CKM Matrix and CP Violation in Standard Model

Types of CP Violation. B^0 oscillation

Lecture 16

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Fisica delle Particelle Elementari, Anno Accademico 2015-16

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Measuring Complex Phase of CKM Matrix

- Branching fractions and lifetimes sensitive to magnitude of CKM elements
  - Decay probabilities usually include $|V_{ij}|^2$
  - We looked for decays involving only one CKM element to make interpretation of experimental result possible

- Complex phase of CKM is a relative phase between matrix elements

- We need processes with interference of two different CKM elements

$$A_1 = Ae^{i\alpha}$$

$$A_2 = Be^{i\beta}$$

$$A_{tot} = A_1 + A_2$$

Sensitive to phase difference!

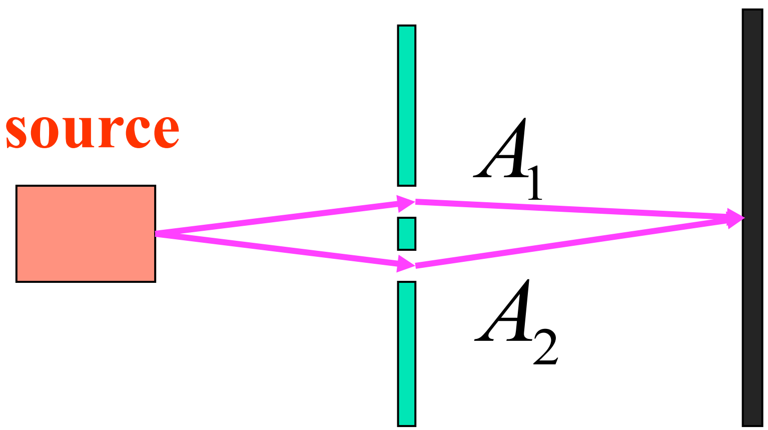
$$\boxed{|A_{tot}|^2 = |A|^2 + |B|^2 + ABe^{i(\alpha-\beta)} + ABe^{-i(\alpha-\beta)}}$$

CP Violation

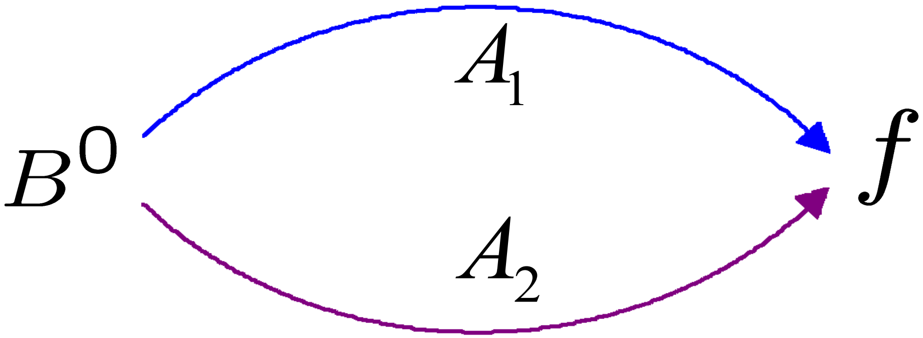
- CP violation can be observed by comparing decay rates of particles and antiparticles

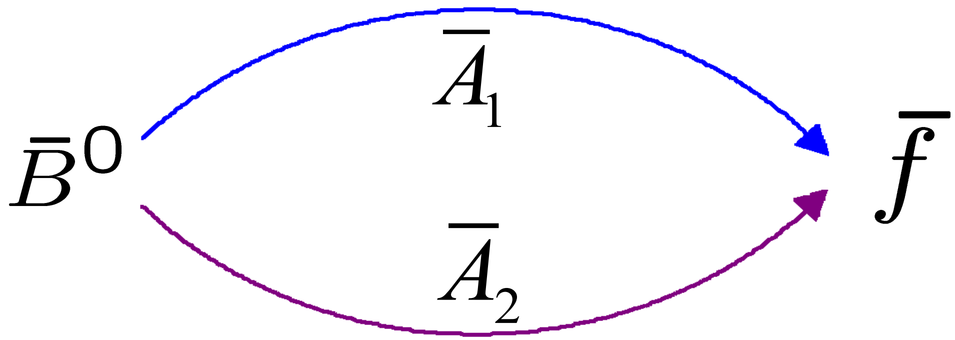
$$\Gamma(a \to f) \neq \Gamma(\bar{a} \to \bar{f}) \Rightarrow \text{CP Violation}$$

- The difference in decay rates arises from a different interference term for the matter vs. antimatter process. Analogy to double-slit experiment:



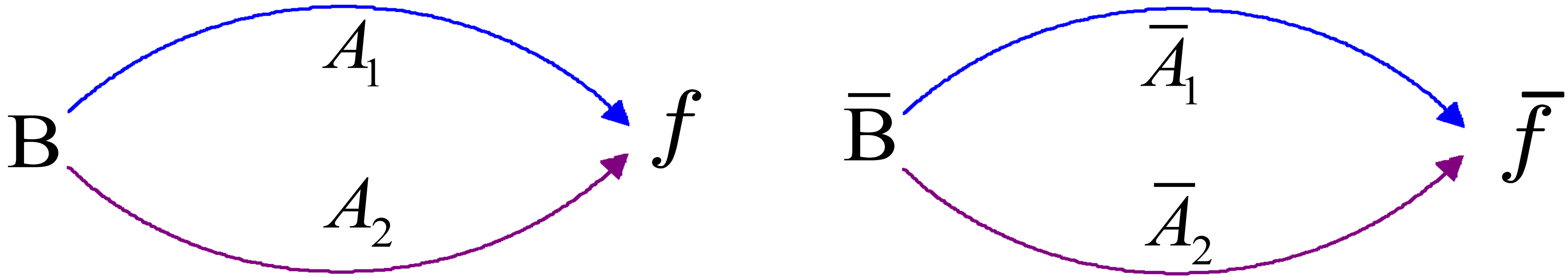
Classical double-slit experiment:
Relative phase variation due to different
path lengths: interference pattern in space





CP Violation in B Meson System

Identify B final states which are arrived at by two paths



In B^0 system, $B^0 \rightleftharpoons \bar{B}^0$ oscillation provides one path

other path(s) come from weak decay of B hadron

In $B^{\pm}$system $\Rightarrow$ no oscillation possible,

2 (or more) amplitudes must come from different weak decay of B

B Meson is heavy $\Rightarrow$ many final states, multiple "paths."

2 classes of B decays come into play: "Tree" $\Rightarrow$ spectator decay like

"Penguin" $\Rightarrow$ FCNC loop diagrams with u,c,t

CP Violation Is a Quantum Phenomenon

- CPV is due to Quantum interference between two or more amplitudes

- Phase of QM amplitudes is the key

- Need to consider two types of phases
  - *CP-conserving phases*: <u>don't change sign under CP</u>
    - Sometimes called *strong phases* since they can arise from strong, final-state interactions
  - *CP-violating phases*: <u>these do change sign under CP transformation</u>
    - originate in the Weak interaction sector

$$A = A\boxed{e^{i\varphi}}e^{i\delta}$$

$$\bar{A} = A\boxed{e^{-i\varphi}}e^{i\delta}$$

How can CP asymmetries arise ?

- Suppose a decay can occur through two different processes, with amplitudes A_1 and A_2

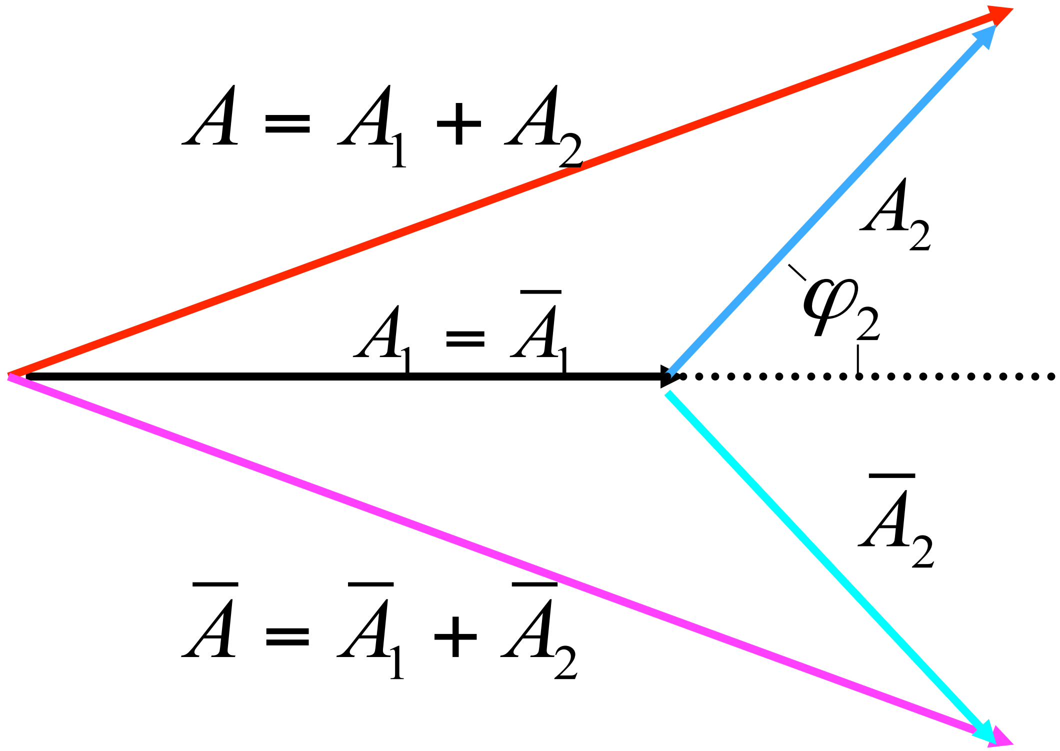
- First, consider the case in which there is a (relative) CP-violating phase between A_1 and A_2 only

$$A = A_1 + a_2 e^{i\varphi_2}$$

$$\bar{A} = A_1 + a_2 e^{-i\varphi_2}$$

- Different decay rate for particle and anti-particle
  - Since new term added
- But no direct CP asymmetry

$$A = \bar{A}$$



How can CP asymmetries arise ?

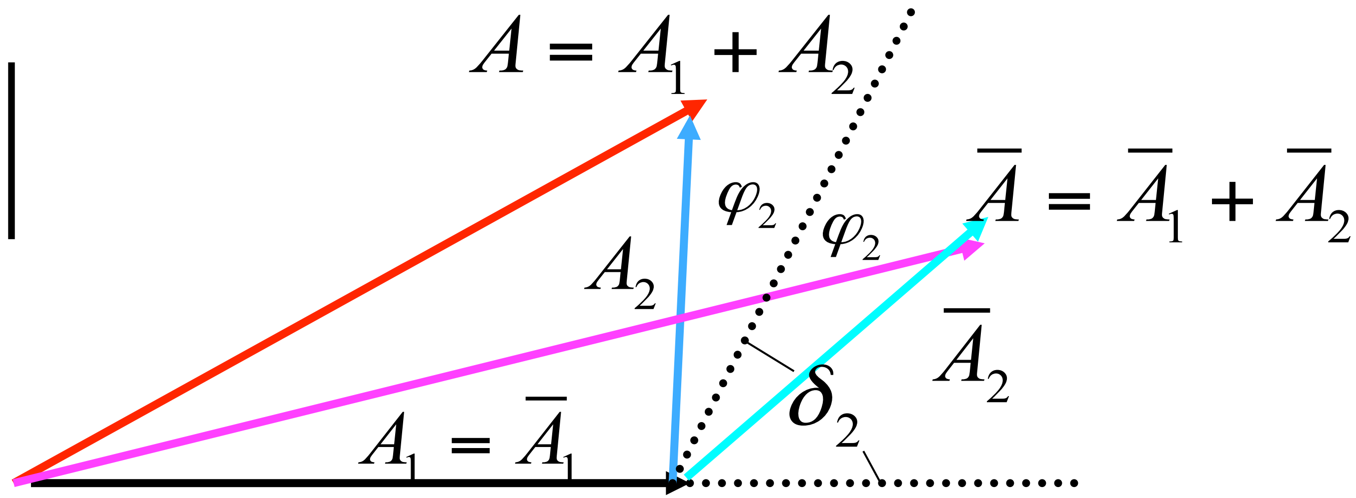
- Next, introduce a relative *CP-conserving* phase in addition to the relative *CP-violating* phase

$$A = A_1 + a_2 e^{i(\varphi_2 + \delta_2)}$$

$$\bar{A} = A_1 + a_2 e^{i(-\varphi_2 + \delta_2)}$$

- Now have a Direct CP Violation

$$|A| \neq |\bar{A}|$$



Definition of CP Asymmetry

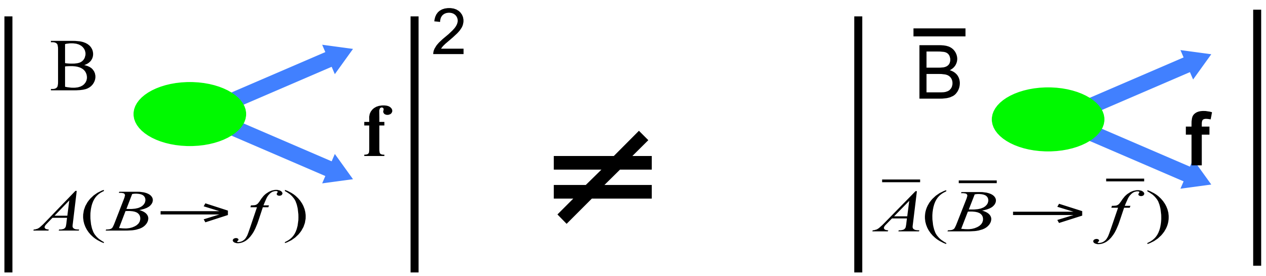
$$Asymmetry = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{|A_1|^2 + |A_2|^2 + |A_1||A_2|\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

To extract the CP-violating phase from an observed CP asymmetry, we need to know the value of the CP-conserving phase difference

