Title: Particle Physics 4

Date: Jun 08, 2006 10:30 AM

URL: http://pirsa.org/06060009

Abstract:

OUTLINE

- CP Violation in the SM is large, specially in the B system.

-Why we expect new CP violation sources

- CP violation and New Physics

-Where and how to look for New Physics through study of CPV .

- Deviations from the SM

- $B \to \phi K_s$, $B \to \pi K$ and others

- Implications for collider physics(LHC)

-Conclusions

OUTLINE

- CP Violation in the SM is large, specially in the B system.

-Why we expect new CP violation sources

- CP violation and New Physics

-Where and how to look for New Physics through study of CPV .

- Deviations from the SM

- $B \to \phi K_s$, $B \to \pi K$ and others

- Implications for collider physics(LHC)

-Conclusions

OUTLINE

- CP Violation in the SM is large, specially in the B system.

-Why we expect new CP violation sources

- CP violation and New Physics

-Where and how to look for New Physics through study of CPV .

- Deviations from the SM

- $B \to \phi K_s$, $B \to \pi K$ and others

- Implications for collider physics(LHC)

-Conclusions

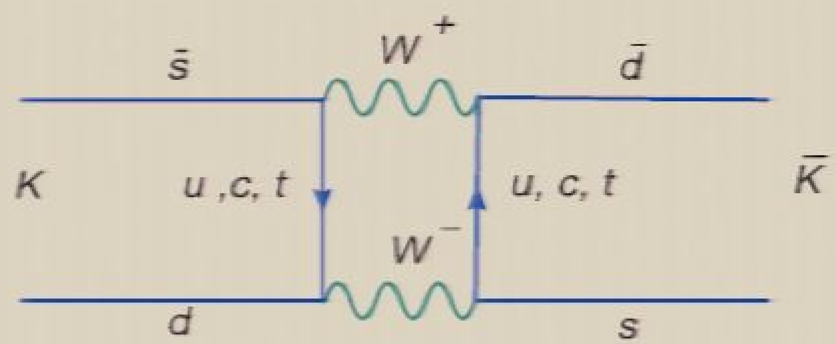
CPV in the SM

- CPV in the SM comes from charged current interactions:

$$\begin{pmatrix} u & c & t \end{pmatrix} V_{CKM} \begin{pmatrix} d \\ s \\ t \end{pmatrix} W$$

- In the SM, CP violation is due to a complex phase in the CKM matrix:

$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



where $\lambda = 0.22$

$\epsilon \sim$ phase of $K - \bar{K}$ mixing $\sim i\eta A^2\lambda^4 \sim 10^{-3}\eta \Rightarrow \eta \sim 1.$

Why is B Special?

In the SM, CP violation is due to a complex phase in the CKM matrix:

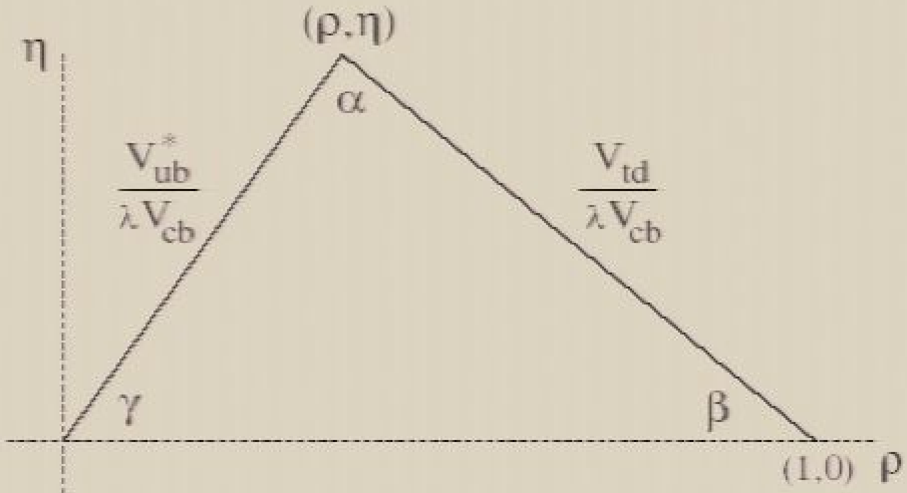
$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where $\lambda = 0.22$.

Note: (i) relative sizes of CKM matrix elements, (ii) large phases occur only in corners: V_{ub} and V_{td}.

