CP Violation in B Decays

Status of the Unitarity Triangle

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October 27, 2005

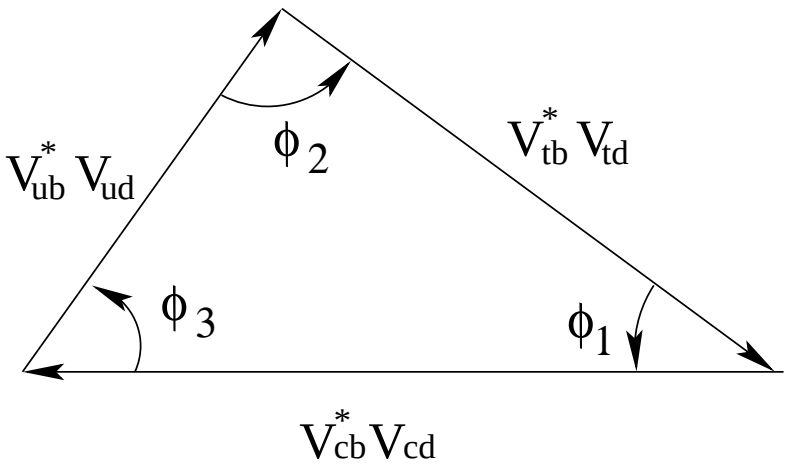
PANIC05, Santa Fe

Unitarity Triangle: Testing Ground for the Standard Model

CKM matrix for describing weak interactions of quarks

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} + O(\lambda^4)$$

- Unitarity condition of $V_{\rm CKM}$ leads to a triangular relation in complex ρ-η plane
- Validity can be thoroughly tested by B decay measurements
- QCD (hadronic) effects must be understood for translating the measurements to CKM



$$\begin{aligned} \phi_1 &= \beta \\ \phi_2 &= \alpha \\ \phi_3 &= \gamma \end{aligned}$$

$$\begin{aligned} V_{td} &= |V_{td}| e^{-i\phi_1} \\ V_{ub} &= |V_{ub}| e^{-i\phi_3} \end{aligned}$$

CP Violation in B Decays: $(B \to f) \neq (\bar{B} \to \bar{f})$

- Counting

$$\frac{N_{\bar{B}} - N_B}{N_{\bar{B}} + N_B}$$

- Time-dependent analysis

$$\frac{N_{\bar{B}}(\Delta t) - N_B(\Delta t)}{N_{\bar{B}}(\Delta t) + N_B(\Delta t)}$$

- Dalitz analysis (pick a particle in final state f that decays to three-body)

$$\left|M_{\bar{B}}(m_+^2, m_-^2)\right|^2 \quad \text{vs} \quad \left|M_B(m_+^2, m_-^2)\right|^2$$

- Time-dependent Dalitz analysis

$$\left|M_{\bar{B}}(m_+^2, m_-^2)(\Delta t)\right|^2 \quad \text{vs} \quad \left|M_B(m_+^2, m_-^2)(\Delta t)\right|^2$$

All CP Violation Must Be Described by CKM Angles

$V_{td} = |V_{td}|e^{-i\phi_1}$ (B^0-$\bar{B}^0$ mixing)

- Mixing-assisted (time-dependent) CPV
  - $B^0 \to J/\psi K^0$ ($\sin 2\phi_1$)
  - $B^0 \to \phi K^0$ ($\sin 2\phi_1$ from loop diagram)
- CPV in B^0-$\bar{B}^0$ mixing itself
  - Ony SM CPV in B that is not seen yet (B_s system is yet to be explored at LHC)

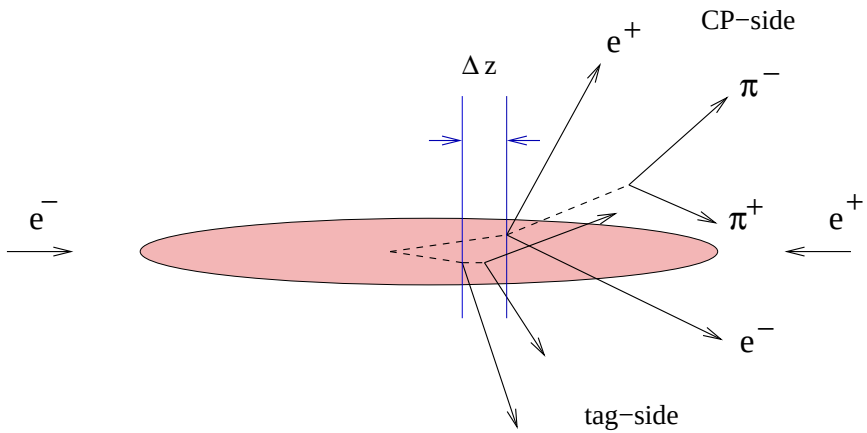
$V_{ub} = |V_{ub}|e^{-i\phi_3}$ ($b \to u$ decays)

- Direct CPV (Interference with other diagrams)
  - $B^0 \to \pi^+\pi^-$ (seen by Belle, not confirmed by BaBar)
  - $B^0 \to K^+\pi^-$ (seen by BaBar and Belle)
  - $B^+ \to DK^+$ Dalitz analysis (2.4σ effect seen by BaBar and Belle, best for ϕ_3)

Both V_{td} and V_{ub} are involved

- Mixing-assisted CPV for final states containing V_{ub}
  - $B^0 \to \pi^+\pi^-$ (seen by Belle, not confirmed by BaBar)
  - $B^0 \to \rho^+\rho^-$ (consistent with zero, best for ϕ_2)

Asymmetric Energy e^+e^- Collision at $\Upsilon(4S)$



$$\psi(t) = |B_1^0> |\bar{B}_2^0> - |\bar{B}_1^0> |B_2^0>$$

When one is B^0, the other is $\bar{B}^0$ at any t
(C is conserved in $\Upsilon(4S) \to B\bar{B}$)

$\Delta t \simeq (z_{cp} - z_{\rm tag})/(\gamma\beta c)$
B flight-length in x-y: only $\sim 30\mu$

$(z_{cp} - z_{\rm tag}) \ll e^+e^-$ interaction region

The other B (tag-side) provides a time reference and flavor tagging at $\Delta t = 0$

