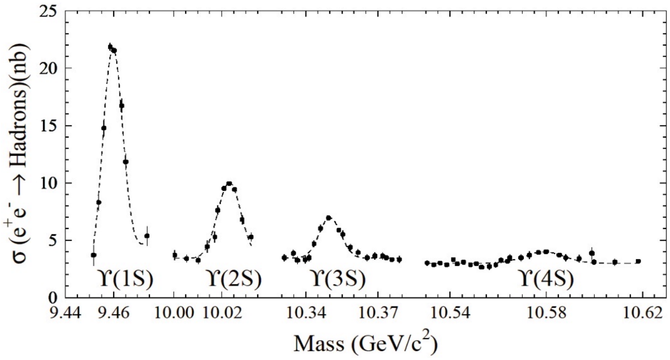
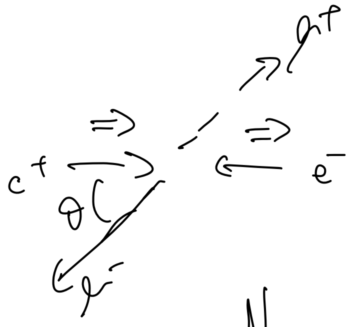
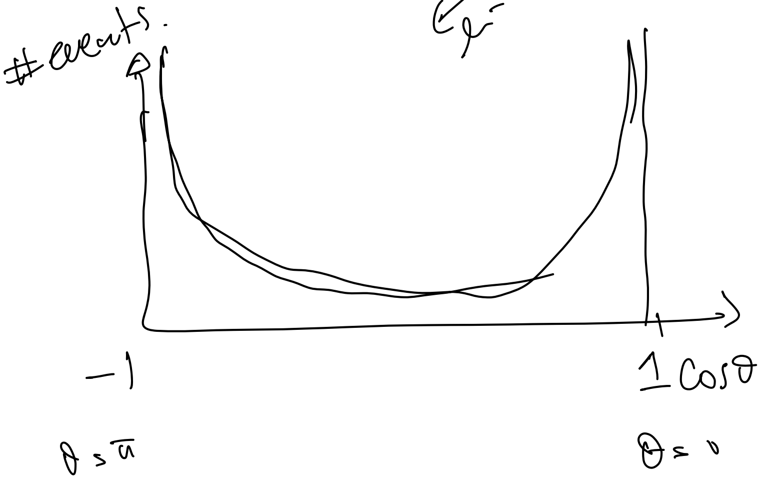


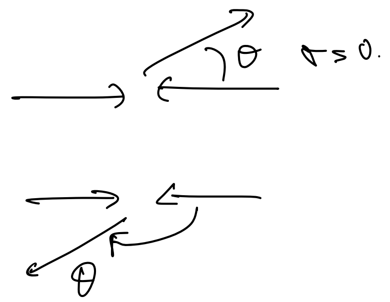
$$e^+e^- \to \Upsilon(4S) \to \left.\begin{array}{l} e^+e^- \\ \mu^+\mu^- \\ \tau^+\tau^- \\ u\bar{u} \\ d\bar{d} \\ c\bar{c} \\ s\bar{s} \end{array}\right\} 3/4.$$

