Beijing, August 2005

Flavour Dynamics & ~~C~~P in the SM*: A Tale of Great Successes, Little Understanding -- and Promise for the Future!

Ikaros Bigi, Notre Dame du Lac

Lecture III (5)

~~C~~P in B Decays --
the `Expected' Triumph of a Peculiar Theory

Recap from Lecture II

CKM Dynamics -- a reasonable description of flavour dynamics with a very peculiar set of parameters connected to central mysteries of the SM --

has to produce a host of large ~~CP~~ in B decays with no plausible deniability

Nature has been extremely kind to us in implementing this \`Paradigm of large ~~CP~~ in B decays' by arranging for

(i) huge top quark mass, (ii) \`long' B lifetime,

(iii) $\Upsilon(4S)$ being above BB, yet below BB* threshold,

(iv) charm initiating the development of μvertex detectors

$$L(\Lambda) \rightarrow L(\mu) = \Sigma_i \, c_i(\mu,\Lambda) \, O_i(\mu)$$

c numbers providing gateway for heavy d.o.f. with frequencies $> \mu$

local operators containing dynamical, i.e. active fields with frequencies $\leq \mu$

New Physics!

$K \rightarrow \mu^+\nu\pi$ $Pol_\perp(\mu) = \langle \mathbf{s}_\mu \cdot (\mathbf{p}_\mu \times \mathbf{p}_\pi)/|\mathbf{p}_\mu \times \mathbf{p}_\pi|\rangle$ -- T odd moment

$K^+ \rightarrow \mu^+\nu\pi^0$

$Pol_\perp(\mu) = (-1.7 \pm 2.3 \pm 1.1)\times 10^{-3}$ vs. $Pol_\perp^{SM}(\mu) < 10^{-6}$

➻ a clean search for CP via Higgs dyn.

Why not search in $K_L \rightarrow \mu^+\nu\pi^-$?

Menu for Lecture III

I Establishing CKM as a Theory: ~~CP~~ in B Decays

Intermezzo 1 — "Praise the gods 2x for EPR correlations"

Intermezzo 2 — On Final State Interactions & CPT

II On Measuring other ~~CP~~ Observables in $B_{d,u}$ Decays

III ~~CP~~ in B_s Decays -- an Independent Chapter in Nature's Book

IV Rare B Decays

V Summary of Lecture III

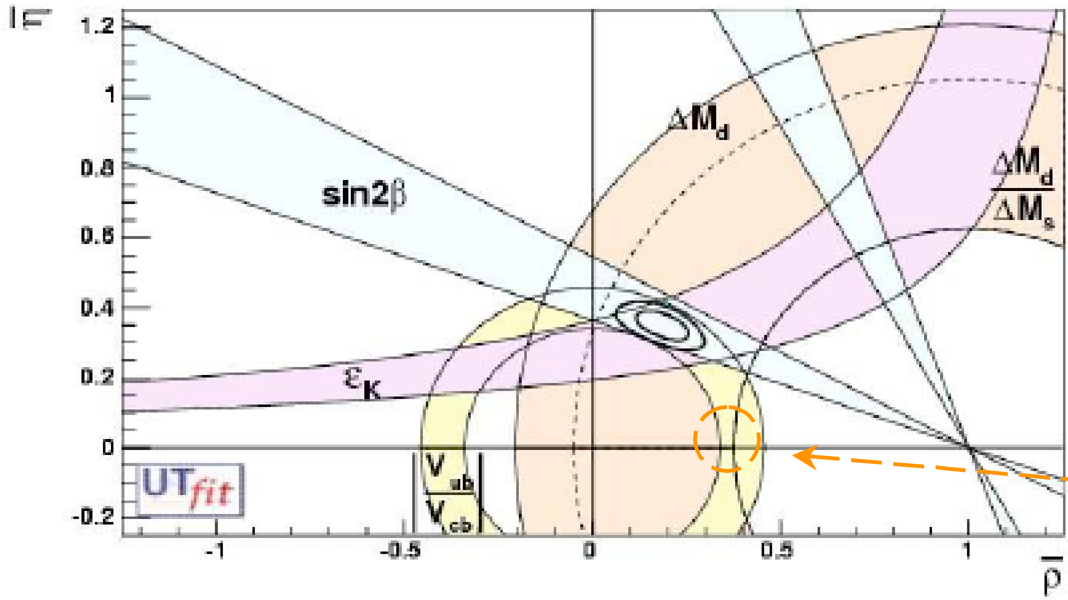
I Establishing CKM as a Theory: ~~CP~~ in B Decays

Era of beauty factories: BABAR, BELLE, CDF, D0

Act 1: $B \to \psi K_S$ predicted in 1980

- 1997/98 OPAL $\sin 2\phi_1 = 3.2^{+1.8}_{-2.0} \pm 0.5$
- 1999 CDF: $\sin 2\phi_1 = 0.79 \pm 0.44$
- 2003 BELLE: $\sin 2\phi_1 = 0.733 \pm 0.057 \pm 0.028$
  BABAR: $\sin 2\phi_1 = 0.741 \pm 0.067 \pm 0.03$
  world average $\sin 2\phi_1 = 0.736 \pm 0.049$
- 2004 world average $\sin 2\phi_1 = 0.726 \pm 0.037$
- Summer 2005
  world average $\sin 2\phi_1 = 0.685 \pm 0.032 \pm ??$

➥ it is there, it is huge -- as expected!



$\sin 2\,\phi_1|_{WA'04} = 0.726 \pm 0.037$ vs. $\sin 2\,\phi_1|_{CKM} = 0.725 \pm 0.065$

at present:
without ε_K & $\sin 2\phi_1$ `flat' CKM triangle still allowed
[unless accept QCD Fact.'s verdict on $BR(B \to K\,\pi)$]

if $\Delta M(B_s)$ measured `soon':

$|V(ub)/V(cb)|$ & $\Delta M(B_s)$ require non-trivial CKM triangle
`CP insensitive observables imply CP!'

➥ summer '01:

- CKM paradigm has become a ***tested*** theory!
- `demystification of ~~CP~~':

  if dynamics can support ~~CP~~, it can be large!

  i.e., observable phases can be large!

➬ `demystification' **completed**

if **find** ~~CP~~ **anywhere** in lepton sector

☞ CKM explains naturally why CP invariance is a `near miss' in K_L decays: 1st & 2nd families almost decoupled from 3rd!

