CP Violation

and the

CKM Matrix

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Why is $\not{CP}$ interesting?

Observations of $\not{CP}$;
Status and Prospects of the "Unitarity triangle"

$\not{CP}$ in B decays

Beyond the Kobayashi-Maskawa mechanism

Lattice 2001, Berlin, 19/08/2001

$\not{C}\!\!\not{P}$ in the context of contemporary particle phenomenology

Structural Simplicity of the SM related to gauge symmetry

$\mathcal{L}_{gauge}$

[LEP/SLD '89 - '00]

Important questions in particle physics are related to symmetry breaking

$\mathcal{L}_{Yuk} + \mathcal{L}_{Higgs} + \ldots\ldots$

Electroweak
[LEP]
LHC 2006 - ..
(+ Tevatron)

gauge symmetry

CP
B factories
2000 - ...

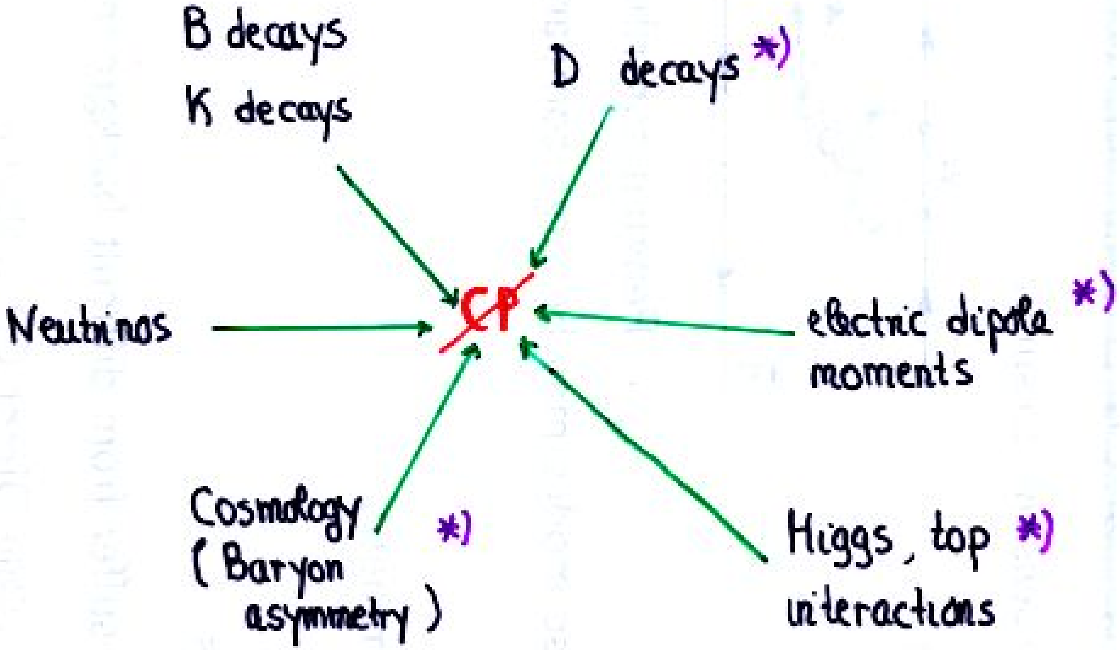
flavour symmetry

Lepton number
(B-L, lepton flavour baryon number)

Neutrino experiments
... - 1998 - ....

SUSY
GUT
.....

$\not{CP}$ relates to various areas of phenomenology and theoretical tools:



*) usually requires some physics beyond the SM

Tools:

- chiral PT (K)
- heavy quark expansion (B)
- perturbative QCD + renormalisation group
- lattice QCD ("weak matrix el's")

Standard Model of $\not{CP}$ – trivial and mysterious

$\theta \cdot \frac{g_s^2}{32\pi^2} G^A_{\mu\nu} \tilde{G}^A_{\mu\nu}$

$\theta < 10^{-9}$ [from Electric Dipole Moments]

Strong CP Problem

$\frac{f_{ij}}{\Lambda} [(\bar{L}^c_L)_i i\tau^2 \phi][\phi^T i\tau^2 L]$

Majorana neutrino masses

3 $\not{CP}$ - Phases

$J_\nu \propto \underbrace{|U_{e3}|}_{\lesssim 0.1\,?} \sin\delta$

SM of $\not{CP}$

$\frac{g_w}{\sqrt{2}} \bar{u}_{Li} \gamma^\mu V_{ij} d_{Lj} W^+_\mu + h.c.$

CKM matrix

1 $\not{CP}$ phase [responsible for $K_L \to \pi^+\pi^-$]

$u_i \sim (u,c,t)$
$d_i \sim (d,s,b)$

$J_q \sim 4 \cdot 10^{-5} \sin\delta_{KM}$

charged (but not neutral!) current interactions

- only a few phases
- additional, poorly understood suppression

Standard Model of $\not{C}\not{P}$

$$-\mathcal{L}_{Yuk.} = Y^d_{ij}\,\bar{Q}'_{Li}\,\phi\, d'_{Rj} + Y^u_{ij}\,\bar{Q}'_{Li}\,\tilde{\phi}\, u'_{Rj} + Y^e_{ij}\,\bar{L}'_{Li}\,\phi\, e'_{Rj} + h.c.$$

$$\Big\downarrow \qquad d'_L = U^d_L d_L\,,\quad u'_L = U^u_L u_L\,,\ \ldots$$

flavour-diagonal, CP conserving Z^0, H^0 interactions
flavour-non-diagonal $W^\pm$ interactions which may "naturally" violate CP if more than two generations

