Measurements of $\phi_1(\beta)$ & $\phi_2(\alpha)$

Kai-Feng Chen
National Taiwan University

The Belle Collaboration

National Taiwan University

Oct. 6th-11th, 2003
Weak Interaction & Neutrinos Workshop

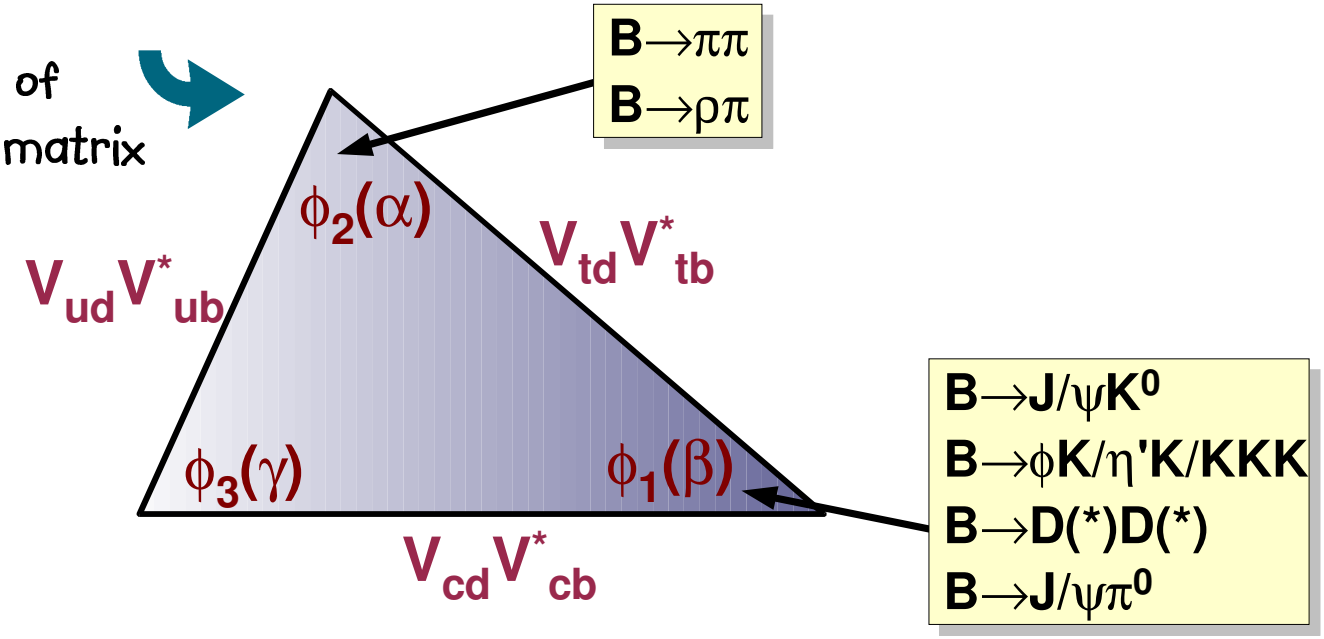
Unitarity Triangle

CPV in the quark mixing matrix

- **CPV from the complex phase in the quark mixing matrix:**

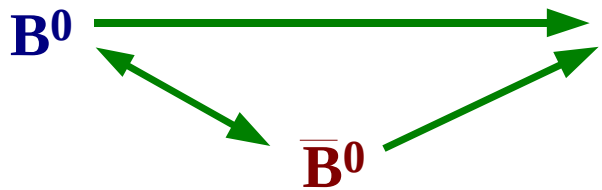
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-(\lambda^2/2) & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-(\lambda^2/2) & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Property of unitarity matrix



Time Dependent Measurement

The time-dependent *CP* asymmetries



$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}; t) - \Gamma(B^0 \to f_{CP}; t)}{\Gamma(\overline{B^0} \to f_{CP}; t) + \Gamma(B^0 \to f_{CP}; t)}$$

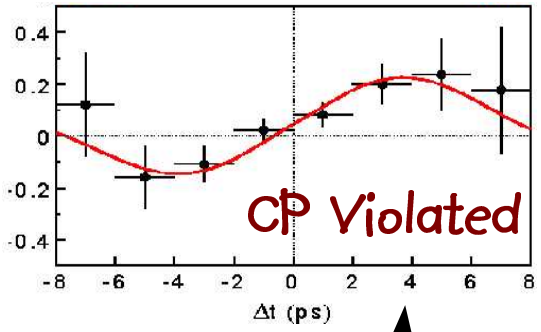
$$= A_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

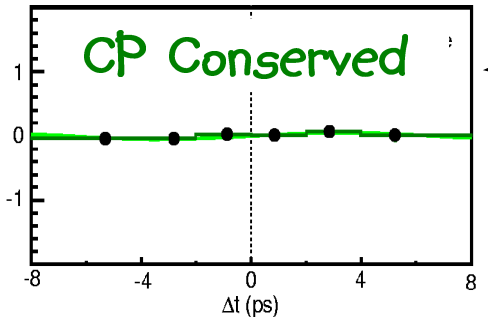
$S_f = \sin 2\phi_1$ if $f_{CP} = J/\psi K$

Indicates direct CP violation

$A_f = 0$ if $f_{CP} = J/\psi K$

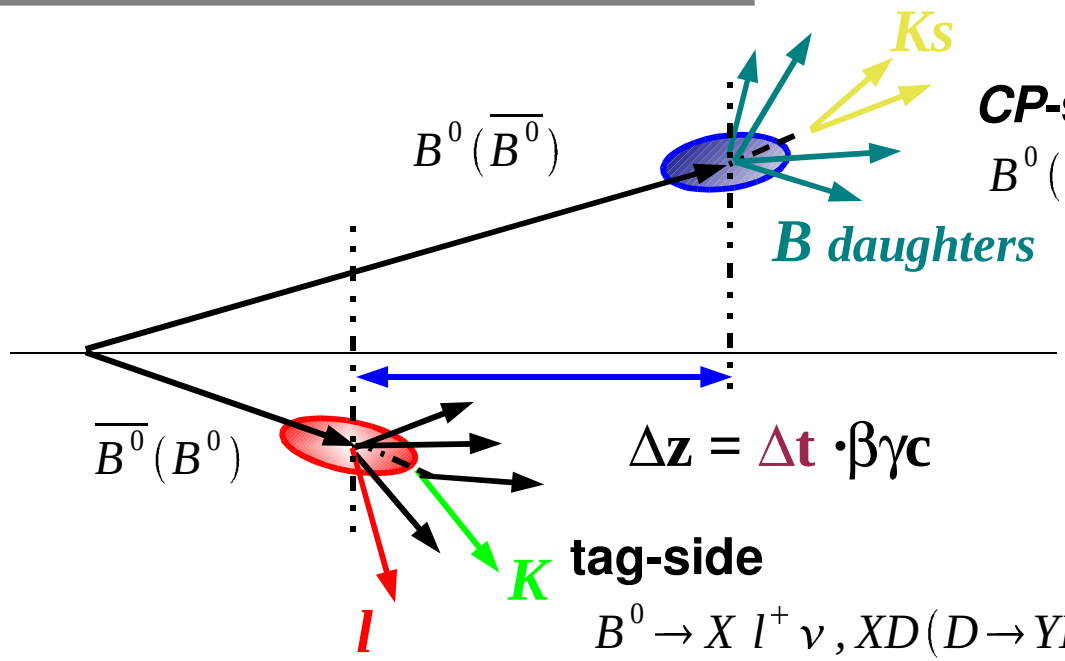
(C = -A in BABAR)





Time Dependent Measurement

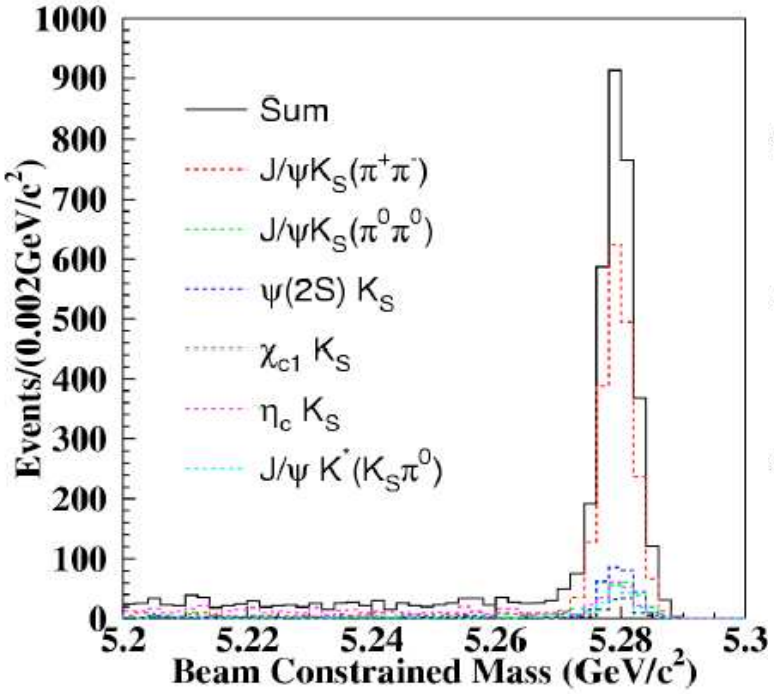
Principle of the measurement

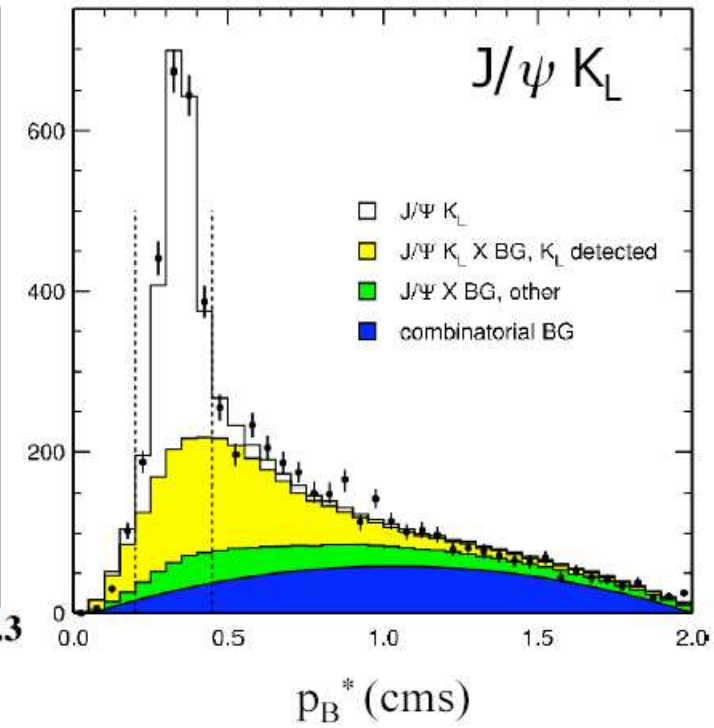


- Full reconstruct one of the CP-eigenstate as the CP-side.
- The b-flavor is determined by the accompanying B meson.
- Determine the CP parameters by the Δt distribution.

Measurement of $\phi_1(\beta)$

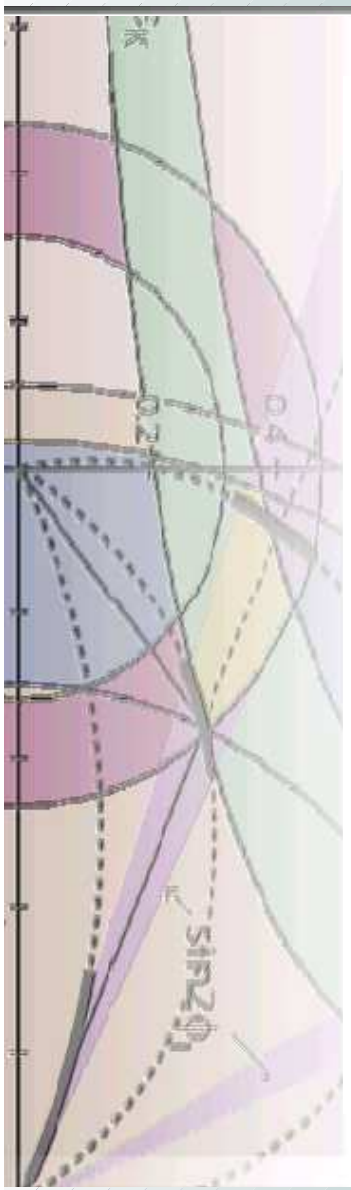
Belle2003 : b → ccs sample

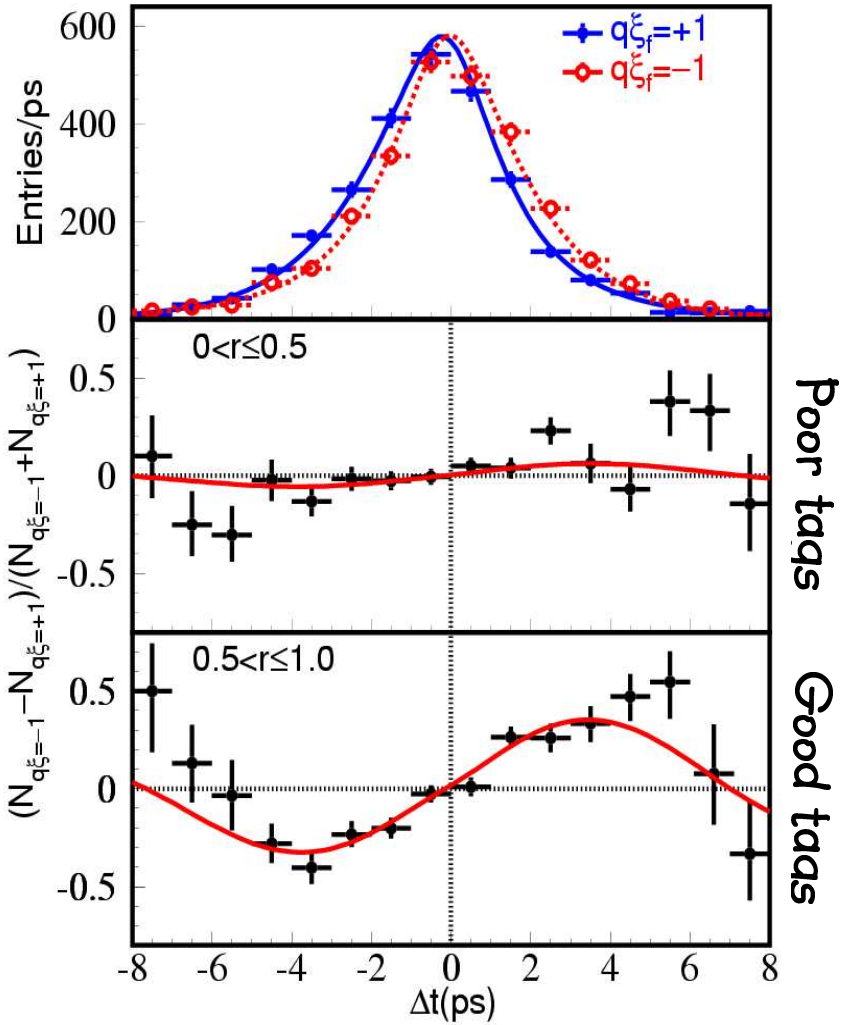




- 140fb^{-1}, 152M $B\bar{B}$ pairs.
- 2911 $\xi_f = -1$ events included in the fit.
- J/ψ K_L: 2332 with a purity of 60%

