CP VIOLATION IN THE STANDARD MODEL

J. ROSNER - TEVATRON RUN II 9/23/99

A bit of history

The Cabibbo-Kobayashi-Maskawa matrix

Aspects of kaon physics

- ϵ'/ϵ
- $K \to \pi \nu \bar{\nu}$

Topics in B decays

- Pairs of pseudoscalars
- Pseudoscalar + Vector
- Lifetimes
- Special aspects of B_s

Baryogenesis

A BIT OF HISTORY

Strangeness (1953)

$$\pi^- p \to K^0 \Lambda$$

$S =$ 0 0 1 −1

$\boxed{K^0 (S=1) \neq \bar{K}^0 (S=-1)}$

Violated in weak decays: both $\Rightarrow \pi\pi$

Gell-Mann – Pais (1955)

$$K_1^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}} \to 2\pi \, ; \quad K_2 = \frac{K^0 - \bar{K}^0}{\sqrt{2}} \not\to 2\pi$$

$\tau = 0.089$ ns $\qquad \tau = 51.7$ ns

(based on C, then CP invariance)

CCFT (1964)

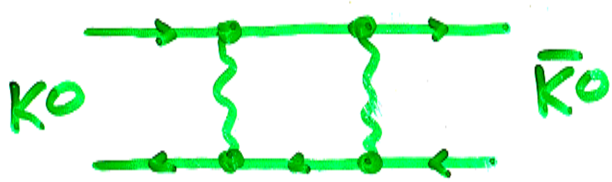
Long-lived kaon $\to 2\pi$

$K_S \cong K_1 + \epsilon K_2$; $\quad K_L \cong K_2 + \epsilon K_1$

$|\epsilon| \approx 2.28 \times 10^{-3} \qquad \mathrm{Arg}(\epsilon) = \pi/4$

Kobayashi-Maskawa (1973) [Cabibbo 1963]

Phases in couplings ⇒ CP violation (e.g. in ϵ)



u, c, t in loops

$\epsilon \sim \mathrm{Im}(V_{td}^2)$
(for real V_{ts})

MORE HISTORY

Charm (1974-6) $J/\psi = c\bar{c}$; $D = c\bar{q}$; …

Beauty (1977-9) $\Upsilon = b\bar{b}$; $B = b\bar{q}$, …

Direct $\not{CP}$ (1976-81) $$\frac{A(K_L \to \pi_i \pi_j)}{A(K_S \to \pi_i \pi_j)} \equiv \eta_{ij}$$

$\eta_{+-} = \epsilon + \epsilon'$

$\eta_{00} = \epsilon - 2\epsilon'$ Calculable in CKM theory

(Gilman-Wise, …)

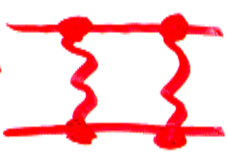
$\Rightarrow \mathrm{Re}(\epsilon'/\epsilon) = (21.2 \pm 4.6)10^{-4}$ (1999)

Wolfenstein (1983)

$$V_{CKM} = \begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}$$

$\lambda = \sin\theta_c \simeq 0.22$ $A \simeq 0.8$ (7%)

B^0-$\bar{B}^0$ mixing (1987) $\frac{\Delta m}{\Gamma} \sim 0.7 \Rightarrow$ large m_t

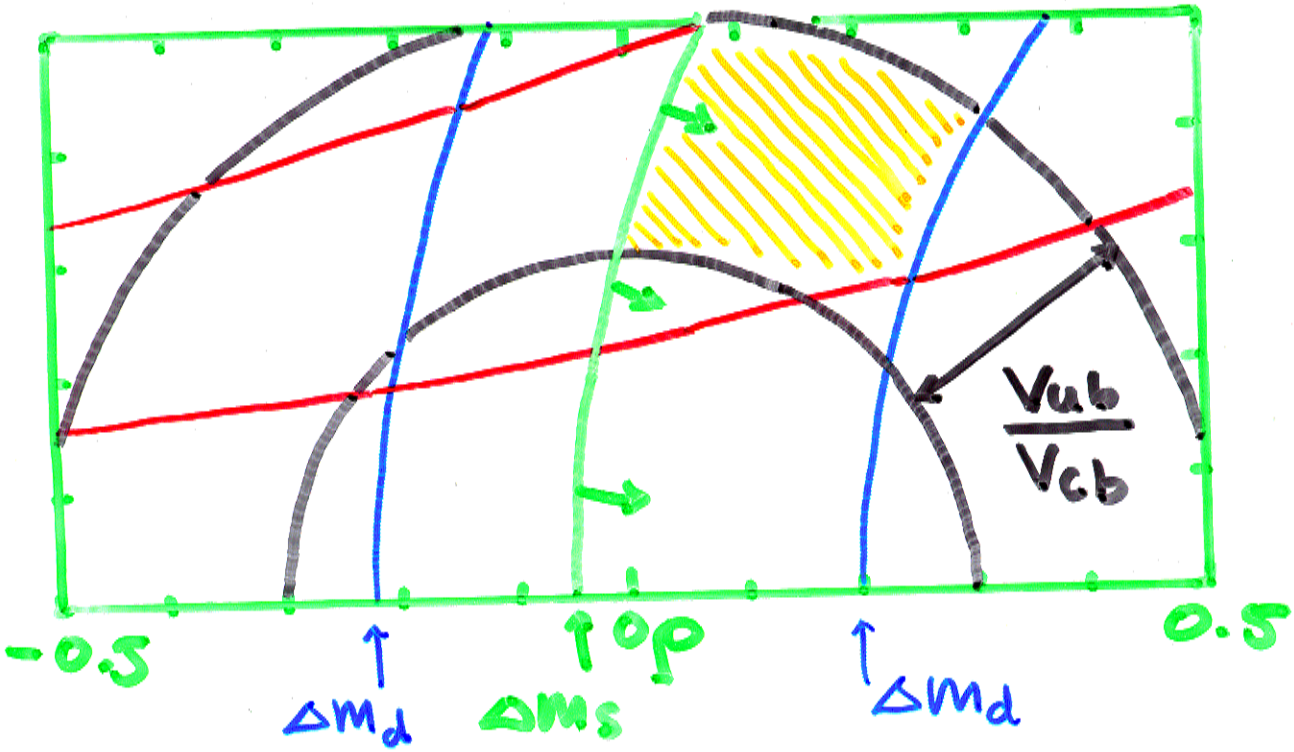
B^0  $\bar{B}^0$ $\Rightarrow |V_{td}| \Rightarrow |1-\rho-i\eta| \simeq 1 \pm 0.2$ (1999)

