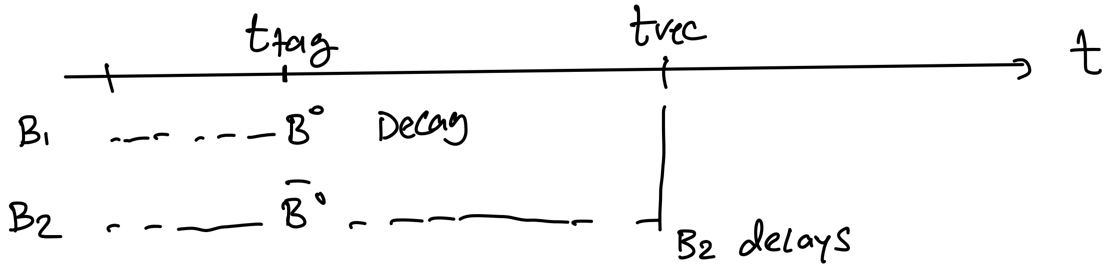
CP Violation at B Factory

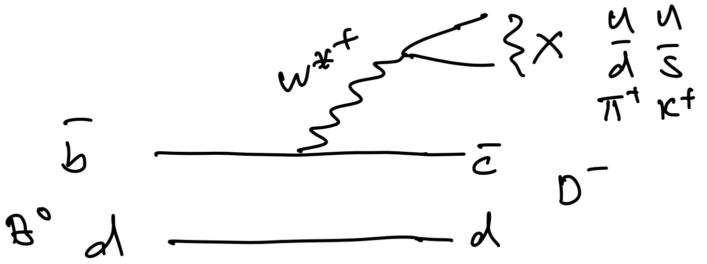
$e^+e^- \to \Upsilon(4S) \to |B^0\bar{B}^0\rangle \to$ $B_1 \to$ CP eigen state

$B_2 \to$ tag/flavor eigenstate

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



t_{tag}: time of decay $B \to$ flavor eigenstate



$B^0 \to D^-\pi^+$

$D^- K^+$

$D^- \ell^+\nu$

$$Q = m_B - m_D - m_X$$
$$= 5.279 - 1.86 - m_X.$$

$B^0 \longrightarrow \ell^+$ tagger for $\bar{b}$ quark.

$\bar{B}^0 \longrightarrow \ell^-$ flavor tag for b quark.

For $t = t_{tag}$ $B_2 = \bar{B}^0$

$t > t_{tag}$ $\bar{B}^0$ can oscillate or decay.

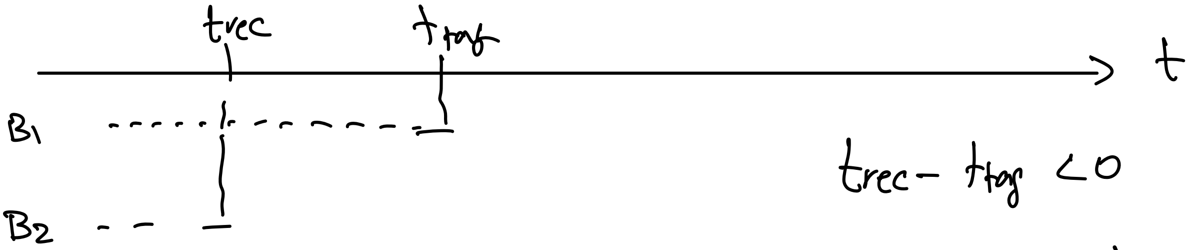
$t_{rec} > t_{tag}$: B_2 decays.

2 scenarios: $\begin{cases} B_1 = B^0 \\ B_2 = \bar{B}^0 \end{cases}$ no oscillation $\begin{cases} B_1 = B^0 \\ B_2 = B^0 \end{cases}$

$\Downarrow$

B_2 oscillated after t_{tag}.

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



$t_{rec} - t_{tag} < 0$

$\Delta t = t_{rec} - t_{tag}$

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

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

$$\Delta t = \frac{\Delta z}{\beta \gamma c}$$

Δz: distance between decay vertices of B_1 and B_2.

$\sqrt{s} = 10.58$ GeV $= m(\Upsilon(4S))$

$Q = m(\Upsilon(4S)) - 2m_B \Rightarrow P_B^* \simeq 300$ MeV.

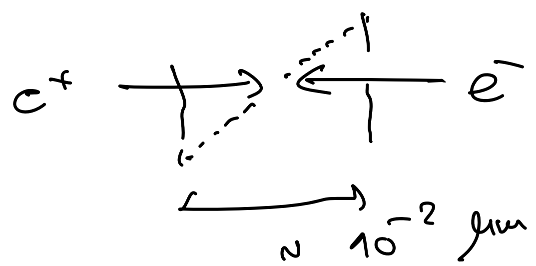
$$(\beta\gamma)_{B^*} = \frac{300 \text{ MeV}}{5 \text{ GeV}} = \frac{0.3}{5} \simeq 0.06$$

$\tau_B = 1.5$ fs $= 1.5 \times 10^{-15}$ s.

$\langle d \rangle = \beta\gamma c\tau = 0.06 \times 3 \times 10^{10} \frac{\text{cm}}{\text{s}} \times 1.5 \times 10^{-15}$ s.

$\simeq 10^{-6}$ cm.

