

CP Violation

$$K_S \rightarrow \pi^+ \pi^-$$

$$K_L \rightarrow \pi^+ \pi^0 \pi^0 + \pi^- \pi^+ \pi^- \sim 2/1000$$

$$CP|K_S\rangle = +1|K_S\rangle$$

$$CP|K_L\rangle = -1|K_L\rangle$$

$$CP = -1 \xrightarrow{H_{\text{weak}}} CP \neq +1$$

$K_L \qquad \qquad \pi^+ \pi^-$

$$\begin{array}{ccc} \xleftarrow{\quad} & CP & \xRightarrow{\quad} \\ \nu & \longrightarrow & \bar{\nu} \end{array}$$

$$\frac{N_{\text{anti-baryons}}}{N_{\text{Baryons}}} \sim 10^{-4} - 10^{-6} \qquad \frac{N_{\text{baryons}}}{N_{\text{photons}}} \sim 10^{-18}$$

1967: Sakharov

During evolution

- Baryon # violation
- Non-equilibrium
- C and CP violation.

Conditions to have matter dominated universe

∇ observed in weak interactions

But insufficient to explain matter-antimatter asym. of the universe

Experimental probes of CP violation

$$1) \quad CP \text{ eigenstate} \longrightarrow CP \text{ eigenstate}$$

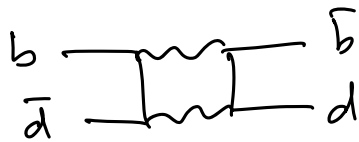
$(K_L) \rightarrow -1 \qquad (\pi^+ \pi^-) \rightarrow +1$

$$2) \quad A \rightarrow f \neq \bar{A} \rightarrow \bar{f}$$

events

Direct CP violation

$$3) \quad B^0 \leftrightarrow \bar{B}^0 \quad K^0 \leftrightarrow \bar{K}^0$$

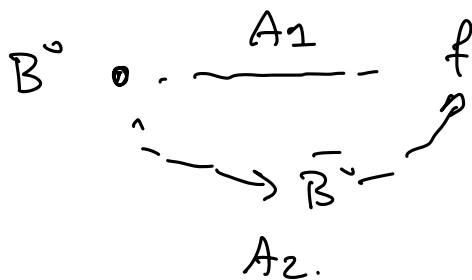


$$P(B^0 \rightarrow \bar{B}^0) \stackrel{?}{=} P(\bar{B}^0 \rightarrow B^0)$$

if $\neq \Rightarrow$ CP violation in meson mixing/oscillation

$$A_{CP} = \frac{\#(B^0 \rightarrow \bar{B}^0) - \#(\bar{B}^0 \rightarrow B^0)}{\#(B^0 \rightarrow \bar{B}^0) + \#(\bar{B}^0 \rightarrow B^0)} \approx 10^{-4}$$

4) Interference between mixing and decay.

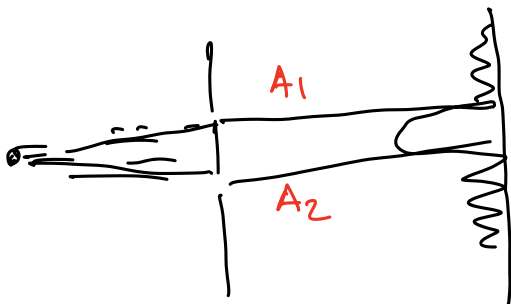


$\Lambda^+ \pi^-$

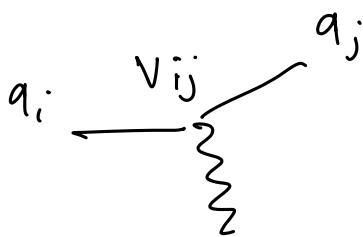
$K^+ K^-$

$J/\psi K_S$

$J/\psi K_L$



$A = f(\text{CKM matrix elements})$



$$V_{ij} g r^n (1 - r^n)$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

In SM there are conditions on V

$$V V^\dagger = V^\dagger V = \mathbb{1}$$

$$V^\dagger = \begin{pmatrix} V_{ud}^* & - & - \\ V_{us}^* & - & - \\ V_{ub}^* & - & - \end{pmatrix}$$

$V^\dagger V = \mathbb{1} \Rightarrow 9$ conditions.

