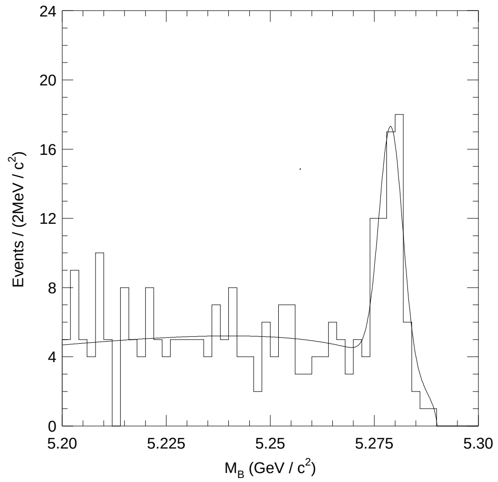
Reject charmonia$\to p\bar{p}$.

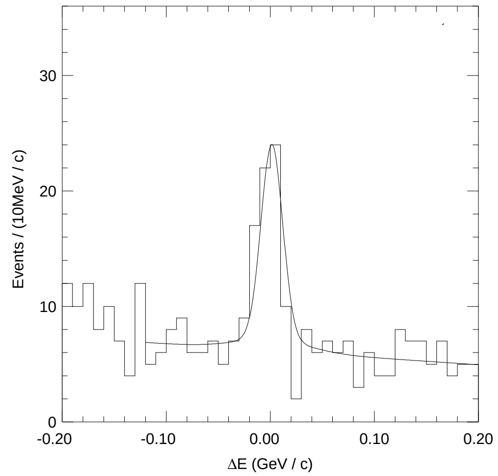
Preliminary

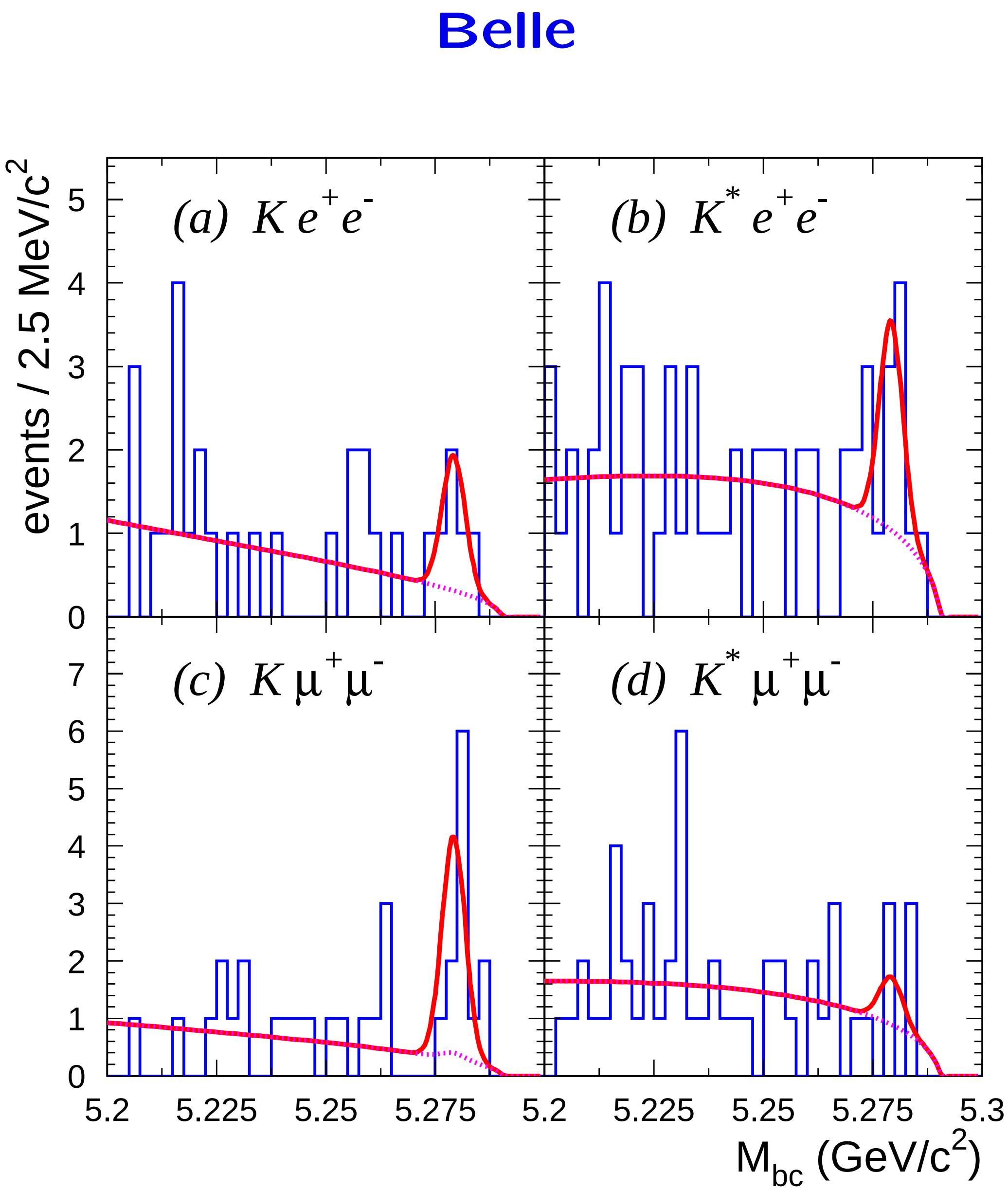
	$Br(\times 10^{-6})$
$p\bar{p}K^+$	$4.2 \pm 0.8 \pm 0.6$ $(M_{p\bar{p}} < 3.4\text{GeV})$
$p\bar{p}$	< 1.6
$\Lambda\bar{\Lambda}$	< 2.3
$\bar{\Lambda}p$	< 2.1

