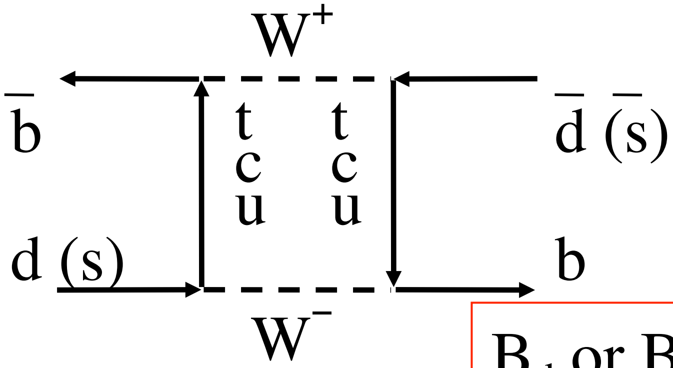
Physics of CP Violation (IV)

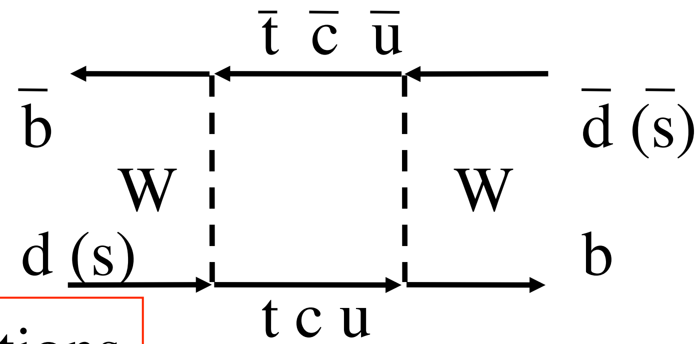
Special Lecture at
Tsinghua Univiersity, Beijing, China
21-25 March 2011

Tatsuya Nakada
École Polytechnique Fédéale de Lausanne (EPFL)

B meson system

The short distance effect dominates in the oscillations.





B_d or B_s oscillations

$$H^{\Delta B=2}_{\text{effective}} = \frac{G_F^2 m_W^2}{16\pi^2} \sum_{\substack{i,j=\\ u,c,t}} \lambda_i^q \lambda_j^q \left(\left\langle B^0 \middle| M^q_{V-A} \middle| \overline{B}^0 \right\rangle B_{ij} + \left\langle B^0 \middle| M^q_{S-P} \middle| \overline{B}^0 \right\rangle C_{ij} \right)$$

q = d for B_d and s for B_s

CKM elements $\lambda_i^q = V_{ib} V_{iq}^*$

quark operators

$$M_{V-A} = \left[\bar{q} \gamma_\mu (1-\gamma_5) b \right] \left[\bar{q} \gamma^\mu (1-\gamma_5) b \right]$$

$$M_{S-P} = \left[\bar{q} (1-\gamma_5) b \right] \left[\bar{q} (1-\gamma_5) b \right]$$

integrating out W $\left.\begin{matrix} B_{ij} \\ C_{ij} \end{matrix}\right\}$ Real part $\rightarrow M_{12}$, Imaginary part $\rightarrow \Gamma_{12}$

$|\lambda^{d}_{t}{}^{2}| = |V_{tb}{}^{2} V_{td}{}^{*2}| \approx A^2\lambda^6$ $\quad S_0(x_t) \approx 2.5 \quad \Leftarrow$ dominating

$|\lambda^{d}_{c}{}^{2}| = |V_{cb}{}^{2} V_{cd}{}^{*2}| \approx A^2\lambda^6$ $\quad S_0(x_c) \approx 0.00024$

$|\lambda^{d}_{c}\lambda^{d}_{t}| = |V_{cb}V_{cd}{}^{*}V_{tb}V_{td}{}^{*}| \approx A^2\lambda^6$ $\quad S_0(x_c, x_t) \approx 0.0021$

$|\lambda^{s}_{t}{}^{2}| = |V_{tb}{}^{2} V_{ts}{}^{*2}| \approx A^2\lambda^4$ $\quad S_0(x_t) \approx 2.5 \quad \Leftarrow$ dominating

$|\lambda^{s}_{c}{}^{2}| = |V_{cb}{}^{2} V_{cs}{}^{*2}| \approx A^2\lambda^4$ $\quad S_0(x_c) \approx 0.00024$

$|\lambda^{s}_{c}\lambda^{s}_{t}| = |V_{cb}V_{cs}{}^{*}V_{tb}V_{ts}{}^{*}| \approx A^2\lambda^4$ $\quad S_0(x_c, x_t) \approx 0.0021$

top-loop dominate for M_{12} $\rightarrow$ m_b can be neglected, i.e. C_{tt}=0

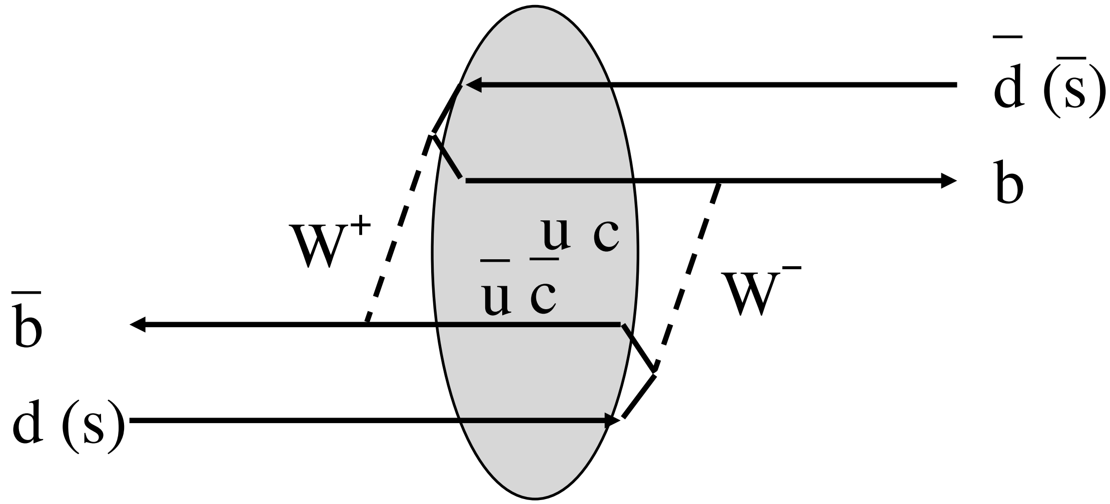
$$M_{12}^{q} = \frac{G_F^2}{12\pi^2} f_{B_q}^2 B_{B_q} m_{B_q} m_W^2 \lambda_t^{q^2} \eta_B S_0(x_t)\, e^{i(\pi-\theta_{CP})}$$

$\eta_B = 0.55$ QCD correction

$B_B f_B{}^2 = 0.83(223\pm40)^2\ \mathrm{MeV}^2$ for B_d **lattice calculations**

(no experimental measurement on f_B)

Γ_{12}



absorptive terms (no top)

m_b can not be neglected, i.e. $C_{ij} \neq 0$

$\lambda_u = -\lambda_c - \lambda_t$ unitarity relation

$$\Gamma_{12}^q \approx \frac{G_F^2}{8\pi} f_B^2 B_B m_B m_b^2 \left[\lambda_t^{q\,2} + \frac{8}{3} \lambda_t^q \lambda_c^q z_c + O\left(z_c^2\right) \right] e^{-i\theta_{CP}}$$

$z_c = (m_c/m_b)^2 \approx 0.09$

$$\frac{\Gamma_{12}^q}{M_{12}^q} = -\frac{3\pi x_\mathrm{b}}{2S_0(x_\mathrm{t})}\left[1 + \frac{8\lambda_\mathrm{c}^q}{3\lambda_\mathrm{t}^q} z_\mathrm{c} + O\left(z_\mathrm{c}^2\right)\right]$$

where,

$$\frac{\lambda_\mathrm{c}^d}{\lambda_\mathrm{t}^d} = \frac{(\hat{\rho}-1)+i\hat{\eta}}{(\hat{\rho}-1)^2+\hat{\eta}^2} \qquad \frac{\lambda_\mathrm{c}^s}{\lambda_\mathrm{t}^s} = -\left(1+i\lambda^2\eta\right)$$

$\Longrightarrow$ $\dfrac{|\Gamma_{12}|}{|M_{12}|} \approx 4\times 10^{-3}$ i.e. small for both B_d and B_s

$$\zeta = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} + \frac{i}{2}\Gamma_{12}}} \approx \left(1 - \frac{1}{2}\mathrm{Im}\frac{\Gamma_{12}}{M_{12}}\right)e^{-i\phi_M}$$

for $|\Gamma_{12}/ M_{12}| << 1$

$\phi_M = \arg M_{12}$

$$\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) = -\frac{4\pi x_b z_c}{S_0(x_t)}\,\mathrm{Im}\left(\frac{\lambda_c^q}{\lambda_t^q}\right) = \begin{cases} -\dfrac{4\pi x_c}{S_0(x_t)}\dfrac{\hat{\eta}}{(\hat{\rho}-1)^2+\hat{\eta}^2} \approx -6\times 10^{-4} & \mathrm{B_d} \\ \dfrac{4\pi x_c}{S_0(x_t)}\lambda^2\eta \approx 2\times 10^{-5} & \mathrm{B_s} \end{cases}$$

→ $|\zeta| \approx 1$ i.e. CP violation in oscillation is small!

$$\arg\Gamma_{12} - \arg M_{12} \approx \begin{cases} \pi + 0.15 & \mathrm{B_d} \\ \pi - 0.005 & \mathrm{B_s} \end{cases}$$

Weak eigenstates with definite masses and decay widths:

$$|B_\pm\rangle = \frac{1}{\sqrt{1+|\zeta|^2}}\left(|B^0\rangle \pm \zeta|\overline{B}^0\rangle\right)$$

$$m_\pm = M \pm |M_{12}| \quad \Gamma_\pm = \Gamma \mp |\Gamma_{12}|\cos(\arg\Gamma_{12} - \arg M_{12}) \quad \text{for } |\Gamma_{12}/M_{12}| << 1$$

$$\Delta m = m_+ - m_- = 2|M_{12}| \qquad \Delta\Gamma = \Gamma_- - \Gamma_+ = 2|\Gamma_{12}| \times \begin{cases} 1 - O(10^{-2}) & \mathrm{B_d} \\ 1 - O(10^{-5}) & \mathrm{B_s} \end{cases}$$

$$|B_+\rangle \equiv |B_h\rangle,\ |B_-\rangle \equiv |B_l\rangle$$

B-heavy decays slower

For B_d,
experimental knowledge:

$$\Delta m = 0.472\times10^{12}\ \hbar s^{-1},\ \tau = 1.55\times10^{-12}\ s$$

$$\frac{\Delta\Gamma}{\overline{\Gamma}} = \frac{|\Gamma_{12}|}{|M_{12}|}(\Delta m\times\tau) \approx 3\times10^{-3}$$

Negligible decay widths difference.

SM
$\sim4\times10^{-3}$

For B_s,
experimental knowledge:

$$\Delta m = 17.77\times10^{12}\ \hbar s^{-1},\ \tau = 1.44\times10^{-12}\ s$$

$$\frac{\Delta\Gamma}{\overline{\Gamma}} = \frac{|\Gamma_{12}|}{|M_{12}|}(\Delta m\times\tau) > 7\times10^{-2}$$

Non negligible decay widths difference.

SM
$\sim4\times10^{-3}$

K

$$\left|K_{S(L)}\right\rangle = \frac{1}{\sqrt{2}(1-\mathrm{Re}\,\varepsilon)}\left[\left|K^0\right\rangle + (-)(1-2\varepsilon)e^{-i\phi_\Gamma}\left|\overline{K}^0\right\rangle\right]$$

$$\varepsilon = \frac{|M_{12}||\Gamma_{12}|\Delta_{M-\Gamma}}{4|M_{12}|^2+|\Gamma_{12}|^2}\left(1+i\frac{2|M_{12}|}{|\Gamma_{12}|}\right)$$

$\phi_\Gamma = \arg \Gamma_{12}$.

ε: complex

heavier meson decays little slower

For B

$$\left|B_{l(h)}\right\rangle = \frac{1}{\sqrt{2}(1-\varepsilon_B)}\left[\left|B^0\right\rangle - (+)(1-2\varepsilon_B)e^{-i\phi_M}\left|\overline{B}^0\right\rangle\right]$$

$$\varepsilon_B = \frac{1}{4}\mathrm{Im}\frac{\Gamma_{12}}{M_{12}}$$

$\phi_M = \arg M_{12}$.

ε_B: real

heavier meson decays slower

B^0 at $t = 0$

$$\left|B^0(t)\right\rangle = f_+(t)\left|\mathrm{B}^0\right\rangle + (1-2\varepsilon_B)e^{-i\phi_M} f_-(t)\left|\overline{\mathrm{B}}^0\right\rangle$$

$$f_\pm(t) = \frac{1}{2}\left(e^{-i\lambda_{\mathrm{h}}t} \pm e^{-i\lambda_{\mathrm{l}}t}\right)$$

$$= \frac{1+\varepsilon_B}{\sqrt{2}}\left(e^{-i\lambda_{\mathrm{h}}t}\left|\mathrm{B_h}\right\rangle + e^{-i\lambda_{\mathrm{l}}t}\left|\mathrm{B_l}\right\rangle\right)$$

$\overline{B}^0$ at $t = 0$

$$\left|\overline{\mathrm{B}}^0(t)\right\rangle = (1+2\varepsilon_B)e^{i\phi_M} f_-(t)\left|\mathrm{B}^0\right\rangle + f_+(t)\left|\overline{\mathrm{B}}^0\right\rangle$$

$$= \frac{(1+\varepsilon_B)e^{i\phi_M}}{\sqrt{2}}\left(e^{-i\lambda_{\mathrm{h}}t}\left|\mathrm{B_l}\right\rangle - e^{-i\lambda_{\mathrm{l}}t}\left|\mathrm{B_h}\right\rangle\right)$$

Useful to know...

$$\left|f_\pm(t)\right|^2 = \frac{1}{2}e^{-\overline{\Gamma}t}\left(\cosh\frac{\Delta\Gamma}{2}t \pm \cos\Delta m t\right)$$

$$f_+(t)f_-^*(t) = \frac{1}{2}e^{-\overline{\Gamma}t}\left(\sinh\frac{\Delta\Gamma}{2}t + i\sin\Delta m t\right)$$

Time dependent decay rates

Four kinds of decay final states:

- unique CP eigenstate,

  e.g. K and B $\rightarrow \pi^+\pi^-$, B $\rightarrow$ J/ψ K_S

- mixed CP eigenstate,

  e.g. K and B $\rightarrow \pi^+\pi^-\pi^0$, $B_s \rightarrow$ J/ψ ϕ

- flavour specific, semileptonic and **hadronic**

  e.g. K and B $\rightarrow \ell^+ \nu X^-$ vs K and $\overline{B} \rightarrow \ell^- \nu X^+$

  $B \rightarrow K^+\pi^-$ vs $\overline{B} \rightarrow K^-\pi^+$

- **flavour non-specific**,

  e.g. $B \rightarrow D^-\pi^+, \rightarrow D^+\pi^-$ vs $\overline{B} \rightarrow \underline{D}^-\pi^+, \rightarrow D^+\pi^-$

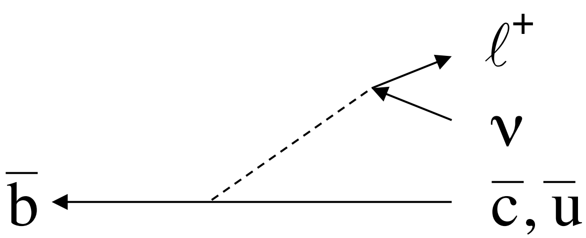
  $B_s \rightarrow D_s^-K^+, \rightarrow D_s^+K^-$ vs $\overline{B}_s \rightarrow D_s^-K^+, \rightarrow D_s^+K^-$

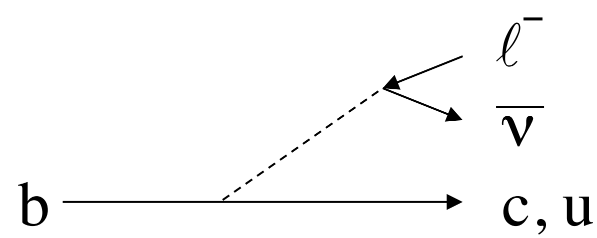
-not possible in the kaon system-

Semileptonic decays:

$$A_+ = \langle \ell^+ X_h^- \nu | H_W | \mathrm{B}^0 \rangle, \ \overline{A}_- = \langle \ell^- X_h^+ \overline{\nu} | H_W | \overline{\mathrm{B}}^0 \rangle$$

Like for the kaon system





$$\langle \ell^- X_h^+ \overline{\nu} | H_W | \mathrm{B}^0 \rangle = \langle \ell^+ X_h^- \nu | H_W | \overline{\mathrm{B}}^0 \rangle = 0$$

