Constraints on γ and Strong Phases from $B \to \pi K$ Decays

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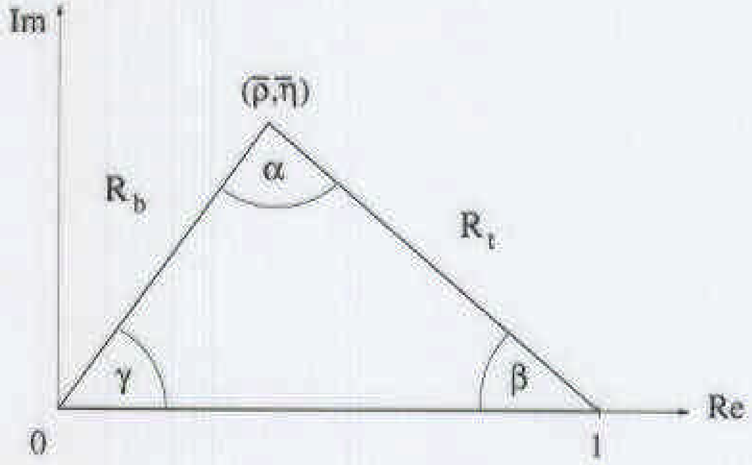
- Introduction
- Probing γ with $B \to \pi K$ Decays:
  - "mixed": $B^{\pm} \to \pi^{\pm} K$, $B_d \to \pi^{\mp} K^{\pm}$
  - charged: $B^{\pm} \to \pi^{\pm} K$, $B^{\pm} \to \pi^{0} K^{\pm}$
  - neutral: $B_d \to \pi^{0} K$, $B_d \to \pi^{\mp} K^{\pm}$.
- Constraints on Strong Phases
- Conclusions and Outlook

[A. Buras & R.F., hep-ph/0003323, to appear in *Eur. Phys. J.* **C**]

Introduction

- To obtain direct information on γ in an experimentally feasible way, $B \to \pi K$ decays appear very promising:



- Experimental history:
  - CLEO '97–'00: CP-averaged $\langle \mathrm{BR} \rangle$s $= \mathcal{O}(10^{-5})$.
  - CLEO '99: first preliminary results on CP asymmetries.
  - Experimental uncertainties are still very large ...

Mode	$\langle \mathrm{BR} \rangle / 10^{-6}$	$\mathcal{A}_{\mathrm{CP}} / 10^{-2}$
$B_d \to \pi^{\mp} K^{\pm}$	$17.2^{+2.5}_{-2.4} \pm 1.2$	0.04 ± 0.16
$B^{\pm} \to \pi^0 K^{\pm}$	$11.6^{+3.0+1.4}_{-2.7-1.3}$	0.29 ± 0.23
$B^{\pm} \to \pi^{\pm} K$	$18.2^{+4.6}_{-4.0} \pm 1.6$	-0.18 ± 0.24
$B_d \to \pi^0 K$	$14.6^{+5.9+2.4}_{-5.1-3.3}$	?

[CLEO Collaboration, hep-ex/0001009 and hep-ex/0001010]

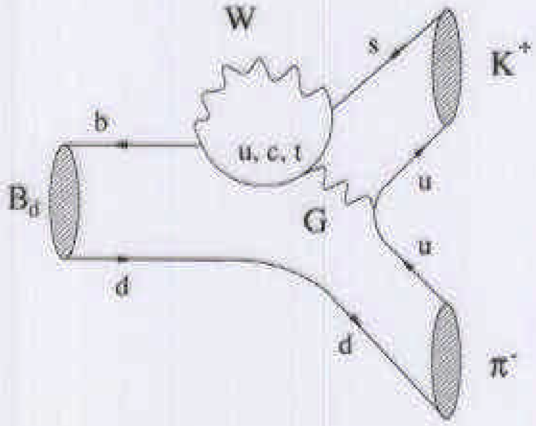
Japanese conventions

ϕ_2

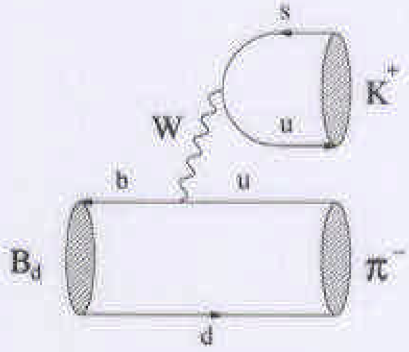
ϕ_3 ϕ_4

- $B \to \pi K$ decays are governed by QCD penguins:

  - Example: $B_d^0 \to \pi^- K^+$



"penguins"



"tree"

  - $|V_{us}V_{ub}^*/(V_{ts}V_{tb}^*)| \approx 0.02 \quad \Rightarrow$ penguins dominate!