Measurement of $\phi_1(\beta)$





Belle2003 : b → ccs results

$$\sin 2\phi_1 = 0.733 \pm 0.057 \pm 0.028$$

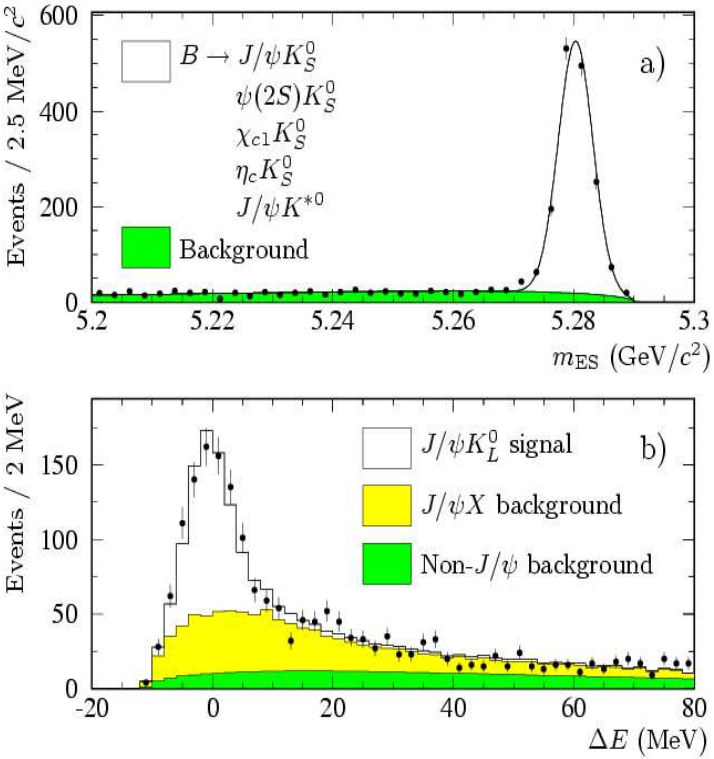
- Belle 2003 summer 140fb^{-1} result.

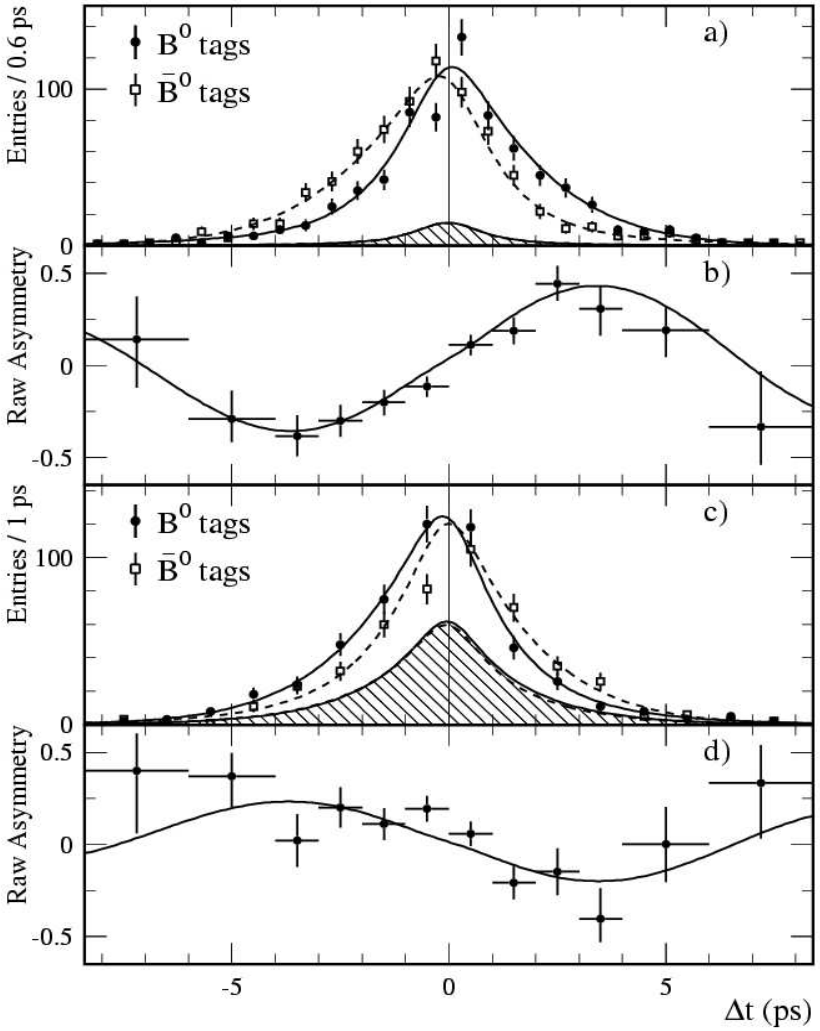
$$|\lambda_{ccs}| = 1.007 \pm 0.041\,(stat.)$$

→ Consistent with no direct CPV

Measurement of $\phi_1(\beta)$

BaBar2002 : b → ccs results



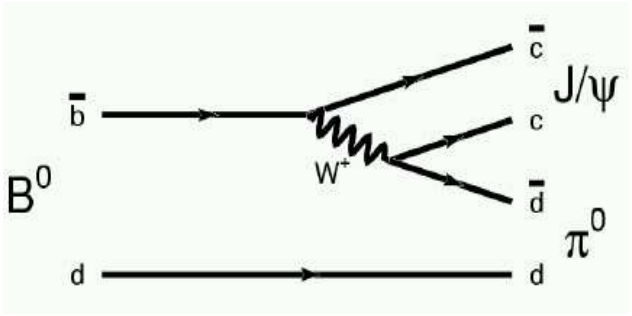


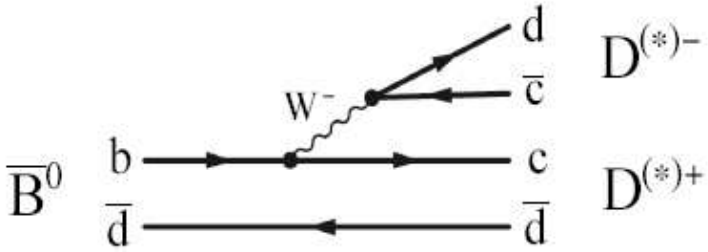
$$\sin 2\phi_1 = 0.741 \pm 0.067 \pm 0.034$$

- 81 fb^{-1} result.

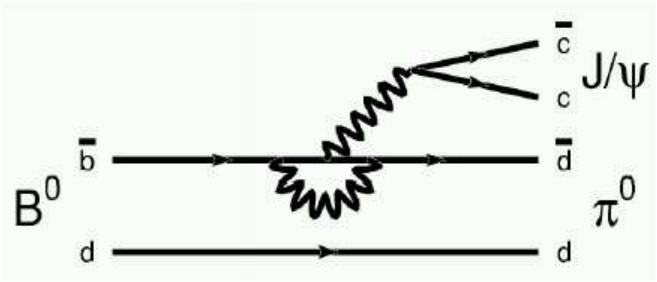
CPV in b → cc̄d Decays

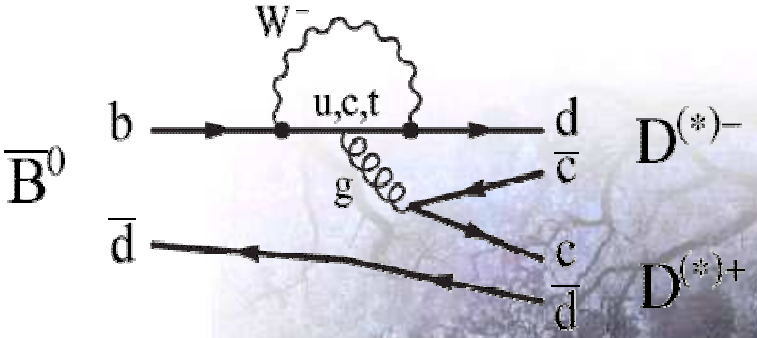
Trees





Penguin

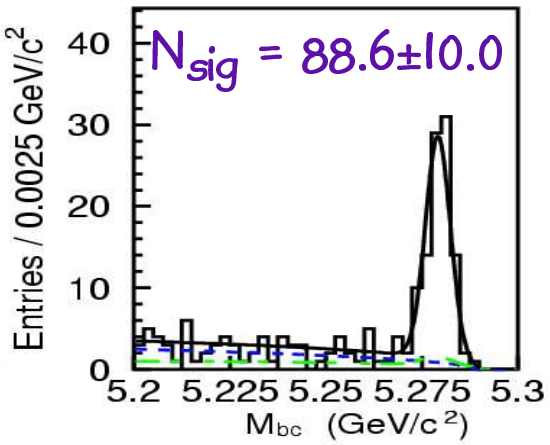


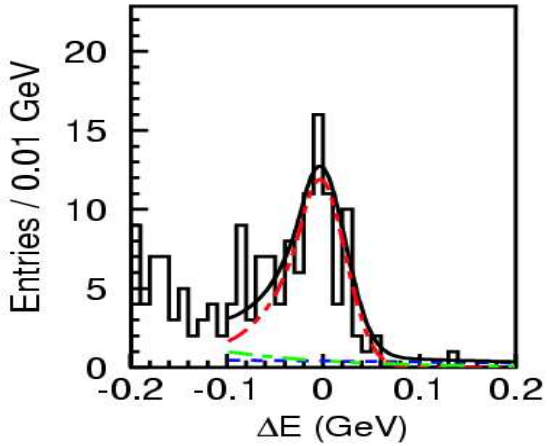


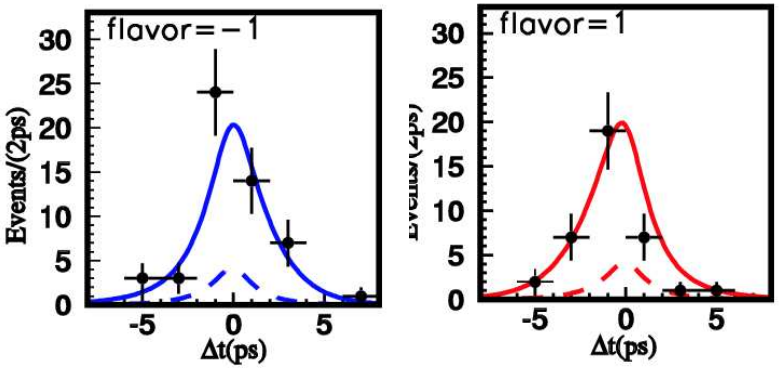
- **The b → cc̄d decays have the same CP phase of B → J/ψ Ks, but may have penguin contributions.**

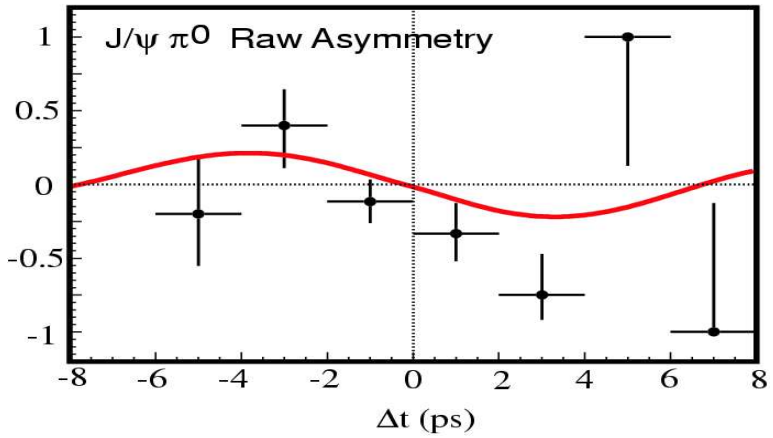
CPV in B → J/ψ π0

Belle 140fb-1 results









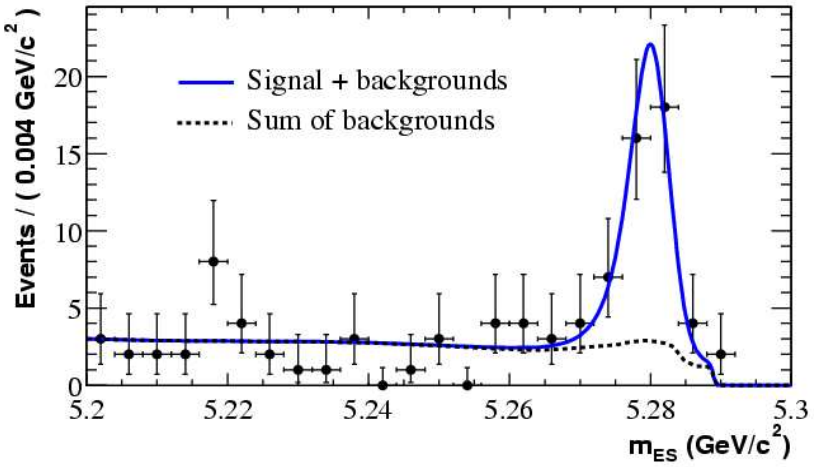
$$sin2\,\phi_1^{eff} = 0.72 \pm 0.42 \pm 0.08$$