CKM matrix

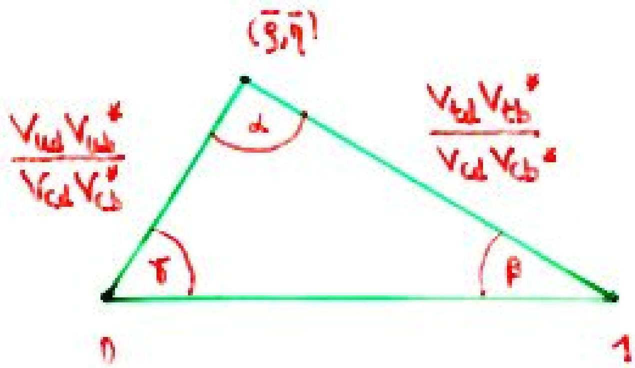
$$V = U^{u\dagger}_L U^d_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

unitary
1 Phase

$$\sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad [\lambda \approx 0.2]$$

"Unitarity Triangle"

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



Questions we would like to have the answer to :

- Is CP broken spontaneously (as gauge symmetry is) or explicitly ?

  [explicit in the SM unless $\delta_{KM} = 0$ but may be spontaneous in a more fundamental theory]

- Is $\cancel{CP}$ small because $\cancel{CP}$ - phases are small (" approximate CP symmetry ") or for other reasons ?

- Is the KM mechanism the only source of $\cancel{CP}$ at the TeV scale ?

  [probably not if there is new physics a the TeV scale , but then the question arises why we have not seen <u>more</u> $\cancel{CP}$ already.]

Unitarity triangle constraints

$$V_{ub} = |V_{ub}| e^{-i\gamma} = A\lambda^3 (\rho - i\eta)$$

$$V_{td} = |V_{td}| e^{-i\beta} = A\lambda^3 (1 - \rho - i\eta)$$

[PDG phase convention]

$\lambda = |V_{us}| \simeq 0.22$

$V_{cb} \leftrightarrow A\lambda^2$

Observables

$|V_{cb}|$
$|V_{ub}|$
$\Delta M_{B_d}, \Delta M_{B_s}$

CP - conserving

① ϵ
① ϵ'/ϵ
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$

$K\bar{K}$ mixing
\+ rare decays (K)

future

③ $\sin 2\beta$
⋮

$B\bar{B}$ mixing
\+ rare decays (B)

Recent fits: Ciuchini et al [hep-ph/0012308]
Höcker et al*) [hep-ph/0104062]

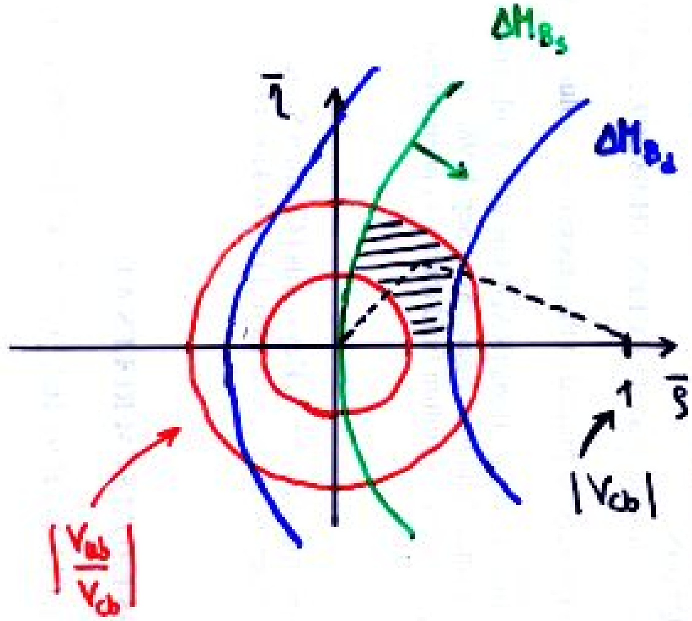
*) quote fit ranges from this

CP conserving constraints

$|V_{cb}|$, $|V_{ub}|$ from semi-leptonic B decay inclusive or exclusive

$|V_{cb}|$: $\pm$ 5%
heavy quark expansion

$|V_{ub}|$: $\pm$ 20%



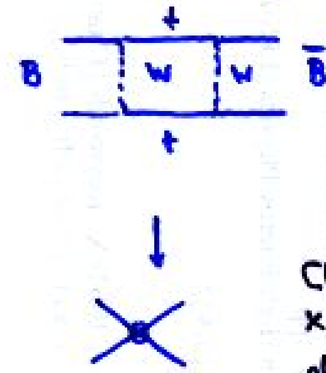
inclusive : heavy quark expansion, but need to suppress $b \to c$ backgrounds

cuts on $\frac{d\Gamma}{dq^2 dm_X^2} \longrightarrow \pm 5\%$??
[Bauer et al. Becher, Neubert]

exclusive: must rely on lattice QCD for $B \to M$ form factor to compare with $d\Gamma/dq^2$ at large q^2

probably a combination of both

$B\bar{B}$ mixing



CKM factor × matrix element of four fermion operator

ΔM_{B_d} : $f_{B_d}\sqrt{B_{B_d}}$ $\pm$ 15%

$\frac{\Delta M_{B_d}}{\Delta M_{B_s}}$: $\frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$ $\pm$ 6%

$\Uparrow$

lattice QCD

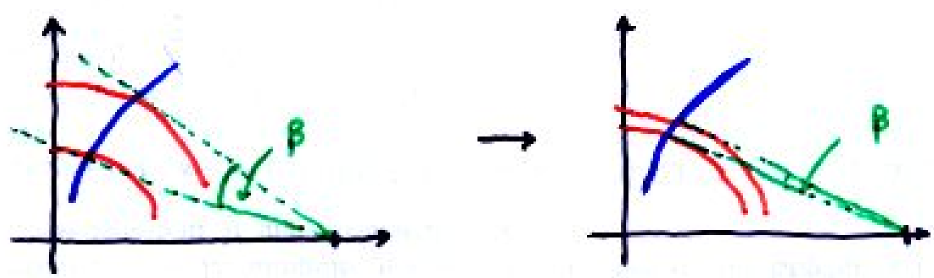
Improving the accuracy of $\left|\frac{V_{ub}}{V_{cb}}\right|$ is very important, because:

- it is the only constraint that is based on a tree process, hence insensitive to new physics

  ↪ determines the "true" KM parameters

- it is "orthogonal" to $B\bar{B}$ mixing

  ↪ determines the allowed range of $\sin 2\beta$ for comparison with direct measurement



Note: If ΔM_{B_s} follows the SM expectation it will be measured at the Tevatron in 2002-2003

$\cancel{CP}$ in kaon decays

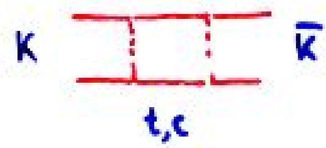
$\cancel{CP}$ in mixing (indirect)

$$K_L \approx K_2 + \bar{\varepsilon} K_1$$

$K_2 \downarrow 3\pi$ — CP odd

$K_1 \downarrow 2\pi$ — CP even

related to $K\bar{K}$ mixing



$|\varepsilon_K| \approx 2.27 \cdot 10^{-3}$ $\longrightarrow$ $\bar{\eta}\,(1.3 \pm 0.05 - \bar{\rho})$

[measured first in 1964]

uncertainties: B_K ← lattice!

$|V_{cb}|$

$\cancel{CP}$ in decay (direct)

$$\frac{\Gamma(K_L \to \pi^0\pi^0)\,\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\,\Gamma(K_L \to \pi^+\pi^-)} = 1 - 6 \cdot \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

- inconclusive before 1999

	NA48 (CERN)	KTeV (Fermilab)
1999	18.5 ± 7.3	28.0 ± 4.1 [rev. to 23.2 ± 4.4]
2001	15.3 ± 2.6	20.7 ± 2.8

$\times 10^{-4}$

$\cancel{CP}$ in decay amplitude established for the first time!

The theory of ε'/ε is more complicated than that of any other quantity discussed so far

- Short-distance physics : a lot of work but done (Munich + Rome)

$$\varepsilon'/\varepsilon \approx 16\cdot 10^{-4} \left[\frac{\mathrm{Im}\, V_{ts}^* V_{td}}{1.2\cdot 10^{-4}} \right] \cdot \left(\frac{110\,\mathrm{MeV}}{m_s(2\,\mathrm{GeV})} \right)^2 \cdot \left\{ \underbrace{B_6^{(1/2)} (1-\Omega_{IB})}_{\text{QCD penguin}} - 0.4 \left(\frac{\bar{m}_t}{165\,\mathrm{GeV}} \right)^{2.5} \underbrace{B_8^{(3/2)}}_{\text{Electroweak penguin}} \right\}$$

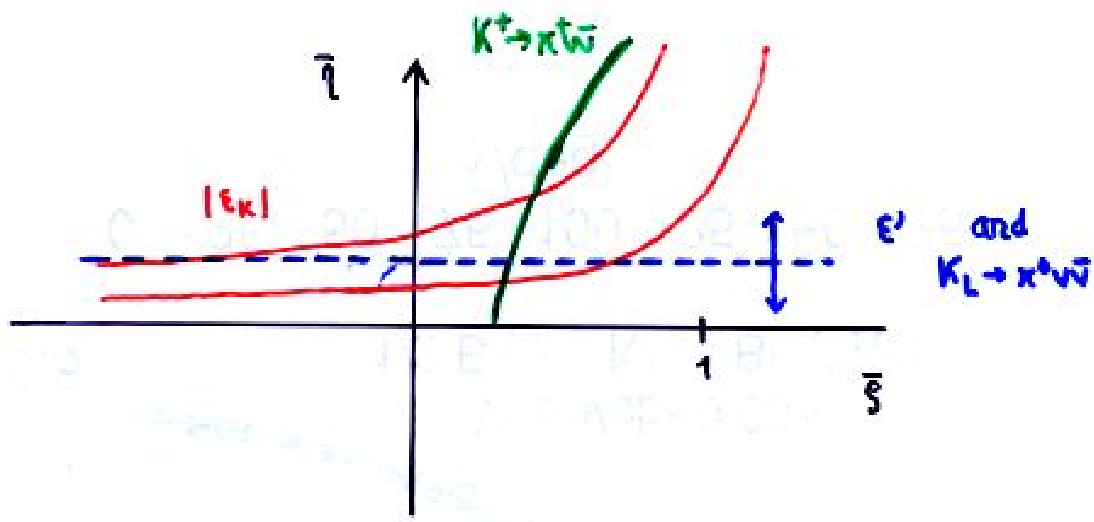
$B_i \propto \langle \pi\pi | O_i | K \rangle$ hadronic matrix elements

Pre 99 : $B_{6,8} \approx 1$, $\Omega_{IB} = 0.25$ $\Rightarrow$ $\varepsilon'/\varepsilon \approx 6\cdot 10^{-4}$ too small

Since then we learnt : serious calculations must account for final state interactions

$\hookrightarrow$ Chiral PT [Pallante, Pich, Scimemi]
gives right magnitude (enhancement of $B_6^{(1/2)}$)

$\hookrightarrow$ Lattice QCD can settle this [Lellouch, Lüscher ; Lin et al.]
when ? (want 10% accuracy !)