- The role of EW penguins (large top-quark mass!):

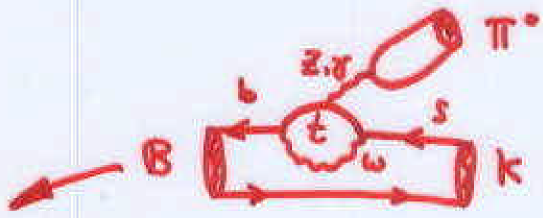
  - $B_d^0 \to \pi^- K^+$, $B^+ \to \pi^+ K^0$:

    contribute in colour-suppressed form and are expected to play a minor role: "factorization" $\to \mathcal{O}(1\%)$.

  - $B^+ \to \pi^0 K^+$, $B_d^0 \to \pi^0 K^0$:

    contribute also in colour-allowed form and may compete with tree-diagram-like topologies!


B
b
W
s
K
t
Z,γ
π


π°
Z,γ
b
s
t
W
B
K

- Important $SU(2)$ isospin relation:

$$\sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0)$$

$$= \sqrt{2}A(B^0_d \to \pi^0 K^0) + A(B^0_d \to \pi^- K^+)$$

$$= -[(T+C) + P_{\rm ew}] \propto \left[e^{i\gamma} + q_{\rm ew}\right].$$

  - Amplitude relation with analogous phase structure also for the "mixed" $B^+ \to \pi^+ K^0$, $B^0_d \to \pi^- K^+$ system.

- Combinations of $B \to \pi K$ decays to probe γ:

  - $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$ ("mixed")

    [R.F. ('95); R.F. & Mannel ('97); Gronau & Rosner ('98)]

  - $B^\pm \to \pi^\pm K$, $B^\pm \to \pi^0 K^\pm$ ("charged")

    [Gronau, Rosner, London ('94); Neubert, Rosner; Buras, R.F. ('98)]

  - $B_d \to \pi^0 K$, $B_d \to \pi^\mp K^\pm$ ("neutral")

    [Buras & R.F. ('98–'00)]

- Interestingly, already CP-averaged branching ratios may lead to highly non-trivial constraints on γ.

[R.F. and T. Mannel, *Phys. Rev.* **D57** (1998) 2752; M. Neubert and J.L. Rosner, *Phys. Lett.* **B441** (1998) 403]

Probing γ with $B \to \pi K$ Decays

- The key quantities:

$$R \equiv \frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\overline{B_d^0} \to \pi^+ K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \overline{K^0})} = 0.95 \pm 0.28$$

$$R_{\rm c} \equiv 2 \left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+) + \mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \overline{K^0})}\right] = 1.27 \pm 0.47$$

$$R_{\rm n} \equiv \frac{1}{2} \left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\overline{B_d^0} \to \pi^+ K^-)}{\mathrm{BR}(B_d^0 \to \pi^0 K^0) + \mathrm{BR}(\overline{B_d^0} \to \pi^0 \overline{K^0})}\right] = 0.59 \pm 0.27.$$

- Employing the $SU(2)$ flavour symmetry and dynamical assumptions, concerning mainly the smallness of FSI:

$$\boxed{R_{\rm (c,n)} = R_{\rm (c,n)}\left(\gamma, q_{\rm (c,n)}, r_{\rm (c,n)}, \delta_{\rm (c,n)}\right).}$$

- Here the following variables are involved:
  - $q_{\rm (c,n)}$: ratio of EW penguins to "trees".
  - $r_{\rm (c,n)}$: ratio of "trees" to QCD penguins.
  - $\delta_{\rm (c,n)}$: strong phase between "trees" and QCD penguins.

[A. Buras & R.F., *Eur. Phys. J.* **C11** (1999) 93]

- The $q_{(\mathrm{c,n})}$ can be fixed through theoretical arguments:

  - $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$: $q \approx 0$, as EW penguins contribute only in colour-suppressed form.