$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* = 1.$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 \quad \lambda \lambda \lambda^5$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \quad \lambda^3 \lambda^3 \lambda^3$$

$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0 \quad \lambda^4 \lambda^2 \lambda^2$$

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \quad \lambda^3 \lambda^3 \lambda^3$$

$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 \quad \lambda^4 \lambda^2 \lambda^2$$

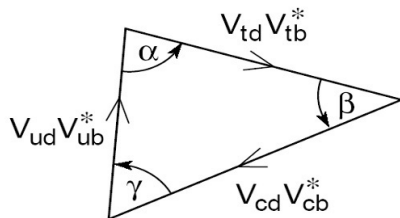
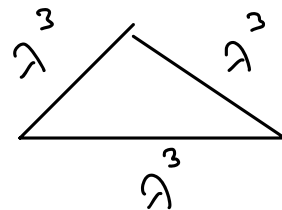
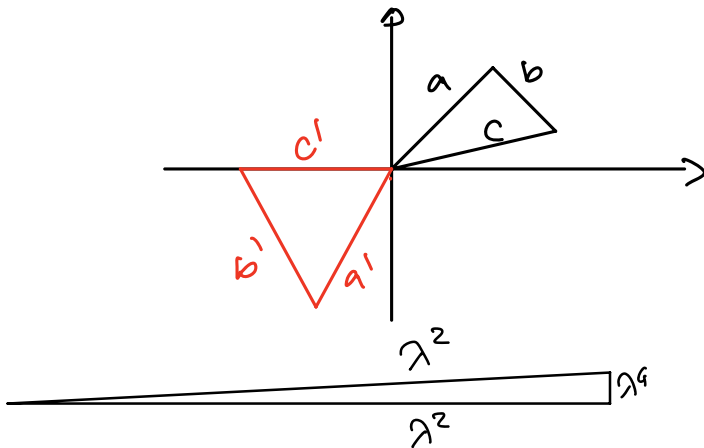
$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \quad \lambda \lambda \lambda^5$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

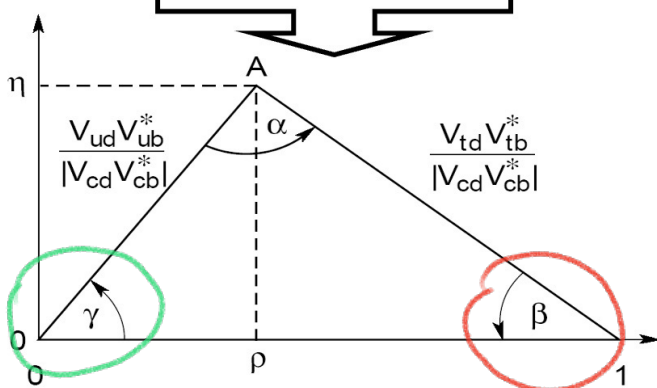
$$\lambda = \sin \theta_c$$

relation between complex numbers.

$$a+b+c=0$$



Rescaling, aligning



$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

measure $\beta, \gamma \neq 0 \Rightarrow$ CKM has complex phase \Rightarrow CP violation

CKM matrix: 3 real parameters + 1 pure complex phase.

$B^0 \rightarrow f$ vs $\bar{B}^0 \rightarrow \bar{f}$ Direct CP

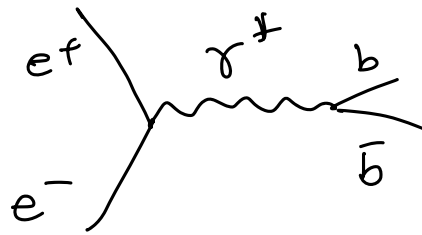
$B^0 \rightarrow f$ vs $B^0 \rightarrow \bar{B}^0 \rightarrow f$ Interference.