No strong phase and only one diagram

$$|A_+| = |\overline{A}_-|$$

B^0 at $t = 0 \rightarrow \ell^- X_h \bar{\nu}$ at t

$$R_-(t) = \left| \langle \ell^- X_h \bar{\upsilon} | H_W | B^0(t) \rangle \right|^2$$

$$= \left| f_+(t) \langle \ell^- X_h \bar{\upsilon} | H_W | B^0 \rangle + (1 - 2\varepsilon_B) e^{-i\phi_M} \langle \ell^- X_h \bar{\upsilon} | H_W | \bar{B}^0 \rangle f_-(t) \right|^2$$

$$= \left| f_+(t) A_- + (1 - 2\varepsilon_B) e^{-i\phi_M} \bar{A}_- f_-(t) \right|^2$$

$$= (1 - 4\varepsilon_B) |\bar{A}_-|^2 |f_-(t)|^2$$

$\bar{B}^0$ at $t = 0 \rightarrow \ell^+ X_h \nu$ at t

$$\bar{R}_+(t) = \left| \langle \ell^+ X_h \upsilon | H_W | \bar{B}^0(t) \rangle \right|^2$$

$$= (1 + 4\varepsilon_B) |A_+|^2 |f_-(t)|^2$$

CP violation in B-$\bar{\text{B}}$ mixing

$$A_{CP}^{\ell}(t) = \frac{\bar{R}_+(t) - R_-(t)}{\bar{R}_+(t) + R_-(t)}$$

$$= 4\varepsilon_B = \text{Im} \frac{\Gamma_{12}}{M_{12}}$$

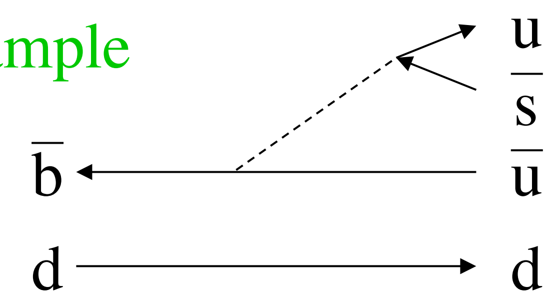
$\sim 10^{-3}$ (B_d)

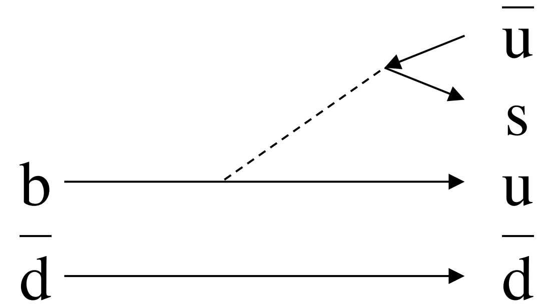
to $\sim 10^{-5}$ (B_s)

Flavour specific hadronic decays:

$$A_K = \langle K^+\pi^- | H_W | B^0 \rangle, \quad \overline{A}_K = \langle K^-\pi^+ | H_W | \overline{B}^0 \rangle$$

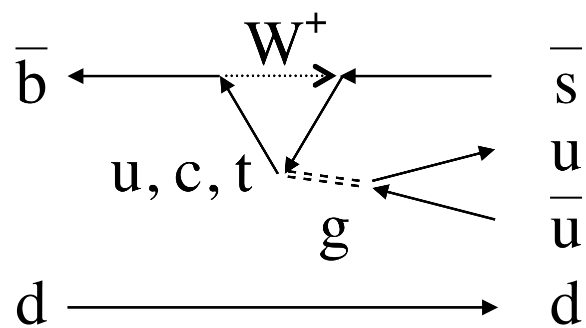
Example





$$\langle K^-\pi^+ | H_W | B^0 \rangle = \langle K^+\pi^- | H_W | \overline{B}^0 \rangle = 0$$

Kπ: $I = 3/2$ and $1/2$



+ γ and Z^0 penguins

Two isospin eigenstates and tree + penguin contributions

most likely → $|A_K| \neq |\overline{A}_K|$ ~~CP~~ in decay amplitudes

B^0 at $t = 0 \rightarrow K^-\pi^+$ at t

$$R_{K^-\pi^+}(t) = (1 - 4\varepsilon_B)|\bar{A}_K|^2 |f_-(t)|^2$$

$\bar{B}^0$ at $t = 0 \rightarrow K^+\pi^-$ at t

$$\bar{R}_{K^+\pi^-}(t) = (1 + 4\varepsilon_B)|A_K|^2 |f_-(t)|^2$$

CP violation in B-$\bar{B}$ mixing and CP violation in decay amplitudes are mixed...

~~CP~~ in decay amplitudes only can be extracted by ...

B^0 at $t = 0 \rightarrow K^+\pi^-$ at t

$$R_{K^+\pi^-}(t) = |A_K|^2 |f_+(t)|^2$$

$\bar{B}^0$ at $t = 0 \rightarrow K^-\pi^+$ at t

$$\bar{R}_{K^-\pi^+}(t) = |\bar{A}_K|^2 |f_+(t)|^2$$

$$A^K_{CP}(t) = \frac{\bar{R}_{K^-\pi^+}(t) - R_{K^+\pi^-}(t)}{\bar{R}_{K^-\pi^+}(t) + R_{K^+\pi^-}(t)} = \frac{|\bar{A}_K|^2 - |A_K|^2}{|\bar{A}_K|^2 + |A_K|^2}$$

A^K_{CP} BABAR −0.133±0.030±0.009 BELLE −0.101±0.025±0.005

Observation of ~~CP~~ in decay amplitudes: **much faster progress than K**

CP eigenstates $CP\left|f^{CP}\right\rangle = \sigma_{CP}\left|f^{CP}\right\rangle$ σ_{CP}: CP eigenvalue of f^{CP}

$$A_{f^{CP}} = \left\langle f^{CP}\right|H_W\left|B^0\right\rangle,\ \bar{A}_{f^{CP}} = \left\langle f^{CP}\right|H_W\left|\bar{B}^0\right\rangle$$

B^0 at $t = 0 \rightarrow f^{CP}$ at t

$$\begin{aligned}
R_{f^{CP}}(t) &= \left|\left\langle f^{CP}\right|H_W\left|B^0(t)\right\rangle\right|^2 \\
&= \left|f_+(t)\left\langle f^{CP}\right|H_W\left|B^0\right\rangle + (1-2\varepsilon_B)e^{-i\phi_M}\left\langle f^{CP}\right|H_W\left|\bar{B}^0\right\rangle f_-(t)\right|^2 \\
&= \left|\bar{A}_{f^{CP}}\right|^2 (1-2\varepsilon_B)^2 \left|(1+2\varepsilon_B)e^{i\phi_M}\frac{A_{f^{CP}}}{\bar{A}_{f^{CP}}} f_+(t) + f_-(t)\right|^2 \\
&= \left|\bar{A}_{f^{CP}}\right|^2 (1-4\varepsilon_B)\left|L_{f^{CP}} f_+(t) + f_-(t)\right|^2 \\
&= \left|\bar{A}_{f^{CP}}\right|^2 (1-4\varepsilon_B)\left\{\left|L_{f^{CP}}\right|^2\left|f_+(t)\right|^2 + \left|f_-(t)\right|^2 + 2\,\mathrm{Re}\left[L_{f^{CP}} f_+(t) f_-(t)^*\right]\right\}
\end{aligned}$$

$$L_f^{CP} = (1+4\varepsilon_B)e^{i\phi_M}\frac{A_{f^{CP}}}{\bar{A}_{f^{CP}}}$$

$$\boxed{\left|f_\pm(t)\right|^2 = \frac{1}{2} e^{-\overline{\Gamma} t}\left(\cosh\frac{\Delta\Gamma}{2}t \pm \cos\Delta m t\right)}$$

$$\left|L_{f^{\mathrm{CP}}}\right|^2 \left|f_+(t)\right|^2 + \left|f_-(t)\right|^2$$

$$= \frac{1}{2} e^{\overline{\Gamma} t}\left[\left(1 + \left|L_{f^{\mathrm{CP}}}\right|^2\right)\cosh\frac{\Delta\Gamma}{2}t - \left(1 - \left|L_{f^{\mathrm{CP}}}\right|^2\right)\cos\Delta m t\right]$$

$$\boxed{f_+(t) f_-^*(t) = \frac{1}{2} e^{-\overline{\Gamma} t}\left(\sinh\frac{\Delta\Gamma}{2}t + i\sin\Delta m t\right)}$$

$$2\,\mathrm{Re}\left[L_{f^{\mathrm{CP}}} f_+(t) f_-(t)^*\right]$$

$$= 2\,\mathrm{Re}\,L_{f^{\mathrm{CP}}}\,\mathrm{Re}\left[f_+(t) f_-(t)^*\right] - 2\,\mathrm{Im}\,L_{f^{\mathrm{CP}}}\,\mathrm{Im}\left[f_+(t) f_-(t)^*\right]$$

$$= e^{-\overline{\Gamma} t}\left(\mathrm{Re}\,L_{f^{\mathrm{CP}}}\sinh\frac{\Delta\Gamma}{2}t - \mathrm{Im}\,L_{f^{\mathrm{CP}}}\sin\Delta m t\right)$$

$$R_{f^{CP}}(t) = \frac{\left|\bar{A}_{f^{CP}}\right|^2 (1-4\varepsilon_B)}{2} e^{-\bar{\Gamma} t}\left\{I_+^{CP}(t) - I_-^{CP}(t)\right\}$$

$$I_+^{CP}(t) = \left(1+\left|L_f^{CP}\right|^2\right)\cosh\frac{\Delta\Gamma}{2}t + 2\,\mathrm{Re}\,L_f^{CP}\sinh\frac{\Delta\Gamma}{2}t$$

$$I_-^{CP}(t) = \left(1-\left|L_f^{CP}\right|^2\right)\cos\Delta m t + 2\,\mathrm{Im}\,L_f^{CP}\sin\Delta m t$$

$\overline{\mathrm{B}}^0$ at $t=0 \longrightarrow \mathrm{f}^{\mathrm{CP}}$ at t

$$\bar{R}_{f^{CP}}(t) = \frac{\left|\bar{A}_{f^{CP}}\right|^2}{2} e^{-\bar{\Gamma} t}\left\{I_+^{CP}(t) + I_-^{CP}(t)\right\}$$

CP violating term

"CP conserving" part

$$I_{+}^{CP}(t) = \left(1 + \left|L_f^{CP}\right|^2\right)\cosh\frac{\Delta\Gamma}{2}t + 2\,\mathrm{Re}\,L_f^{CP}\sinh\frac{\Delta\Gamma}{2}t$$

"CP violating" part

$$I_{-}^{CP}(t) = \left(1 - \left|L_f^{CP}\right|^2\right)\cos\Delta m t + 2\,\mathrm{Im}\,L_f^{CP}\sin\Delta m t$$

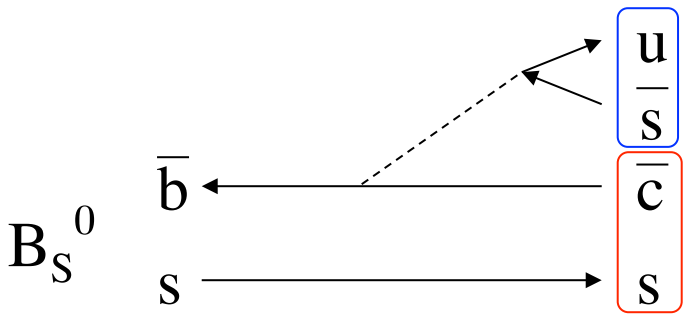
$$L_f^{CP} = (1 + 4\varepsilon_B)e^{i\phi_M}\frac{A_{f^{CP}}}{\bar{A}_{f^{CP}}}$$

Mixed CP eigenstates

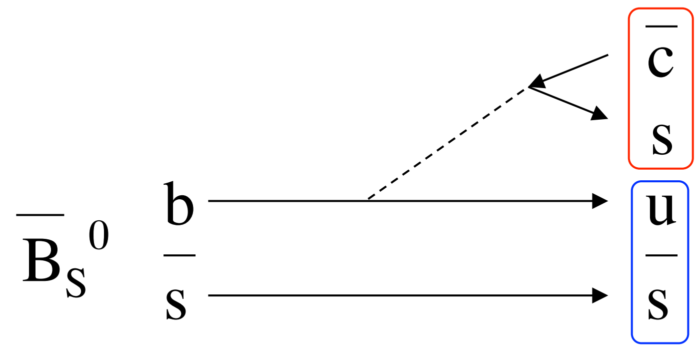
$$\left|\mathrm{f}^{\mathrm{CP}}\right\rangle = \left|\mathrm{f}_{+}^{\mathrm{CP}}\right\rangle + \left|\mathrm{f}_{-}^{\mathrm{CP}}\right\rangle,\; CP\left|\mathrm{f}^{\mathrm{CP}}\right\rangle = \left|\mathrm{f}_{+}^{\mathrm{CP}}\right\rangle - \left|\mathrm{f}_{-}^{\mathrm{CP}}\right\rangle$$

Flavour non specific hadronic decays:

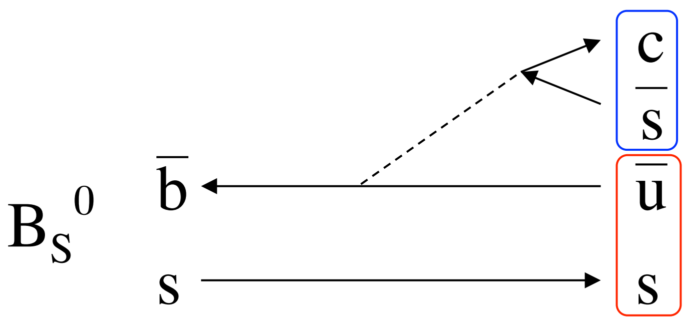
Example $$A_f = \langle D_s^- K^+ | H_W | B_s^0 \rangle, \quad \bar{A}_f = \langle D_s^- K^+ | H_W | \bar{B}_s^0 \rangle$$



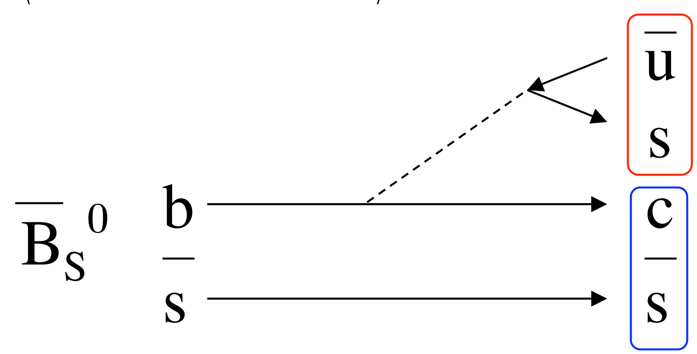
D_s^- K^+



$$A_{\bar{f}} = \langle D_s^+ K^- | H_W | B_s^0 \rangle, \quad \bar{A}_{\bar{f}} = \langle D_s^+ K^- | H_W | \bar{B}_s^0 \rangle$$



D_s^+ K^-



B^0 at $t = 0 \rightarrow$ f at t

$$R_f(t) = \left| \langle f | H_W | B^0(t) \rangle \right|^2$$

$$= \left| f_+(t) \langle f | H_W | B^0 \rangle + (1 - 2\varepsilon_B) e^{-i\phi_M} \langle f | H_W | \overline{B}^0 \rangle f_-(t) \right|^2$$

$$= \frac{|A_f|^2}{2} e^{-\overline{\Gamma} t} \left\{ I_+^f(t) + I_-^f(t) \right\}$$

$$I_+^f(t) = \left(1 + |L_f|^2\right) \cosh \frac{\Delta\Gamma}{2} t + 2 \,\mathrm{Re}\, L_f \sinh \frac{\Delta\Gamma}{2} t$$

$$I_-^f(t) = \left(1 - |L_f|^2\right) \cos \Delta m t + 2 \,\mathrm{Im}\, L_f \sin \Delta m t$$

$$L_f = (1 - 4\varepsilon_B) e^{-i\phi_M} \frac{\overline{A}_f}{A_f}$$

$\overline{B}^0$ at $t = 0 \rightarrow$ f at t

$$\overline{R}_f(t) = \left| \langle f | H_W | \overline{B}^0(t) \rangle \right|^2$$

$$= \frac{|A_f|^2}{2} e^{-\overline{\Gamma} t} \left\{ I_+^f(t) - I_-^f(t) \right\}$$

B^0 at $t = 0 \rightarrow \overline{\mathrm{f}}$ at t

$$R_{\bar{f}}(t) = \frac{|A_{\bar{f}}|^2}{2} e^{-\Gamma t} \left\{ I_+^{\bar{f}}(t) + I_-^{\bar{f}}(t) \right\}$$

$\overline{B}^0$ at $t = 0 \rightarrow \overline{\mathrm{f}}$ at t

$$\overline{R}_{\bar{f}}(t) = \frac{|A_{\bar{f}}|^2}{2} e^{-\Gamma t} \left\{ I_+^{\bar{f}}(t) - I_-^{\bar{f}}(t) \right\}$$

$$I_+^{\bar{f}}(t) = \left(1 + |L_{\bar{f}}|^2\right) \cosh \frac{\Delta\Gamma}{2} t + 2 \operatorname{Re} L_{\bar{f}} \sinh \frac{\Delta\Gamma}{2} t$$

$$I_-^{\bar{f}}(t) = \left(1 - |L_{\bar{f}}|^2\right) \cos \Delta m t + 2 \operatorname{Im} L_{\bar{f}} \sin \Delta m t$$

$$L_{\bar{f}} = (1 - 4\varepsilon_B) e^{-i\phi_M} \frac{\overline{A}_{\bar{f}}}{A_{\bar{f}}}$$

Four time dependent decay rates.

