Particle Physics: The Standard Model

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May 16, 2013

- The Particles
- $W^\pm$ couples to $SU(2)_L$ doublets
- Z°: no FCNC (Z° cannot change flavor just like γ)
- Assumption MassEigenstates=EWEigenstates
- Why?

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$\begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu_L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau_L} \\ \tau_L \end{pmatrix}$$

$$\begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \\ e_R & \mu_R & \tau_R \end{matrix}$$

$$\begin{matrix} \gamma \\ g \\ W^\pm, Z^\circ \\ H \end{matrix}$$

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$$\begin{pmatrix} \nu_{\mathrm{e_L}} \\ \mathrm{e_L} \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu_\mathrm{L}} \\ \mu_\mathrm{L} \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau_\mathrm{L}} \\ \tau_\mathrm{L} \end{pmatrix}$$

$$\begin{matrix} \mathrm{u_R} & \mathrm{c_R} & \mathrm{t_R} \\ \mathrm{d_R} & \mathrm{s_R} & \mathrm{b_R} \\ \mathrm{e_R} & \mu_\mathrm{R} & \tau_\mathrm{R} \end{matrix}$$

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$$\gamma$$
$$g$$
$$W^{\pm}, Z^\circ$$
$$H$$

- Another perspective: meson lifetimes
- Weak decays of mesons differ by orders of magnitude?
- How can the s decay weakly? $m_c > m_s$?
- Keep leptons untouched
- Introduce the CKM matrix

Properties of the c

$$\begin{aligned} m_0 &= 1.27\mathrm{GeV} \\ \tau &= (1.040 \cdot 10^{-12})\mathrm{s} \quad c\bar{d} \\ c\tau &= 311.8\mu\mathrm{m} \end{aligned}$$

Properties of the s

$$\begin{aligned} m_0 &= 100 \pm 25\mathrm{MeV} \\ \tau &= (1.24 \cdot 10^{-8})\mathrm{s} \quad u\bar{s} \\ c\tau &= 3.7\mathrm{m} \end{aligned}$$

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Definition

d is the mass Eigenstate

d' is the isospin partner of u

V: unitary 3×3 matrix $V^\dagger V = 1_3$

Cannot simplify: masses not equal

$$\mathcal{L}_{Yuk} = -\bar{u} m_u u - \bar{c} m_c c - \bar{t} m_t t - \bar{d} m_d d - \bar{s} m_s s - \bar{b} m_b b$$

$$= -\begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix}$$

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\begin{aligned}
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&= -\begin{pmatrix} \bar{\mathrm{u}} & \bar{\mathrm{c}} & \bar{\mathrm{t}} \end{pmatrix} \begin{pmatrix} m_\mathrm{u} & 0 & 0 \\ 0 & m_\mathrm{c} & 0 \\ 0 & 0 & m_\mathrm{t} \end{pmatrix} \begin{pmatrix} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{pmatrix} \\
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&\quad - \begin{pmatrix} \bar{\mathrm{d}}' & \bar{\mathrm{s}}' & \bar{\mathrm{b}}' \end{pmatrix} \mathrm{V} \begin{pmatrix} m_\mathrm{d} & 0 & 0 \\ 0 & m_\mathrm{s} & 0 \\ 0 & 0 & m_\mathrm{b} \end{pmatrix} \mathrm{V}^\dagger \begin{pmatrix} \mathrm{d}' \\ \mathrm{s}' \\ \mathrm{b}' \end{pmatrix}
\end{aligned}$$

Properties of V

- Cabibbo, Kobayashi, Maskawa
- V complex: $3 \times 3 \times 2$
- $VV^\dagger = 1_3$: 9 constraints
- 5 phases absorbed
- 3 real mixing angles, 1 complex phase