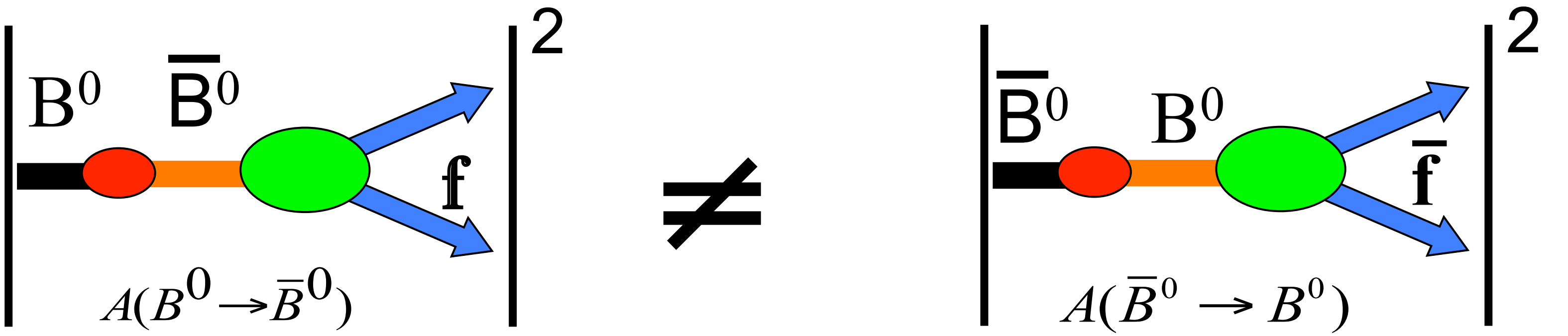
***B* system: extraordinary laboratory for quantum interference experiments: many final states, multiple "paths"→ Lots of channels for CP Violation**

Overview of CP Violating Processes

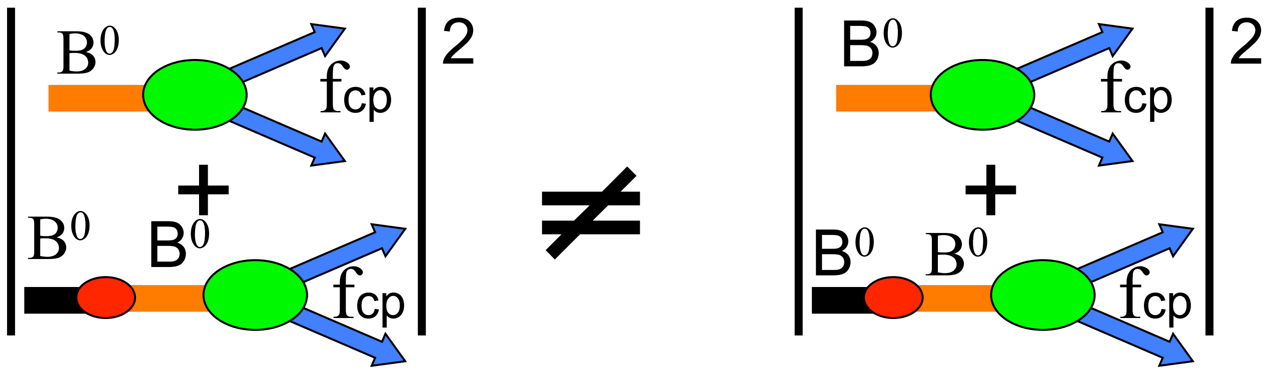
CP Violation
in Decay
a.k.a.
Direct CPV



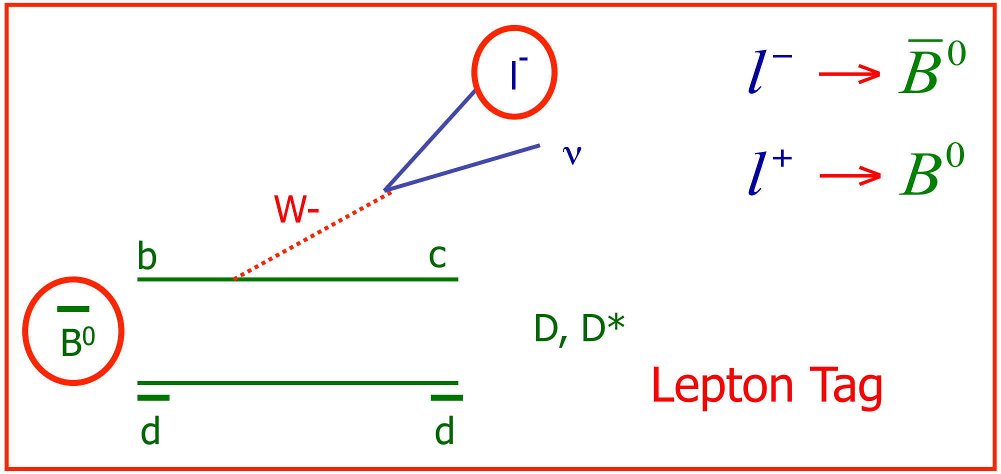
CP Violation
in Mixing

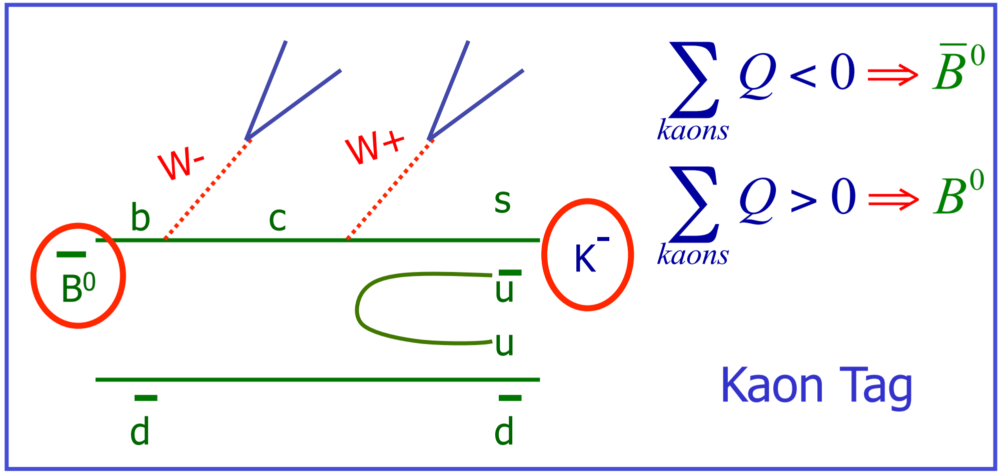


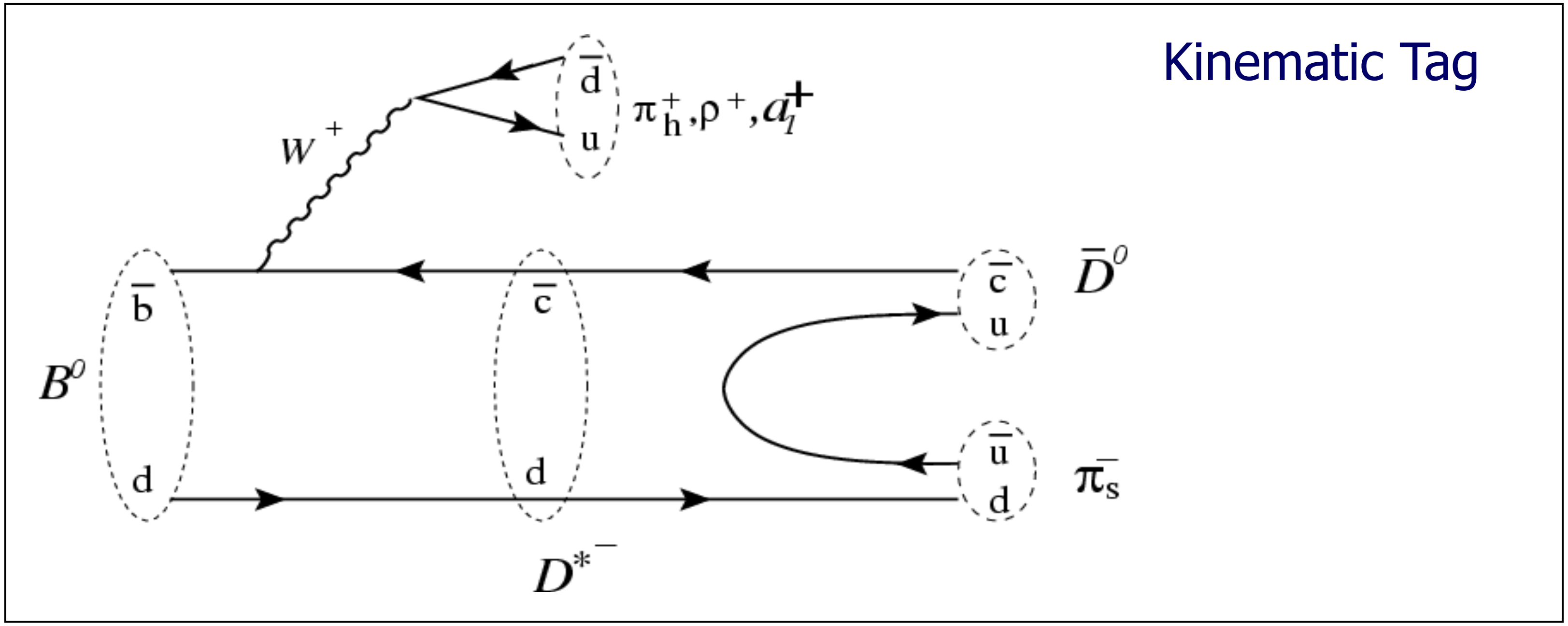
CP Violation
in interference
between Mixing
and Decay



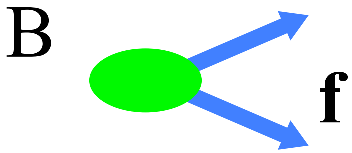
Separating B^0 and $\bar{B}^0$ mesons

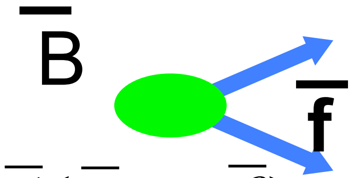






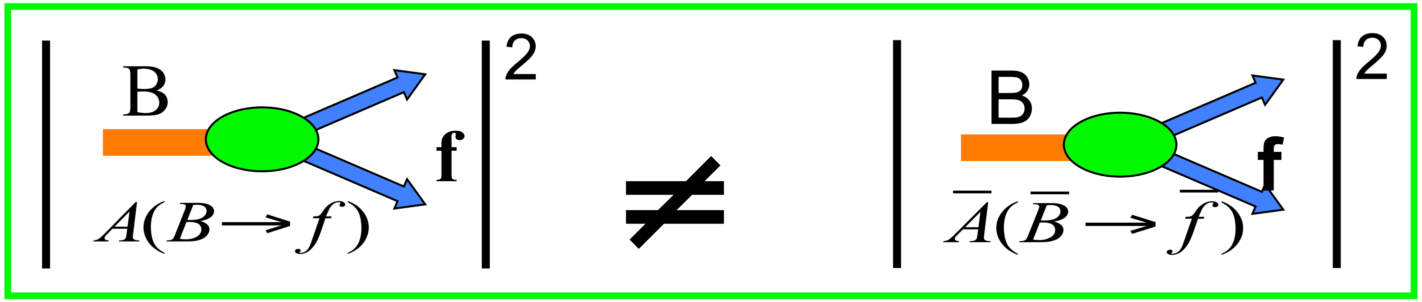
Direct CP Violation

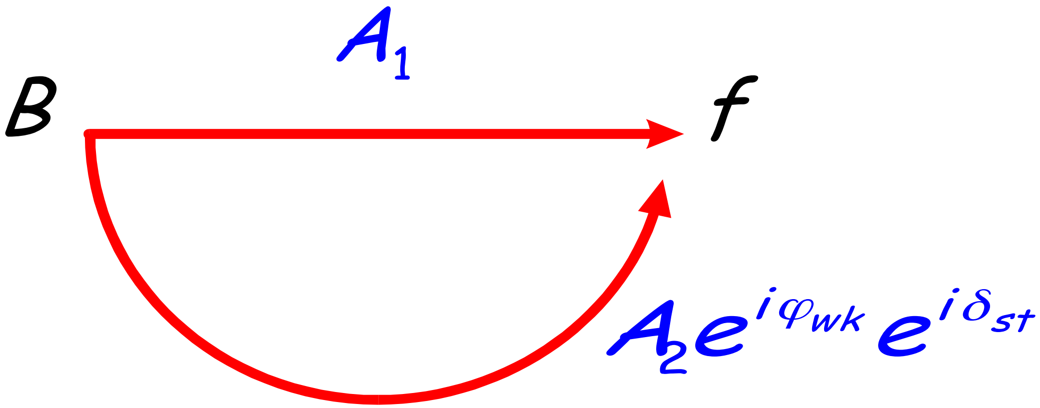


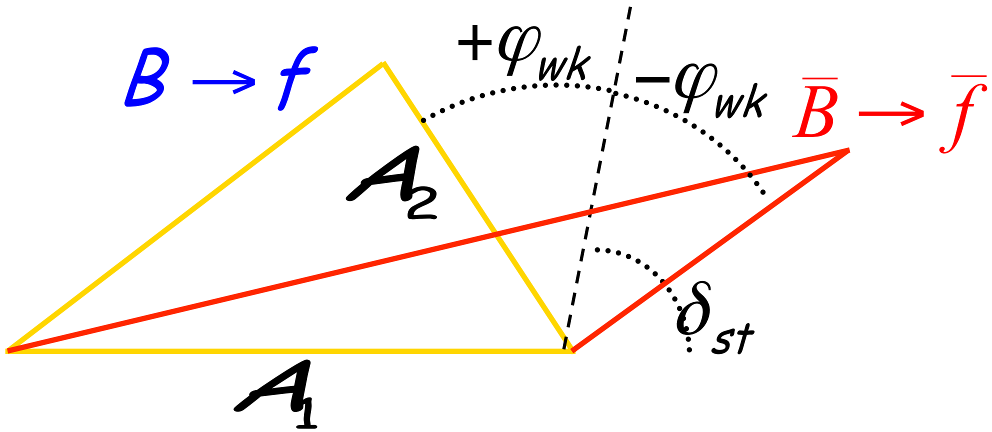


$$\left| A(B \longrightarrow f) \right|^2 \neq \left| \overline{A}(\overline{B} \longrightarrow \overline{f}) \right|^2$$

