Current Status of CP Violation

(Experimental Results on Beauty)

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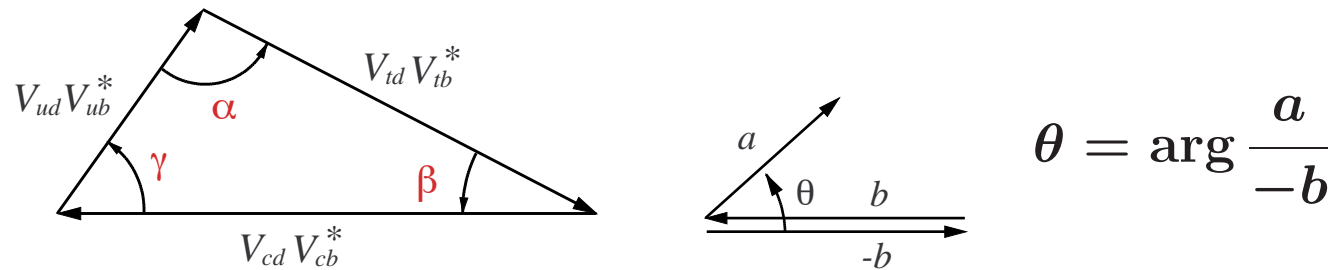**Tohoku University**

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Plan:
1. $\sin 2(\phi 1/\beta)$ by $(c\bar{c})K_{S,L}$ modes
2. $\sin 2(\phi 1/\beta)$ by $b \to s$ penguin modes
3. $\sin 2(\phi_2/\alpha)$ by $\pi\pi$ modes
4. Modes related to ϕ_3/γ
5. Future prospects

CPV in B Meson System

$$\mathcal{L}_{qW}(x) = \frac{g}{\sqrt{2}} \sum_{i,\,j=1,3} V_{i\,j} \; \bar{u}_{iL} \; \gamma_\mu d_{jL} \; W^\mu$$

$u_i = (u, c, t)$, $d_i = (d, s, b)$, and V=CKM matrix (unitary):
e.g: orthogonality of d-column and b-column:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
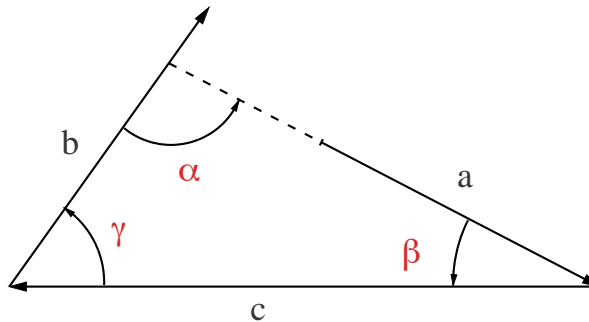

$$\alpha/\phi_2 \equiv \arg\left(\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}\right), \quad \beta/\phi_1 \equiv \arg\left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right), \quad \gamma/\phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right)$$

For any complex numbers a, b, c, trivially

$$\alpha + \beta + \gamma = \pi \quad (\text{mod } 2\pi)$$

$$\alpha \equiv \arg\left(\frac{a}{-b}\right), \quad \beta \equiv \arg\left(\frac{b}{-c}\right), \quad \gamma \equiv \arg\left(\frac{c}{-a}\right).$$

$\rightarrow$ **The condition $\alpha + \beta + \gamma = \pi$ (mod2π) holds even if the triangle does not close (unitarity test)** It simply tests if the angles measured are as defined in (3) in terms of V_{CKM}.

$\rightarrow$ **It is critical to measure the length of the sides.**

e^+e^- **B-Factories**

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0, B^+B^-$$

B's nearly at rest in the $\Upsilon(4S)$ frame:
$$\beta_B \sim 0.06$$

	PEPII(BaBar)	KEKB(Belle)	CESR(CLEO2.x)
type	asymmetric	asymmetric	symmetric
#ring	double	double	single
E_{beam} (GeV)	$9(e^-)/3.1(e^+)$	$8(e^-)/3.5(e^+)$	$5.29(e^\pm)$
$\beta_{\Upsilon(4S)}$ in lab.	0.49	0.39	0
full xing angle	0 mrad	22 mrad	4.6 mrad
$\mathcal{L}_{\text{max}}(\times 10^{33}/\text{cm}^2\text{s})$	6.6	10.6	1.25
$\int \mathcal{L}dt$ (recd. fb^{-1})	130.7	158.7	13.7
off resonance	9%	9%	1/3

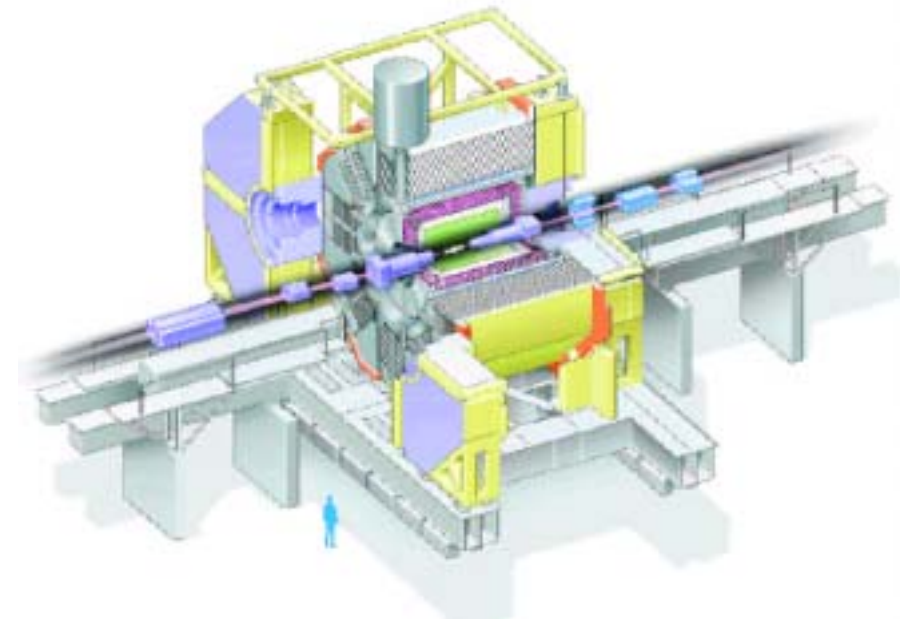# Basic design: Vertexing(Si)-Central tracker(DC)-PID-SC coil -EM calorimeter(CsI)-Muon system(RPC)

BaBar detector
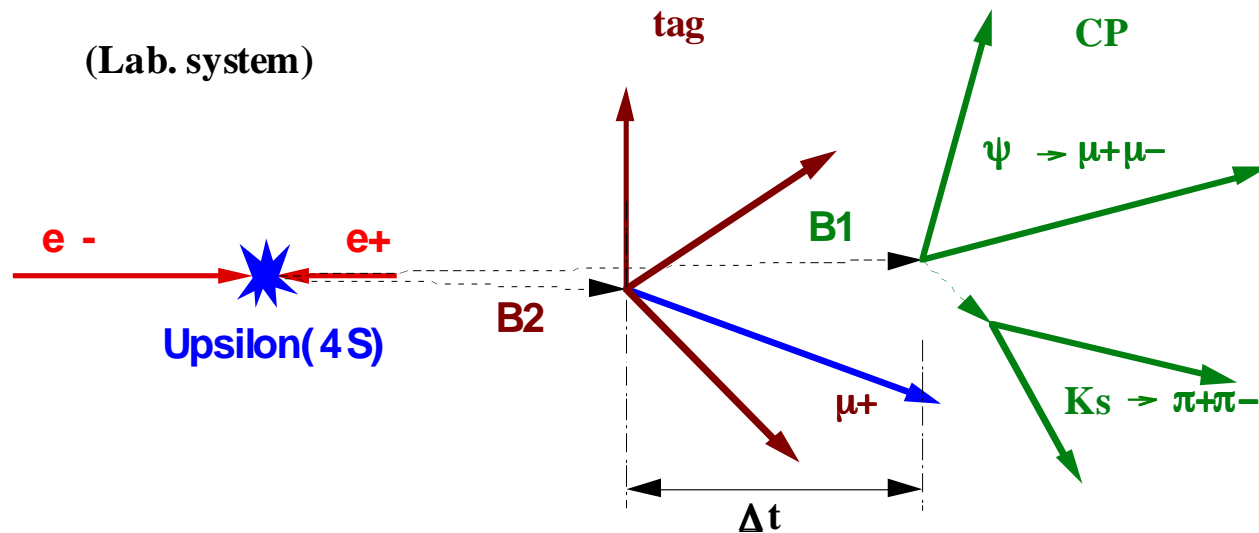

- PID=DIRC(Cerenkov)

Belle detector

- PID=Aerogel+TOF

Measurement of $\sin 2(\phi_1/\beta)$ at asym. B-factories

$$\Upsilon(4S) \to B^0 \bar{B}^0 \to (tag)(J/\Psi K_S)$$

$$\Delta t \equiv t_{CP} - t_{tag} \sim \frac{\Delta z}{\beta \gamma\, c}$$

(t: decay time in the B rest frame)

CP-side Reconstruction and Flavor Tagging
Belle(78 fb^{-1})/BaBar(82 fb^{-1})

mode	CP	N_{evt}	purity
ΨK_S	$-$	1278/1144	0.96/0.96
$\Psi' K_S$	$-$	172/150	0.93/0.97
$\chi_{c1} K_S$	$-$	67/80	0.96/95
$\eta_c K_S$	$-$	122/132	0.71/0.73
$CP-$ total		1639/1506	0.94/0.94
ΨK_L	$+$	1230/988	0.63/0.55
ΨK^{*0}	$+/-$	89/147	0.92/0.81

Flavor tagging:

lepton $(b \to \ell^- X)$

$K^{\pm}$ $(b \to c \to s)$

Λ $(b \to c \to s)$

low-energy $\pi^{\pm}$ (D^{*+})

high-energy tracks

Full B Reconstruction
(When all B decay products are detected)

$$B \rightarrow f_1 \cdots f_n$$

(In the $\Upsilon 4S$ frame)

$E_B = 5.28$ GeV and $|\vec{P}_B| = 0.35$ GeV/c are known.
Use energy-momentum conservation:

- $E_B = \Sigma_i^n E_i \rightarrow \Delta E \equiv E_B - E_{\text{beam}}$
- $\vec{P}_B = \Sigma_i^n \vec{P}_i \rightarrow M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - P_B^2}$

(In the lab. frame: no need to boost)

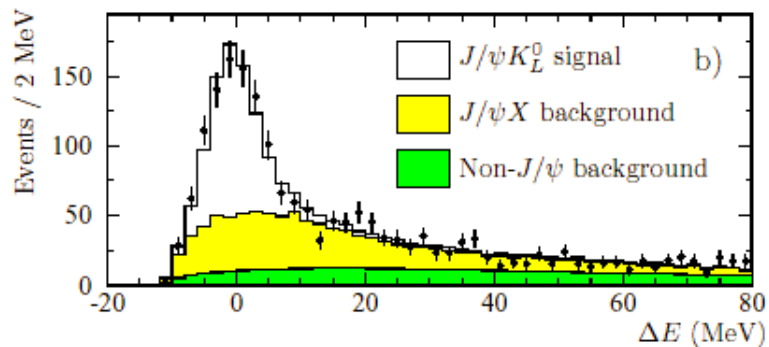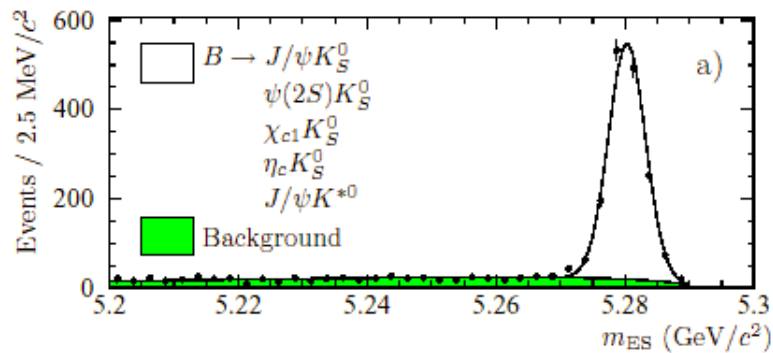$$q_\Upsilon = (E_\Upsilon, \vec{P}_\Upsilon), \quad q_B = (E_B, \vec{P}_B)$$

- $M_{ES} = \sqrt{s/2 + \vec{P}_\Upsilon \cdot \vec{P}_B)^2 / E_\Upsilon^2 - \vec{P}_B^2}$
- $\Delta E = (q_\Upsilon \cdot q_B)/\sqrt{s} - \sqrt{s}$
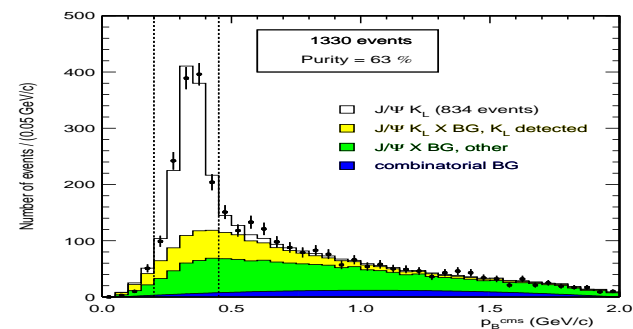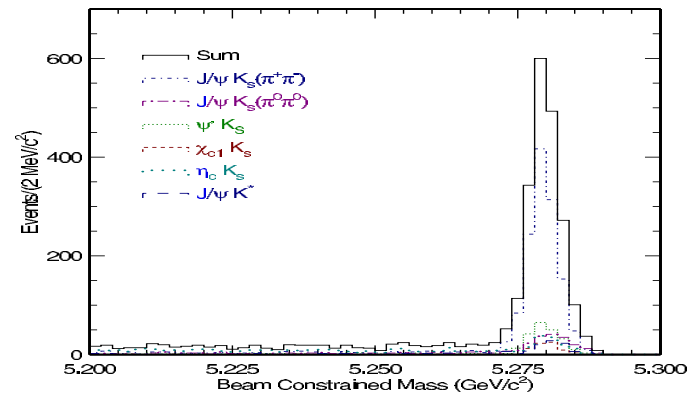
$M_{bc} = M_{ES}$ if masses are correct.
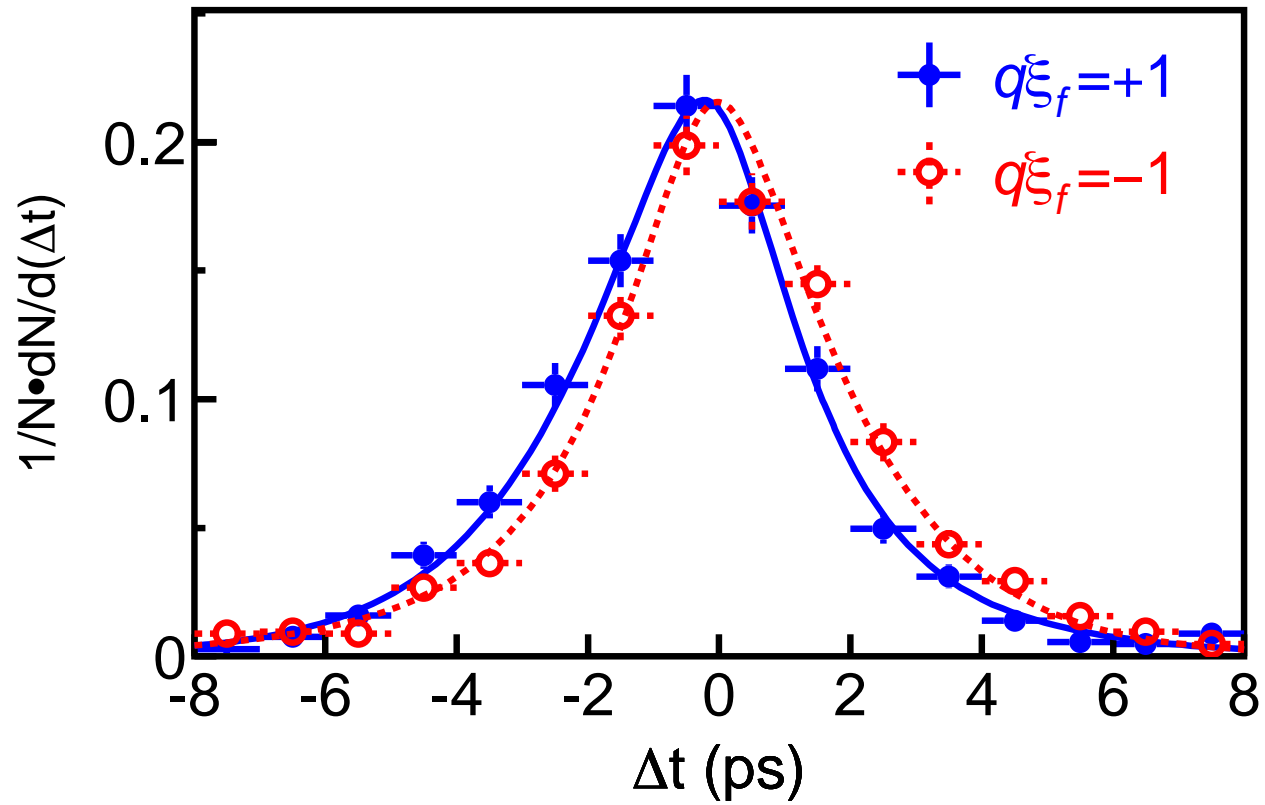
Charmonium $K_{S,L}$ Mode Reconstruction

