Direct CP violation and determination of γ

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outline

- present status of α and γ & motivation

  methods and current data, HFAG, LP03:
- $B^0(t) \to \pi^+\pi^-$
- $B \to K\pi$, anomaly
- $B^+ \to \eta\pi^+$
- $B \to DK$
- $B \to VP$
- conclusion and prospects

Acknowledgments

collaborators

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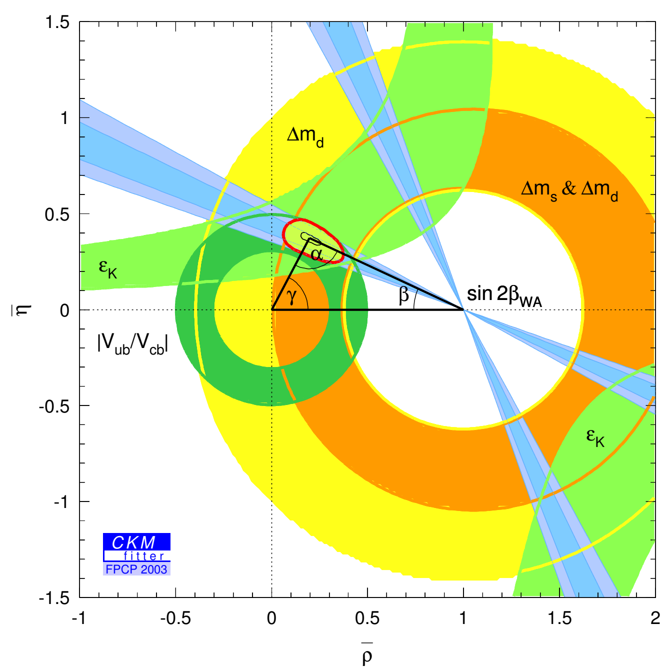
CKM matrix

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad {\rm Arg}V_{ub} = -\gamma \quad {\rm Arg}V_{td} = -\beta$$



present bounds & motivation

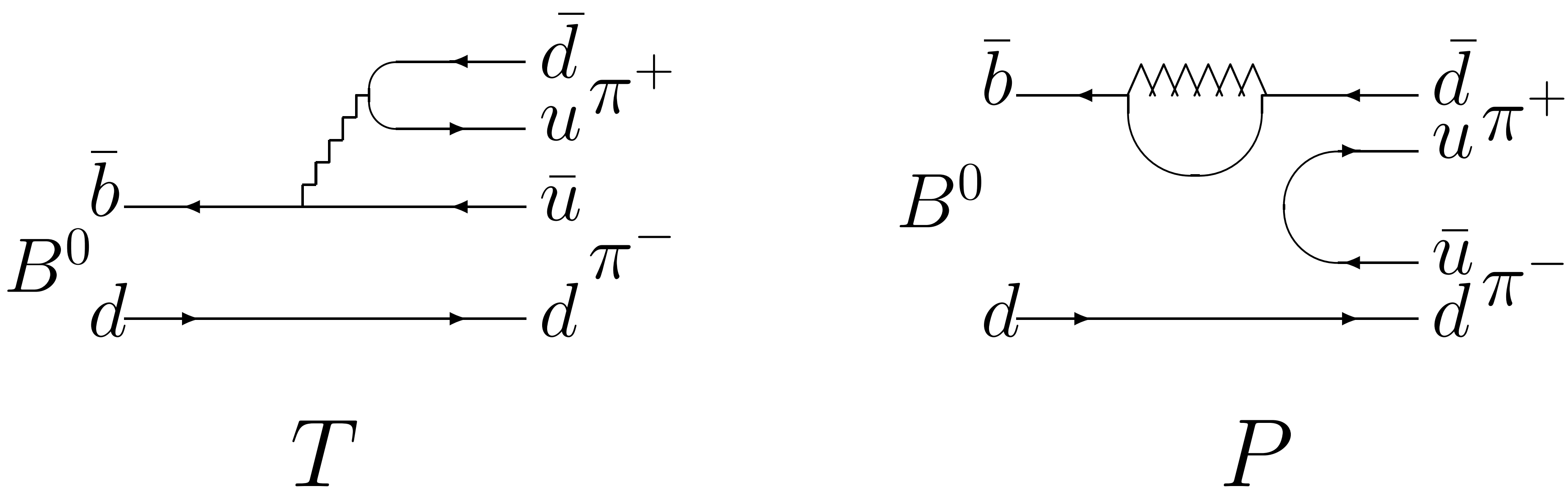
CKM fitter (95% c.l. bounds):