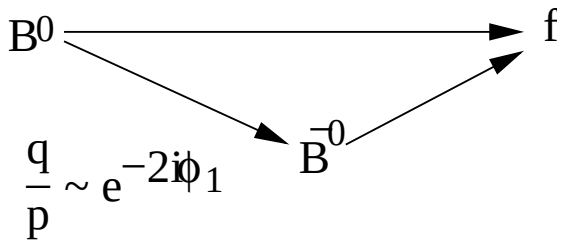
Parameters	BaBar	Belle
e^+e^- energy	$3.1 \times 9\,\mathrm{GeV}$	$3.5 \times 8.5\,\mathrm{GeV}$
$\gamma\beta$	0.56	0.425
Interaction region ($h \times v \times l$)	$120\,\mu\mathrm{m} \times 5\,\mu\mathrm{m} \times 8.5\,\mathrm{mm}$	$80\,\mu\mathrm{m} \times 2\,\mu\mathrm{m} \times 3.4\,\mathrm{mm}$
Typical $(z_{CP} - z_{\rm tag})$	$260\mu\mathrm{m}$	$200\mu\mathrm{m}$
σ_z (CP-side)	$50\,\mu\mathrm{m}$	$75\,\mu\mathrm{m}$
σ_z (tag-side)	$100 \sim 150\,\mu\mathrm{m}$	$140\,\mu\mathrm{m}$

Mixing-assisted CP Violation

Interference between $(B^0 \to f)$ and $(B^0 \to \bar{B}^0 \to f)$ leads to time-dependent asymmetry

$$\frac{\Gamma(\bar{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\bar{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = \underbrace{\frac{2Im\lambda}{1+|\lambda|^2}}_{S_f} \sin(\Delta m_d \Delta t) - \underbrace{\frac{1-|\lambda|^2}{1+|\lambda|^2}}_{C_f} \cos(\Delta m_d \Delta t)$$

$$\lambda = \frac{q}{p}\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)}$$



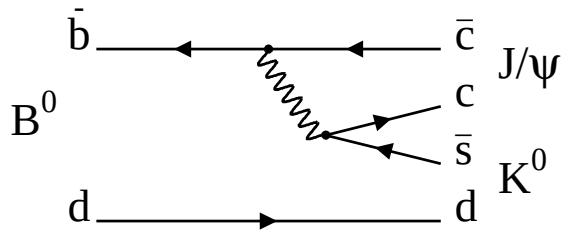
Theoretically clean measurements come from $J/\psi K_S^0$ and other $b \to c\bar{c}s$ tree decays

- one diagram dominates, $f = f_{cp}$
- no weak phase in the diagram

  $S_f = \sin 2\phi_1$ for $J/\psi K_S^0$

  In general, $\sin 2\phi_1 = -\eta_f \times S_f$ (η_f is CP value)
- SM corrections are small $\mathcal{O}(10^{-4})$

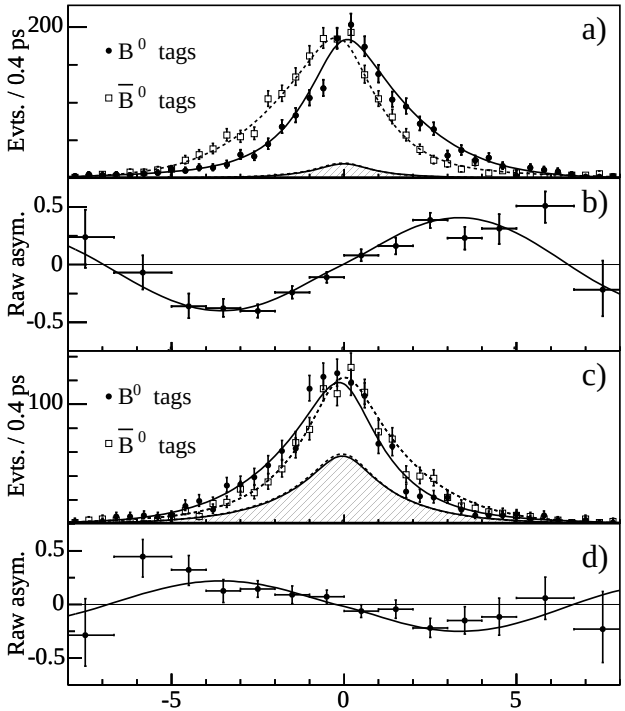
  Mannel, Boos, Reuter, PRD 70, 036006 (2004)



Fit to Δt Distributions

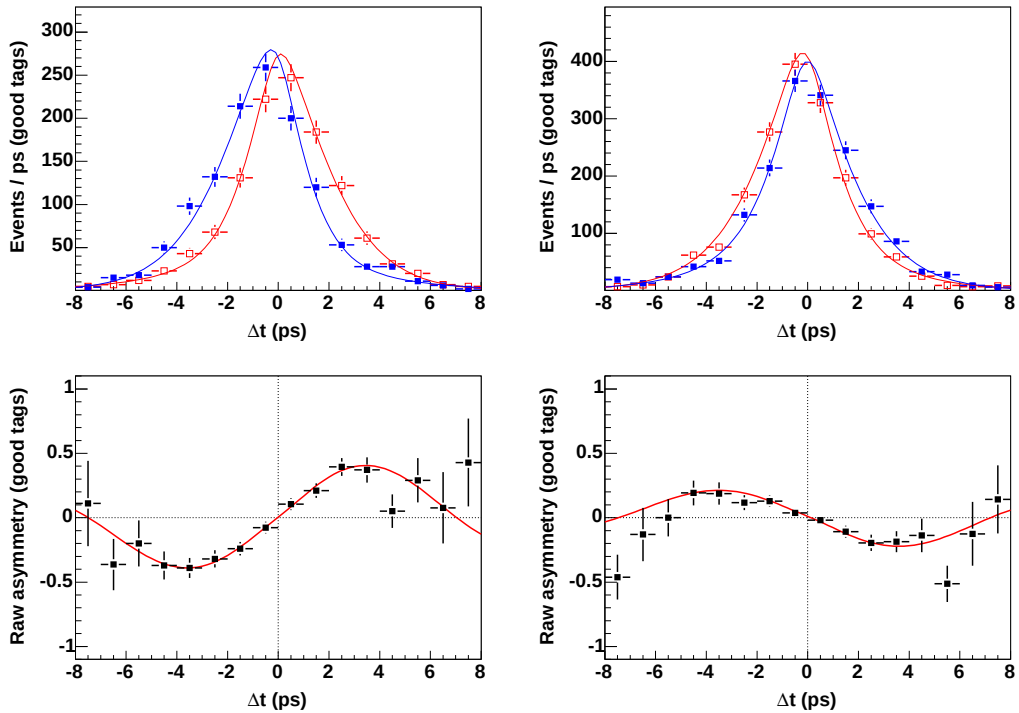
BaBar ($227 \times 10^6 B\bar{B}$)

