Flavour physics : Lecture 1

History, CP violation, Neutral meson mixing

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Why Flavour physics

Role of flavour physics in building up the Standard Model

- $\tau - \theta$ puzzle $\Rightarrow$ Parity violation
- Cabibbo angle $\Rightarrow$
  weak coupling universality $\oplus$ quark mixing
- GIM mechanism $\Rightarrow$ no FCNC at tree level, charm
- CKM paradigm $\Rightarrow$ (at least) three quark families
- Large B–$\overline{B}$ mixing $\Rightarrow$ heavy top quark
- Rate of radiative B decay $\Rightarrow$ top quark mass

- The standard model looks complete now,
  with no confirmed signals of BSM physics at the LHC yet !
- Flavour physics may give some indirect hints....

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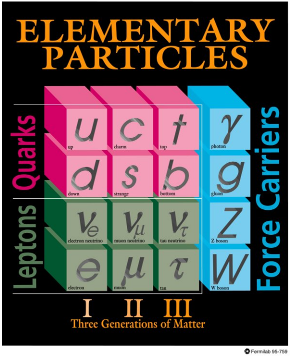
Flavour structure of the Standard Model



- Three families of quarks and leptons
- Quark masses (GeV):

up	charmed	top
0.005	1.5	175
down	strange	bottom
0.01	0.1	5

- Mixing between families:
  Strong within the same family,
  Weak across families

The meson nomenclature

- Pions:
  $\pi^+ \equiv u\bar{d}$, $\pi^- \equiv d\bar{u}$, $\pi^0 \equiv (u\bar{u} - d\bar{d})/\sqrt{2}$ $(\sim 0.15$ GeV)
- Strange mesons (Kaons):
  $K^+ \equiv u\bar{s}$, $K^- \equiv s\bar{u}$, $K^0 \equiv d\bar{s}$, $\overline{K^0} \equiv s\bar{d}$ $(\sim 0.5$ GeV)
- Charmed mesons:
  $D^+ \equiv c\bar{d}$, $D_s^+ \equiv c\bar{s}$, $D^0 \equiv c\bar{u}$
  (And antiparticles: $\sim 1.5 - 1.8$ GeV)
- B mesons:
  $B^+ \equiv u\bar{b}$, $B^0 \equiv d\bar{b}$, $B_s \equiv s\bar{b}$, $B_c \equiv c\bar{b}$
  (And antiparticles: $\sim 5 - 6.5$ GeV)
- Quarkonia:
  $\phi \equiv s\bar{s}$ $(\sim 0.7$ GeV)
  $J/\psi \equiv c\bar{c}$ $(\sim 3.1$ GeV)
  $\Upsilon \equiv b\bar{b}$ $(\sim 10$ GeV)

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3. The Kobayashi-Maskawa mechanism
4. Neutral meson mixing and oscillations
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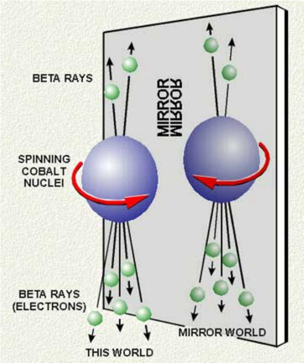
Discovery of parity violation: 1956-57



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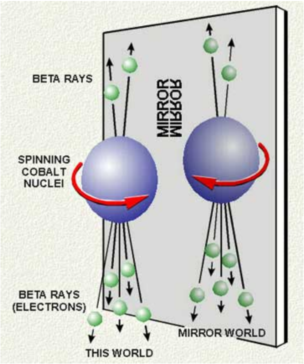

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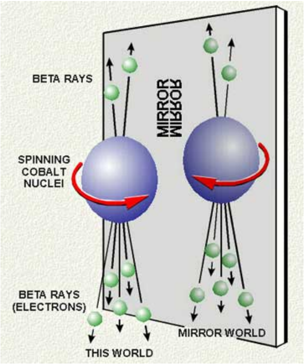

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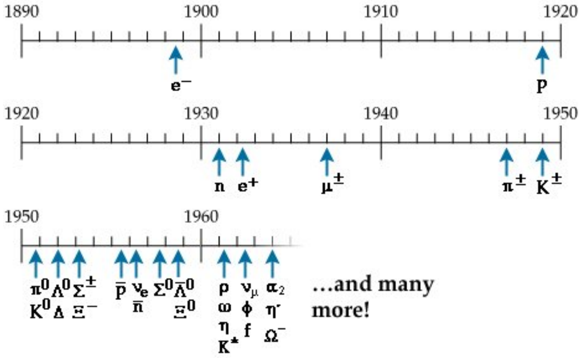
The particle zoo (1960's)



$$p \equiv uud$$
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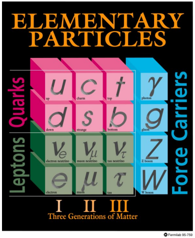