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

motivation

- search for direct CP violation
- stronger constraints on α and γ
- values conflicting with CKM fits $\Rightarrow$ new physics
- violation of rate relations (isospin) $\Rightarrow$ new physics

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



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

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

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

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

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

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

(1) isospin for α

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

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

$\mathcal{B}(10^{-6}):$ 5.27 ± 0.79 4.55 ± 0.44 1.97 ± 0.47

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

- $\mathcal{B}(\pi^0\pi^0)$ not very small $\Rightarrow$ $|\Delta\alpha| \leq 49^\circ$ 90% c.l. not useful
  Charles > Grossman, Quinn > MG, London, Sinha's
- full isospin analysis requires B^0 flavor tagging in $B \to \pi^0\pi^0$

(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

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

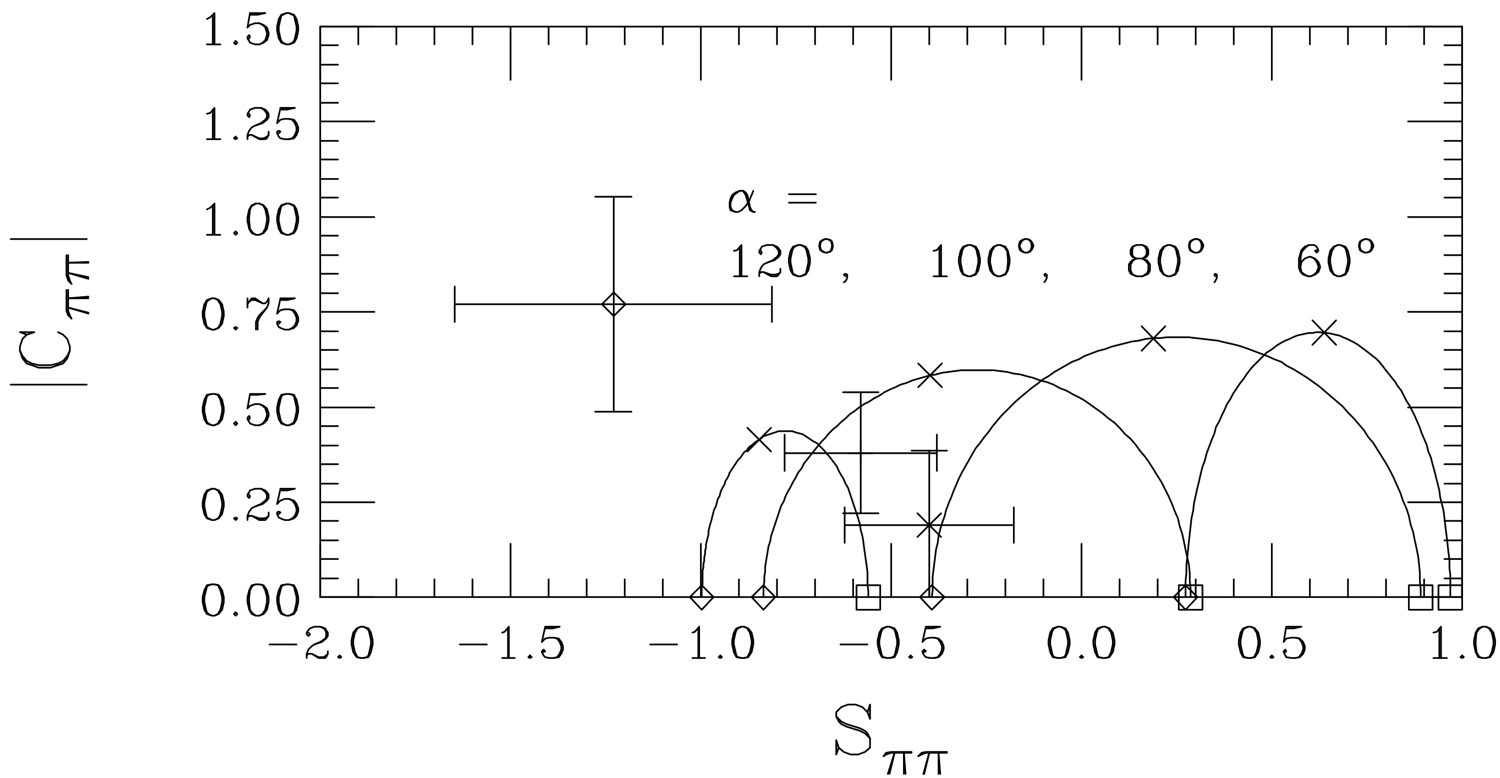
2 approximations

- neglect tiny term with phase γ in $B^+ \to K^0\pi^+$
- factorization of P (will 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 $\mathcal{B}(B^0 \to \pi^+\pi^-)/\mathcal{B}(B^+ \to K^0\pi^+) = 0.23 \pm 0.03$



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

$S_{\pi\pi} = -0.58 \pm 0.20, \; C_{\pi\pi} = -0.38 \pm 0.16$ favors large α

$$B \to K\pi$$

$B \to K\pi$

- $B^0 \to K^+\pi^-$ vs $B^+ \to K^0\pi^+$ MG, Rosner; Fleischer, Mannel

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

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

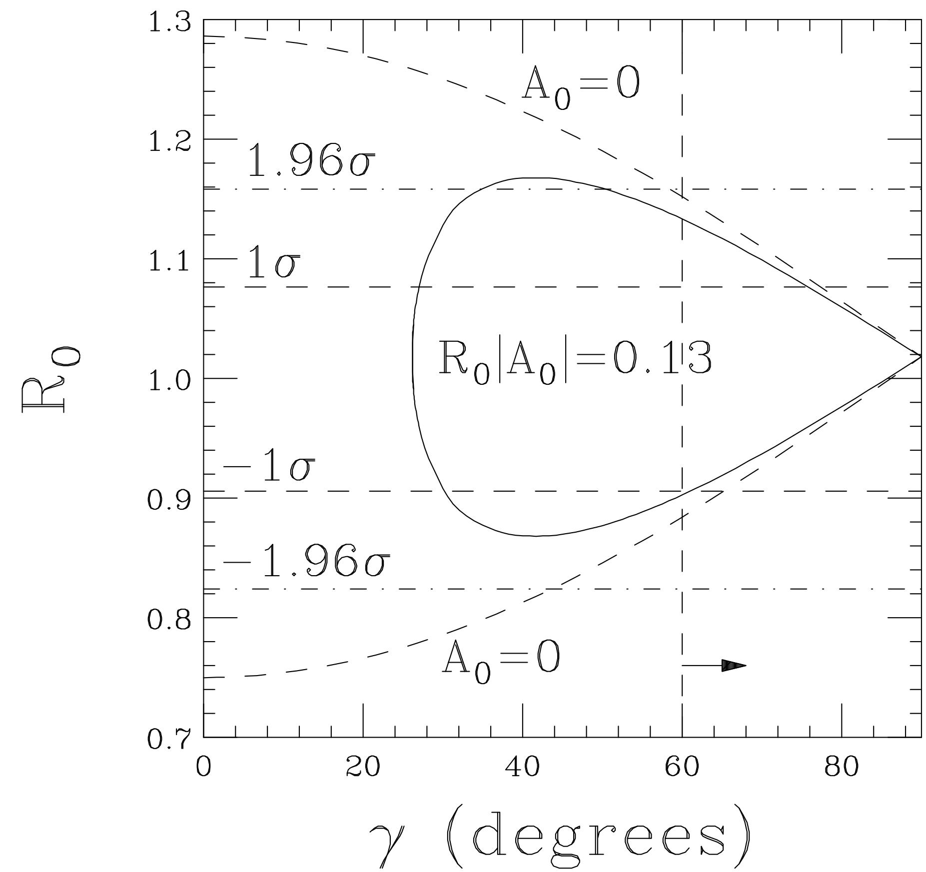
$$R_0 = \frac{\bar{\Gamma}(K^\pm\pi^\mp)}{\bar{\Gamma}(K^0\pi^\pm)} = 1 - 2r\cos\delta_0\cos\gamma + r^2 \geq \sin^2\gamma$$

