CP VIOLATION In The Standard Model

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Quarks		Leptons		Bosons
up	down	electron	neutrino e	photon
charm	oo strange	muon	neutrino µ	gluon
top	beauty	tau	heutrino τ	Z ⁰ W [±]

FERMION GENERATIONS

 $N_G = 3$ Identical CopiesMasses are the only differenceQ=0 $\begin{pmatrix} v'_j & u'_j \\ l'_j & d'_j \end{pmatrix}$ Q=+2/3 $(j=1,\cdots,N_G)$ WHY ?

$$\mathcal{L}_{Y} = \sum_{jk} \left\{ \left(\vec{u}_{j}^{\prime}, \vec{d}_{j}^{\prime} \right)_{L} \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d_{kR}^{\prime} + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u_{kR}^{\prime} \right] + \left(\vec{v}_{j}^{\prime}, \vec{l}_{j}^{\prime} \right)_{L} c_{jk}^{(\ell)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_{kR}^{\prime} \right\} + \text{h.c.}$$

$$\mathbf{SSB}$$

$$\mathcal{L}_{Y} = -\left(1 + \frac{H}{V} \right) \left\{ \vec{d}_{L}^{\prime} \cdot \mathbf{M}_{d}^{\prime} \cdot d_{R}^{\prime} + \vec{u}_{L}^{\prime} \cdot \mathbf{M}_{u}^{\prime} \cdot u_{R}^{\prime} + \vec{l}_{L}^{\prime} \cdot \mathbf{M}_{l}^{\prime} \cdot l_{R}^{\prime} + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices $\begin{bmatrix} \mathbf{M}'_{d}, \mathbf{M}'_{u}, \mathbf{M}'_{l} \end{bmatrix}_{jk} = -\begin{bmatrix} c^{(d)}_{jk}, c^{(u)}_{jk}, c^{(l)}_{jk} \end{bmatrix} \frac{\mathbf{v}}{\sqrt{2}}$

CP Violation

DIAGONALIZATION OF MASS MATRICES

 $\mathbf{M}'_{d} = \mathbf{H}_{d} \cdot \mathbf{U}_{d} = \mathbf{S}_{d}^{\dagger} \cdot \mathcal{M}_{d} \cdot \mathbf{S}_{d} \cdot \mathbf{U}_{d} \qquad \mathbf{H}_{f} = \mathbf{H}_{f}^{\dagger}$ $\mathbf{M}'_{u} = \mathbf{H}_{u} \cdot \mathbf{U}_{u} = \mathbf{S}_{u}^{\dagger} \cdot \mathcal{M}_{u} \cdot \mathbf{S}_{u} \cdot \mathbf{U}_{u} \qquad \mathbf{U}_{f} \cdot \mathbf{U}_{f}^{\dagger} = \mathbf{U}_{f}^{\dagger} \cdot \mathbf{U}_{f} = 1$ $\mathbf{M}'_{l} = \mathbf{H}_{l} \cdot \mathbf{U}_{l} = \mathbf{S}_{l}^{\dagger} \cdot \mathcal{M}_{l} \cdot \mathbf{S}_{l} \cdot \mathbf{U}_{l} \qquad \mathbf{S}_{f} \cdot \mathbf{S}_{f}^{\dagger} = \mathbf{S}_{f}^{\dagger} \cdot \mathbf{S}_{f} = 1$



$$\mathcal{L}_{Y} = -\left(1 + \frac{H}{V}\right) \left\{ \overline{\mathbf{d}} \cdot \mathcal{M}_{d} \cdot \mathbf{d} + \overline{\mathbf{u}} \cdot \mathcal{M}_{u} \cdot \mathbf{u} + \overline{l} \cdot \mathcal{M}_{l} \cdot l \right\}$$

 $\mathcal{M}_{u} = \operatorname{diag}\left(m_{u}, m_{c}, m_{t}\right) \quad ; \quad \mathcal{M}_{d} = \operatorname{diag}\left(m_{d}, m_{s}, m_{b}\right) \quad ; \quad \mathcal{M}_{l} = \operatorname{diag}\left(m_{e}, m_{\mu}, m_{\tau}\right)$

$$\mathbf{d}_{L} \equiv \mathbf{S}_{d} \cdot \mathbf{d}'_{L} \quad ; \quad \mathbf{u}_{L} \equiv \mathbf{S}_{u} \cdot \mathbf{u}'_{L} \quad ; \quad l_{L} \equiv \mathbf{S}_{l} \cdot l'_{L}$$
$$\mathbf{d}_{R} \equiv \mathbf{S}_{d} \cdot \mathbf{U}_{d} \cdot \mathbf{d}'_{R} \quad ; \quad \mathbf{u}_{R} \equiv \mathbf{S}_{u} \cdot \mathbf{U}_{u} \cdot \mathbf{u}'_{R} \quad ; \quad l_{R} \equiv \mathbf{S}_{l} \cdot \mathbf{U}_{l} \cdot l'_{R}$$

 $\overline{\mathbf{f}}'_{L} \mathbf{f}'_{L} = \overline{\mathbf{f}}_{L} \mathbf{f}_{L} \quad ; \quad \overline{\mathbf{f}}'_{R} \mathbf{f}'_{R} = \overline{\mathbf{f}}_{R} \mathbf{f}_{R} \qquad \longrightarrow \qquad \mathcal{L}'_{\mathrm{NC}} = \mathcal{L}_{\mathrm{NC}}$ $\overline{\mathbf{u}}'_{L} \mathbf{d}'_{L} = \overline{\mathbf{u}}_{L} \cdot \mathbf{V} \cdot \mathbf{d}_{L} \quad ; \qquad \mathbf{V} \equiv \mathbf{S}_{u} \cdot \mathbf{S}_{d}^{\dagger} \qquad \longrightarrow \qquad \mathcal{L}'_{\mathrm{CC}} \neq \mathcal{L}_{\mathrm{CC}}$ $\mathbf{QUARK MIXING}$

