Flavour Physics and

CP Violation

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(III)

Lecture III

- Rare Decays:
  - Example: $B_{s,d} \to \mu^+\mu^-$
- How Could New Physics Enter in the Roadmap of Quark-Flavour Physics?
- What about New Physics in $B_d \to J/\psi K_{\rm S}$?
- Challenging the Standard Model through $B_d \to \phi K_{\rm S}$
- The $B \to \pi\pi, \pi K$ Puzzles & Rare K and B Decays:

$\to$ Example of a systematic strategy to search for NP

1. "$B \to \pi\pi$ puzzle"
2. "$B \to \pi K$ puzzle"
3. Connection with rare K and B decays

Rare B Decays $\rightarrow$ complement CP-B!

- These processes originate from $b \to s$ or $b \to d$ flavour-changing neutral current transitions, i.e. do *not* receive tree contributions in the SM:
  - $B \to K^* \gamma$, $B \to \rho\gamma$, ...
  - $B \to K^* \mu^+\mu^-$, $B \to \rho\mu^+\mu^-$, ...
  - $B_{s,d} \to \mu^+\mu^-$

  $\oplus$ inclusive decays: $b \to s\gamma$, $b \to s\ell^+\ell^-$, ...

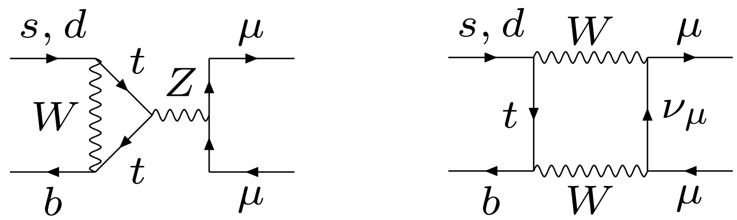
- Characteristic features in the SM:
  - Exhibit small branching ratios at the $10^{-4}...10^{-10}$ level.
  - Do not – apart from $B \to \rho\gamma$ – show sizeable CP violation in the SM.

Important probes to search for new physics!

[Many reviews: Ali; Buras; Greub; Hurth; Mannel; Misiak; ...]

A More Detailed Example: $B_{s,d} \to \mu^+\mu^-$

- Originate from Z penguins and box diagrams in the SM:



- Belong to the cleanest decays in the field of rare B decays:
  - Only the matrix element of a quark current is required: f_{B_q}
  - NLO QCD corrections were calculated.
  - Long-distance contributions are expected to be negligible.

[Buchalla & Buras (1993); Buchalla, Isidori & Rey (1997)]

- Branching ratios in the SM: $\rightarrow$ LHC

$$\text{BR}(B_s \to \mu^+\mu^-) = 4.1\times10^{-9}\left[\frac{f_{B_s}}{0.24\,\text{GeV}}\right]^2\left[\frac{m_t}{167\,\text{GeV}}\right]^{3.12}\left[\frac{|V_{ts}|}{0.040}\right]^2\left[\frac{\tau_{B_s}}{1.5\,\text{ps}}\right]$$

$$\text{BR}(B_d \to \mu^+\mu^-):\quad s \to d \quad\Rightarrow\quad \mathcal{O}(10^{-10})$$

[Details: Buras & R.F., hep-ph/9704376]

- Current experimental upper bounds:

$$\begin{aligned} \mathrm{BR}(B_s \to \mu^+\mu^-) &< 5.0\times 10^{-7} \quad \text{[D0 @ 95% C.L. ('04)]} \\ \mathrm{BR}(B_d \to \mu^+\mu^-) &< \begin{cases} 8.3\times 10^{-8} & \text{[BaBar @ 90% C.L. ('04)]} \\ 16\times 10^{-8} & \text{[Belle @ 90% C.L. ('03)]} \end{cases} \end{aligned}$$

- f_{B_s} and f_{B_d}, which can be fixed through non-perturbative methods or leptonic $B_{s,d}$ decays, would allow extractions of $|V_{ts}|$ and $|V_{td}|$.

- Relations:

$$\frac{\mathrm{BR}(B_d \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)} = \left[\frac{\tau_{B_d}}{\tau_{B_s}}\right]\left[\frac{M_{B_d}}{M_{B_s}}\right]\left[\frac{f_{B_d}}{f_{B_s}}\right]^2\left|\frac{V_{td}}{V_{ts}}\right|^2$$

$$\frac{\Delta M_d}{\Delta M_s} = \left[\frac{M_{B_d}}{M_{B_s}}\right]\left[\frac{f_{B_d}}{f_{B_s}}\right]^2 \underbrace{\left[\frac{\hat{B}_{B_d}}{\hat{B}_{B_s}}\right]}_{\text{"bag" parameters}} \left|\frac{V_{td}}{V_{ts}}\right|^2$$

$\Rightarrow$ complementary determinations of the UT side R_t! Moreover:

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \left[\frac{\tau_{B_s}}{\tau_{B_d}}\right]\left[\frac{\hat{B}_{B_d}}{\hat{B}_{B_s}}\right]\left[\frac{\Delta M_s}{\Delta M_d}\right]$$

... exhibits smaller theoretical uncertainties since $(f_{B_s}/f_{B_d})^2$ cancels and $\hat{B}_{B_s}/\hat{B}_{B_d} = 1$ up to tiny $SU(3)$-breaking corrections! [Buras (2003)]

How Could

New Physics

Enter?

Twofold Impact of NP: Effective Hamiltonians ...

- Possibility I: **Modification of the "Strength" of the SM Operators**

  – New short-distance functions, which depend on the NP parameters, such as masses of charginos, squarks, $\tan\bar{\beta} \equiv v_2/v_1$ in the MSSM.

  – The NP particles enter in new box and penguin diagrams, and are "integrated out", as the W and top (see Lecture I):

$$\underbrace{C_k(\mu = M_W) \to C_k^{\rm SM} + C_k^{\rm NP}}_{\text{initial conditions for RG evolution}}$$

  – The $C_k^{\rm NP}$ may also involve new CP-violating phases.

- Possibility II: **New Operators**

  – Operators, which are absent or strongly suppressed in the SM, may actually play an important rôle:

$$\underbrace{\{Q_k\} \to \{Q_k^{\rm SM}, Q_l^{\rm NP}\}}_{\text{operator basis}}$$

  – In general, new sources of flavour and CP violation.

Classification of New Physics

- Class A: **Models with *Minimal Flavour Violation***

  – The flavour-changing processes are governed by the CKM matrix, in particular no new sources for CP violation, and the only relevant operators are those present in the SM.

  – NP enters therefore only in the Wilson coefficients of the SM operators through new particles in loops.

  – The short-distance structure involves only 7 "master functions":

$$S(v),\ X(v),\ Y(v),\ Z(v),\ E(v),\ D'(v),\ E'(v).$$

  – Interesting tests of this scenario through correlations! Example:

$$\text{BR}(B_{d,s} \to \mu^+\mu^-) \propto Y_0(x_t)^2 \;\to\; Y(v)^2$$

$$\Delta M_{d,s} \propto S_0(x_t) \;\to\; S(v)$$

$\Rightarrow$ relations of the $B_{s,d} \to \mu^+\mu^-$ discussion are still valid!

  – Examples: THDM-II and the constrained MSSM if $\tan\bar{\beta}$ is not too large, models with one extra universal dimension.