$$(A = -0.01 \pm 0.29 \pm 0.07)$$

CPV in $B \to J/\psi\, \pi^0$

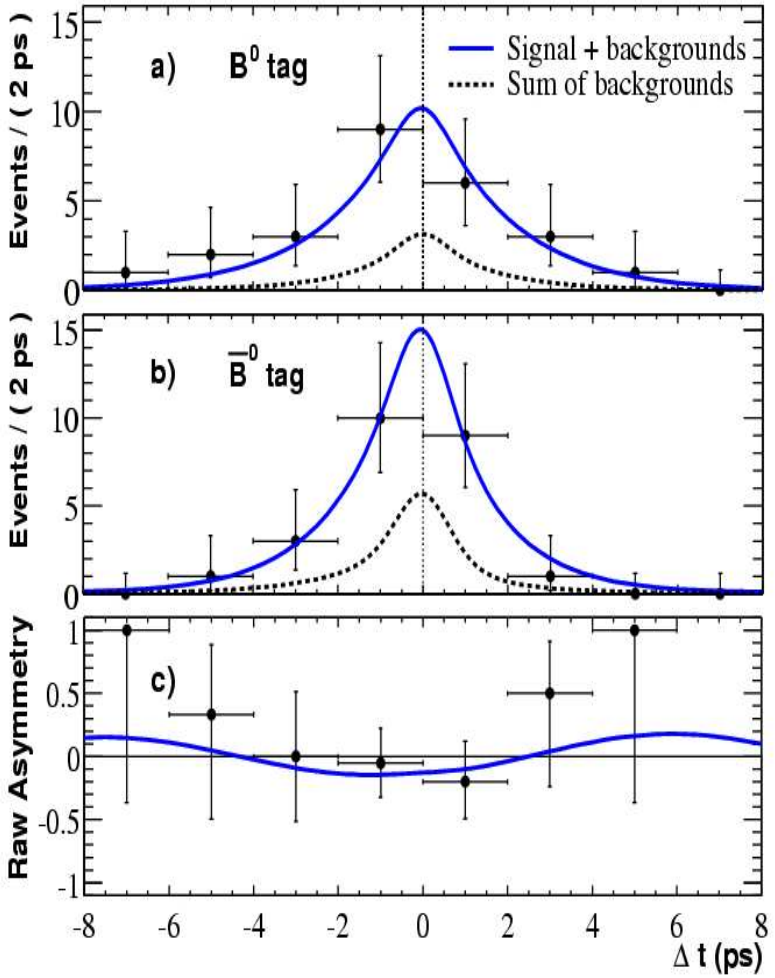
BaBar 81fb^{-1} results

$N_{sig} = 40 \pm 7$



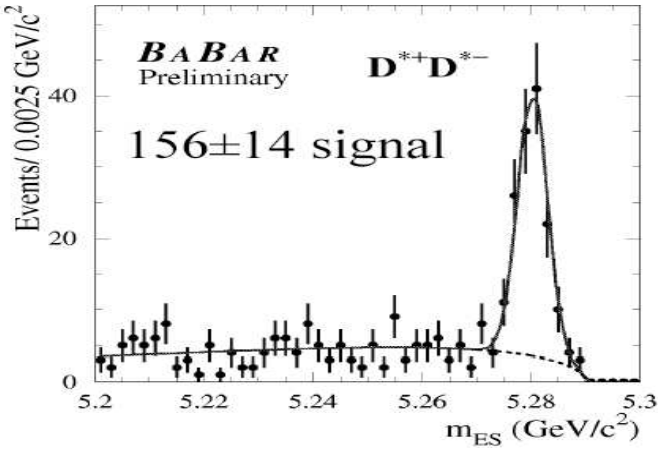
$$sin2\,\phi_1^{eff} = 0.05 \pm 0.49 \pm 0.16$$

$$(A = -C = -0.38 \pm 0.41 \pm 0.09)$$



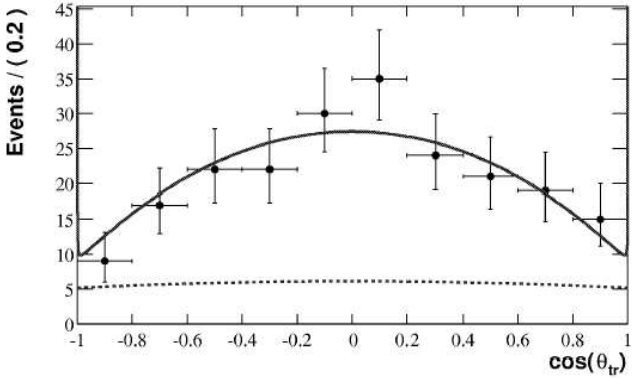
CPV in B → D*+D*−

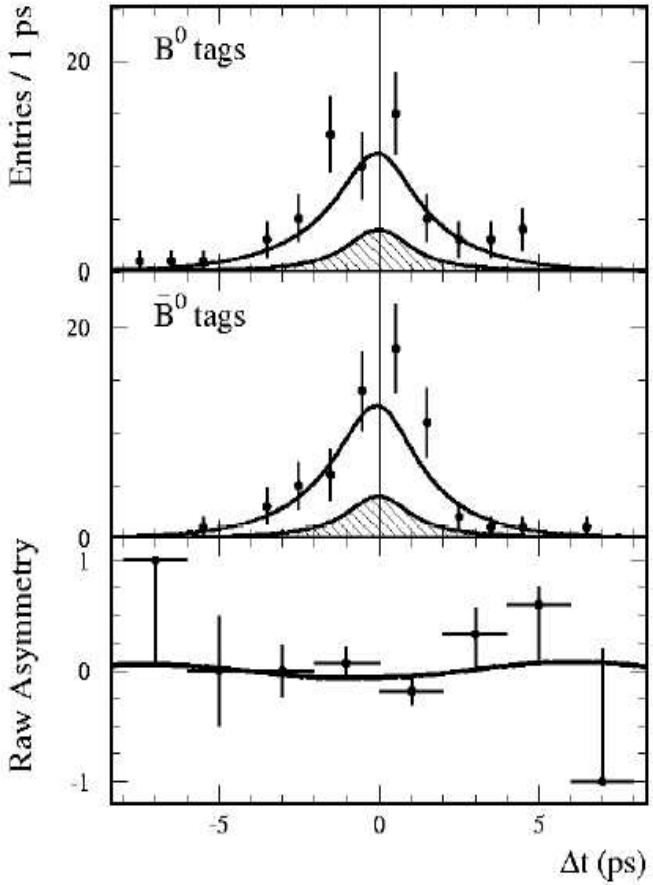
BaBar 81fb-1 results



$$R_{\perp} = 0.063 \pm 0.055 \pm 0.009$$

→ Almost CP-even





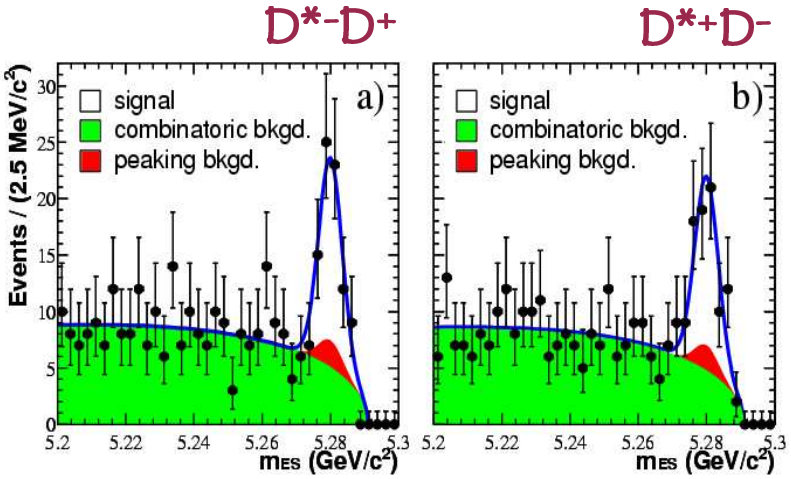
$$sin2\,\phi_1^{eff} = -0.05 \pm 0.29 \pm 0.10$$

(~2.5σ away from b → ccs)

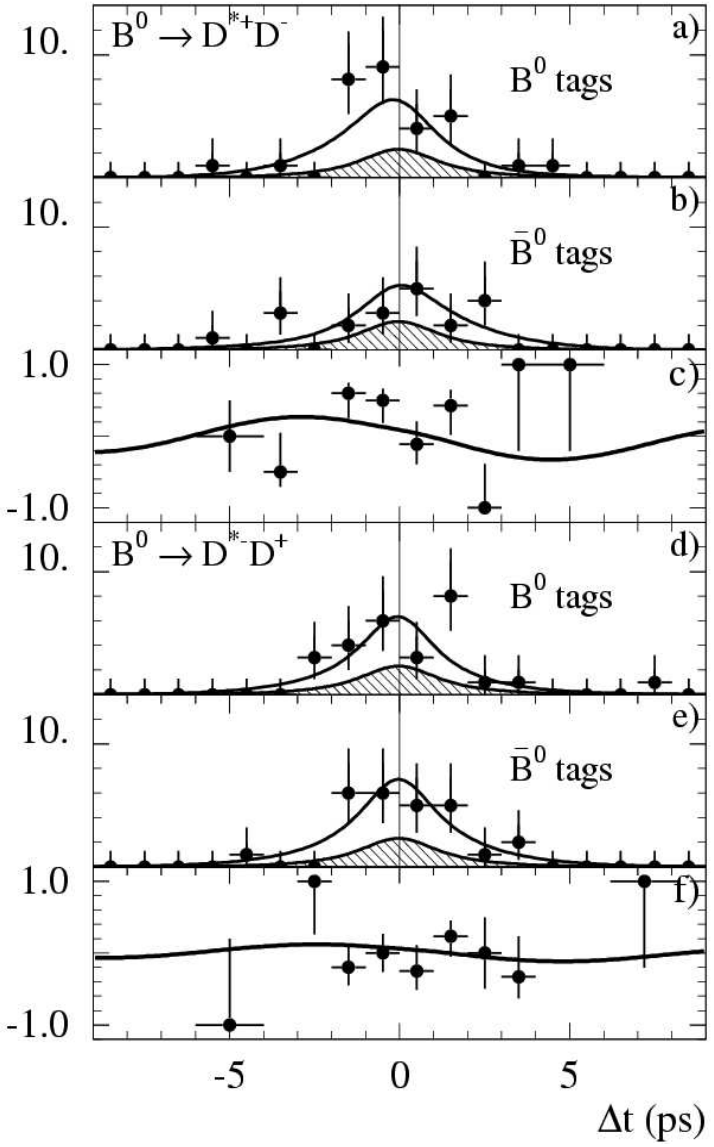
CPV in B → D*+D−

BaBar 81fb-1 results

$$
\begin{aligned}
S_{-+} &= -0.24 \pm 0.69 \pm 0.12, \\
C_{-+} &= -0.22 \pm 0.37 \pm 0.10, \\
S_{+-} &= -0.82 \pm 0.75 \pm 0.14, \\
C_{+-} &= -0.47 \pm 0.40 \pm 0.12.
\end{aligned}
$$



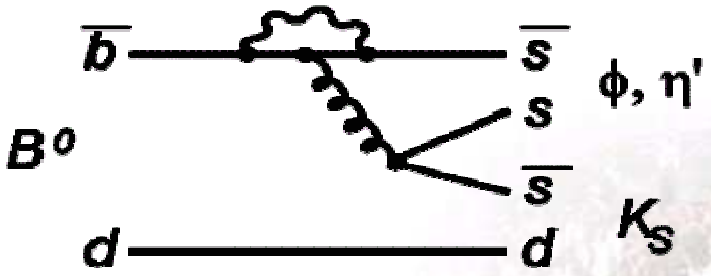
113±13 signal yield in total

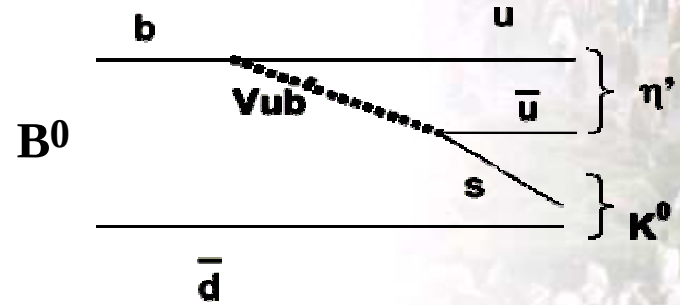


CPV in b → sq̄q Decays

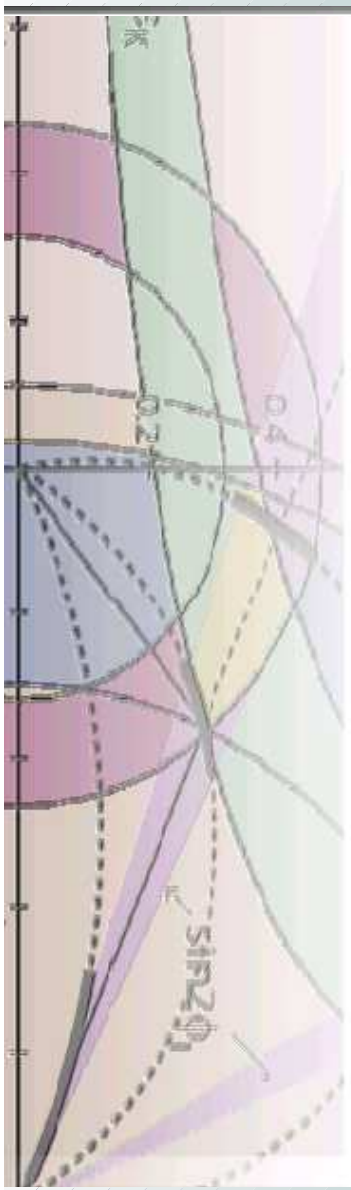
Penguin dominated decays

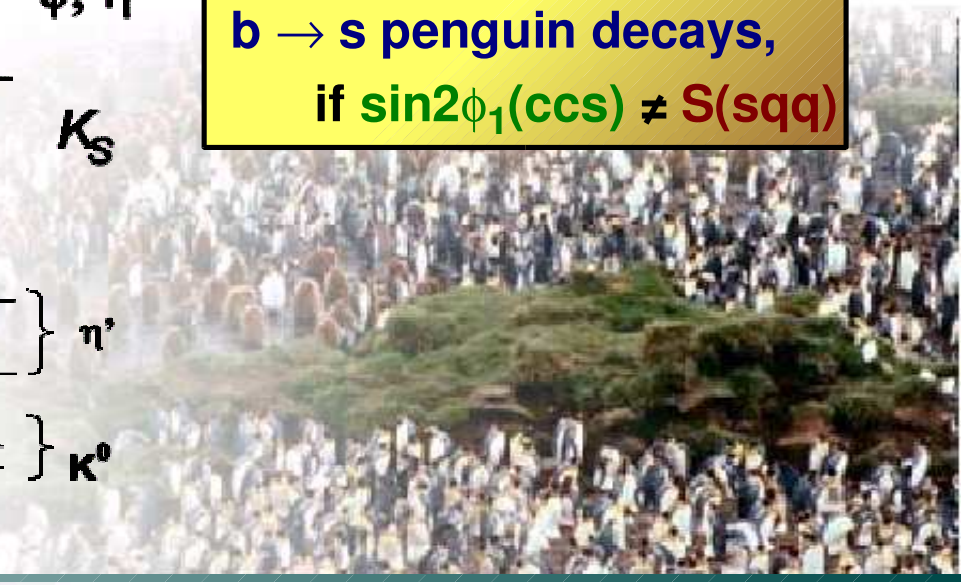
- Search of CPV in B → φKs/KKKs/η'Ks.
- For pure b → s penguin in SM, S = $-\xi_f \cdot \sin 2\phi_1$.
- Bf of η'K (~6×10^{-5}) is larger than the theory prediction.