  - $B^\pm \to \pi^\pm K$, $B^\pm \to \pi^0 K^\pm$: $q_c \approx 0.63$ can be fixed through the $SU(3)$ flavour symmetry (no dynamics !).
    [M. Neubert and J. Rosner, *Phys. Lett.* **B441** (1998) 403]

  - $B_d \to \pi^0 K$, $B_d \to \pi^\mp K^\pm$: $q_\mathrm{n} \approx 0.63$ can also be fixed through the $SU(3)$ flavour symmetry.
    [A. Buras & R.F., *Eur. Phys. J.* **C11** (1999) 93]

- The $r_{(\mathrm{c,n})}$ can be fixed through experimental information:

  - $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$: $r \approx 0.18$ can be fixed using factorization, ($B_d \to \pi l \nu_l$ helps); $B_s \to \pi K$.
    [R.F. ('95); Gronau and Rosner ('98,'00)]

  - $B^\pm \to \pi^\pm K$, $B^\pm \to \pi^0 K^\pm$: $r_c \approx 0.21$ can be fixed from the $B^+ \to \pi^+\pi^0$ branching ratio by using the $SU(3)$ flavour symmetry (no dynamics !).
    [Gronau, Rosner and London, *Phys. Rev. Lett.* **73** (1994) 21]

  - $B_d \to \pi^0 K$, $B_d \to \pi^\mp K^\pm$: $r_\mathrm{n} \approx 0.17$ can also be fixed through $SU(3)$ from $B^+ \to \pi^+\pi^0$.
    [A. Buras & R.F., *Eur. Phys. J.* **C11** (1999) 93]

- <u>Comments on FSI effects:</u>

  - Whereas the determination of q and r as sketched above may be affected by FSI effects, this is <u>not</u> the case for $q_{\rm c,n}$ and $r_{\rm c,n}$, since here $SU(3)$ suffices.

  - Nevertheless, we have to assume that $B^+ \to \pi^+ K^0$ or $B_d \to \pi^0 K$ do <u>not</u> involve a CP-violating weak phase:

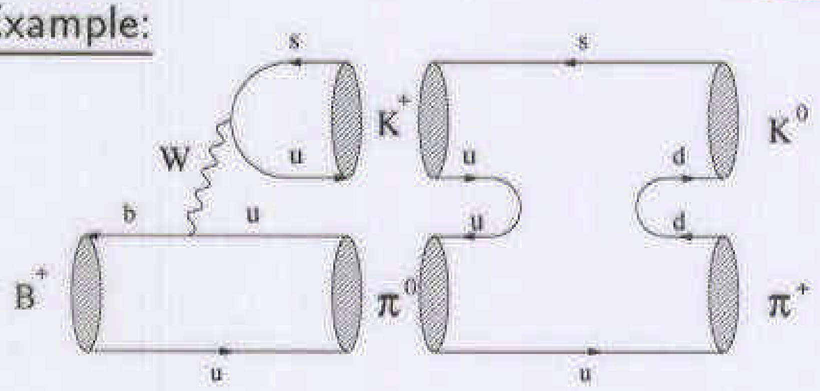
$$A(B^+ \to \pi^+ K^0) = -|\tilde{P}|e^{i\delta_{\tilde{P}}} = A(B^- \to \pi^- \overline{K^0}).$$

  - <u>This relation may be affected by rescattering processes:</u>

$$A(B^+ \to \pi^+ K^0) = -|\tilde{P}|e^{i\delta_{\tilde{P}}}\left[1 + \rho\, e^{i\theta} e^{i\gamma}\right].$$

$\lesssim \lambda^2 R_b \approx 0.02$

    * <u>Example:</u>



  - Can be taken into account through additional input, e.g. $SU(3)$ and data on $B^\pm \to K^\pm K$. In the case of the <u>neutral strategy,</u> FSI effects can be included in an <u>exact manner</u> with the help of $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^0 K_{\rm S})$.

Back to the Constraints on γ ...

- Central quantity:

$$R_{(c,n)}\left(\gamma, q_{(c,n)}, r_{(c,n)}, \delta_{(c,n)}\right).$$

- The strong phase $\delta_{(c,n)}$ suffers from large hadronic uncertainties and is essentially unknown!!

