Physics of CP Violation and Rare Decays

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Introduction

Rare phenomena have been an indirect way to probe the high energy frontier.

Successful examples:

K^0-$\bar{K}^0$ oscillations, $K_L \to \mu^+\mu^-$, CP violating $K_L \to \pi^+\pi^-$ decays etc.

GIM mechanism, charm quark, third family of quarks etc.

$B \to \ell^+ \ell^-$ not seen, $\Delta m(B_d) \approx 100\times\Delta m(K^0)$, etc.

top must exist, $m_t > 80$ GeV/c^2, etc.

CP violation: an interference term

$$A_{\text{Standard Model}} \times A_{\text{New Physics}}$$

can be isolated: a linear effect = enhanced sensitivities

Forbidden decays: Processes not allowed by the Standard Model.

In principle, one event is a discovery.

$\mu \to 3e$, $\mu \to e\gamma$: best limit on LFCNC coupling.

CP violation has an important implication to cosmology: baryon genesis

CP violation with the KM mechanism is not sufficient for this…

-call for new physics-

I) Time development of the particle (*P*) and antiparticle($\bar{P}$)

$|P\rangle$, $|\overline{P}\rangle$ particle, antiparticle state **at rest**

-eigenstates of strong and electromagnetic interactions-

$$\left(H_s + H_{em}\right)|P\rangle = m|P\rangle, \left(H_s + H_{em}\right)|\overline{P}\rangle = m|\overline{P}\rangle$$

(CPT assumed; they are also flavour eigenstates)

$|f\rangle$ weak interaction decay products

-eigenstates of strong and electromagnetic interactions-

$$\left(H_s + H_{em}\right)|f\rangle = E_f|f\rangle$$

A general state

$$|\psi(t)\rangle = a(t)|P\rangle + b(t)|\bar{P}\rangle + \sum_f c_f(t)|f\rangle$$

($|a(t)|^2$: fraction of P $|b(t)|^2$: fraction of $\bar{P}$ at t)

is obtained by solving Schrödeinger equation,

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = (H_s + H_w + H_{em})|\psi(t)\rangle$$

Due to decays

$$|a(0)|^2 + |b(0)|^2 = 1 \qquad |a(t)|^2 + |b(t)|^2 = \text{ decreases}$$

$$|c_f(0)|^2 = 0 \qquad |c_f(t)|^2 = \text{ increases}$$

$$|a(t)|^2 + |b(t)|^2 + \sum_f |c_f(t)|^2 = 1$$ unitarity

-perturbation, Wigner-Weiskopf, CPT and unitarity assumed-

$$-i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \Lambda \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}, \quad \Lambda = \begin{pmatrix} M & M_{12} \\ M_{12}^{*} & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma \end{pmatrix}$$

$a(t)$ and $b(t)$ are decouppled from $c_f(t)$

if $M_{12}, \Gamma_{12} \neq 0$ mixing of P and $\bar{P}$

Usually, particles are produced in flavour eigenstates:

i.e. P or $\bar{P}$ at $t = 0$, then then evolve with time t.

$$|P(t)\rangle = f_+(t)|P\rangle + \zeta f_-(t)|\bar{P}\rangle$$

or

$$|\bar{P}(t)\rangle = \frac{1}{\zeta} f_-(t)|P\rangle + f_+(t)|\bar{P}\rangle$$

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

$$\lambda_\pm = m_\pm - \frac{i}{2}\Gamma_\pm, \quad \zeta = \sqrt{\frac{\Lambda_{21}}{\Lambda_{12}}}$$

: eigenvalues of Λ

corresponding eigenstates $\quad \left| P_{\pm} \right\rangle = \frac{1}{\sqrt{1+|\zeta|^2}} \left(| P \rangle \pm \zeta \, | \overline{P} \rangle \right)$

- Elements of mass and decay matrices

$$M = m_0 + \langle P | H_W | P \rangle + \sum_f \mathbf{P} \left(\frac{\langle P | H_W | f \rangle \langle f | H_W | P \rangle}{m_0 - E_f} \right)$$

f's are all possible *P* decay states common to; virtual and real

$$M_{12} = \langle P | H_W | \overline{P} \rangle + \sum_f \mathbf{P} \left(\frac{\langle P | H_W | f \rangle \langle f | H_W | \overline{P} \rangle}{m_0 - E_f} \right)$$

f's are all possible decay states common to *P* and *P*; virtual and real

$$\Gamma = 2\pi \sum_f \left| \langle P | H_W | f \rangle \right|^2 \delta\left(m_0 - E_f\right)$$

f's are all possible **real** decay states
i.e. Γ is a decay width.

$$\Gamma_{12} = 2\pi \sum_f \langle P | H_W | f \rangle \langle f | H_W | \overline{P} \rangle \delta\left(m_0 - E_f\right)$$

f's are all possible **real** decay states,
common to P and $\overline{P}$.

Neutral kaon system $\Gamma_+ = \Gamma_S,\ \Gamma_- = \Gamma_L$
$m_+ = m_S,\ m_- = m_L$

$$\tau_S = \frac{1}{\Gamma_S} = (0.8934 \pm 0.0008) \times 10^{-10}\,\mathrm{s}$$

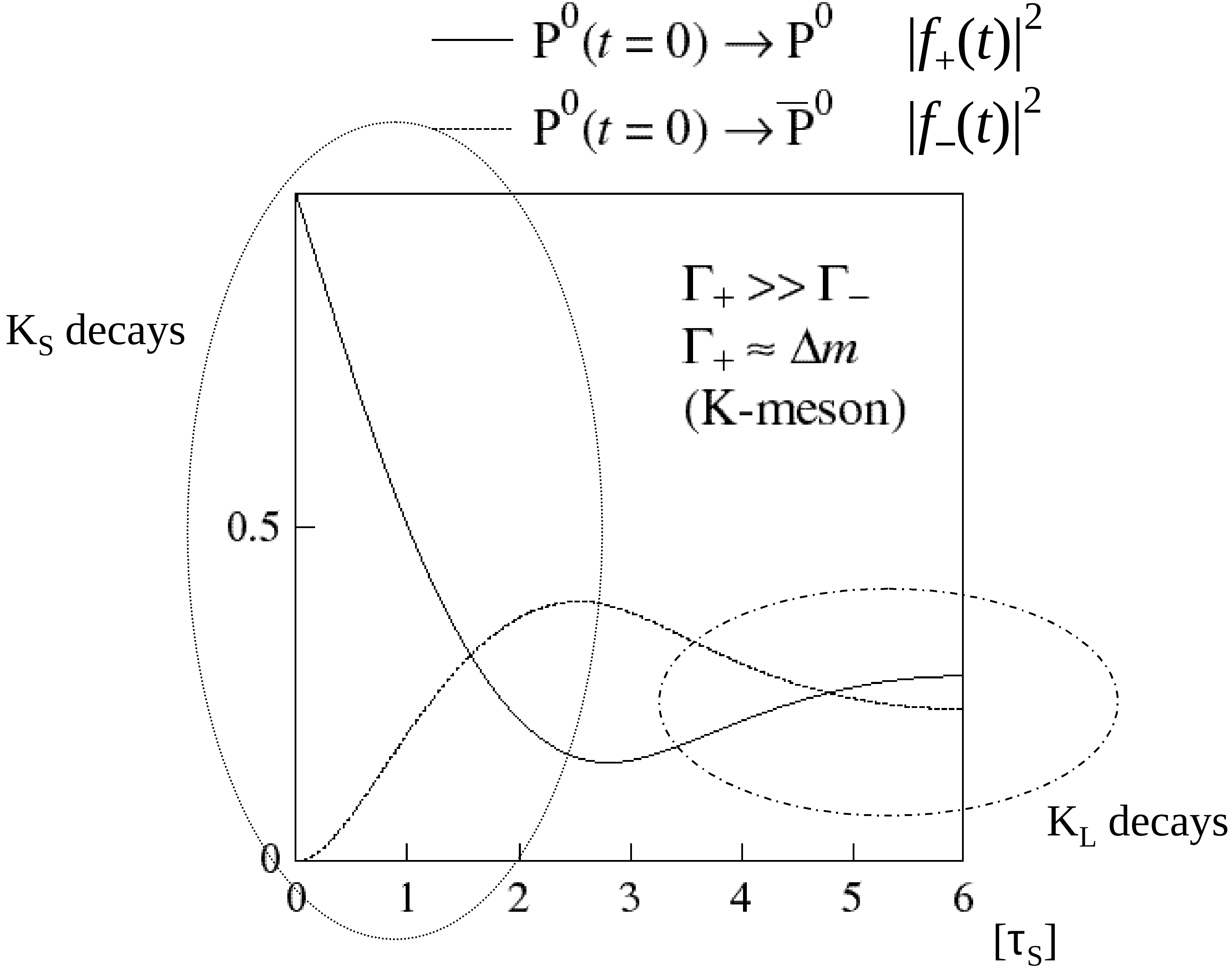
$$\tau_L = \frac{1}{\Gamma_L} = (5.17 \pm 0.04) \times 10^{-8}\,\mathrm{s}$$

$$\Delta m = m_L - m_S = (0.5301 \pm 0.0014) \times 10^{10}\,\hbar \mathrm{s}^{-1}$$

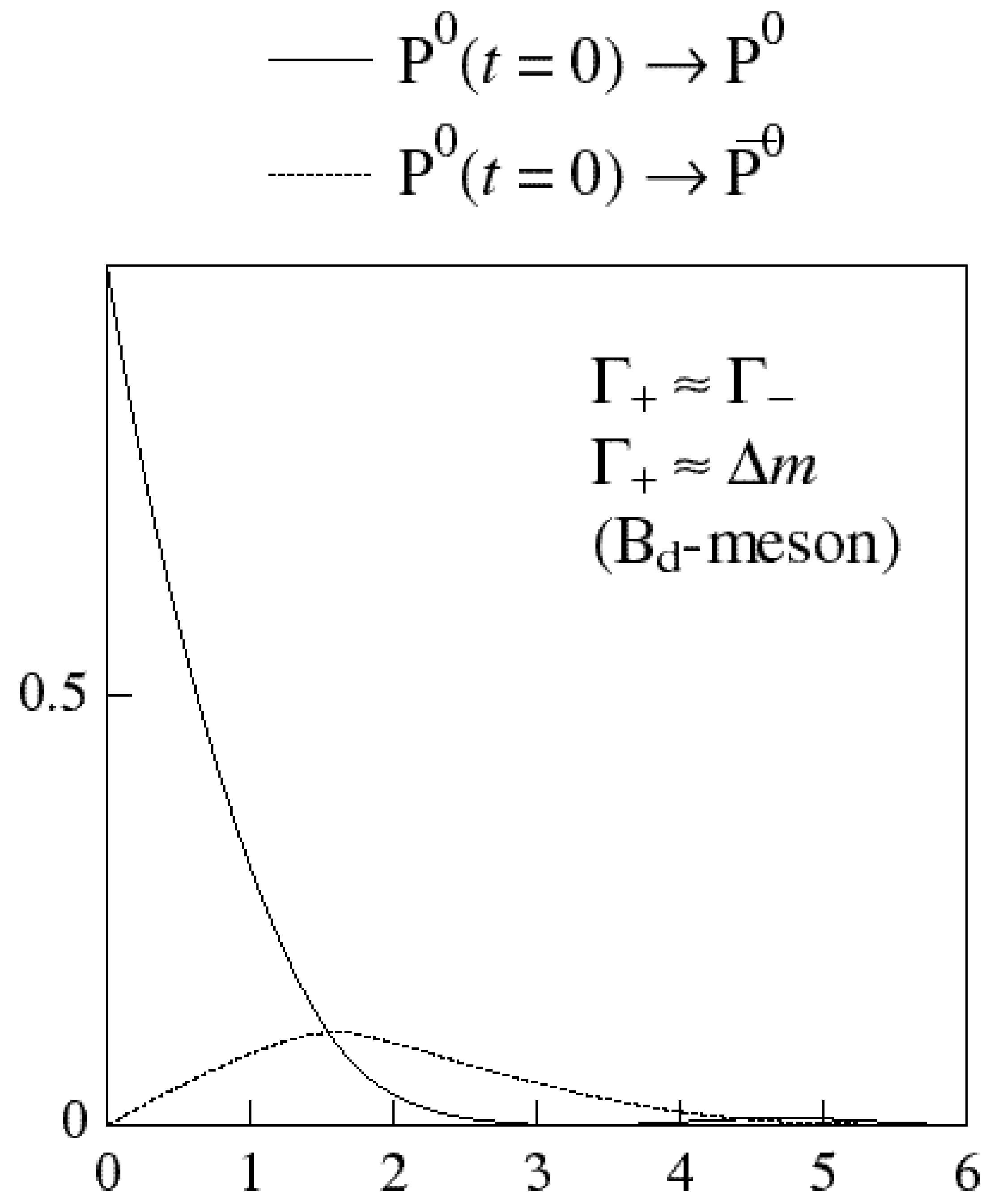
$K_S \to 2\pi$ and almost no $K_L \to 2\pi$

$$\zeta = (1 + 2\varepsilon) e^{-i \arg \Gamma_{12}}$$

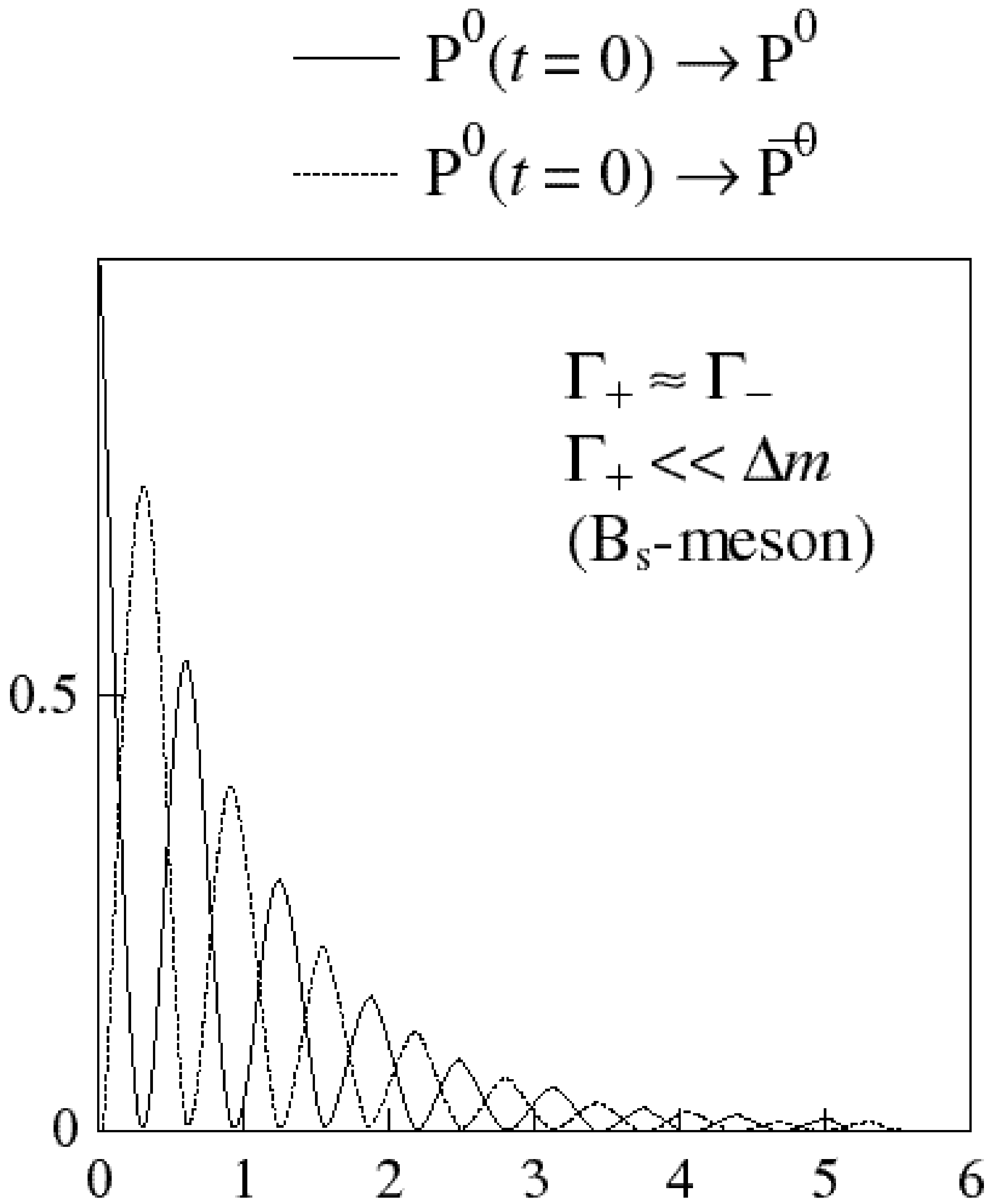
$$\varepsilon = \frac{|M_{12}||\Gamma_{12}|}{4|M_{12}|^2 + |\Gamma_{12}|^2} \left(1 + i\frac{2|M_{12}|}{|\Gamma_{12}|}\right) \sin\Big(\overbrace{\arg M_{12} - \arg \Gamma_{12}}^{\text{very close to } \pi}\Big)$$



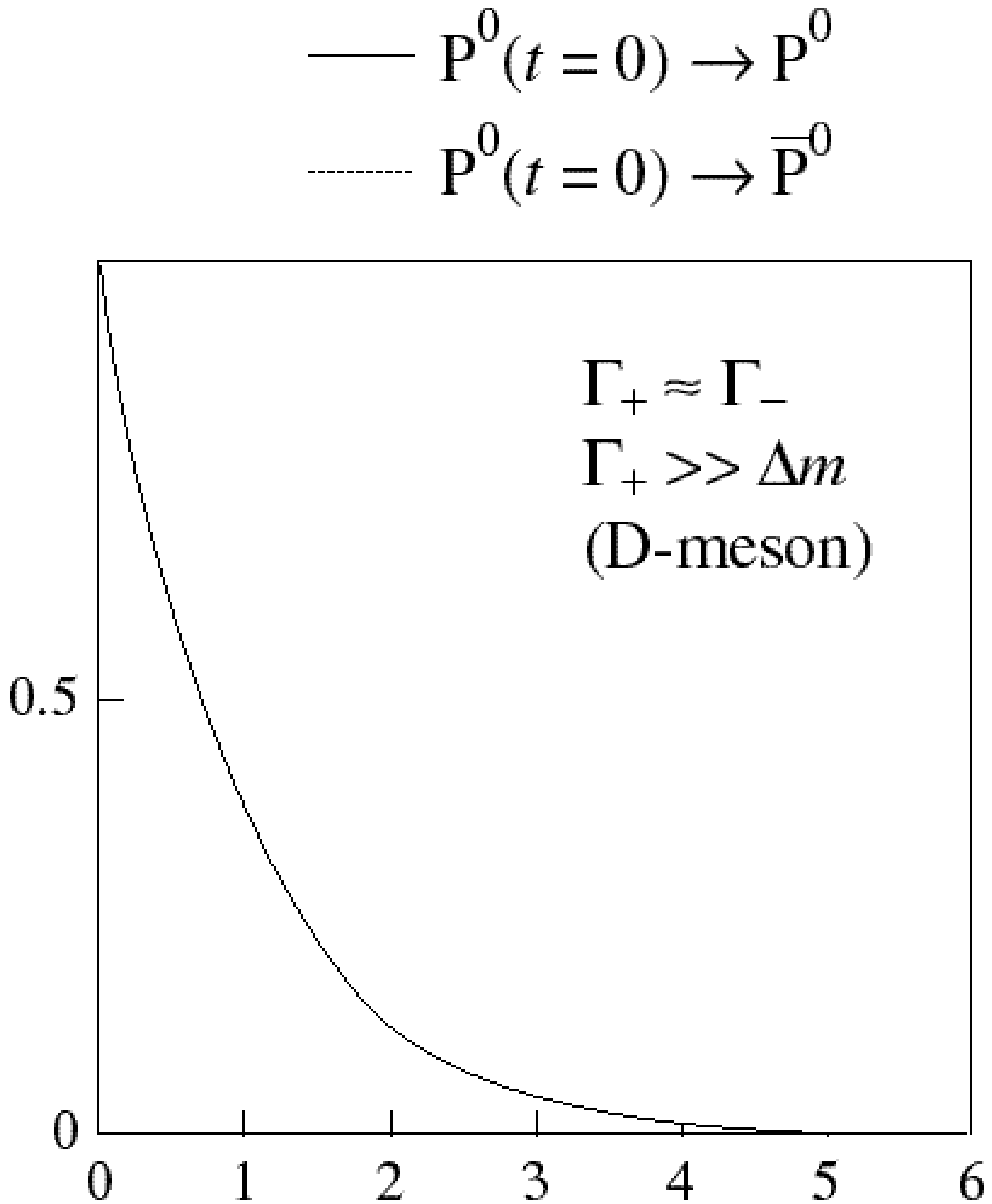
$P^0(t=0) \rightarrow P^0$ $|f_+(t)|^2$
$P^0(t=0) \rightarrow \overline{P}^0$ $|f_-(t)|^2$
K_S decays
$\Gamma_+ >> \Gamma_-$
$\Gamma_+ \approx \Delta m$
(K-meson)
0.5
0
0
1
2
3
4
5
6
$[\tau_S]$
K_L decays



