Theory of CP Violation

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CP as Natural Symmetry of Gauge Theories

P and C alone are *not* natural symmetries:
consider chiral gauge theory:

$$\mathcal{L} = -\tfrac{1}{4}\, F_{\mu\nu}F^{\mu\nu} + \psi_L^\dagger i\bar{\sigma} D\psi_L \; (+\psi_R^\dagger i\sigma\partial\psi_R)$$

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$\mathcal{L}$ violates P:	right-handed fermions do not couple to gauge bosons
$\mathcal{L}$ violates C:	left-handed antifermions do not couple to gauge bosons
$\mathcal{L}$ preserves CP:	both left-handed fermions and right-handed antifermions couple to gauge bosons

Massless gauge theories are invariant under CP and T.

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But CP IS violated!

CP violation in K decays known since 1964; observed in B decays in 1999.

Origin in SM: Yukawa interactions:

$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\text{kinetic energy + gauge IA}} + \underbrace{\mathcal{L}_H(\phi)}_{\text{Higgs potential} \to \text{spontaneous symmetry breaking}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\text{Yukawa IA} \to \text{fermion masses}}$$

$$\underbrace{\qquad\qquad}_{\text{gauge sector}} \qquad \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{scalar sector}}$$

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$$\mathcal{L}_Y = -\lambda_d^{ij} \bar{Q}_L^i \cdot \Phi d_R^j - (\lambda_d^{ij})^* \bar{d}_R^j \Phi^\dagger \cdot Q_L^i + \ldots$$

λ_d: general, not necessarily symmetric or Hermitian matrices (Yukawa couplings), not constrained by gauge symmetry

CP: $\lambda_d \leftrightarrow \lambda_d^* \Rightarrow$ (explicit) CP violation if λ_d complex

CP violation happens in the scalar sector!

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Next generation of accelerators (LHC 2007/8):

- direct Higgs searches
- indirect effects: CP in B decays

} complementary tests of the scalar sector!

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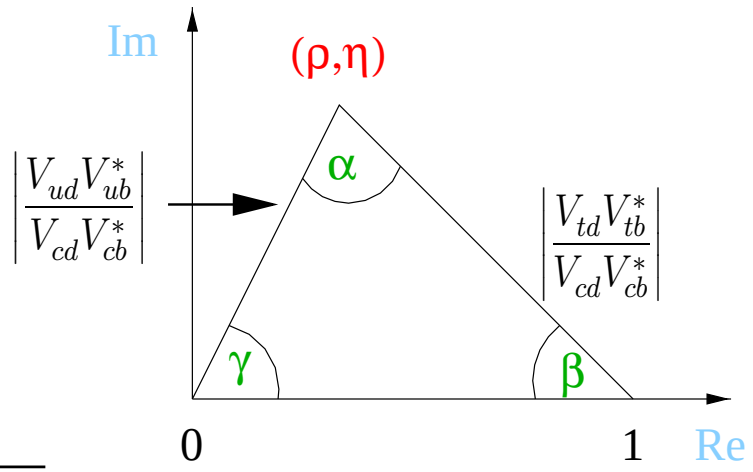