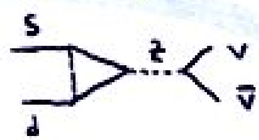


- $|\epsilon_K| \longrightarrow \bar{\eta} > 0$
- ϵ'/ϵ not used as an constraint at present
- Future : rare kaon decays

$K^+ \to \pi^+ \nu\bar{\nu}$ [Br $\sim 7 \cdot 10^{-11}$ expected] CP conserving

$K_L \to \pi^0 \nu\bar{\nu}$ [Br $\sim 3 \cdot 10^{-11}$ expected] CP violating

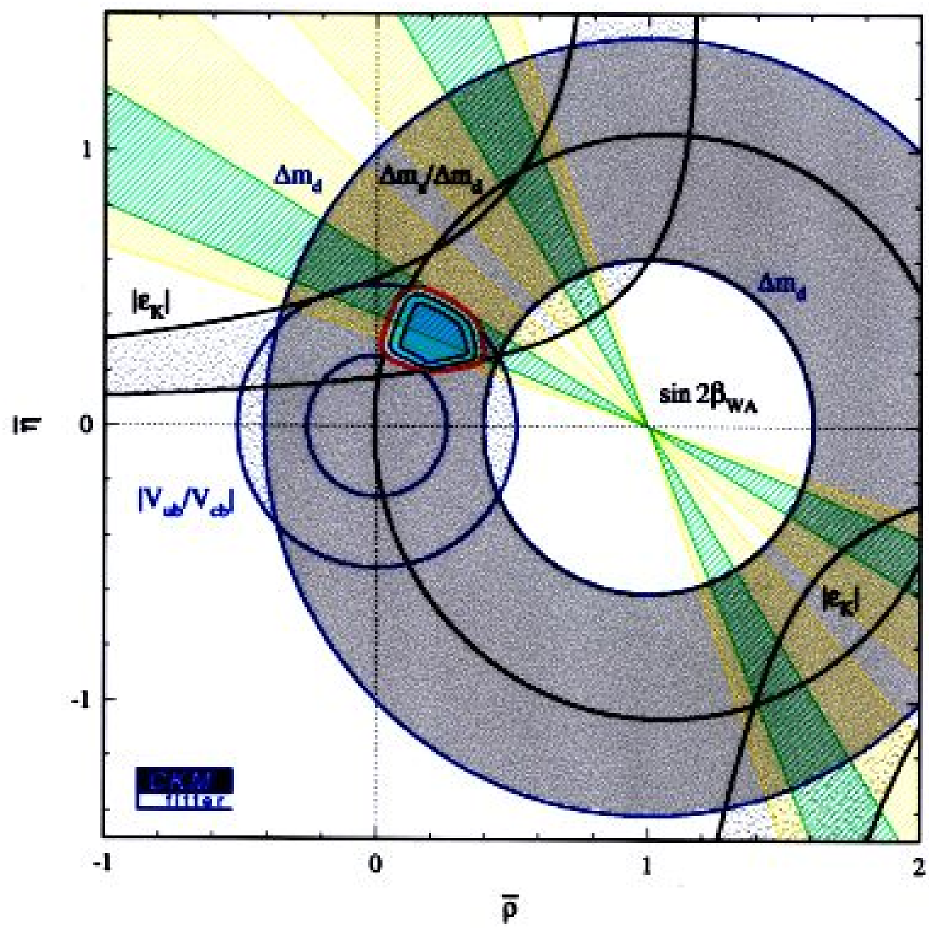
Theory very accurate [Buchalla, Buras]



+ boxes

In ~ 2010 we may have an accurate determination of the unitarity triangle from kaon decays alone (or discover new physics ....)

Constraints on the unitarity triangle [$(\bar{\rho}, \bar{\eta})$ resp.]



$\bar{\rho} = 0.21 \pm 0.17$ $\qquad$ $\bar{\eta} = 0.35 \pm 0.14$

$\sin(2\beta) = 0.68 \pm 0.21$

$\sin(2\alpha) = -0.24 \pm 0.72$

$\gamma = (58 \pm 24)^\circ$

[From Höcker et al., http://www.slac.stanford.edu/ laplace/ckmfitter.html, and hep-ph/0104062.]

$\not{C}\not{P}$ in B decay + mixing

Interference of mixing & decay

$$\begin{tikzcd} B^0 \arrow[rr, "e^{-2i\beta}"] \arrow[dr, "A"'] & & \bar{B}^0 \arrow[dl, "\bar{A}"] \\ & f_{CP} & \end{tikzcd}$$

$$\lambda \equiv e^{-2i\beta}\,\frac{\bar{A}}{A}$$

Time-dependent asymmetry

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to f_{CP}) - \Gamma(B^0(t)\to f_{CP})}{\Gamma(\bar{B}^0(t)\to f_{CP}) + \Gamma(B^0(t)\to f_{CP})}$$

direct $\not{C}\not{P}$

$$= \frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2}\sin\Delta M_{B_d}t - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos\Delta M_{B_d}t$$

$$\approx \underset{(\pm 1)}{\eta_{f_{CP}}}\,\sin 2(\beta+\delta_W)\,\sin\Delta M_{B_d}t$$

if the decay amplitude A is dominated by a single phase
$A = |A|e^{i\delta_W}$
$[\to\ |\lambda|=1]$

"Golden mode":

$B\to J/\psi K_S$ — single phase to 1% accuracy

$\delta_W \approx 0 \quad (b\to c\bar{c}s)$

$\eta_{CP} = -1$

$\Rightarrow$ Clean measurement of the $B\bar{B}$ mixing phase (also beyond the SM)
(relative to $b\to c\bar{c}s$)

$\sin 2\beta$ in the SM
(related to phase of V_{td})

$\sin 2\beta$ measurements

CDF (2000) $\quad 0.79^{+0.41}_{-0.44}$

	BaBar	Belle
2000 (Osaka)	0.12 ± 0.38	0.45 ± 0.45
2001 (spring)	0.34 ± 0.21	0.58 ± 0.34
2001 (summer)	0.59 ± 0.15	0.99 ± 0.15

World Average $\quad \sin 2\beta = 0.79 \pm 0.10$

[to be compared to indirect det. $\quad 0.68 \pm 0.21$ (Höcker et al.)