BaBar

Belle

K_S modes: cut on ΔE, plot M.

K_L: only its direction measured $\rightarrow$ either P_B or ΔE.

$q = +1$ **Tag side is** B^0
$q = -1$ **Tag side is** $\bar{B}^0$, ξ_f : **CP eigenvalue. -1 for** $J/\Psi K_S$

We observed:

If the tagside is B^0, the $J/\Psi K_S$ side tends to decay later than the tagside.

$$CP \begin{cases} \text{particle} \leftrightarrow \text{antiparticle} \\ \text{mirror inversion (no effect)} \end{cases}$$
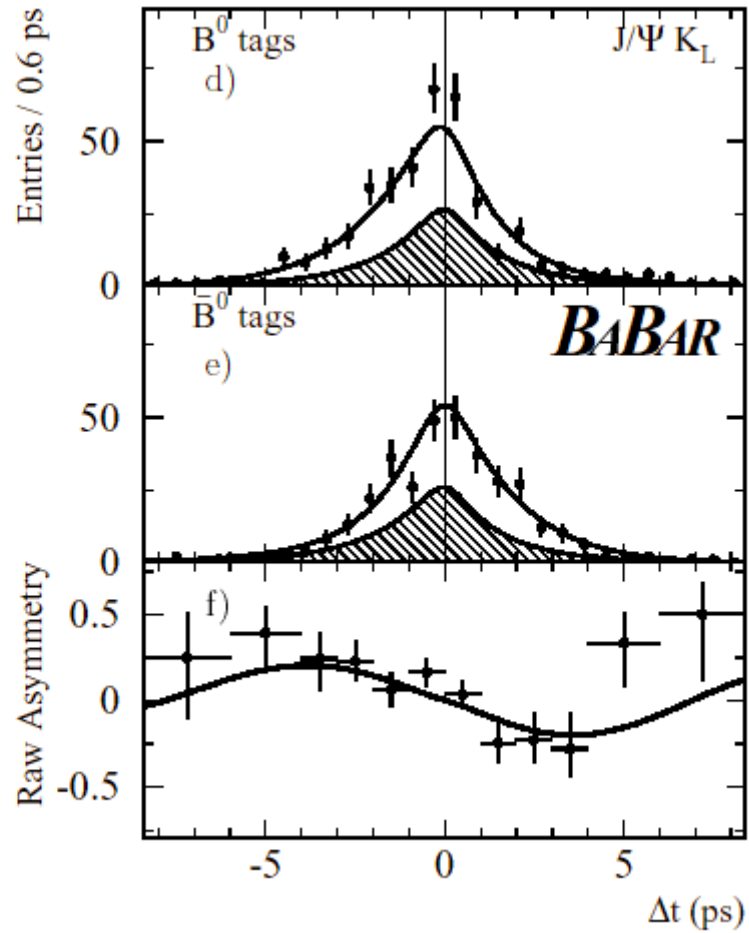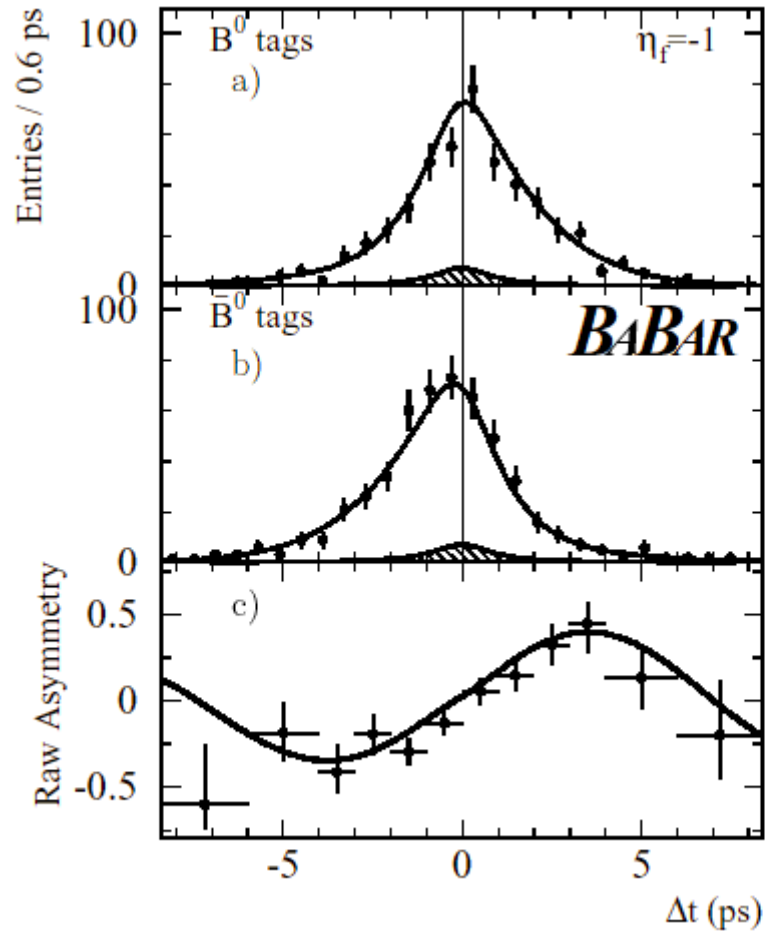
$\downarrow$

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

:Inconsistent with observation.

$\rightarrow CP$ violation

CP−   **CP+**

Asymmetry is opposite for CP + and −.

Flavor-tagged $\Upsilon(4S) \to B^0 \bar{B}^0$

General expression for the decay time distribution.

$$
\begin{cases} B_H = p B^0 - q \bar{B}^0 \\ B_L = p B^0 + q \bar{B}^0 \end{cases},
\qquad
\begin{aligned} B_i(t) &= B_i \, e^{-i\omega_i t} \\ (\omega_i &= m_i + i\tfrac{\gamma_i}{2}) \end{aligned}
\qquad (i = H, L)
$$

$$
(\, CP|B^0\rangle = |\bar{B}^0\rangle \,)
$$

$$
\boxed{\Gamma(\Delta t) \propto e^{-\gamma |\Delta t|} \left[1 + q(S \sin \delta m \Delta t + A \cos \delta m \Delta t) \right]}
$$

$$
\Delta t \equiv t_{\text{signal}} - t_{\text{tag}}
$$
$$
q = +, - \text{ for } B^0, \bar{B}^0 \text{ tag}
$$

$$
S \equiv \frac{2\,\text{Im}\lambda}{|\lambda|^2 + 1}, \qquad
A \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \qquad
\lambda \equiv \frac{q\bar{A}}{pA}
$$

f : CP Eigenstate

In SM, we expect (phase convention: $CP|B^0\rangle = |\bar{B}^0\rangle$)

$$\frac{q}{p} = e^{-2i\phi_1} \quad \rightarrow \quad \left|\frac{q}{p}\right| = 1 \text{ (experimentally, later)}$$

$|\lambda| \neq 1(A \neq 0)$ means $|A(\bar{B}^0 \rightarrow f)| \neq |A(B^0 \rightarrow f)|$: (direct CPV)

If $CP|f\rangle = \xi_f|f\rangle$, and the decay is CP invariant
$((CP)S(CP)^\dagger = S)$,

$$\lambda = \underbrace{\frac{q}{p}}_{e^{-2i\phi_1}} \underbrace{\frac{\langle f|(CP)^\dagger}{\xi_f^*\langle f|}}_{} \underbrace{\frac{(CP)S(CP)^\dagger}{S}}_{} \underbrace{\frac{(CP)|\bar{B}^0\rangle}{|\bar{B}^0\rangle}}_{} = e^{-2i\phi_1}\xi_f$$

$$\frac{\langle f|S|\bar{B}^0\rangle}{}$$

With $A = 0$,

$$\Gamma(\Delta t) \propto e^{-\gamma|\Delta t|}(1 + qS\sin\delta m\Delta t), \quad S = -\xi_f\sin 2\phi_1$$

Results on Charmonium-$K_{S,L}$ Analyses

$$S \; : \; \Delta t \leftrightarrow -\Delta t \; \textbf{asymmetry}$$

$$A \; : \; q+ \leftrightarrow q- \; \textbf{area asymmetry}$$

$$\sin 2(\phi_1/\beta) = \begin{cases} 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{sys}) \; (\text{Belle}) \\ 0.741 \pm 0.067(\text{stat}) \pm 0.034(\text{sys}) \; (\text{BaBar}) \end{cases}$$

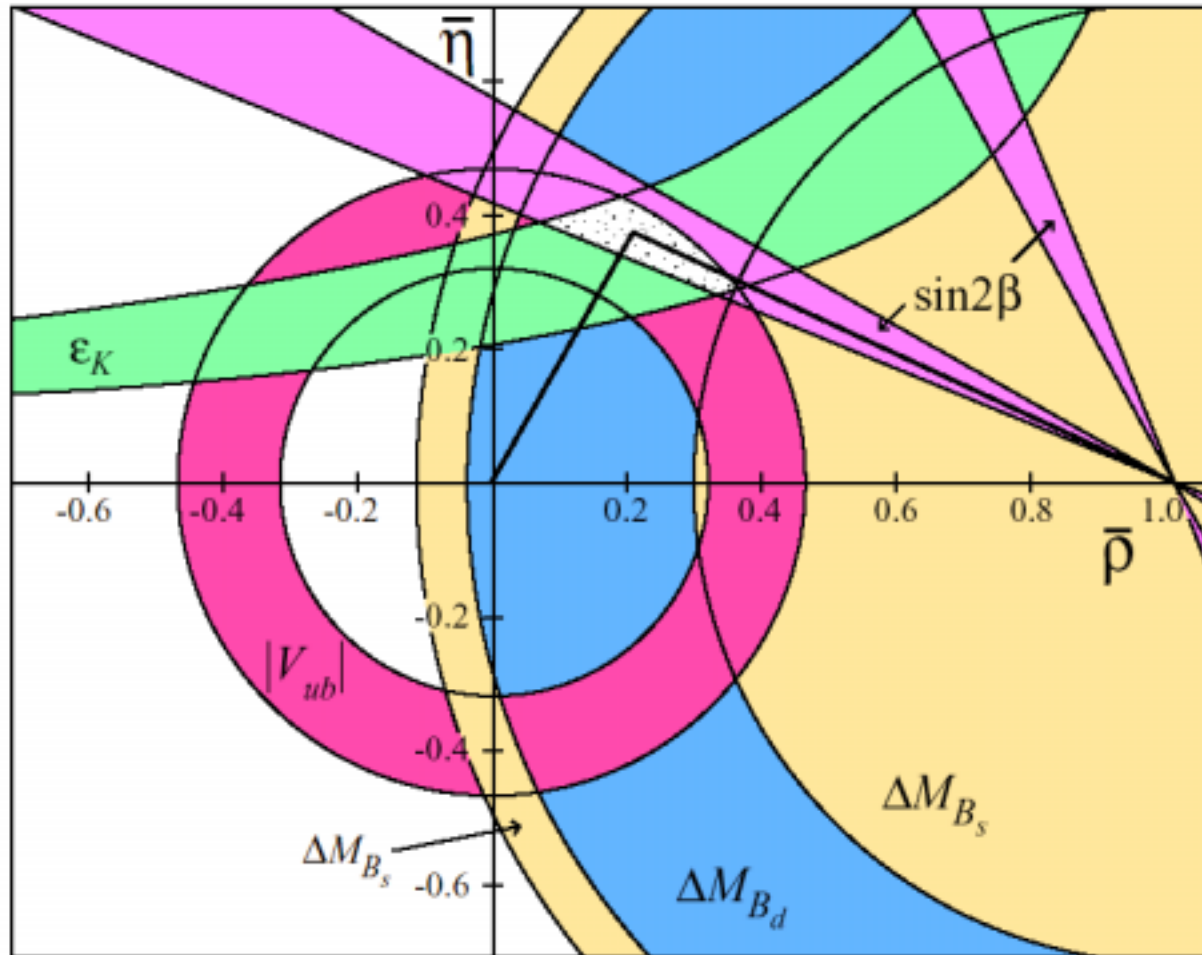(**HFAG** average) $\sin 2(\phi_1/\beta) = 0.734 \pm 0.055$

Direct CPV (Belle, BaBar combined)

$$A_{Belle}(\equiv -C_{BaBar}) = -0.052 \pm 0.047$$

No indication of direct CPV.

(Belle result to be updated for 140 fb^{-1} at LP03)

PDG2002 updated

All regions cross at one point!

