CP VIOLATION
In The Standard Model

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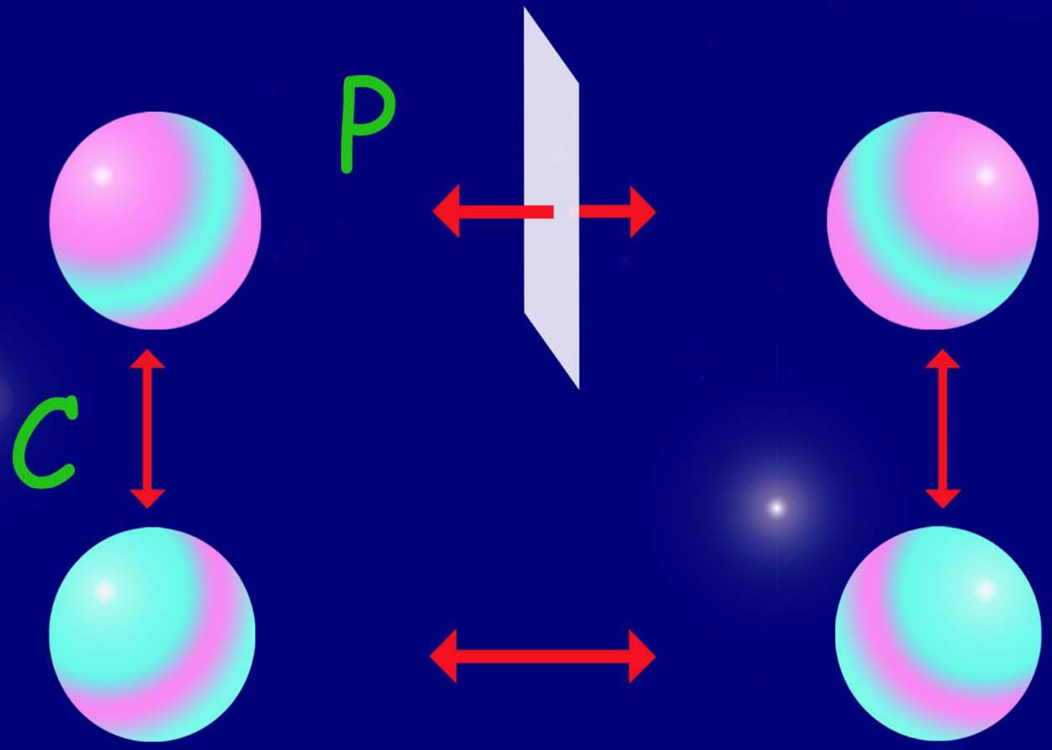


- Slight (~ 0.2 %) $\not{CP}$ in K^0 decays (1964)
- Sizeable $\not{CP}$ in B^0 decays (2001)
- CP : Symmetry of nearly all observed phenomena
- C , P : Violated maximally in weak interactions
- Huge Matter – Antimatter Asymmetry in our Universe → Baryogenesis

CPT Theorem: $\not{CP} \Longleftrightarrow \not{T}$

Thus, $\not{CP}$ requires:

- Complex Phases
- Interferences

Quarks Leptons Bosons

FERMION GENERATIONS

$N_G = 3$ Identical Copies

Masses are the only difference

$Q=0$ $\quad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix}$ $\quad Q=+2/3$

$Q=-1$ $\quad\quad\quad\quad\quad\quad\quad$ $Q=-1/3$

$(j = 1, \cdots, N_G)$

WHY ?

$$\mathcal{L}_Y = \sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] + \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c_{jk}^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right) \left\{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \bar{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \bar{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d \, , \mathbf{M}'_u \, , \mathbf{M}'_l \right]_{jk} = - \left[c_{jk}^{(d)} \, , c_{jk}^{(u)} \, , c_{jk}^{(l)} \right] \frac{v}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d$$
$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u$$
$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l$$

$$\mathbf{H}_f = \mathbf{H}_f^\dagger$$
$$\mathbf{U}_f \cdot \mathbf{U}_f^\dagger = \mathbf{U}_f^\dagger \cdot \mathbf{U}_f = 1$$
$$\mathbf{S}_f \cdot \mathbf{S}_f^\dagger = \mathbf{S}_f^\dagger \cdot \mathbf{S}_f = 1$$

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right)\left\{\bar{\mathrm{d}}\cdot\mathcal{M}_d\cdot\mathrm{d} + \bar{\mathrm{u}}\cdot\mathcal{M}_u\cdot\mathrm{u} + \bar{l}\cdot\mathcal{M}_l\cdot l\right\}$$

$$\mathcal{M}_u = \mathrm{diag}(m_u, m_c, m_t) \quad ; \quad \mathcal{M}_d = \mathrm{diag}(m_d, m_s, m_b) \quad ; \quad \mathcal{M}_l = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

$$\mathrm{d}_L \equiv \mathbf{S}_d \cdot \mathrm{d}'_L \quad ; \quad \mathrm{u}_L \equiv \mathbf{S}_u \cdot \mathrm{u}'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$
$$\mathrm{d}_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathrm{d}'_R \quad ; \quad \mathrm{u}_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathrm{u}'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates ≠ Weak Eigenstates

$$\bar{\mathrm{f}}'_L\, \mathrm{f}'_L = \bar{\mathrm{f}}_L\, \mathrm{f}_L \quad ; \quad \bar{\mathrm{f}}'_R\, \mathrm{f}'_R = \bar{\mathrm{f}}_R\, \mathrm{f}_R \quad \Longrightarrow \quad \mathcal{L}'_{NC} = \mathcal{L}_{NC}$$

$$\bar{\mathrm{u}}'_L\, \mathrm{d}'_L = \bar{\mathrm{u}}_L \cdot \mathbf{V} \cdot \mathrm{d}_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \Longrightarrow \quad \mathcal{L}'_{CC} \neq \mathcal{L}_{CC}$$

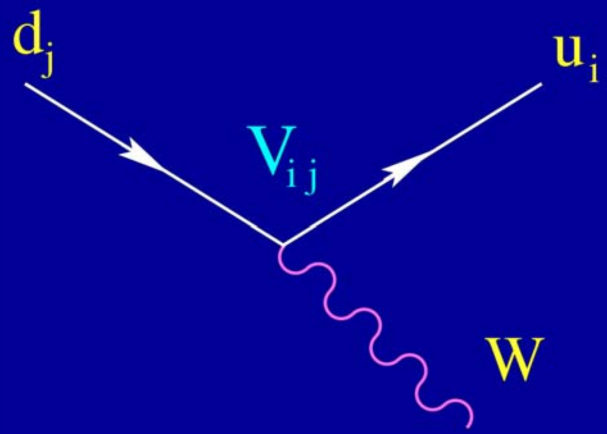
QUARK MIXING

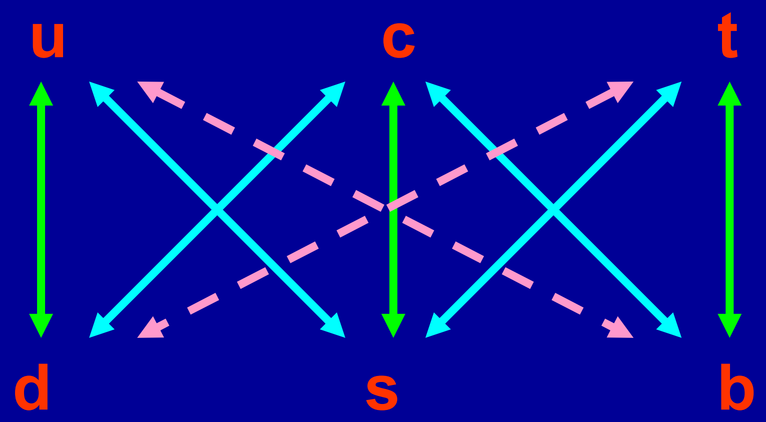
$$\mathcal{L}_{NC}^{Z} = \frac{e}{2\sin\theta_W \cos\theta_W}\, Z_\mu \sum_f \bar{f}\, \gamma^\mu \left[v_f - a_f\, \gamma_5 \right] f$$

