Phenomenological methods for UT angles

CP violation beyond $B \to J/\psi K_S$

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outline

- present status of α and γ & motivation

  currently accessible data and methods:
- $B^0(t) \to \pi^+\pi^-$
- $B \to K\pi$
- $B^+ \to \eta\pi^+$
- $B \to DK$
- conclusion and prospects

Acknowledgments

collaborators

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present bounds & motivation

CKM fitter (95% c.l. bounds):

- $20^\circ \leq \phi_1 \equiv \beta \leq 27^\circ$
- $78^\circ \leq \phi_2 \equiv \alpha \leq 122^\circ$
- $38 \leq \phi_3 \equiv \gamma \leq 80^\circ$

motivation

- further constrain $\phi_2 \equiv \alpha$ and $\phi_3 \equiv \gamma$
- values conflicting with CKM fits: clues for new physics
- search for direct CP violation

$B^0(t) \to \pi^+\pi^-$

$$A(B^0 \to \pi^+\pi^-) = |T|e^{i\gamma} + |P|e^{i\delta} \qquad |P/T| \sim 0.3$$

$$\Gamma(B^0(t) \to \pi^+\pi^-) \propto e^{-\Gamma t}\left[1 + C_{\pi\pi}\cos\Delta(mt) - S_{\pi\pi}\sin(\Delta mt)\right]$$

$$S_{\pi\pi} = \frac{2\mathrm{Im}(\lambda_{\pi\pi})}{1+|\lambda_{\pi\pi}|^2} = \sqrt{1 - C_{\pi\pi}^2}\,\sin\alpha_{\mathrm{eff}} \neq \sin 2\alpha$$

$$-A_{\pi\pi} \equiv C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2} \neq 0$$

$$\lambda_{\pi\pi} \equiv e^{-2i\beta}\frac{A(\overline{B}^0 \to \pi^+\pi^-)}{A(B^0 \to \pi^+\pi^-)}$$

(1) isospin for α

need to measure $B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$ MG, DL

$$\sqrt{2}A(\pi^+\pi^0) - A(\pi^+\pi^-) = \sqrt{2}A(\pi^0\pi^0)$$

$\mathcal{B}(10^{-6}):$ 5.27 ± 0.79 4.55 ± 0.44 $< 3.6\ (90\%\ \mathrm{c.l.})$

isospin triangles for B and $\bar{B}$ don't match
mismatch angle 2θ gives $\alpha = \alpha_{\mathrm{eff}} - \theta$ (includes EWP)

- upper limit $\mathcal{B}(\pi^0\pi^0) < 3.6\ (90\%\ \mathrm{c.l.})$ not very strong
  $\Rightarrow$ $|\theta| \lesssim 60^\circ$ not yet useful
  Charles > Grossman, Quinn > MG, London, Sinha's
- $2\mathcal{B}(\pi^+\pi^0)/\tau_+ > \mathcal{B}(\pi^+\pi^-)/\tau_0$!
  $\Rightarrow$ lower limit $\mathcal{B}(\pi^0\pi^0) > 0.22\ (90\%\ \mathrm{c.l.})$ = first clue

(2) flavor SU(3)

$$A(B^0 \to \pi^+\pi^-) = |T|e^{i\gamma} + |P|e^{i\delta}$$

can measure α from $C_{\pi\pi},\ S_{\pi\pi}$ IF $|P|$ were known
(or IF we use $|P/T| \sim 0.3$) Charles; MG, Rosner

$$A(B^+ \to K^0\pi^+) = |P'|e^{i\delta'} = |P|e^{i\delta'}\frac{f_K}{f_\pi \tan\theta_c}$$