If symm e^+e^- beam:



$\sim 10^{-2}$ μm. not useful / easy to measure experimentally

use Lorentz boost to increase Δz.

e^- $\longrightarrow$ 9 GeV $\quad$ $\longleftarrow$ e^+ 3.1 GeV $\quad$ $\longrightarrow z$

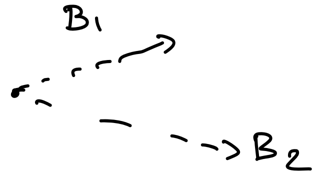
$P_{tot} = 9 - 3.1 = 5.9$ GeV. $\longrightarrow z$

$$(\beta\gamma)_{cm} = \frac{5.9}{\sqrt{s}} = \frac{5.9}{10.58}\frac{GeV}{GeV} = 0.56$$

Center of mass.

$(\beta\gamma)^*_B \simeq 0.06.$

In the LAB



$$\Delta t \simeq \frac{\Delta z}{\beta\gamma c}$$

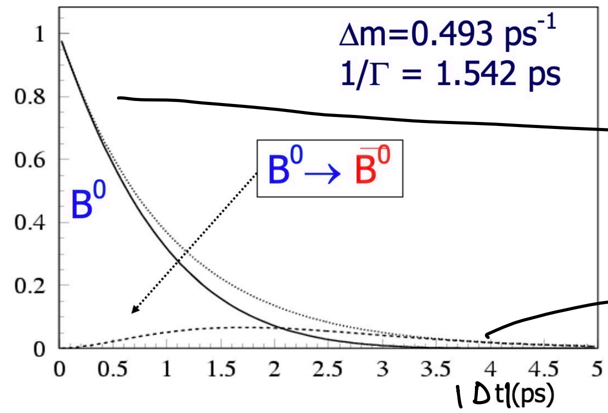
$\Delta z \simeq 300\ \mu m.$

this can be measured.

$$A = \frac{\#(B^0\bar{B}^0) - \#(B^0B^0 \text{ or } \bar{B}^0\bar{B}^0)}{\#(B^0\bar{B}^0) + \#(B^0B^0 \text{ or } \bar{B}^0\bar{B}^0)}$$

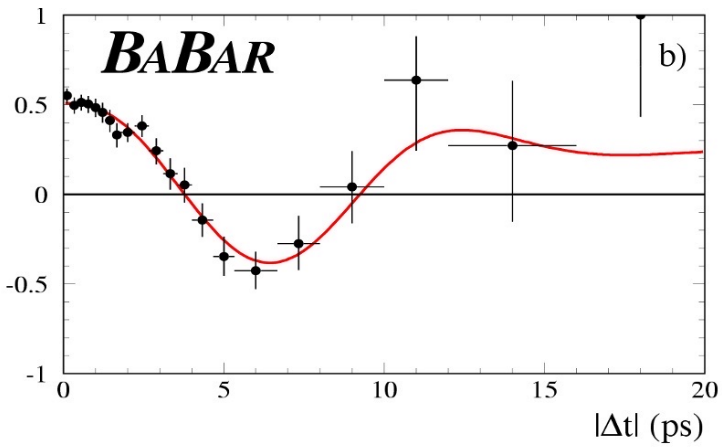
oscillation amplitude.

$$= \frac{(1+\cos\Delta m\Delta t) - (1-\cos\Delta m\Delta t)}{(1+\cos\Delta m\Delta t) + (1-\cos\Delta m\Delta t)} = \cos\Delta m\Delta t$$



$$(1+\cos\Delta m\Delta t)\,\frac{1}{2}\,e^{-\Gamma t}$$

$$(1-\cos\Delta m\Delta t)\,\frac{1}{2}\,e^{-\Gamma t}$$



$0.5 = 1 - 2w$

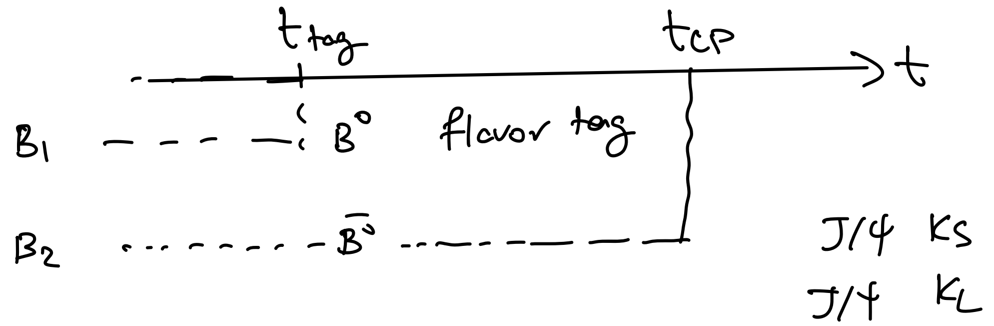
w: prob of wrong flavor tag.

$$P(\text{survived}) = e^{-t/\tau} \qquad t = 7\tau \Rightarrow P(\text{surv}) = e^{-7}$$

$$\#(B^0\bar{B}^0) = (1-w)\, N(B^0\bar{B}^0) + w\, N(B^0B^0)$$

w: prob. of making a mistake in flavor tag.