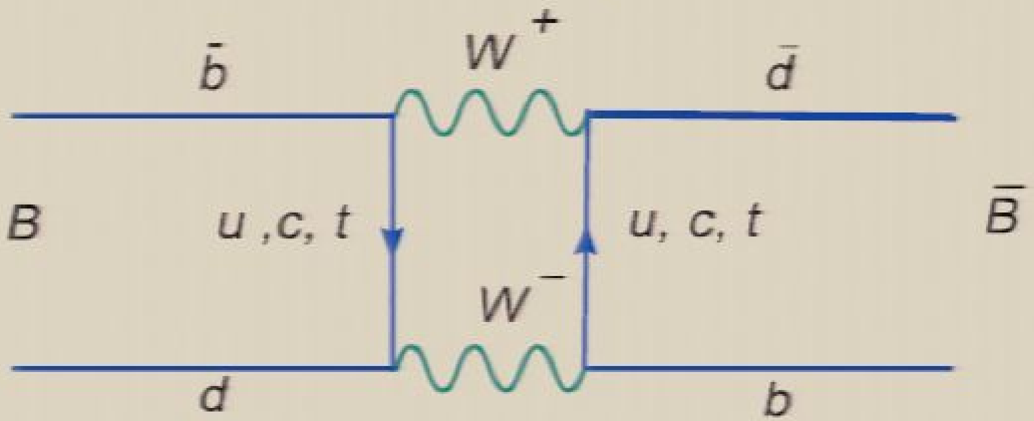
Unitarity Triangle:

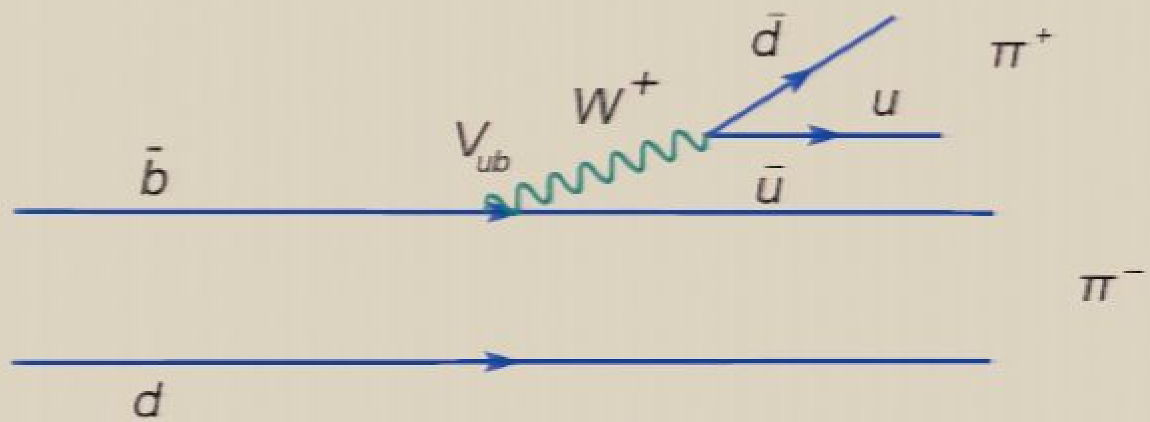
$$V_{CKM} \simeq \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & |V_{ts}| & |V_{tb}| \end{pmatrix}$$



- $Arg[V_{td}] \sim \eta \sim O(1)$- Large
- $Arg[V_{ub}] \sim \eta \sim O(1)$- Large

These elements can be probed in B decays:





- $B - \bar{B} \sim (V_{td})^2 \sim e^{-2i\beta} \quad 2\beta \sim 43^0$

$Arg[V_{ub}] = \gamma \sim 60^0$ - CPV in the B system is large in the SM.

New Phases from New Physics

- CPV in the SM is large.

- All CPV $\propto \eta$

- V_{CKM} is unitary: $V_{CKM}^{\dagger} V_{CKM} = 1 \Rightarrow$ 3 angles and 6 phases.

- Weak Interactions couple only to LH quarks: Can reabsorb 5 phases in quark field definitions
- Only one weak phase η.

- Consider a NP scenario, e.g. Left-Right Symmetric Models:

- New phases associated with the RH mixing matrix, V_R.

- Can no longer absorb the phases of V_R: 6 new phases.

