Penguin pollution in B! J/ψ K_S decay

Hsiang-nan Li

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Outlines

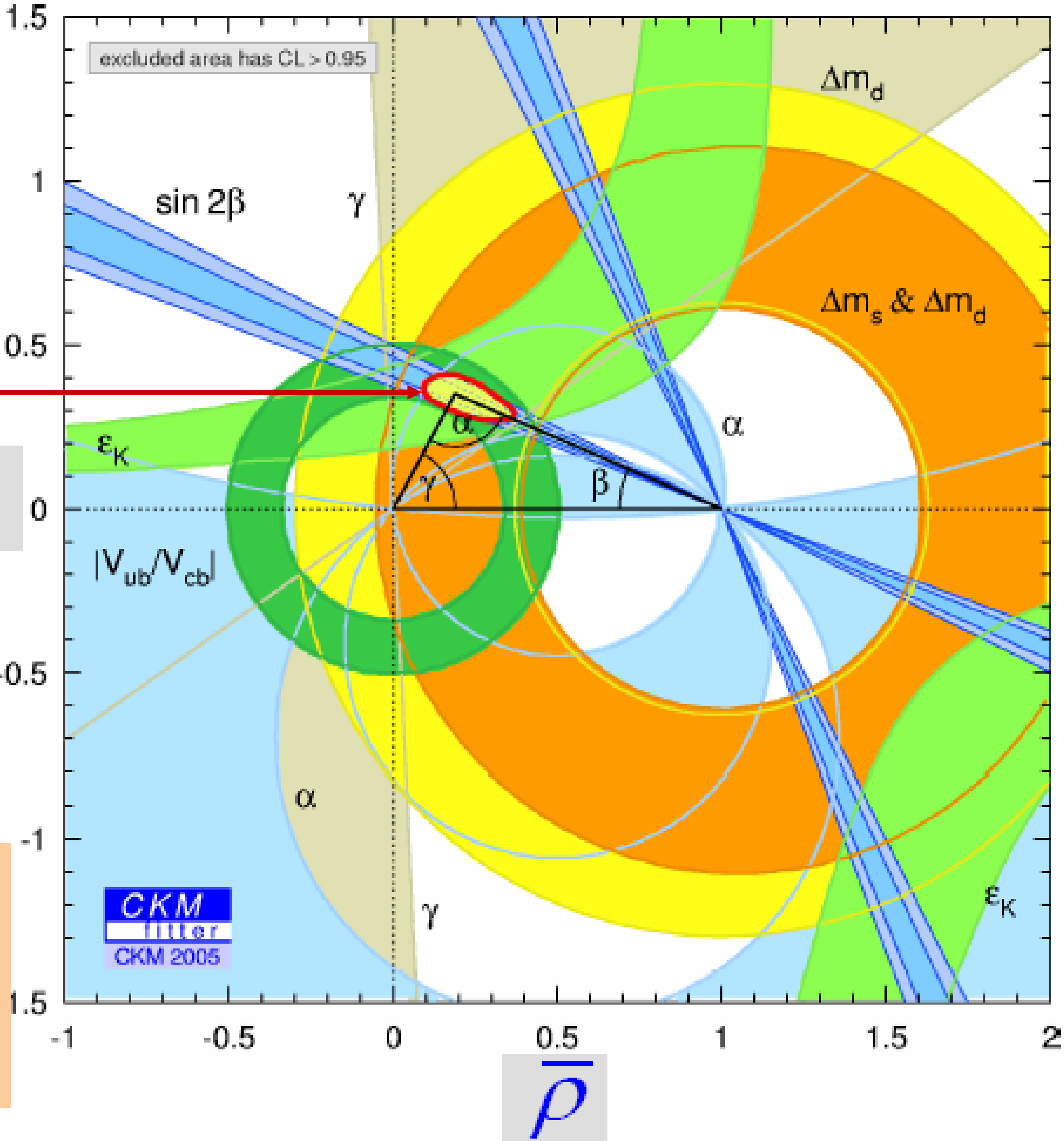
- Introduction
- B-Bbar mixing
- Penguin correction
- Conclusion

Introduction

- Tree-dominated B^0! J/ψ K_S is the golden mode for extracting sin(2ϕ_1) from $S_{J/\psi\ K_S}$.
- Penguin pollution is believed to be negligible, but a complete and reliable estimate of its effect is not yet available.
- This estimate is essential for precision measurement, ie., for revealing new physics.

Constraints on (ρ, η)

If no overlap…
New physics?



Combined *BABAR* and Belle data; plots courtesy of CKM fitter group.

Previous estimates

- Boos, Mannel, Reuter (04): naïve estimate
- Only the u-quark loop from tree operators was included. Penguin operators have been overlooked---underestimate.
  $\Delta S_{J/\psi\, K_S} = S_{J/\psi\, K_S}$-sin(2$\phi_1$)» O($10^{-4}$)
- Ciuchini, Pierini, Silvestrini (05): rely on input of B^0! $J/\psi\pi^0$ data to fix the penguin amplitude $\Delta S_{J/\psi\, K_S}$=0.000±0.017» O(10^{-2}).
- Theoretical uncertainty comes from exp error---overestimate.