CP Violation

$$\mathcal{L}_{NC}^{Z} = \frac{e}{2\sin\theta_{W}\cos\theta_{W}} Z_{\mu} \sum_{f} \overline{f} \gamma^{\mu} \left[v_{f} - a_{f} \gamma_{5} \right] f$$

Flavour Conserving Neutral Currents

$$\mathcal{L}_{cc} = \frac{g}{2\sqrt{2}} W^{\dagger}_{\mu} \left[\sum_{ij} \overline{u}_{i} \gamma^{\mu} (1-\gamma_{5}) \mathbf{V}_{ij} d_{j} + \sum_{l} \overline{v}_{l} \gamma^{\mu} (1-\gamma_{5}) l \right] + \text{h.c.}$$

Flavour Changing Charged Currents





We measure decays of hadrons (no free quarks)



Important QCD Uncertainties

CP Violation

Vir ___ <u>___</u> 0 5

 $\left| \mathbf{V}_{ud} \right|^{2} + \left| \mathbf{V}_{us} \right|^{2} + \left| \mathbf{V}_{ub} \right|^{2} = 0.9976 \pm 0.0021$

CP Violation

CKM entry	Value	Source
	0.9740 ± 0.0005	Nuclear β decay
	0.9729 ± 0.0012	$n \rightarrow p e^- \overline{v}_e$
	0.9739 ± 0.0005	
	0.2220 ± 0.0025	$K \to \pi e^- \overline{v}_e$
	0.2208 ± 0.0034	au decays
	0.2219 ± 0.0025	$K/\pi \rightarrow \mu v$, Lattice
	0.2217 ± 0.0025	
	0.224 ± 0.012	$v d \rightarrow c X$
	0.97 ± 0.11	$W^+ \rightarrow c \overline{s}$
	0.974 ± 0.013	$W^+ \rightarrow \text{had}, V_{uj}, V_{cd,cb}$
	0.0414 ± 0.0021	$B \to D^* l \ \overline{v}_l$
	0.0410 ± 0.0015	$b \rightarrow c \ l \ \overline{v}_l$
	0.0411 ± 0.0015	
	0.0033 ± 0.0006	$B \to \rho \ l \ \overline{v_l}$
	0.0047 ± 0.0009	$b \rightarrow u \ l \ \overline{v_l}$
	0.0037 ± 0.0005	
	$0.97 {}^{+ 0.16}_{- 0.12}$	$t \rightarrow bW/qW$

(LEP)

 $\sum_{i} \left(\left| \mathbf{V}_{uj} \right|^{2} + \left| \mathbf{V}_{cj} \right|^{2} \right) = 1.999 \pm 0.025$