V_{ub} (1989) $|V_{ub}/V_{cb}| = 0.09 \pm 0.025$ (1999)

$\Rightarrow (\rho^2 + \eta^2)^{1/2} = 0.41 \pm 0.11$

Top (1994-5) $m_t = 174.3 \pm 5.1$ GeV (1999)

(ρ, η) FOR V_{CKM}



$|V_{ub}/V_{cb}| = 0.090 \pm 0.025$ (Falk 1999)

$A = 0.81 \pm 7\%$

$\epsilon \Rightarrow \eta(1 - \rho + 0.44) = 0.51 \pm 0.18$

$B^0 - \bar{B}^0$ mixing: $\Delta m_d = 0.473 \pm 0.016 \text{ ps}^{-1}$

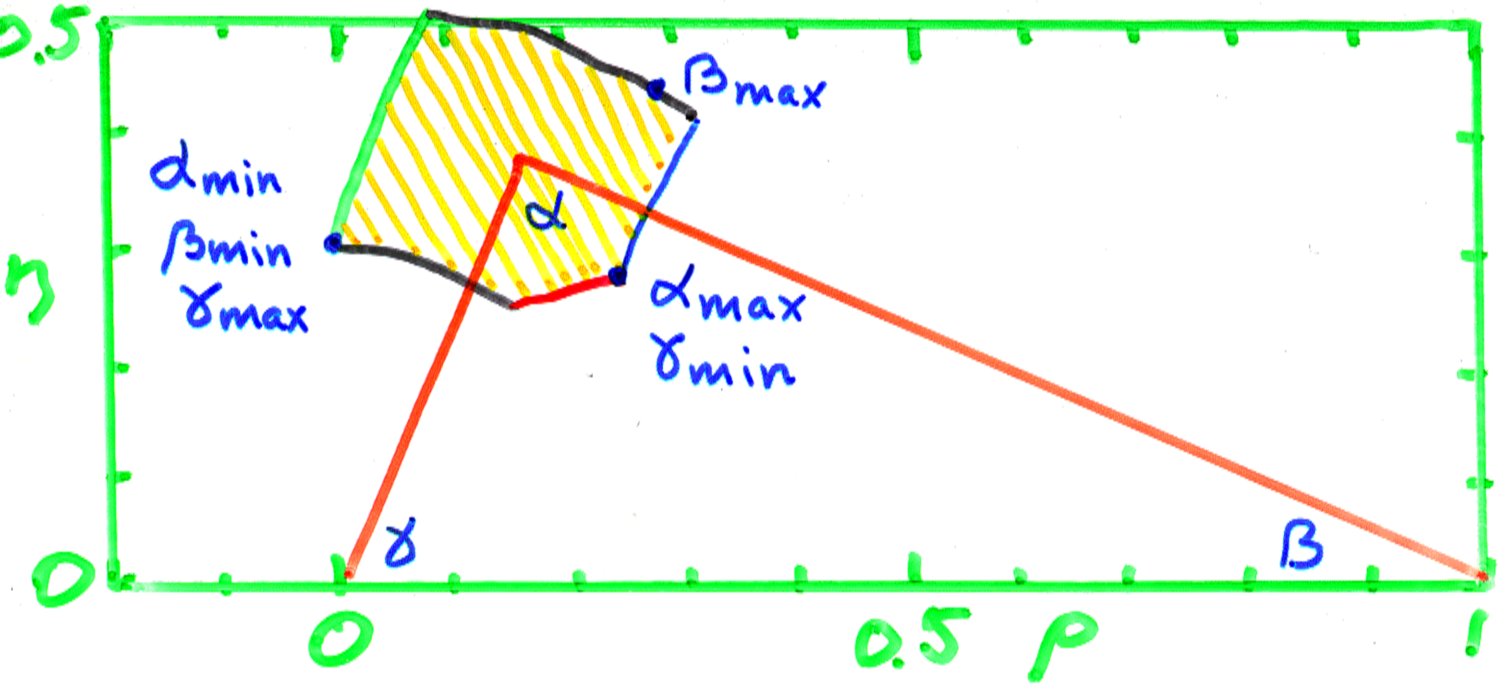
using $f_B \sqrt{B_B} = 200 \pm 40$ MeV

$\Delta m_s > 14.3 \text{ ps}^{-1}$ (95% c.l.)