Bottomline

- CPV in the SM is large: CP is not a symmetry or approximate symmetry of Nature

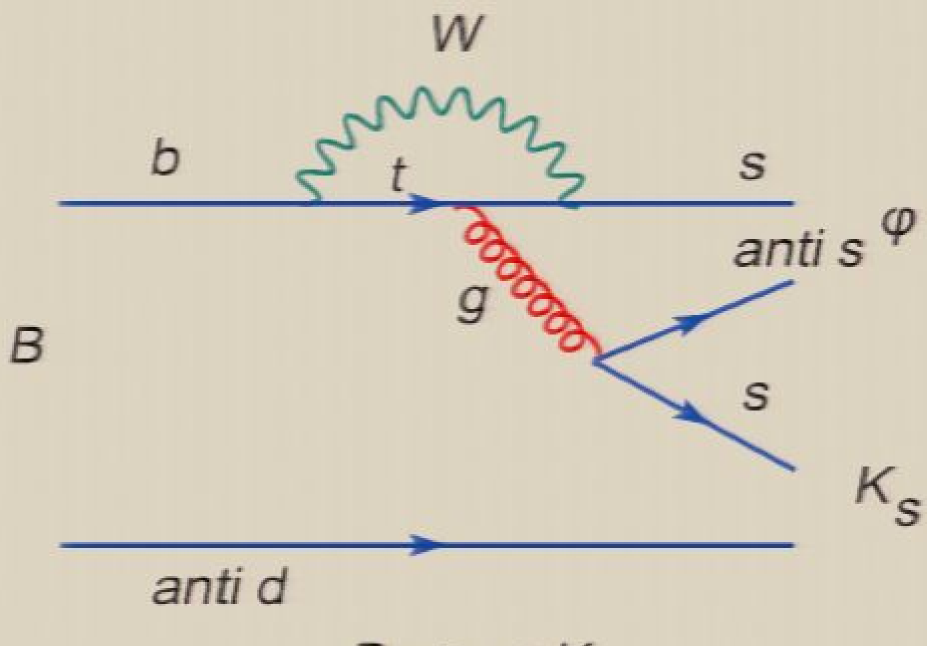
- Any New Physics will have new CP phases.

- No reason to expect the new CP phases are small $\Rightarrow$ it is likely we will see deviations from the SM.

- Study of CPV is a good place to look for NP.

NP- Where?

FCNC are very rare in SM and only arise as quantum corrections or Loops. E.g. $B \to \phi K_s$ ($b \to sg$)



Beyond the SM FCNC may occur at tree level or loops and compete with the SM contribution.

Hence these decays are excellent probes of beyond the SM physics.

NP-How: Direct CP Violation and NP

- Consider the decay $B \to f (f \equiv \phi K_s)$ and the CP conjugate process $\bar{B} \to \bar{f}$

Define **direct** CP asymmetry:

$$a_{dir}^{CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \sim \sin\phi \; ,$$

where ϕ is the CP violating weak phase

- Suppose we have a decay $B \to f$:

$$\begin{aligned} A(B \to f) &= Ae^{i\phi} \\ A(\bar{B} \to \bar{f}) &= Ae^{-i\phi}. \end{aligned}$$

$a_{dir}^{CP} \sim |A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2 = 0$

- Many decays in SM are dominated by a single amplitude and hence a measurement of non zero a_{dir}^{CP} violation is a clear signal of new physics. No hadronic uncertainty involved!

Direct CP Violation

Non zero direct CP violation requires interference of 2 amplitudes. Consider the decay $B \to f$. Suppose

$$A(B \to f) = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} ,$$
$$A(\bar{B} \to \bar{f}) = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} .$$

Hence **direct** CP asymmetry:

$$a_{dir}^{CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = -\frac{2A_1 A_2 \sin\Phi \sin\Delta}{A_1^2 + A_2^2 + 2A_1 A_2 \cos\Phi \cos\Delta} ,$$

where $\Phi \equiv \phi_1 - \phi_2$ and $\Delta \equiv \delta_1 - \delta_2$.

Note: direct CP asymmetry depends on unknown strong phases. Cannot extract weak phase information (Φ) without hadronic input.

Mixing Induced CP Violation

There is another signal of CP violation. Use B^0–$\bar{B}^0$ mixing. Choose final state f accessible to both B^0 and $\bar{B}^0$. (Simplest is CP eigenstate.) Then $B^0 \to f$ and $B^0 \to \bar{B}^0 \to f$ interfere. This leads to indirect or mixing induced CP violation.