$$B^0 = \bar{b}d$$

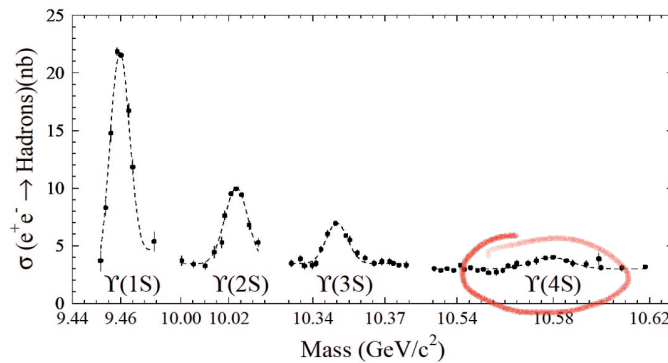
$$\bar{B}^0 = b\bar{d}$$

$$m_B = 5.279 \text{ GeV}$$

$e^+e^- \rightarrow b\bar{b}$ bound state.



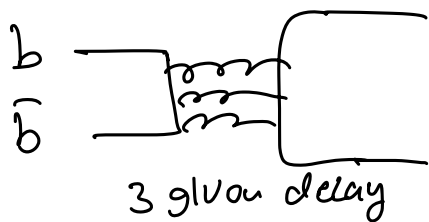
Bound state $\Upsilon(1S), \Upsilon(2S) \dots \Upsilon(4S)$.



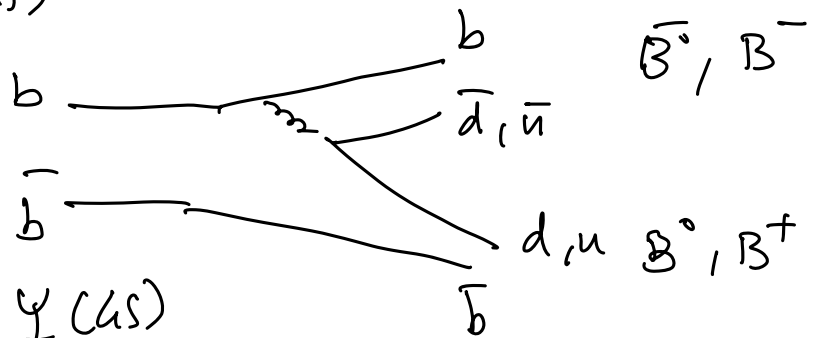
$$m(\Upsilon(1S)) < 2 m_B$$

$$Q(\Upsilon \rightarrow B^0 \bar{B}^0) = m_\Upsilon - 2 m_B$$

$$Q > 0 \Rightarrow \Upsilon(4S) \quad m = 10.58 \text{ GeV}.$$



3 gluon decay



\bar{B}^0, B^-

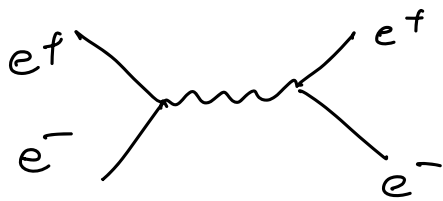
B^0, B^+

$$m(\Upsilon(1S)) < 2 m_B.$$

$$m(\Upsilon(4S)) > 2 m_B.$$

$\Upsilon(4S)$ decay to open beauty. B, \bar{B}

$$\sqrt{s} = 10.58 \text{ GeV}$$

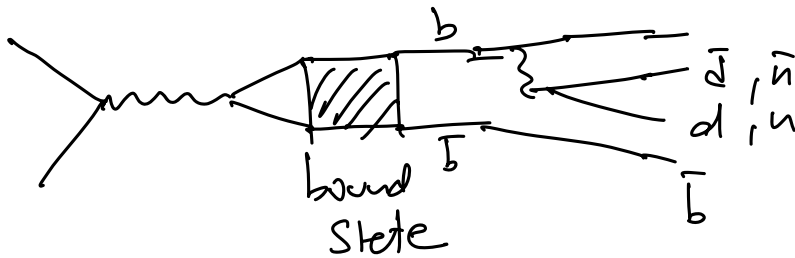


$$e^+e^- \rightarrow \begin{matrix} e^+e^- \\ \mu^+\mu^- \\ \tau^+\tau^- \\ u\bar{u} \\ d\bar{d} \\ c\bar{c} \\ b\bar{b} \end{matrix}$$

