CP Physics with BABAR

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Summary:

- **Mixing of neutral B mesons**
- **Formalism for Coherent B $\overline{\mathrm{B}}$ states**
- **CP violation in B decays**
- **CP violation in the Standard Model**
- **Experimental Requirements to Search for CP violation**
- **Hadronic vs e^+e^- colliders**
- **BaBar detector**
- **Performances of BaBar**
- **Example of CP analysis from BaBar**

Introduction

CP violation has been so far observed only in the K system

The K-decay observations, together with other measurements, place constraints on the parameters of the CKM matrix

Many CP-violating effects are expected in B decays: some cleanly predicted by the Standard Model.

If enough independent observations of CP violation in B decays can be made, it will be possible to test the Standard Model predictions for CP violation.
CP violation can be related to the disappearance of antimatter from the Universe

Charge Conjugation C interchanges particles and antiparticles

Parity P sends (t, x) -> (t, -x)

Electromagnetic and strong interactions are symmetric w.r.t. C and P separately

Weak interactions violate C and P separately

CP transformation properties:

term	$\overline{\psi}_i\psi_j$	$i\overline{\psi}_i\gamma^5\psi_j$	$\overline{\psi}_i\gamma^\mu\psi_j$	$\overline{\psi}_i\gamma^\mu\gamma^5\psi_j$
CP−transformed term	$\overline{\psi}_j\psi_i$	$-i\overline{\psi}_j\gamma^5\psi_i$	$-(-1)^\mu\overline{\psi}_j\gamma^\mu\psi_i$	$-(-1)^\mu\overline{\psi}_j\gamma^\mu\gamma^5\psi_i$

term	H	A	$W^{\pm\mu}$	∂_μ
CP−transformed term	H	$-A$	$-(-1)^\mu W^{\mp\mu}$	$(-1)^\mu\partial_\mu$

$(-1)^\mu = 1$ for $\mu=0$, $(-1)^\mu = -1$ for $\mu=1,2,3$

Each combination of fields and derivatives that appears in the Lagrangian transforms under CP to its hermitian conjugate

There are coefficients in front of these expressions which represent either coupling constants or particle masses

If any of these quantities are complex, then the coefficients in front of CP-related terms are complex conjugates of each other.

In such a case, CP is not necessarily a good symmetry of the Lagrangian.

There can be CP-violating effects, namely rate differences between pairs of CP conjugate processes.

Mixing of Neutral B Mesons

An arbitrary linear combination of the neutral B-meson flavor eigenstates

$$a|B^0\rangle + b|\overline{B}^0\rangle,$$

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

is governed by a time-dependent Schrodinger equation
M and Γ are 2x2 Hermitian matrices

The light B_L and heavy B_H mass eigenstates are given by:

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

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

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

The mass difference Δm_B and width difference $\Delta\Gamma_B$ between the neutral B mesons are:

$$\Delta m_B \equiv M_H - M_L, \quad \Delta\Gamma_B \equiv \Gamma_H - \Gamma_L$$

Finding the eigenvalues one gets:

$$(\Delta m_B)^2 - \frac{1}{4}(\Delta\Gamma_B)^2 = 4(|M_{12}|^2 - \frac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m_B \Delta\Gamma_B = 4\,\mathcal{R}e(M_{12}\Gamma_{12}^*).$$

$$\frac{q}{p} = -\frac{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}{2(M_{12} - \frac{i}{2}\Gamma_{12})} = -\frac{2(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}$$

$\Delta\Gamma_B$ has never been measured. Expected O(10^{-2})

From B mixing:

$$\Delta m_B/\Gamma_B \sim 0.7$$

One can assume:

$$\Delta\Gamma_B << \Delta \mathbf{m_B}$$

and the expressions of the previous slide become:

$$\Delta m_B = 2|M_{12}|, \quad \Delta\Gamma_B = 2\,\mathcal{R}e(M_{12}\Gamma^*_{12})/|M_{12}|$$

$$q/p = -|M_{12}|/M_{12}.$$

The time evolution of a a state that at t=0 is a pure B^0 ($\overline{B}^0$) is:

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

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

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m_B\, t/2),$$

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

$$M = 1/2(M_H + M_L)$$

Formalism for Coherent $B\bar{B}$ states

At $e^+ e^-$ collider, at the energy of the Y(4S), the B^0 and $\bar{B}^0$ mesons are produced in a coherent L=1 state

Until one decays, there is exactly one B^0 and one $\bar{B}^0$

Once one particle decays, the other continues to evolve and events with two B^0 (or two $\bar{B}^0$) decays are possible with probability governed by the time between the two decay

Two B, coming from Υ decay, are identified by the angle θ that they make with the e^- direction in the Υ rest frame:

$$S(t_f, t_b) = \frac{1}{\sqrt{2}}\{B^0_{\rm phys}(t_f, \theta, \phi)\overline{B}^0_{\rm phys}(t_b, \pi-\theta, \phi+\pi) - \overline{B}^0_{\rm phys}(t_f, \theta, \phi)B^0_{\rm phys}(t_b, \pi-\theta, \phi+\pi)\}\sin(\theta)$$