Aside: requires large B^0–$\bar{B}^0$ mixing. Large mixing measured in 1987. One of the most important discovery in particle physics in the last 20 years.

Size of mixing was great surprise. $\Delta M_d \sim m_t^2$, as it was expected that $m_t \sim 10$ GeV! Experiment: $m_t/M_W \sim 2$.

Large B^0–$\bar{B}^0$ mixing: get **indirect** CP asymmetry:

$$\Gamma(B^0(t) \to f) \sim B + a_{dir} \cos(\Delta M t) + a_{mix} \sin(\Delta M t)$$

with

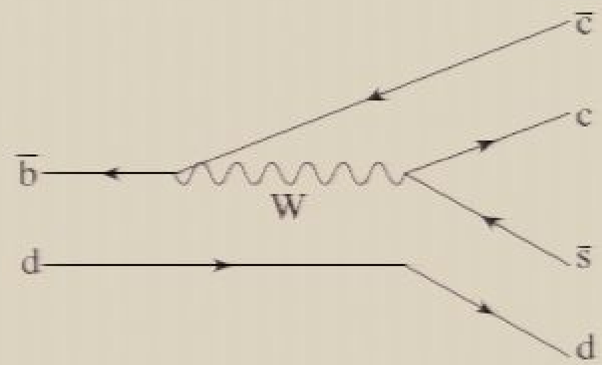
$$B \equiv \frac{1}{2}\left(|A|^2 + |\bar{A}|^2\right) \ , \ a_{dir} \equiv \frac{1}{2}\left(|A|^2 - |\bar{A}|^2\right) \ , \ a_{mix} \equiv \mathrm{Im}\left(e^{-2i\beta} A^* \bar{A}\right) \ .$$

Point: $\Gamma(B^0(t) \to f)$ gives 3 measurements.

Note: if there is only a single decay amplitude in $B^0 \to f$, i.e. $A_2 = 0$, then $a_{dir} = 0$, but $a_{mix} \neq 0$. This is the most interesting case, since all dependence on hadronic physics cancel.

Idea: measure α, β, γ in ways independent of strong phases.

β: $B_d^0(t) \to J/\psi K_s$. Decay dominated by tree $T' \sim V_{cb}^* V_{cs}$ (real).
Indirect CPV measures phase of B_d^0–$\bar{B}_d^0$ mixing: $2\,\arg(V_{tb}^* V_{td}) = -2\beta$.



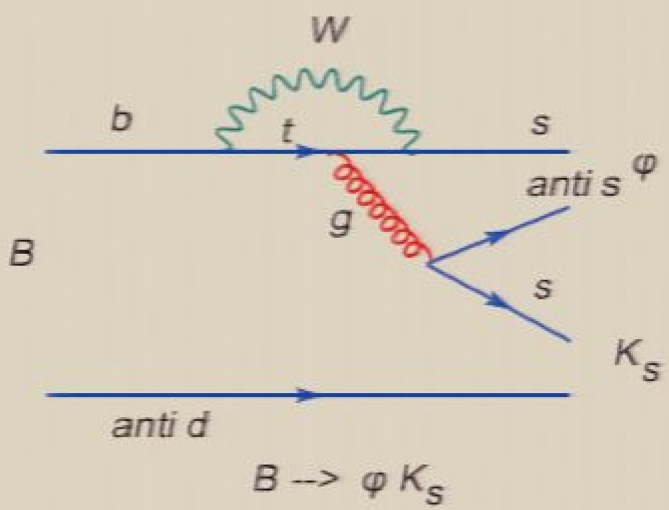
Both BaBar and Belle have measured this:

$$a_{mix}(B \to J/\psi K_s) = \sin 2\beta = 0.685 \pm 0.032 \ .$$

- This agrees with other independent measurements- confirms SM.