Standard model predictions

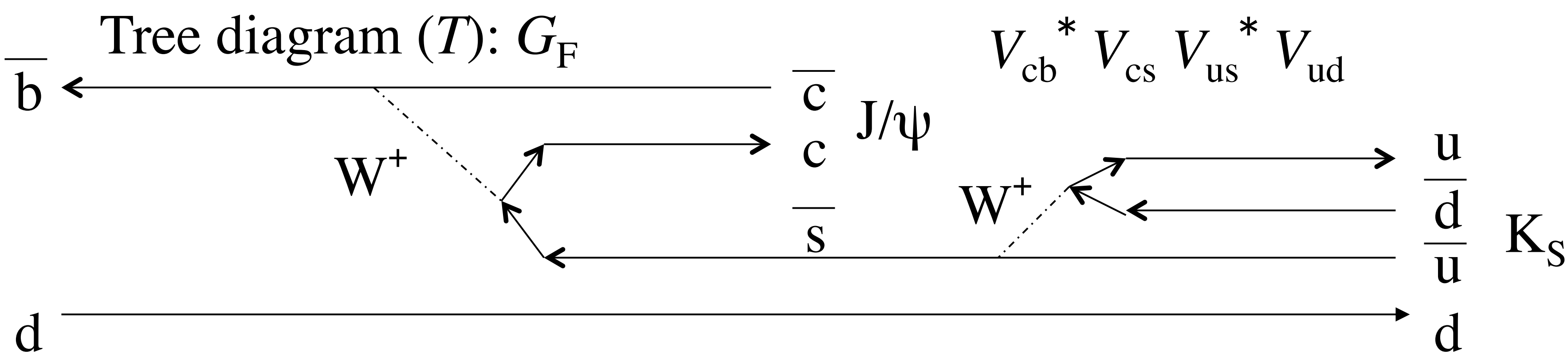
CP eigenstates generated by b → c + W decays

$B^0 \rightarrow J/\psi\ K_S$

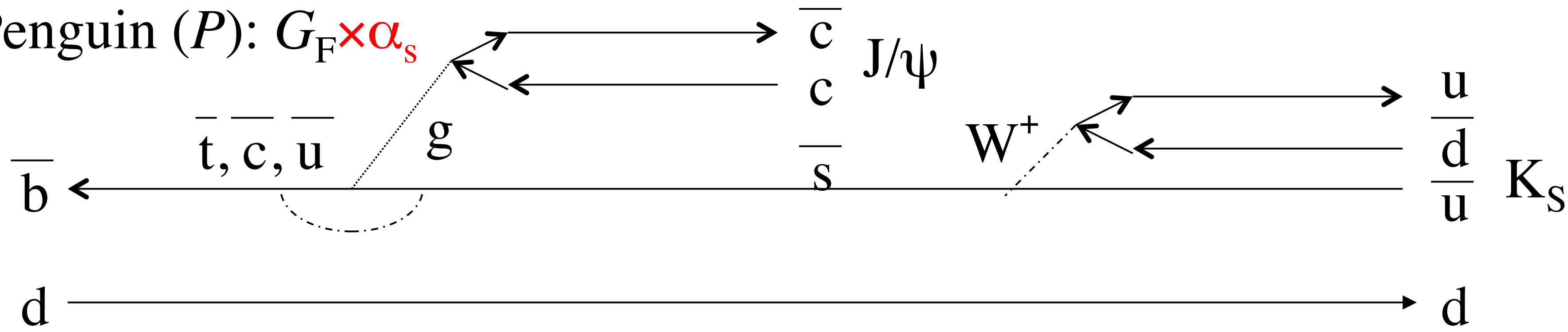
$CP(J/\psi\ K_S) = CP(J/\psi)\times CP(K_S)\times(-1)^l = -1$

$I = 1/2$

B^0 decay



Penguin (P): $G_F \times \alpha_s$



$$\{\ V_{tb}^*\ V_{ts}\ F(m_t^2) + V_{cb}^*\ V_{cs}\ F(m_c^2) + V_{ub}^*\ V_{us}\ F(m_u^2)\ \}\ V_{us}^*\ V_{ud}$$

$$F(m_c^2) \approx F(m_u^2) \equiv F$$

$$\{\ V_{tb}^*\ V_{ts}\ F(m_t^2) + [\ V_{cb}^*\ V_{cs} + V_{ub}^*\ V_{us}\ ]\ F\ \}\ V_{us}^*\ V_{ud}$$

$$V_{tb}^*\ V_{ts} + V_{cb}^*\ V_{cs} + V_{ub}^*\ V_{us} = 0$$

$$V_{tb}^*\ V_{ts}\ [\ F(m_t^2) - F\ ]\ V_{us}^*\ V_{ud}$$

$$A_{J/\psi K_S} \propto [V_{cb}^*\ V_{cs} + V_{tb}^*\ V_{ts}\ P/T\ ]\ V_{us}^*\ V_{ud}$$

Final state interaction between J/ψ and K_S are elastic (???).

Only one state (I=1/2) is involved.

$$A_{J/\psi K_S} \propto [V_{cb}^* V_{cs} + V_{tb}^* V_{ts}\, P/T\,]\, V_{us}^* V_{ud}\, e^{i\delta}$$

$$\overline{A}_{J/\psi K_S} \propto - [V_{cb} V_{cs}^* + V_{tb} V_{ts}^*\, P/T\,]\, V_{us} V_{ud}^*\, e^{i\delta} e^{-i\theta CP}$$

CP(J/ψK_S)

$$\longrightarrow \quad |A_{J/\psi K_S}| = |\overline{A}_{J/\psi K_S}|$$

Unitarity: $V_{tb}^* V_{ts} + V_{cb}^* V_{cs} + V_{ub}^* V_{us} = 0$

$$|V_{tb}^* V_{ts}| \approx |V_{tb}^* V_{ts}| = A\lambda^2 << |V_{ub}^* V_{us}| = A\lambda^4 \sqrt{\rho^2+\eta^2}$$

$$V_{tb}^* V_{ts} = - V_{cb}^* V_{cs} + O(\lambda^4)$$

$$\arg V_{tb}^* V_{ts} \approx \arg V_{cb}^* V_{cs} + \pi + O(\lambda^2)$$

Penguin is suppressed by the strong interactions: P/T < 1

$$\frac{A_{J/\psi K_S}}{\bar{A}_{J/\psi K_S}} = -\frac{V_{cb}^* V_{cs} V_{us}^* V_{ud}\left(1 - e^{iO\left(10^{-3}\right)}\right)}{V_{cb} V_{cs}^* V_{us} V_{ud}^*\left(1 - e^{-iO\left(10^{-3}\right)}\right)} e^{i\theta_{CP}}$$

$$\approx -\frac{V_{cb}^* V_{cs} V_{us}^* V_{ud}}{V_{cb} V_{cs}^* V_{us} V_{ud}^*} e^{i\theta_{CP}}$$

$$= -e^{i\left(\theta_{CP} + 2\arg V_{cs} + 2\arg V_{ud} - 2\arg V_{cb} - 2\arg V_{us}\right)}$$

From

$$M_{12}^q = \frac{G_F^2}{12\pi^2} f_{B_q}^2 B_{B_q} m_{B_q} m_W^2 \lambda_t^{q\,2} \eta_B S_0\left(x_t\right) e^{i(\pi - \theta_{CP})}$$

$$\arg M_{12} = \pi - \theta_{CP} + 2\arg \lambda_t^d$$

$$= \pi - \theta_{CP} + 2\arg V_{tb} - 2\arg V_{td}$$

$$L_f^{CP} = (1+4\varepsilon_B)e^{i\phi_M}\frac{A_{f^{CP}}}{\bar{A}_{f^{CP}}}$$

$$L_{\mathrm{J/\psi K_S}}^{CP} = -1 \times e^{i\pi} \times$$

$$(1+4\varepsilon_B)e^{i(2\arg V_{\mathrm{tb}} - 2\arg V_{\mathrm{td}} - \theta_{\mathrm{CP}})} e^{i(\theta_{\mathrm{CP}} + 2\arg V_{\mathrm{cs}} + 2\arg V_{\mathrm{ud}} - 2\arg V_{\mathrm{cb}} - 2\arg V_{\mathrm{us}})}$$

$$= (1+4\varepsilon_B)e^{i2\underbrace{(\arg V_{\mathrm{tb}} - \arg V_{\mathrm{cb}} + \arg V_{\mathrm{cs}} - \arg V_{\mathrm{us}} + \arg V_{\mathrm{ud}} - \arg V_{\mathrm{td}})}}$$

This phase is invariant under
the redefinition of the quark phases:
$\equiv \beta$ or ϕ_1

With an accuracy of $\sim 10^{-3}$

$$L_{\mathrm{J/\psi K_S}}^{CP} = e^{i2\beta}$$

Interpretation of β:

$$\beta = \arg V_{tb} - \arg V_{cb} + \arg V_{cs} - \arg V_{us} + \arg V_{ud} - \arg V_{td}$$

The first 2×2 submatrix is unitary to λ^4

$$V_{ud} V_{us}{}^* + V_{cd} V_{cs}{}^* = 0 + O(\lambda^5)$$

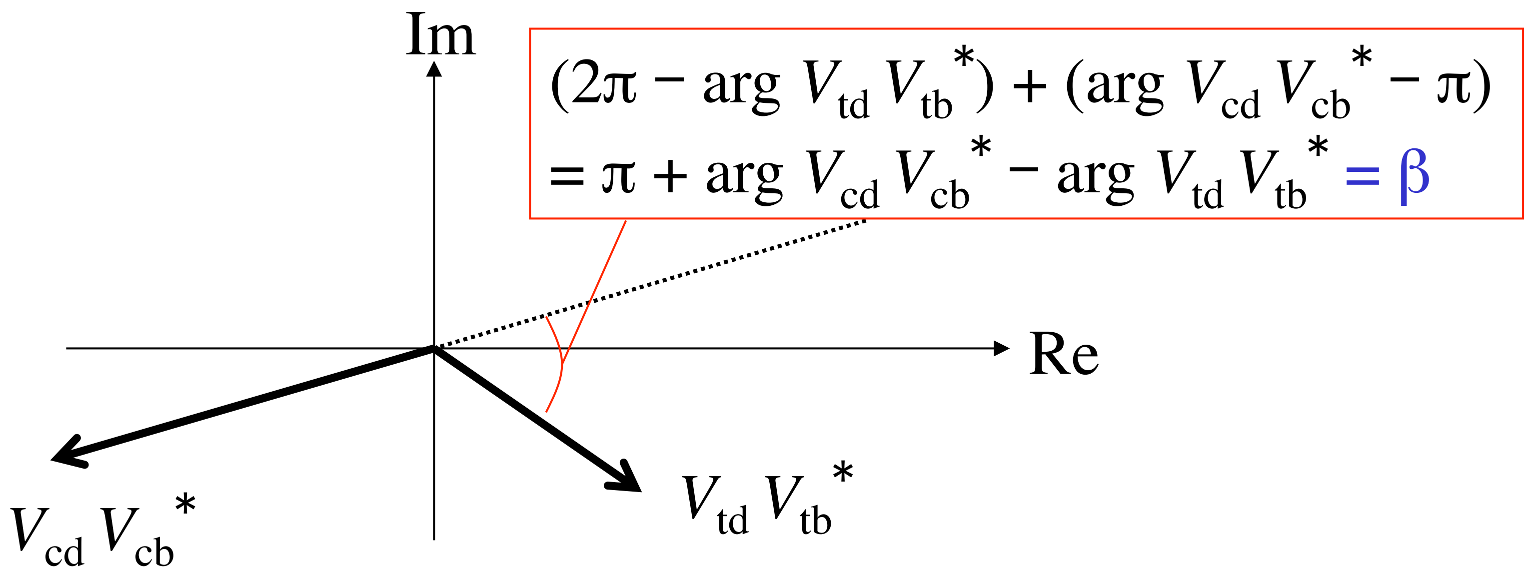
~10^{-4}

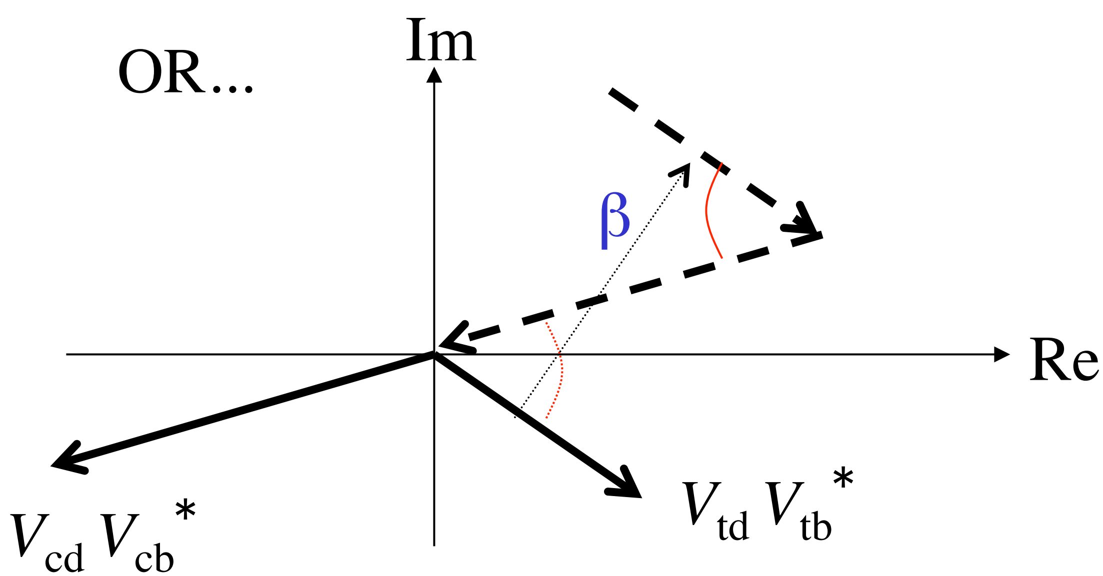
$$(\arg V_{ud} - \arg V_{us}) - (\arg V_{cd} - \arg V_{cs}) \approx \pi$$

$$\arg V_{cs} \approx \pi - \arg V_{ud} + \arg V_{us} + \arg V_{cd}$$

$$\begin{aligned} \beta &\approx \pi + \arg V_{tb} - \arg V_{cb} + \arg V_{cd} - \arg V_{td} \\ &= \pi + (\arg V_{cd} - \arg V_{cb}) - (\arg V_{td} - \arg V_{tb}) \\ &= \pi + \arg V_{cd} V_{cb}{}^* - \arg V_{td} V_{tb}{}^* \end{aligned}$$

$$\beta = \pi + \arg V_{cd} V_{cb}{}^* - \arg V_{td} V_{tb}{}^* + O(10^{-4})$$


Im
Re
$(2\pi - \arg V_{td} V_{tb}^*) + (\arg V_{cd} V_{cb}^* - \pi)$
$= \pi + \arg V_{cd} V_{cb}^* - \arg V_{td} V_{tb}^* = \beta$
$V_{td} V_{tb}^*$
$V_{cd} V_{cb}^*$


OR…
Im
Re
β
$V_{td} V_{tb}^*$
$V_{cd} V_{cb}^*$

"CP conserving" part

$$I_+^{CP}(t) = \left(1 + \left|L_f^{CP}\right|^2\right)\cosh\frac{\Delta\Gamma}{2}t + 2\,\mathrm{Re}\,L_f^{CP}\sinh\frac{\Delta\Gamma}{2}t$$

$$\approx 2$$

"CP violating" part

$$I_-^{CP}(t) = \left(1 - \left|L_f^{CP}\right|^2\right)\cos\Delta m t + 2\,\mathrm{Im}\,L_f^{CP}\sin\Delta m t$$

$$\approx 2\sin 2\beta \sin\Delta m t$$

Time dependent decay rates

Initial B^0: $$R_{J/\psi K_S}(t) \propto e^{-\bar{\Gamma}t}\{1 - \sin 2\beta \sin\Delta m t\}$$

Initial $\overline{B}^0$: $$\bar{R}_{J/\psi K_S}(t) \propto e^{-\bar{\Gamma}t}\{1 + \sin 2\beta \sin\Delta m t\}$$

Correct to an accuracy of 10^{-3}

Another way to look at it...