$\eta_f = -1$(above), +1(below)



Belle ($386 \times 10^6 B\bar{B}$)

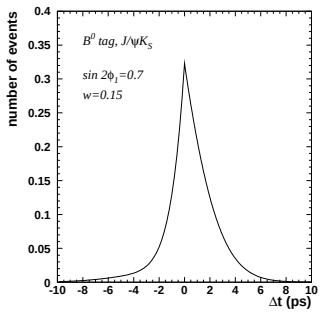
$J/\psi K_S^0$ $J/\psi K_L^0$



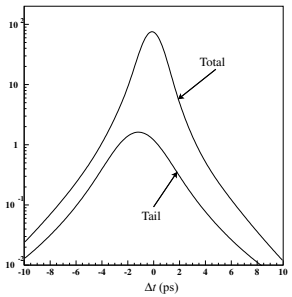
Observed Δt distribution

$\text{True } \Delta t \otimes \Delta t \text{ Resolution}$

Signal



Δt resolution



Unbinned maximum likelihood fit

Likelihood of each event P_i contains $\sin 2\phi_1$ as a free parameter. Maximize $L = \prod_i P_i$

$\sin 2\phi_1$ from $b \to c\bar{c}s$ Modes

BaBar/Belle Averages Heavy Flavor Averaging Group http://www.slac.stanford.edu/xorg/hfag/

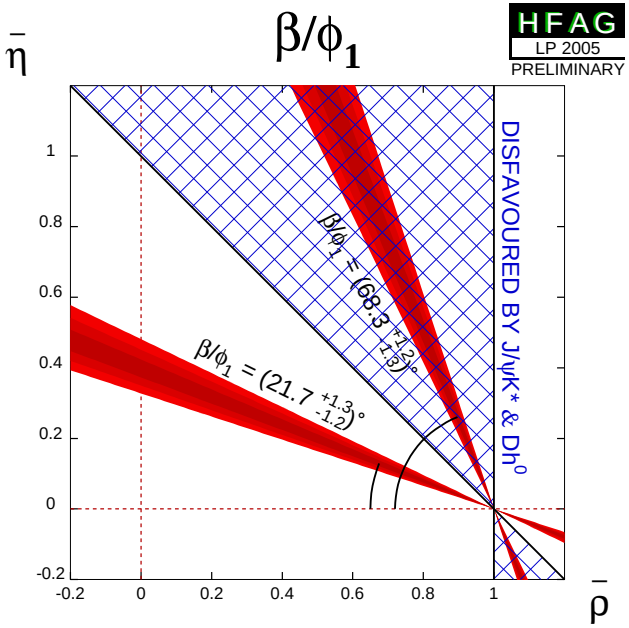
$$\sin 2\phi_1 = 0.685 \pm 0.032 \left\{ \begin{array}{l} 0.722 \pm 0.040 \pm 0.023 \text{ (BaBar } 227 \times 10^6 B\bar{B}) \\ 0.652 \pm 0.039 \pm 0.020 \text{ (Belle } \ 386 \times 10^6 B\bar{B}) \end{array} \right\}$$

$$C = 0.016 \pm 0.046 \left\{ \begin{array}{l} +0.051 \pm 0.033 \pm 0.014 \text{ (BaBar)} \\ -0.010 \pm 0.026 \pm 0.036 \text{ (Belle)} \end{array} \right\}$$

$\phi_1 = 68^\circ$ solution is disfavored by

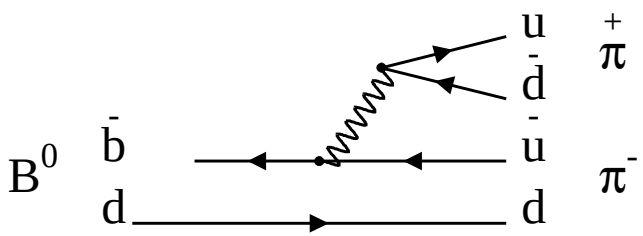
- Time-dependent angular analysis of $B^0 \to J/\psi K^{*0}$
- Time-dependent Dalitz analysis of $B^0 \to D^0\pi^0$

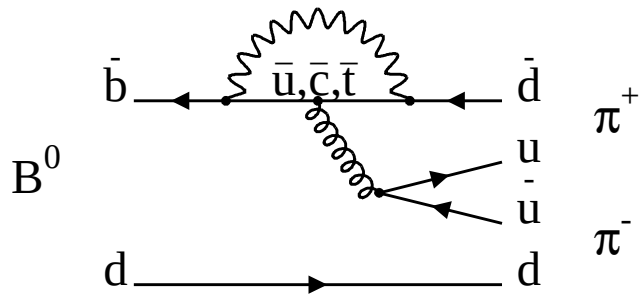
$$\bar{\rho} \equiv \rho(1 - \frac{\lambda^2}{2}), \quad \bar{\eta} \equiv \eta(1 - \frac{\lambda^2}{2})$$



Time Dependence of $B^0 \to \pi^+\pi^-$

Contributions from tree and penguin diagrams





$$\lambda_{\pi\pi} = e^{-2i\phi_1} \cdot \frac{|T|e^{-i\phi_3} + |P|e^{+i\delta}}{|T|e^{+i\phi_3} + |P|e^{+i\delta}} = e^{2i\phi_2} \cdot \frac{|T| + |P|e^{+i\phi_3+i\delta}}{|T| + |P|e^{-i\phi_3+i\delta}}$$

Δt fit gives $\sin 2\phi_2^{\rm eff}$ (not $\sin 2\phi_2$):

