CP Violation from B-factories

- Results from BaBar and Belle -

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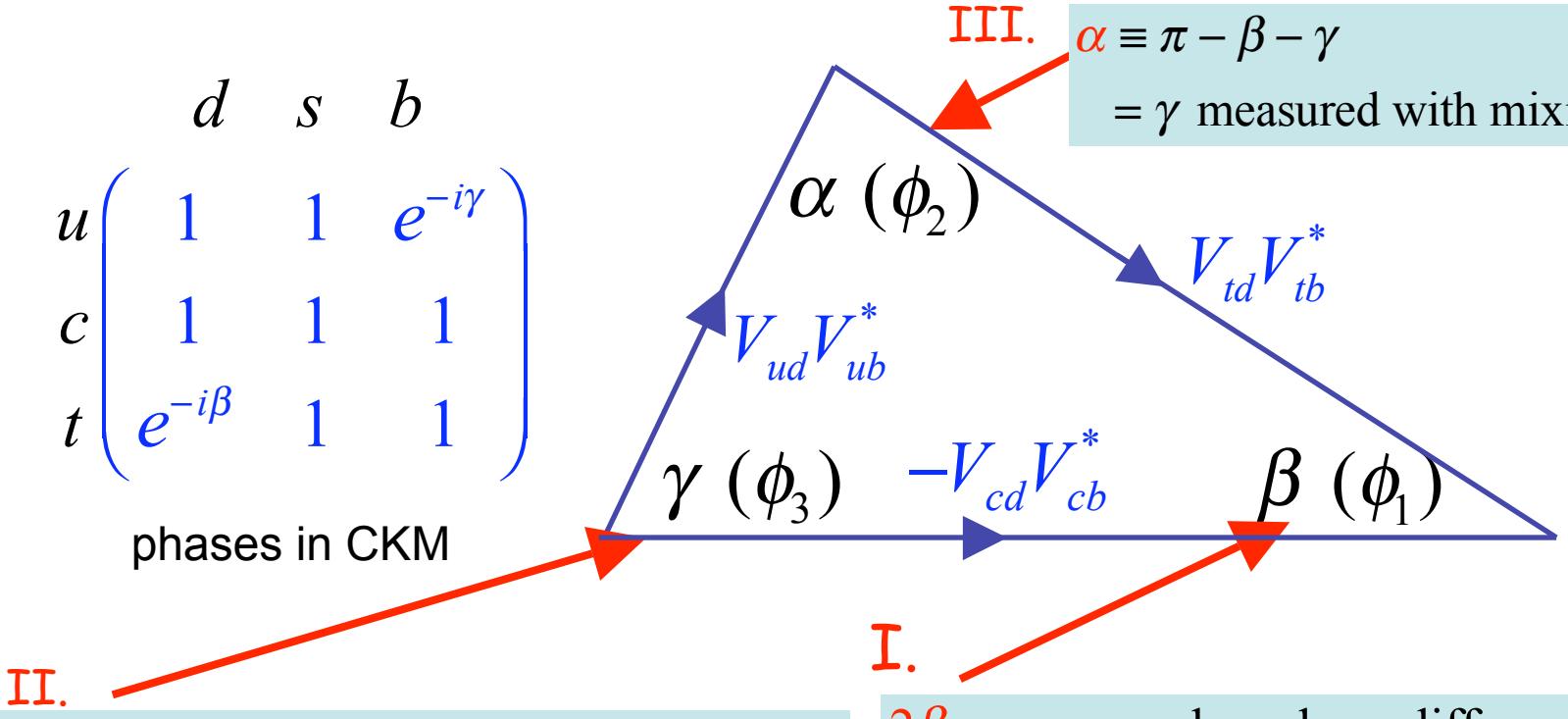
Why (still) flavor physics ?

- If New Physics at TeV, it might manifest itself in flavor physics at B-factories via CPV in B /D, rare B/D and rare tau decays.
  - If it does not show up, we still want to know why.
- What is the role of measurements of B meson system in this context ?
- In particular, CKM angle measurements.

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

$$\begin{array}{c} \\ u \\ c \\ t \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix} \end{array}$$

phases in CKM



γ = measured as phase difference between $b \to u$ and $b \to c$ transitions

Mesaured in tree-level processes,

and therefore insensitive to

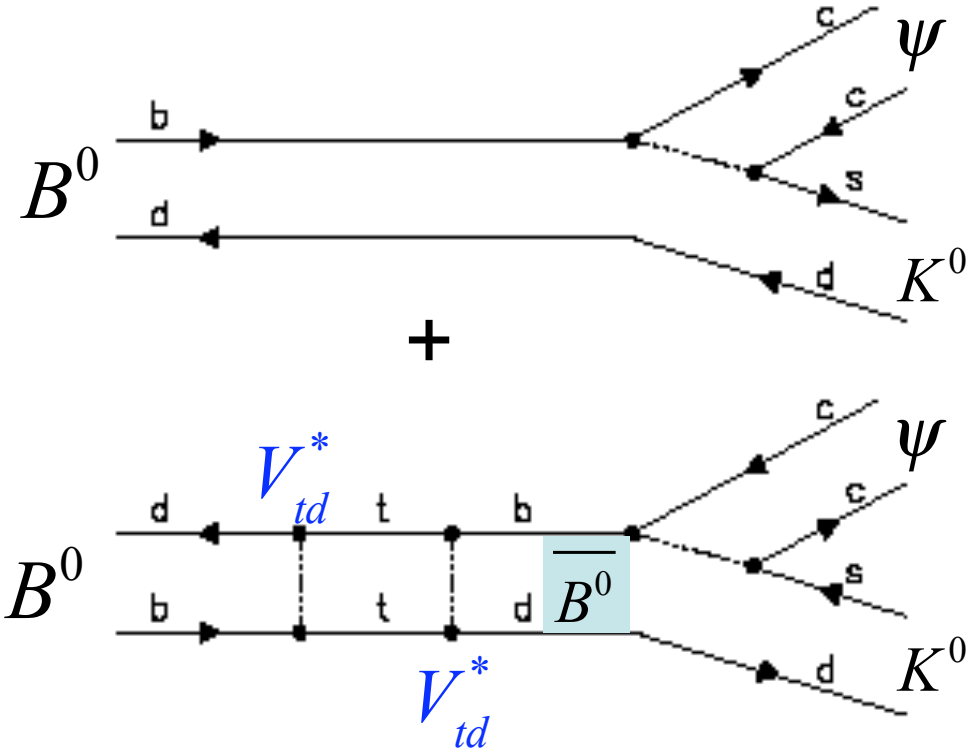
New Physics.

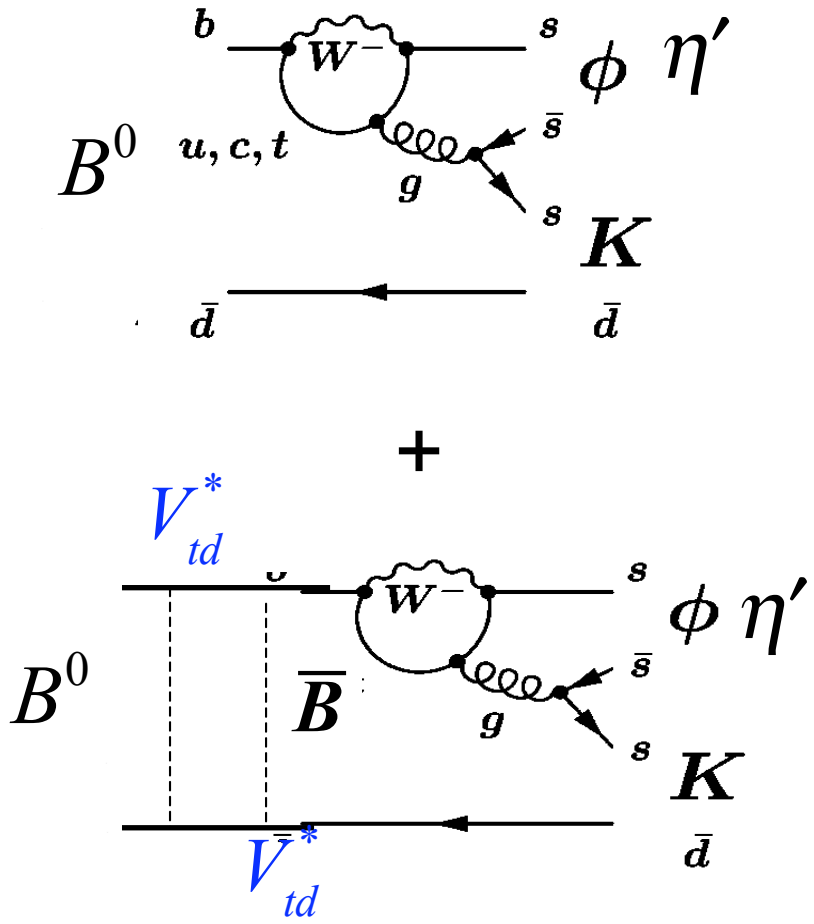
2β = measured as phase difference between $B^0 \to \bar{B}^0 \to f$ and $B^0 \to f$ decay paths.

Measured in tree and loop processes.

Loop probes New Physics.

$\sin 2\beta$: tree vs loop

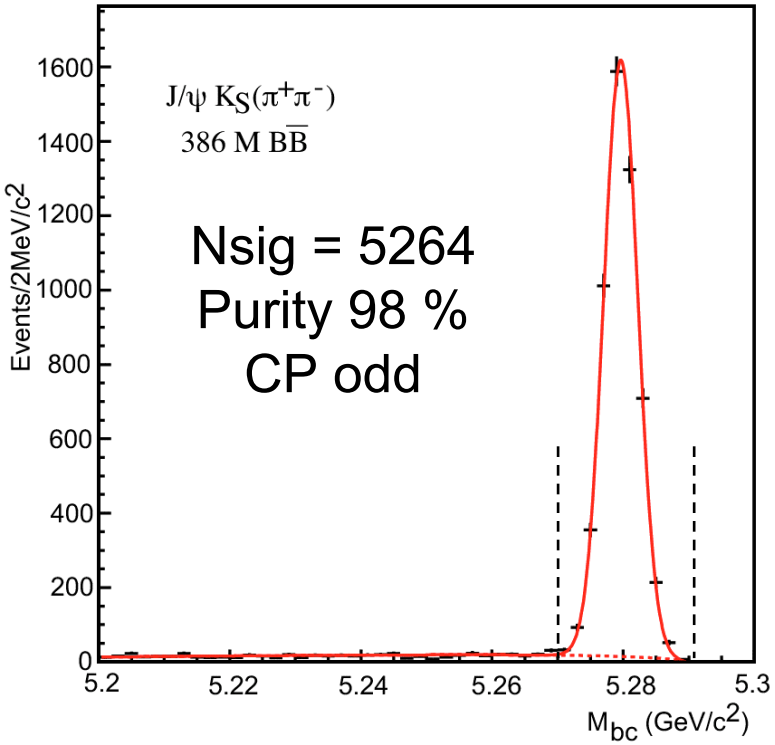




Unless threre is a new phase(s) in a loop, measurements of mixing-induced CP violation should give the same $\sin 2\beta$.

