CP Violation

$K_S \to \pi^+\pi^-$

$K_L \to \pi^+\pi^0\pi^0 + \varepsilon\ \pi^+\pi^-$

$\sim 2/1000$

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

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

$\underset{K_L}{CP=-1} \xrightarrow[H_{weak}]{} \underset{\pi^+\pi^-}{CP=+1}$

$\nu \xrightarrow{CP} \bar{\nu}$

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

1967: Sakharov — Conditions to have matter dominated universe

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

$C\!\!\!/P\!\!\!/$ observed in weak interactions

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

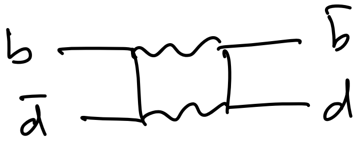
Experimental probes of CP violation

1) CP eigenstate $(K_L)\ -1$ $\longrightarrow$ CP eigenstate $(\pi^+\pi^-)\ +1$

2) $A \to f \neq \bar{A} \to \bar{f}$

\# events $\qquad$ Direct CP violation

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

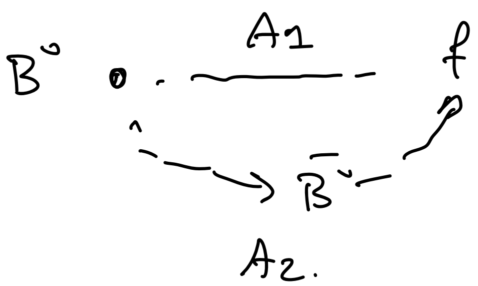


$$P(B^0 \to \bar{B}^0) \stackrel{?}{=} P(\bar{B}^0 \to B^0)$$

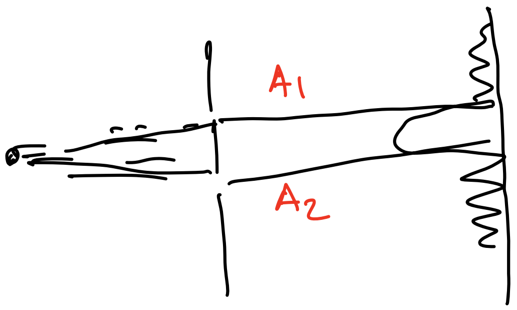
if $\neq$ $\Rightarrow$ CP violation in meson mixing/oscillation

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

4) Interference between mixing and decay.



$\pi^+\pi^-$
K^+K^-
$J/\psi\ K_S$
$J/\psi\ K_L$



$A = f($CKM matrix elements$)$.

$$V_{ij}\, g \gamma^\mu (1-\gamma^5)$$

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

In SM there are conditions on V

$$V V^\dagger = V^\dagger V = \mathbb{1} \qquad V^\dagger = \begin{pmatrix} V_{ud}^* & - & \cdot \\ V_{us}^* & \cdot & \cdot \\ V_{ub}^* & - & \cdot \end{pmatrix}$$

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

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

$$\begin{aligned}
|V_{ud}|^2 &+ |V_{us}|^2 + |V_{ub}|^2 = 1 \\
|V_{cd}|^2 &+ |V_{cs}|^2 + |V_{cb}|^2 = 1 \\
|V_{td}|^2 &+ |V_{ts}|^2 + |V_{tb}|^2 = 1
\end{aligned}
\qquad
\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

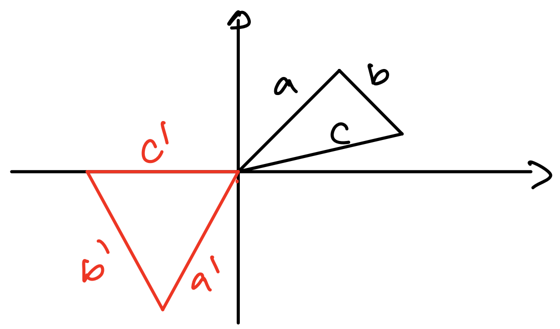
$$\begin{aligned}
&V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 && \lambda\ \lambda\ \lambda^5 \\
&\boxed{V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0} && \lambda^3\ \lambda^3\ \lambda^3 \\
&V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0 && \lambda^4\ \lambda^2\ \lambda^2 \\
&V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 && \lambda^3\ \lambda^3\ \lambda^3 \\
&V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 && \lambda^4\ \lambda^2\ \lambda^2 \\
&V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 && \lambda\ \lambda\ \lambda^5
\end{aligned}$$