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

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, London, Rosner, 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 $\delta_{\rm EWP} = 0.80$

The $K\pi$ anomaly

Isospin sum rule MG, Rosner, hep-ph/0307095 (Lipkin)

$$\frac{2[\Gamma(B^+ \to K^+\pi^0) + \Gamma(B^0 \to K^0\pi^0)]}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$= 1 + \frac{|P'_{\rm EW}|^2}{|P'|^2} + \frac{{\rm Re}(T'^* P'_{\rm EW})}{|P'|^2} \quad \text{no linear } \Delta {\rm I} = 1$$

$\Delta I = 1:$ $< 4\%$

experiment: $24 \pm 10\%$ new physics?

$$R_n \equiv \bar{\Gamma}(B^0 \to K^+\pi^-)/2\bar{\Gamma}(B^0 \to K^0\pi^0) = 0.81 \pm 0.10$$

$$R_c \equiv 2\bar{\Gamma}(B^+ \to K^+\pi^0)/\bar{\Gamma}(B^+ \to K^0\pi^+) = 1.31 \pm 0.15$$

$R_c = R_n + \mathcal{O}(|P'_{\rm EW}|^2/|P'|^2)$ underestimate π^0 detec. effic.?

$$B^+ \to \eta(\eta')\pi^+$$

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

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

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

Chiang, MG, Rosner
hep-ph/0306021

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

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

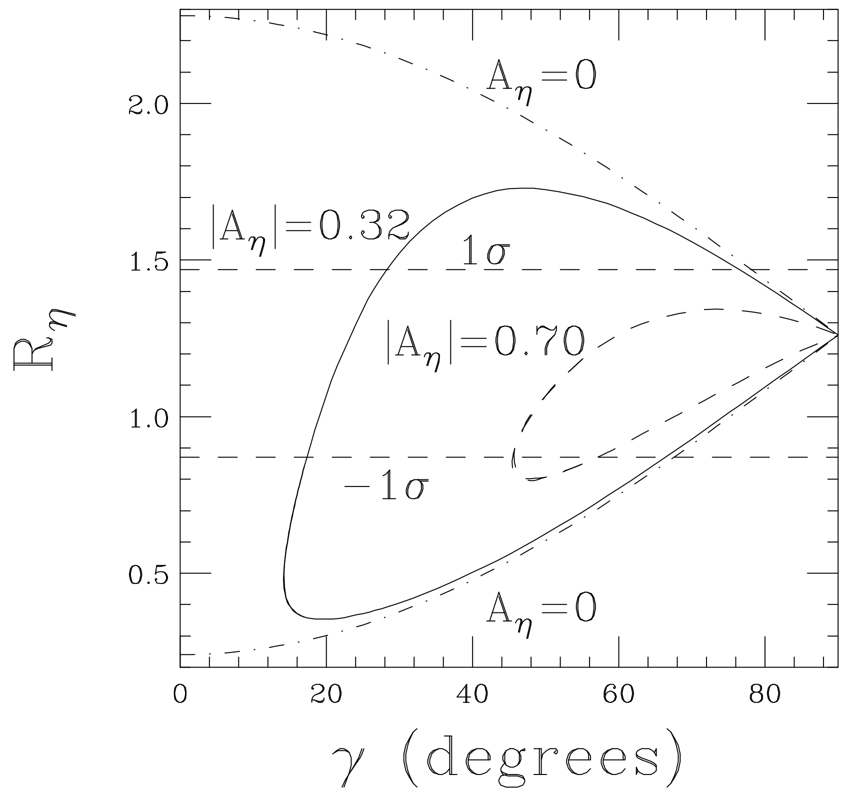
$$R_\eta = \frac{3\bar{\Gamma}(\eta\pi^\pm)}{2\bar{\Gamma}(\pi^\pm\pi^0)} = 1 + r_\eta^2 + 2r_\eta \cos\delta\cos\gamma = 1.17 \pm 0.30 \ {}^{\text{BaBar}}_{\text{Belle}}$$