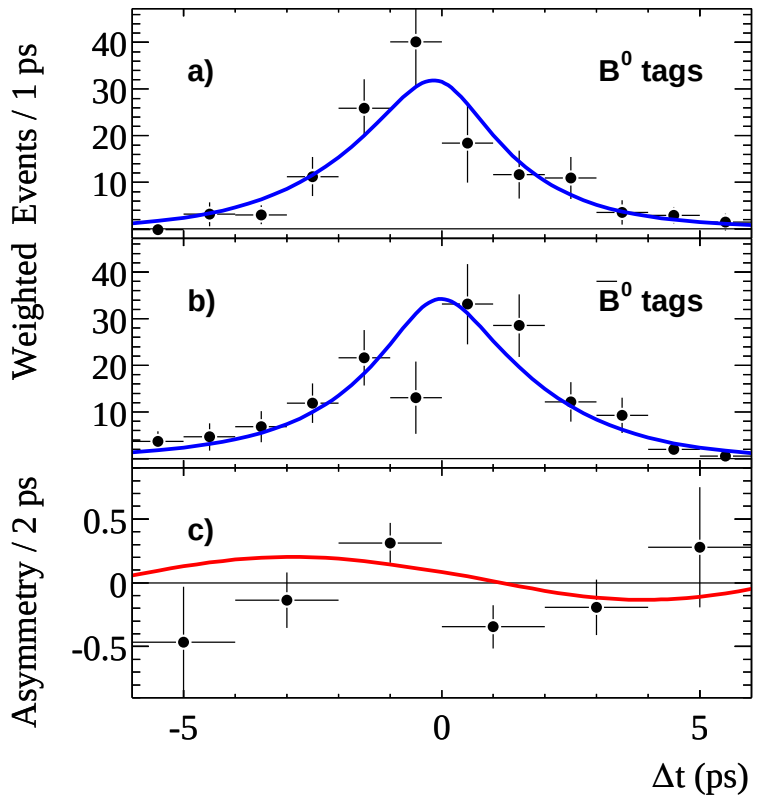
$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2}\, \sin 2\phi_2^{\rm eff}$$

If penguin contribution can be neglected, $S_{\pi\pi} \simeq \sin 2\phi_2$

We know a sizable penguin contribution is present. How do we extract ϕ_2 from $\phi_2^{\rm eff}$?

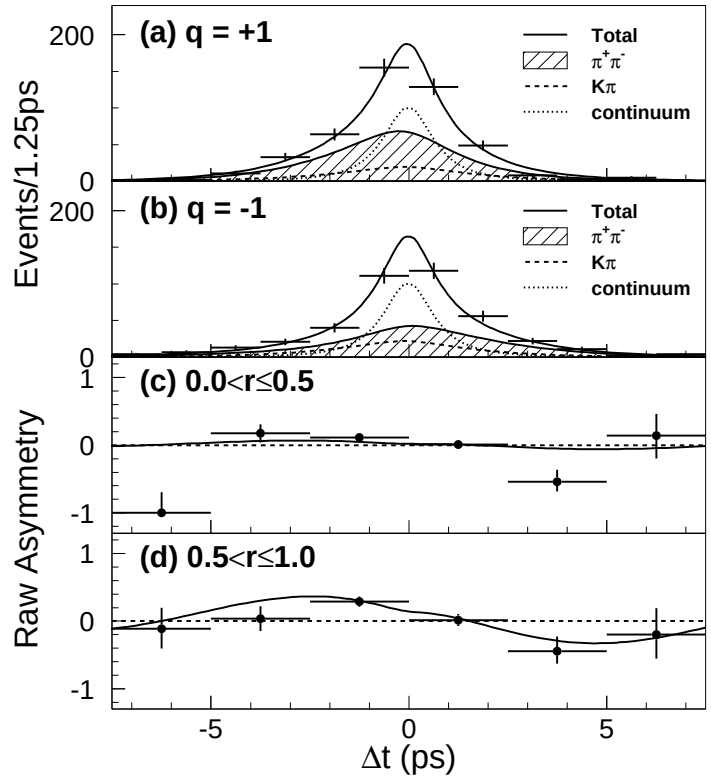
$B^0 \to \pi^+\pi^-$: Yields, Δt Distributions, Asymmetries

BaBar ($227 \times 10^6 B\bar{B}$)



$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$

Belle($275 \times 10^6 B\bar{B}$)



$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$
$$C_{\pi\pi} = -0.59 \pm 0.12 \pm 0.06$$

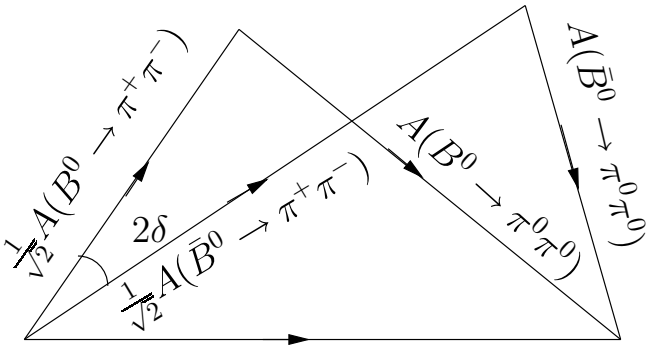
BaBar/Belle average of $S_{\pi\pi} = -0.50 \pm 0.12$ indicates $\sin 2\phi_2^{\rm eff} \neq 0$.
While BaBar $C_{\pi\pi}$ is consistent with 0, Belle observes direct CPV at 4σ.

Isospin Relation for Estimating $|\phi_2 - \phi_2^{\rm eff}|$

- $B \to \pi\pi$ produces only $(\pi\pi)_{I=0}$ and $(\pi\pi)_{I=2}$

  B and π have 0 spin, Bose-Einstein statistics
- Only $(\pi\pi)_{I=0}$ from penguin, both $(\pi\pi)_{I=0}$ and $(\pi\pi)_{I=2}$ from tree
- $|A(B^+ \to \pi^+\pi^0)| = |A(B^- \to \pi^-\pi^0)|$ $I = 2$ only, pure tree
- Triangular relation of branching fractions: $S_{\pi\pi} \simeq \sin 2\phi_2^{\rm eff} = \sin 2(\phi_2 + \delta)$

  $2\delta \simeq 0$ for $\mathcal{B}(\pi^0\pi^0) \ll \mathcal{B}(\pi^+\pi^0)$



$|A(B^- \to \pi^-\pi^0)| = |A(B^+ \to \pi^+\pi^0)|$

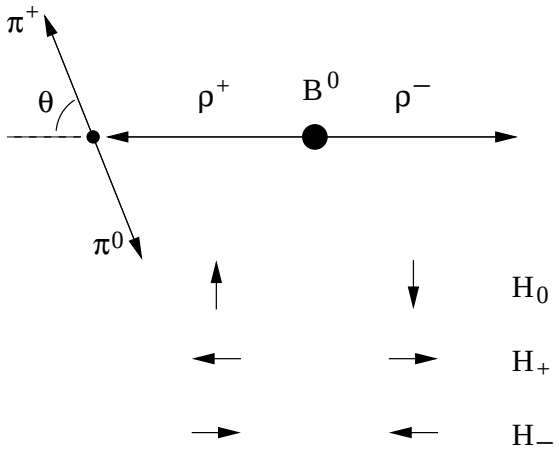
$B \to \pi\pi$ Branching Fractions ($\times 10^6$)

Mode	BaBar	Belle
$\pi^+\pi^0$	$5.8 \pm 0.6 \pm 0.4$	$5.0 \pm 1.2 \pm 0.5$
$\pi^+\pi^-$	$5.5 \pm 0.4 \pm 0.3$	$4.4 \pm 0.6 \pm 0.3$
$\pi^0\pi^0$	$1.17 \pm 0.32 \pm 0.10$	$2.3^{+0.44+0.2}_{-0.5-0.3}$

Measured $\mathcal{B}(\pi^0\pi^0)$ is too large to neglect.