B-Bbar mixing

Ingredients of the CP Asymmetry Measurement

1. Determine initial state: "tag" using other B

$$A_{CP}(\Delta t) \equiv \frac{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}$$

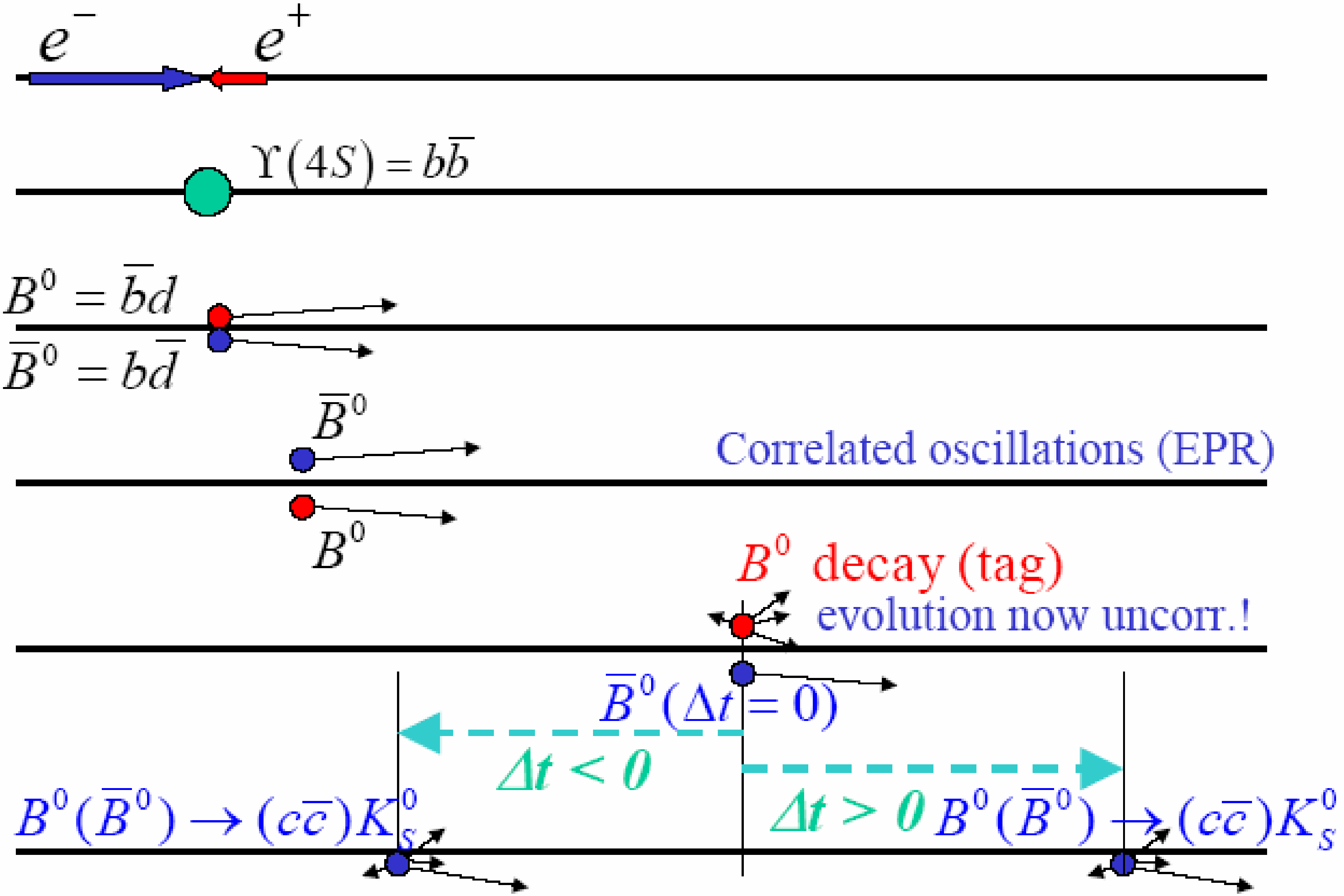
2. Reconstruct the final state system.

3. Measure Δt dependence

Different final states f_{CP} provide access to different CKM elements and hence different CP-violating phases.

Reason for time dependence: one of the amplitudes is due to mixing.

Time-dependent CP asymmetry measurement



Common formalism for $P^0\overline{P}^0$ oscillations

$$H = H_0 + H_w$$

Strong and EM interactions (H_0)

Weak interactions induce (H_w)
$$\begin{cases} P^0 \leftrightarrow \overline{P}^0 \\ P^0 \rightarrow f \\ \overline{P}^0 \rightarrow \overline{f} \end{cases}$$

$$\left|\Psi(t)\right\rangle = a(t)\left|P^0\right\rangle + b(t)\left|\overline{P}^0\right\rangle + \sum_f c_f(t)\left|f\right\rangle$$

We can recast the formalism in terms of a 2-dimensional vector space in which we only care about P^0 and $\overline{P}^0$

$$\left|P^0\right\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \left|1\right\rangle \qquad \left|\overline{P}^0\right\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \left|2\right\rangle$$

← very important to remember this!