- However, we can get rid of $\delta_{(c,n)}$ by keeping it as a "free" variable, yielding minimal and maximal values for $R_{(c,n)}$:

$$R^{ext}_{(c,n)}\Big|_{\delta_{(c,n)}} = \text{complicated expression}\left(\gamma, q_{(c,n)}, r_{(c,n)}\right)$$

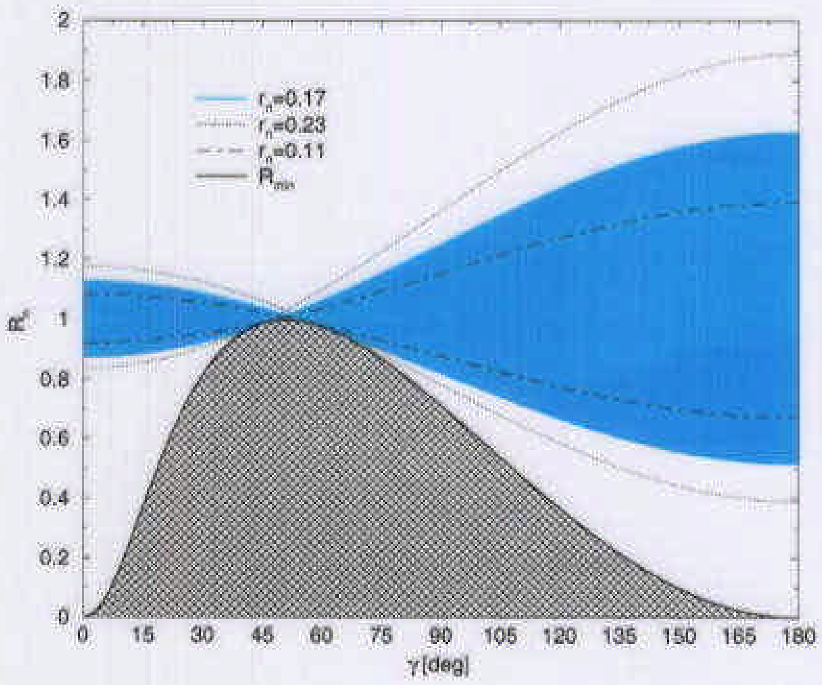
- Keeping in addition $r_{(c,n)}$ as a "free" variable, we obtain another – less restrictive – minimal value for $R_{(c,n)}$:

$$R^{min}_{(c,n)}\Big|_{r_{(c,n)},\delta_{(c,n)}} = \kappa(\gamma, q_{(c,n)})\sin^2\gamma\,.$$

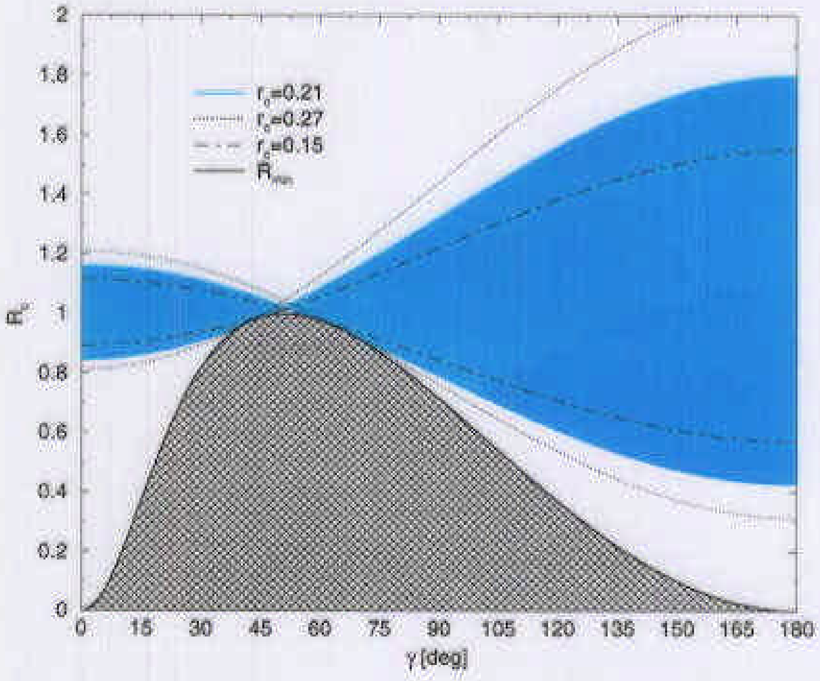
- These extremal values of $R_{(c,n)}$ imply constraints on γ, as the following cases are excluded:

$$\boxed{R^{exp}_{(c,n)} < R^{min}_{(c,n)}, \quad R^{exp}_{(c,n)} > R^{max}_{(c,n)}.}$$