- baryon # of Universe (Sakharov '65)
  1. baryon number changing processes √
  2. ~~CP~~ !
  3. Universe out of thermal equilibrium
     EWSB & GUTSB √

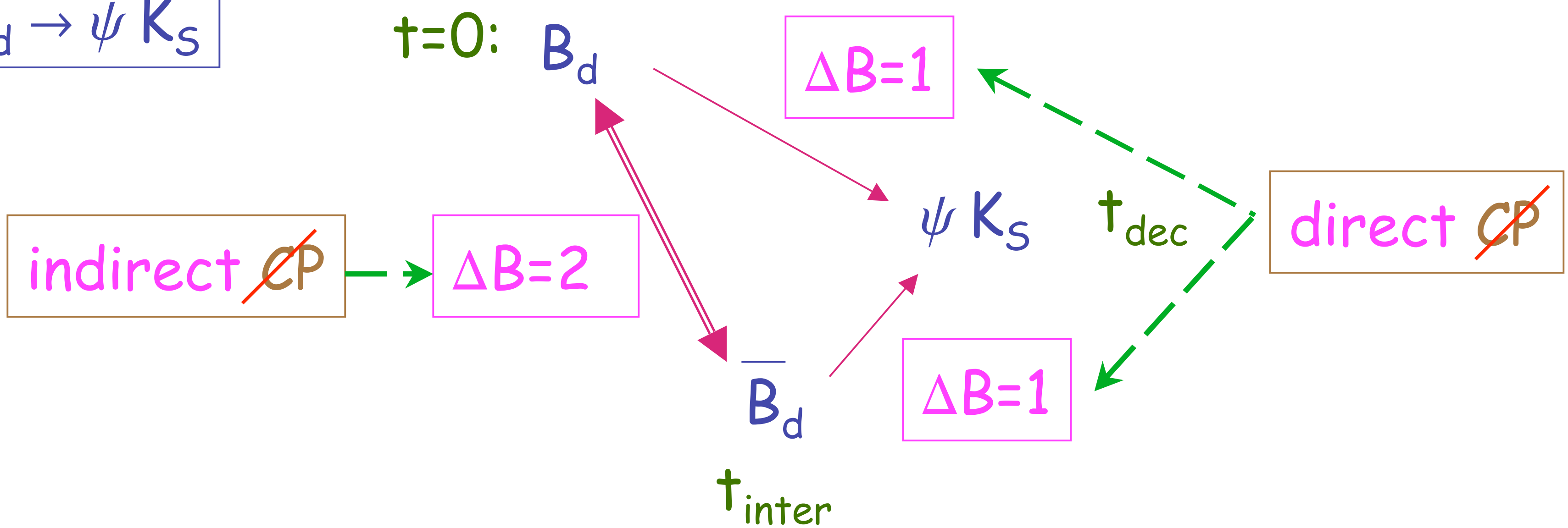
- 😐 *standard* CKM irrelevant for baryon number of universe
- ☺ New Physics exists!
- ☺ New CP Paradigm: ~~CP~~ phases can be large

Intermezzo 1

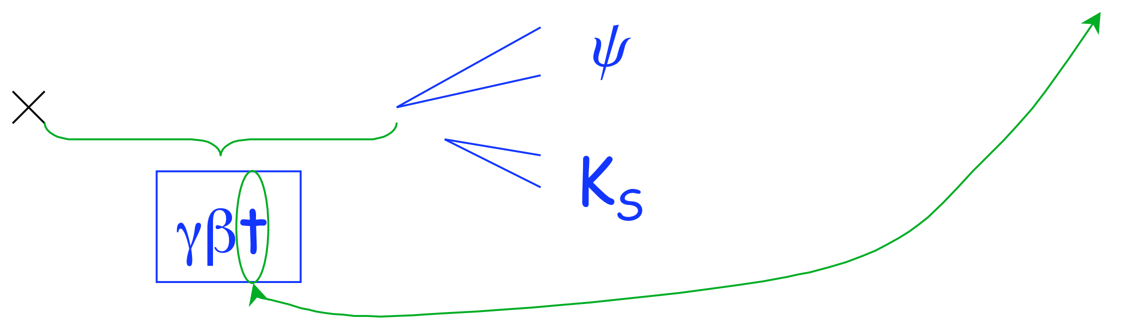
"Praise the gods 2x for EPR correlations"

due to CPT √ ~~CP~~ realized through complex phases

$B_d \to \psi K_S$



☺ $\text{rate}(B_d\ [\bar{B}_d](t_{dec}) \to \psi K_S) \propto e^{-\Gamma t}(1 - [+]\ A \sin\Delta m_d t)$

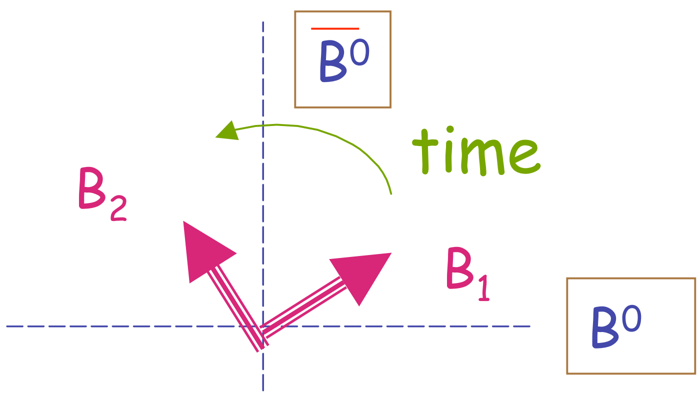


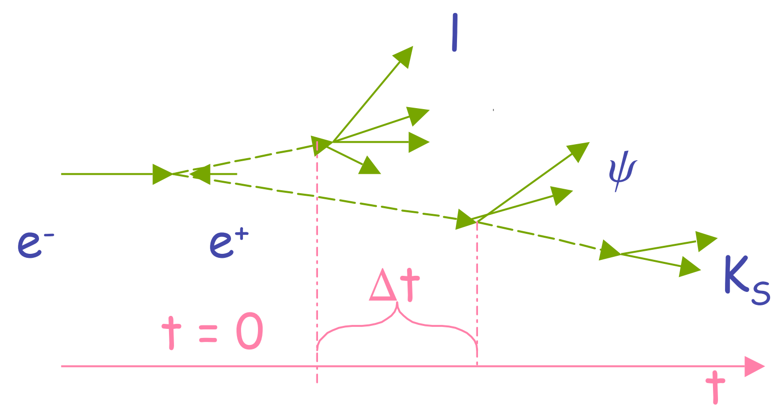
☹ $e^+e^- \to B_d \bar{B}_d$: $c\tau$ ~ 0.45 mm vs. product. region ~ 1 mm

asymmetry washed out?

☺ EPR to the rescue!

$e^+e^- \to B_1 B_2$ in C=- : Bose-Einstein $B_1 \perp B_2$ -- till decay!