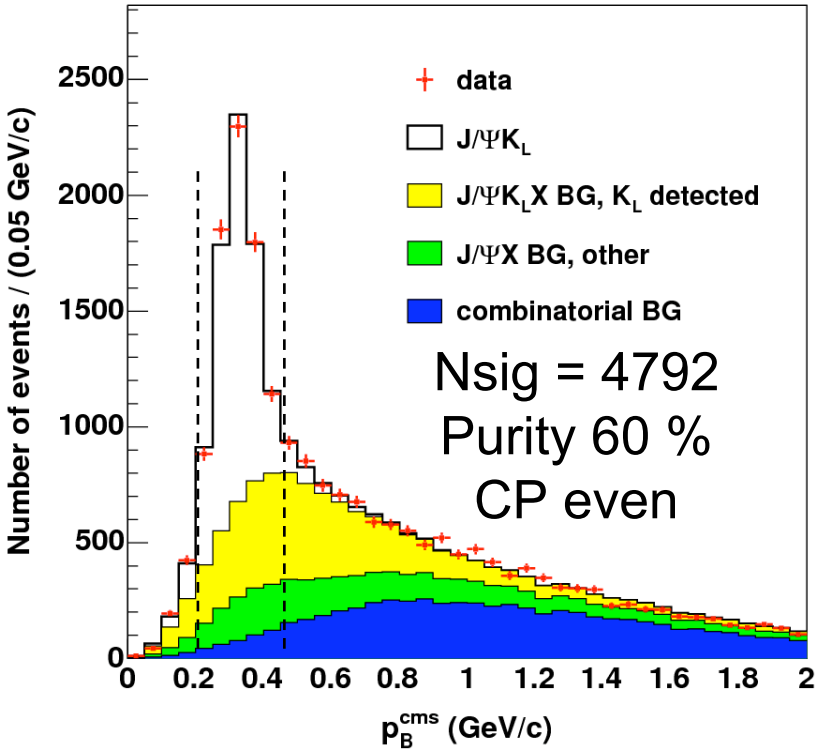
Belle 2005 update : $B^0 \rightarrow J/\psi\, K^0$ w/386 M $B\bar{B}$ pairs

$B^0 \rightarrow J/\psi\, K^0_S$

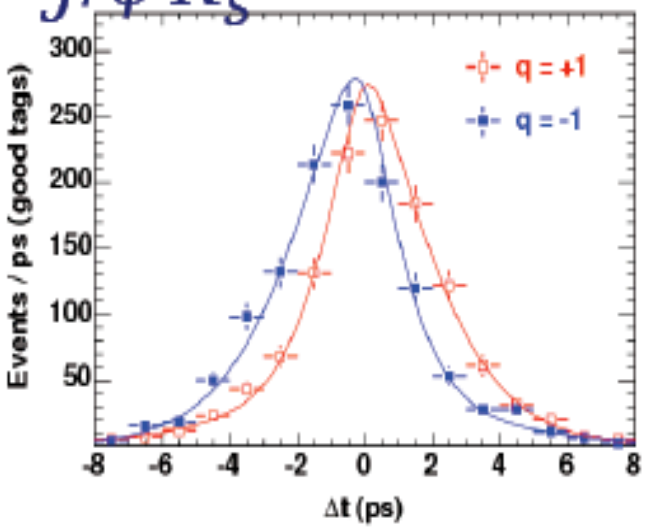


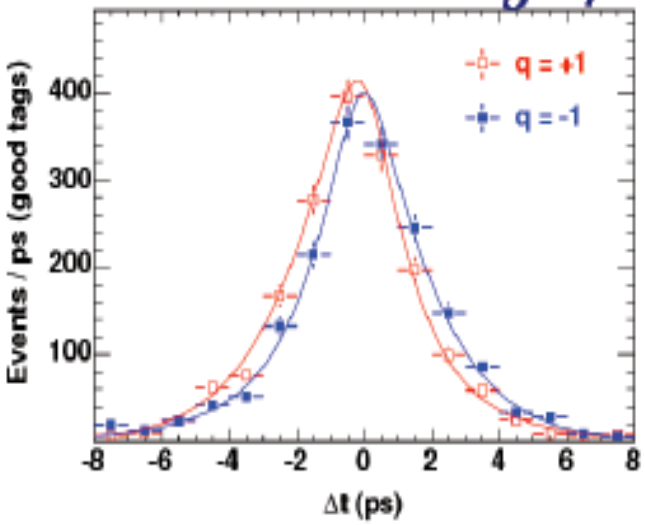
$$M_{bc} = \sqrt{E^{*2}_{beam} - P^{*2}_{J/\psi Ks}}$$