Extraction of ϕ_2 from $B \to \pi\pi$ requires full isospin analysis with significantly more data.

$B^0 \to \rho^+\rho^-$: Same As $\pi\pi$ Except Three Helicity Amplitudes



$$A_{\parallel} = \frac{H_+ + H_-}{\sqrt{2}} \; (CP \text{ even})$$

$$A_{\perp} = \frac{H_+ - H_-}{\sqrt{2}} \; (CP \text{ odd})$$

$$A_0 = H_0 \; (CP \text{ even})$$

H_0 is called longitudinally polarized !

Measured $\rho^+\rho^-$ can be a mixture of CP-even and CP-odd

- Asymmetry is diluted (recall $\sin 2\phi_2^{\rm eff} = \eta_f \times S_f$). Isospin relation holds separately.
- Require angular analysis (each helicity state shows different θ dependence)

Two very fortunate observations

- $\rho^+\rho^-$ almost pure CP-even

  $f_L = 0.978 \pm 0.014^{+0.021}_{-0.029}$ (BaBar)

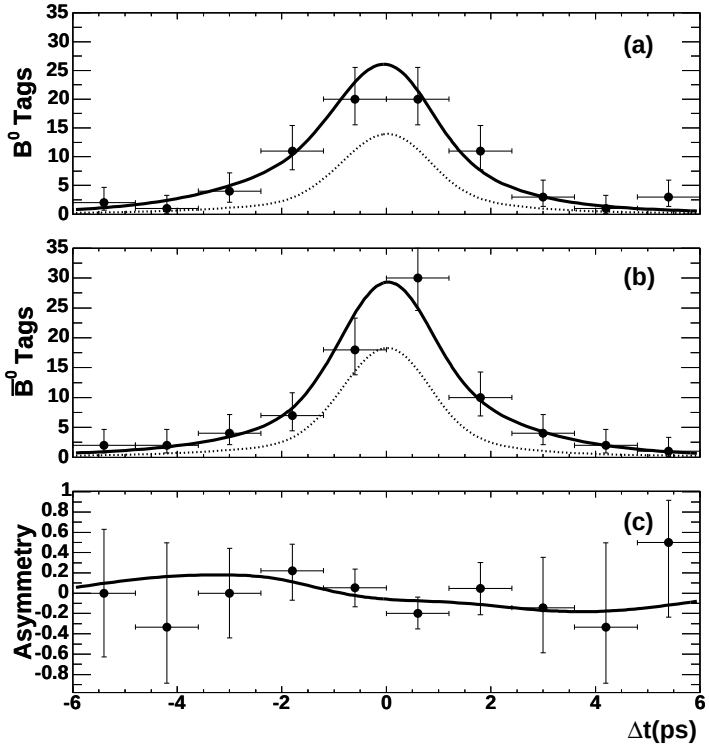
  $0.951^{+0.033+0.029}_{-0.039-0.031}$ (Belle)
- $\mathcal{B}(\rho^0\rho^0)$ very small (penguin $\simeq 0$)

$B \to \rho\rho$ Branching Fractions ($\times 10^6$)

Mode	BaBar	Belle
$\rho^+\rho^0$	$22.5^{+5.7}_{-5.4} \pm 5.8$	$31.7 \pm 7.1^{+3.8}_{-6.7}$
$\rho^+\rho^-$	$30 \pm 4 \pm 5$	$24.4 \pm 2.2^{+3.8}_{-4.1}$
$\rho^0\rho^0$	≤ 1.1	

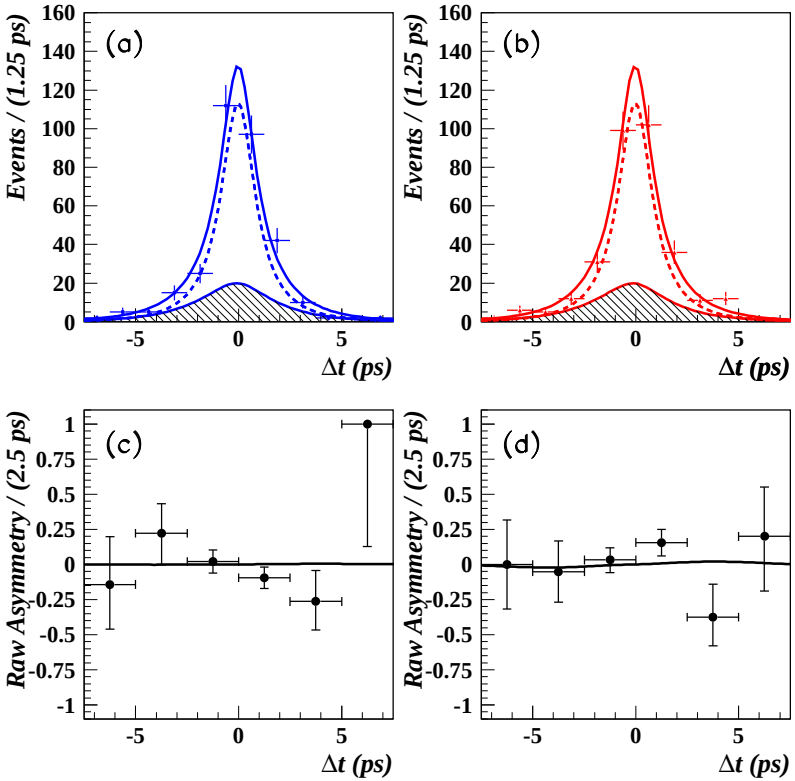
$B^0 \to \rho^+\rho^-$: Δt Distributions, Asymmetries

BaBar($232 \times 10^6 B\bar{B}$)



$$S_{\rho\rho,L} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$
$$C_{\rho\rho,L} = -0.03 \pm 0.18 \pm 0.09$$