$P^0(t=0) \to P^0$
$P^0(t=0) \to \bar{P}^0$
$\Gamma_+ \approx \Gamma_-$
$\Gamma_+ \approx \Delta m$
(B_d-meson)
0.5
0
0
1
2
3
4
5
6



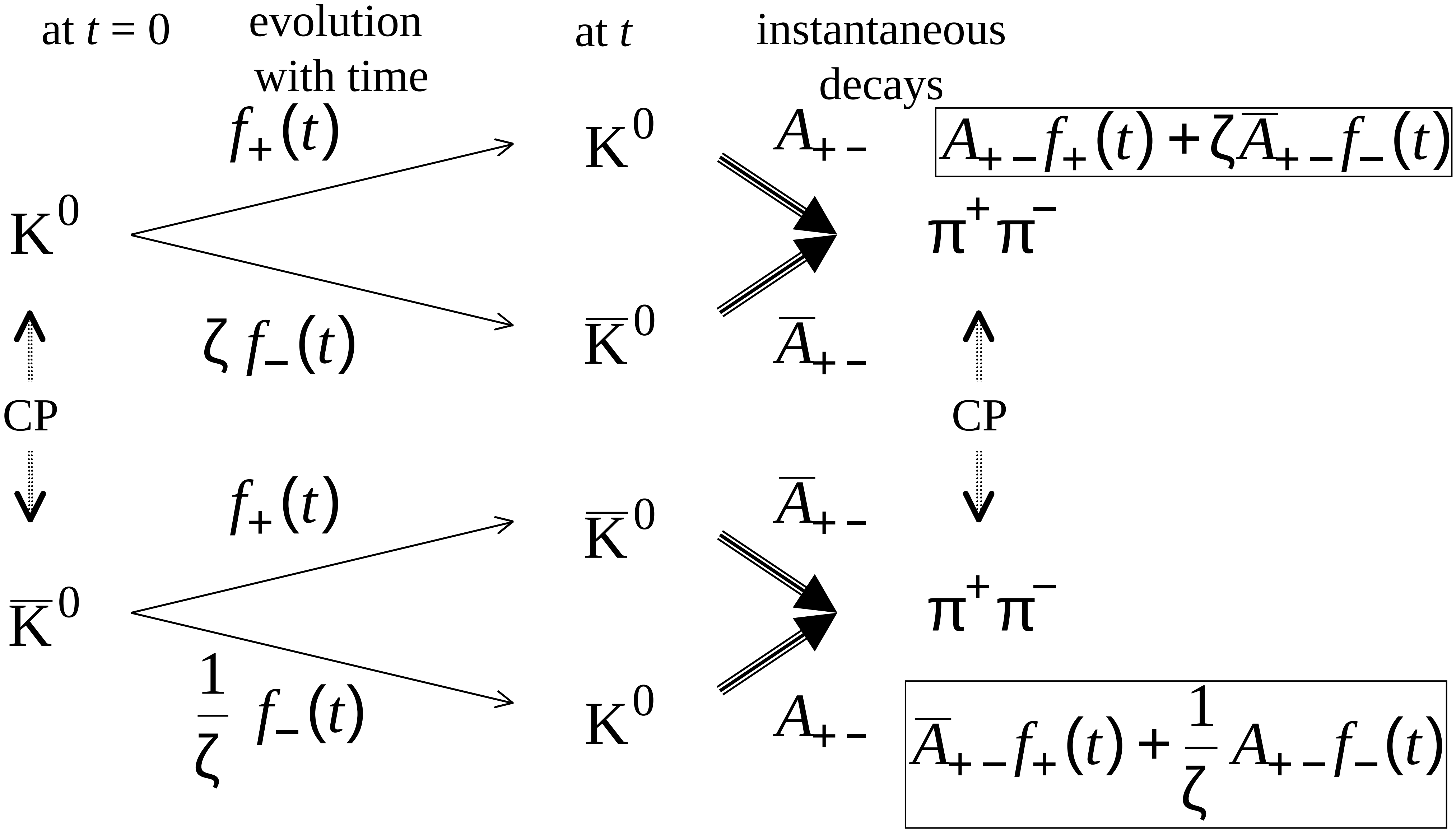
$P^0(t=0) \rightarrow P^0$
$P^0(t=0) \rightarrow \bar{P}^0$
$\Gamma_+ \approx \Gamma_-$
$\Gamma_+ << \Delta m$
(B_s-meson)
0.5
0
0
1
2
3
4
5
6



$P^0(t=0) \rightarrow P^0$
$P^0(t=0) \rightarrow \overline{P}^0$
$\Gamma_+ \approx \Gamma_-$
$\Gamma_+ >> \Delta m$
(D-meson)
0.5
0
0
1
2
3
4
5
6

II) CP Violation in the neutral kaon system

Let us consider $K \rightarrow 2\pi$ decays $\qquad CP(2\pi)_K = +1$



Initially K^0

$$\Gamma(t) = |A_{+-}|^2 |f_+(t)| + |\bar{A}_{+-}|^2 |\zeta|^2 |f_-(t)| + \left(A_{+-}^* \bar{A}_{+-} \zeta f_+^*(t) f_-(t) \right)$$

Initially $\bar{K}^0$

$$\bar{\Gamma}(t) = |\bar{A}_{+-}|^2 |f_+(t)| + |A_{+-}|^2 \frac{1}{|\zeta|^2} |f_-(t)| + \left(\bar{A}_{+-}^* A_{+-} \frac{1}{\zeta} f_+^*(t) f_-(t) \right)$$

1) CP violation in the decay amplitude:

$$|A_{+-}| \neq |\bar{A}_{+-}|$$

most visible at $t = 0$, $f_+(0) = 1$, $f_-(0) = 0$

2) CP violation in the oscillations:

$$|\zeta|^2 \neq 1$$

develops with time t

And the third term…

Initially K^0

$$+ \left(A_{+-}^{*}\overline{A}_{+-}\zeta\right)\left(f_{+}^{*}(t)\,f_{-}(t)\right) - \left(A_{+-}^{*}\overline{A}_{+-}\zeta\right)\left(f_{+}^{*}(t)\,f_{-}(t)\right)$$

Initially $\overline{K}^0$

$$+ \left(A_{+-}^{*}\overline{A}_{+-}\frac{1}{\zeta^{*}}\right)\left(f_{+}^{*}(t)\,f_{-}(t)\right) + \left(A_{+-}^{*}\overline{A}_{+-}\frac{1}{\zeta^{*}}\right)\left(f_{+}^{*}(t)\,f_{-}(t)\right)$$

3) CP violation in the interplay between the decay and oscillation:

$$\left(A_{+-}^{*}\overline{A}_{+-}\zeta\right) \neq 0$$

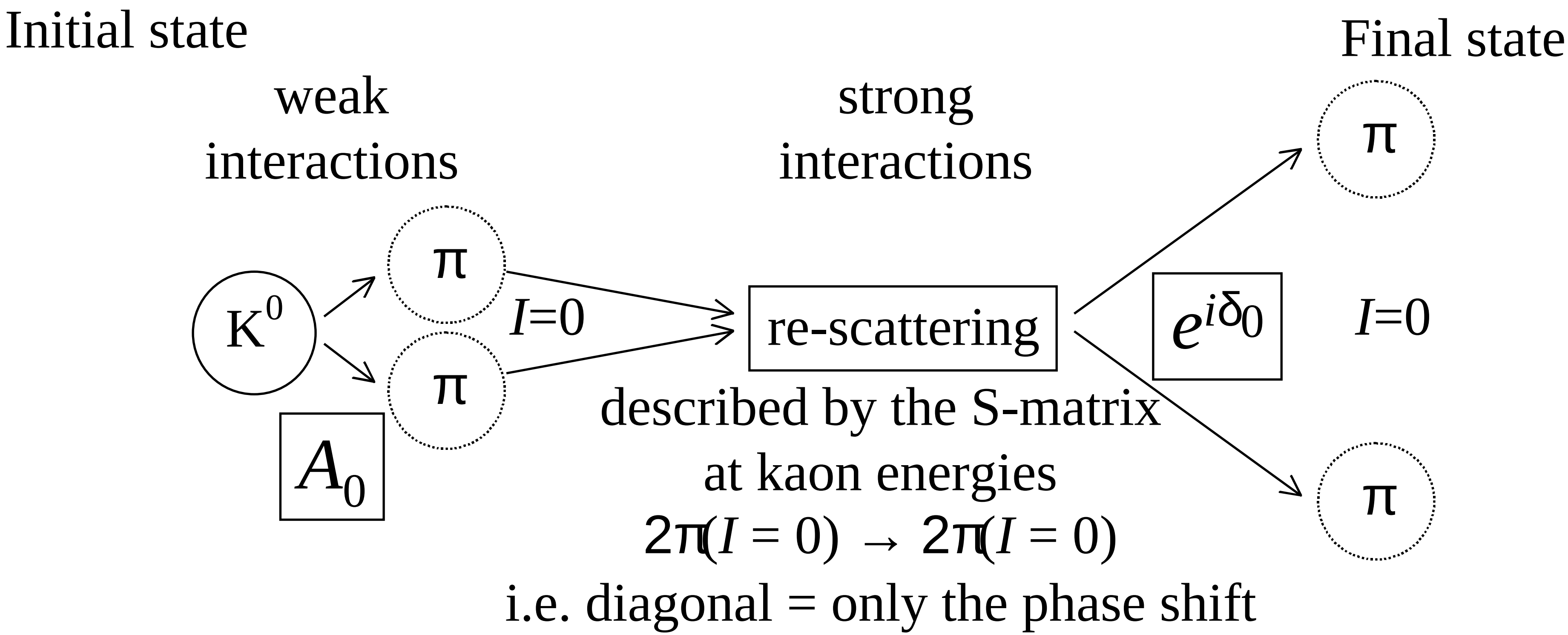
develop with time *t*

(for small $\not\!{CP}$ in the oscillation, $\zeta \approx 1/\zeta$)

III) Different mechanisms for CP violation

1) CP violation in the decay amplitude

Decay Amplitudes



for K^0: $A_0\, e^{i\delta_0}$ for $\bar{K}^0$: $A_0\, e^{i\delta_0}$

$$A_{+-} = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2} \qquad \overline{A}_{+-} = \sqrt{\frac{2}{3}} A_0^* e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2^* e^{i\delta_2}$$

$$\frac{A_{+-}}{\overline{A}_{+-}} = (1 + 2\varepsilon')e^{i2\phi_0} \qquad \varepsilon' = \frac{i}{\sqrt{2}} \left|\frac{A_2}{A_0}\right| \sin(\phi_2 - \phi_0) e^{i(\delta_2 - \delta_0)}$$

$\phi_i = \arg A_i$

$\left|\frac{A_2}{A_0}\right| \sim 0.045$

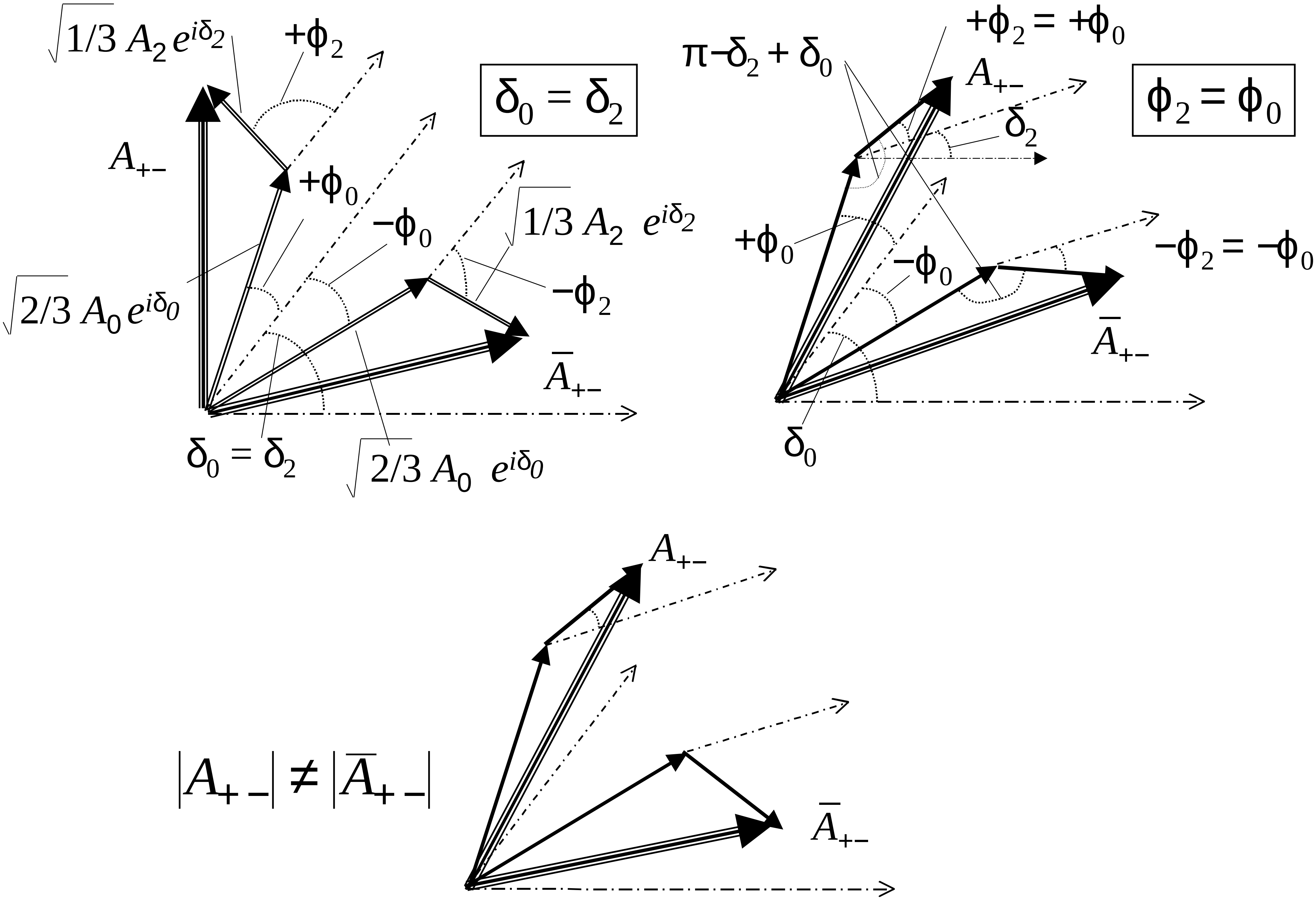
-ΔI = 1/2 rule, from $B(\pi^0\pi^0)/Br(\pi^+\pi^-) \approx 0.46$; 0.5 if A_2=0-

$$\varepsilon' = \frac{1}{\sqrt{2}} \left|\frac{A_2}{A_0}\right| \sin(\phi_0 - \phi_2) \sin(\delta_2 - \delta_0)$$

$\delta_2 - \delta_0$: ~42° from $\pi\pi$ scattering data

> If $\phi_2 \neq \phi_0$ (weak phases) and $\delta_2 \neq \delta_0$ (strong phases), CP violation in the decay amplitudes ($\varepsilon' \neq 0$).

-interference between I = 0 and I = 2 decay amplitudes-



$\sqrt{1/3}\, A_2\, e^{i\delta_2}$
$+\phi_2$
$\delta_0 = \delta_2$
A_{+-}
$+\phi_0$
$-\phi_0$
$\sqrt{1/3}\, A_2\, e^{i\delta_2}$
$\sqrt{2/3}\, A_0\, e^{i\delta_0}$
$-\phi_2$
$\bar{A}_{+-}$
$\delta_0 = \delta_2$
$\sqrt{2/3}\, A_0\, e^{i\delta_0}$
$+\phi_2 = +\phi_0$
$\pi - \delta_2 + \delta_0$
A_{+-}
$\phi_2 = \phi_0$
δ_2
$+\phi_0$
$-\phi_0$
$-\phi_2 = -\phi_0$
$\bar{A}_{+-}$
δ_0
A_{+-}
$|A_{+-}| \neq |\bar{A}_{+-}|$
$\bar{A}_{+-}$

2) CP violation in the oscillations

note: $|\zeta|^2 |f_-(t)|^2$ probability for the initial K^0 oscillates to $\bar{K}^0$

$\frac{1}{|\zeta|^2} |f_-(t)|^2$ probability for the initial $\bar{K}^0$ oscillates to K^0

} CP and T

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

$$M_{12}^* e^{i0} - \frac{1}{2}\Gamma_{12}^* e^{i\pi/2}$$

$$M_{12} e^{i0} - \frac{1}{2}\Gamma_{12} e^{i\pi/2}$$

like $\delta_0 = 0 \neq \delta_2 = \pi/2$ needs $\arg M_{12} \neq \arg \Gamma_{12}$

$$|\zeta|^2 = 1 + 4 \quad \varepsilon$$

$$\varepsilon = \frac{|M_{12}||\Gamma_{12}|}{4|M_{12}| + |\Gamma_{12}|} \sin(\arg M_{12} - \arg \Gamma_{12})$$

ε: small

$$2|M_{12}| = |m_S - m_L|$$

$$2|\Gamma_{12}| = |\Gamma_S - \Gamma_L|$$

not related to CP violation

If $\arg M_{12} \neq \arg \Gamma_{12}$,
CP violation in the K^0- $\bar{K}^0$ oscillations ($\varepsilon \neq 0$).

-interference between the dispersive and absorptive terms in the oscillations-

3) CP violation in the interplay between the decay and oscillation

$$A_{+-}^{*}\bar{A}_{+-}\zeta = |\bar{A}_{+-}|^{2}(1+2\varepsilon')(1+2\varepsilon)e^{i(2\arg A_0 - \arg\Gamma_{12})}$$

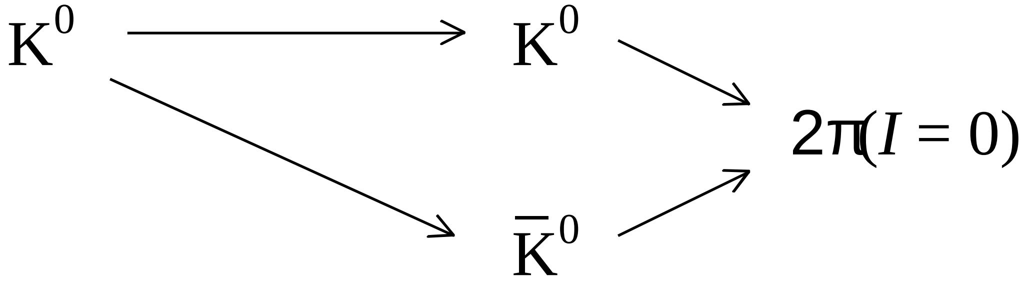
$$\left(A_{+-}^{*}\bar{A}_{+-}\zeta\right) = |\bar{A}_{+-}|^{2}\left[2(\quad \varepsilon' + \quad \varepsilon) + \left(2\arg A_0 - \arg\Gamma_{12}\right)\right]$$

~1

$$\varepsilon = \frac{2|M_{12}|}{|\Gamma_{12}|} \quad \varepsilon$$

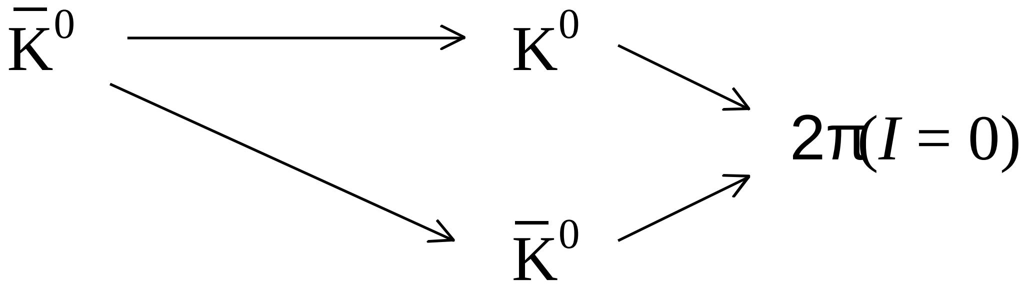
$$\varepsilon' = \frac{1}{\sqrt{2}}\left|\frac{A_2}{A_0}\right| \sin(\phi_2 - \phi_0)\cos(\delta_0 - \delta_2)$$

$$e^{i\phi_0} f_+(t) + e^{i(\phi_\zeta - \phi_0)} f_-(t)$$



ε

$$e^{-i\phi_0} f_+(t) + e^{-i(\phi_\zeta - \phi_0)} f_-(t)$$



ϕ_0 and $\phi_\zeta - \phi_0$ are like weak phases,
$f_+(t)$ and $f_-(t)$ are like strong interactions with different phases
if $\phi_0 \neq \phi_\zeta - \phi_0$ CP violation

Can

$2\arg A_0 + \arg \Gamma_{12}$

be neglected?