B^0 at $t = 0 \rightarrow J/\psi K_S$ at t

$$R_{J/\psi K_S}(t) = \left| \langle J/\psi K_S | H_W | B^0(t) \rangle \right|^2$$

$$= \frac{1}{2} \left| e^{-i\lambda_h t} \langle J/\psi K_S | H_W | B_h \rangle + e^{-i\lambda_l t} \langle J/\psi K_S | H_W | B_l \rangle \right|^2$$

$$\propto e^{-\bar{\Gamma} t} \left| 1 + e^{i\Delta m t} \eta_{J/\psi K_S} \right|^2, \qquad \eta_{J/\psi K_S} = \frac{A^l_{J/\psi K_S}}{A^h_{J/\psi K_S}}$$

$$\propto e^{-\bar{\Gamma} t} \left(1 + \left| \eta_{J/\psi K_S} \right|^2 + 2 \operatorname{Re} \eta_{J/\psi K_S} \cos \Delta m t - 2 \operatorname{Im} \eta_{J/\psi K_S} \sin \Delta m t \right)$$

$\eta_{J/\psi K_S}$ is a CP violation parameter like η_{+-} for the kaon system

$$\eta_{\mathrm{J}/\psi\mathrm{K_S}} = \frac{A^{\mathrm{l}}_{\mathrm{J}/\psi\mathrm{K_S}}}{A^{\mathrm{h}}_{\mathrm{J}/\psi\mathrm{K_S}}}$$

$$= \frac{A_{\mathrm{J}/\psi\mathrm{K_S}} - (1-2\varepsilon_{\mathrm{B}})e^{-i\phi_M}\bar{A}_{\mathrm{J}/\psi\mathrm{K_S}}}{A_{\mathrm{J}/\psi\mathrm{K_S}} + (1-2\varepsilon_{\mathrm{B}})e^{-i\phi_M}\bar{A}_{\mathrm{J}/\psi\mathrm{K_S}}}$$

$$= \frac{L_{\mathrm{J}/\psi\mathrm{K_S}} - 1}{L_{\mathrm{J}/\psi\mathrm{K_S}} + 1}$$

$$\approx \frac{e^{2i\beta} - 1}{e^{2i\beta} + 1}$$

$$= \frac{i\sin 2\beta}{1+\cos 2\beta}$$

$\eta_{\mathrm{J}/\psi\mathrm{K_S}}$ is is imaginary to $\sim 10^{-3}$

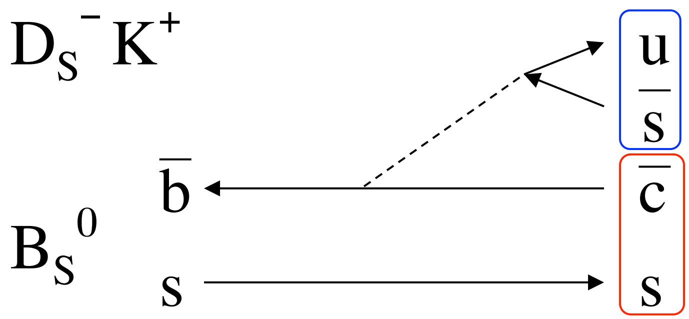
$$R_{\mathrm{J}/\psi \mathrm{K_S}}(t) \propto e^{-\overline{\Gamma} t}\left(1 + \left|\eta_{\mathrm{J}/\psi \mathrm{K_S}}\right|^2 + 2\,\mathrm{Re}\,\eta_{\mathrm{J}/\psi \mathrm{K_S}} \cos \Delta m t - 2\,\mathrm{Im}\,\eta_{\mathrm{J}/\psi \mathrm{K_S}} \sin \Delta m t\right)$$

$$= e^{-\overline{\Gamma} t}\left(1 + \frac{\sin^2 2\beta}{(1+\cos 2\beta)^2} - \frac{2\sin 2\beta}{1+\cos 2\beta}\sin \Delta m t\right)$$

$$= \frac{e^{-\overline{\Gamma} t}}{1+\cos 2\beta}\left(1 - \sin 2\beta \sin \Delta m t\right)$$

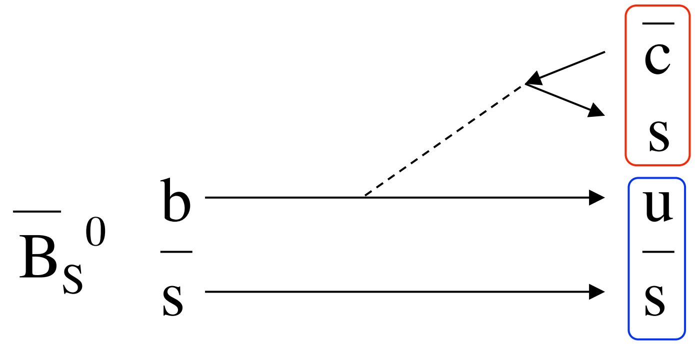
$$\overline{R}_{\mathrm{J}/\psi \mathrm{K_S}}(t) \propto \frac{e^{-\overline{\Gamma} t}}{1+\cos 2\beta}\left(1 + \sin 2\beta \sin \Delta m t\right)$$

If sin2β ≈ $O(1)$, B_l and B_h are far from the CP eigenstates, (differen from K_S, K_L), although $\varepsilon_B \approx 0$!



$V_{cb}^{*} V_{us} \times \text{Tree-1}$

$D_s^- K^+$



$V_{ub} V_{cs}^{*} \times \text{Tree-2}$

$$\frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}} = \frac{V_{ub} V_{cs}^{*} \times \text{Tree-2}}{V_{cb}^{*} V_{us} \times \text{Tree-1}}$$

$$= r \times e^{i(\arg V_{ub} - \arg V_{us} + \arg V_{cb} - \arg V_{cs})} e^{i\Delta} e^{-i\theta_{CP}}$$

$$r = \left|\frac{V_{ub} V_{cs}}{V_{cb} V_{us}}\right| \times \left|\frac{\text{Tree - 2}}{\text{Tree - 1}}\right|$$

$$= \frac{A\lambda^3 \sqrt{\rho^2 + \eta^2}}{A\lambda^3} \times \left|\frac{\text{Tree - 2}}{\text{Tree - 1}}\right|$$

~0.4

Δ: Tree-1 Tree-2 “strong phase” difference

Only D_s-K elastic scattering

From

$$M_{12}^q = \frac{G_F^2}{12\pi^2} f_{B_q}^2 B_{B_q} m_{B_q} m_W^2 \lambda_t^{q\,2} \eta_B S_0(x_t)\, e^{i(\pi-\theta_{CP})}$$

$$\arg M_{12} = \pi - \theta_{CP} + 2\arg\lambda_t^s$$

$$= \pi - \theta_{CP} + 2\arg V_{tb} - 2\arg V_{ts}$$

$$L_f = (1-4\varepsilon_B)e^{-i\phi_M}\frac{\overline{A}_f}{A_f}$$

$$L_{D_s^- K^+} = -(1-4\varepsilon_B)e^{i(\theta_{CP}+2\arg V_{ts}-2\arg V_{tb})}$$

$$\times r e^{i(\arg V_{ub}-\arg V_{us}+\arg V_{cb}-\arg V_{cs}-\theta_{CP})} e^{i\Delta}$$

$$= -(1-4\varepsilon_B) r e^{i\overbrace{(\arg V_{ub}-\arg V_{us}+\arg V_{cb}-\arg V_{cs}+2\arg V_{ts}-2\arg V_{tb})}} e^{i\Delta}$$

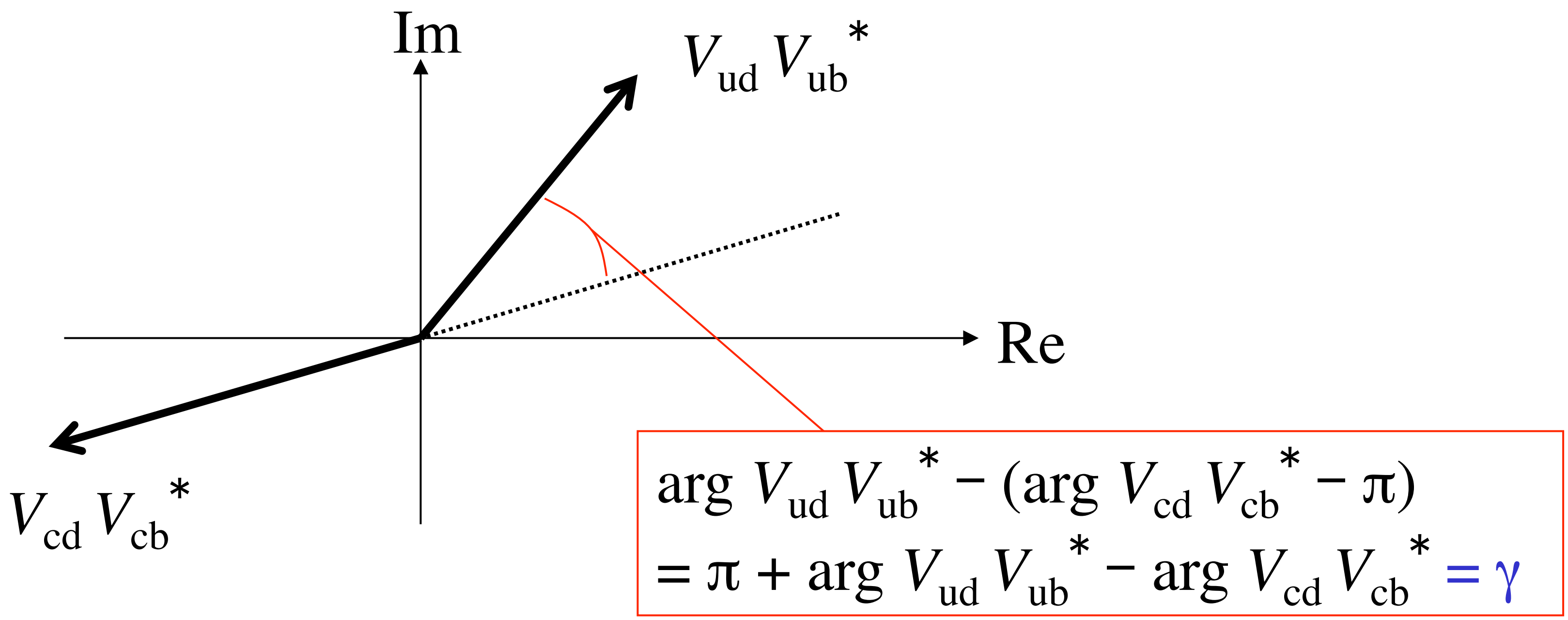
This phase is invariant under
the redefinition of the quark phases:
$\equiv -\gamma + 2\delta\gamma$ or $-\phi_3 + 2\delta\phi_3$

$$= -r e^{i(-\gamma+2\delta\gamma+\Delta)}$$ with an accuracy of $\sim 10^{-4}$

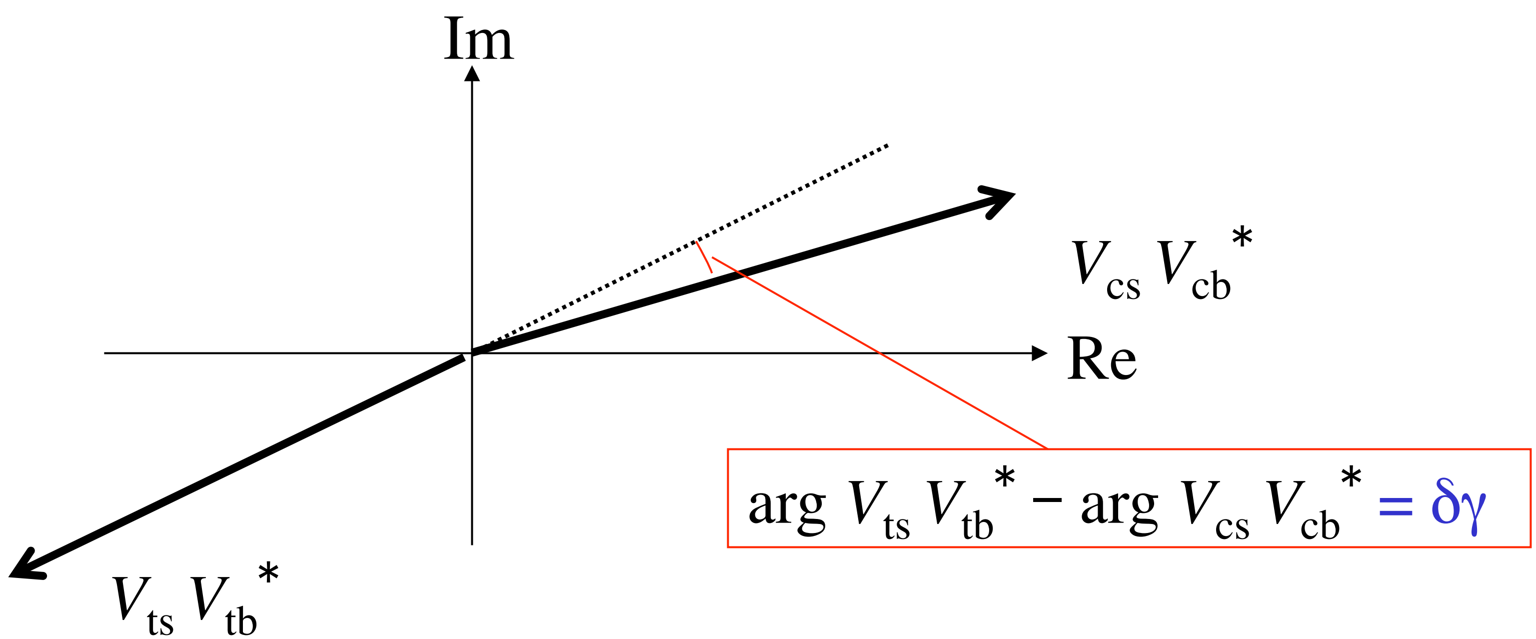
$$\arg V_{ub} - \arg V_{us} + \arg V_{cb} - \arg V_{cs} + 2\arg V_{ts} - 2\arg V_{tb}$$
$$= \arg V_{ub} - \arg V_{us} - \arg V_{cb} + \arg V_{cs}$$
$$+ 2(\arg V_{cb} - \arg V_{cs} + \arg V_{ts} - \arg V_{tb})$$

$$\boxed{\arg V_{cs} \approx -\pi - \arg V_{ud} + \arg V_{us} + \arg V_{cd}}$$

$$= \arg V_{ub} - \arg V_{ud} - \arg V_{cb} + \arg V_{cd} - \pi$$
$$+ 2(\arg V_{cb} - \arg V_{cs} + \arg V_{ts} - \arg V_{tb})$$
$$= \arg V_{cd}V_{cb}^{*} - \arg V_{ud}V_{ub}^{*} - \pi + 2(\arg V_{ts}V_{tb}^{*} - \arg V_{cs}V_{cb}^{*})$$
$$= 2\delta\gamma - \gamma$$

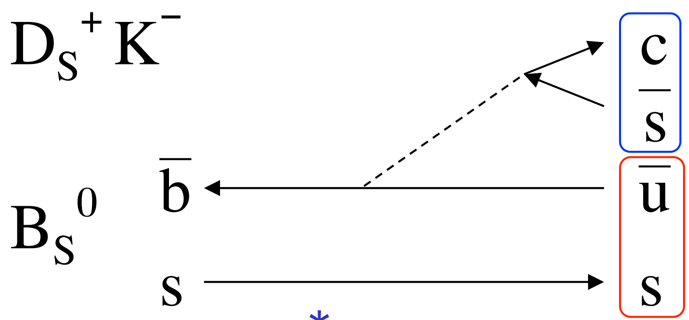


Im
Re
$V_{ud} V_{ub}^*$
$V_{cd} V_{cb}^*$
$\arg V_{ud} V_{ub}^* - (\arg V_{cd} V_{cb}^* - \pi)$
$= \pi + \arg V_{ud} V_{ub}^* - \arg V_{cd} V_{cb}^* = \gamma$



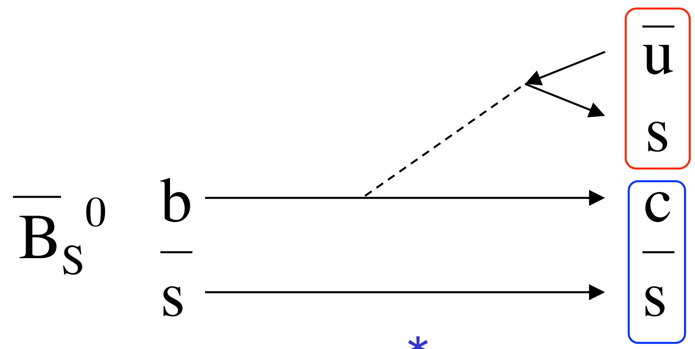
Im
Re
$V_{cs} V_{cb}^*$
$V_{ts} V_{tb}^*$
$\arg V_{ts} V_{tb}^* - \arg V_{cs} V_{cb}^* = \delta\gamma$