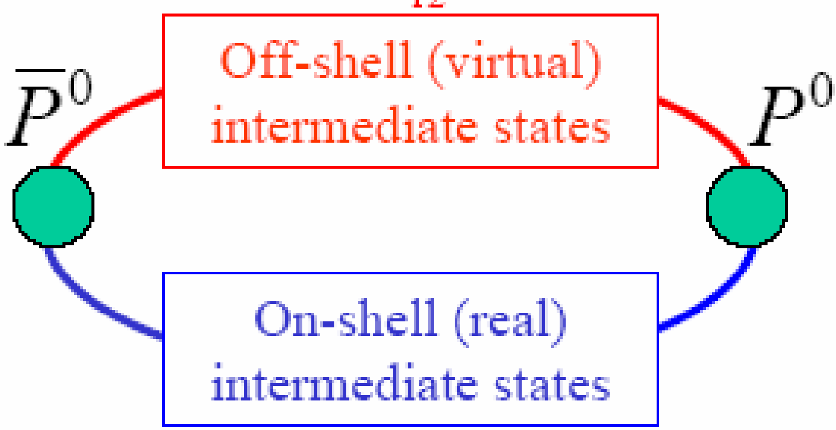
$$\boldsymbol{H}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \qquad \boldsymbol{H}^\dagger \neq \boldsymbol{H}$$

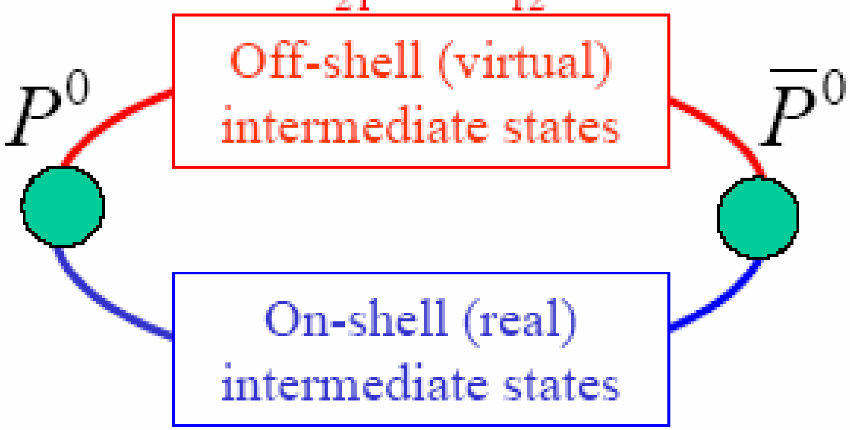
Results from 2nd order time-dependent pert. theory

Get specific form of ***H*** in terms of matrix elements of H_w.

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

mass matrix — crucial factor! — decay matrix





Solution to the eigenvalue problem

$$\boldsymbol{H} = H_{11}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \begin{pmatrix}0 & H_{12}\\ H_{21} & 0\end{pmatrix} = H_{11}\boldsymbol{I} + \boldsymbol{K}$$

H, ***K*** have same eigenvectors.

$$\begin{pmatrix}0 & H_{12}\\ H_{21} & 0\end{pmatrix}\begin{pmatrix}p\\ q\end{pmatrix} = \mu\begin{pmatrix}p\\ q\end{pmatrix} \quad \Rightarrow \quad \mu^2 = H_{12}H_{21}$$

$$\Rightarrow \quad \alpha \equiv \frac{q}{p} = \left(\frac{H_{21}}{H_{12}}\right)^{1/2} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right)^{1/2}$$

To get eigenvalues of ***H***, just add H_{11}

$$\mu_\pm = H_{11} \pm (H_{12}H_{21})^{1/2}$$

$$= M_\pm - \tfrac{i}{2}\Gamma_\pm$$

$$M_\pm = M \pm \mathrm{Re}(H_{12}H_{21})^{1/2}$$

$$\Gamma_\pm = \Gamma \mu 2 \,\mathrm{Im}(H_{12}H_{21})^{1/2}$$

$$\Delta M = -2\,\mathrm{Re}(H_{12}H_{21})^{1/2} \qquad \Delta\Gamma = 4\,\mathrm{Im}(H_{12}H_{21})^{1/2}$$

Time evolution of the mass eigenstates

We have obtained eigenstates of ***H*** in terms of superpositions of the flavor-eigenstates:

$$\left|P^0_+\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left(\left|P^0\right\rangle + \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\left|P^0_-\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}}\left(\left|P^0\right\rangle - \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\alpha \equiv \frac{q}{p} = \left(\frac{M^*_{12} - \frac{i}{2}\Gamma^*_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}\right)^{1/2}$$

Since these are the eigenstates of ***H***, their time dependence is simple!