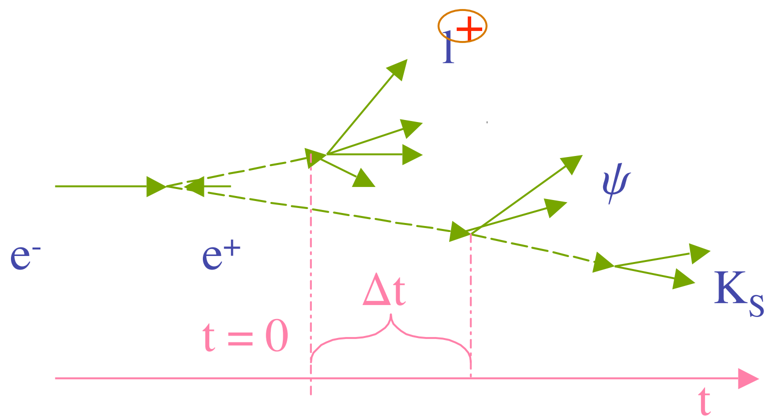


➥ need to measure only Δt time interval between decays

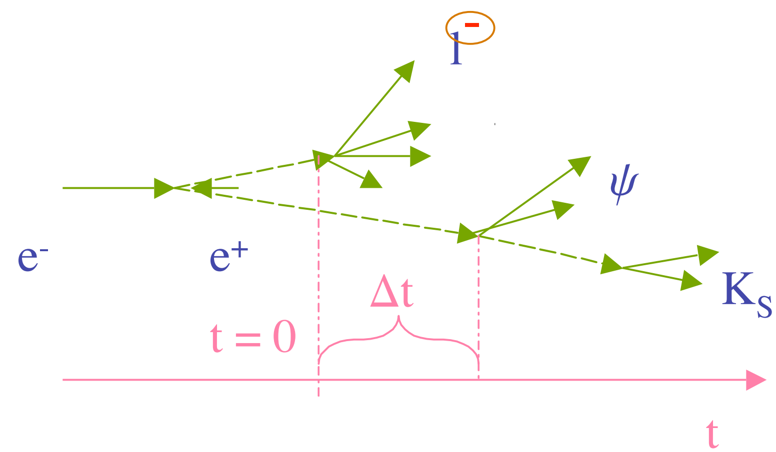
rate($e^+e^- \to B_d\bar{B}_d \to [l^\pm X]_t[\psi K_S]_{t+\Delta t}$) ~ ... (1 $\pm$ $A\sin\Delta m_d\Delta t$)

☹ symmetric $e^+e^- \to \Upsilon(4S) \to BB$:
cannot resolve B decay vertices & $\int d\Delta t ... \sin\Delta m_d \Delta t = 0$!

☺ P. Oddone: asymmetric e^+e^- collider to give boost to BB!

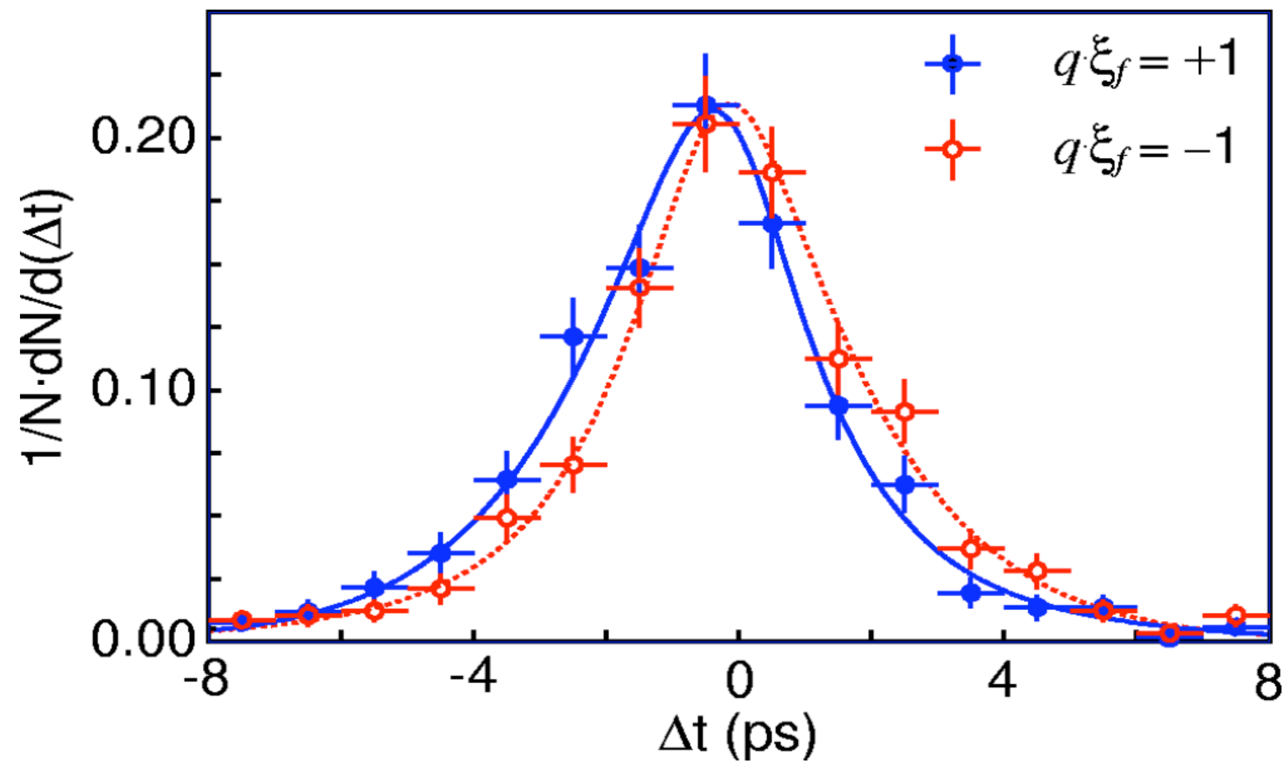


vs.

