Cabibbo-Kobayashi-Maskawa Matrix
and
CP Violation in Standard Model

Shahram Rahatlou
University of Rome

SAPIENZA
UNIVERSITÀ DI ROMA

Lecture 4

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

CPV in Mixing and Decay Interference

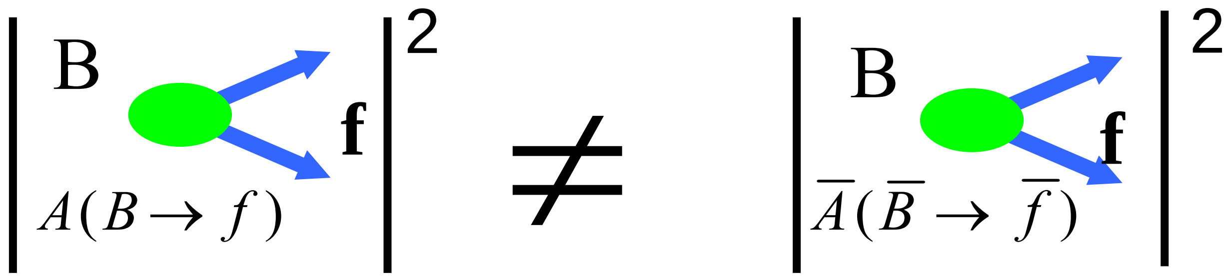
Lezioni di Fisica delle Particelle Elementari

Outline of Today's Lecture

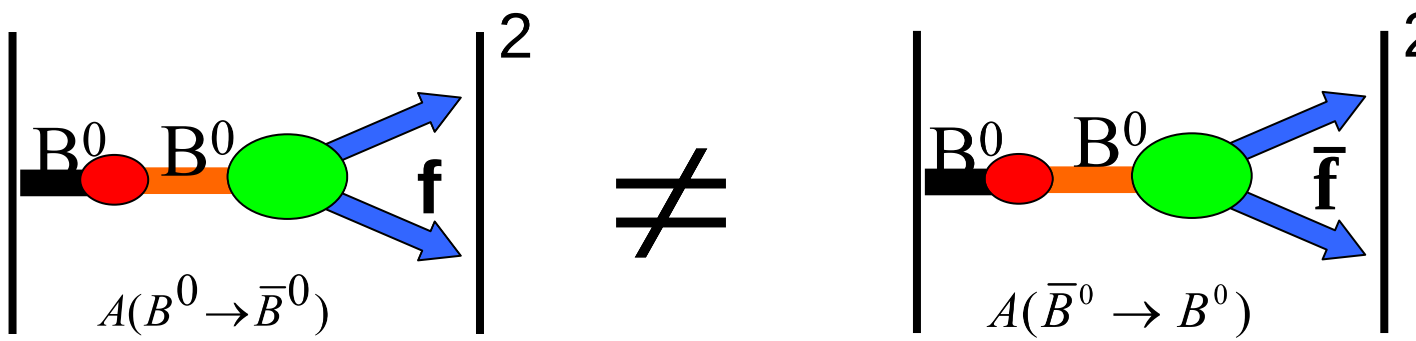
- Evolution of entangled 2-state quantum system
  - Example of B^0-B^0 oscillation
- Formalism of time-dependent CP violation
- Search for CP Violation in Mixing
- Observation of CP Violation in Interference between Decay and Mixing

CP Violating Processes

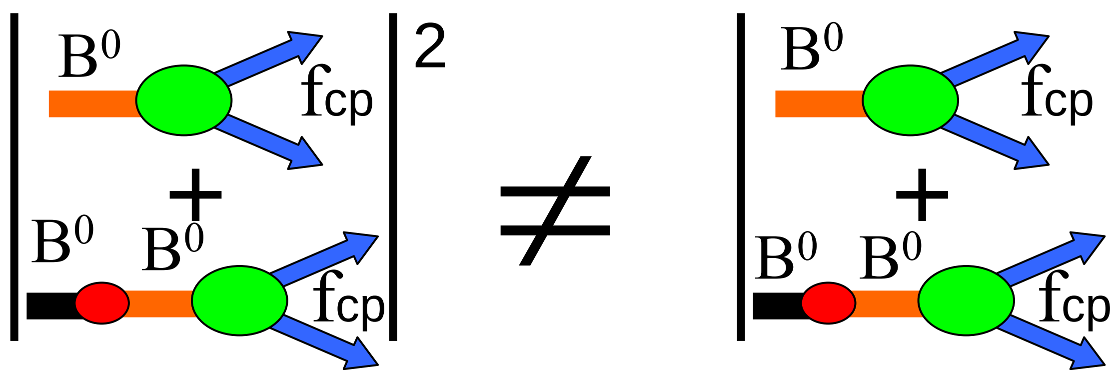
CP Violation
in Decay
a.k.a.
Direct CPV



CP Violation
in Mixing



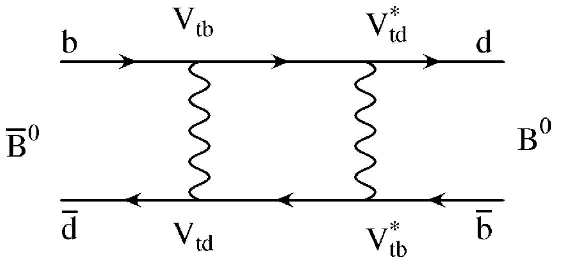
CP Violation
in interference
between Mixing
and Decay



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

B^0_d-$\bar{B}^0_d$ Oscillation and CP Violation

- Necessary ingredient for two types of CP Violation



- Oscillation is an example of superposition principle in a two-state quantum system
  - Oscillation occurs because mass and flavor eigenstates are different

- Flavor eigenstates $|B^0\rangle$ and $|\overline{B}^0\rangle$: physical states with definite quark structure and are produced as a consequence of the quark-level strong interactions.

- CP eigenstates $|B_{CP=1}\rangle$ and $|B_{CP=-1}\rangle$: eigenstates of the the CP operation

$$CP|B_{CP=1}\rangle = +|B_{CP=1}\rangle$$
$$CP|B_{CP=-1}\rangle = -|B_{CP=-1}\rangle$$

- Mass eigenstates $|B_L\rangle$ and $|B_H\rangle$: eigenstates of the full Hamiltonian and, hence, with definite mass M and decay width $\Gamma \equiv 1/\tau$. These states evolve in time in a definite fashion according to

$$|B_L, t\rangle = \mathrm{e}^{-\Gamma_L t}\mathrm{e}^{-iM_L t}|B_L, t=0\rangle \quad (2.28)$$
$$|B_H, t\rangle = \mathrm{e}^{-\Gamma_H t}\mathrm{e}^{-iM_H t}|B_H, t=0\rangle\ . \quad (2.29)$$

Phenomenology of B^0 Time Development

- An initially B^0 or $\overline{B}^0$ system evolves with time as a mixture of flavor eigenstates

$$|\psi(t) = a|B^0\rangle + b|\overline{B}^0\rangle$$

- Evolution regulated by time-dependent Schrödinger equation

Wigner-Weisskopf Approximation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \mathbf{H}\begin{pmatrix} a \\ b \end{pmatrix} \equiv (\mathbf{M} - \frac{i}{2}\mathbf{\Gamma})\begin{pmatrix} a \\ b \end{pmatrix}$$

- M and Γ computed to 2nd order of perturbation theory

$$M_{ij} = m_B\delta_{ij} + \langle i|H_W^{\Delta B=2}|j\rangle + P\sum_n \frac{1}{m_B - E_n}\langle i|H_W^{\Delta B=1}|n\rangle\langle n|H_W^{\Delta B=1}|j\rangle$$

$$\Gamma_{ij} = 2\pi\sum_n \delta(E_n - m_B)\langle i|H_W^{\Delta B=1}|n\rangle\langle n|H_W^{\Delta B=1}|j\rangle\ .$$

  - Virtual intermediate states contribute to M
  - Γ receives contributions from physical states to which B^0 or B^0 can decay

Mass Eigenstates of Effective Hamiltonian

- Solving the Schroedinger equation

$$H|\psi\rangle = \lambda|\psi\rangle$$

- Two complex eigenvalues

$$\lambda_\pm = M - \frac{i}{2}\Gamma - \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12})}$$

- Mass eigenstates

$$\begin{aligned} |B_L, t\rangle &= \mathrm{e}^{-\Gamma_L t}\mathrm{e}^{-iM_L t}|B_L, t=0\rangle \\ |B_H, t\rangle &= \mathrm{e}^{-\Gamma_H t}\mathrm{e}^{-iM_H t}|B_H, t=0\rangle \end{aligned}$$

$$\Delta m_d \equiv m_H - m_L \equiv \mathcal{R}e(\lambda_+ - \lambda_-)$$

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L \equiv 2\mathcal{I}m(\lambda_+ - \lambda_-)$$

$$\Gamma = 1/\tau_{B^0} = \frac{1}{2}(\Gamma_H + \Gamma_L)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L$$

$$M = \frac{1}{2}(M_H + M_L)$$

$$\Delta m_d = M_H - M_L$$

Interpretation of Effective Hamiltonian

- The effective Hamiltonian for the two-state system is not Hermitian since mesons decay

Quark masses, strong, and EM interactions

$B^0 \to f \to \overline{B}^0$ transitions

f = off-shell $\quad$ f = on-shell

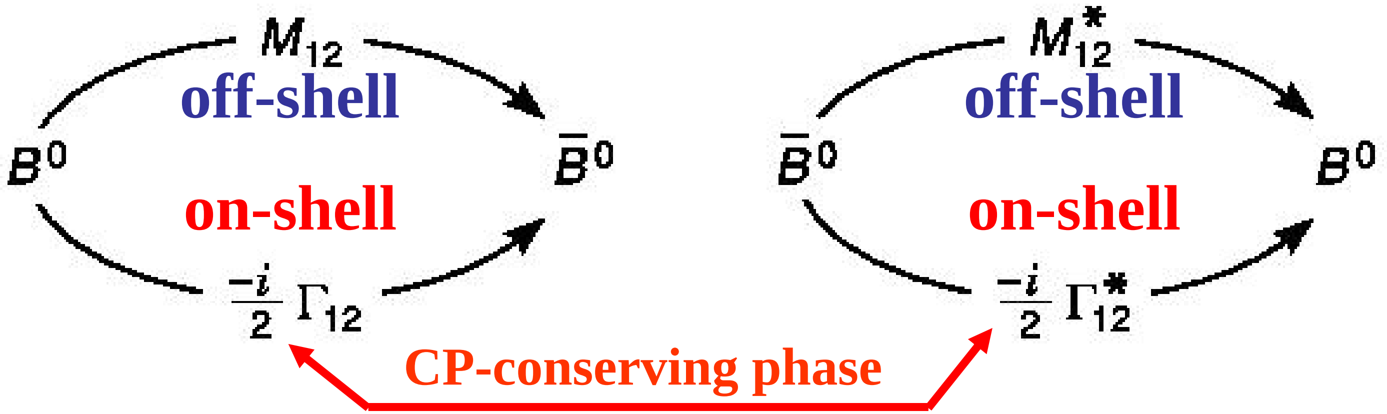
$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M^*_{12} & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma \end{pmatrix}$$

Decays

$$M_{12} = (V_{tb}V_{td}^*)^2 \frac{G_F^2}{8\pi^2} \frac{M_W^2}{m_B} S\left(\frac{m_t^2}{M_W^2}\right) \eta_B \, b_B(\mu) \, \langle B^0 | Q(\mu) | \overline{B}^0 \rangle$$

what we are after $\quad$ calculable perturbatively $\quad$ nonperturbative

Driving $B^0 \leftrightarrow B^0$ Oscillation



In B^0 meson system, final states that both B^0 and $\bar{B}^0$ can decay into have very small rates

Decays like $b \rightarrow c\,\bar{c}d$ or $b \rightarrow u\,\bar{u}d$ are suppressed due to associated CKM elements in W decay

$$\left|\frac{\Gamma_{12}}{M_{12}}\right| = O\left(\frac{m_b^2}{m_t^2}\right) \ll 1$$

B Oscillation is driven by M_{12}, which is dominated by Top quark in the loop

Differences between K and B Mesons

- Formalism for time evolution can be applied to both K and B mesons

- B mesons
  - Very few common states accessible by both B^0 and B^0
  - Comparable lifetime and oscillation frequency

$$\Delta\Gamma/\Gamma \lesssim \mathcal{O}(10^{-2}) \qquad x_d \equiv \Delta m_d/\Gamma = 0.73 \pm 0.05$$

  - Mass eigenstates have very similar lifetimes but different masses

$$\Delta\Gamma \ll \Delta m_d$$

- Kaons
  - Mass eigenstates with similar masses
  - Very different lifetimes

$$\Delta\Gamma_K = \Gamma_K - \Gamma_L \cong \Gamma_K + \Gamma_L \cong \Gamma_K$$