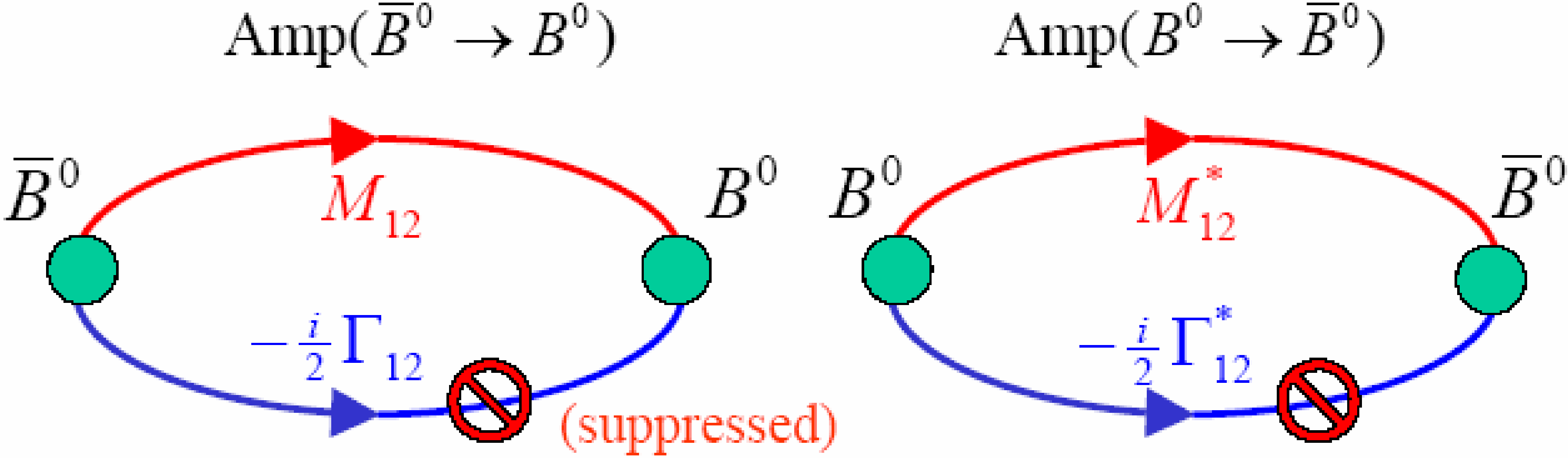
$$\left|P^0_+(t)\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}} e^{-i(M_+ - \frac{i}{2}\Gamma_+)t}\left(\left|P^0\right\rangle + \alpha\left|\bar{P}^0\right\rangle\right)$$

$$\left|P^0_-(t)\right\rangle = \frac{1}{\sqrt{1+|\alpha|^2}} e^{-i(M_- - \frac{i}{2}\Gamma_-)t}\left(\left|P^0\right\rangle - \alpha\left|\bar{P}^0\right\rangle\right)$$

exponential time dependence: see prev. page

Phenomenology of $B^0\overline{B}^0$ Oscillations

Oscillations in the $B\overline{B}$ and $K\overline{K}$ systems have very different parameters! This is due to different CKM factors and different intermediate states in the mixing diagrams.



M_{12}: Dominated by $t\bar{t}$ intermediate states; can be calculated reasonably well using input from lattice QCD

Γ_{12}: Small! Few on-shell intermediate states that both B and $\overline{B}$ can reach. (These are the states both can actually decay into.)

Computing the CP asymmetry for final states common to B^0 and $\bar{B}^0$

Time evolution of tagged states

$$\left|B^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle - i\cdot\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\bar{B}^0\right\rangle\right)$$

$$\left|\bar{B}^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|\bar{B}^0\right\rangle - i\cdot\frac{1}{\alpha}\cdot\sin\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle\right)$$

We have used $\Delta\Gamma/\Gamma << 1$ and set $\Gamma \cong \Gamma_1 \cong \Gamma_2$ $\quad M = \frac{1}{2}(M_+ + M_-)$

Goal: calculate $\begin{cases} \left\langle f_{CP}\right|H\left|B^0(t)\right\rangle \\ \left\langle f_{CP}\right|H\left|\bar{B}^0(t)\right\rangle \end{cases}$ $\quad f_{CP}$ = CP eigenstate

$\left\langle f_{CP}\right|H$: Simply project above eq'ns onto this!

