CP Violation

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I) Why CP violation is highly interesting?

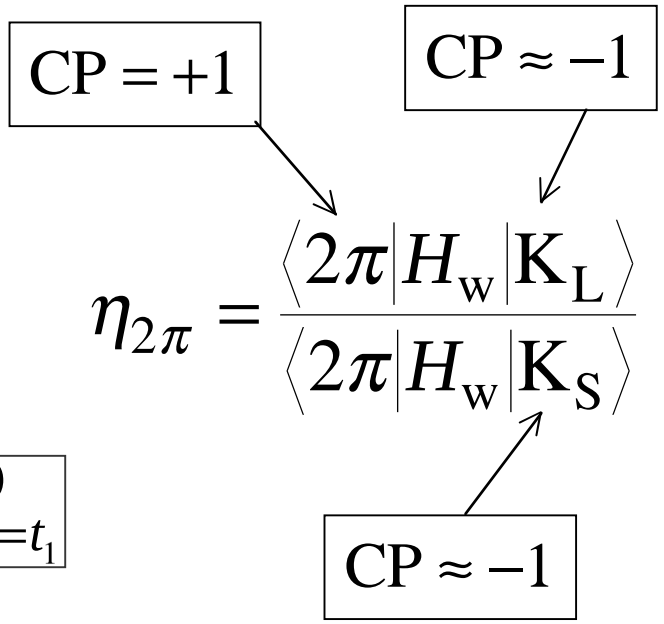
- Currently observed CP violation in the kaon decays can be accommodated within the Standard Model.
  BUT, it cannot exclude that CP violation is **partly** or even **entirely** due to **new physics**.
- Since CP violation is due to an "interference", it is **sensitive to a small effect**.
- Cosmology (baryon genesis) suggests that an **additional source** of CP violation other than the Standard Model is needed.

A promising place to look for new Physics

II) CP violation in the Kaon system

Observed CP violation in the kaon system:

1) Re $\eta_{2\pi}$



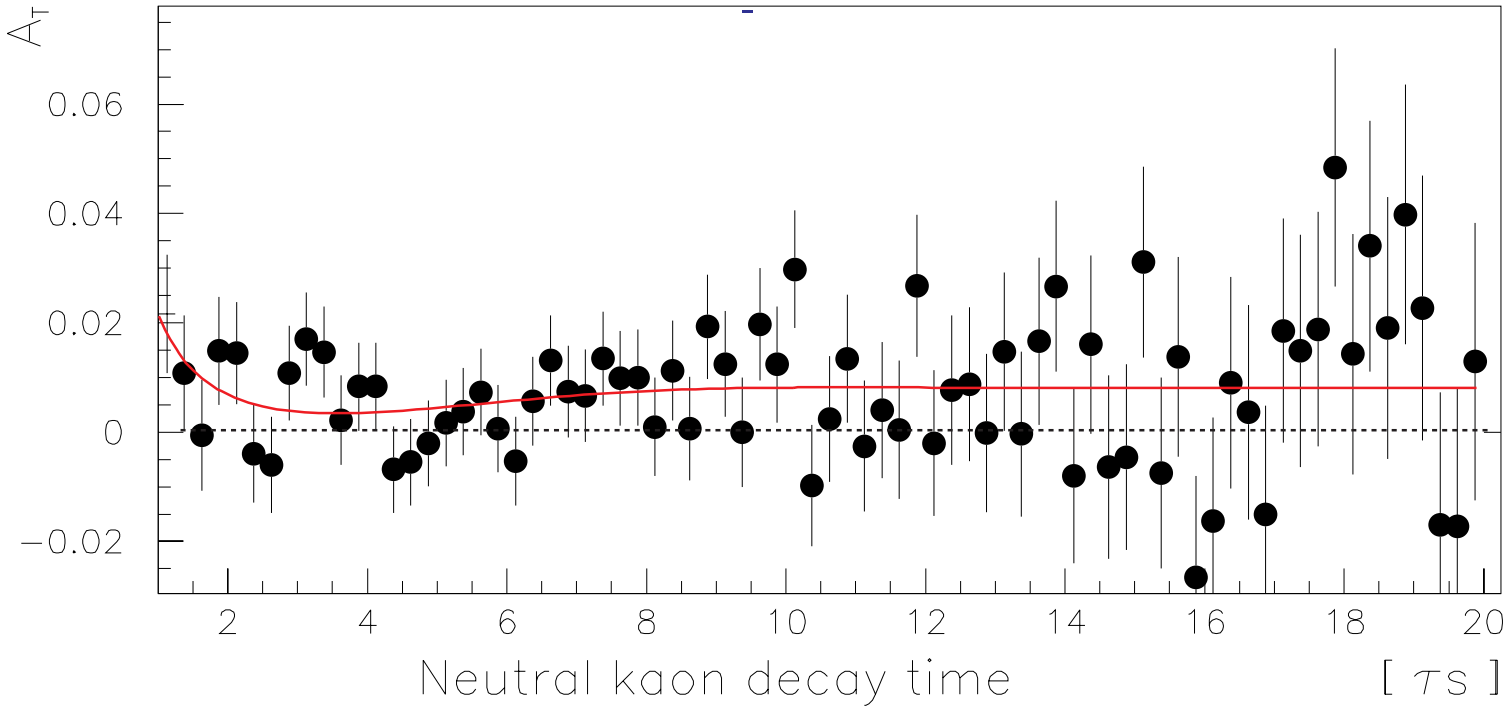
$$K^0_{t=0} \rightarrow \overline{K}^0_{t=t_1} \neq \overline{K}^0_{t=0} \rightarrow K^0_{t=t_1}$$

~~CP~~ and ~~T~~

so called CP violation in K^0- $\overline{K}^0$ oscillations

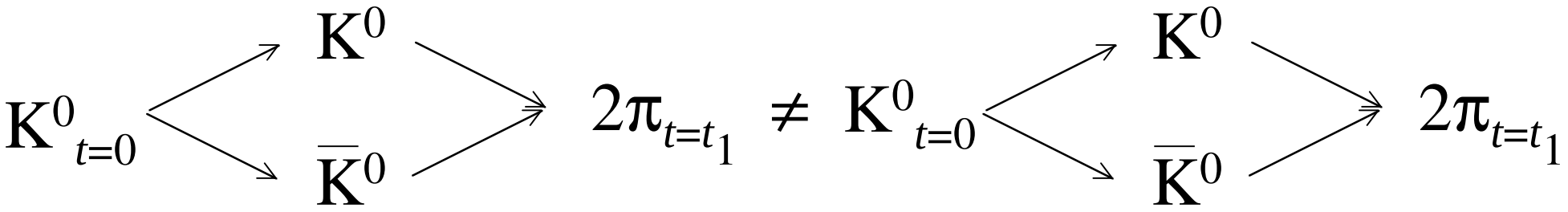
CPLEAR

$$A_T(t) = \frac{\overline{K}^0 \to K^0(t) - K^0 \to \overline{K}^0(t)}{\overline{K}^0 \to K^0(t) + K^0 \to \overline{K}^0(t)}$$



$(8.0 \pm 1.7 \pm 1.0) \times 10^{-3}$

2) Im $\eta_{2\pi}$



So called CP violation in
the interplay between oscillations and decays

3) Current experimental results are

$$\eta_{+-} = \eta_{00}$$

$$\arg \eta_{+-} = \tan^{-1} \Delta m/2\Delta\Gamma \approx 43.5^\circ$$

$$(\Delta m = m_{\mathrm{L}} - m_{\mathrm{S}},\ \Delta\Gamma = \Gamma_{\mathrm{S}} - \Gamma_{\mathrm{L}})$$