Using the expressions for B evolution:

$$S(t_f, t_b) = \frac{1}{\sqrt{2}}e^{-(\Gamma/2+iM)(t_f+t_b)}\{\cos[\Delta m_B(t_f-t_b)/2](B^0_f\overline{B}^0_b - \overline{B}^0_f B^0_b) - i\sin[\Delta m_B(t_f-t_b)/2](\frac{p}{q}B^0_f B^0_b - \frac{q}{p}\overline{B}^0_f\overline{B}^0_b)\}\sin(\theta_f),$$

where:

B_f is moving forward ($\theta_f < \pi/2$, Φ)

B_b is moving backward ($\pi - \theta_f$, $\Phi + \pi$)

The amplitude for one B decaying to the state f_1 at time t_1 and the other B decaying to the state f_2 at time t_2 is :

$$A(t_1,t_2) = \frac{1}{\sqrt{2}} e^{-(\Gamma/2+iM)(t_1+t_2)} \zeta(t_1,t_2) \{ \cos[\Delta m_B (t_1-t_2)/2] (A_1 \overline{A}_2 - \overline{A}_1 A_2)$$

$$-i \sin[\Delta m_B (t_1-t_2)/2] (\tfrac{p}{q} A_1 A_2 - \tfrac{q}{p} \overline{A}_1 \overline{A}_2) \} \sin(\theta_1),$$

where:

A_i is the amplitude for a B to decay to the state f_i

$\overline{A}_i$ is the amplitude for a $\overline{B}$ to decay to the same state f_i

$$\zeta(t_1,t_2) = \begin{cases} +1 & t_1 = t_f,\ t_2 = t_b, \\ -1 & t_1 = t_b,\ t_2 = t_f \end{cases}$$

The time dependent rate can be written as:

$$R(t_1,t_2) = Ce^{-\Gamma(t_1+t_2)}\{(|A_1|^2+|\overline{A}_1|^2)(|A_2|^2+|\overline{A}_2|^2) - 4\,\mathcal{R}e(\frac{q}{p}A_1^*\overline{A}_1)\,\mathcal{R}e(\frac{q}{p}A_2^*\overline{A}_2)$$

$$-\cos(\Delta m_B(t_1-t_2))[(|A_1|^2-|\overline{A}_1|^2)(|A_2|^2-|\overline{A}_2|^2) + 4\,\mathcal{I}m(\frac{q}{p}A_1^*\overline{A}_1)\,\mathcal{I}m(\frac{q}{p}A_2^*\overline{A}_2)]$$

$$+2\sin(\Delta m_B(t_1-t_2))[\mathcal{I}m(\frac{q}{p}A_1^*\overline{A}_1)(\ A_2|^2-|\overline{A}_2|^2) - (|A_1|^2-|\overline{A}_1|^2)\,\mathcal{I}m(\frac{q}{p}A_2^*\overline{A}_2)]\}.$$

To search for CP violation, one looks for event in which:

- **one B decays to a CP eigenstate f_{CP} at time t_{fCP}**
- **the other B decays to a tagging mode with $A_2 = 0$ or $\overline{A}_2 = 0$ at time t_{tag}**

If we take a tagging mode with $A_2 = 0$ and $\overline{A}_2 = \overline{A}_{tag}$, the other B is identified as a B^0 at time $t_2 = t_{tag}$. True also if $t_{fCP} < t_{tag}$

The rate reduces to:

$$R(t_{\rm tag}, t_{f_{CP}}) = Ce^{-\Gamma(t_{\rm tag}+t_{f_{CP}})}|\overline{A}_{\rm tag}|^2|A_{f_{CP}}|^2\{1 + \lambda_{f_{CP}}|^2$$

$$+\cos[\Delta m_B(t_{f_{CP}} - t_{\rm tag})](1 - |\lambda_{f_{CP}}|^2) - 2\sin[\Delta m_B(t_{f_{CP}} - t_{\rm tag})]\,\mathcal{I}m(\lambda_{f_{CP}})\}$$

where:

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

$$\overline{A}_{f_{CP}} = \eta_{f_{CP}}\overline{A}_{\overline{f}_{CP}},$$

η_{CP} is the CP eigenvalues of the state f_{CP}

For the case with $\overline{A}_2 = 0$ and $A_2 = A_{tag}$, the other B is identified as a $\overline{B}^0$ at time t_{tag} and the sign of the cosine and sine terms are reversed in the expression above.

The time dependent CP asymmetry :

$$a_{f_{CP}} = \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}.$$

can be written as:

$$a_{f_{CP}} = \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m_B t) - 2\,\mathcal{I}m\,\lambda_{f_{CP}}\sin(\Delta m_B t)}{1 + |\lambda_{f_{CP}}|^2},$$

CP Violation in B Decays

The possible manifestations of CP violation can be classified in a model-independent way:

- **CP violation in decay, which occurs in both charged and neutral decays, when the amplitude for a decay and its CP conjugate process have different magnitudes**
- **CP violation in mixing, which occurs when the two neutral mass eigenstates cannot be chosen to be CP eigenstates**
- **CP violation in the interference between decays with and without mixing, which occurs in decays into final states that are common to B^0 and $\overline{B}^0$**

CP Violation in Decay

Each contribution to A can be written in three parts: its magnitude A, its weak-phase term $e^{i\phi}$, and its strong phase term $e^{i\delta}$