Decay amplitudes for $B^0(t) \rightarrow f_{CP}$ vs. $\overline{B}^0(t) \rightarrow f_{CP}$

$$\langle f_{CP} | H | B^0(t) \rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt} \langle f_{CP} | H | B^0 \rangle \left(\cos\frac{\Delta M \cdot t}{2} - i \cdot \alpha \cdot \frac{\langle f_{CP} | H | \overline{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} \sin\frac{\Delta M \cdot t}{2} \right)$$

$$\langle f_{CP} | H | \overline{B}^0(t) \rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt} \langle f_{CP} | H | \overline{B}^0 \rangle \left(\cos\frac{\Delta M \cdot t}{2} - i \cdot \frac{1}{\alpha} \cdot \frac{\langle f_{CP} | H | B^0 \rangle}{\langle f_{CP} | H | \overline{B}^0 \rangle} \sin\frac{\Delta M \cdot t}{2} \right)$$

blue: mixing green: decay

The key quantity in these CP asymmetries is:

$$\lambda \equiv \alpha \cdot \frac{\langle f_{CP} | H | \overline{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \cdot \frac{\langle f_{CP} | H | \overline{B}^0 \rangle}{\langle f_{CP} | H | B^0 \rangle}$$

Calculation of the time-dependent CP asymmetry

$$A_{f_{CP}}(t) = \frac{\left|\left\langle f_{CP}\middle|H\middle|\overline{B}^0(t)\right\rangle\right|^2 - \left|\left\langle f_{CP}\middle|H\middle|B^0(t)\right\rangle\right|^2}{\left|\left\langle f_{CP}\middle|H\middle|\overline{B}^0(t)\right\rangle\right|^2 + \left|\left\langle f_{CP}\middle|H\middle|B^0(t)\right\rangle\right|^2}$$

$$= \frac{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)}$$

$$A_{f_{CP}}(t) = S \cdot \sin(\Delta m \cdot t) - C \cdot \cos(\Delta m \cdot t)$$

$$S = \frac{2 \cdot \mathrm{Im}(\lambda)}{1+|\lambda|^2} \qquad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

1 decay amplitude:

$$|\lambda| = 1 \quad \Rightarrow \quad S = \mathrm{Im}(\lambda), \quad C = 0$$

$$A_{f_{CP}}(t) = \mathrm{Im}(\lambda) \cdot \sin(\Delta m \cdot t)$$

Angles of the unitarity triangle

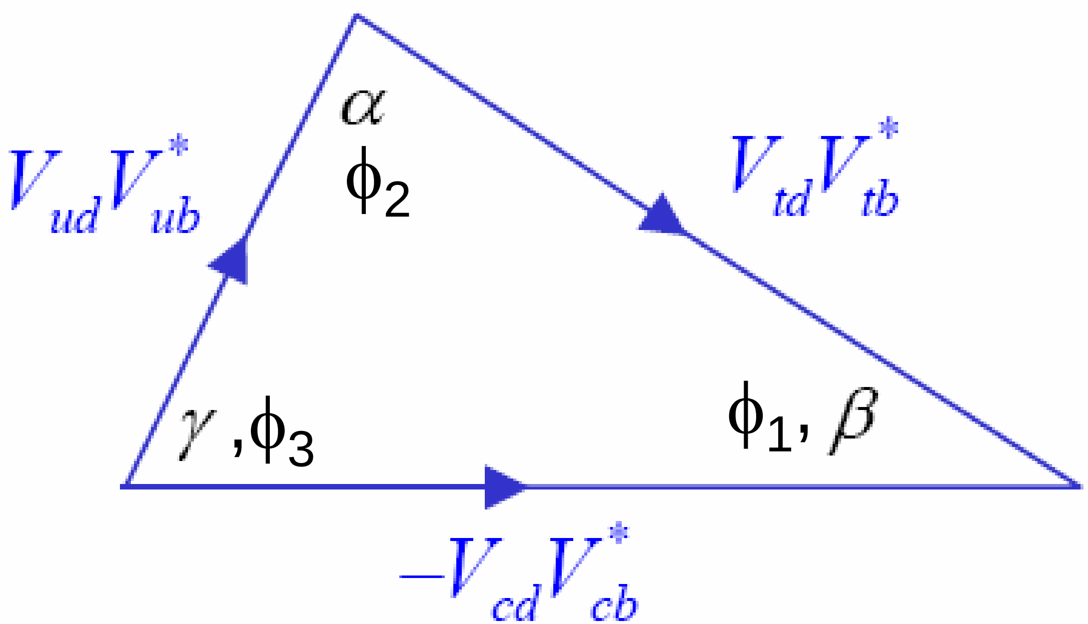
Consider two complex numbers z_1 and z_2.

$$z_1 = |z_1| e^{i\theta_1} \qquad z_2 = |z_2| e^{i\theta_2} \quad \Rightarrow \quad \frac{z_2/|z_2|}{z_1/|z_1|} = e^{i(\theta_2-\theta_1)} \qquad \arg\left(\frac{z_2}{z_1}\right) = \theta_2 - \theta_1$$