0.68 ± 0.15 (Ciuchini et al.)

at 95% CL]

$\Rightarrow$ First measurement of a large CP asymmetry rules out idea of approximate CP

$\Rightarrow$ together with consistency of indirect fit: the KM mechanism is probably the dominant source of $\cancel{CP}$ at the electroweak scale

What could have happened .....

New Physics could have affected $B\bar{B}$ mixing

but:

If the CKM matrix is the only source of flavour-changing processes (+ no new operators in H_{eff}) then new interactions that affect $B\bar{B}$ mixing also affect $K\bar{K}$ mixing

$\longrightarrow$ only small modifications possible

$\sin 2\beta > 0.42$ [Buras, Buras; Ali, London; Bergmann, Perez]

$0.52 \ldots 0.78$ preferred

and $A(J/\psi K)$ still measures the phase of V_{td}

Vice versa:

Very small (or very large) $A(J/\psi K)$ would have implied a new mechanism of flavour violation with (probably) new CP phases in $B\bar{B}$ mixing

$\longrightarrow$ CP problem (see later)

$\not{CP}$ in B decays

- continue to search for $\not{CP}$ in many ways (D, K, EDM ....)

- but: KM mechanism predicts large effects only in B decays (and rare K decays)

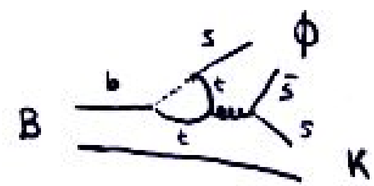
  $\hookrightarrow$ primary focus for coming years :

only 1 phase $\Rightarrow$ verify relations between different processes

search for small deviations

Example : $\bar{B}_d(t) \to \phi K$

$b \to s\bar{s}s$



$$A_{CP}(t) = -\sin 2(\beta + \theta_p) \sin \Delta M_B t + \text{small correction}$$

should also measure $\sin 2\beta$ in the SM ($\theta_p = 0$) and simultaneously is sensitive to NP in QCD penguin amplitude

To carry out this program need to control strong interaction effects

Basic quantities

$\not{CP}$ in decays

$$\Gamma(B\to f) \neq \Gamma(\bar{B}\to \bar{f})$$

e.g.:

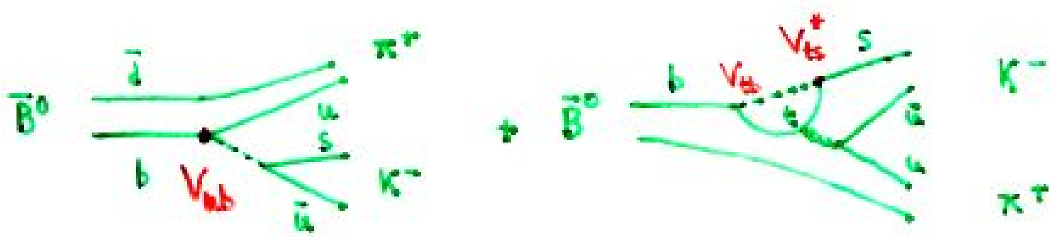
$\bar{B}^0 \to \pi^+ K^-$
vs.
$B^0 \to \pi^- K^+$

Need at least two contributions to the amplitude with different (CKM) weak and strong phases:

$$A(B\to f) = A_1 e^{i\delta_1} e^{i\delta_1^W} + A_2 e^{i\delta_2} e^{i\delta_2^W}$$

$$A(\bar{B}\to \bar{f}) = A_1 e^{i\delta_1} e^{-i\delta_1^W} + A_2 e^{i\delta_2} e^{-i\delta_2^W}$$

e.g.



- few decay channels for K mesons

$\varepsilon'/\varepsilon \sim O(10^{-3})$
(definitively $\neq 0$ since 1999)

- rich phenomenology for B mesons

but: difficult strong interaction problem as far as quantitative interpretation is concerned (also true for mixing asymmetries in general)

Two complementary approaches

- Decay amplitude parametrizations
- SU(2) + SU(3) Flavour symmetry
- Eliminate strong interaction effects
  with help of measurements

"classic", data-driven approach

$$A(B \to f) \propto \langle M_1 M_2 | O | \overset{(-)}{B} \rangle$$

- QCD calculations of decay
  amplitudes
- Heavy quark limit, $m_b \gg \Lambda_{QCD}$
- "theory-driven approach", new

much recent activity ("QCD factorization",
"PQCD")

Determination of γ (phase of V_{ub}^*)

Approach 1

Interference of $b \to c\bar{u}d$ and $b \to u\bar{c}d$ (no penguins)

$B_d(t) \to D^{\pm}\pi^{\mp}$ [Sachs, Dunietz]

$B_d(t) \to D K_S$ [Gronau, London]

$B^{\pm} \to K^{\pm} D_{CP}$ [Gronau, Wyler]

$B_s(t) \to D_s^{\pm} K^{\mp}$ [Aleksan et al.]