V ╼━ 0 5

$ \begin{vmatrix} V_{ud} \\ 0.9740 \pm 0.0005 \\ 0.9769 \pm 0.0013 \\ 0.9744 \pm 0.0005 \\ 0.9744 \pm 0.0005 \\ 0.9744 \pm 0.0005 \\ 0.9744 \pm 0.0005 \\ 0.220 \pm 0.0025 \\ 0.2208 \pm 0.0034 \\ 0.2208 \pm 0.0034 \\ 0.2219 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.974 \pm 0.012 \\ V_{rd} - cX \\ 0.974 \pm 0.013 \\ W^* \to c\overline{x} \\ 0.974 \pm 0.013 \\ W^* \to had, V_{ui}, V_{cd,cb} \\ V_{ub} \\ 0.0414 \pm 0.0021 \\ 0.0414 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ 0.0041 \pm 0.0005 \\ W_{ub} \\ 0.0033 \pm 0.0006 \\ B \to \rho \mid \overline{v}_i \\ 0.0037 \pm 0.0005 \\ W_{ub} \mid V_{ub} \mid V$	CKM entry	Value	Source	
$ \begin{split} & \begin{array}{ c c c c } & 0.9769 \pm 0.0013 \\ 0.9744 \pm 0.0005 \\ \hline N \rightarrow p \ e^{-\overline{v}_e} \\ 0.2202 \pm 0.0025 \\ 0.2208 \pm 0.0034 \\ \hline t \ decays \\ 0.2219 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ \hline U_{cd} & 0.224 \pm 0.012 \\ \hline V_{cd} & 0.97 \pm 0.11 \\ \hline W^+ \rightarrow c \overline{s} \\ 0.974 \pm 0.013 \\ \hline W^+ \rightarrow had, V_{ui}, V_{cd,cb} \\ \hline V_{cb} & 0.0414 \pm 0.0021 \\ \hline 0.0410 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ \hline D \rightarrow c \ \overline{v}_l \\ \hline 0.0033 \pm 0.006 \\ \hline B \rightarrow \rho \ \overline{v}_l \\ \hline b \rightarrow c \ \overline{v}_l \\ \hline 0.0037 \pm 0.005 \\ \hline V_{cb} & 0.0037 \pm 0.005 \\ \hline V_{cb} & 0.097 \pm 0.16 \\ \hline V_{cb} & 0.97 \pm $	$ V_{ud} $	0.9740 ± 0.0005	Nuclear β decay	
$ \begin{vmatrix} 0.9744 \pm 0.0005 & K \to \pi e^{-}\overline{v}_{e} \\ 0.220 \pm 0.0025 & K \to \pi e^{-}\overline{v}_{e} \\ 0.2208 \pm 0.0034 & \tau \text{ decays} \\ 0.2219 \pm 0.0025 & K/\pi \to \mu\nu, \text{ Lattice} \\ 0.2217 \pm 0.0025 & Vd \to c X \end{vmatrix} $ $ \begin{vmatrix} V_{cd} & 0.224 \pm 0.012 & \nu d \to c X \\ V_{cd} & 0.97 \pm 0.11 & W^{*} \to c \overline{s} \\ 0.974 \pm 0.013 & W^{*} \to \text{had}, V_{uj}, V_{cd,cb} \\ V_{cb} & 0.0414 \pm 0.0021 & B \to D^{*} l \overline{v}_{l} \\ 0.0411 \pm 0.0015 & b \to c l \overline{v}_{l} \\ 0.0033 \pm 0.0006 & B \to \rho l \overline{v}_{l} \\ 0.0037 \pm 0.0005 & b \to u l \overline{v}_{l} \end{aligned} $ $ \begin{vmatrix} V_{ub} & 0.0033 \pm 0.0006 & B \to \rho l \overline{v}_{l} \\ 0.0037 \pm 0.0005 & b \to u l \overline{v}_{l} \end{vmatrix} $		0.9769 ± 0.0013	$n \rightarrow p e^- \overline{v}_e$	Serebrov et al
$ \begin{split} & V_{uv} & 0.2220 \pm 0.0025 & K \to \pi e^{-\overline{v}_e} \\ & 0.2208 \pm 0.0034 & \tau \text{ decays} \\ & 0.2219 \pm 0.0025 & V \text{ decays} \\ & 0.2217 \pm 0.0025 & V \text{ decays} \\ & V_{uv}, \text{ Lattice} \\ \hline V_{ed} & 0.224 \pm 0.012 & V \text{ decays} \\ & 0.97 \pm 0.11 & W^+ \to c\overline{s} \\ & 0.974 \pm 0.013 & W^+ \to \text{had}, V_{ui}, V_{ed,eb} \\ \hline V_{eb} & 0.0414 \pm 0.0021 & B \to D^* l \overline{v}_l \\ & 0.0410 \pm 0.0015 & b \to c l \overline{v}_l \\ & 0.0033 \pm 0.0006 & B \to \rho l \overline{v}_l \\ & 0.0037 \pm 0.0005 & b \to u l \overline{v}_l \\ \hline V_{ub} / \sqrt{\sum_q V_{iq} ^2} & 0.97^{+0.16}_{-0.12} & t \to bW/qW \end{split} $		0.9744 ± 0.0005		
$ \begin{vmatrix} 0.2208 \pm 0.0034 \\ 0.2219 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.2217 \pm 0.0025 \end{vmatrix} \begin{array}{c} K/\pi \to \mu\nu, \text{Lattice} \\ K/\pi \to \mu\nu, \text{Lattice} \\ \hline V_{cd} \end{vmatrix} \\ 0.224 \pm 0.012 \\ vd \to c X \\ 0.97 \pm 0.11 \\ W^+ \to c \overline{s} \\ 0.974 \pm 0.013 \\ W^+ \to had, V_{ui}, V_{cd,cb} \\ \hline V_{cb} \end{vmatrix} \\ \begin{array}{c} 0.0414 \pm 0.0021 \\ 0.0410 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ 0.0047 \pm 0.0009 \\ 0.0037 \pm 0.0005 \\ \hline V_{ub} \end{vmatrix} \\ \begin{array}{c} 0.0033 \pm 0.0006 \\ 0.0037 \pm 0.0005 \\ 0.0037 \pm 0.0005 \\ \hline V_{ub} \end{vmatrix} \\ \begin{array}{c} V_{rb} \sqrt{\sum_{g} V_{rg} ^2} \\ 0.97 \stackrel{+ 0.16}{- 0.12} \\ \hline V \to bW/gW \\ \end{matrix} $		0.2220 ± 0.0025	$K \to \pi e^- \overline{v}_e$	
$ \begin{vmatrix} 0.2219 \pm 0.0025 \\ 0.2217 \pm 0.0025 \\ 0.2217 \pm 0.0025 \end{vmatrix} K/\pi \to \mu\nu, \text{ Lattice} \\ \begin{vmatrix} V_{cd} \end{vmatrix} & 0.224 \pm 0.012 & \nu d \to c X \\ \begin{vmatrix} V_{cs} \end{vmatrix} & 0.97 \pm 0.11 & W^* \to c \overline{s} \\ 0.974 \pm 0.013 & W^* \to \text{had}, V_{uj}, V_{cd,cb} \\ \end{vmatrix} \\ \begin{vmatrix} V_{cb} \end{vmatrix} & 0.0414 \pm 0.0021 & B \to D^* \overline{v}_l \\ 0.0410 \pm 0.0015 & b \to c \overline{v}_l \\ 0.0411 \pm 0.0015 & b \to c \overline{v}_l \\ \end{vmatrix} \\ \begin{vmatrix} V_{ub} \end{vmatrix} & 0.0033 \pm 0.0006 & B \to \rho \overline{v}_l \\ 0.0037 \pm 0.0005 & b \to u \overline{v}_l \\ \end{vmatrix} $		0.2208 ± 0.0034	au decays	