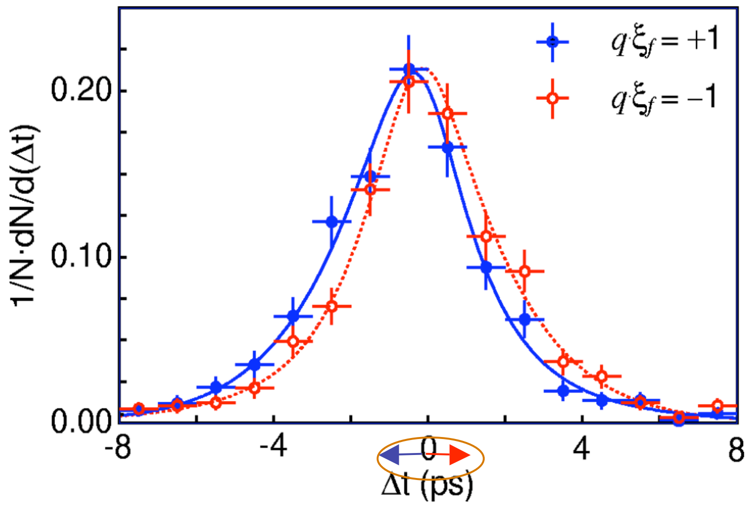


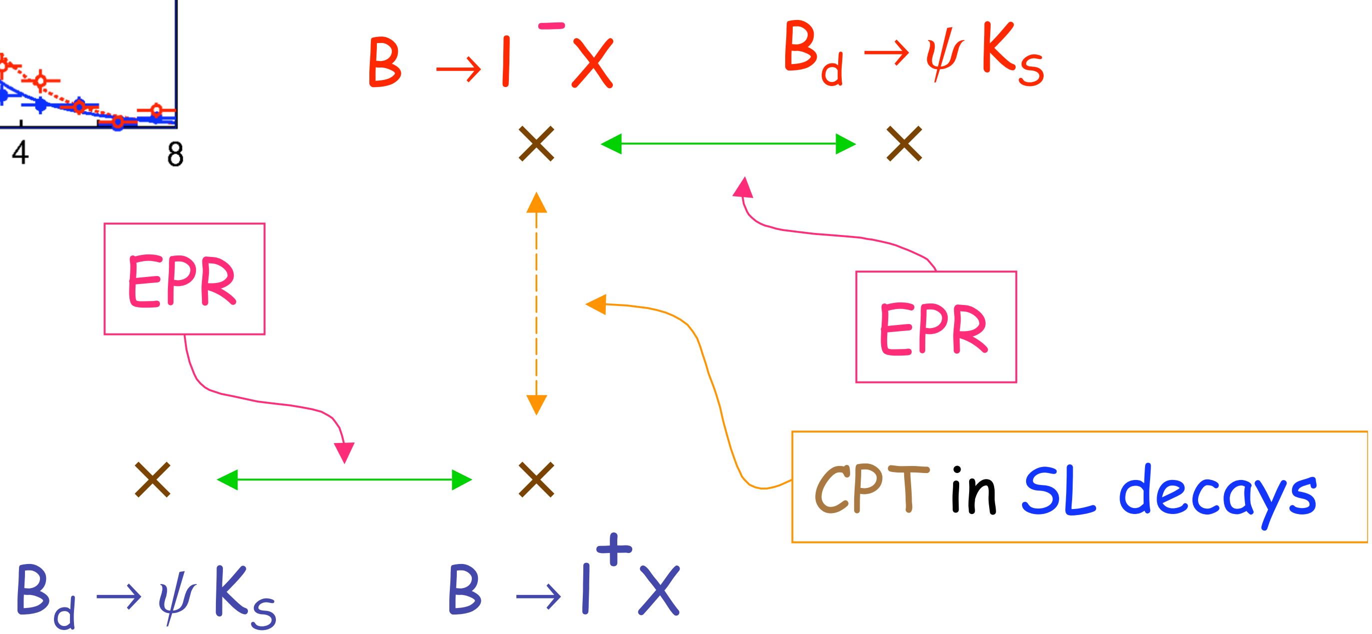
- if $e^+e^- \to l^+ X + \psi K_S \neq e^+e^- \to l^- X + \psi K_S$

- ~~CP~~ !



There is even more to it: $\not{CP} \Leftrightarrow \not{T}$ in B decays





➥ $\not{CP} \Leftrightarrow \not{T}$ in $B \to \psi K_S$

assuming CPT merely in SL B decays

Act 2: $B \to \pi^+ \pi^-$

$$\frac{R_+(\Delta t) - R_-(\Delta t)}{R_+(\Delta t) + R_-(\Delta t)} = S \sin \Delta m_d \Delta t + C \cos \Delta m_d \Delta t,\ S^2 + C^2 \leq 1$$

$$S = \frac{2\, \mathrm{Im}\, (q/p)\rho(f_{CP})}{1 + |(q/p)\rho(f_{CP})|^2},\quad C = \frac{1 - |(q/p)\, \rho(f_{CP})|^2}{1 + |(q/p)\rho(f_{CP})|^2}$$

if $S(f_1) \neq \eta\,(f_1)\, \eta\,(f_2)\, S(f_2)$ or $C(f) \neq 0 \Rightarrow$ direct ~~CP~~!

- Summer 2005

  BELLE: $S = -0.67 \pm 0.16 \pm 0.06,\ C = +0.56 \pm 0.12 \pm 0.06$

➥ ~~CP~~ with 5.2 σ

direct ~~CP~~ with 3.3 σ [superweak: $C=0$, $S = -(0.75 - 0.82)$]

BABAR: $S = -0.30 \pm 0.17 \pm 0.03,\ C = +0.09 \pm 0.15 \pm 0.04$

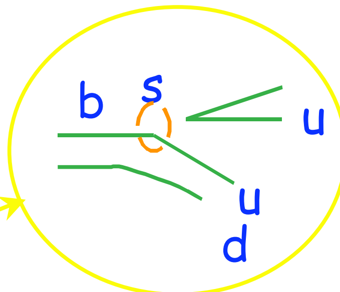
➥ guestimate: $90^\circ < \phi_2 < 146^\circ$ consistent with

indirect estimates $77^\circ < \phi_2 < 122^\circ$

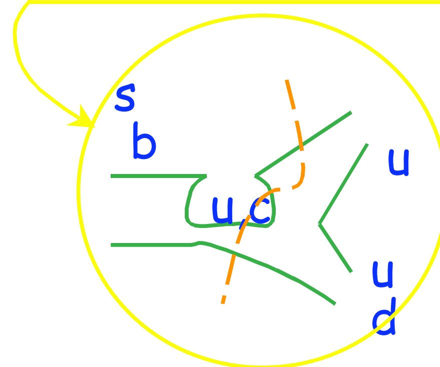
Act 3: More on Direct ~~CP~~

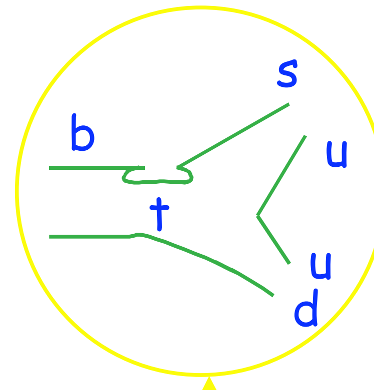
$B_d \to \pi^- K^+$

local operator with weak phase



nonlocal operator with strong phase





local operator not needed, but there

1987: $BR(B_d \to \pi^- K^+) \sim 10^{-5}$, $A_{CP} = -0.10$

2004

BABAR *hep-ex/0408057, submitted to PRL*

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

4.2σ

Belle **Confirmation at ICHEP04**

Signal (274M $B\bar{B}$ pairs): 2140 ± 53

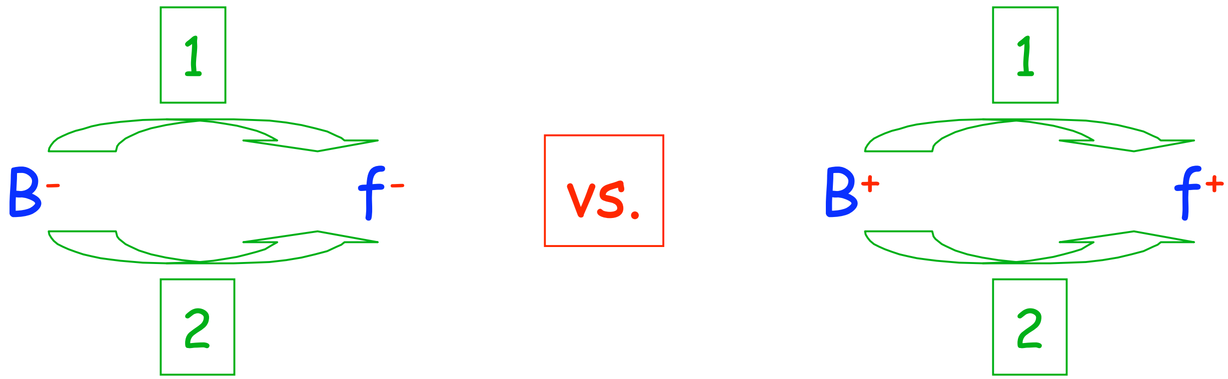
$$A_{CP} = -0.101 \pm 0.025 \pm 0.005$$

3.9σ

Average $A_{CP} = -0.114 \pm 0.020$

Intermezzo 2

On Final State Interactions & CPT



$$\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+) \propto \sin(\phi_1^w - \phi_2^w)\,\sin(\delta_1^{str} - \delta_2^{str})$$