Yes, since $2\pi(I = 0)$ dominates the final state!

$$\Gamma_{12} = 2\pi \sum_f \langle K^0 | H_W | f \rangle \langle f | H_W | \overline{K}^0 \rangle \delta(m_0 - E_f)$$

$$A_0 \overline{A}_0 + A_2 \overline{A}_2 + A_{3\pi}^* \overline{A}_{3\pi}$$

$$\approx A_0 \overline{A}_0$$

Experimentally, $\left|\frac{A_2}{A_0}\right| \approx 0.045, \quad \left|\frac{A_{3\pi}}{A_0}\right| \approx 0.041$

$$\arg \zeta = -\arg \Gamma_{12} = 2 \arg A_0$$

IV) Experiments to look for a difference in $K^0_{t=0} \to \pi^+\pi^-$ and $\bar{K}^0_{t=0} \to \pi^+\pi^-$

-strangeness conservation in the strong interaction-

A classic experiment: $K^+ n \to K^0 p$, $K^- p \to \bar{K}^0 n$ D.Banner et al., PRD 1993

A modern experiment: $p\bar{p} \to K^0 K^- \pi^+$, $\bar{K}^0 K^+ \pi^-$ CPLEAR, PLB 1999

$$|P(t)\rangle = \frac{\sqrt{1+|\zeta|^2}}{2}\left(e^{-im_S t - \frac{\Gamma_S}{2}t}|K_S\rangle + e^{-im_L t - \frac{\Gamma_L}{2}t}|K_L\rangle \right)$$

$$|\bar{P}(t)\rangle = \frac{\sqrt{1+|\zeta|^2}}{2\zeta}\left(e^{-im_S t - \frac{\Gamma_S}{2}t}|K_S\rangle - e^{-im_L t - \frac{\Gamma_L}{2}t}|K_L\rangle \right)$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\zeta|^2}}\left(|K^0\rangle + \zeta|\bar{K}^0\rangle\right), \quad |K_L\rangle = \frac{1}{\sqrt{1+|\zeta|^2}}\left(|K^0\rangle - \zeta|\bar{K}^0\rangle\right)$$

$$R_{+-}(t) = \frac{\left(1+|\zeta|^2\right)|A_S^{+-}|^2}{4}\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2|\eta_{+-}|e^{-\bar{\Gamma} t}\cos\left(\Delta m t - \varphi_{+-}\right)\right]$$

$$\bar{R}_{+-}(t) = \frac{\left(1+|\zeta|^2\right)|A_S^{+-}|^2}{4|\zeta|^2}\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} - 2|\eta_{+-}|e^{-\bar{\Gamma} t}\cos\left(\Delta m t - \varphi_{+-}\right)\right]$$

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \approx \varepsilon + \varepsilon'$$

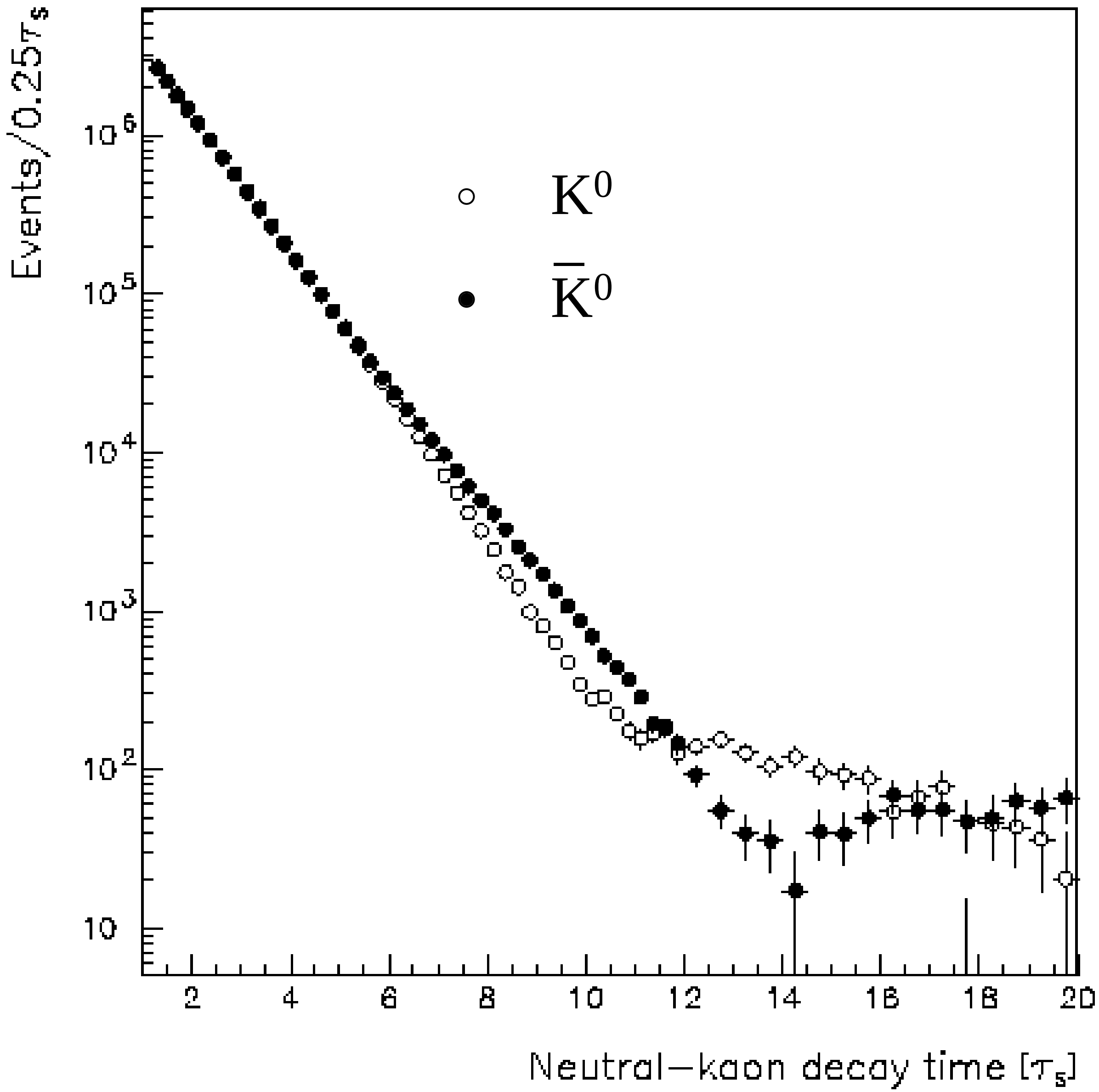
If CP is conserved,
$CP(K_S) = +1$, $CP(K_L) = -1$
$\eta_{+-} = 0$

$$\bar{\Gamma} = \frac{\Gamma_L + \Gamma_S}{2}$$

$$\varphi_{+-} = \arg \eta_{+-}$$

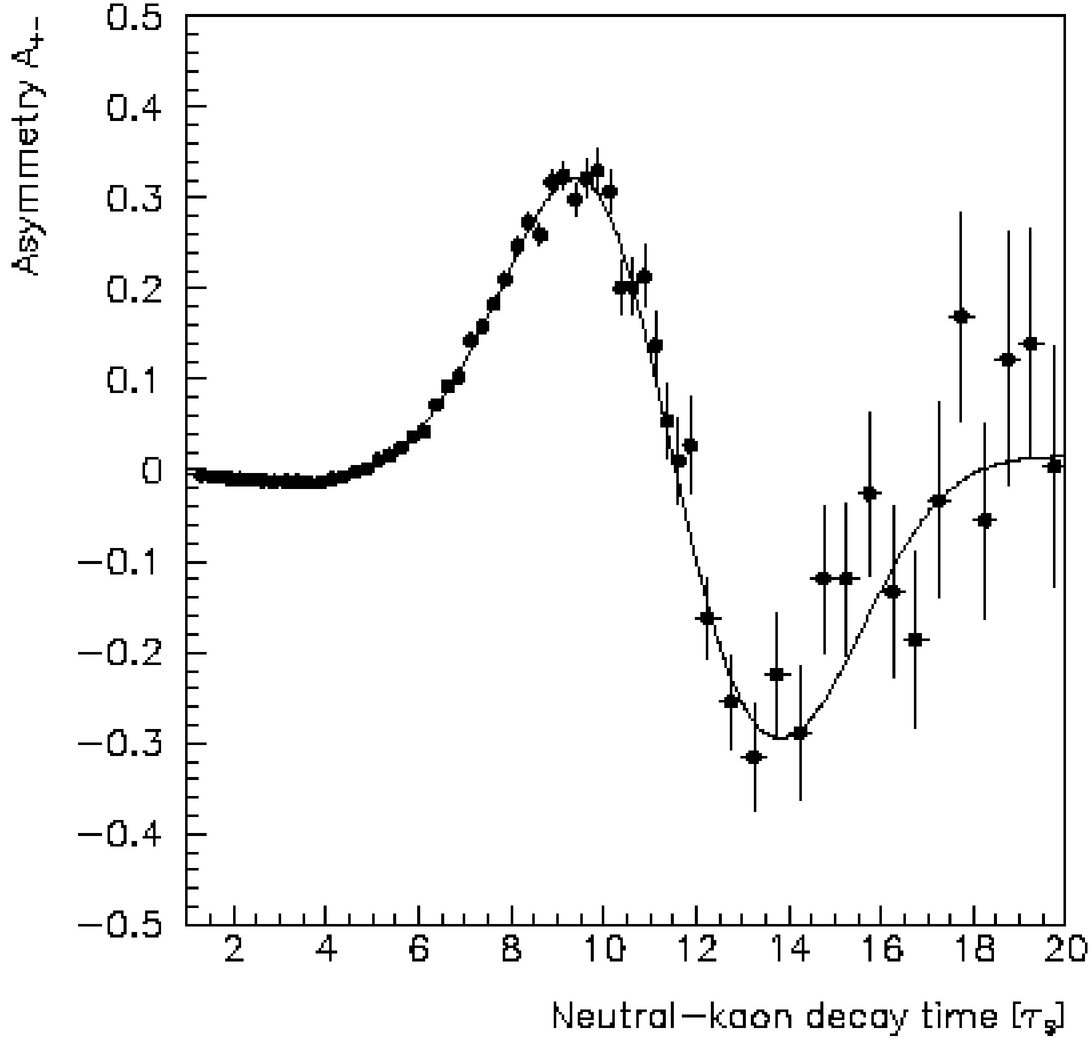
CPLEAR measurement PLB 99	PDG 98
$\lvert\eta_{+-}\rvert = (2.264 \pm 0.035)\times 10^{-3}$	WA($\pm$ 0.019)
$\varphi_{+-} = (43.19 \pm 0.73)°$	WA($\pm$ 0.6)

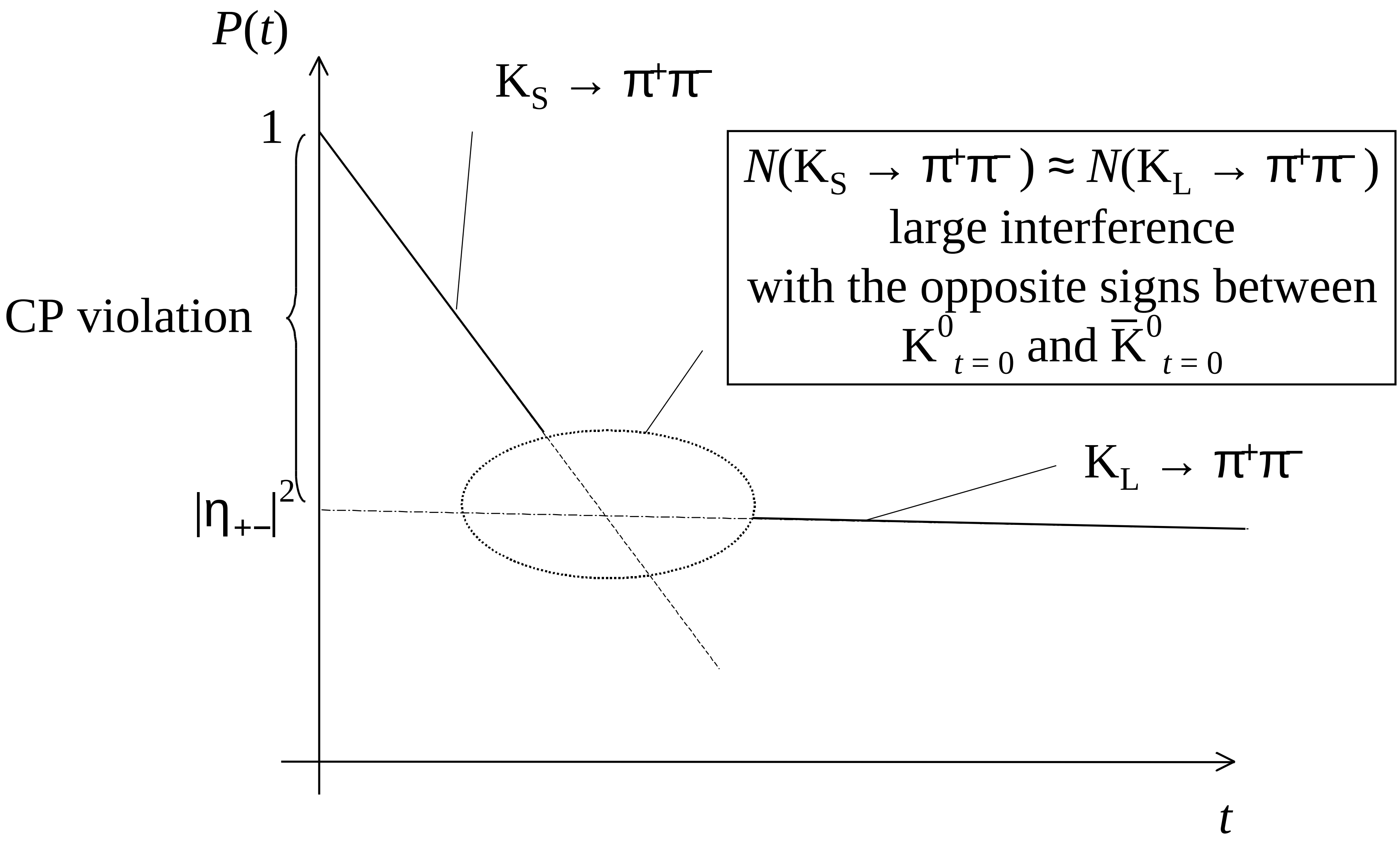
CPLEAR
$R_{+-}(t)$
and
$\overline{R}_{+-}(t)$



CPLEAR
CP asymmetry

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





P(t)
1
CP violation
|η+−|2
KS → π+π−
N(KS → π+π−) ≈ N(KL → π+π−)
large interference
with the opposite signs between
K0 t = 0 and K̄0 t = 0
KL → π+π−
t

Structure of η_{+-}

CP violation in the oscillations

CP violation in the decays

$$\eta_{+-} = \varepsilon + \varepsilon'$$

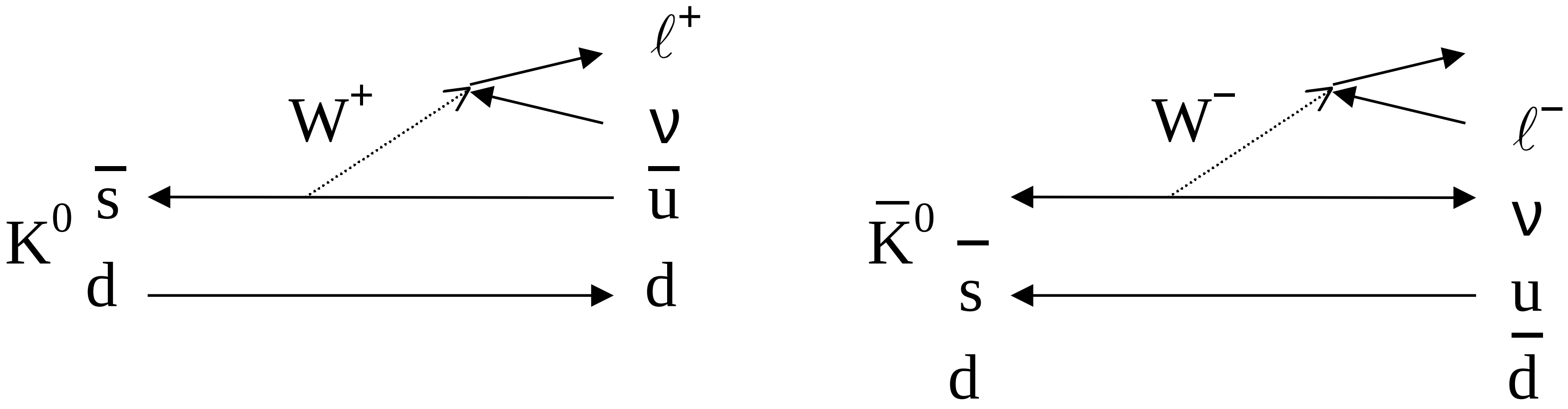
$$\eta_{+-} = \varepsilon + \varepsilon'$$

CP violation due to the interplay between the oscillations and decays

V) Experimental observation of CP violation in K^0- $\bar{K}^0$ oscillations

Identification of initial state: $p\bar{p} \to K^0 K^- \pi^+, \bar{K}^0 K^+ \pi^-$
Identification of final state: $K^0 \to \pi^- \nu \ell^+, \bar{K}^0 \to \pi^+ \nu \ell^-$

-$\Delta Q = \Delta S$ rule in the weak interactions- CPLEAR



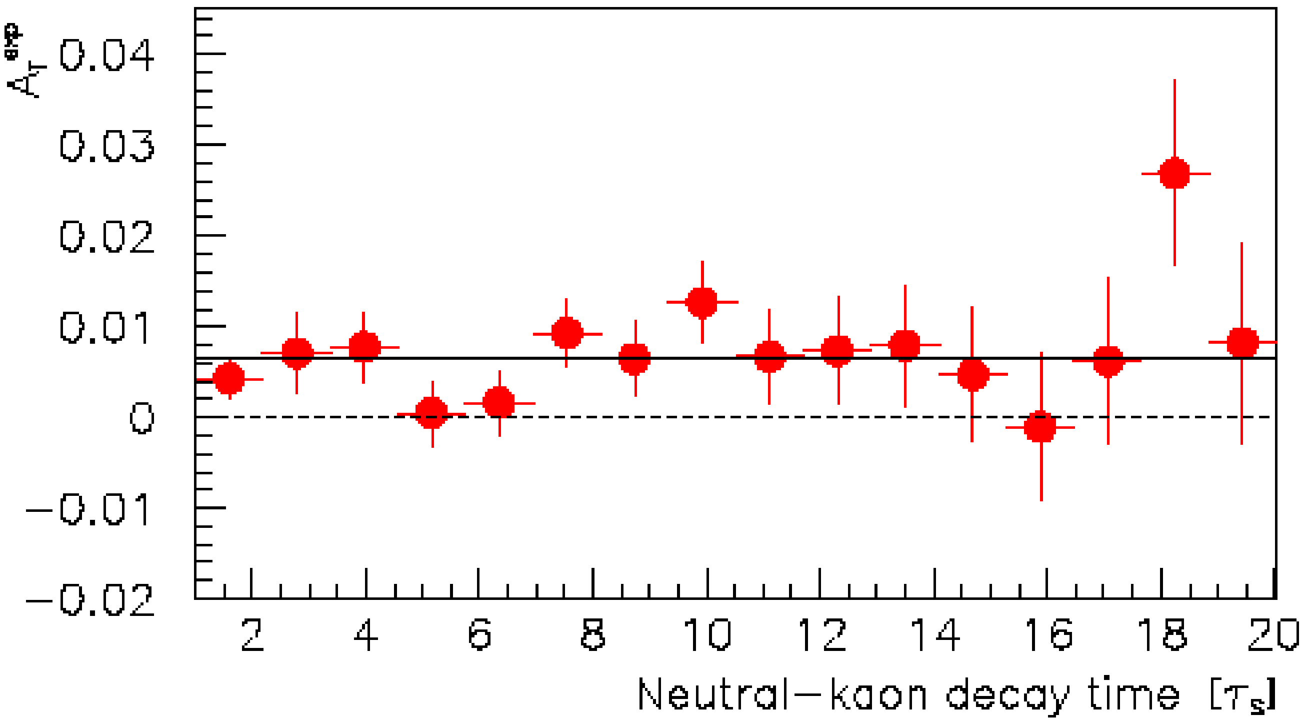
$$\frac{\bar{R}_{\ell^+}(t) - R_{\ell^+}(t)}{\bar{R}_{\ell^+}(t) + R_{\ell^+}(t)} = 4 \quad \varepsilon$$

CPLEAR measurement PLB 98

$\varepsilon = (1.65 \pm 0.40)\times 10^{-3}$

can be compared with

$\eta_{+-} = (1.550 \pm 0.035)\times 10^{-3}$



A_T^{exp}
0.04
0.03
0.02
0.01
0
−0.01
−0.02
2
4
6
8
10
12
14
16
18
20
Neutral−kaon decay time [τ_S]

VI) Experimental observation of CP violation in K^0- $\bar{K}^0$ decay amplitudes

$$|\eta_{+-}|^2 = \frac{\left|A\left(K_L \to \pi^+\pi^-\right)\right|^2}{\left|A\left(K_S \to \pi^+\pi^-\right)\right|^2} = \frac{N_S^{+-}}{N_L^{+-}} \frac{N\left(K_L \to \pi^+\pi^-\right)}{N\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon'$$

$$|\eta_{00}|^2 = \frac{\left|A\left(K_L \to \pi^0\pi^0\right)\right|^2}{\left|A\left(K_S \to \pi^0\pi^0\right)\right|^2} = \frac{N_S^{00}}{N_L^{00}} \frac{N\left(K_L \to \pi^0\pi^0\right)}{N\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\varepsilon'$$

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1 - 6 \quad \frac{\varepsilon'}{\varepsilon}$$

$$= \frac{N_S^{00} N_L^{+-}}{N_L^{00} N_S^{+-}} \frac{N\left(K_L \to \pi^0\pi^0\right) N\left(K_S \to \pi^+\pi^-\right)}{N\left(K_S \to \pi^0\pi^0\right) N\left(K_L \to \pi^+\pi^-\right)}$$

Measure

$\pi^+\pi^-$ and $\pi^0\pi^0$ at the same time: $N_S^{00} = N_S^{+-},\ N_L^{00} = N_L^{+-}$

NA31, NA48

K_L is regenerated from K_S: $N_L^{00} = rN_S^{00},\ N_L^{+-} = rN_S^{+-}$

E731, KTeV

Only the measured decay rates are required.