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

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

R_η vs γ for a range in A_η

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



large asymmetry is important

need more precise measurements of R_η, A_η

$$B \to DK$$

γ from $B^\pm \to DK^\pm$ MG, London, Wyler, variants

interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$

$D^0_{\mathrm{CP}\pm} = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$, $D^0_{\mathrm{CP}+} \to K^+ K^-$

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

no penguin $\quad$ $b \to c\bar{u}s$ phase=0 $\quad$ $b \to u\bar{c}s$ phase=$-\gamma$

ratio $r \sim 0.2$ $\quad$ measured $\quad$ difficult to measure

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

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

$R_\pm, A_\pm$ determine γ $\quad$ $\sin^2\gamma \le R_\pm$, both $R_\pm \ge 1$ unlikely

experimental situation

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

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

do not require knowledge of B and D decay BR's

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

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

$$A_{\mathrm{av}} = 0.11 \pm 0.11$$

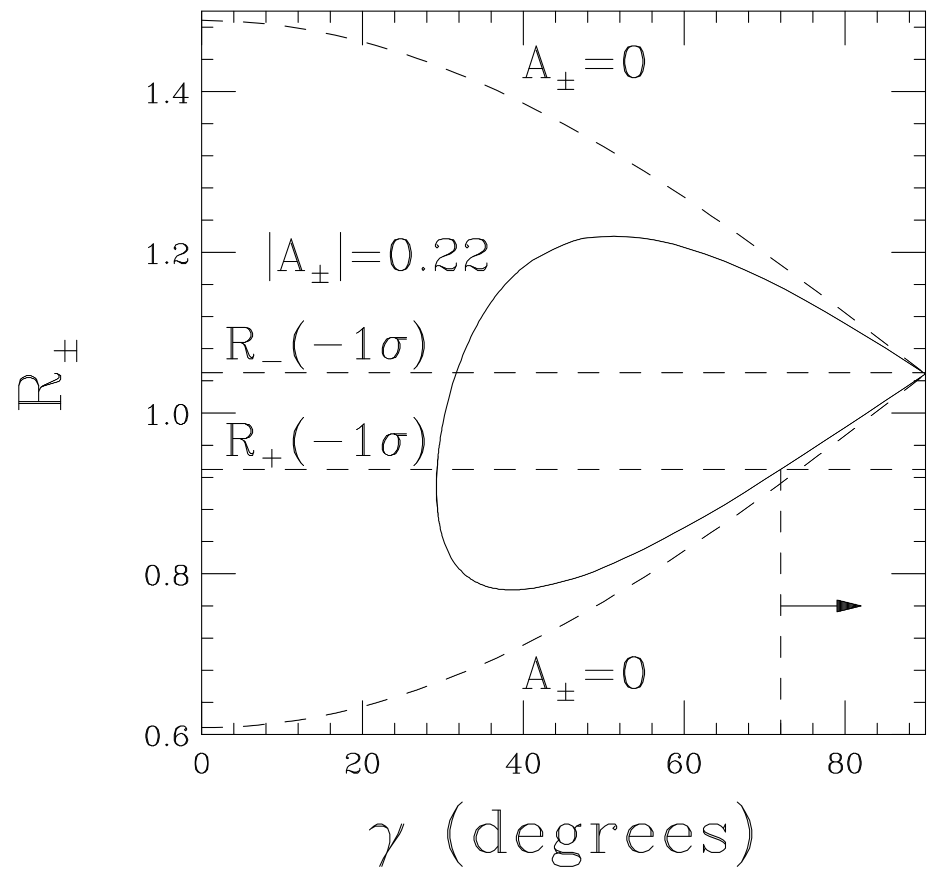
$$r = \sqrt{(R_+ + R_-)/2 - 1} = 0.44^{+0.14}_{-0.22}$$