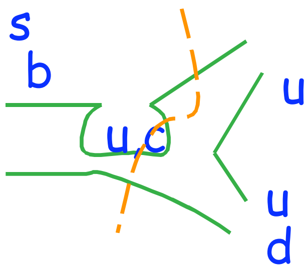
➥ need both nontrivial weak & strong phase shifts!

✍ often not appreciated: CPT constraints on strong phase shifts

simple toy scenario: 2 final states a,b that can rescatter into each other

$$\Delta\Gamma(B \to a) = 4\, \mathcal{T}^{resc}_{ab}\, \mathrm{Im}\, T^*_a T_b = -\,\Delta\Gamma(B \to b)$$

Penguins are very smart -- know about CPT constraints!



~~CP~~ in $B \to K + \pi$'s compensated by $B \to D\overline{D}_s + \pi$'s ...

Caveat: T odd moments -- $\langle \mathbf{p}_1 \bullet (\mathbf{p}_2 \times \mathbf{p}_3) \rangle$ -- can be induced by FSI with T invariant dynamics!

remember $K_{\mu 3}$ decays

reason: T anti-linear

$$[X,P] = i\hbar$$

a Paradigm of large ~~CP~~ in B decays established in qualitative & quantitative agreement with CKM theory in 3 quite distinct B_d channels

- commensurate with ~~T~~ and with
- large direct ~~CP~~ in 2 channels

yet …

- this should not have come as a shock …
- it does not weaken the need to search for NP in B decays

II On Measuring other $\not{CP}$ Observables in B Decays

Observables ?

Caveat: must be re-phasing invariant under $|B^0\rangle \to e^{-i\xi}|B^0\rangle$

- $|T(B \to f)| \neq |T(\bar{B} \to \bar{f})|$ — $\Delta B = 1$
- $|q| \neq |p|$ — $\Delta B = 2$
- $\mathrm{Im}(q/p)\bar{\rho}(f)$, $\bar{\rho}(f) = T(\bar{B} \to f)/T(B \to f)$ — $\Delta B = 1$ & $\Delta B = 1$

- B^{ch}, Λ_b: only direct $\not{CP}$
- $\bar{B}^0 \to l^+ X$ vs. $B^0 \to l^- X$: only indirect $\not{CP}$ within SM
- $B^0/\bar{B}^0 \to f$: direct & indirect $\not{CP}$

$$\not{CP} = S \sin\Delta M_B t + C \cos\Delta M_B t$$

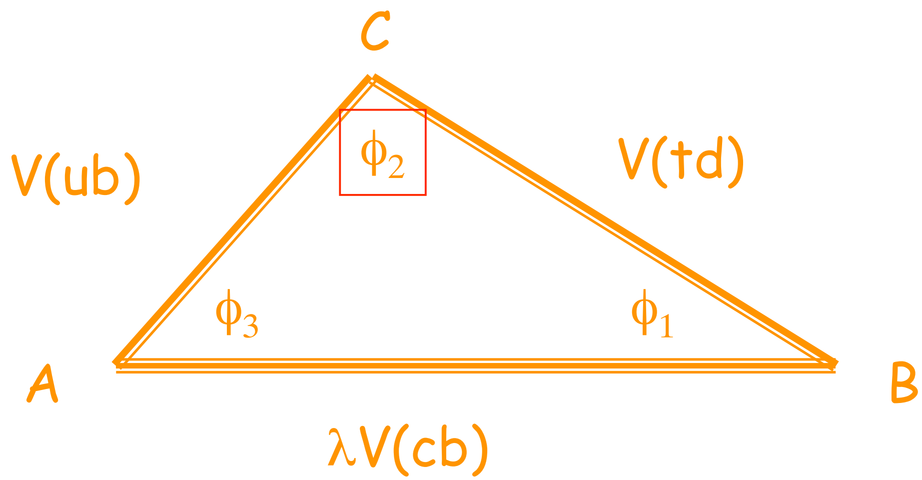
$$C = \frac{1 - |(q/p)\,\bar{\rho}(f_{CP})|^2}{1 + |(q/p)\,\bar{\rho}(f_{CP})|^2}$$ unambiguously direct

$$S = \frac{2\,\mathrm{Im}\,(q/p)\overline{\rho}(f_{CP})}{1 + |(q/p)\,\overline{\rho}(f_{CP})|^2}$$

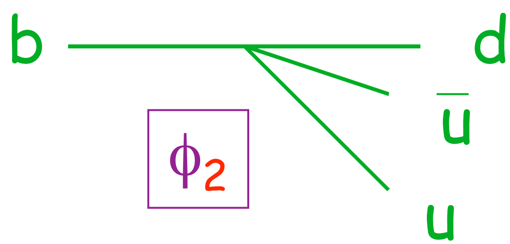
- seen in single channel only: no true distinction direct/indirect
- if $S(f_1) \neq \eta\,(f_1)\,\eta\,(f_2)\,S(f_2) \Rightarrow$ direct ~~CP~~ !

➽ this source of $\Delta B=1$ ~~CP~~ might not be seen via C contribution

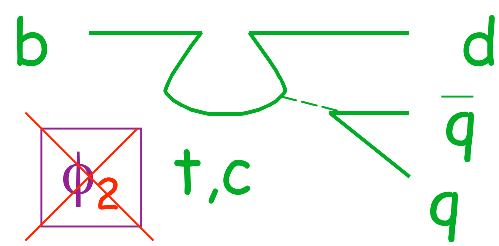
II.1 ϕ_2 from ~~CP~~ in $B_d \to$ pions



2 operators contribute:



`tree'



`Penguin'

`pollution'

blame us -- not the Penguins!

to isolate `pollution' through isospin decomposition:

- $B^{0,\pm} \rightarrow \pi^{+,0}\pi^{-,0}, \pi^{\pm}\pi^{0}$

  challenging experimentally, yet reliable theoretically

- $B^{0,\pm} \rightarrow \rho^{+,0}\pi^{-,0}, \rho^{\pm}\pi^{0}, \pi^{+,0}\rho^{-,0}, \pi^{\pm}\rho^{0}$

less challenging experimentally, yet reliable theoretically??