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



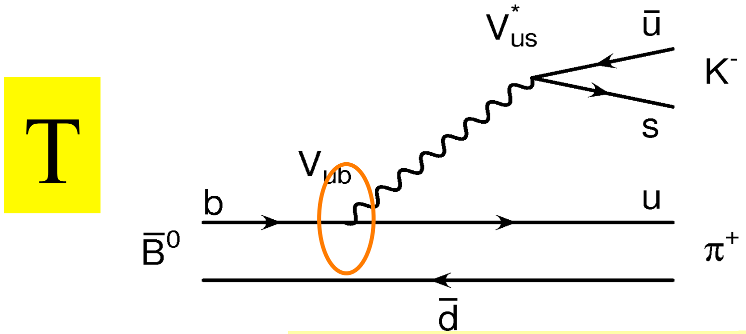


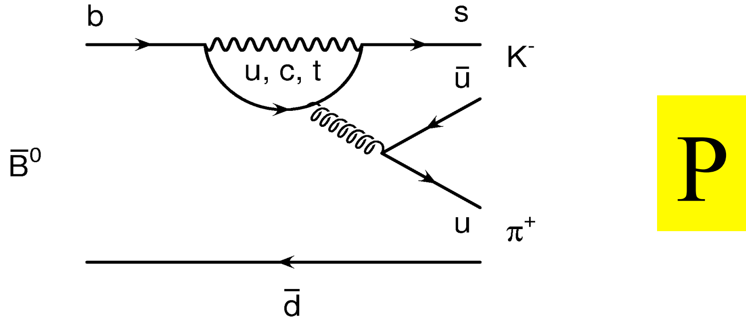


$$\Gamma(B \to f) = \left| A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}} \right|^2, \quad \Gamma(\bar{B} \to \bar{f}) = \left| A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$A_{CP} = \frac{Br\left(\bar{B} \to \bar{f}\right) - Br\left(B \to f\right)}{Br\left(\bar{B} \to \bar{f}\right) + Br\left(B \to f\right)} \equiv \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2} \neq 0 \to \text{Direct } CPV$$

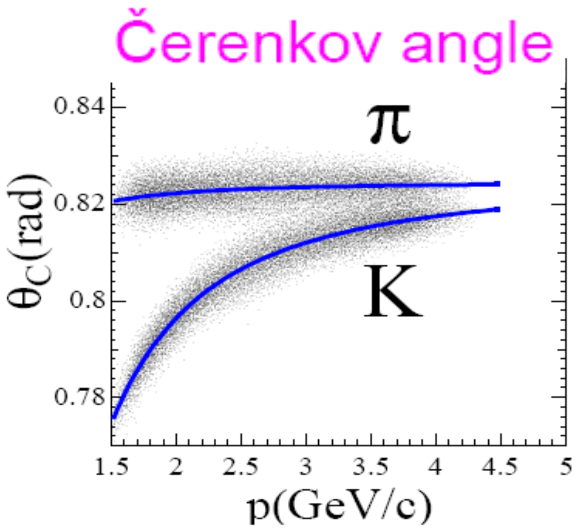
Direct CP Violation in $B^0 \rightarrow K^- \pi^+$

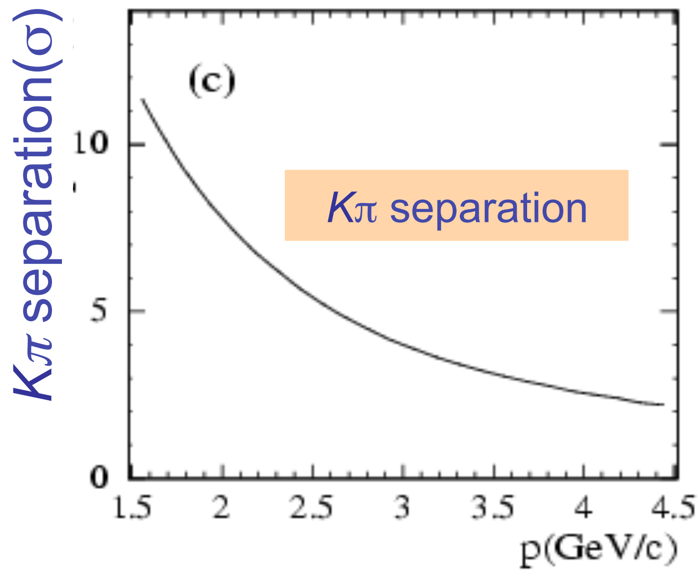


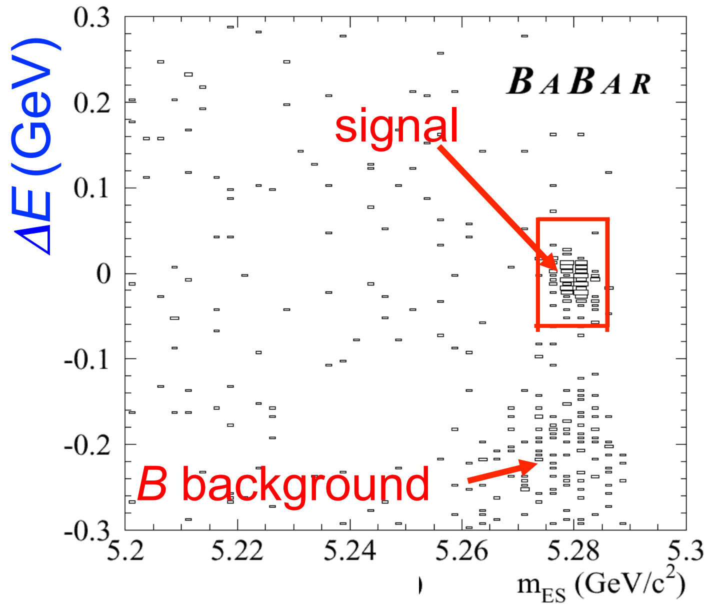


$$SM\ amplitude = \lambda^2 e^{i\gamma} T + P \qquad A_{K\pi} \sim \sin(\gamma)$$

- Loop diagrams from New Physics (e.g. SUSY) can modify SM asymmetry via P
- Clean mode with "large" rate : 2 x 10^{-5}
- Measure *charge* asymmetry, reject large $B \rightarrow \pi\pi$ background with Particle ID







Observation of Direct CPV in B0→K⁻π⁺

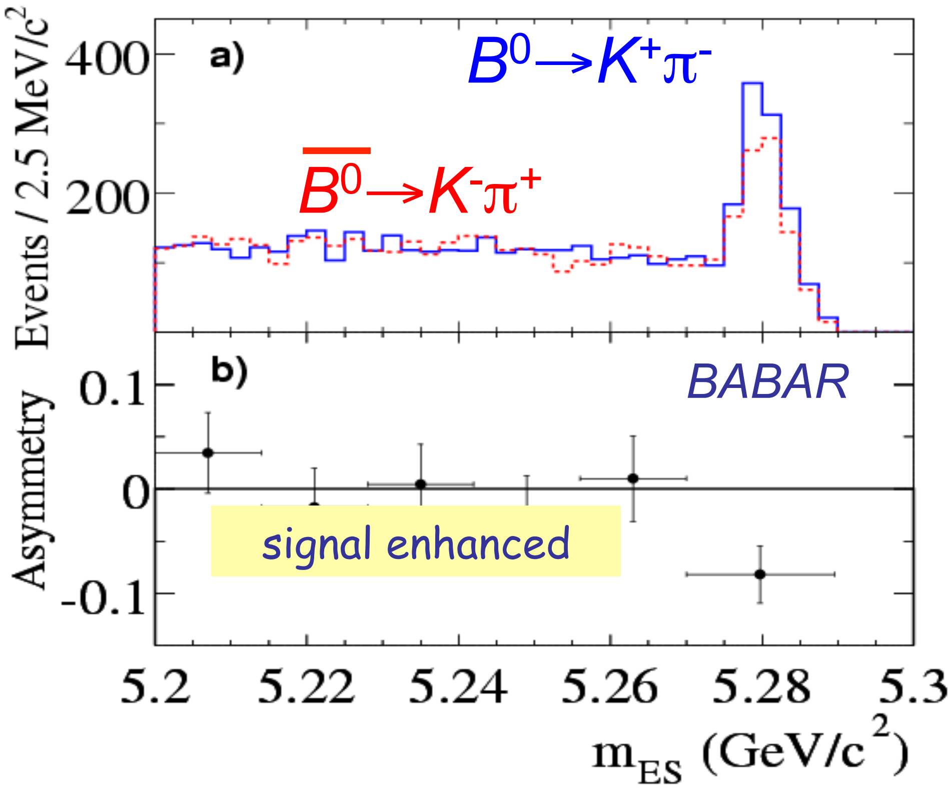
$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)}$$