0.2217 ± 0.0025 $ V_{cd} $ 0.224 ± 0.012 $vd \rightarrow cX$ $ V_{ca} $ 0.97 ± 0.11 $W^+ \rightarrow c\overline{s}$ $ V_{cb} $ 0.974 ± 0.013 $W^+ \rightarrow had, V_{ui}, V_{cd,cb}$ $ V_{cb} $ 0.0414 ± 0.0021 $B \rightarrow D^+ l \overline{v}_l$ $ V_{cb} $ 0.0414 ± 0.0015 $b \rightarrow c l \overline{v}_l$ $ V_{ub} $ 0.0033 ± 0.0006 $B \rightarrow \rho l \overline{v}_l$ $ V_{ub} $ 0.0033 ± 0.0006 $B \rightarrow \rho l \overline{v}_l$ $ V_{ub} $ 0.0037 ± 0.0005 $b \rightarrow u l \overline{v}_l$ $ V_{ub} /\sqrt{\sum_q V_{tq} ^2}$ $0.97^{+0.16}_{-0.12}$ $t \rightarrow bW/qW$		0.2219 ± 0.0025	$K/\pi \rightarrow \mu v$, Lattice	
$\begin{aligned} \begin{vmatrix} V_{cd} & 0.224 \pm 0.012 & vd \rightarrow c X \\ \begin{vmatrix} V_{cs} & 0.97 \pm 0.11 & W^+ \rightarrow c \overline{s} \\ 0.974 \pm 0.013 & W^+ \rightarrow had, V_{uj}, V_{cd,cb} \\ \end{vmatrix} \\ \begin{vmatrix} V_{cb} & 0.0414 \pm 0.0021 & B \rightarrow D^* l \overline{v}_l \\ 0.0410 \pm 0.0015 & b \rightarrow c l \overline{v}_l \\ 0.0411 \pm 0.0015 & 0 \rightarrow c l \overline{v}_l \\ \end{vmatrix} \\ \begin{vmatrix} V_{ab} & 0.0033 \pm 0.0006 & B \rightarrow \rho l \overline{v}_l \\ 0.0037 \pm 0.0009 & b \rightarrow u l \overline{v}_l \\ \end{vmatrix} \\ \end{vmatrix}$		0.2217 ± 0.0025		
$ \begin{vmatrix} V_{cs} \\ 0.97 \pm 0.11 \\ 0.974 \pm 0.013 \\ \end{vmatrix} \\ W^{+} \rightarrow had, V_{uj}, V_{cd,cb} \\ 0.0414 \pm 0.0021 \\ 0.0410 \pm 0.0015 \\ 0.0410 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ \end{vmatrix} \\ B \rightarrow D^{*} I \overline{v}_{l} \\ b \rightarrow c I \overline{v}_{l} \\ 0.0033 \pm 0.0006 \\ 0.0047 \pm 0.0009 \\ b \rightarrow u I \overline{v}_{l} \\ \end{vmatrix} $		0.224 ± 0.012	$v d \rightarrow c X$	
$ \begin{array}{ c c c c c c } \hline 0.974 \pm 0.013 & W^+ \rightarrow \mathrm{had}, V_{uj}, V_{cd,cb} \\ \hline V_{cb} & 0.0414 \pm 0.0021 & B \rightarrow D^* l \overline{v}_l \\ \hline 0.0410 \pm 0.0015 & b \rightarrow c l \overline{v}_l \\ \hline 0.0411 \pm 0.0015 & b \rightarrow c l \overline{v}_l \\ \hline 0.0033 \pm 0.0006 & B \rightarrow \rho l \overline{v}_l \\ \hline 0.0047 \pm 0.0009 & b \rightarrow u l \overline{v}_l \\ \hline 0.0037 \pm 0.0005 & t \rightarrow b W / q W \end{array} $	$ V_{cs} $	0.97 ± 0.11	$W^+ ightarrow c \overline{s}$	
$ \begin{vmatrix} V_{cb} \\ 0.0414 \pm 0.0021 \\ 0.0410 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ 0.0411 \pm 0.0015 \\ \end{vmatrix} \begin{array}{l} B \to D^* l \overline{v}_l \\ b \to c l \overline{v}_l \\ b \to c l \overline{v}_l \\ 0.0033 \pm 0.0006 \\ 0.0047 \pm 0.0009 \\ 0.0037 \pm 0.0005 \\ \end{vmatrix} \begin{array}{l} B \to \rho l \overline{v}_l \\ b \to u l \overline{v}_l \\ b \to u l \overline{v}_l \\ \end{array} $		0.974 ± 0.013	$W^+ \rightarrow \text{had}, V_{uj}, V_{cd,cb}$	
$ \begin{vmatrix} & 0.0410 \pm 0.0015 \\ & 0.0411 \pm 0.0015 \\ & 0.0411 \pm 0.0015 \\ & 0.0033 \pm 0.0006 \\ & 0.0047 \pm 0.0009 \\ & 0.0037 \pm 0.0005 \\ & b \rightarrow u \ \overline{v_l} \\ & 0.0037 \pm 0.0005 \\ & t \rightarrow bW/qW \end{aligned} $		0.0414 ± 0.0021	$B \rightarrow D^* l \overline{\nu_l}$	
$ \begin{array}{c c} 0.0411 \pm 0.0015 & & & \\ \hline V_{ub} & 0.0033 \pm 0.0006 & & & & & & & \\ 0.0047 \pm 0.0009 & & & & & & & \\ 0.0037 \pm 0.0005 & & & & & & & \\ \hline V_{ib} / \sqrt{\sum_{q} V_{iq} ^2} & 0.97 \stackrel{+ 0.16}{_{- 0.12}} & & & & t \rightarrow bW / qW \end{array} $		0.0410 ± 0.0015	$b \rightarrow c l \overline{v_l}$	
$ \begin{vmatrix} V_{ub} & 0.0033 \pm 0.0006 & B \to \rho \ l \ \overline{v}_l \\ 0.0047 \pm 0.0009 & b \to u \ l \ \overline{v}_l \\ 0.0037 \pm 0.0005 & t \to bW \ / qW \end{vmatrix} $		0.0411 ± 0.0015		
$\frac{ V_{tb} }{\sqrt{\sum_{q} V_{tq} ^{2}}} = \frac{0.0047 \pm 0.0009}{0.0037 \pm 0.0005} \qquad b \to u \ l \ \overline{v}_{l}} = \frac{b}{\sqrt{V_{tb}}}$		0.0033 ± 0.0006	$B \rightarrow \rho l \overline{v_l}$	
$\frac{0.0037 \pm 0.0005}{\left V_{tb} \right / \sqrt{\sum_{q} \left V_{tq} \right ^{2}}} 0.97^{+0.16}_{-0.12} \qquad t \to bW / qW$		0.0047 ± 0.0009	$b \rightarrow u l \overline{v_i}$	
$ V_{tb} / \sqrt{\sum_{q} V_{tq} ^2}$ $0.97^{+0.16}_{-0.12}$ $t \to bW/qW$		0.0037 ± 0.0005		
		$0.97 {}^{+ 0.16}_{- 0.12}$	$t \rightarrow bW/qW$	