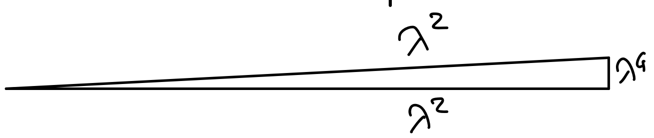
$$\begin{array}{cccc}
 & & & V_{ub} \\
\mathbf{V}_{CKM} = & \left(\begin{array}{ccc} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}\right) + O(\lambda^4) \\
 & V_{td} & &
\end{array}$$

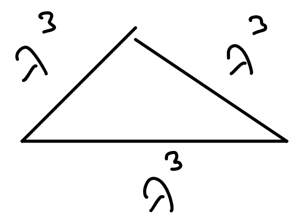
$\lambda = \sin\theta_c$

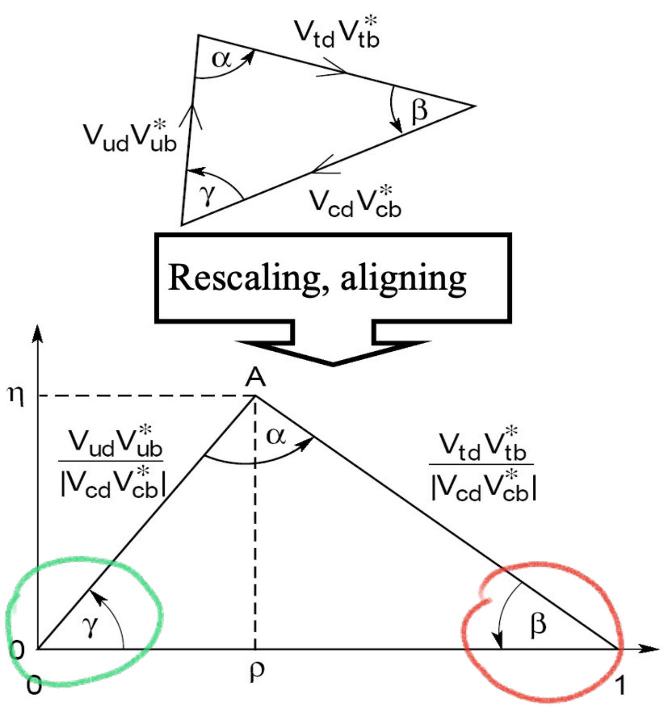
relation between complex numbers.

$a + b + c = 0$









$$\begin{array}{cccc}
 & & & V_{ub} \\
 & \left(\begin{array}{ccc} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{array}\right) \\
 & V_{td} & &
\end{array}$$

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

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

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

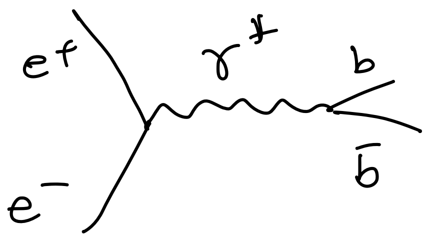
$B^0 \to f$ vs $B^0 \to \bar{B}^0 \to f$ Interference.