$B \rightarrow \pi\pi\pi$: $\rho\pi$ vs. $\sigma\pi$ vs. ?? (U. Meissner, S. Gardner)

- $B^{0,\pm} \rightarrow \rho^{+,0}\rho^{-,0}, \rho^{\pm}\rho^{0}$

even better experimentally, yet even worse theoretically

$B \rightarrow \pi\pi\pi\pi$: $\rho\rho$ vs. $\sigma\rho$ vs. $\sigma\sigma$ vs. $\rho\pi\pi$ vs. $\sigma\pi\pi$ vs. ...

Caveat: the σ -- even if it exists -- not described by Breit-Wigner parametrization

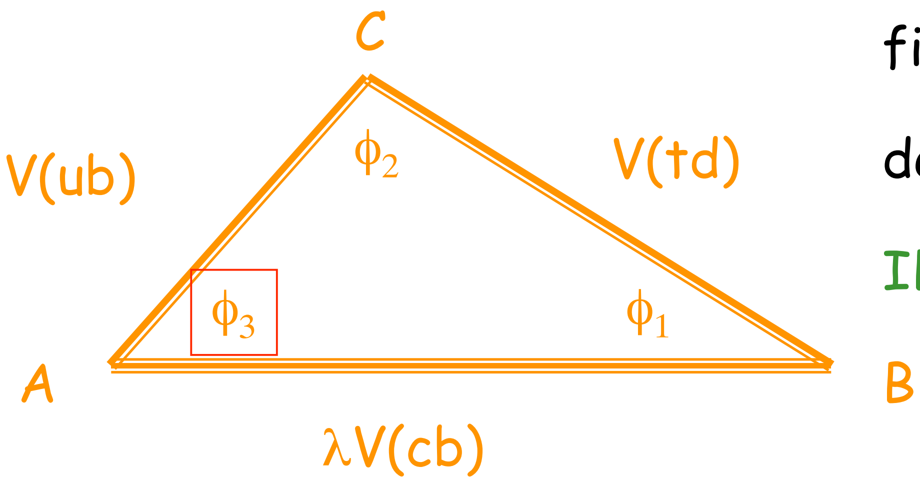
memento: precision -- say ±5% --required!

- need expertise from low-energy hadronization

  (chiral dynamics, Dalitz plot)
- valuable information to be gained from

  $D_{(s)} \to l\,\nu\,K\pi\,/\pi\pi/KK$

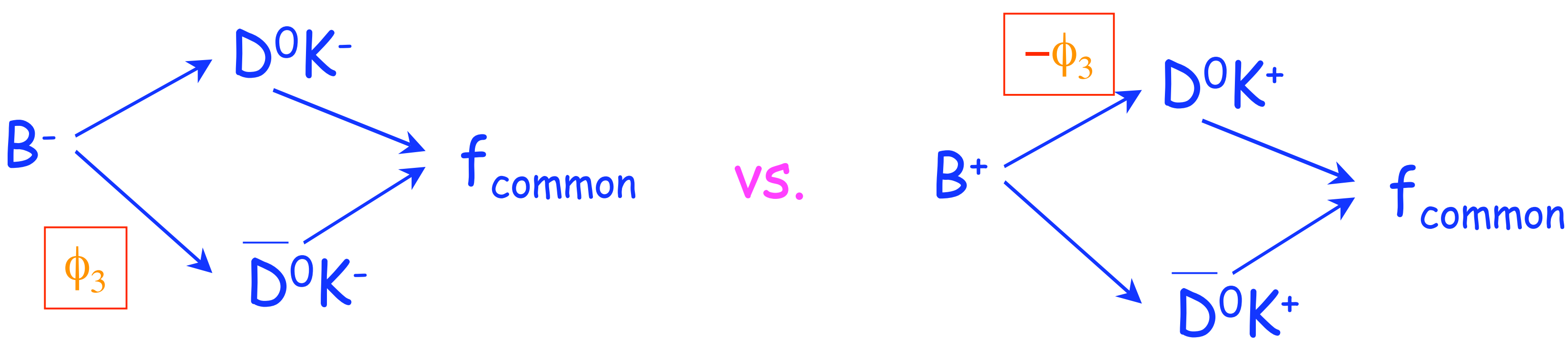
II.2 ϕ_3 from $\not{CP}$ in $B^\pm \to D^{neut} K^\pm$



first mentioned by Sanda in '80

dedicated paper

IB, A.Sanda, PLB211 ('85)213



original idea: $f_{common} = h_1 h_2$ -- $K_S\pi^0, K^+K^-, \pi^+\pi^-, K^+\pi^-, K^-\pi^+$

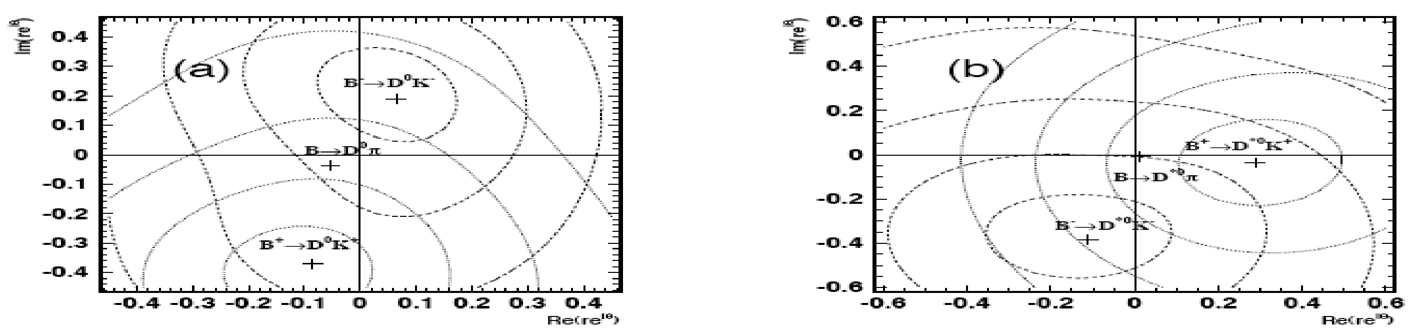
drawback: small BR's

new idea implemented by BELLE:
use f_{common} = $K_S\pi^+\pi^-$ coupled with Dalitz plot analysis
requires a lot of investment if effort -- yet pays handsome profit in cross checks ⟹ confidence!