$\Rightarrow |V_{ts}/V_{td}| > 4.3$

Superweak case $(\eta = 0)$ disfavored even without kaon information

BOUNDS ON α, β, γ



		degrees	ρ	η
α	min	72	−0.01	0.30
	max	113	0.25	0.27
β	min	17	−0.01	0.30
	max	31	0.29	0.43
γ	min	48	0.25	0.27
	max	92	−0.01	0.30

$\alpha = \pi - \beta - \gamma$

$\beta = \tan^{-1} \frac{\eta}{1-\rho}$

$\gamma = \tan^{-1} \frac{\eta}{\rho}$

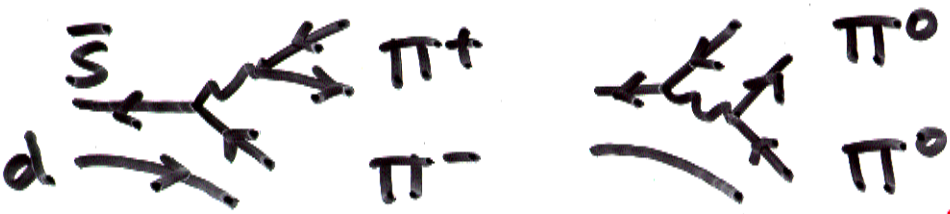
$-0.71 \le \sin(2\alpha) \le 0.59$

$0.59 \le \sin(2\beta) \le 0.89$

$0.54 \le \sin^2 \gamma \le 1$

CKM AND $K_{S,L} \to \pi\pi$ RATES

"Tree" amplitudes



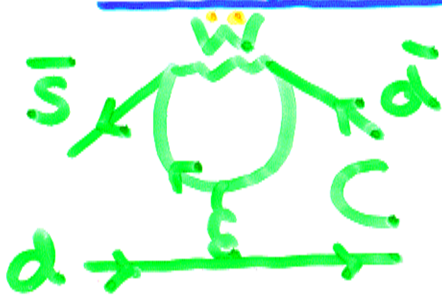
$\Rightarrow I_{\pi\pi} = 0, 2$

$\Downarrow$

ϵ'

No CKM phase

"Penguin" amplitude



$\pi^+ \; \pi^0$

$\pi^- \, , \; \pi^0$

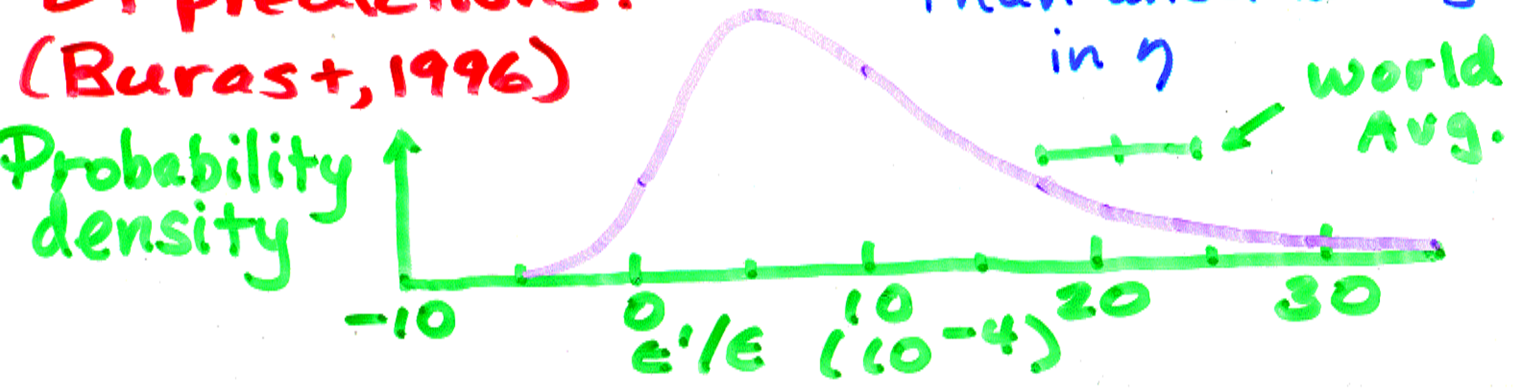
$\Rightarrow I_{\pi\pi} = 0$ only

CKM phase from top in loop

Relative phase of amplitudes generates a small difference from 1 of ratio

$$R \equiv \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \Big/ \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} = 1 + 6 \,\mathrm{Re}\,\frac{\epsilon'}{\epsilon}$$

One range of predictions: (Buras+, 1996) $\longleftrightarrow$ Much greater range than uncertainty in η



$K \to \pi \ell^+ \ell^-$ INFORMATION

$K^+ \to \pi^+ \nu \bar{\nu}$

Measures $|V_{td} + \text{charm}| \Rightarrow |1.4 - \rho - i\eta|$

$$\mathcal{B} \simeq 10^{-10} \left| \frac{1.4 - \rho - i\eta}{1.4} \right|^2 \quad (\pm\, m_c,\ A \text{ errors})$$

$0 \lesssim \rho \lesssim 0.3 \Rightarrow \mathcal{B} \simeq (0.8 \pm 0.2) \times 10^{-10}$ (" ")

Measurement to 10% ↗ to constrain (ρ, η)
(if in accord with standard model!)

One BNL E787 event $\Rightarrow \mathcal{B} \simeq \dfrac{4 \times 10^{-10}}{2 \text{ to } 3}$

More data expected

$K_L \to \pi^0 \ell^+ \ell^-$

$\cancel{CP}$: direct and indirect (ϵ) | Each $\Rightarrow \mathcal{B} \simeq$ few $\times 10^{-12}$

Direct contribution probes η

May be background limited

exp. | $\mathcal{B}(K_L \to \pi^0 e^+ e^-) \leq 5.64 \times 10^{-10}$ (90% c.l.)
" " $\mu^+\mu^-$ " 3.4 " "

$K_L \to \pi^0 \gamma\gamma \to \pi^0 e^+ e^-$: CP-conserving "contaminant"

$K_L \to \pi^0 \nu \bar{\nu}$

$\cancel{CP}$: purely a probe of η

$\mathcal{B} \simeq 3 \times 10^{-11}$ $(\sim A^4 \eta^2)$

$\mathcal{B}_{exp} \leq 5.9 \times 10^{-7}$ (using $\pi^0 \to e^+ e^- \gamma$)