Year	Exp.	Result [10^{-4}]
1993	E731	7.4±5.9
1993	NA31	23.0±6.5
1999	KTeV (20%)	28.0±4.1
1999	NA48 (preliminary)	18.5±7.3

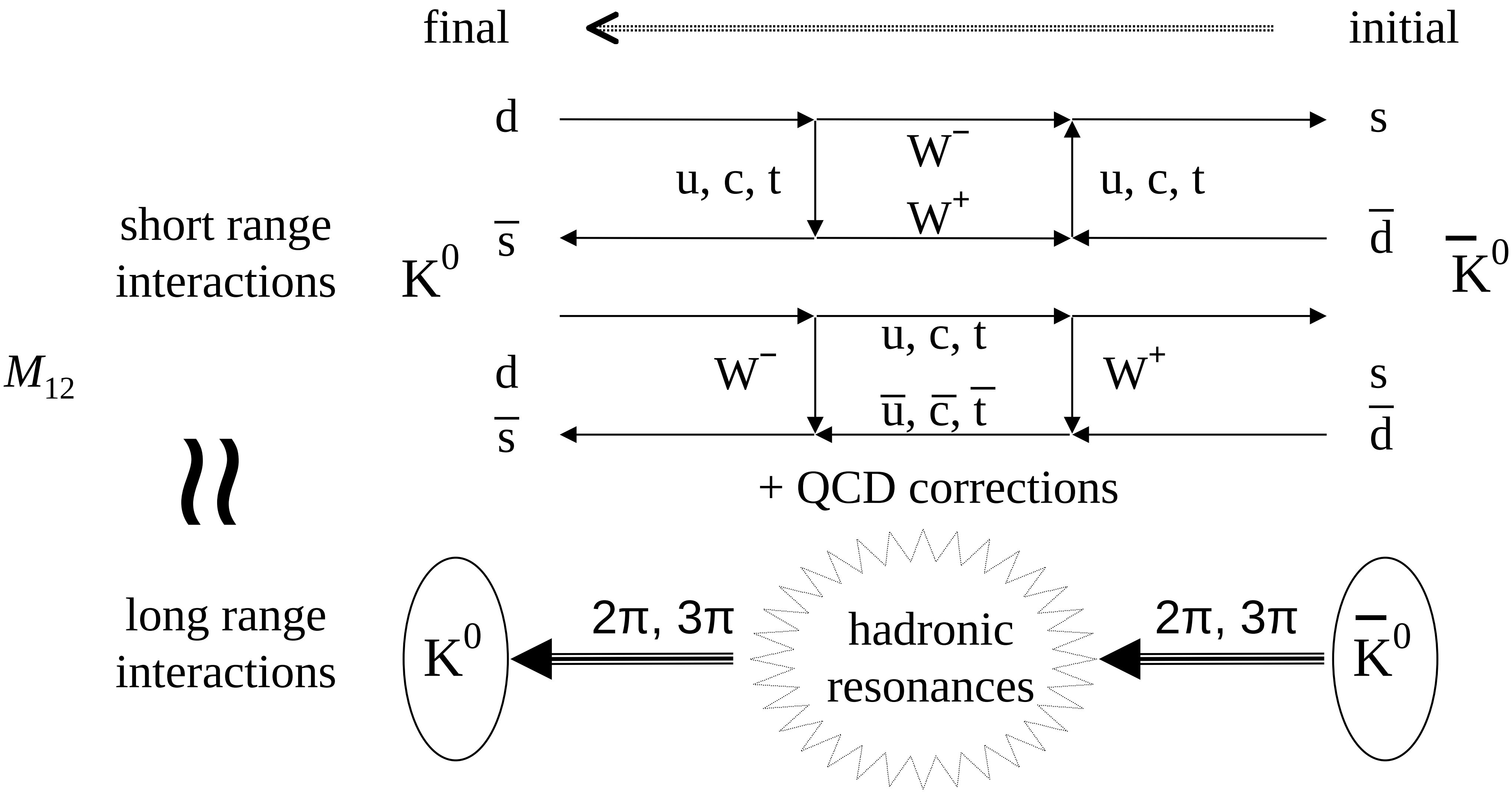
$$\frac{\varepsilon'}{\varepsilon} = (21.2 \pm 4.7) \times 10^{-4}$$

(error scaled up)

a pretty good evidence for

$$\frac{\varepsilon'}{\varepsilon} > 0$$

VII) Standard Model for the kaon system



Large uncertainties in the theoretical calculations of $|M_{12}|$

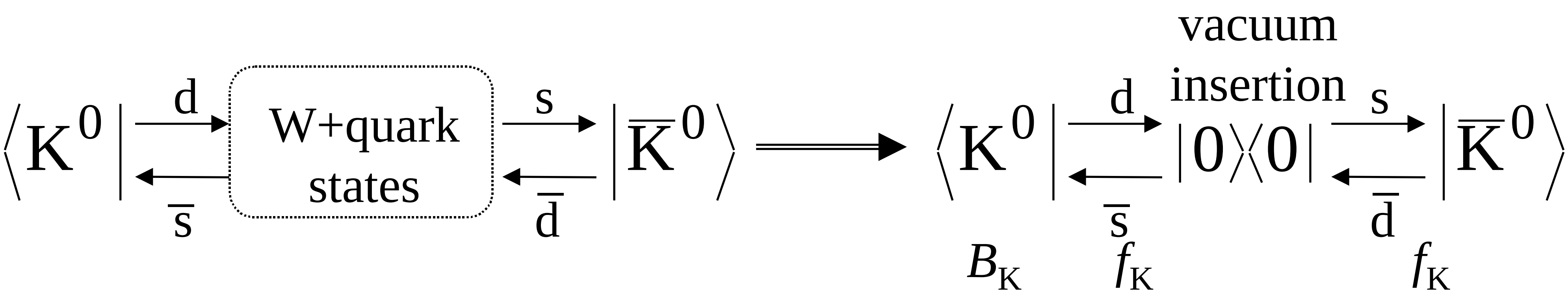
CKM matrix and Wolfenstein's parameters

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

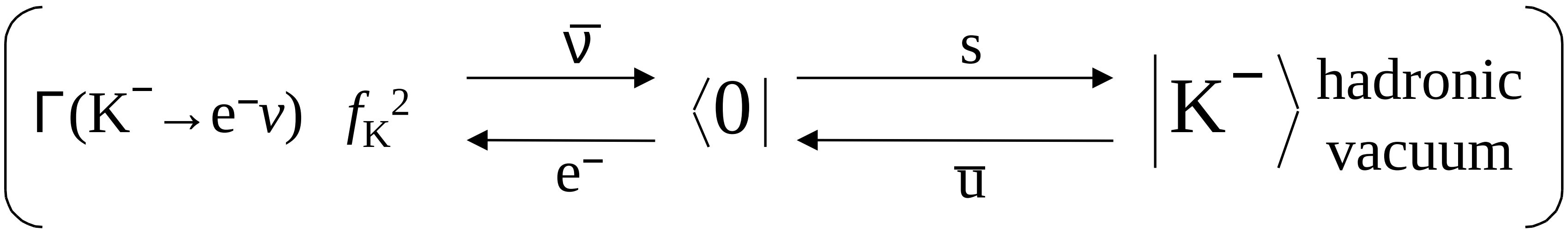
$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda\left[1 + A^2\lambda^4(\rho + i\eta)\right] & \left(1-\frac{\lambda^2}{2}\right) & A\lambda^2 \\ A\lambda^3\left[1-(\rho + i\eta)\left(1-\frac{\lambda^2}{2}\right)\right] & -A\lambda^2\left[\left(1-\frac{\lambda^2}{2}\right) + \lambda^2(\rho + i\eta)\right] & 1 \end{pmatrix}$$

$A \sim 1$, $\lambda \sim 0.22$, $\rho \neq 0$ but $\eta \neq 0$???

Short distance part



B parameters have to be obtained from some QCD calculations.



$$M_{12} = -\frac{G_F^2}{12\pi^2} f_K^2 B_K m_K m_W^2 \left[v_c \eta_1 S_0(x_c) + v_t \eta_2 S_0(x_t) + v_{ct} \eta_3 S_0(x_c, x_t) \right]$$

G_F: Fermi constant
m_K: Kaon mass
m_W: W mass

$\eta_1 = 1.38 \pm 0.20$
$\eta_2 = 0.57 \pm 0.01$
$\eta_3 = 0.47 \pm 0.04$
} QCD corrections

$v_t = V_{ts}^2 V_{td}^2 \quad \approx \lambda^{10} \quad S_0(x_t) \approx 2.5 \quad 6.6\times10^{-7}$

$v_c = V_{cs}^2 V_{cd}^2 \quad \approx \lambda^{2} \quad S_0(x_c) \approx 0.00024 \quad 1.2\times10^{-5}$

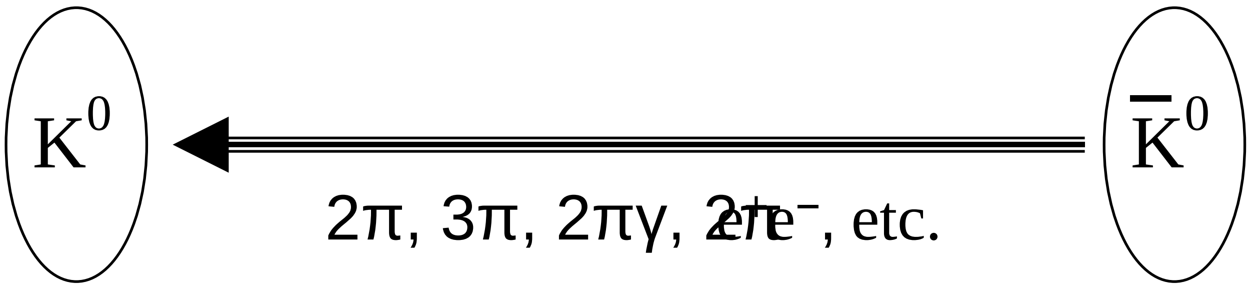
$v_{ct} = V_{cs} V_{cd} V_{ts} V_{td} \quad \approx \lambda^{6} \quad S_0(x_c) \approx 0.0021 \quad 2.4\times10^{-7}$

net contributions

$x_c=(m_c/m_W)^2,\ x_t=(m_t/m_W)^2$

the biggest contribution is from the charm loop

Standard Model Γ_{12} for the kaon system



Theoretical calculation on $|\Gamma_{12}|$ very difficult.

However, $|M_{12}|$. $|\Gamma_{12}|$ are measured experimentally;
arg M_{12} can be determined from the short distance interactions.

theoretical short distance calculation

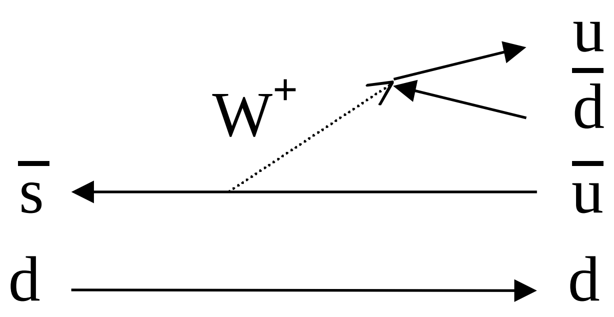
$$\arg M_{12} = \frac{\operatorname{Im} M_{12}}{|M_{12}|} = \frac{2 \operatorname{Im} M_{12}}{|m_S - m_L|}$$

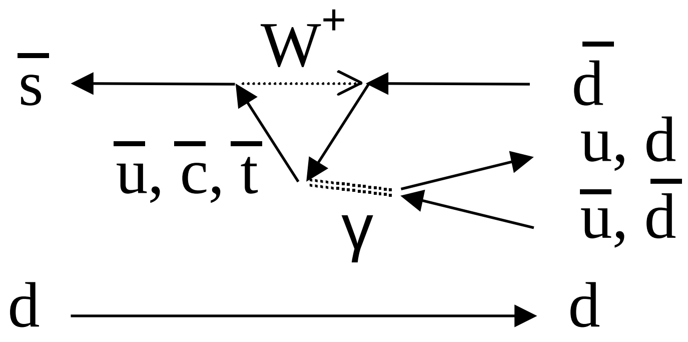
experimental value

$\arg \Gamma_{12} = 0$ in the CKM phase convention

ε can now be calculated.

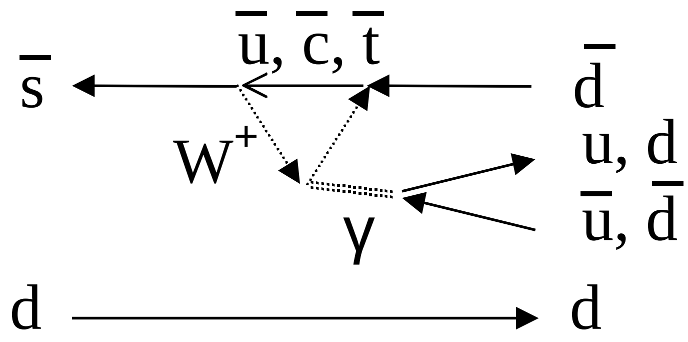
The ε′ in the Standard Model

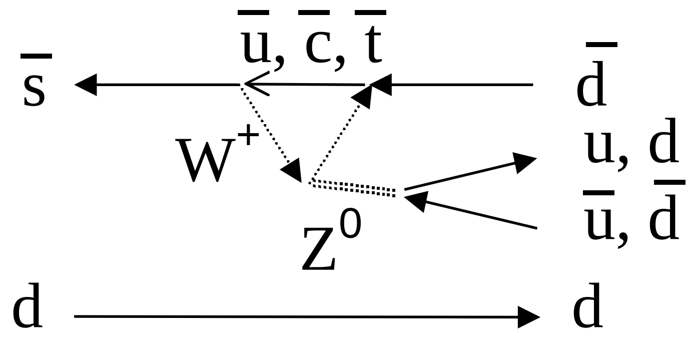




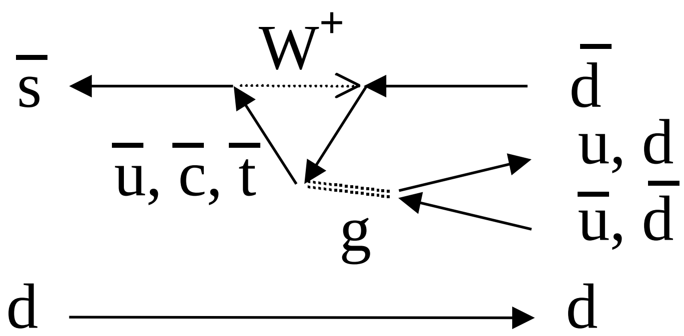
$I = 0$ and $I = 2$

$V_{ud}V_{us}$ tree





$V_{ud}V_{us}$, $V_{cd}V_{cs}$, $V_{td}V_{ts}$ } γ and Z^0 penguin



$I = 0$

$V_{ud}V_{us}$, $V_{cd}V_{cs}$, $V_{td}V_{ts}$ } g penguin

QCD and non-perturbative effects
very very complicated calculations !!

$$0.03 \times 10^{-3} \lessapprox \frac{\varepsilon'}{\varepsilon} \lessapprox 3 \times 10^{-3}$$ (Buras 99)

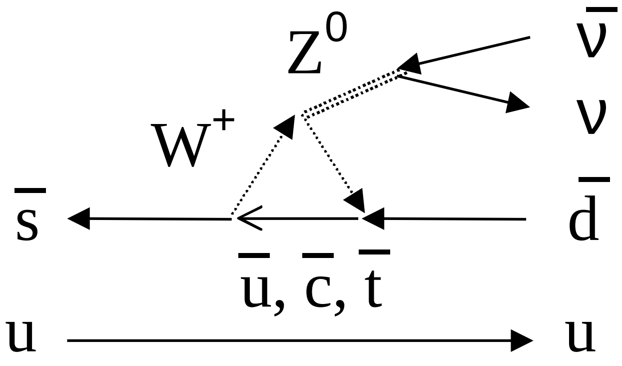
↑

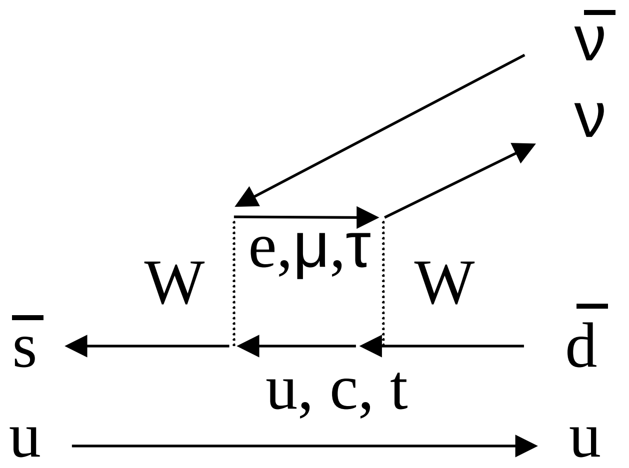
with stretching
all the parameters

1) The Standard Model predictions are compatible with the measurement.
2) Hadronic uncertainties in the theoretical predictions are too large to make a precision test.

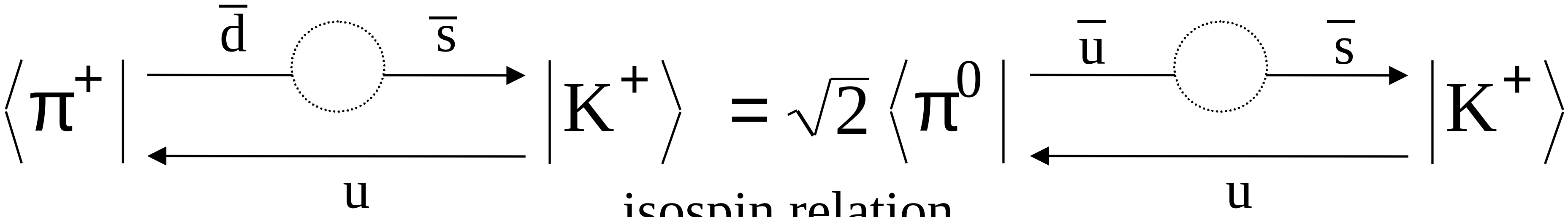
VIII) Other interesting kaon decays:

$K^+ \to \pi^+ \nu \bar{\nu}$





$V_{td}V_{ts}$
$V_{cd}V_{cs}$



isospin relation

Use $K^+ \to \pi^0 e^+ \nu$ (data) for the hadronic matrix element.