Flavour Conserving Neutral Currents

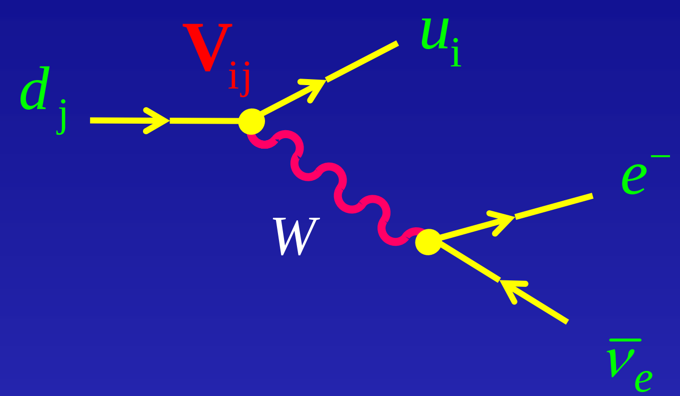
$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i\, \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_l \bar{\nu}_l\, \gamma^\mu (1-\gamma_5)\, l \right] + \text{h.c.}$$

Flavour Changing Charged Currents





Measurements of V_{ij}



$$\Gamma(d_j \to u_i \, e^- \, \bar{\nu}_e) \propto \left| \mathbf{V}_{ij} \right|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\lvert V_{ud}\rvert$	0.9740 ± 0.0005 0.9729 ± 0.0012 0.9739 ± 0.0005	Nuclear β decay $n \to p e^- \bar{\nu}_e$
$\lvert V_{us}\rvert$	0.2220 ± 0.0025 0.2208 ± 0.0034 0.2219 ± 0.0025 0.2217 ± 0.0025	$K \to \pi e^- \bar{\nu}_e$ τ decays $K/\pi \to \mu\nu$, Lattice
$\lvert V_{cd}\rvert$	0.224 ± 0.012	$\nu d \to c X$
$\lvert V_{cs}\rvert$	0.97 ± 0.11 0.974 ± 0.013	$W^+ \to c\bar{s}$ $W^+ \to$ had, V_{uj}, $V_{cd,cb}$
$\lvert V_{cb}\rvert$	0.0414 ± 0.0021 0.0410 ± 0.0015 0.0411 ± 0.0015	$B \to D^* l \bar{\nu}_l$ $b \to c l \bar{\nu}_l$
$\lvert V_{ub}\rvert$	0.0033 ± 0.0006 0.0047 ± 0.0009 0.0037 ± 0.0005	$B \to \rho l \bar{\nu}_l$ $b \to u l \bar{\nu}_l$
$\lvert V_{tb}\rvert / \sqrt{\sum_q \lvert V_{tq}\rvert^2}$	$0.97\,^{+\,0.16}_{-\,0.12}$	$t \to bW / qW$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9976 \pm 0.0021$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = 1.999 \pm 0.025 \quad \text{(LEP)}$$

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\lvert V_{ud}\rvert$	0.9740 ± 0.0005 0.9769 ± 0.0013 0.9744 ± 0.0005	Nuclear β decay $n \to p e^- \bar{\nu}_e$
$\lvert V_{us}\rvert$	0.2220 ± 0.0025 0.2208 ± 0.0034 0.2219 ± 0.0025 0.2217 ± 0.0025	$K \to \pi e^- \bar{\nu}_e$ τ decays $K/\pi \to \mu\nu$, Lattice
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$\lvert V_{tb}\rvert / \sqrt{\sum_q \lvert V_{tq}\rvert^2}$	$0.97\,^{+\,0.16}_{-\,0.12}$	$t \to bW / qW$

Serebrov et al

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9986 \pm 0.0021$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = 1.999 \pm 0.025 \quad \text{(LEP)}$$

QUARK MIXING MATRIX

- **Unitary** $N_G \times N_G$ **Matrix:** N_G^2 **parameters**

$$\mathbf{V} \cdot \mathbf{V}^\dagger = \mathbf{V}^\dagger \cdot \mathbf{V} = \mathbf{1}$$

- $2\, N_G - 1$ **arbitrary phases:**

$$u_i \to e^{i\phi_i}\, u_i \quad ; \quad d_j \to e^{i\theta_j}\, d_j \quad \Longrightarrow \quad \mathbf{V}_{ij} \to e^{i(\theta_j - \phi_i)}\, \mathbf{V}_{ij}$$

$\Downarrow$

$\mathbf{V}_{ij}$ **Physical Parameters:**

$\frac{1}{2} N_G \left(N_G - 1\right)$ **Moduli** ; $\frac{1}{2} (N_G - 1)\ (N_G - 2)$ **phases**

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

$$V = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Rightarrow \quad \text{No } \not{CP}$$

- **$N_f = 3$:** 3 angles, 1 phase (CKM)

$c_{ij} \equiv \cos\theta_{ij} \quad ; \quad s_{ij} \equiv \sin\theta_{ij}$

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

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

$\lambda \approx \sin\theta_C \approx 0.222 \quad ; \quad A \approx 0.84 \quad ; \quad \sqrt{\rho^2 + \eta^2} \approx 0.41$

$\delta_{13} \neq 0 \quad (\eta \neq 0) \quad \Rightarrow \quad \not{CP}$

Standard Model $\not{CP}$: 3 fermion families needed

$$\not{CP} \quad \Longleftrightarrow \quad \mathbf{H}(M_u^2) \cdot \mathbf{H}(M_d^2) \cdot \mathbf{J} \neq 0$$

$$\mathbf{H}(M_u^2) \equiv (m_t^2 - m_c^2)\,(m_c^2 - m_u^2)\,(m_t^2 - m_u^2)$$

$$\mathbf{H}(M_d^2) \equiv (m_b^2 - m_s^2)\,(m_s^2 - m_d^2)\,(m_b^2 - m_d^2)$$

$$\mathbf{J} = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta_{13} = \left| A^2 \lambda^6 \eta \right| < 10^{-4}$$

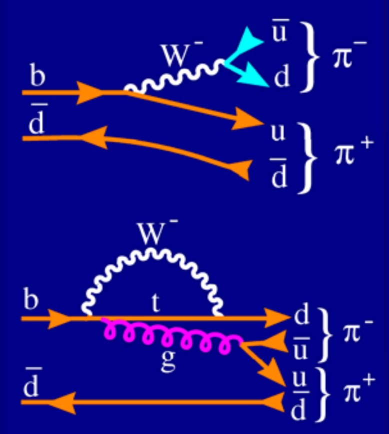
$\Rightarrow$

- Low-Energy Phenomena
- Small Effects $\sim$ **J**
- Big Asymmetries $\Longleftrightarrow$ Suppressed Decays
- B Decays are an optimal place for $\not{CP}$ signals

DIRECT $\not{CP}$

$$\left|\mathbf{T}(P \to f)\right| \neq \left|\mathbf{T}(\bar{P} \to \bar{f})\right|$$

$\bar{B}_d^0$



$$\mathbf{T}(P \to f) = T_1\, e^{i\phi_1}\, e^{i\delta_1} + T_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$\mathcal{CP}$