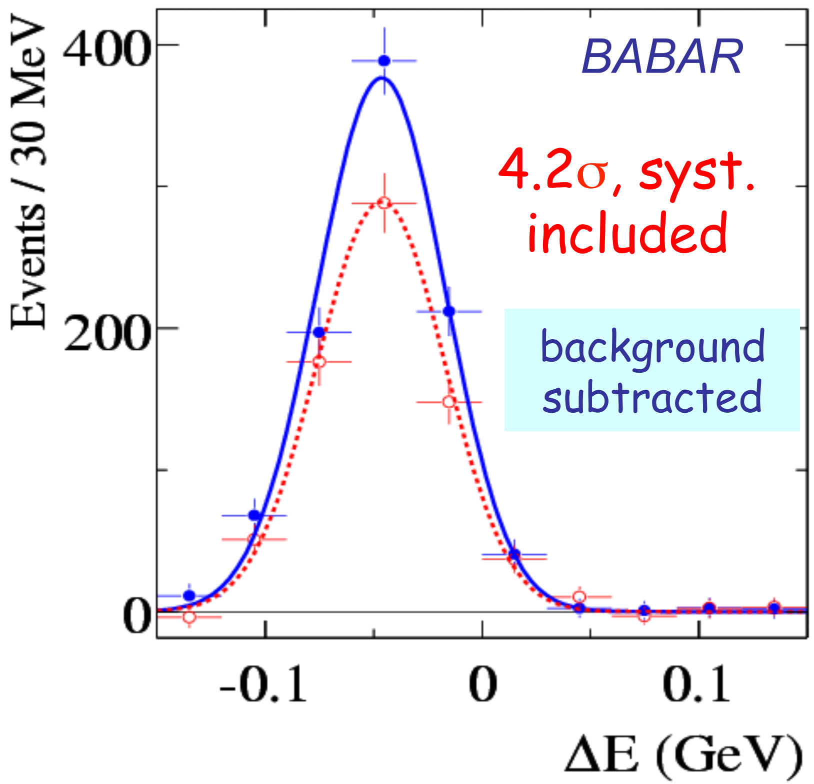
$$n_{K\pi} = 1606 \pm 51$$

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

$$\left.\right\} \quad n\left(B^0 \to K^+\pi^-\right) = 910$$

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

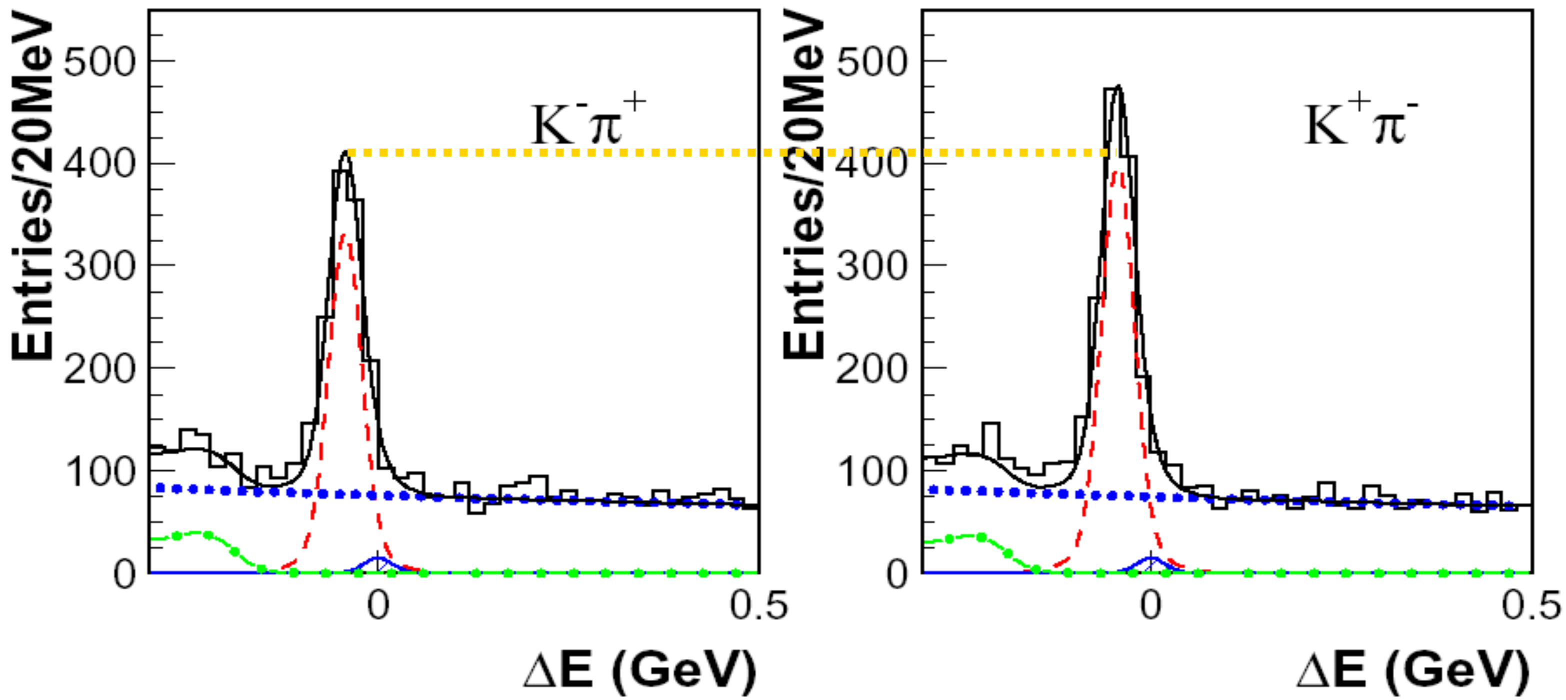




Confirmation of Direct CPV by Belle

A_{CP} = -0.101 ± 0.025 ± 0.005

3.9σ significance



274M $B\bar{B}$

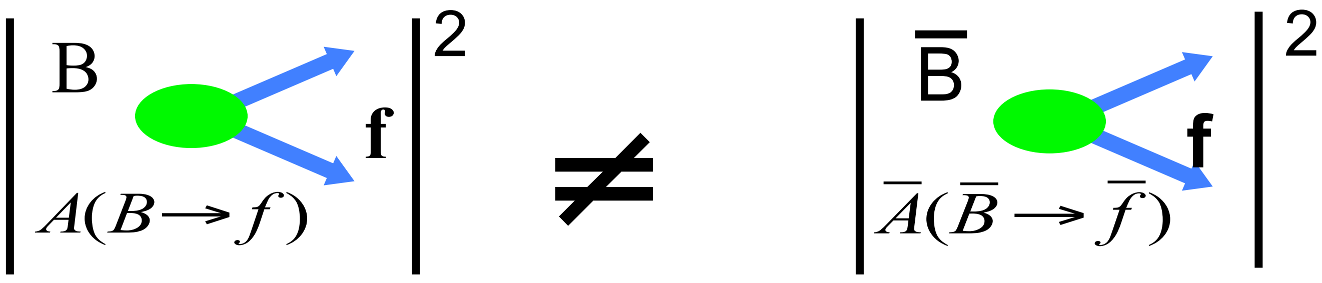
Signal=2139 ±53

Non-Perturbative QCD uncertainties large,
Standard Model CP Violation not precisely predictable

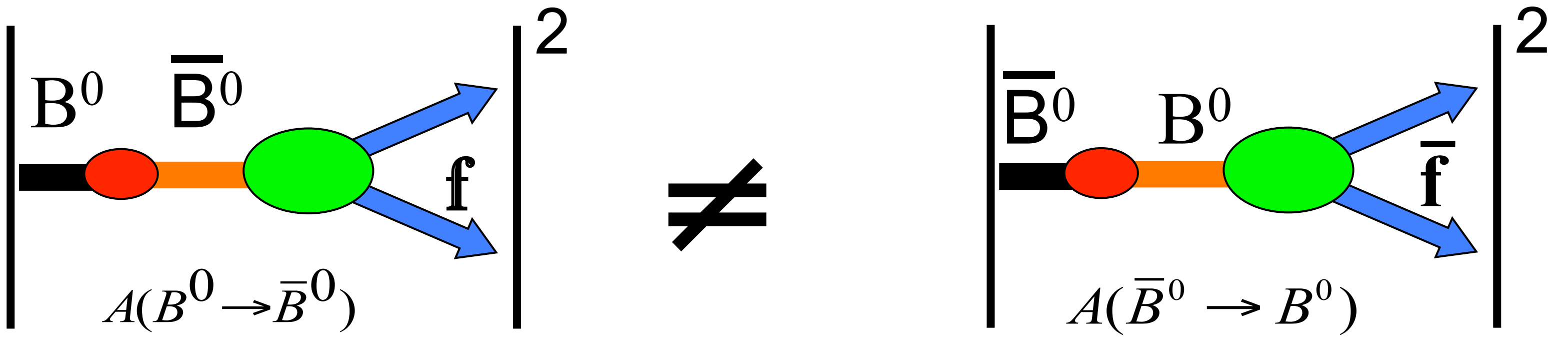
⇒ insufficient to prove or rule out contribution from New Physics

Overview of CP Violating Processes

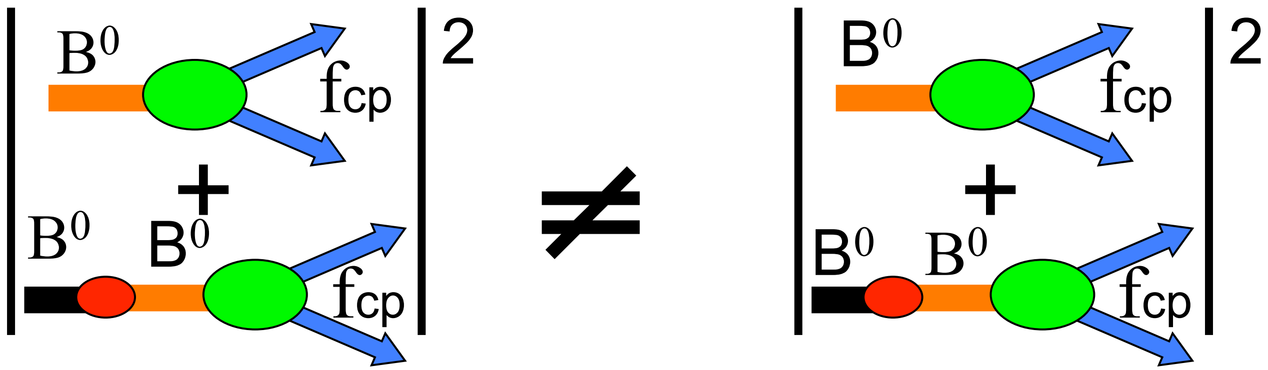
CP Violation
in Decay
a.k.a.
Direct CPV



CP Violation
in Mixing

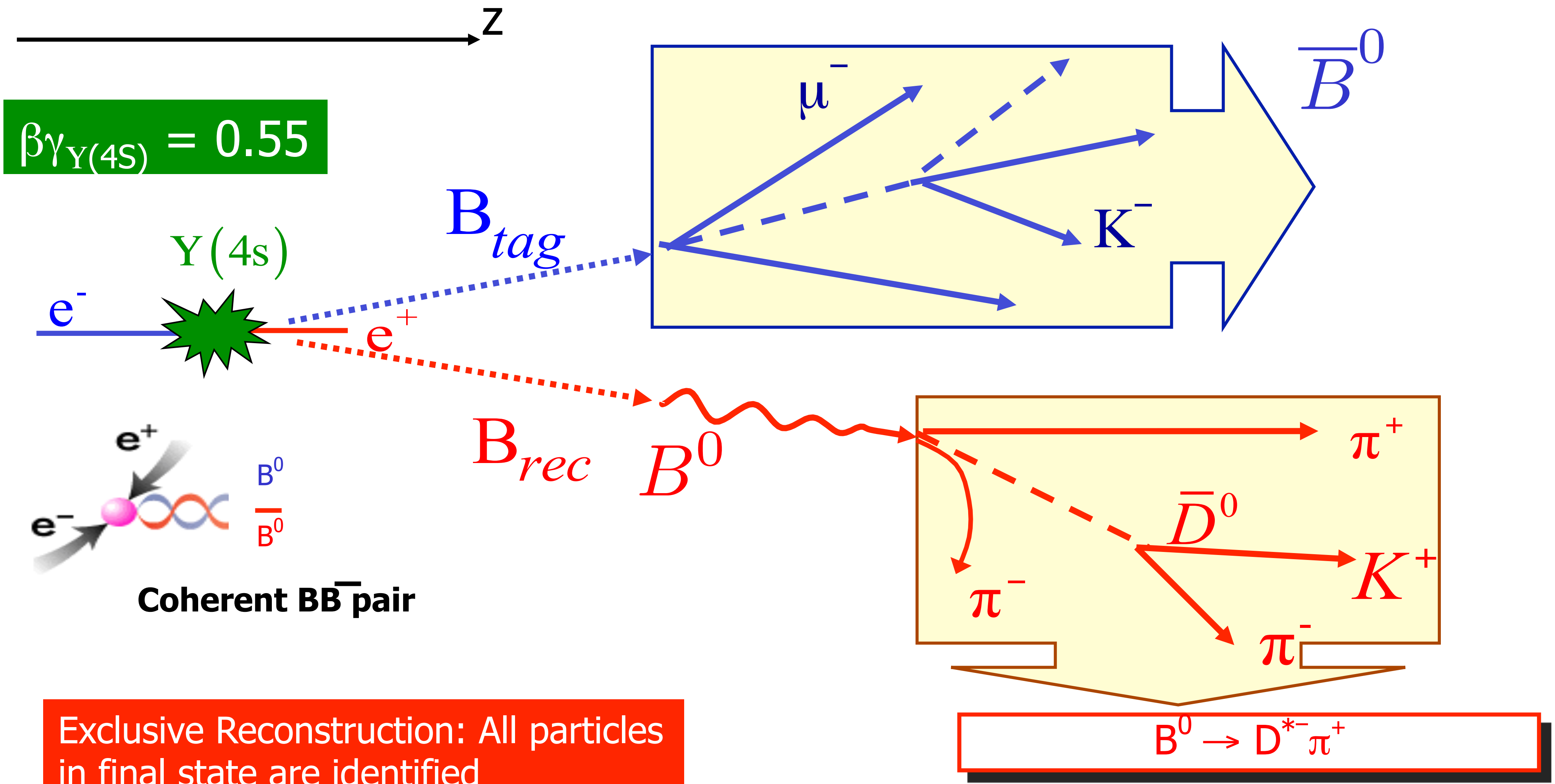


CP Violation
in interference
between Mixing
and Decay



Snapshot of $B\bar{B}$ Event at BaBar

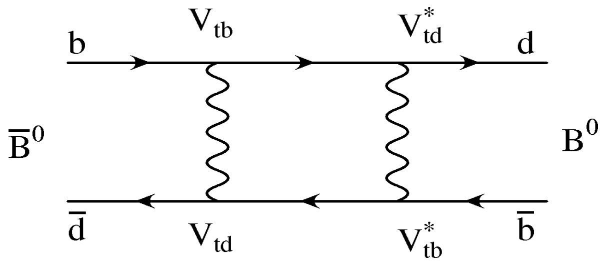
Inclusive Reconstruction: Look at some of decay products carrying information about their mother



Exclusive Reconstruction: All particles in final state are identified

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

B^0_d-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

$$\begin{aligned} CP|B_{CP=1}\rangle &= +|B_{CP=1}\rangle \\ CP|B_{CP=-1}\rangle &= -|B_{CP=-1}\rangle \end{aligned}$$

- 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

$$|B_L, t\rangle = \mathrm{e}^{-\Gamma_L t}\mathrm{e}^{-iM_L t}|B_L, t=0\rangle \qquad (2.28)$$

$$|B_H, t\rangle = \mathrm{e}^{-\Gamma_H t}\mathrm{e}^{-iM_H t}|B_H, t=0\rangle \ . \qquad (2.29)$$

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

$$\begin{aligned} M_{ij} &= m_B\delta_{ij} + \langle i|H_W^{\Delta B=2}|j\rangle + P\sum_n \frac{1}{m_B - E_n}\langle i|H_W^{\Delta B=1}|n\rangle\langle n|H_W^{\Delta B=1}|j\rangle \\ \Gamma_{ij} &= 2\pi\sum_n \delta(E_n - m_B)\langle i|H_W^{\Delta B=1}|n\rangle\langle n|H_W^{\Delta B=1}|j\rangle\ . \end{aligned}$$

  - 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

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

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

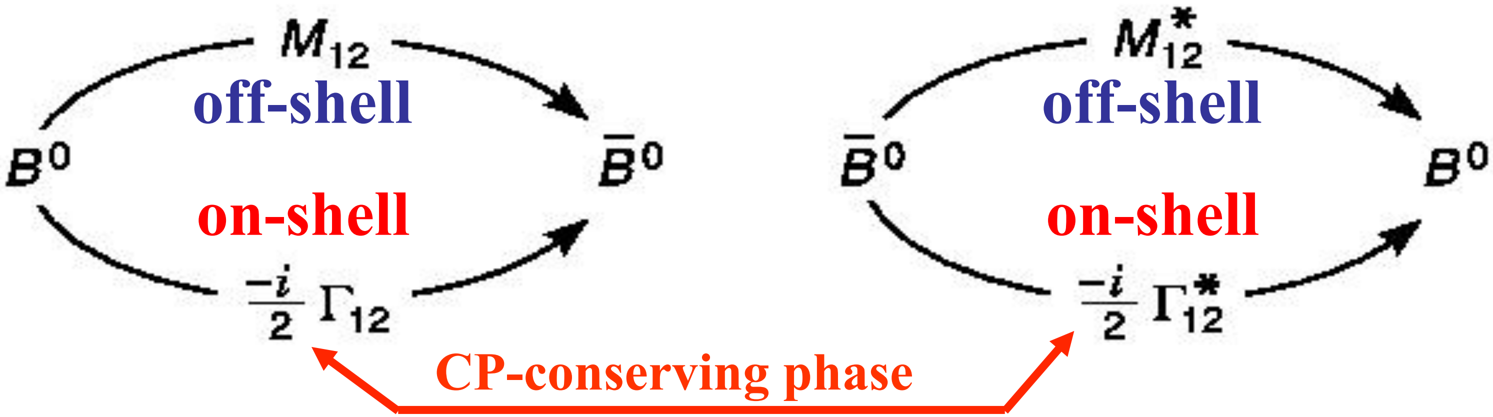
$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M^*_{12} & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma \end{pmatrix}$$

