Phys 772 : Week 11 Thursday

* CP violation in the B sector

V_{CKM} : unitary matrix to transform weak and mass eigenstates in charged current reactions

$$N = 3 \rightarrow \begin{cases} 3 \text{ mixing angles}, \theta_{12} = \sin^{-1}\lambda, \theta_{23}, \theta_{13} \\ 1 \text{ CP violating phase}, \delta = \tan^{-1}\frac{\eta}{\rho} \end{cases}$$

previous lecture : $K^0 - \bar{K}^0$ mixing

$$CP\,|K^0\rangle = -|\bar{K}^0\rangle \quad \text{and} \quad CP\,|\bar{K}^0\rangle = -|K^0\rangle$$

↳ no CP violation in strong interaction
→ $|K^0\rangle$ and $|\bar{K}^0\rangle$ are good eigenstates

$$CPT\,|K^0\rangle = |K^0\rangle \qquad CPT\,|\bar{K}^0\rangle = |\bar{K}^0\rangle$$

↳ $m_{K^0} = m_{\bar{K}^0}$

$\Rightarrow$ mass matrix $\begin{pmatrix} m_{K^0} & 0 \\ 0 & m_{\bar{K}^0} \end{pmatrix}$

no interaction terms between K^0, $\bar{K}^0$

Enter the weak interaction, $m_{K\bar{K}}$

$m_{K\bar{K}}$ real : $K^0_{1,2} = \dfrac{K^0 \mp \bar{K}^0}{\sqrt{2}} = K^0_{S,L}$

$$\begin{cases} CP\,|K^0_S\rangle = +\,|K^0_S\rangle \\ CP\,|K^0_L\rangle = -\,|K^0_L\rangle \end{cases}$$

$$\Delta m_K = 2 m_{K\bar{K}} \sim G_F^2 m_c^2 |V_{cd}|^2 |V_{cs}|^2 f_K^2 m_K$$

oscillation probability $|K^0\rangle \to |\bar{K}^0\rangle$:

$$\sin^2\left(\frac{\Delta m_K t}{2}\right)$$

but measure the appearance of K^0_S decays after many decay lengths

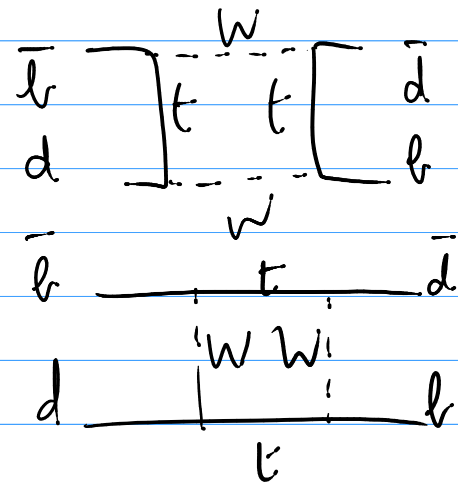
$m_{K\bar{K}}$ complex: mass eigenstates $K^0_{S,L}$ are now different from CP eigenstates $K^0_{1,2}$

$$|K^0_S\rangle = p|K^0\rangle - q|\bar{K}^0\rangle = \frac{|K^0_1\rangle + \tilde{\varepsilon}|K^0_2\rangle}{\sqrt{1+\tilde{\varepsilon}^2}}$$

$$|K^0_L\rangle = p|K^0\rangle + q|\bar{K}^0\rangle = \frac{\tilde{\varepsilon}|K^0_1\rangle + |K^0_2\rangle}{\sqrt{1+\tilde{\varepsilon}^2}}$$

(formula for $p, q, \tilde{\varepsilon}$ below)

* $B^0 - \bar{B}^0$ system



$$\begin{cases} CP\,|B_d^0\rangle = -\,|\bar{B}_d^0\rangle \\ \quad |d\bar{b}\rangle \qquad\qquad |b\bar{d}\rangle \\ CP\,|B_s^0\rangle = -\,|\bar{B}_s^0\rangle \\ \quad |s\bar{b}\rangle \qquad\qquad |b\bar{s}\rangle \end{cases}$$

↳ CP eigenstates

$$|B_H\rangle = p\,|B^0\rangle + q\,|\bar{B}^0\rangle$$

$$|B_L\rangle = p\,|B^0\rangle - q\,|\bar{B}^0\rangle$$

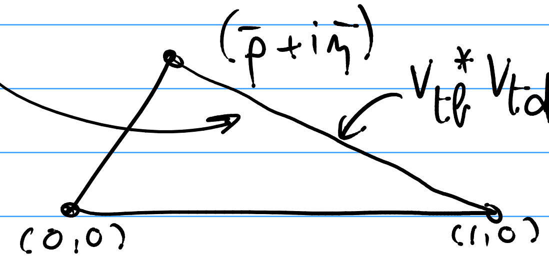
$$\frac{q}{p} = \frac{1-\tilde{\varepsilon}}{1+\tilde{\varepsilon}} = \left(\frac{M^*_{B\bar{B}} - i\,\frac{\Gamma^*_{B\bar{B}}}{2}}{M_{B\bar{B}} - i\,\frac{\Gamma_{B\bar{B}}}{2}}\right)^{1/2}$$