 $\sum_{i} |V_{uj}|$

(LEP)

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 $V_{cj}^{2} = 1.999 \pm 0.025$

CP Violation

 $\left| \left| \mathbf{V}_{ud} \right|^2 + \left| \left| \mathbf{V}_{us} \right|^2 + \left| \left| \mathbf{V}_{ub} \right|^2 \right|^2 = 0.9986 \pm 0.0021$

QUARK MIXING MATRIX

• Unitary $N_{\rm G} \times N_{\rm G}$ Matrix: $N_{\rm G}^2$ parameters $\mathbf{V} \cdot \mathbf{V}^{\dagger} = \mathbf{V}^{\dagger} \cdot \mathbf{V} = \mathbf{1}$

• $2N_{\rm G} - 1$ arbitrary phases:

$$u_{i} \rightarrow e^{i\phi_{i}} u_{i} ; d_{j} \rightarrow e^{i\theta_{j}} d_{j} \longrightarrow V_{ij} \rightarrow e^{i(\theta_{j}-\phi_{i})} V_{ij}$$

$$V_{ij}$$
Physical Parameters: $\frac{1}{2}N_{\rm G}\left(N_{\rm G}-1\right)$ Moduli; $\frac{1}{2}(N_{\rm G}-1)\left(N_{\rm G}-2\right)$ phases

• $N_f = 2$: 1 angle, 0 phases (Cabibbo)

$$\mathbf{V} = \begin{bmatrix} \cos \theta_{\rm C} & \sin \theta_{\rm C} \\ -\sin \theta_{\rm C} & \cos \theta_{\rm C} \end{bmatrix} \longrightarrow \qquad \text{No } \mathcal{O} \mathcal{P}$$

• $N_f = 3$: 3 angles, 1 phase (CKM) $c_{ij} \equiv \cos \theta_{ij}$; $s_{ij} \equiv \sin \theta_{ij}$

$$\mathbf{V} = \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{bmatrix}$$

$$\approx \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3 (\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

 $\lambda \approx \sin \theta_{\rm c} \approx 0.222$; $A \approx 0.84$; $\sqrt{\rho^2 + \eta^2} \approx 0.41$ $\delta_{13} \neq 0$ $(\eta \neq 0)$ \longrightarrow CP

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Standard Model C

3 fermion families needed

$$\begin{array}{c} \checkmark & \mathbf{H}(M_{u}^{2}) \cdot \mathbf{H}(M_{d}^{2}) \cdot \mathbf{J} \neq 0 \\ \\ \mathbf{H}(M_{u}^{2}) \equiv (m_{t}^{2} - m_{c}^{2}) (m_{c}^{2} - m_{u}^{2}) (m_{t}^{2} - m_{u}^{2}) \\ \\ \mathbf{H}(M_{d}^{2}) \equiv (m_{b}^{2} - m_{s}^{2}) (m_{s}^{2} - m_{d}^{2}) (m_{b}^{2} - m_{d}^{2}) \\ \\ \\ \mathbf{J} = c_{12} c_{13}^{2} c_{23} s_{12} s_{13} s_{23} \sin \delta_{13} = \left| A^{2} \lambda^{6} \eta \right| < 10^{-4} \\ \end{array}$$

- Low-Energy Phenomena
- Small Effects ~ J
- Big Asymmetries \longleftrightarrow Suppressed Decays
- B Decays are an optimal place for CP signals





$$|\mathbf{T}(\mathbf{P} \rightarrow \mathbf{f})| \neq |\mathbf{T}(\overline{\mathbf{P}} \rightarrow \overline{\mathbf{f}})|$$



$$\mathbf{T}(\mathbf{P} \rightarrow \mathbf{f}) = \mathbf{T}_{1} e^{i\phi_{1}} e^{i\delta_{1}} + \mathbf{T}_{2} e^{i\phi_{2}} e^{i\delta_{2}}$$
$$\mathcal{CP}$$
$$\mathcal{CP}$$
$$\mathbf{CP}$$
$$\mathbf{T}(\overline{\mathbf{P}} \rightarrow \overline{\mathbf{f}}) = \eta_{f} \eta_{P}^{*} \left\{ \mathbf{T}_{1} e^{-i\phi_{1}} e^{i\delta_{1}} + \mathbf{T}_{2} e^{-i\phi_{2}} e^{i\delta_{2}} \right\}$$

$$\frac{\Gamma(\mathbf{P} \to \mathbf{f}) - \Gamma(\overline{\mathbf{P}} \to \overline{\mathbf{f}})}{\Gamma(\mathbf{P} \to \mathbf{f}) + \Gamma(\overline{\mathbf{P}} \to \overline{\mathbf{f}})} = \frac{-2 T_1 T_2 \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1)}{T_1^2 + T_2^2 + 2 T_1 T_2 \cos(\phi_2 - \phi_1) \cos(\delta_2 - \delta_1)}$$

One needs:

- 2 Interfering Amplitudes
- 2 Different Weak Phases
- 2 Different FSI Phases

$$\begin{bmatrix} \sin(\phi_2 - \phi_1) \neq 0 \end{bmatrix}$$
$$\begin{bmatrix} \sin(\delta_2 - \delta_1) \neq 0 \end{bmatrix}$$