CP VIOLATION IN B DECAYS

⓪ No simple $K_S - K_L$ analog

Possible $\Delta\Gamma/\Gamma \sim 0.1$ for B_s's

① Decays to CP eigenstates

$$\boxed{\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & & f \\ & \bar{B}^0 \arrow[ur] & \end{tikzcd}} \neq \boxed{\begin{tikzcd} \bar{B}^0 \arrow[rr] \arrow[dr] & & f \\ & B^0 \arrow[ur] & \end{tikzcd}}$$

Interference between mixing and decay

$f = J/\psi\ K_S$: $\Rightarrow$ $\sin(2\beta)$

if no additional mixing source

$f = \pi^+\pi^-$: $\Rightarrow \approx \sin(2\alpha)$

but need $\pi^\pm\pi^0$, $\pi^0\pi^0$ (e.g.) to sort out decay amplitudes

② "Self-tagging" decays

$$A(B \to f) = a_1 e^{i(\phi_1+\delta_1)} + a_2 e^{i(\phi_2+\delta_2)}$$

$$A(\bar{B} \to \bar{f}) = \quad - \quad -$$

Weak phases change sign under CP

$$A \equiv \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} \left.\begin{array}{l} \sim \sin(\phi_1 - \phi_2) \\ \times \sin(\delta_1 - \delta_2) \end{array}\right\} \text{Need both} \neq 0$$

EXAMPLE: CDF $B^0 \to J/\psi\, K_S$

$$\frac{\Gamma(B^0 \to J/\psi\, K_S) - \Gamma(\bar{B}^0 \to J/\psi\, K_S)}{\Gamma(B^0 \to J/\psi\, K_S) + \Gamma(\bar{B}^0 \to J/\psi\, K_S)}$$

is proportional to $\sin(2\beta)$

where $-\beta$ is the phase of V_{td}

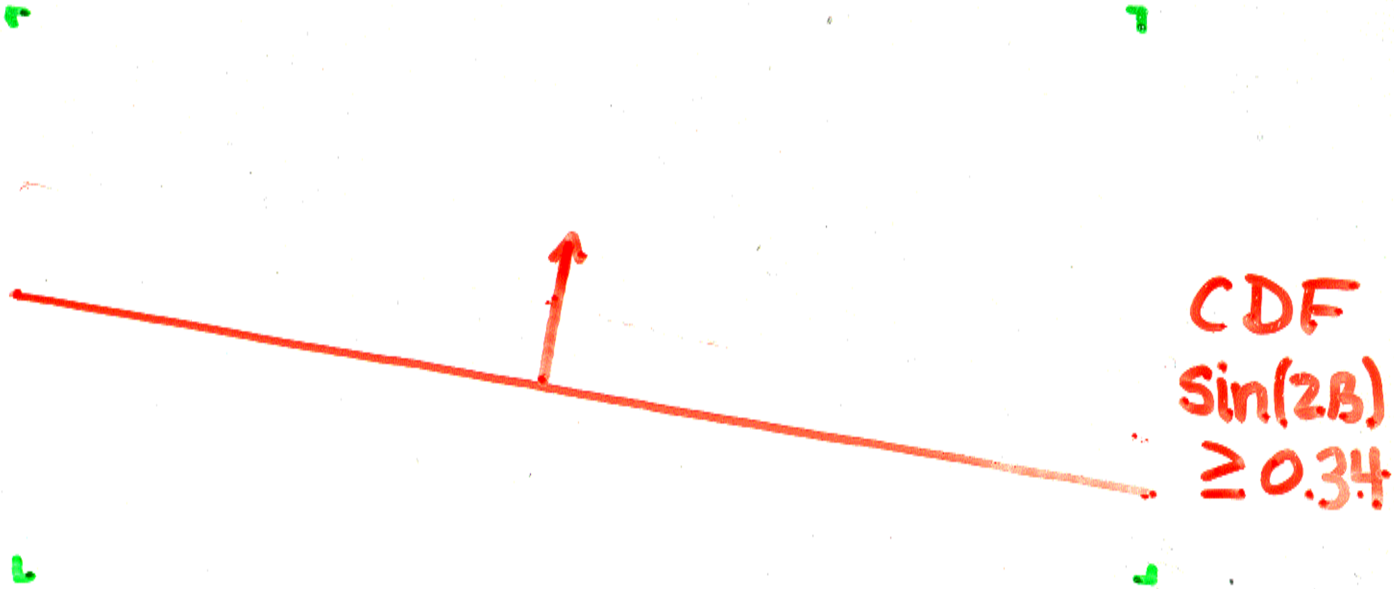
(2β is the phase of the B^0-$\bar{B}^0$ mixing amplitude)

To measure this, need to "tag" the initial B: was it a $\bar{B}^0$ or B^0?

Methods: (1) "opposite-side": Strong interactions always produce b & $\bar{b}$ in pairs

(2) "same-side": $\bar{B}^0$ likes to "resonate" with a π^-, B^0 with π^+

Result: $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$


CDF
$\sin(2\beta)$
≥ 0.34

POCKET GUIDE TO DIRECT CP ASYMMETRIES

Suppose $\left.\begin{matrix}\sin(\phi_1-\phi_2)\\ \sin(\delta_1-\delta_2)\end{matrix}\right\} = O(1)$

$$A = O\left(\frac{a_1 a_2}{a_1^2 + a_2^2}\right) \sim \frac{a_2}{a_1} \sim \sqrt{\frac{N_2}{N_1}}$$

for $|a_2| \ll |a_1|$

$N_i = \text{const.}\, |a_i|^2$ (rate)

$\delta A \sim O\left(\frac{1}{\sqrt{N_1}}\right)$ $\boxed{\frac{A}{\delta A} \sim O(\sqrt{N_2})}$

To see an asymmetry at significant level need the rate from rarer amplitude (a_2) to correspond to a significant signal

Look for B decays with:

- At least 2 ampls.
- Large rate for smaller ampl.
- Weak phase difference
- Good chance for strong phase diffc.