Cabibbo

(2 generations):

$$\begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

Wolfenstein

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Diagonal entries dominate

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Charged Current

$$\begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu \begin{pmatrix} d_L{}' \\ s_L{}' \\ b_L{}' \end{pmatrix}$$

$$= \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

Decays

$$\begin{array}{cccc} d & \rightarrow & u + W^- & V_{11} \\ s & \rightarrow & u + W^- & V_{12} \\ b & \rightarrow & u + W^- & V_{13} \end{array}$$

- $V_{11} = 0.98$, $V_{12} = 0.2$
- charmed mesons: $V_{11}^2 G^2 \rightarrow 0.96 G^2$
- strange mesons: $V_{12}^2 G^2 \rightarrow 0.04 G^2$ longer lifetime

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Neutral Current

Neutral currents couple to right- and left-handed quarks:

$$\begin{pmatrix} \bar{d}' & \bar{s}' & \bar{b}' \end{pmatrix} \gamma^\mu \left(-\frac{1}{2}\frac{1-\gamma_5}{2} + \frac{1}{3}\sin^2\theta_W\right) \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

$$= \begin{pmatrix} \bar{d} & \bar{s} & \bar{b} \end{pmatrix} V^\dagger \gamma^\mu \left(-\frac{1}{2}\frac{1-\gamma_5}{2} + \frac{1}{3}\sin^2\theta_W\right) V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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$V^\dagger V = 1_3$: does not have a Lorentz index, only family index

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And the up-type sector?

$$\begin{pmatrix} \overline{u}'_L & \overline{c}'_L & \overline{t}'_L \end{pmatrix} \gamma^\mu \begin{pmatrix} d_L{}' \\ s_L{}' \\ b_L{}' \end{pmatrix}$$

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define: $V_3 = V_2^\dagger V$

$V_3 V_3^\dagger = (V_2^\dagger V)(V_2^\dagger V)^\dagger = V_2^\dagger V V^\dagger V_2 = 1$

$\rightarrow$ 1 matrix sufficient

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- C: transforms particles into anti-particles
- P: inverts momentum

EM Interactions

	e^-	$\rightarrow$	γe^-
	L	$\rightarrow$	$-1R$
P	e^-	$\rightarrow$	γe^-
	R	$\rightarrow$	$+1L$
C	e^+	$\rightarrow$	γe^+
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CP	e^+	$\rightarrow$	γe^+
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EW Interactions

	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
	L	$\rightarrow$	LLR
P	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
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CPT always conserved

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$$\begin{array}{lccc} & \mu^- & \rightarrow & \nu_{\mu_L} e^- \bar{\nu}_{e_L} \\ & L & \rightarrow & LLR \\ P & \mu^- & \rightarrow & \nu_{\mu_L} e^- \bar{\nu}_{e_L} \\ & R & \rightarrow & RRL \\ C & \mu^+ & \rightarrow & \bar{\nu}_{\mu_L} e^+ \nu_{e_L} \\ & L & \rightarrow & LLR \\ CP & \mu^+ & \rightarrow & \bar{\nu}_{\mu_L} e^+ \nu_{e_L} \\ & R & \rightarrow & RRL \end{array}$$

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P	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
	R	$\rightarrow$	RRL
C	μ^+	$\rightarrow$	$\bar{\nu}_{\mu_L} e^+ \nu_{e_L}$
	L	$\rightarrow$	LLR
CP	μ^+	$\rightarrow$	$\bar{\nu}_{\mu_L} e^+ \nu_{e_L}$
	R	$\rightarrow$	RRL

CPT always conserved

- *C*: transforms particles into anti-particles
- *P*: inverts momentum

EM Interactions

	e^-	$\rightarrow$	γe^-
	L	$\rightarrow$	$-1R$
P	e^-	$\rightarrow$	γe^-
	R	$\rightarrow$	$+1L$
C	e^+	$\rightarrow$	γe^+
	L	$\rightarrow$	$-1R$
CP	e^+	$\rightarrow$	γe^+
	R	$\rightarrow$	$+1L$