- The dependence of the extremal values of $R_{\rm n}$ (neutral $B \to \pi K$ system) on γ for $q_{\rm n} = 0.63$:



- The dependence of the extremal values of $R_{\rm c}$ (charged $B \to \pi K$ system) on γ for $q_{\rm c} = 0.63$:



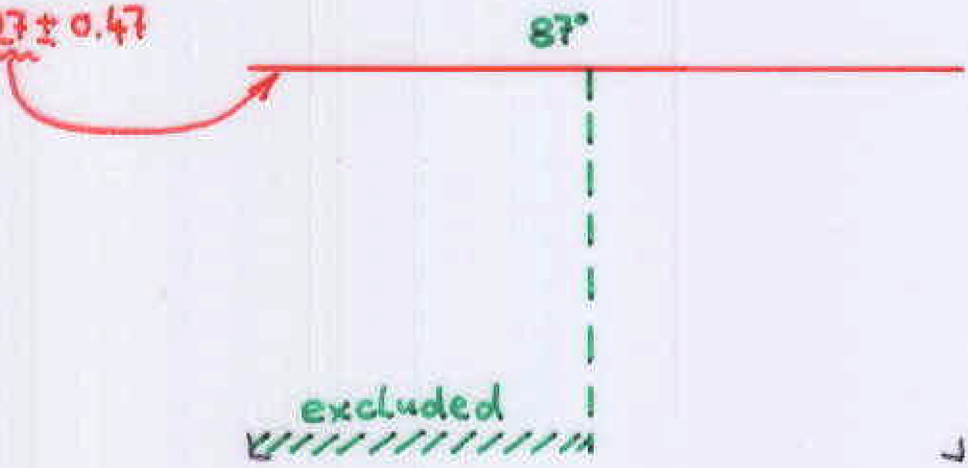
[A. Buras & R.F., hep-ph/0003323, to appear in *Eur. Phys. J.* **C**]

CLEO '00:

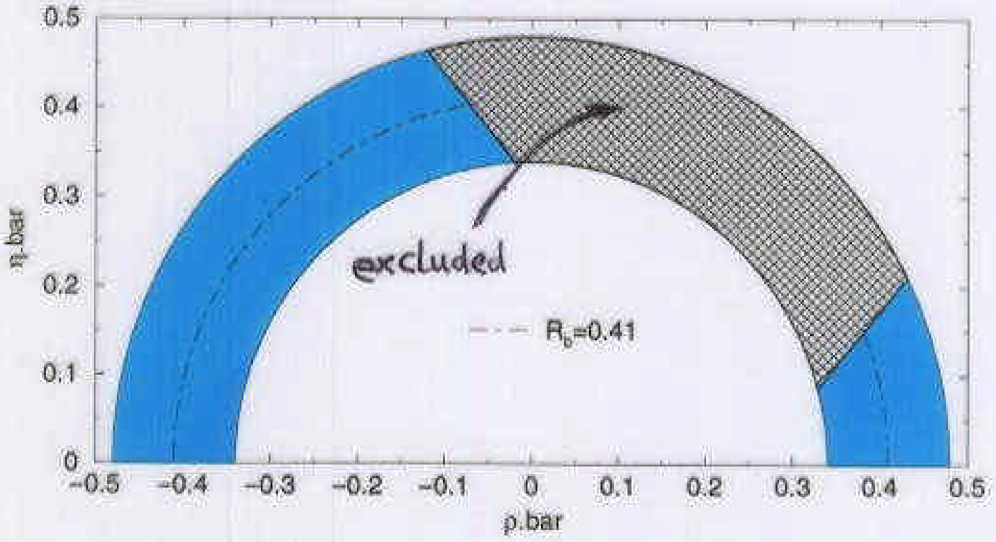
$R_m = 0.59 \pm 0.27$

CLEO '00:

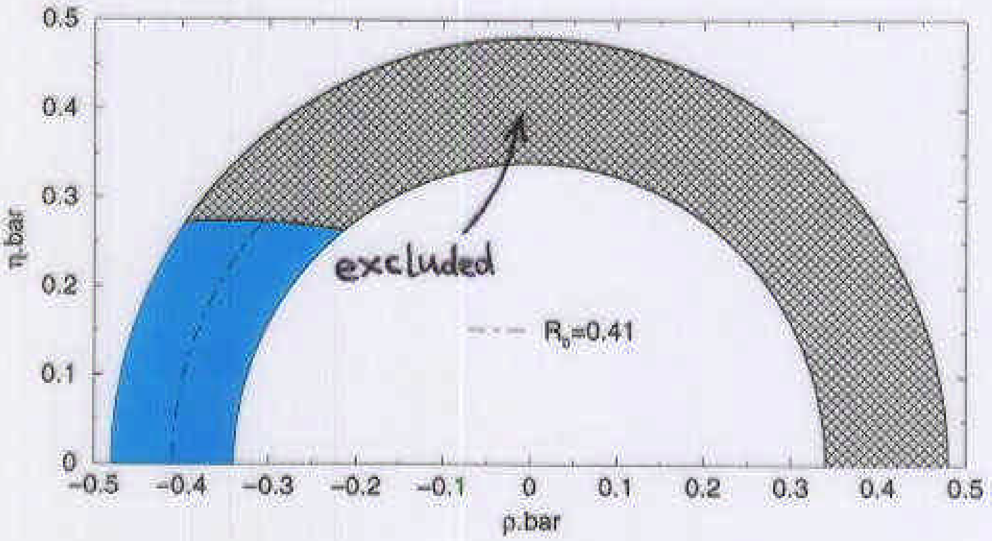
$R_c = 1.27 \pm 0.47$



- Constraints in the $\overline{\varrho}$–$\overline{\eta}$ plane implied by $R_{\rm n}^{\rm min}|_{r_{\rm n},\delta_{\rm n}}$ for $R_{\rm n} = 0.6$ and $q_{\rm n} = 0.63 \times [0.41/R_b]$:



- Constraints in the $\overline{\varrho}$–$\overline{\eta}$ plane implied by $R_{\rm n}^{\rm ext}|_{\delta_{\rm n}}$ for $R_{\rm n} = 0.6$, $r_{\rm n} = 0.17$ and $q_{\rm n} = 0.63 \times [0.41/R_b]$:



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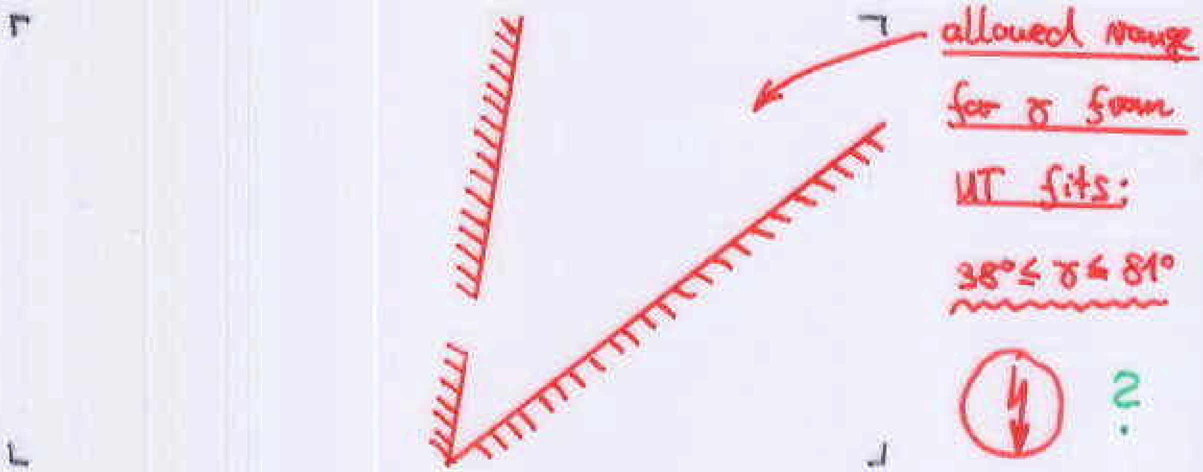
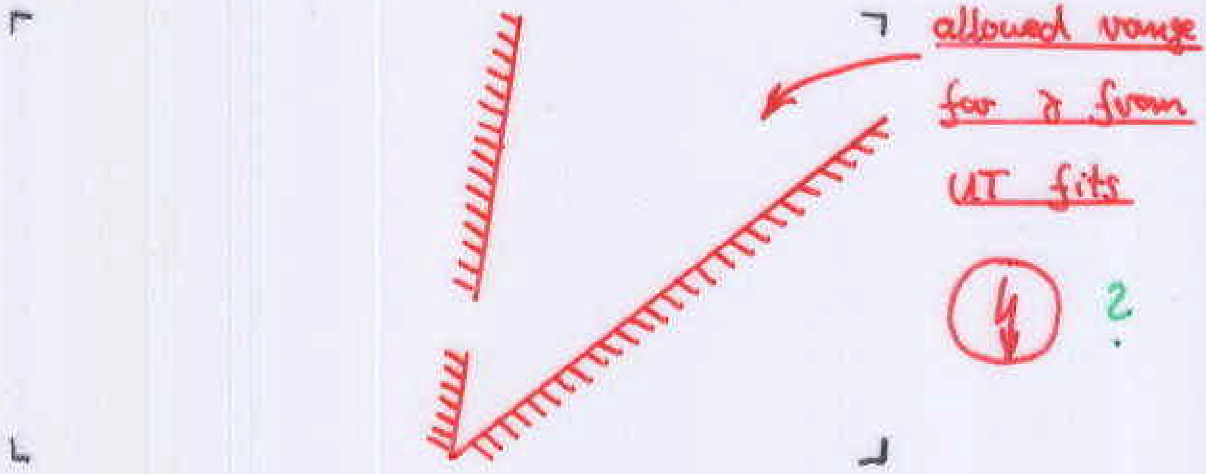

allowed range
for γ from
UT fits:
38° ≤ γ ≤ 81°
?


allowed range
for γ from
UT fits
?

Constraints on Strong Phases

- The observables $R_{(c,n)}$ allow us to determine $\cos\delta_{(c,n)}$ as a function of γ, thereby providing also constraints on these CP-conserving strong phases:

$$\cos\delta_{(c,n)} = \text{function}\left(\gamma, R_{(c,n)}, q_{(c,n)}, r_{(c,n)}\right).$$

- The CLEO data reported in January 2000 are in favour of $\cos\delta_c > 0$ and $\cos\delta_n < 0$.

- Such a pattern would be in conflict with the theoretical expectation of equal signs for $\cos\delta_c$ and $\cos\delta_n$!

- If future data should confirm this "puzzle", it may be an indication for one of the following features:

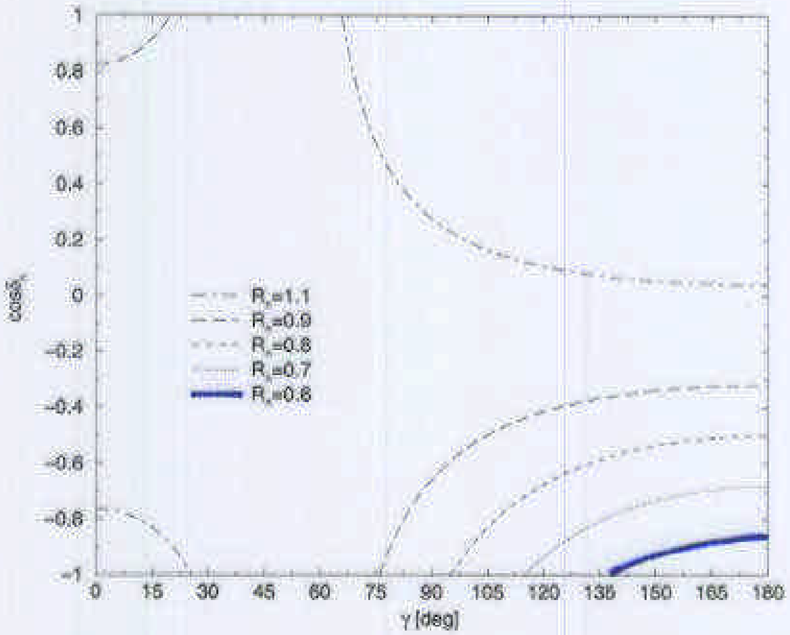
  - New-physics contributions to the EW penguin sector.