$$\sqrt{s} = 10.58\ \text{GeV}. \qquad 1/4 \quad \{ \ b\bar{b}$$

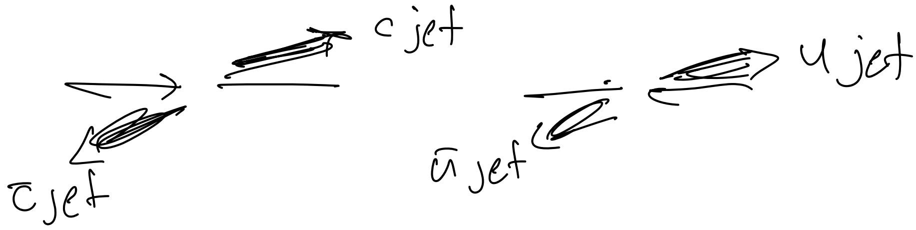
$e^+e^- \to \mu^+\mu^-$







Background events

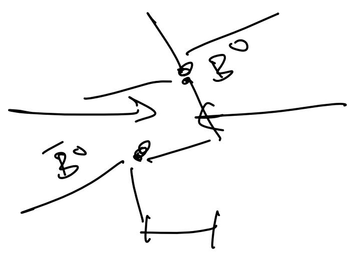


signal events: $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$

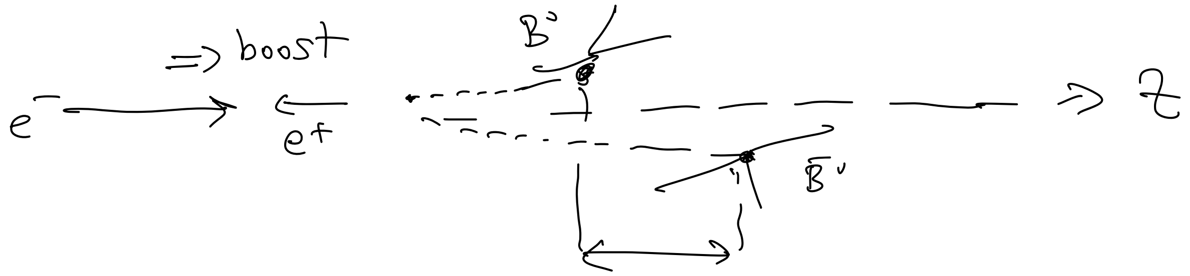
$\sqrt{s} = 10.58$ GeV. $\qquad m_B = 5.28$ GeV.

$\Rightarrow \quad Q = \sqrt{s} - 2m_B \simeq 300$ MeV.

$$\beta\gamma = \frac{p}{m} \simeq \frac{300\ \text{MeV}}{5.28\ \text{GeV}} \qquad e^+e^- \to B^0\bar{B}^0.$$



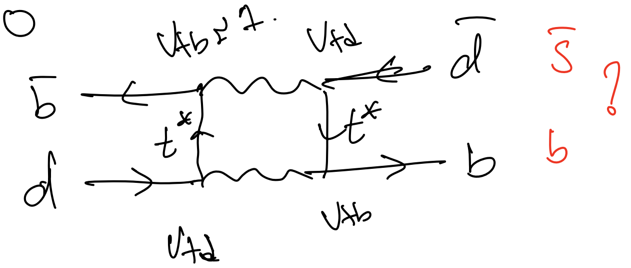
SLAC: $E_{e^-} = 9$ GeV. $\quad E_{e^+} = 3.1$ GeV. $\quad$ asymm. beam.



Quantum entanglement in $B^0\bar{B}^0$ system.

$$|\psi\rangle = |B^0,t\rangle\,|\bar{B}^0,t\rangle \qquad \forall t>0$$

weak interaction $\Longrightarrow$ $B^0 \longleftrightarrow \bar{B}^0$



$B^0, \bar{B}^0$ stable $\Longrightarrow$ infinite oscillation.

$B^0 \longrightarrow \bar{B}_s^0$

$m_{B^0} \neq m_{\bar{B}_s}$: Not possible.

$\tau_B = 1.5$ ps.

$$P(B^0 \text{ remains } B^0, t) = e^{-t/\tau}$$

$$P(\bar{B}^0 \text{ remains } \bar{B}^0, t) = e^{-t/\tau}$$

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

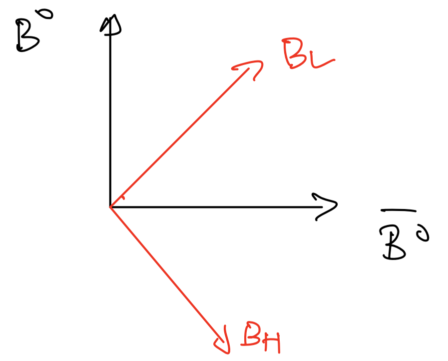
$B^0, \bar{B}^0$ flavor eigenstates produced in nature.