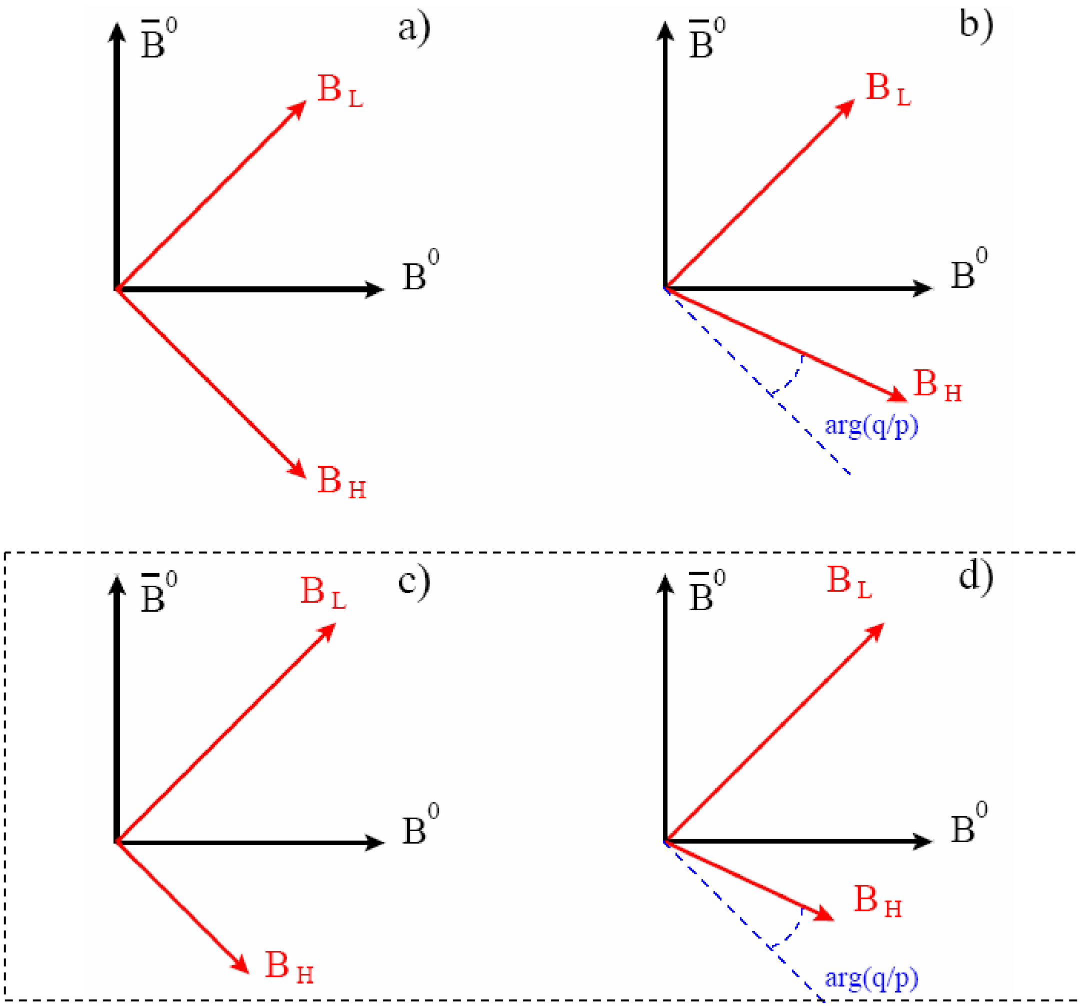
Relation Between Mass and Flavor states

$$|B_L\rangle \ = \ p|B^0\rangle + q|\bar{B}^0\rangle \qquad |B^0\rangle \ = \ \frac{1}{2p}(|B_L\rangle + |B_H\rangle)$$

$$|B_H\rangle \ = \ p|B^0\rangle - q|\bar{B}^0\rangle \qquad |\bar{B}^0\rangle \ = \ \frac{1}{2q}(|B_L\rangle - |B_H\rangle)$$

$$\delta \equiv \langle B_L|B_H\rangle \equiv |p|^2 - |q|^2$$

$\delta=0$
arg(q/p)=0
No CP Violation



$\delta=0$
arg(q/p)≠0
CP Violation

$\delta\neq0$
regardless arg(q/p)
CP Violation

CPV
in
Mixing

Time Development of Physical States

- Evolution of a pure B^0 or B^0 state at t=0

$$\left|B^0_{phys}(t)\right\rangle = \frac{1}{2p}\left(e^{-\Gamma_L t}e^{-iM_L t}\left(p\left|B^0\right\rangle + q\left|\overline{B}^0\right\rangle\right) + e^{-\Gamma_H t}e^{-iM_H t}\left(p\left|B^0\right\rangle - q\left|\overline{B}^0\right\rangle\right)\right)$$

$$\left|\overline{B}^0_{phys}(t)\right\rangle = \frac{1}{2q}\left(e^{-\Gamma_L t}e^{-iM_L t}\left(p\left|B^0\right\rangle + q\left|\overline{B}^0\right\rangle\right) - e^{-\Gamma_H t}e^{-iM_H t}\left(p\left|B^0\right\rangle - q\left|\overline{B}^0\right\rangle\right)\right)$$

- After some math

$$\left|B^0_{phys}(t)\right\rangle = g_+(t)\left|B^0\right\rangle + \left(q/p\right)g_-(t)\left|\overline{B}^0\right\rangle$$

$$\left|\overline{B}^0_{phys}(t)\right\rangle = \left(p/q\right)g_-(t)\left|B^0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle$$

$$\Gamma = 1/\tau_{B^0} = \frac{1}{2}(\Gamma_H + \Gamma_L)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L$$

$$M = \frac{1}{2}(M_H + M_L)$$

$$\Delta m_d = M_H - M_L$$

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos\left(\Delta m_d t/2\right)$$

$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i\sin\left(\Delta m_d t/2\right)$$

Prob of $B^0 \rightarrow \overline{B}^0$ oscillates as function of time !

Time evolution of B^0 and $\overline{B}^0$ mesons

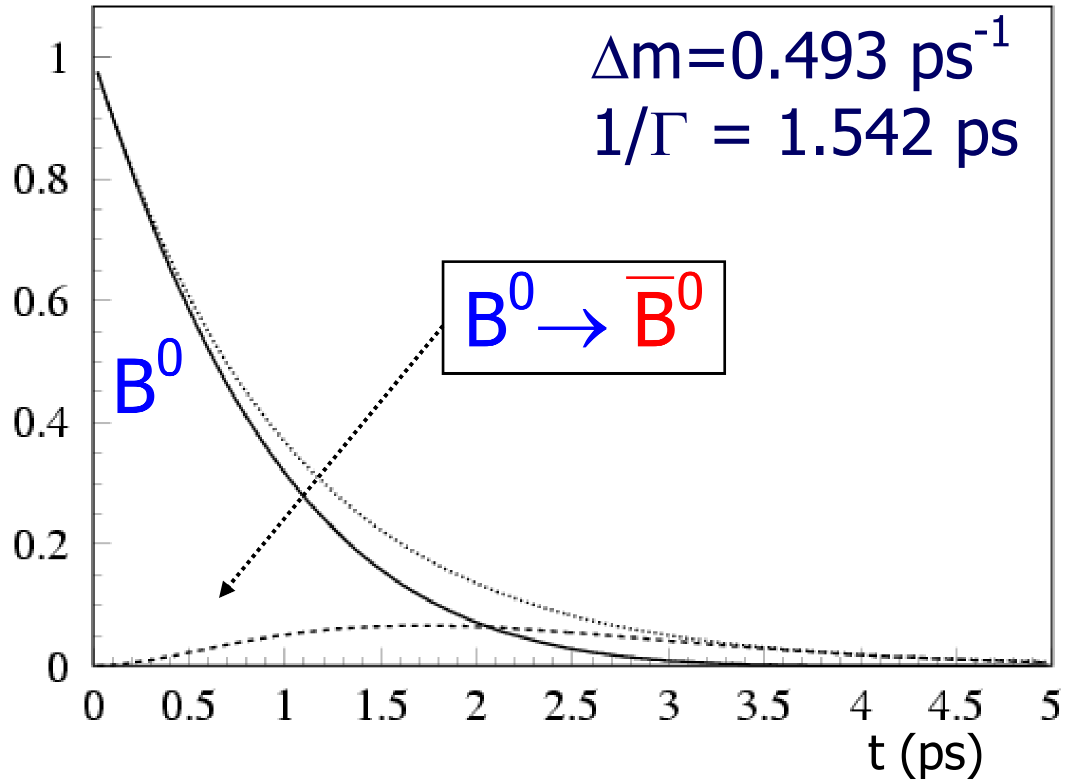
$$|B^0(t)\rangle = e^{-iMt}e^{-\Gamma t}\left(\cos\frac{\Delta m\, t}{2}\,|B^0\rangle + i\,\sin\frac{\Delta m\, t}{2}\cdot\frac{q}{p}\,|\overline{B^0}\rangle\right)$$

$$|\overline{B^0}(t)\rangle = e^{-iMt}e^{-\Gamma t}\left(i\,\sin\frac{\Delta m\, t}{2}\cdot\frac{p}{q}\,|B^0\rangle + \cos\frac{\Delta m\, t}{2}\,|\overline{B^0}\rangle\right)$$

$$\frac{q}{p} = \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} = e^{-i2\beta}$$

$$P(B^0 \to \overline{B}^0) \propto e^{-\Gamma t}\left(1-\cos(\Delta m\, t)\right)$$

Slow oscillation compared to the lifetime



Quantum Entanglement in $\Upsilon(4S)\rightarrow B^0\bar{B}^0$ Decays

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

Spin = 1 0 0

- Strong interaction: CP is and flavor beauty number are conserved
  - Must have one **b** and one **anti-b** quarks in final state

$$|B^0_{\rm phys}\overline{B}^0_{\rm phys}\rangle = \frac{a}{\sqrt{2}}\,|B_L B_H\rangle + \frac{b}{\sqrt{2}}\,|B_H B_L\rangle$$

- Time evolution given by mass eigenstates

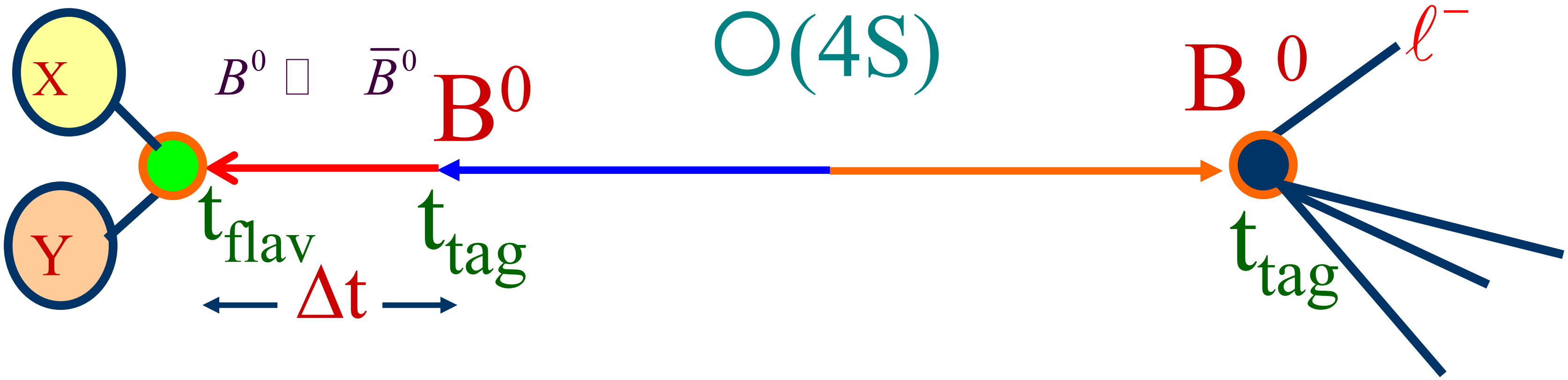
$$|B^0_{\rm phys}\overline{B}^0_{\rm phys};t_1,t_2\rangle = a\,{\rm e}^{i\lambda_+ t_1}{\rm e}^{i\lambda_- t_2}|B_L B_H\rangle + b\,{\rm e}^{i\lambda_- t_1}{\rm e}^{i\lambda_+ t_2}|B_H B_L\rangle$$

- Bose-Einstein Statistics requires wave function $|\Psi>$to be symmetric at all times

$$|\Psi\rangle \;=\; |\Psi_{\rm flavor}\rangle|\Psi_{\rm space}\rangle$$

- L=-1 implies asymmetric spatial wave function
- We need a=-b which means a B^0 and a $\bar{B}^0$ meson at all times until one of them decays!
  - Example of Einstein-Podolsky-Rosen Paradox

Quantum Correlation at ϒ(4S)



- Decay of first B (B^0) at time t_{tag} ensures the other B is B^0
  - End of Quantum entanglement ! Defines a ref. time (clock)

- At $t > t_{tag}$, B^0 has some probability to oscillate into B^0 before it decays at time t_{flav} into a flavor specific state