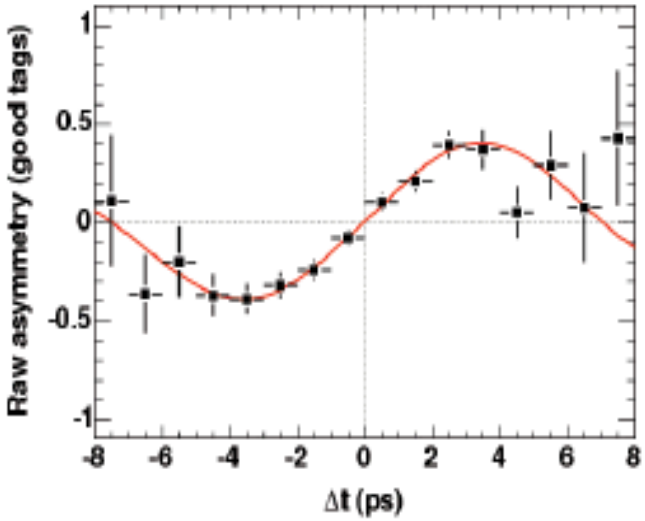
$B^0 \rightarrow J/\psi\, K^0_L$

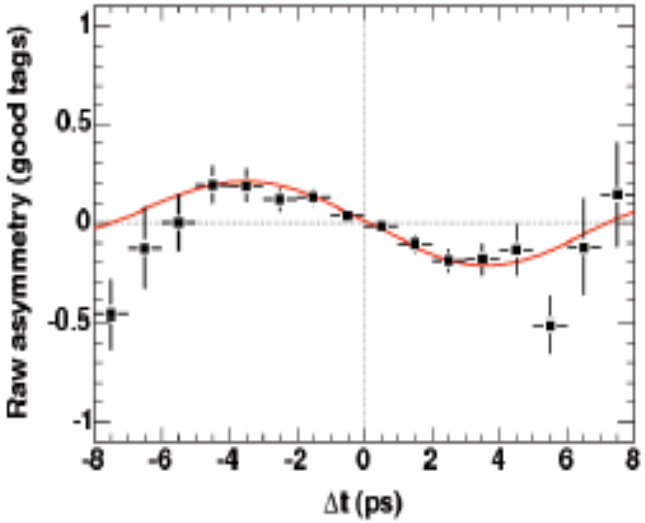


$J/\psi K_S$ $Belle\,(386\times10^6\,B\bar{B})$ $J/\psi K_L$



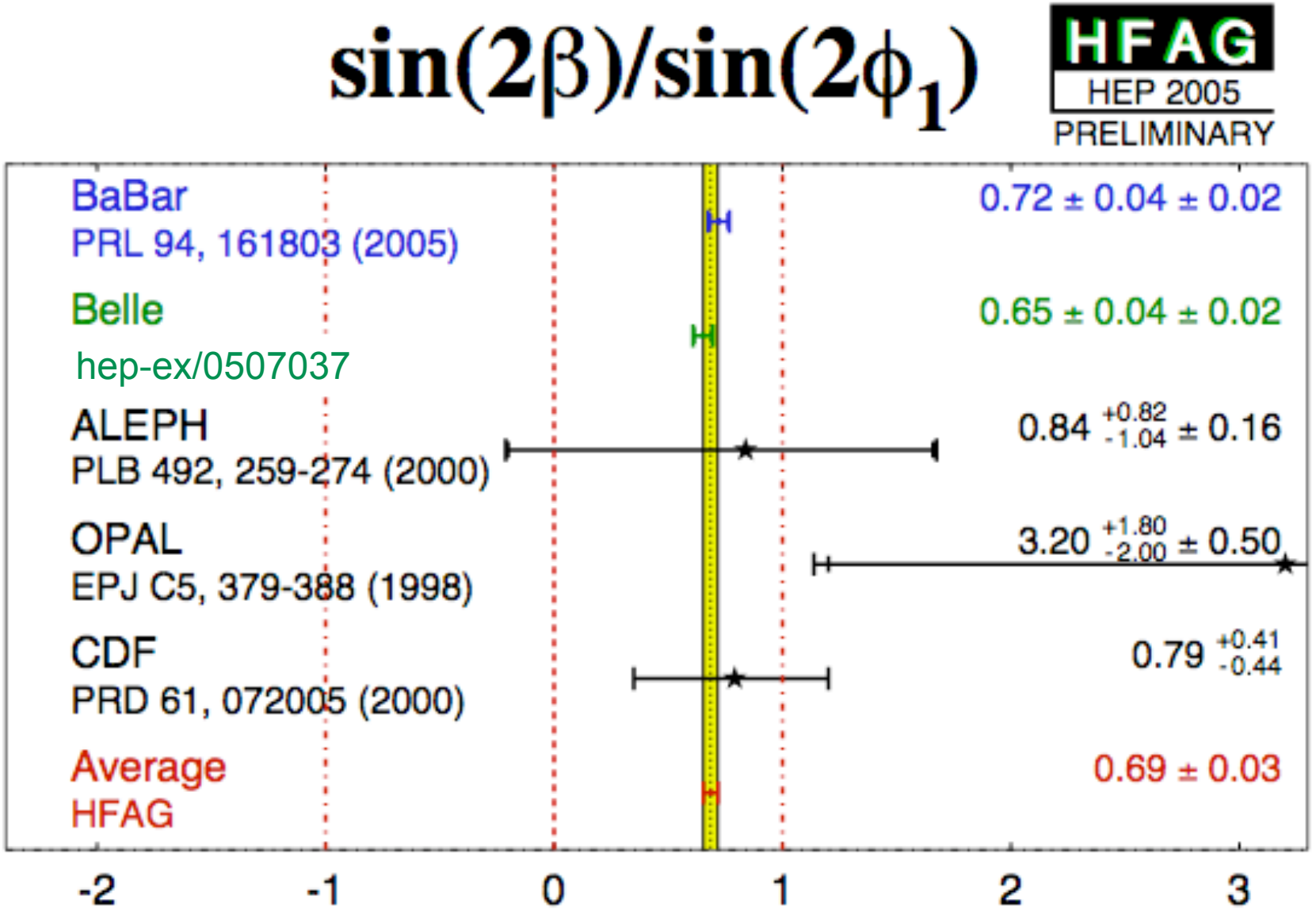




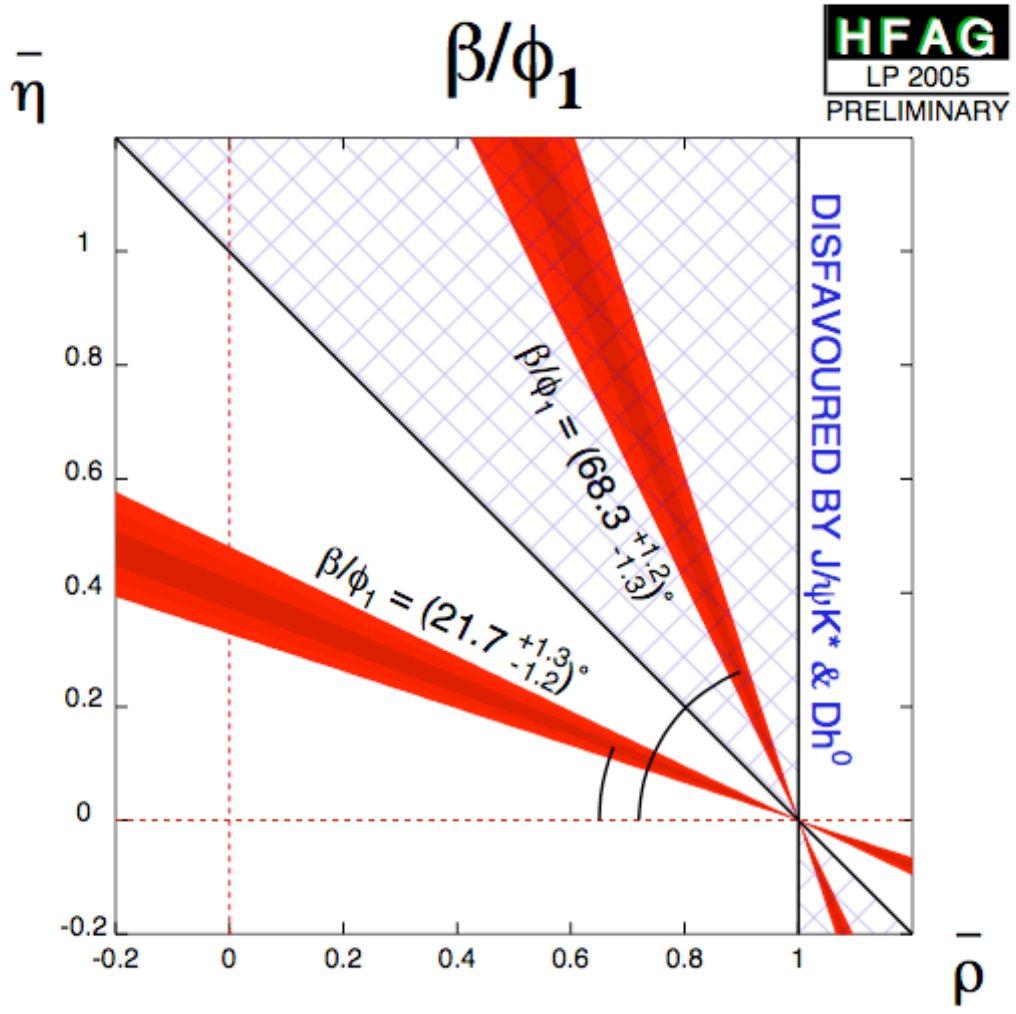


$$\frac{\Gamma\left(\overline{B^0}(\Delta t)\to f\right)-\Gamma\left(B^0(\Delta t)\to f\right)}{\Gamma\left(\overline{B^0}(\Delta t)\to f\right)+\Gamma\left(B^0(\Delta t)\to f\right)}=D\sin 2\beta\sin(\Delta m_d\Delta t)$$

$$\sin 2\beta = 0.652 \pm 0.039 \pm 0.020$$



HFAG=Heavy Flavor Averaging Group

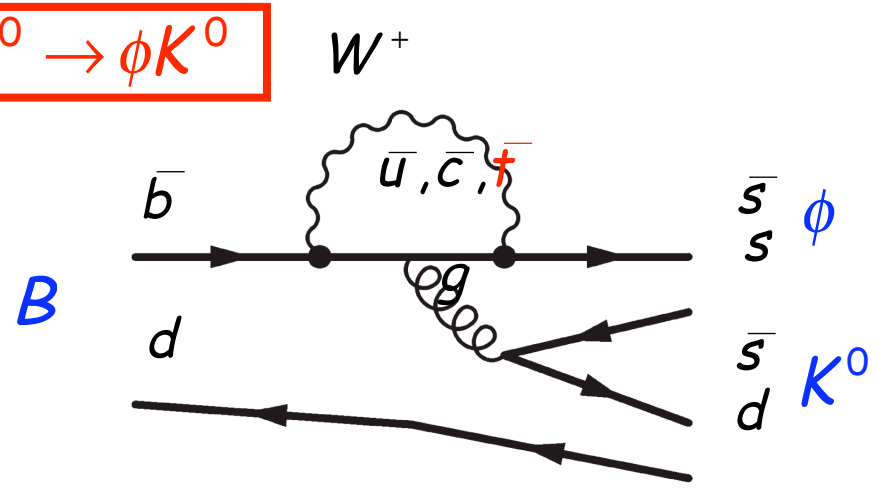


$\beta = 68^{\circ}$ solution is disfavored $(>2\sigma)$ by

- Time dependent angular analysis of $B^0 \to J/\psi K^{*0}$ (BaBar)
- Time dependent Dalitz analysis of $B^0 \to D^0\pi^0$ (Belle)

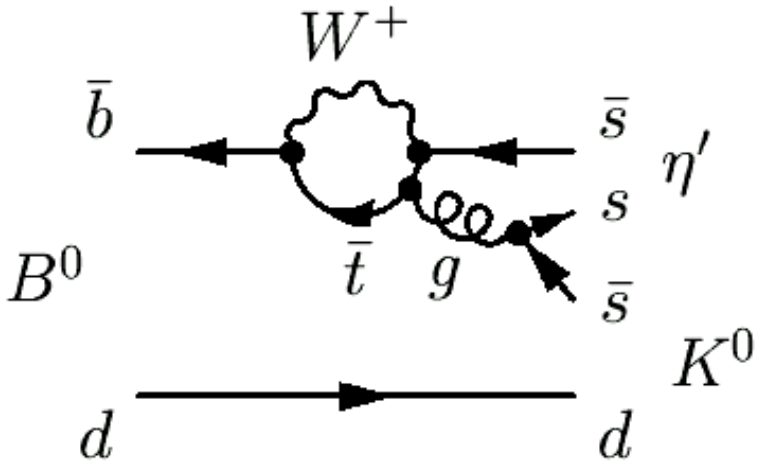
Loops: *How New Physics contributes to b→s*

$B^0 \to \phi K^0$

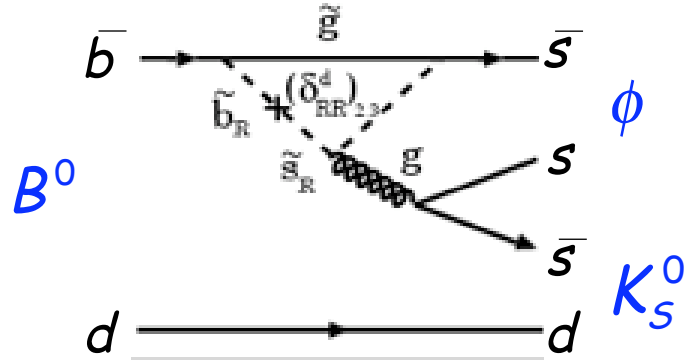


"Internal Penguin"

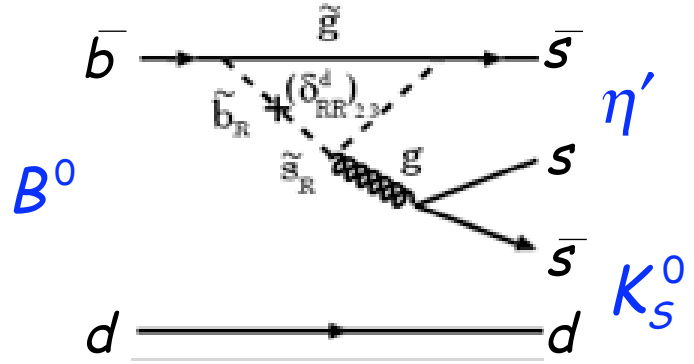
$B^0 \to \eta' K^0$



New physics in loops?



Many new phases are possible in SUSY



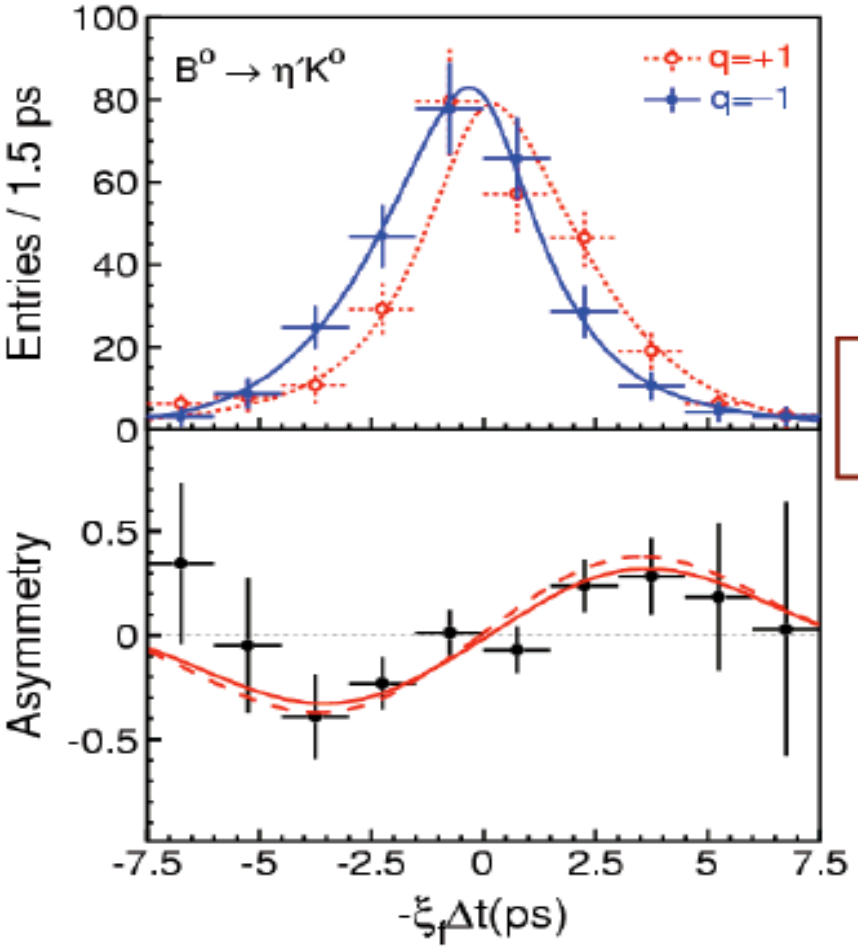
Gluino-squark loop dominates.

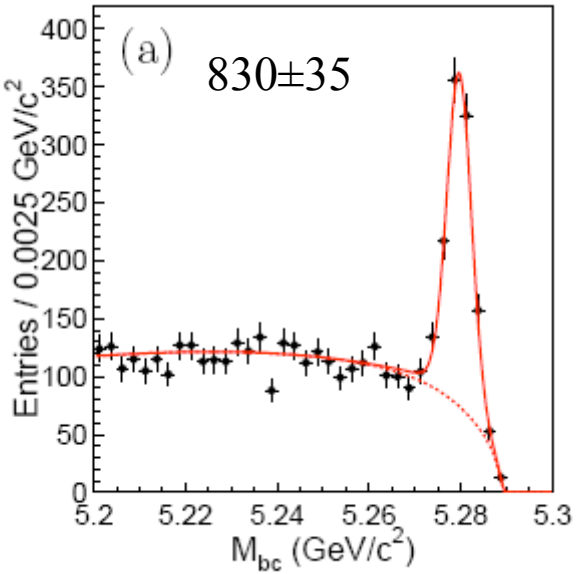
$\Delta \sin 2\beta$ can be significant (~0.2 or more).