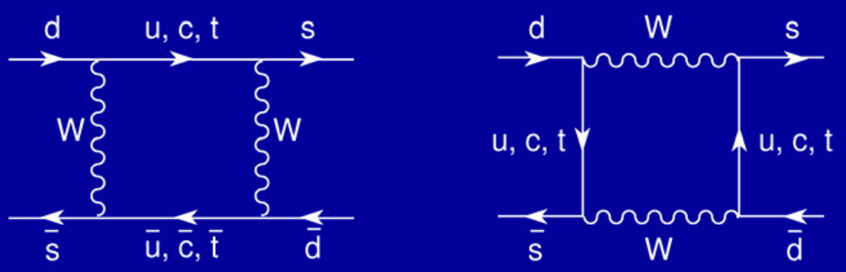
$$\mathbf{T}(\bar{P} \to \bar{f}) = \eta_f\, \eta_P^*\, \left\{T_1\, e^{-i\phi_1}\, e^{i\delta_1} + T_2\, e^{-i\phi_2}\, e^{i\delta_2}\right\}$$

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

One needs:

- **2 Interfering Amplitudes**
- **2 Different Weak Phases** $\quad\left[\sin(\phi_2 - \phi_1) \neq 0\right]$
- **2 Different FSI Phases** $\quad\left[\sin(\delta_2 - \delta_1) \neq 0\right]$

INDIRECT $\not{C}\!\not{P}$: $K^0 - \bar{K}^0$ MIXING



$$\langle \bar{K}^0 | \mathbf{H} | K^0 \rangle \sim \left\{ \sum_{ij} \lambda_i \lambda_j \; S(r_i, r_j) \; \eta_{ij} \right\} \langle O_{\Delta S=2} \rangle$$

$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

$$\langle O_{\Delta S=2} \rangle = \alpha_s(\mu)^{-2/9} \langle \bar{K}^0 | (\bar{s}_L \gamma^\alpha d_L)(\bar{s}_L \gamma_\alpha d_L) | K^0 \rangle \equiv \left(\frac{4}{3} M_K^2 f_K^2 \right) \hat{B}_K$$

$$|K_L^0\rangle \sim p\, |K^0\rangle + q\, |\bar{K}^0\rangle \qquad\qquad q/p \equiv (1 - \bar{\varepsilon}_K)/(1 + \bar{\varepsilon}_K)$$

$$K^0 \to \pi^- l^+ \nu_l \quad (\bar{s} \to \bar{u}) \quad ; \quad \bar{K}^0 \to \pi^+ l^- \bar{\nu}_l \quad (s \to u)$$

$$\frac{\Gamma(K_L^0 \to \pi^- l^+ \nu_l) - \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L^0 \to \pi^- l^+ \nu_l) + \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu}_l)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\, \mathrm{Re}(\bar{\varepsilon}_K)}{1 + |\bar{\varepsilon}_K|^2} = (0.327 \pm 0.012)\%$$

$$\Rightarrow \quad \mathrm{Re}(\bar{\varepsilon}_K) = (1.64 \pm 0.06) \cdot 10^{-3}$$

DIRECT $\not{CP}$ in $K \to \pi\pi$

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

$$\varepsilon_K = (2.271 \pm 0.017)\cdot 10^{-3}\; e^{i\phi_\varepsilon}$$

$$\phi_\varepsilon = (43.5 \pm 0.5)^\circ$$

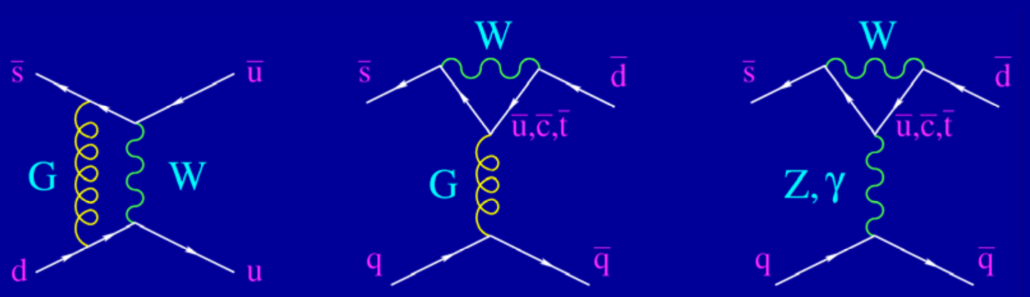
Buras et al

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

$$\mathrm{Re}\left(\varepsilon'_K/\varepsilon_K\right) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (17.2 \pm 1.8)\cdot 10^{-4}$$

NA48, NA31

KTeV, E731



- Short-distance OPE

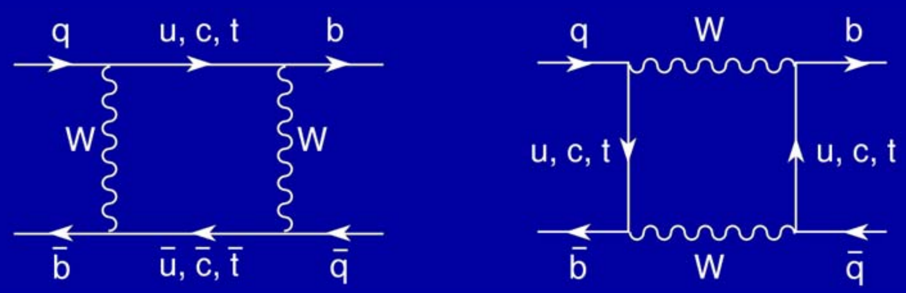
  Ciuchini et al, Buras et al

- Long-distance χPT

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

$$\mathrm{Re}\left(\varepsilon'_K/\varepsilon_K\right)_{\mathrm{Th}} = \left(19\,^{+11}_{-9}\right)\cdot 10^{-4}$$

$B^0 - \bar{B}^0$ MIXING



$$V_{ud} V_{ub}^* \sim V_{cd} V_{cb}^* \sim V_{td} V_{tb}^* \sim A\lambda^3$$

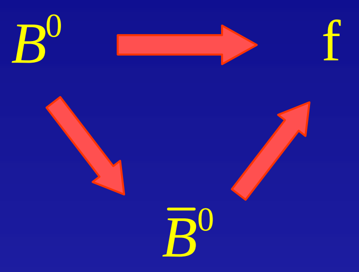
$$\langle \bar{B}^0 | \mathrm{H} | B^0 \rangle \sim |V_{td}|^2 \, S(r_t, r_t) \left(\frac{4}{3} M_B^2 f_B^2 \right) \hat{B}_B$$

$$\Delta M_{B_d^0} = (0.502 \pm 0.006) \text{ ps}^{-1} \quad \Rightarrow \quad |V_{td}|$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.770 \pm 0.011$
- $\Delta M_{B_s^0} > 14.5 \text{ ps}^{-1}$ (95% C.L.) $\qquad |V_{ts}|^2 \gg |V_{td}|^2$
- $\Delta\Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1 \qquad \Delta\Gamma_{B_s^0} = (0.47\,^{+0.19}_{-0.24} \pm 0.01) \text{ ps}^{-1}$ CDF
- $\mathrm{Re}\left(\varepsilon_{B_d^0}\right) = -0.0007 \pm 0.0017 \qquad |q/p| - 1 \sim m_c^2 / m_t^2$

$\not{CP}$ very small

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



$$\mathrm{T_f} \to \mathrm{T}[B^0 \to \mathrm{f}\,] \quad ; \quad \bar{\mathrm{T}}_{\mathrm{f}} \to -\mathrm{T}[\bar{B}^0 \to \mathrm{f}\,] \quad ; \quad \bar{\rho}_{\mathrm{f}} \equiv \bar{\mathrm{T}}_{\mathrm{f}} / \mathrm{T_f}$$

$$\mathrm{T}_{\bar{\mathrm{f}}} \to \mathrm{T}[B^0 \to \bar{\mathrm{f}}\,] \quad ; \quad \bar{\mathrm{T}}_{\bar{\mathrm{f}}} \to -\mathrm{T}[\bar{B}^0 \to \bar{\mathrm{f}}\,] \quad ; \quad \rho_{\bar{\mathrm{f}}} \equiv \mathrm{T}_{\bar{\mathrm{f}}} / \bar{\mathrm{T}}_{\bar{\mathrm{f}}}$$

$$\mathcal{CP}\; B^0 = -\bar{B}^0 \qquad ; \qquad \mathcal{CP}\; \mathrm{f} = \bar{\mathrm{f}}$$