If several amplitudes contribute to $B^0 \to f$, the amplitude A_f and the CP conjugate amplitude $\overline{A}_{\overline{f}}$ are given by:

$$A_f = \sum_i A_i e^{i(\delta_i + \phi_i)}, \quad \overline{A}_{\overline{f}} = e^{2i(\xi_f - \xi_B)} \sum_i A_i e^{i(\delta_i - \phi_i)}$$

where:

$CP\,|B^0\rangle = e^{2i\zeta_B}\,|\overline{B}^0\rangle \qquad CP\,|\overline{B}^0\rangle = e^{-2i\zeta_B}\,|B^0\rangle$

$CP\,|f\rangle = e^{2i\zeta_f}\,|\overline{f}\rangle \qquad CP\,|\overline{f}\rangle = e^{-2i\zeta_f}\,|f\rangle$

The interesting quantity is:

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| = \left|\frac{\sum_i A_i e^{i(\delta_i - \phi_i)}}{\sum_i A_i e^{i(\delta_i + \phi_i)}}\right| .$$

$$|\overline{A}_{\overline{f}}/A_f| \neq 1 \quad \Longrightarrow \quad CP \text{ violation.}$$

This type of CP violation is called CP violation in decay or direct CP violation.

It results from the CP-violating interference among various terms in the decay amplitude.

CP Violation in Mixing

A quantity that is independent of phase conventions and physically meaningful is:

$$\left|\frac{q}{p}\right|^2 = \left|\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\right|.$$

When CP is conserved, the mass eigenstates must be CP eigenstates. In that case the relative phase between M_{12} and Γ_{12} vanishes

$$q/p| \neq 1 \quad \Longrightarrow \quad CP \text{ violation.}$$

This type of CP violation is here called CP violation in mixing; it is often referred to as indirect CP violation.

It results from the mass eigenstates being different from the CP eigenstates. CP violation in mixing has been observed unambiguously in the neutral kaon system.

For the neutral B system, this effect could be observed through the asymmetries in semileptonic decays:

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

Expected to be small

CP Violation in the Interference Between Decays With and Without Mixing

CP eigenstates, f_{CP} , are accessible in both B^0 and $\overline{B}^0$ decays.
Let's consider:

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

$$\lambda \neq \pm 1 \quad \Longrightarrow \quad CP \text{ violation}$$

It is possible that, to a good approximation, |q/p| = 1 and |A/A| = 1 and still have CP violation:

$$|\lambda| = 1, \quad \mathcal{I}m\,\lambda \neq 0.$$

This type of CP violation is called CP violation in the interference between decays with and without mixing

The asymmetry :

$$a_{f_{CP}} = \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}.$$

that usually is:

$$a_{f_{CP}} = \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m_B t) - 2\,\mathcal{I}m\,\lambda_{f_{CP}}\sin(\Delta m_B t)}{1 + |\lambda_{f_{CP}}|^2},$$

reduces to:

$$a_{f_{CP}} = -\,\mathcal{I}m\,\lambda_{f_{CP}}\sin(\Delta m_B\, t)$$

When it occurs with no CP violation in decay, CP violation in the interference between decays with and without mixing can be cleanly related to Lagrangian parameters

CP violation in the Standard Model

SM accounts for flavor changing quark transition through the coupling of the V-A charged current operator to a W boson:

$$\mathcal{L}_{int} = -\frac{g}{\sqrt{2}}(\mathcal{J}^{\mu} W_{\mu}^{+} + \mathcal{J}^{\mu\dagger} W_{\mu}^{-}).$$

where:

$$\mathcal{J}^{\mu} = \sum_{i,j} V_{ij} J_{ij}^{\mu} = \sum_{i,j} \bar{u}_i \gamma^{\mu} \frac{1}{2}(1-\gamma_5) V_{ij} d_j.$$

V_{ij} **are the elements of the CKM matrix**

i, j run on the three quark generations

Amplitudes for $d_j \rightarrow W^- u_i$ or $\bar{u}_i \rightarrow W^- d_j$ are proportional to V_{ij}

Amplitudes for $\bar{d}_j \rightarrow W^+ \bar{u}_i$ or $u_i \rightarrow W^+ d_j$ are proportional to V^*_{ij}

CKM matrix can be regarded as a rotation from the quark mass eigenstates (d, s, b) to a set of new states (d’, s’, b’) with diagonal coupling to u, c, t

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

A *n* x *n* complex matrix has $2n^2$ real parameters

Unitarity gives *n* constraints for the normalization of each column and $n(n-1)$ constraints from the orthogonality between each pair of columns A unitary matrix has n^2 indipendent real parameters

Of these $1/2x\ n(n-1)$ are real rotation angle, the others are phases

The freedom to select the phases of the quark field can be used to absorb $2n - 1$ phases of the CKM matrix

The number of physical parameters is $n^2 - (2n - 1) = (n-1)^2$

With 3 generations: 3 real rotation angle and 1 phase

Conditions to have CP violation:

angles different from 0**,** $\pi/2$;

phase different from 0, π

$$(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_t^2 - m_u^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2) \neq 0$$

at least 3 generations

J defined by:

$$\mathcal{I}m[V_{ij} V_{kl} V_{il}^* V_{kj}^*] = J \sum_{m,n=1}^{3} \epsilon_{ikm} \epsilon_{jln}$$

must be different from zero

A standard parametrisation of CKM matrix uses the set of angles θ_{12}, θ_{23}, θ_{13} **and** δ_{13}

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

where:

$c_{12} = \cos\theta_{12}$, $s_{12} = \sin\theta_{12}$, . . .