"Compelling Evidence" for CP Violation in a b→s mode

$$\frac{\Gamma\left(\overline{B^0}(\Delta t)\to f\right)-\Gamma\left(B^0(\Delta t)\to f\right)}{\Gamma\left(\overline{B^0}(\Delta t)\to f\right)+\Gamma\left(B^0(\Delta t)\to f\right)} = D\sin 2\beta\sin(\Delta m_d\Delta t)$$

$\eta' K^0$ (*background subtracted*)



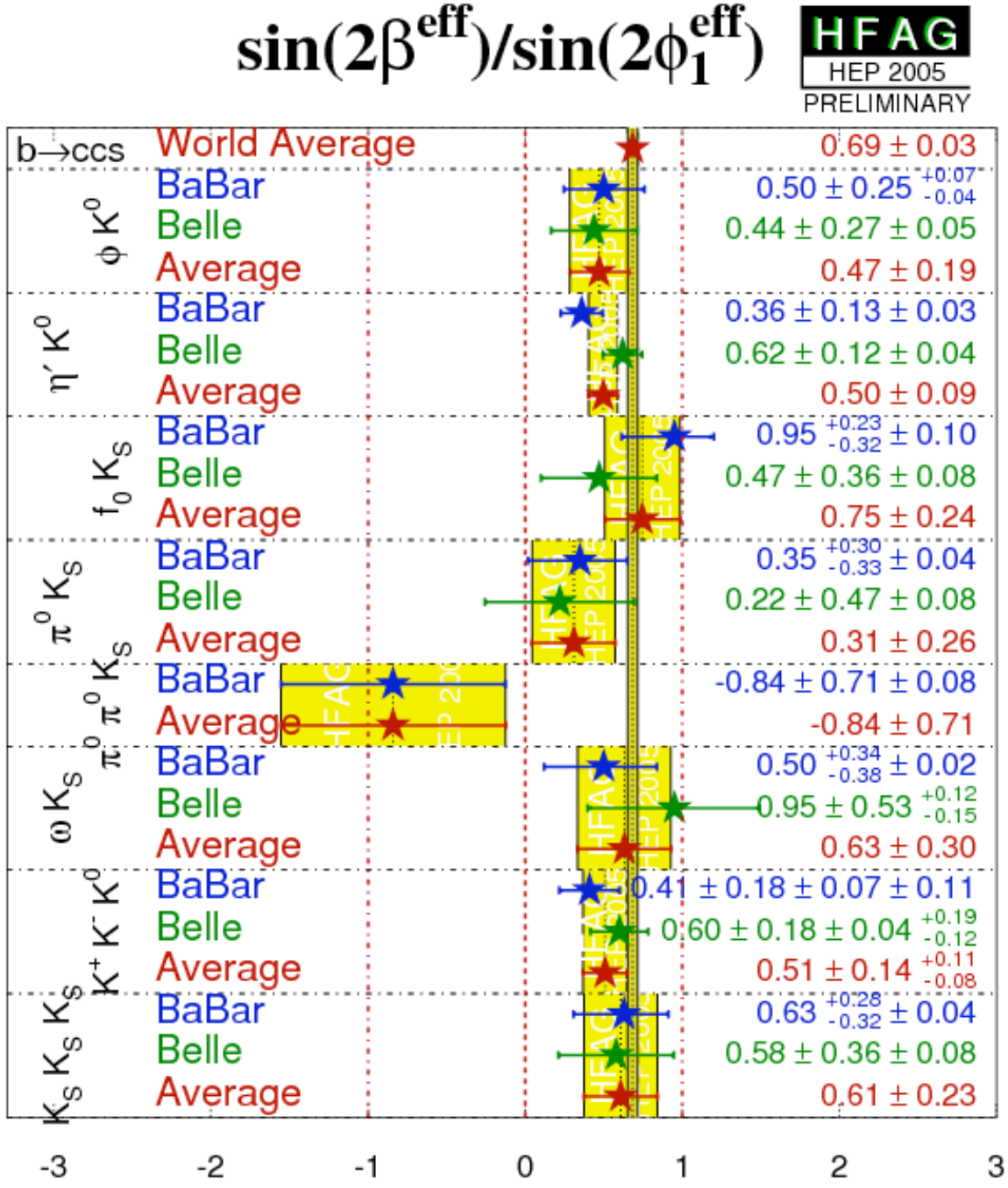


$$''\sin 2\phi_1\,'' = +0.62 \pm 0.12 \pm 0.04$$
$$A = -0.04 \pm 0.08 \pm 0.06$$

significance $> 4\sigma$

Belle 386M BB pairs

(Belle data: hep-ex/0507037)



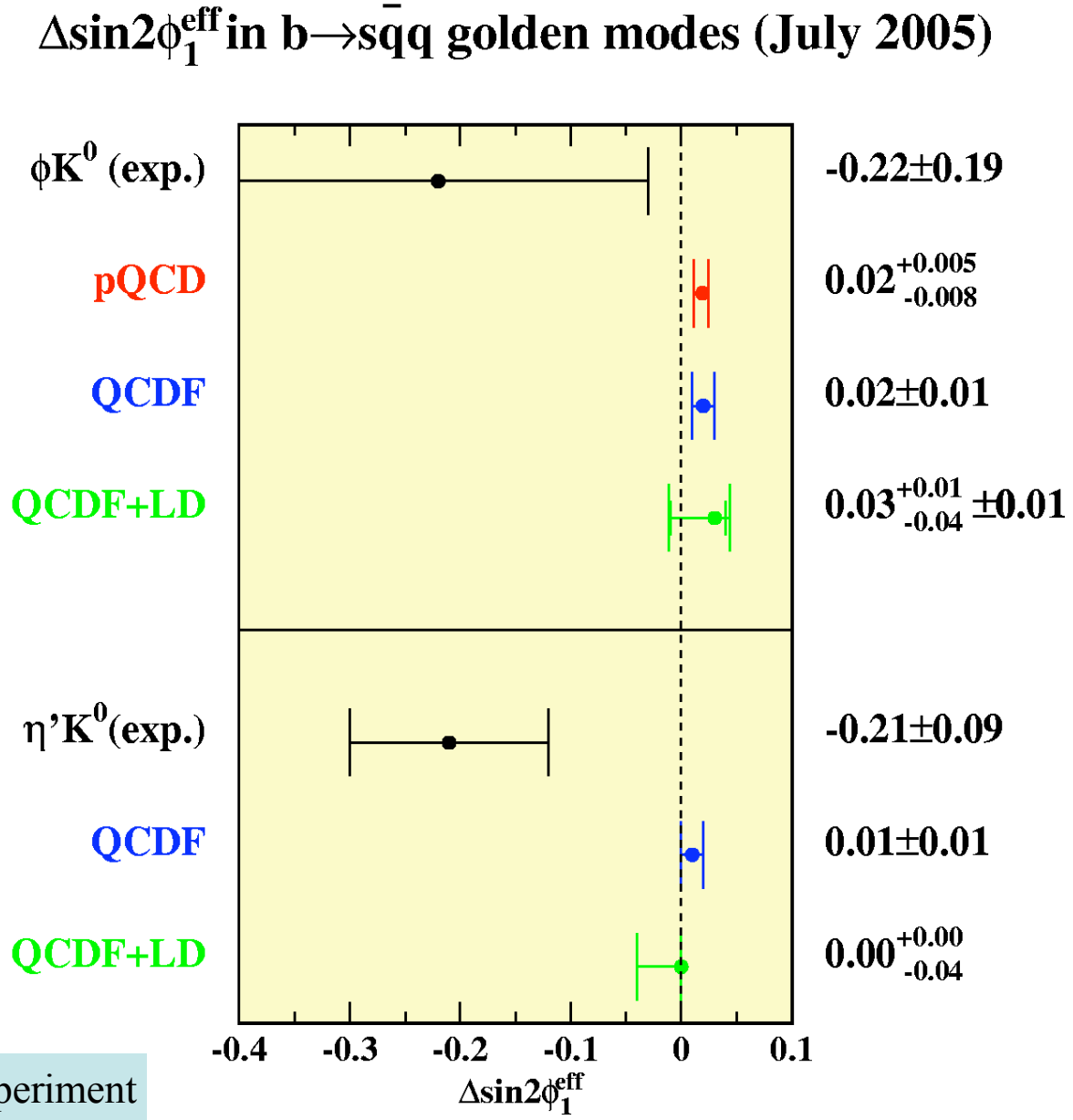
Almost all are systematically below the sin(2β) value from B→J/ψ K^0 modes

New Physics ??

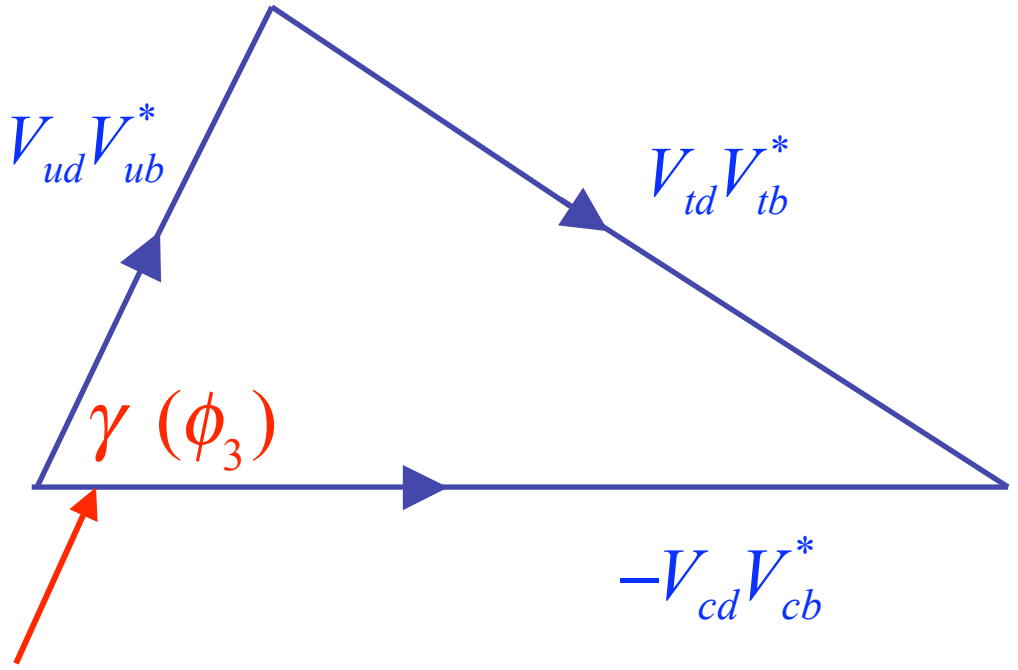
Very large effects of order unity, $\Delta S \sim 1$, are now ruled out.

Theory corrections are small and opposite in sign to the exp deviations.

A minimum of 1000 fb^{-1} / each experiment is required.



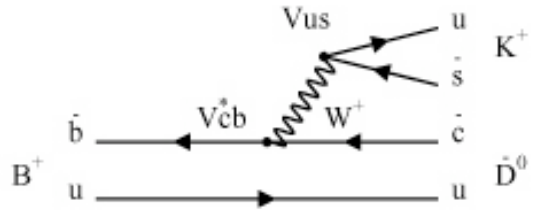
(Deviation from $B \rightarrow \psi K^0$ result)

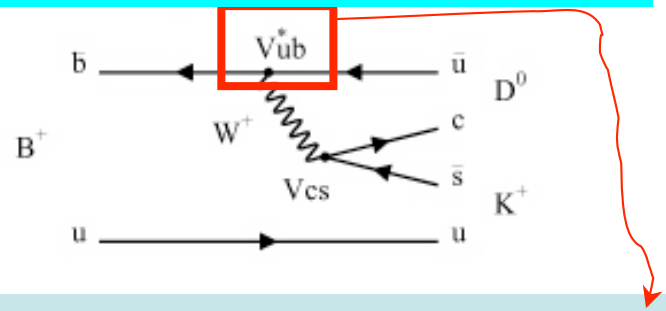


Tree-level processes are immune to New Physics.

$B^+ \to [K_S\pi^+\pi^-]_D K^+$ Dalitz analysis $\gamma=\phi_3$

This final state arises from V_{us} suppressed and V_{ub} suppressed diagrams.





$$A(B^+ \to \overline{D^0}K^+) = A_B$$

$$A(B^+ \to D^0K^+) = A_B r_B e^{i(\delta+\phi_3)}$$

r_B= suppression due to Cabibbo and color matching
= 0.1~0.2

δ= strong phase

$\overline{D^0}$ & D^0 can decay to the same final state $K^0_S\pi^+\pi^-$.
The interference of the above amplitudes gives ϕ_3.

The sensitivity to ϕ_3 is proportional to r_B.