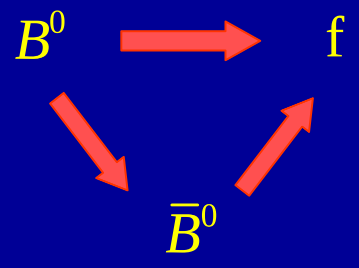
$$\Gamma[B^0(t) \to \mathrm{f}\,] \sim \frac{1}{2} e^{-\Gamma t} |\mathrm{T_f}|^2 \left\{ \left(1 + |\bar{\rho}_{\mathrm{f}}|^2\right) + \left(1 - |\bar{\rho}_{\mathrm{f}}|^2\right) \cos(\Delta M\, t) - 2\, \mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_{\mathrm{f}}\right) \sin(\Delta M\, t) \right\}$$

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

$$C_{\mathrm{f}} \equiv \frac{1 - |\bar{\rho}_{\mathrm{f}}|^2}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad S_{\mathrm{f}} \equiv \frac{2\, \mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_{\mathrm{f}}\right)}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad C_{\bar{\mathrm{f}}} \equiv -\frac{1 - |\rho_{\bar{\mathrm{f}}}|^2}{1 + |\rho_{\bar{\mathrm{f}}}|^2} \quad ; \quad S_{\bar{\mathrm{f}}} \equiv \frac{-2\, \mathrm{Im}\left(\frac{p}{q}\, \rho_{\bar{\mathrm{f}}}\right)}{1 + |\rho_{\bar{\mathrm{f}}}|^2}$$

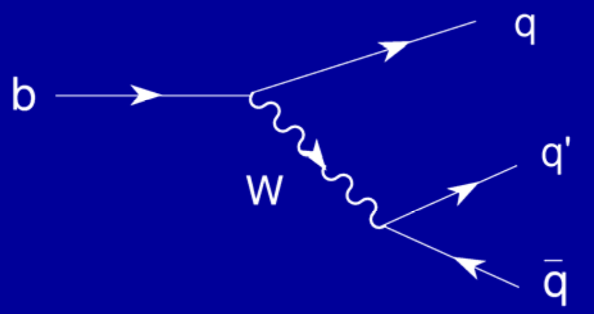
$$\Delta\Gamma \ll \Delta M \quad \Rightarrow \quad \frac{q}{p} \approx \frac{\mathbf{V}_{tb}^*\, \mathbf{V}_{tq}}{\mathbf{V}_{tb}\, \mathbf{V}_{tq}^*} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & (B_d^0) \\ 0 & (B_s^0) \end{cases}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



CP self-conjugate: $\bar{\mathrm{f}} = \eta_{\mathrm{f}}\ \mathrm{f}$

$$\frac{q}{p} \approx \frac{\mathbf{V}_{tb}^{*}\ \mathbf{V}_{tq}}{\mathbf{V}_{tb}\ \mathbf{V}_{tq}^{*}} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & \left(B_d^0\right) \\ 0 & \left(B_s^0\right) \end{cases}$$



Assumption: Only 1 decay amplitude

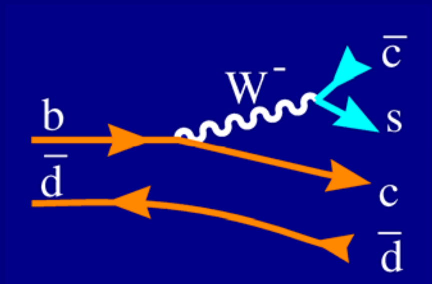
$$\frac{\mathrm{A}_{b\to q\bar{q}q'}}{\mathrm{A}_{\bar{b}\to \bar{q}q\bar{q}'}} = \frac{\mathbf{V}_{qb}\ \mathbf{V}_{qq'}^{*}}{\mathbf{V}_{qb}^{*}\ \mathbf{V}_{qq'}} = e^{-2i\phi_D}$$

$$\frac{\Gamma\left(B^0 \to \mathrm{f}\right) - \Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right)}{\Gamma\left(B^0 \to \mathrm{f}\right) + \Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right)} = \eta_{\mathrm{f}}\ \sin(2\phi)\ \sin(\Delta M\, t) \quad ; \quad \phi = \phi_M + \phi_D$$