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

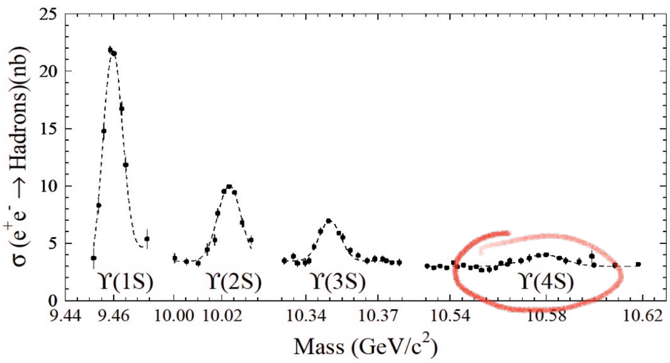
$\bar{B}^0 = b\bar{d}$

$m_B = 5.279$ GeV

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



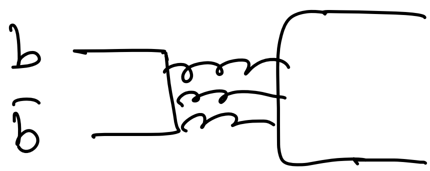
Bound state $\Upsilon(1S)$, $\Upsilon(2S)$ -- $\Upsilon(4S)$.



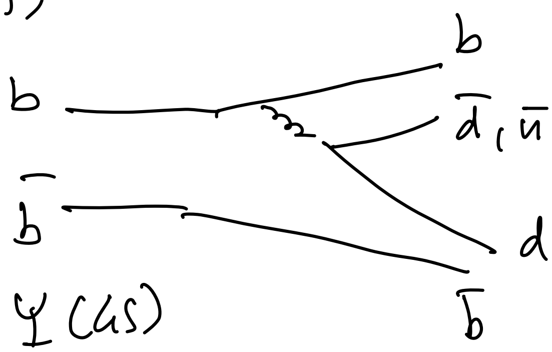
$m(\Upsilon(1S)) < 2\, m_B$

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

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



3 gluon decay



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

B^0, B^+

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

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

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

$\sqrt{s} = 10.58$ GeV $\qquad e^+e^- \longrightarrow e^+e^-$

$\mu^+\mu^-$

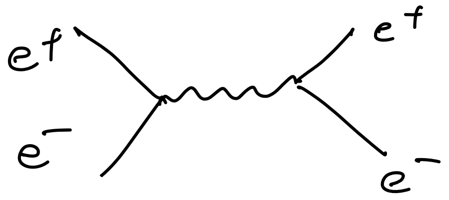
$\tau^+\tau^-$

$u\bar{u}$

$d\bar{d}$

$c\bar{c}$

$b\bar{b}$

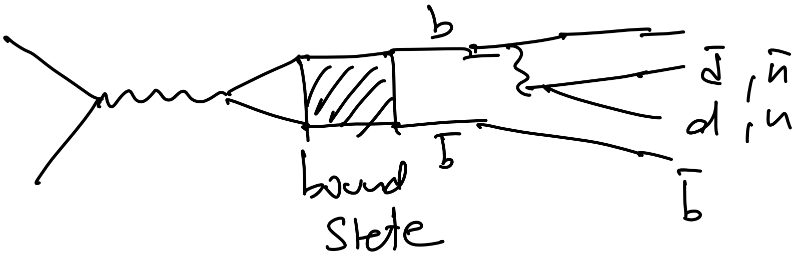


$$\frac{\sigma(e^+e^- \to U(4S) \to bb)}{\sigma(e^+e^- \to U(4S) \to TOT)} = \frac{1.2nb}{3.5nb} = 25\%$$