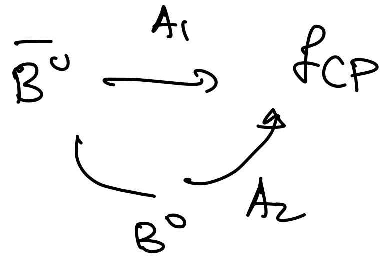
CP violation in interference

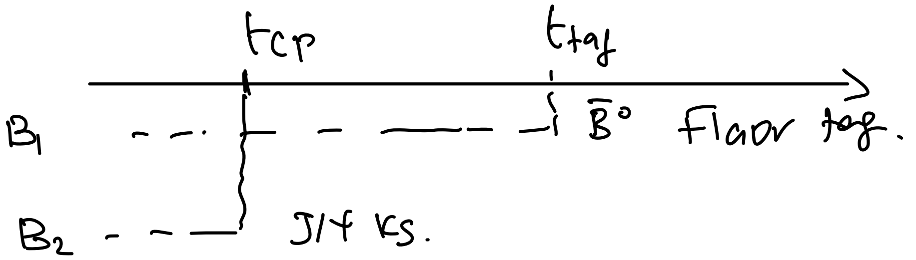


$\Delta t > 0$

$B_2 = \bar{B}^0$ at t_{tag}.

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





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

$J/\psi = c\bar{c}$ bound state

$K_S = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0) \simeq K_1$ $\qquad K^0: \bar{s}d \qquad \bar{K}^0 = s\bar{d}$

$K_L = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$

$$CP(J/\psi\, K_S) = P(J/\psi\, K_S)\, C(J/\psi\, K_S)$$
$$= (-1)^L\, P(J/\psi)\, P(K_S)\, C(J/\psi)\, C(K_S)$$

$$\Upsilon(4S) \longrightarrow B^0\bar{B}^0$$
$$S \quad 1 \qquad\quad 0 \quad 0 \quad \Rightarrow L = 1.$$

$$CP(J/\psi K_L) = (-1)^L \underbrace{CP(K_S)}_{+1} CP(J/\psi) \qquad CP(K_L) = -1.$$

$$P(J/\psi) = -1.$$

$$C(J/\psi) = (-1)^{L+S} = (-1)^{0+1} = -1. \qquad = CP(J/\psi) = +1.$$

$$CP|J/\psi K_S\rangle = (-1)\,|J/\psi K_S\rangle$$

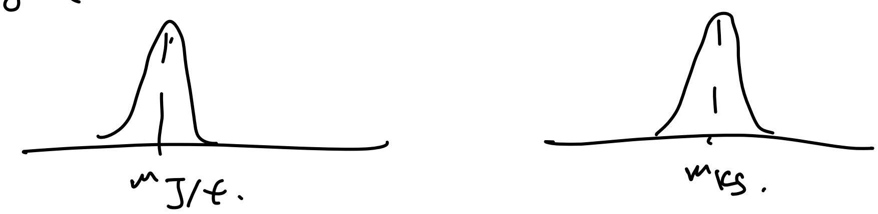
$$CP|J/\psi K_L\rangle = (+1)\,|J/\psi K_L\rangle$$

$J/\psi \to e^+e^-$ invariant mass $m_{\ell\ell}$

$K_S \to \pi^+\pi^-$ $m_{\pi\pi}$.

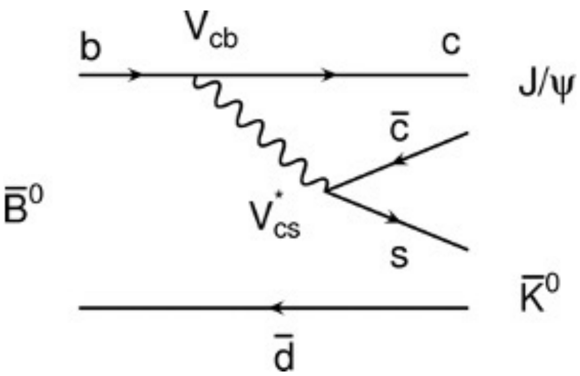
$e^+e^- \longrightarrow B_{tag}(\ell, K, --)\ B_{CP}(\ell\bar{\ell}^+, \pi^+\pi^-)$

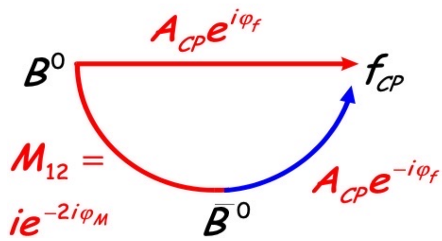
e^+e^-



$m_{\pi\pi}$

$B \to \ell\ell\pi\pi$ Clear experimental signature.
m_B



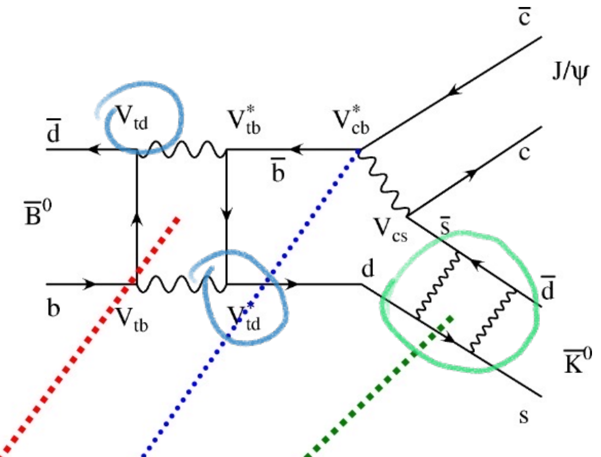


No complex phase in V_{cb}, V_{cs} in Wolfenstein paramet.