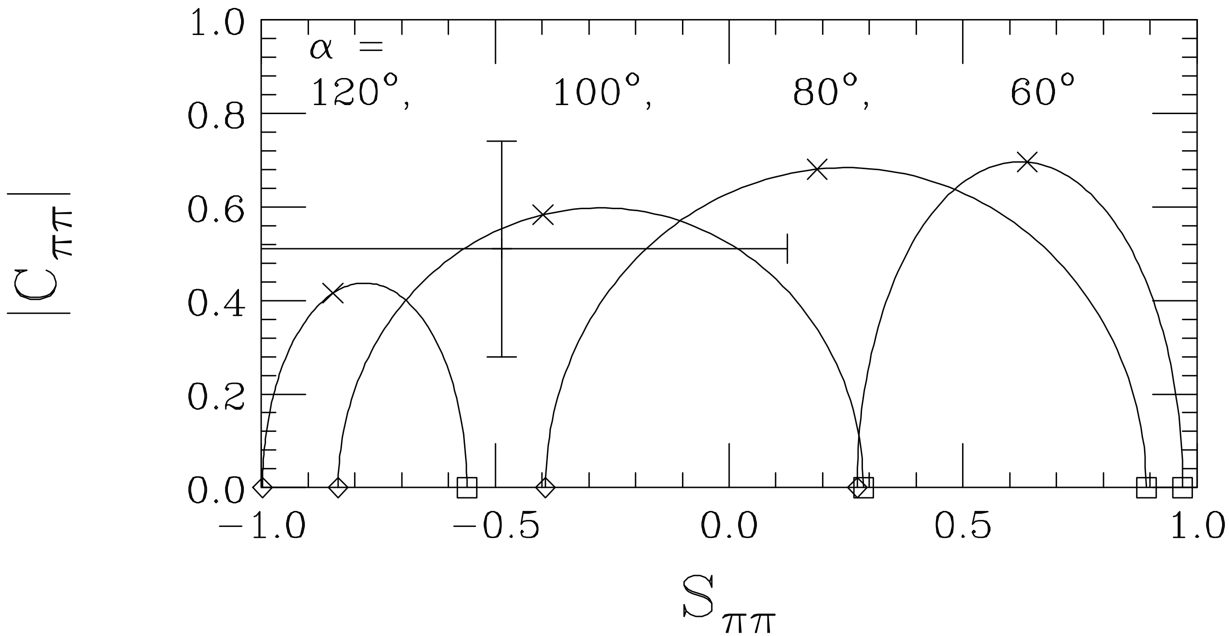
2 approximations

- neglect term with phase γ in B^+ ($B^0 \to K^+K^-$)
- factorization of P (to be checked in $B^+ \to \overline{K}^0 K^+$)

$|T/P|,\ \delta,\ \alpha$ from $S_{\pi\pi},\ C_{\pi\pi},\ \mathcal{B}(B^0 \to \pi^+\pi^-)/\mathcal{B}(B^+ \to K^0\pi^+)$

$C_{\pi\pi},\ S_{\pi\pi}$ vs α

insensitive to $\mathcal{B}(B^0 \to \pi^+\pi^-)/\mathcal{B}(B^+ \to K^0\pi^+) = 0.232 \pm 0.028$



$\Diamond:\ \delta = 0$ $\quad\Box:\ \delta = \pi$ $\quad\times:\ \delta = \pi/2$

$S_{\pi\pi} = -0.49 \pm 0.61\ (\chi = 2.3),\ C_{\pi\pi} = -0.51 \pm 0.23\ (\chi = 1.2)$

$B \to K\pi$

- $B^0 \to K^+\pi^-$ vs $B^+ \to K^0\pi^+$ Fleis., Man.; MG, JR

$$A(B^0 \to K^+\pi^-) = |P'|e^{i\delta_0} - |T'|e^{i\gamma} \qquad \text{neglect EWP}^c$$

$$A(B^+ \to K^0\pi^+) = |P'|e^{i\delta_0} \qquad r \equiv |T'|/|P'|$$

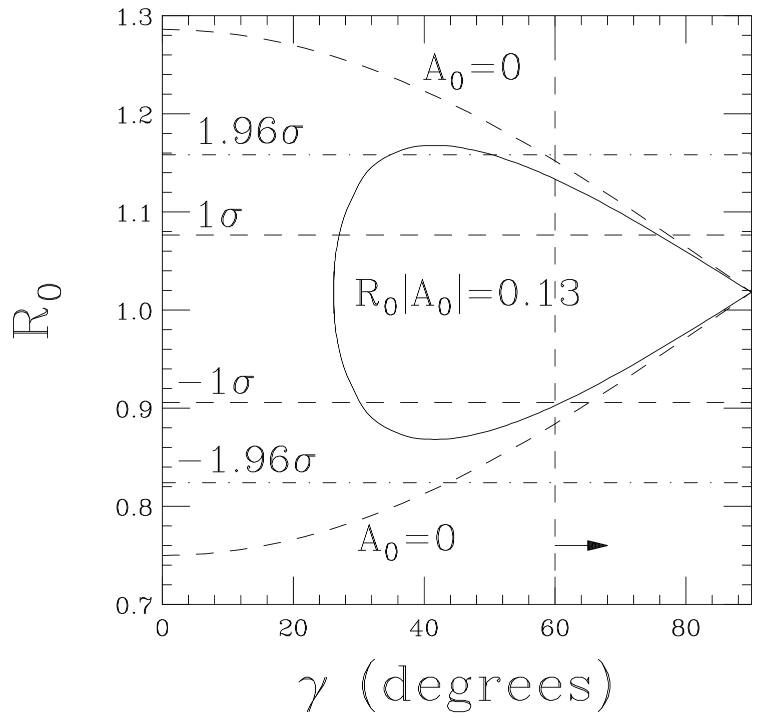
$$R_0 = \frac{\bar{\Gamma}(K^\pm\pi^\mp)}{\bar{\Gamma}(K^0\pi^\pm)} = 1 - 2r\cos\delta_0\cos\gamma + r^2 \geq \sin^2\gamma$$