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$$\frac{|\mathsf{NDIRECT}|\langle \mathcal{P} : \mathsf{K}^{0} - \overline{\mathsf{K}}^{0} \mathsf{MIXING}}{\langle \mathcal{R}^{0} |\mathsf{H}| \mathcal{K}^{0} \rangle - \left\{ \sum_{ij} \lambda_{i} \lambda_{j} S(r_{i}, r_{j}) \eta_{ij} \right\} \langle \mathcal{O}_{\Delta S = 2} \rangle}{\langle \mathcal{O}_{\Delta S = 2} \rangle}$$

$$\frac{\langle \mathfrak{K}^{0} |\mathsf{H}| \mathcal{K}^{0} \rangle - \left\{ \sum_{ij} \lambda_{i} \lambda_{j} S(r_{i}, r_{j}) \eta_{ij} \right\} \langle \mathcal{O}_{\Delta S = 2} \rangle}{\lambda_{i} = V_{id} V_{is}^{*} ; r_{i} = m_{i}^{2} / M_{W}^{2} \quad (i = u, c, t)}$$

$$\langle \mathcal{O}_{\delta S = 2} \rangle = \alpha_{s}(\mu)^{-2/9} \langle \overline{\mathsf{K}}^{0} | (\overline{s}_{L} \gamma^{a} d_{L}) (\overline{s}_{L} \gamma_{a} d_{L}) | \mathcal{K}^{0} \rangle = \left(\frac{4}{3} M_{K}^{2} f_{K}^{2}\right) \hat{B}_{K}$$

$$| \mathcal{K}_{L}^{0} \rangle - p | \mathcal{K}^{0} \rangle + q | \overline{\mathcal{K}}^{0} \rangle$$

$$\frac{\langle \mathcal{K}^{0} \to \pi^{-} l^{+} v_{l} \quad (\overline{s} \to \overline{u}) ; \overline{\mathcal{K}}^{0} \to \pi^{+} l^{-} \overline{v}_{l} \quad (s \to u)$$

$$\frac{\Gamma(\mathcal{K}_{L}^{0} \to \pi^{-} l^{+} v_{l}) - \Gamma(\mathcal{K}_{L}^{0} \to \pi^{+} l^{-} \overline{v}_{l})}{\Gamma(\mathcal{K}_{L}^{0} \to \pi^{-} l^{+} v_{l}) + \Gamma(\mathcal{K}_{L}^{0} \to \pi^{+} l^{-} \overline{v}_{l})} = \frac{|p|^{2} - |q|^{2}}{|p|^{2} + |q|^{2}} = \frac{2 \operatorname{Re}(\overline{x}_{K})}{1 + |\overline{s}_{K}|^{2}} = (0.327 \pm 0.012)\%$$

 $Re(\bar{\epsilon}_{\kappa}) = (1.64 \pm 0.06) \cdot 10^{-3}$

CP Violation

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DIRECT C/P in $K \rightarrow \pi \pi$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+ \pi^-)}{T(K_S \to \pi^+ \pi^-)} \approx \varepsilon_K + \varepsilon'_K$$

$$\eta_{00} \equiv \frac{T(K_L \to \pi^0 \pi^0)}{T(K_S \to \pi^0 \pi^0)} \approx \varepsilon_K - 2\varepsilon'_K$$

$$\varepsilon_{K} = (2.271 \pm 0.017) \cdot 10^{-3} e^{i\phi}$$

 $\phi_{c} = (43.5 \pm 0.5)^{\circ}$



$$\eta \left[\left(1 - \rho \right) A^2 + 0.22 \right] A^2 \hat{\boldsymbol{B}}_{\boldsymbol{K}} = 0.143$$

$$\operatorname{Re}\left(\varepsilon_{K}^{\prime}/\varepsilon_{K}\right) \approx \frac{1}{6} \left\{ 1 - \left| \frac{\eta_{00}}{\eta_{+-}} \right|^{2} \right\} = (17.2 \pm 1.8) \cdot 10^{-4}$$
 NA48, NA3
KTeV, E73



- Short-distance OPE
 Ciuchini et al, Buras et al
- Long-distance χPT

Pallante-Pich-Scimemi Cirigliano-Ecker-Neufeld-Pich





$$V_{ud} V_{ub}^* \sim V_{cd} V_{cb}^* \sim V_{td} V_{tb}^* \sim A\lambda^3$$
$$\left\langle \overline{B}^0 \left| \mathbf{H} \left| \overline{B}^0 \right\rangle - \left| V_{td} \right|^2 S(r_t, r_t) \left(\frac{4}{3} M_B^2 f_B^2 \right) \hat{B}_B$$

 $\Delta M_{B_d^0} = (0.502 \pm 0.006) \text{ ps}^{-1}$

very small

$$\rightarrow$$
 V_{td}

$$\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.770 \pm 0.011$$

$$\Delta M_{B_s^0} > 14.5 \text{ ps}^{-1} \quad (95\% \text{ C.L.})$$

$$\Delta \Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$$

■
$$\operatorname{Re}\left(\varepsilon_{B_{d}^{0}}\right) = -0.0007 \pm 0.0017$$

$$|V_{ts}|^{2} \gg |V_{td}|^{2}$$

$$\Delta \Gamma_{B_{s}^{0}} = (0.47 + 0.19) + 0.01 \text{ ps}^{-1} \qquad \text{CDF}$$