$D_s^+ K^-$



$V_{ub}^* V_{cs} \times \text{Tree-2}$

$D_s^+ K^-$



$V_{cb} V_{us}^* \times \text{Tree-1}$

$$\frac{\bar{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} = \frac{V_{cb} V_{us}^* \times \text{Tree-1}}{V_{ub}^* V_{cs} \times \text{Tree-2}}$$

$$= \frac{1}{r} \times e^{i(\arg V_{cb} - \arg V_{us} + \arg V_{ub} - \arg V_{cs})} e^{-i\Delta} e^{-i\theta_{CP}}$$

$$L_{D_s^+ K^-} \approx -e^{i(\theta_{CP} + 2\arg V_{ts} - 2\arg V_{tb})}$$

$$\times \frac{1}{r} e^{i(\arg V_{cb} - \arg V_{us} + \arg V_{ub} - \arg V_{cs} - \theta_{CP})} e^{-i\Delta}$$

$$= -\frac{1}{r} e^{i(\arg V_{ub} - \arg V_{us} + \arg V_{cb} - \arg V_{cs} + 2\arg V_{ts} - 2\arg V_{tb})} e^{-i\Delta}$$

$$= \frac{1}{r} e^{i(-\gamma + 2\delta\gamma - \Delta)}$$

B_s^0 at $t = 0 \rightarrow D_S^- K^+$ at t

$$R_{D_s^- K^+}(t) = \frac{\left|A_{D_s^- K^+}\right|^2}{2} e^{-\bar{\Gamma} t} \left\{ I_+^{D_s^- K^+}(t) + I_-^{D_s^- K^+}(t) \right\}$$

$$I_+^{D_s^- K^+}(t) = \left(1 + r^2\right) \cosh \frac{\Delta\Gamma}{2} t - 2r \cos\left(\gamma - 2\delta\gamma - \Delta\right) \sinh \frac{\Delta\Gamma}{2} t$$

$$I_-^{D_s^- K^+}(t) = \left(1 - r^2\right) \cos \Delta m t + 2r \sin\left(\gamma - 2\delta\gamma - \Delta\right) \sin \Delta m t$$

$\overline{B}_s^0$ at $t = 0 \rightarrow D_S^- K^+$ at t

$$\bar{R}_{D_s^- K^+}(t) = \frac{\left|A_{D_s^- K^+}\right|^2}{2} e^{-\bar{\Gamma} t} \left\{ I_+^{D_s^- K^+}(t) - I_-^{D_s^- K^+}(t) \right\}$$

B_s^0 at $t = 0 \rightarrow D_S^+ K^-$ at t

$$R_{D_s^+K^-}(t) = \frac{\left|A_{D_s^+K^-}\right|^2}{2} e^{-\bar{\Gamma}t}\left\{I_+^{D_s^+K^-}(t) + I_-^{D_s^+K^-}(t)\right\}$$

$$I_+^{D_s^+K^-}(t) = \left(1 + \frac{1}{r^2}\right)\cosh\frac{\Delta\Gamma}{2}t - 2\frac{1}{r}\cos(\gamma - 2\delta\gamma + \Delta)\sinh\frac{\Delta\Gamma}{2}t$$

$$I_-^{D_s^-K^+}(t) = \left(1 - \frac{1}{r^2}\right)\cos\Delta mt + 2\frac{1}{r}\sin(\gamma - 2\delta\gamma + \Delta)\sin\Delta mt$$

$\overline{B}_s^0$ at $t = 0 \rightarrow D_S^+ K^-$ at t

$$\bar{R}_{D_s^-K^+}(t) = \frac{\left|A_{D_s^-K^+}\right|^2}{2} e^{-\bar{\Gamma}t}\left\{I_+^{D_s^-K^+}(t) - I_-^{D_s^-K^+}(t)\right\}$$

r, $\gamma - 2\delta\gamma + \Delta$, $\gamma - 2\delta\gamma - \Delta$ can be determined: $\rightarrow$ $\gamma - 2\delta\gamma$

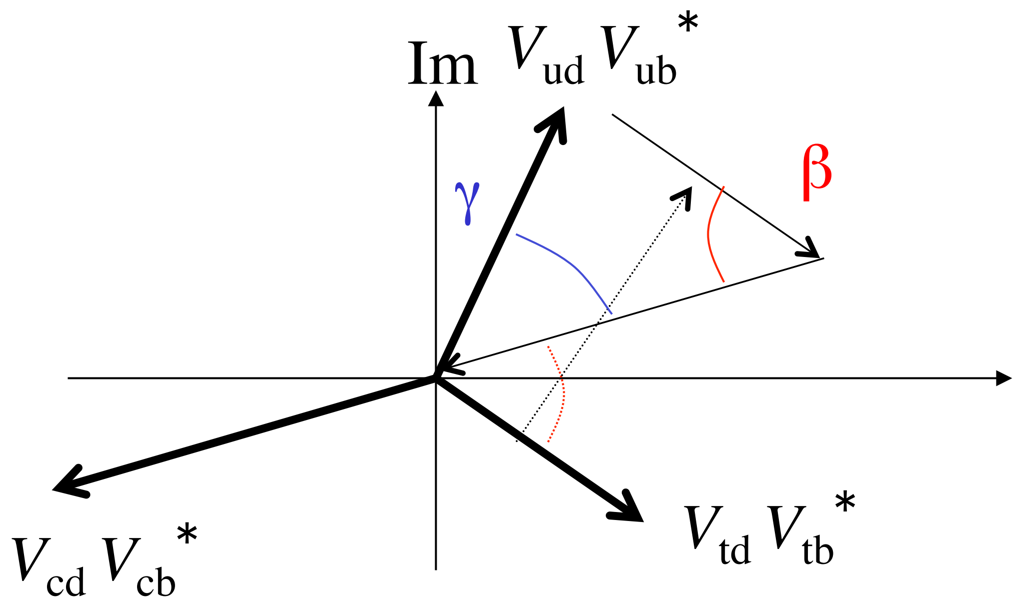
$B_d \rightarrow J/\psi\ K_S$: 2β

$B_d \rightarrow D^{*\pm}\pi^{\mu}$, $\gamma + 2\beta$

$B_s \rightarrow J/\psi\ \phi$: $-\ 2\delta\gamma$

$B_s \rightarrow D_s^{\pm}K^{\mu}$, $\gamma - 2\delta\gamma$

γ and β can be extracted.



CKM parameters

Measurements	CKM elements
Δm_d (B^0-$\bar{B}^0$ oscillations)	$\lvert V_{tb} V_{td}^* \rvert$
Δm_s (B_s^0-$\bar{B}_s^0$ oscillations)	$\lvert V_{tb} V_{ts}^* \rvert$
$\Gamma(B \to D^* \ell\nu)$	$\lvert V_{cb} \rvert$
$\Gamma(B \to \rho\ell\nu)$	$\lvert V_{ub} \rvert$

n, π, K decays → $\sin\theta_c = \lambda = 0.22$

unitarity → $\lvert V_{td} \rvert = 1$

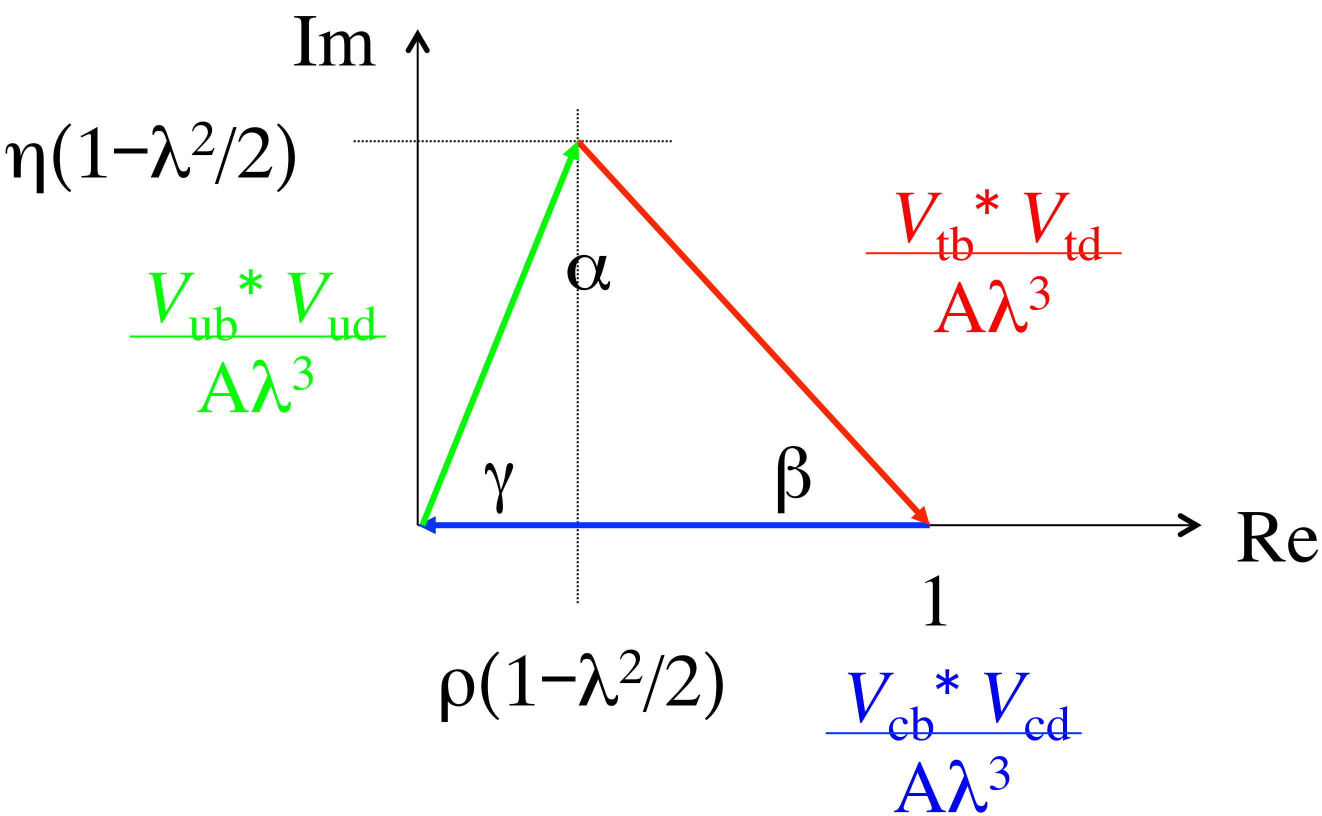
Wolfenstein parametrization

$$\lvert V_{cb} \rvert = A\,\lambda^2$$
$$\lvert V_{ub} \rvert = A\,\lambda^3 \sqrt{\rho^2 + \eta^2}$$
$$\lvert V_{td} \rvert = A\,\lambda^3 \sqrt{(1 - \tilde{\rho})^2 + \tilde{\eta}^2}$$
$$\lvert V_{ts} \rvert = A\,\lambda^2$$

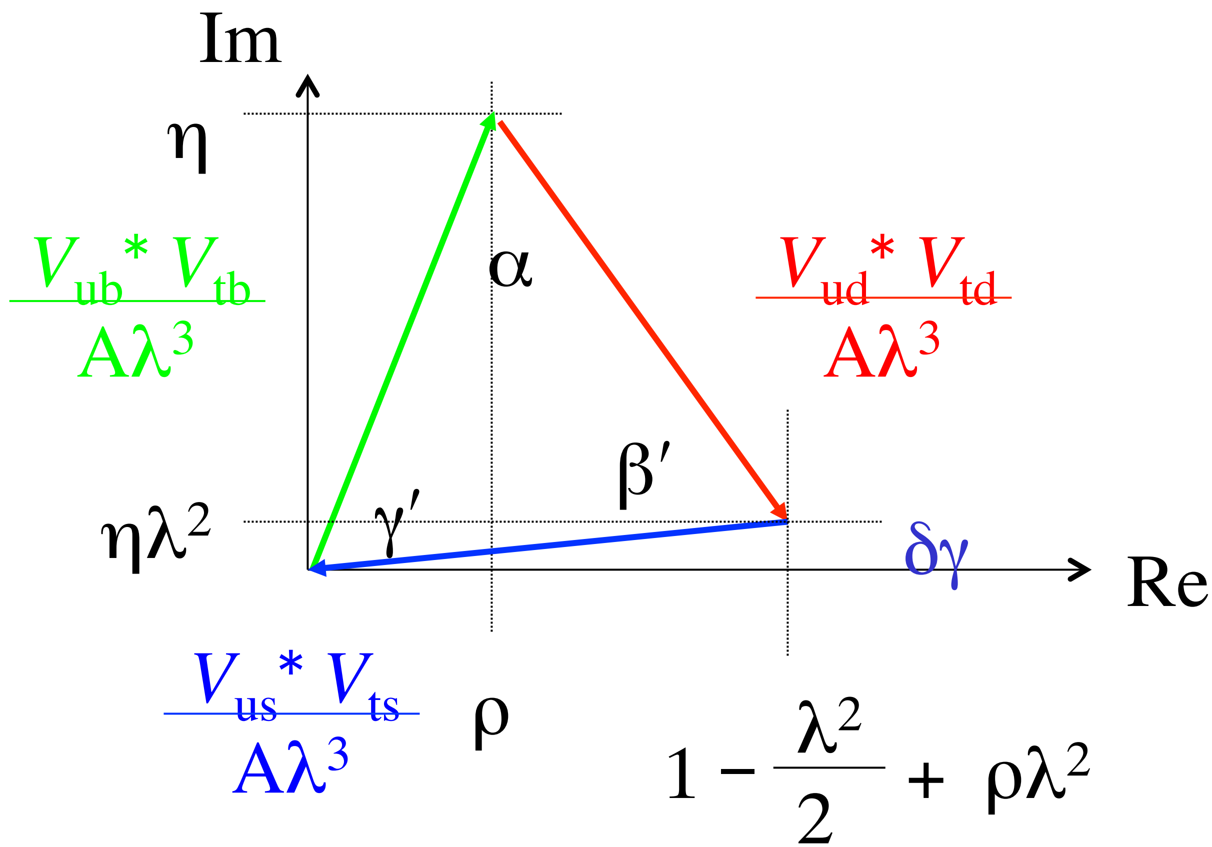
$$\tilde{\eta} = \eta\,(1 - \lambda^2/2)$$
$$\tilde{\rho} = \rho\,(1 - \lambda^2/2)$$

1) $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

Using the Wolfenstein's parametrization (λ, A, ρ, η)



$$2)\ V_{ud}^{*} V_{td} + V_{us}^{*} V_{ts} + V_{ub}^{*} V_{tb} = 0$$



$$\gamma' + \delta\gamma = \gamma$$

$$\beta' - \delta\gamma = \beta$$

$$\arg V_{td} = -\beta$$
$$\arg V_{ub} = -\gamma$$
$$\arg V_{ts} = \delta\gamma + \pi$$