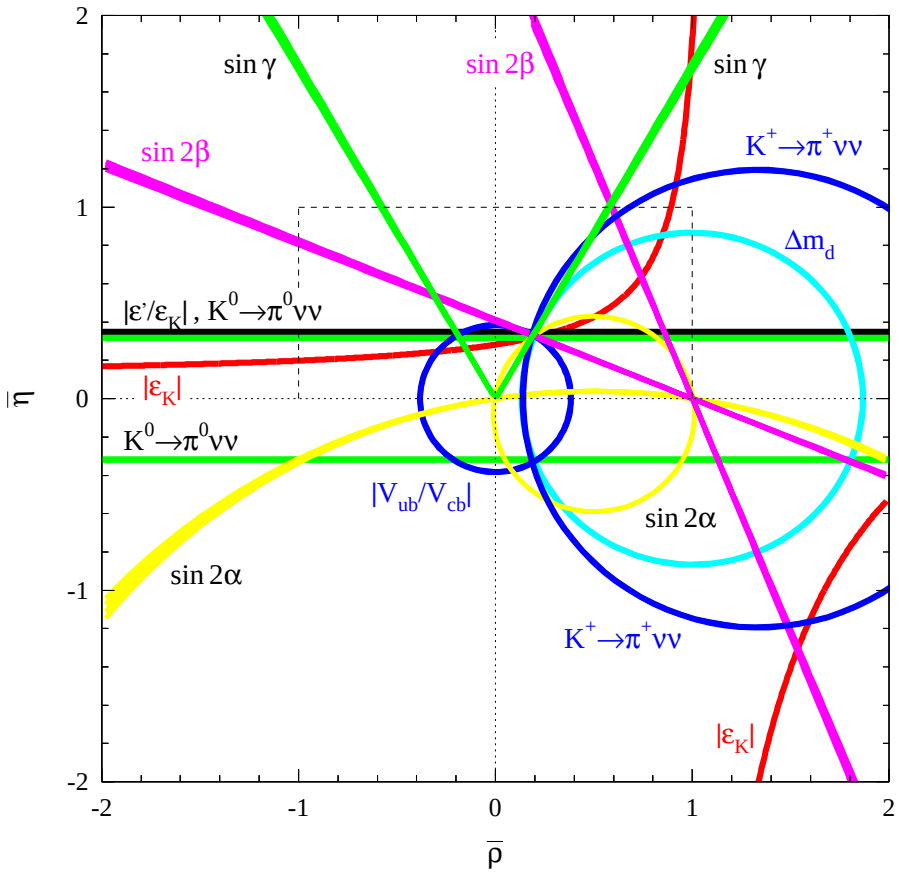
Visualise unitarity relation

$$\sum V_{dj}V_{jb}^* = 0$$

as triangle in complex plane:

unitarity triangle (UT)

Experimental Determination of UT



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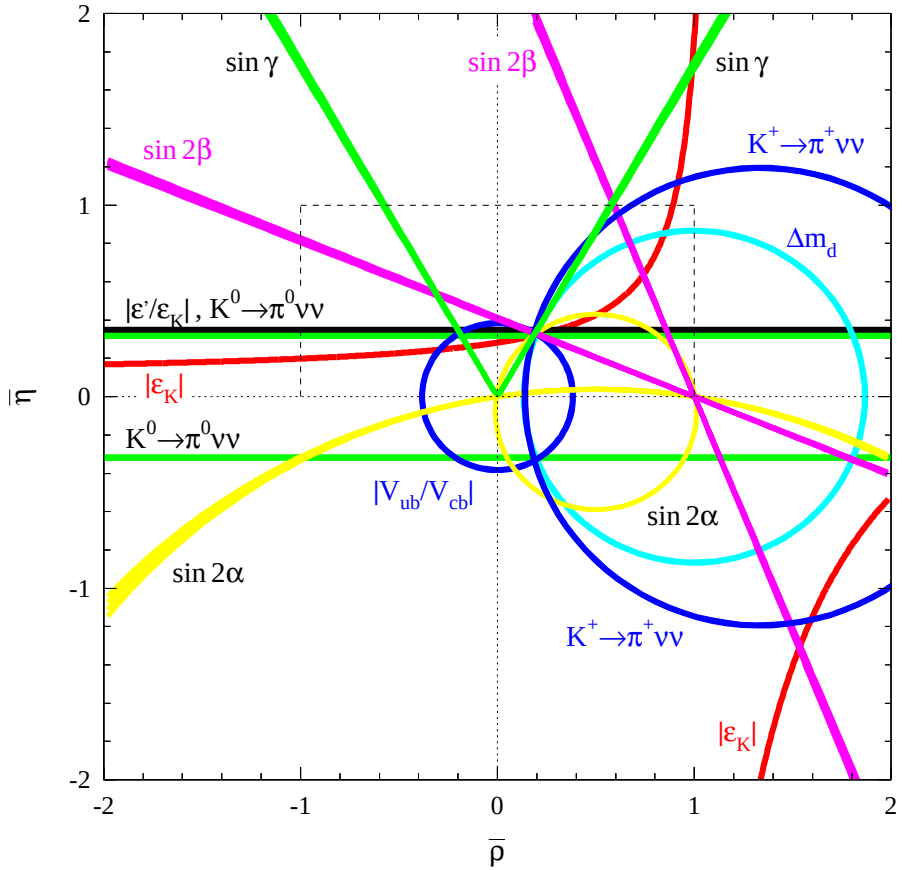