Belle ($275 \times 10^6 B\bar{B}$)

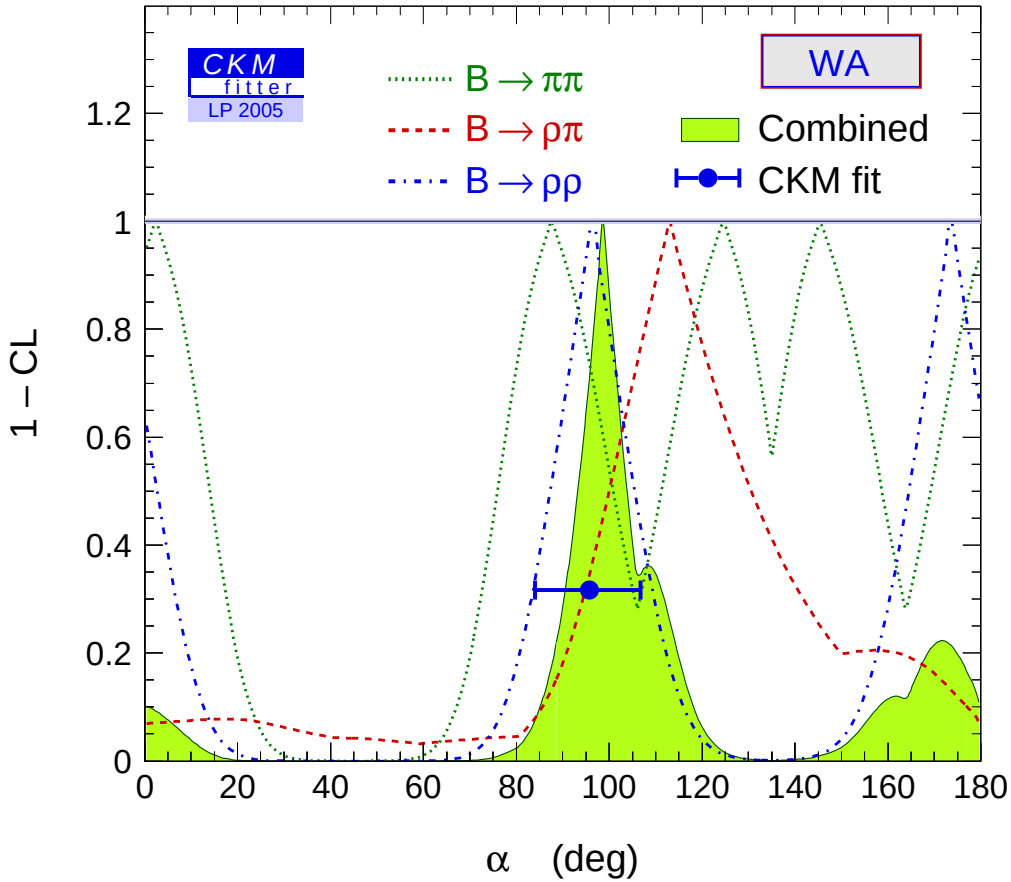


$$S_{\rho\rho,L} = 0.09 \pm 0.42 \pm 0.08$$
$$C_{\rho\rho,L} = 0.00 \pm 0.30^{+0.09}_{-0.10}$$

Both $S_{\rho\rho}$ and $C_{\rho\rho}$ for longutudinally polarized componenent prefer near-zero values.

ϕ_2 takes $\sim 90^\circ$ or mirror solution (recall $S_{\rho\rho} \simeq \sin 2\phi_2$).

ϕ_2 extraction using $\rho\rho$, $\pi\pi$, and $\rho\pi$



$\rho\rho$ only

$\phi_2 = (96 \pm 13)^\circ$ and mirror solution

$\rho\rho$, $\pi\pi$, $\rho\pi$ combined

$\phi_2 = (99^{+13}_{-8})^\circ$

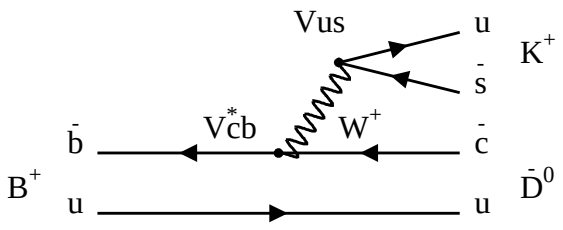
CKM fit (without ϕ_2 results)

$\phi_2 = (97^{+13}_{-19})^\circ$

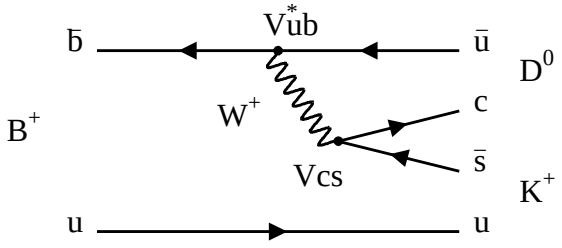
- $\rho\rho$ gives the best ϕ_2. $\rho\pi$ (time-dependent Dalitz analysis) helps to remove mirror solution
- $\pi\pi$ has limited power due to large $|\phi_2 - \phi_2^{\rm eff}|$ uncertainty
- Good agreement with CKM fit result without ϕ_2

ϕ_3 from $B^+ \to DK^+$

Contribution from external tree and Internal tree diagrams



Cabibbo-favored



Cabibbo-suppressed and color-suppressed

Reconstruct D^0 and $\bar{D}^0$ with common decay modes. The two are indistinguishable and interfere.
Presence of ϕ_3 shows up as differences of decay rate or D decay pattern between B^+ and B^- data.