CP contents in $\Psi K^{*0}(\to K_S \pi^0)$
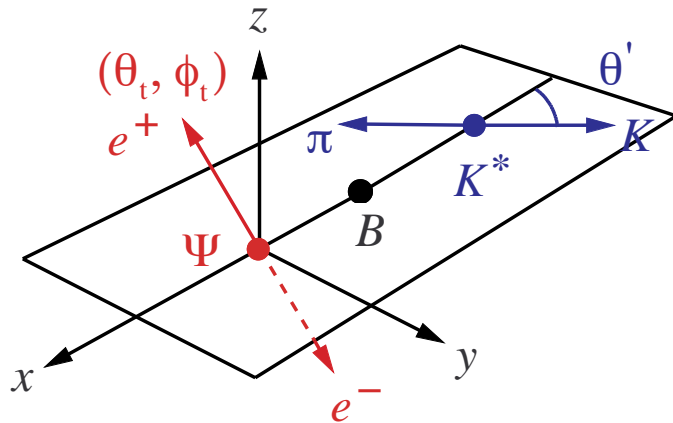
B (spin-0) $\to \Psi$ (spin-1) K^{*0} (spin-1)
3 polarization states: helicities $= (++, --, 00)$

$\to A_\parallel = \frac{1}{2}(H_{++} + H_{--}), \quad A_0 = H_{00}, \quad A_\perp = \frac{1}{2}(H_{++} - H_{--})$

$A_\parallel, A_0$: $CP+$, $\quad A_\perp$: $CP-$

Full angular analysis of the isospin-related modes
$[\Psi K^{*0}(K^+\pi^-), \Psi K^{*+}(K^+\pi^0, K^0\pi^+)]$

$|A_\parallel|^2 + |A_0|^2 + |A_\perp|^2 = 0$

$|A_0|^2$	0.617 ± 0.020
$|A_\perp|^2$	0.192 ± 0.023
$\arg(A_\parallel)$	2.83 ± 0.19
$\arg(A_\perp)$	-0.09 ± 0.13

(Belle 29.4 fb^{-1})

No indication of FSI phases.
$\mathrm{frac}(CP-) = 0.191 \pm 0.023(\mathrm{stat}) \pm 0.026(\mathrm{sys})$

(ΨK^{*0} used as incoherent sum of $CP\pm$ in the previous analysis)

ΨK^{*0} Δt Fulll Angular Analysis (Belle 78fb^{-1})

$$\frac{d\Gamma}{d\vec{\theta}d\Delta t} \propto e^{-\frac{|\Delta t|}{\tau_B}} \sum_{i=1}^{6} g_i(\vec{\theta})a_i(\Delta t)$$

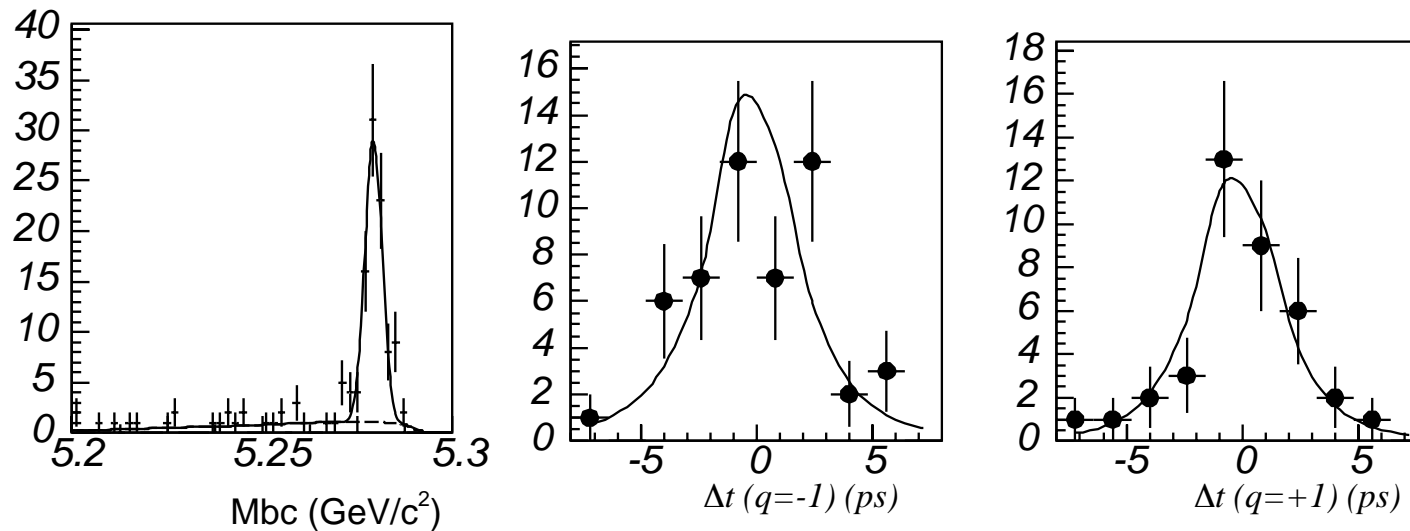$$\vec{\theta} \equiv (\cos\theta_t, \phi_t, \cos\theta')$$

Information on $\cos 2\phi_1$ (as well as on $\sin 2\phi_1$) thourgh interference of $A_{\parallel/0}$ and $A_\perp$: (B. Kaiser)

$$a_{5/6} = q\big[\text{Im}(A^*_{\parallel/0}A_\perp)\cos\delta m\Delta t$$
$$-\text{Re}(A^*_{\parallel/0}A_\perp)\cos 2\phi_1 \sin\delta m\Delta t\big]$$

$$\begin{cases} g_5 = \sin^2\theta' \sin 2\theta_t \sin\phi_t \\ g_6 = \frac{1}{\sqrt{2}}\sin 2\theta' \sin 2\theta_t \cos\phi_t \end{cases}$$

$\Psi K^{*0}(\to K_S \pi^0)$ Results (Belle)

Unbinned likelihood fit to $(\vec{\theta}, \Delta t)$ distribution.

$\sin 2\phi_1$ floated:

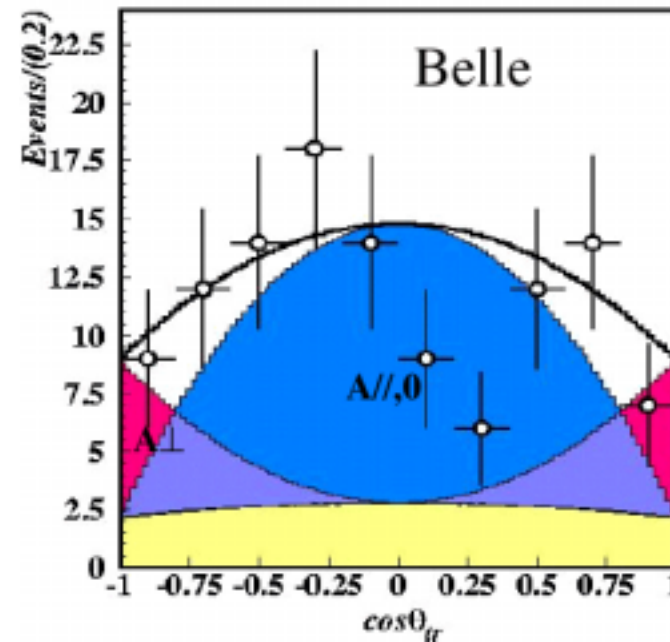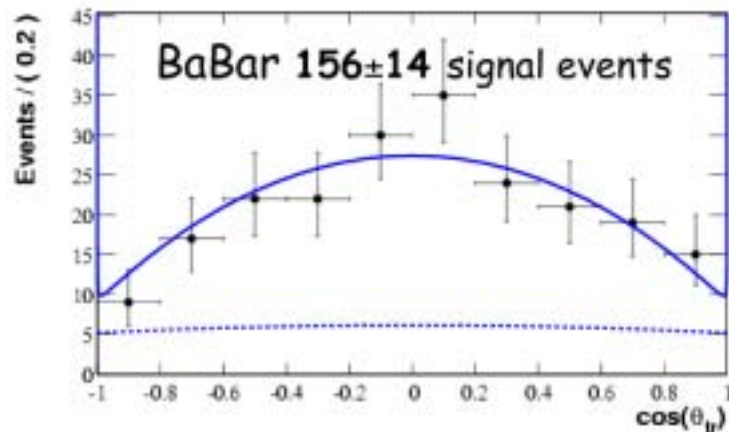$$\sin 2\phi_1 = 0.13 \pm 0.51 \pm 0.06 \,, \quad \cos 2\phi_1 = 1.40 \pm 1.28 \pm 0.19 \,.$$

$\sin 2\phi_1 = 0.82$ fixed:

$$\cos 2\phi_1 = 1.02 \pm 1.05 \pm 0.19 \,.$$

$B \to D^{*+}D^{*-}$ CP Fractions

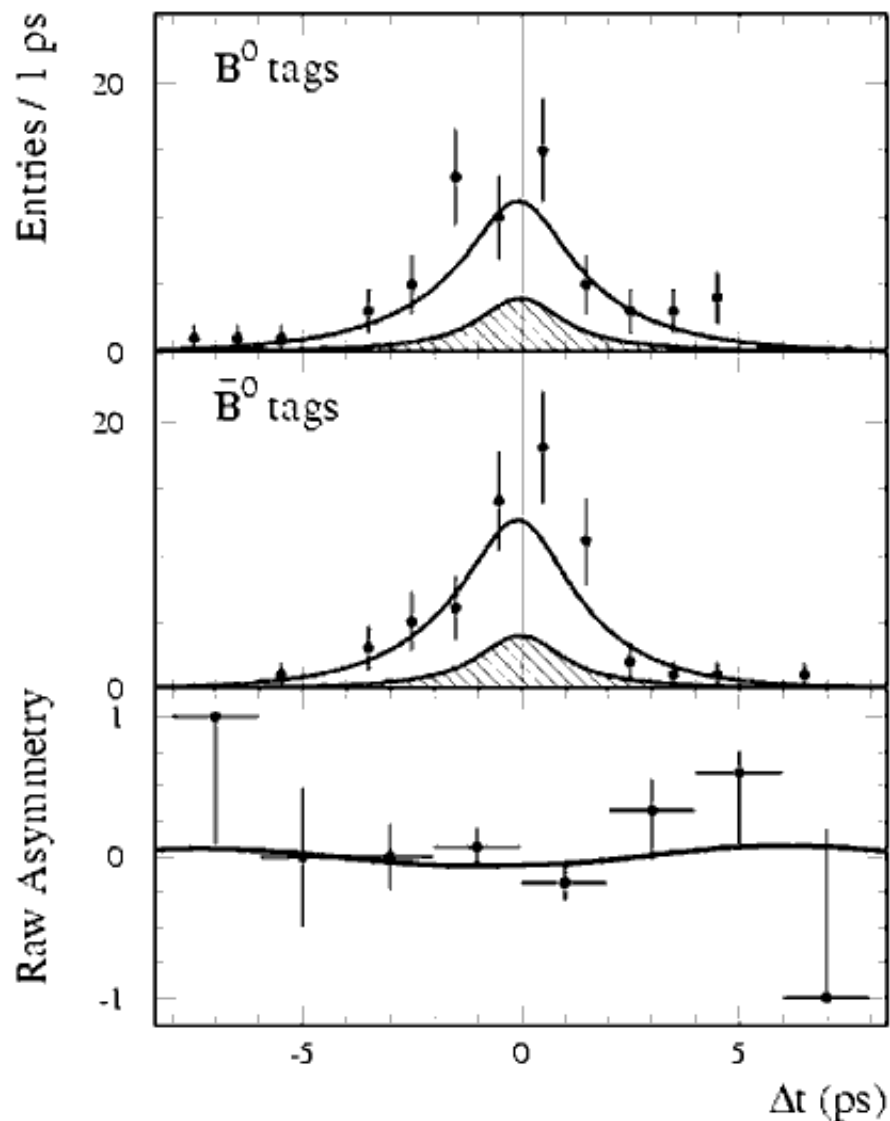$CP+ (A_\parallel, A_0):$ $\cos^2 \theta_t$
$CP- (A_\perp):$ $\sin^2 \theta_t$

- frac$(CP-) = 0.063 \pm 0.055 \pm 0.009$ **(BaBar)**
- **Consistent with HQET+Factoriization (Rosner).**

$B \rightarrow D^{*+}D^{*-}$ $(\Delta t, \theta_t)$ Fit (BaBar)

$$f(\theta_t, \Delta t) = e^{-\frac{\Delta t}{\tau_B}}[G(\lambda_i; \theta_t)$$
$$+ q(S(\lambda_i; \theta_t)\sin \Delta m \Delta t$$
$$- C(\lambda_i; \theta_t)\cos \Delta m \Delta t)]$$

$\lambda_-(CP-)$ **fixed in fit.**

$\text{Im}\lambda_+ = 0.05 \pm 0.29 \pm 0.10$
$|\lambda_+| = 0.75 \pm 0.19 \pm 0.02$

If no Penguin (SM):
$\text{Im}\lambda_+ = -\sin 2\beta, \ |\lambda_+| = 1$
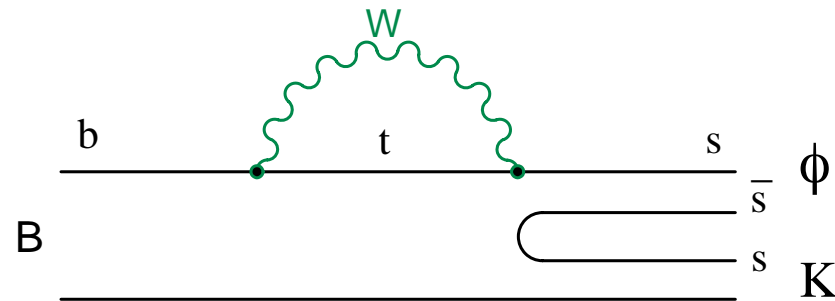
$\text{Im}\lambda_+ : \ > 2\sigma$ **from** $\sin 2\beta$

Time-dependent CPV of $b \to s$ penguin modes

$$\bar{B}^0 \to \begin{cases} \phi K_S \\ K^+ K^- K_S (\text{no } \phi, D0, \chi_{c0}) \\ \eta' K_s \end{cases}$$

In SM, expect $S \sim -\xi_f \sin 2\phi_1 \,, \quad A \sim 0$

Deviation therefrom $\to$ new physics in $b \to s$

(e.g. the W-loop replaced by a charged Higgs loop)

Continuum Suppression

Most rare modes: background is dominated by
continuum $e^+e^- \to q\bar{q}$ 2-jet events.

- **Event shape variables: Fox-Wolfram R_l, thrust, etc.**
  continuum: skinny, $B\bar{B}$: spherical.
- **Angle(B candidate axis, axis of the rest)**
  continuum: aligned, $B\bar{B}$: uniform.
- **Angle(B, beam)**
  continuum: $1 + \cos^2\theta$, B: $\sin^2\theta$.
- **Fisher: $F = \Sigma_i\, c_i X_i$ (above$+X_i$ energy flow etc.)**
  Adjust c_i to maximize the separation.

