Weak Phases and CP Violation

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Outline

- Precision tests of weak phases
  - $\beta \equiv \phi_1 : B \to J/\psi K_S$ (other charmonuim, K_L, K^{*0})
  - $\alpha = \pi - \beta - \gamma \equiv \phi_2$: Isospin in $B \to \pi\pi, \quad \rho\pi, \quad \rho\rho$
  - $\gamma \equiv \phi_3 : B \to DK$
- Direct CP asymmetries in $B \to K\pi$
- Signal beyond the Standard Model in $b \to s$ transitions?
  - Asymmetry $\neq \sin 2\beta$ in $B(t) \to \pi^0 K_S, \quad \eta' K_S, \quad \phi K_S, \ldots$
- Conclusion
- WA Data taken from CKM05, to be updated after LP03
- No time to discuss B_s decays, a single reminder

PRECISION TESTS

OF WEAK PHASES

Precision β: $B^0(t) \to J/\psi K_S$

$A(B^0 \to \psi K_S) \sim V_{cb}^* V_{cs}$ has a single real CKM phase
$\Rightarrow B^0(t) \to J/\psi K_S$ & other $b \to c\bar{c}s$ measure $\sin 2\beta$ precisely

interference between B^0-$\bar{B}^0$ mixing and decay Sanda, Carter
Bigi, 1981

$$A(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to \psi K_S) - \Gamma(B^0(t) \to \psi K_S)}{\Gamma(\bar{B}^0(t) \to \psi K_S) + \Gamma(B^0(t) \to \psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

with other charmonium, K_L: $\sin 2\beta_{\rm WA} = 0.726 \pm 0.037$

transversity $B \to J/\psi K^{*0}$ favors $\cos 2\beta > 0, \; \beta = (23.3 \pm 1.5)^\circ$
$({\rm Babar}: \cos 2\beta = 2.72^{+0.50}_{-0.79} \pm 0.27)$

value of β fits beautifully all other CKM constraints (next)

conclusion : KM phase is the dominant source of CPV

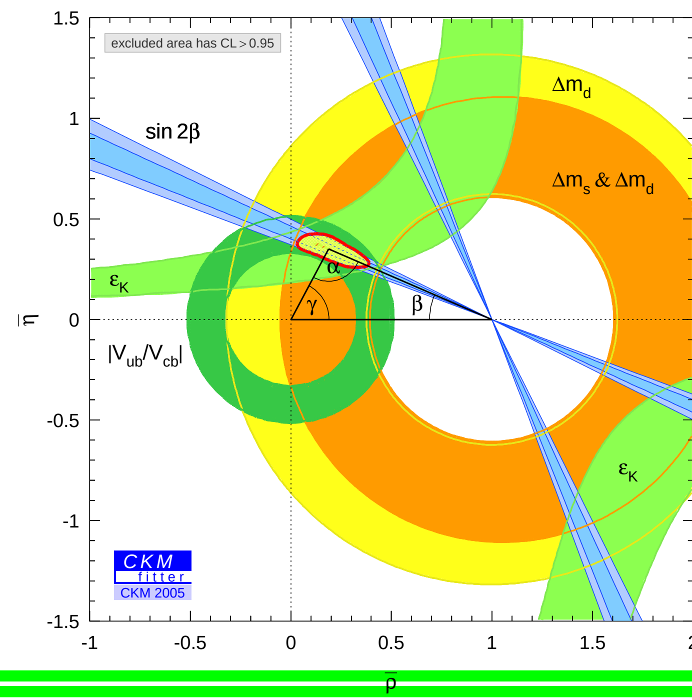
CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\beta = -\mathrm{Arg} V_{td} = (23.3 \pm 1.5)^\circ$$

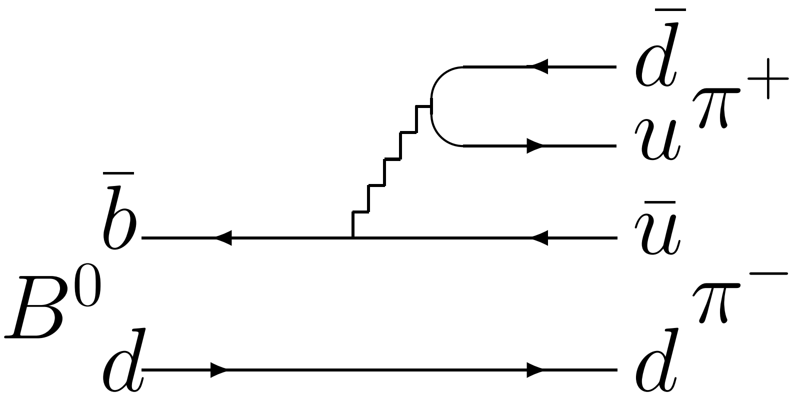
$$\gamma = -\mathrm{Arg} V_{ub} = (58 \pm 12)^\circ$$