{ NA31,CPLEAR (CERN)
{ E731, E773 (FNAL)

This is compatible with

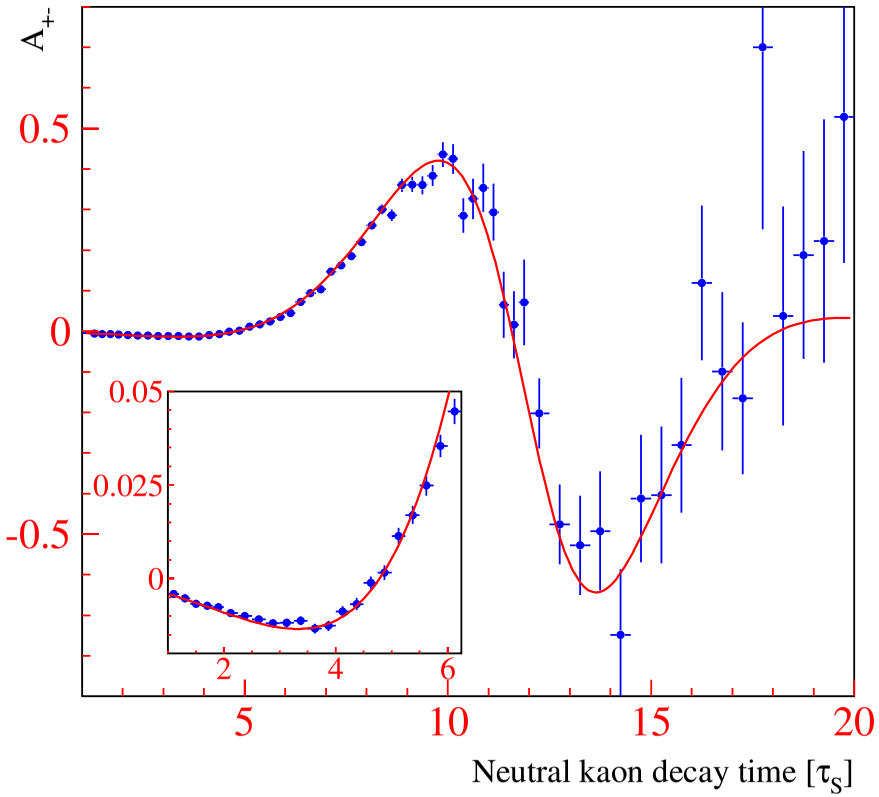
Standard Model

but also with

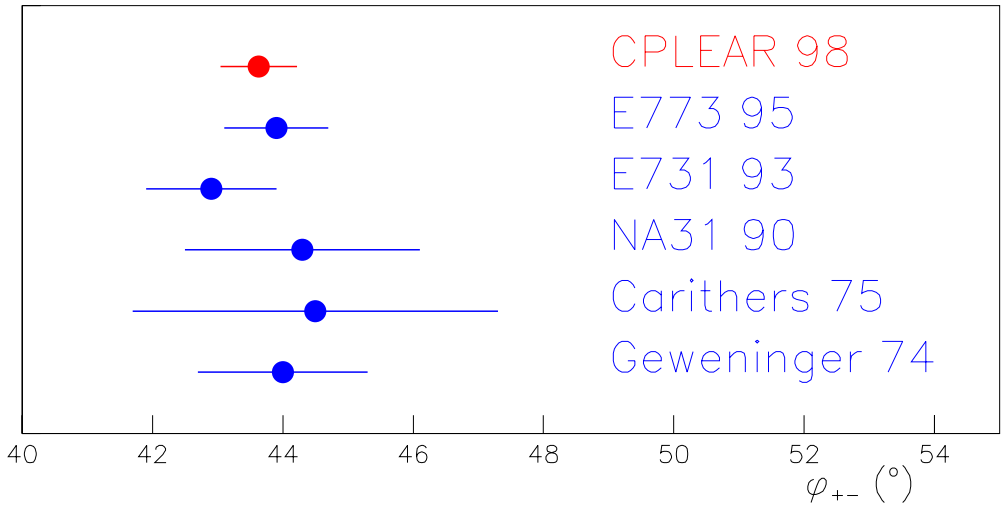
Superweak Model

CPLEAR

$$\frac{\overline{K}^0 \to \pi^+\pi^-(t) - K^0 \to \pi^+\pi^-(t)}{\overline{K}^0 \to \pi^+\pi^-(t) - K^0 \to \pi^+\pi^-(t)}$$



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



4) Experimental attempt to exclude the Superweak model

1) To show

$|\eta_{+-}| \neq |\eta_{00}|$

so called $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$

or CP violation in decay:

due to penguins

NA48 (CERN), KTeV(FNAL)

2) To show

$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \approx 10^{-11}$

Being discussed at FNAL and BNL

Standard model predictions are uncertain for η_{+-} and η_{00}

hadronic effects: long range interactions

penguins etc.

$Br(K_L \to \pi^0 \nu\bar{\nu})$ is experimentally really hard.

Another place to look for CP violation?

III) CP Violation and B-meson System

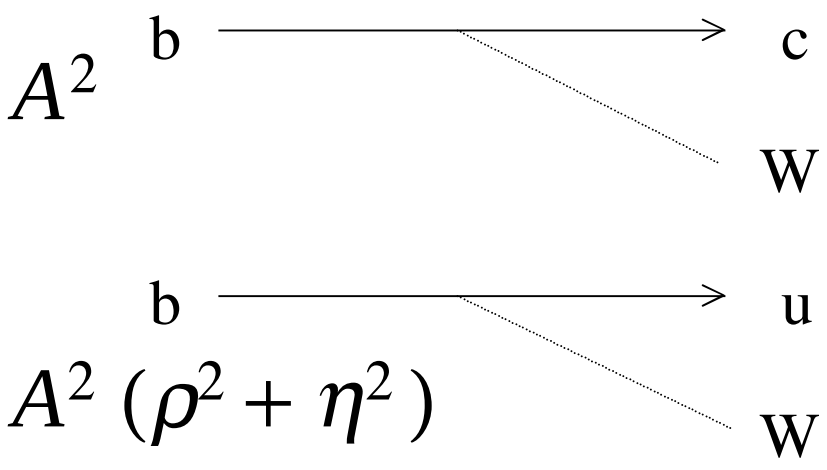
If there is nothing else but the standard model,

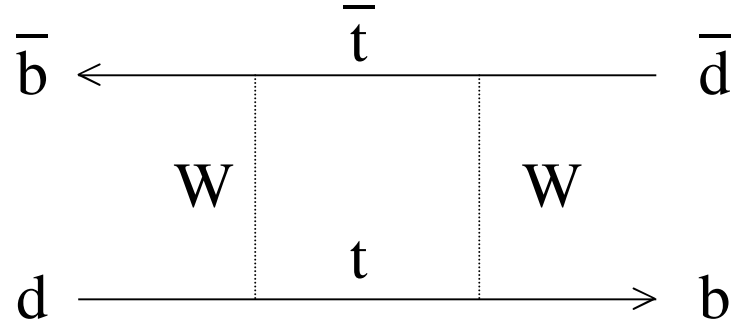
$|V_{cb}|$, $|V_{ub}|$ B-meson decays

Δm_d B_d-$\bar{B}_d$ oscillations

will fix all the Wolfenstein's parameters,

A, ρ and η (λ is well known).