$$|q/p| - 1 \sim m_{c}^{2} / m_{t}^{2}$$

CP Violation

$B^{0} - \overline{B}^{0}$ mixing and direct CP

$$T_{f} \to T[B^{0} \to f] \quad ; \quad \overline{T}_{f} \to -T[\overline{B}^{0} \to f] \quad ; \quad \overline{\rho}_{f} \equiv \overline{T}_{f} / T_{f}$$
$$T_{\overline{f}} \to T[B^{0} \to \overline{f}] \quad ; \quad \overline{T}_{\overline{f}} \to -T[\overline{B}^{0} \to \overline{f}] \quad ; \quad \rho_{\overline{f}} \equiv T_{\overline{f}} / \overline{T}_{\overline{f}}$$
$$CP \ B^{0} = -\overline{B}^{0} \qquad : \qquad CP \ f = \overline{f}$$



$$\Gamma[B^{0}(t) \to \mathbf{f}] \sim \frac{1}{2} e^{-\Gamma t} |\mathbf{T}_{\mathbf{f}}|^{2} \left\{ \left(1 + |\overline{\rho}_{\mathbf{f}}|^{2}\right) + \left(1 - |\overline{\rho}_{\mathbf{f}}|^{2}\right) \cos(\Delta M t) - 2 \operatorname{Im}\left(\frac{q}{p} \overline{\rho}_{\mathbf{f}}\right) \sin(\Delta M t) \right\}$$

$$\Gamma[\overline{B}^{0}(t) \to \overline{\mathbf{f}}] \sim \frac{1}{2} e^{-\Gamma t} |\overline{\mathbf{T}}_{\mathbf{f}}|^{2} \left\{ \left(1 + |\rho_{\mathbf{f}}|^{2}\right) + \left(1 - |\rho_{\mathbf{f}}|^{2}\right) \cos(\Delta M t) - 2 \operatorname{Im}\left(\frac{p}{q} \rho_{\mathbf{f}}\right) \sin(\Delta M t) \right\}$$

A. Pich - Benasque 2005

 $B^{0} - \overline{B}^{0} \text{ MIXING AND DIRECT } \mathcal{O}^{P}$ $B^{0} \longrightarrow f \qquad CP \text{ self-conjugate:} \quad \overline{f} = \eta_{f} f$ $Q^{0} \longrightarrow f \qquad \frac{q}{p} \approx \frac{V_{tb}^{*} V_{tq}}{V_{tb} V_{tq}^{*}} = e^{-2i\phi_{M}} \quad ; \qquad \phi_{n} \approx \begin{cases} \beta & (B_{d}^{0}) \\ 0 & (B_{n}^{0}) \end{cases}$

qAssumption: Only 1 decay amplitude $\stackrel{q'}{\sim}$ $\frac{A_{b \rightarrow q \bar{q} q'}}{A_{\bar{b} \rightarrow \bar{q} q \bar{q}'}} = \frac{\mathbf{V}_{qb} \, \mathbf{V}_{qq'}^*}{\mathbf{V}_{qb}^* \, \mathbf{V}_{qq'}} = e^{-2i\phi_D}$

 $\frac{\Gamma(B^0 \to f) - \Gamma(\overline{B}^0 \to \overline{f})}{\Gamma(B^0 \to f) + \Gamma(\overline{B}^0 \to \overline{f})} = \eta_f \sin(2\phi) \sin(\Delta M t) \qquad ; \qquad \phi = \phi_M + \phi_D$

Direct information on the CKM matrix

CP Violation



 $\frac{\Gamma(B^0 \to J/\psi K_s) - \Gamma(\overline{B}^0 \to J/\psi K_s)}{\Gamma(B^0 \to J/\psi K_s) + \Gamma(\overline{B}^0 \to J/\psi K_s)} \neq 0$



CP Violation

UNITARITY TRIANGLES

$$V_{ui} V_{uj}^* + V_{ci} V_{cj}^* + V_{ti} V_{tj}^* = 0 \qquad (i \neq j)$$



$$\mathbf{V} \approx \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3 (\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

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



$$\mathbf{UT_{fit}} \quad \overline{\eta} \equiv \eta \left(1 - \frac{1}{2}\lambda^2\right) = 0.347 \pm 0.025$$
$$\mathbf{UT_{fit}} \quad \overline{\rho} \equiv \rho \left(1 - \frac{1}{2}\lambda^2\right) = 0.196 \pm 0.045$$
$$\alpha = 96.1 \pm 7.0^\circ \ ; \ \beta = 23.4 \pm 1.5^\circ \ ; \ \gamma = 60.3 \pm 6.8^\circ$$

CP Violation





 $\Gamma[B^0(t) \to \mathbf{f}] \sim \left\{ 1 + C_{\mathbf{f}} \cos(\Delta M t) - S_{\mathbf{f}} \sin(\Delta M t) \right\}$

$\overline{B}^0_d \to \pi^+ \pi^-$	$C_{\pi\pi}$	$S_{\pi\pi}$
BABAR	- 0.09 ± 0.15 ± 0.04	- 0.30 ± 0.17 ± 0.03
BELLE	- 0.56 ± 0.12 ± 0.06	- 0.67 ± 0.16 ± 0.06

 $\phi \simeq \beta + \gamma = \pi - \alpha$

- $C_{\rm f} \equiv \frac{1 |\overline{\rho}_{\rm f}|^2}{1 + |\overline{\rho}_{\rm f}|^2} \neq 0$ Direct CP, Penguins
- Isospin Relations

(Gronau – London)



Significant penguin pollution

 $P / T = 0.3 \pm 0.1$ (Buras et al)

- FSI phases (ambiguities)
 - EW penguins
 - $B \to \pi \rho$, $\rho \rho$, $a_1 \pi$

A. Pich – Benasque 2005

MEASURING HADRONIC CONTAMINATIONS

- Time Evolution
- Transversity Analysis: $B \rightarrow V V$
- Isospin Relations (Gronau-London)
- **D**⁰- $\overline{\mathbf{D}}^0$ **Mixing** (Gronau-Wyler, Atwood-Dunietz-Soni)