Belle (78 fb^{-1})
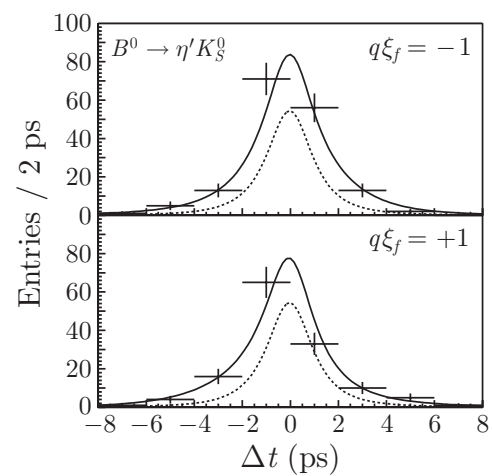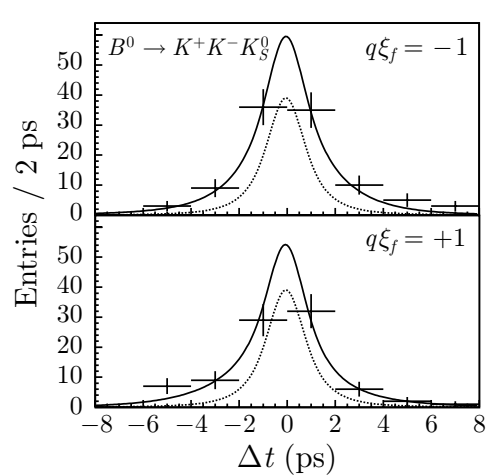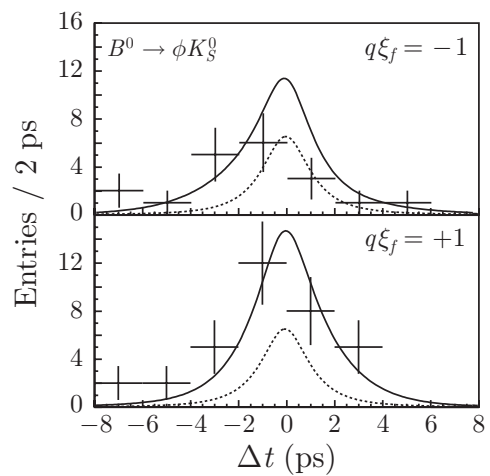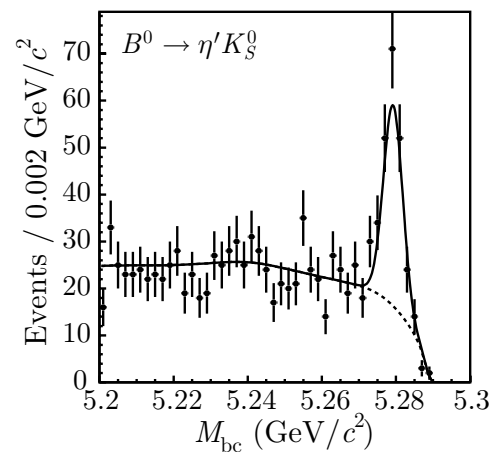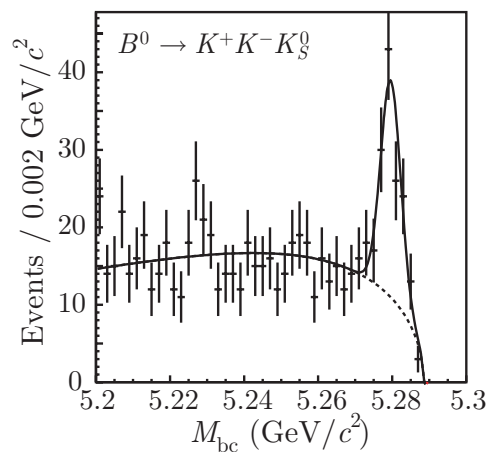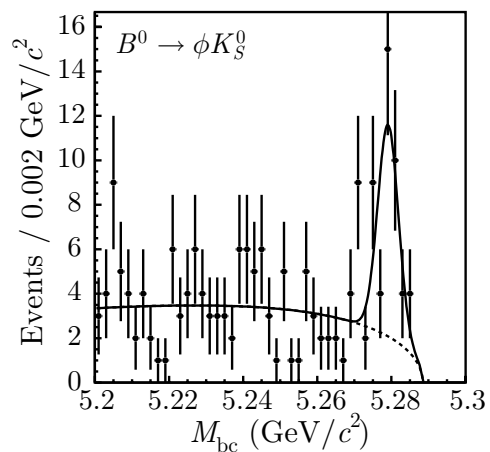
Belle $b \to s$ Penguins

$$A_{cp}(\Delta t) = d(S \sin \delta m \Delta t + A \cos \delta m \Delta t)$$

Plot $-\xi_f A_{cp}$:
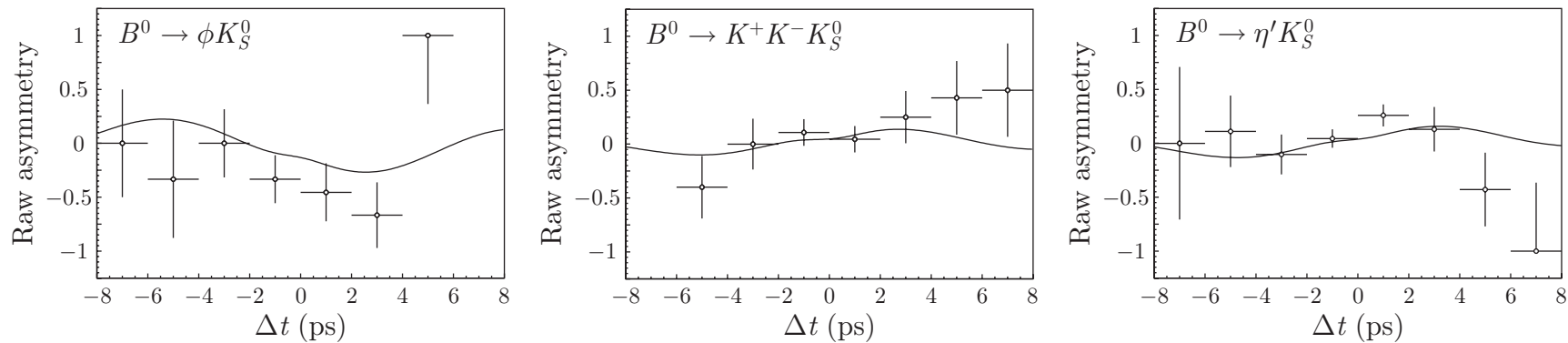
(78fb^{-1})	"$\sin 2\phi_1$"$(-\xi_f S)$	A
ϕK_S	$-0.73 \pm 0.64 \pm 0.22$	$-0.56 \pm 0.41 \pm 0.16$
$K^+ K^- K_S$(non res.)	$+0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0}$	$-0.40 \pm 0.33 \pm 0.10^{+0}_{-0.26}$
$\eta' K_S$	$+0.71 \pm 0.37^{+0.05}_{-0.06}$	$+0.26 \pm 0.22 \pm 0.03$
$J/\Psi K_{S/L}$ etc.	0.735 ± 0.055	-0.052 ± 0.047

$CP(K^+ K^- K_S) = +$ mostly (the last sys errors).

BaBar $b \to s$ Penguins
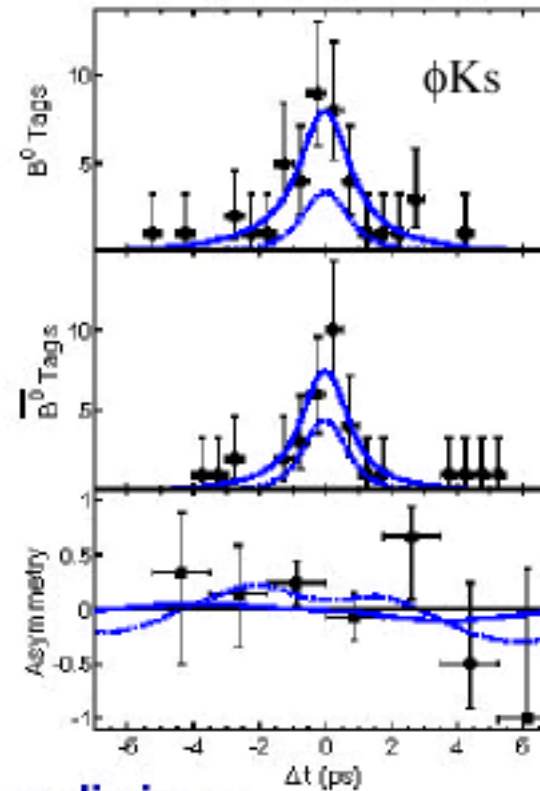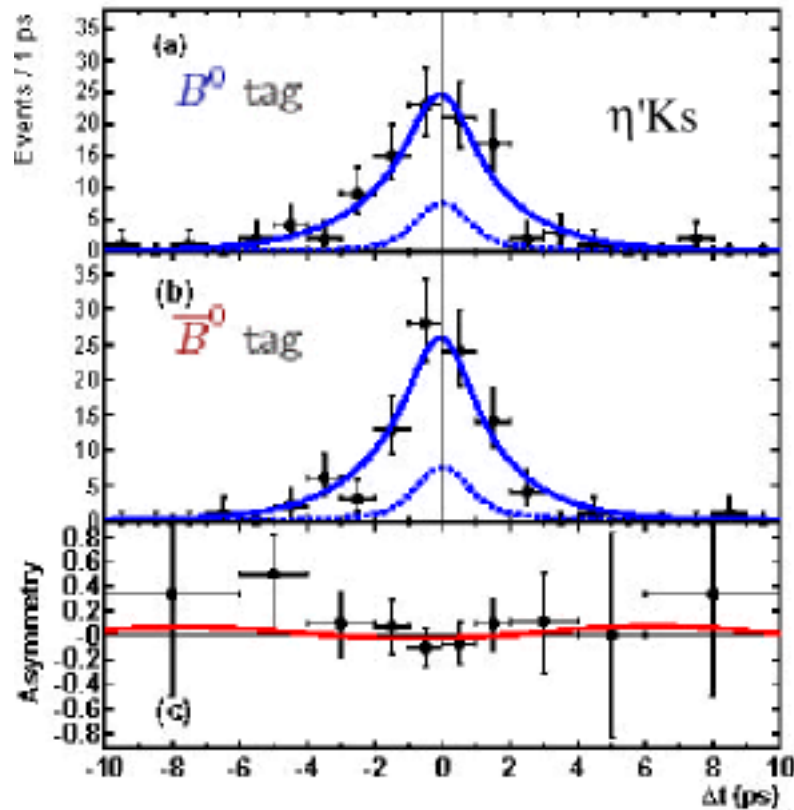
$$S_{\eta'K_S} = 0.02 \pm 0.34 \pm 0.03 \qquad S_{\phi K_S} = -0.18 \pm 0.51 \pm 0.07$$
$$C_{\eta'K_S} = 0.10 \pm 0.22 \pm 0.03 \qquad C_{\phi K_S} = -0.80 \pm 0.38 \pm 0.12$$

$$S_{\eta'K_s} = S_{\phi K_s} = "\sin 2\beta"$$

CP content of $K^+K^-K_S$ (Belle)

(Belle 79 fb^{-1})

	Signal yield (evts)	$\mathcal{B}$(90% U.L.)($\times 10^{-6}$)
$K^+K^-K^+$	565 ± 30	$33.0 \pm 1.8 \pm 3.2$
$K^0K^+K^-$	149 ± 15	$29.0 \pm 3.4 \pm 4.1$
$K_S K_S K^+$	66.5 ± 9.3	$13.4 \pm 1.9 \pm 1.5$
$K_S K_S K_S$	$12.2^{+4.5}_{-3.8}$	$4.3^{+1.6}_{-1.4} \pm 0.75$
$K^+K^-\pi^+$	93.7 ± 23.2	$9.3 \pm 2.3 (< 13)$
$K^0K^-\pi^+$	26.8 ± 16.6	$8.4 \pm 5.2 (< 15)$

$K^+K^-K^+$ $\qquad\qquad$ $K_S K^+K^-$ $\qquad\qquad$ $K_S K_S K^+$
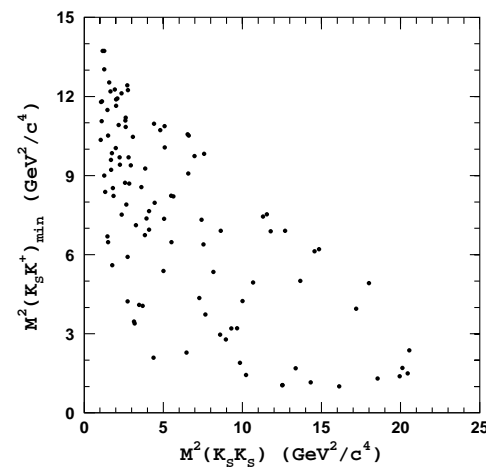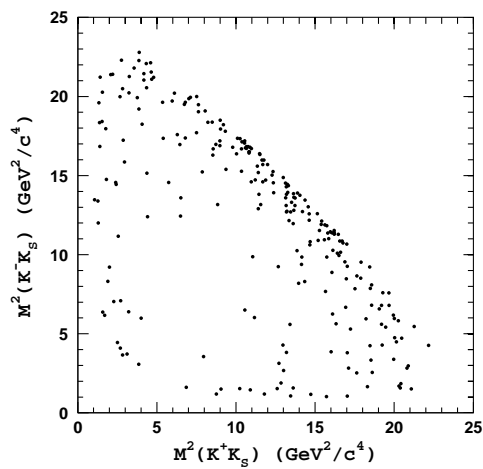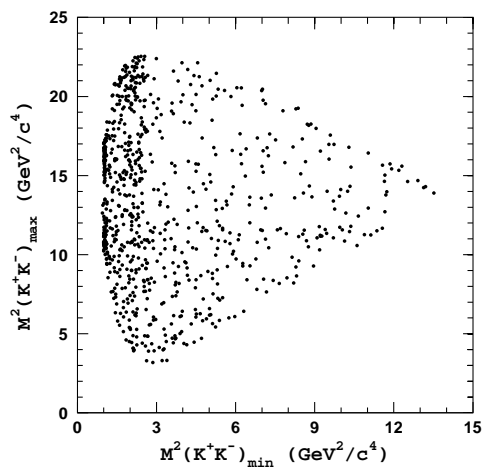
$(K^+K^-)K_S$ **system:**

- $L_{(K^+K^-)-K_S} = L_{K^+-K^-} \equiv L$ (B **is spinless**)
- $CP(K^+K^-) = +$ **(any** L**, since** $C = P$**)**
- $CP(K^+K^-K_S) = \underbrace{CP(K^+K^-)}_{+}\underbrace{CP(K_S)}_{+}(-)^L = (-)^L$

Even/odd $L_{K^+-K^-} \rightarrow$ **even/odd** $CP(K^+K^-K_S)$

On the other hand,

Expect $B \rightarrow K\bar{K}K$ **to be dominated by** $b \rightarrow s$ **penguin. In fact:**
since no $b \rightarrow s$ **penguin (odd** $s/\bar{s}$**) in** $K\bar{K}\pi$ **(even** $s/\bar{s}$**),**

$$F \equiv \frac{\Gamma^{3K}_{b\rightarrow u}}{\Gamma^{3K}_{\text{total}}} \sim \frac{\mathcal{B}(K^+K^-\pi^+)}{\mathcal{B}(K^+K^-K^+)}\left(\frac{f_K}{f_\pi}\right)^2 \tan^2\theta_c = 0.022 \pm 0.005$$