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

CKM matrix relevant for B Physics

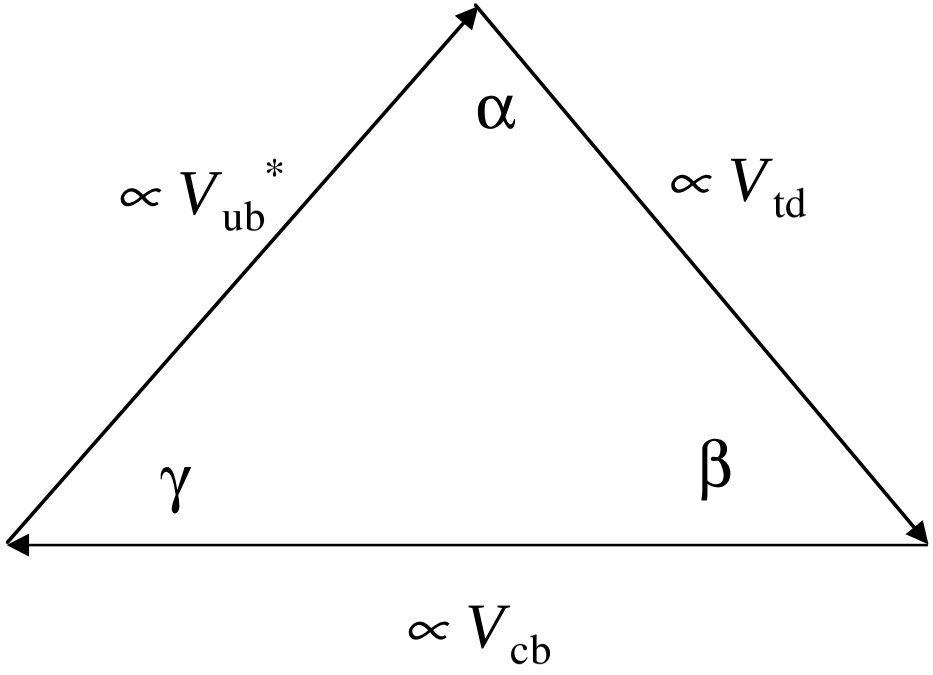
(CP violation is all due to $\eta \neq 0$)

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

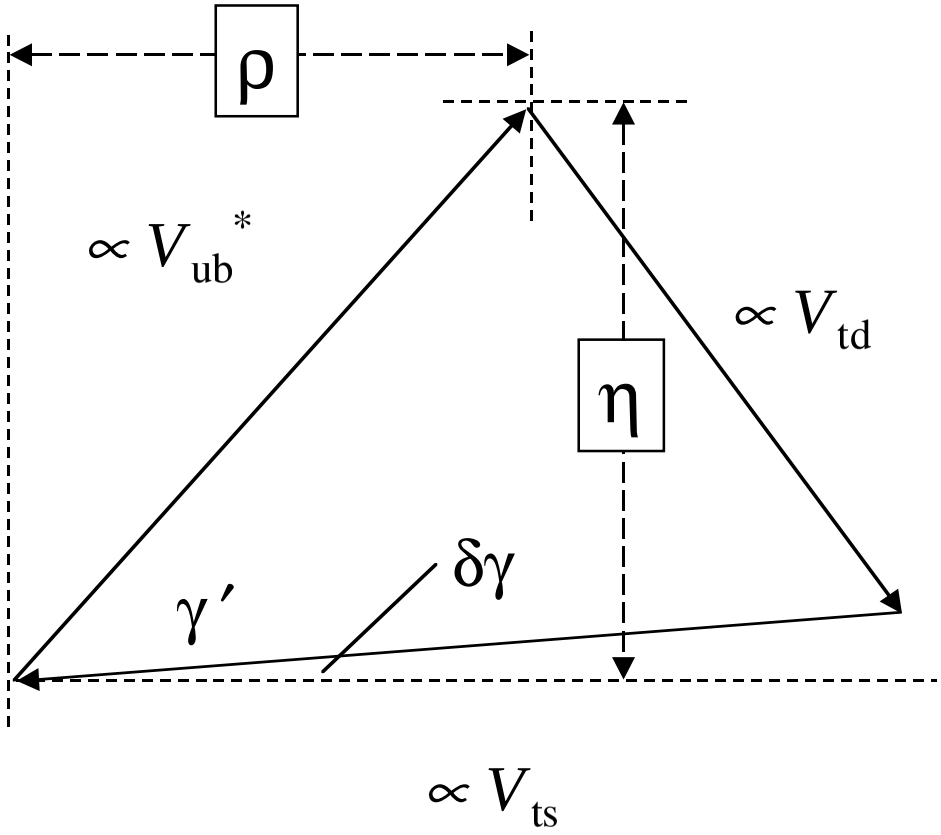
$$+ \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\eta\lambda^5 & 0 & 0 \\ (\rho + i\eta)\lambda^5/2 & (1/2-\rho)A\lambda^4 - iA\eta\lambda^4 & 0 \end{pmatrix}$$

CKM Unitarity Triangles

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



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



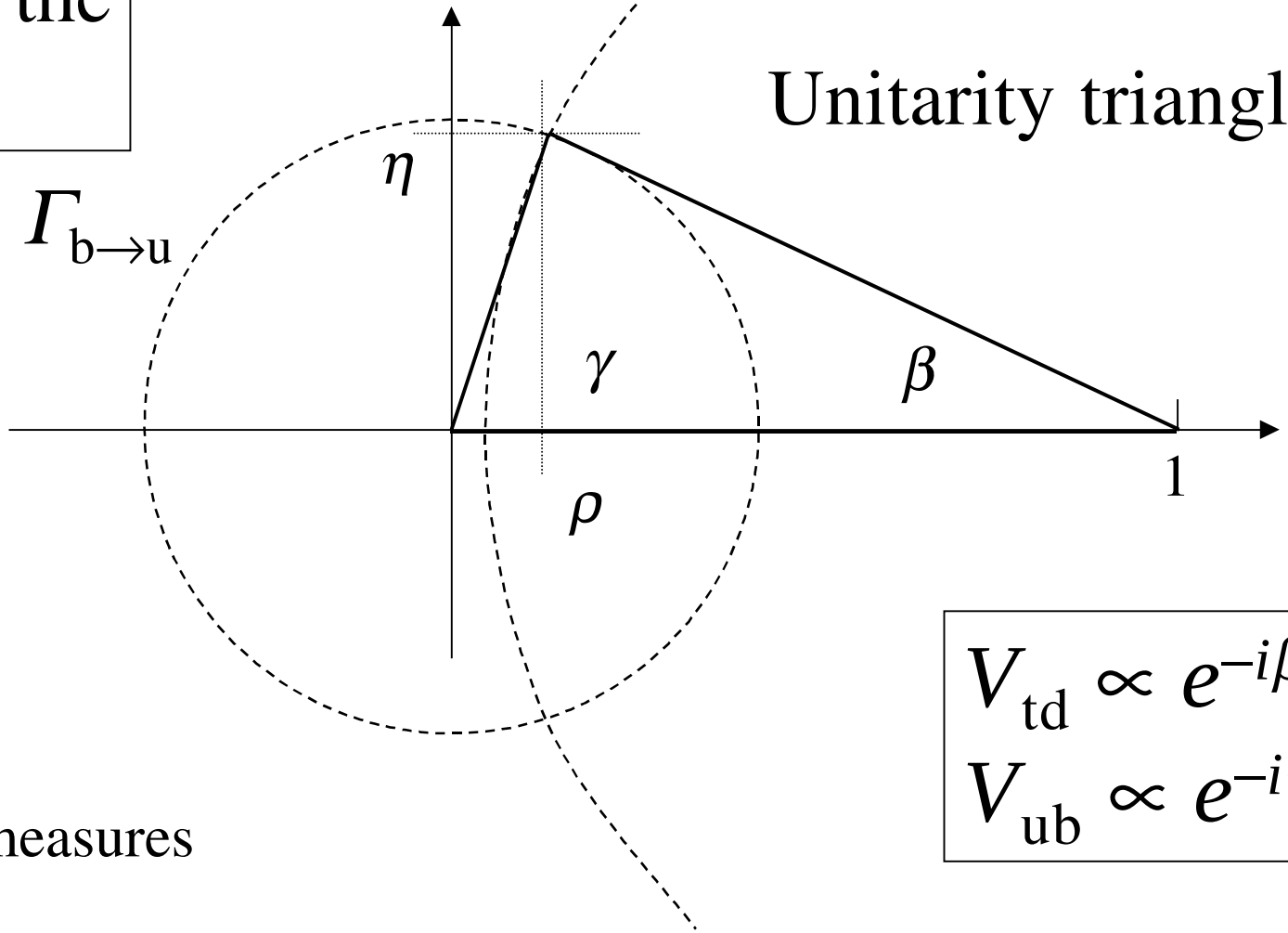
$$\arg V_{cb} = 0,\ \arg V_{ub} = -\gamma,\ \arg V_{td} = -\beta,\ \arg V_{ts} = \pi + \delta\gamma$$