$\Longrightarrow$

INTERESTING LEVELS

Current bounds on many branching ratios are a few times 10^{-5} (i.e. a few times dominant contrib.)

Subdominant rates are $\lambda^2 \sim 1/20$ of these

Thus $\sim 5 \times 20$ factor in data would permit study of interference between dominant and subdomin. amplitudes

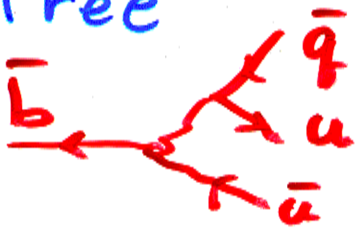
The above assumes most favorable situation for strong phase diffc. $(\delta_1 - \delta_2)$.

Methods exist for learning weak phases using asymmetries in direct decays even if final state phase differences vanish

Typically these require some b.r.'s @ few $\times 10^{-7}$ to be known.

MAIN AMPLITUDES

"Tree"



"Penguin"

Dominates $B^0 \to \pi^+\pi^-$

$\boxed{\Delta S = 0 \quad V_{ub}^* V_{ud} \quad \text{Phase } \gamma}$

$V_{tb}^* V_{td}$

Phase $-\beta$

Relative phase $\gamma + \beta = \pi - \alpha$

$|\Delta S = 1| \quad V_{ub}^* V_{us}$

Phase γ

$\boxed{V_{tb}^* V_{ts} \quad \text{Phase } \pi}$

Dominates $B \to K\pi$

Relative phase $\gamma - \pi$

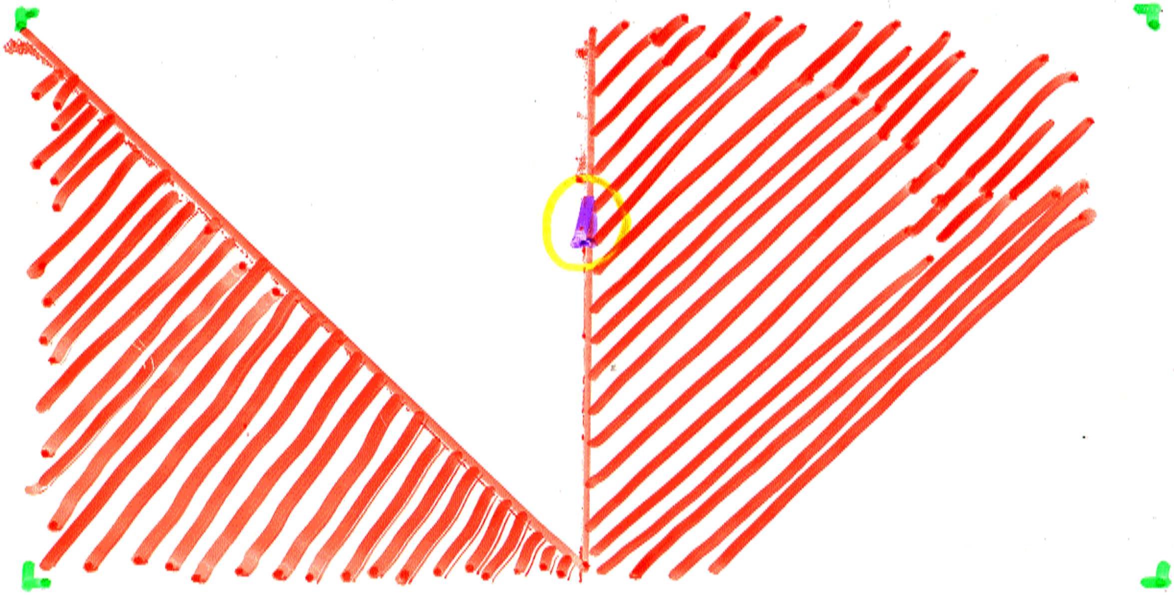
Many methods for learning α, γ even when strong phases are present:

$B \to K\pi$ ratios: Gronau et al.
Fleischer
Neubert-Rosner

$B^0 \to \pi^+\pi^-$ Destructive T-P interfer.