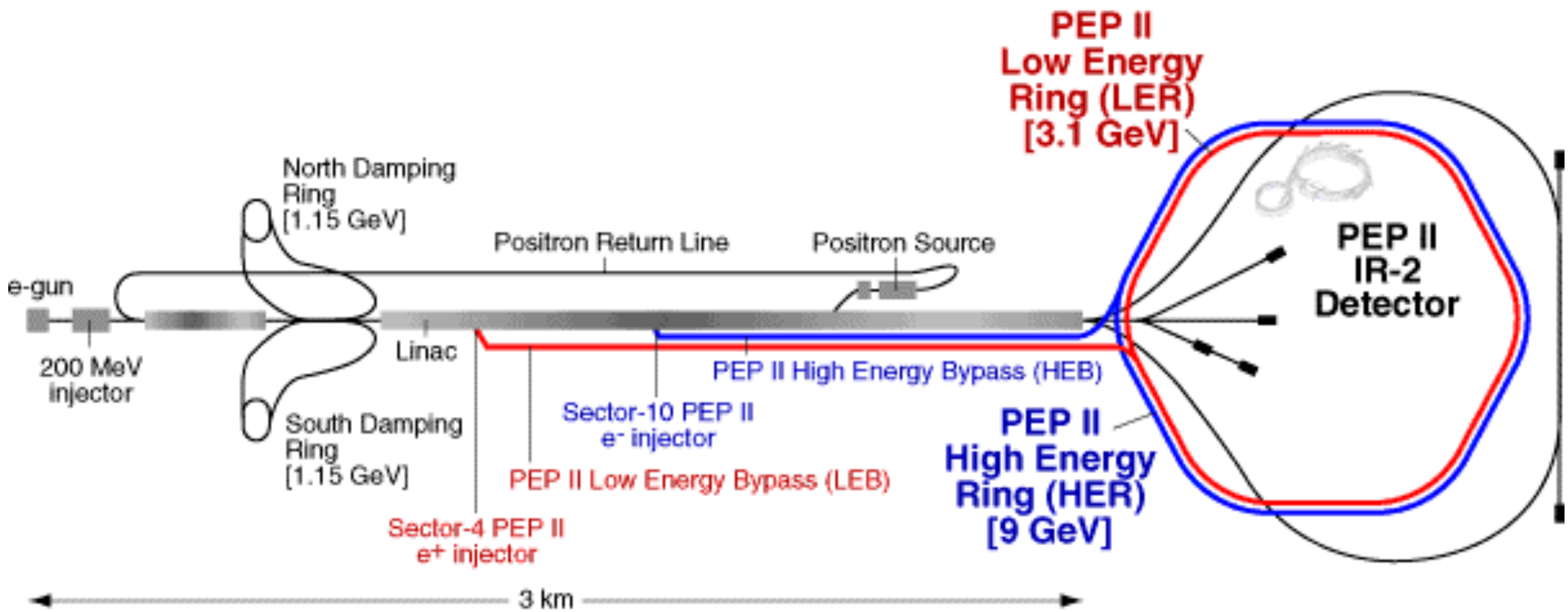
$$\beta = \tan^{-1} \frac{\eta}{1-\rho} \left(1 - \frac{\lambda^2}{2(1-\rho)} \right)$$

$$\gamma = \tan^{-1} \frac{\eta}{\rho}$$

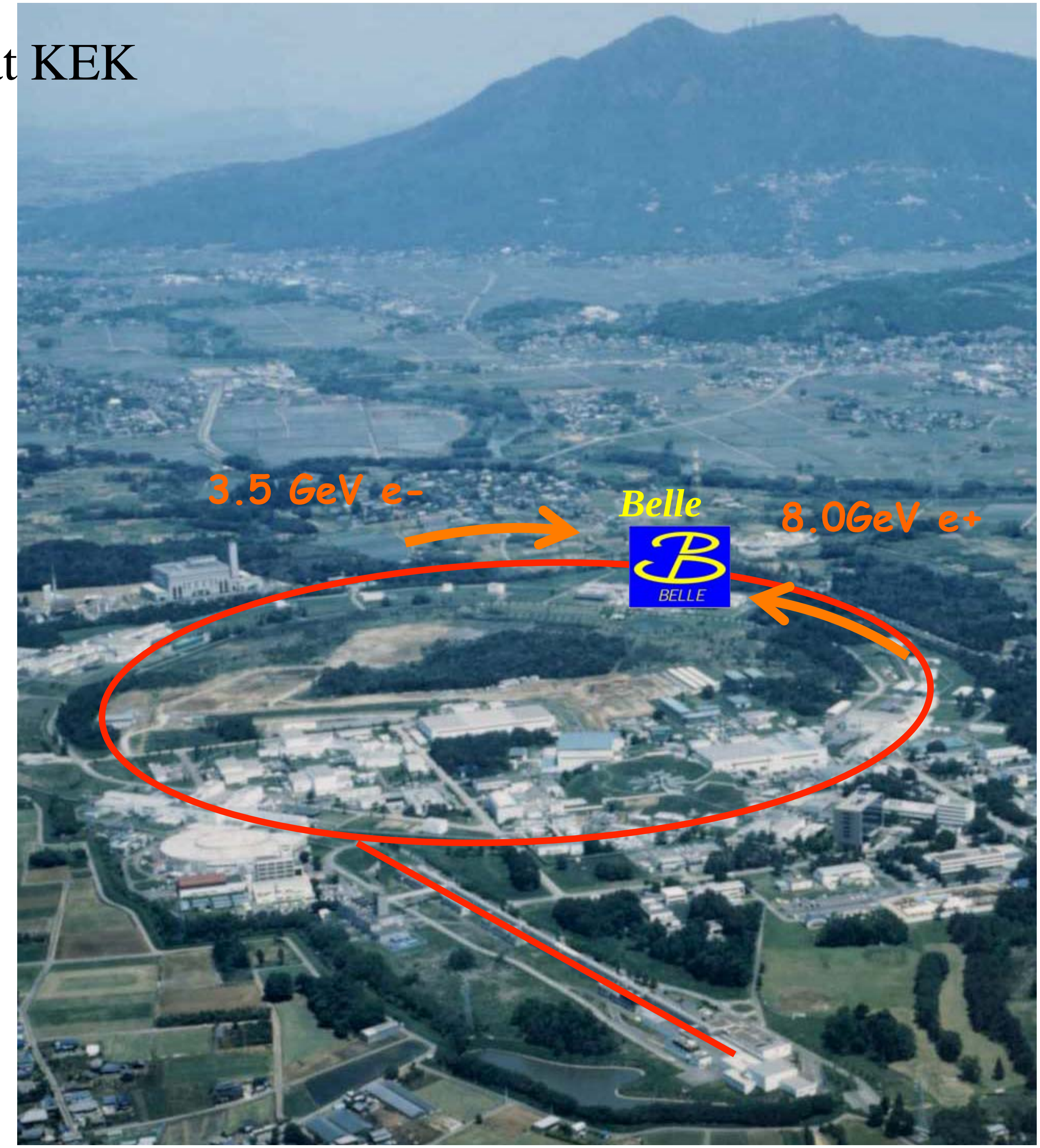
$$\delta\gamma = \eta\lambda^2$$

If we ignore the λ^2 correction, 1) and 2) are degenerate.

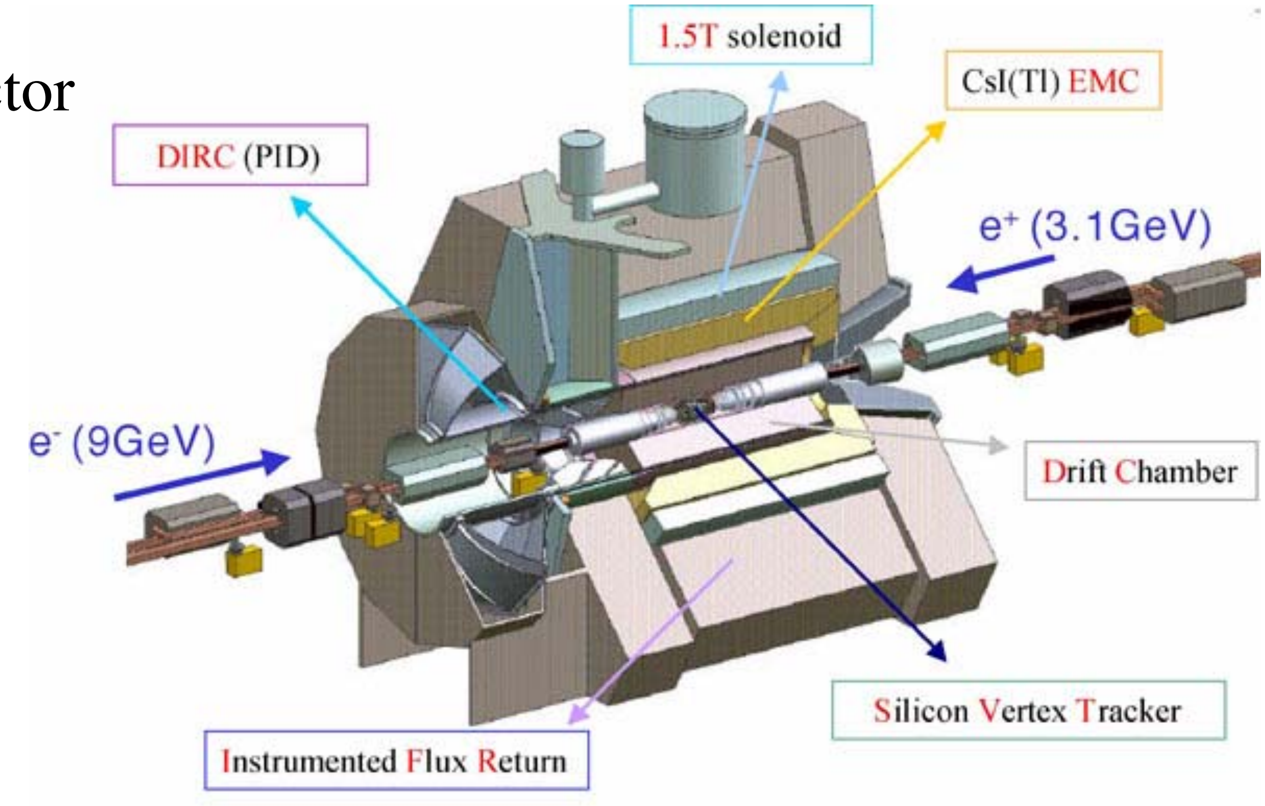
PEP II at SLAC



KEKB at KEK



BABAR detector



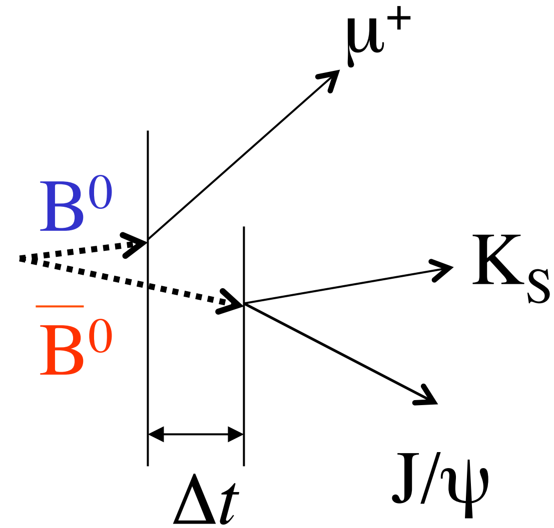
in the lab. frame

e^- → ← e^+

↓

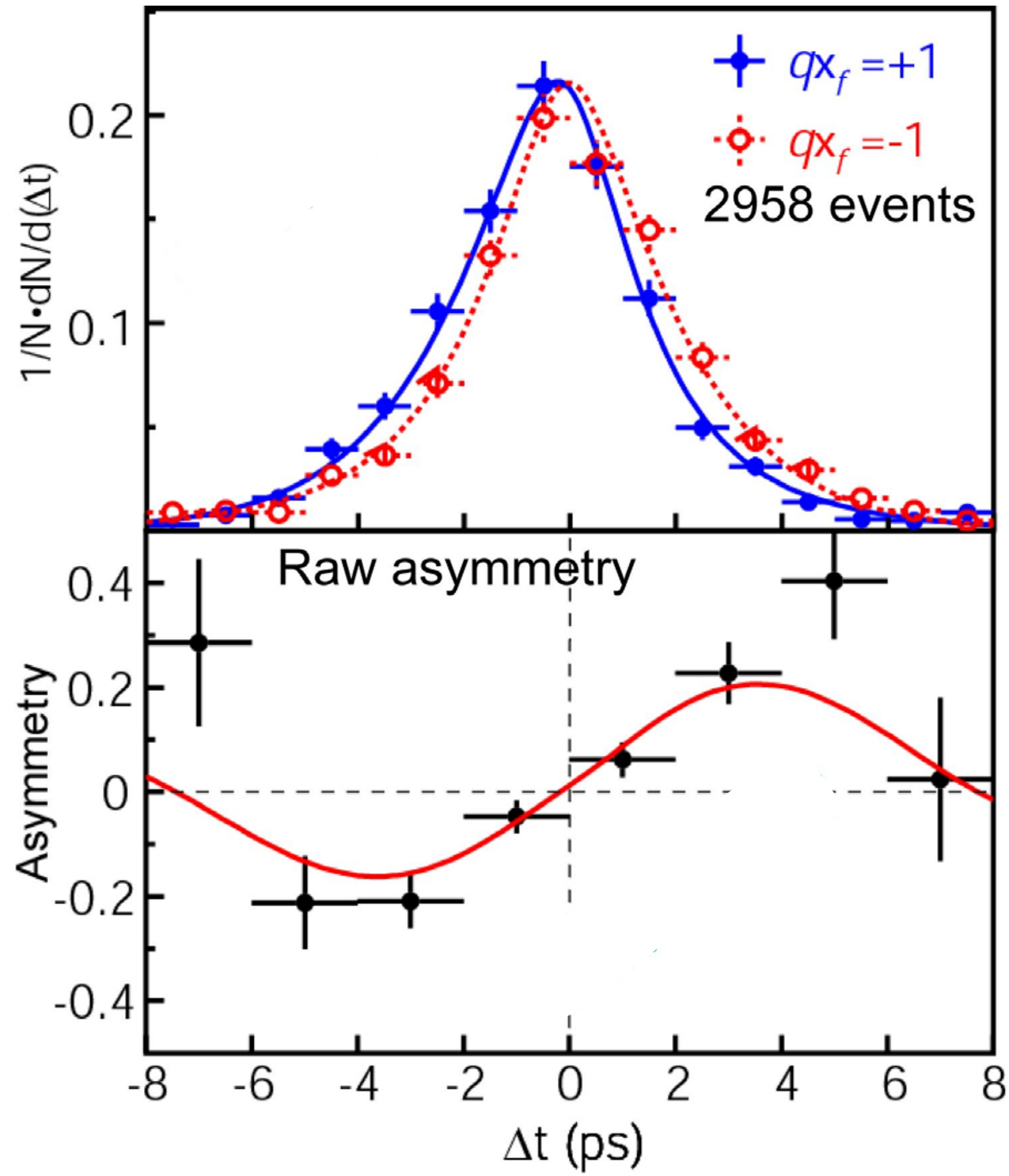
$\Upsilon(4S)$ ⇛ boost

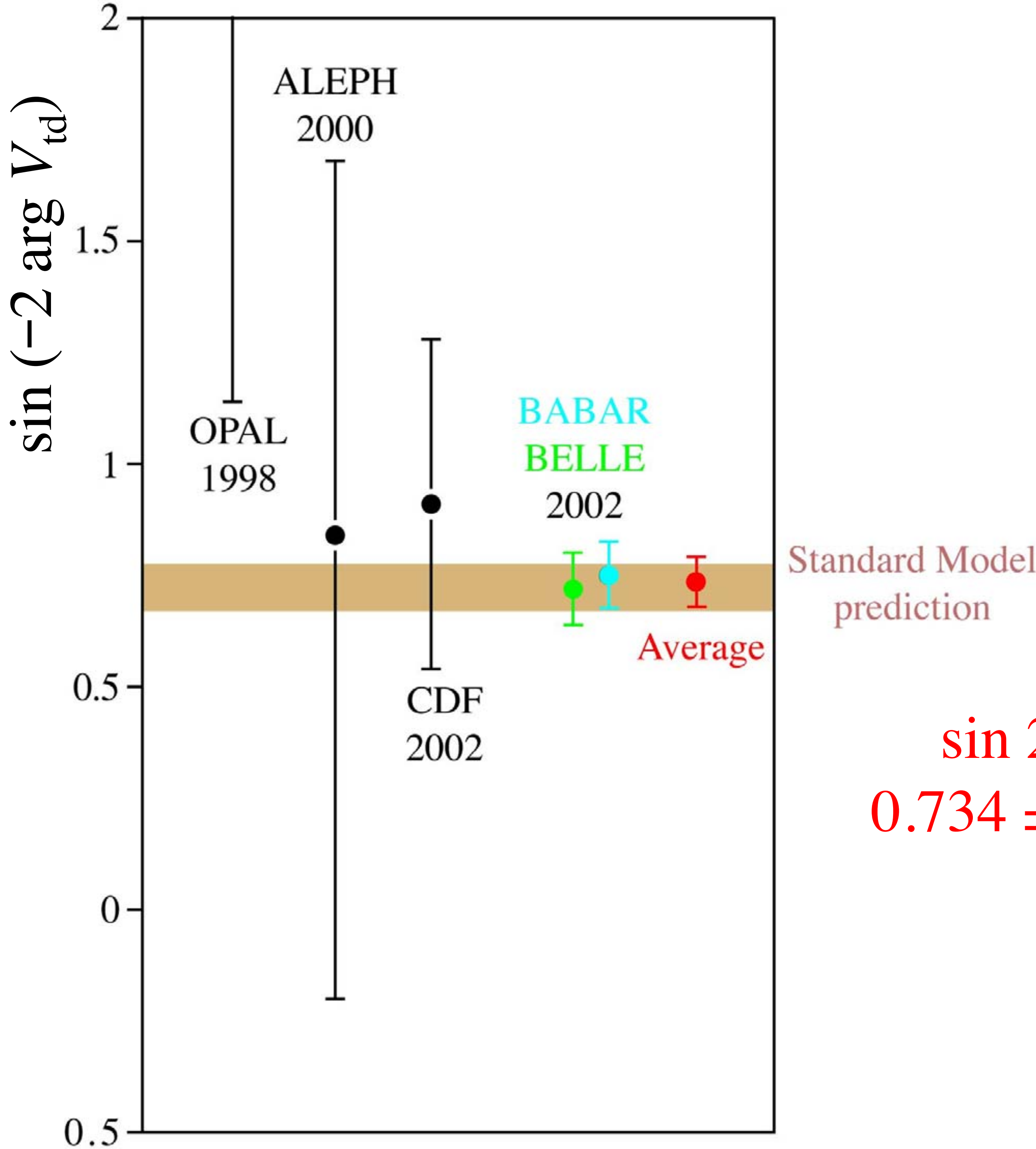
boosted $\overline{B}^0 B^0$ system
(remains always $\overline{B}^0 B^0$)