From the neutral kaon system $\eta > 0$

β and γ are defined by the sides

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

Unitarity triangle



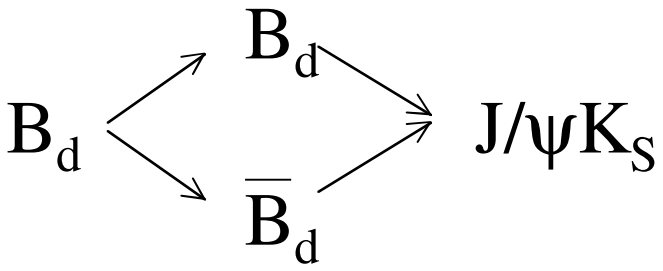
$$V_{td} \propto e^{-i\beta}$$
$$V_{ub} \propto e^{-i\gamma}$$

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

CP violation in

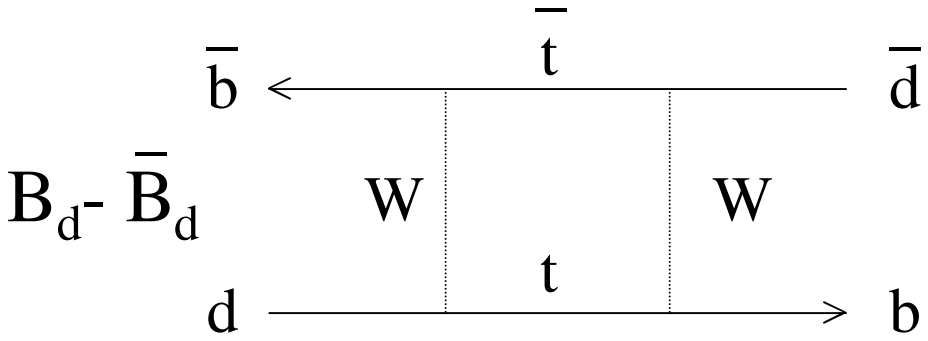
$B_d \to J/\psi\, K_S$ v.s. $\bar{B}_d \to J/\psi\, K_S$

measures the phase of V_{td}, i.e. β

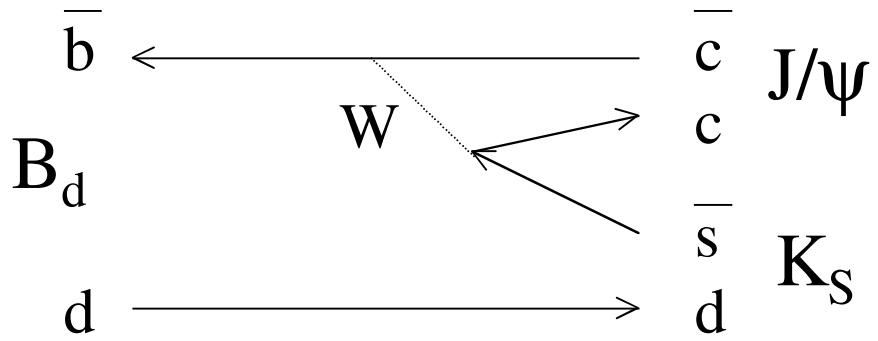


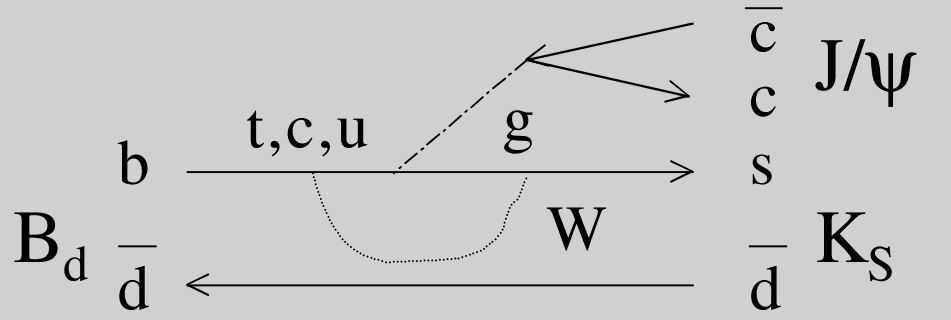
compare two β measurements = consistency test

$H_{B\text{-}\bar{B}} \propto (V_{tb}^{*}\, V_{td})^2 \propto e^{2i\beta}$



$A_{B\to J/\psi Ks} \propto V_{cb}^{*}\, V_{cs} \propto e^{0i}$





Penguin effect is negligible

By 2005, CLEO, BaBar, BELLE, CDF, D0
and HERA-B will have

-accurate $|V_{ub}|$, $|V_{cb}|$ and

-β from CP violation in $B_d \rightarrow J/\psi\ K_S$ with $\sigma \sim 0.025$

(Expected range in the Standard Model: $0.3<\sin 2\beta<0.8$)

Possibilities are

a) There will be already a sign of new physics:

-precision measurements in different decay modes in order to pin down the details of new physics.

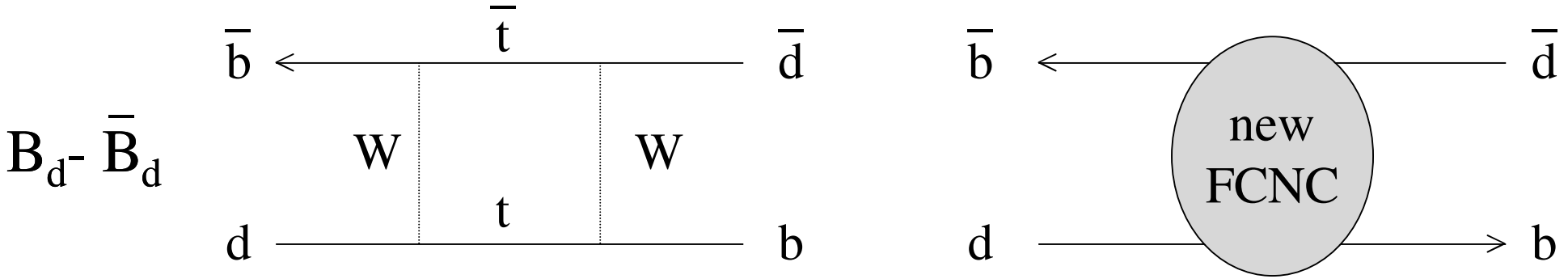
b) Measurements look "consistent" with the Standard model.