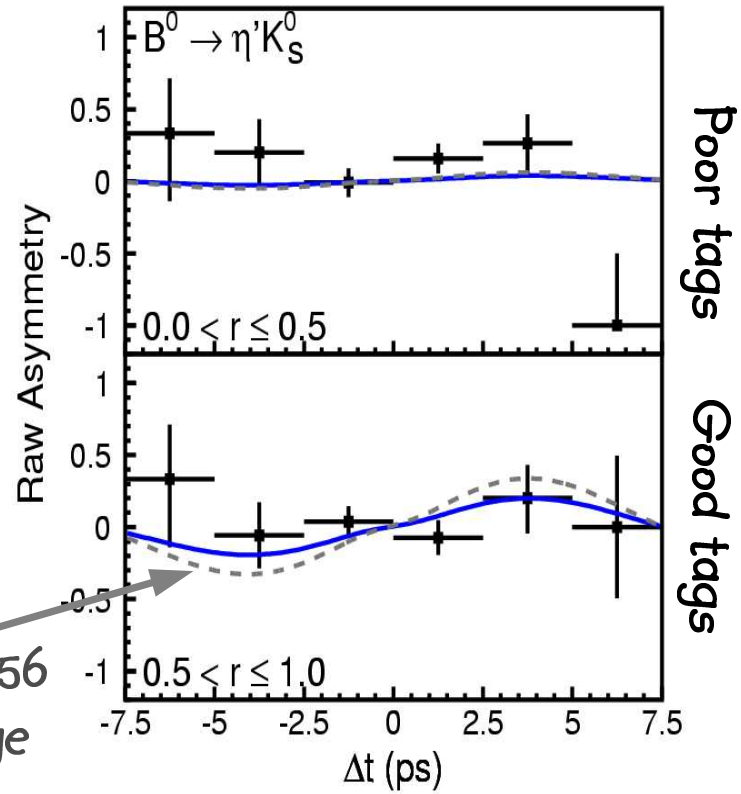
Probe for new physics in b → s penguin decays, if $\sin2\phi_1$(ccs) ≠ S(sqq)





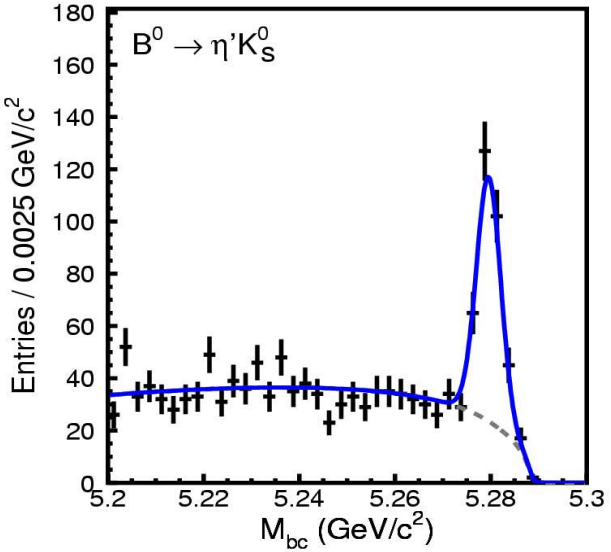
CPV in B → η'Ks

Belle 140fb^{-1} results



For
S = 0.731±0.056
(world average
of sin2φ1)

N_{sig} = 244±21

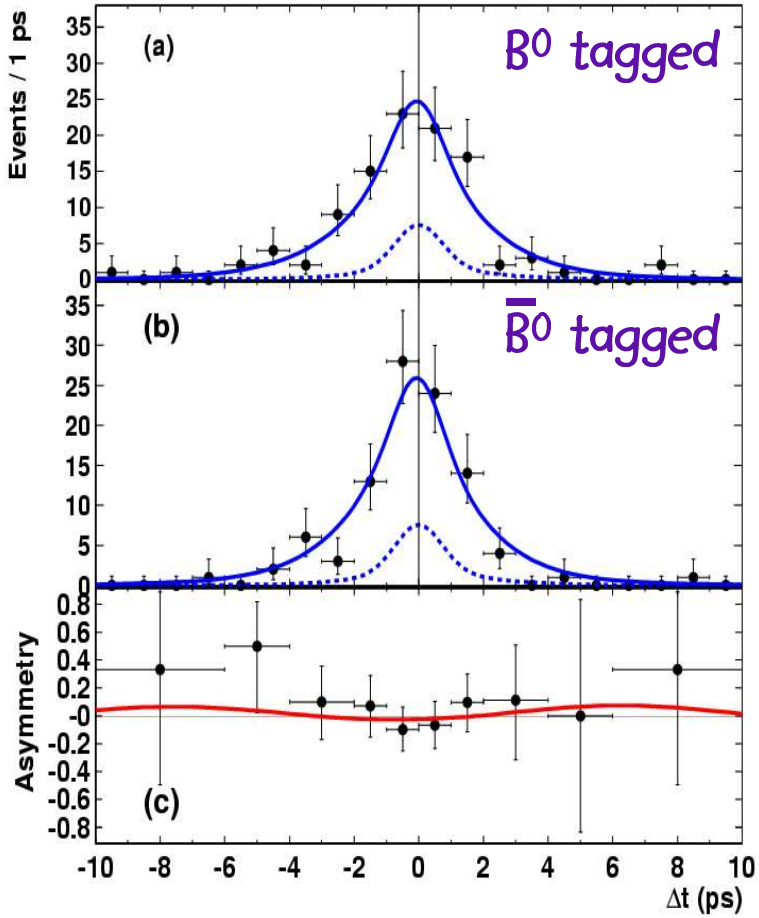


$$S_{\eta' K} = 0.43 \pm 0.27 \pm 0.05$$

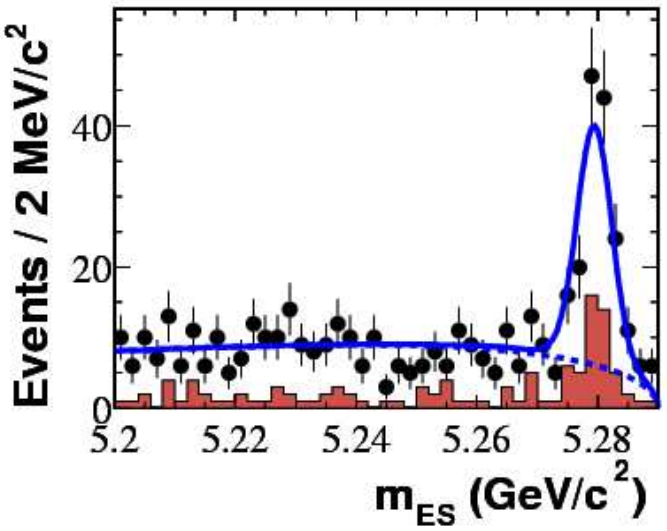
$$(A = -0.01 \pm 0.16 \pm 0.04)$$

CPV in B → η'Ks

BaBar 81fb-1 results



N_{sig} = 203±19

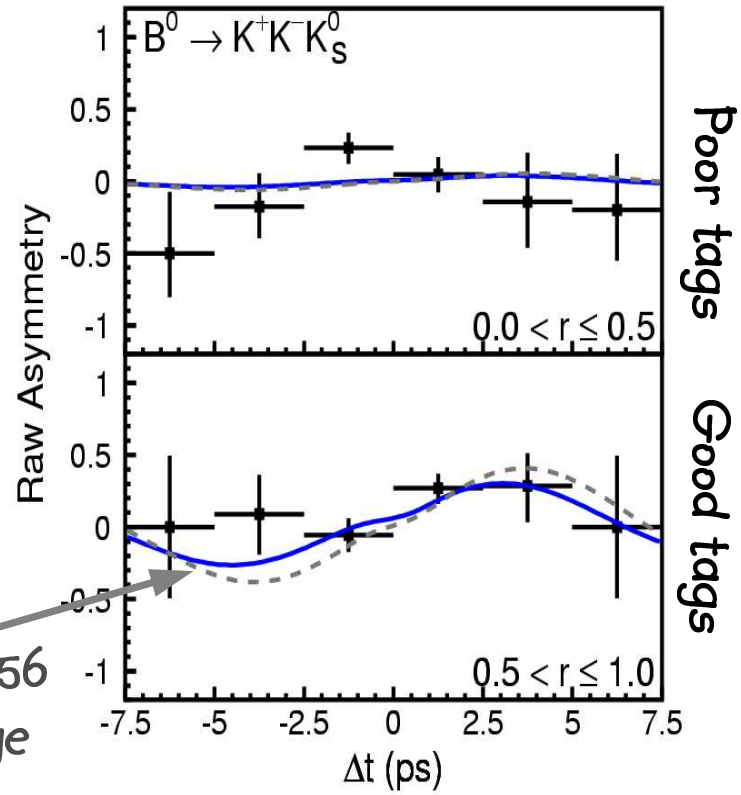


$$S_{\eta' K} = 0.02 \pm 0.34 \pm 0.03$$

$$(A = -0.10 \pm 0.22 \pm 0.03)$$

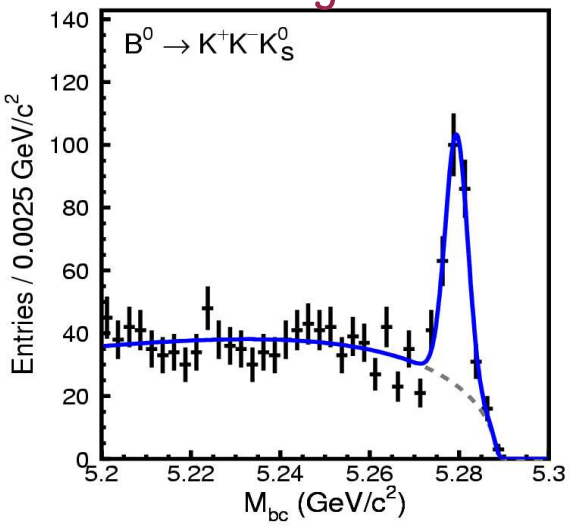
CPV in B → KKKs (φKs excl.)

Belle 140fb^{-1} results



For
S = 0.731±0.056
(world average
of sin2φ1)

N_{sig} = 199±18



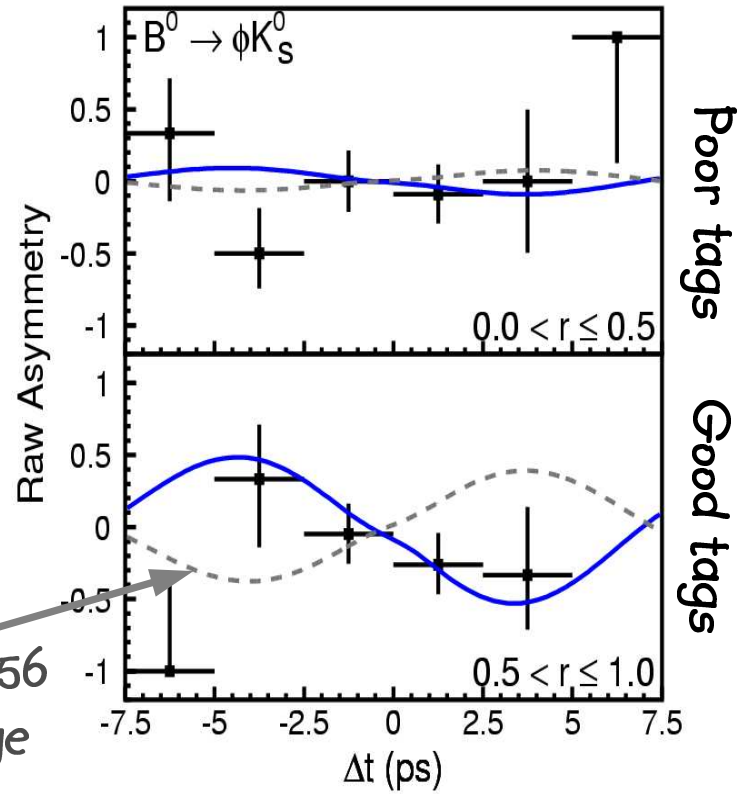
$$S_{KKKs} = 0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0.00}$$

$$(A = -0.01 \pm 0.16 \pm 0.04)$$

Error due to the
uncertainty in the CP content
f_{even} = 1.03±0.15±0.05

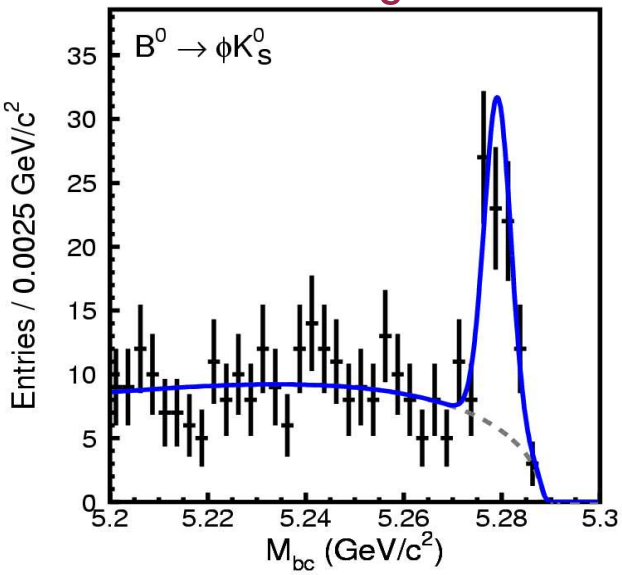
CPV in B → φKs

Belle 140fb^{-1} results



For
S = 0.731±0.056
(world average
of sin2φ1)