B_L, B_H $\quad$ mass/hamiltonian eigenstates.

$\swarrow$ light $\quad \downarrow$ heavy.

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

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



$$\psi_{B_{L/H}}(t) = e^{-im_{L/H}t}\, e^{-\Gamma_{L/H}t}$$

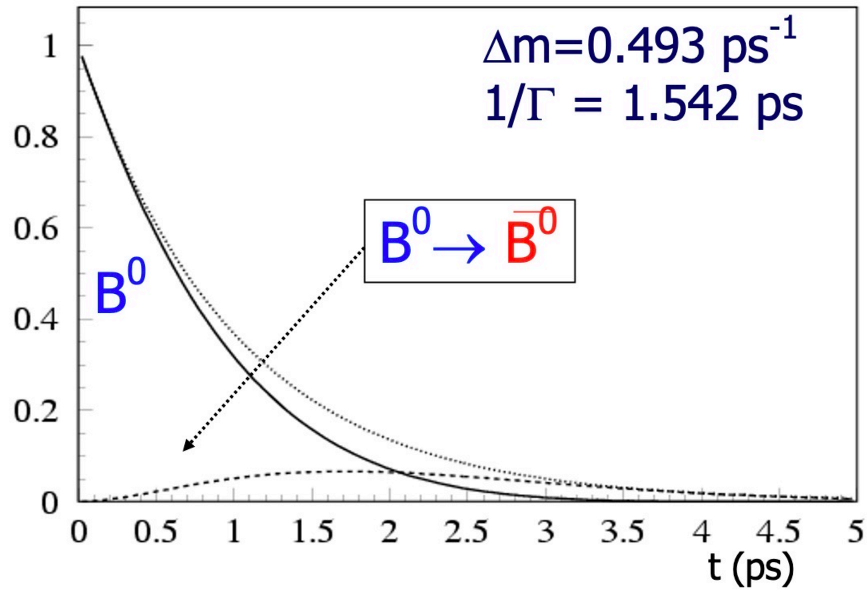
In rest frame of $B_{L/H}$.

$\Delta\Gamma \ll \Gamma$. $\quad \tau_{B^0} = \tau_{\bar{B}^0} \quad \tau_{B_L} \simeq \tau_{B_H} = 1.5$ ps.

$\Delta m \simeq 0.32$ MeV. $\quad m_B = 5.28$ GeV.

$$P(B^0 \text{ remain } B^0, t) = \frac{e^{-t/\tau}}{2}(1 + \cos\Delta m t)$$

$$P(B^0 \to \bar{B}^0; t) = \frac{e^{-t/\tau}}{2}(1 - \cos\Delta m t)$$



Mixing asymm: $\dfrac{\# B^0 - \# \bar{B}^0}{\# B^0 + \# \bar{B}^0}$?