- Class B:

  – In contrast to Class A, new operators arise. However, there are still no new CP-violating phases beyond the CKM matrix present.

  – Typical examples of new Dirac structures:

$$(\mathrm{V}-\mathrm{A})\otimes(\mathrm{V}+\mathrm{A}),\ (\mathrm{S}-\mathrm{P})\otimes(\mathrm{S}\pm\mathrm{P}),\ \sigma_{\mu\nu}(\mathrm{S}-\mathrm{P})\otimes\sigma^{\mu\nu}(\mathrm{S}-\mathrm{P}),$$

  which correspond to contributions to $B^0_{d,s}$–$\bar{B}^0_{d,s}$ mixing that become relevant in the MSSM with large $\tan\bar{\beta}$.

- Class C:

  – Differs from Class A through new CP-violating phases in the Wilson coefficients of the usual SM operators, but we have still negligible contributions from new operators:

$$\boxed{C_k^{\mathrm{NP}} \longrightarrow \text{complex!}}$$

  – Example: MSSM with $\tan\bar{\beta}$ not too large and with non-diagonal elements in the squark mass matrices.

- Class D:

  - Models with new complex phases, new operators and new flavour-changing contributions that are not described by the CKM matrix:

    $\longrightarrow$ general case, i.e. very involved!

  - Examples: multi-Higgs models with complex phases in the Higgs sector, general SUSY models, models with spontaneous CP violation and left–right-symmetric models.

- Class E:

  - The three-generation CKM matrix is not unitary:

    $\longrightarrow$ unitarity triangle does not close!

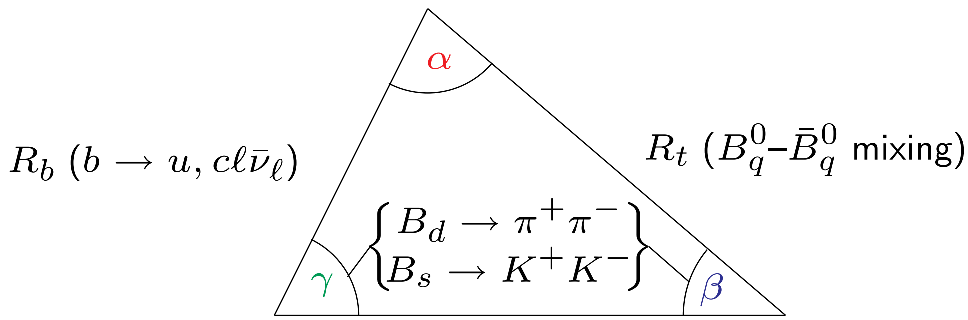
  - Example: models with four generations.

[Classification by A.J. Buras, hep-ph/0402191 $\longrightarrow$ more details]

A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$



$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\}$$ only trees

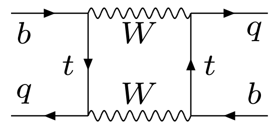
$$\left.\begin{array}{ll} B_d \to D^{(*)\pm}\pi^\mp : & \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : & \gamma + \phi_s \end{array}\right\}$$ only trees

- Moreover "rare" decays: $B \to K^*\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

New Physics $\Rightarrow$ **Discrepancies**

Avenues for New Physics to Manifest Itself ...

- B_q^0–$\overline{B_q^0}$ mixing:



  – Exchange of NP particles in boxes or new tree contributions:

$$\Delta M_q = \Delta M_q^{\rm SM} + \Delta M_q^{\rm NP} \quad (\to R_t)$$
$$\phi_q = \phi_q^{\rm SM} + \phi_q^{\rm NP} \quad (\to \mathcal{A}_{\rm CP}^{\rm mix})$$

  – B_d system: data from the B factories are available (see below).

  – B_s system: essentially unexplored $\to$ LHCb!

- Decay Amplitudes:

  – Typically *small* effects if SM tree processes play the dominant rôle.

  – Potentially *large* effects in the penguin sector through new particles in the loop diagrams or new contributions at the tree level.

  – Corresponding hints in the current B-factory data:

    ♢ $B_d \to \phi K_{\rm S}$: $(\sin 2\beta)_{\phi K_{\rm S}} \stackrel{?}{=} (\sin 2\beta)_{\psi K_{\rm S}}$

    ♡ $B \to \pi K$: puzzling pattern of certain branching ratios!

What About

New Physics in

$B_d \to J/\psi K_{\mathrm{S}}$?

A possible loop hole, but ...

- Lecture II: $\longrightarrow$ impressive agreement between $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi K_{\rm S})$ and the CKM fits for $\sin 2\beta$. Nevertheless, NP could still be hiding there...

- However, the key quantity is actually: $\boxed{\phi_d = \phi_d^{\rm SM} + \phi_d^{\rm NP} = 2\beta + \phi_d^{\rm NP}}$

- $(\sin\phi_d)_{\psi K_{\rm S}} = 0.725 \pm 0.037$: $\quad \Rightarrow \quad \underbrace{\phi_d = \left(46.5^{+3.2}_{-3.0}\right)^\circ}_{\text{CKM fits: } 40^\circ \lesssim 2\beta \lesssim 50^\circ} \vee \underbrace{\left(133.5^{+3.0}_{-3.2}\right)^\circ}_{\text{NP}}$

  [R.F. & Matias ('02); R.F., Matias & Isidori ('03)]

- Both solutions can be distinguished through the sign of $\cos\phi_d$:
  - $\cos\phi_d = +0.7 > 0 \;\Rightarrow\; \phi_d \sim 47^\circ \;\Rightarrow\;$ SM
  - $\cos\phi_d = -0.7 < 0 \;\Rightarrow\; \phi_d \sim 133^\circ \;\Rightarrow\;$ NP
  - BaBar (2004): $B_d \to J/\psi[\to \ell^+\ell^-]K^*[\to \pi^0 K_{\rm S}]$

    $$\cos\phi_d = 2.72^{+0.50}_{-0.79} \pm 0.27 \quad \longrightarrow \quad \text{favours the SM case!}$$
  - Follows also indirectly from $B_d \to D^{(*)\pm}\pi^\mp$ and $B \to \pi\pi, \pi K$ decays.

  [R.F. (2003); Buras, R.F., Recksiegel & Schwab (2004)]

- NP contributions at the decay amplitude level:

  – Have to compete with SM tree-diagram-like topologies, which play the dominant rôle in $B \to J/\psi K$ modes:

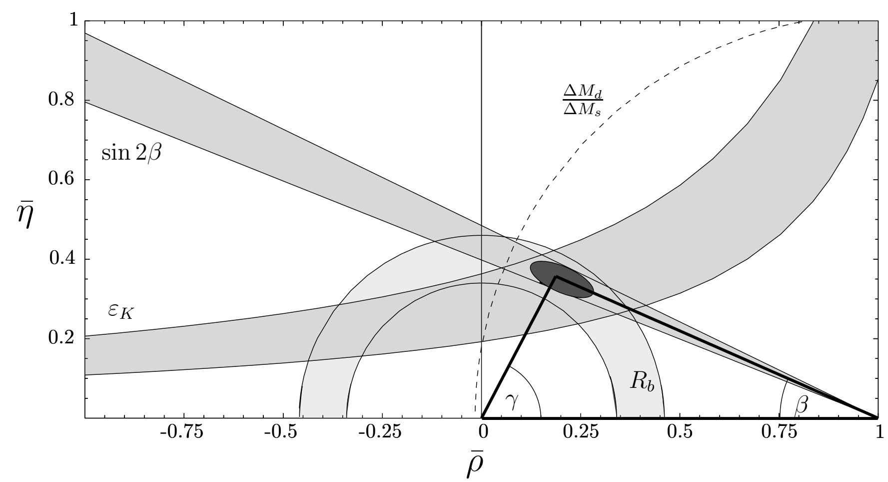
$$\Rightarrow \quad \boxed{\text{NP effects generically } \lesssim 10\%}$$