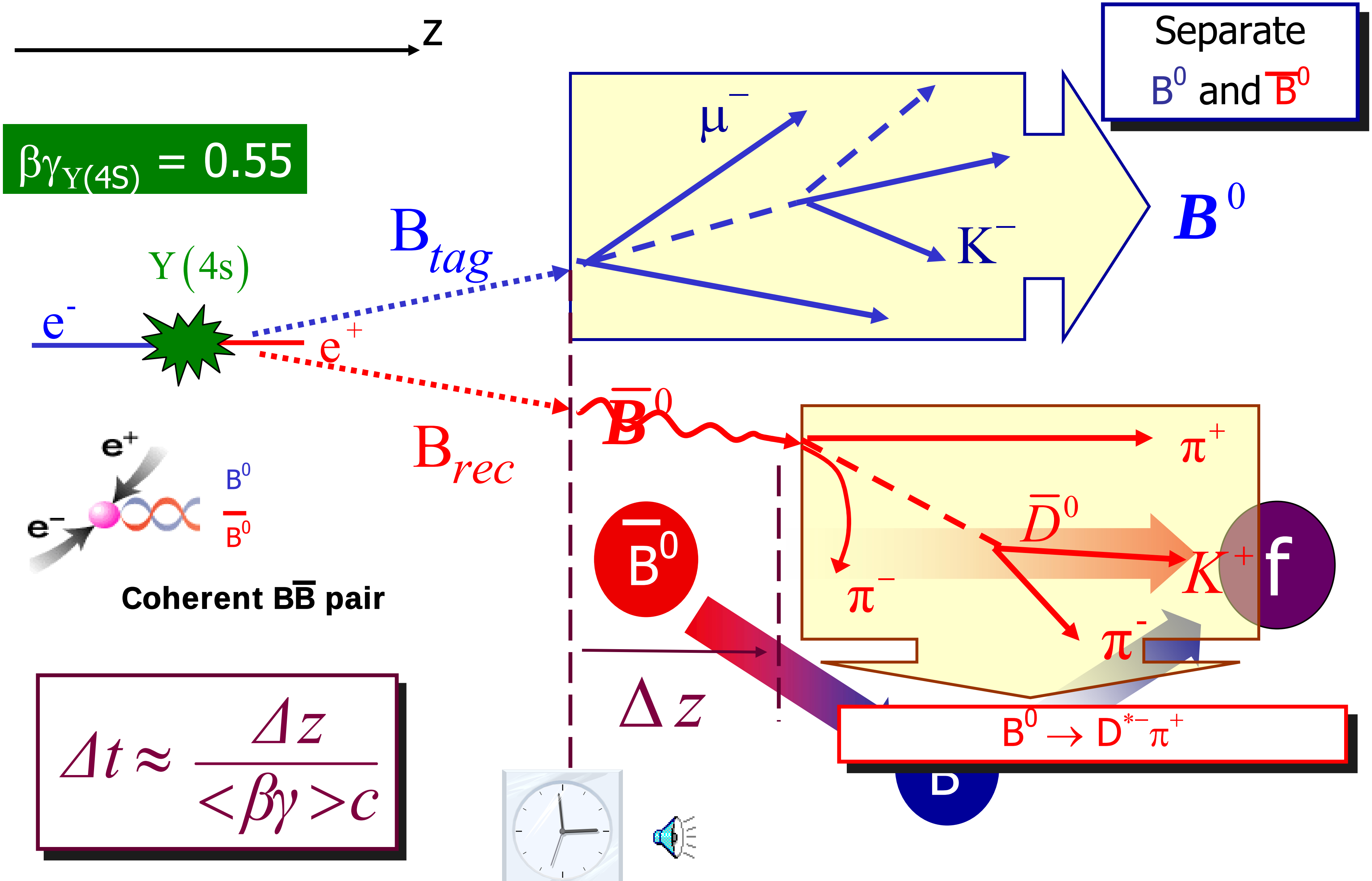
- Two possibilities in the ϒ(4S) event depending on whether the 2nd B oscillated or not:

$$\text{no oscillation/mixing} \Rightarrow B^0\ \bar{B}^0 \text{ in final state}$$

$$\text{oscillation/mixing} \Rightarrow \bar{B}^0\ \bar{B}^0 \text{ in final state}$$

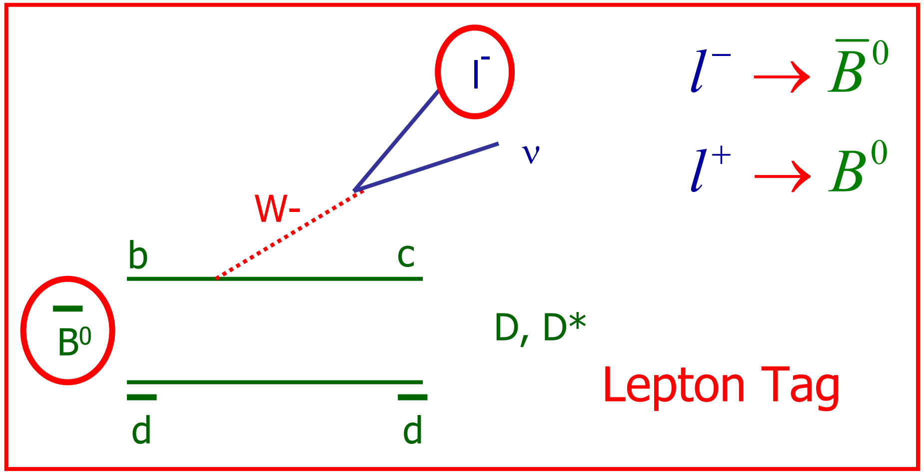
Time Evolution of $\Upsilon(4S) \rightarrow B^0B^0$