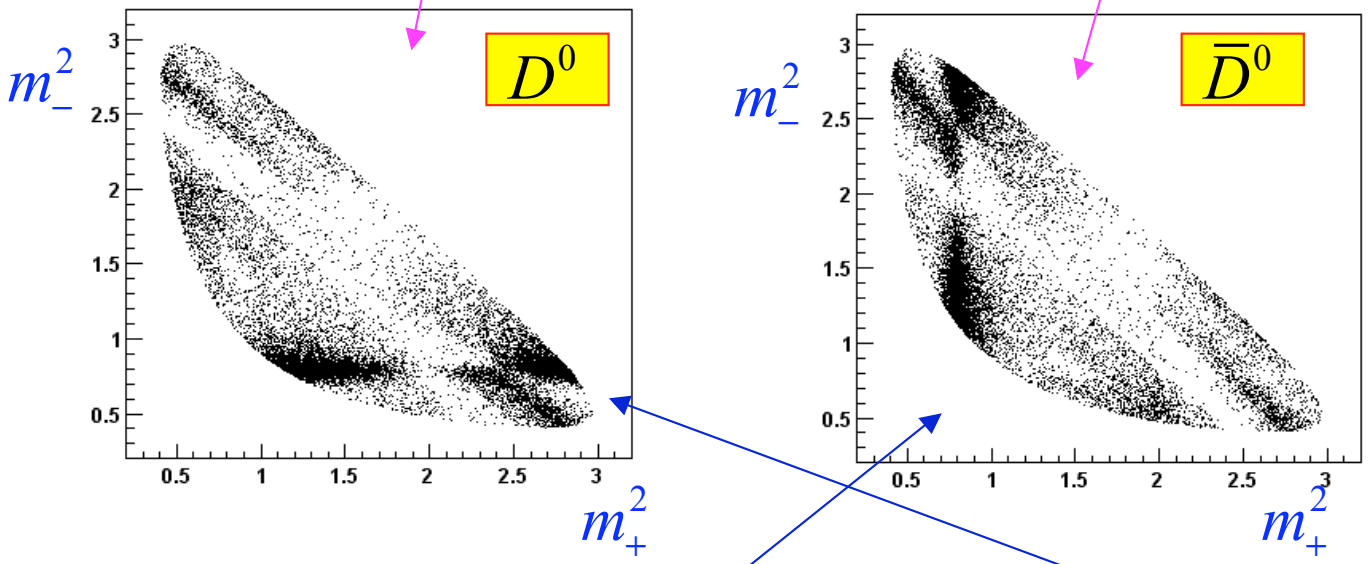
$$A(B^- \to D^0K^-) = \overline{A_B}$$

$$A(B^- \to \overline{D^0}K^-) = \overline{A_B} r_B e^{i(\delta-\phi_3)}$$

Decay amplitudes

Density of Dalitz plot distribution is proportional to |Amplitude|^2.

B$^+$: $M_+ = f(m_+^2, m_-^2) + re^{i\phi_3 + i\delta} f(m_-^2, m_+^2)$



obtain from tagged D^0 ($D^{*+} \to D^0\pi^+$) sample

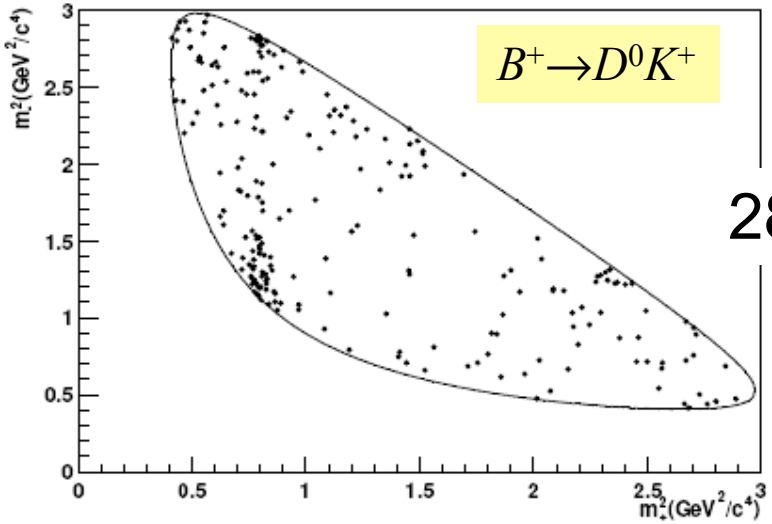
B$^-$: $M_- = f(m_-^2, m_+^2) + re^{-i\phi_3 + i\delta} f(m_+^2, m_-^2)$ $\quad r = \frac{|A_2|}{|A_1|}$

m_+=m($K_s\pi^+$), $\quad m_-$=m($K_s\pi^-$)

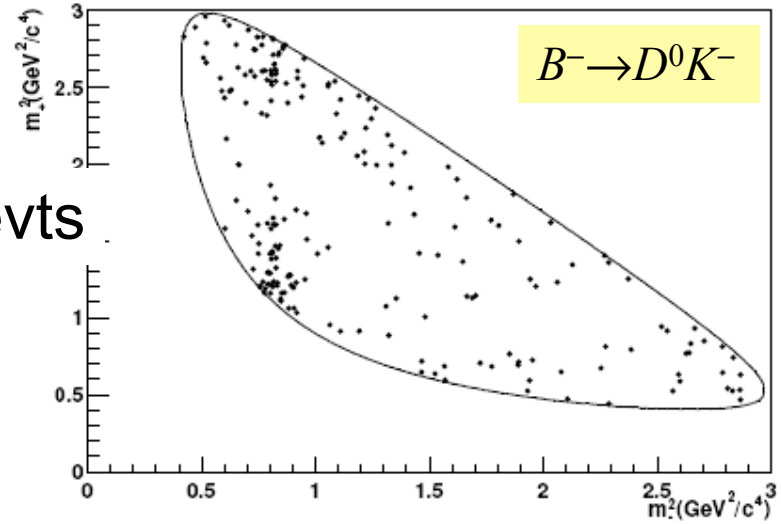
To extract ϕ_3, δ and r, we need to know $f(m_+^2, m_-^2)$, Dalitz distribution of $D \to K_S\pi^+\pi^-$.

$B^{+/-} \to D^0 K^{+/-}$: $K_S \pi^+\pi^-$ Dalitz plot distributions

227M

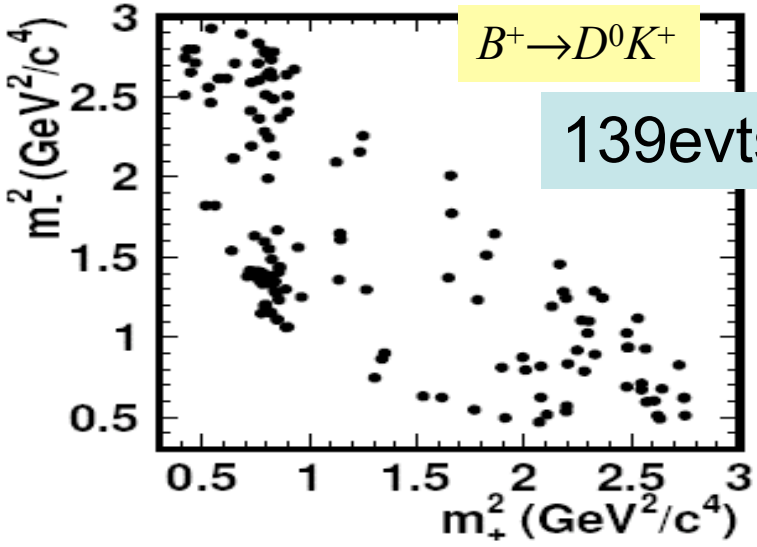


282evts

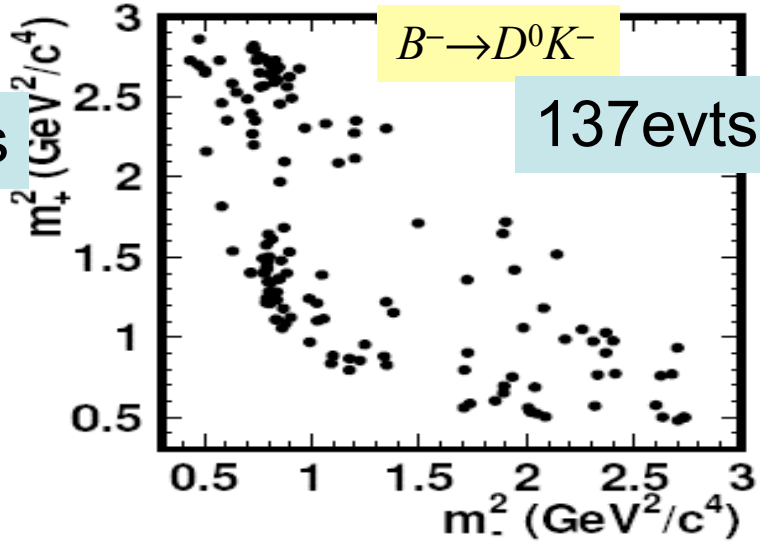


BELLE

275M



139evts



137evts

Differences between B^+ and B^- signifies direct CP violation.

Above, D^0 is super-position of D^0 and $\overline{D^0}$

γ/ϕ_3 results

Dalitz analysis

$$\phi_3 = [68^{+14}_{-15} \pm 13(sys) \pm 11(model)]^\circ$$

$$[22^\circ, 113^\circ]$$

$$r_B(D^0K) = 0.21 \pm 0.08 \pm 0.03 \pm 0.04$$
$$r_B(D^{*0}K) = 0.12^{+0.16}_{-0.11} \pm 0.02 \pm 0.04$$
$$r_B(D^0K^*) = 0.24^{+0.17}_{-0.18} \pm 0.09 \pm 0.04 \pm 0.$$

[hep-ex/0411049,0504013

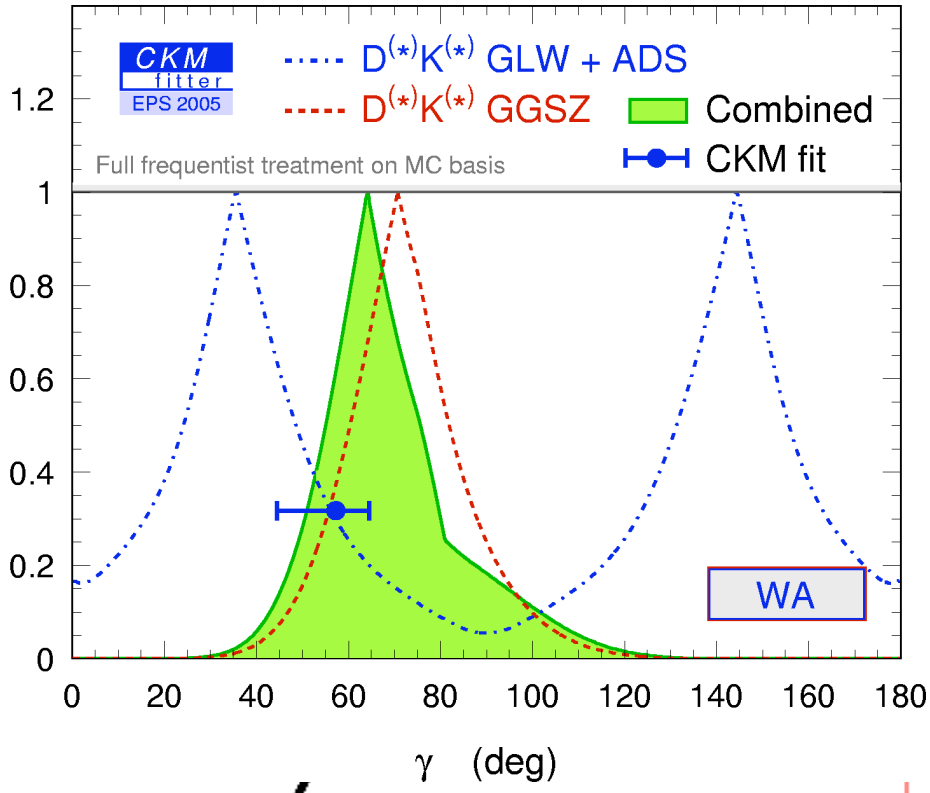
Dalitz analysis

$$\gamma = [70 \pm 31^{+12}_{-10}(sys)^{+14}_{-11}(model)]^\circ$$

$$[12^\circ, 137^\circ]$$

$$r_B(D^0K) = 0.118^{+0.079}_{-0.096} \pm 0.034^{+0.036}_{-0.034}$$
$$r_B(D^{*0}K) = 0.169 \pm 0.096^{+0.03\ \ -0.029}_{-0.028^*\ -0.026}$$