Decays

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

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

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

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

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

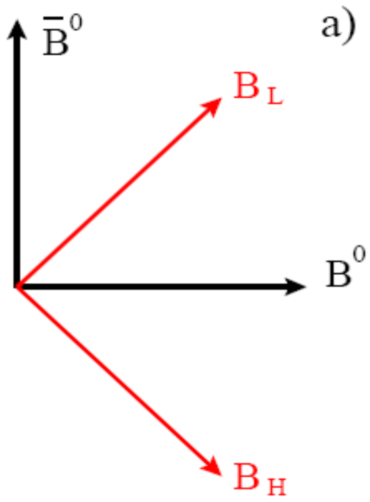
Relation Between Mass and Flavor states

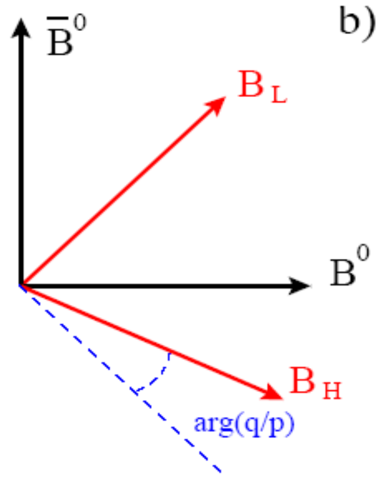
$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle, \qquad |B^0\rangle = \frac{1}{2p}(|B_L\rangle + |B_H\rangle)$$

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

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

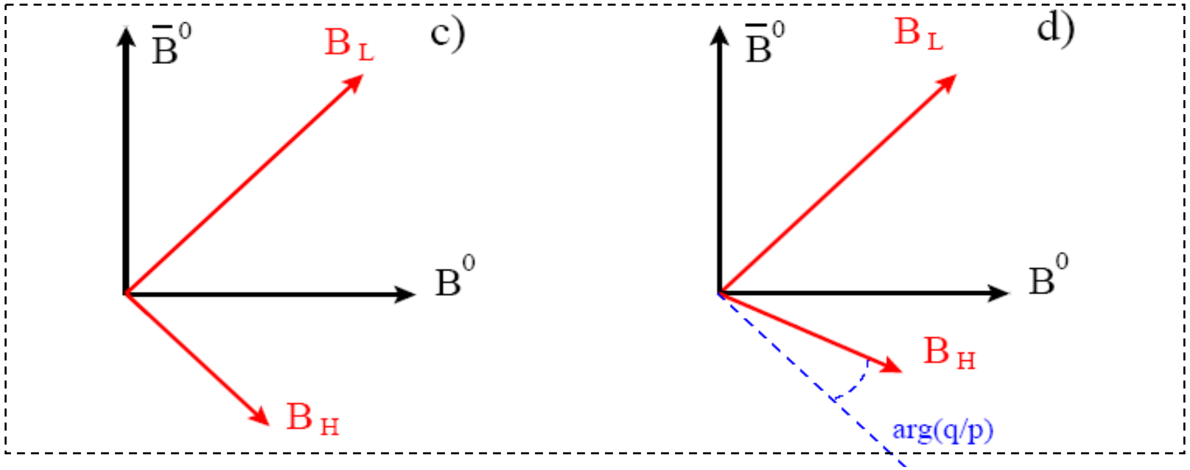
δ=0
arg(q/p)=0
No CP Violation





δ=0
arg(q/p)≠0
CP Violation

δ≠0
regardless arg(q/p)
CP Violation



CPV
in
Mixing

Time Development of Physical States

- Evolution of a pure B0 or B0 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

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

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

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

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

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

$$\Delta m_d = M_H - M_L$$

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

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

$\boxed{\text{Prob of } B^0 \to \overline{B}^0 \text{ oscillates as function of time !}}$

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

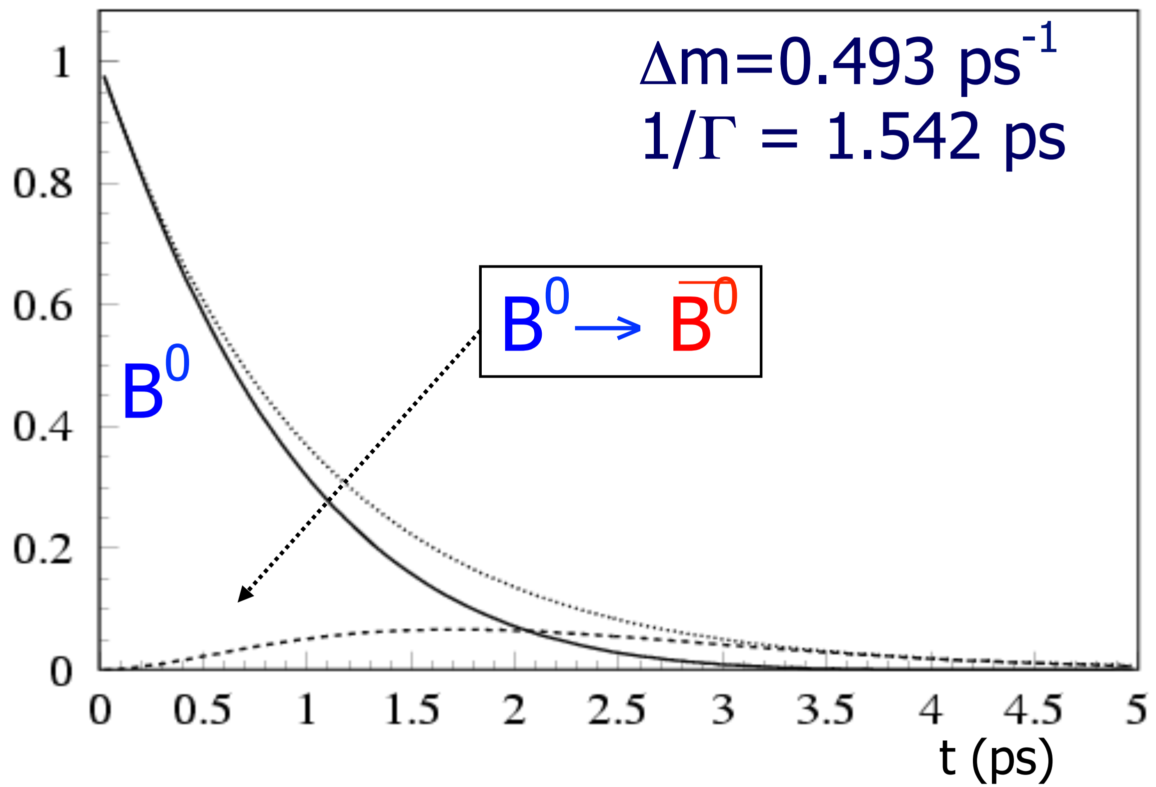
$$|B^0(t)\rangle = e^{-iMt}e^{-\Gamma t}\left(\cos\frac{\Delta m\, t}{2}\,|B^0\rangle + i\,\sin\frac{\Delta m\, t}{2}\cdot\frac{q}{p}\,|\overline{B^0}\rangle\right)$$

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

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

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

Slow oscillation compared to the lifetime



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

$$\Upsilon(4s) \rightarrow B^0 \bar{B}^0$$

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

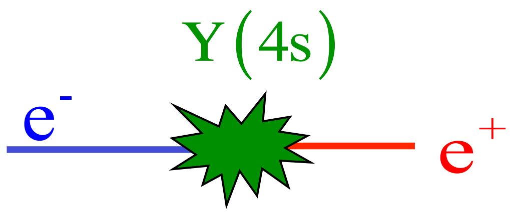
$$|\Psi\rangle = |\Psi_{\rm flavor}\rangle|\Psi_{\rm space}\rangle$$

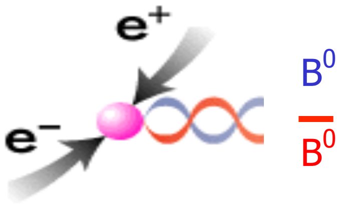
- L=-1 implies asymmetric spatial wave function
- We need a=-b which means a B^0 and a B^0 meson at all times until one of them decays!
  - Example of Einstein-Podolsky-Rosen Paradox