$$\alpha = \pi - \beta - \gamma = (99 \pm 12)^\circ$$



α in $B \to \pi^+\pi^-$

two amplitudes with different weak phases



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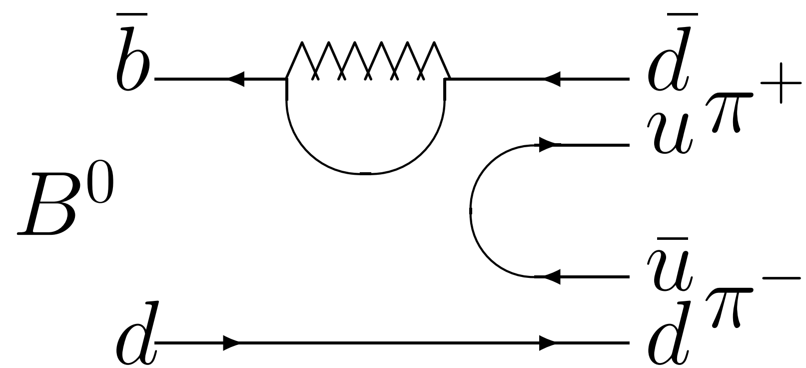


P

$A(B^0 \to \pi^+\pi^-) = |T|e^{i\gamma} + |P|e^{i\delta}$ $\qquad |P/T| \sim 0.5\ (B \to K\pi)$

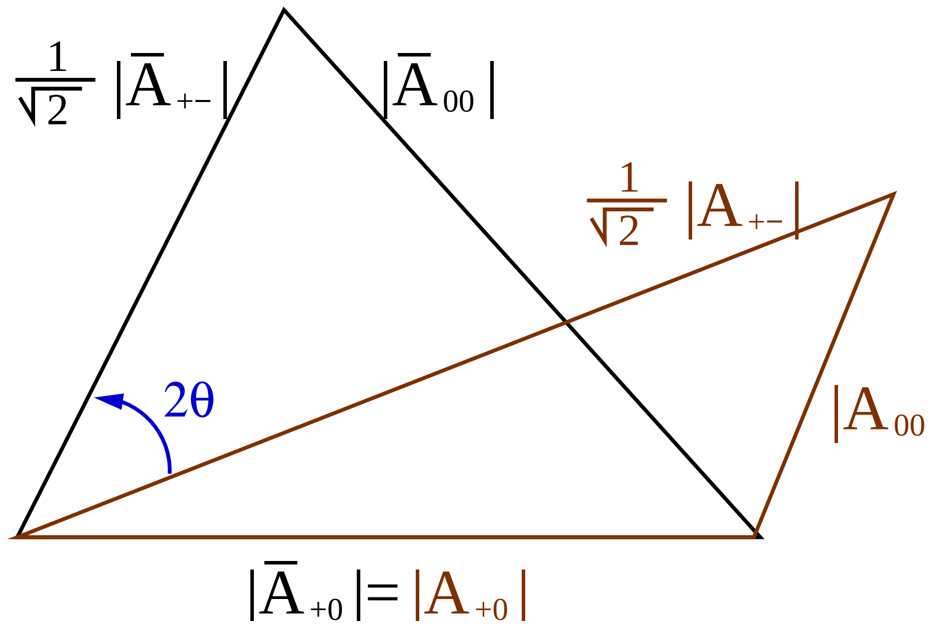
$$\Gamma(B^0(t) \to \pi^+\pi^-) \propto e^{-\Gamma t}\Gamma_{\pi\pi}\left[1 + C_{\pi\pi}\cos\Delta(mt) - S_{\pi\pi}\sin(\Delta mt)\right]$$

3 measurables, $\Gamma_{\pi\pi}, C_{\pi\pi}, S_{\pi\pi}$ for 4 parameters, $|T|, |P|, \delta, \gamma$