$\Rightarrow$ No complex phase in $\bar{B} \to J/\psi K_S$

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

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix} \quad e^{-i\gamma} : V_{ub}. \quad e^{-i\beta} : V_{td}$$

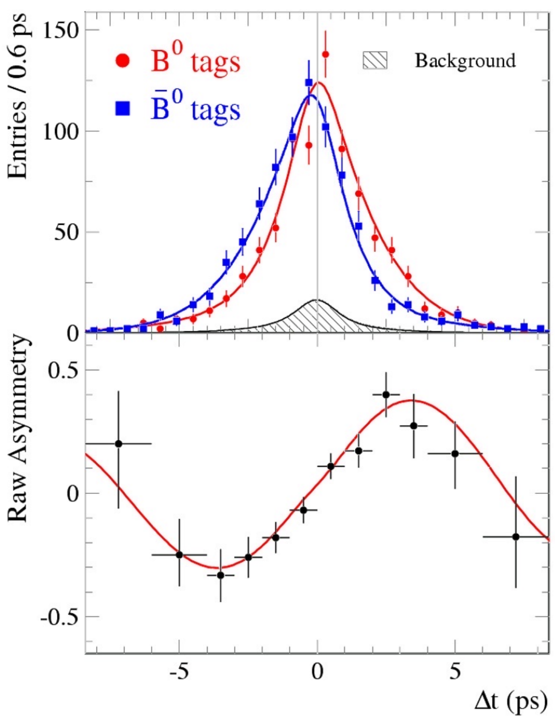


$$\lambda_{\psi K_S} = \frac{q_B}{p_B}\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} \quad \sim e^{-i2\beta}$$

$$\left.\begin{array}{l} f(\bar{B}^0 \rightarrow J/\psi K_S) \\ f(B^0 \rightarrow J/\psi K_S) \end{array}\right\} \text{ function } \sin(\Delta m \Delta t)\sin 2\beta.$$

$\#(\bar{B}^0 \text{ tagged} \rightarrow J/\psi K_S)$.

$\#(B^0 \text{ tagged} \rightarrow J/\psi K_S)$ function



B^0 tag $\Rightarrow$ $B_{CP} = \bar{B}^0$ at t_{tag}.

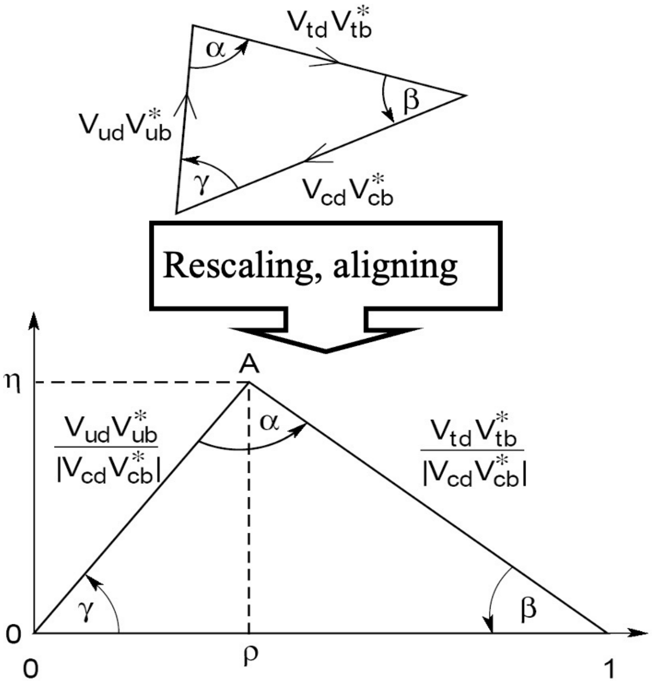
$$e^{-\Gamma t}(1 + \sin 2\beta \sin \Delta m \Delta t)$$

$\bar{B}^0$ tag $\Rightarrow$ $B_{CP} = B^0$ at t_{tag}

$$e^{-\Gamma t}(1 - \sin 2\beta \sin \Delta m \Delta t)$$

$$A_{CP} = \frac{\#(B^0 \text{ tag}) - \#(\bar{B}^0 \text{ tag})}{\# + \#}$$

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



amplitud $\neq 0$.

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

$\Rightarrow \beta \neq 0$.

$\Rightarrow V_{td}$ is complex.

$\Rightarrow$ Kobayashi-Maskawa mechanism for $\cancel{CP}$ correct.

$\Rightarrow$ complex phase in CKM matrix.

KM mechanism $\Rightarrow$ 3 generations of quarks/matter

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}_L$$

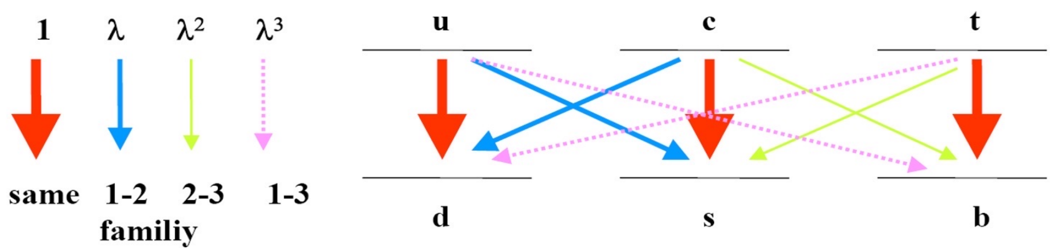
doublet of weak isospin.

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$e_R, \bar{\nu}_R, u_R, d_R, \ldots$ singlets of weak isospin.