$$B^- \to D^0(\to K_S \pi^+ \pi^-) K^-$$

$$r = 0.33 \pm 0.10 \quad \text{(Belle)}$$

$R_\pm$ vs γ for $|A_\pm|^{1\sigma} < 0.22,\ r_{\rm min}^{1\sigma} = 0.22$

lower (upper) branch of R_+ (R_-): $\cos\delta\cos\gamma < 0$



$\gamma > 72^\circ$ (1σ): need smaller error in $R_\pm$

non-CP, mixed-flavor D decay modes

Dalitz plot for $D \to K_S\pi^+\pi^-$ in $B^\pm \to D^0(\bar{D}^0)K^\pm$

Giri, Grossman, Soffer, Zupan

$$f(m_+^2, m_-^2) \equiv A(\bar{D}^0 \to K_S\pi^+\pi^-)$$

$$A((K_S\pi^+\pi^-)_D K^+) \propto f(m_+^2, m_-^2) + re^{i(\delta+\gamma)} f(m_-^2, m_+^2)$$

Belle, hep-ex/0308043, 140 fb^{-1}:

- model f by sum of resonances: $K^{*\pm}, \rho^0, \omega, f_0, f_2, \sigma ...$
- fit resonance amps $\&$ phases in tagged $\bar{D}^0$ decays
- given f, determine $r,\ \delta,\ \gamma$ from $\Gamma((K_S\pi^+\pi^-)_D K^\pm)$

90 $\%$ c.l: $0.15 < r < 0.50,\ 104^\circ < \delta < 214^\circ,\ \ 61^\circ < \gamma < 142^\circ$

$$B \to VP$$

$B \to VP$

global fit to all $B \to VP$ decays:
$\rho\pi,\ \omega\pi,\ \rho\eta,\ \rho\eta',\ K^*\pi,\ K^*\eta,\ K^*\eta',\ \rho K, \omega K,\ \phi K$
Chiang, MG, Luo, Rosner, Suprun, hep-ph/0307395

- flavor SU(3) including SU(3) breaking
- 33 data points for rates and asymmetries; 12 parameters
- good fit: $\chi^2/\mathrm{d.o.f.} \approx 1$
- predictions for unobserved decays
- tests SU(3) breaking = ratio of decay constants
- small strong phases between tree and penguin
- $51^\circ < \gamma < 74^\circ$ at 95% c.l.

conclusion and prospects

- direct CP asymmetries and γ require interference
- $|P/T|_{\pi\pi} \sim 0.3, \;\; |T/P|_{K\pi} \sim 0.2, \;\; |C/T|_{DK} \sim 0.2$; $|P/T|_{B^+ \to \eta(\eta')\pi^+} \sim 0.5 - 1.0 \Rightarrow$ potential large asym
- $\exists$ strict bounds on $K\pi$ asymmetries $\sim 10\%$
- watch the anomaly in $K\pi$ rates: new physics ?
- ratios of $K\pi$ rates, and of DK rates, are sensitive to γ; current ratios in $B \to K\pi$ & $DK \;\Rightarrow\; 1\sigma$ bounds on γ; bounds at 95% c.l. require reducing errors by < 2
- $B \to D(K_S\pi^+\pi^-)K$ seems promising
- current bounds in $B \to K\pi$ assume conservative SU(3) breaking, can be improved by experimental tests of SU(3) breaking

further references

- $B^0 \to \pi^+\pi^-$: Silva + Wolfenstein
  Fleischer + Matias
  Beneke *et al* (also $B \to K\pi,\ VP$)
  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
- $B \to VP$: Ali *et al*, Kramer *et al*