$B \to \phi K_s$- Mixing CP

$B \to \phi K_s$ is a pure penguin process dominated by single amplitude



$A(B \to \phi K_s) \approx (P_t - P_c) V_{tb} V_{ts}^*$ and so in SM

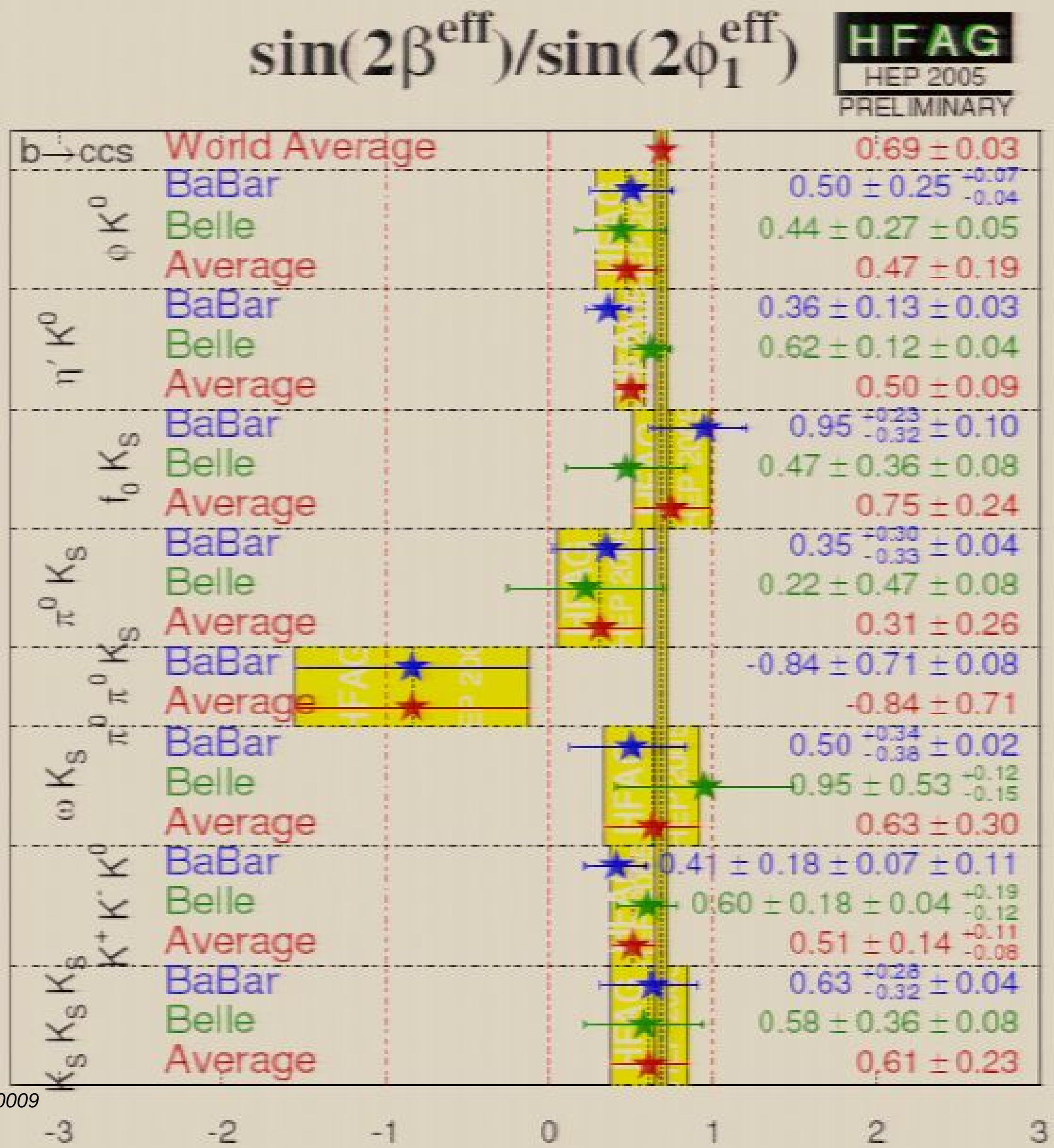
$$a_{mix}(B \to \phi K_s) = \sin 2\beta = 0.685 \pm 0.032 \ .$$

but Expt:$a_{mix}(B \to \phi K_s) = 0.47 \pm 0.19$.

There are many other final states, $\eta' K_s, \pi^0 K_s, f_0 K_s, ...$ for which $a_{mix} = \sin 2\beta$ in the SM.