-what could happen?

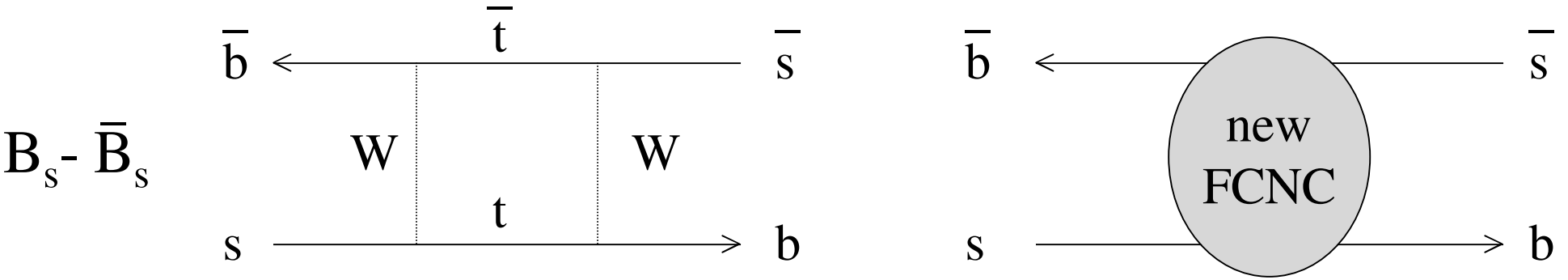
Let's make the following "interesting" scenario.

A model for new physics

$$H_{B\text{-}\bar{B}} \propto \left[\{(1-\rho)^2 + \eta^2\} + r^2_{db}\right] e^{2i(\beta + \phi_{db})}$$

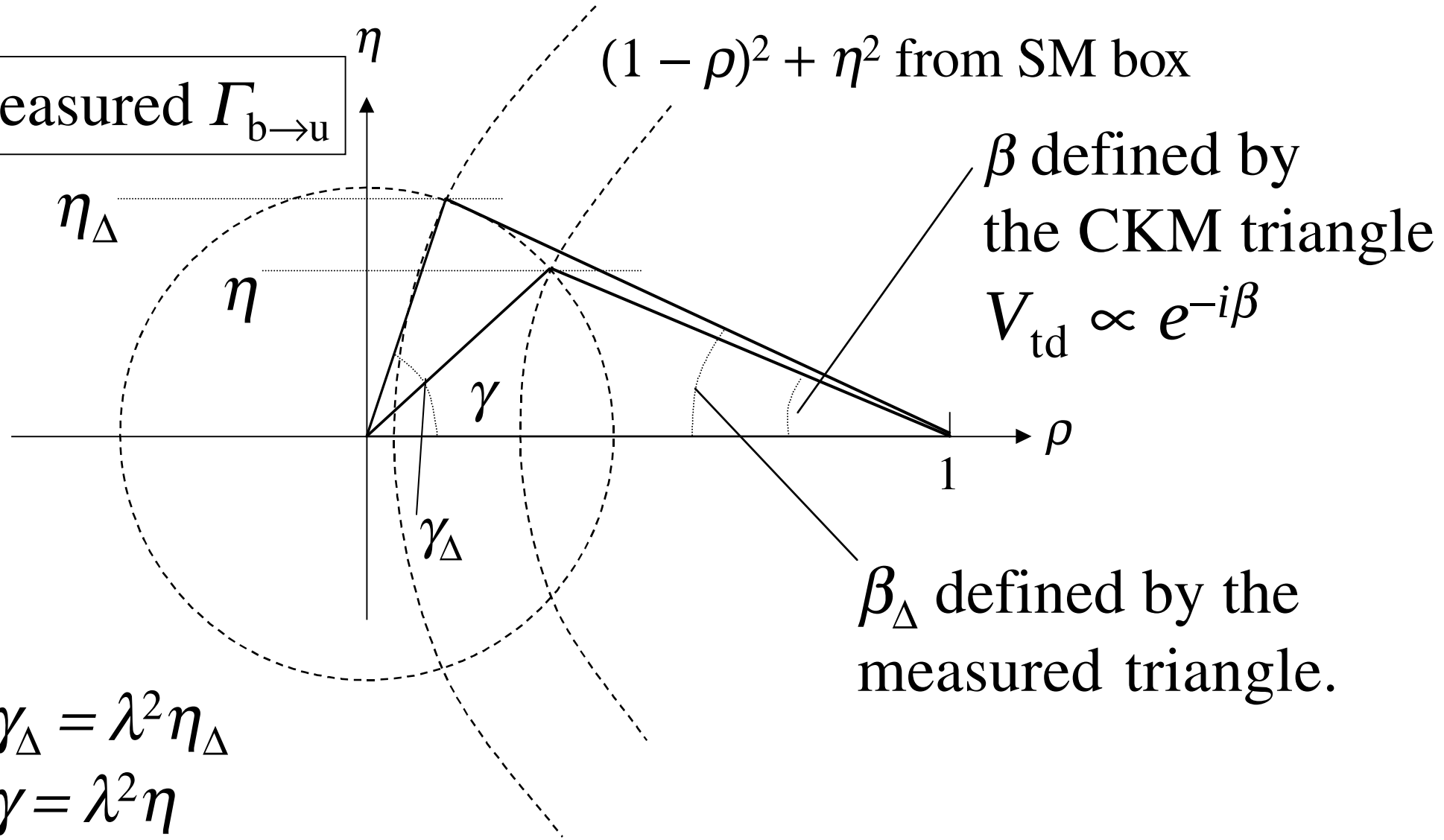


$$H_{B\text{-}\bar{B}} \propto \left[\ \lambda^{-2} + r^2_{sb}\ \right] e^{-2i(\delta\gamma + \phi_{sb})}$$



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

Measured $\Gamma_{b\rightarrow u}$



$\delta\gamma_\Delta = \lambda^2\eta_\Delta$

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

CP violation in

$$B_d \to J/\psi\, K_S \text{ v.s. } \bar{B}_d \to J/\psi\, K_S$$

$$B_d\text{-}\bar{B}_d \propto e^{2i(\beta + \phi_{db})} \quad B_d \to J/\psi\, K_S \propto V_{cb}^{*} V_{cs} \propto e^{0i}$$

measures $\beta_{J/\psi K} = \beta + \phi_{db}$

If the model is such that numerically $\phi_{db} \approx \beta_\Delta - \beta$

"$\beta_{J/\psi K} = \beta_\Delta$"

CP measurement and triangle measurements agree each other.

$\to$ Look consistent with the Standard Model!