$$A_0 = \frac{\Gamma(K^-\pi^+) - \Gamma(K^+\pi^-)}{\Gamma(K^-\pi^+) + \Gamma(K^+\pi^-)} = -2r\sin\delta_0\sin\gamma/R_0$$

eliminate δ_0 and plot $(R_0)_{\rm exp} = 0.99 \pm 0.09$ vs γ for allowed range $|A_0|_{\rm exp} < 0.13$ $\quad 0.13 < r_{\rm th} < 0.21$ ($B \to \pi\pi/K\pi$)
most conservative bounds on γ at $r = 0.13$

R_0 vs γ for $|A_0| < 0.13,\ r = 0.13$

lower branch: $\cos\delta_0 \cos\gamma > 0$



$\gamma \geq 60^\circ\ (1\sigma)$: need smaller error in R_0

another $B \to K\pi$ ratio

- $B^+ \to K^+\pi^0/K^0\pi^+$ MG, DL, JR, Neubert

$$\sqrt{2}A(B^+ \to K^+\pi^0) = |P'|e^{i\delta_c} - |T' + C'|(e^{i\gamma} - \delta_{\rm EWP})$$

$$A(B^+ \to K^0\pi^+) = |P'|e^{i\delta_c} \qquad r_c \equiv |T' + C'|/|P'|$$

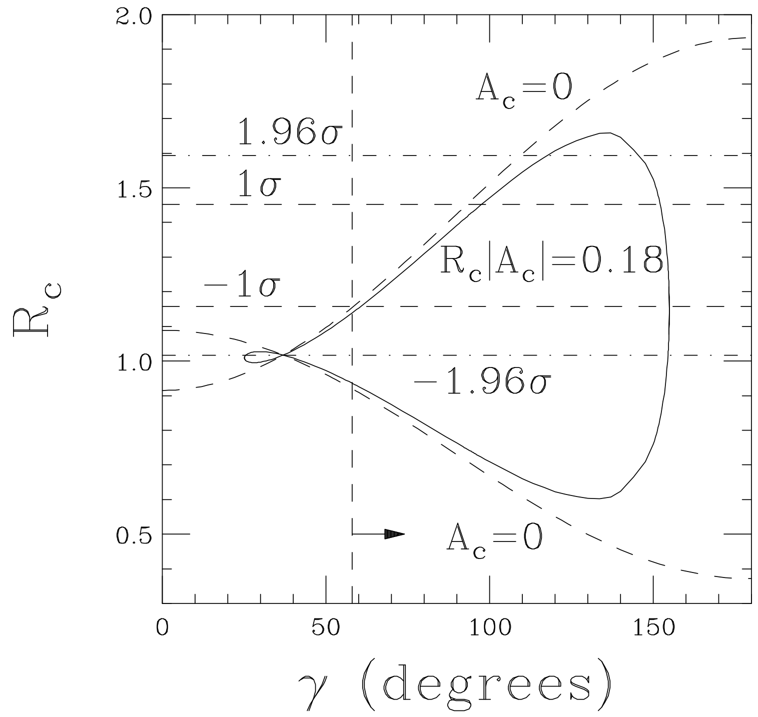
$$R_c = \frac{2\bar{\Gamma}(K^\pm\pi^0)}{\bar{\Gamma}(K^0\pi^\pm)} = 1 - 2r_c\cos\delta_c(\cos\gamma - \delta_{\rm EWP}) + \mathcal{O}(r_c^2)$$