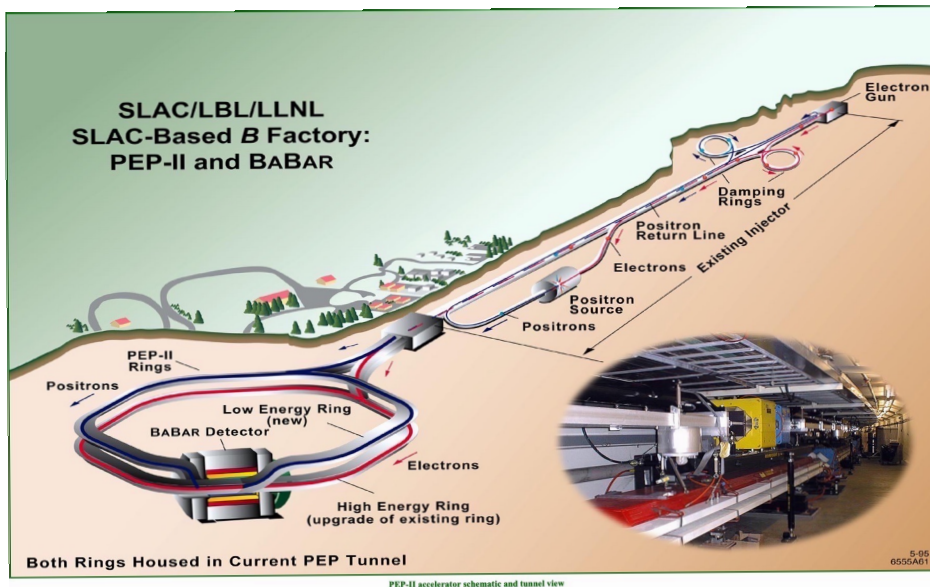
$$\frac{\sigma(e^+e^- \rightarrow U(4S) \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow U(4S) \rightarrow \text{TOT})} = \frac{1.2 \text{ nb}}{3.5 \text{ nb}} = 25\%$$

B-Factory at $\Upsilon(4S)$

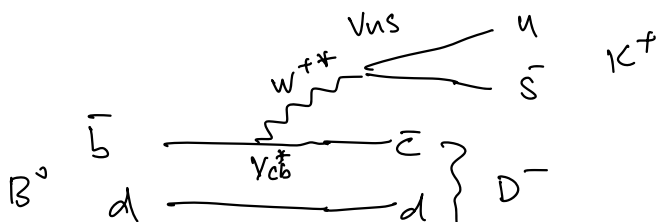
$$e^+e^- \rightarrow b\bar{b} \equiv \Upsilon(4S) \rightarrow \begin{matrix} B^0\bar{B}^0 \\ B^+B^- \end{matrix} \quad \begin{matrix} \approx 50\% \\ 50\% \end{matrix}$$