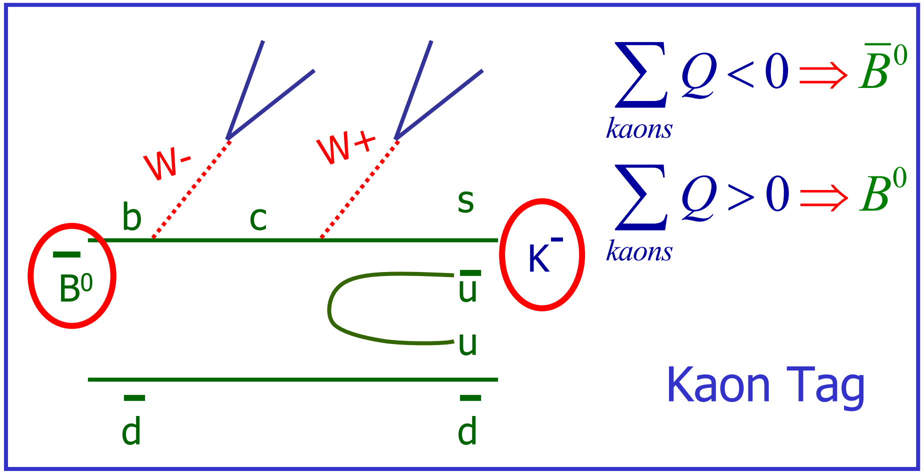
$\beta\gamma_{\Upsilon(4S)} = 0.55$

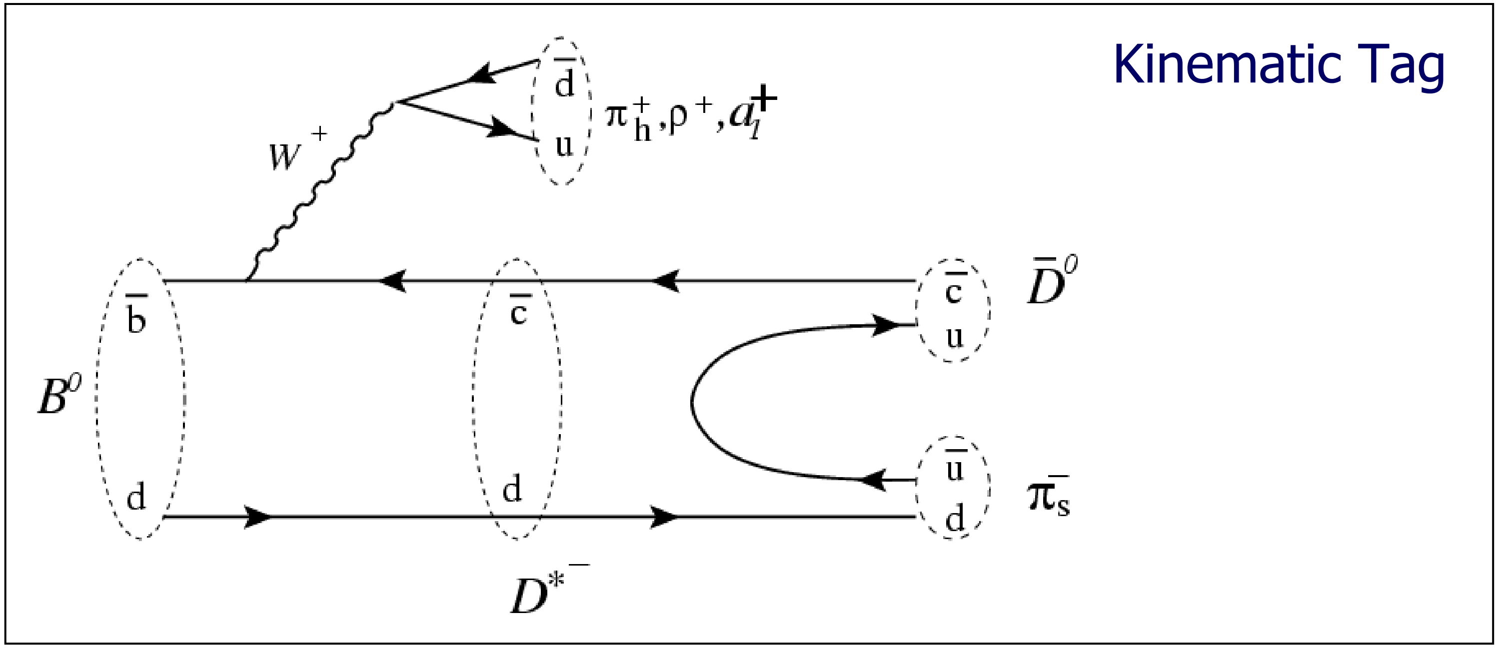


$$\Delta t \approx \frac{\Delta z}{<\beta\gamma>c}$$

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

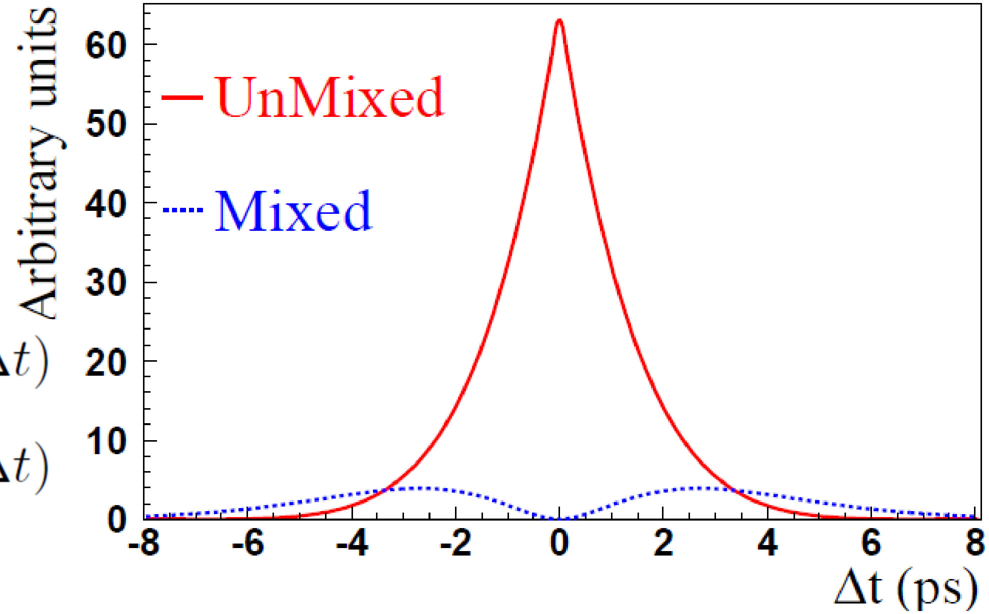




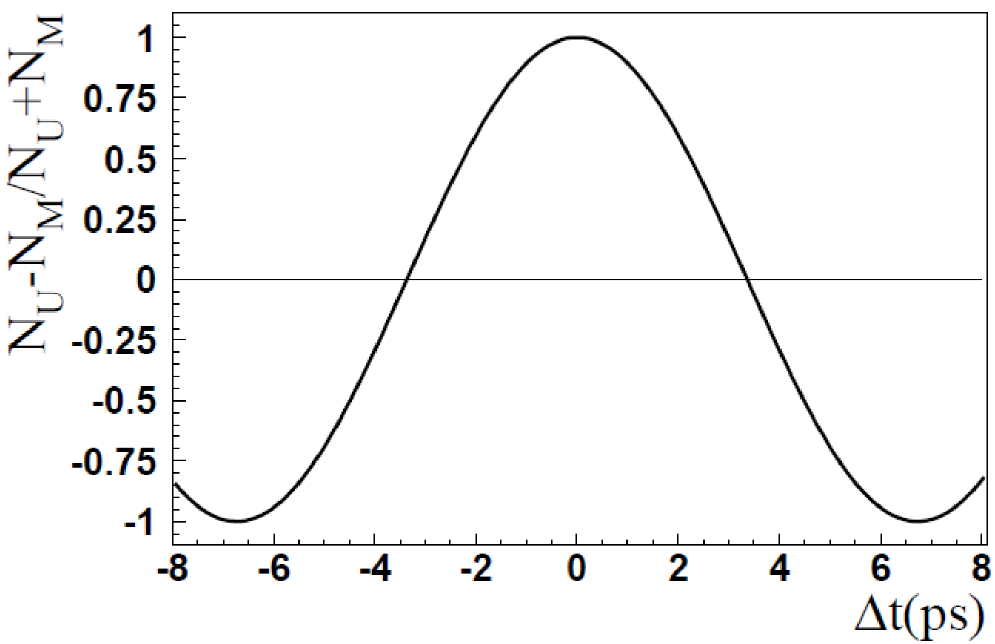


Time Dependent B Oscillation (Or Mixing) at $\Upsilon(4S)$

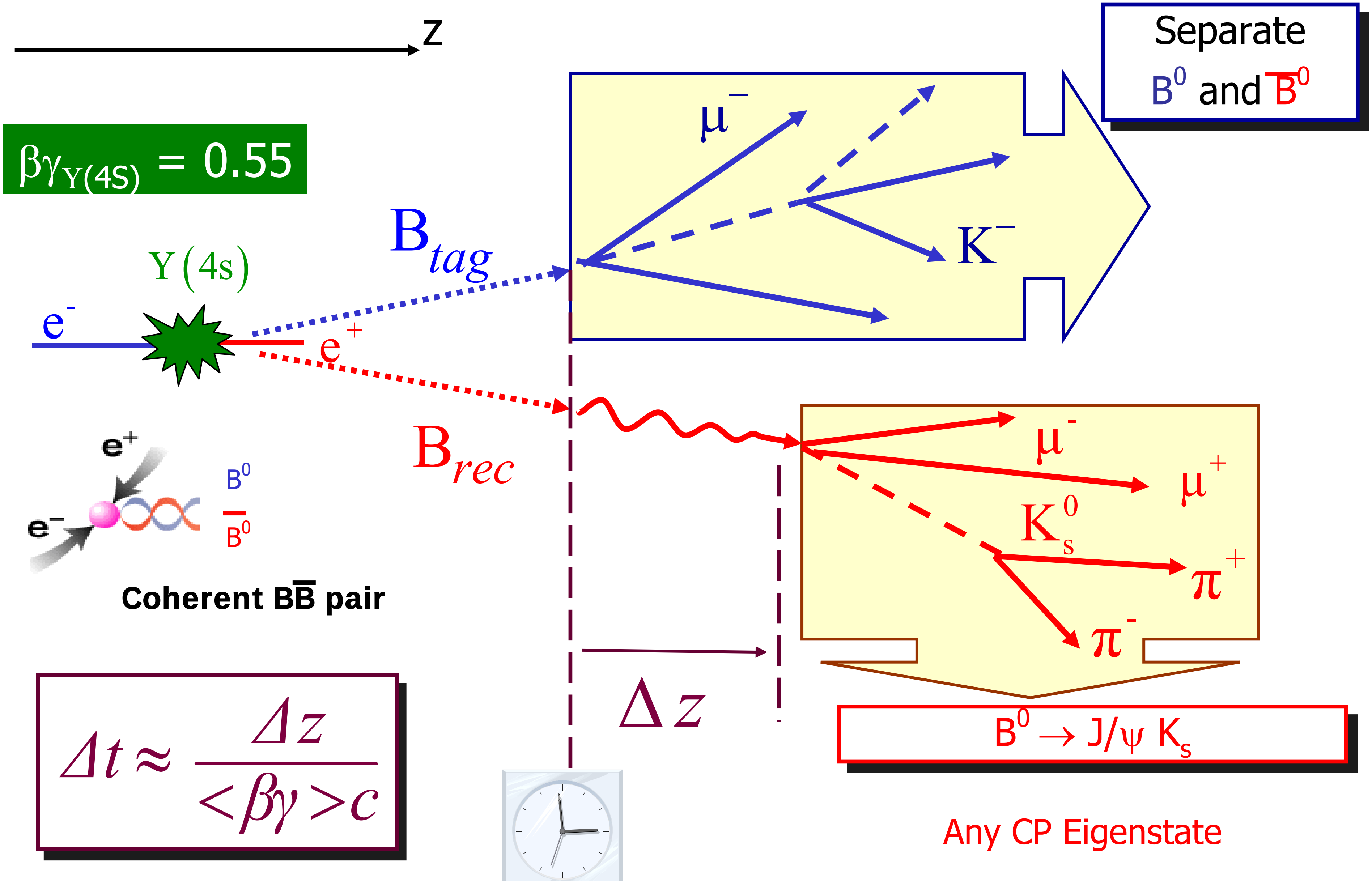
$$f_{\rm unmix}(\Delta t) \propto e^{-\Gamma|\Delta t|}\,(1+\cos\Delta m_d \Delta t)$$
$$f_{\rm mix}(\Delta t) \propto e^{-\Gamma|\Delta t|}\,(1-\cos\Delta m_d \Delta t)$$



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



CP Violation in Interference between Mixing and Decay



$$\Delta t \approx \frac{\Delta z}{<\beta\gamma>c}$$

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

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

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

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

- 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 $|\lambda| = \left|\frac{q}{p}\right|\left|\frac{\overline{A}}{A}\right| \neq 1$

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

$$\Phi_M = \beta$$

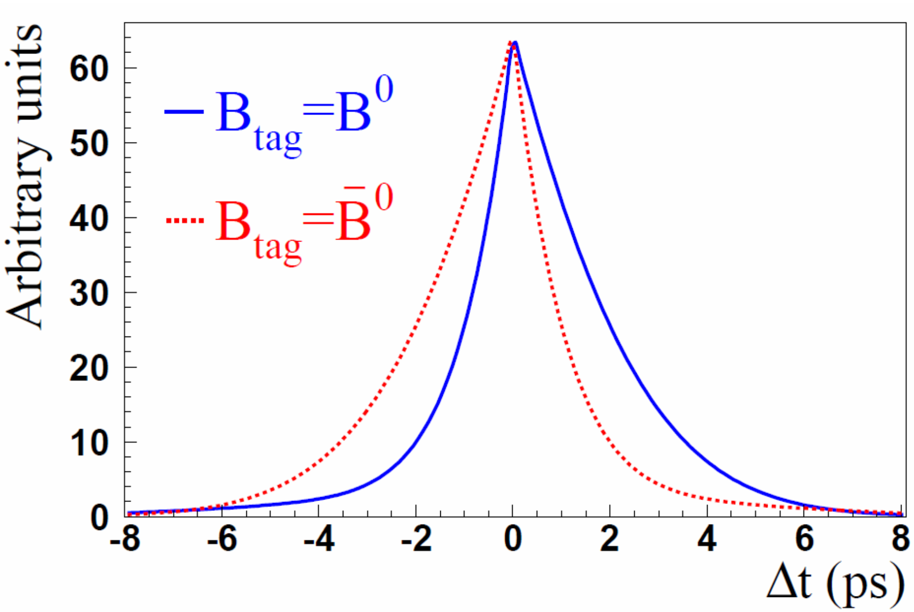
$$A_f = Ae^{i(\Phi_W+\delta)}$$
$$\bar{A}_f = \eta_{f_{CP}} Ae^{i(-\Phi_W+\delta)}$$

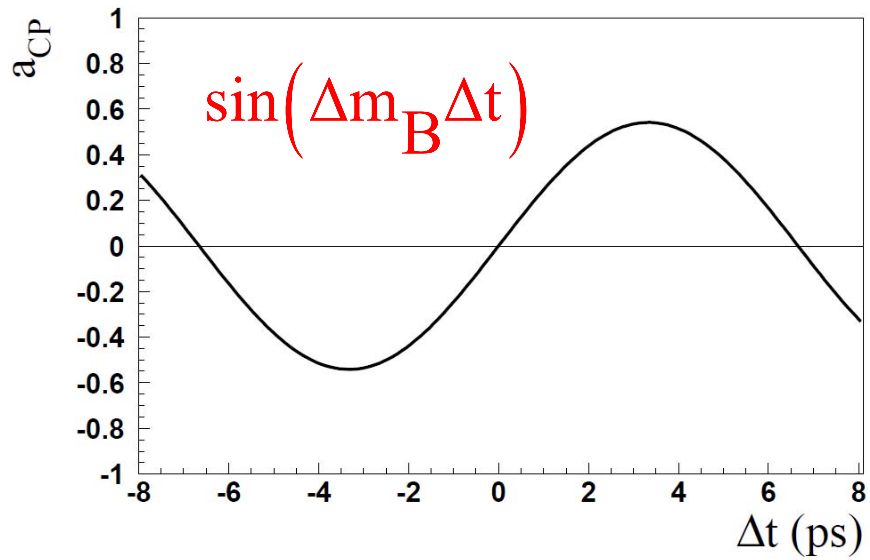
$$\lambda_{f_{CP}} = \eta_{f_{CP}} e^{-2i(\Phi_W - \Phi_M)}$$

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

- 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

Why do We Need Time Dependence?





$$\int_{-\infty} a_{f_{CP}}\, d\Delta t = 0$$

At $\Upsilon(4S)$: integrated asymmetry is zero
→ must do a time-dependent analysis !

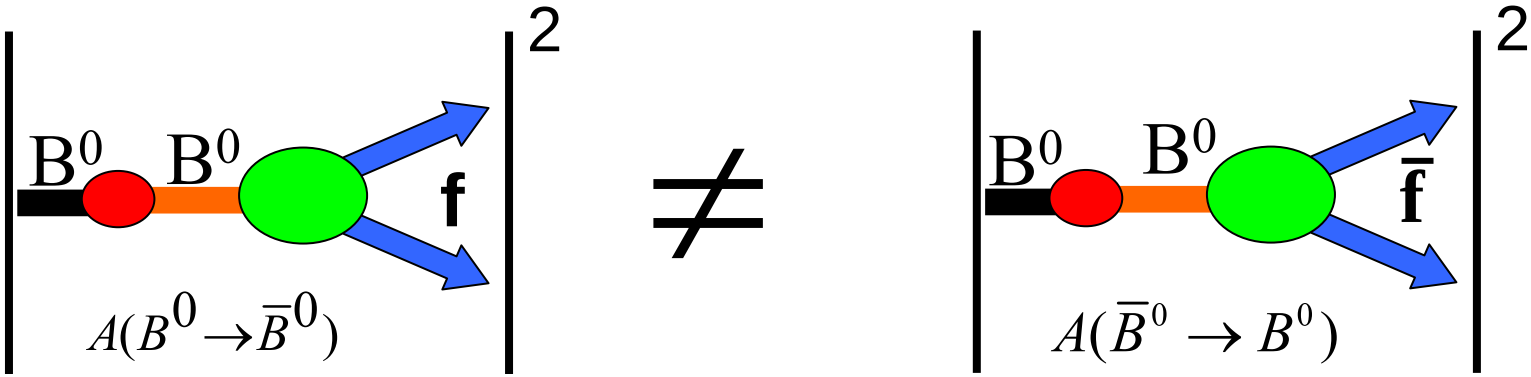
This is impossible to do in a conventional symmetric energy collider producing $\Upsilon(4S) \rightarrow BB$!!

Measurements of CP Violation

- CP Violation in Decay
- CP Violation in Mixing
- CP Violation in interference between decay and mixing

CP Violation in Mixing

CPV in B^0 Mixing



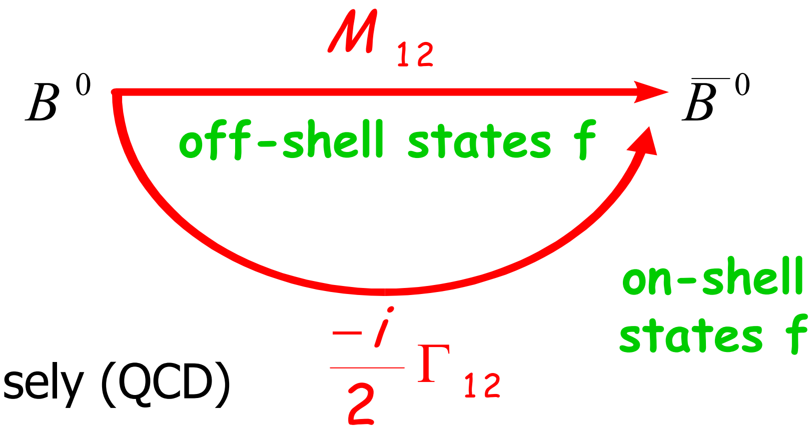
Occurs when Mass eigenstates ≠ CP eigenstates

($|q/p| \neq 1$ and $\langle B_H | B_L \rangle \neq 0$)

The Box diagrams provide the required 2 phases

Strong phases depend on quark masses and non-perturbative physics.

Asymmetries are small and hard to calculate precisely (QCD)



$$a_{sl} = \frac{\Gamma\left(\overline{B}^0_{phys}(t) \to \ell^+ \nu X\right) - \Gamma\left(B^0_{phys}(t) \to \ell^- \nu X\right)}{\Gamma\left(\overline{B}^0_{phys}(t) \to \ell^+ \nu X\right) + \Gamma\left(B^0_{phys}(t) \to \ell^- \nu X\right)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx O(10^{-4})$$

CPV in B^0 Mixing

Time-dependent *CP* Asymmetry:

$$A_T(t) = \frac{\Gamma(\overline{B}^0_{phys}(t) \to \ell^+ \nu X) - \Gamma(B^0_{phys}(t) \to \ell^- \overline{\nu} X)}{\Gamma(\overline{B}^0_{phys}(t) \to \ell^+ \nu X) + \Gamma(B^0_{phys}(t) \to \ell^- \overline{\nu} X)}$$

Search for asymmetry in same-sign dilepton sample

same – sign $\ell^\pm \ell^\pm$ events occur in mixed events where

one $\overline{B}^0 \to B^0 \to X\ell^+\upsilon$; other $B^0 \to Y\ell^+\upsilon \Rightarrow \ell^+\ell^+$

one $B^0 \to \overline{B}^0 \to X\ell^-\upsilon$; other $\overline{B}^0 \to Y\ell^-\upsilon \Rightarrow \ell^-\ell^-$

$$A_T^{obs}(\Delta t) = \frac{N(\ell^+\ell^+, \Delta t) - N(\ell^-\ell^-, \Delta t)}{N(\ell^+\ell^+, \Delta t) + N(\ell^-\ell^-, \Delta t)} = A_T \times \frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}$$