EW Interactions

	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
	L	$\rightarrow$	LLR
P	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
	R	$\rightarrow$	RRL
C	μ^+	$\rightarrow$	$\bar{\nu}_{\mu_L} e^+ \nu_{e_L}$
	L	$\rightarrow$	LLR
CP	μ^+	$\rightarrow$	$\bar{\nu}_{\mu_L} e^+ \nu_{e_L}$
	R	$\rightarrow$	RRL

CPT always conserved

- *C*: transforms particles into anti-particles
- *P*: inverts momentum

EM Interactions

$$\begin{array}{llll} & e^- & \rightarrow & \gamma e^- \\ & L & \rightarrow & -1R \\ P & e^- & \rightarrow & \gamma e^- \\ & R & \rightarrow & +1L \\ C & e^+ & \rightarrow & \gamma e^+ \\ & L & \rightarrow & -1R \\ CP & e^+ & \rightarrow & \gamma e^+ \\ & R & \rightarrow & +1L \end{array}$$

EW Interactions

$$\begin{array}{llll} & \mu^- & \rightarrow & \nu_{\mu_L} e^- \bar{\nu}_{e_L} \\ & L & \rightarrow & LLR \\ P & \mu^- & \rightarrow & \nu_{\mu_L} e^- \bar{\nu}_{e_L} \\ & R & \rightarrow & RRL \\ C & \mu^+ & \rightarrow & \bar{\nu}_{\mu_L} e^+ \nu_{e_L} \\ & L & \rightarrow & LLR \\ CP & \mu^+ & \rightarrow & \bar{\nu}_{\mu_L} e^+ \nu_{e_L} \\ & R & \rightarrow & RRL \end{array}$$

CPT always conserved

- C: transforms particles into anti-particles
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EM Interactions

$$
\begin{array}{llll}
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 & L & \rightarrow & -1R \\
CP & e^+ & \rightarrow & \gamma e^+ \\
 & R & \rightarrow & +1L
\end{array}
$$

EW Interactions

$$
\begin{array}{llll}
 & \mu^- & \rightarrow & \nu_{\mu_L} e^- \bar{\nu}_{e_L} \\
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$$

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	L	$\rightarrow$	$-1R$
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	R	$\rightarrow$	$+1L$

EW Interactions

	μ^-	$\rightarrow$	$\nu_{\mu_L} e^- \bar{\nu}_{e_L}$
	L	$\rightarrow$	LLR
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CPT always conserved

Neutral Kaons

$$K^\circ = |\bar{s}d\rangle$$
$$\bar{K}^\circ = -|s\bar{d}\rangle$$

-: strong Isospin anti-particle

Charge Conjugation

$$CK^\circ = C(|\bar{s}d\rangle)$$
$$= |s\bar{d}\rangle$$
$$= -\bar{K}^\circ$$
$$C\bar{K}^\circ = -|\bar{s}d\rangle$$
$$= -K^\circ$$

not Eigenstates of C

Parity

- $(-1)^\ell$ from $Y_{\ell m}(\pi - \theta, \pi + \phi) = (-1)^\ell Y(\theta, \phi)$
- multiplicative: $P(p_1 p_2) = P(p_1) \cdot P(p_2)$
- Spinor: $\gamma^0 \psi$ (DIRAC equation)
  - $\gamma^0 u(\mathbf{p}') = u(\mathbf{p})$
  - $\gamma^0 v(\mathbf{p}') = -v(\mathbf{p})$
- relative (-1) between particle and anti-particle

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CP

$$CP K^\circ = (-1)\cdot(-1)^\ell(-\bar{K}^\circ)$$
$$= \bar{K}^\circ$$
$$CP\bar{K}^\circ = (-1)\cdot(-1)^\ell(-K^\circ)$$
$$= K^\circ$$

CP Eigenstates

$$(+1):\quad K_1 = \frac{1}{\sqrt{2}}(K^\circ + \bar{K}^\circ)$$
$$(-1):\quad K_2 = \frac{1}{\sqrt{2}}(K^\circ - \bar{K}^\circ)$$

strong prod, weak decay

$\pi^+\pi^-$

$$C(\pi^+\pi^-) = \pi^-\pi^+$$
$$P(\pi^+\pi^-) = P(\pi^-)P(\pi^+)$$
$$= 1$$
$$CP(\pi^+\pi^-) = 1$$