The phase δ_{13} produces the CP violation

In this parametrization:

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta.$$

Wolfenstein parametrization:
expansion in the parameter $\lambda = \sin\theta_C \sim 0.22$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$s_{12} \equiv \lambda, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$$

In this parametrization:

$$J = A^2\eta\lambda^6$$

Unitarity conditions coming from inner products between the columns, can be written as:

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0.$$

and can be rapresented as triangles in the complex plane Expressing them in powers of λ

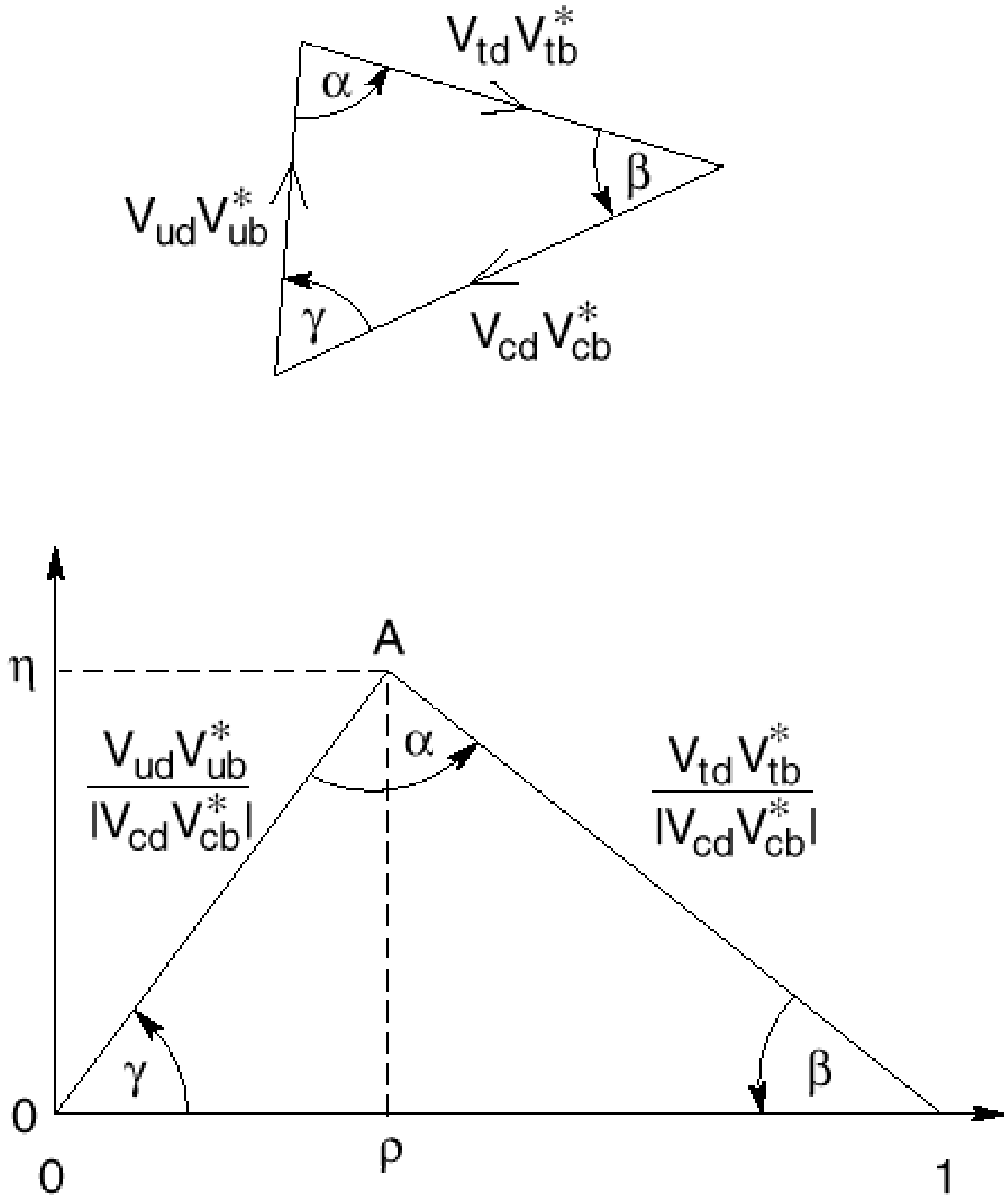
$$\mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$
$$\mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0$$
$$\mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0.$$

The Unitary Triangles:

- **are equal in area**
- **the area is |J|/2**

In the first and in the third triangles, one side is much shorter than the other two.
CP violation is small in the leading K decays (the first triangle) and in the leading B_s decays (the third triangle).