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

z

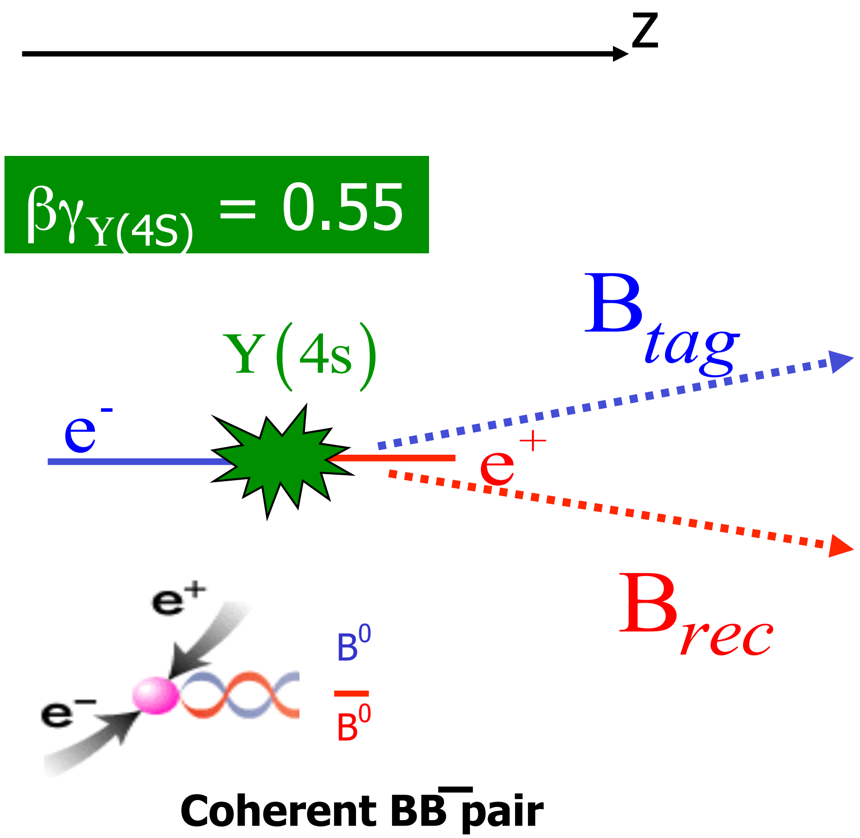
$\beta\gamma_{\Upsilon(4S)} = 0.55$



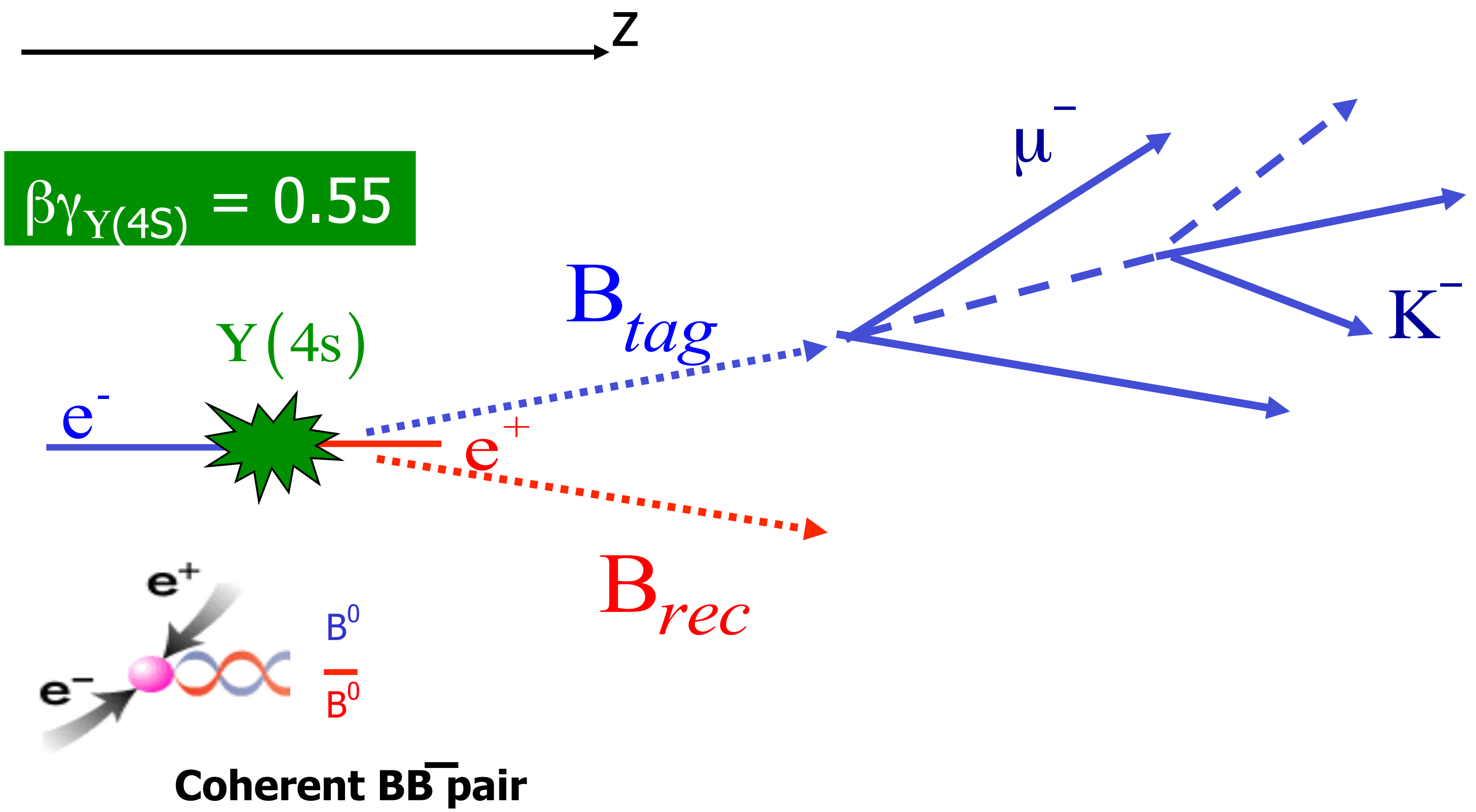


Coherent $B\bar{B}$ pair

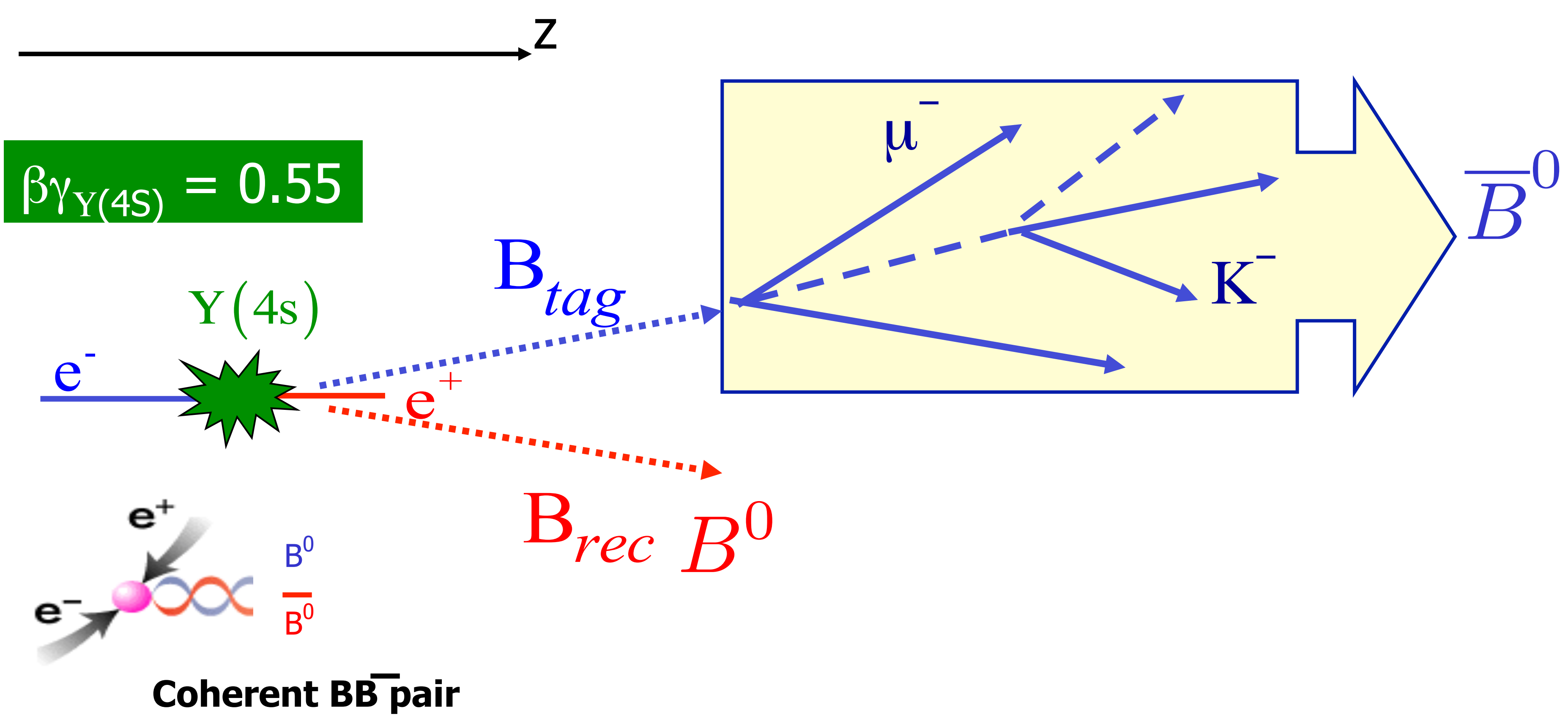
Time Evolution of $\Upsilon(4S) \rightarrow B^0\overline{B^0}$



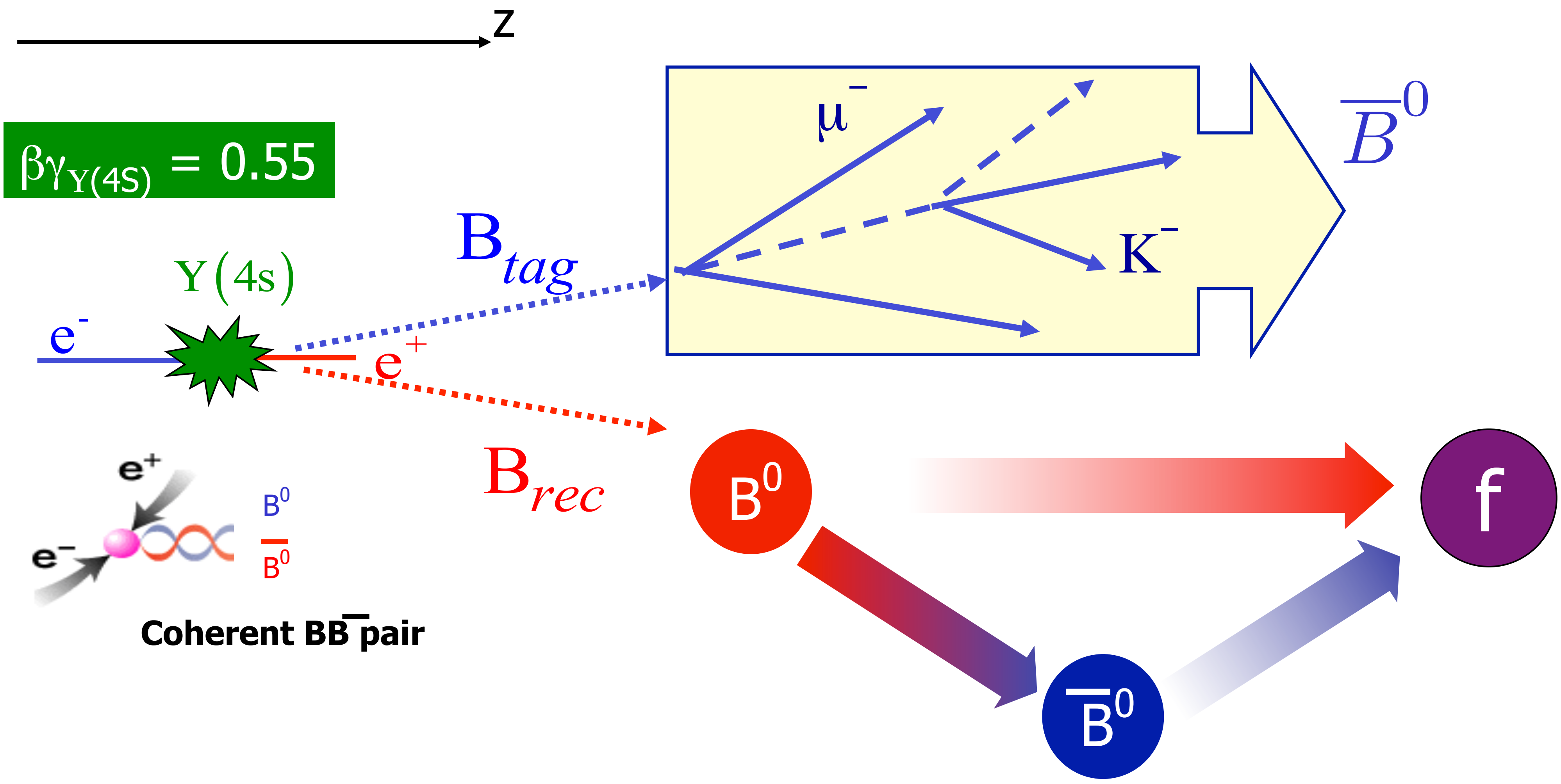
Time Evolution of $\Upsilon(4S) \to B^0\overline{B^0}$



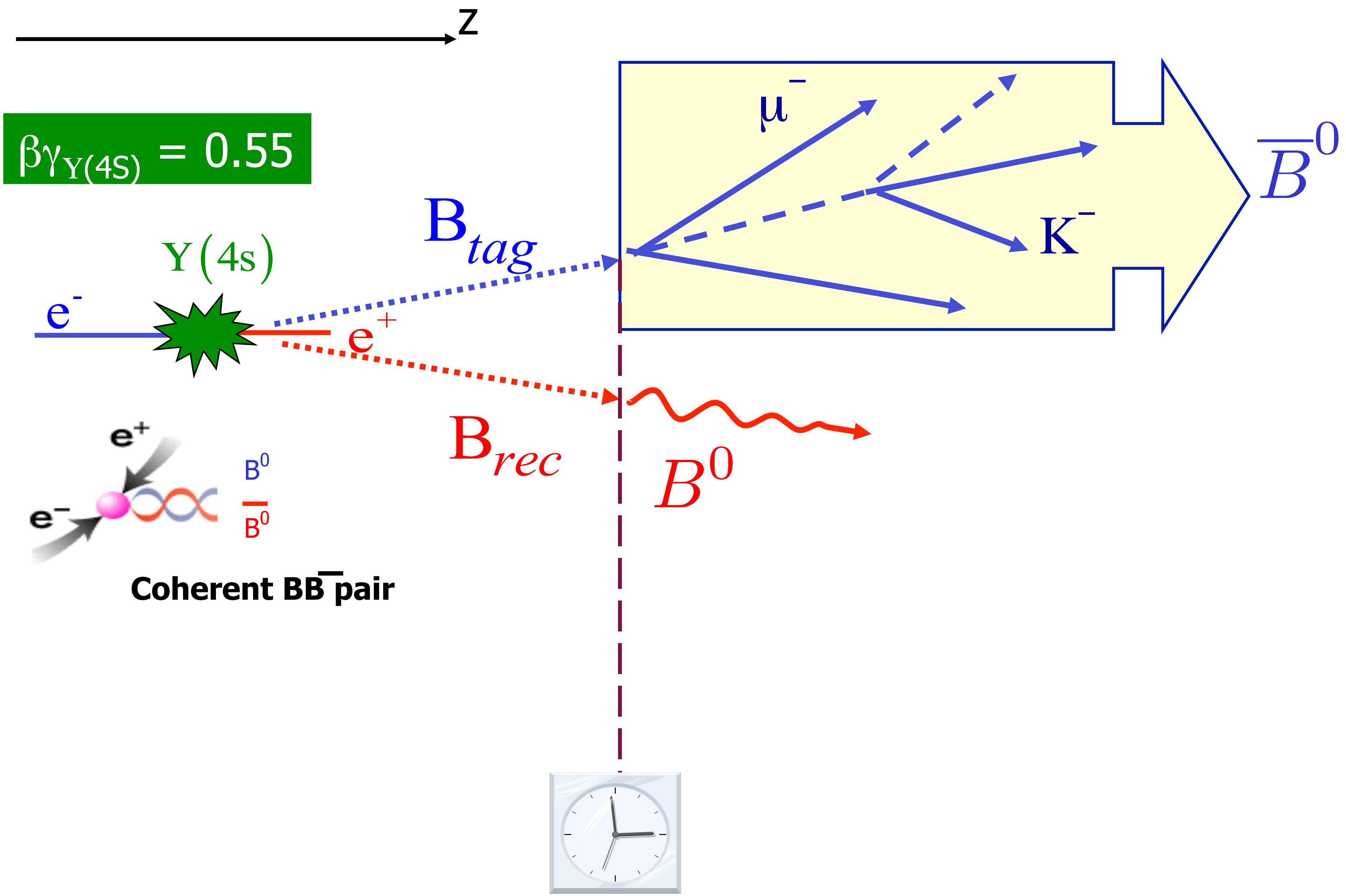
Time Evolution of $\Upsilon(4S) \to B^0\bar{B}^0$



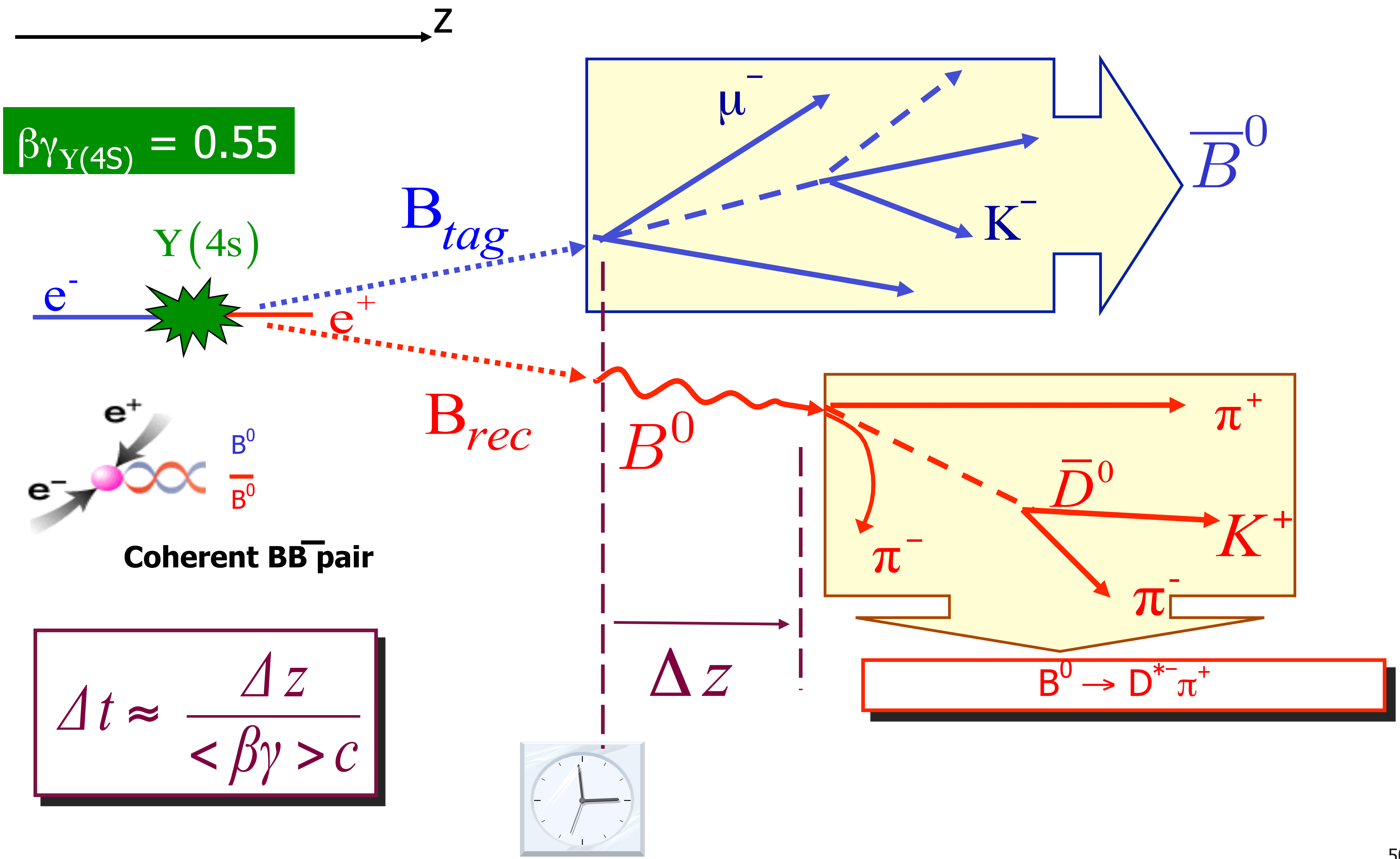
Time Evolution of $\Upsilon(4S) \rightarrow B^0\overline{B^0}$