  – Could be detected through appropriate observables, which exploit also direct CP violation and the charged $B^\pm \to J/\psi K^\pm$ decays:

$$\Rightarrow \quad \boxed{\textit{no} \text{ indications in the current } B\text{-factory data ...}}$$

[R.F. & Mannel (2001)]

- Situation in the $\overline{\rho}$–$\overline{\eta}$ plane:



$$\Rightarrow \quad \boxed{\text{space for NP in } B_d^0\text{–}\overline{B_d^0} \text{ mixing is getting smaller and smaller ...}}$$

Challenging the

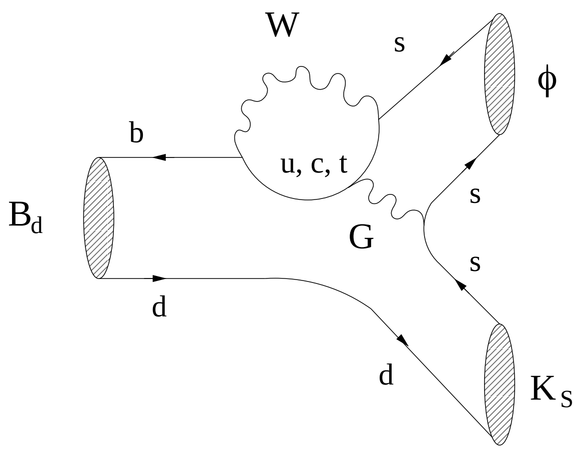
Standard Model

Through $B_d \to \phi K_{\rm S}$

$\longrightarrow$ Belle data have triggered excitement ...

CP Violation in $B_d \to \phi K_S$

- Decay in CP eigenstate: $\underbrace{(+1)}_{\phi} \times \underbrace{(+1)}_{K_S} \times \underbrace{(-1)^1}_{L=1} = -1.$



$\Rightarrow$ $B_d \to \phi K_S$ is a pure *penguin* process!

$\lambda_j^{(s)} \equiv V_{js}V_{jb}^* \quad (j \in \{u, c, t\})$

- Structure of the decay amplitude: $\left[K_S = \left(\overline{K^0} + K^0\right)/\sqrt{2}\right]$

$$A(B_d^0 \to \phi K_S) = \lambda_u^{(s)} A_P^u + \lambda_c^{(s)} A_P^c + \lambda_t^{(s)} A_P^t$$

- Unitarity of the CKM matrix: $\lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \;\Rightarrow$

$$A(B_d^0 \to \phi K_S) \propto \left[1 + \lambda^2 b e^{i\Theta} e^{i\gamma}\right] \qquad b e^{i\Theta} = \left(\frac{R_b}{1-\lambda^2}\right)\left[\frac{A_P^u - A_P^t}{A_P^c - A_P^t}\right] \sim \mathcal{O}(1)$$

- Consequently: $$\xi^{(d)}_{\phi K_S} = +e^{-i\phi_d}\left[\frac{1+\lambda^2 b e^{i\Theta} e^{-i\gamma}}{1+\lambda^2 b e^{i\Theta} e^{+i\gamma}}\right]$$

- Since the essentially "unknown" hadronic parameter $be^{i\Theta}$ enters in a *doubly Cabibbo-suppressed* way:

$$\begin{aligned}\mathcal{A}^{\rm dir}_{\rm CP}(B_d\to\phi K_S) &= 0+\mathcal{O}(\lambda^2)\\ \mathcal{A}^{\rm mix}_{\rm CP}(B_d\to\phi K_S) &= -\sin\phi_d+\mathcal{O}(\lambda^2)\end{aligned}$$

- On the other hand: $\mathcal{A}^{\rm mix}_{\rm CP}(B_d\to J/\psi\, K_S) = -\sin\phi_d + \mathcal{O}(\lambda^3) \quad \Rightarrow$

$$\boxed{\mathcal{A}^{\rm mix}_{\rm CP}(B_d\to\phi K_S) = \mathcal{A}^{\rm mix}_{\rm CP}(B_d\to J/\psi K_S)+\mathcal{O}(\lambda^2)} \quad (*)$$

[R.F. ('97); Grossman & Worah ('97); London & Soni ('97)]

- $B_d\to\phi K_S$ is a sensitive probe for new physics:
  - Dominated by QCD penguins
    [London & Peccei ('89); Deshpande & Trampetic ('90); ...]
  - EW penguins have a sizeable impact [R.F. ('94); Deshpande & He ('94)]
  - Model-independent NP analyses [R.F. & Mannel ('01)]

$\longrightarrow$ $\boxed{(*) \text{ could well be violated through NP!}}$

Experimental Picture of $B_d \to \phi K_S$

- Time evolution of the data:

  – LP '03:

$$\mathcal{A}_{CP}^{dir}(B_d \to \phi K_S) = \begin{cases} -0.38 \pm 0.37 \pm 0.12 & \text{(BaBar)} \\ +0.15 \pm 0.29 \pm 0.07 & \text{(Belle)} \end{cases}$$

$$\mathcal{A}_{CP}^{mix}(B_d \to \phi K_S) = \begin{cases} -0.45 \pm 0.43 \pm 0.07 & \text{(BaBar)} \\ +0.96 \pm 0.50^{+0.11}_{-0.09} & \text{(Belle)} \end{cases}$$

  – ICHEP '04:

$$\mathcal{A}_{CP}^{dir}(B_d \to \phi K_S) = \begin{cases} +0.00 \pm 0.23 \pm 0.05 & \text{(BaBar)} \\ -0.08 \pm 0.22 \pm 0.09 & \text{(Belle)} \end{cases}$$

$$\mathcal{A}_{CP}^{mix}(B_d \to \phi K_S) = \begin{cases} -0.50 \pm 0.25^{+0.04}_{-0.07} & \text{(BaBar)} \\ -0.06 \pm 0.33 \pm 0.09 & \text{(Belle)} \end{cases}$$

- On the other hand: $\boxed{\mathcal{A}_{CP}^{mix}(B_d \to J/\psi K_S) = -0.725 \pm 0.037}$ $\Rightarrow$

  – Belle indicates CP-violating NP contributions to $b \to s\bar{s}s$ processes!

  – But the data moved towards the SM, and no confirmation from BaBar.

  – Hopefully, clarification soon ($\to$ monitor also similar modes).