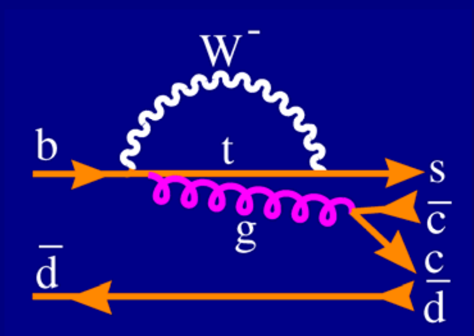
Direct information on the CKM matrix

$\bar{B}_d^0 \to J/\Psi K_S^0$

$\phi \simeq \beta$



$V_{cb} V_{cs}^* \sim A\lambda^2$

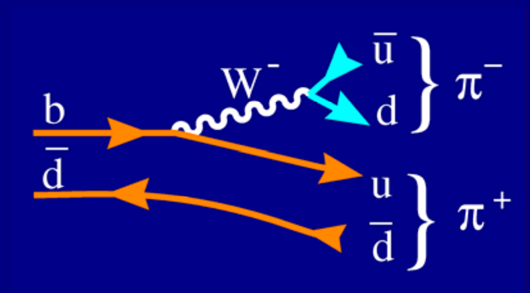


$V_{tb} V_{ts}^* \sim -A\lambda^2$

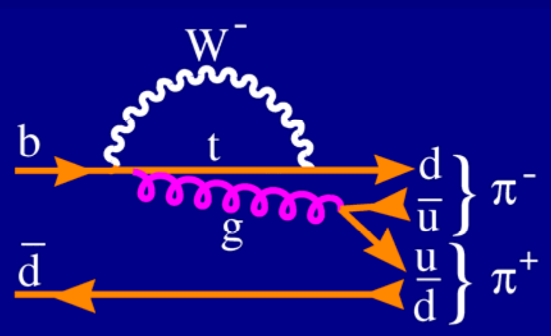
***

$\bar{B}_d^0 \to \pi^+\pi^-$

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



$V_{ub} V_{ud}^* \sim A\lambda^3(\rho - i\eta)$

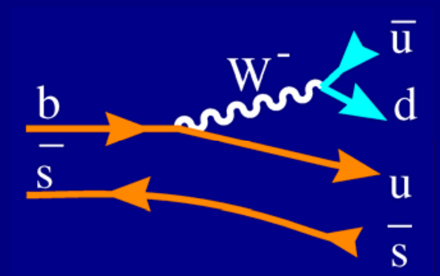


$V_{tb} V_{td}^* \sim A\lambda^3(1-\rho+i\eta)$

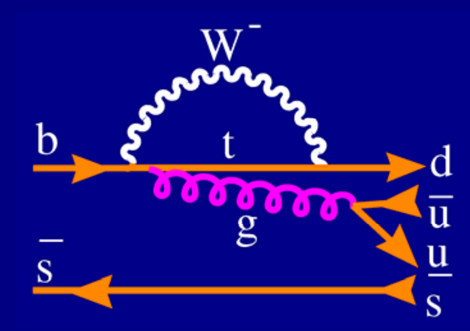
**

$\bar{B}_s^0 \to \rho^0 K_S^0$

$\phi \neq \gamma$



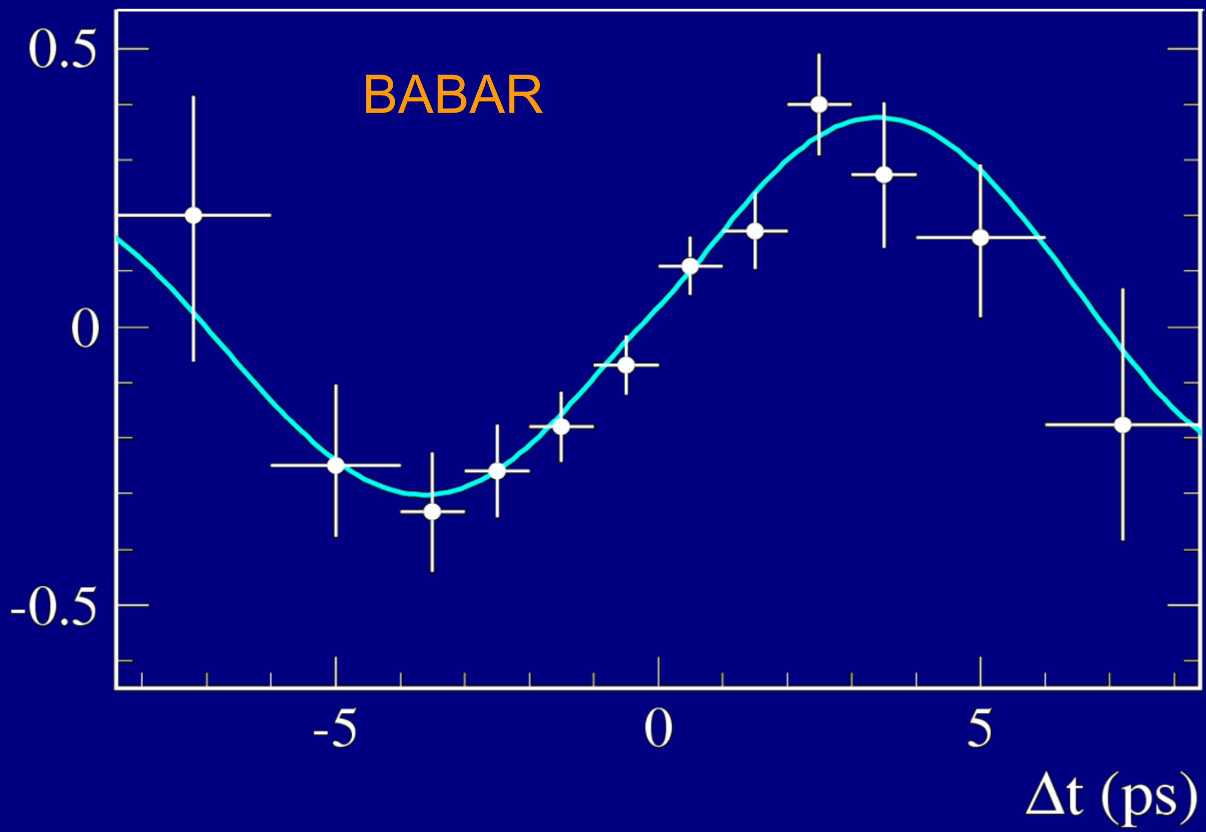
$V_{ub} V_{ud}^* \sim A\lambda^3(\rho - i\eta)$



$V_{tb} V_{td}^* \sim A\lambda^3(1-\rho+i\eta)$

BAD

$$\frac{\Gamma(B^0 \to J/\psi\, K_S) - \Gamma(\bar{B}^0 \to J/\psi\, K_S)}{\Gamma(B^0 \to J/\psi\, K_S) + \Gamma(\bar{B}^0 \to J/\psi\, K_S)} \neq 0$$



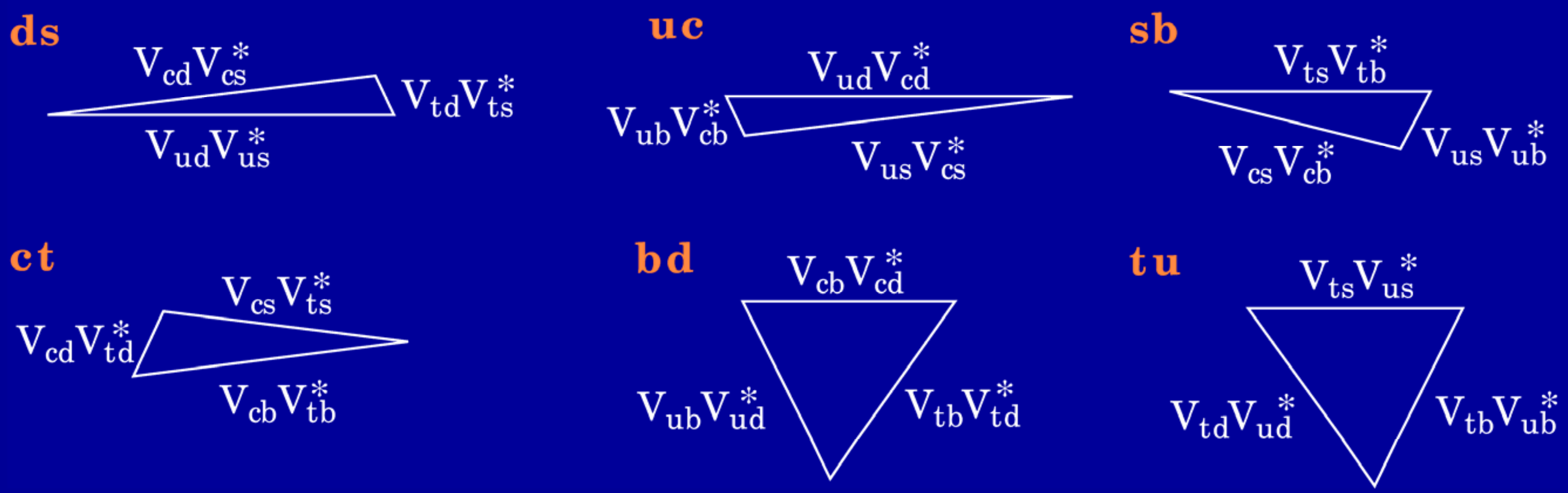
$\not{CP}$ Signal

$J/\psi\, K_{S,L}\,,\ \psi(2S)\, K_S\,,\ \chi_c\, K_S\,,\ \eta_c\, K_S$ → $\sin(2\beta) = 0.726 \pm 0.037$

[BABAR, BELLE, ALEPH, CDF, OPAL]