$\longrightarrow$ family mass.

experim. observation.



weak interaction strength suppressed across families.

$$Z^0 \longrightarrow \begin{array}{l} e^+e^- \\ \mu^+\mu^- \\ \vdots \\ \nu\bar{\nu} \\ u\bar{u} \\ \vdots \\ b\bar{b} \\ \chi\bar{\chi} \end{array}$$

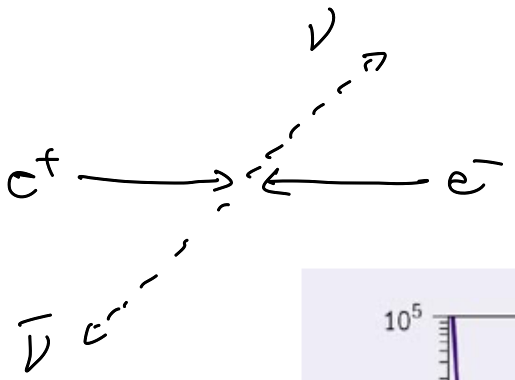
$e^+e^- \longrightarrow Z^0 \longrightarrow$ measure Z^0 decay width.

$\sqrt{s} = M_{Z^0}$

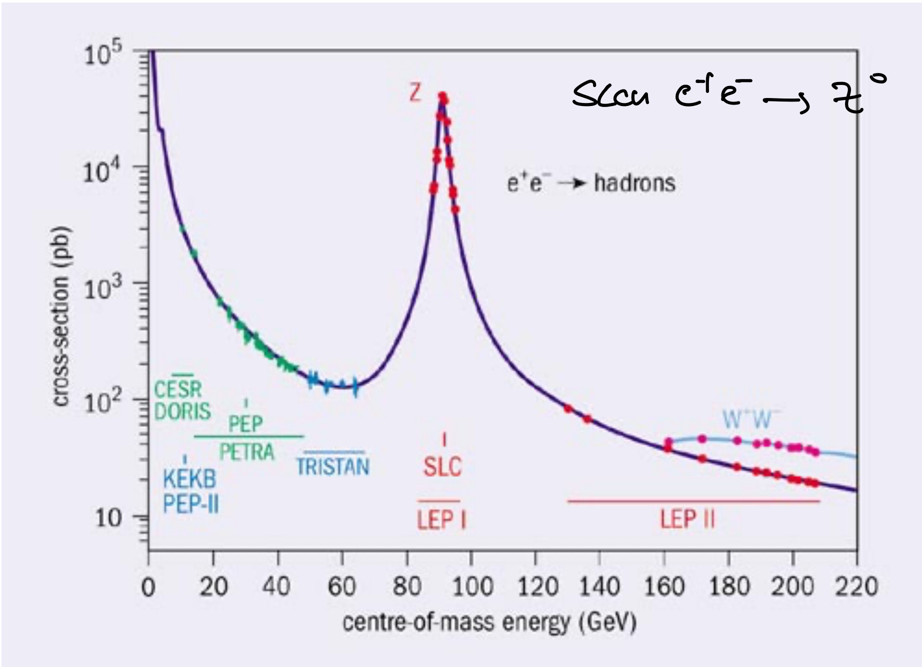
In particular: $Z^0 \longrightarrow \begin{array}{l} \nu_e\bar{\nu}_e \\ \nu_\mu\bar{\nu}_\mu \\ \nu_\tau\bar{\nu}_\tau \\ \nu_x\bar{\nu}_x \end{array}$

Experimentally.

$Z^0 \longrightarrow$ invisible



Measure at LEP.

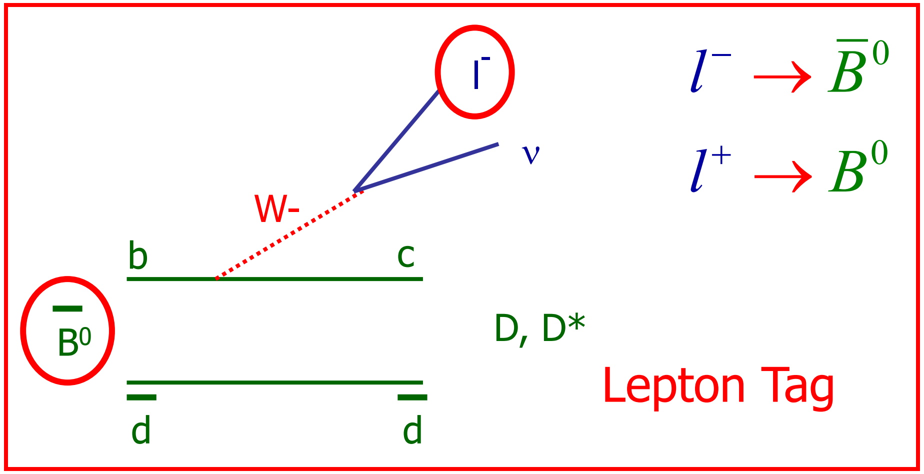


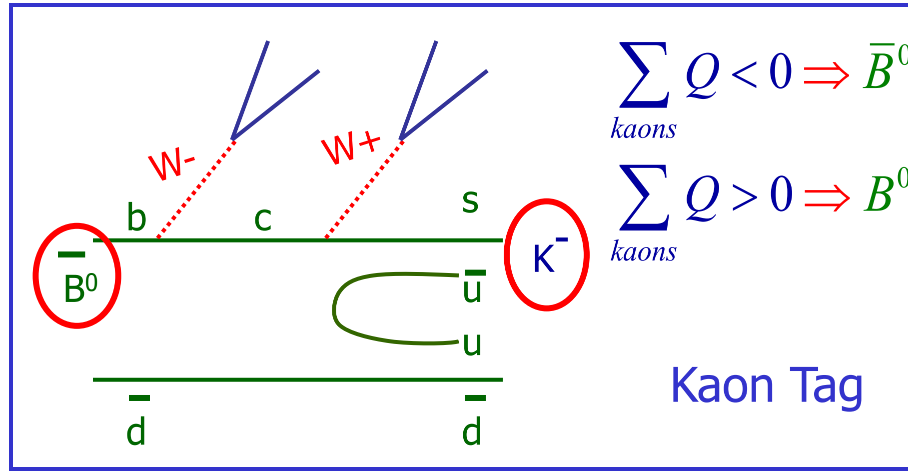
$\Gamma_{Z^0} \propto$ # families of neutrinos.