- each mode provides enough observables to eliminate all strong interaction parameters
- experimentally difficult (small Br's , small asymmetries, rapid B_s oscillations)

Approach 2

Interference of $b \to u\bar{u}\, d/s$ (tree) with $b \to d/s\; q\bar{q}$ (penguin)

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

- accurately measured
- to determine γ need calculation of penguin-to-tree ratio including strong interaction phase

QCD Factorization

[MB, Buchalla, Neubert, Sachrajda]

In the heavy quark limit the b quark decays into very energetic quarks

Methods from heavy quark expansion + soft-collinear factorization ("colour transparency") imply

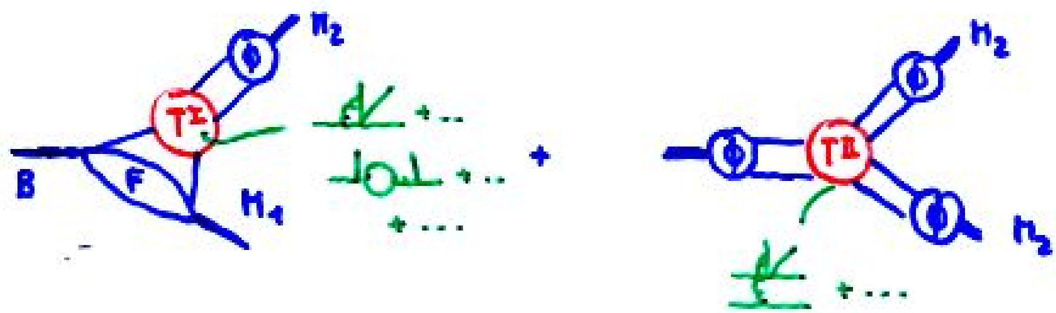
$$A(B \to M_1 M_2) =$$

$$F^{B\to M_1}_{(0)} \cdot \int_0^1 du\, T^{I}_{(u)} \Phi_{M_2(u)} + \int d\xi\, du\, dv\, T^{II}_{(u,v,\xi)} \Phi_{B}(\xi) \Phi_{M_1}(u) \Phi_{M_2}(v)$$

form factor

light-cone distribution amplitude

perturbative QCD



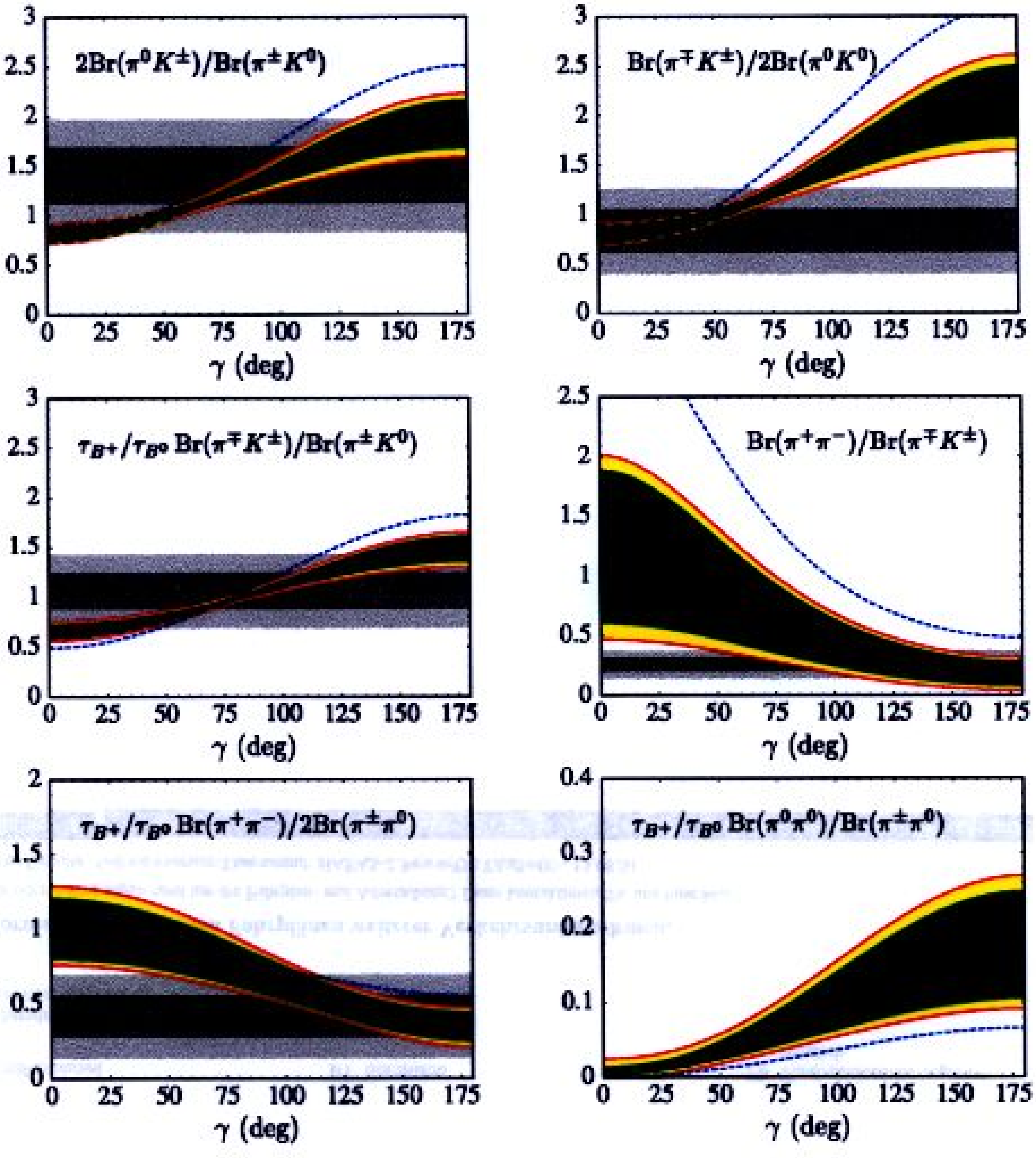
- valid up to $1/m_b$ corrections?
  (some can be large)

- exp. tests possible

  [so far no test that strong phases can be computed accurately ; important information from direct CP asymmetries soon]