Isospin requires $\Gamma_{\pi^+\pi^0}, \Gamma_{\pi^0\pi^0}, \bar{\Gamma}_{\pi^0\pi^0}$

$\sin(2\alpha_{\rm eff}) = S_{\pi\pi}/\sqrt{1 - C^2_{\pi\pi}}$ $\quad 2\alpha = 2\alpha_{\rm eff} - 2\theta$

$\alpha_{\rm eff} = (106 \pm 4)^\circ$ (164 ± 4 excluded) $\quad$ MG, London



$\mathcal{B}(\pi^+\pi^-)$	$\mathcal{B}(\pi^+\pi^0)$	$\mathcal{B}(\pi^0\pi^0)$	$S_{\pi^+\pi^-}$	$C_{\pi^+\pi^-}$
4.6 ± 0.4	5.5 ± 0.6	1.45 ± 0.29	-0.50 ± 0.12	-0.37 ± 0.10

all quantities measured, $\quad$ limits on $C_{\pi^0\pi^0} = -0.28 \pm 0.39$

Bounds on $\theta \equiv \alpha_{\rm eff} - \alpha$

- triangle inequalities: $|\sin\theta| < \sqrt{\frac{\Gamma_{00}}{\Gamma_{+0}}}$ Grossman, Quinn

  $$\cos 2\theta \geq \frac{\left(\frac{1}{2}\Gamma_{+-}+\Gamma_{+0}-\Gamma_{00}\right)^2-\Gamma_{+-}\Gamma_{+0}}{\Gamma_{+-}\Gamma_{+0}\sqrt{1-C_{+-}^2}}$$ MG, London, Sinha[2]

  $$\Rightarrow |\alpha_{\rm eff} - \alpha| < 36^\circ$$

- $|P/T| \leq 1, |\delta| \leq 90^\circ$ checked exptly, removes sign ambig.

  $\alpha_{\rm eff} - \alpha > 0$ $\boxed{\alpha = (88 \pm 18)^\circ}$ MG, Lunghi, Wyler

  agrees with CKM bounds $\alpha = (99 \pm 12)^\circ$

- expect slow progress in $C_{\pi^0\pi^0} = -0.28 \pm 0.39$ for complete I-triangles. SU(3): $C_{\pi^0\pi^0} = -1.0 \pm 0.4$

- using SU(3) and $B \to K\pi$: $\alpha = (99 \pm 18)^\circ$
  SU(3) breaking in Penguin? MG, Rosner

$B \to \rho\rho$

- $B \to \rho\rho$ almost pure longitudinal $\to$ identical to $B \to \pi\pi$

$$f_L^{+-} = 0.98 \pm 0.01^{+0.02}_{-0.03} \qquad f_L^{+0} = 0.97^{+0.03}_{-0.07} \pm 0.04$$

- small $\mathcal{B}(\rho^0\rho^0) < 1.1 \times 10^{-6}$ $(90\%$ c.l.)

$$\mathcal{B}(\rho^+\rho^-) = (30 \pm 6) \times 10^{-6}, \qquad \mathcal{B}(\rho^0\rho^+) = (26 \pm 6) \times 10^{-6}$$

$\Rightarrow$ stronger bound on $|\alpha_{\text{eff}} - \alpha|$ than $B \to \pi\pi$

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

$$\Rightarrow \alpha_{\text{eff}} = (100 \pm 9)^\circ, \qquad |\alpha_{\text{eff}} - \alpha| < 11^\circ (1\sigma)$$

$\boxed{\alpha = (100 \pm 14)^\circ}$ can sign($\alpha_{\text{eff}} - \alpha$) be resolved?

- best single measurement, CKM bounds $\alpha = (99 \pm 12)^\circ$
$\mathcal{B}(\rho^0\rho^0) = (0.54 \pm 0.39) \times 10^{-6}$, expect slow progress

$B \to \rho\pi$

- Dalitz t-dependent analysis $B \to \pi^+\pi^-\pi^0$ Snyder, Quinn
- includes $\rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0$ with interference
- many (27) measurables depending on many (12) parameters including α
- statistics limited, Babar: $\alpha = (113^{+28}_{-17} \pm 6)^\circ$
- other resonances $\rho(1450), \rho(1700)$, S-wave $\pi\pi$?
- using quasi two-body $B \to \rho^\pm\pi^\mp$ related by SU(3) to $B \to K^*\pi,\ \rho K$: $\alpha = (94 \pm 16)^\circ$ MG, Zupan