Extract V_{td} with a relatively small theoretical uncertainties.

Current Standard Model predictions:

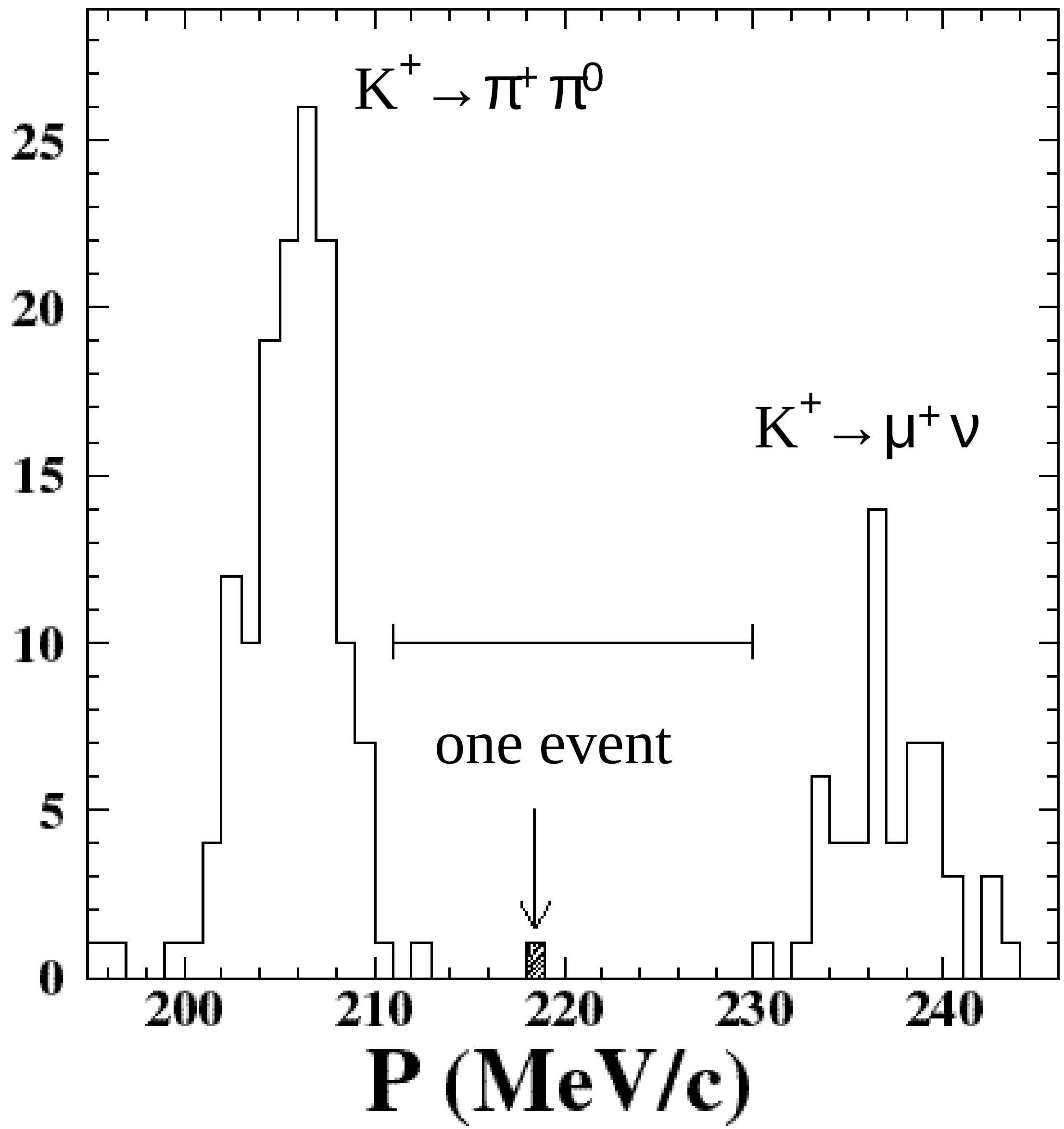
$$5\times10^{-11} \le Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) \le 12\times10^{-11}$$

(isospin breaking taken into account)

BNL787, 1995 data: $(4.2\ {}^{+9.7}_{-3.5})10^{-10}$ PRL 97
based on one event

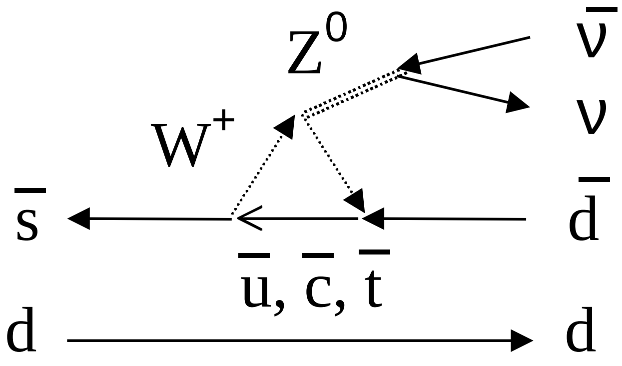
More data are taken
1996-1997 data, no new candidate
1998 data, total sensitivity = 8×10^{-11}
Ultimate sensitivity = 0.8-1.5×10^{-11}

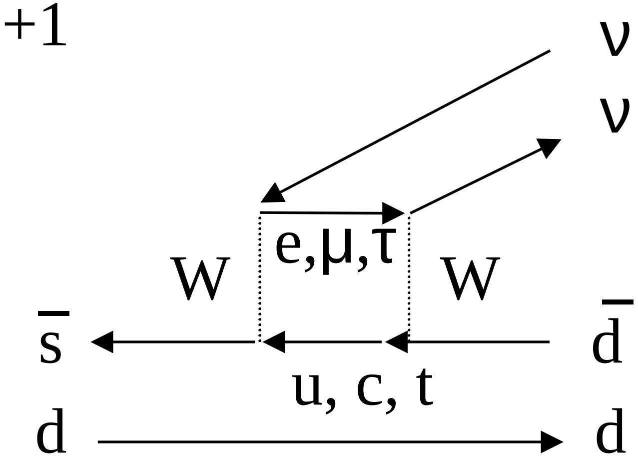
$|V_{td}|$ measurement from the kaon decays



K+ → π+ π0
K+ → μ+ ν
one event
0
5
10
15
20
25
200
210
220
230
240
P (MeV/c)

$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ CP violating, $CP(\pi^0\nu\bar{\nu}) = +1$





$$A(K^0 \rightarrow \pi^0\nu\bar{\nu}) = a \qquad A(\bar{K}^0 \rightarrow \pi^0\nu\bar{\nu}) = a$$

$$|A(K_L \rightarrow \pi^0\nu\bar{\nu})|^2 = \frac{1}{2}\,|\,(\quad a + i \quad a) - (1+2\varepsilon)\,(\quad a - i \quad a)\,|^2$$

(in the KM phase convention)

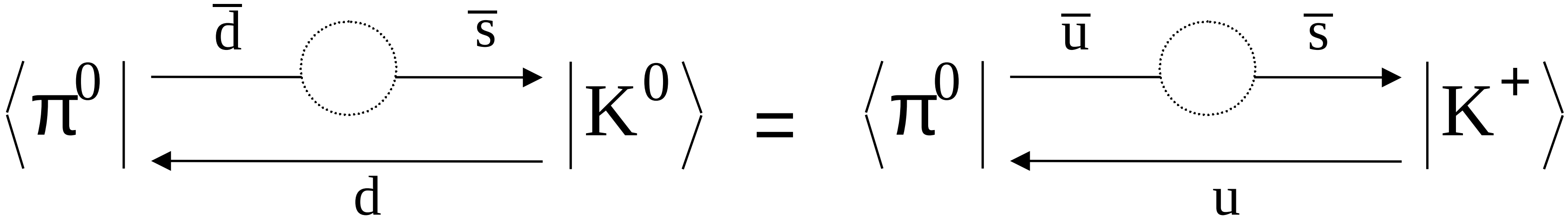
$$\left|\frac{a(s \rightarrow c \rightarrow d)}{a(s \rightarrow t \rightarrow d)}\right| \approx 0.3 \quad \text{in the Standard Model} \quad \left|\frac{a}{a}\right| >> |\varepsilon|$$

$$\boxed{Br(K_L \rightarrow \pi^0\nu\bar{\nu}) \quad (\quad a)^2}$$

If $a = 0$, $\quad Br(K_L \rightarrow \pi^0\nu\bar{\nu}) \quad |\varepsilon|^2\,|a|^2$

Imaginary part can come only from $\bar{s} \to \bar{t} \to \bar{d}$.

hadronic part: $K^0 \to \pi^0 \nu \bar{\nu} = K^+ \to \pi^0 e^+ \nu$



rather reliable calculation

$$Br_{K_L \to \pi^0 \upsilon \bar{\upsilon}} = Br_{K^+ \to \pi^0 e^+ \upsilon} \frac{\tau_L}{\tau_+} \frac{3\alpha^2}{|V_{us}|^2 2\pi^2 \sin^4 \Theta_W} \left[\left(V_{td} V_{ts}^*\right) X(x_t) \right]^2$$

$$\approx 3 \times 10^{-11}$$

$Br(K^0 \to \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-6}$ 90% CL(KTeV, PLB 99) $\pi^0 \to \gamma\gamma$

5.9×10^{-7} $\pi^0 \to ee\gamma$

several future plans but a tough experiment

BNL, FNAL $\sim 10^{-12}$

Theoretical accuracy of the Standard Model predictions
in the kaon sector will be limited to >10%
(may be) except $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ which will be experimentally challenging!

IX) B system: introduction

CP Violation in B meson decays

A place to look for new physics…

1) CP violation is expected in many decay modes, allowing to study the pattern of CP violation.

2) For some decay modes, uncertainties in the Standard Model prediction is $<10^{-2}$, i.e. precision tests possible.

Four kinds of decay final states:

- unique CP eigenstate,

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

- mixed CP eigenstate,

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

- flavour specific, semileptonic and **hadronic**

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

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

- **flavour non-specific**,

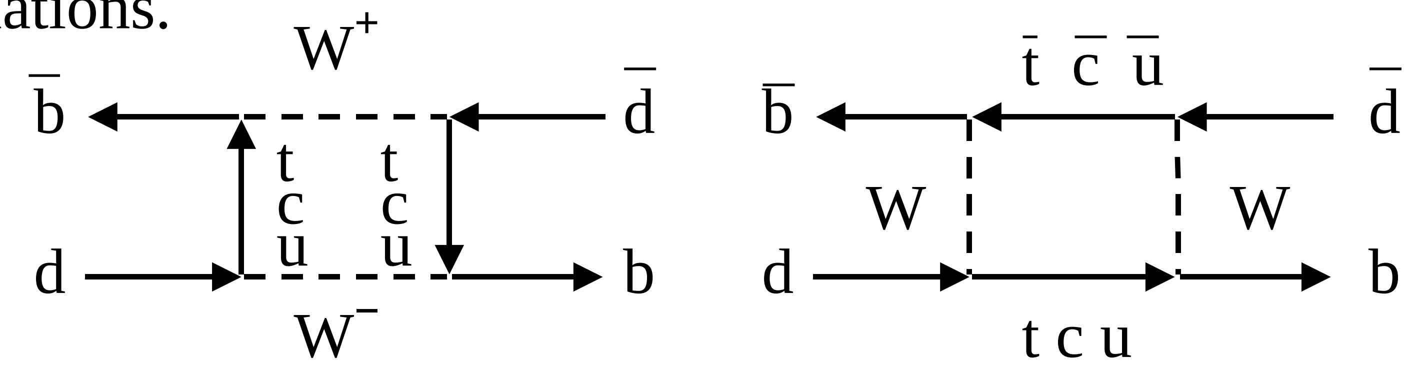
  e.g. $B \rightarrow D^-\pi^+, \rightarrow D^+\pi^-$ vs $\bar{B} \rightarrow D^-\pi^+, \rightarrow D^+\pi^-$

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

-bolds are not possible in the kaon system-

In the B meson system, the short distance effect dominates in the oscillations.

M_{12}



quark mass terms

dominating term $t\text{-}\bar{t}$, $(V_{tb}\ V_{td})^2 \sim \lambda^6 \times 2.5$

$c\text{-}\bar{c}$ $(V_{cb} V_{cd})^2 \sim \lambda^6 \times 0.00024$

$t\text{-}\bar{c}+c\text{-}\bar{t}$ $2 \times V_{tb}\ V_{td}\ \ V_{cb}\ V_{cd} \sim \lambda^6 \times 0.0021$

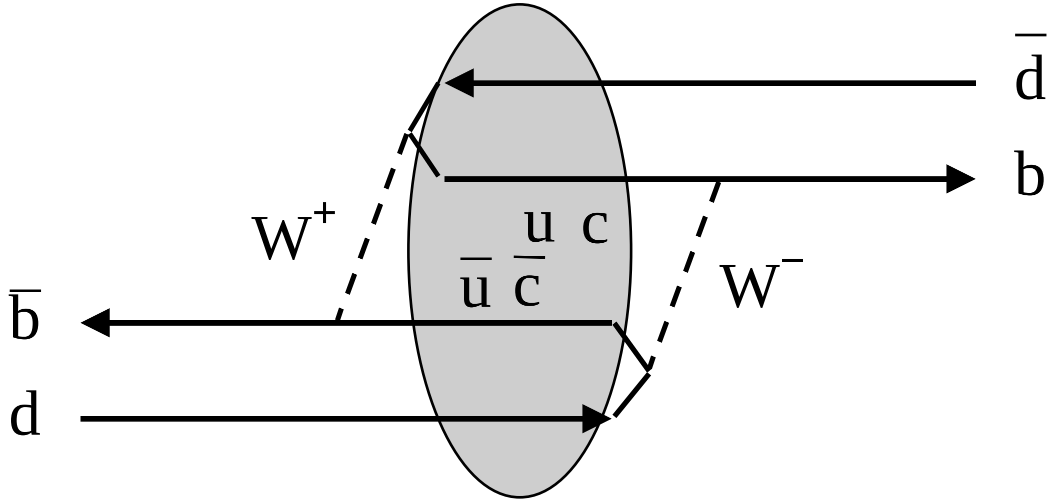
$$M_{12} = \frac{G_F^2}{12\pi^2} f_B^2 B_B m_B m_W^2 \eta_B \left(V_{tb} V_{td}^*\right)^2 S_0\left(x_t\right)$$

$\eta_B = 0.55$ (QCD correction)

$B_B f_B^{\ 2} = (200 \pm 40)^2$ **large uncertainty**

$\arg M_{12} = \arg\,(V_{tb}\ V_{td}^{\ *})^2$($= -2 \arg V_{td}$ in the Wolfenstein's parameterisation)

Γ_{12}



u-ū	$(V_{ub}\, V_{ud})^2 \sim \lambda^6$
u-c̄+c-ū	$2 \times V_{ub}\, V_{ud}\;\; V_{cb}\, V_{cd} \sim 2 \times \lambda^6$
c-c̄	$(V_{cb} V_{cd})^2 \sim \lambda^6$

CKM unitarity relation: $V_{tb} V_{td} = - V_{cb} V_{cd} - V_{ub} V_{ud}$

$$(V_{tb} V_{td})^2 = (V_{cb} V_{cd})^2 + (V_{ub} V_{ud})^2 + 2 V_{cb} V_{cd} V_{ub} V_{ud}$$

If $m_u = m_c = m_t \quad \arg M_{12} = \arg \Gamma_{12}$

No CP violation (GIM)

In reality $m_u << m_c << m_t$

$$\frac{\Delta\Gamma}{\Delta m} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \approx \left(\frac{m_b}{m_t}\right)^2 = O\left(10^{-3}\right) << 1$$

for both B_d and B_s

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

$$\left|\mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}\right| \approx \frac{\Delta\Gamma}{\Delta m}\,\frac{8}{3}\left(\frac{m_c}{m_b}\right)^2 \eta \times \begin{cases} \dfrac{1}{(1-\rho)^2 + \eta^2} & \mathrm{B_d} \\ \lambda^2 & \mathrm{B_s} \end{cases}$$

$|\zeta| = 1 + O(<10^{-3})$ CP violation in B-$\bar{\mathrm{B}}$ oscillations small

$$\zeta \approx e^{-i(\pi + 2\arg V_{td})} \qquad \mathrm{B_d}$$

$$\zeta \approx e^{-i(\pi + 2\arg V_{ts})} \qquad \mathrm{B_s}$$

Γ_{12}: Unlikely to be affected by new physics

M_{12}: Could be affected by new physics

$\Delta\Gamma/\Delta m \sim O(10^{-3})$ for both B_s and B_d

$\Delta\Gamma/(\Gamma_+ + \Gamma_-) = 10^{-3}$ for B_d (using measured Δm and B_d lifetime)