$B \to \pi\pi, \pi K$ Puzzles

& Connection with

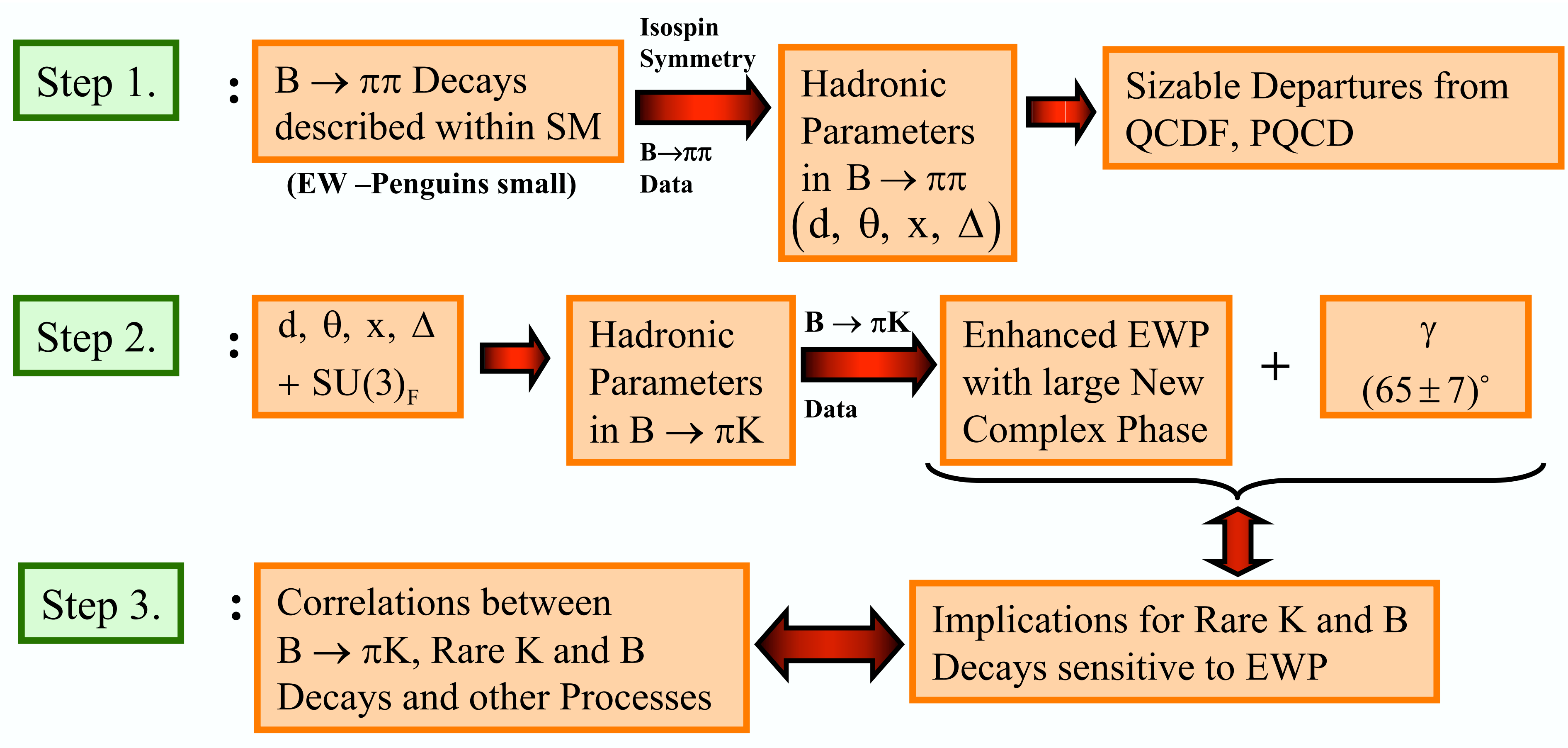
Rare K and B Decays

$\longrightarrow$ <u>example of a systematic strategy to search for NP:</u>

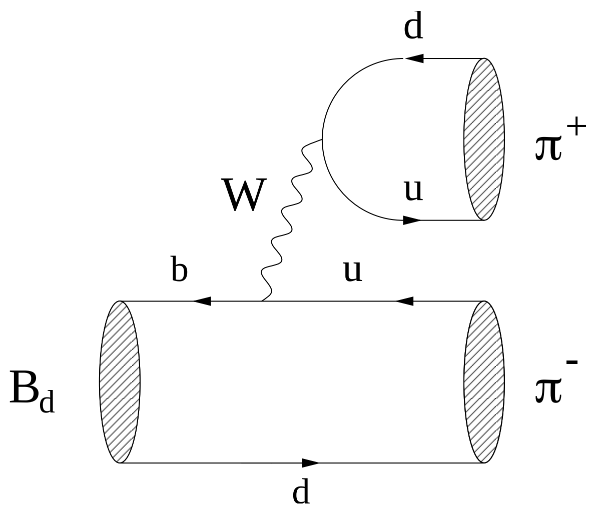
... leads us to a NP scenario of Class C!

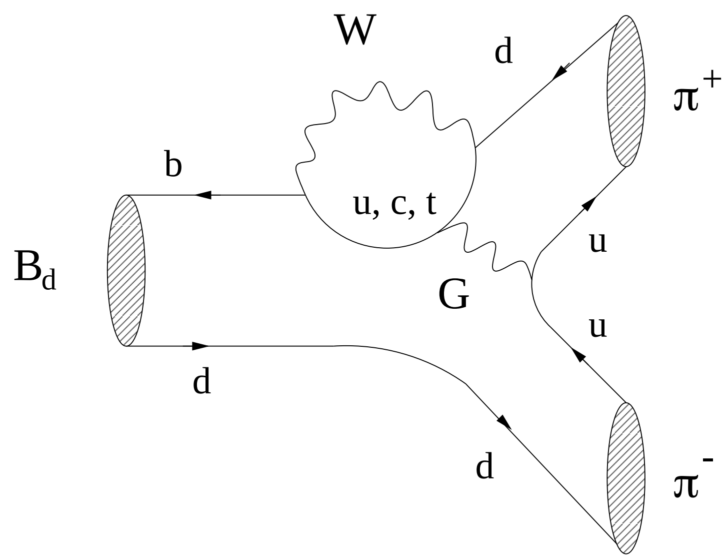
[Buras, R.F., Recksiegel & Schwab (2003–2004); numerics refers to hep-ph/0410407]

Logical Structure



Step 1: $B \longrightarrow \pi\pi$





$$B_d^0 \longrightarrow \pi^+\pi^-, \quad \bar{B}_d^0 \longrightarrow \pi^+\pi^-$$

$$B_d^0 \longrightarrow \pi^0\pi^0, \quad \bar{B}_d^0 \longrightarrow \pi^0\pi^0$$

$$B^+ \longrightarrow \pi^+\pi^0, \quad B^- \longrightarrow \pi^-\pi^0$$

Input Observables

- Two independent ratios of the CP-averaged branching ratios:

$$R_{+-}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B^\pm \to \pi^\pm\pi^0)}{\mathrm{BR}(B_d \to \pi^+\pi^-)}\right]\frac{\tau_{B_d^0}}{\tau_{B^+}} = 2.20 \pm 0.31$$

$$R_{00}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B_d \to \pi^0\pi^0)}{\mathrm{BR}(B_d \to \pi^+\pi^-)}\right] = 0.67 \pm 0.14$$

  – The BRs for $B_d \to \pi^+\pi^-$ and $B_d \to \pi^0\pi^0$ are found to be surprisingly small and large, respectively, whereas that for $B^\pm \to \pi^\pm\pi^0$ looks OK.

- CP-violating observables of $B_d \to \pi^+\pi^-$:

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = -0.37 \pm 0.11, \quad \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) = +0.61 \pm 0.14$$

  – Experimental picture is not yet settled (HFAG averages).