($F = 0.023 \pm 0.013$ **using** $K_S K^- \pi^+$ **and** $K_S K^- K^+$)

We can assume $3K$ **modes are** 100% **due to** $b \rightarrow s$ **penguin.**

Then,

$$\bar{B}^0(b\bar{d}) \rightarrow \begin{pmatrix} s \\ \bar{d} \end{pmatrix} + \begin{matrix} (s\bar{s}) \\ (u\bar{u}) \end{matrix} \rightarrow \begin{matrix} K^-(s\bar{u}) \ K^+(\bar{s}u) \\ \bar{K}^0(s\bar{d}) \end{matrix}$$

$$\downarrow$$

$u \leftrightarrow d, \ \bar{u} \leftrightarrow \bar{d}$ everywhere
(isospin)
$$\downarrow$$

$$B^-(b\bar{u}) \rightarrow \begin{pmatrix} s \\ \bar{u} \end{pmatrix} + \begin{matrix} (s\bar{s}) \\ (d\bar{d}) \end{matrix} \rightarrow \begin{matrix} \bar{K}^0(s\bar{d}) \ K^0(\bar{s}d) \\ K^-(s\bar{u}) \end{matrix}$$

$\bar{B}^0 \rightarrow K^+K^-\bar{K}^0$ and $B^- \rightarrow \bar{K}^0K^0K^-$ have the same rate
and the same kinematic configuration.

also : $(\bar{K}^0K^0)_{L\,even} \rightarrow K_SK_S, K_LK_L$, $(\bar{K}^0K^0)_{L\,odd} \rightarrow K_SK_L$.

$$\frac{CP(K^+K^-\bar{K}^0)+}{CP(K^+K^-\bar{K}^0)\mathrm{any}} = \frac{K^+K^-\bar{K}^0(L_{K^+K^-}\mathrm{even})}{K^+K^-\bar{K}^0(L_{K^+K^-}\mathrm{any})} = \frac{\bar{K}^0K^0K^-(L_{\bar{K}^0K^0}\mathrm{even})}{\bar{K}^0K^0K^-(L_{\bar{K}^0K^0}\mathrm{any})}$$

$$= \frac{2(K_SK_SK^-)}{(K^+K^-\bar{K}^0)} = \begin{cases} 0.86 \pm 0.15 \pm 0.05 \ (\mathrm{incl.} \ \phi K_S) \\ 1.04 \pm 0.19 \pm 0.06 \ (\phi K_S \ \mathrm{removed}) \end{cases}$$

$b \to s$ Penguin Δt Analyses Summary

BABAR ϕK_S — $-0.18 \pm 0.51 \pm 0.07$

BELLE ϕK_S — $-0.73 \pm 0.64 \pm 0.22$

BABAR $\eta' K_S$ — $0.02 \pm 0.34 \pm 0.03$

BELLE $\eta' K_S$ — $0.71 \pm 0.37^{+0.05}_{-0.06}$

BELLE $K^+ K^- K_S$ — $0.49 \pm 0.43 \pm 0.11$

penguin loop WA — 0.19 ± 0.20

$\sin 2\phi_1$ WA — 0.73 ± 0.06

$-\xi_f \, S$
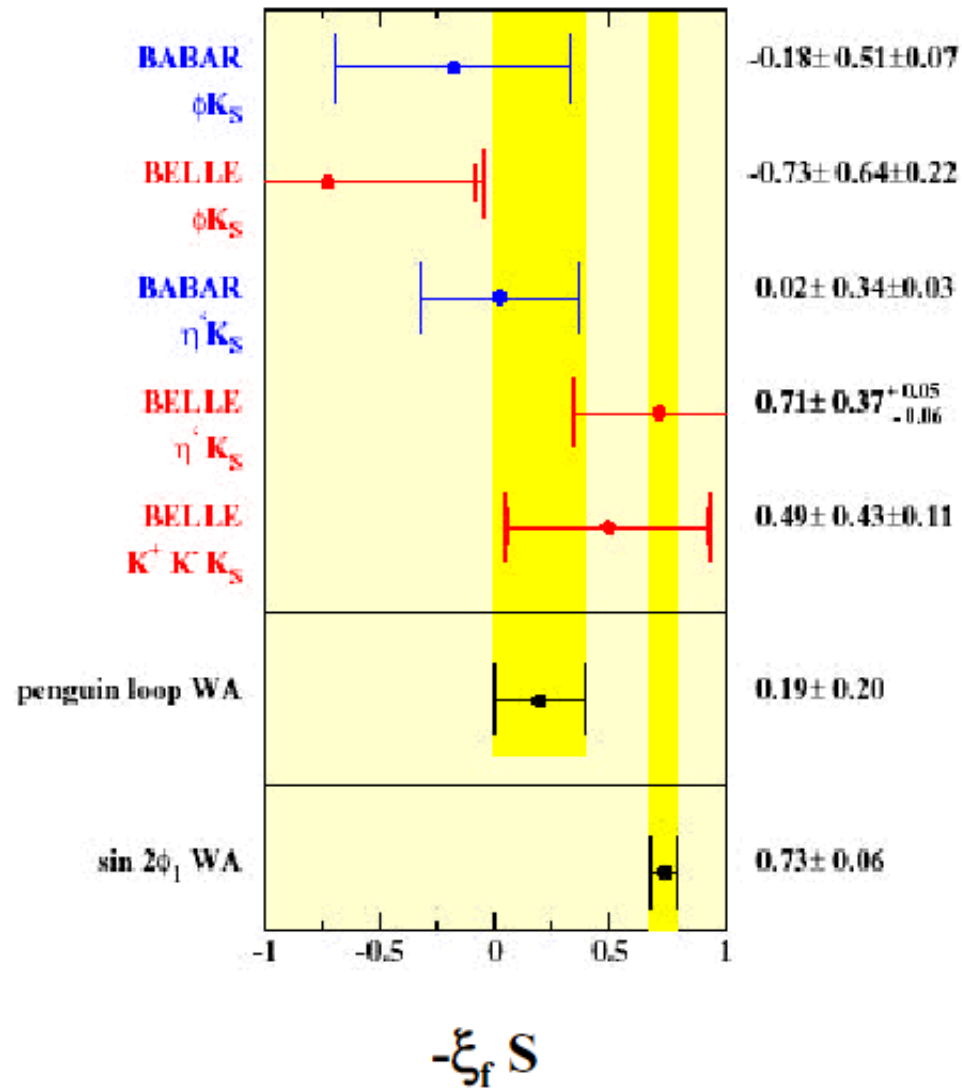
Average of sss modes:
more than 2σ away
from $(c\bar{c})X_s$ mode.

Time-dependent CPV analysis of $\pi^+\pi^-$

$$\frac{d\Gamma}{d\Delta t} \propto e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q(S_{\pi\pi} \sin \delta m \Delta t + A_{\pi\pi} \cos \delta m \Delta t)\right]$$

$$S_{\pi\pi} = \frac{\text{Im}\lambda}{|\lambda|^2 + 1}, \quad A_{\pi\pi} = -C_{\pi\pi} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}.$$

$$|S_{\pi\pi}|^2 + |C_{\pi\pi}|^2 \leq 1$$

Tree
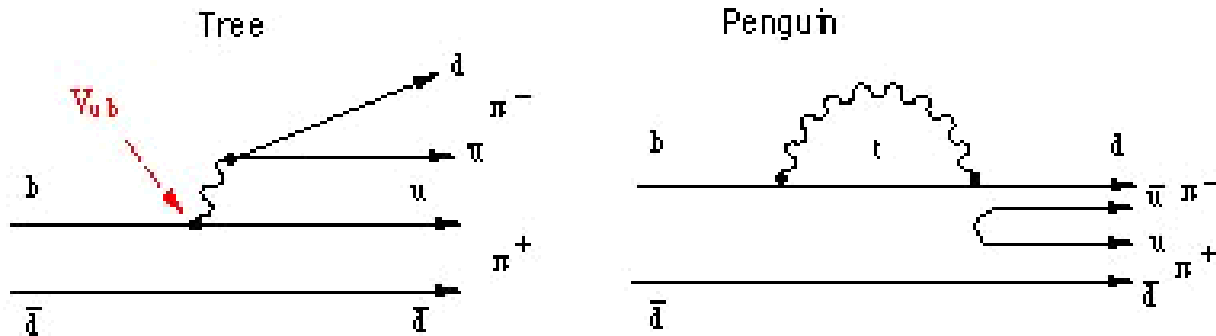
Penguin

Expect:

$S_{\pi\pi} = \sin 2(\phi_2/\alpha)$ IF SM no penguin polution

$A_{\pi\pi} = 0$ IF no direct CPV

Belle $\pi^+\pi^-$ Δt Fit

Belle (78 fb^{-1})

- **Use the same flavor tagging as the ϕ_1 analysis.**
- **Unbinned likelihood fit for Δt distribution.**
- $K^-\pi^+$ **asymmetry known** (~ 0).
  - $\rightarrow$ **Its shape is known.**

- $(q+ \text{ area}) > (q- \text{ area}) \rightarrow A_{\pi\pi} > 0.$
- **Left-right asymmetry** $\rightarrow S_{\pi\pi}.$
  - **(opposite signs for $q\pm$)**
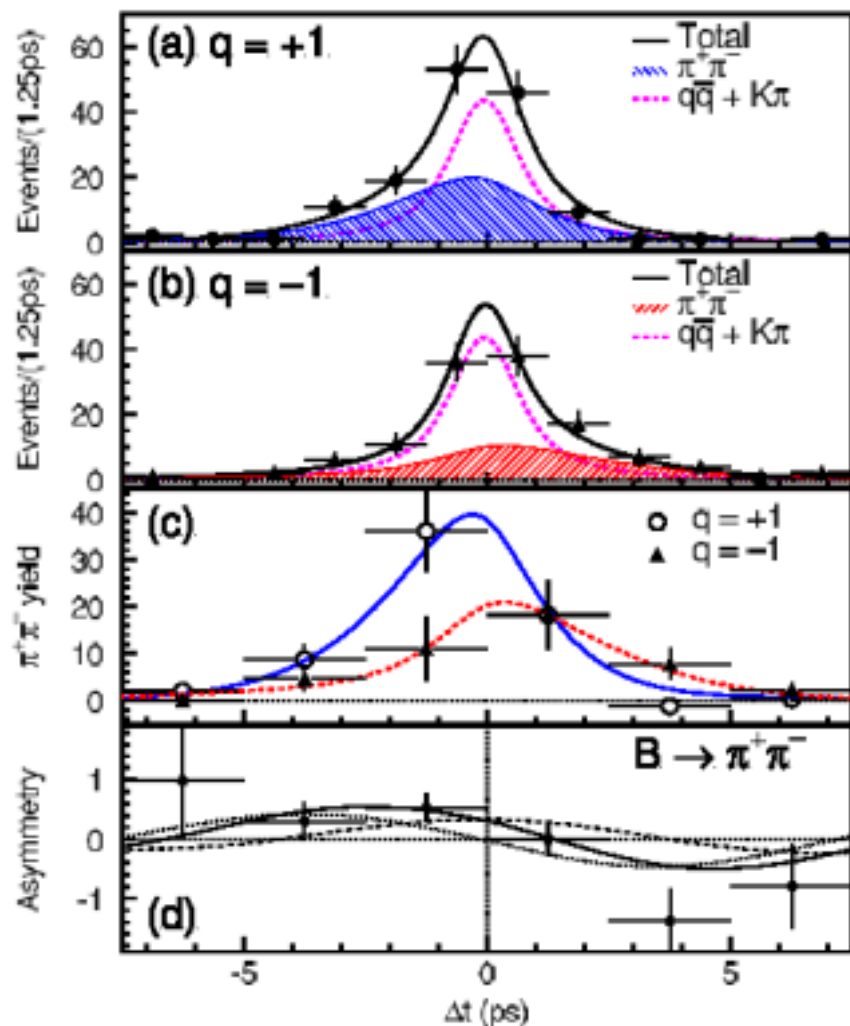
$$S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$$

$$A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$$

Statical errors estimated by 'pseudo experiments' (Gives more consevative errors in general than the fit output.)

Belle $\pi^+\pi^-$ Result

Feldman-Cousin

CPV ($S_{\pi\pi}$,$A_{\pi\pi}$) at 3.4σ.
Direct CPV ($A_{\pi\pi}$) at 2.2σ.

$$\lambda = e^{-2i\phi_2}\frac{1 + |P/T|e^{i(\delta+\phi_3)}}{1 + |P/T|e^{i(\delta-\phi_3)}}$$

Assuming, $\phi_3 = \pi - \phi_1 - \phi_2$,
$\phi_1 = 23.5°$ (Belle, BaBar), and
$|P/T| = 0.15 \sim 0.45$ (th. av.$\sim$ 0.3)
fit for ϕ_2 and δ :

$$\rightarrow 78 < \phi_2 < 152°$$

$\delta \sim -100°$: large strong phase

CL=0.683

CL=0.955

CL=0.9973

CL=0.99994

CL at (0,0) = 0.9993

CL at (-sin2ϕ_1,0)=0.981

$A_{\pi\pi}$

$S_{\pi\pi}$
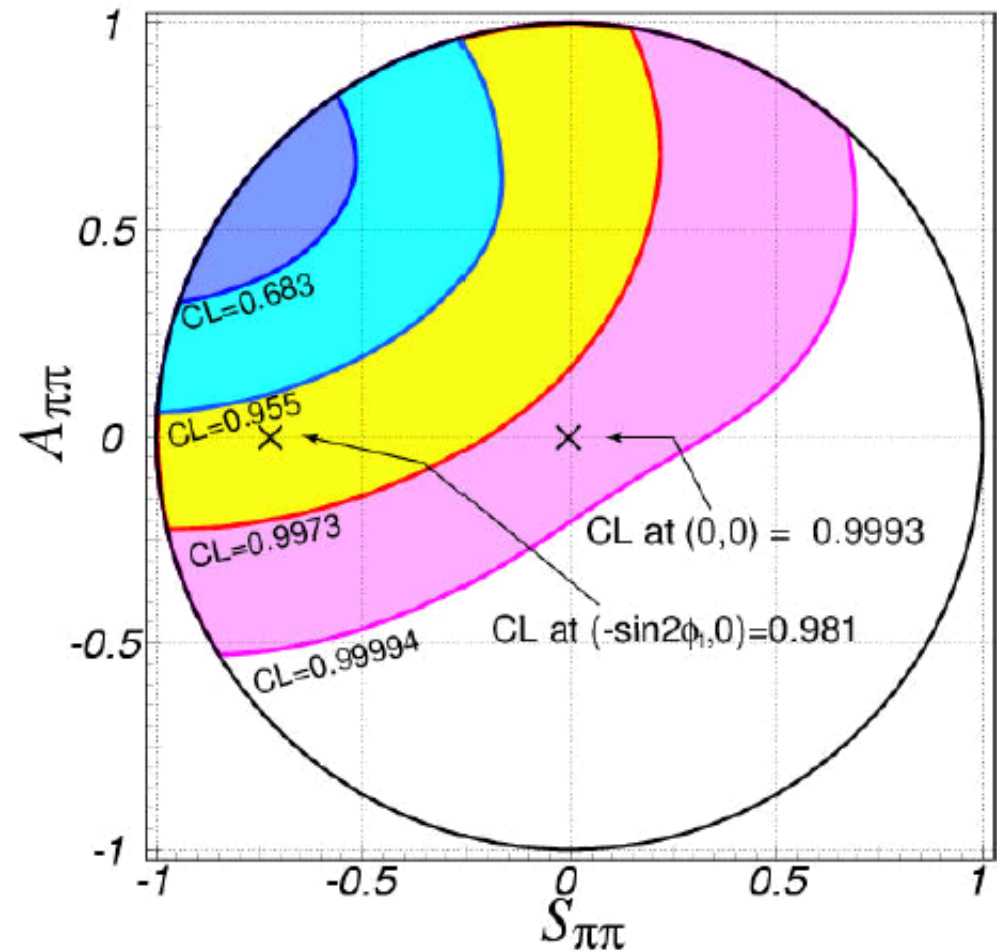
BaBar $\pi^+\pi^-$ Δt Analysis