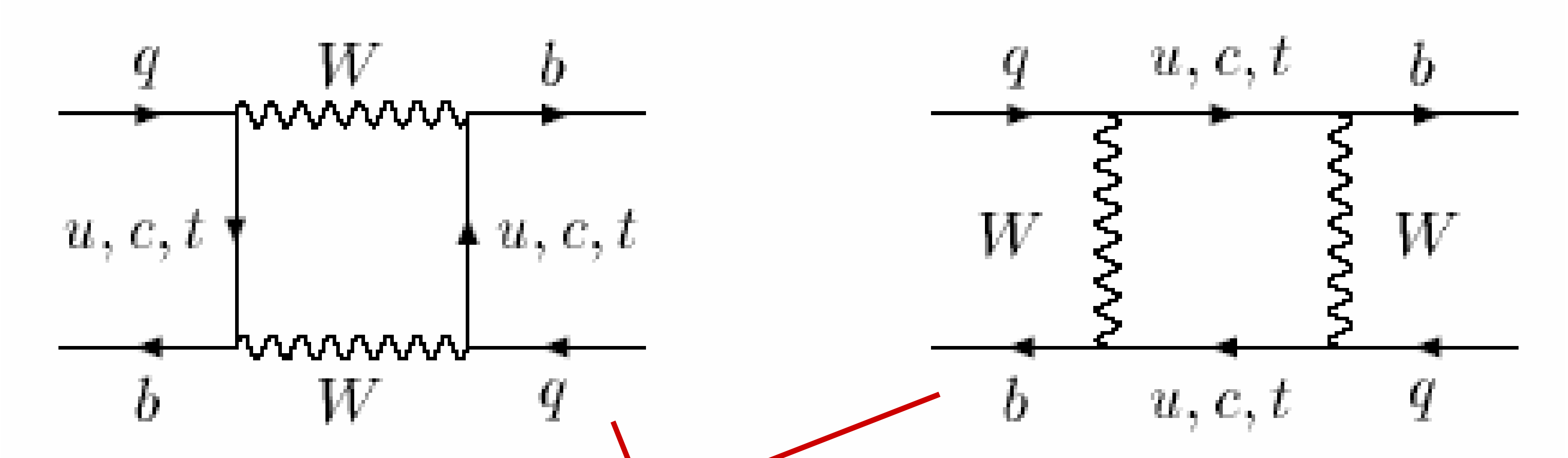
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



Calculating λ



$$B^0 \to J/\psi K_S^0 \quad \lambda = (-1) \cdot \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \cdot \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \quad \mathrm{Im}(\lambda) = \sin(2\beta)$$

$$(b \to c\bar{c}s) \times (K^0 \to K_S^0)$$

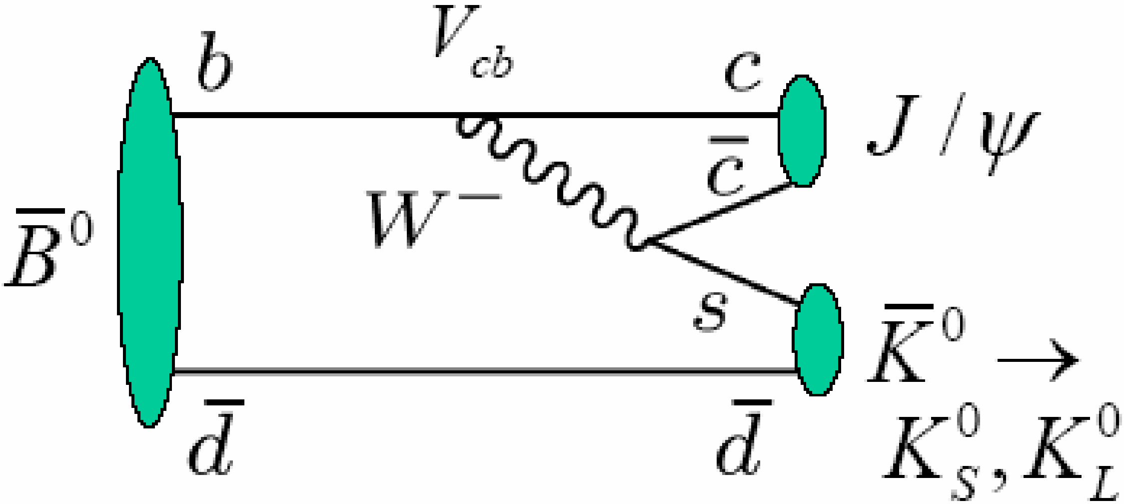
decay

K-Kbar mixing

Final states for sin(2β) from charmonium

- To obtain interference between direct decay and decay after oscillation, must use final states that both B^0 and $\bar{B}^0$ can decay to.

$$B^0(\bar{B}^0) \to J/\psi K_S^0$$
$$\to J/\psi K_L^0$$
$$\to \psi(2S) K_S^0$$
$$\to \chi_{c1} K_S^0$$
$$\to \eta_c K_S^0$$
$$\to J/\psi K^{*0}$$



Two distinct final states:
1. $\pi^+\pi^-$ (→K_S)
2. long flight-length & interaction in calorim. →K_L