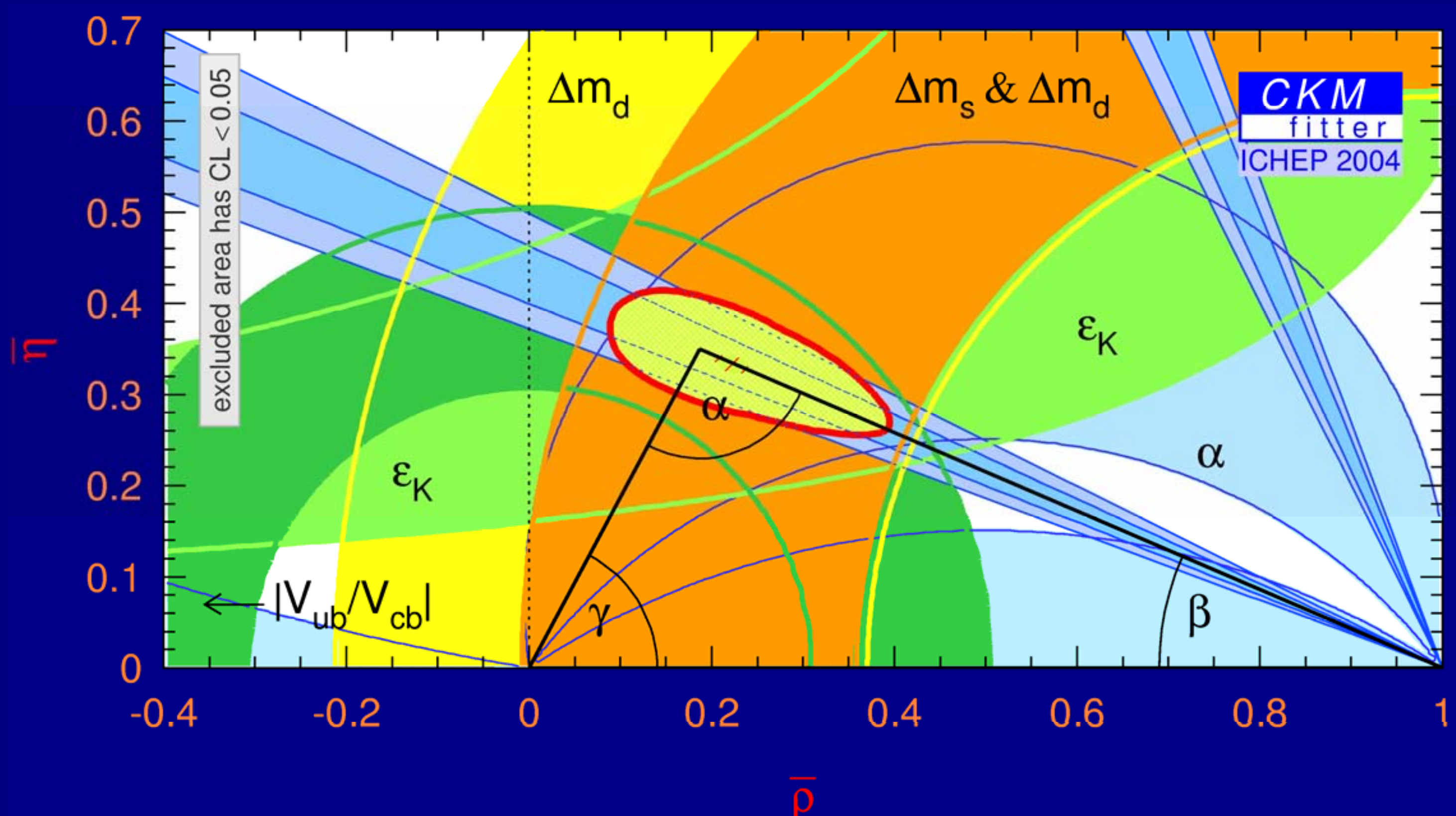
UNITARITY TRIANGLES

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

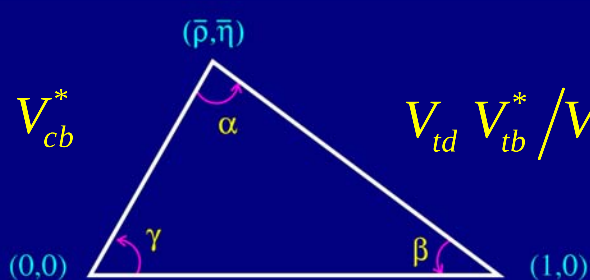


$$\mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

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



$V_{ud}\,V_{ub}^{*} \big/ V_{cd}\,V_{cb}^{*}$



$V_{td}\,V_{tb}^{*} \big/ V_{cd}\,V_{cb}^{*}$

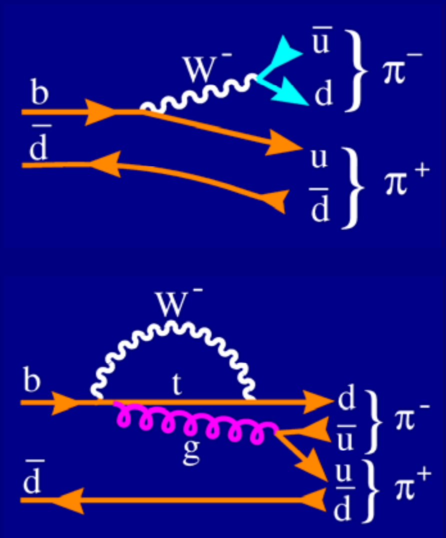
UT*fit*

$$\bar{\eta} \equiv \eta\left(1-\frac{1}{2}\lambda^2\right) = 0.347 \pm 0.025$$

$$\bar{\rho} \equiv \rho\left(1-\frac{1}{2}\lambda^2\right) = 0.196 \pm 0.045$$

$$\alpha = 96.1 \pm 7.0^\circ \;;\; \beta = 23.4 \pm 1.5^\circ \;;\; \gamma = 60.3 \pm 6.8^\circ$$

$\overline{B}_d^0$



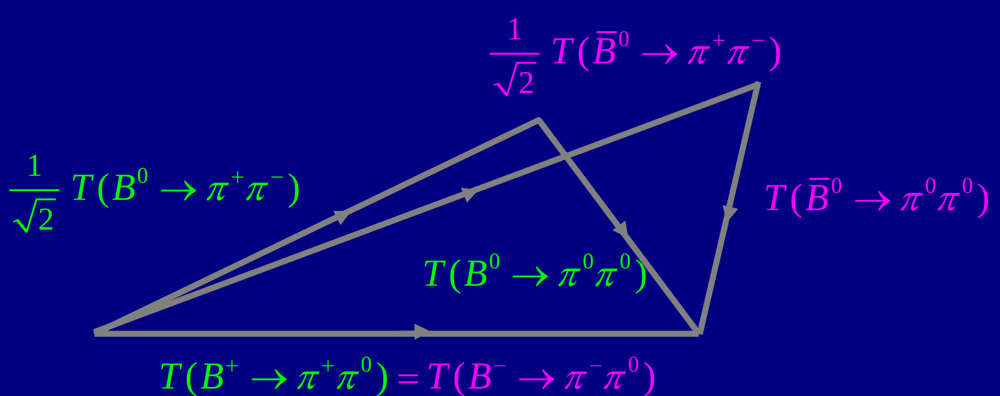
$$\Gamma[B^0(t) \to f] \sim \left\{1 + C_f \cos(\Delta M\, t) - S_f \sin(\Delta M\, t)\right\}$$

$\overline{B}_d^0 \to \pi^+\pi^-$	$C_{\pi\pi}$	$S_{\pi\pi}$
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

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

- $C_f \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \neq 0$ ➡ **Direct $\not{CP}$, Penguins**

- **Isospin Relations** (Gronau – London)



- Significant penguin pollution

  P / T = 0.3 ± 0.1 (Buras et al)

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

MEASURING HADRONIC CONTAMINATIONS

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

$$\sqrt{2}\,\mathrm{T}(B^+ \to D^0_+ K^+) = \mathrm{T}(B^+ \to D^0 K^+) + \mathrm{T}(B^+ \to \bar{D}^0 K^+)$$

$$\sqrt{2}\,\mathrm{T}(B^0_d \to D^0_+ K_S) = \mathrm{T}(B^+ \to D^0 K_S) + \mathrm{T}(B^+ \to \bar{D}^0 K_S)$$