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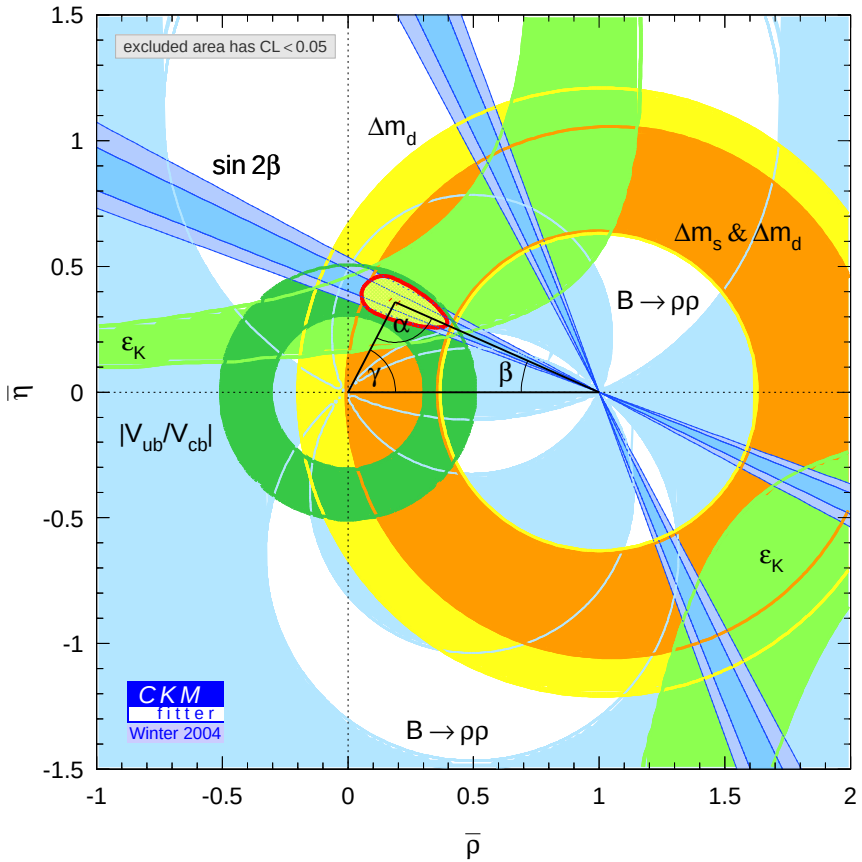


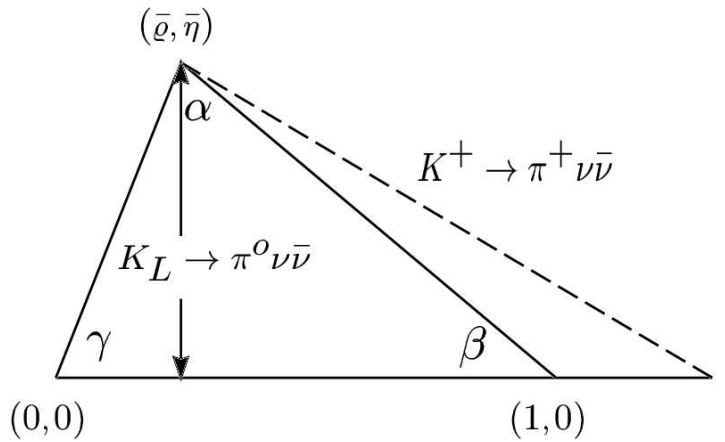
The reality. . .

UT from K Decays

Experimentally favoured: ϵ_K: th. uncertainty from B_K, m_t, $|V_{cb}|$

Theoretically favoured: $B(K^+ \to \pi^+ \nu\bar{\nu})$, $B(K_L \to \pi^0 \nu\bar{\nu})$

- hadronic matrix elements from $K \to \pi\ell\nu$
- SD dominated (W-box, Z-penguin)
- QCD corrections known to NLO: small residual scale-dependence
- BR $\sim O(10^{-11})$
- complete determination of UT
- with strong dependence on $|V_{cb}|$ and (less strong) on m_t



! npQCD potentially more dangerous than in B decays (ϵ'/ϵ etc.)