BABAR and BELLE may have difficulty to access γ+β

CP violation in $B_d \to \pi^+ \pi^-$

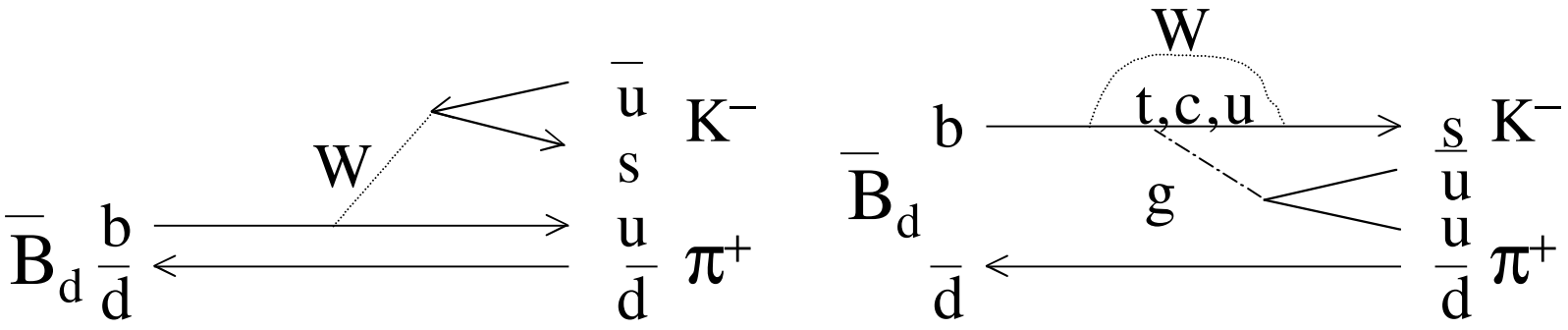
-experimental problem

small branching fraction < 8×10^{-6} (CLEO)

-theoretical problem

large penguin contribution

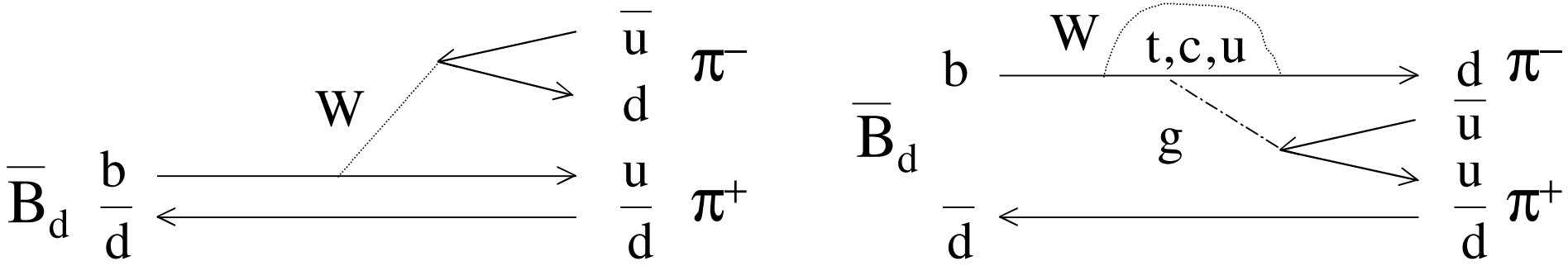
CLEO: $Br(\pi^+\pi^-) < Br(K^+\pi^-) \approx 1.4 \times10^{-5} \to$ penguin is large



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

Top penguin dominates in $B_d \to K\pi$ $\qquad$ $(P(m_t^2) < 1)$

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



$\mathrm{Br}(\pi^+\pi^-) < \mathrm{Br}(K^+\pi^-) \rightarrow$ penguin is large; $P(m_t) > \lambda\ (= 0.22)$

$V_{ud}^* V_{ub} \propto e^{-i\gamma}$

$$V_{td}^* V_{tb}\,[P(m_t^2) - P(m_c^2)] + V_{ud}^* V_{ub}\,[P(m_u^2) - P(m_c^2)] \propto [P(m_t^2) - P(m_c^2)]\, e^{i\beta} + [P(m_u^2) - P(m_c^2)]\, e^{-i\gamma}$$

Problem: tree and penguin have different phases

CP violation in $B_d \to \pi^+\pi^-$ is not really possible for
CDF and D0: no particle ID, HERA-B: not enough statistics

$B_d \to \pi^+\pi^-$ can be used only if we know penguin/tree.

A way out:

measure Br($\pi^+\pi^0$) and Br($\pi^0\pi^0$) $\to$ **not enough statistics**

CP violation in $B_d \to \rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$

- experimental problem
  - decay time dependent Dalitz plot analysis
    - $\to$ not enough statistics
- theoretical problem
  - assume $\pi^+\pi^-\pi^0$ to be always $\rho\pi$

CDF, D0 and HERA-B may be able to measure $\Delta m(\mathrm{B_s})$
If $\Delta m(\mathrm{B_s})/\Gamma_\mathrm{b}$ <20. Does this help? Not really.

$$\frac{\Delta m(\mathrm{B_d})}{\Delta m(\mathrm{B_s})} = \frac{A^2\lambda^4\left[(1-\rho)^2+\eta^2\right]+r(\mathrm{db})}{A^2\lambda^2+r(\mathrm{sb})}$$

-It helps to reduce hadronic uncertainties:

$f_\mathrm{B}{}^2B$ (~20% error, lattice calculation)

$f_\mathrm{B}{}^2B(\mathrm{B_d})/f_\mathrm{B}{}^2B(\mathrm{B_s})$ is much better known (~5% error)

-It is interesting if $\Delta m(\mathrm{B_s})$ is really large; new physics.

But it is out of their sensitivities.

How can LHC attack the problem?

1) Improve $\beta_{J/\psi K}$ measurement.

ATLAS, CMS: $\sigma \sim 0.02$/year

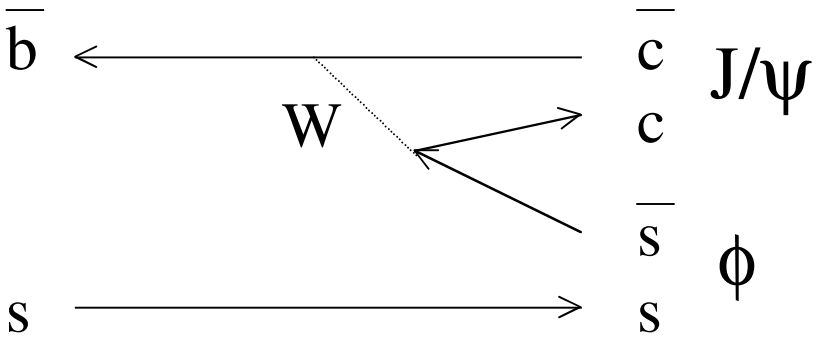
LHCb: $\sigma \sim 0.01$/year

2) Measure other angles using B_s

CP violation in $B_s \rightarrow J/\psi\phi$ measures $\delta\gamma_{J/\psi\phi} = \delta\gamma + \phi_{sb}$

$$B_s - \bar{B}_s \propto e^{-2i(\delta\gamma + \phi_{sb})}$$

$$B_s \rightarrow J/\psi\,\phi \propto V_{cb}^{*} V_{cs} \propto e^{0i}$$



Penguin effect is negligible

If the model is such that numerically $\phi_{sb} \approx \delta\gamma_{\Delta} - \delta\gamma$

"$\delta\gamma_{J/\psi\phi} = \delta\gamma_{\Delta}$"

It will still look consistent.

J/ψ φ is a easy final state to reconstruct

if the decay time resolution is good enough!