At present, the best approach is to reconstruct

$$B^+ \to [K_S^0 \pi^+ \pi^-]_D K^+$$

and examine difference in $D \to K_S^0 \pi^+ \pi^-$ Dalitz plots for B^+ and B^- data

Giri, Grossman, Soffer, Zupan, PRD 68, 054018 (2003), Bondar, Belle Internal Note (2002)

$B^+ \to [K_S^0\pi^+\pi^-]_D K^+$ Dalitz Analysis

Neutral D from $B^+ \to DK^+$ is mostly $\bar{D}^0$ but contains ~10% D^0 (call $\tilde{D}^0$)

<u>$\tilde{D}^0$ amplitudes</u>

$$B^+ \to \underbrace{[K_S\pi^+\pi^-]_D}\, K^+$$
$$\hookrightarrow f(m_+^2, m_-^2) + re^{i(+\phi_3+\delta)} f(m_-^2, m_+^2)$$

$$B^- \to \underbrace{[K_S\pi^+\pi^-]_D}\, K^-$$
$$\hookrightarrow f(m_-^2, m_+^2) + re^{i(-\phi_3+\delta)} f(m_+^2, m_-^2)$$

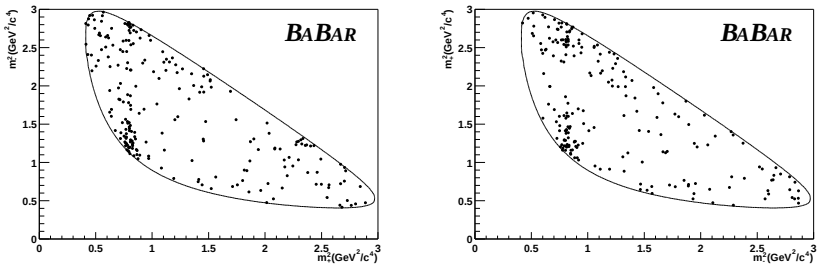
r, δ	amplitude ratio and strong phase difference of CSD and CFD
$f(m_+^2, m_-^2)$	$\bar{D}^0 \to K_S^0\pi^+\pi^-$ amplitude expressed by $m_{K_S\pi^+}$ and $m_{K_S\pi^-}$ (precisely determined from $\bar{D}^0$ sample in $e^+e^- \to c\bar{c}$ data)

Dalitz distributions of $\tilde{D}^0 \to K_S^0\pi^+\pi^-$ will look different if $r \neq 0$ and $\phi_3 \neq 0$. r, ϕ_3, and δ can be extracted from the difference.

Dalitz Distributions

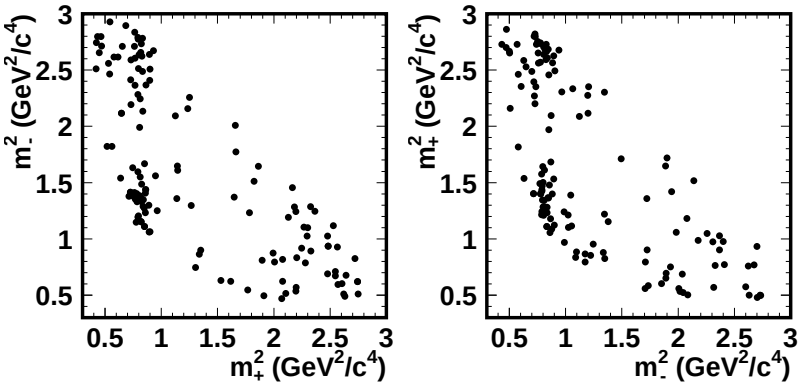
BaBar ($227 \times 10^6 B\bar{B}$)

$B^+ \to \tilde{D}^0 K^+$ $B^- \to \tilde{D}^0 K^-$



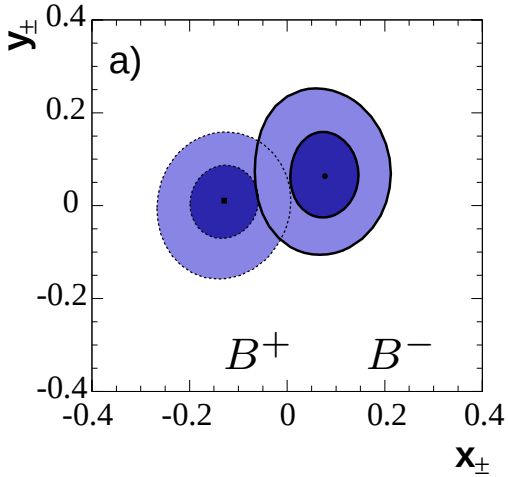
Belle ($275 \times 10^6 B\bar{B}$)

$B^+ \to \tilde{D}^0 K^+$ $B^- \to \tilde{D}^0 K^-$

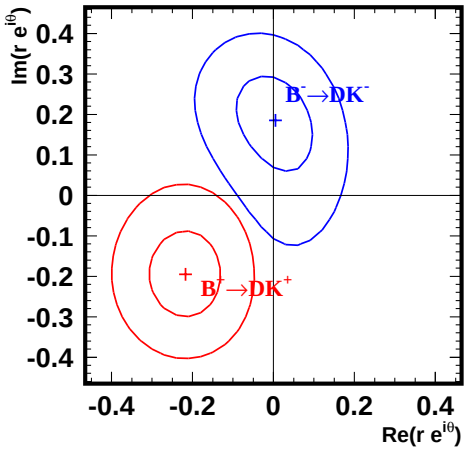


Confidence level contours in $x_\pm = Re(r_\pm e^{i(\pm\phi_3+\delta)})$, $y_\pm = Im(r_\pm e^{i(\pm\phi_3+\delta)})$

BaBar



Belle

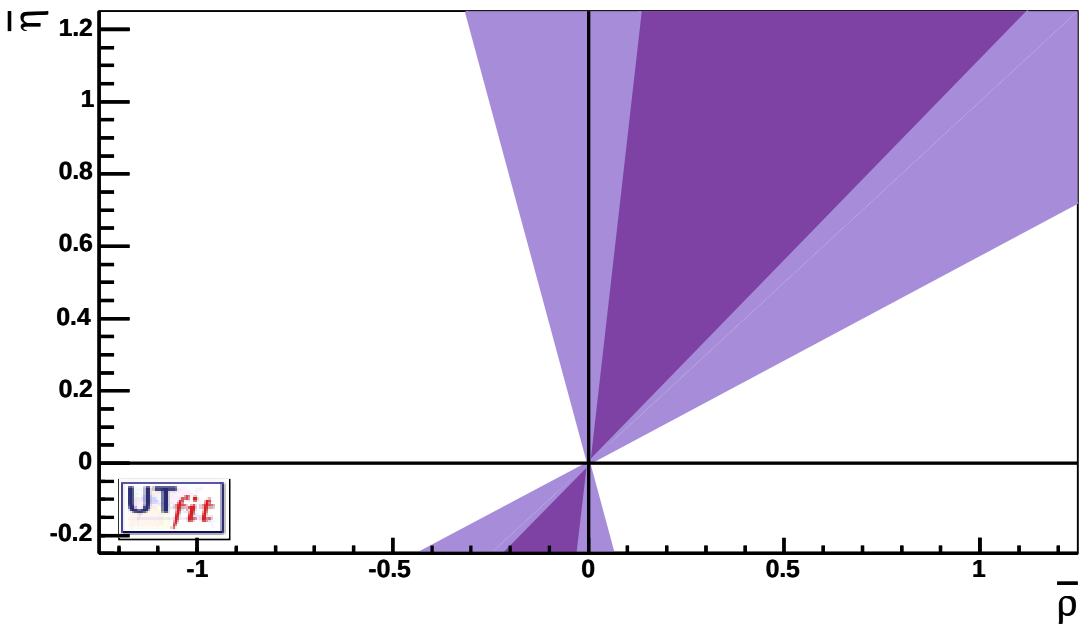


Deviation from origin indicates $r \neq 0$. Difference of B^+ and B^- signifies $\phi_3 \neq 0$ (CPV)