$\pi^+\pi^-\pi^0$

$$C(\pi^0) = C(\gamma)^2 = 1$$
$$P(\pi^0) = -1$$
$$CP(\pi^+\pi^-\pi^0) = CP(\pi^+\pi^-)\cdot CP(\pi^0)$$
$$= -1$$

CP

$$CP\mathrm{K}^\circ = (-1)\cdot(-1)^\ell(-\bar{\mathrm{K}}^\circ) = \bar{\mathrm{K}}^\circ$$

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CP Eigenstates

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CP

$$\begin{aligned} CP\mathrm{K}^\circ &= (-1)\cdot(-1)^\ell(-\bar{\mathrm{K}}^\circ) \\ &= \bar{\mathrm{K}}^\circ \\ CP\bar{\mathrm{K}}^\circ &= (-1)\cdot(-1)^\ell(-\mathrm{K}^\circ) \\ &= \mathrm{K}^\circ \end{aligned}$$

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Lifetimes

Kaon mass: $494 MeV$

$$
\begin{aligned}
K_1 &\rightarrow \pi^+\pi^- \\
\tau_S &= 0.9 \cdot 10^{-10} s \\
K_2 &\rightarrow \pi^+\pi^-\pi^0 \\
\tau_L &= 5.2 \cdot 10^{-8} s
\end{aligned}
$$

phase space:

$$
\begin{aligned}
m(\pi^+\pi^-) &\approx 280 MeV \\
m(\pi^+\pi^-\pi^0) &\approx 420 MeV
\end{aligned}
$$

K_2 was initially “overlooked”

Time dependence

Decay is described by weak Eigenstates with a well-defined lifetime:

$$
\begin{aligned}
|K_1(t)\rangle &= |K_1(0)\rangle \exp^{-iM_S t} \exp^{-\Gamma_S t/2} \\
|K_2(t)\rangle &= |K_2(0)\rangle \exp^{-iM_L t} \exp^{-\Gamma_L t/2}
\end{aligned}
$$

strong as f(weak):

$$
\begin{aligned}
\mathrm{K}^\circ &= \frac{1}{\sqrt{2}}(|K_1\rangle + |K_2\rangle) \\
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Oscillation

$A(t)$: amplitude to produce at $t = 0$ a K° and find at t a $\overline{\mathrm{K}}^\circ$:

$$
\begin{aligned}
A(t) &= \langle \overline{\mathrm{K}}^\circ(t) | \mathrm{K}^\circ(t=0) \rangle \\
&= \tfrac{1}{2}(\langle K_1(t)| - \langle K_2(t)|)(|K_1(t=0)\rangle + |K_2(t=0)\rangle) \\
&= \tfrac{1}{2}(\langle K_1(t)|K_1(t=0)\rangle - \langle K_2(t)|K_2(t=0)\rangle) \\
&= \tfrac{1}{2}(\exp^{-iM_S t}\exp^{-\Gamma_S t/2} - \exp^{-iM_L t}\exp^{-\Gamma_L t/2}) \\
A(t)A^\star(t) &= \tfrac{1}{4}(\exp^{-\Gamma_S t} + \exp^{-\Gamma_L t} - 2\cos(\Delta M t)\exp^{-(\Gamma_L+\Gamma_S)t/2})
\end{aligned}
$$

- $\Gamma_S \gg \Gamma_L$: decay with Γ_L
- oscillation with frequency $\Delta M = M_L - M_S$

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\end{aligned}
$$

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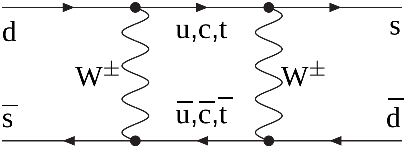
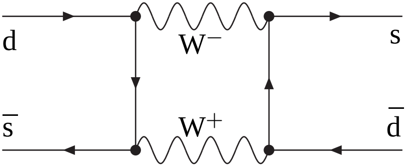
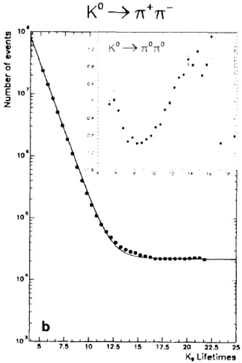
- oscillation with frequency $\Delta M = M_L - M_S$



Follow fermion line: transition between generations inevitable!