$B^0 \to K^{*+}\pi^-$ Constructive T-P interference

Examine suggestions favoring $\gamma > \frac{\pi}{2}$



Global CLEO fit: $\gamma = 113^{+25}_{-23}{}^\circ$

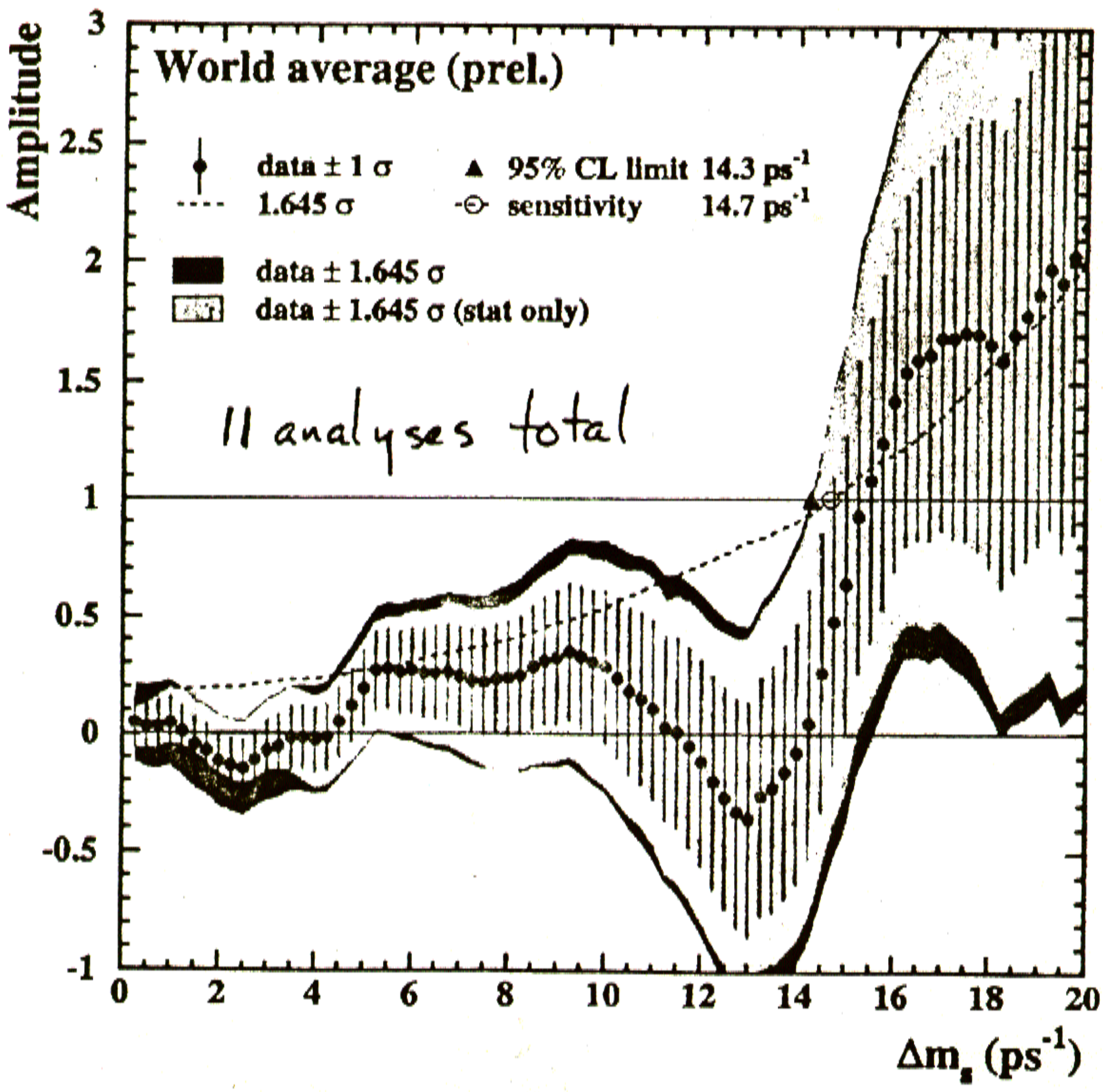
Should see ΔM_s near present limits!

B_s MIXING - G. BLAYLOCK

Lepton-Photon 99

Private compilation (not blessed) using Bosc working group machinery

$\Delta m_s > 14.3\ ps^{-1}$ ($12.4\ ps^{-1}$ last week)

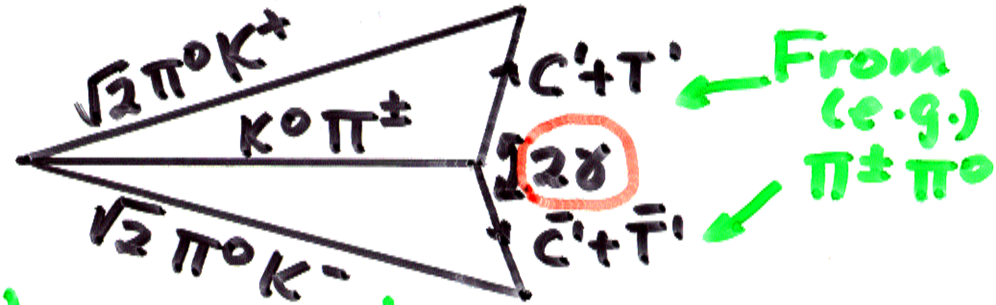


INTERESTING RATE RATIOS

$\Delta S = 0$ amps: P = penguin T = tree C = color suppressed
$|\Delta S| = 1$: P' T' C'

$K^{\pm}\pi^0 / K^0\pi^{\pm}$

Gronau-London-JLR



Desh-He: EW penguins!
Neubert-JLR: calculable

$K^{\pm}\pi^{\mp} / K^0\pi^{\pm}$ $\equiv R = \dfrac{|T'+P'|^2 + |\bar{T}'+\bar{P}'|^2}{|P'|^2 + |\bar{P}'|^2}$

Fleischer-Mannel: $\sin^2\gamma \le R$ useful if $R < 1$

Gronau-JLR: combine with $\cancel{CP}$ asymms. to learn γ even if $R \ge 1$

$\pi^+\pi^- / |T|^2$ $= \dfrac{|T+P|^2 + |\bar{T}+\bar{P}|^2}{|T|^2 + |T'|^2}$

Learn $|T|$ (e.g.) from $\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}$

$K^{*+}\pi^- / \phi K$ $= \dfrac{|p'+t'|^2 + |\bar{p}'+\bar{t}'|^2}{0.7\,[\,|p'|^2 + |\bar{p}'|^2\,]}$

Electroweak penguin correction (Fleischer; Desh-He)