$S(\Delta t) = signal$

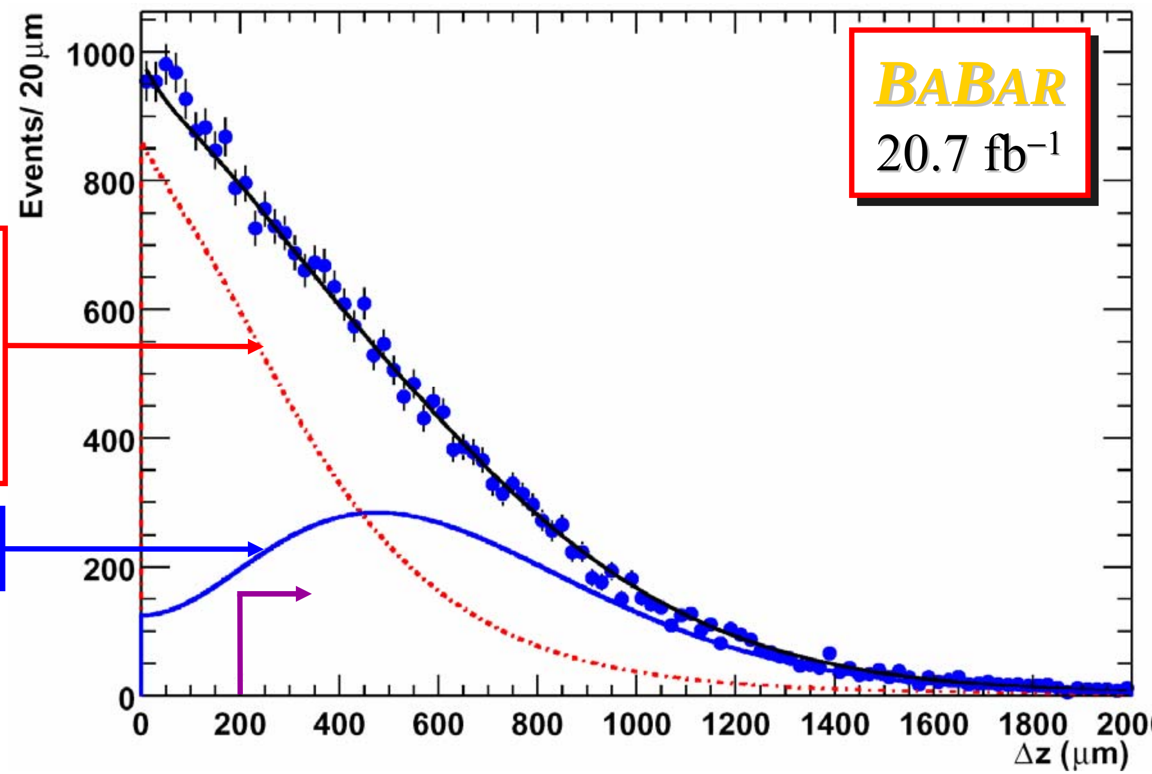
$B(\Delta t) = background$ from B decay and continuum

CPV in B^0 Mixing

Time dependent measurement, time measured from ΔZ

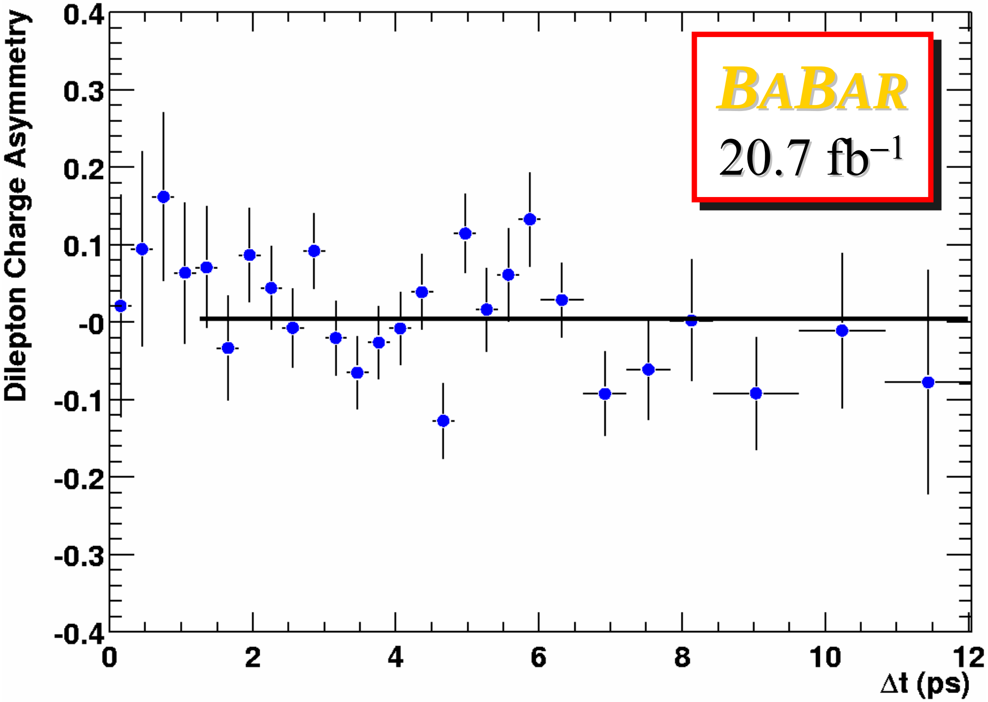
Sample backgrounds $B(\Delta t)$:
4.3% continuum
24% direct+cascade
12% direct+fake

$B^0 B^0, \bar{B}^0 \bar{B}^0$ signal $S(\Delta t)$



Measurement region > 200μm

CPV in B^0 Mixing



Find: $+0.005 \pm 0.012_{(stat)} \pm 0.014_{(syst)}$

Conclude: $\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) =$
$+0.0012 \pm 0.0029_{(stat)} \pm 0.0036_{(syst)}$
$|q/p| = 0.998 \pm 0.006_{(stat)} \pm 0.007_{(syst)}$

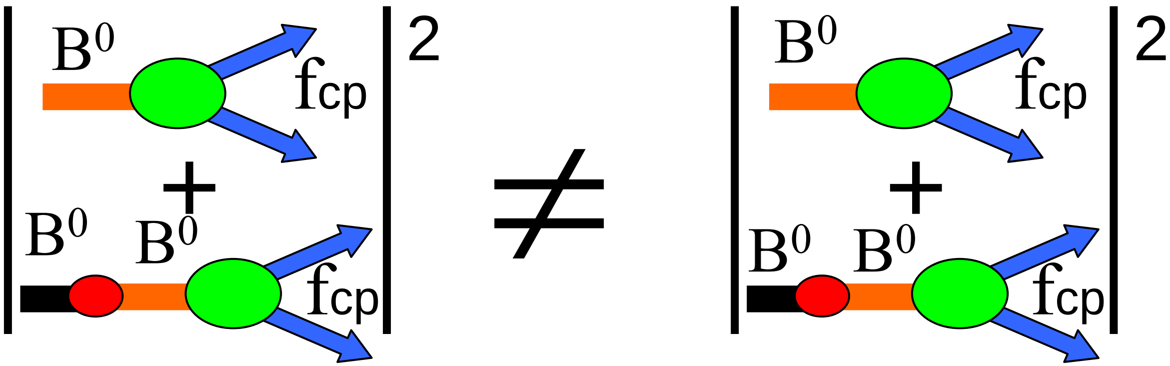
So far, no experimental evidence of large *CP* violation in B^0 mixing

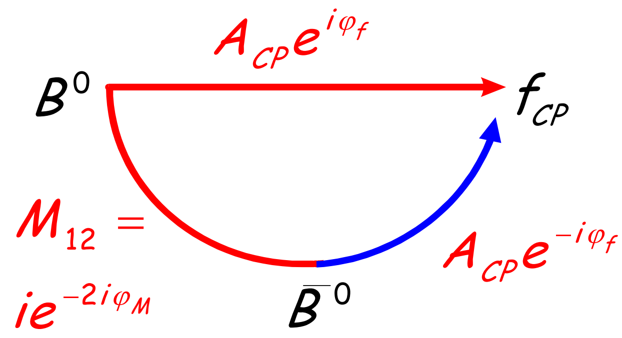
$\Rightarrow$ To a good approximation:

$$|q/p| = 1 \text{ and } q/p = e^{-2i\varphi_M} = -|M_{12}|/M_{12}$$

CP Violation in interference between decay and mixing

CPV In Interference Between Mixing and Decay





Neutral B Decays into CP final state f_{CP} accesible by both B^0 & $\bar{B}^0$decays

This is CPV when $\left|\frac{q}{p}\right| = 1$ and $\left|\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right| = 1$ and the CP parameter of interest is $\lambda_{f_{CP}} \equiv \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$

CPV Asymmetry is defined as :

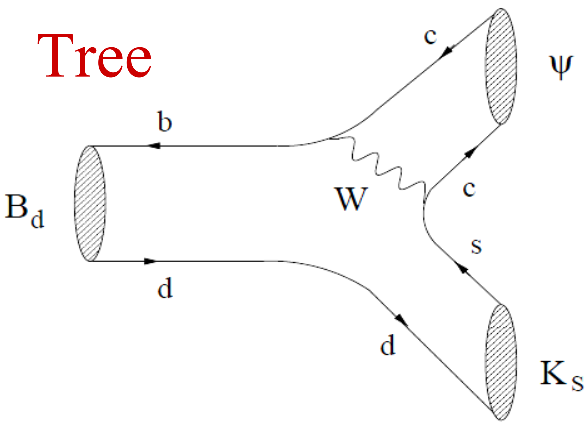
$$a_{f_{CP}} = \frac{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)} = \frac{2Im\lambda_{f_{CP}}}{1+\left|\lambda_{f_{CP}}\right|^2}\sin\left(\Delta m_B t\right) - \frac{\left(1-\left|\lambda_{f_{CP}}\right|^2\right)}{1+\left|\lambda_{f_{CP}}\right|^2}\cos\left(\Delta m_B t\right)$$

When B decay is dominated by a single diagram, $\left|\lambda_{f_{CP}}\right| = 1 \Rightarrow a_{f_{CP}} = Im\lambda_{f_{CP}} \sin\left(\Delta m_B t\right)$

CP asymm. can be very large and can be cleanly related to CKM angles

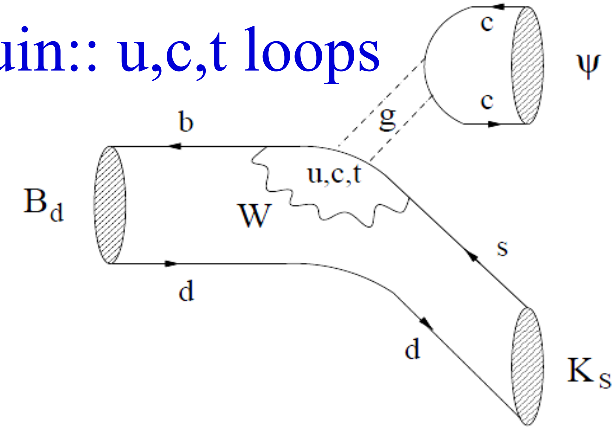
Golden Decay Mode $B^0 \rightarrow J/\psi K^0$

Tree



$$\bar{A}_T = V_{cb} V_{cs}^* T_{c\bar{c}s}$$

Penguin:: u,c,t loops



$$\bar{A}_P = V_{tb} V_{ts}^* P_t + V_{cb} V_{cs}^* P_c + V_{ub} V_{us}^* P_u$$

Use Unitarity relation $V_{tb} V_{ts}^* + V_{cb} V_{cs}^* + V_{ub} V_{us}^*$ to rearrange terms

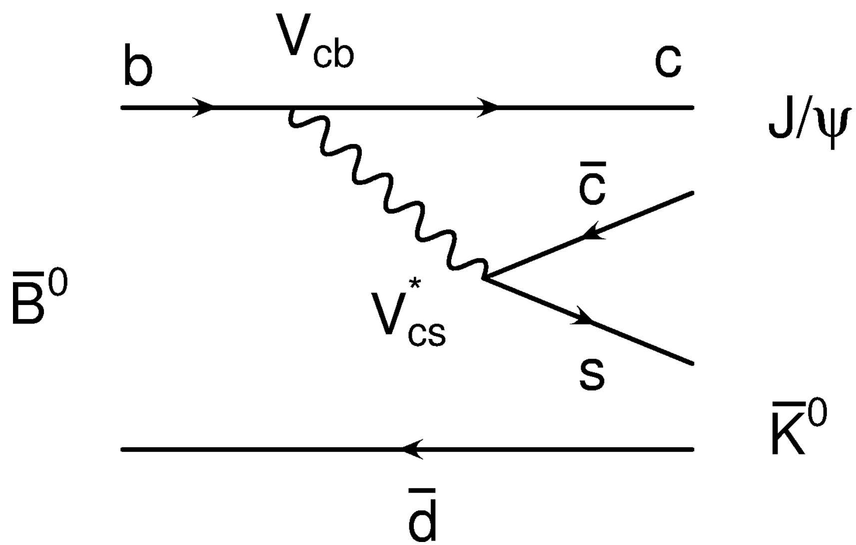
$$\bar{A} = \bar{A}_T + \bar{A}_P = V_{cb} V_{cs}^* (T_{c\bar{c}s} + P_c - P_t) + V_{ub} V_{us}^* (P_u - P_t)$$

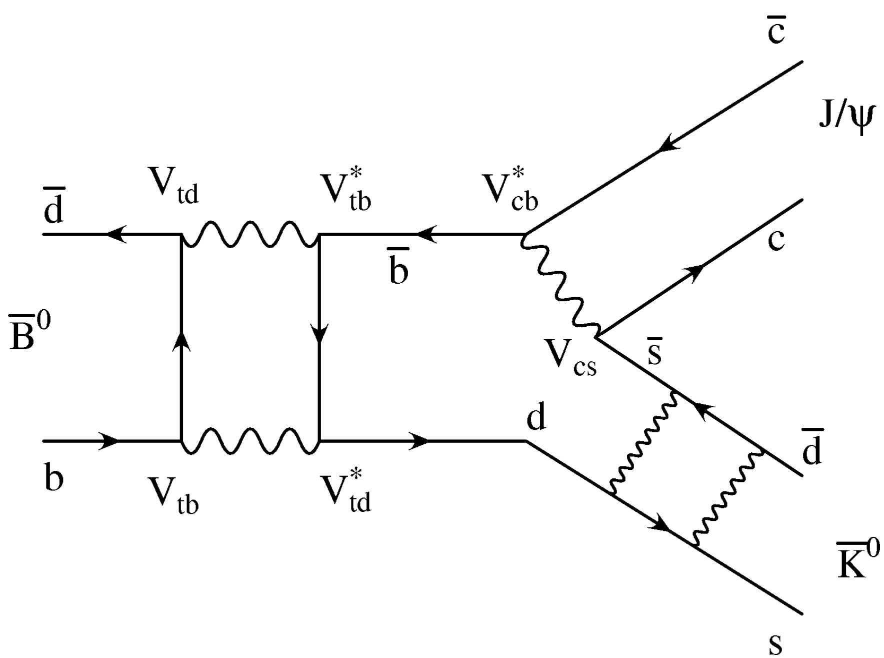
$$= (V_{cb} V_{cs}^*)\, T + \cancel{(V_{ub} V_{us}^*)}\, P$$

Since $\left| \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \right| \Box \frac{1}{50} \Rightarrow (V_{cb} V_{cs}^*)$ T is the dominant amplitude

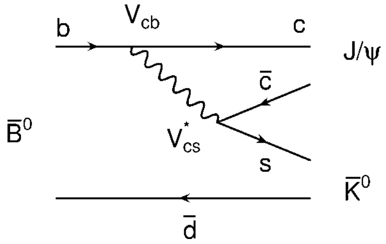
expect $\left| \frac{\bar{A}}{A} \right|$-1 $= 10^{-2}$ Hence "Platinum" mode !