Why not 2-body modes?

$B^+ \to p\bar{p}K^+$






Belle
(a) K e+e-
(b) K* e+e-
(c) K μ+μ-
(d) K* μ+μ-
events / 2.5 MeV/c2
Mbc (GeV/c2)

Charm Physics

A. Lifetimes

1. $\tau_{D_S^+}/\tau_{D^0} \quad = \quad \begin{cases} 1.17 \pm 0.02 \pm 0.01 & \text{(Belle)} \\ 1.20 \pm 0.02 & \text{(PDG)} \end{cases}$

   Annihilation diagram important.

2. $\tau_{\Xi_c^+}/\tau_{\Lambda_c^+} = \begin{cases} 2.8 \pm 0.03 & \text{(CLEO)} \\ 2.1 \pm 0.01 & \text{(FOCUS)} \end{cases}$

   Theoretical expectation: $1.2 \sim 1.7$

B. D^0-$\bar{D}^0$ Mixing

1. $y_{cp} \equiv \frac{\Gamma_{CP+} - \Gamma_{CP-}}{\Gamma_{CP+} + \Gamma_{CP-}} \sim \frac{\tau_{K\pi}}{\tau_{KK}} - 1$

   $\sigma_{y_{cp}} \sim 1\%$. Consistent with zero.

2. $x = \frac{\Delta m}{\Gamma}$, $y = \frac{\Delta \Gamma}{2\Gamma}$

   $\sigma_{x,y} \sim$ a few %. Consistent with zero.

C. $R_{DCSD} = \frac{Br(D^0 \to K^+\pi^-)}{Br(D^0 \to K^-\pi^+)}$

CLEO, FOCUS, BaBar, Belle.

$R_{DCSD} = 0.3\text{-}0.4\%$. Error$\sim 0.05\%$.

D. $D^0 \to K_L\pi^0$ vs $K_S\pi^0$ Belle

E. $A_{CP} \equiv \frac{\Gamma_{D\to f} - \Gamma_{\bar{D}\to\bar{f}}}{\Gamma_{D\to f} - \Gamma_{\bar{D}\to\bar{f}}}$ CLEO

D^0: $K^+K^-, \pi^+\pi^-, K_S\phi, K_S\pi^0, \pi^0\pi^0, K_SK_S$

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

No evidence of CPV.

F. Semieptonic decays. CLEO

$D^+ \to \bar{K}^{*0}\ell^+\nu$, $\Lambda_c \to \Lambda e^+\nu$: Form factors.

HQET $\to B$ system.

$\Omega_c^0 \to \Omega^- e^+\nu$

CLEO-c

- Lower the CESR energy to the charm region.
- Only minor modification to the CLEO detector.
- Collect $\sim$3fb^{-1}/yr.

