b PHYSICS
THEORETICAL ISSUES

J. Rosner LHC 2003 Symp. 5/3/03

Examples of current questions

Others may be timely in LHC era

Collabs.: T. Andre, C.-W. Chiang, M. Gronau, Z. Luo, D. Suprun

CKM matrix: unitarity, parameters

$B^0 \to$ CP eigenstates

$J/\psi K_S$, $\pi^+\pi^-$, ϕK_S, $\eta' K$

Direct CP asymmetries

$B \to K\pi$, $\eta\pi$

$B \to X_s \gamma$, $X_s \ell^+\ell^-$

Sample of B_s issues

Mixing & $B_s \to \mu^+\mu^-$

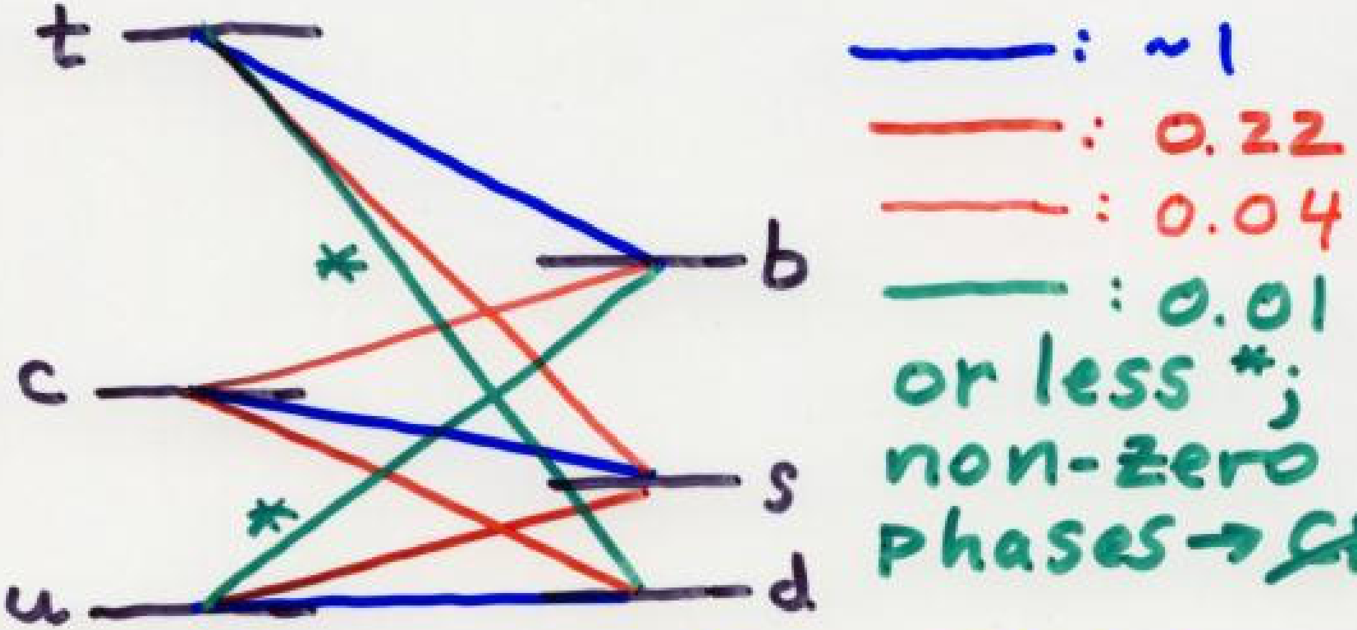
$J/\psi\, \phi$, $J/\psi\, \eta$ (expect $\cancel{CP}$ small)

2-body hadronic decays

Excited states ($\bar{B}K$ molecule?)