ATLAS, CMS: σ ~ 0.03/year

LHCb:σ ~ 0.01/year

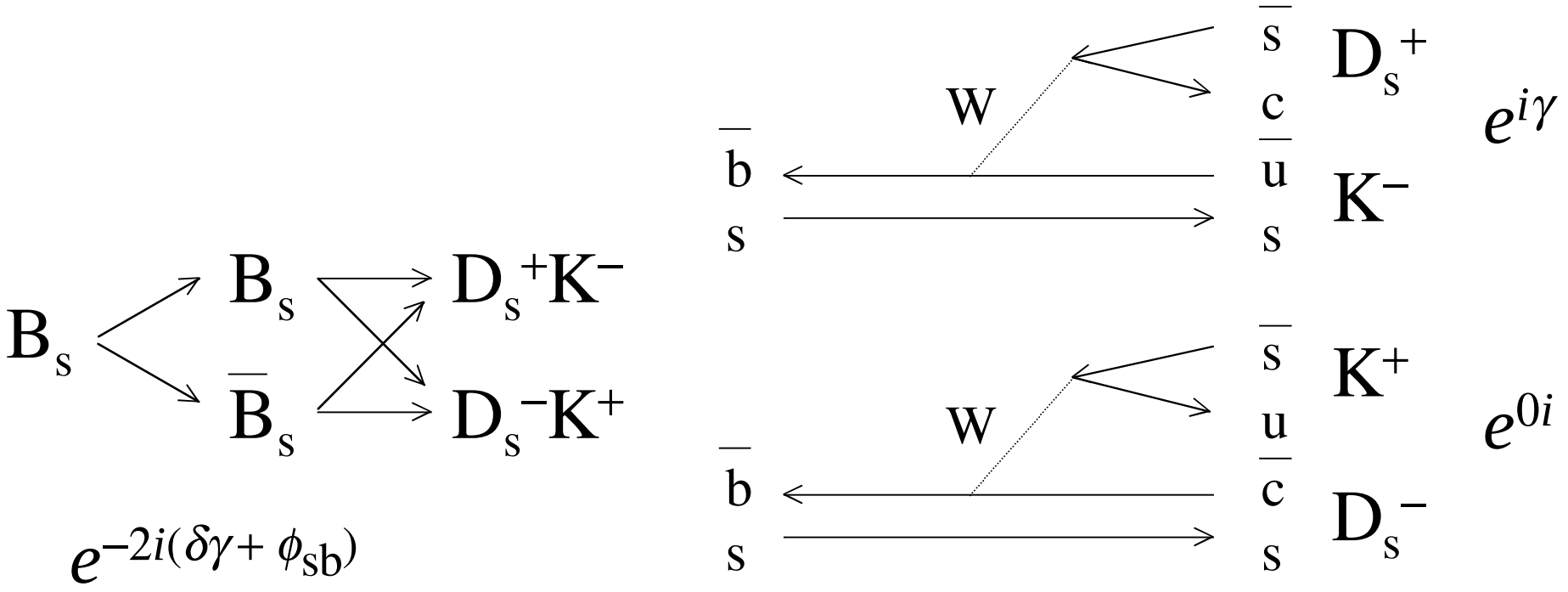
*additional complication: J/ψ φ
- CP = +1 (l = 0, 2)
- CP = −1 (l = 1)

-angular momentum configuration has to be studied-

We need to do much more!

CP violation in

$B_s \to D_s^+ K^-, D_s^- K^+ \qquad \bar{B}_s \to D_s^+ K^-, D_s^- K^+$



+ c.c.

measures $\gamma_{DsK} = \gamma - 2\delta\gamma - 2\phi_{sb} \equiv \gamma - 2\delta\gamma_{\Delta}$

There is no more freedom left to make

$\gamma_{DsK} = \gamma_{\Delta} - 2\delta\gamma_{\Delta}$

No hadronic uncertainty

Measured γ_{DsK} disagrees with what one expects from the triangle relation $\Rightarrow$ New Physics

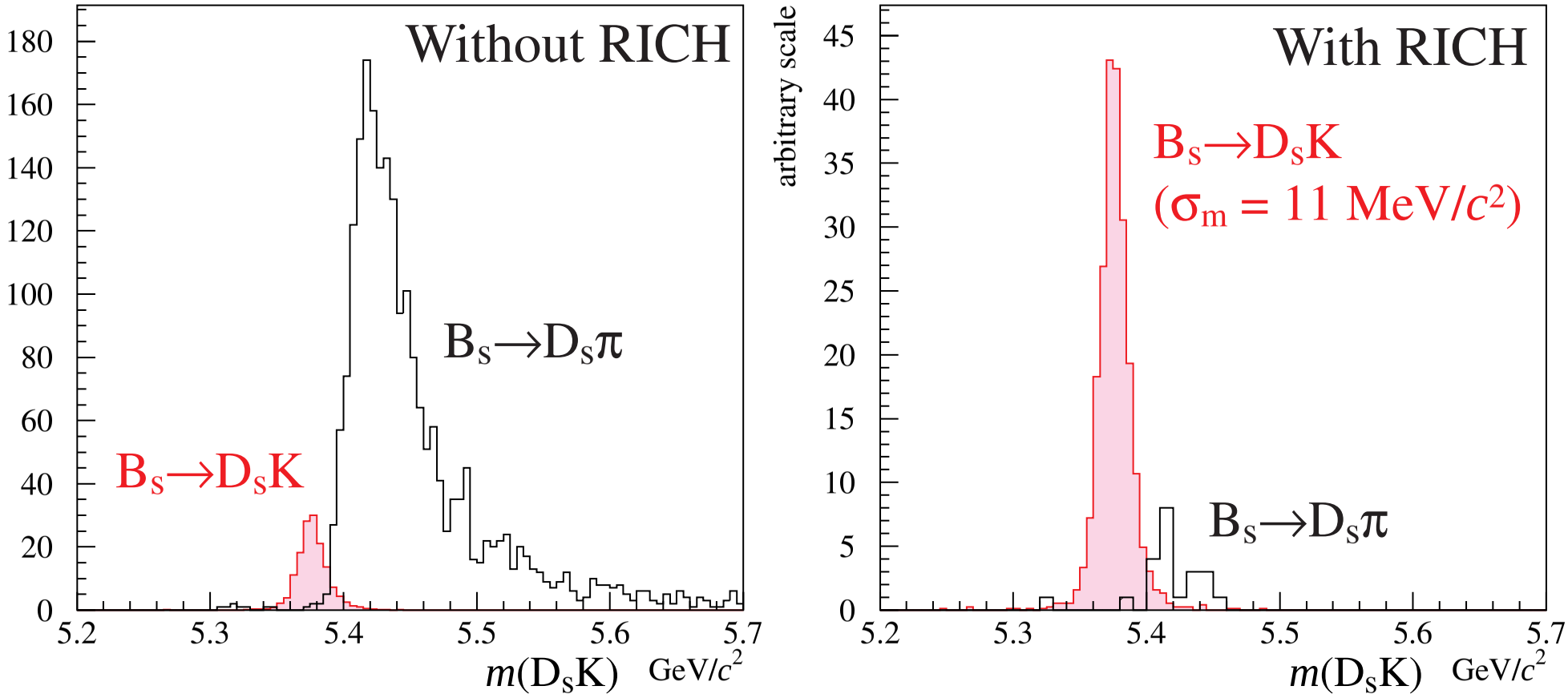
What are experimentally needed?

- decay time resolution
- K/π separation

$B_s \to D_s K$

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

Importance of particle identification and mass resolution



3) Further CP violation studies with B_d which require very high statistics (difficult for BaBar and Belle).

$B_d \to D^0 K^{*0}$, $\overline{D}^0 K^{*0}$, $D_{1,2} K^{*0}$

$\overline{B}_d \to D^0 \overline{K}^{*0}$, $\overline{D}^0 \overline{K}^{*0}$, $D_{1,2} \overline{K}^{*0}$

measure γ.