N_{sig} = 68±11



$$S_{\phi Ks} = -0.96 \pm 0.50^{+0.09}_{-0.11}$$

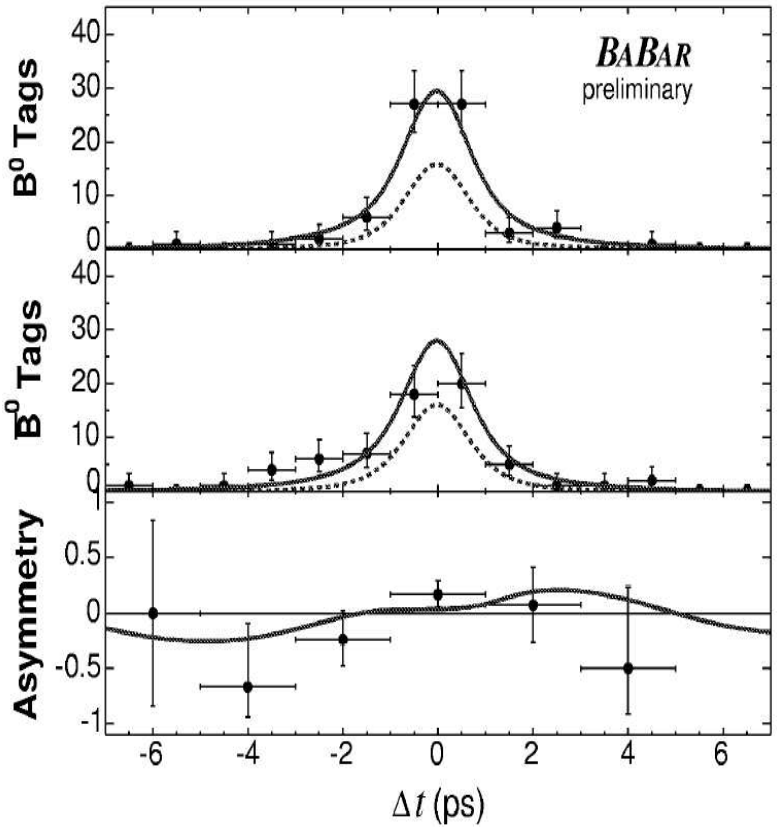
3.5σ away from sin2φ1 WA
by a Feldman-Cousins CL study.

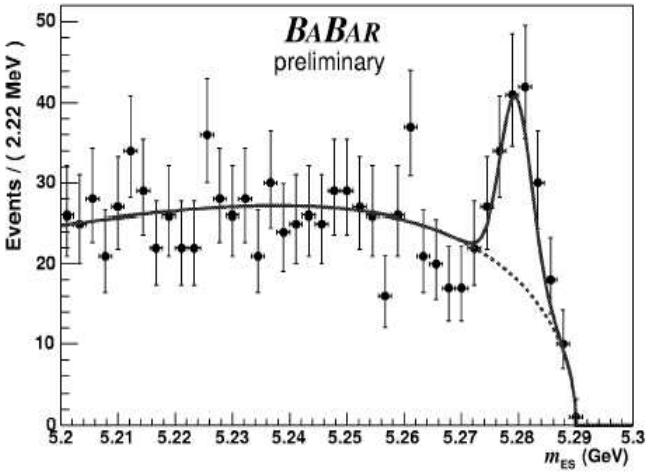
$$(A = -0.15 \pm 0.29 \pm 0.07)$$

CPV in B → φKs

Babar 110fb^{-1} results

N_{sig} = 70±9





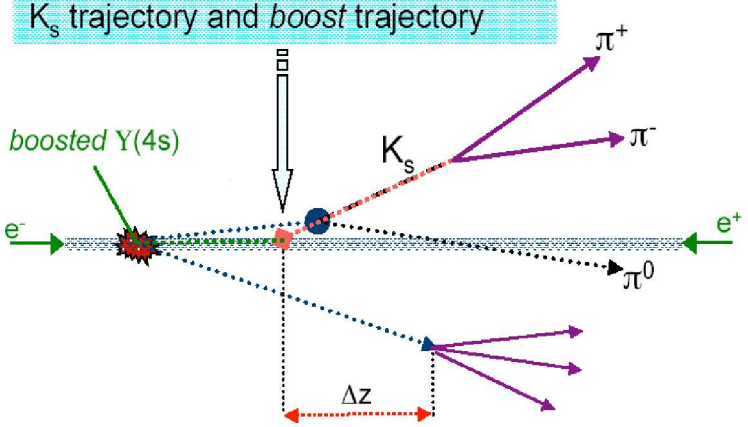
$$S_{\phi Ks} = 0.45 \pm 0.43 \pm 0.07$$

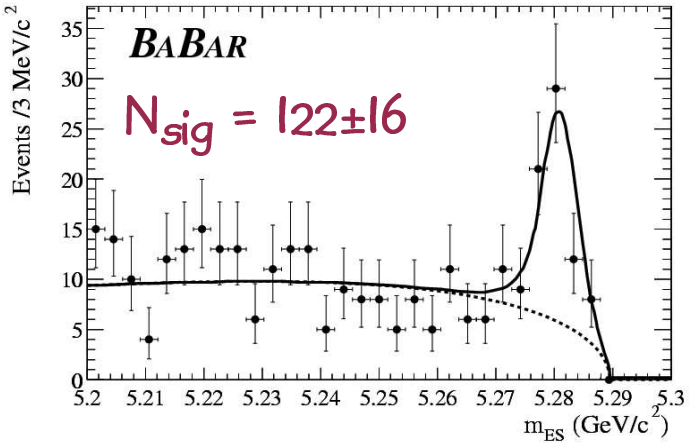
$$(A = -C = 0.38 \pm 0.37 \pm 0.12)$$

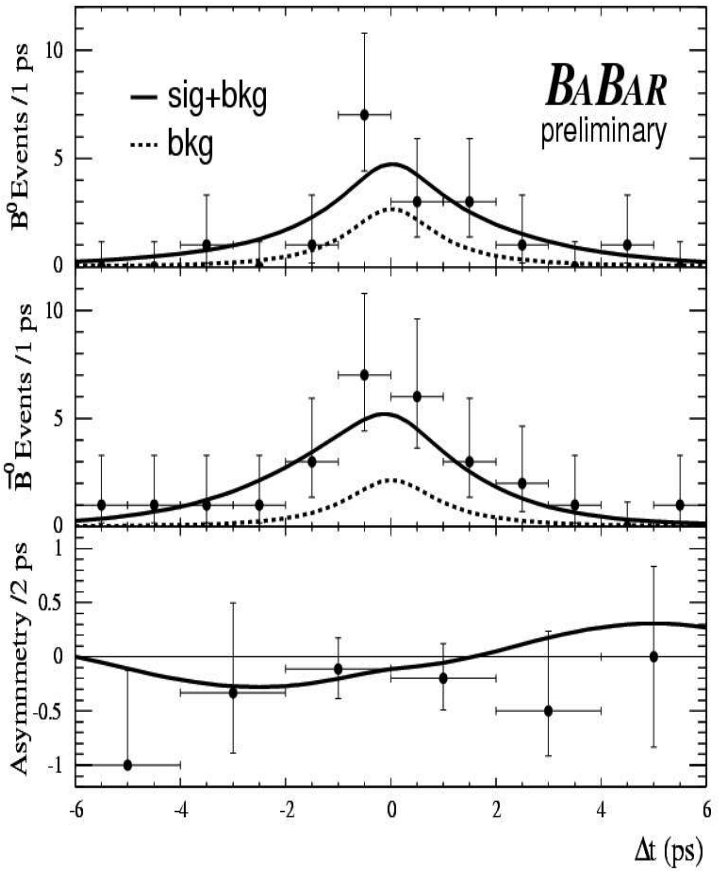
CPV in B → Ksπ0

Babar 110fb-1 results

Reconstruct B → $K_s \pi^0$ vertex using K_s trajectory and *boost* trajectory



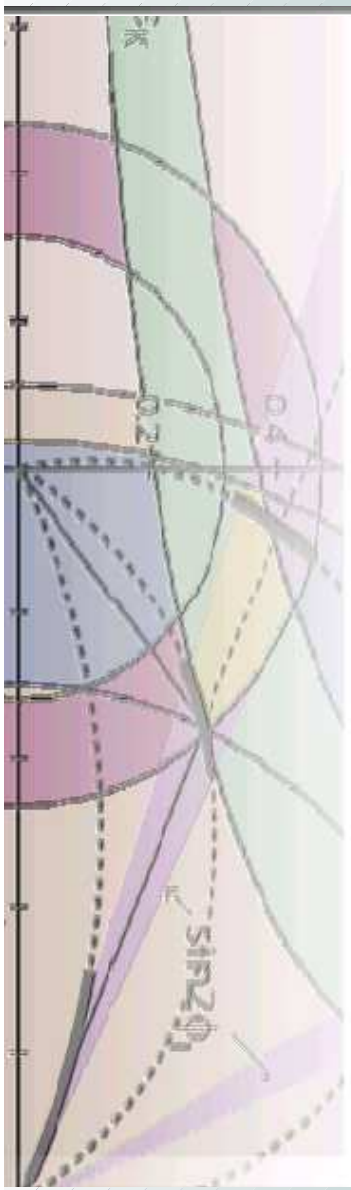


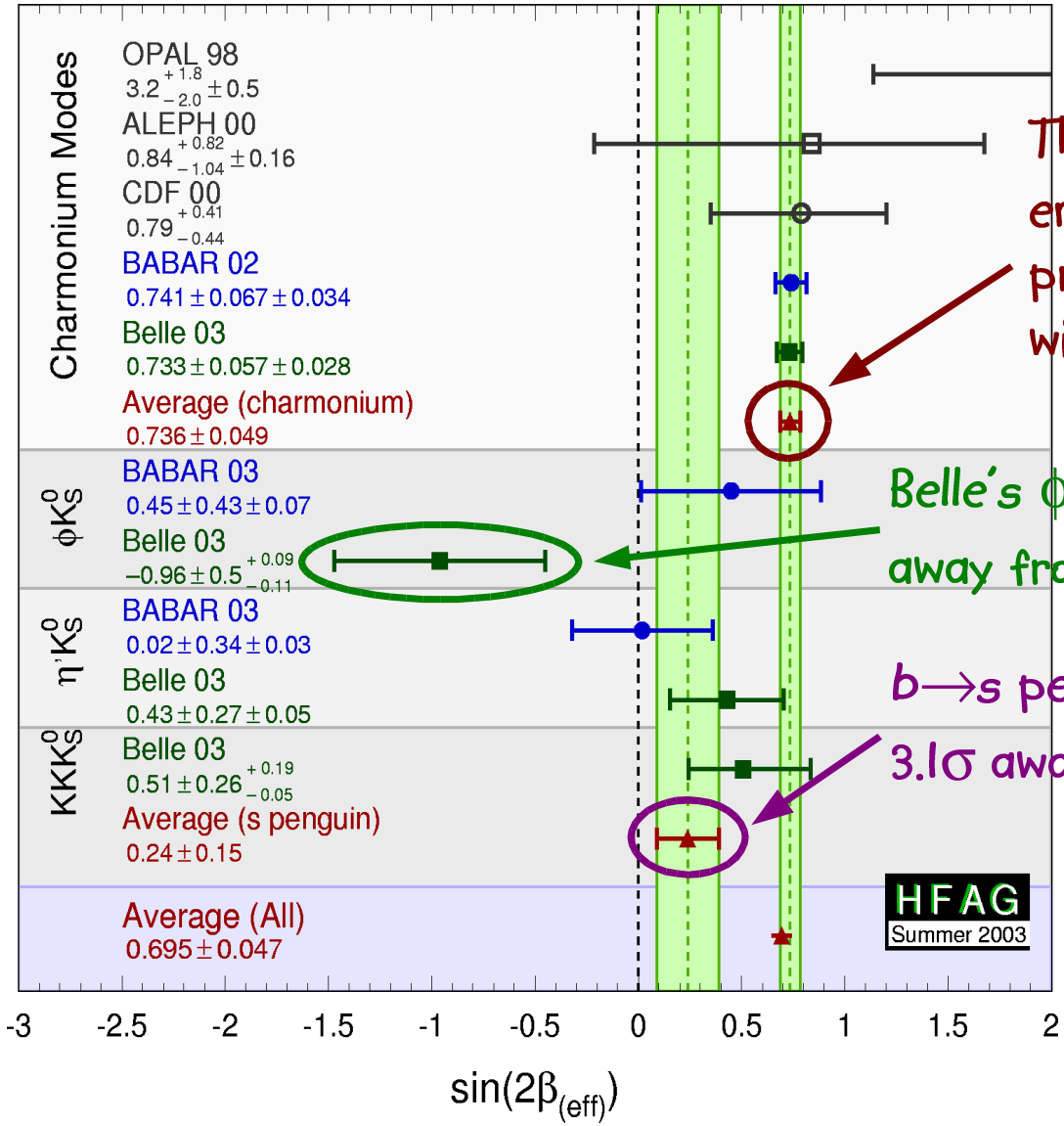


$$S_{Ks\,\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.11$$

$$\left(C = 0.40^{+0.27}_{-0.28} \pm 0.10 \right)$$

Summary of $\phi_1(\beta)$ Measurements





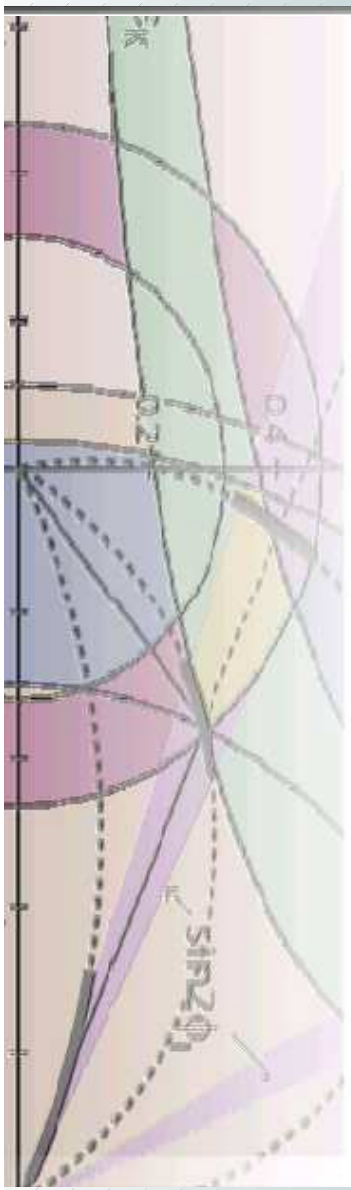
The sin2ϕ_1 study already enter the stage of precise measurement, with an error of < 0.05