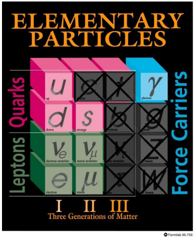

Universality of weak interactions: Cabibbo angle

Interrelated coupling constants:

- (i) muon decay: $g_{e\mu}$
  $\mu^- \to \nu_\mu e^- \bar{\nu}_e$
- (ii) neutron decay : g_{ud}
  $n \to p e^- \bar{\nu}_e$ $(d \to u e^- \bar{\nu}_e)$
- (ii) kaon decay: g_{us}
  $K^- \to \pi^0 e^- \bar{\nu}_e$ $(s \to u e^- \bar{\nu}_e)$

$$\boxed{|g_{e\mu}|^2 = |g_{ud}|^2 + |g_{us}|^2}$$

Universality:

- There is only one coupling constant, $g = g_{e\mu}$
- u quark couples to only one combination of d and s:
  $$d' = \cos\theta_c \cdot d + \sin\theta_c \cdot s$$
- Cabibbo angle θ_c: the first quark mixing angle

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Suppression of flavor-changing neutral currents

- Cabibbo angle unable to explain why
$$\Gamma(K_L \to \mu^+\mu^-) << \Gamma(K^+ \to \mu^+\nu_\mu)$$
- Possible explanation via another "c" quark: charge $+2/3$, couples to
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- The $s \to u \to d$ and $s \to c \to d$ contribution cancel, leading to the suppression of FCNC $s \to d$
- GIM mechanism: existence of the "charmed" quark.

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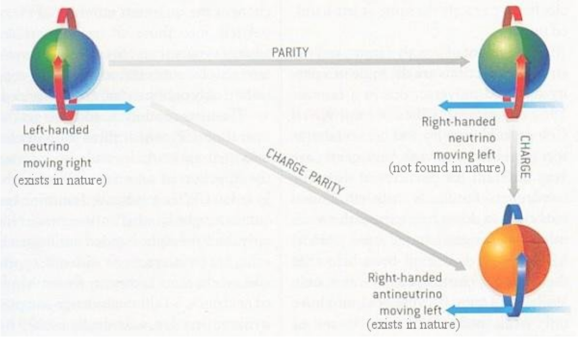
Can Charge ⊕ Parity may be conserved ?

Parity: left landed $\leftrightarrow$ right handed



- Neutrinos violate parity: they are only left-handed
- But antineutrinos are right-handed !
- Does that mean C and P violations cancel each other to give CP conservation ?

Prediction of CP violation in K decay

$$K^0 \equiv d\bar{s} \qquad \overline{K^0} \equiv s\bar{d}$$

- CP eigenstates:

$$K_1 \equiv (K^0 + \overline{K})/\sqrt{2} \qquad \text{(CP even)}$$
$$K_2 \equiv (K^0 - \overline{K})/\sqrt{2} \qquad \text{(CP odd)}$$

- CP even decay channel: $\pi\pi$
- CP odd decay channel: $\pi\pi\pi$
- CP conservation $\Rightarrow$

$$K_1 \rightarrow \pi\pi \text{ short-lived, } K_{\text{Short}}$$
$$K_2 \rightarrow \pi\pi\pi \text{ long-lived, } K_{\text{Long}}$$

- Original $K^0 = (K_{\text{Short}} + K_{\text{Long}})/\sqrt{2}$

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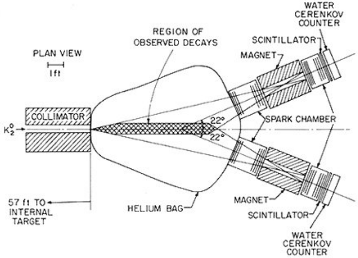
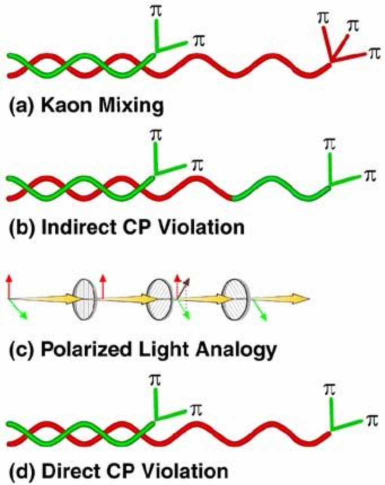
Discovery of CP violation: 1964