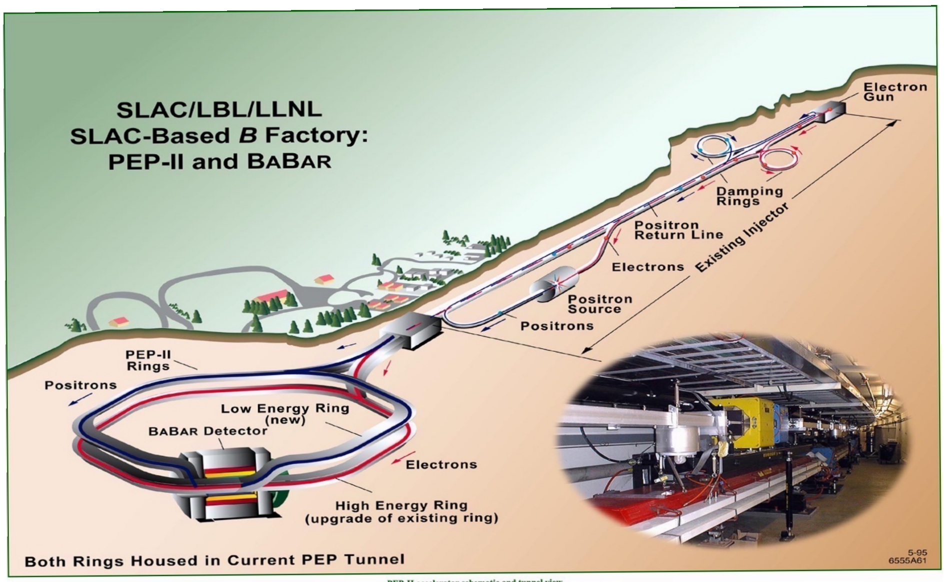
B- Factory at $\Upsilon(4S)$

$e^+e^- \longrightarrow b\bar{b} \equiv \Upsilon(4S) \longrightarrow B^0\bar{B}^0 \simeq 50\%$