BaBar (81 fb^{-1})
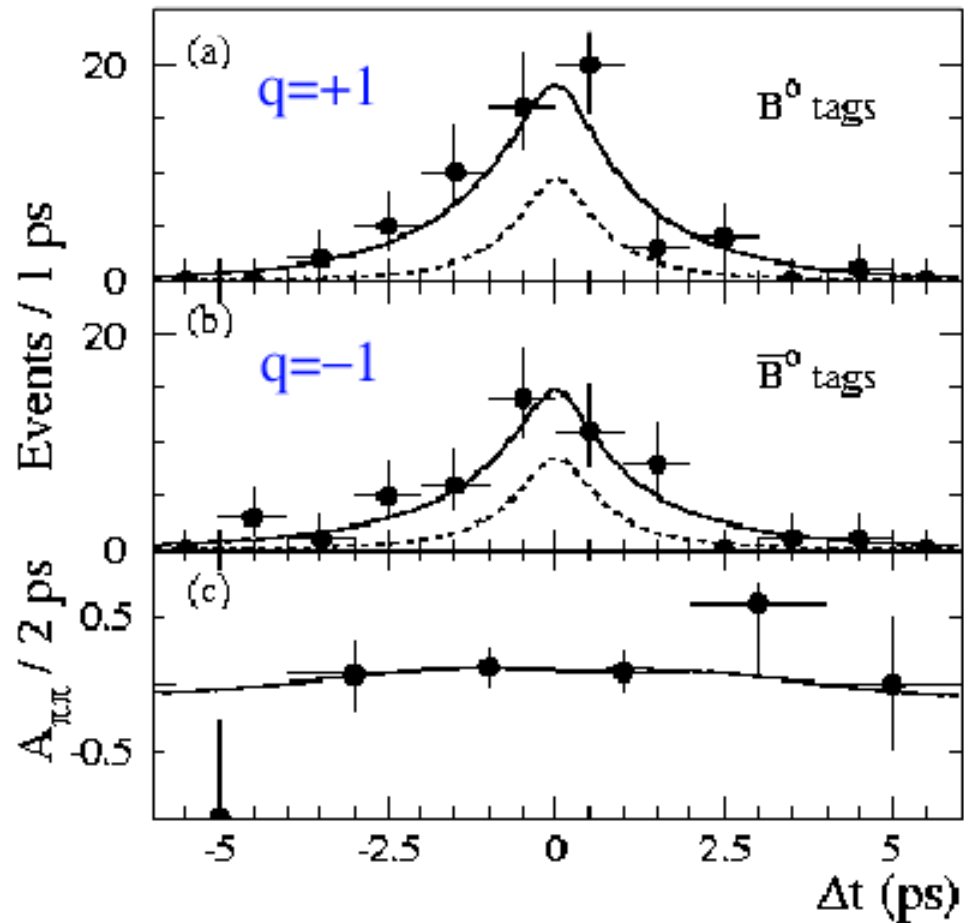
$$S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05$$
$$C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04$$

No indication of CPV (indirect or direct).

Feldman & Cousins confidence interval
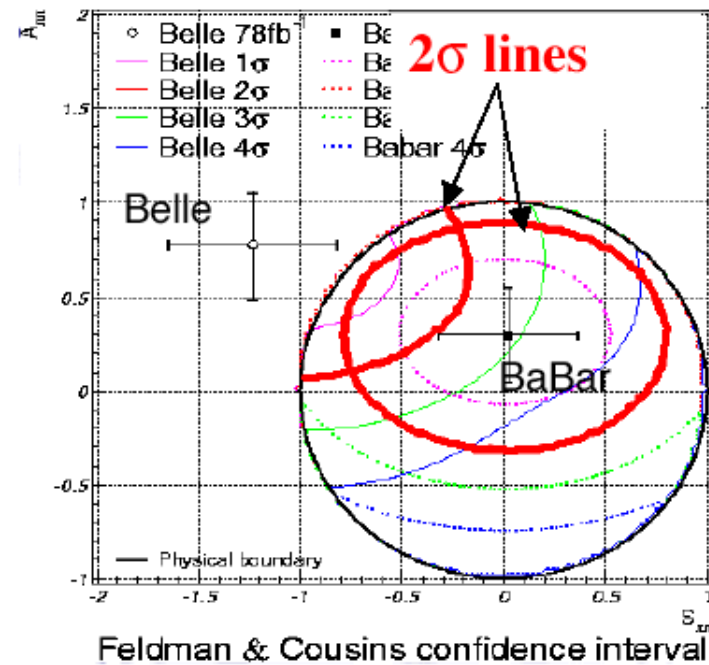
$\rho^{\pm}\pi^{\mp}$ Δt Analyses (BaBar)

Two final states :
$\rho^+\pi^-$ and $\rho^-\pi^+ \to (S, C)$ for each.

Total integrated yield asummetry A :
$\rho^+\pi^- \leftrightarrow \rho^-\pi^+$ (regardless of tag)
(different from A_{CP} or from $A(\text{Belle}) = -C(\text{BaBar})$)

Parametrize as

$$f_{\rho^{\pm}}(\Delta t) = (1 \pm A)e^{-\frac{\Delta t}{\tau_B}}\left[1 + q\left\{(S \pm \Delta S)\sin \delta m t - (C \pm \Delta C)\cos \delta m t\right\}\right]$$

$\rho^{\pm}\pi^{\mp}$ Results (BaBar)

BaBar (81 fb^{-1})
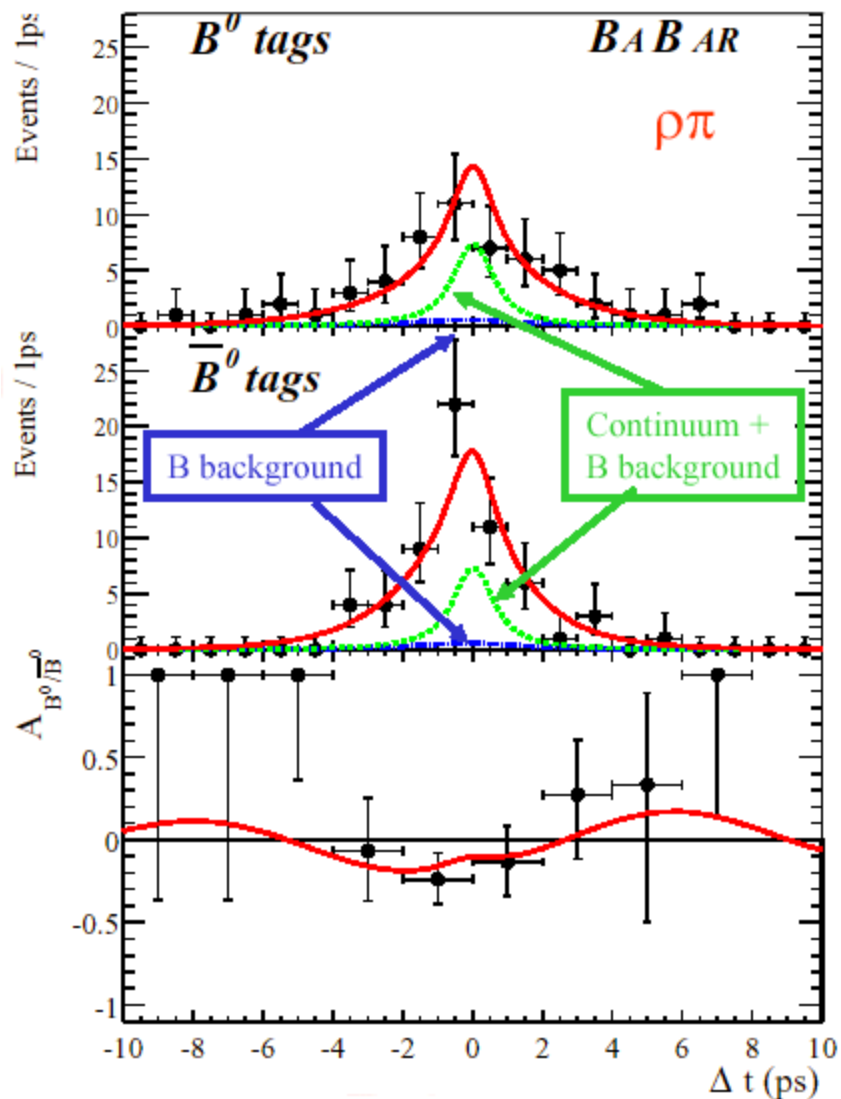
$$A_{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$$

$$S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03$$
$$\Delta S_{\rho\pi} = 0.15 \pm 0.25 \pm 0.03$$

$$C_{\rho\pi} = 0.36 \pm 0.18 \pm 0.04$$
$$\Delta C_{\rho\pi} = 0.28 \pm 0.18 \pm 0.04$$

From all these, one can extract usual A_{CP}:

$$A_{CP}(\bar{B}^0 \to \rho^+\pi^-) = -0.62^{+0.24}_{-0.28} \pm 0.06$$
$$A_{CP}(\bar{B}^0 \to \rho^-\pi^+) = -0.11^{+0.16}_{-0.17} \pm 0.04$$

Slightly more than 2σ of DCPV.

$D^{(*)}\pi$, Δt Analyses ($2\beta + \gamma$, BaBar)

$$D^+\pi^- \propto e^{-\gamma\Delta t}\left[1 + q(C\cos\delta mt - S^+\sin\delta mt)\right]$$

$$D^-\pi^+ \propto e^{-\gamma\Delta t}\left[1 - q(C\cos\delta mt - S^-\sin\delta mt)\right]$$

$$C \sim 1\,, \quad S^{\pm} \sim 2r\sin(2\beta + \gamma \pm \delta)$$

$$r = \frac{|A(B^0 \to D^+\pi^-)|}{|A(\bar{B}^0 \to D^+\pi^-)|} \quad \textbf{(expect} \sim 0.02\textbf{)}$$

- **Most of the info on mixed modes. Dip location + height asymmetry.**
- **Existense of negative Δt is advantageous (vs hadron machines)**

r = 0.1

D*+pi−

D*−pi+

dt

−6   −4   −2   2   4   6
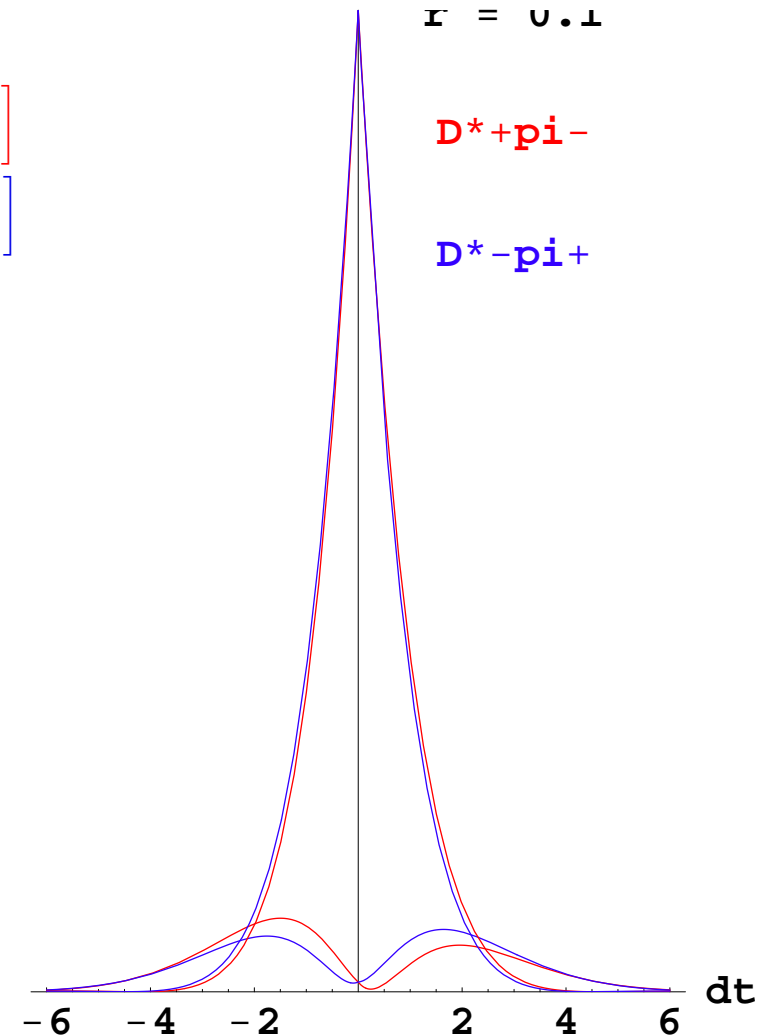
$D^{(*)}\pi$ Δt Distributions (BaBar)

Full reconstruction
$D^+\pi^-$ (5207 evs)
$D^{*+}\pi^-$ (4746 evs).