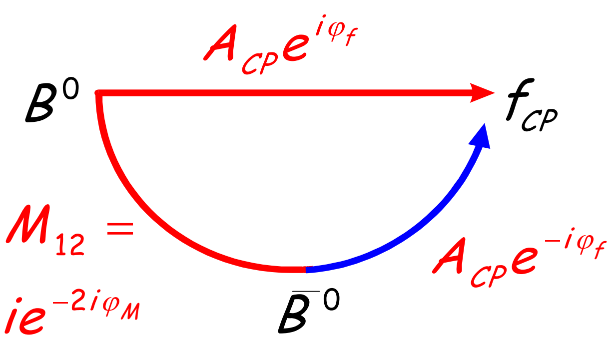
Golden Decay Mode $B^0 \rightarrow J/\psi K^0$

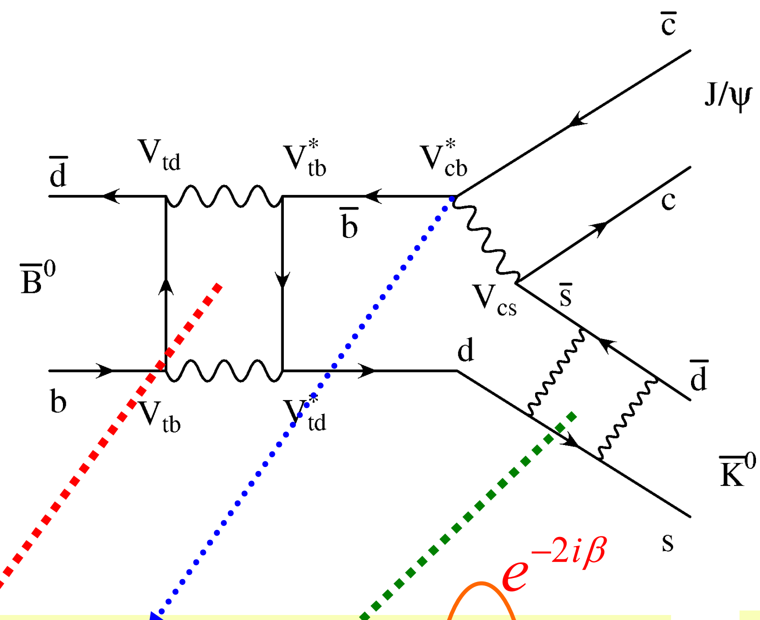




CPV In Interference Between Mixing and Decay: $B^0 \rightarrow J/\psi K^0$







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

$$\Rightarrow \mathrm{Im}(\lambda_{\psi K_S}) = \sin(2\beta)$$

$$\Rightarrow \left|\lambda_{\psi K_S}\right| = 1$$

$$\lambda_{\psi K_L} = -\lambda_{\psi K_S}$$

$$\Gamma\left(B^0 \rightarrow J/\psi K_{S,L}\right) \propto e^{-t/\tau}\left[1 - \eta_{CP}\sin 2\beta \sin(\Delta m t)\right]$$

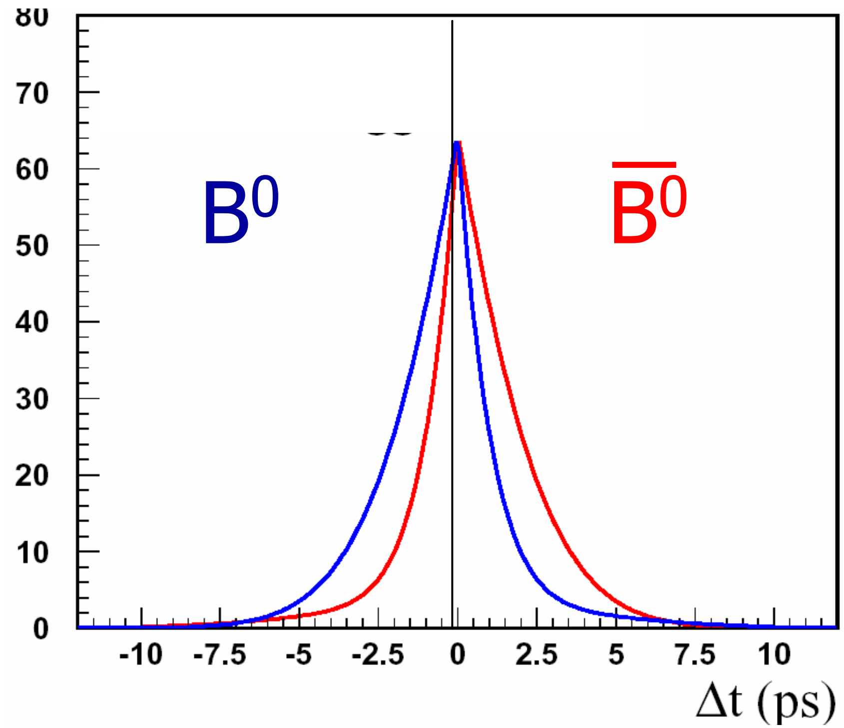
$$\Gamma\left(\bar{B}^0 \rightarrow J/\psi K_{S,L}\right) \propto e^{-t/\tau}\left[1 + \eta_{CP}\sin 2\beta \sin(\Delta m t)\right]$$

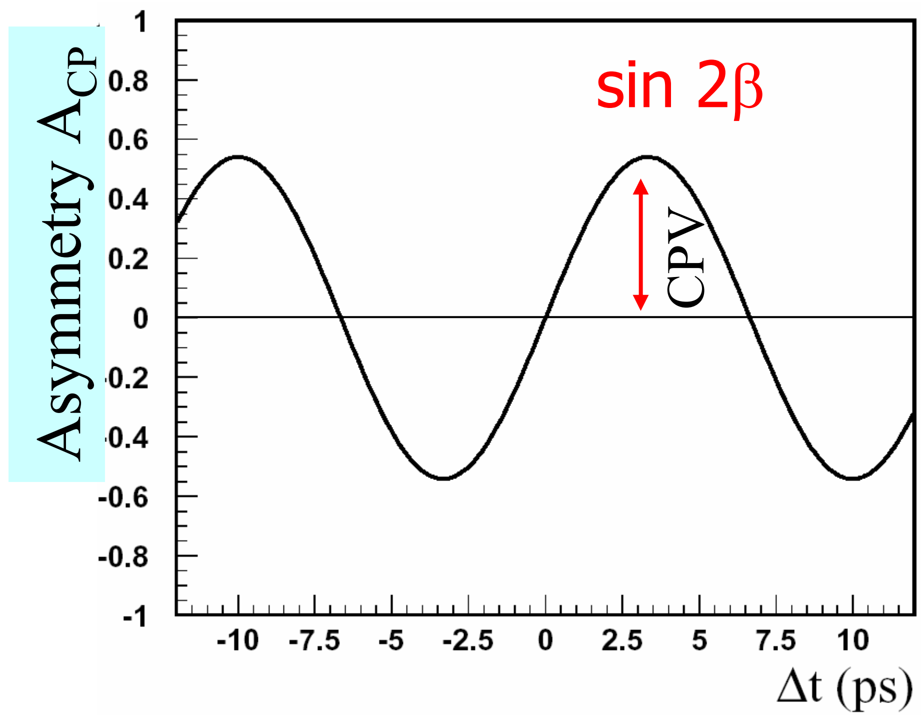
η_{CP} = -1 (+1) for $J/\psi\ K^0_{S(L)}$

Same is true for a variety of B →(cc) s final states

Time-Dependent CP Asymmetry with a Perfect Detector

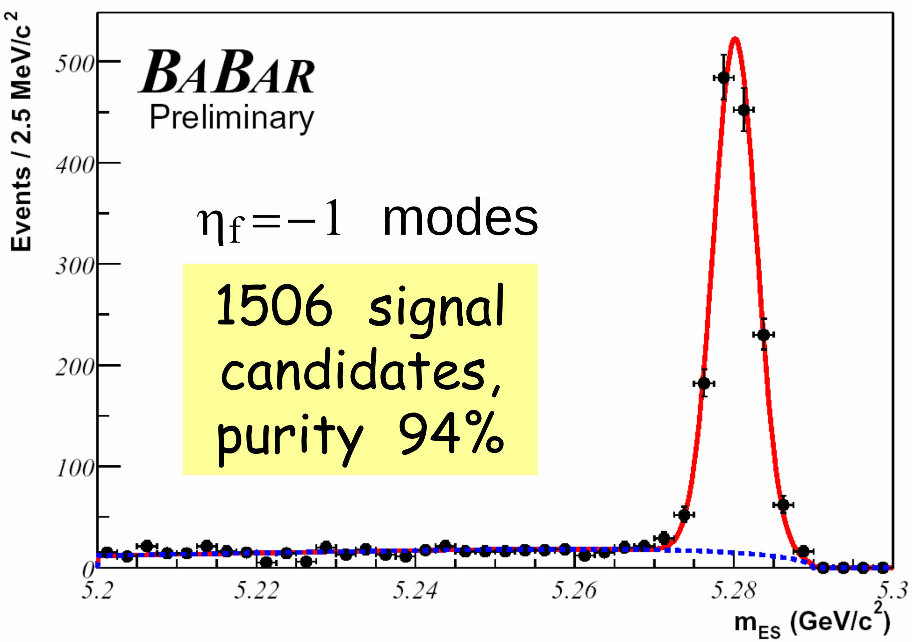
- Perfect measurement of time interval t=Δt
- Perfect tagging of B^0 and B^0 meson flavors
- For a B decay mode such as $B^0 \rightarrow \psi K_s$ with $|\lambda_f|=1$





$$A_{CP}(\Delta t) = \sin 2\beta \, \sin(\Delta m \Delta t)$$

Charmonium+K^0 CP Sample for BABAR ('02)



$\eta_f = -1$ modes

$B^0_{CP} \to J/\psi K^0_S\{\to \pi^+\pi^-\}$

$B^0_{CP} \to J/\psi K^0_S\{\to \pi^0\pi^0\}$

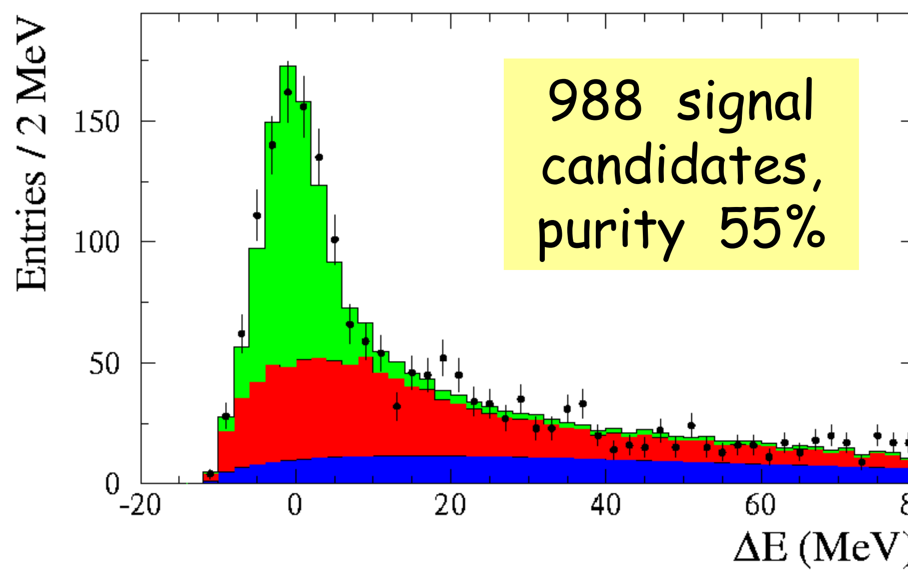
$B^0_{CP} \to \psi(2S)\{\to \ell^+\ell^-$ or $J/\psi\pi^+\pi^-\}K^0_S$

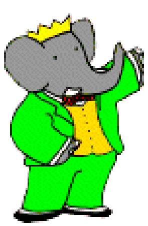
$B^0_{CP} \to \chi_{c1}\{\to J/\psi\gamma\}K^0_S$