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

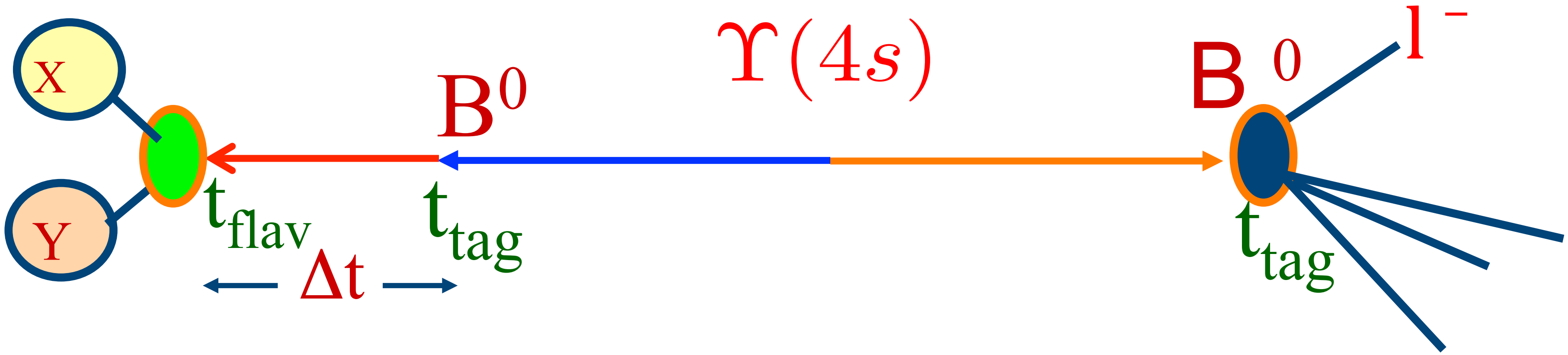


Time Evolution of $\Upsilon(4S) \to B^0\overline{B^0}$



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

Quantum Correlation at $\Upsilon(4S)$



- 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)

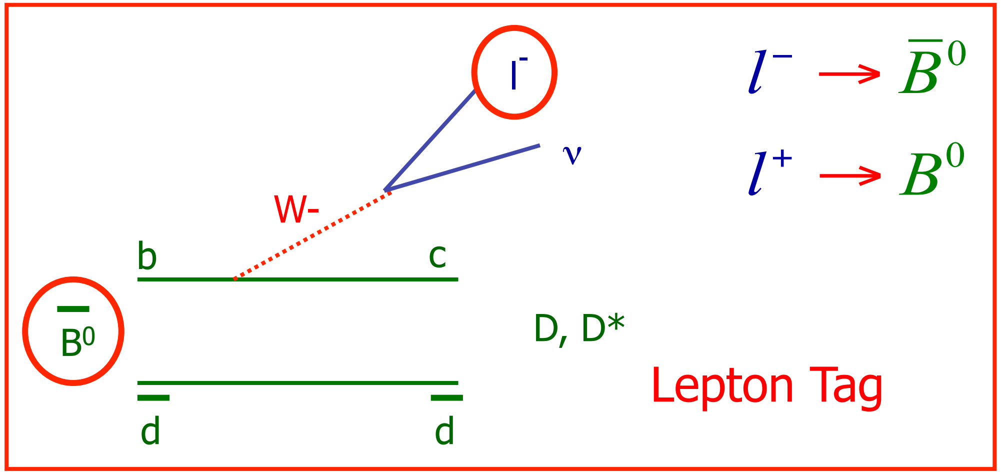
- At $t > t_{tag}$, B^0 has some probability to oscillate into B^0 before it decays at time t_{flav} into a flavor specific state

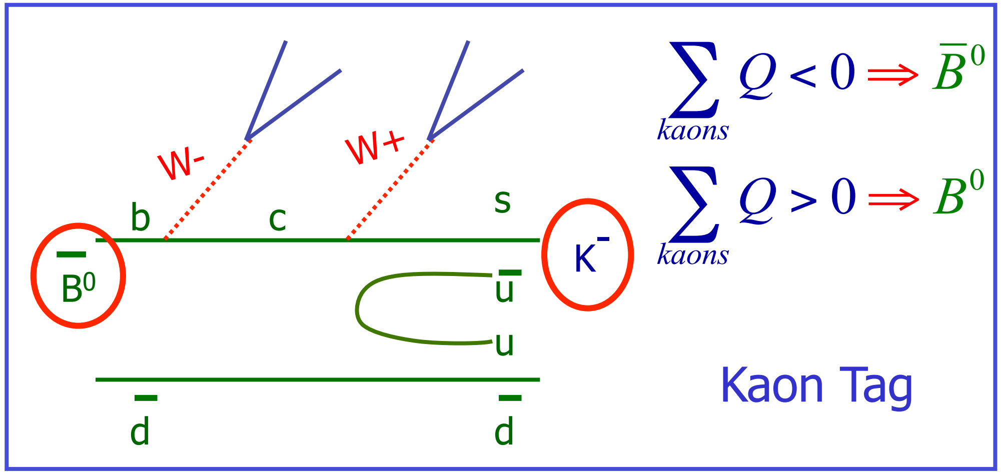
- Two possibilities in the $\Upsilon(4S)$ event depending on whether the 2nd B oscillated or not:

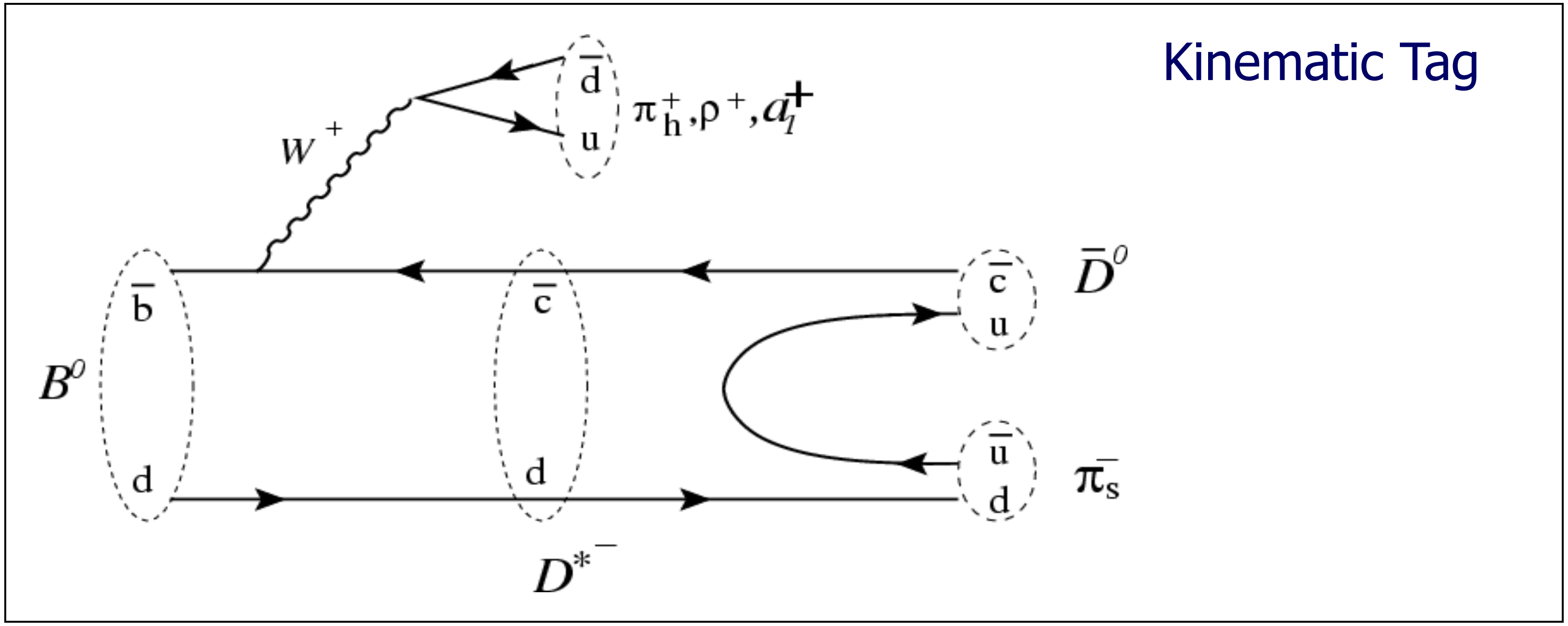
$$\text{no oscillation/mixing} \Rightarrow B^0\ \bar{B}^0 \text{ in final state}$$

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

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







Flavor Tagging Performance

The large sample of fully reconstructed events provides the precise determination of the tagging parameters required in the CP fit

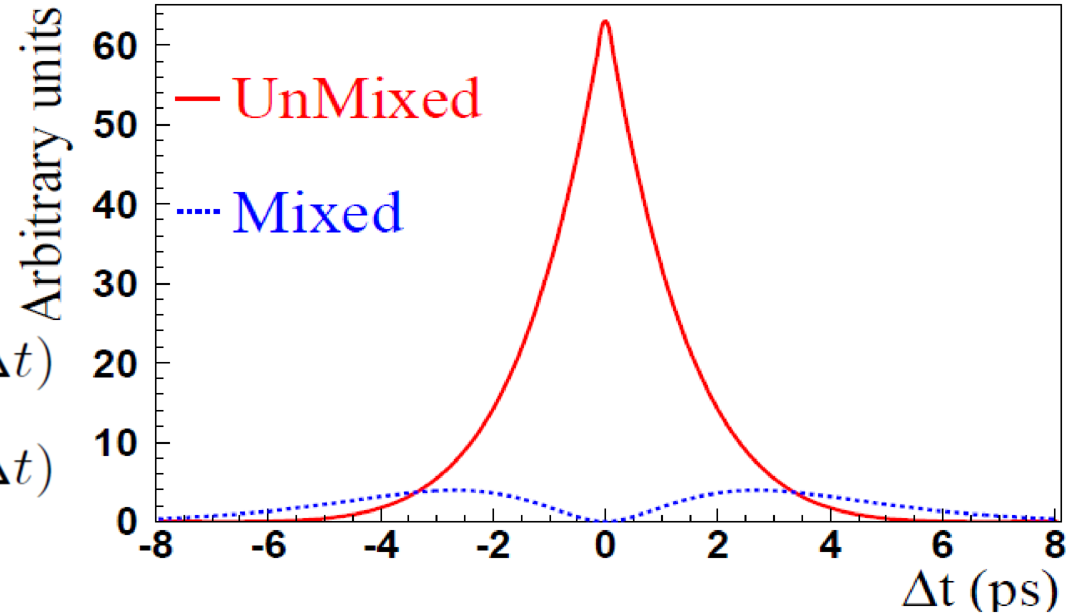
Tagging category	Fraction of tagged events ε (%)	Wrong tag fraction w (%)	$Q = \varepsilon(1-2w)^2$ (%)
Lepton	11.1 ± 0.2	**8.6 ± 0.9**	7.6 ± 0.4
Kaon	**34.7 ± 0.4**	18.1 ± 0.7	14.1 ± 0.6
NT1	7.7 ± 0.2	22.0 ± 1.5	2.4 ± 0.3
NT2	14.0 ± 0.3	37.3 ± 1.3	0.9 ± 0.2
ALL	67.5 ± 0.5		**25.1 ± 0.8**

Highest "efficiency"

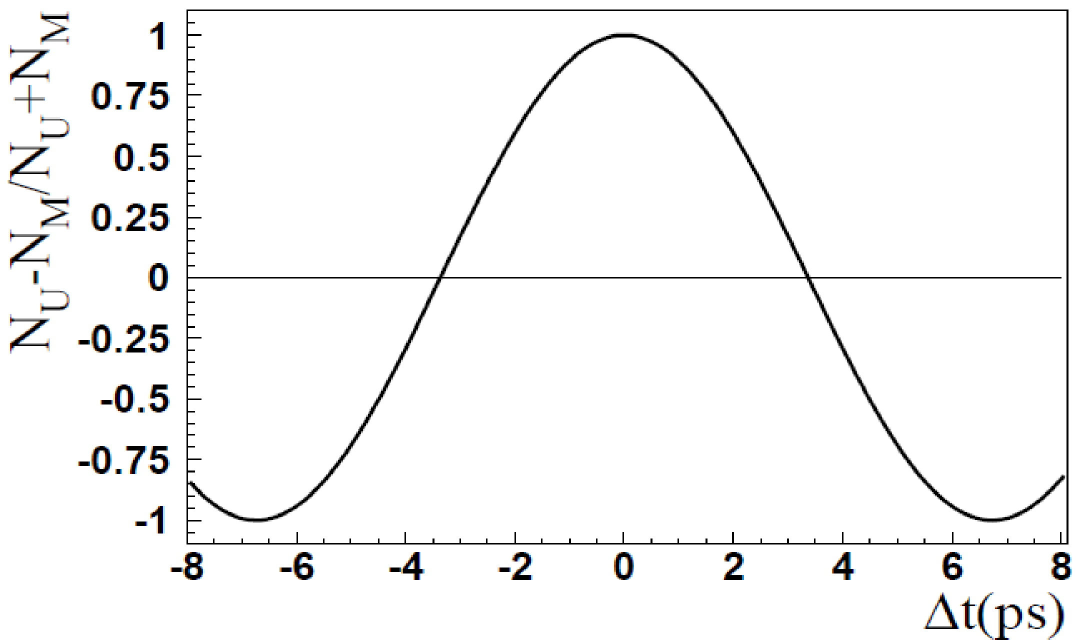
Smallest mistag fraction

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

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



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



Δt Resolution Function

$$R(\delta\Delta t) = (1 - f_{tail} - f_{outl}) \cdot G_{core}(\delta\Delta t, S_{core}, \delta_{core,i})$$ Core