The most exciting physics of CP violation lies in the B system, related to the second triangle. The openness of this triangle predicts large CP asymmetries in B decays.
It is usually referred as " the Unitarity Triangle"



$V_{td}V_{tb}^*$
α
β
$V_{ud}V_{ub}^*$
γ
$V_{cd}V_{cb}^*$
A
η
α
$\frac{V_{ud}V_{ub}^*}{|V_{cd}V_{cb}^*|}$
$\frac{V_{td}V_{tb}^*}{|V_{cd}V_{cb}^*|}$
γ
β
0
0
ρ
1

The rescaled Unitarity Triangle is derived

- **choosing a phase convention such that $(V_{cd}V^*_{cb})$ is real**
- **dividing the lengths of all sides by $|V_{cd}V^*_{cb}|$**

Two vertices of the rescaled Unitarity Triangle are thus fixed at (0,0) and (1,0).
The coordinates of the remaining vertex are (ρ,η)
The angles are:

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \equiv \pi - \alpha - \beta.$$

Three ways to determine the CKM elements:

- **direct measurements**
- **indirect measurements**
- **unitarity condition**

Direct measurement:

- **Nuclear beta decays -> $|V_{ud}|$**
- **Semileptonic kaons and hyperon decays -> $|V_{us}|$**
- **ν production of charm -> $|V_{cd}|$**
- **Semileptonic D decays -> $|V_{cs}|$**
- **Semileptonic B decays -> $|V_{cb}|$**
- **Spectrum endpoint in semileptonic B decays -> $|V_{ub}/V_{cd}|$**

Indirect measurements:

- **$B^0 \overline{B}^0$ mixing ->$|V^*_{tb} V_{td}|$**

Taking into account all information:

$$\lambda = 0.2205 \pm 0.0018, \quad A = 0.826 \pm 0.041.$$

$$-0.15 \le \rho \le +0.35, \quad +0.20 \le \eta \le +0.45,$$

$$0.4 \le \sin 2\beta \le 0.8, \quad -0.9 \le \sin 2\alpha \le 1.0, \quad 0.23 \le \sin^2 \gamma \le 1.0.$$

From CP asymmetries it's possible, in principle, to extract α, β, γ

CP violation and B decay amplitude

Most b decay amplitude have contributions from Tree and Penguin diagrams

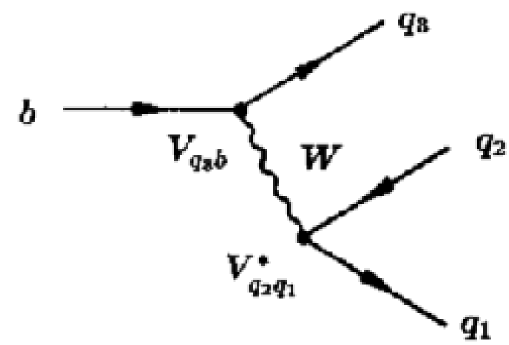
$$A(c\bar{c}s) = (T_{c\bar{c}s} + P_s^c - P_s^t)V_{cb}V_{cs}^* + (P_s^u - P_s^t)V_{ub}V_{us}^*,$$

$$A(u\bar{u}s) = (P_s^c - P_s^t)V_{cb}V_{cs}^* + (T_{u\bar{u}s} + P_s^u - P_s^t)V_{ub}V_{us}^*$$

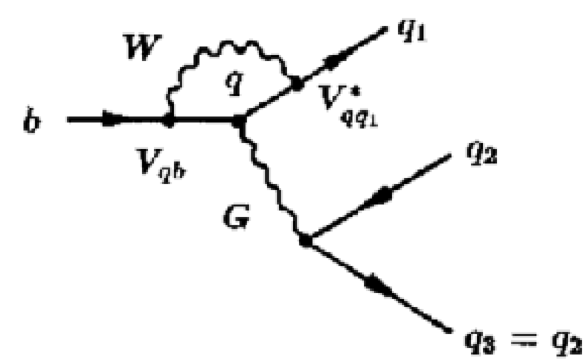
$$A(c\bar{c}d) = (P_d^t - P_d^u)V_{tb}V_{td}^* + (T_{c\bar{c}d} + P_d^c - P_d^u)V_{cb}V_{cd}^*,$$

$$A(u\bar{u}d) = (P_d^t - P_d^c)V_{tb}V_{td}^* + (T_{u\bar{u}d} + P_d^u - P_d^c)V_{ub}V_{ud}^*$$

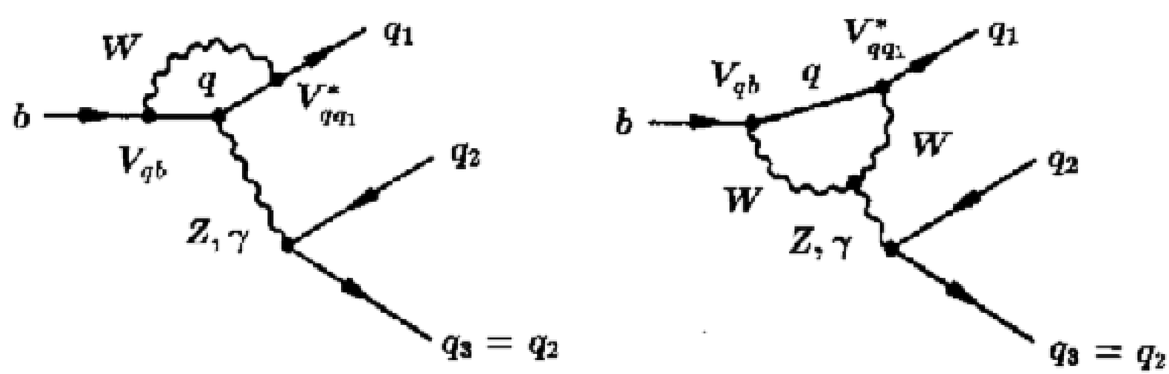
Tree Diagrams:



QCD Penguin Diagrams:



EW Penguin Diagrams:



In the B mesons:

- **CP violation in decay is expected to be small and can be ignored in hadronic decays**
- **Direct CP violation requires at least two contribution with different weak and strong phases**
- **CP violation from interference of decays with and without mixing has clear relationship between asymmetries and CKM parameters**

In many decays direct CP violation and CP violation from interference of decays with and without mixing are both present.
Decays with small direct CP violation are of great interest

According to their amplitude structure, B decays can be classified in different classes:

Decays dominated by a single term: b -> $c\bar{c}s$, b->$s\bar{s}s$
SM predicts small direct CP violation effect
B -> J/ψ K, B -> ϕ K

Decays with a small second term: b -> $c\bar{c}d$, b->$u\bar{u}d$
Depending on the relative size of Tree and Penguin contributions, direct CP violation can play a non negligible role
B -> D D, B -> ππ

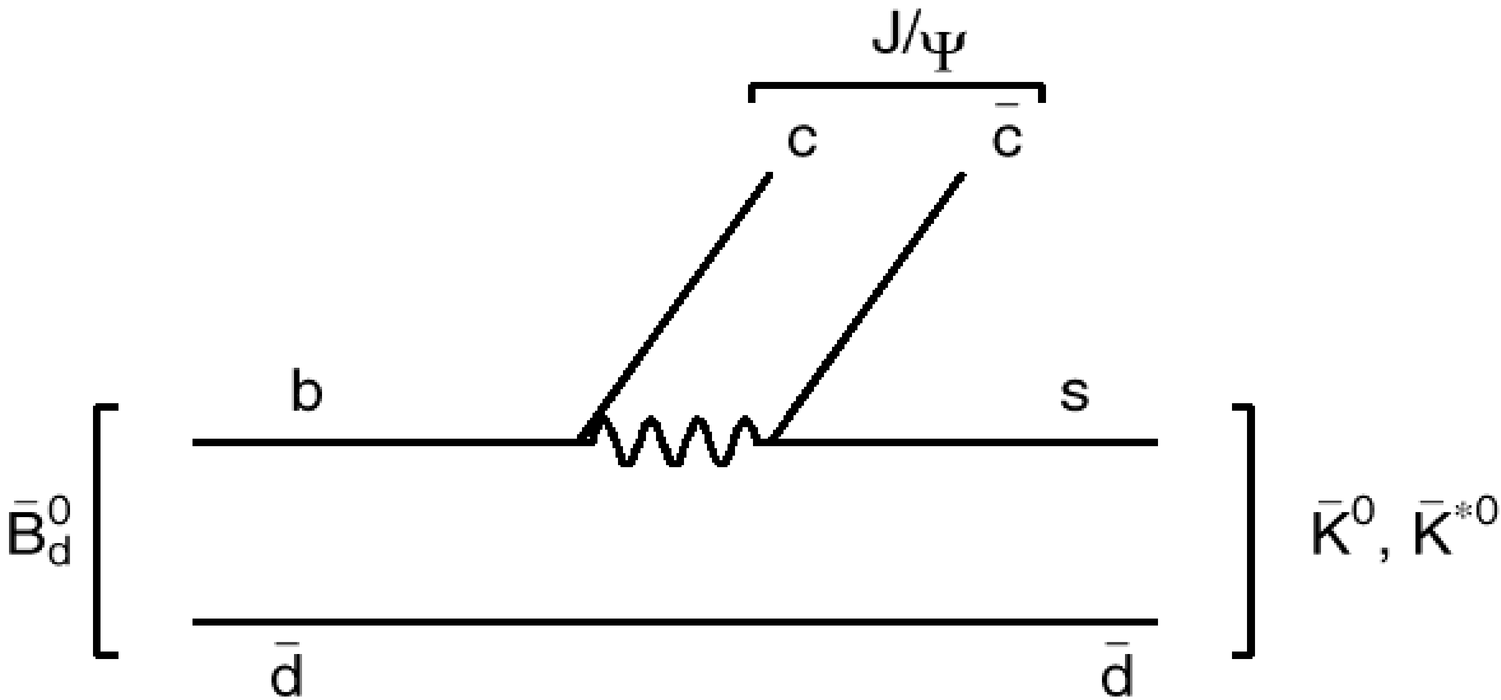
Decays with suppressed tree contribution: b->$u\bar{u}s$
Tree suppressed by CKM matrix element
B -> ρ K

Decays with no Tree contribution: b->$s\bar{s}d$
Interference between Penguin with quark of different charge in the loop B -> KK

Modes that can be used to measure β

B -> J/ψ K^0, B -> J/ψ K* (with K* -> $K^0\pi^0$)

Br(B -> J/ψ K^0**) ~ 5*10^{-4},**   **Br(**B -> J/ψ K***) ~ 1.4*10^{-3}**



Dominant penguin has the same weak phase as the tree. The term with different phase is a Cabibbo-suppressed penguin. Small Direct CP violation. Clean extraction of angle β