  – Theoretical interpretation to be discussed below yields constraints for the UT in nice accordance with the SM ...

Hadronic Parameters: Isospin Symmetry

- Observables involve the following hadronic parameters:
  - Ratio of "penguin" to "tree" amplitudes (see Lecture II):

$$de^{i\theta} \equiv \frac{1}{R_b}\left[\frac{A_{\rm P}^c - A_{\rm P}^t}{A_{\rm T}^u + A_{\rm P}^u - A_{\rm P}^t}\right] \equiv \frac{1}{R_b}\left[\frac{\mathcal{P}_{tc}}{\mathcal{T} - (\mathcal{P}_{tu} - \mathcal{E})}\right]$$

  - Ratio of "colour-suppressed" to "colour-allowed tree" amplitudes:

$$xe^{i\Delta} \equiv \left[\frac{\mathcal{C} + (\mathcal{P}_{tu} - \mathcal{E})}{\mathcal{T} - (\mathcal{P}_{tu} - \mathcal{E})}\right]$$

- Can be *cleanly* and *unambiguously* determined from the $B \to \pi\pi$ data:[1]

$$d = 0.51^{+0.26}_{-0.20}, \quad \theta = +(140^{+14}_{-18})^\circ; \qquad x = 1.15^{+0.18}_{-0.16}, \quad \Delta = -(59^{+19}_{-26})^\circ \quad (1)$$

- Theoretical picture: [QCDF: Buchalla & Safir ('04); PQCD: Keum & Sanda ('03)]

$$d|_{\rm QCDF} = 0.29 \pm 0.09, \quad \theta|_{\rm QCDF} = -\,(171.4 \pm 14.3)^\circ$$
$$d|_{\rm PQCD} = 0.23^{+0.07}_{-0.05}, \qquad +139^\circ < \theta|_{\rm PQCD} < +148^\circ$$

[1] EW penguins have a tiny impact on the $B \to \pi\pi$ system, but are included in our numerical analysis.

CP Violation in $B_d \to \pi^0\pi^0$

- The hadronic parameters in (1) allow the following *predictions*:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^0\pi^0)\Big|_{\rm SM} = -0.28^{+0.37}_{-0.21}$$
$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^0\pi^0)\Big|_{\rm SM} = -0.63^{+0.45}_{-0.41}$$

$\Rightarrow$ exciting perspective of *large* CP violation!

- First B-factory results were reported @ ICHEP '04:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^0\pi^0) = \begin{cases} -(0.12 \pm 0.56 \pm 0.06) & \text{(BaBar)} \\ -(0.43 \pm 0.51\,^{+0.17}_{-0.16}) & \text{(Belle)} \end{cases}$$

$$\Rightarrow \quad \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^0\pi^0) = -(0.28 \pm 0.39)$$

$\Rightarrow$ encouraging argeement with our prediction!

Three Lessons from the $B \to \pi\pi$ Analysis

1. The data indicate large non-factorizable effects.

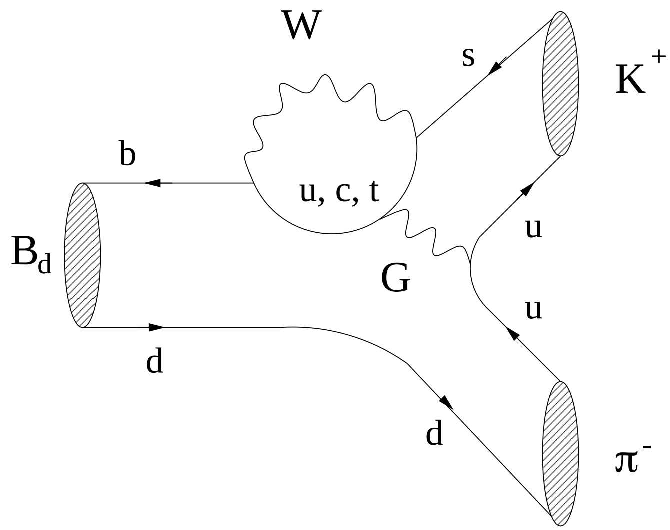
2. Sizeable CP asymmetries are expected in the $B_d \to \pi^0\pi^0$ channel.

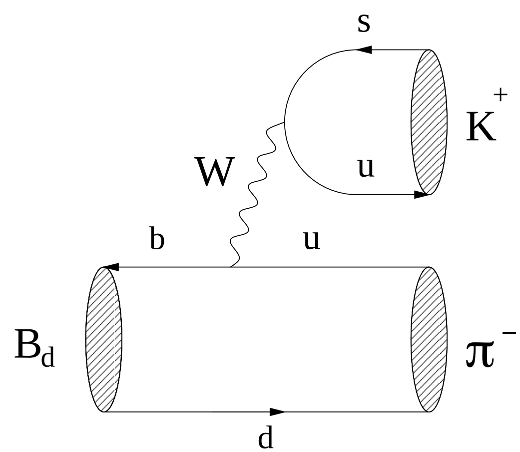
3. The current data can be nicely accommodated in the SM.

More accurate input data will lead to sharper and sharper pictures ...

[In accordance with analyses by Ali *et al.* ('04); Bauer *et al.* ('04); Chiang *et al.*; ...]

Step 2: $B \to \pi K$





$$\left.\begin{array}{ll} B^+ \to \pi^+ K^0, & B^- \to \pi^- \bar{K}^0 \\ B_d^0 \to \pi^- K^+, & \bar{B}_d^0 \to \pi^+ K^- \end{array}\right\}$$

colour-suppressed EW penguins
(expected to be tiny)

$$\left.\begin{array}{ll} B^+ \to \pi^0 K^+, & B^- \to \pi^0 K^- \\ B_d^0 \to \pi^0 K^0, & \bar{B}_d^0 \to \pi^0 \bar{K}^0 \end{array}\right\}$$

colour-allowed EW penguins
(significant)

Main Ingredients of Our $B \to \pi K$ Analysis

- Starting point:

  – Hadronic $B \to \pi\pi$ parameters determined in Step 1.

  – SM CKM fits (insignificantly affected by EW penguins).

- Working hypothesis:

  i) $SU(3)$ flavour symmetry of strong interactions

  ii) Neglect penguin annihilation and exchange topologies

  Internal consistency checks OK ($\to$ LHCb)

- We may then determine the hadronic $B \to \pi K$ parameters through their $B \to \pi\pi$ counterparts:

$\Rightarrow$ **Prediction of the $B \to \pi K$ observables in the SM**

Observables with a *Tiny* Impact of EW Penguins

- Direct CP violation in $B_d \to \pi^\mp K^\pm$ (was established @ ICHEP '04):

  – Average of the corresponding BaBar and Belle data:

$$\boxed{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm) = +0.113 \pm 0.019}$$

  – In our strategy, we obtain the following prediction:

$$\boxed{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm) = +0.127^{+0.102}_{-0.066}}$$