$$\tilde{\varepsilon} = \frac{i\,\mathrm{Im}\,M_{B\bar{B}}}{\Delta m}, \quad \Delta m = m_H - m_L = 2|M_{B\bar{B}}|$$

$$\Delta m \sim G_F^2 M_W^2\, m_{B^0}\, \underbrace{|V_{tq}|^2}_{\downarrow}\, \underbrace{|V_{tb}|^2}_{\approx 1}\, f_B^2$$

V_{td}, V_{ts} for B_d^0, B_s^0

Unitarity triangle :



Detection: B-tagging at asymmetric colliders

$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$ (boosted) < detect one $\bar{B}^0$ / know other B^0 was there

$b\bar{b}$ quarkonium state

$\to$ at $t=0$: $|B^0\rangle = \frac{1}{2p}\left(|B_H\rangle + |B_L\rangle\right)$

at t later: $\cos\left(\frac{\Delta m}{2}t\right)|B^0\rangle - i\sin\left(\frac{\Delta m}{2}t\right)\frac{q}{p}|\bar{B}^0\rangle$

but also factors $\underbrace{e^{-imt}}_{\text{phase evolution}}$ $\underbrace{e^{-\frac{\Gamma}{2}t}}_{\text{decay}}$

$\to$ measure time dependence of tagged particle decays

$\bar{B}^0$: $b \to c\,\ell^-\bar{\nu}$

B^0: $\bar{b} \to \bar{c}\,\ell^+\nu$

Oscillation time $\frac{2\pi}{\Delta m}$: larger Δm $\to$ faster oscillation $\to$ need higher resolution of reconstructed vertices

CP violation:

- indirect CP violation by $M^*_{B\bar{B}} \neq M_{B\bar{B}}$
- direct CP violation by $\Gamma_B \neq \Gamma_{\bar{B}}$

$$\to A(t) = \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to f)}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to f)}$$

$$f = \underbrace{J/\psi\, K_S^0,\ \pi^+\pi^-,\ \rho K_S^0}_{\text{CP eigenstates}}$$

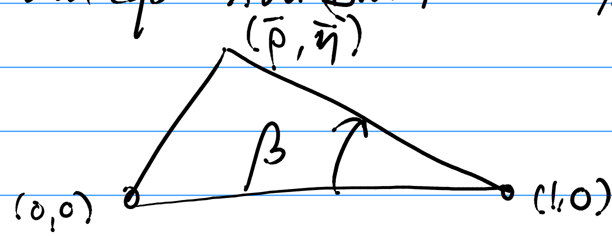
CP eigenstates → good quantum number

$$\hookrightarrow A(t) = -\eta_f \sin 2(\varphi_M - \varphi) \sin(\Delta m t)$$

phase shifts

for $J/\psi\, K_S^0$ final state

$$A(t) = \pm \sin 2\beta \sin(\Delta m t) \to \text{measurement of } \beta$$



* CP and T violation → electric dipole moments

Since CP violation is present → must also have T violation (in Lorentz invariant, CPT conserving framework)

electric dipole moment $\vec{d}$ → $H = -\vec{d} \cdot \vec{E}$

$$\to \mathcal{L}_{EDM} = -\frac{1}{2} i d \bar{\psi} \sigma^{\mu\nu} \gamma^5 \psi F_{\mu\nu}$$

In terms of form factors:

$$\bar{d} = -i \frac{qe}{m} g_2(0) \bar{S} \qquad \left(\bar{\mu}_p = g_p g_N \bar{S}_p\right)$$

magneton

At tree level this is T violating → must be zero at tree level.

At loop level CP violation in V_{CKM} gives contributions through W exchanges
→ very small effects $< 10^{-32}$ e·cm (d_n)
10^{-38} e·cm (d_e)

$d_e < 10^{-28}$ e·cm

$d_n < 10^{-26}$ e·cm

→ large range of experimental improvement possible → could include CP violating effects from new physics BSM

* Flavor changing neutral currents (FCNC) only at higher loop level in SM, but expected for new physics

↳ no off-diagonal Z couplings: $\cancel{\bar{u}\gamma^\nu c Z_\nu}$

$\cancel{\bar{e}\gamma^\nu \mu Z_\nu}$

example: $\mu \to e\gamma$ (MEG)

This restriction is caused by the Higgs mechanism transformations from weak eigenstates to mass eigenstates → more Higgses will not modify this.

But more Z' bosons will couple to different weak eigenstates → basis transformations will introduce FCNC