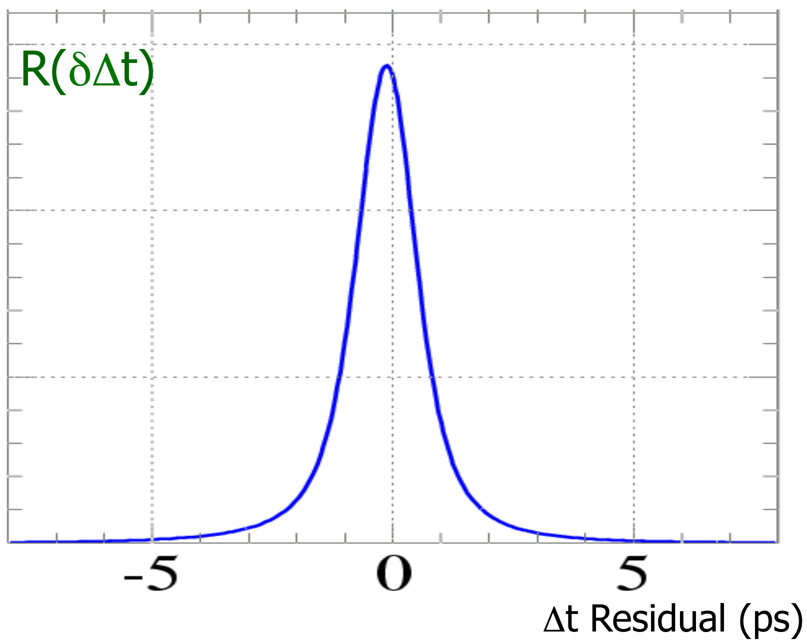
$$+ f_{tail} \cdot G_{tail}(\delta\Delta t, S_{tail}, \delta_{tail})$$ Tail

Outlier $$+ f_{outl} \cdot G_{outl}(\delta\Delta t, \sigma_{outl} = 0\,ps, \delta_{outl} = 8\,ps)$$

$$\sigma_{core} = S_{core} \cdot \sigma_{\Delta t}^{evt}$$

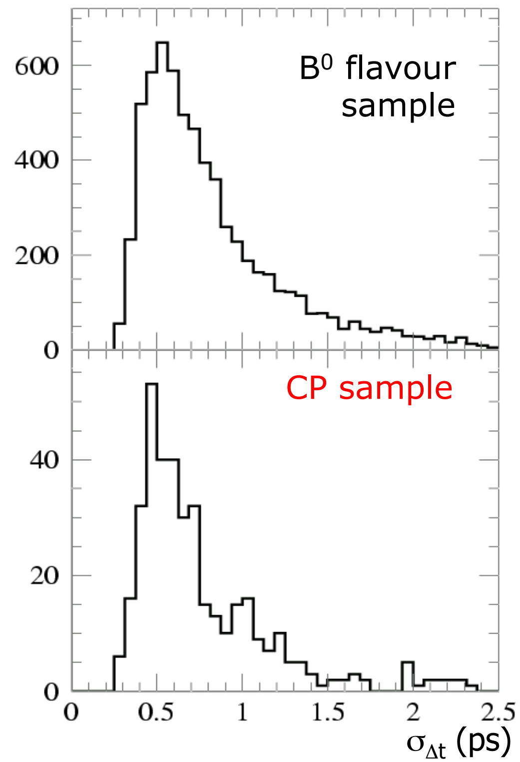
$$\sigma_{tail} = S_{tail} \cdot \sigma_{\Delta t}^{evt}$$

Use the event-by-event uncertainty on Δt



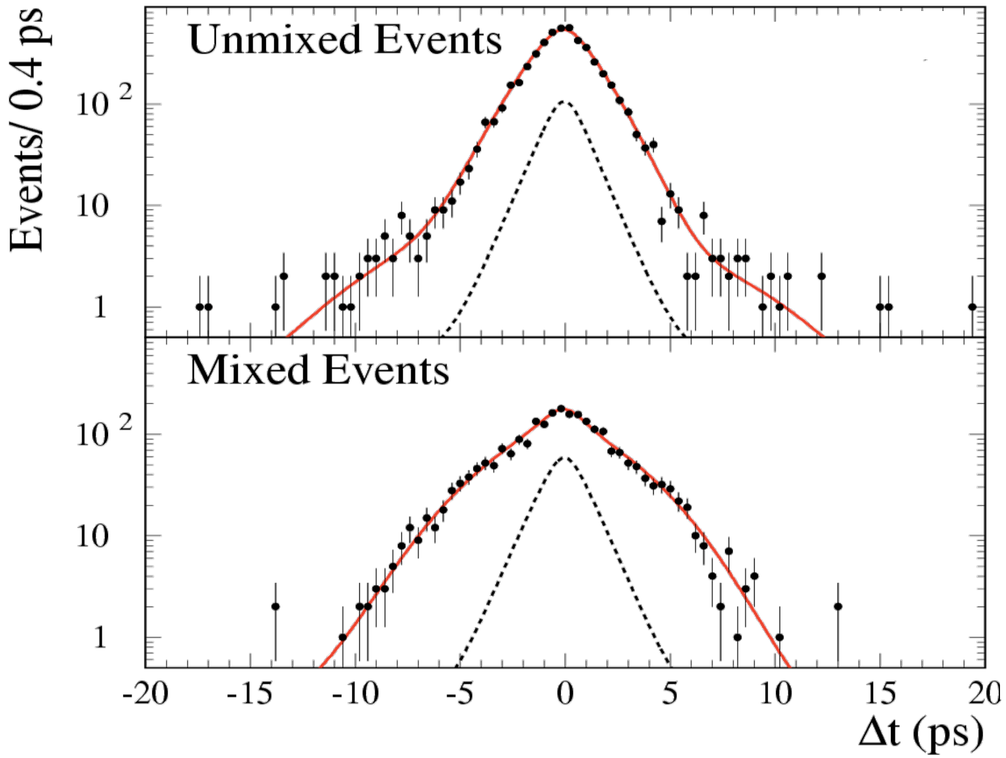
Parameter
S_{Core}
S_{Tail}
f_{Tail} (%)
f_{Outlier} (%)
$\delta_{\text{Core,Lepton}}$
$\delta_{\text{Core,Kaon}}$
$\delta_{\text{Core,NT1}}$
$\delta_{\text{Core,NT2}}$
δ_{Tail}

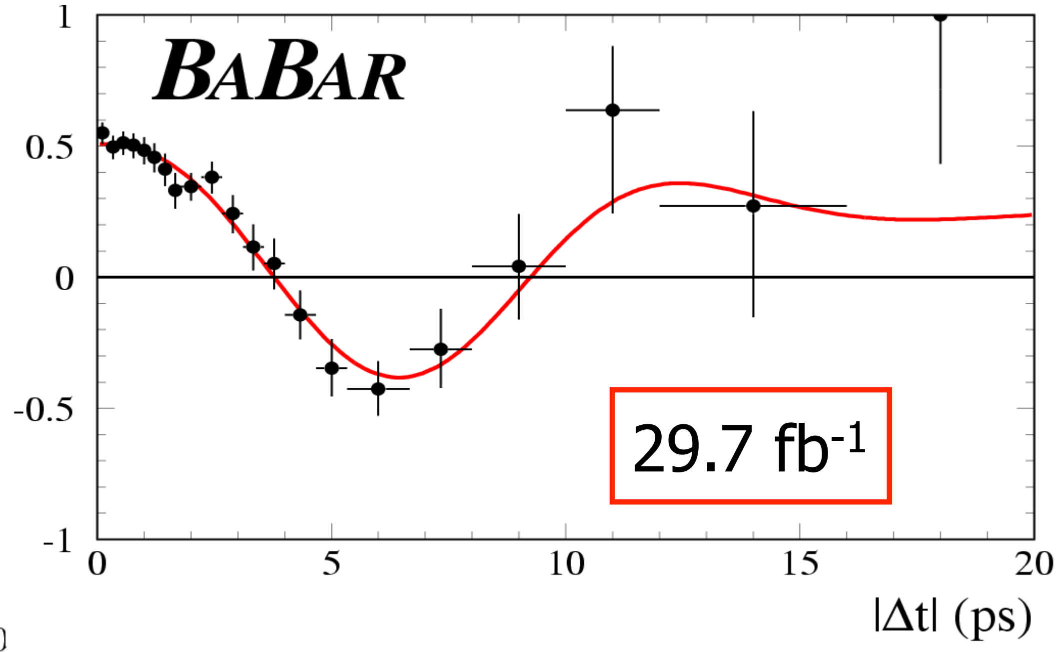
Different bias scale factor
For each tagging category



$B^0\overline{B}^0$ Mixing Fit Result

$$Asym\,(\Delta t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \sim (1 - 2\langle w \rangle) \times \cos(\Delta m_d \Delta t)$$





Δm_d = 0.516 ± 0.016 (stat) ± 0.010 (syst) ps^{-1}

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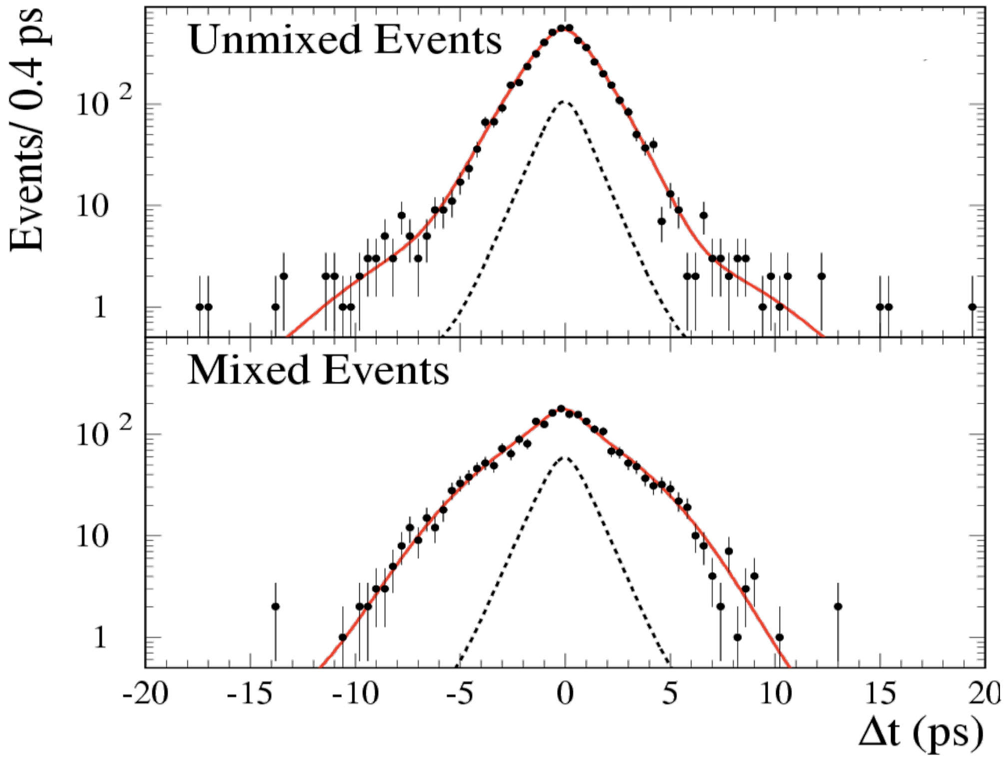

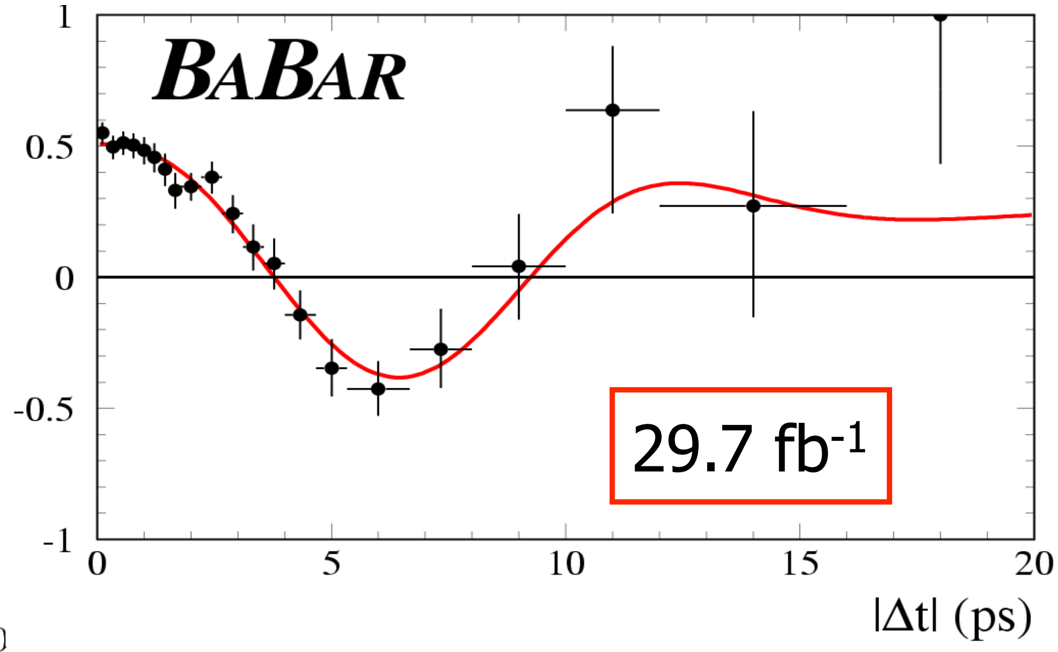

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