PRL 95 (2005) 121802

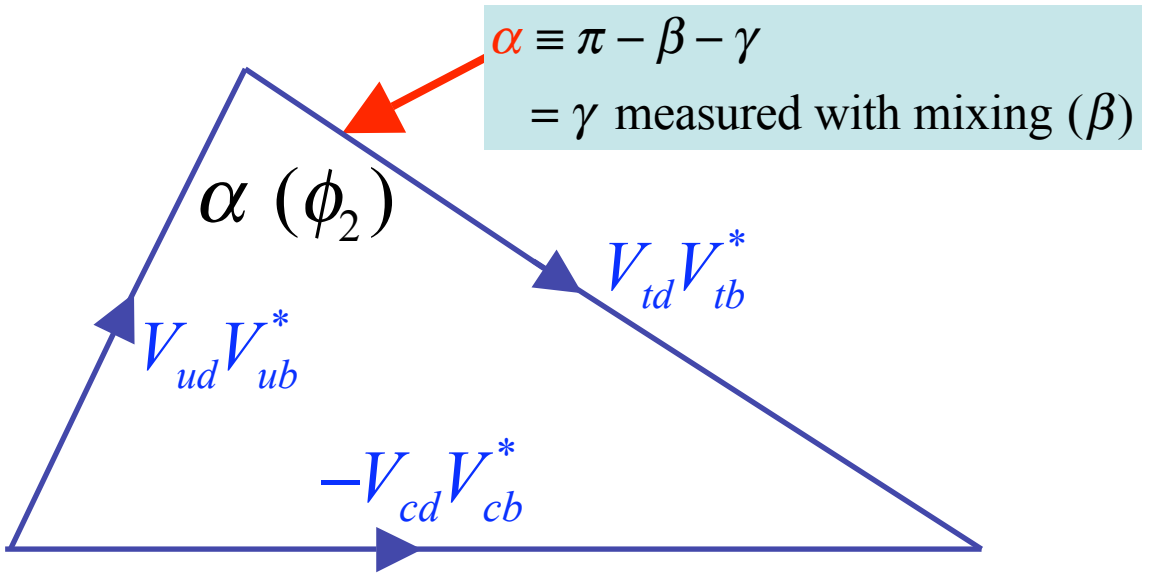


All results combined

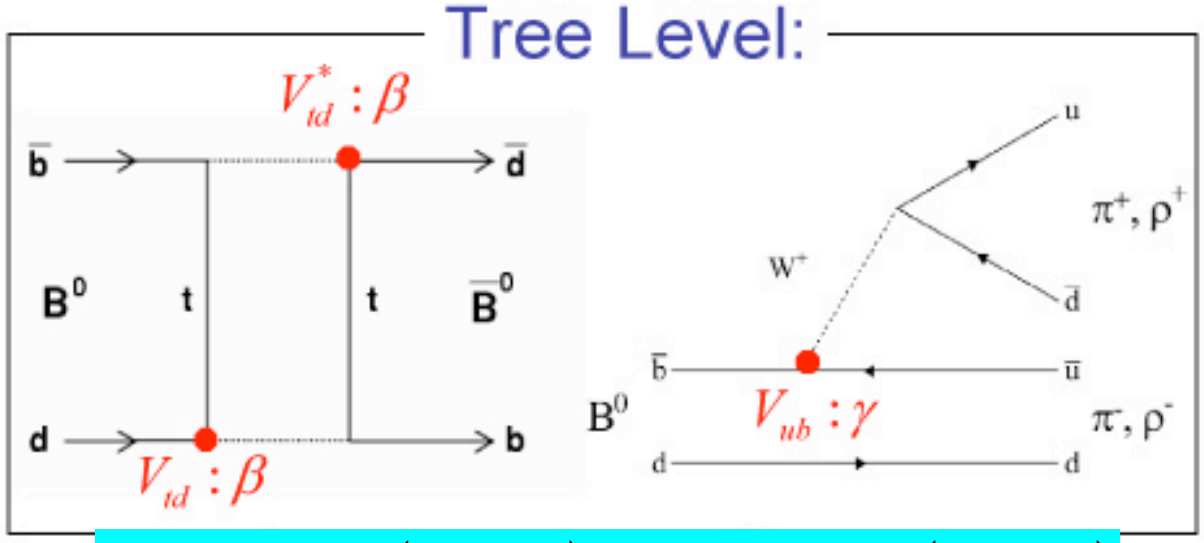
$\phi_3(\gamma)$ [deg]

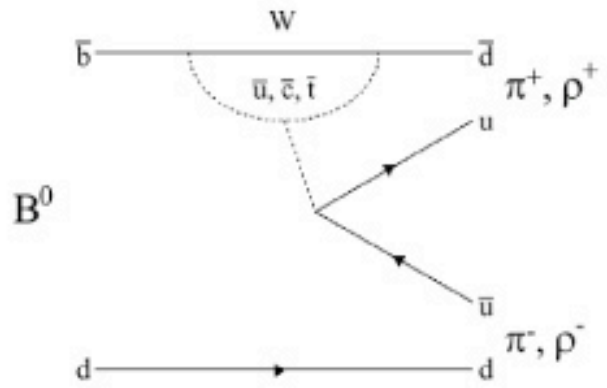
$$\phi_3 = 63 \pm {}^{15}_{12}\ \text{deg.}$$

(Non-trivial constraint)


$\alpha \equiv \pi - \beta - \gamma$
$= \gamma$ measured with mixing (β)
$\alpha\ (\phi_2)$
$V_{td}V_{tb}^*$
$V_{ud}V_{ub}^*$
$-V_{cd}V_{cb}^*$

CP Violation in $B^0 \to \rho^+\rho^-$ and $\pi^+\pi^-$ (Charmless two-body decays)





$$Asym = S\sin(\Delta m_d \Delta t) + A(=-C)\cos(\Delta m_d \Delta t)$$

Δt = decay time interval of two B mesons

$$C_{\rho\rho} = 0$$
$$S_{\rho\rho} = \sin(2\alpha)$$

$$C_{\rho\rho} \propto \sin(\delta)$$
$$S_{\rho\rho} = \sqrt{1 - C_{\rho\rho}^2}\,\sin(2\alpha_{\text{eff}})$$
$$\delta = \delta_P - \delta_T$$

$\alpha(\phi_2)_{eff}$ is shifted from $\alpha(\phi_2)$ due to loops (aka penguin pollution).

VV final state is a mixture of CP eigenstates, while $\pi^+\pi^-$ is CP even.

$\rho\rho$ could be less sensitive to (or more diffcult to extract) α.

Miracles in $B^0 \to \rho^+\rho^-$

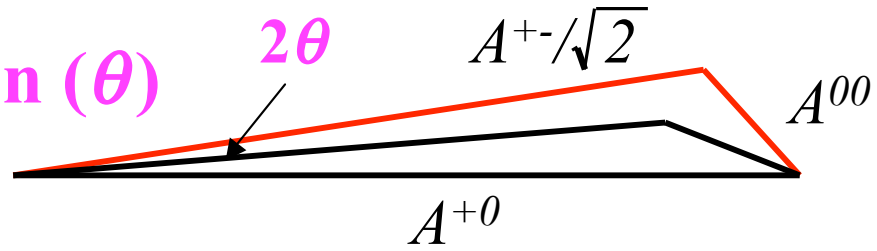
1. *Penguin contribution turns out to be small.*

$Br\left(B^0 \to \rho^0\rho^0\right) < 1.1\times10^{-6}\ (90\%C.L.) \quad \ll Br\left(B^0 \to \rho^+\rho^-\right), Br\left(B^+ \to \rho^+\rho^0\right)$

BaBar PRL94, 131801(2005) $\sim 30\times10^{-6}$

Gronau-London, PRL **65** 3381 (1990)

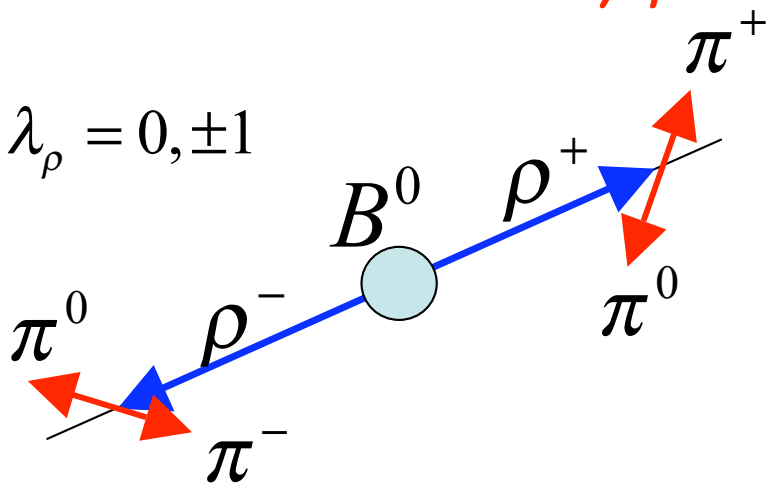
⇒ **small Penguin pollution (θ)**



$$\left|\alpha_{eff} - \alpha\right| < 14^\circ\ (90\%\text{C.L.})$$

$$\left|\alpha_{eff} - \alpha\right| < 35^\circ\ (90\%\text{C.L.})\ \text{for}\ B^0 \to \pi^+\pi^-$$

2. $\rho\rho$ final state *turns out to be fully polarized longitudinally.*



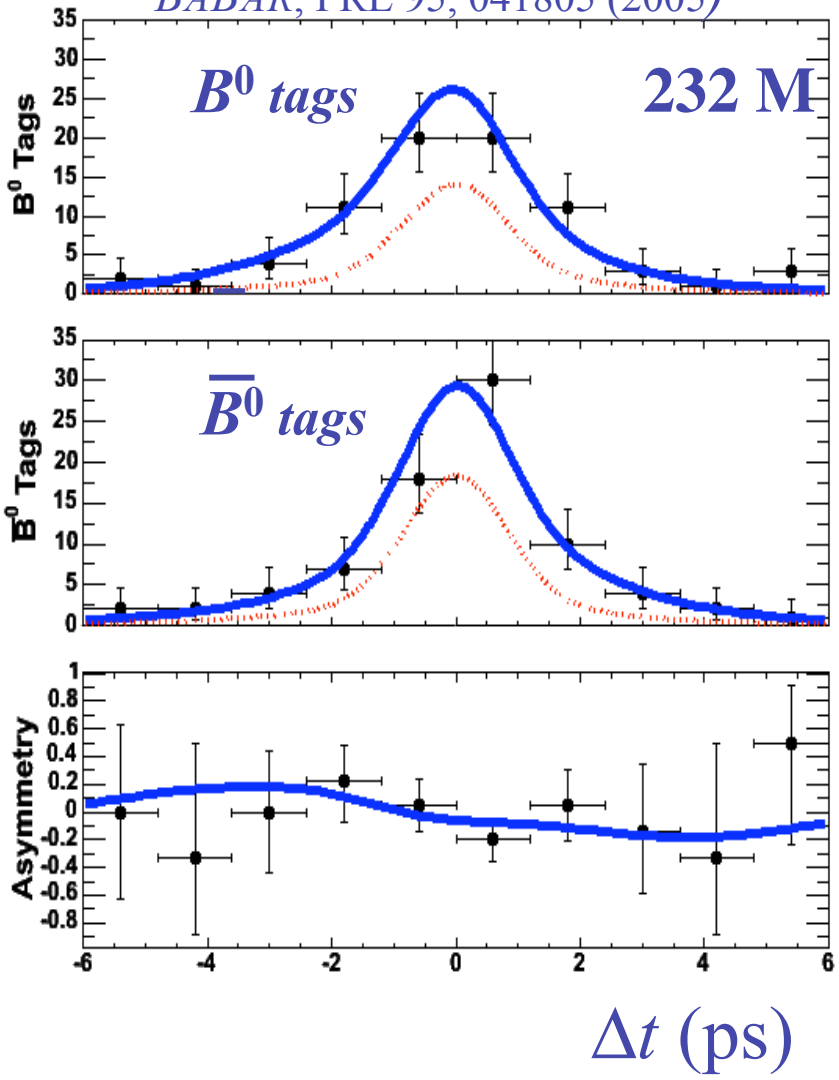
Angular analysis shows a longitudinal fraction of the final state to be

BaBar	$f_L = 0.978 \pm 0.014^{+0.021}_{-0.029}$	PRL95,041805 (2005)
Belle	$f_L = 0.941^{+0.034}_{-0.040} \pm 0.030$	hep-ex/0601024

The longitudinally polarized state is a CP even eigenstate.