$B^0 \rightarrow J/\psi\ K_S$

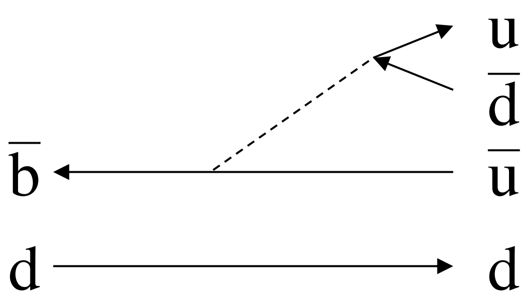
$\overline{B^0} \rightarrow J/\psi\ K_S$



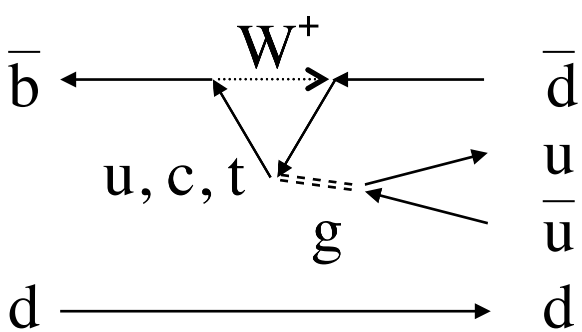


$\sin 2\beta =$
0.734 ± 0.055

$B_d \to \pi\pi, \rho\pi, \rho\rho$



$V_{ub} \to \gamma$



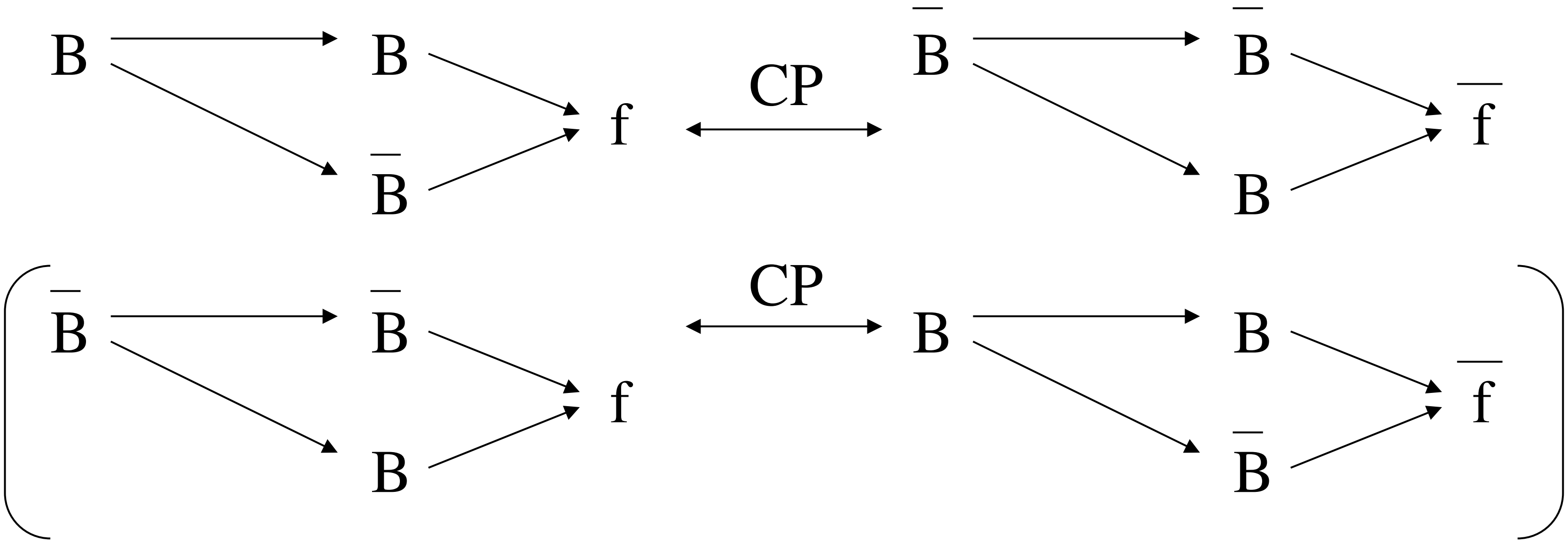
+ γ and Z^0 penguins

$V_{td} \to \beta$

$\pi\pi$, $\rho\pi$: penguin contribution cannot be neglected

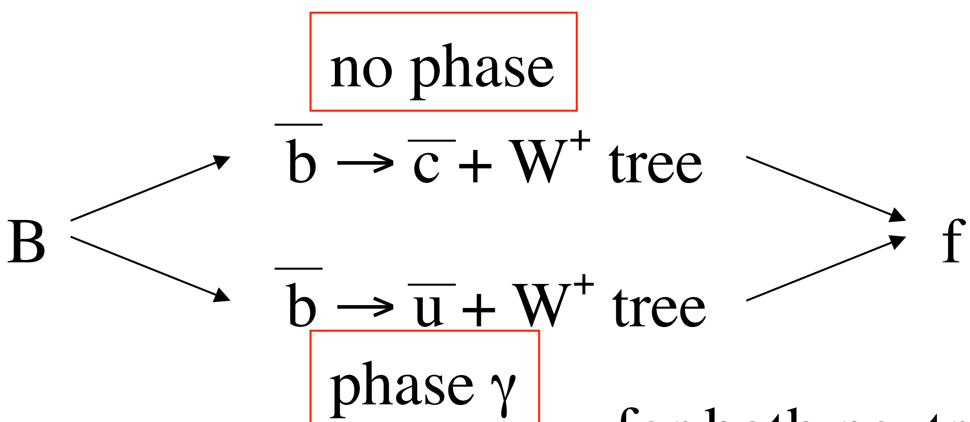
$\rho\rho$: penguin contribution seems to be very small

Processes we have looked at are:



only for the neutral B mesons

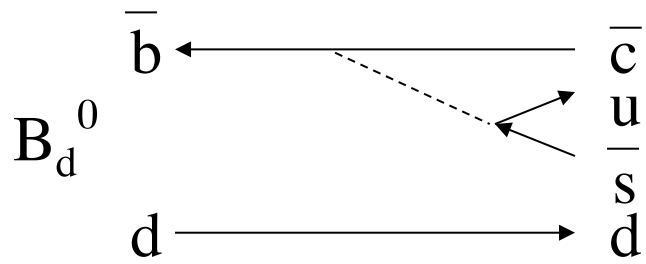
Another way to mix tow decay processes



for both neutral and charged B mesons

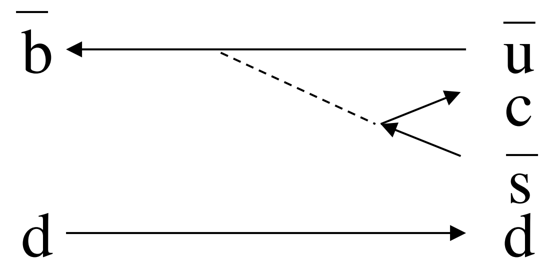
Another way to determine γ without new physics contamination

$\overline{D}^0 K^{*0}(\rightarrow K^+\pi^-)$



$V_{cb}^* V_{us} \times$ Tree-1

$D^0 K^{*0}(\rightarrow K^+\pi^-)$



$V_{ub}^* V_{cs} \times$ Tree-2

$\overline{D}^0 \rightarrow K_S\pi^+\pi^- \leftarrow D^0$ K-$\overline{\text{K}}$ mixing (GLW)

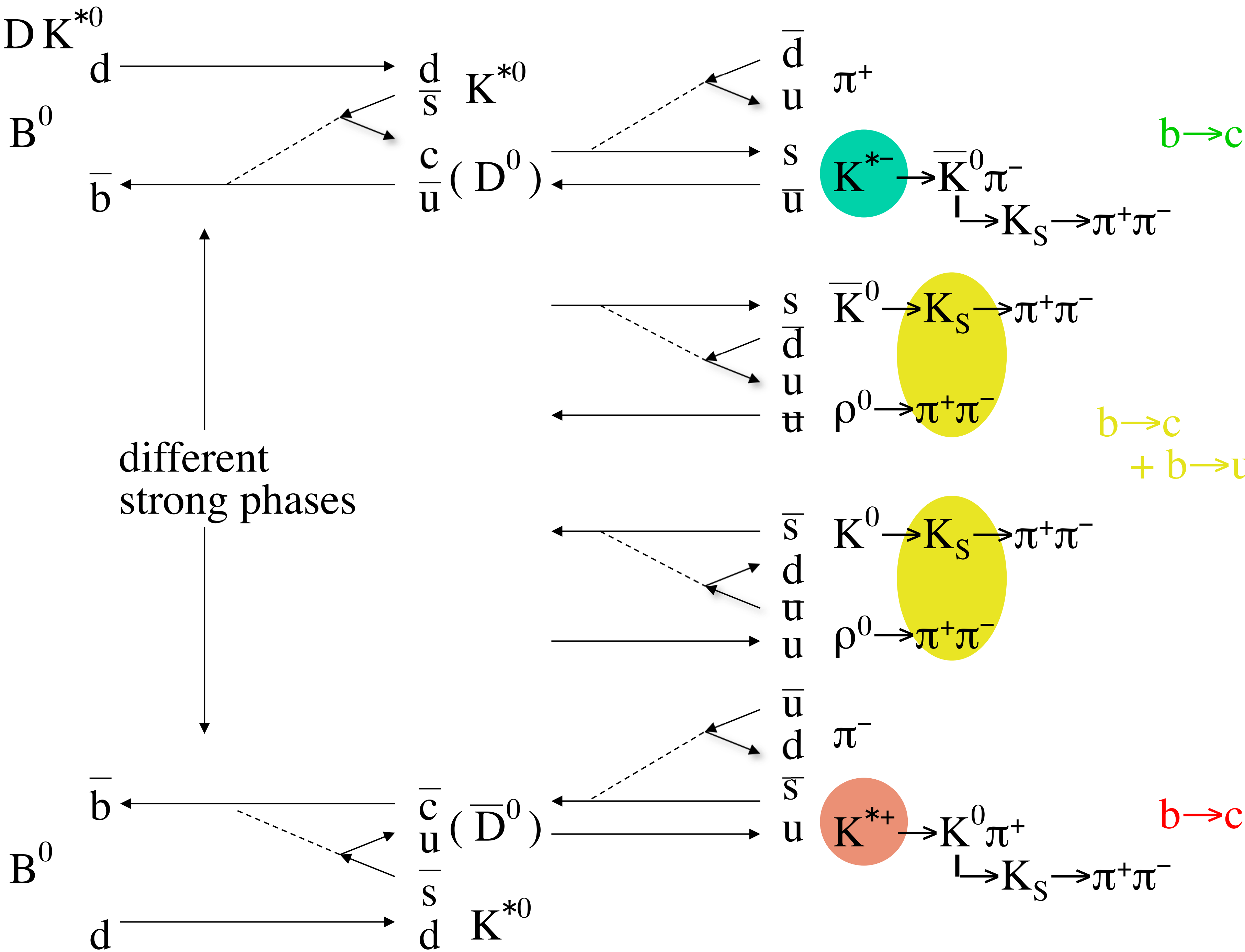
$\overline{D}^0 \rightarrow K^+K^-, \pi^+\pi^- \leftarrow D^0$ D-$\overline{\text{D}}$ mixing (GGSZ)

$\overline{D}^0 \rightarrow K^+\pi^-, K^+\pi^-\pi^+\pi^- \leftarrow D^0$ Doubblly Cabibbo Suppressed Decay (ADS)

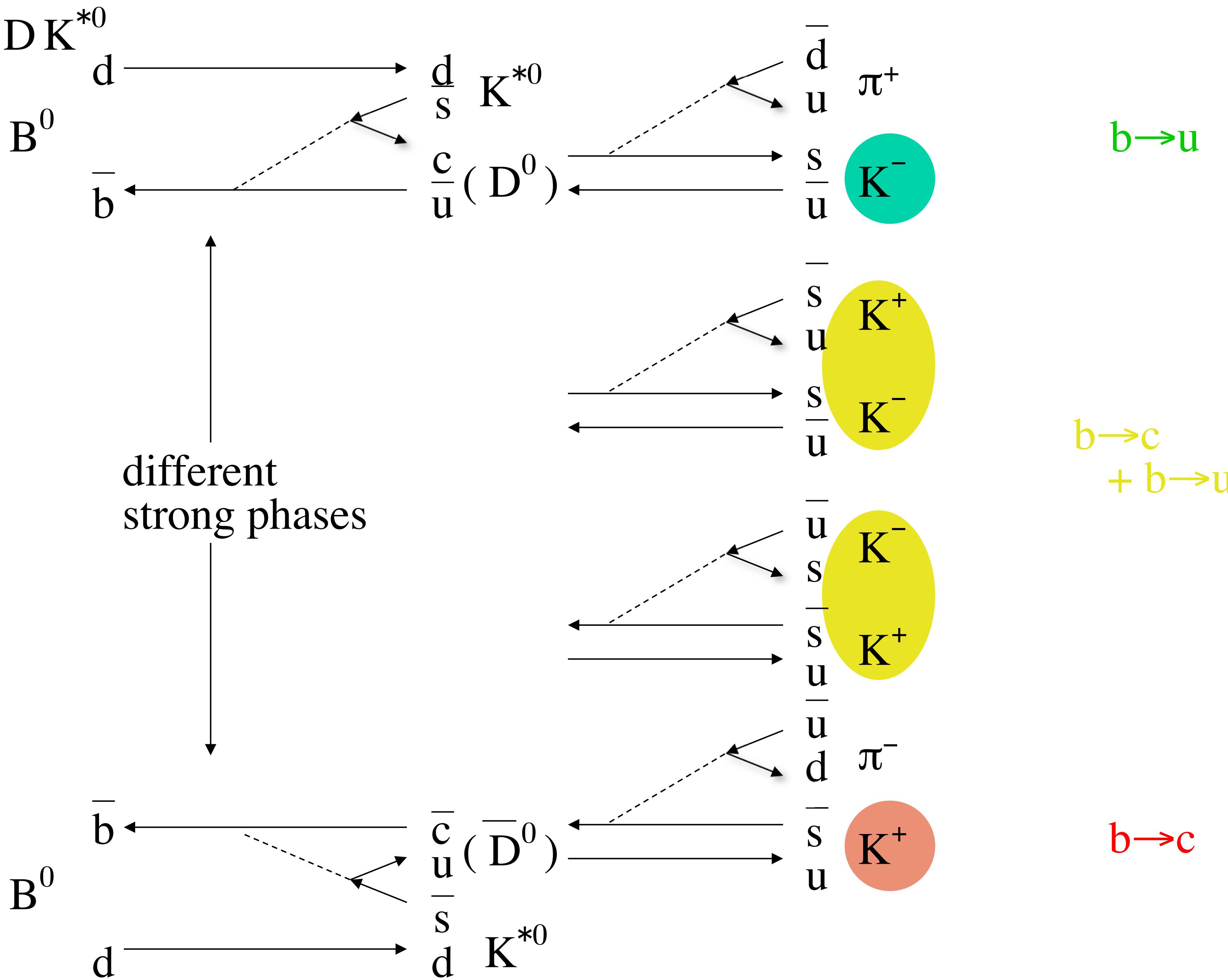
$$V_{cb}^* \underbrace{V_{us} \times \overbrace{\text{Tree-1} + V_{ub}^*}^{\text{strong phase}}}_{\text{weak phase } \gamma} \overbrace{V_{cs} \times \text{Tree-2}}$$