Heavier $Q = -1/3$ quarks

WEAK QUARK TRANSITIONS



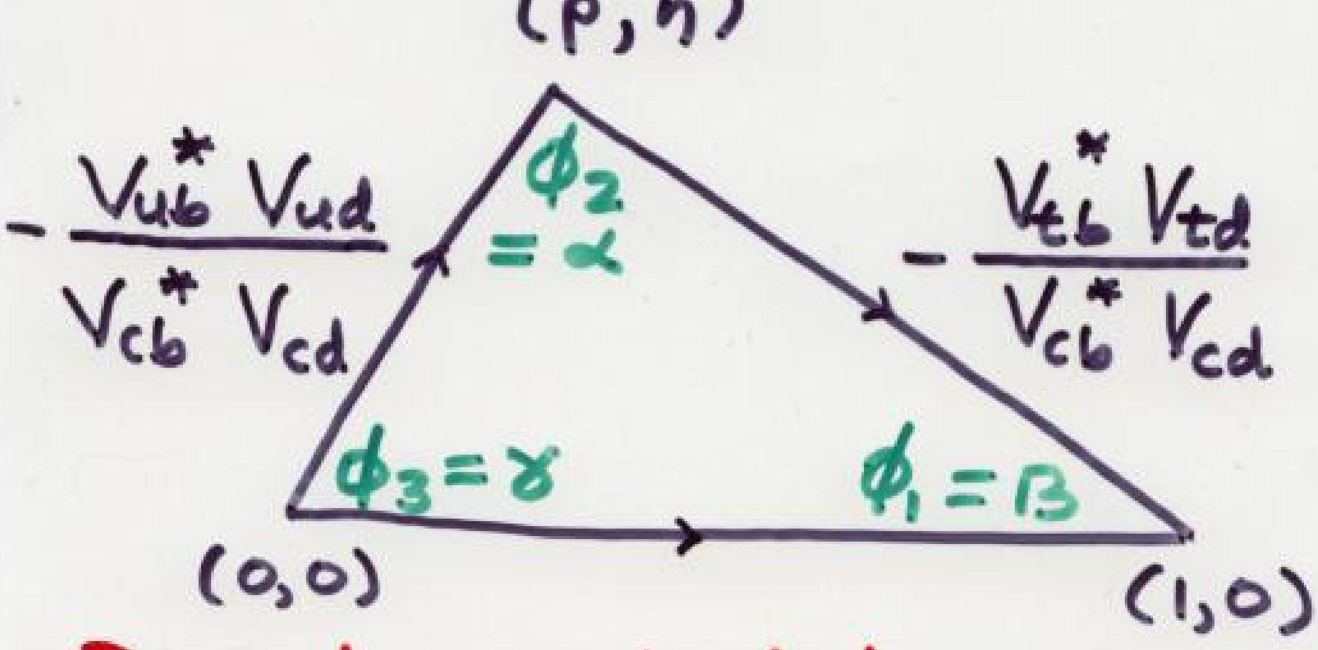
Encoded in 3x3 unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix V:

$$
V = \begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad d \quad & \quad s \quad & \quad b \quad \end{array} \\
\begin{bmatrix}
1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1
\end{bmatrix}
\end{array}
$$

$$\bar{\rho} \equiv \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\eta} \equiv \eta\left(1-\frac{\lambda^2}{2}\right)$$

THE UNITARITY TRIANGLE

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



Direct constraints:

$V_{us} \simeq 0.22$ strange decays

$V_{cb} \simeq 0.041$ $b \to c$ decays

$|V_{ub}/V_{cb}| \simeq 0.08 - 0.10$ $b \to u$ decays

Indirect constraints:

CP-violating $K - \bar{K}$ mixing $\sim \mathrm{Im} V_{td}^2$

$B^0 - \bar{B}^0$ mixing $\Rightarrow |V_{td}| \Rightarrow |1 - \bar{\rho} - i\bar{\eta}|$

$B_s^0 - \bar{B}_s^0$ mixing $\Rightarrow |V_{ts}/V_{td}| > 4.4$

$\Rightarrow$ $\bar{\rho} \simeq 0$ to 0.4
$\bar{\eta} \simeq 1/4$ to $1/2$ (roughly)

ANGLES FROM CP VIOLATION IN B^0 DECAYS TO CP EIGENSTATES

Mixing phase $= 2\phi_1$

$$\begin{tikzcd} B^0 \arrow[rr, "A"] \arrow[dr] & & f \\ & \bar{B}^0 \arrow[ur, "\bar{A}"'] & \end{tikzcd}$$

Interference between decay and mixing

$$\mathcal{A} = \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to f)}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to f)} = \text{rate asymmetry}$$

$$\Gamma\left(\begin{matrix} B^0(t) \\ \bar{B}^0 \end{matrix} \to f\right) \sim e^{-\Gamma t}\left[1 \mp \mathcal{A}_f \cos \Delta m t \mp S_f \sin \Delta m t\right]$$

$$\mathcal{A}_f \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}; \quad S_f \equiv \frac{2 \,\mathrm{Im}\, \lambda}{|\lambda|^2 + 1}; \quad \lambda \equiv e^{-2i\phi_1} \frac{\bar{A}}{A}$$