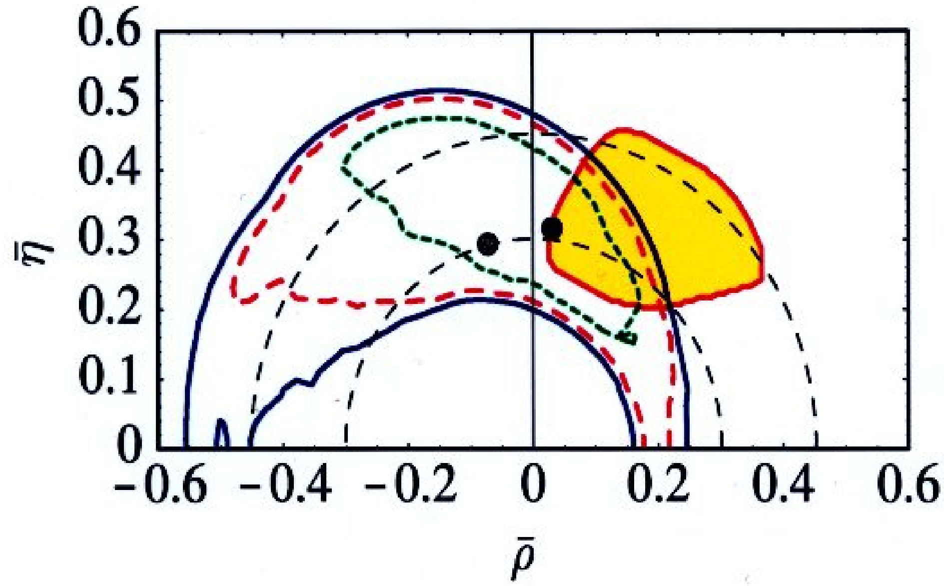
QCD factorization for $B \to \pi\pi, \pi K$ decays

Some ratios of CP-averaged branching fractions are sensitive to γ and $|V_{ub}|$:



Implies a constraint in the $(\bar{\rho}, \bar{\eta})$ plane.

Global fit to six $\pi\pi$, πK CP-averaged branching fractions (no CP asymmetries used) with QCD factorization theory; compare with standard unitarity triangle fit



95%, 90% and 68% confidence level contours obtained with the same method used by Höcker et al. for the standard CKM fit (yellow region). Green dot: overall best fit with $\chi^2/\mathrm{dof} \approx 0.55$. Only $\bar{\eta} > 0$ shown.

[similar fits with different theory input: Hou et al; He et al., Ciuchini et al.]

- consistent with standard fit to meson-antimeson mixing and $|V_{ub}|$, but:
- preference for larger γ and/or smaller $|V_{ub}|$
- with more data perform QCD theory consistency checks and Standard Model tests

Together with $|V_{ub}|$ charmless B decays imply a CP-violating phase in B decay (as compared to phase of V_{td} from mixing)

Resumé on strong interaction effects

QCD calculations – though probably not very precise – will be necessary and invaluable to interpret data from first generation B factories beyond simple measurements like $A_{mix}(B \to J/\psi K)$

Next two years should be interesting:

$$S_{\pi\pi} = 0.03^{+0.53}_{-0.56} \pm 0.11 \quad \text{(Babar)} \longrightarrow \sin 2\alpha \; ? \; (\bar\rho, \bar\eta)$$

$(B_{d}(t) \to \pi^+\pi^-)$

$$A_{CP}(\pi^+K^-) = (-4.8 \pm 6.8)\,\% \longrightarrow \gamma \;\; ? \;\; \text{strong phases}$$

(Babar, Cleo, Belle)

etc.

Second generation experiments (LHCb, BTeV) will probably supply enough data to rely more and more on symmetries alone

↪ decisive test of the KM picture but very likely lots of discussion on hadronic physics and fake new physics signals (?!)

How could the lattice community contribute?

- Standard UT fit is now entirely in the hands of lattice QCD
  (up to, perhaps, $|V_{ub}|$)

- Much harder to make impact on non-leptonic, exclusive decays

  - light-cone distribution amplitudes, in particular of B mesons
  - form factors

  to assist amplitude calculations with perturbative methods

  - $\langle \pi\pi | (\bar{q}_2 \Gamma q_3)(\bar{q}_1 \Gamma' b) | \bar{B} \rangle$??

    inelastic rescattering dominates

    [cf. $\langle \pi\pi | O | K \rangle$
    only elastic rescattering]

$\not{CP}$ in extensions of the SM

Reappraisal of the KM mechanism (1973)

predicted three generations on basis of ϵ_K !

predicted relations between CP-violating quantities that a priori might have turned out different
[ϵ_K, ϵ'/ϵ, $\sin 2\beta$, nothing in charm]

KM mechanism now emerges as the dominant source of $\not{CP}$ at the EW scale – a triumph for the standard theory [cf. electroweak precision tests]

Probably not the final word on $\not{CP}$. Why?

Strong CP problem ($\theta = 0$) and Cosmological CP problem call for explanation

solution probably related to scales $\gg$ TeV ?

Theoretical appeal of realizing the full Poincaré group in the Lagrangian $\Rightarrow$ spontaneous CP (and P) violation

EW hierarchy problem requires extending the SM, but extensions often have too many new sources of $\not{CP}$: <u>CP problem</u>

From EW baryogenesis to leptogenesis .....