CLEO $B \to PP$ RESULTS

Mode	Amplitudes	B.r. (10^{-6})	σ
$\pi^+\pi^-$	$-(T+P)$	$4.7^{+1.8}_{-1.5} \pm 0.6$	4.2
$\pi^+\pi^0$	$-(T+C+P_{EW})/\sqrt{2}$	$5.4^{+2.1}_{-2.0} \pm 1.5$	3.2
$K^+\pi^-$	$-(T'+P')$	$18.8^{+2.8}_{-2.6} \pm 1.3$	11.7
$K^+\pi^0$	$-(T'+P'+C'+P'_{EW})/\sqrt{2}$	$12.1^{+3.0}_{-2.8}{}^{+2.1}_{-1.4}$	6.1
$K^0\pi^+$	P'	$18.2^{+4.6}_{-4.0} \pm 1.6$	7.6
$K^0\pi^0$	$(P'-C'-P'_{EW})/\sqrt{2}$	$14.8^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	4.7
$K^+\eta'$	$(3P'+4S'+T'+C'-\frac{1}{3}P'_{EW})/\sqrt{6}$	$80^{+10}_{-9} \pm 8$	16.8
$K^0\eta'$	$(3P'+4S'+C'-\frac{1}{3}P'_{EW})/\sqrt{6}$	$88^{+18}_{-16} \pm 9$	11.7

$S' \Leftrightarrow$


needed for large $K\eta'$ rates

If only P': $\Gamma(K^+\pi^-) = 2\Gamma(K^+\pi^0) = \Gamma(K^+\pi^-) = 2\Gamma(K^0\pi^0)$

First-order corr.: $\Gamma(K^+\pi^-) + \Gamma(K^0\pi^+)$
(Lipkin) $= 2[\Gamma(K^+\pi^0) + \Gamma(K^0\pi^0)]$

$$R^* = \frac{\Gamma(B^\pm \to K^0\pi^\pm)}{2\Gamma(B^\pm \to K^\pm\pi^0)} = 0.75 \pm 0.28$$ consistent with 1

$$R \equiv \frac{\Gamma(B^0 \to K^\pm\pi^\mp)}{\Gamma(B^\pm \to K^0\pi^\pm)} = 1.03 \pm 0.31$$ " "

TREE-PENGUIN INTERFERENCE IN $B^0 \to \pi^+\pi^-$

He-Hou-Yang PRL 83, 1100
Hou-Smith-Würthwein, in preparation
Gronau-JLR Technion-Ph-99-33, EFI 99-40

All rates in branching ratio units of 10^{-6}

(T) $B^+ \to \pi^+\pi^0$: $|T+C|^2/2 = 5.4 \pm 2.5$

Beneke +: $\mathrm{Re}(C/T) \simeq 0.1$

$\Rightarrow$ $\boxed{|T| = 3.0 \pm 0.7}$

Consistent with estimates from $B \to \pi \ell \nu$ (Gibbons; Gao-Würthwein)

T alone would give a b.r. of
$B(\pi^+\pi^-) = (9 \pm 4) \times 10^{-6}$

(P) $B^+ \to K^0\pi^+ \Rightarrow |P'|^2 = 18.2 \pm 4.6$
$|P'| = 4.3 \pm 0.5$

$\boxed{|P| \simeq \lambda |P'| = 0.94 \pm 0.12}$

$\pi^+\pi^-$ charge-averaged b.r. $\Rightarrow$

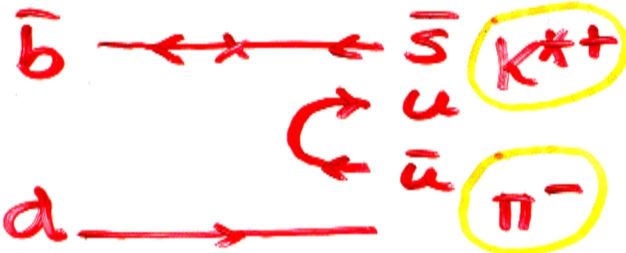
$|T|^2 + |P|^2 - 2|T||P| \cos\alpha \cos\delta = 4.7 \pm 1.8$

$\Rightarrow$ $\boxed{\cos\alpha \cos\delta = 0.9 \pm 0.9}$

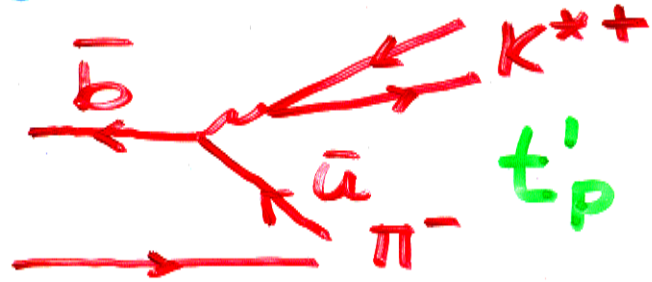
For $\cos\delta > 0$ favors $\cos\alpha > 0$ at 1σ

TREE-PENGUIN INTERFERENCE IN $B^0 \to K^{*+}\pi^-$

$\mathcal{B}(B^0 \to K^{*+}\pi^-) = (22^{+8+4}_{-6-5}) \times 10^{-6}$



p_P' +



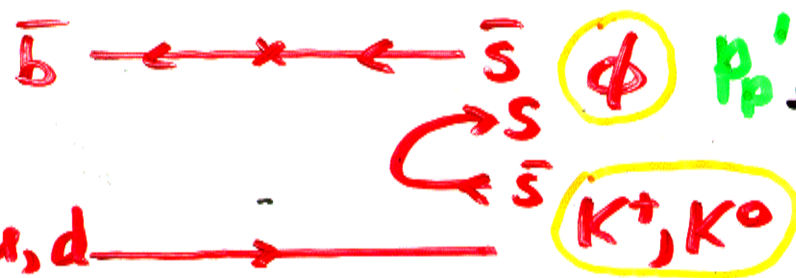
t_P'

Spectator in a pseudoscalar

b.r. units of 10^{-6}, 90% c.l.