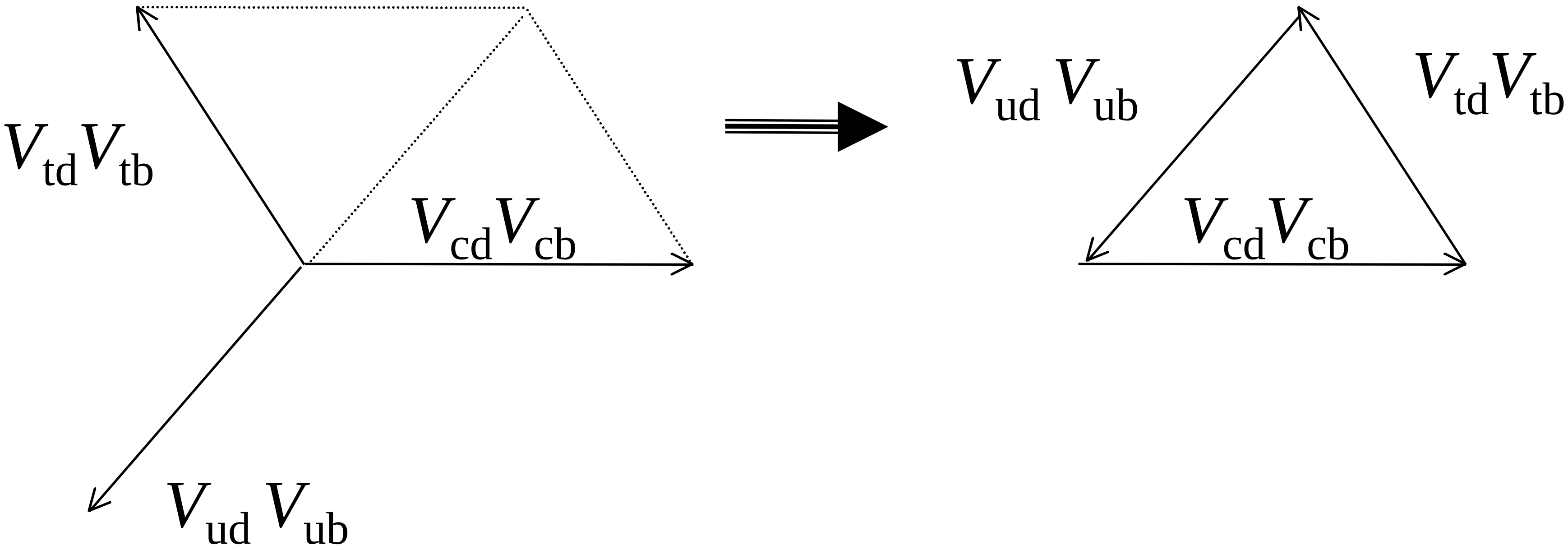
B-light and B-heavy

$\Delta m(B_s)/\Delta m(B_d) = |V_{ts}/V_{td}|^2 = 1/\lambda^2 \sim 20$

$\Delta\Gamma/(\Gamma_+ + \Gamma_-) \sim 0.1$ for B_s not negligible

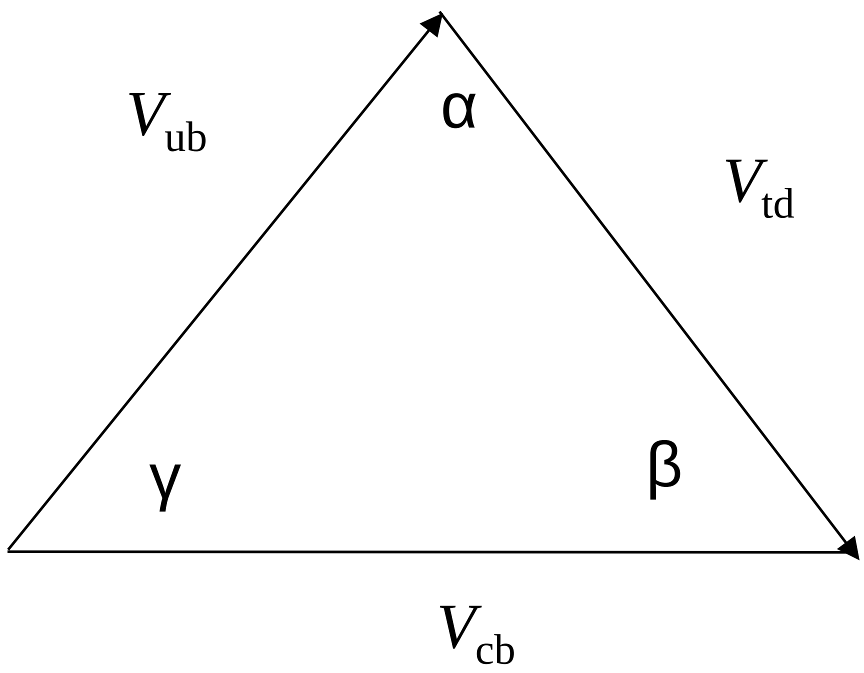
Unitarity triangle

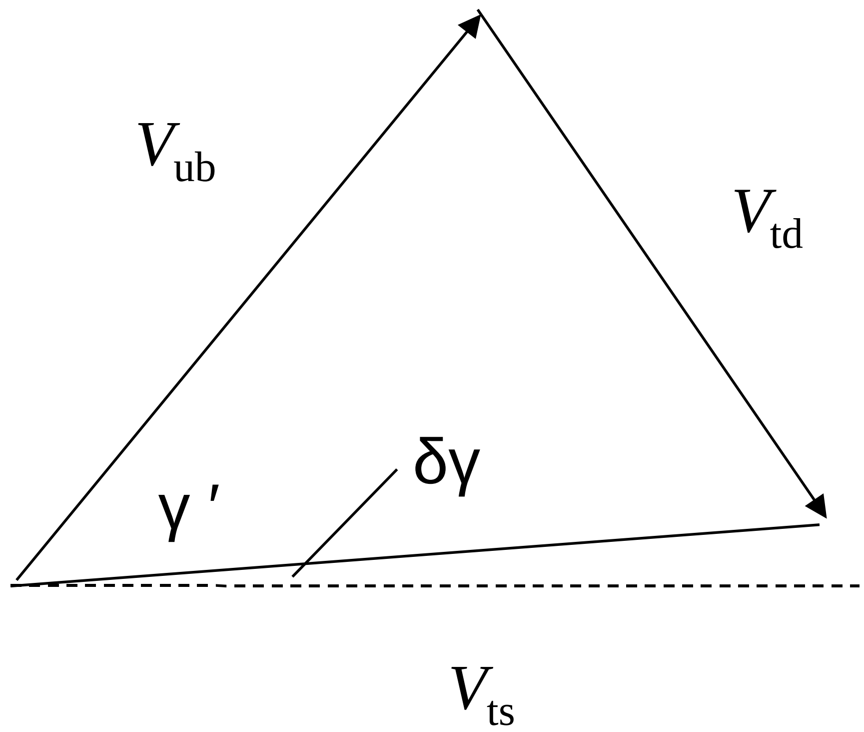
$$V_{td} V_{tb} + V_{cd} V_{cb} + V_{ud} V_{ub} = 0$$



Unitarity triangles

$$V_{td}\, V_{tb} \; + V_{cd}\, V_{cb} \; + V_{ud}\; V_{ub} \; = 0 \qquad V_{td}\, V_{ud} \; + V_{ts}\, V_{us} \; + V_{tb}\; V_{ub} \; = 0$$





$$\arg V_{cb} = 0\,,\ \arg V_{ub} = -\,\gamma,\ \arg V_{td} = -\,\beta\,,\ \arg V_{ts} = \pi + \gamma - \gamma\,'$$

$$B_d\!: \zeta \approx e^{-\,i\,2\,\beta} \qquad\qquad B_s\!: \zeta \approx e^{\;i\,2\,\delta\gamma}$$

X) Time evolution

B^0 at $t = 0$

$$\left|B^0(t)\right\rangle = f_+(t)\left|B^0\right\rangle + e^{-i2\beta} f_-(t)\left|\overline{B}^0\right\rangle$$

$$= \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t}\left|B_l\right\rangle + e^{-im_h t}\left|B_h\right\rangle\right)$$

$$\left|B_{l,h}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B^0\right\rangle \pm e^{-i2\beta}\left|\overline{B}^0\right\rangle\right)$$

$$f_\pm(t) = \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t} \pm e^{-im_h t}\right)$$

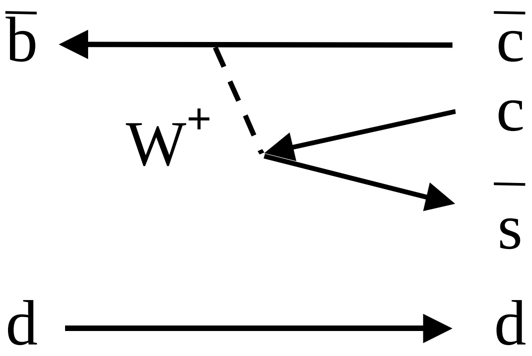
$\overline{B}^0$ at $t = 0$

$$\left|\overline{B}^0(t)\right\rangle = e^{i2\beta} f_-(t)\left|B^0\right\rangle + f_+(t)\left|\overline{B}^0\right\rangle$$

$$= \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t}\left|B_l\right\rangle - e^{-im_h t}\left|B_h\right\rangle\right)$$

XI) CP violation parameters

$J/\psi\ K_S$

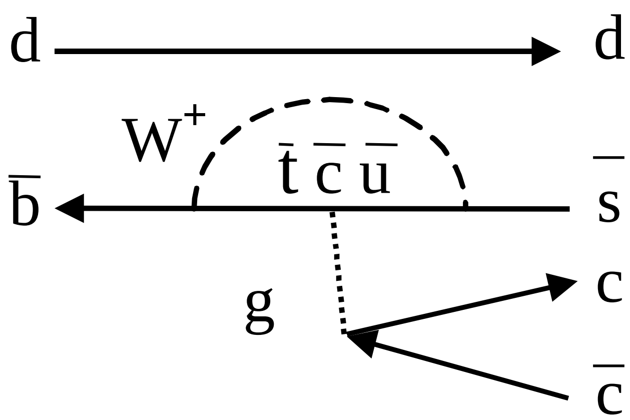


J/ψ

λ^2

$$\arg\left(V_{cb}\ V_{cs} V_{us}\ V_{ud}\right) = 0$$

$K_S \longrightarrow \pi\ \pi$



$K_S \longrightarrow \pi\ \pi \quad \lambda^2 \times \alpha_s$

$$\arg\left(V_{tb}\ V_{ts} V_{us}\ V_{ud}\right) = -\underbrace{\delta\gamma}_{\text{very small}} + \pi$$

J/ψ

very small

$\lambda^2\eta$

$\arg A_{J/\psi\ K_S} \approx 0$ with a very good approximation

$CP(J/\psi\, K_S) = -1$, $\quad \bar{A}_{J/\psi\, K_S} / A_{J/\psi\, K_S} = -1$

with absence of CP violation $CP(B_l) = +1$, $CP(B_h) = -1$

like K system

$$\eta_{J/\psi K_S} = \frac{\langle J/\psi\, K_S | H_W | B_l \rangle}{\langle J/\psi\, K_S | H_W | B_h \rangle}$$

$$= \frac{A_{J/\psi K_S} + e^{-i2\beta} \bar{A}_{J/\psi K_S}}{A_{J/\psi K_S} - e^{-i2\beta} \bar{A}_{J/\psi K_S}}$$

$$= \frac{1 - e^{-i2\beta}}{1 + e^{-i2\beta}}$$

$$= \frac{i \sin 2\beta}{1 + \cos 2\beta} \longrightarrow \text{pure imaginary}$$

CP violation in the interplay between the oscillation and decay

Time dependent decay rates

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

$$= \frac{e^{-\Gamma t}}{4} \left| e^{i\Delta m t} \langle J/\psi\ K_S | H_W | B_l \rangle + \langle J/\psi\ K_S | H_W | B_h \rangle \right|^2$$

$$= \frac{\left| A_h^{J/\psi\ K_S} \right|^2}{4} e^{-\Gamma t} \left| e^{i\Delta m t} \eta_{J/\psi\ K_S} + 1 \right|^2$$

$$= \frac{\left| A_h^{J/\psi\ K_S} \right|^2}{4(1 + \cos 2\beta)} e^{-\Gamma t} (1 - \sin 2\beta \times \sin \Delta m t)$$

$$\overline{\Gamma}_{J/\psi K_S}(t) = \frac{\left| A_h^{J/\psi\ K_S} \right|^2}{4(1 + \cos 2\beta)} e^{-\Gamma t} (1 + \sin 2\beta \times \sin \Delta m t)$$

Or well known CP asymmetry:

$$A_{J/\psi K_S}(t) = \frac{\overline{\Gamma}_{J/\psi K_S}(t) - \Gamma_{J/\psi K_S}(t)}{\overline{\Gamma}_{J/\psi K_S}(t) + \Gamma_{J/\psi K_S}(t)}$$

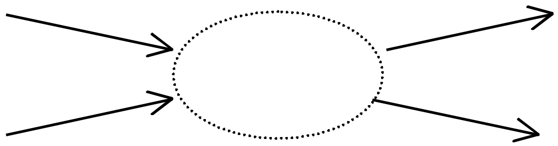
$$= \sin 2\beta \times \sin \Delta m t$$

sin2β can be measured with a theoretical uncertainties of ~O(%) or less

A difficult channel $B \to \pi^+\pi^-$

1) many re-scattering possibilities:

$B \to 2\pi(I = 0)$

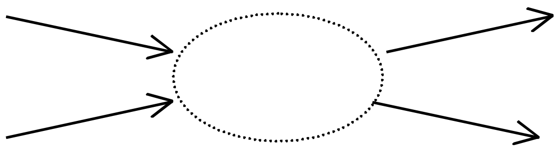


$n\pi(I = 0)$

S matrix is not necessarily diagonal at $\sqrt{s} = m_B$.

or even

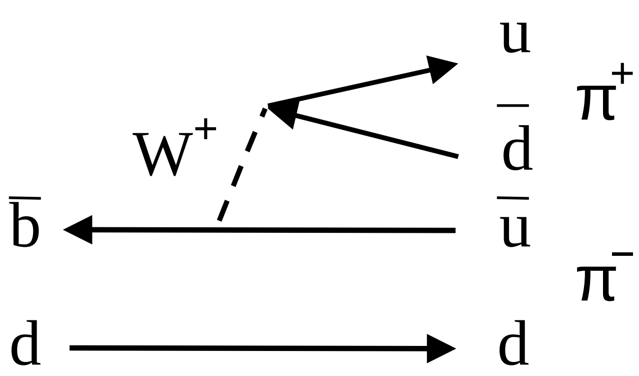
$B \to D\bar{D}$



2π

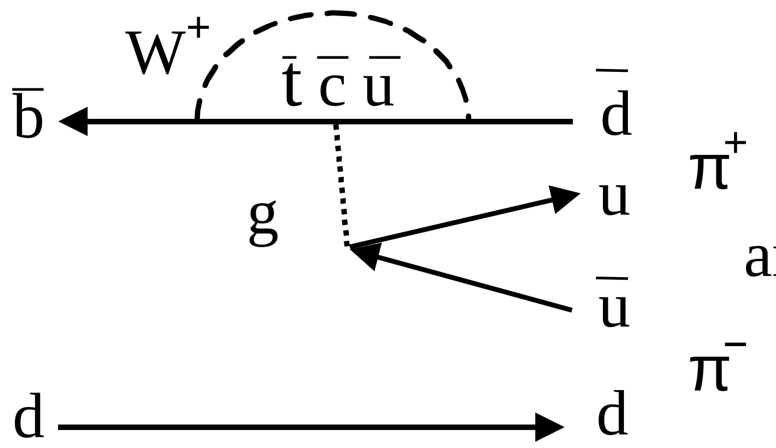
2) the penguin diagram with a different weak phase and large contribution.

$\pi^+ \pi^-$



λ^3

arg $(V_{ub} \;\; V_{ud}) = \gamma$



$\lambda^3 \times \alpha_s$

arg $(V_{tb} \; V_{td}) = -\beta$

observation:

CLEO: $Br(\pi^+\pi^-) \approx 0.5 \times 10^{-5} < Br(K^+\pi^-) \approx 1.4 \times 10^{-5}$

$\Downarrow$

penguin contribution dominates for $B_d \rightarrow K^+\pi^-$

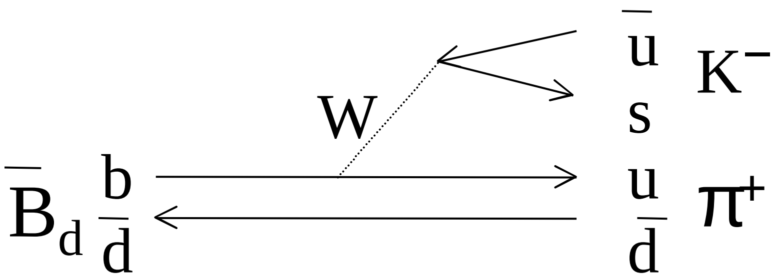
$\Downarrow$

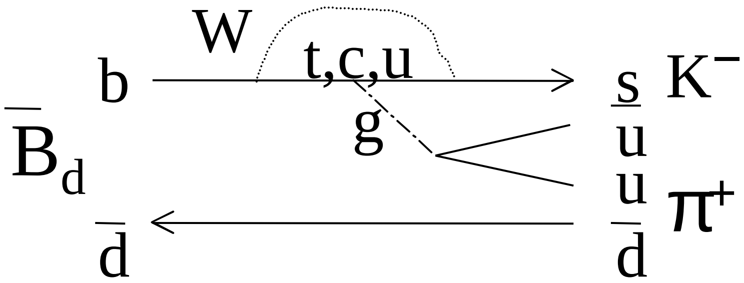
penguin contribution in $B_d \rightarrow \pi\pi > 20\%$

$B_d \to K\pi$

top penguin dominates $\left(P\,(m_t^2) < 1\right)$

$\Gamma_T \quad (V_{us}\ V_{ub})^2 \quad \lambda^8 \qquad \Gamma_P \quad [P(m_t^2)\times V_{ts}\ V_{tb}]^2 \quad \boldsymbol{P^2(m_t^2)} \times \lambda^4$

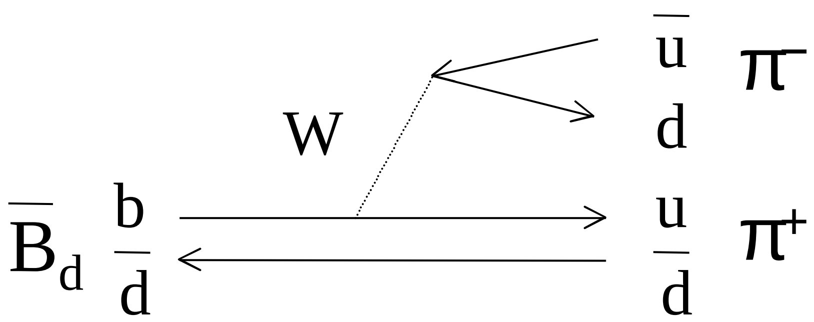


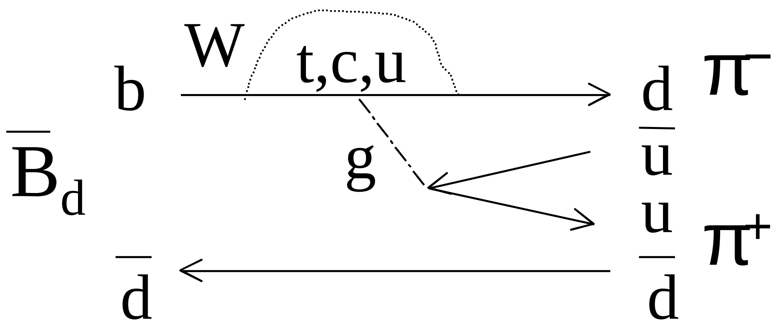


$B_d \to \pi\pi$

penguin is suppressed by $P\,(m_t^2) < 1$

$\Gamma_T \quad (V_{ud}\ V_{ub})^2 \quad \lambda^6 \qquad \Gamma_P \quad [P(m_t^2)\times V_{td}\ V_{tb}]^2 \quad P^2(m_t^2) \times \lambda^6$





$Br(\pi^+\pi^-) < Br(K^+\pi^-) \to P\,(m_t) > \lambda\ (= 0.22)$

To solve the penguin "pollution",

-a better theory backed up by data

or/and

-measure Br($B_d \to \pi^+\pi^-$), Br($B_d \to \pi^0\pi^0$), Br($B_u \to \pi^\pm\pi^0$)

or/and

-time dependent Dalitz plot analysis of $B_d \to \rho^+\pi^-$, $B_d \to \pi^+\rho^-$, $B_d \to \rho^0\pi^0$

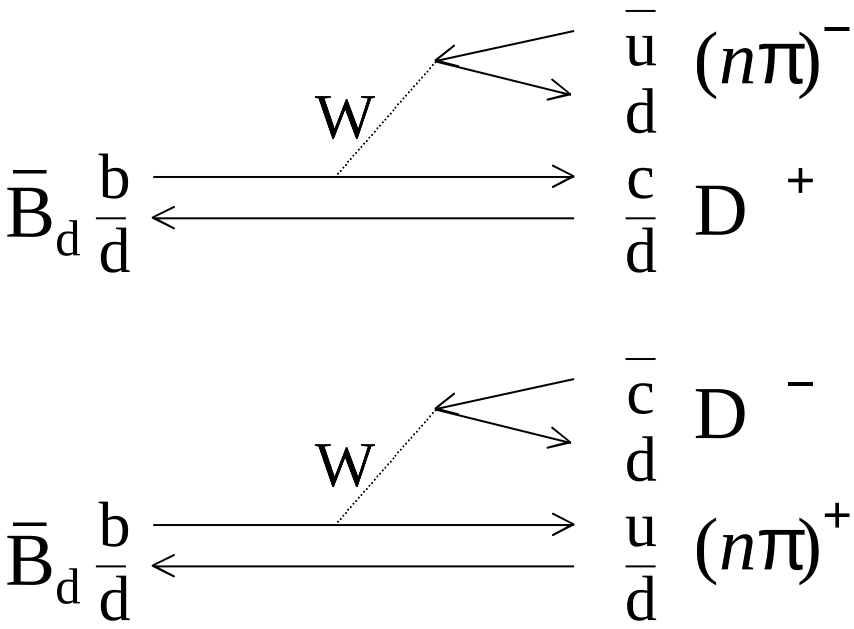
Quite a challenge… can we ever get down to <% uncertainties?
(some re-scattering problems still remain…)

find simpler final states

$\gamma + 2\beta$ can be measured by studying
the oscillation amplitudes of the **four time-dependent decay rates**
$B_d \to D^-(n\pi)^+$, $D^+(n\pi)^-$ and $\bar{B}_d \to D^-(n\pi)^+$, $D^+(n\pi)^-$

Only tree decay amplitudes

B_d-$\bar{B}_d$ oscillations



$V_{ud}\ V_{cb}$ $\lambda^2\, e^{i0}$

$V_{cd}\ V_{ub}$ $\lambda^4\, e^{-i\gamma}$

$e^{-i2\beta}$

$\gamma + 2\beta$

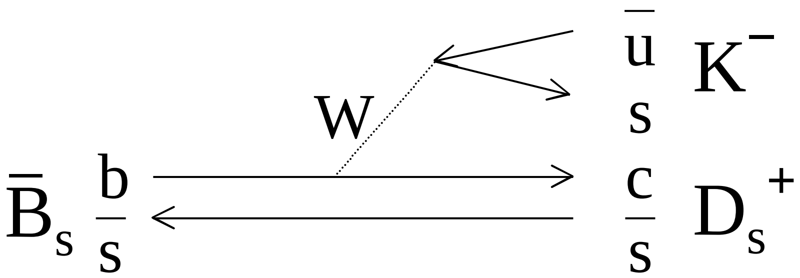
Strong phase difference
between the two trees
can also be extracted