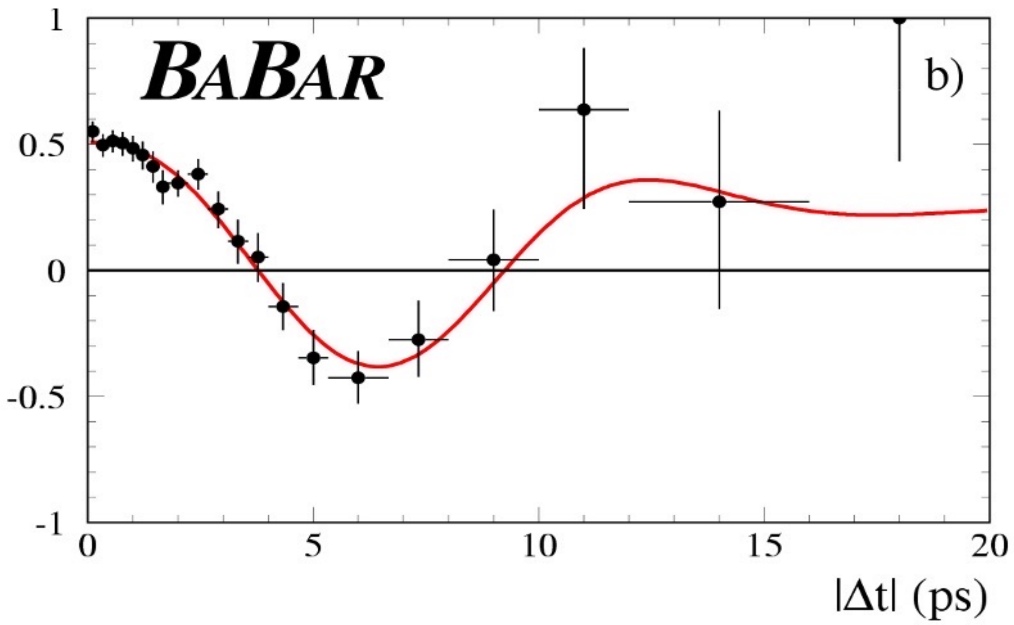
$e^+e^- \longrightarrow B^0 \bar{B}^0 \quad t=0.$

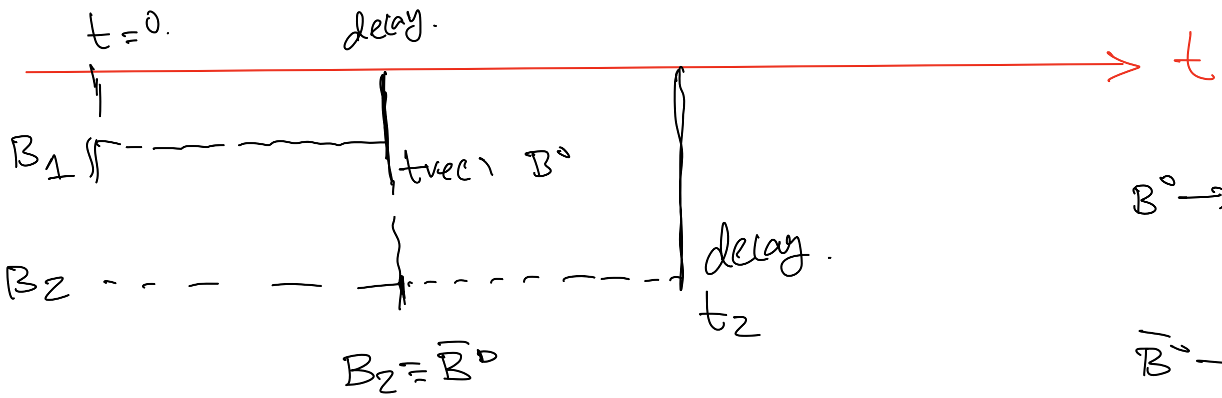
$t>0$: $\quad B^0 \bar{B}^0$ (no oscillation).

$B^0 B^0$ ($\bar{B}^0 \to B^0$ oscillated).

$\bar{B}^0 \bar{B}^0$ ($B^0 \to \bar{B}^0$ oscillated).

$$A_{\text{mixing oscillation}} = \frac{(\# B^0B^0 + \# \bar{B}^0\bar{B}^0) - \# B^0\bar{B}^0}{(\text{———}) + (\text{———})} = \cos\Delta m \Delta t$$





$B^0 \to D^- K^+$
$\quad\quad\;\; D^- \pi^+$

$\bar{B}^0 \to D^+ K^-$
$\quad\quad\;\; D^+ \pi^-$

because of entanglement.