Expt:$a_{mix}(combined) = 0.50 \pm 0.06$.

a_{mix} for $b \rightarrow s$ transitions



• Note that NP will effect different final states differently.

$$H_{NP} \sim \bar{s}\gamma_5 b \bar{s}\gamma_5 s$$

There can be a contribution to $B \to \eta' K_s$ but not to $B \to \phi K_s$ as

$$\bar{s}\gamma_5 b \to B \to K_s$$

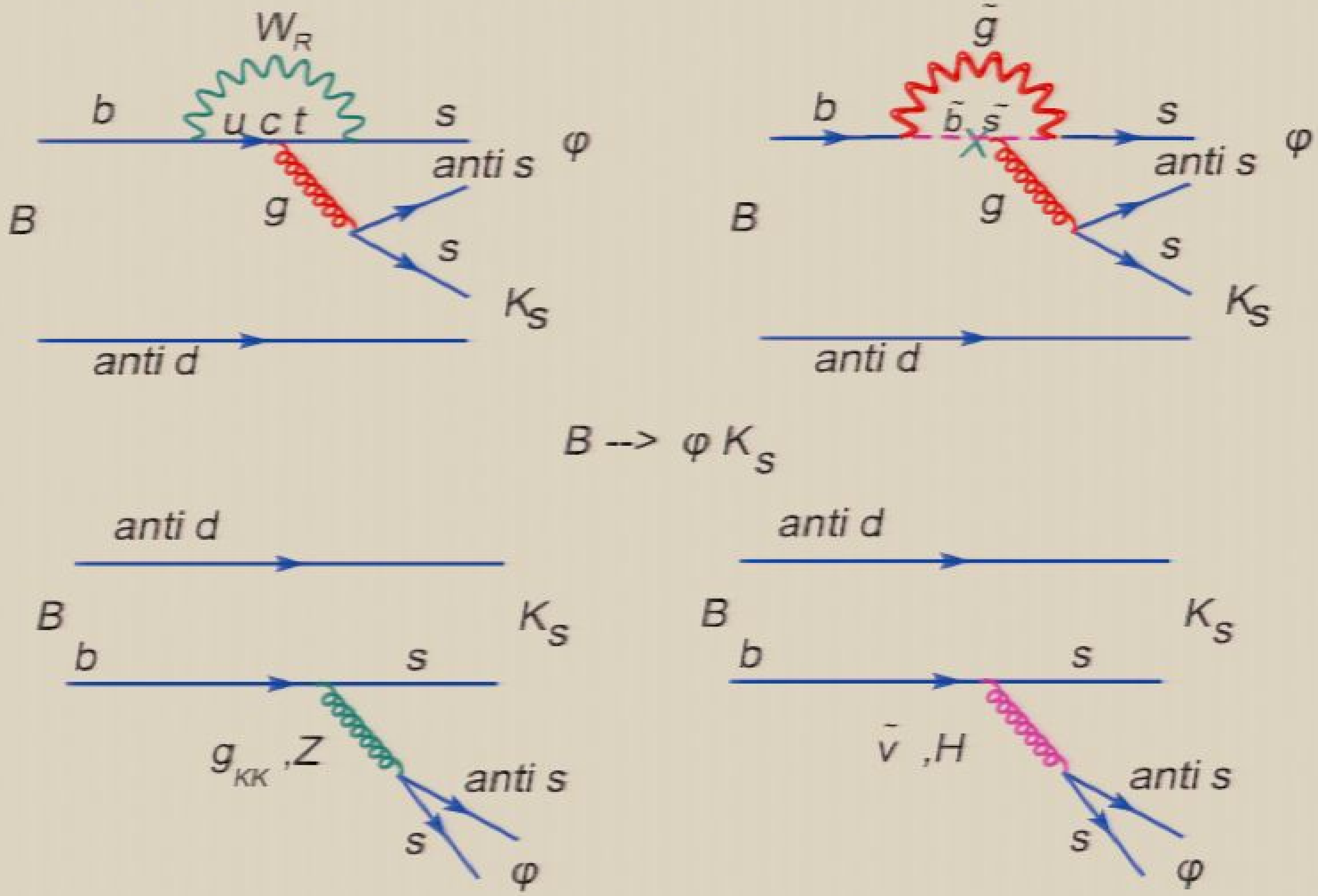
$$\bar{s}\gamma_5 s \to \eta'$$

but not ϕ.

• Hence by observing NP effects in different final states allows us to obtain information about the Lorentz structure of NP.

$B \to \phi K_s$-NP models

- Many NP models can produce deviation from the SM for $B \to \phi K_s$



NP in other Decays

- If there is NP in $B \to \phi K_s$ then it should show up in other places: In $B \to \phi K^*$ which is also a $b \to s\bar{s}s$ transition.