Average α

Averaging $B \to \pi\pi, B \to \rho\rho$ using isospin alone

$$\alpha = (96 \pm 11)^\circ$$

Other CKM constraints ($V_{cb}, V_{ub}, \epsilon_K, \Delta m_{d,s}$)

$$\alpha = (99 \pm 12)^\circ$$

TOTAL AVERAGE

$$\alpha = (97 \pm 8)^\circ$$

including bounds from SU(3): $\delta\alpha = 6^\circ - 7^\circ$

CKMfitter: $(97.9^{+5.0}_{-6.4})^\circ$ UTFit: $(94.9 \pm 6.6)^\circ$

How precise are isospin methods for α?

- electroweak penguin amplitudes can be included

$$H_{\rm eff,EWP}^{\Delta I=3/2} \propto H_{\rm eff,Tree}^{\Delta I=3/2} \Rightarrow \quad \begin{array}{l} \alpha = \alpha_{\rm eff} - \theta - \delta_{\rm EWP} \\ \delta_{\rm EWP} = (1.5 \pm 0.4)^\circ \end{array}$$

Neubert, Rosner MG, Pirjol, Yan

- effect of π^0-η-η' mixing: $|\delta_{\pi-\eta-\eta'}| < 1.4^\circ$ MG, Zupan
- $\rho - \omega$ mixing important locally but small overall

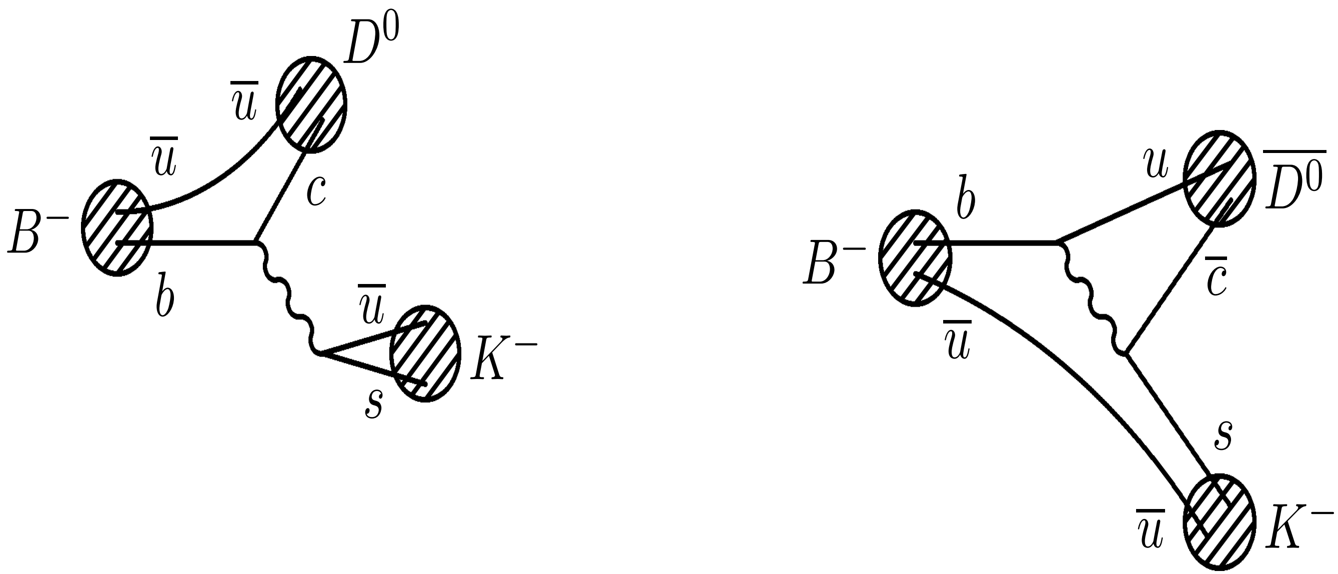
$$|\frac{A(B^+ \to \rho^+ \omega)}{A(B^+ \to \rho^+ \rho^0)}| = 0.69 \pm 0.14, \quad \frac{\Gamma_\omega}{\Gamma_\rho} = 0.06 \quad \Rightarrow \quad \text{overall} < 2\%$$

- $\Gamma_\rho \neq 0 \quad \Rightarrow \quad I = 1$ for two ρ mesons with different “mass"

effect $\sim \mathcal{O}(\frac{\Gamma_\rho^2}{m_\rho^2}) \sim 4\%$ Falk, Ligeti, Nir, Quinn