$$A_c = \frac{\Gamma(K^-\pi^0) - \Gamma(K^+\pi^0)}{\Gamma(K^-\pi^0) + \Gamma(K^+\pi^0)} = -2r_c\sin\delta_c\sin\gamma/R_c$$

eliminate δ_c and plot $(R_c)_{\rm exp} = 1.31 \pm 0.15$ vs γ for allowed range $|A_c|_{\rm exp} < 0.11$ $\quad 0.18 < (r_c)_{\rm th} < 0.22$ $(B^+ \to \pi^+\pi^0/\pi^+K^0)$ $\delta_{\rm EWP} = 0.65 \pm 0.15$; conservative bounds on γ at $\delta_{\rm EWP} = 0.80$

R_c vs γ for $R_c|A_c| < 0.18,\ r_c = 0.22$

lower branch: $\cos\delta_c(\cos\gamma - \delta_{\rm EW}) > 0$



$\gamma > 58^\circ$ (1σ): need smaller error in R_c

$B^+ \to \eta\pi^+$

$\eta = (s\bar{s} - u\bar{u} - d\bar{d})/\sqrt{3}$ Chiang, MG, Rosner

octet-singlet mixture, $\sin\theta_{8,1} = -1/3$

$$\sqrt{3}A((B^+ \to \eta\pi^+) = |T + C|e^{i\gamma} + |2P + s|e^{i\delta}$$

$$\sqrt{2}A(B^+ \to \pi^+\pi^0) = |T + C|e^{i\gamma} \quad \uparrow \quad \uparrow \; = \; \text{singlet}$$

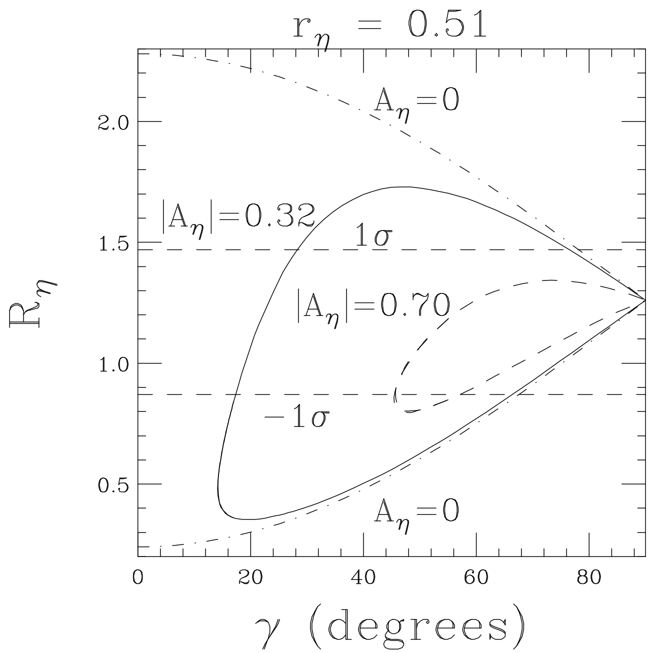
$$R_\eta = \frac{3\bar{\Gamma}(\eta\pi^\pm)}{2\bar{\Gamma}(\pi^\pm\pi^0)} = 1 + r_\eta^2 + 2r_\eta \cos\delta\cos\gamma = 1.17 \pm 0.30 \ {}^{\text{BaBar}}_{\text{Belle}}$$

$$A_\eta = \frac{\Gamma(\eta\pi^-) - \Gamma(\eta\pi^+)}{\Gamma(\eta\pi^-) + \Gamma(\eta\pi^+)} = -2r_\eta \sin\delta\sin\gamma/R_\eta = -0.51 \pm 0.19 \ \text{BaBar}$$

$$r_\eta \equiv \frac{|2P + s|}{|T + C|} \gtrsim \frac{2|P|}{|T + C|} = \frac{f_\pi \tan\theta_c}{f_K}\sqrt{\frac{2\mathcal{B}(K^0\pi^+)}{\mathcal{B}(\pi^+\pi^0)}} = 0.51 \pm 0.04$$

R_η vs γ for a range in A_η

upper branch: $\cos\delta\cos\gamma > 0$



large asymmetry - important, but by itself would not improve constraint on γ; need more precise measurements of $R_\eta,\ A_\eta$