- Decays with $b \to s\bar{q}q$ quark transition with $q = u, d$ should be affected like $B \to K\pi, \rho K^*$..

- Models that generate new $b \to sg \to s\bar{q}q$ penguins(SUSY, LR, extra dim) will produce same effect for $q = u, d, s$.

- Models that generate new electroweak terms will in general couple to $q = u, d, s$ differently.

- Hence a combined NP fit to all the decays where there are deviations from SM will point to the flavour nature of NP.

$B \to K\pi$ puzzle

Table 1:

Mode	$BR(10^{-6})$	A_{dir}	A_{mix}
$B^+ \to \pi^+ K^0$	24.1 ± 1.3	-0.020 ± 0.034	
$B^+ \to \pi^0 K^+$	12.1 ± 0.8	0.04 ± 0.04	
$B_d^0 \to \pi^- K^+$	18.2 ± 0.8	-0.108 ± 0.017	
$B_d^0 \to \pi^0 K^0$	11.5 ± 1.0	-0.09 ± 0.14	0.31 ± 0.26

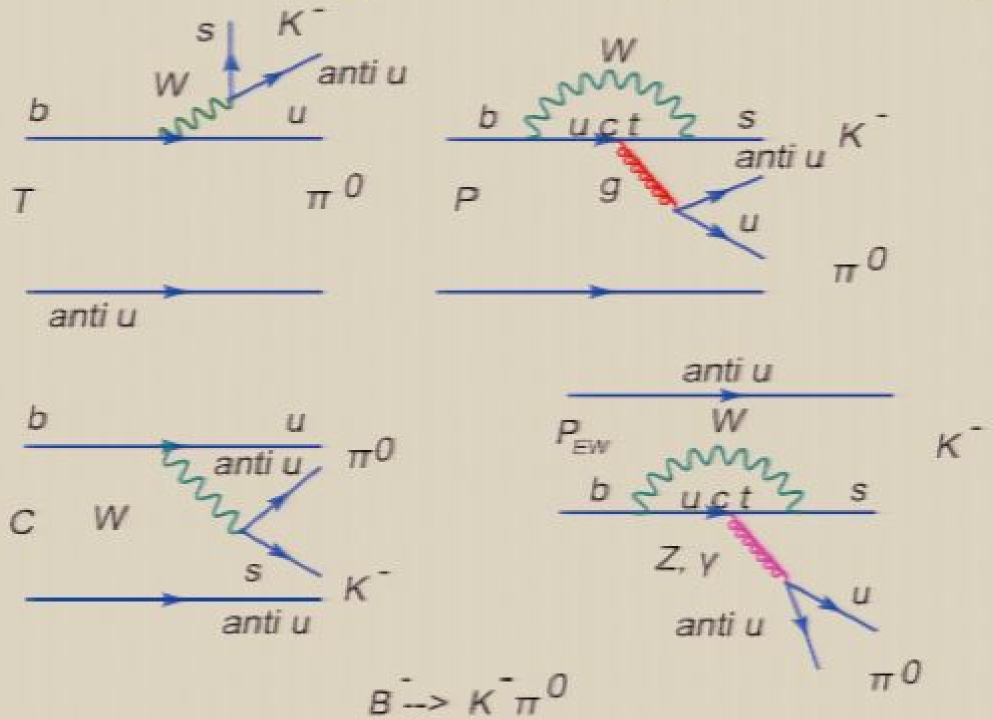
- Puzzles:

$A_{dir}(B^+ \to \pi^0 K^+) = A_{dir}(B_d^0 \to \pi^- K^+)$ using isospin if electroweak penguins(EWP) are neglected. In the SM the EWP are not big enough to explain the data. Need new EWP to explain the data.

$B_d^0 \to \pi^0 K^0$ is dominated by a single amplitude and so in SM $A_{dir} = 0$ and $A_{mix} = \sin 2\beta = 0.685 \pm 0.032$ in disagreement with data. Again need new EWP to explain the data as EWP affect final states with π^0

$B \to K\pi$- SM

- In the SM the amplitudes for the four decays can be related by isospin.
The four decays can be represented by the following amplitudes:



- $\frac{|T|}{|P|} = \frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\frac{c_1}{c_t} \sim 0.2 \quad \frac{|C|}{|P|} \sim \frac{1}{N_c}\frac{|T|}{|P|} \sim 0.04 \quad \frac{|P_{EW}|}{|P|} \sim 0.14$

$B \to K\pi$- SM

•We have 4 decays and 9 measurements, x^i_{exp}

$x^i_{exp} = f^i(|T|, |C|, |P|, |P_{EW}|, \delta)$. δ is the strong phase we can neglect $|C|$ and so we have four parameters.