One amplitude is much
larger than others
↓
a vary small CP asymmetry

γ (more precisely $\gamma - 2\delta\gamma$) can be measured by studying the oscillation amplitudes of the **four time-dependent decay rates** $B_s \to D_s^- K^+$, $D_s^+ K^-$ and $\bar{B}_s \to D_s^- K^+$, $D_s^+ K^-$

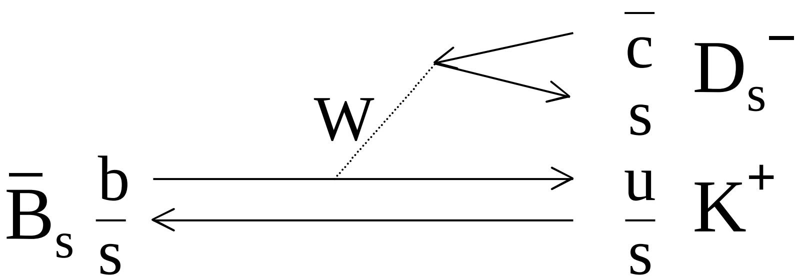
Only tree decay amplitudes

B_s-$\bar{B}_s$ oscillations



$V_{us}\ V_{cb}$ $\quad \lambda^3 e^{-i0}$ $\qquad e^{i2\delta\gamma}$

$\gamma - 2\delta\gamma$



$V_{cs}\ V_{ub}$ $\quad \lambda^3 e^{-i\gamma}$

Strong phase difference between the two trees can also be extracted

Two amplitudes
are of the same order
↓
could be a large CP asymmetry

NB: Do not forget
$\Delta\Gamma \neq 0$
i.e.
$\cosh \Delta\Gamma\, t \neq 1$
$\sinh \Delta\Gamma\, t \neq 0.$

$$\Gamma_f(t) \quad \frac{|A_f|^2}{2} e^{-\Gamma t}\left[I_+(t) + I_-(t)\right]$$

$$\bar{\Gamma}_{\bar{f}}(t) \quad \frac{|\bar{A}_{\bar{f}}|^2}{2|\alpha|^2} e^{-\bar{\Gamma} t}\left[\bar{I}_+(t) + \bar{I}_-(t)\right]$$

$+$ c.c.

$$\overset{(-)}{I}_+(t) = \left(1 + |\overset{(-)}{\xi}|^2\right)\cosh\frac{\Delta\Gamma}{2}t - 2\,\mathrm{Re}\,\overset{(-)}{\xi}\sinh\frac{\Delta\Gamma}{2}t$$

$$\overset{(-)}{I}_-(t) = \left(1 - |\overset{(-)}{\xi}|^2\right)\cos\Delta m t - 2\,\mathrm{Im}\,\overset{(-)}{\xi}\sin\Delta m t$$

$$\xi = \zeta\,\frac{\bar{A}_f}{A_f},\;\; \bar{\xi} = \frac{1}{\zeta}\,\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}}$$

Other possibilities

sin $2\delta\gamma$: $B_s \to J/\psi\ \varphi$ and $\overline{B}_s \to J/\psi\ \varphi$

complication:

$S = s(J/\psi) + s(\varphi)$ =	0,	1,	2
$L(J/\psi\text{-}\varphi)$ =	0,	1,	2
$CP(J/\psi\text{-}\varphi)$ =	$+1$,	-1,	$+1$

mixed CP eigenstate

$CP = -1$/$CP = +1$ to be measured

from the angular distribution of the final states

β, $\gamma+2\beta$, $\gamma-2\delta\gamma$, and $\delta\gamma$ can be measured with theoretical uncertainties of $\lesssim 1\%$.

$\Downarrow$

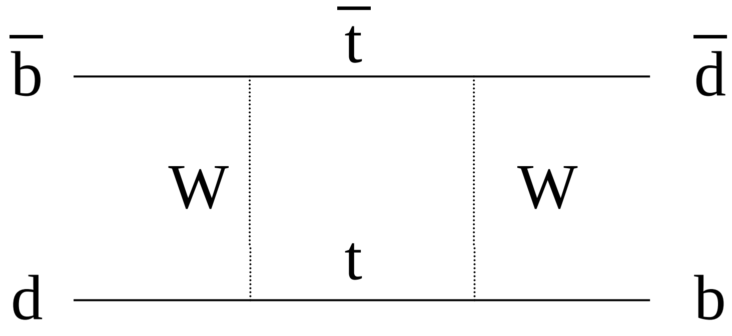
Essential for new physics search!

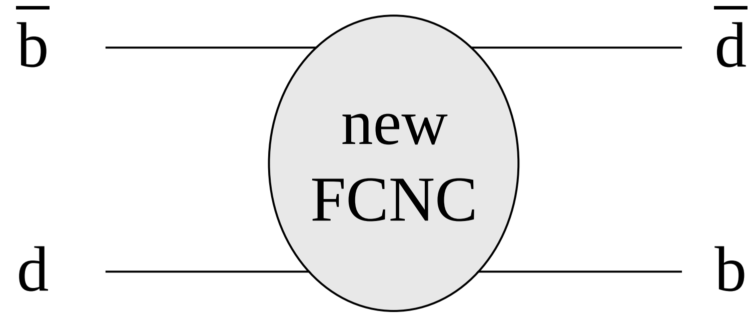
XII) New Physics

A parameterisation of new physics

$$H_{B\text{-}\bar{B}} \quad [\{(1-\rho)^2+\eta^2\}+ r_{db}]\, e^{2i(\beta+\varphi_{db})}$$

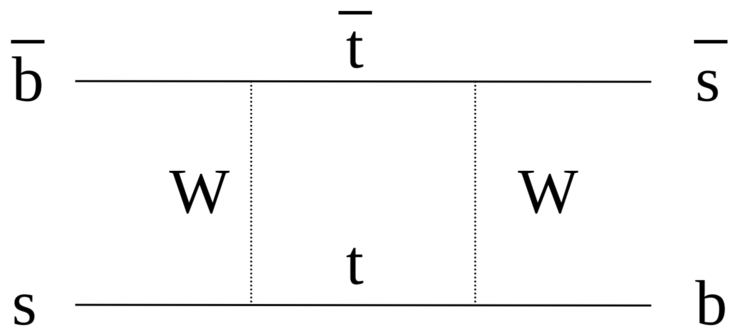
B_d- $\bar{B}_d$

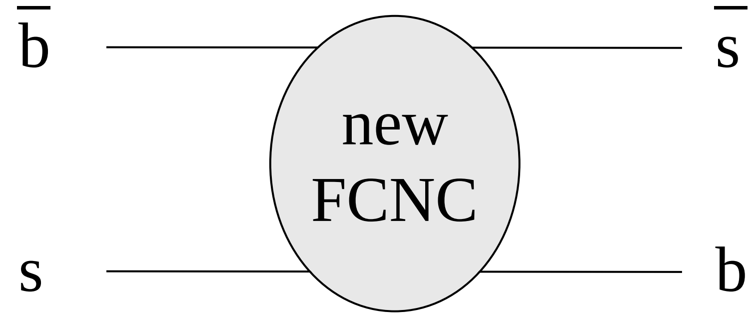




$$H_{B\text{-}\bar{B}} \quad [\,\lambda^{-2}+ r_{sb}\,]\, e^{-2i(\delta\gamma+\varphi_{sb})}$$

B_s- $\bar{B}_s$





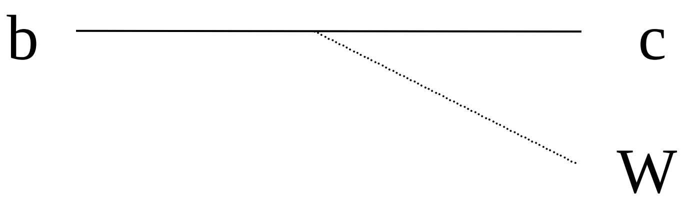
If there is no new physics,

$|V_{cb}|$, $|V_{ub}|$ — B-meson decays (usually semileptonic)

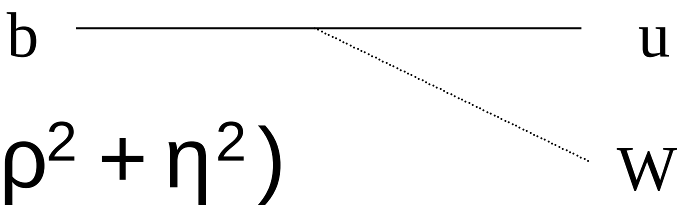
Δm_d — B_d-B_d oscillations

will fix all the Wolfenstein's parameters,

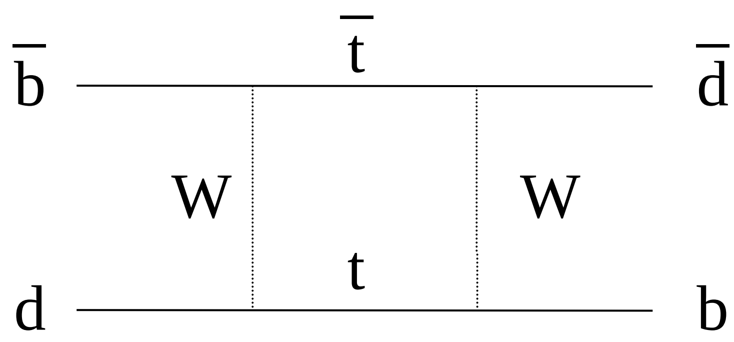
A, ρ and η (λ is well known).



A^2



$A^2(\rho^2+\eta^2)$



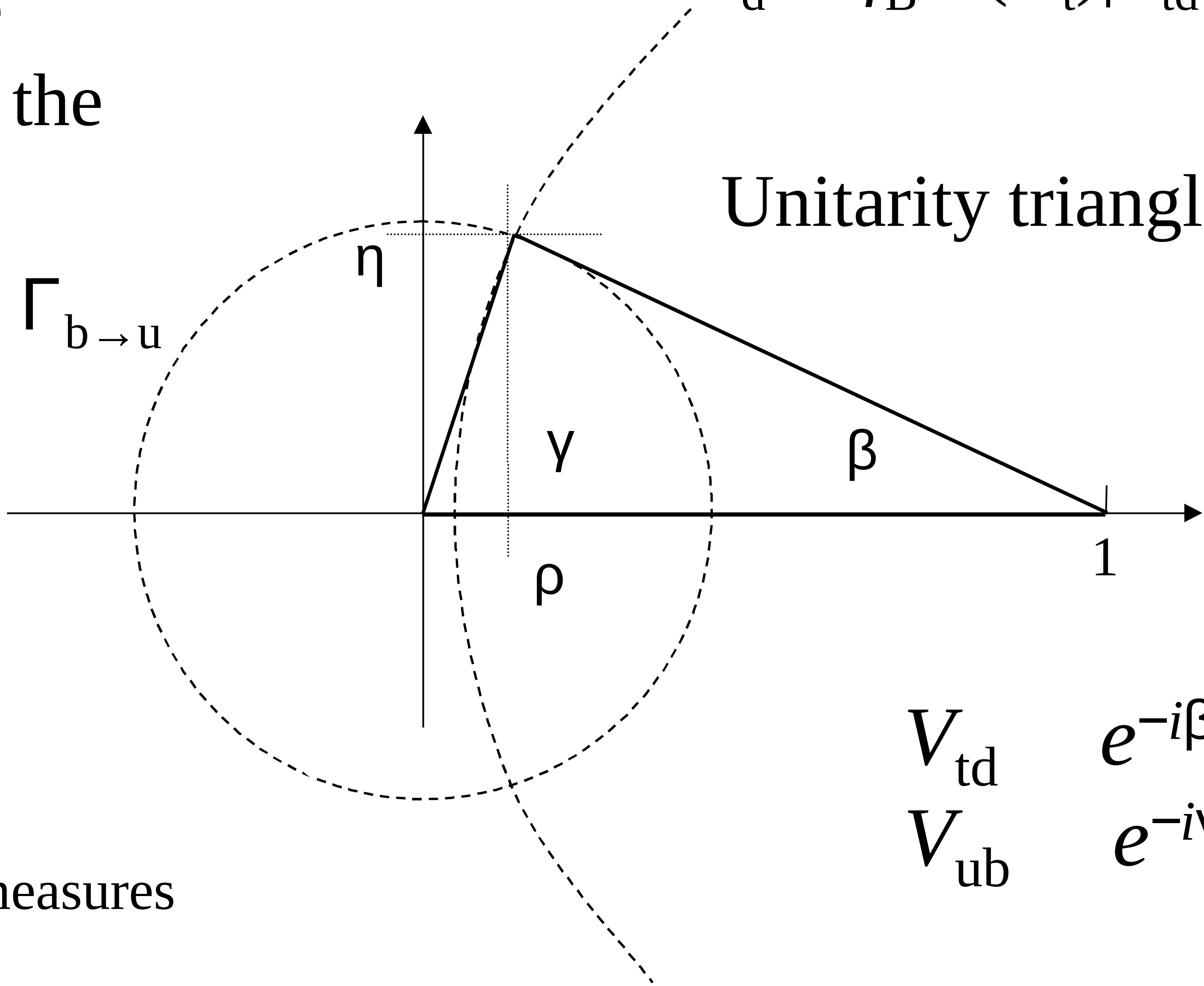
$A^2[(1-\rho)^2+\eta^2]$

From the neutral kaon system η > 0

$\Delta m_d \quad B f_B^2 F(m_t)|V_{td} V_{tb}|^2$

β and γ are defined by the sides

Unitarity triangle



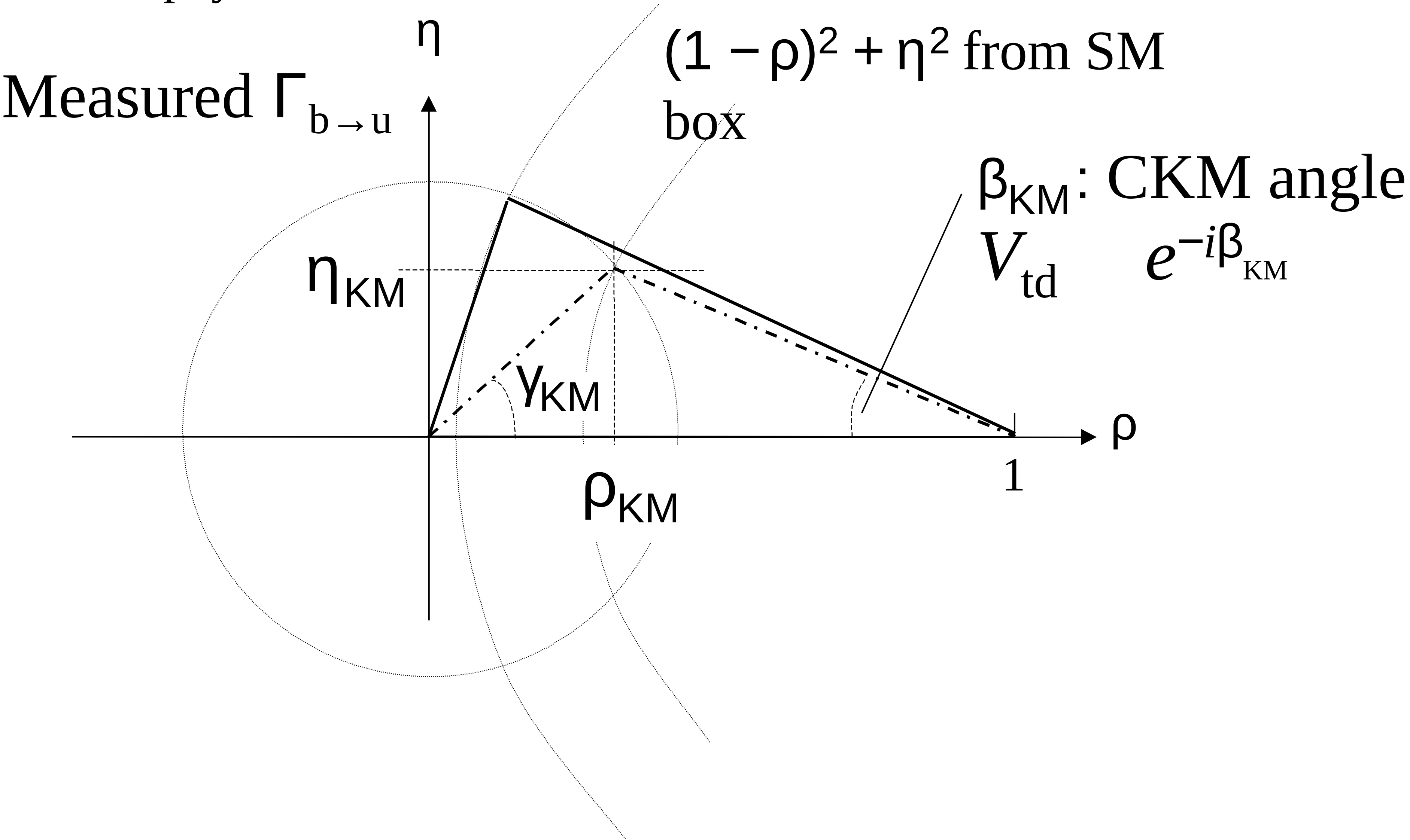
$V_{td} \quad e^{-i\beta}$

$V_{ub} \quad e^{-i\gamma}$

NB:
$Br(K^{\pm} \to \pi^{\pm} \nu\bar{\nu})$ measures also $|V_{td}|$

semileptonic decays are least effected by new physics

Measured $\Delta m(B_d) \rightarrow (1-\rho)^2 + \eta^2 + r_{db}$



CP violation in

$B_d \rightarrow J/\psi\, K_S$ v.s. $\overline{B}_d \rightarrow J/\psi\, K_S$

measures $2\beta_{J/\psi K} = 2(\beta_{KM} + \varphi_{db})$

CP violation in

$B_d \rightarrow D^{+} n\pi$ v.s. $\overline{B}_d \rightarrow D^{-} n\pi$

$B_d \rightarrow D^{-} n\pi$ v.s. $\overline{B}_d \rightarrow D^{+} n\pi$

measures $2(\beta_{KM} + \varphi_{db}) + \gamma_{KM}$

CP violation in

$B_s \rightarrow J/\psi\, \varphi$ v.s. $\overline{B}_s \rightarrow J/\psi\, \varphi$

measures $2\beta_{J/\psi\varphi} = 2(\delta\gamma_{KM} + \varphi_{sb})$

CP violation in

$B_s \rightarrow D_s^{+} K^{-}$ v.s. $\overline{B}_s \rightarrow D_s^{-} K^{+}$

$B_s \rightarrow D_s^{-} K^{+}$ v.s. $\overline{B}_s \rightarrow D_s^{+} K^{-}$

measures $2(\delta\gamma_{KM} + \varphi_{sb}) + \gamma_{KM}$

A consistency test by comparing the two $\gamma_{\mathbf{KM}}$ then combine them to improve the precision

1) γ_{KM} is determined

2) $|V_{ub}|$ and γ_{KM} β_{KM} or (ρ_{KM}, η_{KM})

3) η_{KM} $\delta\gamma_{KM}$

4) (ρ_{KM}, η_{KM}) $|V_{td}|$ and $|V_{ts}|$

determination of CKM parameters

5) $\beta_{J/\psi K}$ and β_{KM} φ_{db}

6) $\beta_{J/\psi\varphi}$ and $\delta\gamma_{KM}$ φ_{sb}

7) Δm_s, Δm_d and (ρ_{KM}, η_{KM}) r_{db} and r_{sb}

determination of new physics parameters

Both CKM and New Physics parameter sets are fully determined.