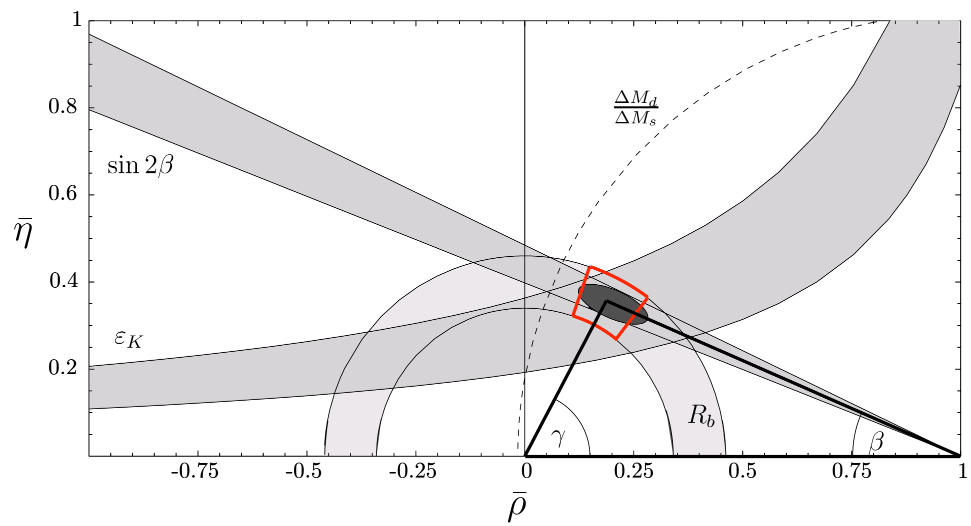
  – Moreover, i) and ii) specified above imply the following relation:

$$H \propto \underbrace{\left(\frac{f_K}{f_\pi}\right)^2 \left[\frac{\text{BR}(B_d \to \pi^+\pi^-)}{\text{BR}(B_d \to \pi^\mp K^\pm)}\right]}_{0.38 \pm 0.04} = \underbrace{-\left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)}{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)}\right]}_{0.31 \pm 0.11}$$

... gives us further confidence in our working assumptions!

– The $B_d \to \pi^\mp K^\pm$ data allow us also to convert the CP asymmetries of the $B_d \to \pi^+\pi^-$ channel into a range for γ:

$$\left.\begin{array}{rcl} \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) & = & G_1(d,\theta;\gamma) \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) & = & G_2(d,\theta;\gamma,\phi_d) \end{array}\right. \oplus \quad H = G_3(d,\theta;\gamma) \quad \Rightarrow$$



- On the other hand, moderate numerical discrepancy for the ratio R of the CP-averaged $B_d \to \pi^\mp K^\pm$, $B^\pm \to \pi^\pm K$ branching ratios:
  – Suggests the sizeable impact of hadronic parameters $(\rho_{\rm c}, \theta_{\rm c})$.
  – These quantities can be constrained through the direct CP asymmetry of the decay $B^\pm \to \pi^\pm K$ and the emerging $B^\pm \to K^\pm K$ signal...

$\Rightarrow$ *no* problems for the SM in this sector!

Observables with a *Sizeable* Impact of EW Penguins

- The key quantities: [Buras & R.F. ('98)]

$$R_{\rm c} \equiv 2\left[\frac{\mathrm{BR}(B^+\to\pi^0K^+)+\mathrm{BR}(B^-\to\pi^0K^-)}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\bar{K}^0)}\right] \stackrel{\rm Exp}{=} 1.00\pm0.08$$

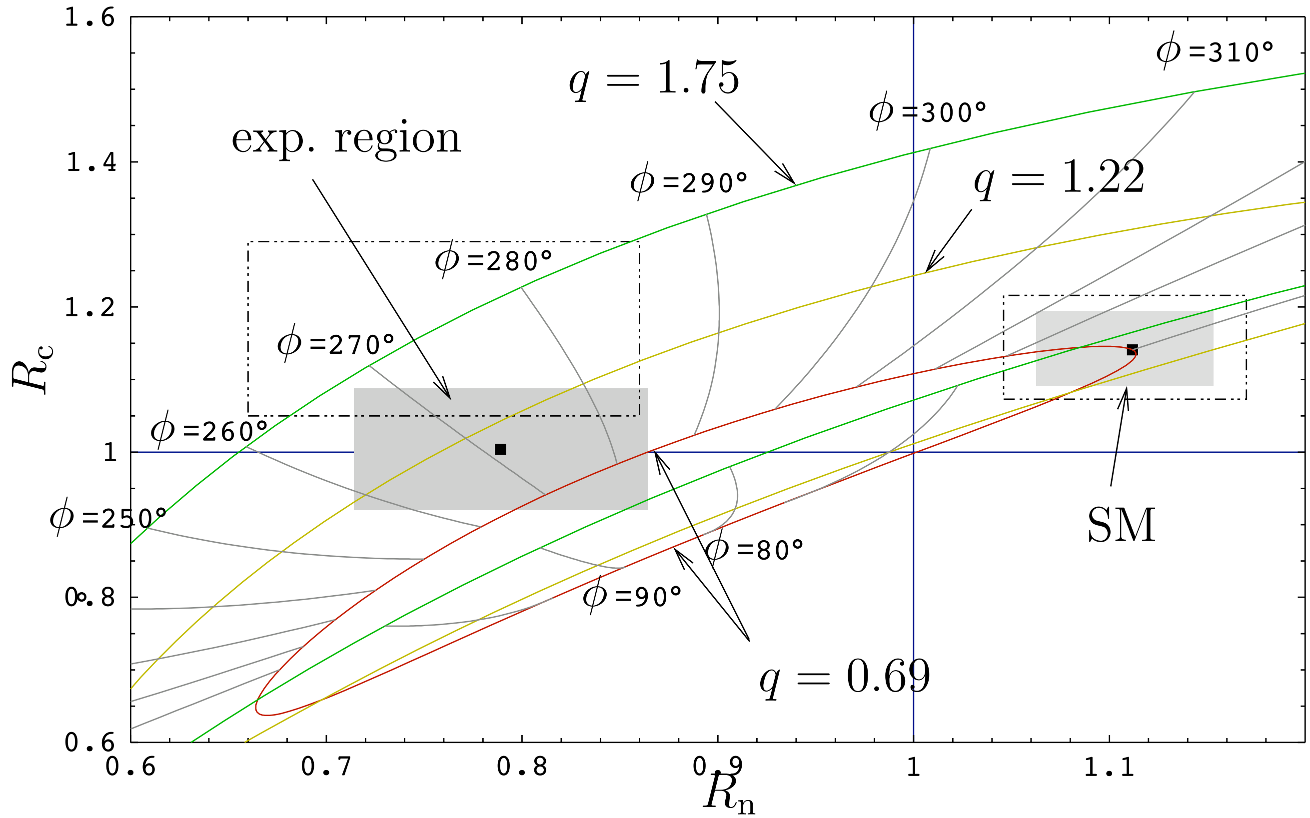
$$R_{\rm n} \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B^0_d\to\pi^-K^+)+\mathrm{BR}(\bar{B}^0_d\to\pi^+K^-)}{\mathrm{BR}(B^0_d\to\pi^0K^0)+\mathrm{BR}(\bar{B}^0_d\to\pi^0\bar{K}^0)}\right] \stackrel{\rm Exp}{=} 0.79\pm0.08$$

- Features of the EW penguins:
  - Enter in colour-allowed form through the modes involving π^0's.
  - Theoretical description through the following parameters:

$$\underbrace{q \stackrel{\rm SM}{=} 0.69 \quad (\to \text{“strength”})}_{SU(3)\ \text{[Neubert \& Rosner ('98)]}}, \quad \phi \stackrel{\rm SM}{=} 0^\circ \ (\to \text{CP-violating phase})$$

  - Provide an interesting avenue for NP to manifest itself...
    [R.F. & Mannel ('97); Grossman, Neubert & Kagan ('99); ...]