Note $|S_f|^2 + |A_f|^2 \leq 1$

$B \to J/\psi K_S$: $\bar{A}/A \simeq 1$, $\mathcal{A} \sim \sin(2\phi_1)$

$B \to \pi^+\pi^-$: $A = -(|T| e^{i\phi_3} + |P| e^{i\delta})$

$\bar{A} = -(|T| e^{-i\phi_3} + |P| e^{i\delta})$

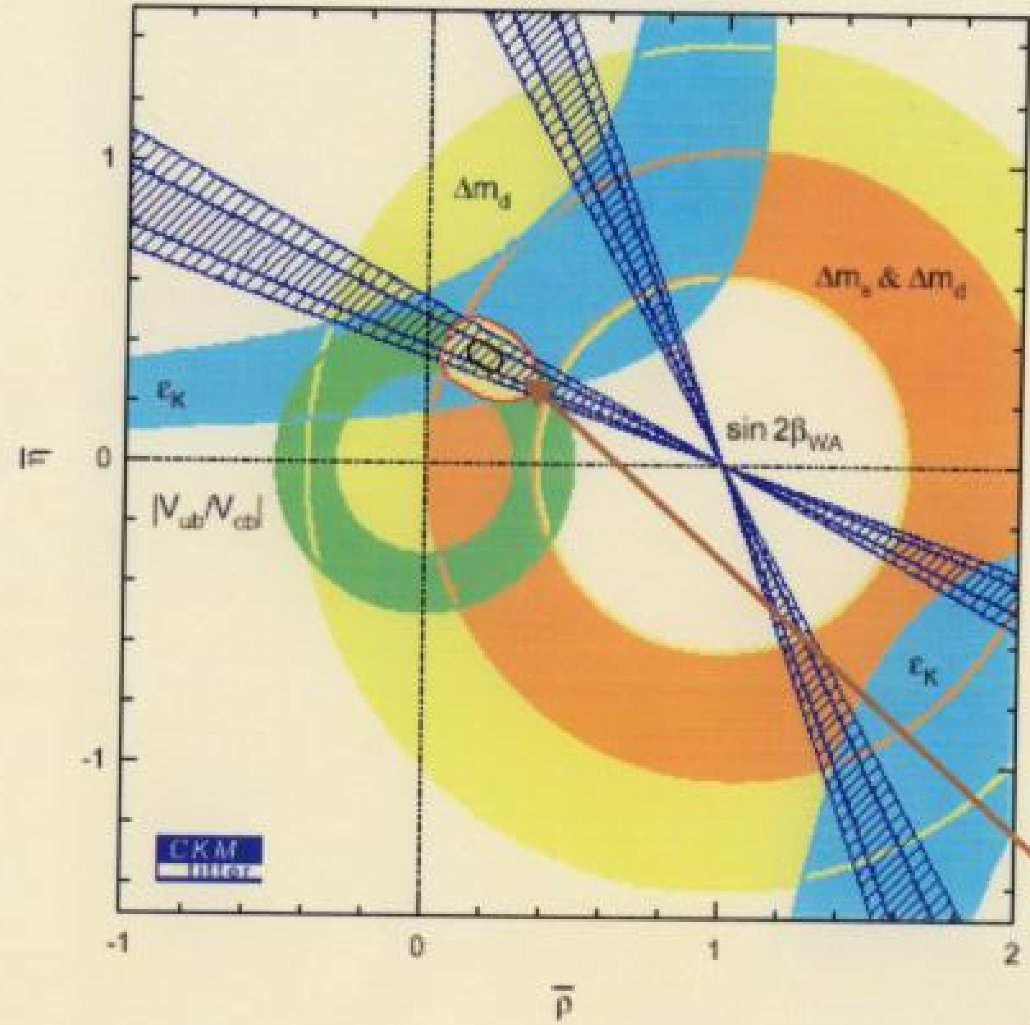
"tree" "penguin"

$\delta =$ relative P/T strong phase

$\mathcal{A} \sim \sin(2\phi_2)$ if P/T neglected

THANKS TO S. OLSEN

Belle & BaBar agree



Agree on value, not name!!

$\sin 2\phi_1$ (BaBar)

$=0.741\pm0.067\pm0.033$

$\sin 2\phi_1$ (Belle)

$=0.719\pm0.074\pm0.035$

$\sin 2\phi_1$ (World Av.)

$=0.734\pm0.055$

Agrees with SM

theory errors ~1%

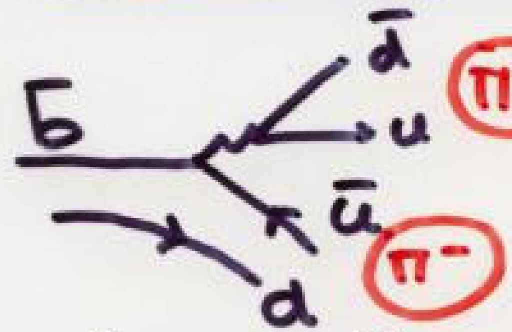
ϕ_2 FROM $B^0 \to \pi^+\pi^-$

Isospin analysis (Gronau, London)

Using $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$: separate $I=0, 2$ amplitudes, relative strong and weak phases

Potential problem: small $B(\pi^0\pi^0) \sim 10^{-6}$

Tree-penguin interference (Gronau, JLR)



"Tree"

Magnitude $|T|$

Weak phase ϕ_3

Strong phase $\equiv 0$

"Penguin"

Magnitude $|P|$

Weak phase 0

Strong phase $\equiv \delta$

What can we measure?