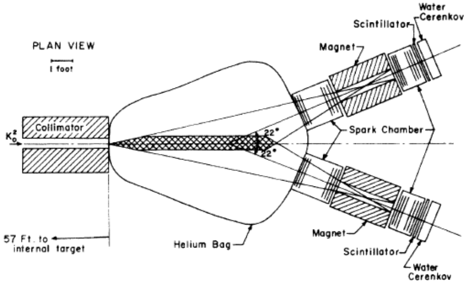


Need *CKM* non-diagonal: $\sim \sin^2\theta_C$



- need interference term!
- $\Delta M \sim 3.5 \cdot 10^{-6} eV$

All settled?



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- K_1 die out (can be regenerated)
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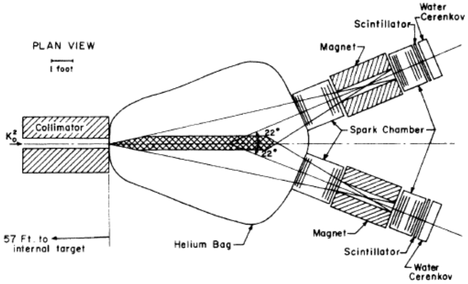

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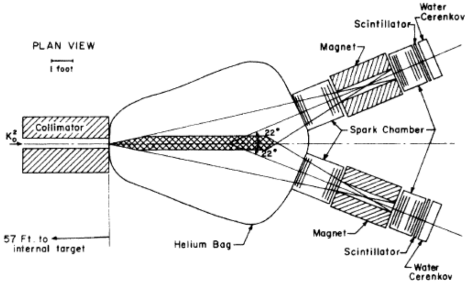

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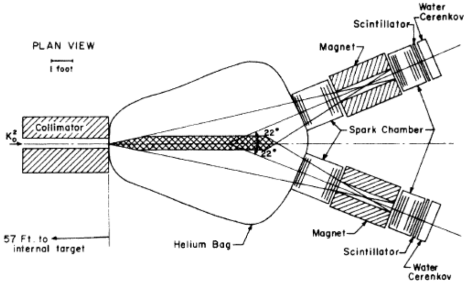

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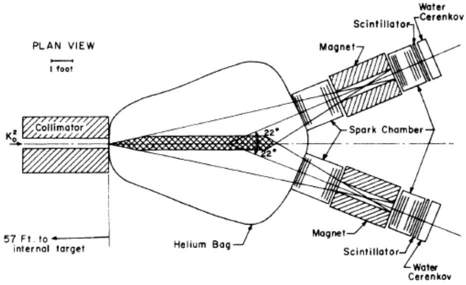

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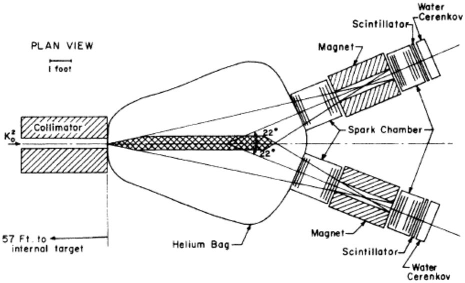

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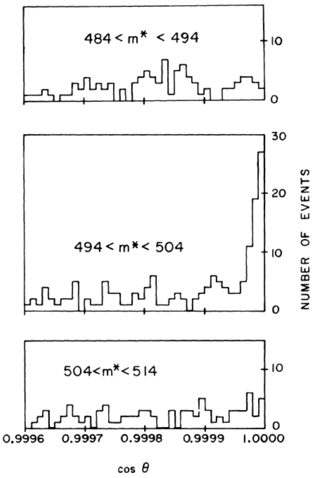