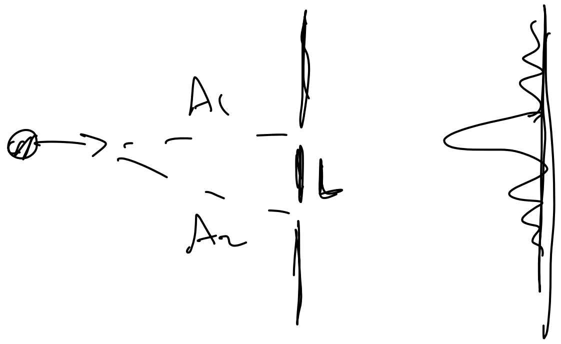
@ t_2, $B_2 = \bar{B}^0 \Rightarrow$ no oscillation

$B_2 = B^0 \Rightarrow$ oscillation.

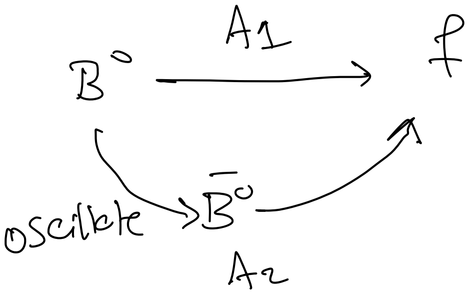
$\Delta t = t_1 - t_2 \gtrless 0$

To study $\cancel{CP}$:

- count $B^0 \to f \neq \bar{B}^0 \to \bar{f}$
  $B^0 \to D^- K^+ \neq \bar{B}^0 \to D^+ K^-$.
  Direct $\cancel{CP}$.
- $B^0 \to \bar{B}^0 \neq \bar{B}^0 \to B^0$.
  $\cancel{CP}$ in mixing.
- $\cancel{CP}$ in interference between decay and mixing.