- Situation in the $R_{\rm n}$–$R_{\rm c}$ plane:



- Allow for NP in the EW penguin sector to resolve this "$B \to \pi K$ puzzle":

$$R_{\rm c,n}\big|_{\rm exp} \quad \Rightarrow \quad \boxed{q = 1.08\,^{+0.81}_{-0.73}, \quad \phi = -(88.8^{+13.7}_{-19.0})^\circ}$$

$\Rightarrow$ *prediction* of CP violation in $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^0 K_{\rm S}$ ...

- Compilation of our predictions for the CP asymmetries:

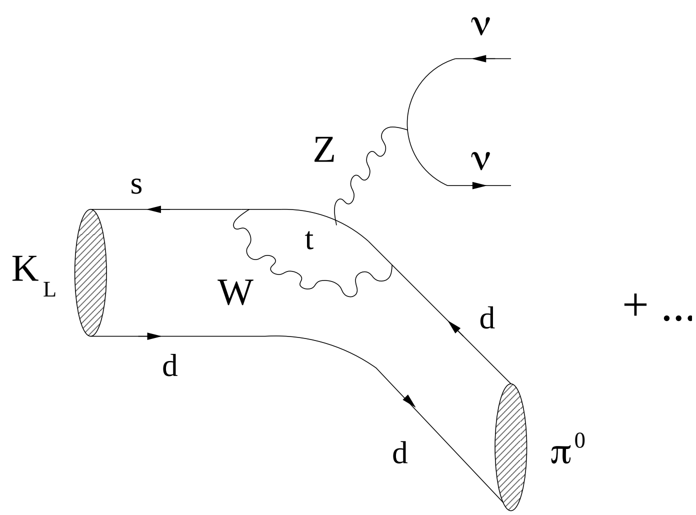
Quantity	Our Prediction	Experiment
$\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to\pi^0\pi^0)$	$-0.28^{+0.37}_{-0.21}$	-0.28 ± 0.39
$\mathcal{A}_{\rm CP}^{\rm mix}(B_d\to\pi^0\pi^0)$	$-0.63^{+0.45}_{-0.41}$	$-0.48^{+0.48}_{-0.40}$
$\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to\pi^\mp K^\pm)$	$0.127^{+0.102}_{-0.066}$	0.113 ± 0.019
$\mathcal{A}_{\rm CP}^{\rm dir}(B^\pm\to\pi^0 K^\pm)$	$0.10^{+0.25}_{-0.19}$	-0.04 ± 0.04
$\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to\pi^0 K_{\rm S})$	$0.01^{+0.15}_{-0.18}$	0.09 ± 0.14
$\mathcal{A}_{\rm CP}^{\rm mix}(B_d\to\pi^0 K_{\rm S})$	$-0.98^{+0.04}_{-0.02}$	$-0.34^{+0.29}_{-0.27}$

$\longrightarrow$ sensitivity on EW penguins!

What about further tests of our NP scenario?

Step 3:

Rare B and K Decays



Z^0 penguins

$\Rightarrow$ ... several spectacular NP effects!

Preliminaries

- Enhanced Z^0 penguins with a large CP-violating NP phase provide an attractive scenario for NP effects in rare K and B decays:
  - Model-independent analyses
  - Studies within particular supersymmetric scenarios ...

  [Buras & Silvestrini (1999); Buras, Colangelo, Isidori, Romanino & Silvestrini (2000); Buchalla *et al.* (2001); Atwood & Hiller (2003); Buras, Ewerth, Jäger & Rosiek (2004)]

- We determine the magnitude and phase of the SD (Inami–Lim) function C that characterizes the Z^0 penguins through the $B \to \pi K$ data:
  - Performing a renormalization-group analysis yields

$$C(\bar{q}) = 2.35\ \bar{q}e^{i\phi} - 0.82, \quad \bar{q} = q\left[\frac{|V_{ub}/V_{cb}|}{0.086}\right] \tag{1}$$

  - Evaluating the relevant box-diagram contributions within the SM and using (1), we obtain the following short-distance functions:

$$X = 2.35\ \bar{q}e^{i\phi} - 0.09 \quad \text{and} \quad Y = 2.35\ \bar{q}e^{i\phi} - 0.64, \tag{2}$$

  which govern rare decays with $\nu\bar{\nu}$ and $\ell^+\ell^-$ in the final states.

[Buras, R.F, Recksiegel & Schwab (2003)]

Constraints from Rare Decays

- *Previous $B \to \pi K$* data:

$$\Rightarrow \quad q = 1.75^{+1.27}_{-0.99}, \quad \phi = -(85^{+11}_{-14})^\circ \quad \Rightarrow \quad |X| \approx |Y| \approx |Z| \approx 4.3^{+3.0}_{-2.4}$$

  - $|X|$: compatible with the $K \to \pi\nu\bar{\nu}$, $B \to X_{s,d}\nu\bar{\nu}$ data.
  - $|Y|$: *violates* $|Y| \leq 2.2$ following from the BaBar and Belle data for $B \to X_s\mu^+\mu^-$, and the KTeV upper bound on $\mathrm{BR}(K_\mathrm{L} \to \pi^0 e^+ e^-)$.
  - $|Z|$: too large to be consistent with the data on ε'/ε.

- Consider only those $(q, \phi)_{B\to\pi K}$ that satisfy $|Y| = 2.2$:

$$\Rightarrow \quad \boxed{\bar{q} = 0.92^{+0.07}_{-0.05}, \quad \phi = -(85^{+11}_{-14})^\circ}$$

  - Nicely compatible with the *new* $B \to \pi K$ data:

$$\Rightarrow \quad q = 1.08\,^{+0.81}_{-0.73}, \quad \phi = -(88.8^{+13.7}_{-19.0})^\circ$$

  - Significant NP effects in several rare decays would emerge...

Various *predictions*	$\Rightarrow$	*Tests* of our NP scenario!

Picture with the Rare-Decay Constraints

Quantity	Old Data	Prediction with RDs	New Data
$R_{\rm c}$	1.17 ± 0.12	$1.00^{+0.12}_{-0.08}$	1.00 ± 0.08
$R_{\rm n}$	0.76 ± 0.10	$0.82^{+0.12}_{-0.11}$	0.79 ± 0.08

$\Rightarrow$ data moved accordingly! [see BFRS NPB paper]

- Define CP-violating phases through the following relations:

$$X = |X|e^{i\theta_X}, \quad Y = |Y|e^{i\theta_Y}, \quad Z = |Z|e^{i\theta_Z}$$

$$\beta_X \equiv \beta - \beta_s - \theta_X, \quad \beta_Y \equiv \beta - \beta_s - \theta_Y, \quad \beta_Z \equiv \beta - \beta_s - \theta_Z$$

[β: usual UT angle, $\beta_s = -\lambda^2\eta = -1^\circ$]

- Short-distance parameters following from our NP analysis:

$$|C| = 2.24 \pm 0.04, \quad \theta_C = -(105 \pm 12)^\circ$$

$$|X| = 2.17 \pm 0.12, \quad \theta_X = -(86 \pm 12)^\circ, \quad \beta_X = (111 \pm 12)^\circ$$

$$|Y| = 2.2 \text{ (input)}, \quad \theta_Y = -(100 \pm 12)^\circ, \quad \beta_Y = (124 \pm 12)^\circ$$

$$|Z| = 2.27 \pm 0.06, \quad \theta_Z = -(108 \pm 12)^\circ, \quad \beta_Z = (132 \pm 12)^\circ$$

- The SM corresponds to the following values [$\theta_C = \theta_X = \theta_Y = \theta_Z = 0^\circ$]:

$$|C| = 0.79, \quad |X| = 1.53, \quad |Y| = 0.98, \quad |Z| = 0.68$$

Rare $K \to \pi\nu\bar{\nu}$ Decays ($\to$ Very Clean!)