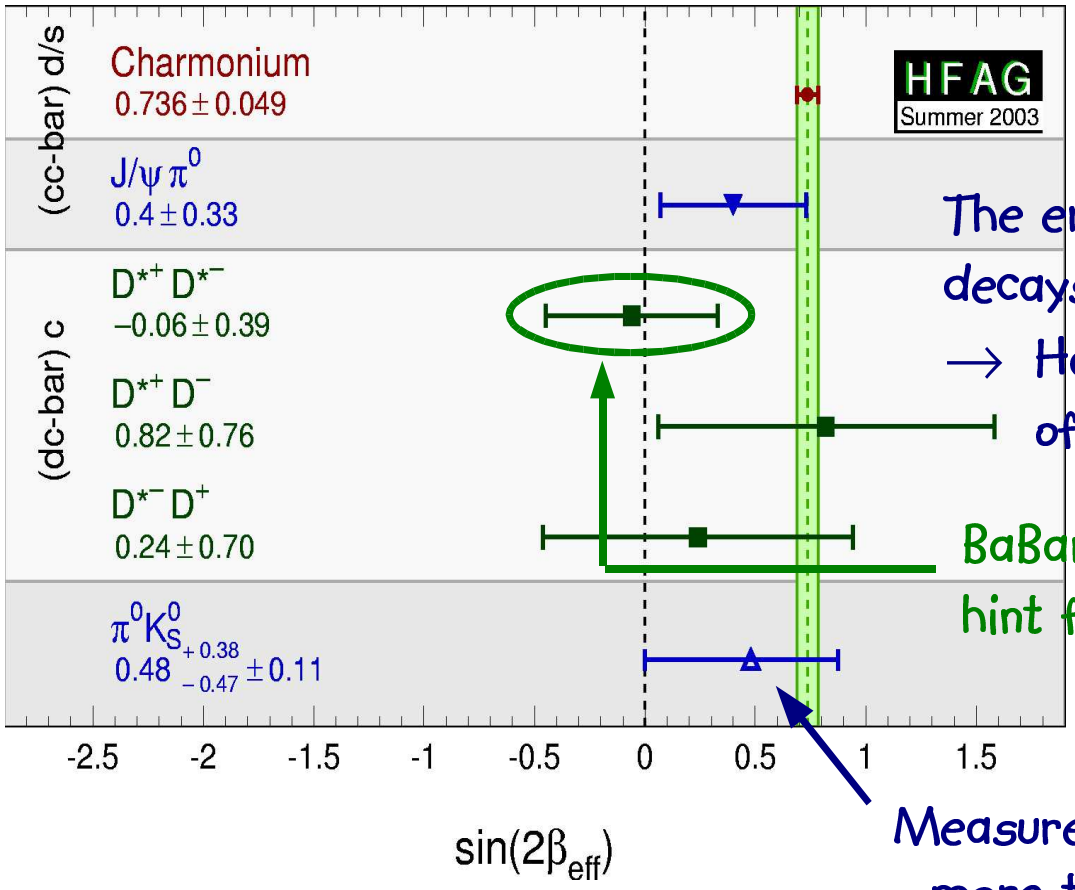
Belle's ϕK_S gives a 3.5σ away from WA of sin2ϕ_1

$b \to s$ penguin WA still gives a 3.1σ away from sin2ϕ_1

Hint of the existence of new physics phase

Summary of $\phi_1(\beta)$ Measurements





The error bars of $b \to ccd$ decays are still large.

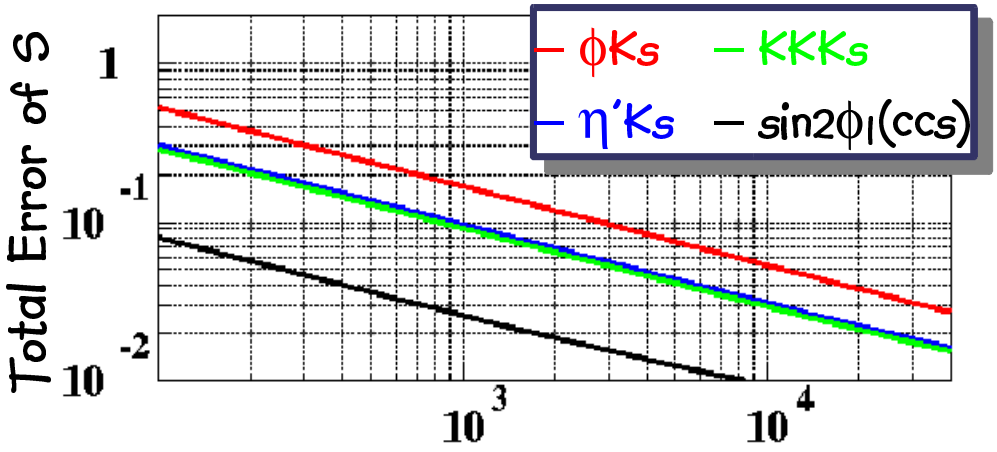
$\to$ Hard to have a conclusion of penguin pollution.

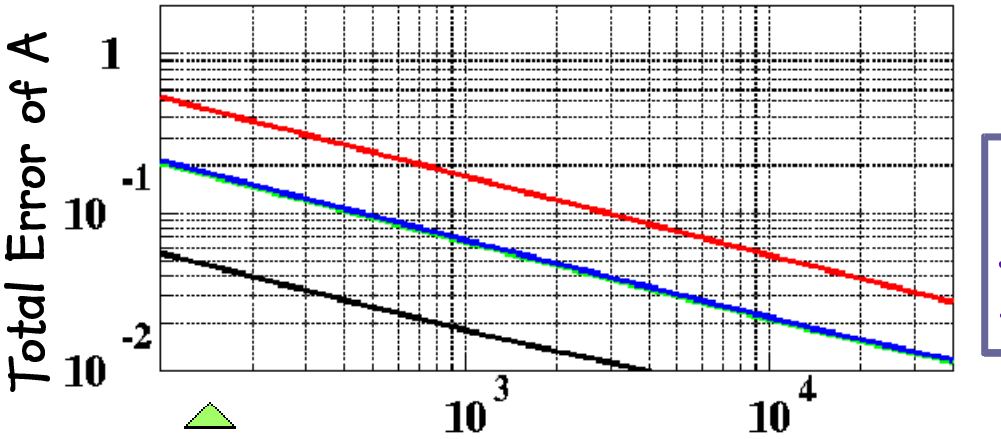
BaBar's D*D* gives a 2.5σ hint for penguin pollution

Measurement with Ks - more technical issue with vertex and its resolution

Summary of $\phi_1(\beta)$ Measurements

Prospects of $\sin 2\phi_1$ from $b \to ccs$ and sqq from Belle





Errors are extrapolated from current data, with smaller statistical and systematic uncertainties as the luminosity increases.

More and more sensitive to new physics phase in the future

Measurement of $\phi_2(\alpha)$

CPV in $B \to \pi\pi$

Time-dependent CP asymmetry in $B \to \pi^+\pi^-$

$$A_{CP}(t) = A_{\pi\pi}\cos(\Delta m\, t) + S_{\pi\pi}\sin(\Delta m\, t)$$

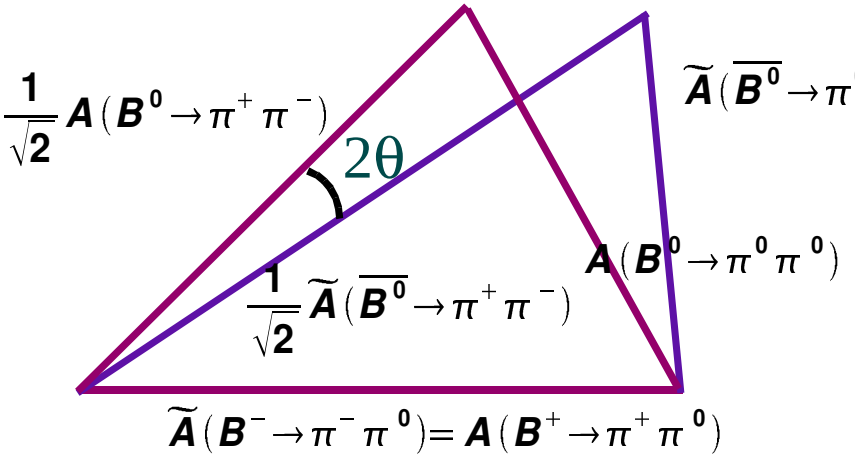
$$\lambda = e^{2i\phi_2}$$
$$A_{\pi\pi} = 0$$
$$S_{\pi\pi} = \sin 2\phi_2$$

Tree only

$$\lambda = e^{2i\phi_2}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$
$$A_{\pi\pi} \propto \sin\delta$$
$$S_{\pi\pi} = \sqrt{1-A_{\pi\pi}}\sin 2\phi_2^{eff}$$

Tree + Penguin

Related to ϕ_2 (need isospin analysis)

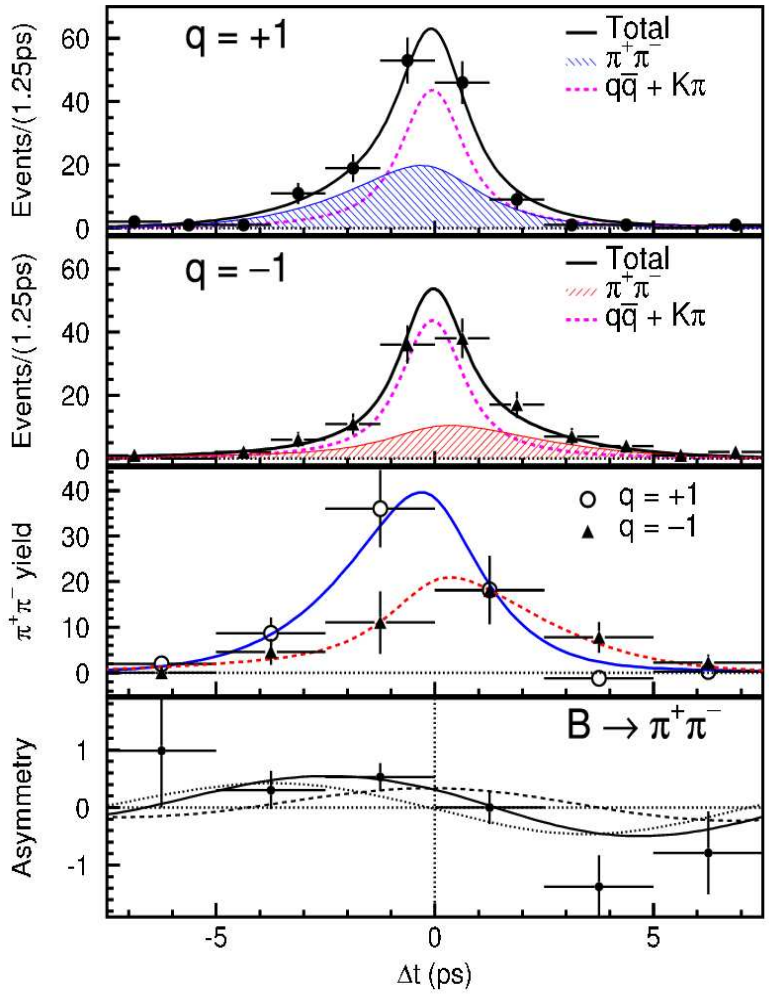


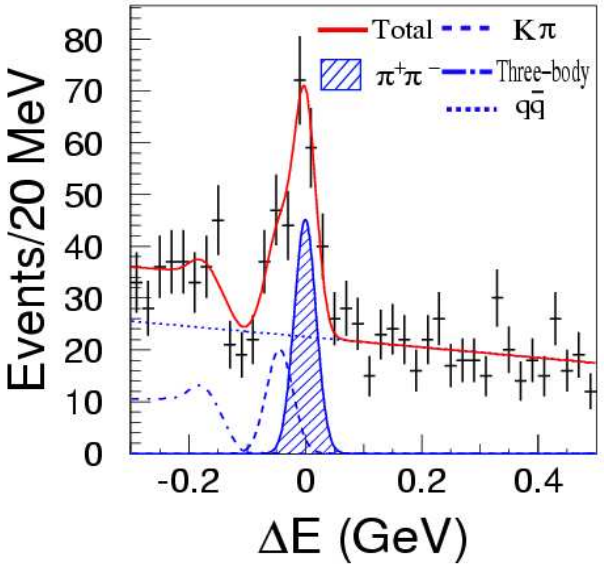
$$\theta = |\phi_2 - \phi_2^{eff}|$$

The branching fractions of $B \to \pi^+\pi^-/\pi^+\pi^0/\pi^0\pi^0$ can be used to constrain ϕ_2