Measurement of CP asymmetry for B→ρ⁺ρ⁻

BABAR, PRL 95, 041805 (2005)



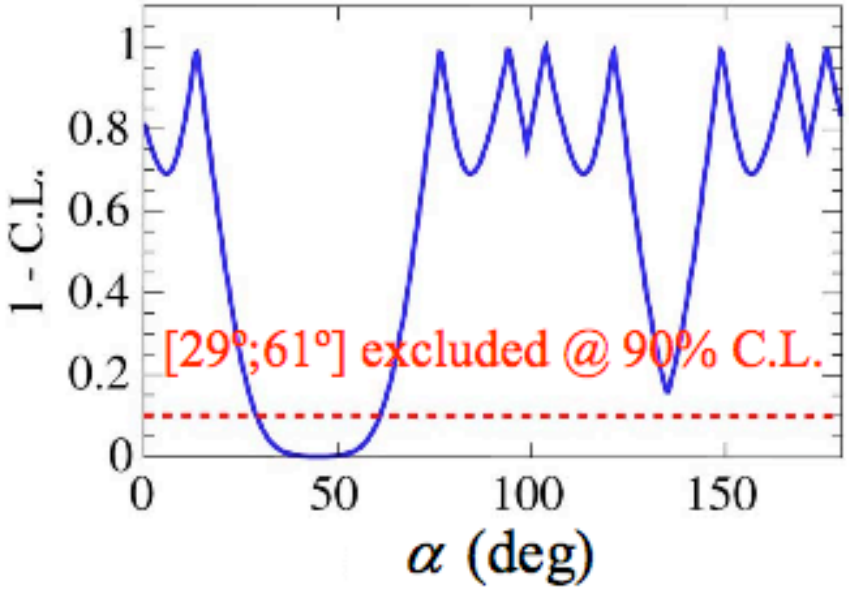
	BaBar	Belle
$S_{\rho\rho}$	$-0.33 \pm 0.24^{+0.08}_{-0.14}$	$0.08 \pm 0.41 \pm 0.09$
$C_{\rho\rho}$	$-0.03 \pm 0.18 \pm 0.09$	$0.00 \pm 0.30 \pm 0.09$

$$S_{\rho\rho} = \sqrt{1 - C_{\rho\rho}^2}\,\sin\left(2\alpha_{\text{eff}}\right)$$

α: combining the *BABAR* measurements

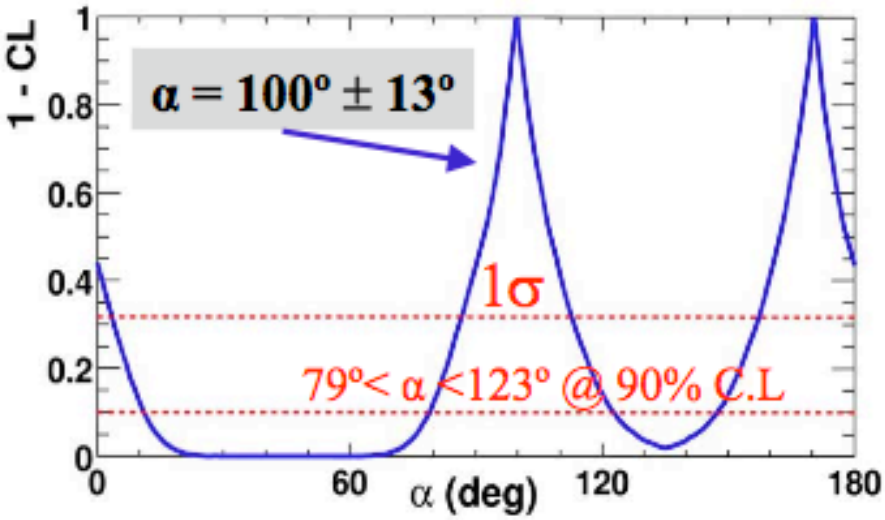
$B \to \pi\pi$

PRL, 94, 181802 (2005)



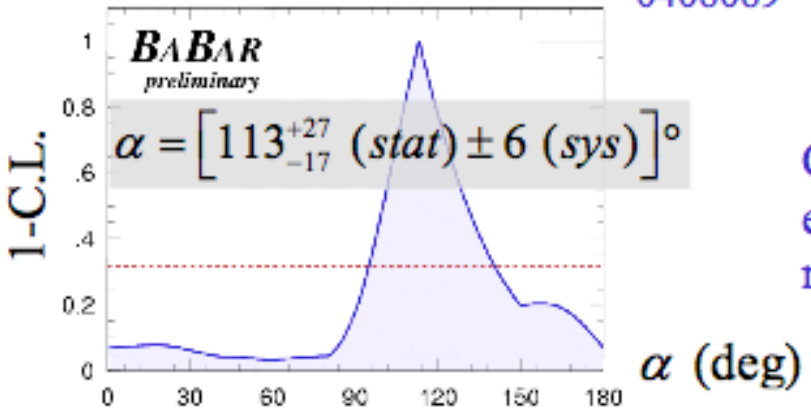
$B \to \rho\rho$

PRL 95, 041805 (2005)

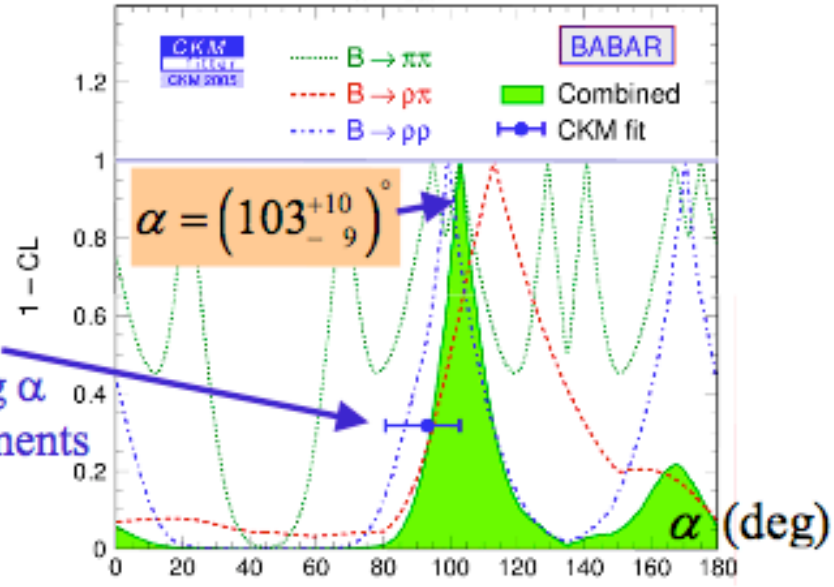


$B \to \pi^+\pi^-\pi^0$ Dalitz

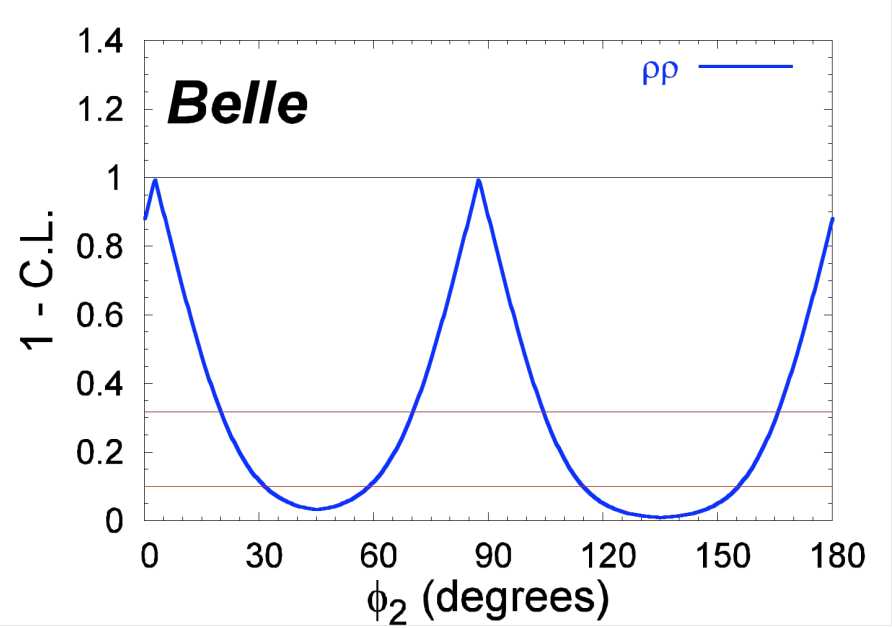
hep-ex/ 0408089

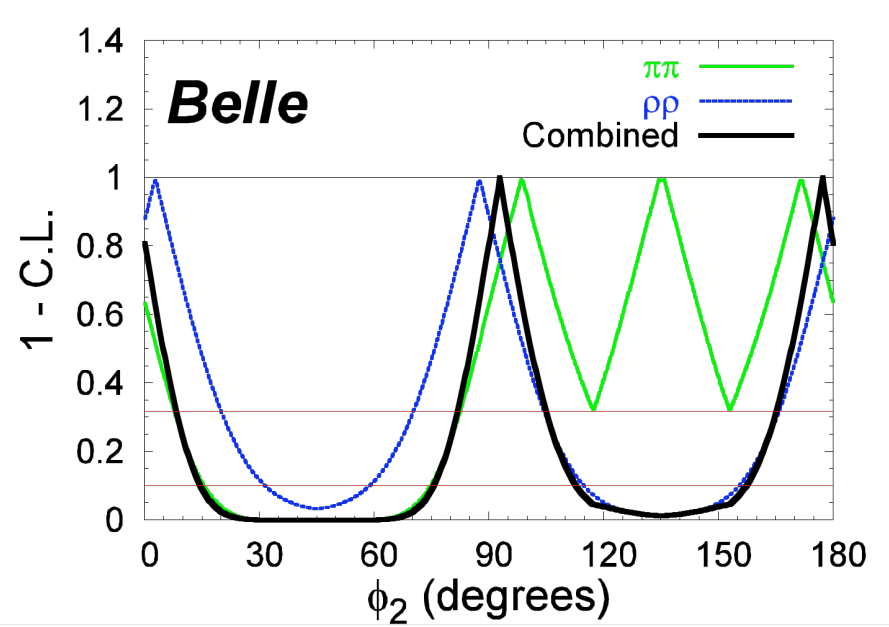


CKM fit excluding α measurements



Belle Constraints on ϕ_2 (α)