A χ^2 fit to the data gives a poor fit- $\chi^2_{min}/d.o.f. = 15.6/5$ (0.8%) (hep-ph/0412086)

•Keep all amplitudes- no assumption about their sizes. W now have eight theoretical parameters: $|P|$, $|P_{uc}|$, $|T|$, $|C|$, γ, and three relative strong phases. With nine pieces of experimental data, we can still perform a fit, which is acceptable: $\chi^2_{min}/d.o.f. = 0.7/1$ (40%). In addition, we find $\gamma = 64^\circ$, consistent with independent measurements.

•However fit gives $|C/T| = 1.8$ about 10 times bigger than expected size. Such large $|C/T|$ are not seen in other decays including decays like $B \to \pi\pi$ which are related to $B \to K\pi$ by SU(3) symmetry- Puzzle

$B \to K\pi$ -NP

- NP in the $K\pi$ system can be parametrized in terms of 3 amplitudes, A_{comb}, A_C^u and A_C^d. (Datta and London)

- For models that produce new QCD penguins (LR models, SUSY with squark mixing, extra dim) the NP is isospin conserving and
$A_{comb} = 0, \quad A_C^u = A_C^d = A_{NP}$
We can now do a fit with
$x_{exp}^i = f^i(|T|, |P|, |P_{EW}|, \delta, A_{NP})$
We obtain a poor fit- NP is not from QCD penguins

- The best fit is obtained for models with
$A_{comb} = A_{NP}, \quad A_C^u \sim A_C^d \sim 0$
This can come from NP that is not isospin conserving.
This points to electroweak penguins(EWP) and to certain color structures of the NP operators- color allowed EWP.

Implications for Colliders

The important question: NP at what scale

The contribution of NP operators to meson mixing can be represented by higher dimension operators:

$$c_{NP}(\bar{d}q)^2/\Lambda^2$$

where $q = s, b$.
The measurement of the K and the B system tell us that $\Lambda \geq 100$ TeV !!! if $c_{NP} \sim 1$

Note $K(B)$ mixing in SM is small because of loop and small parameters like $\lambda = 0.22$

For e.g. B mixing $\sim$ Loop $\times V_{td}^2$ and $V_{td} \sim \lambda^3$

• But we expect $\Lambda \sim TeV$ to stabilize the Higgs mass!

• c_{NP} has the same suppression as in the SM so $\Lambda \sim$ TeV $\Rightarrow$ strong constraints on the flavour structure of NP expected to be revealed at LHC.
or
if $c_{NP} \sim 1$ then flavour physics probes physics at scales way beyond the reach of present or future experiments.

A New Physics Model

- Consider a 2 Higgs doublet model with 2-3 symmetry in the quark and lepton Yukawa coupling (Datta and O'Donnell). The 2-3 symmetry explains the large $\nu_\mu - \nu_\tau$ mixing.

- The breaking of the 2-3 symmetry generates FCNC suppressed by $\frac{m_s}{m_b} \sim \lambda^2$ in the quark sector and FCNC suppressed by $\frac{m_\mu}{m_\tau}$ in the lepton sector. Low energy effective Hamiltonian is

$$H_{NP} = \frac{m_s}{m_b} \frac{1}{m_H^2} \left[\bar{s}\gamma_A b \bar{q}\gamma_A q + .. \right]$$

$\gamma_A = (1 \pm \gamma_5)$ and $q = d, s$.

- Predicts small effect in $B \to \phi K_s$ but large effect in $B \to \eta' K_s$. Can explain the ϕK^*, $K\pi$ and ρK^* puzzle for $m_H \sim$ TeV.

Conclusions

CP Violation is a good place to look for and measure new physics

There are **many** signals of new physics(puzzles) in measurements of CP violation in B decays- $B \to \phi K_s, \phi K^*, \eta' K_s, K\pi, \rho K^* \ldots.$

Combined fit to the NP signals point to a very specific structure of NP. This NP could arise through possible extension in the electroweak sector with extra Z or Higgs.

Hopefully, we will find NP at B factories, measure its parameters and (partially) identify it along with the LHC. Coming years should be very interesting for B physics and all flavour physics.