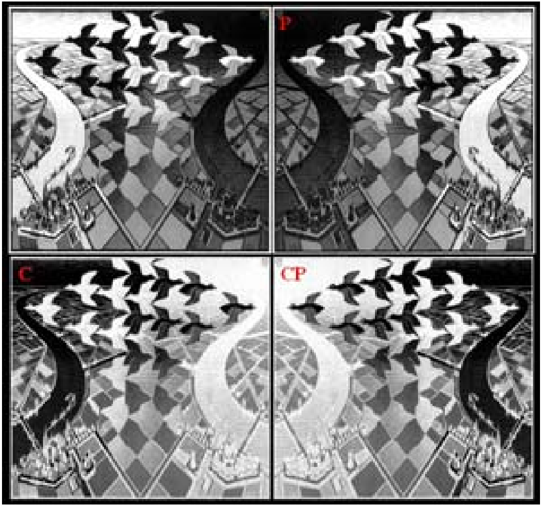
Cronin-Fitch experiment



Nobel prize 1980



Charge-parity violated slightly



"Day and Night", M.C.Escher

Questions raised by the discovery of CP violation

- Is it small or large ? Is CP an approximate symmetry ?
- Is the symmetry breaking spontaneous ?
- Where does it come from ? Are there extra interactions ?

CP violation and complex coupling

- CP violation: $A(X \to Y) \neq A(\overline{X} \to \overline{Y})$
- If all amplitudes are real, $|A(X \to Y)|^2 = |A(\overline{X} \to \overline{Y})|^2$
- CP violation possible if complex numbers involved in

$$\begin{aligned} |A(X \to Y)|^2 &= |A(X \to w \to Y) + A(X \to z \to Y)|^2 \\ |A(\overline{X} \to \overline{Y})|^2 &= |A(\overline{X} \to \overline{w} \to \overline{Y}) + A(\overline{X} \to \overline{z} \to \overline{Y})|^2 \end{aligned}$$

- CP violation $\Rightarrow$ Amplitudes complex $\Rightarrow$ Couplings complex

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The paper and the authors

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Two generations of quarks are not enough

- The mixing matrix between up-type and down-type quarks has to be a 2×2 unitary matrix

$$\mathcal{L} \propto (\overline{u_L}, \overline{c_L}) \begin{pmatrix} \cos\theta e^{i\phi_1} & \sin\theta e^{i\phi_2} \\ -\sin\theta e^{i\phi_3} & \cos\theta e^{i(\phi_2+\phi_3-\phi_1)} \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix}$$

- Can change three relative phases of quarks to get rid of all three complex phases ϕ_1, ϕ_2, ϕ_3

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Paremeter counting for two generations

- 2×2 complex matrix $\Rightarrow$ 4 real + 4 imaginary quantities
- Unitarity $U^\dagger U = \mathbb{I}$: 3 real and 1 imaginary conditions
- 1 real and 3 imaginary parameters left
- Can choose the 3 relative phases between quarks to get rid of the 3 imaginary parameters
- The mixing matrix is completely real

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Three generations work !

- 3×3 matrix $\Rightarrow$ 9 real + 9 imaginary quantities
- Unitarity $U^\dagger U = \mathrm{I}$: 6 real and 3 imaginary conditions
- 3 real and 6 imaginary parameters left
- Can choose the 5 relative phases between quarks to get rid of 5 imaginary parameters
- In addition to 3 real parameters (Euler angles of rotation), one imaginary quantity is unavoidable
- Mixing matrix complex $\Rightarrow$ CP violation may be present

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- Three families needed for the complex nature

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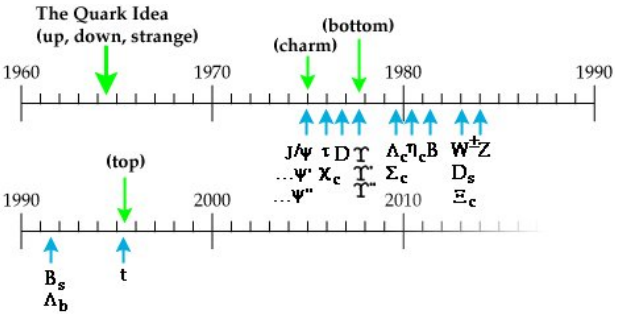
Experimental discovery of the third generation



- Discovery of τ: 1976
- Υ, B, B_s, λ_b contain b quark
- Top quark: 1995
- The last element, ν_τ, discovered in 2000.