Partial reconstruction.
$D^{*+}\pi^-$,
$D^{*+} \to (D^0)\pi^+$.
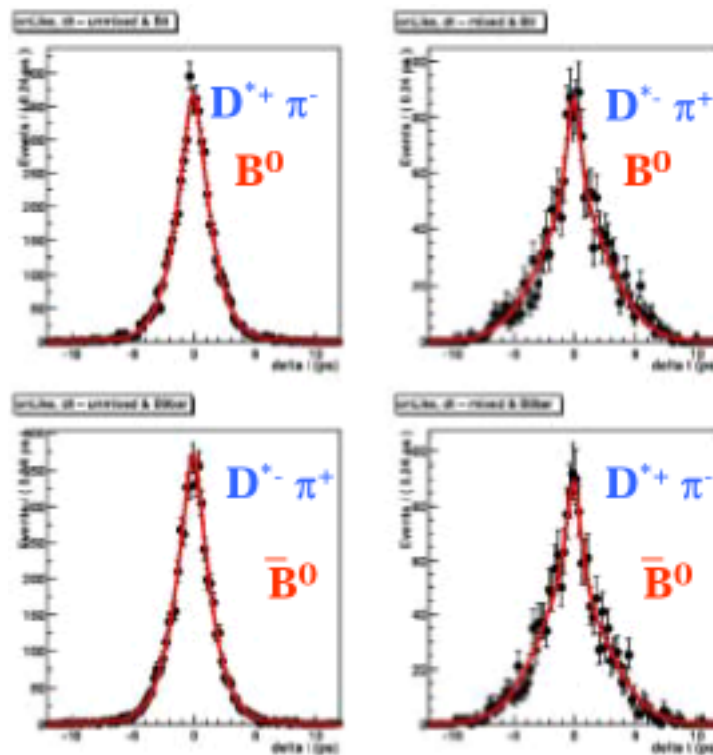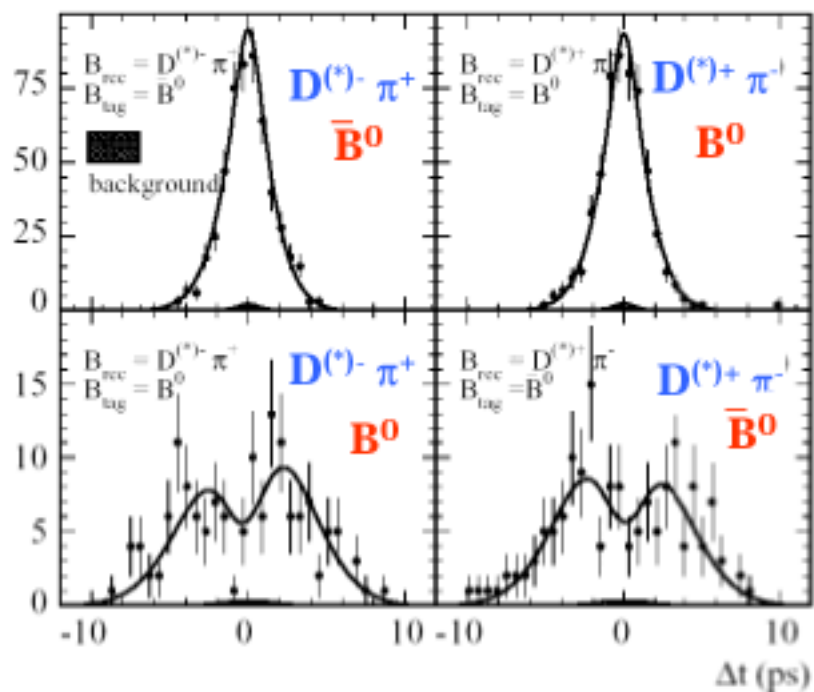
Tag: lepton+K. lepton tags are shown.

$D^{(*)}\pi$ Results (BaBar)

Include tag-side $b \to u$ interference (K-tag only):

$$q2r \sin(2\beta + \gamma - \delta) + 2r' \sin(2\beta + \gamma + q\delta')$$

Same order as the original CPV effect.

Partial $D^*\pi$:

$$2r_* \sin(2\beta + \gamma) \cos\delta_* = -0.063 \pm 0.024 \pm 0.017$$
$$2r_* \cos(2\beta + \gamma) \sin\delta_* = -0.004 \pm 0.037 \pm 0.020$$

Full $D^{(*)}\pi$:

$$2r \sin(2\beta + \gamma) \cos\delta = -0.022 \pm 0.038 \pm 0.021$$
$$2r \cos(2\beta + \gamma) \sin\delta = 0.025 \pm 0.068 \pm 0.035$$
$$2r_* \sin(2\beta + \gamma) \cos\delta_* = -0.068 \pm 0.038 \pm 0.021$$
$$2r_* \cos(2\beta + \gamma) \sin\delta_* = 0.031 \pm 0.070 \pm 0.035$$

Implication of $D^{(*)}\pi$ Analysis on γ (BaBar)

BaBar result on $Br(D_s^{(*)+}\pi^-)$ + SU(3)

$$r = 0.021^{+0.004}_{-0.005}, \quad r_* = 0.017^{+0.005}_{-0.007}.$$

Fit $\sin(2\beta + \gamma)$ and δ, δ_*:

$$\sin(2\beta + \gamma) > 0.76 \quad (90\% \ C.L.)$$

Note: with $\sin 2\beta = 0.735$

$$\sin(2\beta + \gamma) > 0.76 \text{ means } -3^\circ < \gamma < 97^\circ$$

$B \to DK$ for ϕ_3/γ

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

Interference of

$B^- \to D^0K^-/B^- \to \bar{D}^0K^-$

$r \equiv \dfrac{|B|}{|A|} = 0.1\text{-}0.2$

$\sim 10\%$ **asymmetry expected.**
Depends on strong phase δ.

$\#c = 1$ **in final state**
$\to$ **no penguin polution.**
Eventually extract γ.

A

B
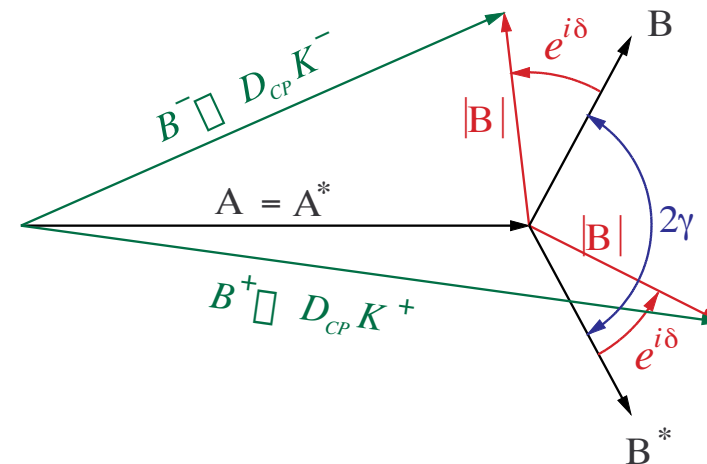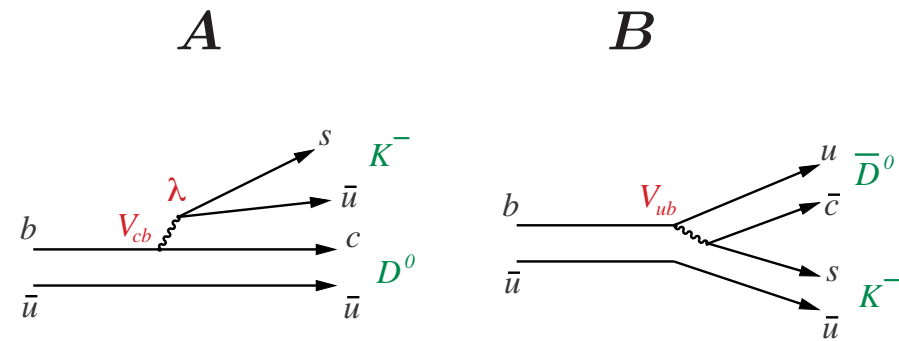
$B^{\pm} \to D_{CP} K^{\pm}$ (Belle 78 fb^{-1})

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

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

CP+ (D_1) :
  $K^+ K^-, \pi^+ \pi^-$

CP− (D_2) :
  $K_S \pi^0, K_S \omega, K_S \eta, K_S \eta'$

PID (π/K separation) important.
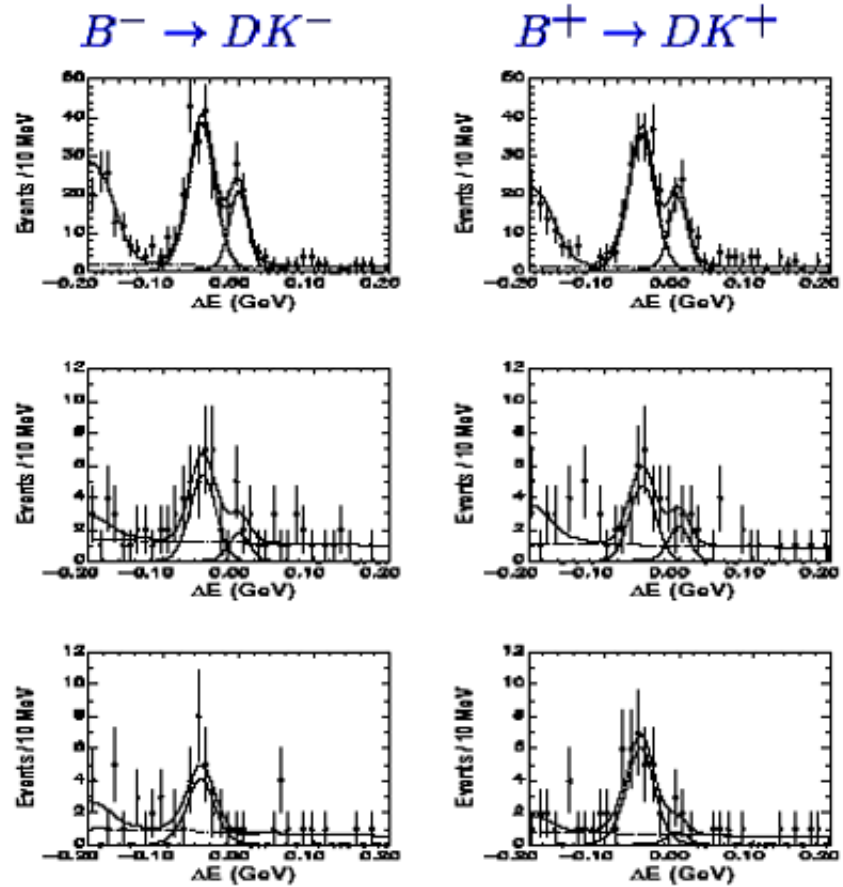
$B^- \to D_{CP}K^-$ (BaBar 81.2 fb^{-1})

$B^\pm \to D_1 K^\pm$
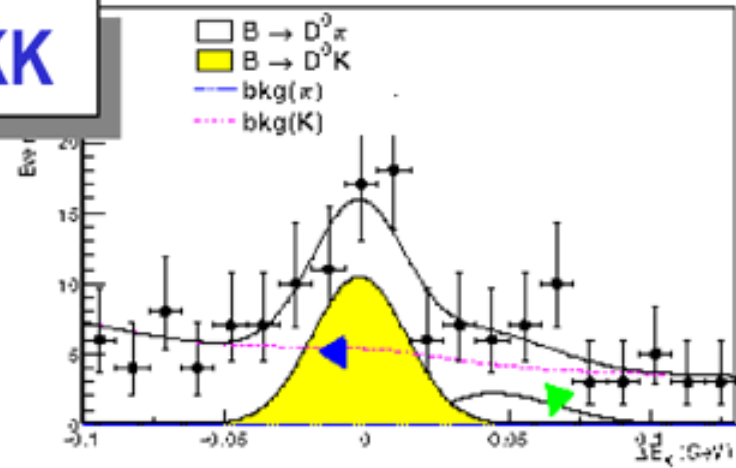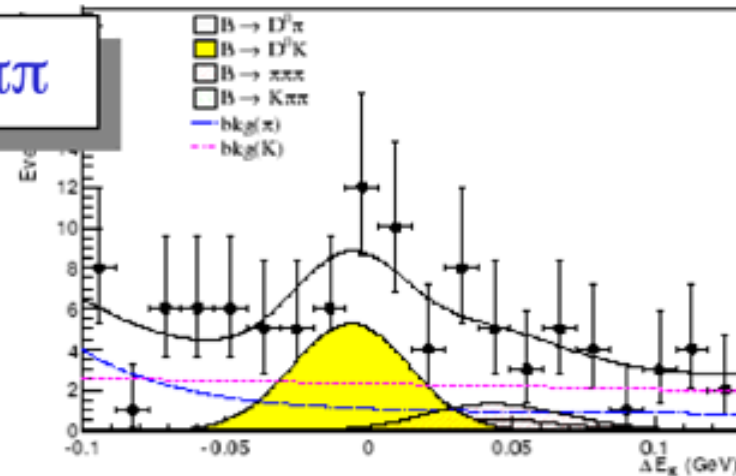
$\Delta E\text{(GeV)}$

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

Rate asymmetry :

$$A_{1/2} = \frac{\mathcal{B}(B^- \to D_iK^-) - \mathcal{B}(B^+ \to D_iK^+)}{\mathcal{B}(B^- \to D_iK^-) + \mathcal{B}(B^+ \to D_iK^+)} = \frac{\pm 2r \sin\phi_3 \sin\delta}{1 + r^2 \pm 2r \cos\phi_3 \cos\delta}$$

Ratio of Cabibbo suppression factors, D_i vs D^0 :

$$R_i = \frac{CS_{Di}}{CS_{D^0}} \ (i=1,2), \quad CS_X = \frac{\Gamma(B^- \to XK^-) + c.c.}{\Gamma(B^- \to X\pi^-) + c.c.} \ (X = D_i, D^0)$$

$$R_{1/2} = 1 + r^2 \pm 2r \cos\phi_3 \cos\delta$$

(Error at $O(r^2)$ if $K^-\pi^+$ is used for D^0 (DCSD).)

Sensitivity to r at $O(r^2)$ $\to$ r cannot be obtained by fit to $A_{1/2}$ and $R_{1/2}$.

However,

$$A_2 \sim -A_1 \quad O(r), \quad \frac{A_1 - A_2}{2} \sim 2r \sin\phi_3 \sin\delta \quad O(r^2)$$

Also, $A_1R_1 = -A_2R_2$

$B^{\pm} \to D_{CP}K^{\pm}$ Results

	$CP+$	$CP-$
Belle (DK)	$A_1 = 0.06 \pm 0.19 \pm 0.04$ $R_1 = 1.21 \pm 0.25 \pm 0.14$	$A_2 = -0.19 \pm 0.17 \pm 0.05$ $R_2 = 1.41 \pm 0.27 \pm 0.15$
BaBar (DK)	$A_1 = 0.17 \pm 0.23 \pm 0.08$ $R_1 = 1.06 \pm 0.26 \pm 0.17$	
Belle(DK^*)	$A_1 = -0.02 \pm 0.33 \pm 0.07$	$A_2 = 0.09 \pm 0.50 \pm 0.04$
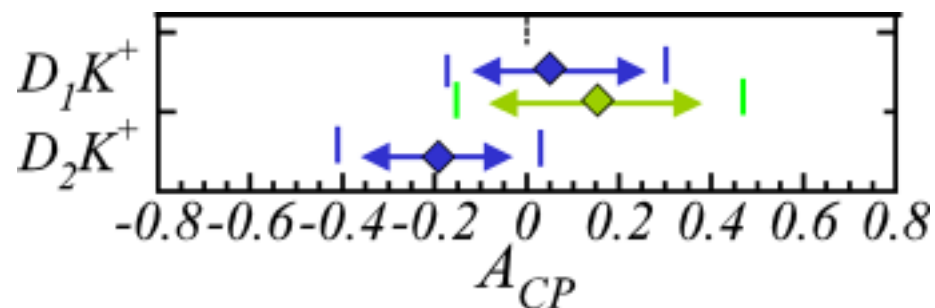
From DK results,

$$2r \sin \phi_3 \sin \delta = \frac{A_1 - A_2}{2} = 0.15 \pm 0.12 \,.$$

$B \rightarrow$ non-charm Rate Asymmetries

Direct CPV by tree-penguin interference.

e.g. for $K^- \pi^0$:

**Statistically more favorable than DK modes,
but theoretically challenging.**

Future: use theoretical models (PQCD, QCD factorization,
Charming penguin, etc.) for A_{CP} and Br's to extract ϕ_3.