double slit experiment



$f_{CP} = J/\psi\, K_S.$

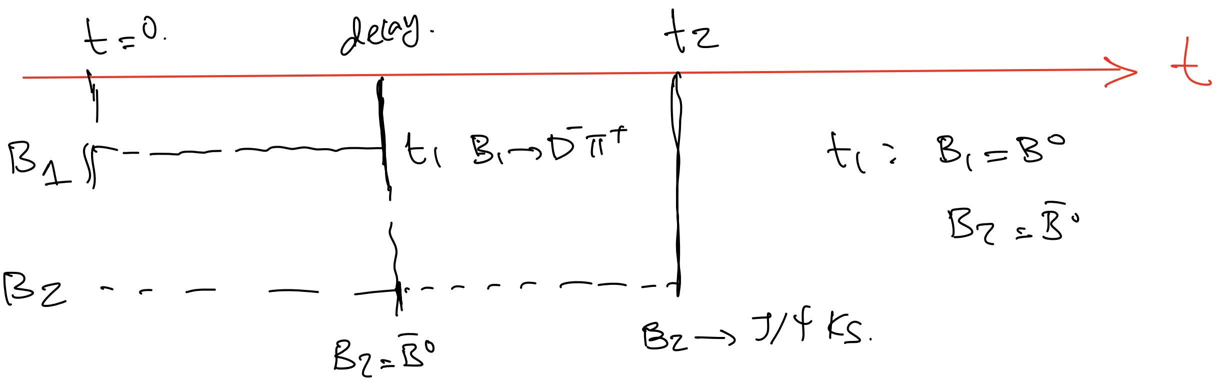
$\bar{f}_{CP} = J/\psi\, K_S.$

$K_S \simeq K_1 \quad CP = 1.$

$f = \pi^+\pi^-$

D^+D^-

$K^0\pi^0$



$t_1: \quad B_1 = B^0$

$B_2 = \bar{B}^0$

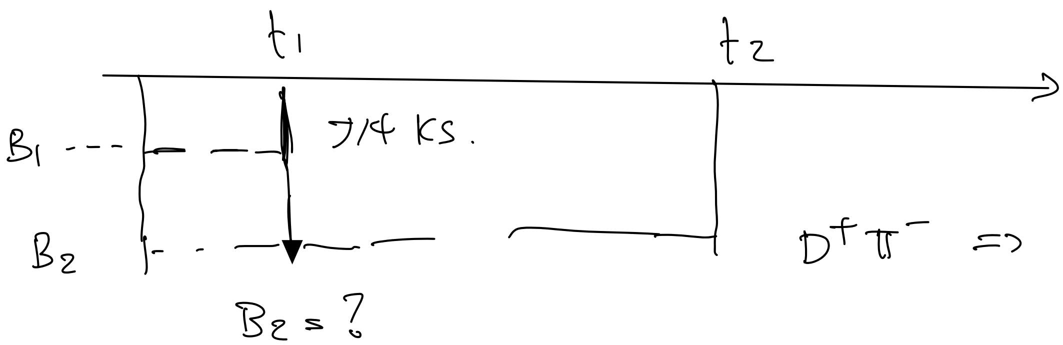
$e^+e^- \longrightarrow B_1 B_2.$ $\quad t=0 \quad B^0, \bar{B}^0$

$t_1: \quad B_2 = \bar{B}^0$ $\quad t_2: \quad B_2 \to J/\psi\, K_S.$

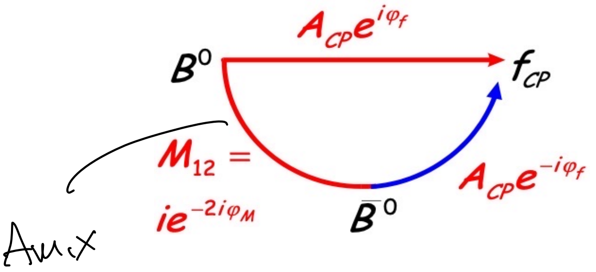
2 possibilities: 1/ $\bar{B}^0$ remains $\bar{B}^0 \longrightarrow J/\psi\, K_S.$

2/ $\bar{B}^0 \longrightarrow B^0 \longrightarrow J/\psi\, K_S.$

B_1: B_{tag}. tag/identify flavor of B_1 and B_2 @ t_1.



$D^+\pi^- \Rightarrow B_2 = \bar{B}^0 @ t_2.$



$A_{CP}: \; B^0 \longrightarrow f_{CP} = |A_{CP}|\, e^{i\varphi_f}$

$\bar{A}_{CP}: \; \bar{B}^0 \longrightarrow f_{CP} = |A_{CP}|\, e^{-i\varphi_f}$

$A_{mix}: \; B^0 \longleftrightarrow \bar{B}^0 = |A_{mix}|\, e^{i\varphi_M}$

$f_{CP} = J/\psi \;\; K_S$

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

$J/\psi \to \ell^+\ell^-, \; e^+e^-, \; \mu^+\mu^-$

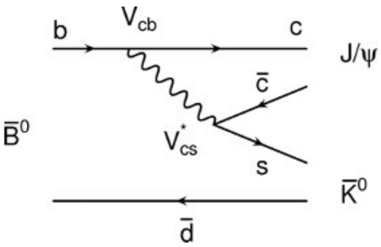
4 charge tracks.
well identified.

3 kinematic constraints.