$$Q = m_{\Upsilon(4S)} - 2m_B = 10.58 - 2 \times 5.28$$



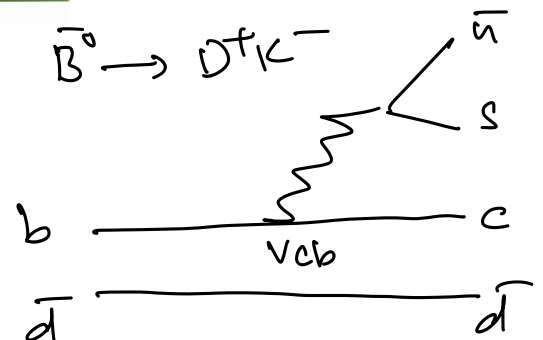
$$B^0 \rightarrow D^- K^+$$



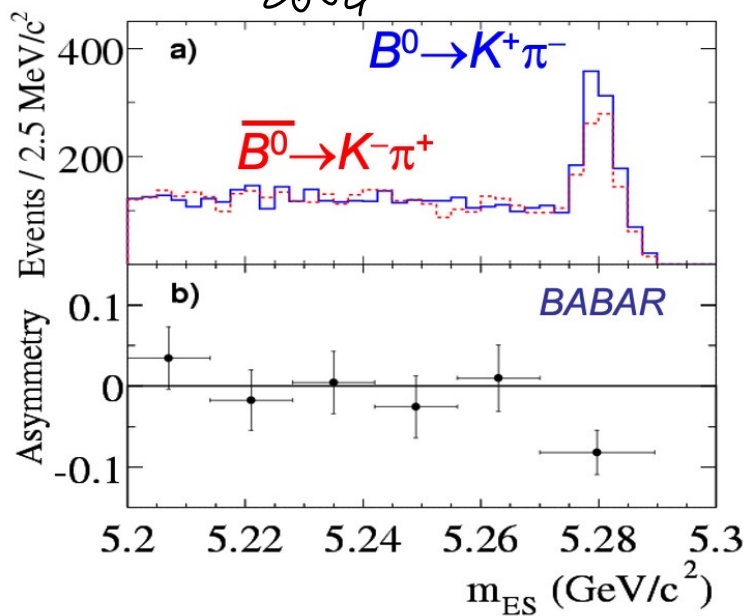
$$\Rightarrow \text{CP}$$

$$V_{us} \approx \sin \theta_c$$

$$\bar{B}^0 \rightarrow D^+ K^-$$



2004



$$n_{K\pi} = 1606 \pm 51$$

$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

$$\left. \begin{array}{l} n(B^0 \rightarrow K^+ \pi^-) = 910 \\ n(\bar{B}^0 \rightarrow K^- \pi^+) = 696 \end{array} \right\}$$

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\bar{B} \rightarrow K^- \pi^+) - \Gamma(B \rightarrow K^+ \pi^-)}{\Gamma(\bar{B} \rightarrow K^- \pi^+) + \Gamma(B \rightarrow K^+ \pi^-)}$$

Direct CP violation.

$$N = \sigma \cdot \mathcal{L} \cdot \Delta t$$

$$\sigma \propto |M|^2 \times \text{BF}$$

$$B \rightarrow DK \ll B \rightarrow D\pi$$

$$|V_{us}|^2 \quad |V_{ud}|^2$$

CP violation in Interference

$$B^0 \rightarrow J/\psi K_S$$

$$\bar{B}^0 \rightarrow J/\psi K_S$$

$$J/\psi \rightarrow \ell^+ \ell^-$$

$$K_S \rightarrow \pi^+ \pi^-$$

Clear experimental signature.

$$e^+ e^- \rightarrow \gamma^* \rightarrow b \bar{b} \rightarrow$$

$$\begin{array}{c} \Rightarrow \\ \leftarrow \\ e^+ \end{array} \quad \begin{array}{c} \Rightarrow \\ \leftarrow \\ e^- \end{array}$$

$$\begin{array}{c} \Leftarrow \\ \Leftarrow \\ e^+ \end{array} \quad \begin{array}{c} \Leftarrow \\ \Leftarrow \\ e^- \end{array}$$

$$\gamma^*$$

$$J=1$$

$$e^+ e^- \rightarrow B^0 \bar{B}^0$$

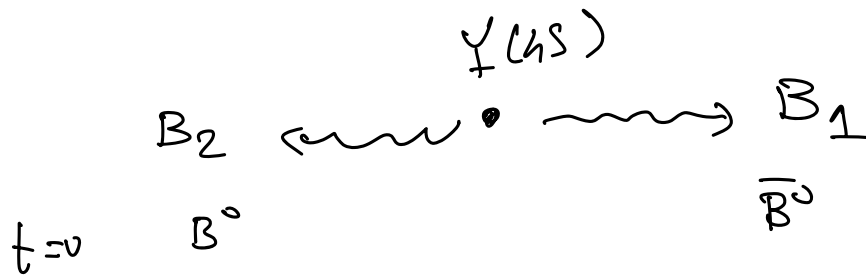
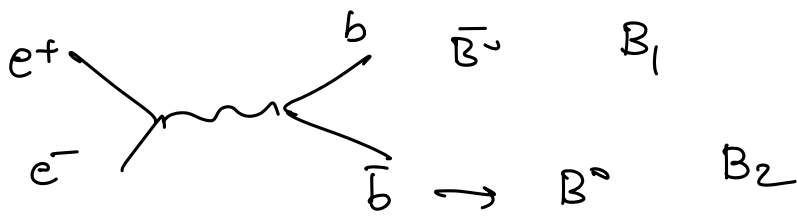
$$J=1$$