- Few years ago baryogenesis at the electroweak scale (through sphaleron transition) was a very attractive scenario

  ↪ closely related to new $\not{CP}$ at the EW scale

Since then :

- $m_H > 114$ GeV
- EW phase transition only crossover (SM) or weakly first order over most of the MSSM parameter space
- Neutrino masses

  ↪ massive right-handed neutrinos

- Leptogenesis appears now more natural

$\not{CP}$ in ν_R decay due to ν mass matrix

Lepton number $\Longrightarrow$ Baryon number through B+L violation (B−L conserved)

↪ Baryogenesis related to scale $M_R \sim 10^{12}-10^{16}$ GeV decoupled from accelerator physics

$\cancel{CP}$ in extensions of the SM

Modifikation	New Sources of CP Violation	Novel $\cancel{CP}$ effects
Extended Higgs sector	Higgspotential more Yukawa-matrices	▪ $\cancel{CP}$ through tree-level FCNC ▪ Flavour-diagonal $\cancel{CP}$ ▪ spontaneous $\cancel{CP}$ possible
Extended gauge sector (LR sym.) [assume natural flavour conservation]	Higgspotential V_R^{CKM}	▪ $\cancel{CP}$ through right-handed charged current ▪ spontaneous $\cancel{CP}$ possible
Extended fermion sector	non-unitary CKM matrix	▪ FCNC of Z bosons
Supersymmetry (MSSM)	mainly soft supersymmetry breaking (squark mass matrices)	▪ 43 $\cancel{CP}$ phases ▪ Flavour-diagonal $\cancel{CP}$ (EDMs) ▪ strong interaction FCNC with $\cancel{CP}$ phases

$\not{CP}$ in extensions of the SM

1) Extended Higgs sector (e.g. two doublets)

- $\not{CP}$ in the Higgs potential
  $\hookrightarrow$ Higgses without definite CP
- $\not{CP}$ in charged Higgs interactions and flavour-changing neutral currents
- $\not{CP}$ in flavour-diagonal interactions e.g. $Ht\bar{t}$
- spontaneous $\not{CP}$ is possible

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\alpha} \end{pmatrix}$$

causes $\not{CP}$

$\Rightarrow$ even the simplest extensions causes TOO MUCH $\not{CP}$ (FCNCs, EDMs, ...)

Either $m_H \gtrsim$ TeV

or

extra structure (such as natural flavour conservation)

no spontaneous $\not{CP}$ with 2 doublets

CKM phase in charged Higgs interactions + usual charged currents

$\not{CP}$ in extensions of the SM

2) Extended gauge sector – left-right symmetry

- attractive because gauge, parity and CP symmetry may all be spontaneously broken
  - all $\not{CP}$ originates from a single Higgs vev

$\Rightarrow$ δ_{KM} small

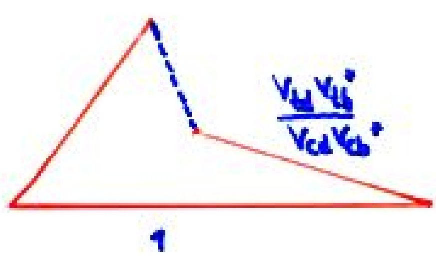
$\Rightarrow$ V_R^{KM} (right-handed charged current) would intervene in ϵ_K, ϵ'/ϵ but less for B-$\bar{B}$ mixing

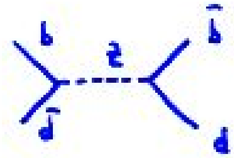
$\Rightarrow$ expect small $\not{CP}$ in B-$\bar{B}$ mixing in contrast to the SM

ruled out

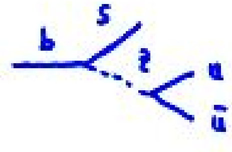
3) Extended fermion sector – 4th quark, SU(2) singlet, vector-like, charge $^2/_3$

- non-unitary CKM matrix





modifies Δm_{B_d}



modifies $B \to \pi K$

- Z boson flavour-changing couplings

$\Rightarrow$ large effects on $B\bar{B}$ mixing and $\not{CP}$ in decays

$\not{CP}$ in extensions of the SM

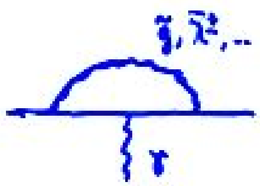
Supersymmetry $\quad \mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{\not{SUSY}}$

Practically all new sources of $\not{CP}$ arise from here

$\Rightarrow$ In SUSY CP violation is closely connected to the question of SUSY breaking

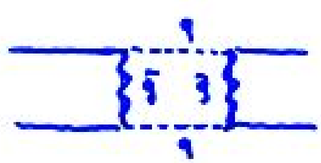
Generic effects:

Flavour-diagonal $\not{CP}$ $\Rightarrow$ large electric dipole moments



- large SUSY masses
  or
- small CP phases

Strong FCNC through quark-squark-gluino vertex



- large SUSY masses
- quark-squark alignment
- degeneracy (super-GIM)
- if Δm_K just satisfied, then need small phases for ε_K

tight constraints exist, but ε_K, ε'/ε may not be connected to δ_{KM} but to SUSY phases

$\Longrightarrow$ large effects in B decays are possible

Summary:

- If SUSY exists need to understand $\cancel{\text{SUSY}}$ to understand why SUSY CP violation is small

- Most other extensions of the SM have naturally too much $\cancel{CP}$

Since we now know that CP is not (in general) an approximate symmetry, this raises a

CP problem

↪ Study of $\cancel{CP}$ may probe / constrain additional theory structure of extensions of the SM

Conclusion

I. Important (and expected) observation of large CP violation in B decays together with ϵ'/ϵ and the consistency of indirect determinations of the unitarity triangle imply

a) KM mechanism of CPV in charged currents is likely the *dominant* source of CPV *at the electroweak scale*
b) Large asymmetry excludes the idea of *approximate* CP symmetry

II. CPV beyond the Standard Model:

a) CP and electroweak symmetry breaking provide complementary motivations to search for extensions of the SM, but:
b) no favoured candidate model for CPV beyond the SM – CP problem in many conventional extensions
c) baryogenesis mechanism probably decoupled from CPV observable at accelerators

III. Expectations for the near future:

a) $\Delta M_{B_s} \approx 17.5\,\mathrm{ps}^{-1}$ to consolidate Ia)
b) CP asymmetry in $B_d(t) \to \pi^+\pi^-$, ΦK as further consistency tests
c) Precise branching fractions and direct CP asymmetries in many charmless decay modes.