$B_d \to D^{*+}\pi^-$, $D^{*-}\pi^+$ $\qquad$ $\overline{B}_d \to D^{*+}\pi^-$, $D^{*-}\pi^+$

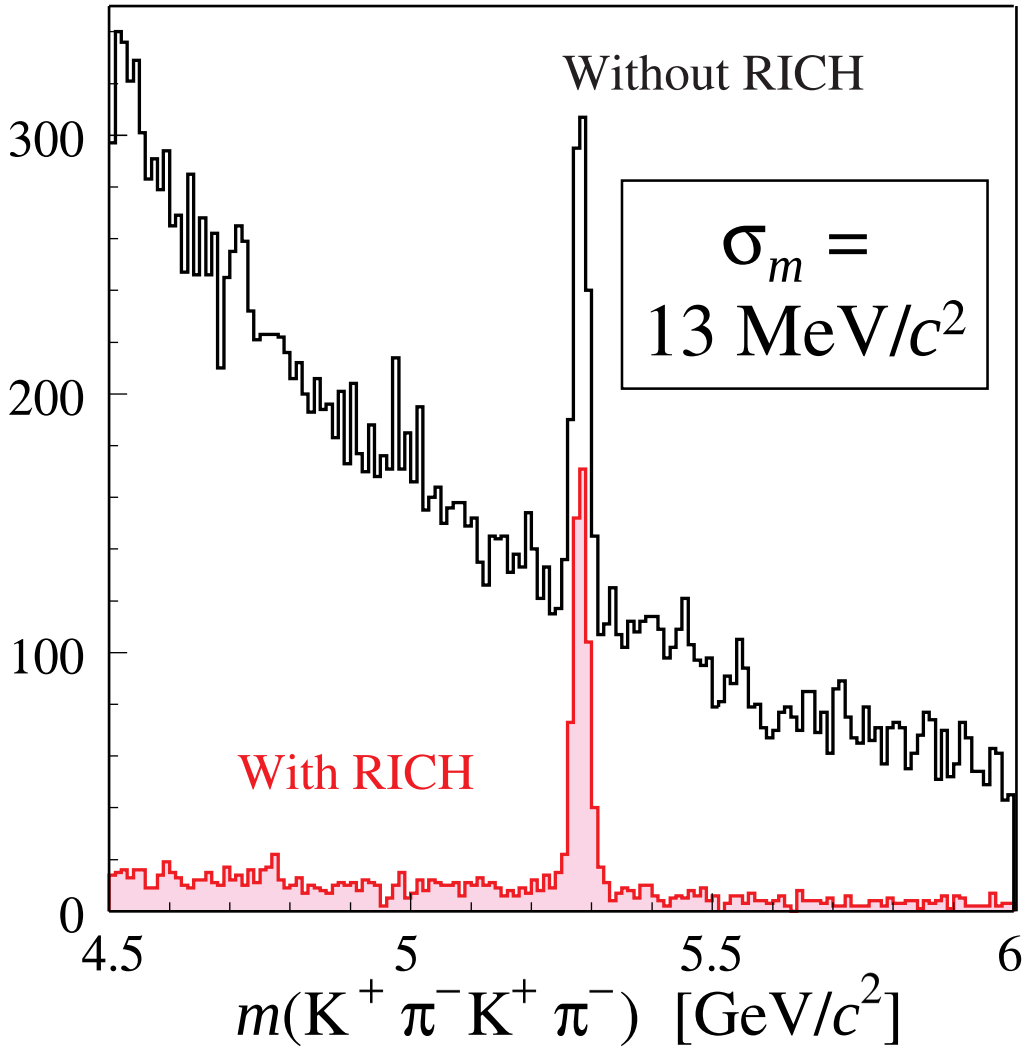
measure $2\beta + \phi_{db} + \gamma$; $\neq 2\beta_\Delta + \gamma_\Delta$ i.e. inconsistent

No hadronic uncertainties.

Experiment requires: $\qquad$ K/π separation

hadron trigger

Very small visible branching fractions
(10^{-7}~10^{-8})
Importance of particle identification



With signal events

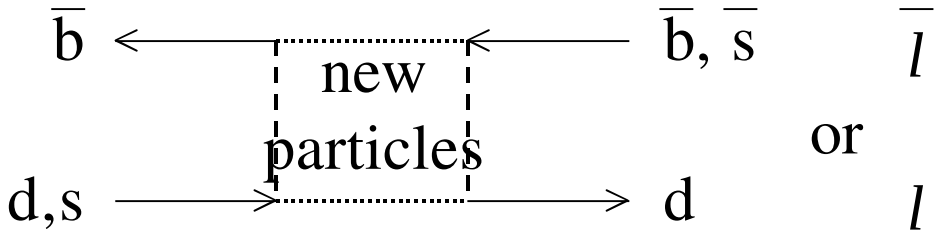
More generally new physics can appear in

$\Delta b = 1$ process

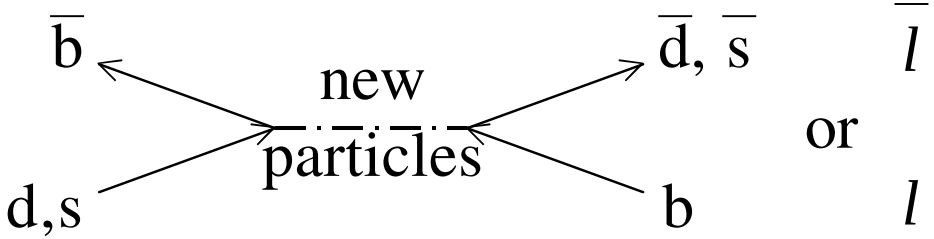
through penguin

$\Delta b = 2$ process

through box



through tree



CP violation must be studied in

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

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

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

$B_{d,s}$ decays via box

Experimental conditions are

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

Rapid B_s oscillations $\rightarrow$ decay time resolution

Including multi-body hadronic final states $\rightarrow$ particle ID
mass resolution

$\rightarrow$ **LHCb experiment**

An example of shopping list:	LHCb	ATLAS/CMS
$B_d \to J/\psi K_S$	✓	✓
$B_s \to J/\psi \phi$	✓	✓
$B_s \to D_S K$	✓	✗ (PID)
$B_d \to DK^*$	✓	✗ (PID,Trigger)
$B_d \to D^*\pi$	✓	✗ (PID)
$B_d \to \pi\pi$	✓	✗ (PID)
$B_d \to K\pi$ ($\not{CP}$ in gluonic penguin)	✓	✗ (PID)
$B_d \to \rho\pi$ (BaBar 160 events, LHCb 670 events)	✓	?
$B_s \to K^*\gamma$ ($\not{CP}$ in radiative penguin)	✓	?
$B_s \to K^* l^+ l^-$ ($\not{CP}$ in radiative penguin)	✓	✓
B_s oscillations, x_s up to	75	38
$B_s \to \mu^+\mu^-$	✓	✓

V) Conclusions

1) New results on CP violation in the neutral kaon system will be available soon (~2000) and may indicate that the Superweak model is not valid.

2) B-meson system will provide a rich field for CP violation studies.

3) BaBar, Belle, CDF, D0 and HERA-B will observe CP violation in $B \rightarrow J/\psi K_S$ (>2000) if CP violation is largely due to the standard model.

4) In order to look for new physics, a dedicated experiment at LHC, i.e. LHCb is needed.