$B \rightarrow$ non-charm Rate Asymmetries

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)}$$

A_{CP} by HFAG (Heavy Flavor Averaging Group) 2003 Winter

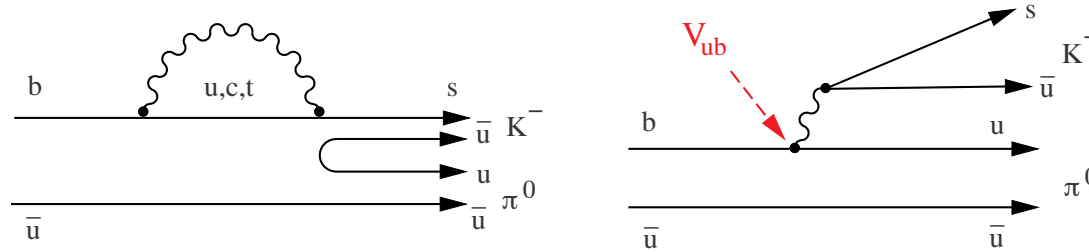| RPP#	Mode	PDG2002 Avg.	BABAR	Belle	CLEO	A_{CP} Avg.
86	$K^0\pi^+$	-0.05 ± 0.14	$-0.17 \pm 0.10 \pm 0.02$	$0.02 \pm 0.09 \pm 0.01$	$0.18 \pm 0.24 \pm 0.02$	-0.05 ± 0.07
87	$K^+\pi^0$	-0.10 ± 0.12	$-0.09 \pm 0.09 \pm 0.01$	$-0.02 \pm 0.19 \pm 0.02$	$-0.29 \pm 0.23 \pm 0.02$	-0.10 ± 0.08
88	$\eta'K^+$	-0.02 ± 0.07	$0.04 \pm 0.05 \pm 0.01$	$-0.02 \pm 0.07 \pm 0.01$	$0.03 \pm 0.12 \pm 0.02$	0.02 ± 0.04
92	ωK^+			$-0.21 \pm 0.28 \pm 0.03$		-0.28 ± 0.19
117	ϕK^+	-0.05 ± 0.20	$-0.05 \pm 0.20 \pm 0.03$			-0.05 ± 0.20
120	ϕK^{*+}	$-0.43^{+0.36}_{-0.31}$	$0.16 \pm 0.17 \pm 0.04$			0.16 ± 0.17
131	$\pi^+\pi^0$		$-0.03^{+0.18}_{-0.17} \pm 0.02$	$0.30 \pm 0.30^{+0.30}_{-0.06}$		0.05 ± 0.15
143	$\omega\pi^+$	-0.21 ± 0.19	$-0.01^{+0.29}_{-0.31} \pm 0.03$		$-0.34 \pm 0.25 \pm 0.02$	-0.21 ± 0.19
88	$K^+\pi^-$	-0.09 ± 0.06	$-0.10 \pm 0.05 \pm 0.02$	$-0.06 \pm 0.09^{+0.09}_{-0.01}$	$-0.04 \pm 0.16 \pm 0.02$	-0.05 ± 0.05
89	$K^0\pi^0$		$0.03 \pm 0.36 \pm 0.09$			0.03 ± 0.37
99	$K^+\rho^-$		$0.19 \pm 0.14 \pm 0.11$			0.19 ± 0.18
103	$K^{*+}\pi^-$				$0.26^{+0.33+0.10}_{-0.34-0.08}$	$0.26^{+0.33+0.10}_{-0.34-0.08}$
115	ϕK^{*0}	0.00 ± 0.27	$0.04 \pm 0.12 \pm 0.02$			0.04 ± 0.12
53	$K^*\gamma$	-0.01 ± 0.07	$-0.044 \pm 0.076 \pm 0.012$	$-0.022 \pm 0.048 \pm 0.017$	$-0.08 \pm 0.13 \pm 0.03$	-0.03 ± 0.04

(In PDG 2002   New since PDG2002)

$B \rightarrow$ non-charm Rate Asymmetries (New)

New since HFAG03,Winter:

A_{CP}	BaBar	Belle
$K^+\pi^-$		$-0.07 \pm 0.06 \pm 0.01$
$K^+\pi^0$		$0.23 \pm 0.11^{+0.01}_{-0.04}$
$K^0\pi^+$		$0.07^{+0.09+0.01}_{-0.08-0.03}$
$\pi^+\pi^0$		$-0.14 \pm 0.24^{+0.05}_{-0.04}$
$\eta\pi^+$	$-0.51^{+0.20}_{-0.18} \pm 0.01$	
ηK^+	$-0.32^{+0.22}_{-0.18} \pm 0.01$	
$\omega\pi^+$	$0.04 \pm 0.17 \pm 0.01$	$0.48^{+0.23}_{-0.20} \pm 0.02$
ωK^+	$-0.05 \pm 0.16 \pm 0.01$	$0.06^{+0.20}_{-0.18} \pm 0.01$
ϕK^+	$0.039 \pm 0.086 \pm 0.011$	$0.01 \pm 0.12 \pm 0.05$
$\rho^0\pi^+$	$-0.17 \pm 0.11 \pm 0.02$	
$\rho^+\pi^0$	$0.23 \pm 0.16 \pm 0.06$	
ρ^+K^-	$0.28 \pm 0.17 \pm 0.08$	$0.22^{+0.22+0.06}_{-0.23-0.02}$
$K^+\pi^-\pi^0$		$0.07 \pm 0.11 \pm 0.01$
$\pi^+\pi^-\pi^+$	$-0.39 \pm 0.33 \pm 0.12$	
$K^+\pi^-\pi^+$	$0.01 \pm 0.07 \pm 0.03$	
$K^+K^-K^+$	$0.02 \pm 0.07 \pm 0.03$	

Remarks on $B \rightarrow$ non-charm Rate Asymmetries

- **Some modes are penguine-dominated.**
  $(K^0\pi^+, \eta'K^+) \rightarrow A_{CP} \sim 0$. **OK.**

- $A_{CP}(\eta\pi^+) = -0.51 \pm 0.20$ **significant?**
  $\eta\pi^+, \eta K^+, \eta'\pi^+$ are thoretically expected to have large A_{CP}. **Interesting to see more stat.**

- **Theoretical uncertainties are still large.**

A_{CP}	exp.	PQCD	QCDF	Charming Penguin
$K^+\pi^-$	-0.08 ± 0.04	$-0.129 \sim -0.219$	0.05 ± 0.09	0.21 ± 0.22
$K^+\pi^0$	0.00 ± 0.07	$-0.100 \sim -0.173$	0.07 ± 0.09	0.22 ± 0.13
$K^0\pi^+$	0.02 ± 0.06	$-0.006 \sim 0.0015$	0.01 ± 0.01	0.0

Models do not agree well, except for $K^0\pi^+$ (penguin dom.).

Future Prospects

e^+e^- machines

- CLEO-c : 30M $D\bar{D}$'s (now running).
- Belle/BaBar : 3-400 fb^{-1} each by 2005 ($\times 5$ more than presented today)
- Proposed :
  Super-KEKB/Belle, Super-PEPII/BaBar.

	Super-Belle	Super-BaBar	now
$I_{\mathrm{beam}}(A)$	3.5/8	9.6/22	1/1.5
$\mathcal{L}(/cm^2 s)$	10^{35}	10^{36}	10^{34}
Starts	~ 2007	~ 2010	
sensitivities	(3yrs)	(1yr)	
$\sigma_{\sin 2\phi_{2\mathrm{eff}}}$	0.060	0.032	0.2
$\sigma_{\sin(2\phi_1+\phi_3)}$	0.077	0.030	0.3
$\sigma_{\phi_3}(DK)$	$\sim 10°$	$\sim 2.5°$	-
$N(X_s \nu\bar{\nu})$		160	
$N(\tau\nu)$		350	

General Purpose Detectors at Hadron Machines

1. **Tevatron Run2. (CDF, D0)**
   - **150 pb^{-1} now $\rightarrow$ 4-5 fb^{-1} by LHC (2007)**
   - **With 2 fb^{-1} ($+B_s, \Lambda_b$ physics)**
     $\sigma_{\sin 2\beta} \sim 0.06$ ($\sim$B-factory now, different sys.)
     $\sigma_{A_{CP}(K^+\pi^-)} \sim 1 \sim 10\%$.

2. **LHC. (ATLAS, CMS)**
   - **B-physics while intensity is not too high.**
   - **$\sigma_{\sin 2\alpha_{\mathrm{eff}}} \sim 0.09$ ($\#\pi^+\pi^- \sim 2.3K$)**
     Not as good as BTeV/LHCb.
   - **$\#(B \rightarrow \mu\mu) \sim 30$**
     $\#(B \rightarrow s\mu\mu) \sim 5K$
     As good as BTeV/LHCb

Dedicated B-Facilities at Hadron Machines
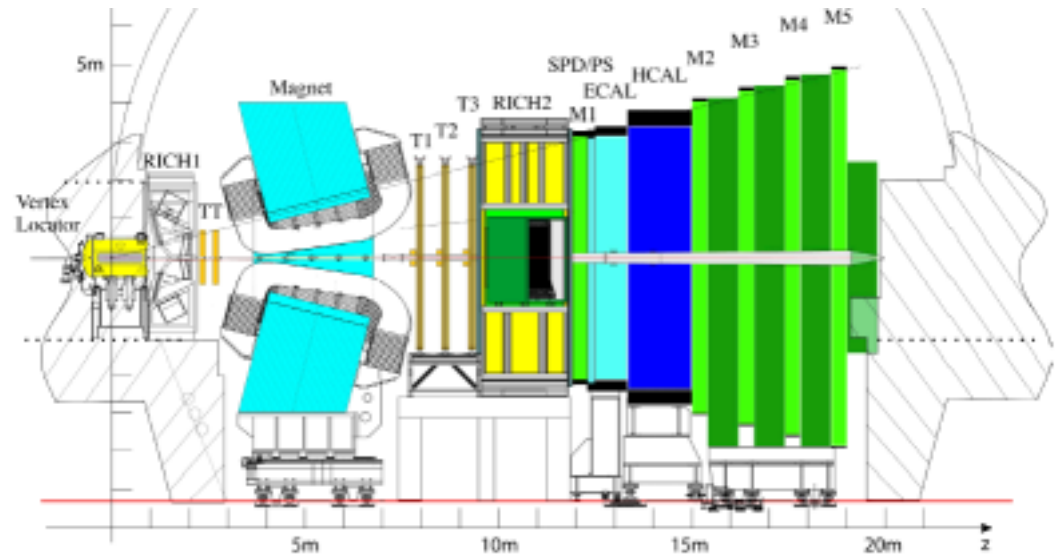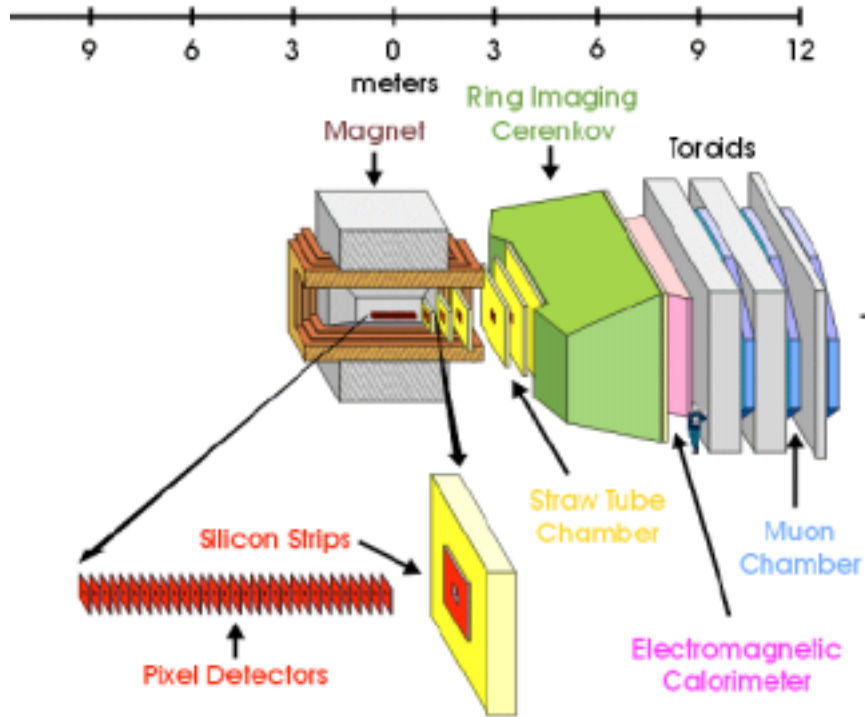
BTeV at Tevatron

$p\bar{p}$ at $E_{CM} = 2$ TeV

Approved by lab.

Pending P5 panel. 2009→

LHCb at LHC

pp at $E_{CM} = 14$ TeV

Under construction.

2007→

BTeV/LHCb Sensitivities/1yr(10^7s)

(#events   sinsitivity)

	LHCb		BTeV	
$\sigma_{b\bar{b}}$	$500\mu b$		$100\mu b$	
$\#b\bar{b}$	10^{12}		1.5×10^{11}	
$B_d \to J/\Psi K_S$	119K	$\sigma_\beta \sim 0.6°$	168K	$\sigma_{\sin 2\beta} \sim 0.017$
$B_d \to \rho^0\pi^0$			0.78K	$\sigma_\alpha \sim 4°$
$B_d \to \pi^+\pi^-$	27K	$\sigma_\alpha^* \sim$ 5-10°	14.6K	$\sigma_A \sim 0.03$
$B_s \to K^+K^-$	35K		18.9K	$\sigma_A \sim 0.02$
$B_s \to D_s K$	8K	$\sigma_\gamma \sim 10°$	7.5K	$\sigma_{\gamma-2\chi} \sim 8°$
$B_s \to J/\Psi\phi$	128K	$\sigma_{2\delta\gamma} \sim 2°$		
$B_s \to J/\Psi\eta/\eta'$			12.6K	$\sigma_{\sin 2\chi} \sim 0.024$

* Requires SU(3) modeling.

pros: B_s, PID, long decay lengths

Summary

- ϵ'/ϵ of K_L has established direct CPV.
- CPV in charmonium$K_{S,L}$ modes firmly established. $\sin 2(\phi_1/\beta) = 0.734 \pm 0.055$ cosistent with SM.
- Hint of deviation of "$\sin 2\phi_1$"(ϕK_S) from SM by Belle, but not by BaBar.
- HInt of direct CPV in $\pi^+\pi^-$ by Belle, but not by BaBar.
- Hint of direct CPV in $\rho^+\pi^-$ (BaBar).
- Accuracy of ϕ_3/γ by $D^{(*)}\pi$ modes is becoming meaningful.
- Sensitivity in A_{CP} of DK modes is approaching interesting region.
- No clear direct CPV in rate asymmetries A_{CP}, except for some hint in $\eta\pi^+$.