$A_{\pi\pi}$, $S_{\pi\pi}$ $\Rightarrow$ $\underline{\phi_3}$ (or $\phi_2 = \pi - \phi_1 - \phi_3$), $\underline{\delta}$

*if $|P/T|$ is known

Flavor SU(3): $|P|$ from $B^+ \to K^0\pi^+$

Factorization: $|T|$ from $B \to \pi \ell \nu$

*Alternative: $B(K^0\pi^+)/B(\pi^+\pi^-)$

$\pi^+\pi^-$ OBSERVABLES

$$R_{\pi\pi} \equiv \frac{B(\pi^+\pi^-)}{B(\pi^+\pi^-)_{\text{Tree}}} = 1 - \left|\frac{P}{T}\right| \cos\delta \cos(\phi_1+\phi_2) + |P/T|^2$$

$$R_{\pi\pi} S_{\pi\pi} = \sin 2\phi_2 + 2\left|\frac{P}{T}\right| \sin(\phi_1-\phi_2)\cos\delta - |P/T|^2 \sin 2\phi_1$$

$$R_{\pi\pi} A_{\pi\pi} = -2|P/T| \sin(\phi_1+\phi_2)\sin\delta$$

S, A coeffs. of $\sin \Delta m t$, $\cos \Delta m t$ terms

P from $B^+ \to K^0\pi^+$, SU(3)
T from $B \to \pi \ell \nu$
$\Big\}$ $|P/T| = 0.28 \pm 0.06$

$\phi_1 = (23.6 \pm 2.3)^\circ$, $R_{\pi\pi} = 0.62 \pm 0.28$

	BaBar	Belle	Average
$S_{\pi\pi}$	$.02 \pm .34 \pm .05$	$-1.23 \pm .41^{+.08}_{-.07}$	$-.48 \pm .27^{\dagger}$
$A_{\pi\pi}$	$.30 \pm .25 \pm .04$	$.77 \pm .27 \pm .08$	$.51 \pm .19^{*}$

$\dagger$: $\times$(scale = 2.31) $*$: $\times$(scale = 1.24)

Values of $\phi_2 = \alpha > 90^\circ$ are favored but with large uncertainty

Not yet settled if $A_{\pi\pi} \neq 0$ ("direct" $\not{CP}$)

$B \to \phi K_S$ vs. $B \to J/\psi K_S$

A test for non-standard penguins

Y. Grossman + M. Worah, PL B395 (97)

	BaBar	Belle	Average
$S_{\phi K}$	$-.18 \pm .51 \pm .07$	$-.73 \pm .64 \pm .22$	$-.38 \pm .41$ †
$A_{\phi K}$	$.80 \pm .38 \pm .12$	$-.56 \pm .41 \pm .16$	$.19 \pm .30$ *

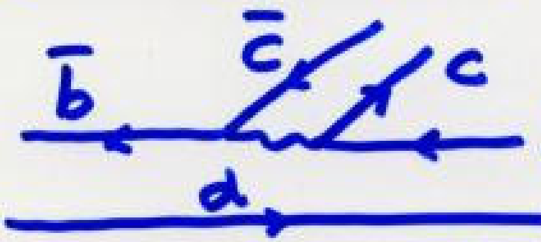
† Should equal $S_{J/\psi K_S} = 0.734 \pm 0.054$ in std. model

* × (scale = 2.3)

$B^0 \to \phi K^0$:

Penguin

$B^0 \to J/\psi K^0$:



Color-suppressed tree

Look for new physics using $S_{\phi K}$, $A_{\phi K}$, and $R \equiv \mathcal{B}(\phi K)/\mathcal{B}(\phi K)_{\text{std. model}}$:

C.-W. Chiang & JLR, hep-ph/0302094

Models generally based on $\bar{b} \to \bar{s}$ or $\bar{b} \to \bar{s} s \bar{s}$ new operators (Hiller, …)

Constraints: $\left\{ \begin{array}{l} B \to (K^+K^-)_{CP=+} K_S \\ \quad \to \eta' K_S \end{array} \right\}$ consist. with SM

$B \to (K^+K^-)_{CP=+} K_S$

Belle: aside from $B \to \phi K_S$, most of $B \to K^+K^-K_S$ has $CP(K^+K^-) = +$ ← "ξ"

hep-ex/0212062:

$$-\xi S = 0.49 \pm 0.43 \pm 0.11 {}^{+0.33}_{-0.00}$$

$\sin(2\phi_1)$ in SM

$$A = -0.40 \pm 0.33 \pm 0.10 {}^{+0.00}_{-0.26}$$

Is it penguin-dominated?