 $\sqrt{2} \operatorname{T}(B^+ \to D^0_+ K^+) = \operatorname{T}(B^+ \to D^0 K^+) + \operatorname{T}(B^+ \to \overline{D}^0 K^+)$

 $\sqrt{2} \operatorname{T}(B^0_d \to D^0_+ K_S) = \operatorname{T}(B^+ \to D^0 K_S) + \operatorname{T}(B^+ \to \overline{D}^0 K_S)$

- Dalitz Analysis
- **SU(3)** Relations: $B \rightarrow \pi K, \pi \pi, ...$

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$$A(B_d^0 \to \pi^{\pm} K^{\pm}) \equiv \frac{\text{Br}(B_d^0 \to \pi^{-} K^{+}) - \text{Br}(\overline{B}_d^0 \to \pi^{+} K^{-})}{\text{Br}(B_d^0 \to \pi^{-} K^{+}) + \text{Br}(\overline{B}_d^0 \to \pi^{+} K^{-})} = 0.113 \pm 0.019$$

$$A(B_d^0 \to \pi^{+} K^{\pm}) = \begin{cases} 0.133 \pm 0.030 \pm 0.009 & \text{BABAR} \\ 0.101 \pm 0.025 \pm 0.005 & \text{BELLE} \end{cases}$$

- $B \rightarrow \pi\pi$ data
- SU(3) symmetry
- Neglect "penguin" and "exchange" topologies

Buras et al

$$A(B_d^0 \to \pi^{\mp} K^{\pm})_{\text{th}} = 0.143 \frac{+0.141}{-0.083}$$



$$Br(K^{+} \to \pi^{+} \nu \,\overline{\nu}) = (7.7 \pm 1.1) \times 10^{-11} \sim A^{4} \left[\eta^{2} + (1.4 - \rho)^{2} \right]$$
$$Br(K_{L} \to \pi^{0} \nu \,\overline{\nu}) = (2.6 \pm 0.5) \times 10^{-11} \sim A^{4} \eta^{2}$$

Buchalla – Buras Isidori , Misiak – Urban Falk et al Marciano - Parsa

Long-distance contributions are negligible $\mathbf{T}(K_L \to \pi^0 v \, \overline{v}) \neq 0$

BNL: few events! Br $(K^+ \to \pi^+ \nu \,\overline{\nu}) \sim 10^{-10}$ KTEV: Br $(K_L \to \pi^0 \nu \,\overline{\nu}) < 5.9 \times 10^{-7}$ (90% C.L.)

New Experiments Needed

CP Violation



- remains a major pending question
- Related to Flavour Structure
- Related to SSB Scalar Sector (Higgs)
- Important cosmological implications (Baryogenesis)
- Sensitive to New Physics
- Highly constrained in the SM: 1 phase only
- Many interesting P signals within experimental reach
- Better control of QCD effects urgently needed

Standard Model Mechanism of *QP* **Complex phases in Yukawa couplings only:** $\boldsymbol{L}_{\boldsymbol{Y}} = \sum_{jk} (\overline{u}'_{j}, \overline{d}'_{j})_{L} \left[\begin{array}{c} c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + \overline{c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix}} u'_{kR} \right] + \text{h.c.}$ **SSB** $\left[\left\langle \phi^{(0)} \right\rangle = v / \sqrt{2} \right]$ $L_{Y} = -\left(1 + \frac{H}{V}\right) \frac{V}{\sqrt{2}} \left\{ \overline{d}'_{jL} c^{(d)}_{jk} d'_{kR} + \overline{u}'_{jL} c^{(u)}_{jk} u'_{kR} + \text{h.c.} \right\}$ $C_{ik}^{(q)}$ diagonalization $L_{Y} = -\left(1 + \frac{H}{v}\right) \left\{ \overline{d}_{jL} m_{d_{j}} d_{jR} + \overline{u}_{jL} m_{u_{j}} u_{jR} + \text{h.c.} \right\}$ $L_{\rm CC} = \frac{g}{2\sqrt{2}} W^{\dagger}_{\mu} \sum_{ij} \overline{u}_{i} \gamma^{\mu} (1-\gamma_5) \mathbf{V}_{ij} d_{j} + \text{h.c.}$ The CKM matrix V_{ii} is the only source of CP

CP Violation















$$L_{\rm CC}^{(l)} = \frac{g}{2\sqrt{2}} W_{\mu}^{\dagger} \sum_{\rm ij} \overline{\nu_{\rm i}} \gamma^{\mu} (1-\gamma_5) \mathbf{V}_{\rm ij}^{(l)} l_{\rm j} + \rm h.c.$$

• IF
$$m_{\nu_i} = 0$$
 \longrightarrow $L_{CC}^{(l)} = \frac{g}{2\sqrt{2}} W_{\mu}^{\dagger} \sum_{l} \overline{\nu_l} \gamma^{\mu} (1 - \gamma_5) l + \text{h.c.}$
 $\overline{\nu_{l_j}} \equiv \overline{\nu_i} V_{ij}^{(l)}$

Separate Lepton Number Conservation (Minimal SM without v_R)

• IF
$$\nu_{\rm R}^{\rm i}$$
 exist and $m_{\nu_{\rm i}} \neq 0$
 $\underline{\mathcal{L}}_{e}, \underline{\mathcal{L}}_{\mu}, \underline{\mathcal{L}}_{\tau}$ $(L_{e} + L_{\mu} + L_{\tau} \text{ Conserved})$

BUT Br $(\mu \to e \gamma) < 1.2 \times 10^{-11}$; Br $(\tau \to \mu \gamma) < 3.1 \times 10^{-7}$ (90% CL)