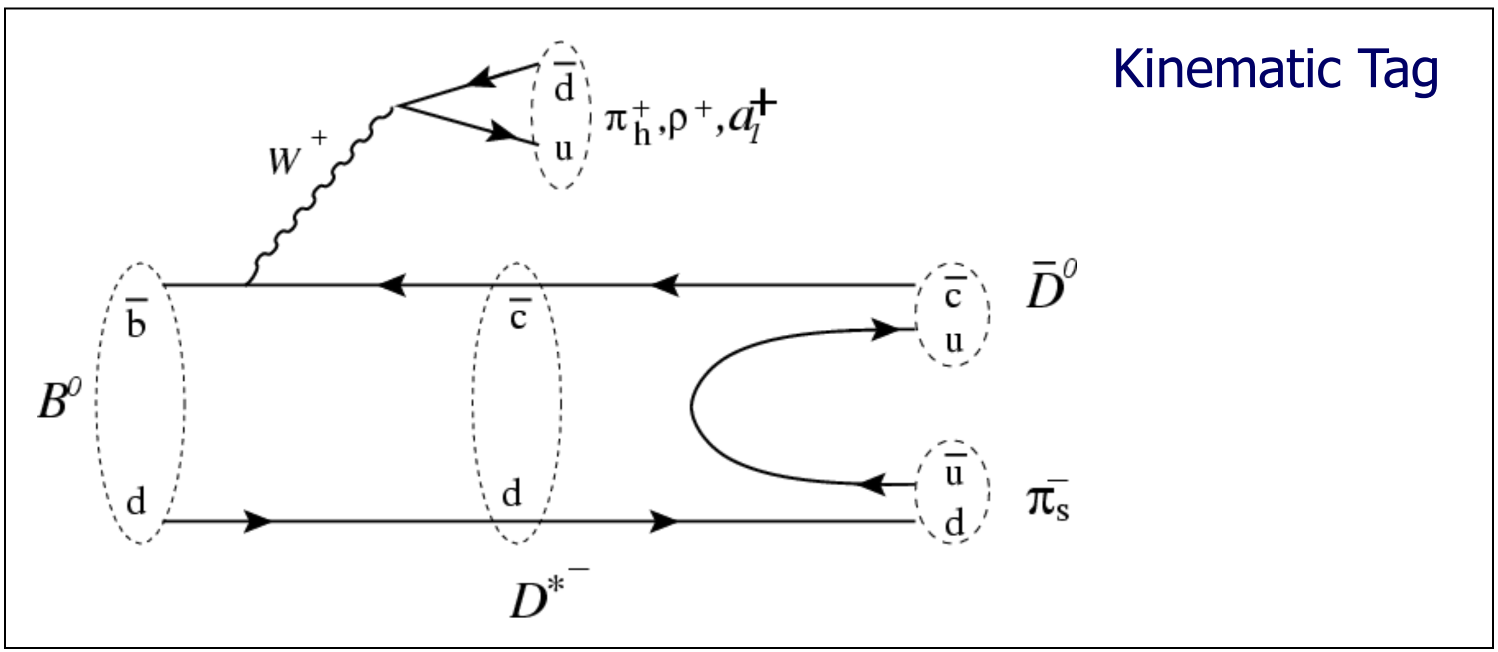
LEP $\Longrightarrow$ 3 families of neutrinos.