CPV in $B \to \pi\pi$

Belle 78fb^{-1} Results





$N_{\pi\pi}$(total)= 163±18

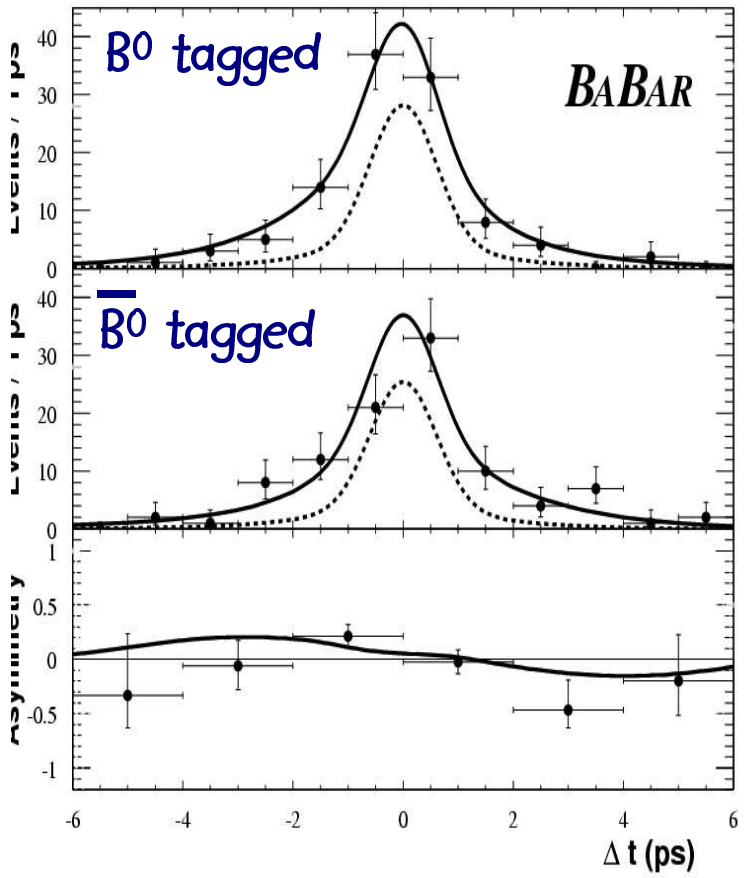
$$A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$$
$$S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$$

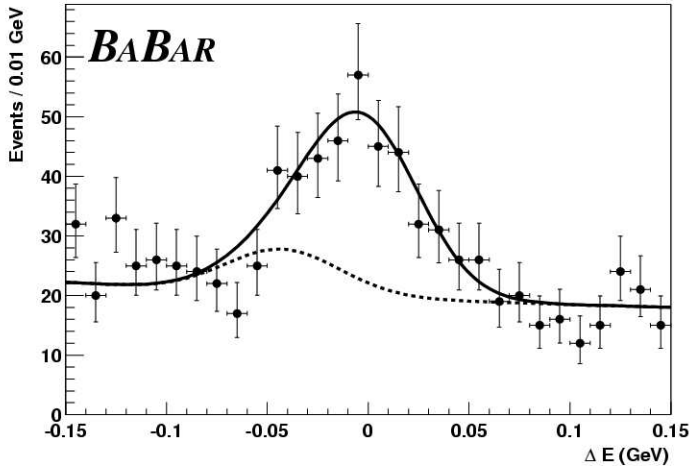
Rule out the CP-conserving case (A,S = 0,0)at CL = 99.93%

CPV in $B \to \pi\pi$

BaBar 113fb^{-1} Results

$N_{\pi\pi}$= 266±24





$$A_{\pi\pi} = -C_{\pi\pi} = +0.19 \pm 0.19 \pm 0.05$$

$$S_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03$$

$$(A_{K\pi} = -0.107 \pm 0.041 \pm 0.013)$$

CPV in B → ππ

Constrain on $\phi_2(\alpha)$

The world averages of Acp(ππ) are given by

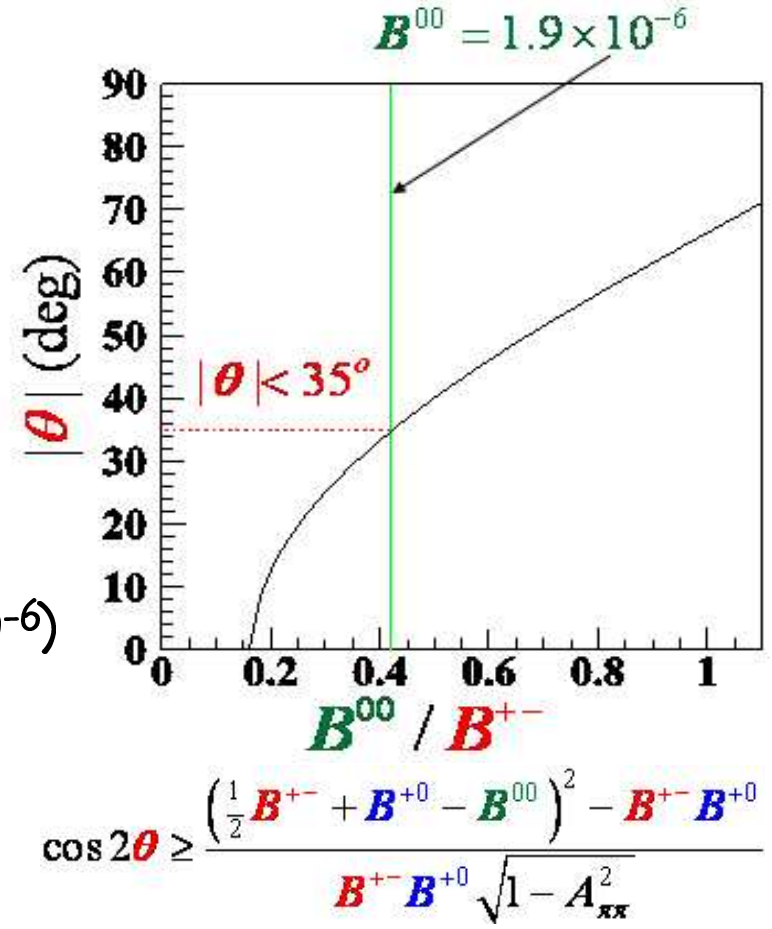
$$\begin{cases} C_{\pi\pi} = -A_{\pi\pi} = -0.38 \pm 0.16 \\ S_{\pi\pi} = -0.58 \pm 0.20 \end{cases}$$

Together with all ππ branching fractions:

$$B(B^0 \to \pi^+\pi^-) = 4.55 \pm 0.44 \ (\times 10^{-6})$$

$$B(B^0 \to \pi^0\pi^0) = 1.90 \pm 0.47$$

$$B(B^+ \to \pi^+\pi^0) = 5.27 \pm 0.79$$



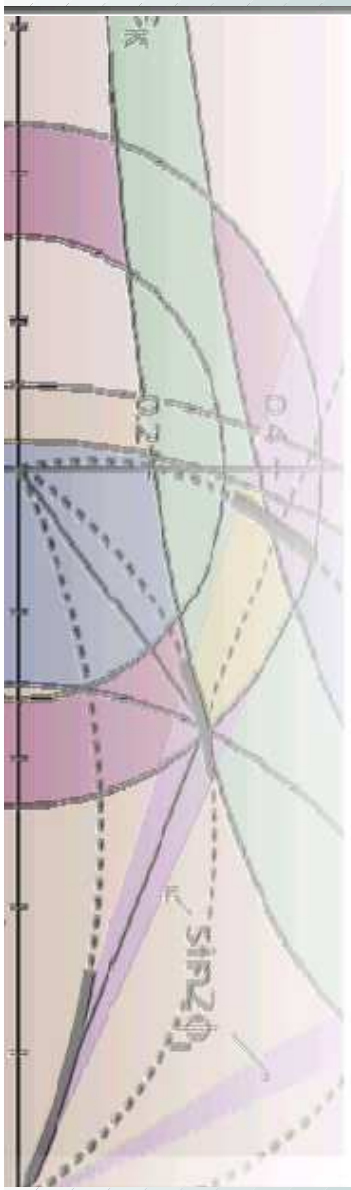
$$\cos 2\theta \geq \frac{\left(\frac{1}{2}B^{+-} + B^{+0} - B^{00}\right)^2 - B^{+-}B^{+0}}{B^{+-}B^{+0}\sqrt{1 - A_{+-}^2}}$$

$\theta = |\phi_2 - \phi_2^{\text{eff}}| < 35^\circ$

No more improvement for this bound, the Acp($\pi^0\pi^0$) is necessary.

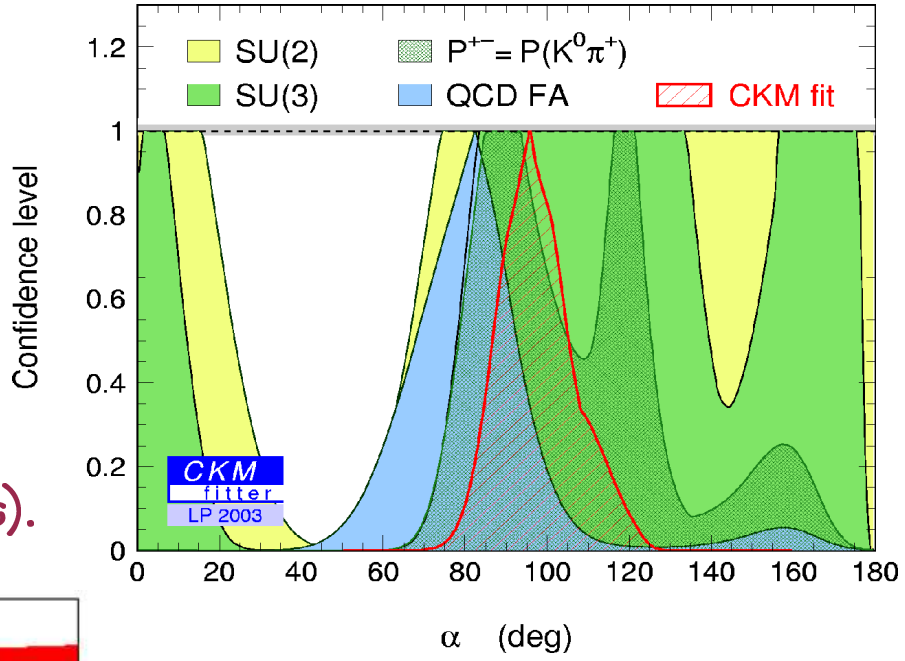
Gronau/London/Sinha/Sinha bound (PLB514, 315 (2001))

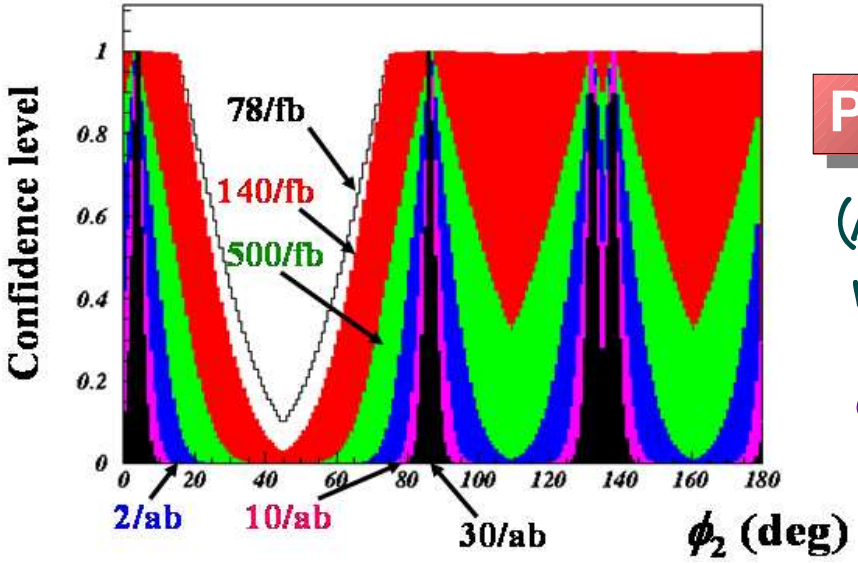
Summary of $\phi_2(\alpha)$ by $B \to \pi\pi$



CPV in $B \to \pi\pi$

One can be constrain $\phi_2(\alpha)$ with several different assumptions, and compare the result from the global CKM fit (+ϕ_1 WA and others).





Prospect for $\phi_2(\alpha)$

($Acp(\pi^0\pi^0)$ assumed to be +0.5, with isospin analysis.)

$\delta\phi_2$ reach 1.6 deg. at 30 ab^{-1}.