$m_{\ell\ell}, \; m_{\pi\pi}, \; m_{\ell\ell\pi\pi}$

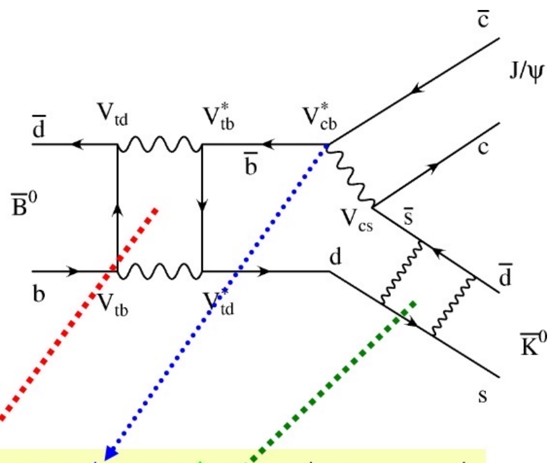
$m_{J/\psi} \quad m_{K_S} \quad m_B$

$A_1 \equiv A_{CP}$



$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \overbrace{A\lambda^3(\rho - i\eta)}^{V_{ub}\;\; e^{-i\gamma}} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underbrace{A\lambda^3(1-\rho-i\eta)}_{V_{td}\;\; e^{-i\beta}} & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$A_2: \; B^0 \longrightarrow \bar{B}^0 \longrightarrow J/\psi \;\; K_S.$



$$\lambda_{\psi K_S} = \frac{q_B}{p_B}\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}} = -\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\frac{V_{cb}V^*_{cd}}{V^*_{cb}V_{cd}}$$

$V_{td} = e^{-i\beta}.$

$$\lambda = \frac{q}{p}\,\frac{\bar{A}}{A}$$

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

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

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

Experimentally $\frac{|q|}{|p|} \simeq 1$ @ 10^{-4} $\Rightarrow$ no $\cancel{CP}$ in mixing.

$\frac{|\bar{A}|}{|A|} = 1$ @ 1% $\qquad \lambda \simeq e^{-i2\beta}$.

$$f(B^0, \Delta t) = \frac{e^{-t/\tau}}{2}\left(1 + \text{Im}\lambda \sin \Delta m \Delta t\right)$$

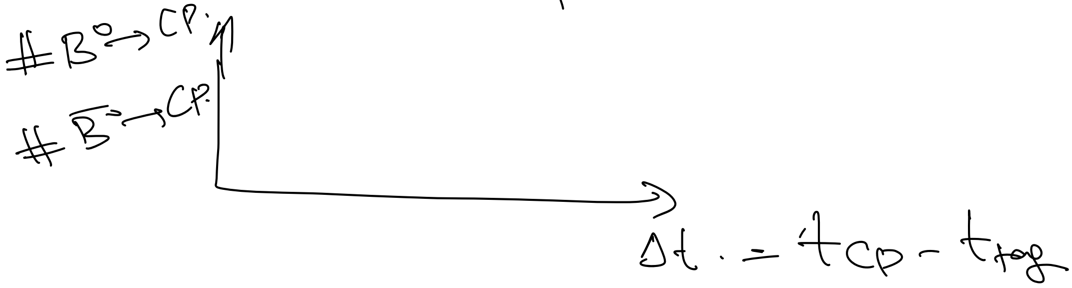
$$f(\bar{B}^0, \Delta t) = \frac{e^{-t/\tau}}{2}\left(1 - \text{Im}\lambda \sin \Delta m \Delta t\right)$$