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

DIRECT $C\!\!\!/P$ 5.9 σ signal

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

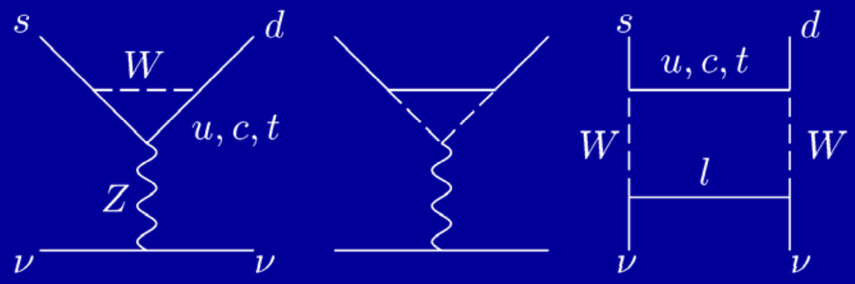
$$A(B_d^0 \to \pi^\mp K^\pm) = \begin{cases} 0.133 \pm 0.030 \pm 0.009 & \text{BABAR} \\ 0.101 \pm 0.025 \pm 0.005 & \text{BELLE} \end{cases}$$

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

Buras et al

$$\Rightarrow \quad A(B_d^0 \to \pi^\mp K^\pm)_{\mathrm{th}} = 0.143\,{}^{+0.141}_{-0.083}$$

$K \to \pi \nu \bar{\nu}$



$$\mathbf{T} \sim F\left(V_{is}^{*} V_{id}, m_i^2/M_W^2\right) \left(\bar{\nu}_L \gamma_\mu \nu_L\right) \langle \pi | \bar{s}_L \gamma_\mu d_L | K \rangle$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (7.7 \pm 1.1) \times 10^{-11} \sim A^4 \left[\eta^2 + (1.4 - \rho)^2\right]$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu \bar{\nu}\right) = (2.6 \pm 0.5) \times 10^{-11} \sim A^4 \eta^2$$

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

Long-distance contributions are negligible

$$\mathbf{T}\left(K_L \to \pi^0 \nu \bar{\nu}\right) \neq 0 \quad \Rightarrow \quad \not{CP}$$

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

New Experiments Needed

SUMMARY

- $\not{CP}$ 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 $\not{CP}$ signals within experimental reach
- Better control of QCD effects urgently needed

Standard Model Mechanism of $\not{CP}$

Complex phases in Yukawa couplings only:

$$\mathcal{L}_Y = \sum_{jk} (\bar{u}'_j, \bar{d}'_j)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] + \text{h.c.}$$

SSB $\left[\langle \phi^{(0)} \rangle = v/\sqrt{2} \right]$

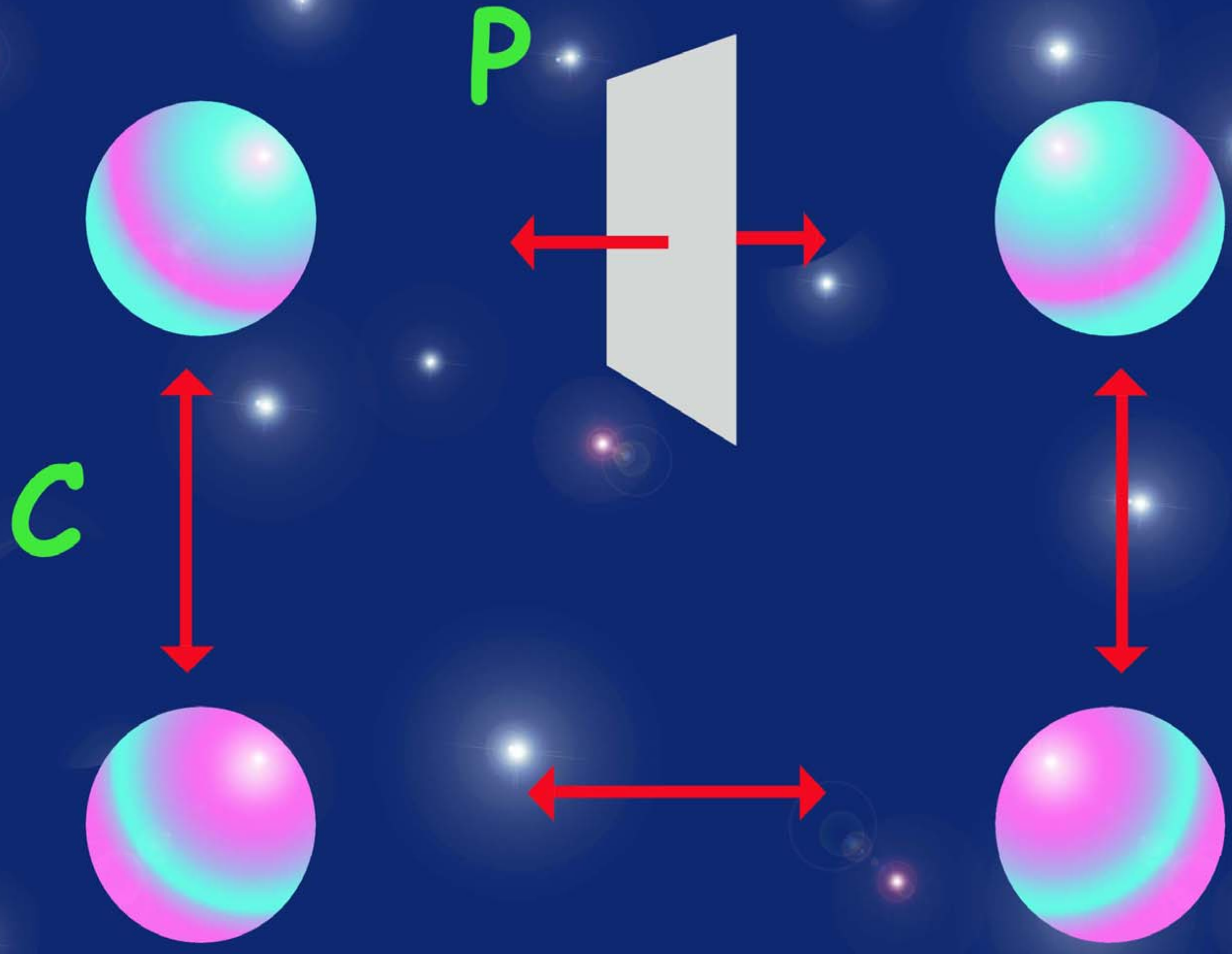
$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \frac{v}{\sqrt{2}} \left\{ \bar{d}'_{jL}\, c^{(d)}_{jk}\, d'_{kR} + \bar{u}'_{jL}\, c^{(u)}_{jk}\, u'_{kR} + \text{h.c.} \right\}$$

$c^{(q)}_{jk}$ diagonalization

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}_{jL}\, m_{d_j}\, d_{jR} + \bar{u}_{jL}\, m_{u_j}\, u_{jR} + \text{h.c.} \right\}$$

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^\dagger_\mu \sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \text{h.c.}$$