- last two effects can be constrained experimentally
- other isospin breaking $(\Delta I = 5/2) \leq 1\%$

γ in $B \to D^{(*)} K^{(*)}$



- measured γ by 2 interfering tree amps $\mathrm{MG, London, Wyler}$
- **every hadronic final state $D^0 \to f$ is accessible to $\bar{D}^0 \to f$**
- no uncertainty from penguin amplitude
- negligible theoretical uncertainty from $D^0 - \bar{D}^0$ mixing
- 2nd amp suppressed $r \sim 0.2$ combine f's for statistics

Several variants

- several variants for D, K: $B^- \to DK^-,\ D^*K^-,\ DK^{*-}$
- tagged and untagged neutral: $B^0 \to DK_S,\ D^*K_S,\ DK^{*0}$
- $D \to f:\ f = (K^+K^-)_{CP},\ \ (K^-\pi^+)_{\text{flavor}},\ \ K_S\pi^+\pi^-$

	GLW	ADS	GGSZ
$\frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)}$:	1	$\sim \lambda^2$	f(Dalitz)

- combine several modes for common B or D decays
- all three types of f's were studied, have a common factor

  in $B \to DK$ $\qquad \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = re^{i\delta}e^{-i\gamma}$
- ADS sets upper limit $r < 0.22\ (90\%\ \text{c.l.})$, measure r soon?
- GLW sensitive to r^2; Babar and Belle measure $R_\pm, \mathcal{A}_\pm$

$$R_\pm \equiv \frac{\mathcal{B}(D_{CP\pm}K)}{\mathcal{B}(D^0_{\text{Flavor}}K)} = 1 + r^2 \pm 2r\cos\delta\cos\gamma,\quad \mathcal{A}_\pm = \pm 2r\sin\delta\sin\gamma$$

3 observables fix r, δ, γ: need more statistics for determining γ

Babar $R_+^{K^*} = 1.77 \pm 0.39,\ R_-^{K^*} = 0.76 \pm 0.30$ Belle = ?

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

- $\mathcal{B}(D^0 \to K_S\pi^+\pi^-) = 3\%,\ \ \mathcal{O}(10^6)$ tagged; $\ m_\pm \equiv m(K_S\pi^\pm)$
- **amplitude** $CP:$ $\begin{array}{l} A(B^-) = f(m_-^2, m_+^2) + re^{i(\delta-\gamma)} f(m_+^2, m_-^2) \\ A(B^+) = f(m_+^2, m_-^2) + re^{i(\delta+\gamma)} f(m_-^2, m_+^2) \end{array}$
- model flavor-tagged $|f(m_+^2, m_-^2)|^2 = \mathbf{\Sigma_1^{17}}$ $\mathrm{(non)resonances}$
- fit $\Gamma[B^\pm \to (K_S\pi^+\pi^-)_D K^\pm]$ to r, δ, γ
- Babar ($B \to DK$ and $B \to D^*K$): $\ \gamma = (70 \pm 31^{+12}_{-10}\ {}^{+14}_{-11})^\circ$
- Belle ($B \to DK$ and $B \to D^*K$): $\ \gamma = (68^{+14}_{-15} \pm 13 \pm 11)^\circ$
- however, Belle DK^*: $\gamma = (112 \pm 35 \pm 9 \pm 11 \pm 8)^\circ$
- last errors from modeling $\mathbf{\Sigma}$ $\mathrm{(non)resonances} \sim 10^\circ$ may be reduced by CLEO-c
- 2-body $D \to f$ are theoretically clean, but low in statistics

Intermediate summary

$\alpha,\ \beta,\ \gamma$ from CP asymmetries agree with $V_{cb}, V_{ub}, \epsilon_K, \Delta m_{d,s}$

$$B \to J/\psi K_S : \quad \beta = (23.3 \pm 1.5)^\circ$$

$$B \to \pi\pi,\ \rho\rho : \quad \alpha = (96 \pm 11)^\circ$$

$$B \to DK : \quad \gamma = (68 \pm 22)^\circ$$

$\alpha + \beta + \gamma = (187 \pm 25)^\circ$ has 180° any significance?