for neutrinos with $m_\nu \leq \frac{M_Z}{2}$

Separating B^0 and $\bar{B}^0$ mesons



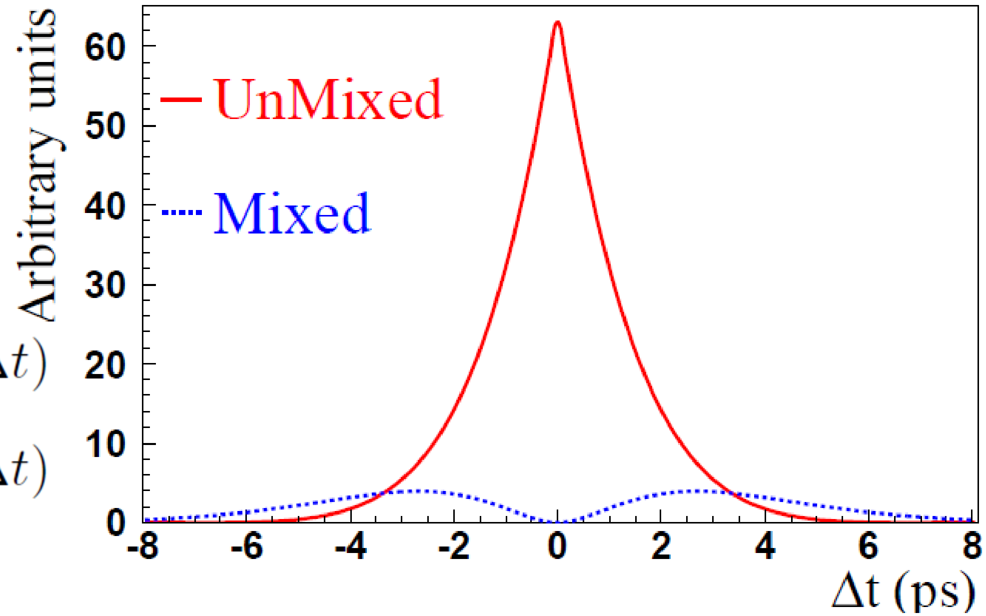




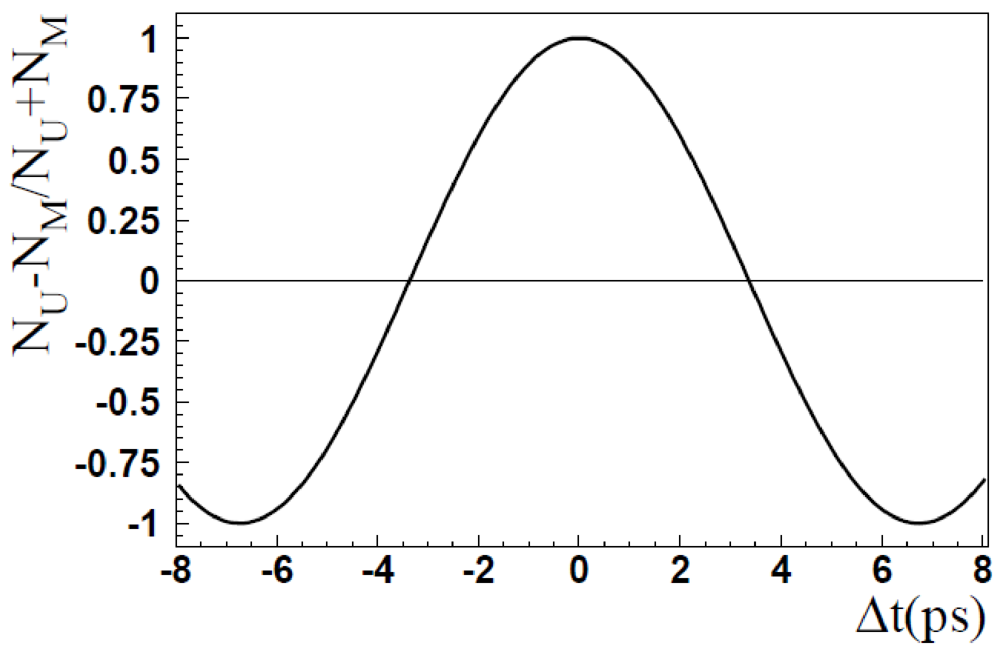
Time Dependent B Oscillation (Or Mixing) at $\Upsilon(4S)$

$$f_{\rm unmix}(\Delta t) \propto e^{-\Gamma|\Delta t|}\left(1+\cos\Delta m_d \Delta t\right)$$

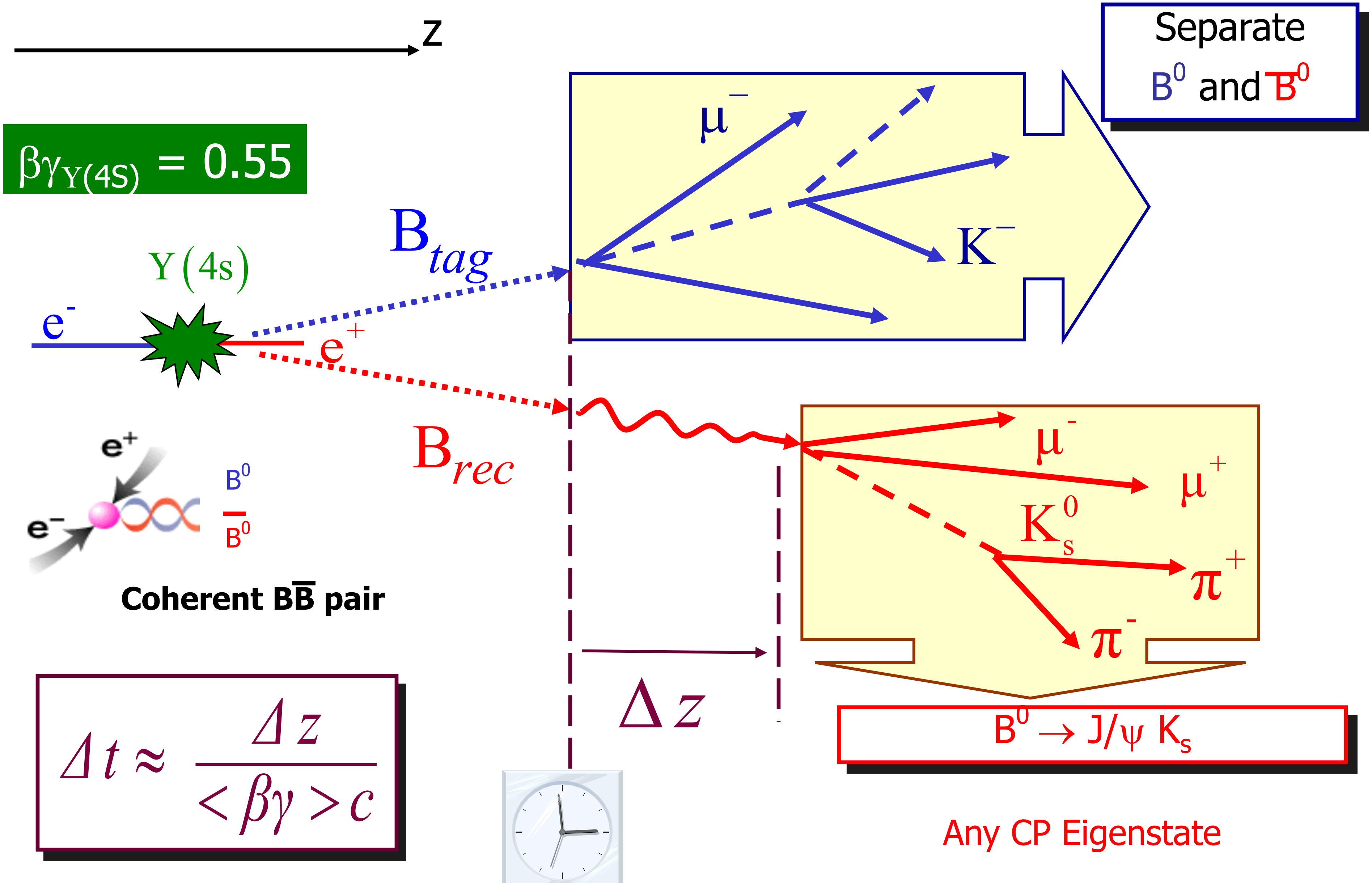
$$f_{\rm mix}(\Delta t) \propto e^{-\Gamma|\Delta t|}\left(1-\cos\Delta m_d \Delta t\right)$$