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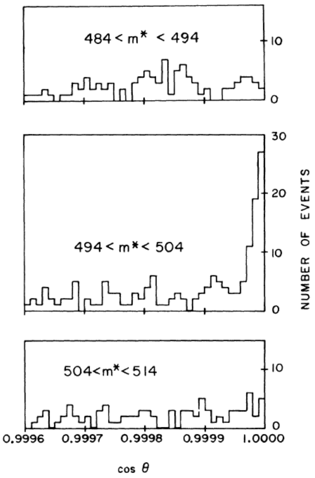
- level: 10^{-3}
- *CP* must be violated!
- *CKM* has a complex phase



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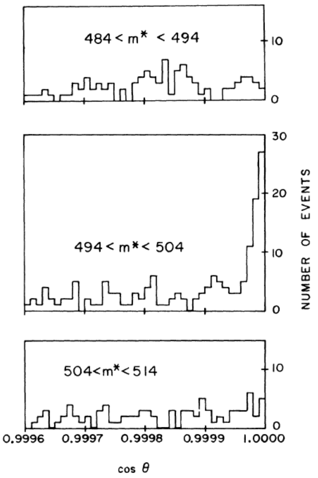

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$$K_S = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1\rangle + \epsilon|K_2\rangle)$$
$$K_L = \frac{1}{\sqrt{1+|\epsilon|^2}}(\epsilon|K_1\rangle + |K_2\rangle)$$

CP violation in mixing

$$|\epsilon| = \sqrt{\frac{\Gamma_L(\pi^+\pi^-)}{\Gamma_S(\pi^+\pi^-)}} = 2.268 \pm 0.023 \cdot 10^{-3}$$

CP violation in decay

$$Re(\frac{\epsilon'}{\epsilon}) = \frac{1}{6}(1 - \frac{\Gamma_L(\pi^0\pi^0)\Gamma_S(\pi^+\pi^-)}{\Gamma_S(\pi^0\pi^0)\Gamma_L(\pi^+\pi^-)})$$
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$$(FNAL) = 7.4 \pm 5.9 \cdot 10^{-4}$$
$$(FNAL) = 28 \pm 4.1 \cdot 10^{-4}$$
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B-sector

- Flavour oscillation in all neutral systems
- $m_{\mathrm{B}^\circ} \sim 5GeV \gg m_{\mathrm{K}^\circ} \sim 0.5GeV$
- lifetime (tag)

Experiments

large production

- dedicated machine: $\mathrm{e^+e^-}$
- or pp
- good PID

- BABAR@SLAC PEP-II
- BELLE@KEK-B
- asymmetric colliders
  - $\mathrm{e^-}$: 9.1GeV
  - $\mathrm{e^+}$: 3.4GeV
- Υ^{4s}:
  - resonance $\mathrm{b\bar{b}}$
  - decay to $\mathrm{B_d^\circ \bar{B}_d^\circ}$ and $\mathrm{B_s^\circ \bar{B}_s^\circ}$
  - $250\mu m$ need great vertex detector

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Back to *CKM*

- V complex
- $V^\dagger V = 1_3$: 9 equations
- 6 equations with complex $= 0$
- 2-coordinate plane: triangle
- α, β, γ

Unitary triangle

$$(V^\dagger V)_{31} = 0 = V^\star_{ub} V_{ud} + V^\star_{cb} V_{cd} + V^\star_{tb} V_{td}$$

Measurements

- Δm_s
- Δm_d
- $\bar{B}^\circ \rightarrow \pi^+\pi^-$
- $\bar{B}^\circ \rightarrow J/\psi K_S$
- $B^+ \rightarrow DK^+$
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- relationship angles-V: Problem Solving
- all measurements in agreement
- no sign of BSM
- impressive progress in 10 years
- D0 like-sign di-muons?