Grossman + hep-ph/0303171, Gronau + JLR /0304178 → $0.2 < -\xi S < 1$ in std. model

REMARKS ON $B \to \eta' K$

Rate is not a problem:

Only need to boost penguin by ~50% via "singlet" contribution

CP asymmetry is not a problem:

	BaBar	Belle	Average
$S_{\eta' K_S}$	$.02 \pm .34 \pm .03$	$.76 \pm .36 {}^{+.05}_{-.06}$	$.37 \pm .37$ †
$A_{\eta' K_S}$	$-.10 \pm .22 \pm .03$	$.26 \pm .22 \pm .23$	$.08 \pm .18$

† $.734 \pm .054$ (+corrs.) in SM

$K\pi$ RATIOS

$B^+ \to K^0\pi^+$ pure penguin: P

$B^0 \to K^+\pi^-$ penguin + tree: $P+T$

T/P: weak relative phase $\gamma \pm \pi$
strong relative phase δ
magnitude ratio r

$$R \equiv \frac{\bar{\Gamma}(B^0 \to K^+\pi^-)}{\bar{\Gamma}(B^+ \to K^0\pi^+)}$$ average over B & $\bar{B}$ — Fleischer-Mannel

Combine with asymmetry to learn about tree-penguin interference

$$A \equiv \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{2\bar{\Gamma}(B^+ \to K^0\pi^+)}$$

$$R = 1 - 2r\cos\gamma\cos\delta + r^2$$

$$A = -2r\sin\gamma\sin\delta$$

Eliminate δ and plot R vs. γ for allowed range of $|A|$

Need estimate of r: improving

$\Rightarrow$ $\boxed{\text{Constraints on } \gamma}$

$B^+ \to K^+\pi^0$: $P + T + \underbrace{C}$ ← color suppressed amplitude
+ Electroweak penguin.
again, constrains γ

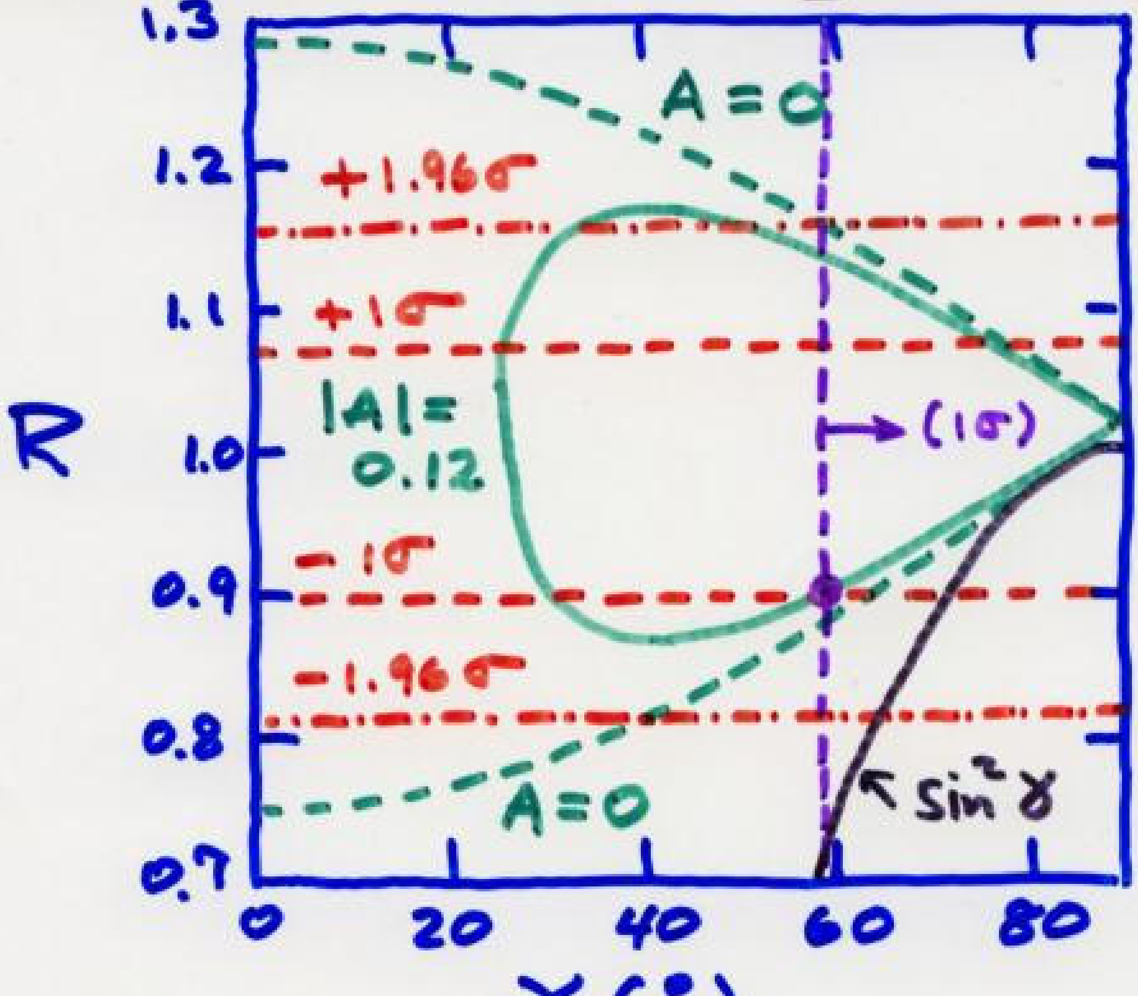
γ BOUNDS FROM $K^+\pi^-/K^0\pi^+$ "