* unaffected by New Physics in B^0-$\bar{B}^0$ mixing, and by NP in $\Delta I = \frac{1}{2}\ \ b \to d\bar{q}q$ which is eliminated by Isospin analysis
* affected by NP in ΔI=$\frac{3}{2}\ \ b \to d\bar{q}q$, may also be observed in nonzero $A_{CP}^{\pi^+\pi^0} = -0.02 \pm 0.07,\ A_{CP}^{\rho^+\rho^0} = -0.09 \pm 0.16$, and by NP in “tree” $b \to u\bar{c}s$ (unlikely but not impossible)

ONE SLIDE

INTERMEZZO

Direct CP asymmetries in $B \to K\pi$

- two direct CP asymmetries measured $\neq 0$:

  $A_{CP}^{\pi^+\pi^-} = +0.37 \pm 0.10 \qquad A_{CP}^{K^+\pi^-} = -0.109 \pm 0.019$

- $A(\pi^+\pi^-) = T + P \qquad A(K^+\pi^-) = \bar{\lambda} T - \bar{\lambda}^{-1} P \qquad \bar{\lambda} \equiv \frac{V_{us}}{V_{ud}}$

  $\Rightarrow \frac{A_{CP}^{\pi^+\pi^-}}{A_{CP}^{K^+\pi^-}} = -\frac{\mathcal{B}(K^+\pi^-)}{\mathcal{B}(\pi^+\pi^-)} \qquad - 3.4 \pm 1.1 = -4.0 \pm 0.4$

- success of flavor SU(3) (1994, improved by f_K/f_π)
- $A_{CP}^{K^+\pi^-} \propto \sin(\text{strong phase})$: failure of QCD-factorization
- $A_{CP}^{K^+\pi^0} = 0.04 \pm 0.04 \neq A_{CP}^{K^+\pi^-}$ puzzle?
- $A_{CP}^{K^+\pi^-} \approx A_{CP}^{K^+\pi^0} + A_{CP}^{K^0\pi^0}$ MG, Rosner

  predict $A_{CP}^{K^0\pi^0} = -0.13 \pm 0.04$ (currently -0.08 ± 0.14)

CP ASYMMETRIES

IN $b \longrightarrow s$ PENGUINS:

NEW PHYSICS IN LOOPS?

The problem of $-\eta_f S_f \neq \sin 2\beta$?

- $b \to s$ penguin-dominated decays $B^0 \to f$: $f = \pi^0 K_S$, $\eta' K_S,\ \phi K_S,\ f_0 K_S,\ \rho^0 K_S,\ \omega K_S,\ K^+K^-K_S,\ K_S K_S K_S$
- $V_{tb}^* V_{ts}$ dominates: $C_f = 0, \quad -\eta_f S_f = \sin 2\beta = 0.73 \pm 0.04$

  $\text{Asymmetry}(t) = -C_f \cos \Delta m t + S_f \sin \Delta m t$

-

f:	$\pi^0 K_S$	$\eta' K_S$	ϕK_S	average
$-\eta_f S_f$:	$0.34^{+0.27}_{-0.29}$	0.43 ± 0.17	0.35 ± 0.21	0.39 ± 0.12

$-\eta_f S_f$ is consistently smaller than $\sin 2\beta$: New Physics?

- what are the effects of $V_{ub}^* V_{us}$ terms?
- can one predict the sign of $-\eta_f S_f - \sin 2\beta$?

Two approaches:

- Flavor SU(3): $\text{MG, Hernandez, London, Rosner}$
  may involve 30% corrections to $-\eta_f S_f - \sin 2\beta$
- QCD-factorization: $\text{Beneke, Buchalla, Neubert, Sachrajda}$
  how large are corrections to calculated $-\eta_f S_f - \sin 2\beta$?

  expand amplitudes and strong phases in $1/m_b$ and α_s

  large $1/m_b$ corrections? how reliable are strong phase calculations? long distance final state interactions?