A. Poluektov *et al.* (Belle Collaboration), hep−ex/0406067, to appear in PRD.

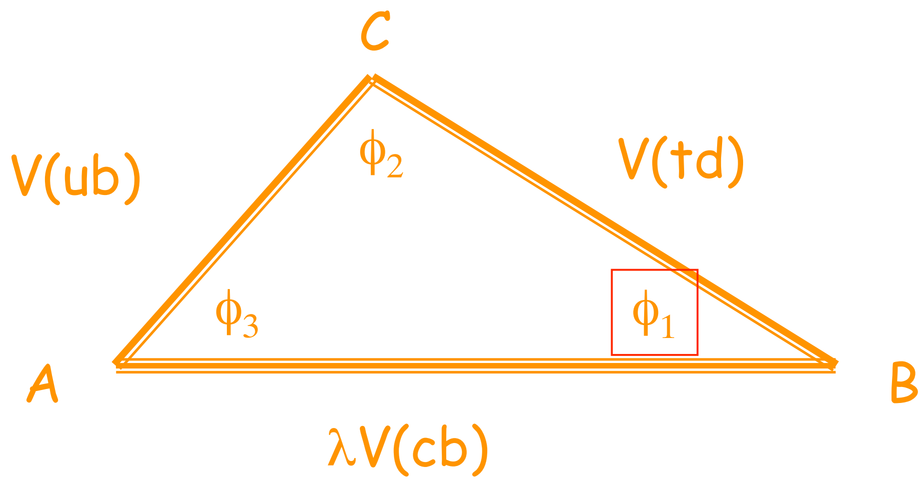
Using $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ $(D^* \to D\pi^0)$

$$\phi_3 = 77^\circ \,{}^{+17^\circ}_{-19^\circ}\,(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model})$$

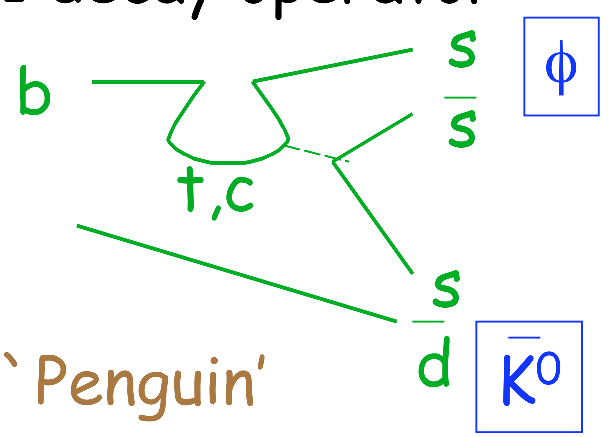


I consider it still a pilot study -- yet a very promising one -- showing the power of using hadronization as a (difficult) ally

II.3 ϕ_1 from ~~CP~~ in $B_d \to$ 3 kaons



1 decay operator:



'Penguin'

excellent for searching for NP

- pure loop effect in SM
- single $\Delta B=1$ operator
- reliable SM prediction

$\sin 2\phi_1(B_d \to \psi K_S) \approx \sin 2\phi_1(B_d \to \phi K_S)$

- ϕ a narrow resonance

measure

$\sin 2\phi_1 = 0.726 \pm 0.037$ from $B_d \to \psi K_S$

Summer 2003

- BELLE: $\sin 2\phi_1^{eff} = -0.96 \pm 0.5 \pm 0.010$
- BABAR: $\sin 2\phi_1^{eff} = +0.45 \pm 0.43 \pm 0.07$

Summer 2004

BABAR [hep-ex/0408072]

"$\sin 2\phi_1$" $= +0.50 \pm 0.25 \,^{+0.07}_{-0.04}$

A $= 0.00 \pm 0.23 \pm 0.05$

BELLE [hep-ex/0409049]

"$\sin 2\phi_1$" $= +0.06 \pm 0.33 \pm 0.09$

A $= +0.08 \pm 0.22 \pm 0.09$

ϕK^0

4.5% (MC)

SVD1:		SVD2:
$S = -0.68 \pm 0.46$	$\leftrightarrow$	$S = +0.78 \pm 0.45$
$A = -0.02 \pm 0.28$		$A = +0.17 \pm 0.33$

many systematic checks, all ok

Summer 2005

measure

$\sin 2\phi_1 = 0.685 \pm 0.032 \pm ??$ from $B_d \to \psi K_S$

$$\text{“}\sin 2\phi_1\text{”} = +0.44 \pm 0.27 \pm 0.05$$
$$A = -0.14 \pm 0.17 \pm 0.07$$

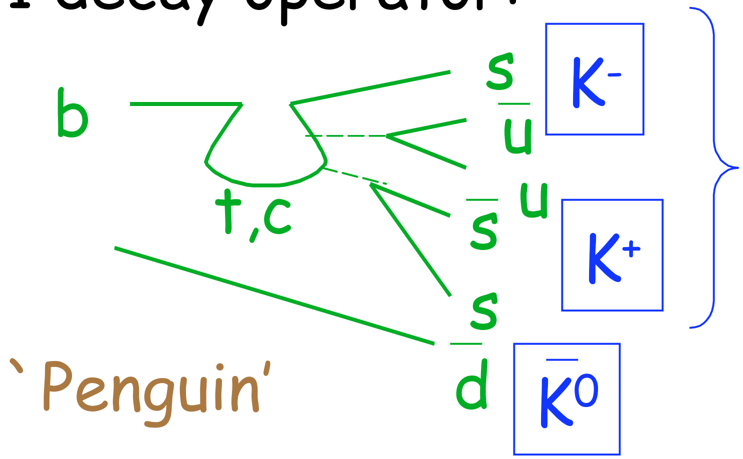
Summer 2003

- BELLE: $\sin 2\phi_1^{eff} = -0.96 \pm 0.5 \pm 0.010$

Summer 2004

$$\text{“}\sin 2\phi_1\text{”} = +0.06 \pm 0.33 \pm 0.09$$
$$A = +0.08 \pm 0.22 \pm 0.09$$

1 decay operator:



$\phi, f_0(980)$, …

$\not{CP}(B_d \to \phi K_S) = - \not{CP}(B_d \to f_0(980) K_S)$

i.e., a smallish `pollution' by $f_0 K_S$

reduces $\not{CP}$ observed in ϕK_S

➥ need to perform full Dalitz plot analysis for

- $B_d \to K^+ K^- K_S$,
- $B_d \to K_S K_S K_S$
- $B^+ \to K^+ K^- K^+$,
- $B^+ \to K^+ K_S K_S$

S. Bianco's razor:

measure $\not{CP}$ in $B_d \to [K^+ K^-]_M K_S$ as function of cut on M

II.4 Superweak $\not{CP}$ in SL B_d Decays

$$a_{SL}(B_d)= \frac{\Gamma(\bar{B}_d \to l^+ X) - \Gamma(B_d \to l^- X)}{\Gamma(\bar{B}_d \to l^+ X) + \Gamma(B_d \to l^- X)}$$

- suppressed by $\Delta\Gamma/\Delta M$
- KM: $a_{SL}(B_d) = \; < 10^{-3}$

III ~~CP~~ in B_s Decays -- an Independent Chapter in Nature's Book

`Think outside the box!' -- several SM relations unlikely to hold beyond minimal extensions of SM

B_u/B_d and B_s 2 different chapters in

Nature's Book on Fundamental Dynamics!