γ from $B^\pm \to DK^\pm$

$D^0_{\rm CP\pm} = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$ MG, London, Wyler; variants

$D^0_{\rm CP+} \to K^+K^-, \quad D^0_{\rm CP-} \to K_S\pi^0, \quad D^0 \to K^-\pi^+$

$$A(B^- \to D^0_\pm K^-) = \frac{1}{\sqrt{2}}[A(B^- \to D^0K^-) \pm A(B^- \to \bar{D}^0K^-)]$$

no penguin, no approximation	$b \to c\bar{u}s$ phase=0	$b \to u\bar{c}s$ phase=$-\gamma$
ratio $r \sim 0.2$	measured	difficult to measure

$$R_\pm = \frac{\Gamma(D^0_{\rm CP\pm}K^-) + \Gamma(D^0_{\rm CP\pm}K^+)}{\Gamma(D^0K^-)} = 1 + r^2 \pm 2r\cos\delta\cos\gamma$$

$$A_\pm = \frac{\Gamma(D^0_{\rm CP\pm}K^-) - \Gamma(D^0_{\rm CP\pm}K^+)}{\Gamma(D^0_{\rm CP\pm}K^-) + \Gamma(D^0_{\rm CP\pm}K^+)} = \pm 2r\sin\delta\sin\gamma/R_\pm$$

experimental situation

$$R(K/\pi) \equiv \frac{\mathcal{B}(B^- \to D^0 K^-)}{\mathcal{B}(B^- \to D^0 \pi^-)} \qquad R(K/\pi)_\pm \equiv \frac{\mathcal{B}(B^\pm \to D^0_{\mathrm{CP}\pm} K^\pm)}{\mathcal{B}(B^\pm \to D^0_{\mathrm{CP}\pm} \pi^\pm)}$$

all 3 quantities measured $\quad \Rightarrow R_\pm = \frac{R(K/\pi)_\pm}{R(K/\pi)}$

$R_+ = 1.09 \pm 0.16 \qquad A_+ = 0.07 \pm 0.13 \quad (\mathrm{Belle, BaBar})$

$R_- = 1.30 \pm 0.25 \qquad A_- = -0.19 \pm 0.18 \quad (\mathrm{Belle})$

$\Rightarrow r = 0.44^{+0.14}_{-0.24} \qquad A_{\mathrm{av}} = 0.11 \pm 0.11$

$R_\pm = 1 + r^2 \pm 2r\cos\delta\cos\gamma \geq \sin^2\gamma$, both $R_\pm \geq 1$ unlikely

either $R_+ < 1$ or $R_- < 1$ implies constraint on γ

one may plot $R_\pm$ vs γ for allowed $A_\pm$ (same as $B^0 \to K^+\pi^-$)

need more precise $R_\pm$ to constrain γ

conclusion and prospects

- α and γ affect direct CP asymmetries, which require interference of two amplitudes with different weak and strong phases
- ratio of interfering amplitudes is typically $\sim 0.2 - 0.3$; strong phases cannot be calculated reliably
- $|(2P+s)/(T+C)|_{\eta\pi^+} \gtrsim 0.5$, $|(2P+4s)/(T+C)|_{\eta'\pi^+} \sim 1$
  prospects: large asymmetries in $B^+ \to \eta\pi^+$, $B^+ \to \eta'\pi^+$
- $\exists$ strict expl. bounds on several direct CP asymmetries
- interference can also be measured in ratios of rates, very important ! reducing errors by < 2 will constrain γ
- $\alpha,\ \gamma$ not as easy as β...we only started... $2\beta+\gamma$ (D$^*\rho$)...
  B_s decays from Tevatron...interesting days ahead...

further references

- $B^0 \to \pi^+\pi^-$: Silva + Wolfenstein
  Fleischer + Matias
  Beneke *et al* (also $B \to K\pi$)
  Keum + Li + Sanda (also $B \to K\pi$)
- $B \to K\pi$: Buras + Fleischer
  Deshpande   He *et al*   Hou *et al*
  Ciuchini *et al*   Ali *et al*
- $B \to \eta/\eta'\pi^+$: Barshay + Rein + Sehgal
  Ahmady + Kou
- $B \to DK$: Atwood + Dunietz + Soni
  Kayser + London + Sinhas
  Grossman *et al*   Fleischer

I APOLOGIZE FOR THOSE FORGOTTEN