$B^+B^- \quad 50\%$

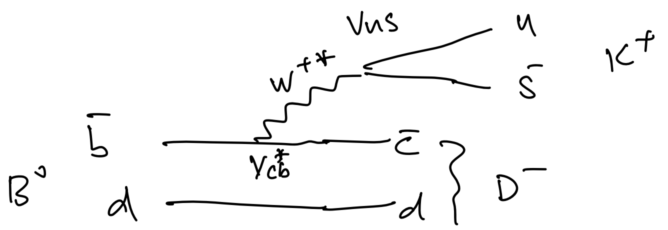


$Q = M_{\Upsilon(4S)} - 2m_B = 10.58 - 2 \times 5.28$

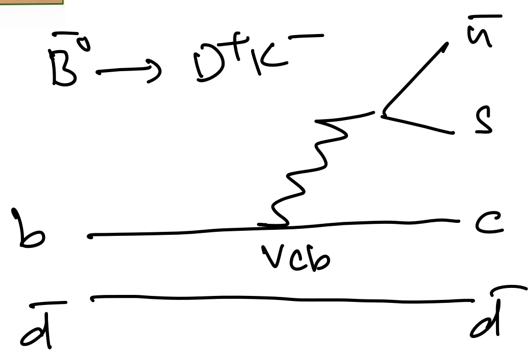


PEP-II accelerator schematic and tunnel view

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

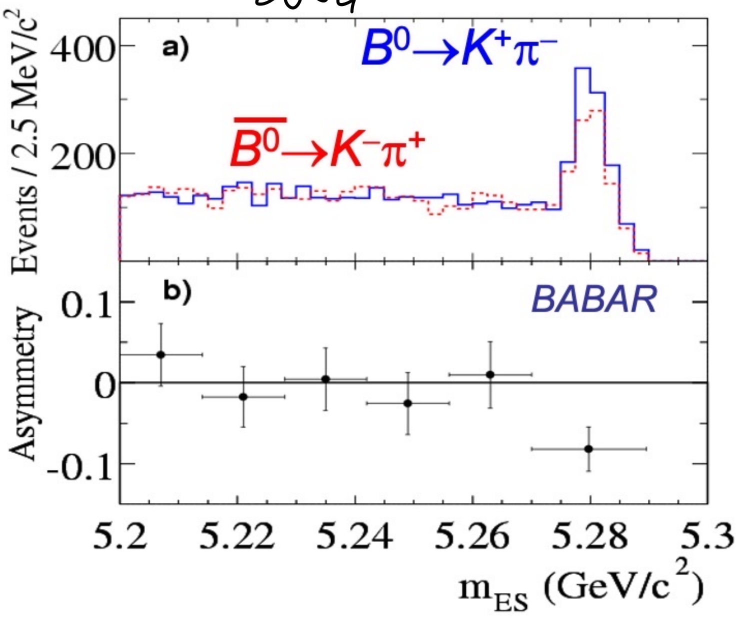


$\overset{CP}{\Longrightarrow}$



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

2004



$$n_{K\pi} = 1606 \pm 51$$
$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

$n(B^0 \to K^+\pi^-) = 910$

$n(\bar{B}^0 \to K^-\pi^+) = 696$

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

Direct CP violation.

$N = \sigma \cdot \mathcal{L} \cdot \Delta t.$ $\qquad \sigma \propto |M|^2 \times BF$

$B \to DK \ll B \to D\pi$

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

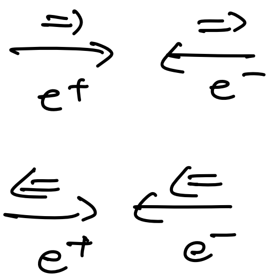
CP violation in Interference

$B^0 \to J/\psi\, K_S$ $\qquad J/\psi \to \ell^+\ell^-$

$\bar{B}^0 \to J/\psi\, K_S$ $\qquad K_S \to \pi^+\pi^-$

Clear experimental signature.

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



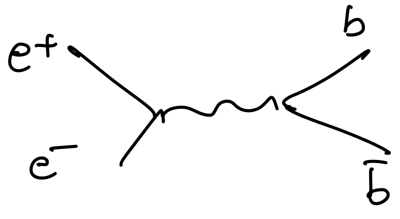
γ^*

$J=1.$

$e^+e^- \to B^0\bar{B}^0$ $\qquad S_{B^0} = S_{\bar{B}^0} = 0.$

$J = \quad 1$

$S \qquad\qquad 0 \quad 0 \quad \Rightarrow \quad L=1$ in final state.



$\bar{B}^0$ $\quad B_1$

$\rightarrow B^0 \quad B_2$

$\Upsilon(4S)$

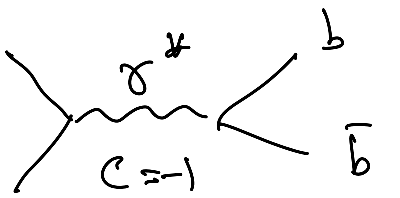
$B_2 \leftsquigarrow \bullet \rightsquigarrow B_1$

$t=0 \quad B^0 \qquad\qquad \bar{B}^0$

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

$t = t_1 \quad B_2 = \bar{B}^0 \qquad\qquad B_1 \rightarrow B^0$

oscillation
through week interection



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

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

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

$$C|B_1B_2\rangle = -1\,|B_1B_2\rangle \Rightarrow b = -a$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle|\bar{B}^0\rangle - |\bar{B}^0\rangle|B^0\rangle\right)$$ Coherent State.
Entanglement

$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \qquad p^2+q^2=1$$

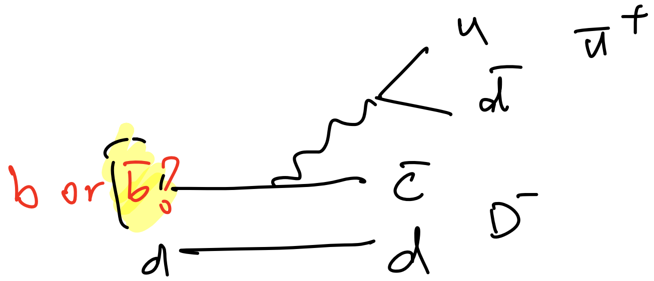
$$|B_H\rangle = q|B^0\rangle + p|\bar{B}^0\rangle \qquad \text{mass eigenstates.}$$

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

In nature $\tau_B = 1.57$ fs.