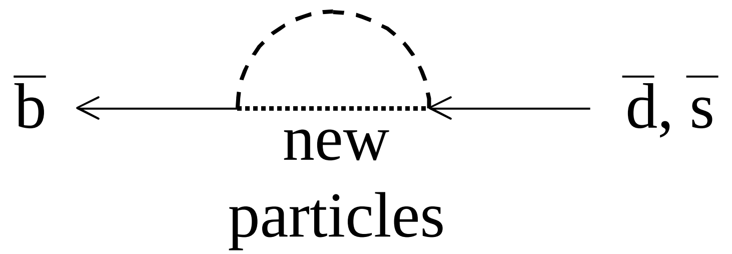
Potential problems for BaBar, BELLE, CDF, D0, HERA-B

$J/\psi K_S$	very high statistics for a precision
$D\ n\pi$	small asymmetries require high statistics
D_sK	need B_s (BaBar, BELLE)
	particle ID at large p (CDF, D0)
	small branching fractions $<10^{-5}$
$J/\psi\varphi$	need B_s (BaBar, BELLE)
	large statistics needed to obtain CP=+1/CP=−1

More generally new physics can appear in

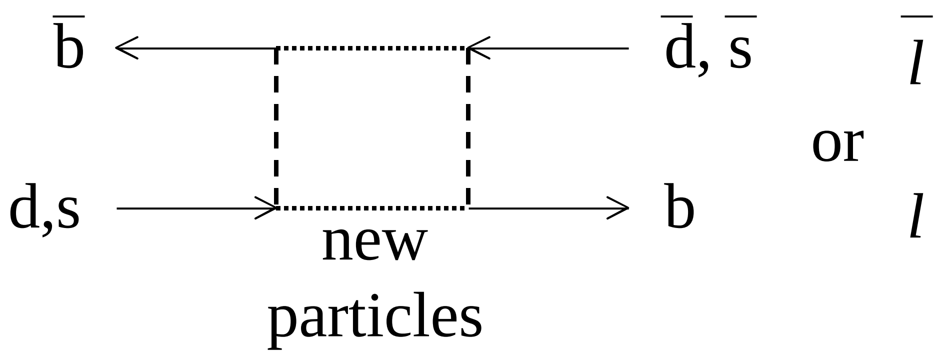
Δb = 1 process

through penguin

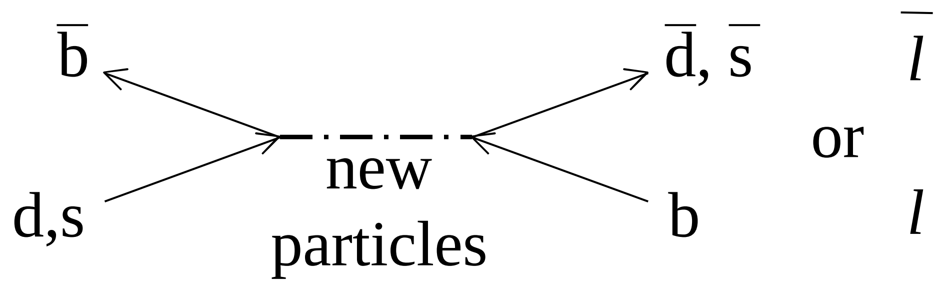


Δb = 2 process

through box



through tree



CP violation must be studied in

B_d decays via Oscillations $b \rightarrow c+W$ and $b \rightarrow u+W$

B_s decays via Oscillations $b \rightarrow c+W$ and $b \rightarrow u+W$

$B_{d,s,u}$ decays via penguins

$B_{d,s}$ decays via box

Experimental requirements are

Small branching fractions → many $B_{d,s,u}$'s

Rapid B_s oscillations → decay time resolution

Including multi-body hadronic final states → particle ID

mass resolution

sensitive trigger

→ a dedicated B experiment @ a hadron collider

XIII) B Experiment

B Physics now and in near future (~2000)

Symmetric e^+e^- colldier at $\Upsilon(4S)$
CLEO II-III

Asymmetric e^+e^- colldier at $\Upsilon(4S)$
BaBar
BELLE

Hadron fixed target
HERA-B

Hadron collider
CDF
D0

	Experiment Now	In preparation (1999 → 2003)	R&D (2003 → ?)
	sym. e^+e^-@ϒ(4S) CLEO II	CLEO III	
$\sigma_{b\bar{b}}$	~1 nb		
L	4×10^{32}	1.7×10^{33}	3×10^{34}
$\sigma_{b\bar{b}}/\sigma_{hadronic}$	$\sim2\times10^{-1}$		
B-hadron	B_u, B_d		
Detector	central		
Trigger	all		
$\sigma_t(B)$	very modest		
Particle ID	e/μ/hadron limited π/K/p	e/μ/π/K/p	

few×10^7 B's by ~2000: Rare decays, direct CP but not J/ψK_S

Experiments in near future(~2000)			
	asym. e^+e^-	hadron	
	ϒ(4S) BaBar/BELLE	p+metal@40GeV HERA-B	$p\bar{p}$@2TeV CDF/D0
$\sigma_{b\bar{b}}$	~1 nb	~760 nb	~60 μb
$B\bar{B}$/sec	3/10	38	6000
$\sigma_{bb}/\sigma_{hadronic}$	$\sim 2\times 10^{-1}$	$\sim 10^{-6}$	$\sim 10^{-3}$
B-hadron	B_u, B_d	B_u,B_d,B_s,B_c	B_u,B_d,B_s,B_c
Detector	slightly forward	forward	central
Trigger	all	J/ψ	high p_t μ
σ_t	modest	good	good
Particle ID	e/μ/π/K/p	e/μ/π/K/p	e/μ/hadron

Around 2005, we will have all combined results of:

σ_β: ~ 0.02 [rad]

$\sigma_{\beta+\gamma}$: depends on how well we understand strong interactions
penguin, re-scattering, SU(3), resonance etc.

x_s: depends on the value, measured if x_s<~40

$\sigma_{\delta\gamma}$: depends on x_s

Physics with "10^8" B's

β+γ, γ, δγ, (x_s) would remain to be still open questions

For a significant improvement (>10^9 B's physics)

→ new generation of experiments

Which is needed to discover New Physics as demonstrated.

Experiments >~2005			
	pp@14TeV ATLAS/CMS approved	pp@14TeV LHCb[&] approved	$p\bar{p}$@2TeV BTeV proposed
$\sigma_{b\bar{b}}$	~500 μb	~500 μb	~60 μb
$B\bar{B}$/sec	500k	100k	6-60k[+]
$\sigma_{b\bar{b}}/\sigma_{hadronic}$	$\sim 5\times 10^{-3}$	$\sim 5\times 10^{-3}$	$\sim 10^{-3}$
B-hadron	B_u,B_d,B_s,B_c	B_u,B_d,B_s,B_c	B_u,B_d,B_s,B_c
Detector	central	forward	double forward
Early trigger (reduction >100)	high p_t μ	medium p_t e/μ/h vertex	vertex
σ_t	good	very good	very good
Particle ID	e/μ/hadron	e/μ/π/K/p	e/μ/π/K/p

$L=10^{33}$ for the first few years, $^{\&}L=2\times10^{32}$ for many years, $^{+}L=1\text{-}10\times10^{32}$

>2005

New generation of experiments could give

σ_β: < 0.01

$\sigma_{\delta\gamma}$: < 0.01

x_s: up to x_s~40 (ATLAS/CMS), ~80 (LHCb/BTeV)

In addition, due to the particle identification capability and efficient trigger, dedicated experiments could give

σ_γ: < 0.1

$\sigma_{\beta+\gamma}$: < 0.1

} **essential for discovering new physics**

using various decay modes.

Also:

$B_s \to K\, l^+l^-$, $K\,\gamma$, $\mu^+\mu^-$, $B_d \to \varphi K_S$, rare D and tau decays etc.

Physics capability of the LHCb detector is due to:

-Trigger efficient for both leptons and hadrons

high p_T hadron trigger   2 to 3 times increase in

$\pi\pi$,Kπ,D π,DK ,$D_s\pi$,D_sK …

-Particle identification e/μ/π/K/p

$\pi\pi$,Kπ,D π,DK ,$D_s\pi$,D_sK

-Good decay time resolution

e.g. 43 fs for $B_s \rightarrow D_s\pi$, 32 fs for $B_s \rightarrow J/\psi\varphi$

-Good mass resolution

e.g. 11 MeV for $B_s \rightarrow D_s\pi$, 17 MeV for $B_d \rightarrow \pi^+\pi^-$

particle ID + mass resolution   redundant background rejection

LHCb Trigger Efficiency

for reconstructed and correctly tagged events

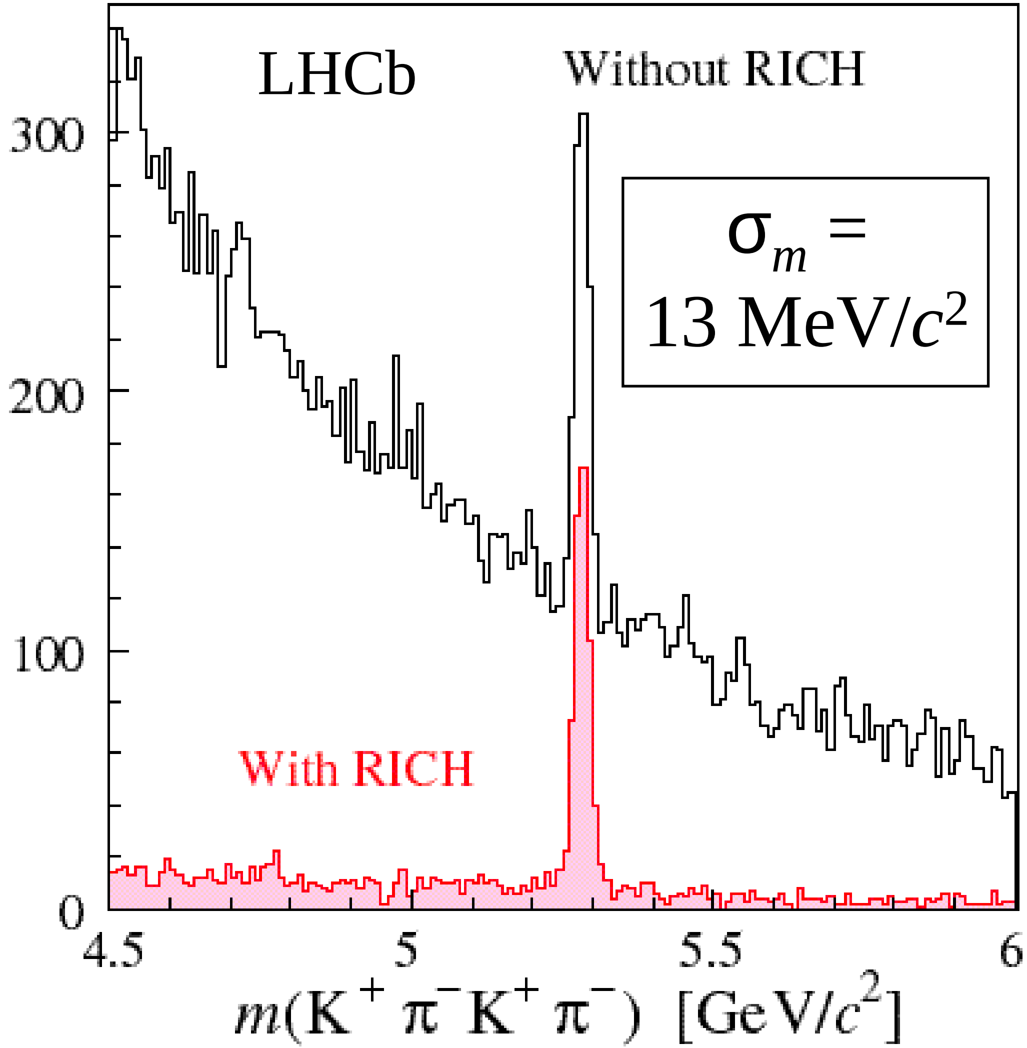
	L0(%)				L1(%)	L2(%)	Total(%)
	μ	e	h	all			
$B_d \to J/\psi(ee)K_S$ + tag	17	**63**	17	72	42	81	**24**
$B_d \to J/\psi(\mu\mu)K_S$ + tag	**87**	6	16	88	50	81	**36**
$B_s \to D_s K$ + tag	15	9	**45**	54	56	92	**28**
$B_d \to DK$	8	3	31	37	59	95	21
$B_d \to \pi^+\pi^-$ + tag	14	8	**70**	76	48	83	**30**

- trigger efficiencies are ~ 30%
- hadron trigger is important for hadronic final states
- lepton trigger is important for final states with leptons

Very small visible branching fractions

(10^{-7}~10^{-8})

Importance of particle identification

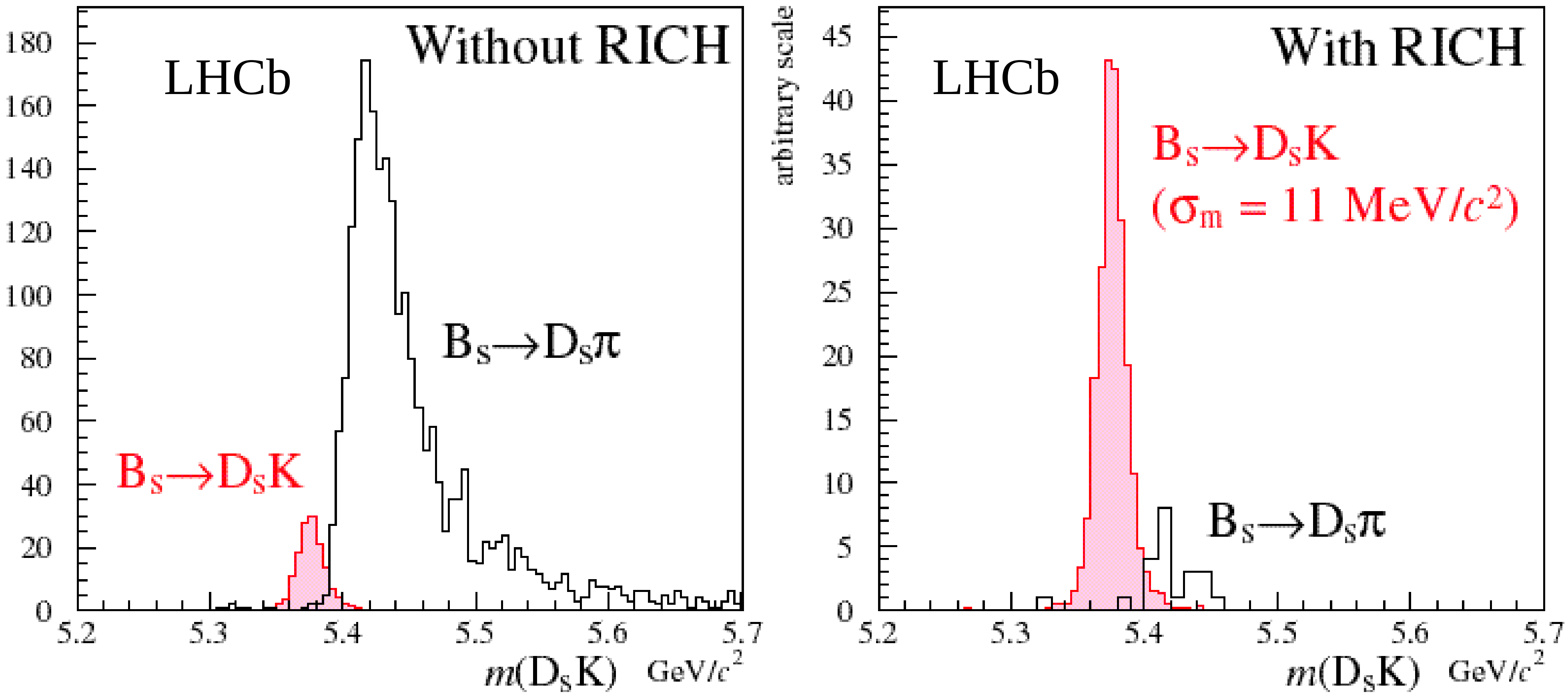


With signal events

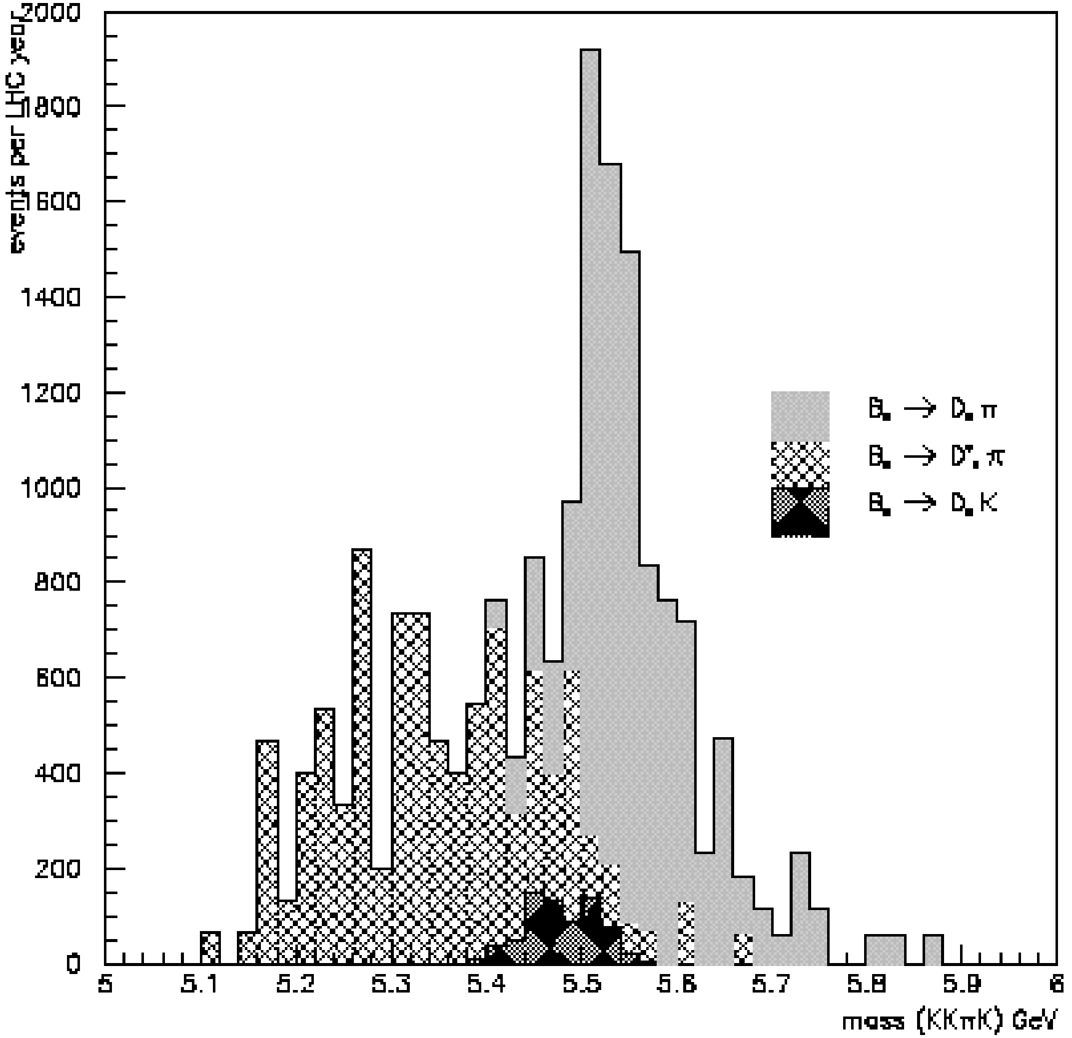
$B_s \rightarrow D_sK$

Major background: $B_s \rightarrow D_s\pi$ (No CP violation)

Importance of particle identification and mass resolution



ATLAS



events per LHC year
2000
1800
1600
1400
1200
1000
800
600
400
200
0
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
6
mass (KKπK) GeV
$B_s \rightarrow D_s \pi$
$B_s \rightarrow D^*_s \pi$
$B_s \rightarrow D_s K$

XIV) Summary of K and B system

K-system

•domination of $2\pi(I = 0)$ final states $\frac{\Gamma_{I=0}}{\Gamma_L + \Gamma_S}$ 0.99

•K_S decays much faster than K_L $y = \frac{\Delta\Gamma}{\overline{\Gamma}}$ 2

•K_S-K_L oscillation frequency $x = \frac{\Delta m}{\overline{\Gamma}}$ 0.95

≈ decay K_S constant

•CP violation in the oscillation 10^{-3}

in the oscillation-decay interplay

B-system

$m(\mathrm{B}) \quad m(\mathrm{K}) \times 10 \qquad \tau(\mathrm{B}) \quad \tau(\mathrm{K}) \times 10^{-2}$

- no dominant final states

- $\mathrm{B_S}$ and $\mathrm{B_L}$ decay constant differences

$$\mathrm{B_d} \quad y = \frac{\Delta\Gamma}{\overline{\Gamma}} \quad 5 \times 10^{-3} \qquad\qquad \mathrm{B_s} \quad y = \frac{\Delta\Gamma}{\overline{\Gamma}} \quad 0.1$$

- $\mathrm{B_S}$-$\mathrm{B_L}$ oscillations vs. decay constants

$$\mathrm{B_d} \quad x = \frac{\Delta m}{\overline{\Gamma}} \quad 0.72 \qquad\qquad \mathrm{B_s} \quad x = \frac{\Delta m}{\overline{\Gamma}} \quad \text{big}$$

$$\Delta m(\mathrm{B_d}) \quad \Delta m(\mathrm{K}) \times 10^{2}$$

- CP violation in the oscillation
  expected to be 10^{-3}

- CP violation in oscillation-decay interplay
  could be 1

Conclusions

CP violation was, is and still will be > 2005 as one of the most mysterious and important subject of particle physics for both
theoretically
and
experimentally.
In the end, we have not yet annihilated !!!