strong phase

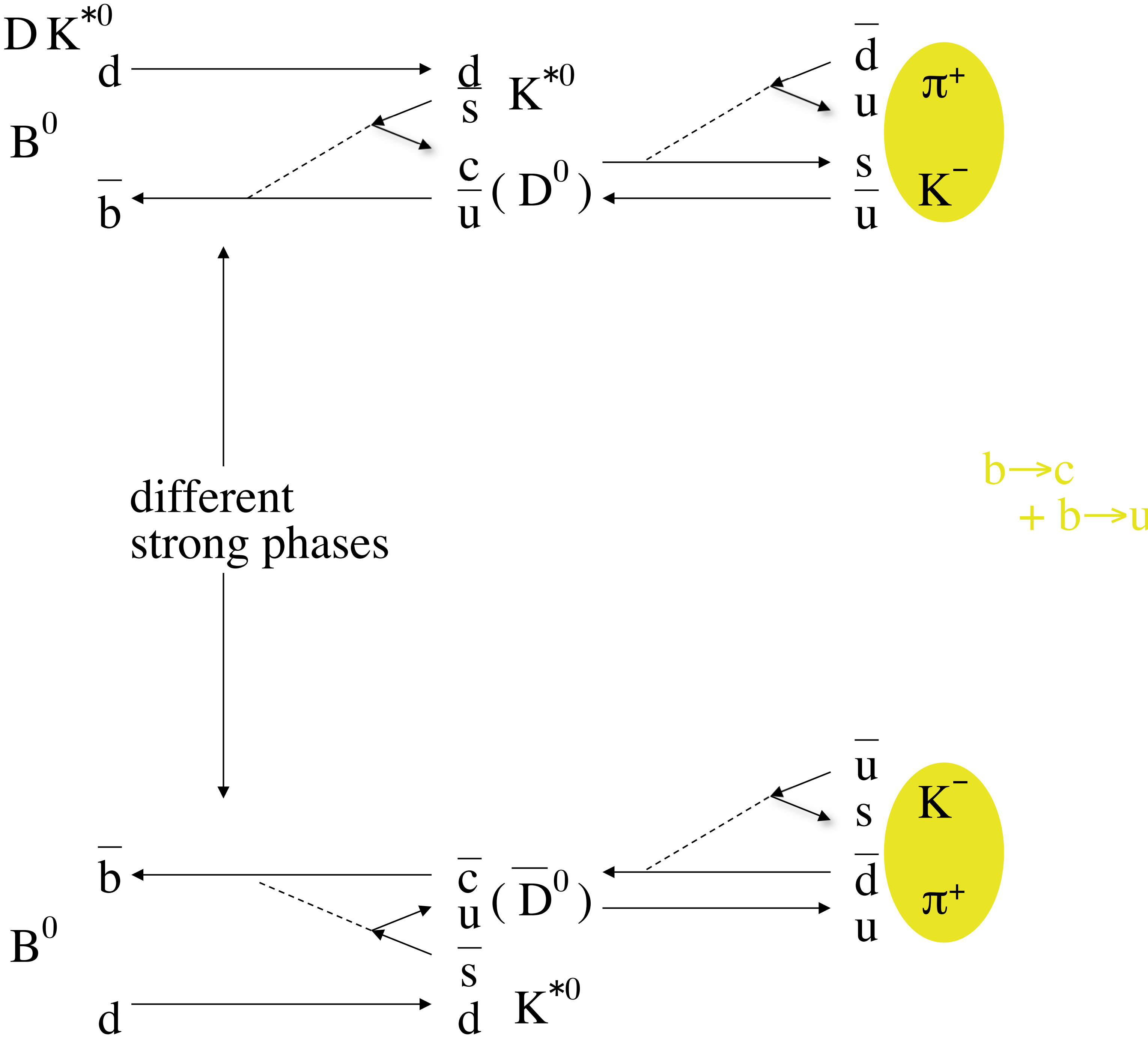
weak phase γ

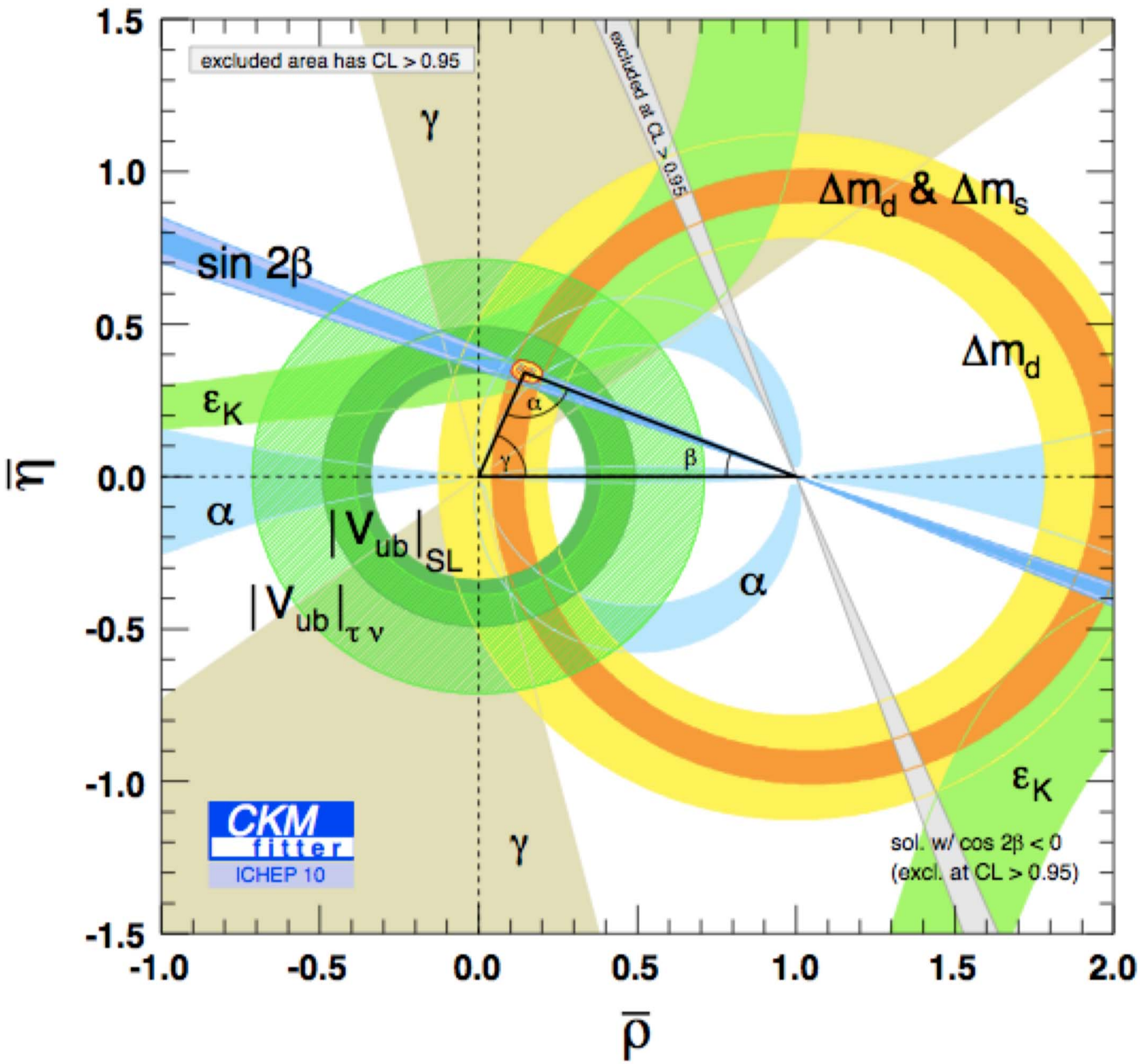


D K*0
B0
d
b̄
d s̄ K*0
c ū (D0)
d̄ u π+
s ū K*− → K̄0 π−
→ KS → π+π−
b→c
s K̄0 → KS → π+π−
d̄ u
ū ρ0 → π+π−
b→c
+ b→u
different
strong phases
s̄ K0 → KS → π+π−
d ū
u ρ0 → π+π−
ū d π−
s̄ K*+ → K0 π+
→ KS → π+π−
b→c
b̄
c̄ u (D̄0)
B0
s̄ d K*0
d



D K*0
B0
d
b̄
d
s̄
K*0
c
ū
(D0)
d̄
u
π+
s
ū
K−
b→u
s̄
u
K+
s
ū
K−
b→c
+ b→u
different
strong phases
ū
s
K−
s̄
u
K+
ū
d
π−
s̄
u
K+
b→c
b̄
c̄
u
(D̄0)
s̄
d
K*0
B0
d

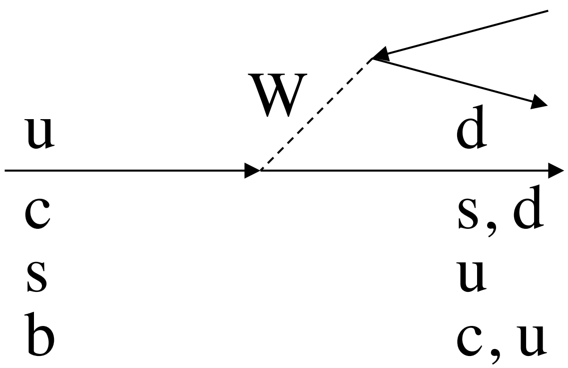

D K*0
B0
d
b
d
s
K*0
c
u
(D0)
d
u
π+
s
u
K−
different
strong phases
b→c
+ b→u
u
s
K−
b
c
u
(D0)
d
π+
u
B0
s
d
K*0
d



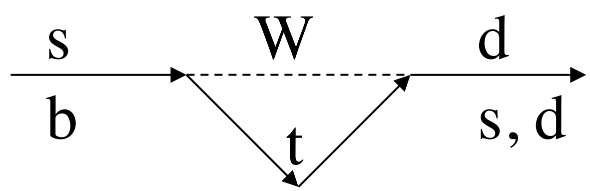
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δmd & Δms
sin 2β
Δmd
εK
α
β
γ
α
|Vub|SL
|Vub|τν
α
εK
CKM fitter
ICHEP 10
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
γ
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

Possible effect of new physics

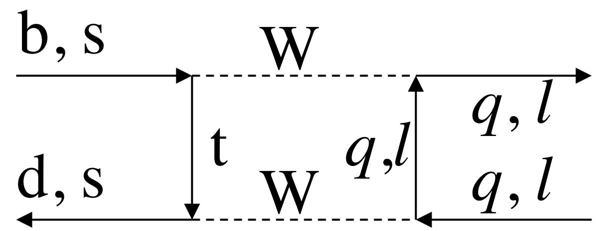
Tree level decays



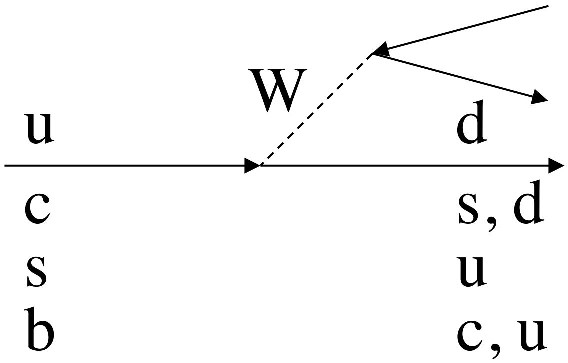
Penguin level decays



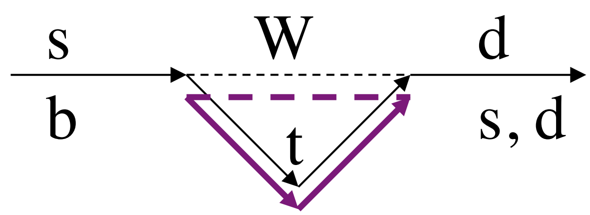
Box level decays



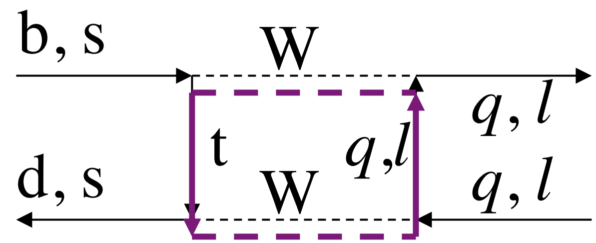
Tree level decays



Penguin level decays



Box level decays



unchanged

+ new particles

Phases

Lorentz structure of the amplitude modified

Absolute values

New phases in new physics loops…

- (ρ, η) determination with loop diagrams
  Δm_d + CPV($B \rightarrow J/\psi K_S$, ε_K)
  and
  (ρ, η) determination with tree diagrams
  CPV($B \rightarrow DK$) and $\Gamma(b \rightarrow u l \nu)$
  would be different

  Better low energy QCD theory for $B_B f_B^2$, B_K, …
  and
  More statistics for CPV($B \rightarrow DK$) γ determination
  $\Rightarrow$LHCb experiments
- CPV($B_s \rightarrow J/\psi\phi$) does not agree with the CKM fit
- CPV($B_s \rightarrow J/\psi\phi$) and CPV($B_s \rightarrow \phi\phi$) are different

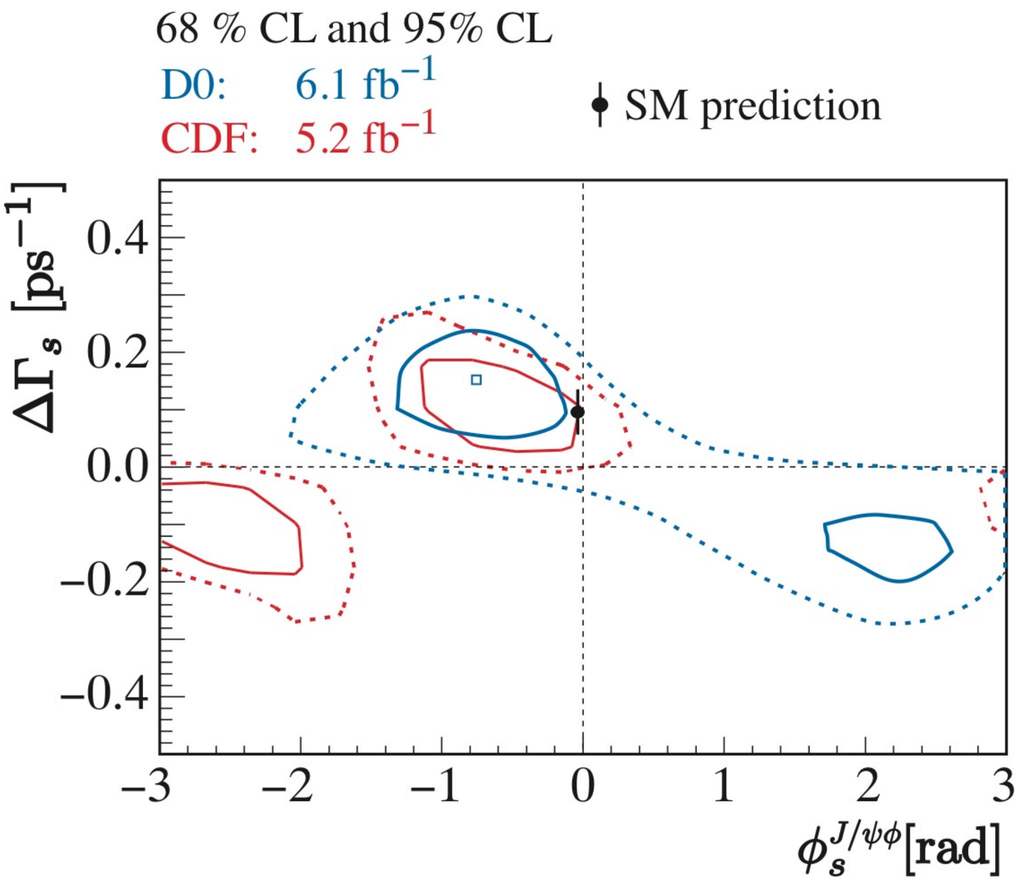
New Lorentz structure in new physics loops…

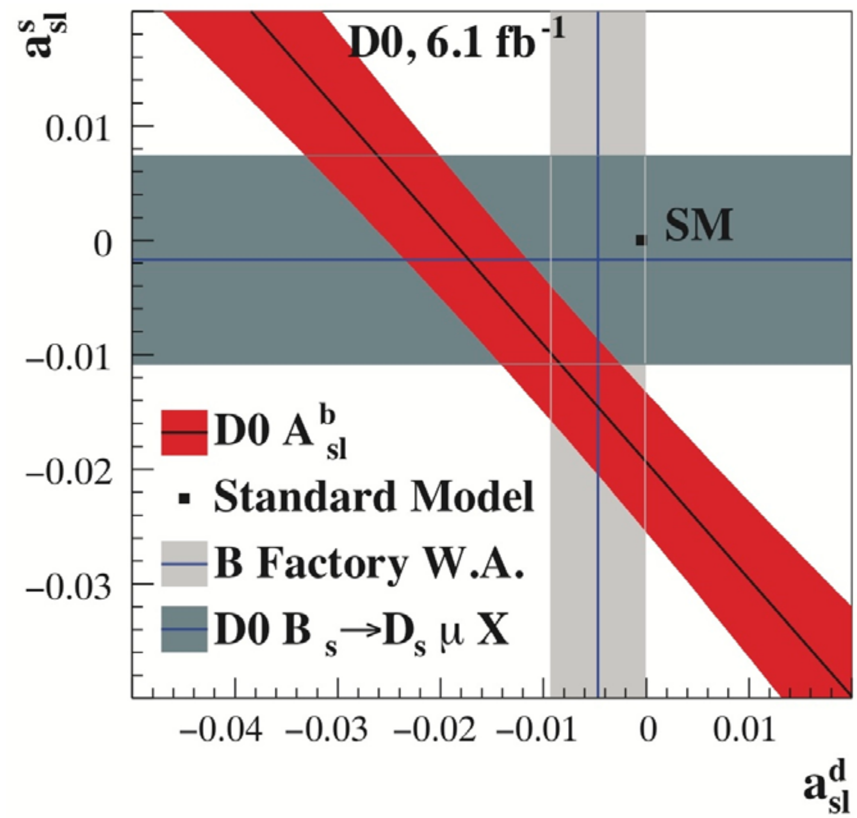
- Angular distribution of the decay particles in $B_d \rightarrow K^{*0}\mu^+\mu^-$ different from the SM: e.g. A_{FS} of $\mu^+\mu^-$
- CPV($B_s \rightarrow \phi\gamma$)

And enhanced rare decays

- $Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$

Are they really signs of new physics?





LHCb will answer.