The CKM matrix $\mathbf{V}_{ij}$ is the only source of $\not{CP}$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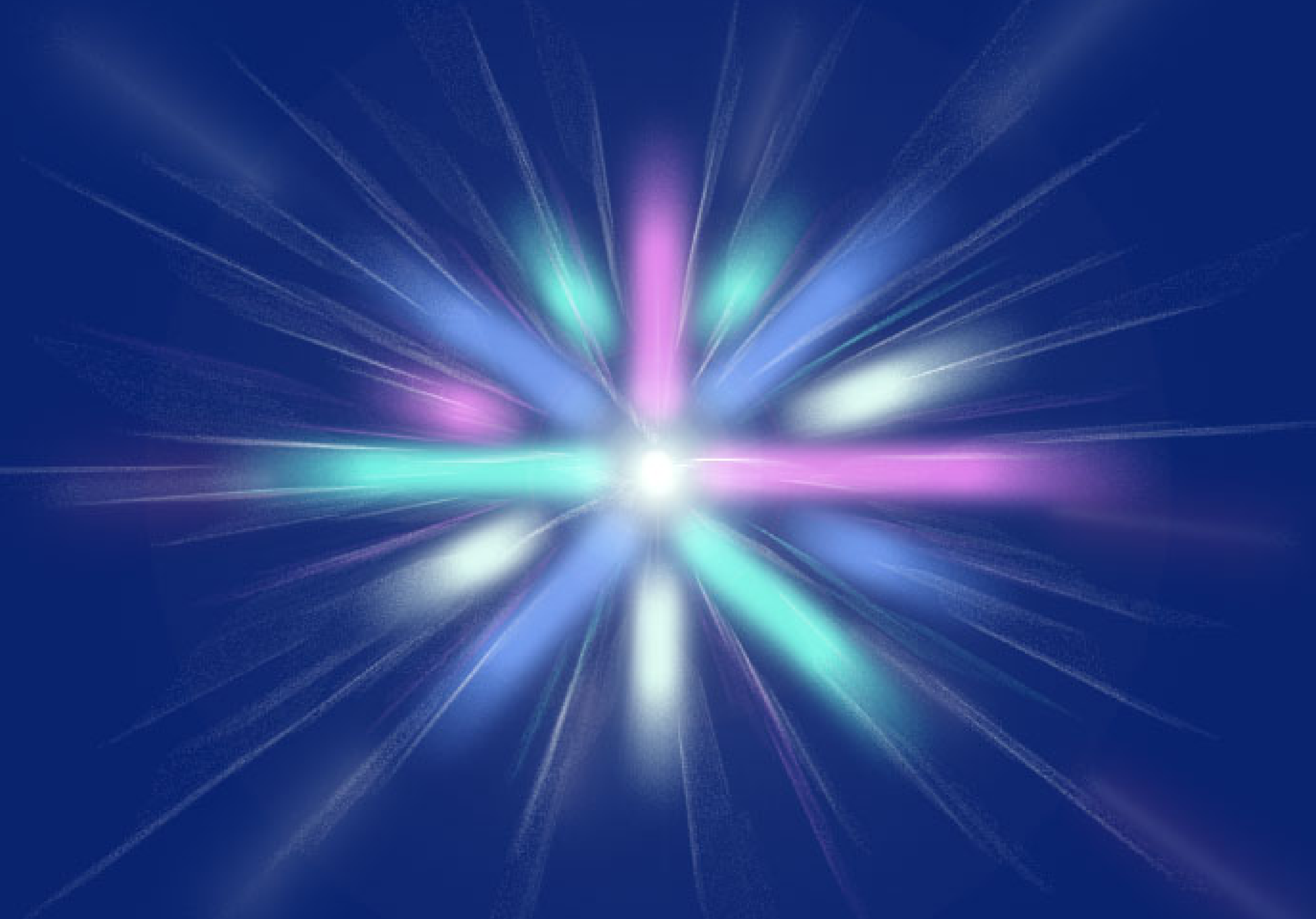

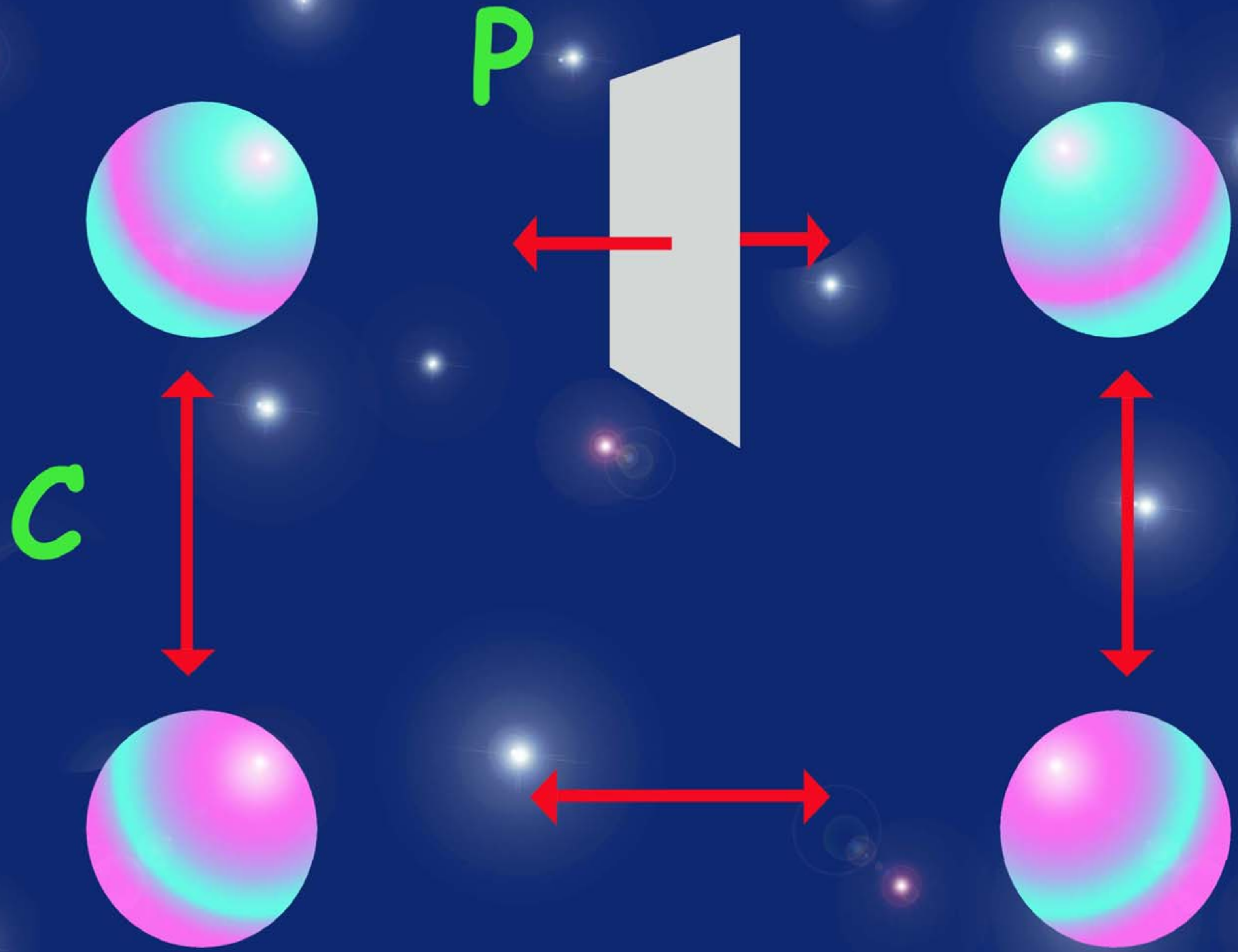
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LEPTON MIXING

$$\mathcal{L}_{CC}^{(l)} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \sum_{ij} \bar{\nu}_i \gamma^\mu (1-\gamma_5) \mathbf{V}_{ij}^{(l)} l_j + \text{h.c.}$$

- **IF** $m_{\nu_i} = 0$ ➡ $\mathcal{L}_{CC}^{(l)} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l + \text{h.c.}$

  $\bar{\nu}_{l_j} \equiv \bar{\nu}_i \mathbf{V}_{ij}^{(l)}$

  Separate Lepton Number Conservation (Minimal SM without ν_R)

- **IF** ν_R^i exist and $m_{\nu_i} \neq 0$

  $\not{L}_e , \not{L}_\mu , \not{L}_\tau$ $\quad (L_e + L_\mu + L_\tau$ Conserved$)$

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

(90 % CL)