$R = 0.99 \pm 0.09$ (BaBar-Belle-CLEO)

$r = 0.17 \pm 0.04$ (T from $B \to \pi \ell \nu$)

Weakest bound for minimum r

Fleischer-Mannel: $R \geq \sin^2\gamma$ (any r, δ)



$A = -0.08 \pm 0.04$ (BaBar-Belle)

$\gamma \geq 59°$ only at 1σ

No bound yet at 95% c.l. (1.96σ)

Errors have decreased by factor of ≈ 2 since M. Gronau + JLR PRD 65 (9/01)

γ BOUNDS FROM $K^+\pi^0/K^0\pi^+$

Updating M. Neubert + JLR, M. Gronau + JLR

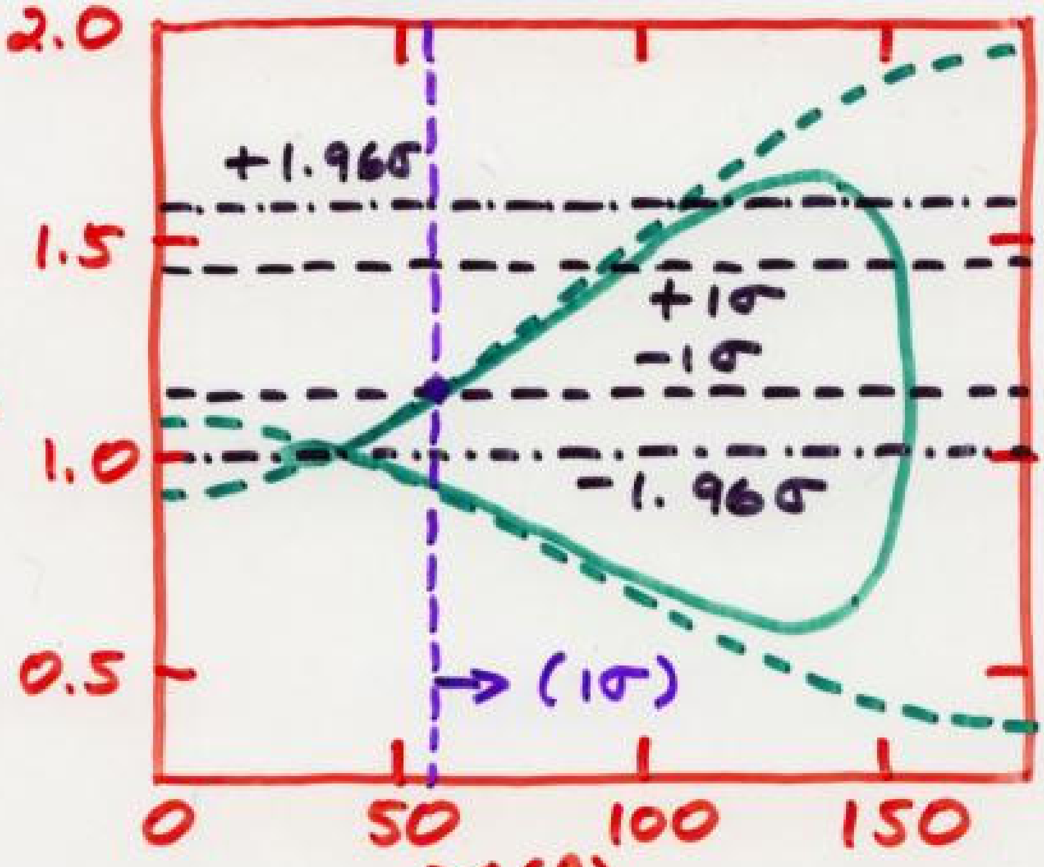
$$R_c \equiv \frac{\bar{\Gamma}(K^+\pi^0)}{\bar{\Gamma}(K^0\pi^+)} = 1.29 \pm 0.15$$

$$r_c = \left|\frac{T+C}{P}\right| = 0.20 \pm 0.02 \left(\begin{array}{c}\pi^+\pi^0 \rightarrow \\ T+C\end{array}\right)$$

$\delta_{EWP} = 0.65 \pm 0.15$ Electroweak penguin parameter

weakest bound for maximum r_c, δ_{EWP}

$$A_c \equiv \frac{\Gamma(K^-\pi^0) - \Gamma(K^+\pi^0)}{2\bar{\Gamma}(K^0\pi^+)} = -0.09 \pm 0.09$$