ϕ_3 Results

BaBar	DK, D^*K, DK^* combined	$(67 \pm 28 \pm 13 \pm 11)^\circ$
Belle	DK, D^*K combined	$(68^{+14}_{-15} \pm 13 \pm 11)^\circ$

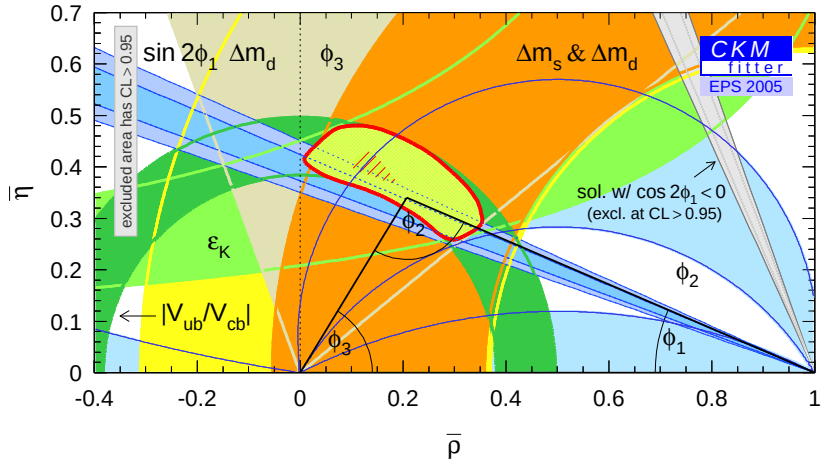
Third errors due to uncertainty of $D \to K_S \pi\pi$ decay model



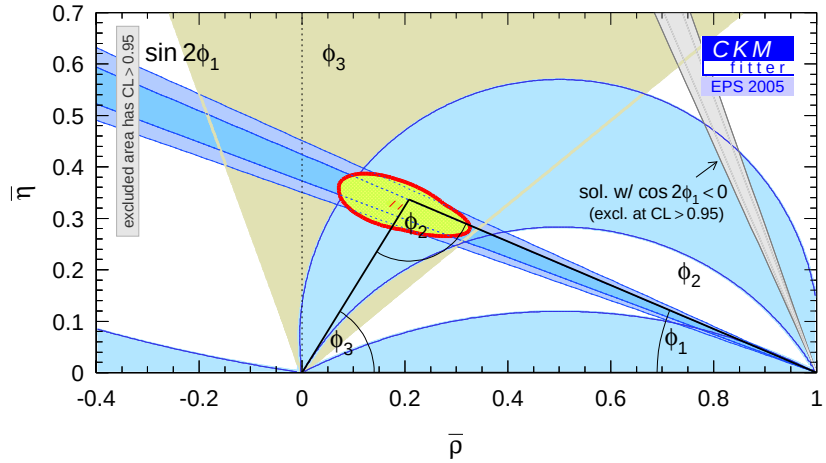
$$\phi_3 = (68 \pm 17)^\circ \;\; 95\%\text{C.L.}$$

Fits to CKM Parameters

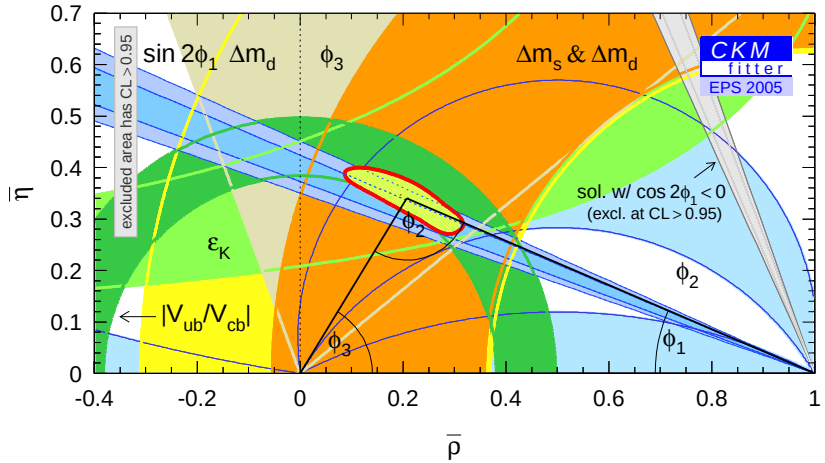
Without angle measurements



Using only angle measurements



Using all measurements



CKMfitter Group http://ckmfitter.in2p3.fr

$$\lambda = 0.226 \pm 0.001$$

$$A = 0.825^{+0.011}_{-0.019}$$

$$\bar{\rho} = 0.207^{+0.036}_{-0.019}$$

$$\bar{\eta} = 0.340 \pm 0.023$$

UTfit Group http://www.utfit.org $\bar{\rho} = 0.214 \pm 0.047, \quad \bar{\eta} = 0.343 \pm 0.028$

Good agreements between fits without CKM angles and with CKM angles only

Summary

- All categories of CP violation in B decays that are expected in the Standard Model were seen except that in B^0-$\bar{B}^0$ mixing itself.

- Precision of $\sin 2\phi_1$ measurements has reached 5%. Significantly improved the Unitarity Triangle constraint.

- ϕ_2 and ϕ_3 measurements began to produce useful results ($\delta_{\phi_2} = 12^\circ$, $\delta_{\phi_3} = 17^\circ$). Best approaches, $\rho^+\rho^-$ for ϕ_2 and $DK^\pm$ Dalitz analysis for ϕ_3, were not on our original list.

- Good agreement of ($\bar{\rho}$, $\bar{\eta}$) from fits with angles only and without angles. Strongly support the Standard Model. Redundant measurements are important because of very different QCD hadronic effects in each mode.

- Ultimate goal is to find deviation from the Standard Model. Higher precision both in experiments and theory is crucial.