$B^0_{CP} \to \eta_c\{\to KK\pi\}K^0_S$

$\eta_f = +1$ mode

$B^0_{CP} \to J/\psi K^0_L$



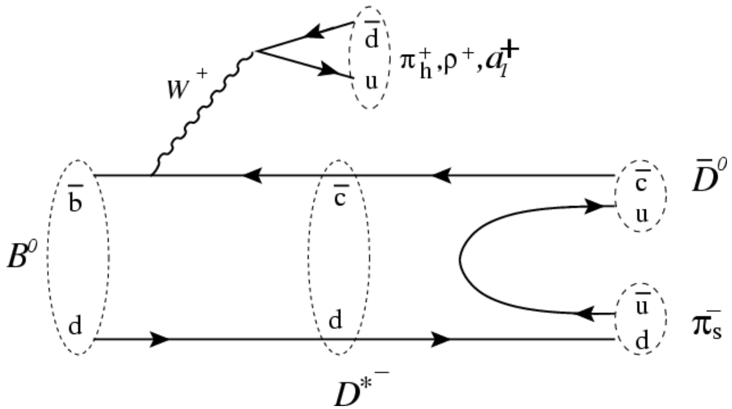


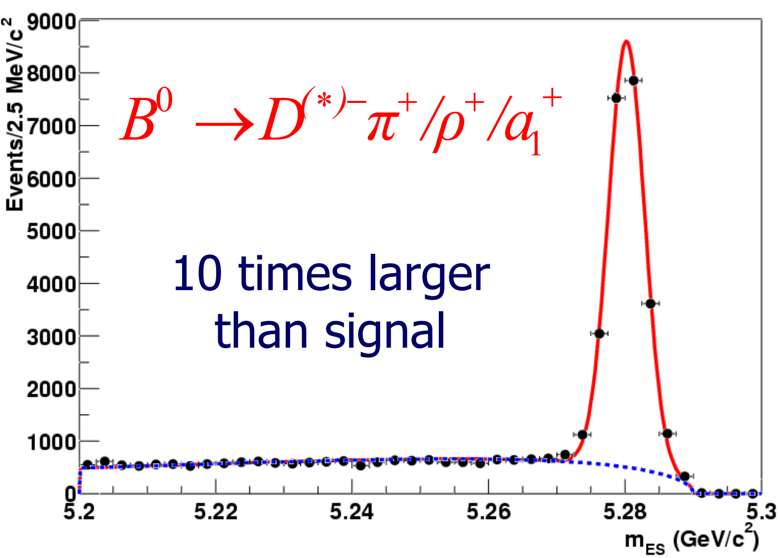
BABAR
81.3 fb^{-1}

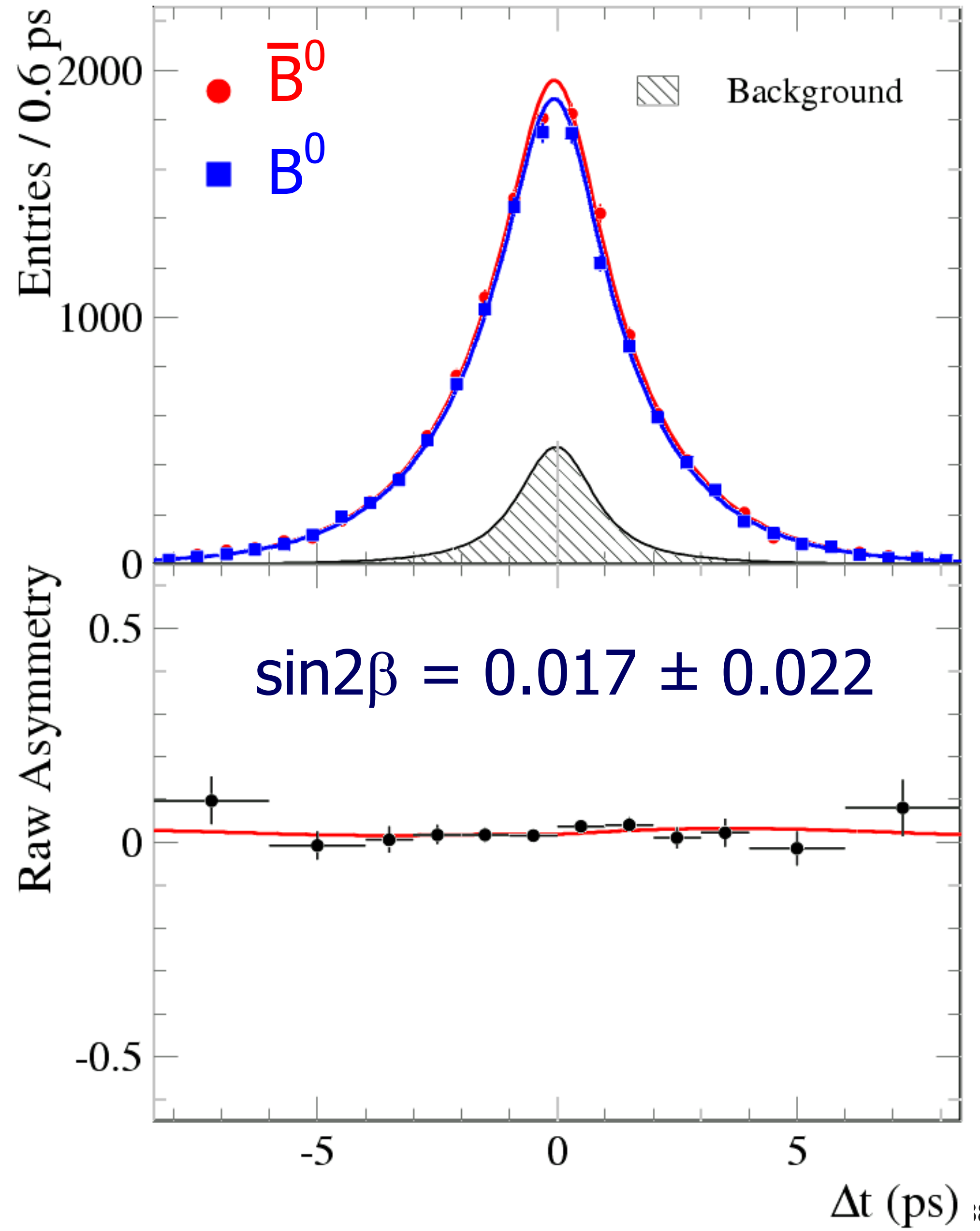
(after tagging & vertexing)

Calibration with Flavor eigenstates

Control Sample with no expected CP asymmetry



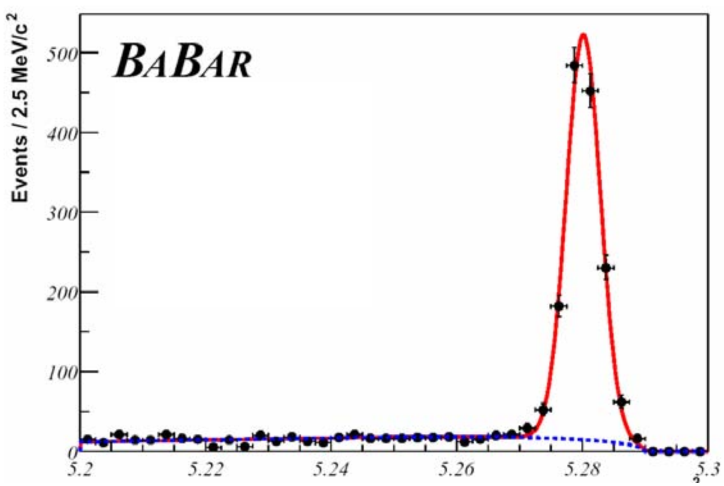


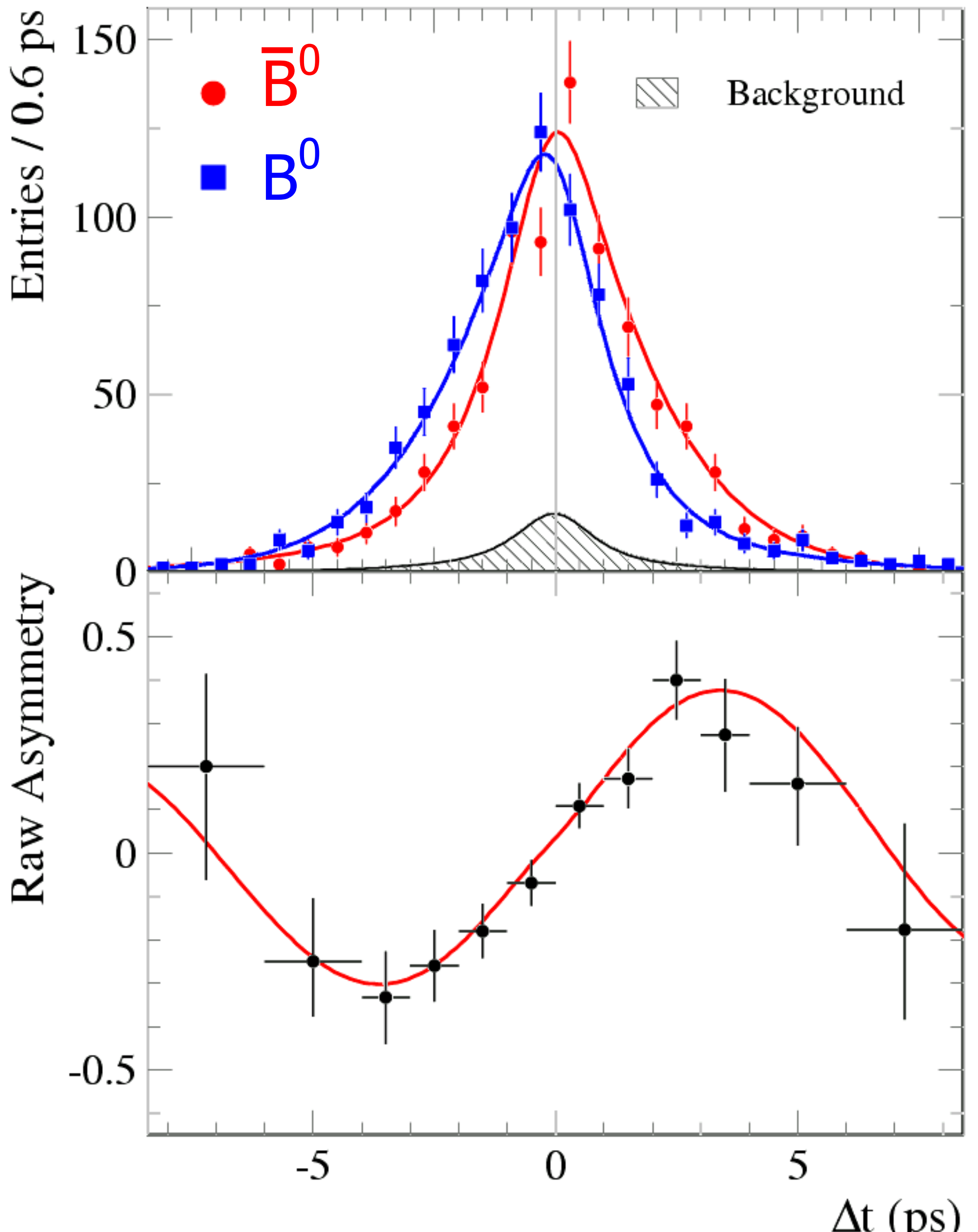


Observation of CP Violation (BaBar 2001)

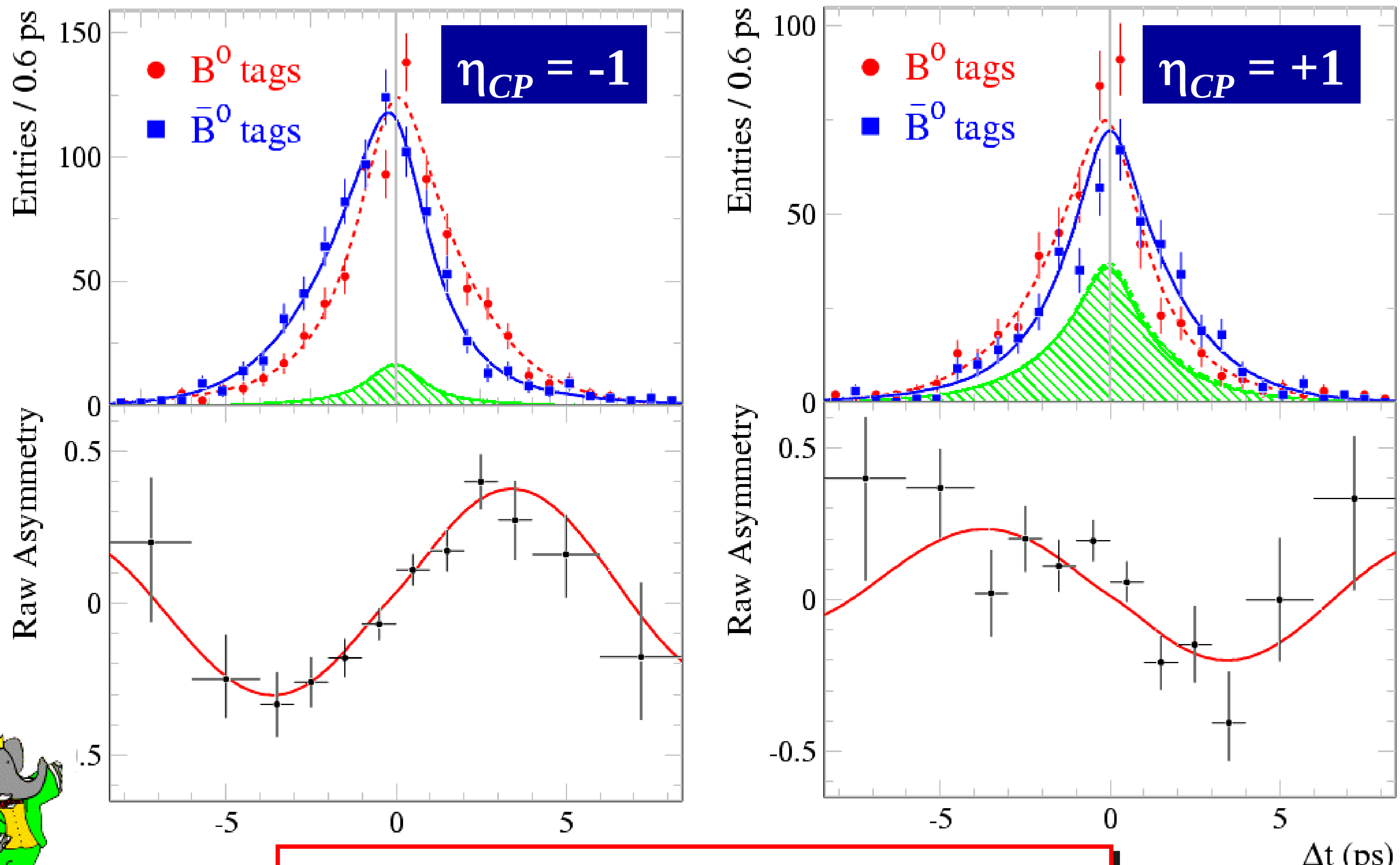
$\sin 2\beta = 0.755 \pm 0.074$

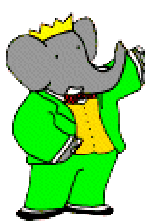
$B^0 \rightarrow J/\psi\ K_S$
$B^0 \rightarrow \psi(2S)\ K_S$
$B^0 \rightarrow \chi_c\ K_S$
$B^0 \rightarrow \eta_c\ K_S$