  - Large non-factorizable $SU(3)$-breaking effects, affecting the determination of the EW penguin parameters $q_{c,n}$.

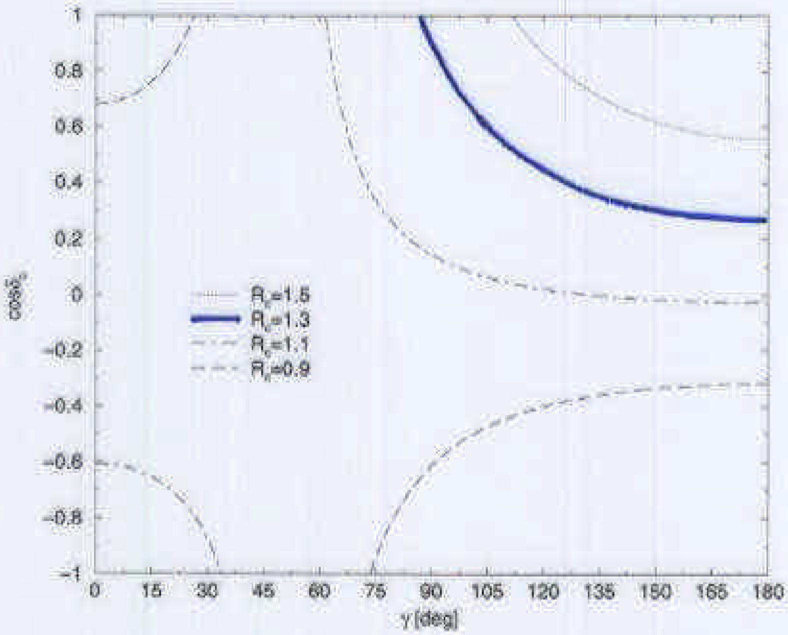
- In order to distinguish between these possibilties, detailed studies of the various patterns of new-physics effects in all $B \to \pi K$ decays are essential, as well as critical analyses of possible sources for $SU(3)$ breaking.

[A. Buras & R.F., hep-ph/0003323, to appear in *Eur. Phys. J.* C]

- Dependence of $\cos\delta_{\rm n}$ on γ for various values of $R_{\rm n}$ in the case of $q_{\rm n} = 0.63$ and $r_{\rm n} = 0.17$:



- Dependence of $\cos\delta_{\rm c}$ on γ for various values of $R_{\rm c}$ in the case of $q_{\rm c} = 0.63$ and $r_{\rm c} = 0.21$:



[A. Buras & R.F., hep-ph/0003323, to appear in *Eur. Phys. J.* C]

Conclusions and Outlook

- The CLEO'00 results for $R_{(\mathrm{c,n})}$ reported last January are in favour of strong constraints on γ, where the second quadrant is preferred [similar conclusions also from other $B \to \pi K$, $\pi\pi$ strategies (Hou et al., ...)]:
  - Such a situation would be in conflict with the standard analysis of the unitarity triangle!

- The observables $R_{(\mathrm{c,n})}$ imply also constraints on $\delta_{(\mathrm{c,n})}$, where CLEO'00 is in favour of $\cos\delta_{\mathrm{c}} > 0$ and $\cos\delta_{\mathrm{n}} < 0$:
  - Such a pattern would be in conflict with the theoretical expectation of equal signs for $\cos\delta_{\mathrm{c}}$ and $\cos\delta_{\mathrm{n}}$!

- Further theoretical studies and better data are required before we can speculate on new physics.

- As soon as CP asymmetries $A_{\mathrm{CP}}^{(\mathrm{c,n})}$ in $B_d \to \pi^{\mp}K^{\pm}$ or $B^{\pm} \to \pi^0 K^{\pm}$ are observed, we may extract γ and $\delta_{(\mathrm{c,n})}$:

$$A_{\mathrm{CP}}^{(\mathrm{c,n})} = A_{\mathrm{CP}}^{(\mathrm{c,n})}\left(\gamma, q_{(\mathrm{c,n})}, r_{(\mathrm{c,n})}, \delta_{(\mathrm{c,n})}\right).$$

- Interesting playground for theorists and the B-factories!