For example for B -> J/ψ Ks **(the "golden mode")**

$$\lambda(B \to \psi K_S) = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)$$

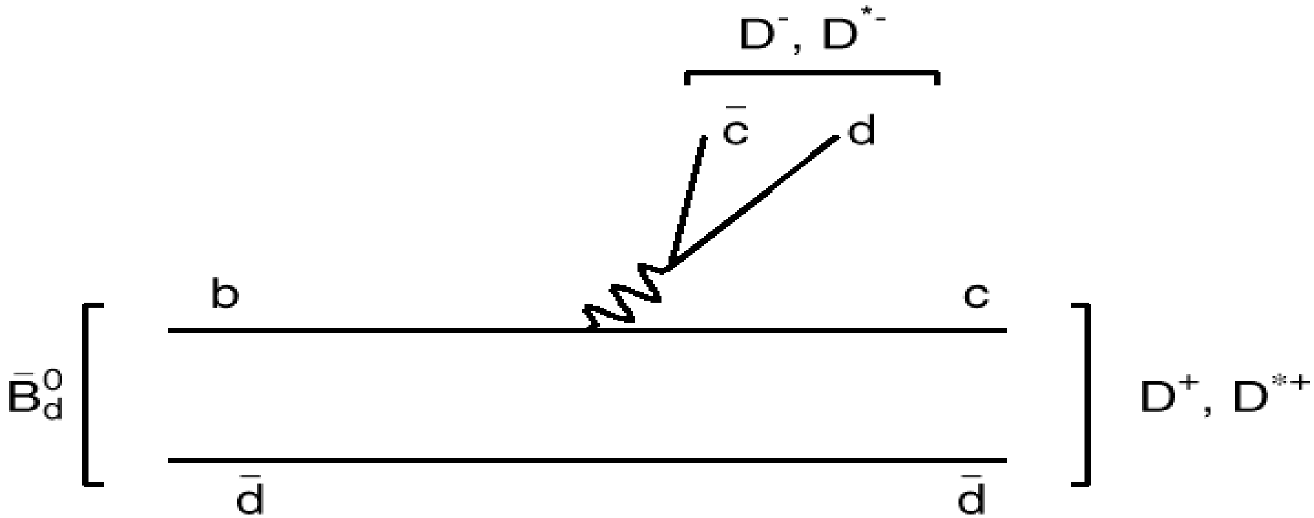
$$\mathcal{I}m\lambda_{\psi K_S} = \sin(2\beta).$$

The CP of the two body state depends on relative angular momentum as (-1)^L

For B -> J/ψ K* **the final state is a mixture of odd and even CP. An angular analysis is needed to separate amplitudes of definite CP**

B -> $D^+ D^-$,   B -> D*D* (with D* -> $D^0 \pi$)

Br(B -> $D^+ D^-$**) ~ $4*10^{-4}$,**   **Br(**B -> D*D***) ~ 10^{-3}**



Tree amplitude is Cabibbo suppressed. Penguin Diagrams contribution (with different phase) is potentially significant.

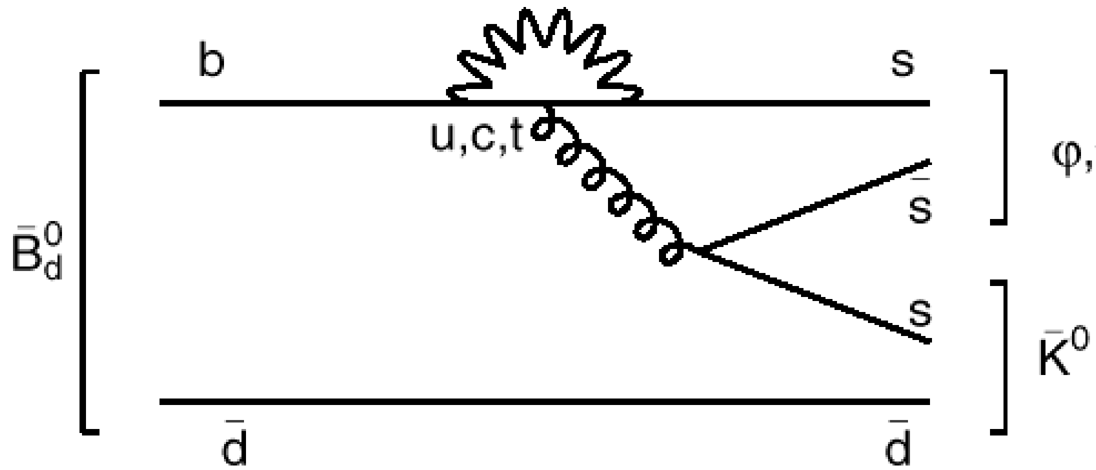
Direct CP violation can play a role

In addition, for the VV case (D* D*), an angular analysis is needed to separate amplitude of definite CP

B->ϕ K^0, B->ϕ K*

Br(B->ϕ K^0**) ,**

Br(B->ϕ K***) < 2*10^{-5}**



No Tree contribution. Two groups of Penguins with different phases, one group is Cabibbo-suppressed. Ignoring the Cabibbo-suppressed term:

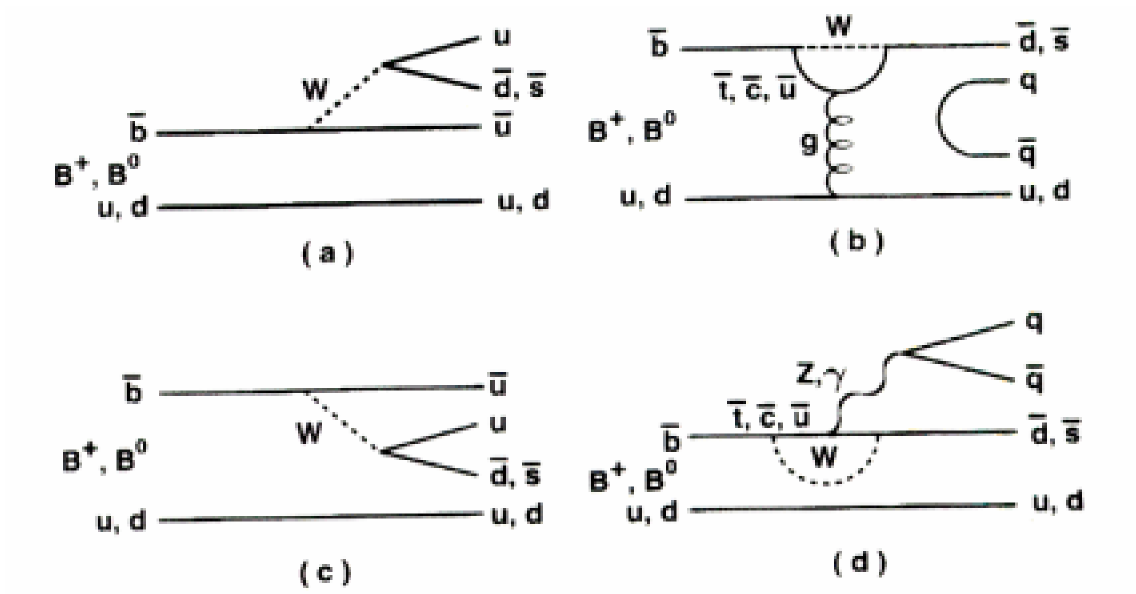
$$\lambda(B_d \to \phi K_S) \cong -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)$$

$$\mathrm{Im}\lambda(B_d \to \phi K_S) \cong \sin 2\beta \; .$$

Modes that can be used to measure α

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

Br($B \to \pi^+ \pi^-$**) ~ 5*10^{-6}**



Penguin terms have phase different from the Tree contributions
Neglecting penguins:

$$\lambda(B \to \pi^+\pi^-) = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right) \implies \mathcal{I}m\lambda_{\pi\pi} = \sin(2\alpha)$$

Recent CLEO results suggest that Penguin contribution is significant

Possible solution: measure rates for Isospin related channels:
$B^+ \to \pi^+ \pi^0$, $B^0 \to \pi^0 \pi^0$
and perform an Isospin Analysis

Basic idea:

Isospin amplitudes $A_{\Delta I,If}$ can be labelled by ΔI value of quark decay and by I_f of final state

Gluon is pure I=0, so the dominant gluonic penguin (b->d) is pure ΔI=1/2
Tree level b->u$\bar{u}$d have both ΔI=3/2 and ΔI=1/2
If the ΔI=3/2 piece can be isolated, then the tree contribution, that contains the weak phase to be measured, is isolated

$$A(B^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2} A_{3/2,2}$$
$$\frac{1}{\sqrt{2}} A(B^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{12}} A_{3/2,2} - \sqrt{\frac{1}{6}} A_{1/2,0}$$
$$A(B^0 \to \pi^0\pi^0) = \frac{1}{\sqrt{3}} A_{3/2,2} + \sqrt{\frac{1}{6}} A_{1/2,0}$$

B->ρπ ($\pi^+\pi^-\pi^o$ final state)

B->ρρ, B-> $a_1\pi$ (4π final state)

Decay modes not yet observed (expected Br ~10^{-5})

Require Isospin analysis

ρρ **requires also angular analysis to separate CP even and CP odd amplitude**

Modes that can be used to measure γ

Direct measurements of γ are difficult

$B^+ \to DK^+$

Relation between amplitude in $B_{u,d} \to K\pi$

Partial reconstruction of $B_d \to D^{(*)}\pi$ **to extract** $\sin(2\beta+\gamma)$

Experimental Requirements to Search for CP violation

Interesting modes have small branching ratio $O(10^{-4})$ - $O(10^{-6})$:
- **you need a lot of B**

$B \to f_{CP}$ decays must be fully reconstructed:
- **high tracking efficiency**
- **good vertexing to have good mass resolution**
- **good particle identification capability to distinguish among different modes and reject background**
- **γ and π^0 reconstruction**
- **identify neutral hadron (K_l)**

the other B must be tagged as B^0 or $\overline{B}^0$

- **you need particle ID capability**

To study the time dependence, one need to measure the distance Δz between the two B decay:

- **very good vertexing**

You have to process a lot of data (BaBar: 300KB/event at ~100 Hz):

- **a robust computing model**
- **well designed and well coded software**