CKM paradigm in modern language

Flavor basis vs. mass basis:

$$U' \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \quad D' \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Charged current in the basis of flavor eigenstates:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{U'_L} \gamma^\mu D'_L W^+_\mu + h.c.$$

- Charged current in the basis of mass eigenstates:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{U_L} \gamma^\mu (V^\dagger_{UL} V_{DL}) D_L W^+_\mu + H.c.$$

V_{UL}, V_{DL}: unitary matrices that change the basis

Cabibbo-Kobayashi-Maskawa (CKM) matrix

Coupling between U_L and D_L: $(g/\sqrt{2}) V_{CKM}$

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Wolfenstein parametrization of the CKM matrix

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\begin{aligned}
V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
\end{aligned}
$$

- $\lambda \approx 0.2$: Cabibbo angle
- η: the imaginary component of V_{CKM}
- η/ρ large $\Rightarrow$ CP violation is large, not approximate
- All CP violation in terms of a single number:
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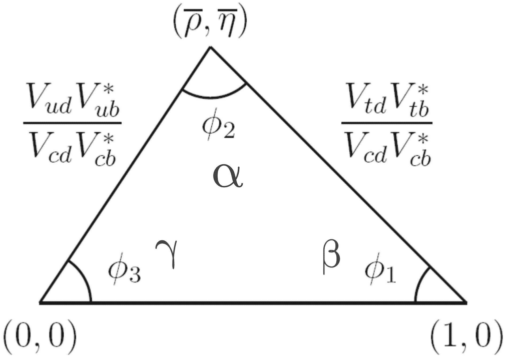
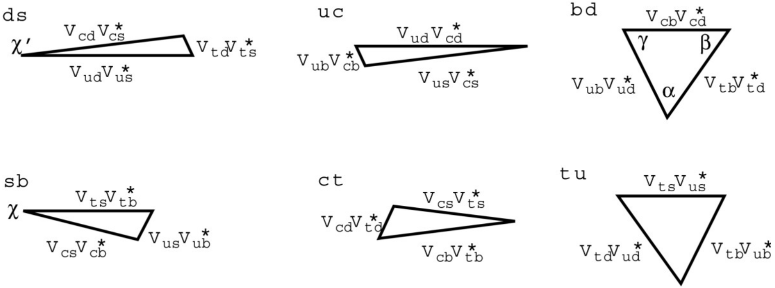
Unitarity relations and triangles

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



$$\alpha \equiv \text{Arg}\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \text{Arg}\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \text{Arg}\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right),$$

More unitarity triangles



- All triangles have the same area, $J/2$
- $\chi \equiv \beta_s \equiv \phi_s \equiv \mathrm{Arg}\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \sim \lambda^2$,
- $\chi' \equiv \beta_K \equiv \mathrm{Arg}\left(-\frac{V_{cd}V_{cs}^*}{V_{cd}V_{cs}^*}\right) \sim \lambda^4$,

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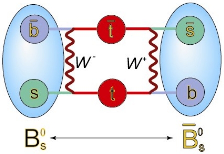
B_q–$\overline{B_q}$ mixing: parametrization



- Oscillation and decay of $a|B_q\rangle + b|\overline{B}_q\rangle$:

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}$$

$$\mathbf{M} \equiv \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \quad , \quad \Gamma \equiv \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$$\mathcal{CP}|B_q\rangle = e^{i\varphi}|\bar{B}_q\rangle,\ \mathcal{CP}|\bar{B}_q\rangle = e^{-i\varphi}|B_q\rangle$$

- CPT invariance : $M_{11} = M_{22}, \quad \Gamma_{11} = \Gamma_{22}$
- Hermiticity : $M_{21} = M_{12}^*, \quad \Gamma_{21} = \Gamma_{12}^*$

Mass difference and lifetime difference

- Mass eigenstates:
  $|B_{L,H}\rangle = p|B_q\rangle \pm q|\bar{B}_q\rangle \qquad (|q|^2 + |p|^2 = 1)$
- Mass difference $\qquad$ Lifetime difference
  $\Delta m = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$
  $(\rightarrow \Delta m > 0, \Delta\Gamma > 0 \text{ in SM})$
- Eigenvalue equations:

$$(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = (4|M_{12}|^2 - |\Gamma_{12}|^2)$$
$$\Delta m \Delta\Gamma = -4\mathrm{Re}(M_{12}^*\Gamma_{12}).$$

$$\Delta m = 2|M_{12}| + O(m_b^4/m_t^4)$$
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Time evolution of a tagged B_q or $\bar{B}_q$ decay

$$A_f \equiv \langle f|B_q\rangle,\ \bar{A}_f \equiv \langle f|\bar{B}_q\rangle\ ,\quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