$$S$$

$$0 \quad 0 \Rightarrow$$

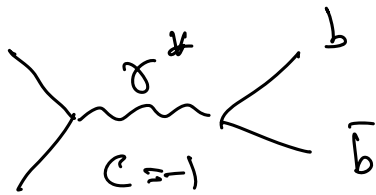
$$S_{B^0} = S_{\bar{B}^0} = 0$$

$L=1$ in final state.



assume $\tau_B \Rightarrow \infty$. No decay.

$t = t_1$ $B_2 \equiv \bar{B}^0$ $B_1 \rightarrow B^0$
 oscillation
 through weak interaction



$$| \text{final state} \rangle = | B_1 B_2 \rangle = \frac{a | B^0 \rangle | \bar{B}^0 \rangle + b | \bar{B}^0 \rangle | B^0 \rangle}{\sqrt{a^2 + b^2}}$$

$C = -1 \Rightarrow$ Must always have 1 b and 1 \bar{b} at all times

$$\Rightarrow 1 B^0, 1 \bar{B}^0$$

$$C | B_1 B_2 \rangle = -1 | B_1 B_2 \rangle \Rightarrow b = -a$$

$$| \Psi \rangle = \frac{1}{\sqrt{2}} (| B^0 \rangle | \bar{B}^0 \rangle - | \bar{B}^0 \rangle | B^0 \rangle)$$

Coherent state.
Entanglement

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

$$p^2 + q^2 = 1$$

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

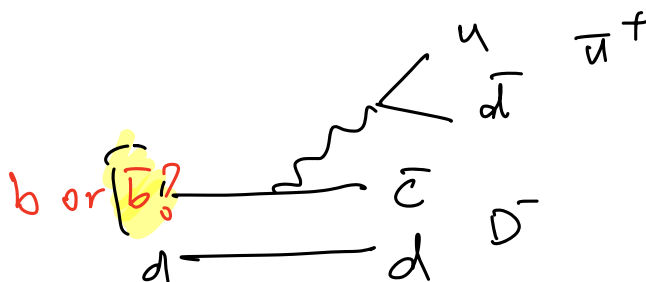
mass eigenstates.

$$| B_{L,H}(t) \rangle = e^{-im_L t} e^{-i\Gamma_{L,H}/2 t} | B_{L,H} \rangle$$

In nature $\tau_B = 1.57 \text{ fs}$.

$t=0$. $B_1 \xrightarrow{\text{muon}} B_2$

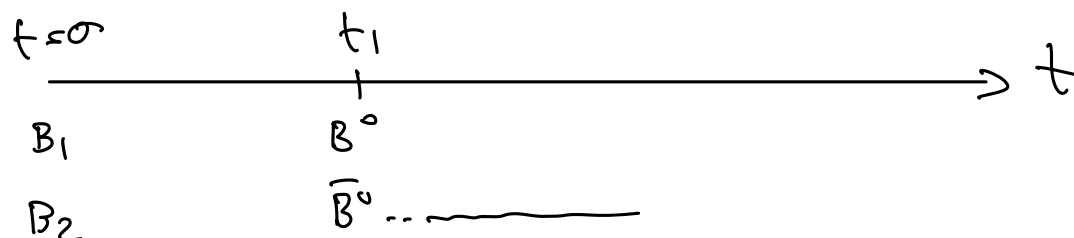
$t_1 > 0$ $B_1 \rightarrow D^- \pi^+$



$D^- \pi^+ \Rightarrow B_1 \equiv B_0$

at $t=t_1$.