Measurement of $\phi_2(\alpha)$ by $B \to \rho\pi$

Time-dependent CPV in $B \to \rho\pi$

$$f_{Q_{tag}}^{\rho^{\pm}h^{\mp}}(\Delta t) = (1 \pm A_{CP}^{\rho h}) \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left[1 + Q_{tag}(S_{\rho h} \pm \Delta S_{\rho h}) \sin(\Delta m_d \Delta t) - Q_{tag}(C_{\rho h} \pm \Delta C_{\rho h}) \cos(\Delta m_d \Delta t)\right]$$

± for change of ρ

$Q_{tag} = +1(-1)$ *for* $B_{tag} = B^0(\overline{B^0})$

$B^0(\overline{B^0}) \to \rho^+\pi^-$

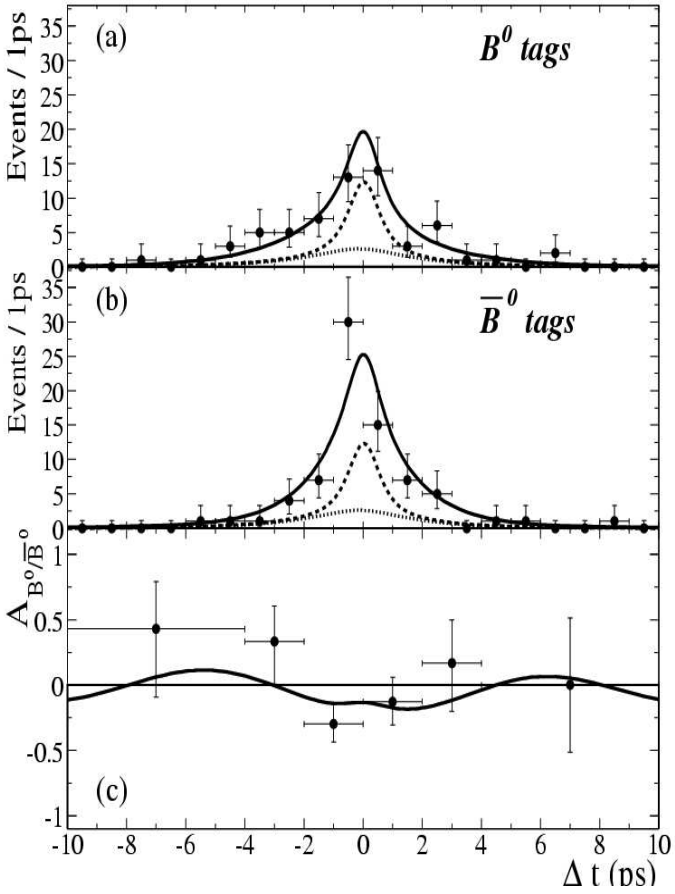
$B^0(\overline{B^0}) \to \rho^-\pi^+$

Fitting Parameters

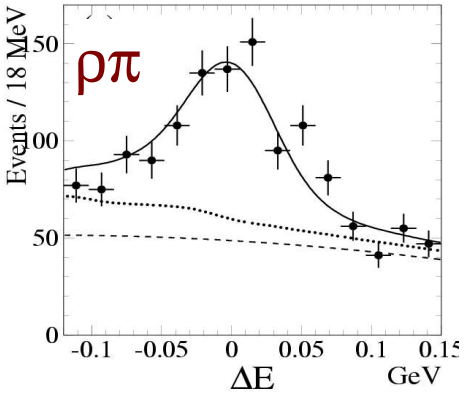
- $A_{\rho\pi}/A_{\rho K}$ → Global charge asymmetry
- $C_{\rho\pi}$ → Direct CP asymmetry
- $S_{\rho\pi}$ → Mixing induced CPV
- $\Delta C_{\rho\pi}$, $\Delta S_{\rho\pi}$ → Connect to two sets of samples:

Measurement of $\phi_2(\alpha)$ by $B \to \rho\pi$

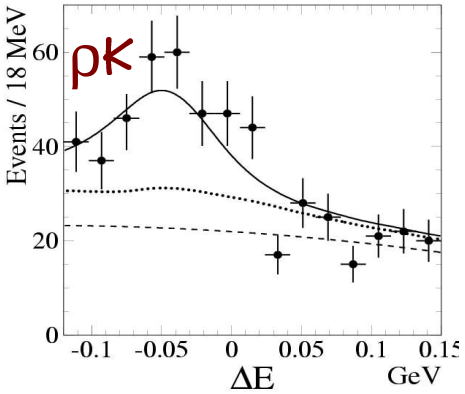
BaBar 110 fb^{-1} results



$N_{\rho\pi}$= 804±49



$N_{\rho K}$ = 260±31



$$A_{\rho\pi} = -0.11 \pm 0.06 \pm 0.03$$

$$A_{\rho K} = 0.18 \pm 0.12 \pm 0.08$$

$$C_{\rho\pi} = 0.35 \pm 0.13 \pm 0.05$$

$$S_{\rho\pi} = -0.13 \pm 0.18 \pm 0.03$$

$$\Delta C_{\rho\pi} = 0.35 \pm 0.13 \pm 0.05$$

$$\Delta S_{\rho\pi} = 0.33 \pm 0.18 \pm 0.03$$

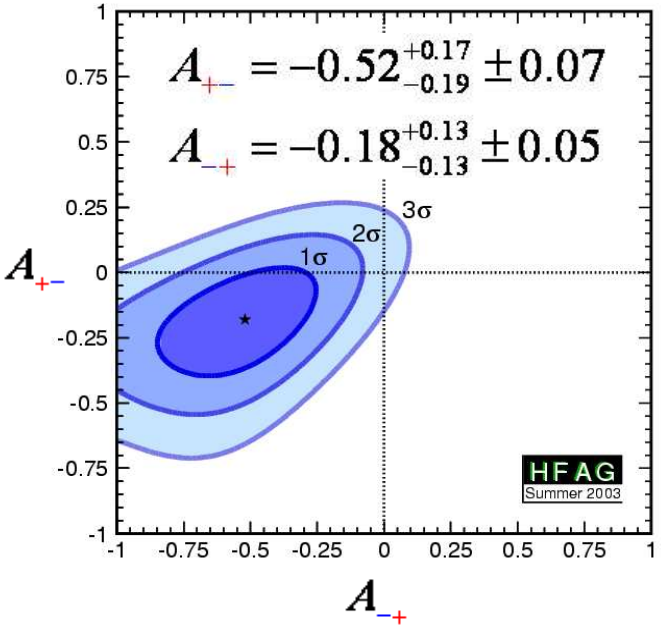
Summary of $\phi_2(\alpha)$ by $B \to \rho\pi$

CPV in $B \to \rho\pi$

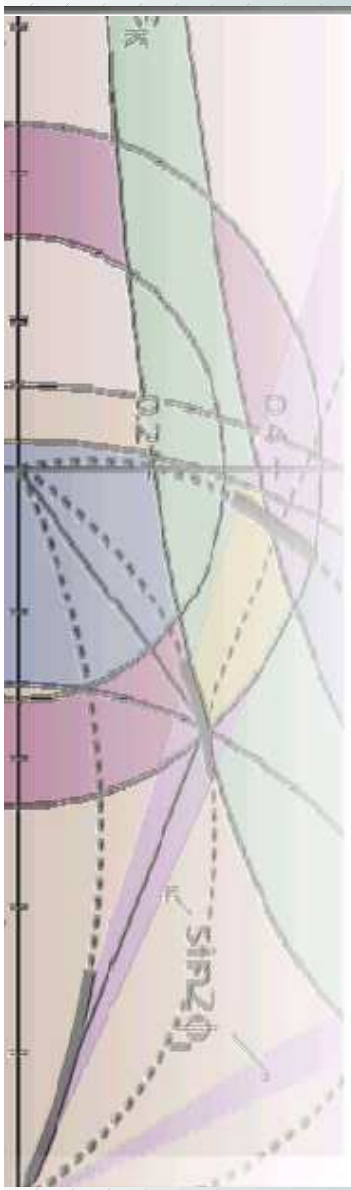
- **Based on a quasi 2-body decay analysis.**
  (With only $B \to \rho^+\pi^-$ and $\rho^-\pi^+$, and the interference region is removed.)
- **Hint of direct CP violation:**

$$A_{+-} \equiv \frac{N(\bar{B}^0_{\rho\pi} \to \rho^+\pi^-) - N(B^0_{\rho\pi} \to \rho^-\pi^+)}{N(\bar{B}^0_{\rho\pi} \to \rho^+\pi^-) + N(B^0_{\rho\pi} \to \rho^-\pi^+)}$$

$$A_{-+} \equiv \frac{N(\bar{B}^0_{\rho\pi} \to \rho^-\pi^+) - N(B^0_{\rho\pi} \to \rho^+\pi^-)}{N(\bar{B}^0_{\rho\pi} \to \rho^-\pi^+) + N(B^0_{\rho\pi} \to \rho^+\pi^-)}$$



Conclusion

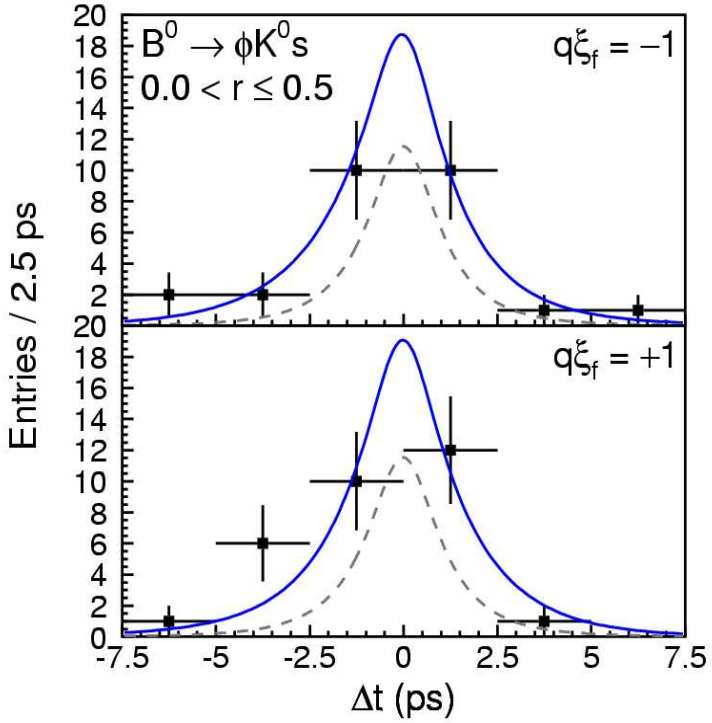


- Large CP violations have been measured in b $\rightarrow$ ccs channels by B factories, and are consistent with CKM framework.
- Hint of new physics phase in b $\rightarrow$ sqq penguin decays. Need to be checked with more data from both experiments.
- CPV measurement in B $\rightarrow \pi\pi$ channel has been established successfully. It's necessary to have more data to constrain on ϕ_2.
- Need full Dalitz analysis for B $\rightarrow \rho\pi$ to extract ϕ_2.

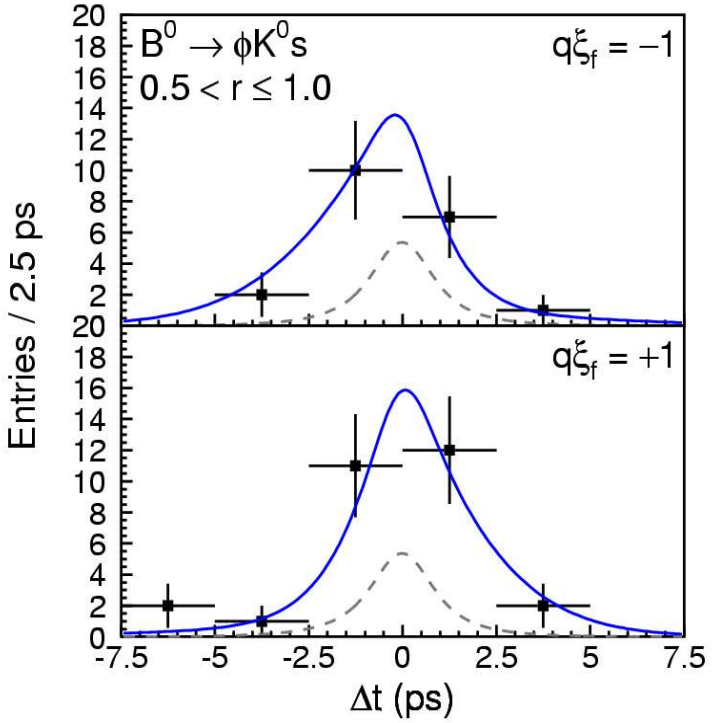
Look forward to high luminosity B factories in the future.

Figures for φKs

Δt distributions of B → φKs events



Poor tags

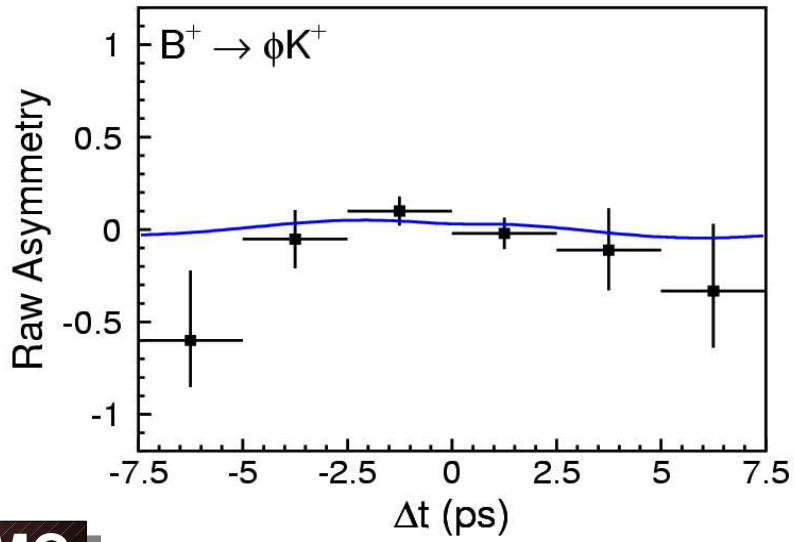


Good tags

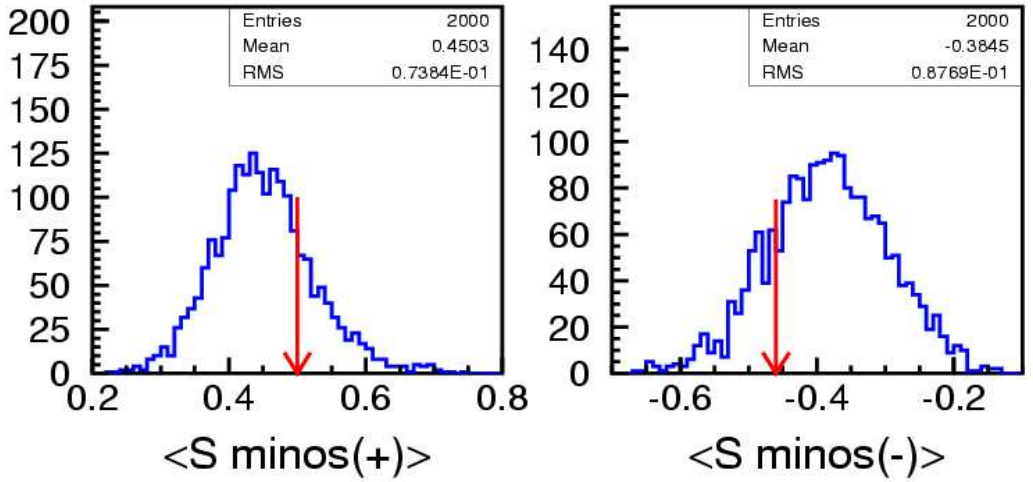
Backup Slides

Figures for φKs

Raw asymmetry plots of $B \to \phi K^+$ events



Expected errors by toy MC



Backup Slides