(λ_f independent of the unphysical phase φ)

$$\Gamma(B_q(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}\times$$
$$\left[\cosh\frac{\Delta\Gamma_q\,t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\sinh\frac{\Delta\Gamma_q\,t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta m\,t)\right],$$

$$\Gamma(\bar{B}_q(t)\to f) = \mathcal{N}_f\,|\bar{A}_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}\times$$
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$$\mathcal{A}_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},\qquad \mathcal{A}_{\rm CP}^{\rm mix} = -\frac{2\,{\rm Im}\lambda_f}{1+|\lambda_f|^2}\quad \mathcal{A}_{\Delta\Gamma} = -\frac{2\,{\rm Re}\lambda_f}{1+|\lambda_f|^2}\,,$$

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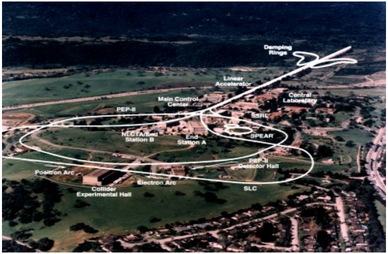
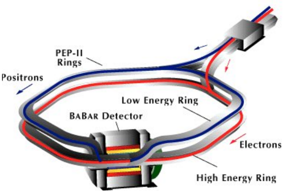
B factories: $B \equiv \bar{b}u, \bar{b}d, \bar{b}s, \bar{b}c, \quad \overline{B} \equiv \bar{u}b, \bar{d}b, \bar{s}b, \bar{c}b$



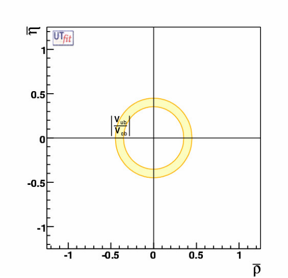
Babar (SLAC, USA)

BELLE (KEK, Japan)



$$e^+e^- \to B\overline{B} \to \text{decayproducts}$$

More and more stringent tests of the CKM mechanism



- Semileptonic decay $B \to D\ell\nu$

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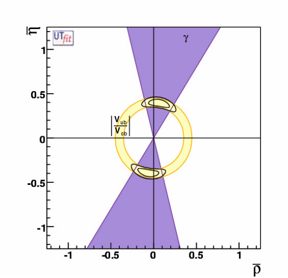

- Semileptonic decay $B \to D\ell\nu$
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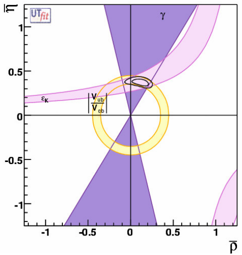

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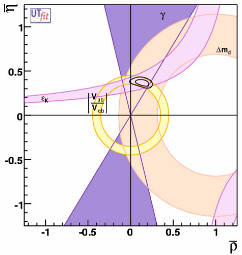

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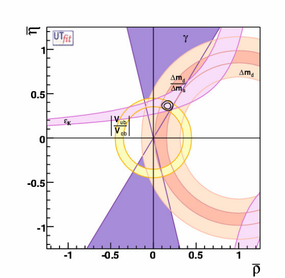

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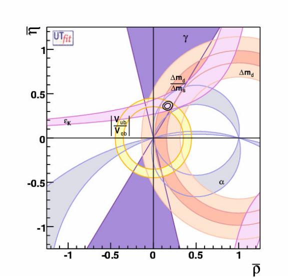

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- Decays to π and K

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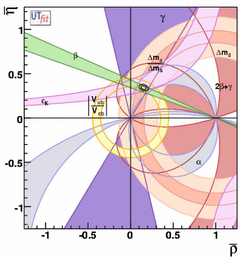

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- CP asymmetry in $B \to J/\psi K_S$

Concluding remarks: end of Lecture 1

- No deviation from the CKM predictions has been observed
  $\Rightarrow$ Constrains many new physics models
- CP violation required for baryon asymmetry, but the CKM is not enough, so there will be life beyond CKM
- Physics beyond the Standard Model must exist !
  - Where to look for it ?
  - How to identify and quantify it ?
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