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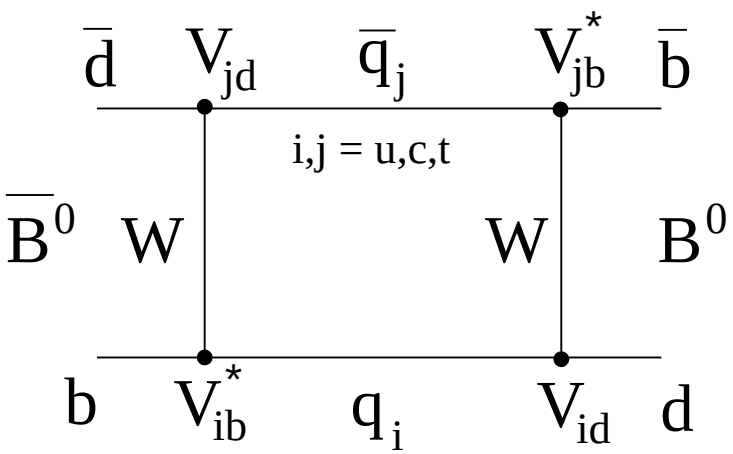
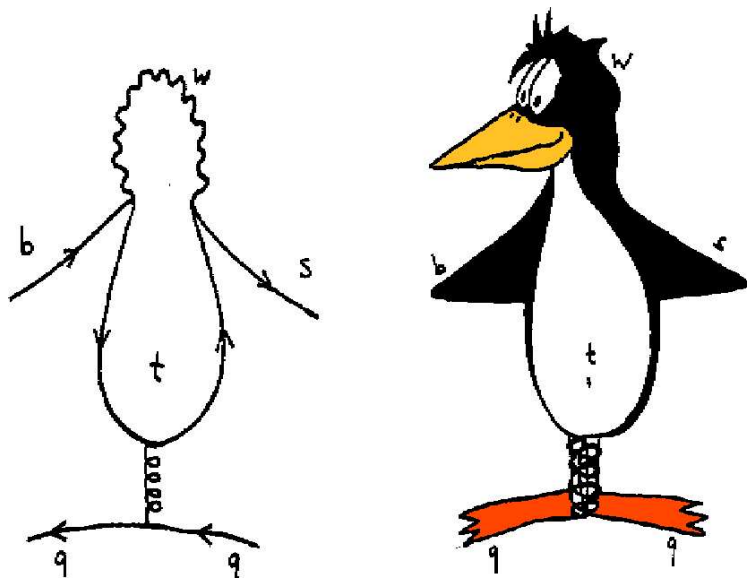
  $\rightarrow$ large and theoretically clean $\rightarrow$ large penguin contributions:

  effects from B^0–$\bar{B}^0$ mixing:





Manifestations of CP Violation

- CP violation in the decay (direct CP violation):

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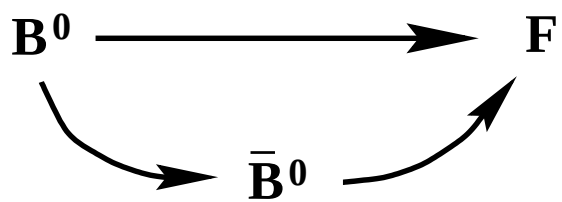
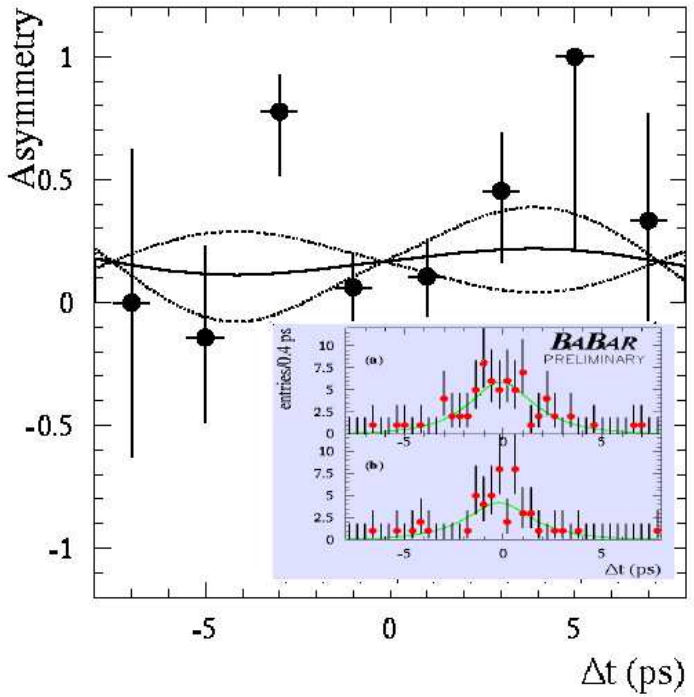
- CP violation in the