- The current experimental picture:

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= (14.7^{+13.0}_{-8.9}) \times 10^{-11} \quad \text{[E949 + E787]} \\ \mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}) &< 5.9 \times 10^{-7} \quad \text{[KTeV]} \end{aligned}$$

- Branching ratios in the SM:

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})\big|_{\mathrm{SM}} &= (8.0 \pm 1.1) \times 10^{-11} \\ \mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu})\big|_{\mathrm{SM}} &= (3.2 \pm 0.6) \times 10^{-11} \end{aligned}$$

- Branching ratios in our NP scenario:

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= (7.5 \pm 2.1) \times 10^{-11} \\ \mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}) &= (31 \pm 10) \times 10^{-11} \quad [\to \text{E391(a)?}] \end{aligned}$$

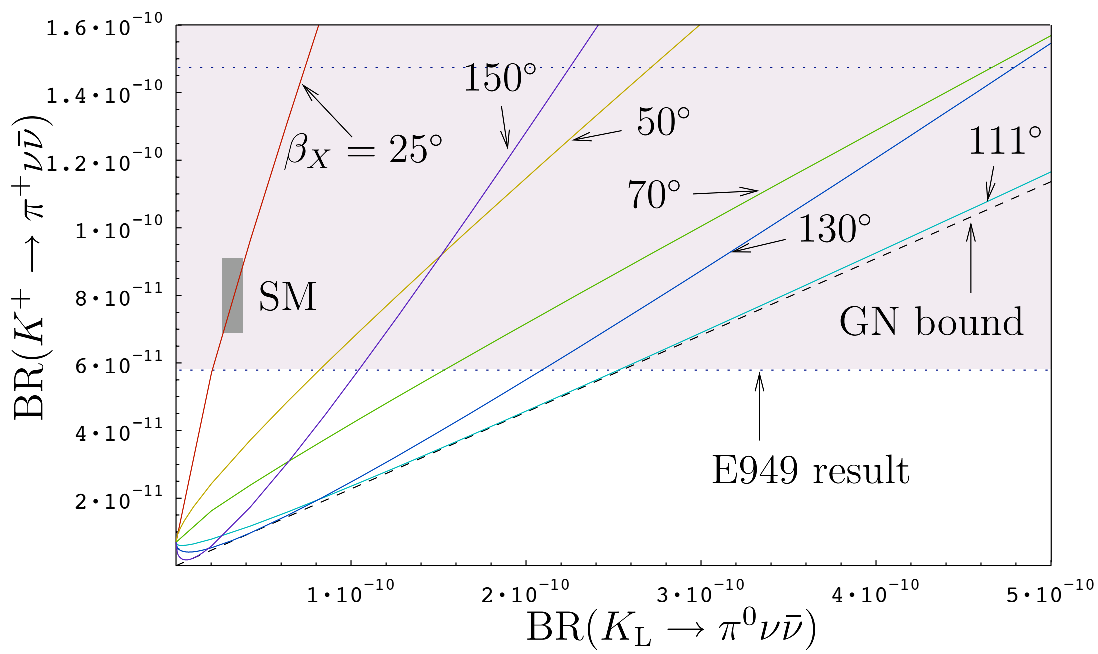
  – This pattern is dominantly the consequence of $\beta_X \approx 111^\circ$:

$$\begin{aligned} \frac{\mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu})}{\mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu})_{\mathrm{SM}}} &= \left|\frac{X}{X_{\mathrm{SM}}}\right|^2 \left[\frac{\sin\beta_X}{\sin(\beta-\beta_s)}\right]^2 \\ \frac{\mathrm{BR}(K_{\mathrm{L}} \to \pi^0\nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})} &\approx 4.4 \times (\sin\beta_X)^2 \approx (4.2 \pm 0.2) \end{aligned}$$

– BR($K_L \to \pi^0\nu\bar{\nu}$) is close to its absolute upper bound: [Grossman & Nir ('97)]

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \leq 4.4 \times \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$$

– BR($K^+ \to \pi^+\nu\bar{\nu}$) as a function of BR($K_L \to \pi^0\nu\bar{\nu}$): [MFV: Buras & R.F. ('01)]



- Moreover:

– In NP scenarios with MFV, which contain also the SM, the $K \to \pi\nu\bar{\nu}$ BRs allow a determination of $\sin 2\beta$. [Buchalla & Buras (1994)]

– However, in our NP scenario, we obtain the following:

$$\underbrace{(\sin 2\beta)_{\pi\nu\bar{\nu}}}_{-(0.69^{+0.23}_{-0.41})} \overset{\mathrm{MFV}}{=} \underbrace{(\sin 2\beta)_{\psi K_S}}_{+(0.725\pm 0.037)} \quad \Rightarrow \quad \text{strong violation of this relation!}$$

Other Spectacular New-Physics Effects ...

- $K_{\mathrm{L}} \to \pi^0 e^+ e^-$:

  – SM $\to$ decay is governed by indirect CP violation:

  $$\mathrm{BR}(K_{\mathrm{L}} \to \pi^0 e^+ e^-) = (3.2^{+1.2}_{-0.8}) \times 10^{-11}$$

  – NP $\to$ decay is governed by direct CP violation:

  $$\mathrm{BR}(K_{\mathrm{L}} \to \pi^0 e^+ e^-) = (7.8 \pm 1.6) \times 10^{-11}$$

  [$K_{\mathrm{L}} \to \pi^0 \mu^+ \mu^-$: Isidori, Smith & Unterdorfer (2004)]

- $B_d \to K^* \mu^+ \mu^-$:

  An integrated forward–backward CP asymmetry [Buchalla *et al.* ('01)]

  $$A_{\mathrm{FB}}^{\mathrm{CP}} = (0.03 \pm 0.01) \times \tan\theta_Y$$

  can be very large in view of $\theta_Y \approx -100^\circ$.

  [See also Choudhury, Gaur & Cornell (2004); ...]

- $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to \mu^+ \mu^-$:

  The branching ratios are enhanced by factors of 2 and 5, respectively.

Conclusions and Outlook

- Flavour physics offers interesting avenues to explore the Standard Model and to search for signals of New Physics:
  - B system:
    - Data are in remarkable agreement with the KM mechanism!
    - But still several unexplored aspects, and hints for discrepancies...

      $\longrightarrow$ LHCb, super-B factory (?)
  - K system:
    - Governed the stage of CP violation for more than 35 years!
    - The future lies on rare decays: $K \to \pi\nu\bar{\nu}$
  - Other important aspects:
    - D system: tiny CP-violating and mixing effects in SM.
    - Search for flavour-violating charged-lepton decays...

The *whole* picture is essential ...

- A fruitful interplay with the NP searches/discoveries by ATLAS and CMS at the LHC is expected...

$\Rightarrow$ Exciting Future!