$$|p_P'|^2 + |t_P'|^2 - 2|p_P'||t_P'|\cos\delta\cos\gamma = 22^{+9}_{-8} > 12$$

$\mathcal{B}(B^+ \to \phi K^+) < 5.9 \times 10^{-6}$



p_P' +

$\simeq -\frac{1}{6} p_P'$

EWP: Fleischer, Desh-He

$0.7|p_P'|^2 \le 5.9$

$\Rightarrow \boxed{|p_P'| \le 2.9}$

Estimate of t_P'

t_V

t_P

$\mathcal{B}(\rho^0\pi^+) = (15 \pm 5 \pm 4) \times 10^{-6}$

$\mathcal{B}(\omega\pi^+) = (11.3^{+3.3}_{-2.9} \pm 1.5) \times 10^{-6}$

$\mathcal{B}(\rho^\mp\pi^\pm) = (35^{+11}_{-10} \pm 5) \times 10^{-6}$

$\Rightarrow$ $|t_P| \le 5.4$, $|t_P'| \le 1.2$

For $\cos\delta > 0$, $\gamma > 107°$

LIFETIMES

Λ_b $\tau = 1.23 \pm 0.08$ ps

$\tau(\Lambda_b)/\tau(B^0) = 0.79 \pm 0.05$ Theory: 0.9–1.0

estimates do not suffice $\Rightarrow$
Nonperturbative effects still matter, even at 5.6 GeV!

Other indications:

① $\bar{b} \to \bar{s}$ penguins need enhancement ($\bar{b} \to c\bar{c}\bar{s} \to \bar{s} + \cdots$)* with respect to factorized short-distance estimates

② $\mathcal{B}(B^0 \to \omega K^0) = (10.0^{+5.4}_{-4.2} \pm 1.5) \times 10^{-6}$ (3.9σ)
far above model estimates except in
* "charming penguin" models

③ Penguin contributions ("P_V'") beyond model estimates needed to understand large $B \to K^* \eta$ rates:

$\mathcal{B}(B^+ \to K^{*+}\eta) = (27.3^{+9.6}_{-8.2} \pm 5.0) \times 10^{-6}$

$\mathcal{B}(B^0 \to K^{*0}\eta) = (13.8^{+5.5}_{-4.4} \pm 1.7) \times 10^{-6}$

B_s $\tau(B_{CP=+}) < \tau(B_{CP=-})$ expected

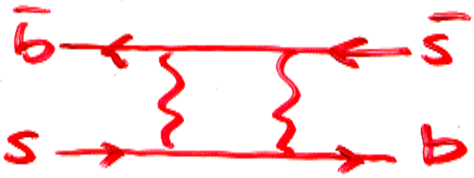
No indication yet but separation methods (some quite elegant) exist.

$B_s \to J/\psi\, \phi$ polarization: CP=± amplitudes

$B \to J/\psi\, K^*$ amplitudes: similar structure

THE STRANGE B

Mixing



$\frac{\Delta m_s}{\Delta m_d} = \mathcal{O}(30)$ expected

① Information on $|V_{ts}/V_{td}|$

② $x_s = \Delta m_s/\Gamma \gg 1$ dilutes CP asymms. in time-integrated decays to CP eigenstates

Lifetime differences

CP eigenstates account for a larger proportion of B_s decays than B_d decays

$B_d = \bar{b}d \rightarrow (\bar{c}u\bar{d}')d$ vs. $B_s = \bar{b}s \rightarrow (\bar{c}u\bar{d}')s$

$(\bar{c}c\bar{s}')d$ $\qquad$ $(\bar{c}c\bar{s}')s$

$d' = d\cos\theta + s\sin\theta \qquad s' = -d\sin\theta + s\cos\theta$

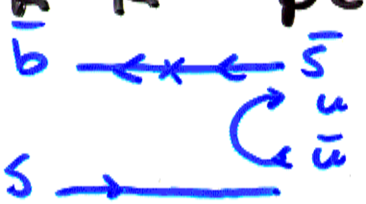
CP eigenstates

$J/\psi\ \phi$: polarizations $\left\{\begin{array}{l} \text{longitudinal} \\ \parallel \text{ linear} \\ \perp \text{ linear} \end{array}\right.$ $\left.\begin{array}{l} \\ \\ \end{array}\right\}$ CP $=+$ $\left\{\begin{array}{l} \ell = 0, 2 \\ \text{combinations} \end{array}\right.$

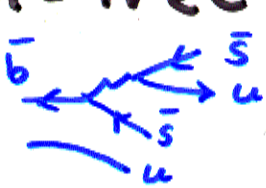
$\perp$ linear CP $= -$ $\qquad \ell = 1$

$\cancel{CP}$ asymm. small in standard model; probe of non-standard physics

K^+K^-: penguin-tree interference



P'



T'

More info. on γ

BARYOGENESIS

Scenarios:

① CKM phases → baryon asymmetry?

Doesn't work unless rescued by new physics, e.g. supersymmetry

② Leptogenesis at high mass scale, ⇒ $L \neq 0$, reprocessed into $B \neq 0$ at electroweak scale

Either scenario needs the 3 Sakharov ingredients:

i) Non-equilibrium
ii) CP violation
iii) B violation

My preference: ②

Lepton number violation already likely if masses of neutrinos have a Majorana contribution (generic!)

CP violation & non-equilibrium easy to arrange at large Majorana mass scale

Remaining mystery: what do CKM phases have to do (if anything) with CP violation at Majorana mass scale?

- continuous progress

a qualitative success

clean interpretation, an exptl. challenge

$\gamma \overset{?}{\simeq} \frac{\pi}{2}$

- Λ_b still a mystery

- mixing, CP eigenstates

-

potential window provided by neutrino masses

The Cabibbo-Kobayashi-Maskawa picture is still a valid description of CP violation in kaons; passes first test in B's.

Physics underlying CKM matrix and quark masses still not understood.