$$\mathcal{A}_{\rm mix}(\Delta t) = \frac{f_{\rm unmix} - f_{\rm mix}}{f_{\rm unmix} + f_{\rm mix}}$$



CP Violation in Interference between Mixing and Decay



Time-Evolution of B Decays to CP Eigenstates

- Probability of $|B^0\rangle|B^0\rangle \rightarrow |f_{CP}\rangle|f_{tag}\rangle$ depends on
  - Difference Δt between decay time of the two B mesons
  - Decay amplitudes

$$A_{f_{CP}} = \langle f_{CP} \,|\, H \,|\, B^0, t\rangle$$

$$\bar{A}_{f_{CP}} = \langle f_{CP} \,|\, H \,|\, \bar{B}^0, t\rangle$$

  - Oscillation parameter

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}} = e^{-i2\beta}$$

  - Flavor of tagging neutral B meson: B^0 or B0

- Convenient parameter to describe time evolution
  - Takes into account combined effect of oscillation and decay

$$\lambda = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}} \frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

Time-Dependent Decay Rates to CP Eigenstates

$$f_{B_{\rm tag}=B^0}(t_{\rm tag}, t_{f_{CP}}) \quad \propto \quad e^{-\Gamma(t_{f_{CP}}-t_{\rm tag})}\Big\{1 + \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos[\Delta m_d(t_{f_{CP}} - t_{\rm tag})] - \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin[\Delta m_d(t_{f_{CP}} - t_{\rm tag})]\Big\}$$

$$f_{B_{\rm tag}=\overline{B}^0}(t_{\rm tag}, t_{f_{CP}}) \quad \propto \quad e^{-\Gamma(t_{f_{CP}}-t_{\rm tag})}\Big\{1 - \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos[\Delta m_d(t_{f_{CP}} - t_{\rm tag})] + \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin[\Delta m_d(t_{f_{CP}} - t_{\rm tag})]\Big\}$$

$$\lambda = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\frac{q}{p}\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

- Expression and complexity of λ depends on specific final states
  - Decay amplitudes A and A can be more or less complicated depending on number of amplitudes contributing to total amplitude

Time-Dependent CP Asymmetry in Interference

$$a_{f_{CP}}(\Delta t) = \frac{f_{B_{\rm tag}=B^0} - f_{B_{\rm tag}=\overline{B}^0}}{f_{B_{\rm tag}=B^0} + f_{B_{\rm tag}=\overline{B}^0}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos\Delta m_d \Delta t$$

$$- \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin\Delta m_d \Delta t$$

- CP Violation occurs if $|\lambda| = \left|\frac{q}{p}\right|\left|\frac{\bar{A}}{A}\right| \neq 1$

$\left|\frac{q}{p}\right| = 1$ No CP Violation in Mixing

$\left|\frac{\bar{A}}{A}\right| = 1$ No Direct CP Violation

- But even with $|\lambda|=1$ it is sufficient to have $\mathrm{Im}\lambda \neq 0$

In Standard Model we expect $|\lambda| \cong 1$ in most of B decays

Simple Case with $|\lambda_{CP}|=1$

$$\Phi_M = \beta$$

$$A_f = A e^{i(\Phi_W + \delta)}$$

$$\bar{A}_f = \eta_{f_{CP}} A e^{i(-\Phi_W + \delta)}$$

$$\lambda_{f_{CP}} = \eta_{f_{CP}} e^{-2i(\Phi_W - \Phi_M)}$$

$$a_{f_{CP}}(\Delta t) = -\mathcal{I}m \lambda_{f_{CP}} \sin \Delta m_d \Delta t = \eta_{f_{CP}} \sin 2\Phi \sin \Delta m_d \Delta t$$

- Very simple expression for CP violating asymmetry
- Amplitude of asymmetry defined by phase difference between mixing parameter q/p and ratio of decay amplitudes
- Complex phase Φ_M depends on specific final state
  - Can probe different angles of Unitarity triangle through different B decays