ΔM_s

within SM: $\Delta M_s/\Delta M_d = B_s f^2(B_s)/B_d f^2(B_d)\ |V(ts)|^2/|V(td)|^2$

$$\Delta M_s \begin{cases} \sim 15 - 30 \ \text{psec}^{-1} & \text{SM-CKM} \\ > 14.5 \ \text{psec}^{-1} & \end{cases}$$

$\Delta\Gamma_s$

	theoret. predict. based on quark box diagram	data
$\Delta\Gamma(B_s)/\Gamma(B_s)$	$0.18(f_B/0.2GeV)^2$ '87	0.65 ± 0.3 CDF
	0.12 ± 0.04 '04	0.23 ± 0.17 D0

my heart wishes $\Delta\Gamma(B_s)/\Gamma(B_s) \sim 0.5$

yet my head tells me $\Delta\Gamma(B_s)/\Gamma(B_s) > 0.25$ very unlikely

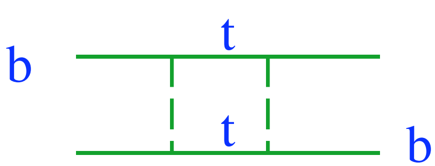
$\Delta\Gamma_s$: $B_s \rightarrow c\,\bar{c}\,s\,\bar{s} \rightarrow \bar{B}_s$

- enhance $\Delta\Gamma_s$
  - ➥ enhance Γ_s

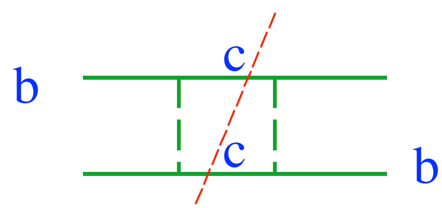
$\Delta\Gamma(B_s)/\Gamma(B_s) > 0.25$ inconsistent with $\langle\tau(B_s)\rangle/\tau(B_d) = 1 \pm \sim 0.01\text{-}0.02$

☞ quark box diagram less reliable for $\Delta\Gamma(B)$ than for $\Delta M(B)$

$\Delta M(B)$



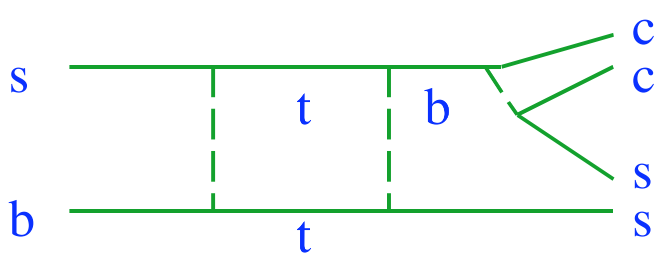
$\Delta\Gamma(B)$



onset of duality?

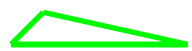
chance for massive impact of NP:

- $B_s \to \mu^+\mu^-$ — in some SUSY scenarios $(tg\beta)^6$!
- ~~CP~~ in $B_s \to \psi\ \phi/\eta$ — in CKM ~ 2 %



quarks of 2nd and 3rd family only!

several × 10 % possible with NP



bs triangle: $V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} = \delta_{bs} = 0$

- ~~CP~~ in $B_s \to \phi\ \phi$ — much more than a repetition of $B_d \to \phi\ K_S$ -- 3 partial waves!
- $B_s \to l^+X$ vs. $B_s \to l^-X$ — in CKM < 10^{-4}, yet could be enhanced by ~ 100!

IV Rare B Decays

IV.1 Loop Induced Transitions

$B \to \gamma X_q$

Rate as well as photon spectrum in remarkable agreement with predictions (see Lecture IV)

$B \to l^+ l^- X_q$

$BR(B \to l^+ l^- X)$ $\begin{cases} =(6.2 \pm 1.1 \pm 1.5) \times 10^{-6} & \text{BELLE/BaBar} \\ = (4.2 \pm 0.7) \times 10^{-6} & \text{SM} \end{cases}$

- larger # of effective operators
- more observables: spectra of leptons, their forward-backward & CP asymmetries

☞ with the statistics of Super-B can (start to) mine this wealth of potential information on New Physics

➥ much wider window to
- find New Physics &
- diagnose its features

G. Hiller: some of this info can be obtained in a model independent way by studying the position of the zero in the lepton forward-backward asymmetry in the exclusive $B \to l^+ l^- K^*$, i.e. at a hadronic collider

Case study

deviations from SM in $B \to \phi K_S$ constrained by $B \to \gamma X_s$

-- unless photon carries wrong helicity

- contributes quadratically to $\Gamma(B \to \gamma X_s)$
- while linearly to $\not{C}P$ in $B \to \phi K_S$

How to check?

- measure photon polarization in $B \to \gamma X_s$

  $B \to \gamma(K\pi)$
- analyze form factors in $B \to l^+l^-X_s$
- measure form factors in $B \to l^+l^-K$, $l^+l^-(K\pi)$
  - rely on LQCD validated in $D \to l\nu K$, $l\nu(K\pi)$

$B \to \nu\nu X_q$

$BR(B \to \nu\nu K)$ $\begin{cases} \leq 7.0 \times 10^{-5} & \text{BaBar} \\ = (3.8^{+1.2}_{-0.6})\times 10^{-6} & \text{SM (BuHiIs)} \end{cases}$

$BR(B \to \nu\nu X)$ $\begin{cases} \leq 7.7 \times 10^{-4} & \text{ALEPH} \\ = 3.5 \times 10^{-5} & \text{SM} \gg BR(B\to l^+l^- X) \end{cases}$

- dynamical info in general different from $B\to l^+l^- X$

can a Super-B detector be sufficiently hermetic?

IV.2 Other Rare B Decays

$B \to \tau\nu D$

search for charged Higgs contrib. in large tan β scenario in

$\Gamma(B \to \tau \nu D) / \Gamma(B \to \mu \nu D)$ (Miki, Miura & Tanaka)

Yet

☹ hadronic form factors drop out only for $m_{b,c} \to \infty$

☺ BPS formalism (Uraltsev) allows to calculate to all orders in $1/m_Q$

if validated in extracting V(cb) from $B \to \tau\nu D$

➥ sensitive probe for non-minimal Higgs dynamics due to novel theoretical tool

$B \to \tau\nu X_c$

see Lecture IV

IV Summary of Lecture III

Success of CKM theory -- while not unexpected -- truly impressive

➥ have a tested theory of $\not{CP}$

`demystification' of $\not{CP}$: it is not intrinsically small

`demystification' completed if $\not{CP}$ found anywhere in lepton sector

Let me clarify `expected'

- the discovery of large CP in B decays validated a theory & a paradigm
- data are the final arbiter: established >>>> expected/predicted
- the discovery of Z^0 and $W^{\pm}$ crowned one of the major intellectual human triumphs of the 2nd half of the 20th century the fact they were predicted by the SM does not detract from that!

only now reaching territory where significant deviations from CKM can `realistically' hoped for

- loop induced transitions -- $B \to l^+ l^- X$, $\nu\nu X$ -- not a luxury, but an essential & highly sensitive probe

- B_s transitions independent chapter in Nature's book