interference of decays with and without mixing

$$\mathcal{A}(B \to F) \neq \mathcal{A}(\bar{B} \to F)$$



Time-dependent CP Asymmetries



Measure time-dependent CP asymmetry:

$$\frac{\Gamma(B_q^0(t) \to F) - \Gamma(\bar{B}_q^0(t) \to F)}{\Gamma(B_q^0(t) \to F) + \Gamma(\bar{B}_q^0(t) \to F)}$$

$$= \left\{ \mathcal{A}_{CP}^{dir}(B_q \to F) \cos(\Delta M_q t) \right.$$

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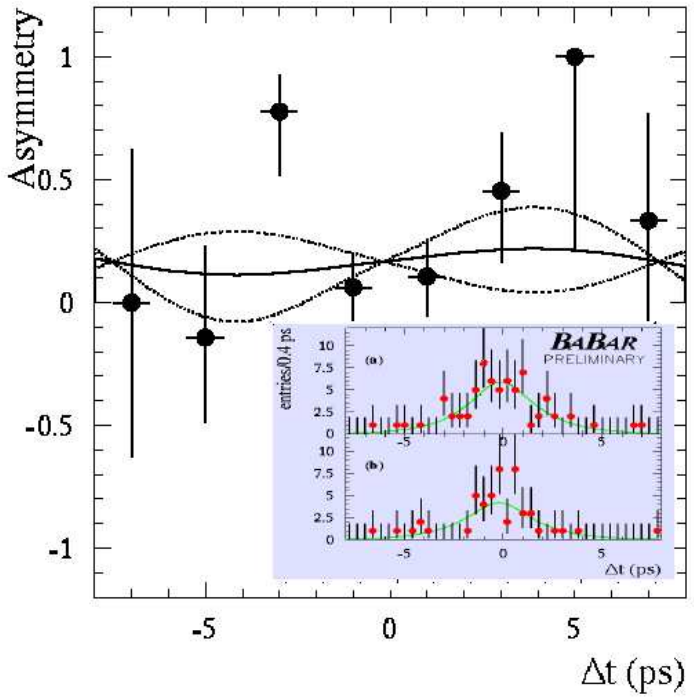

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In general $\mathcal{A}_{CP}^{dir}$ and $\mathcal{A}_{CP}^{mix}$ dependent on hadronic matrix elements.

Special case: one single weak amplitude dominant:

$$\mathcal{A}_{CP}^{mix} = \mathrm{Im}\left(\mp e^{-i\phi_q}\right) \longrightarrow \textbf{“gold-plated” decay}$$

(e.g. $B \to J/\psi K_S$)

$\longrightarrow$ measure mixing phase ϕ_q with small theoretical uncertainty

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Alternative scenarios of CP violation

Recall: CP violation happens in the scalar sector

→ combination of several mechanisms:

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  - electric dipole moment of neutron problematic

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Electroweak baryogenesis?

Outlook

- CP violation related to scalar sector
- nonstandard sources of CP violation to show up as inconsistencies of measurements of parameters of UT
- extraction of UT angles α, β, γ from experiment often hampered by nonperturbative QCD
  - QCD factorisation? (Beneke, Buchalla, Neubert, Sachrajda)
  - Phenomenological methods? (Fleischer, Gronau)
- B/K physics to give indirect hints at new physics
  $\rightarrow$ complementary to results of direct searches
- exciting times for theorists and experimentalists alike!