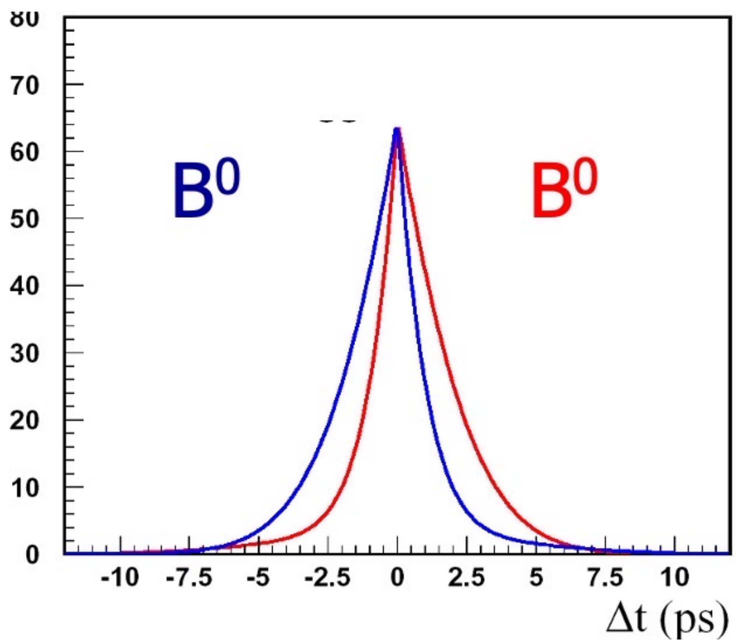
$$\text{Im}\lambda = \sin 2\beta.$$

$$\text{CP asym} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{\#(B^0 \to J/\psi K_S) - \#(\bar{B}^0 \to J/\psi K_S)}{\#(--) + (--)}$$

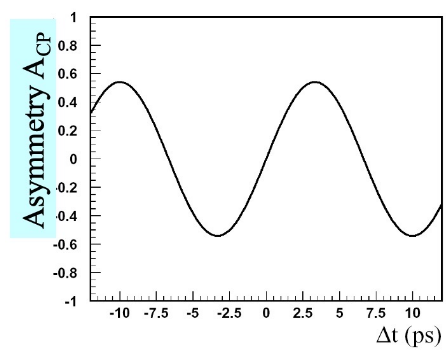
as function of Δt.

$$= \sin 2\beta . \sin \Delta m \Delta t.$$





$$e^{-t/\tau}\left(1 \pm \sin 2\beta \sin \Delta m \Delta t\right)$$



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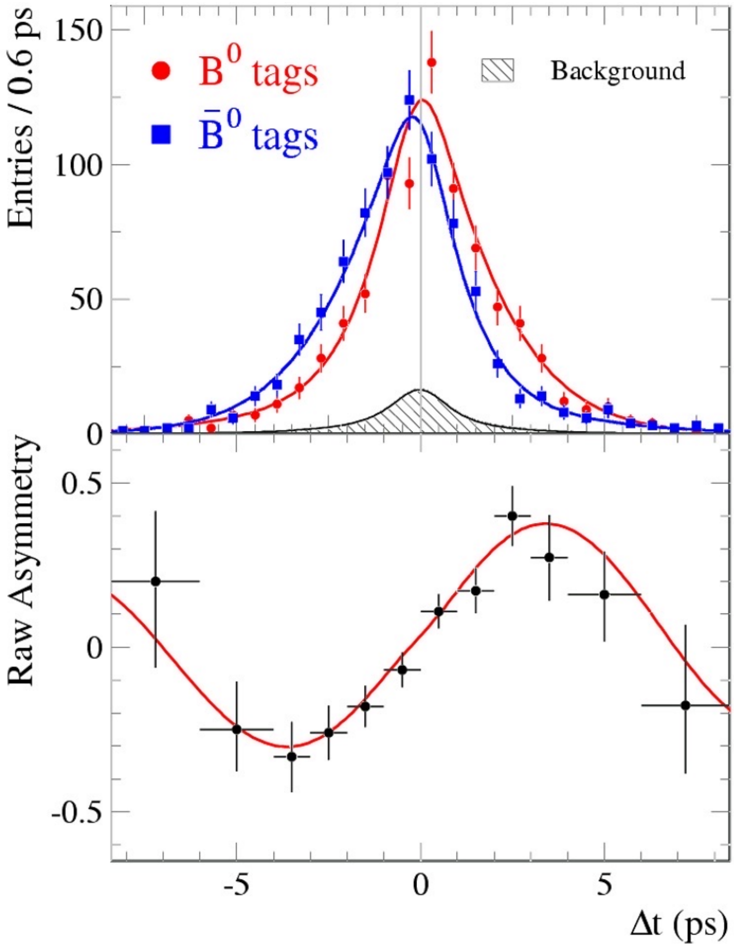

$$\boxed{\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}}$$

$\neq 0 \Rightarrow \sin 2\beta \neq 0$

$\Rightarrow \beta \neq 0$.

$\Rightarrow$ CKM has a complex phase

$\Rightarrow$ KM mechanism works.