  talk by Dan Pirjol

Conclusions are similar

Effect of $V_{ub}^* V_{us}$ terms

$$A(B^0 \to f) = |V_{cb}^* V_{cs} P_f| + |V_{ub}^* V_{us} C_f| e^{i\delta_f} e^{i\gamma} \qquad \xi_f \equiv \frac{|V_{ub}^* V_{us} C_f|}{|V_{cb}^* V_{cs} P_f|}$$

$$\Delta S_f \equiv -\eta_f S_f - \sin 2\beta \approx +2\xi_f \cos 2\beta \sin\gamma \cos\delta_f$$

eliminate δ_f $\downarrow$ $\qquad C_f \approx 2\xi_f \sin\gamma \sin\delta_f$

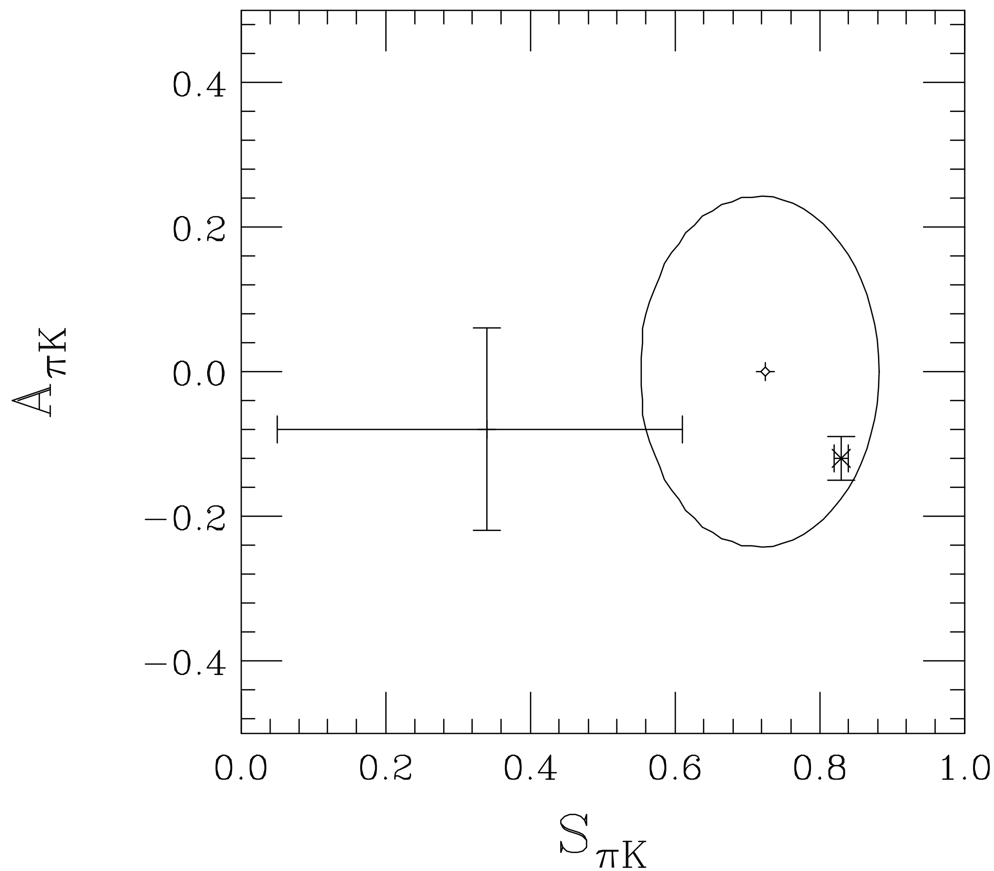
$$(S_f, C_f) \text{ ellipse}: \quad (\Delta S_f)^2 / \cos^2 2\beta + C_f^2 = 4\xi_f^2 \sin^2\gamma$$

- ξ_f determines axes of ellipse
- $V_{ub}^* V_{us}$ term - related by SU(3) to $V_{ub}^* V_{ud}$ term in $\Delta S = 0$
  $\Rightarrow$ measured $\Delta S = 0$ rates set upper bounds on ξ_f
- $\text{sign}(\Delta S_f) = \text{sign}(\cos\delta_f)$; likely $|\delta_f| < 90^\circ \Rightarrow \Delta S_f > 0$