Penguin correction

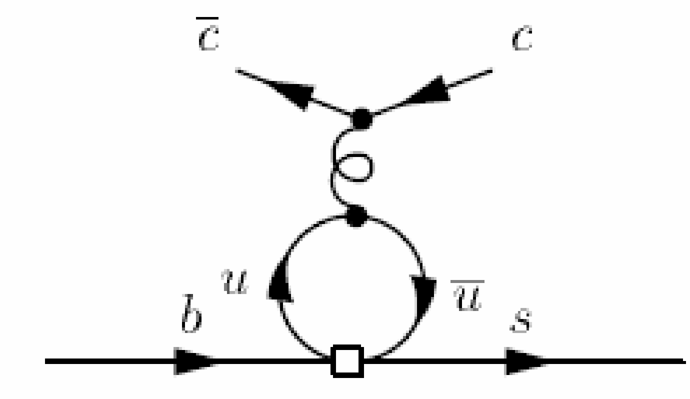
Sources of ΔS

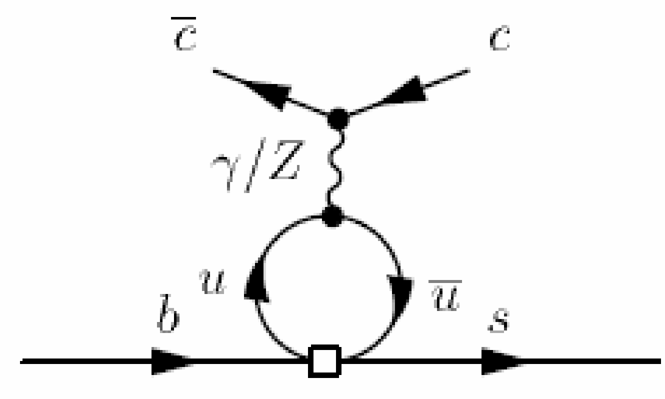
- Corrections to the B-Bbar mixing, to the decay, to the K-Kbar mixing cause ΔS.
- Will concentrate on correction to the decay---penguin pollution.
- If the decay involves additional amplitude with different phase
  $V_{cs}{}^*V_{cb}$! $V_{cs}{}^*V_{cb} + r\ V_{us}{}^*V_{ub}$, S
  deviates from $\sin(2\phi_1)$, ΔS» O(r).
- Direct CP asymmetry A deviates from 0.
- How small is r?

Penguin pollution

$$\mathcal{A}(B^0 \to J/\psi K^0) = V_{cb}^* V_{cs} \left(\mathcal{A}^{(c)}_{J/\psi K^0} + \mathcal{A}^{(t)}_{J/\psi K^0} \right) + V_{ub}^* V_{us} \left(\mathcal{A}^{(u)}_{J/\psi K^0} + \mathcal{A}^{(t)}_{J/\psi K^0} \right)$$

- $A^{(u)}{}_{J/\psi\ K_S}$: u-quark loop

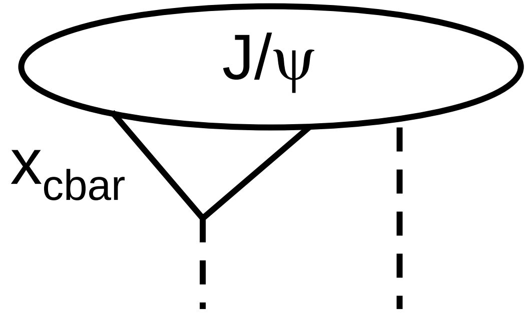


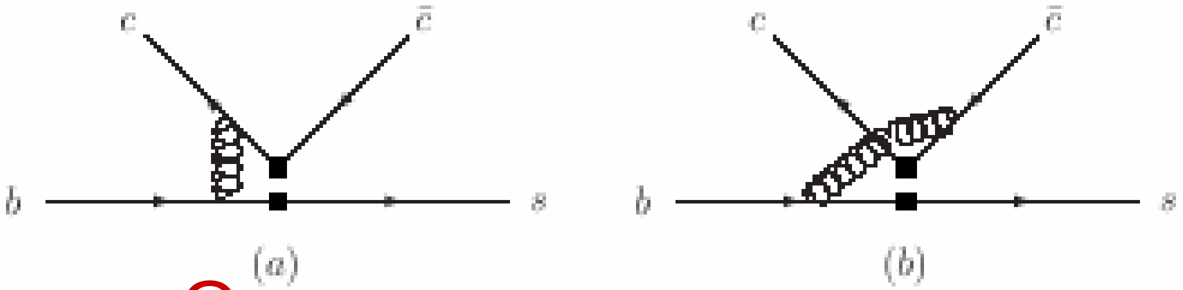


- $A^{(t)}{}_{J/\psi\ K_S}$: penguin contribution through $V_{tb}{}^* V_{ts} = -V_{cb}{}^* V_{cs} - V_{ub}{}^* V_{us}$