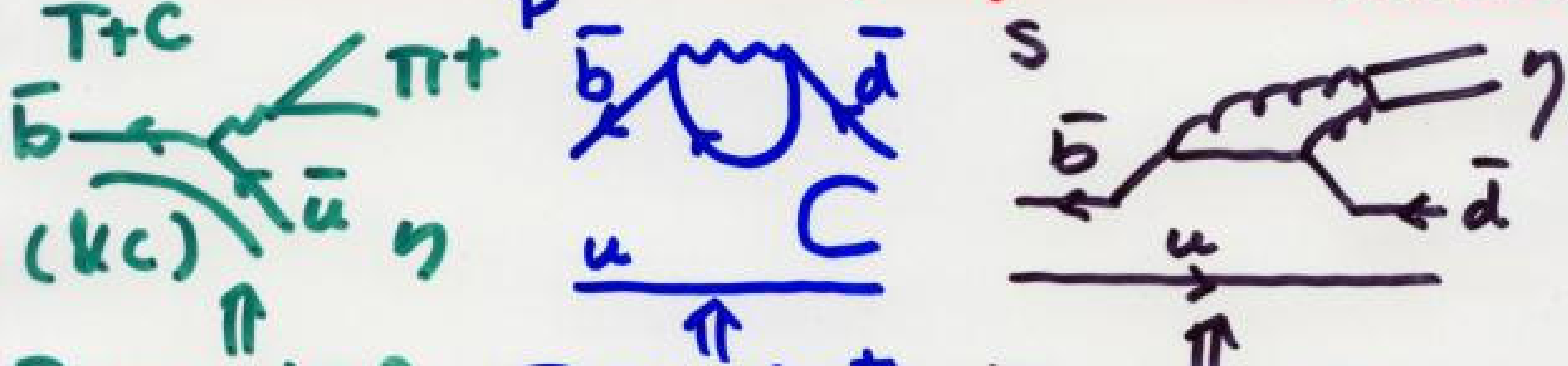


$\gamma \geq 56°$ only at 1σ

No bound yet at 95% c.l. (1.96σ)

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

Evidence for tree-penguin interference?



From $\pi^+\pi^0$ | From $K^0\pi^+$ | From $\eta' K$

	Br. (10^{-6})	A_{CP}
CLEO	$1.2^{+2.8}_{-1.2}$ (< 5.7)	—
BaBar	$4.2^{+1.0}_{-0.9} \pm 0.3$	-0.51 ± 0.19
Belle	$5.2^{+2.0}_{-1.7} \pm 0.6$	—
Avg.	4.1 ± 0.9	-0.51 ± 0.19
$\|T+C\|^2$ alone	3.5	0
$\|P+S\|^2$ alone	1.9	0

weak

strong phase

$$A_{CP} = \frac{-2a_1 a_2 \sin\phi \sin\delta}{a_1^2 + a_2^2 + 2a_1 a_2 \cos\phi \cos\delta}$$

if $A = a_1 + a_2 e^{i\phi} e^{i\delta}$, $\bar{A} = a_1 + a_2 e^{-i\phi} e^{i\delta}$

Rates & A_{CP} suggest $|\sin\phi \sin\delta| > |\cos\phi \cos\delta|$

B_s MIXING & RARE DECAYS

$$\frac{\Delta m_s}{\Delta m_d} = \underbrace{\frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}} \frac{m_{B_s}}{m_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 \simeq 48 \times 2^{\pm 1}$$

ξ^2: $\xi = 1.21 \pm 0.04 \pm 0.05$ latest lattice est.

$|V_{td}| = A\lambda^3 |1 - \bar{\rho} - i\bar{\eta}| \simeq (0.8 \pm 0.2) A\lambda^3$

$|V_{ts}| = A\lambda^2 \quad \lambda = 0.22$

$\Delta m_d = 0.503 \pm 0.007\ ps^{-1}$ ← LEPEWWG 2003

$$\boxed{\Delta m_s \cong 24\ ps^{-1} \times 2^{\pm 1}}$$

$(> 14.4\ ps^{-1}$ @ 95% c.l.)

Will constrain $\bar{\rho}$ significantly

$B_{SM}(B_s \to \mu^+\mu^-) = (3.1 \pm 1.4)\, 10^{-9}$

↗ C. Bobeth + PR D64, 074014 (2001)

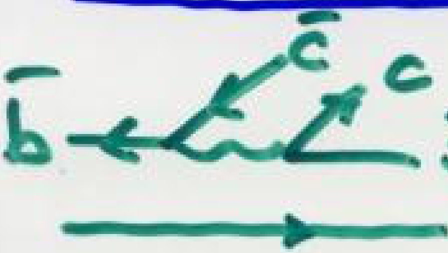
Could be enhanced by effects respecting $b \to s\gamma$ constraint (√SM)

For $B \to X_s \ell^+\ell^-$,* $b \to s\gamma$ see G. Hiller, NP B Proc. Supp. 115, 76 (03)

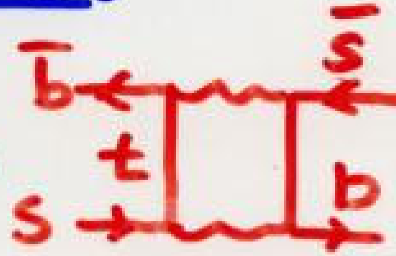
* Forward-backward asymmetries as function of $m(\ell^+\ell^-)$ are interesting.