next two figures from MG, Rosner, Grossman, Zupan

Bounds on $(S, A \equiv -C)$ in $B \to \pi^0 K_S$

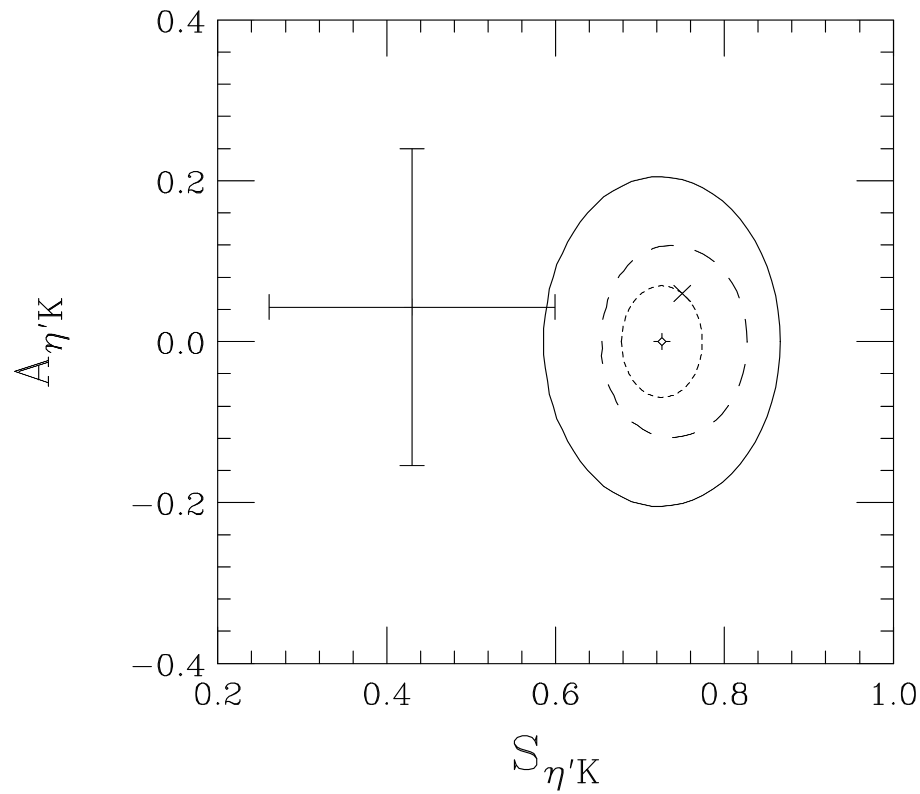
SU(3) related decays: $B \to \pi^0\pi^0, K^+K^-$



x SU(3) fit: $\Delta S = +0.10 \pm 0.02, \quad A = -0.12 \pm 0.03$

Bounds on (S, A) in $B \to \eta' K_S$

SU(3) related decays: $B \to \pi^0\pi^0,\ \pi^0\eta,\ \pi^0\eta',\ \eta\eta,\ \eta\eta',\ \eta'\eta'$



solid: flavor SU(3)
x: SU(3) fit

dashed: neglecting annihilation
dotted: vary δ_f

* $B \to \phi K_S$: no useful bound from SU(3), no limit $\mathcal{B}(K^{*0}\bar{K}^0)$
* $|\Delta S_{\phi K}|, |A_{\phi K}| < 2|\frac{V_{ub}^* V_{us}}{V_{cb}^* V_{cs}}| \simeq 0.05; \quad |\delta_f| < 90^\circ \Rightarrow \Delta S > 0$
* **test in B_s decays** $|S(B_s \to \phi\phi)| < 0.05$ **requires t-dependence**

Intermediate summary $(\eta_f = -1)$

mode	$\Delta S \equiv S - \sin 2\beta$	bound on $\lvert\Delta S\rvert$	likely $\mathrm{sign}\Delta S$
$\pi^0 K_S$	$-0.39^{+0.27}_{-0.29}$	0.15	+
$\eta' K_S$	-0.30 ± 0.17	0.05	+
ϕK_S	-0.38 ± 0.21	0.05	+
average	-0.34 ± 0.12	$\simeq 0.05 - 0.10$	+

seems like a problem; await error reduction by factor 2

Conclusions: methods for α/γ proposed 15 years ago

- α from $B \to \pi\pi,\ \rho\rho,\ \rho\pi$ agree with each other and with other CKM constraints, improves precision to $\delta\alpha = \pm 8^\circ$
- γ from $B \to DK$ agrees with CKM constraints, still statistically limited, $\delta\gamma = \pm 22^\circ$
- $A_{CP}^{K^+\pi^-}$ is incalculable; predict $A_{CP}^{K^0\pi^0} = -0.13 \pm 0.04$
- anomalies in several $b \to s$ asymmetries, $< 2\sigma$ in each, but $> 3\sigma$ (or even $> 4\sigma$?) when combined

KM phase is the dominant source of CP violation

are we seeing first signals of New Physics in $b \to s$?

great progress since B03-Pitt, awaiting B06-Oxford, Sep 2006

question at Beauty06: what's the source of New Physics?