U-quark loop

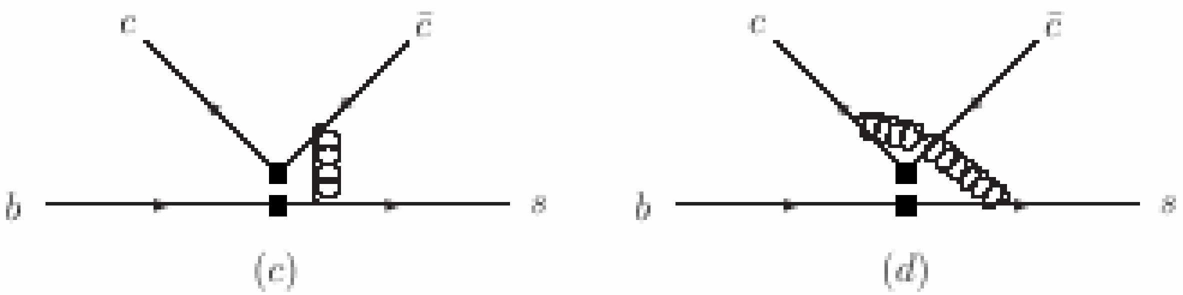
- U-quark loop is small.
- The gluon emission produces the color-octet c-cbar pair. Needs one more gluon.
- If it is hard, higher order, negligible (30%).
- If it is soft, three-parton distribution amplitudes are antisymmetric under interchange of x_c and x_{cbar}. Vanish exactly.
- The photon emission is suppressed by small coupling α (5%).





$O_{3\text{-}10}$

x $F^{BK}(m_{J/\psi})$

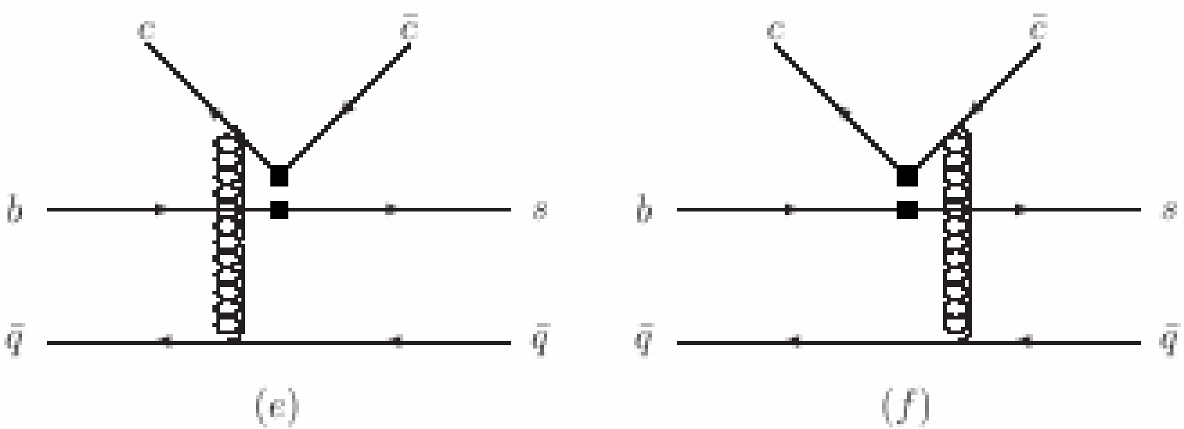


Leading-power penguin contribution at $O(\alpha_s)$

Factorizable amplitude

Compute them in QCDF

End-point singularity from x_q! 0 in QCDF



Nonfactorizable amplitude

Compute them in PQCD

Results

- Penguin pollution is of O(10^{-3})!

$$B(B^0 \to J/\psi K^0) \; = \; \left(6.6^{+3.7\,(+3.7)}_{-2.3\,(-2.3)}\right) \times 10^{-4} \,,$$

$$\Delta S^{\mathrm{decay}}_{J/\psi K_S} \; = \; \left(7.2^{+2.4\,(+1.2)}_{-3.4\,(-1.1)}\right) \times 10^{-4} \,,$$

$$A^{\mathrm{decay}}_{J/\psi K_S} \; = \; -\left(16.7^{+6.6\,(+3.8)}_{-8.7\,(-4.1)}\right) \times 10^{-4} \,,$$

Complete uncertainty

Hadronic uncertainty

- Data $B(B^0 \to J/\psi K^0) = (8.72 \pm 0.33) \times 10^{-4}$
- A larger form factor F^{BK} can account for the central value of the data.

Conclusion

- Perform the most complete analysis of penguin effect up to leading power in $1/m_b$ and to NLO in α_s. It is of $O(10^{-3})$.
- Previous estimate $O(10^{-4})$ by Mannel et al. is due to the overlook of penguin operators.
- $O(10^{-2})$ by Ciuchini et al. comes from exp uncertainty.
- Our result provides a SM reference for verifying new physics from $B^0 \to J/\psi K_S$ data.