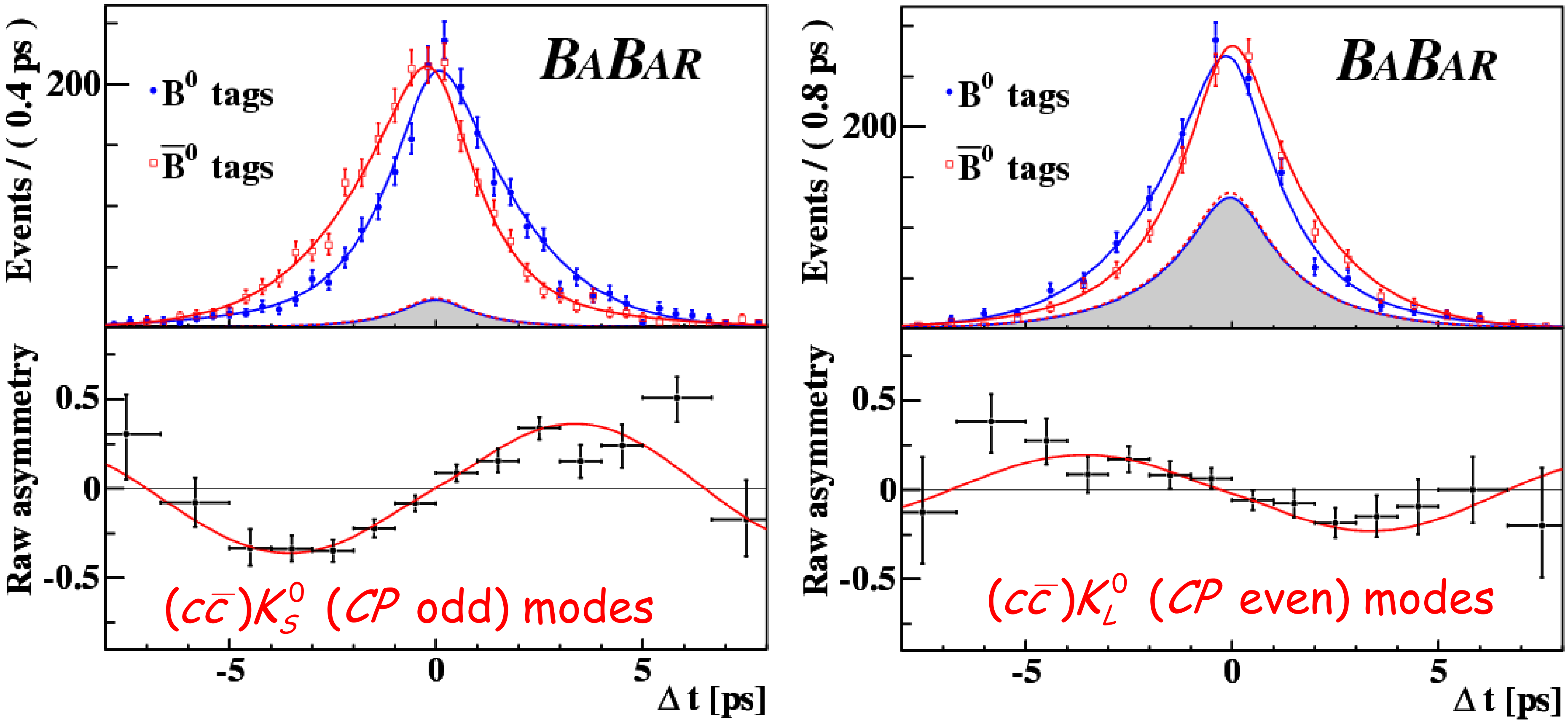
BABAR Result for sin2β (July 2002)





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

Updated (ICHEP04) sin2β results from Charmonium Modes



$205 fb^{-1}$ on peak or $227M\ B\bar{B}$ pairs
7730 CP events (tagged signal)

$$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$$

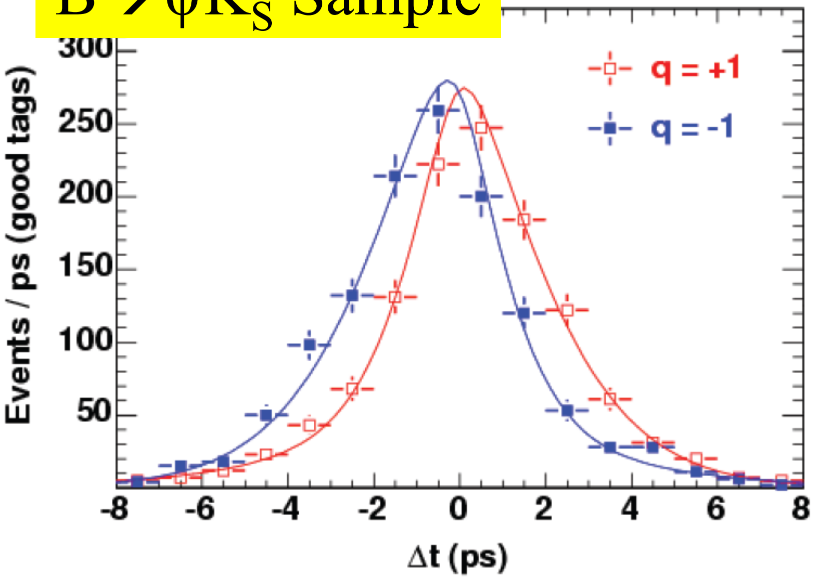
$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} = 0.051 \pm 0.033 \pm 0.014$$

Limit on direct CPV

$c\bar{c}\ K_S$ + $c\bar{c}\ K_L$

Belle Results on sin2β from Charmonium Modes

B→ψK_S Sample

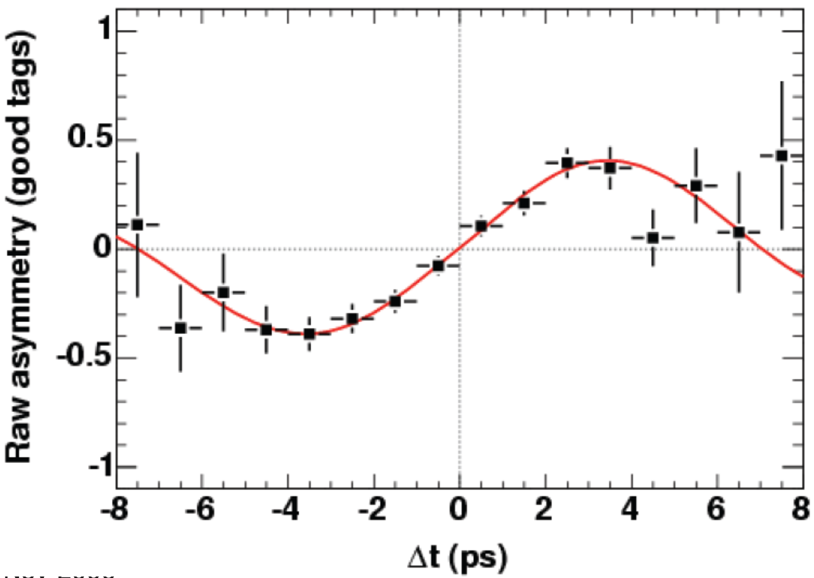


Belle 2005

386M $B\bar{B}$ pairs

$$\sin 2\beta = 0.652 \pm 0.039 \pm 0.020$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} = -0.010 \pm 0.026 \pm 0.036$$

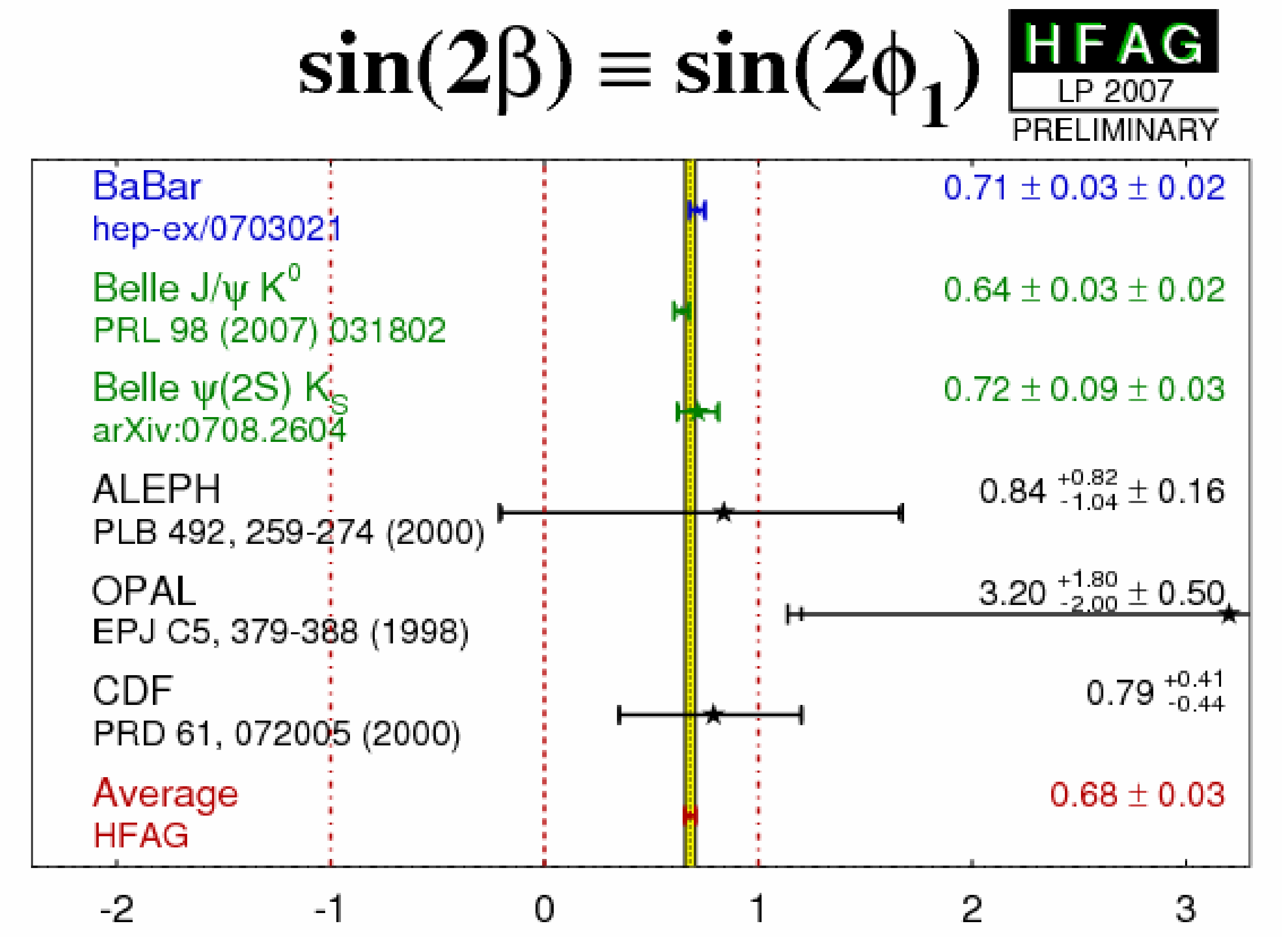


New Belle value lower than in ’03

$$\sin 2\beta = +0.728 \pm 0.056 \pm 0.023$$

but still consistent with BaBar’04

CP Violation in B Decays Firmly Established



Lessons From sin2β Measurement With $B^0 \to J/\psi K^0$

- In 2001, large CP Violation in B system was observed in this mode by BaBar and Belle.
  - First instance of CPV outside the Kaon system.

- First instance of a CPV effect which was **O(1)** in contrast with the Kaon system
  - Confirms the 1972 conjecture of Kobayashi & Maskawa.
  - Excludes models with approximate CP symmetry (small CPV).

- In 2007 sin2β is a precision measurement (5%) and agrees well with the constraints in the ρ-η plane from measurements of the CKM magnitudes (will be discussed in tomorrow's lecture)
- Appears unlikely to find another **O(1)** source of CPV
  - enterprise now moves towards looking for **corrections** rather than alternatives to SM/CKM picture

- Focus now shifts to measurements of time-dependent asymmetries in rare B decays
  - dominated by Penguin diagrams in the SM and where New Physics could contribute to the asymmetries

Tomorrow's Lecture

Measurements of α and γ

Constraints on Unitarity Triangle from measuments of CKM element magnitude and angles