B→ρρ only

hep-ex/0601024

$$\phi_2(\gamma) = (88 \pm 17)^\circ$$

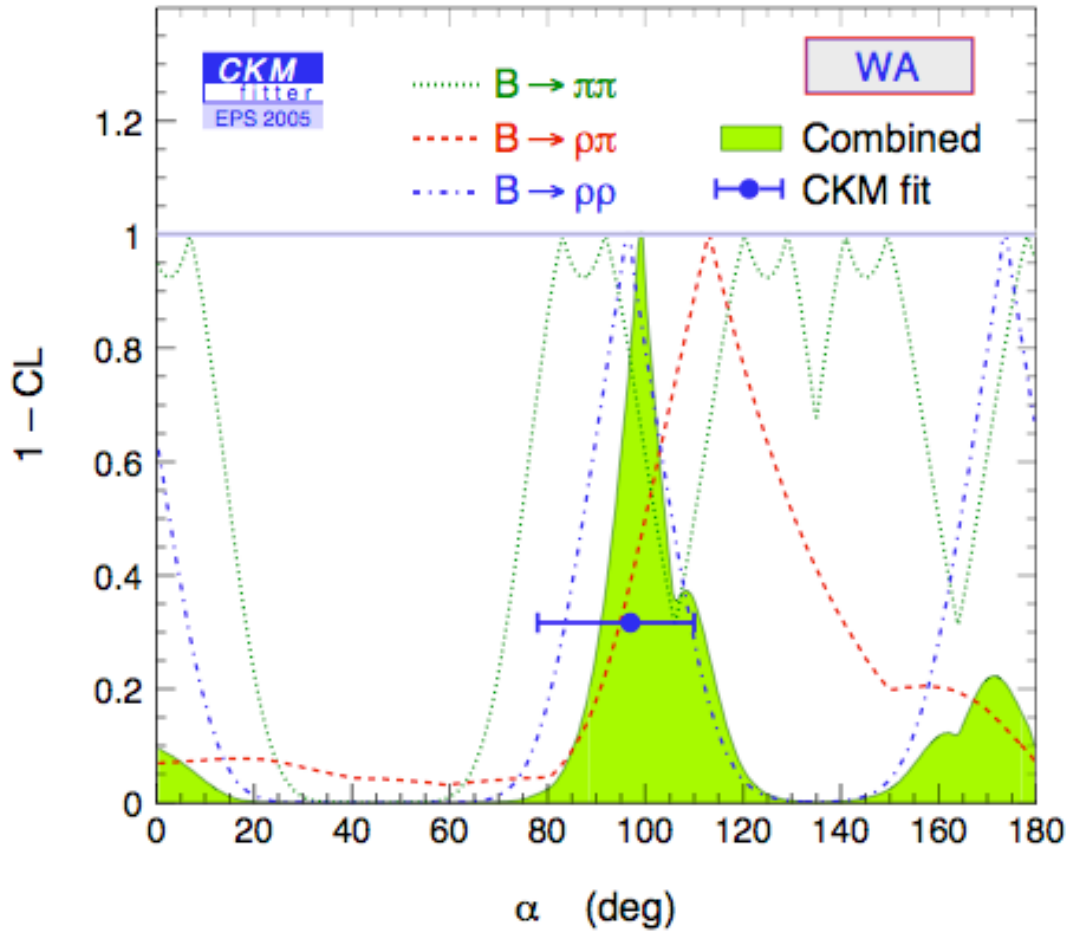
$$59^\circ < \phi_2 < 115^\circ \ (90\%\text{C.L.})$$

B→ππ PRL 95, 10801 (2005) & ρρ combined

$$\phi_2(\gamma) = (93^{+12}_{-11})^\circ$$

$$75^\circ < \phi_2 < 113^\circ \ (90\%\text{C.L.})$$

No $\rho\pi$ yet $\Rightarrow$ mirror solution is still allowed.



BaBar 232M pairs
Belle 275M pairs

	$\alpha(\phi_2)^\circ$
W.A.	$98.6^{+12.6}_{-8.1}$
Indirect	97^{+13}_{-19}
All W.A.	$98.1^{+6.3}_{-7.0}$

$\rho\rho$ yields the best α.

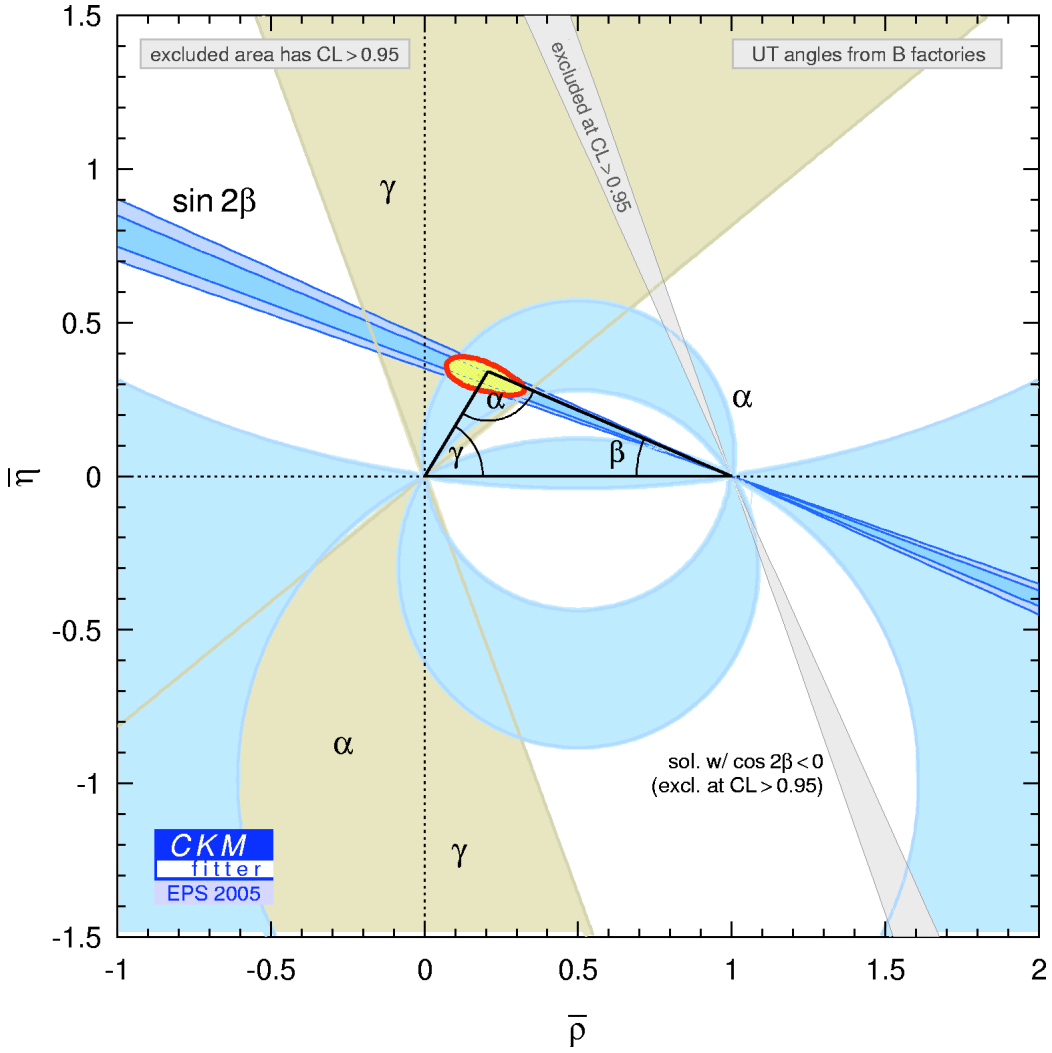
$\rho\pi$ helps to remove mirror solution.

$\pi\pi$ has limited sensitivity.

Good agreement with indirect constraints.


In conclusion

The CKM Triangle Using Angles Only



$$\beta = 21.7^{+1.3}_{-1.2}$$

$$\gamma = 63^{+15}_{-12}$$

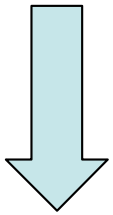
$$\therefore \quad \pi - \beta - \gamma = 95.3^{+15}_{-12}$$

$$\alpha(\equiv \pi - \beta - \gamma) = 98.6^{+12.6}_{-8.1}$$

good agreement

Belle 350 fb^{-1} + BaBar 240 fb^{-1}

(Summer 2005)

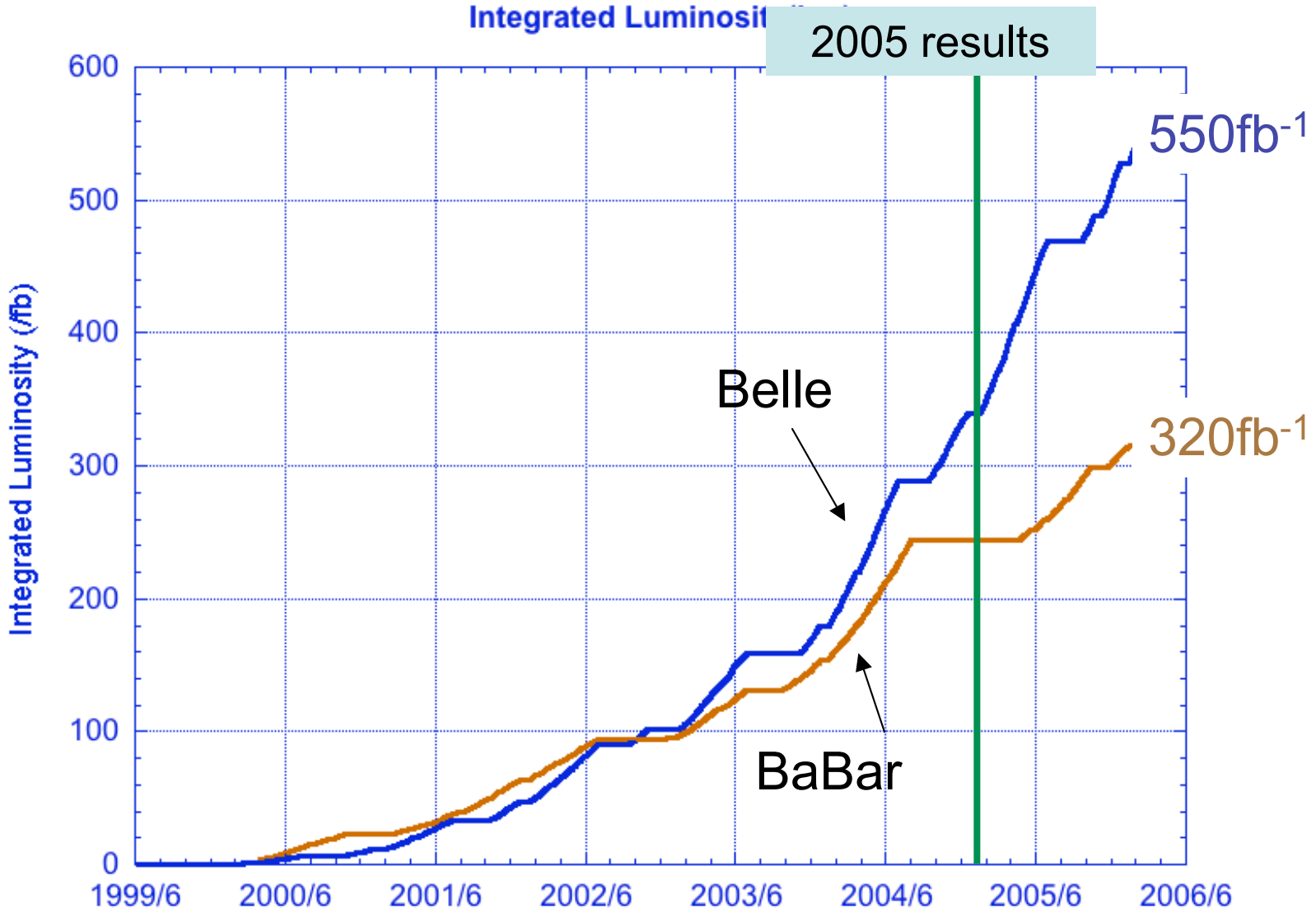


$$\Delta_\phi = \sin 2\beta\left|\phi K^0 - \sin 2\beta\right| J/\psi K^0 = -0.22 \pm 0.19$$

$$\Delta_\eta = \sin 2\beta\left|\eta' K^0 - \sin 2\beta\right| J/\psi K^0 = -0.21 \pm 0.09$$

$1000 fb^{-1}$ for each collaboration brings the error of Δ_η down to 0.04.

Integrated luminosity of Belle and BaBar




End