$t=0.$ $\quad B_1 \leftrightsquigarrow B_2$

$t_1>0$ $\quad B_1 \to D^- \pi^+$



$D^-\pi^+ \Rightarrow B_1 \equiv B_0$
at $t=t_1$.

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

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

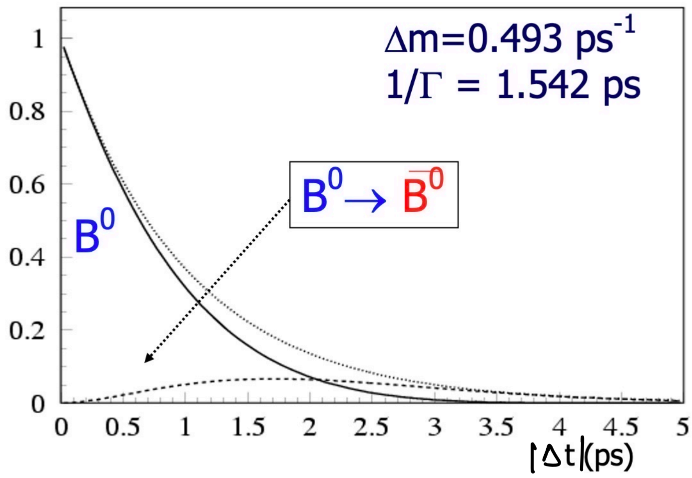
$$P(B^0 \to \bar{B}^0) = \frac{e^{-\Gamma t}}{2}\left(1 - \cos \Delta m \Delta t\right)$$

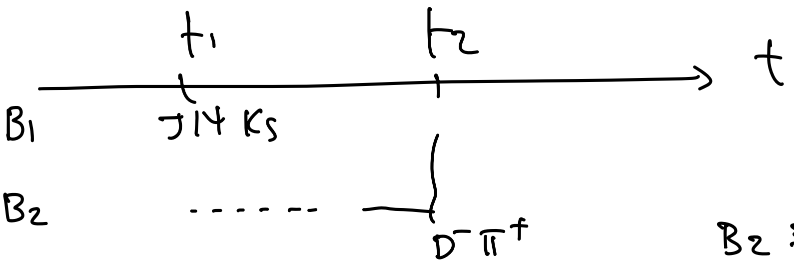
$\Delta m = B_H - B_L$

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

P: prob. of survival

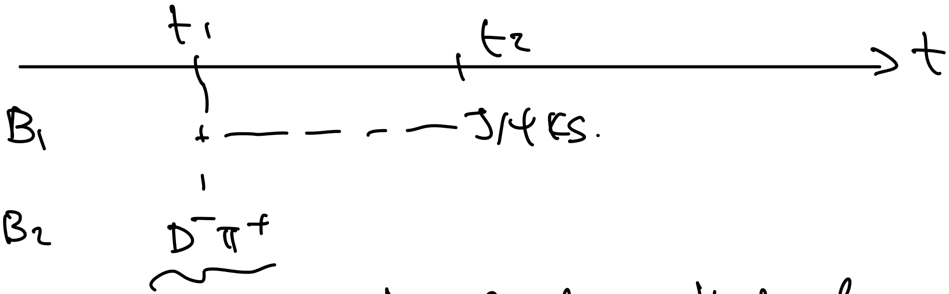
produce B^0 at $t=0$.





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

$B_2 \equiv B^0$



$\Delta t = t_{tag} - t_{CP}$.

t_{tag} : t of decay that fixes flavor of 1 B

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

$$N_{B^0\bar{B}^0}(t_{tag}, t_{CP}) = \mathcal{L}\cdot\sigma\cdot\Delta t \times \underbrace{BF(B\to D^-\pi^+)}_{2.5\times10^{-3}} \times \underbrace{BF(J/\psi\, K_S)}_{9\times10^{-4}}$$