$\Rightarrow B_2 \equiv \bar{B}^0$ at $t=t_1 \Rightarrow B_1 = B^0$ at $t=t_1$.



$$P(B^0 \rightarrow B^0) = \frac{e^{-\Gamma t}}{2} (1 + \cos \Delta m \Delta t)$$

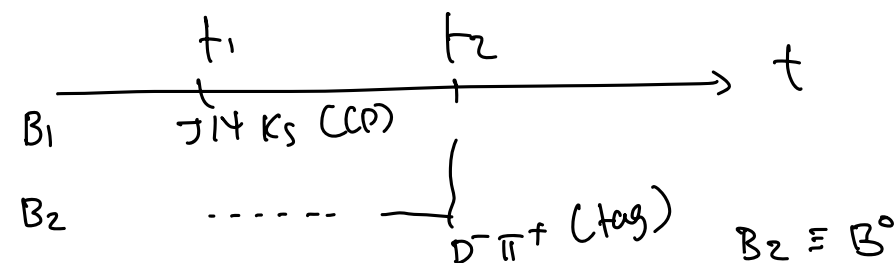
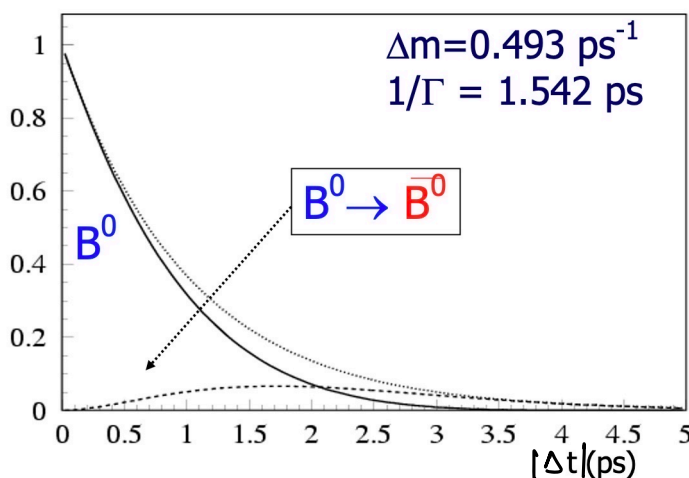
$$\Delta m = B_H - B_L$$

$$\Gamma = \frac{1}{\tau_B}$$

$$P(B^0 \rightarrow \bar{B}^0) = \frac{e^{-\Gamma t}}{2} (1 - \cos \Delta m \Delta t)$$

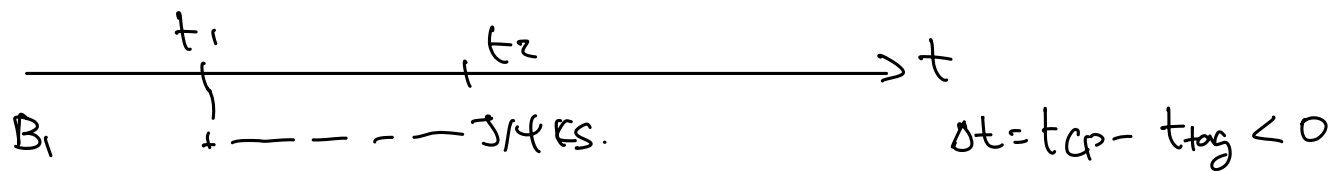
P : prob. of survival

produce B^0 at $t=0$.



$J/\psi K_S$ does not tell the flavor.

$$\Delta t = t_{CP} - t_{tag} > 0$$



B_2 $D^- \pi^+$
 t_{tag} : t of decay that fixes flavor of B (tag)

t_{cp} : t of decay of the other B .

$$N_{B^0 \bar{B}^0}(B \rightarrow D\pi, B \rightarrow J/\psi K_s) = \underbrace{\mathcal{L} \cdot \sigma \cdot \Delta t}_{2.5 \times 10^{-3}} \times \underbrace{BF(B \rightarrow J/\psi K_s)}_{9 \times 10^{-4}}$$

Integrated Luminosity $\mathcal{L}_{int} \times \sigma$