$\rightarrow$ Full-reconstruction tag: 5.7M D^0, 2.3M D^+, 0.3M D_S^+.

- Errors on $f_{D^+,D_s^+} \sim$ 2% (14-33% now).
- Determine $|V_{cs}|, |V_{cd}|$ to 2% (7-16% now).
- $D \rightarrow K^{(*)}$ and $D \rightarrow \pi$ form factors.
- Other interesting stuff (h_c, η_c, etc.)

Tau Updates

A. Forbidden decays.

$$Br(\tau^- \to \mu^-\gamma) \begin{cases} < 1.0 \times 10^{-6} \text{ Belle(01) 19M } \tau\text{'s} \\ < 1.1 \times 10^{-6} \text{ CLEO(00) 12M } \tau\text{'s} \end{cases}$$

Comparable constraining power on NP as
$Br(\mu^- \to e^-\gamma) < 1.2 \times 10^{-11}$
(MEGA/LAMPH(99))

$$\left.\begin{array}{l} Br(\tau^- \to e^- K^0) < 1.8 \times 10^{-6} \\ Br(\tau^- \to \mu^- K^0) < 1.8 \times 10^{-6} \end{array}\right\} \text{Belle(01)}$$

B. CPV

$\tau^- \to \pi^-\pi^0\nu_\tau$(Belle, CLEO), $\bar{K}^0\pi^-\nu_\tau$(CLEO)

No evidence of CPV.

Lots of potential at Babar, Belle.

Kaon Physics

A. ϵ'/ϵ

$$\mathrm{Re}\frac{\epsilon'}{\epsilon} = \begin{cases} (20.7 \pm 1.5 \pm 2.4 \pm 0.5) \times 10^{-4} & \text{KTeV} \\ (15.3 \pm 2.6) \times 10^{-4} & \text{NA48} \end{cases}$$

Direct CPV in neutral K established.

Difficult to extract CKM angles, however.

B. $K^+ \to \pi^+ \nu\bar{\nu}$ (BNL787)

Measures $|V_{ts}^* V_{td}| \to |V_{td}|$ ($|V_{cb}| = |V_{ts}|$)

2 signal candidates found.

$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

(SM expects: $(0.75 \pm 0.29) \times 10^{-10}$)

Upgarde(BNL949): Runing. 5-10 events in 2 yrs.

FNAL CKM: Approved. 100 events with S/N> 10.

(latter half of this decade)

C. $K_L \to \pi^0 \nu \bar{\nu}$

Measures $\mathrm{Im}(V_{ts}^* V_{td}) \to \eta$

$Br(K_L \to \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$

(SM expects: $(2.6 \pm 1.2) \times 10^{-11}$: $> 10^4$ to go.)

KEK E391a: Data taking 03. Sensitivity $O(10^{-10})$.

BNL KOPIO: Latter half of this decade.

50 events with S/N=2.

Future B Facilities

Asymmetric B-factories at present:

	PEP2	KEK-B
$\mathcal{L}_{\max}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	4.51×10^{33}	5.5×10^{33}
$\int \mathcal{L}dt$/day (pb^{-1})	303.4	311.5
$\int \mathcal{L}dt$ (fb^{-1})	64.7	47.2

Each will have $\sim$100fb^{-1} by this summer.
(200fb^{-1} together $\sim$ the original design
for the lifetime of a B-factory)

$\sim$500fb^{-1} each by 2006

This success was definitely helped by healthy competition where each learned from mistakes and good ideas of the other.

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Future B Facilities

- **CDF/D0 Tevatron Run2(a,b).** Fermilab $p\bar{p}$ collider. Running.
  2fb^{-1} by ∼2004, ~ 15fb^{-1} by 2007+.
- **LHCb.** Dedicated B-detector on LHC.
  Starts ∼2007.
  (ATLAS,CMS have also B programs)
- **BTeV.** Dedicated B-detector on Tevatron.
  Starts ∼2008.
- **Super-KEKB.** $\mathcal{L} \sim 10^{35}$ ($\times 20$ present).
  Evolutionary upgrade. Starts ∼2007.
- **Super-BaBar.** $\mathcal{L} \sim 10^{36}$. Quantum leap from the current machine.