~~CP~~ IN B_s DECAYS

$B_s \to J/\psi\,\phi,\ J/\psi\,\eta, \ldots$



Weak phase ≈ 0



Mixing phase ≈ 0

Expect only few % CP asymmetries in standard model

$B_s \to K^+K^-$ vs. $B^0 \to \pi^+\pi^-$ (Fleischer)

P dominant
T less

T dominant
P less

SU(3) ($d \leftrightarrow u$)

Time-dependences allow separation of P and T, weak & strong phases

$\bar{B}_s,\ B^0 \to K^+\pi^-$ (Gronau + JLR)

Kinematic separation is easier

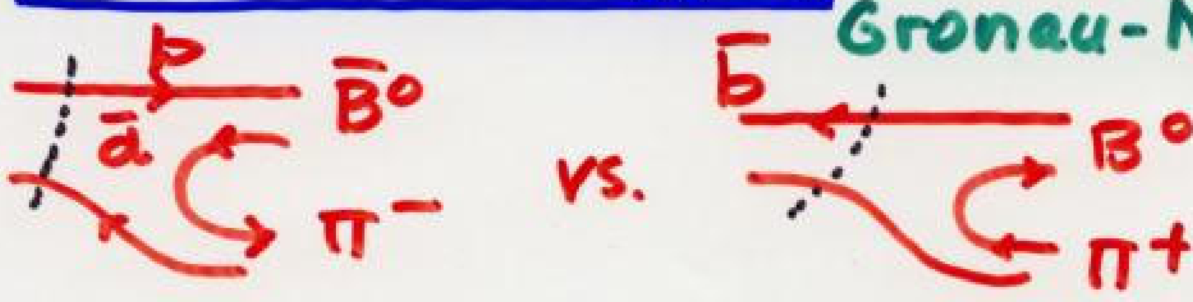
Other SU(3) relations

U-spin subgroup ($d \leftrightarrow s$) often is sufficient

Many tests of flavor SU(3), final-state phase studies enabled

EXCITED STATES

B^0, B_s flavor tagging Ali-Barreiro Gronau-Nippe-JLR



or use U-spin: $B \to B_s$, $\pi \to K$

$B^{(*)}\pi$ may resonate: only partial information exists. Properties studied by Eichten-Hill-Quigg (1993-4)

New sensation (BaBar): DK "molecule"

$$M = 2.32 \text{ GeV}, \quad \Gamma \lesssim 10 \text{ MeV}$$

Decays to $\pi^0 D_s$*

Candidate for $J^P = 0^+$, $I = 0$ (!)

(Lipkin PL 70B; Isgur-Lipkin 99B)

* Via isospin violation

Well below expected $L=1$ $c\bar{s}$ mass

Narrow $\bar{B}K$ state(s)?

$$M(\bar{B}) + M(K) - 40 \text{ MeV} \simeq 5.73 \text{ GeV}$$

Need all-purpose detector! $\to B_s \pi^0$

EXOTIC QUARKS

Example drawn from E_6 GUT:

$$SU(5) \subset SO(10) \subset E_6$$

$$\left.\begin{array}{ccc} 5+10^*+1 & = & 16 \\ 5+5^* & = & 10 \\ 1 & = & 1 \end{array}\right\} \begin{array}{c} 27 \\ \text{(smallest} \\ \text{rep.)} \end{array}$$

Evidence for three 16's of SO(10) [counting right-handed ν's]

10 of SO(10) has vector-like $I=\frac{1}{2}$ leptons and $I=0$ $Q=-1/3$ quarks

These new "h" quarks could mix with b and push its mass down with respect to t

T. Andre and JLR (in progress): Signatures of $\bar{p}p \to h\bar{h}+X$ could include $h \to Z+b$, Higgs $+\, b$

$Z \to \nu\bar{\nu}, \ell^+\ell^-, jj$

$\text{Higgs} \to b\bar{b}$

SUMMARY

The outlook for b physics is rich and limited only by production, detectors.

A qualitative step in rare B decays to hadrons comes at branching ratios $\sim 10^{-7}$, for which interferences of dominant and smaller amplitudes can be well studied.

The problem of flavor:

(a) Many schemes (supersymmetry, technicolor, compositeness, ...) predict flavor-changing effects just below present limits; important to push them further.

(b) Physics underlying flavor (quark masses and mixings) is totally unknown. Understanding it would be a major step.