Challenging the Standard Model through Flavour Physics

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2nd CPNSH Workshop, CERN, 2–3 December 2004

- Setting the Stage

- Illustration: Systematic strategy in 3 steps:

1. "$B \to \pi\pi$ puzzle" in the current B-factory data:

   ... non-factorizable hadronic effects (SM) $\Rightarrow$

2. "$B \to \pi K$ puzzle" in the current B-factory data:

   ... may indicate NP in the EW penguin sector $\Rightarrow$

3. Connection with rare K and B decays:

   ... several spectacular *predictions* $\Rightarrow$ tests!

- Concluding Remarks

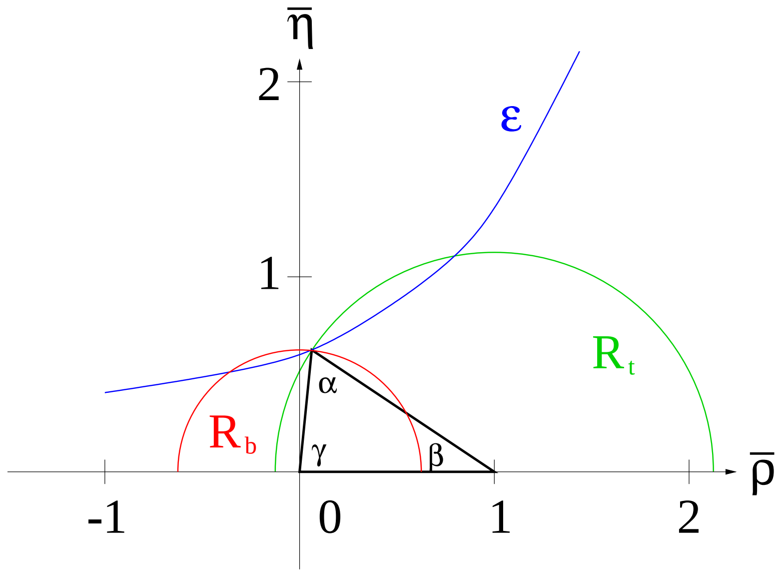
Setting the Stage

Preliminaries

- In this decade, stringent tests of the flavour dynamics of the SM – in particular the Kobayashi–Maskawa mechanism of CP violation – through dedicated B and K experiments!

- Central Target:

Unitarity Triangle (UT) of the CKM Matrix



- Main Goals:

  – Overconstrain the UT as much as possible

  – Search for *discrepancies* with the SM:

... may shed light on NP:

→ | synergy with NP searches at the LHC ... |
|---|

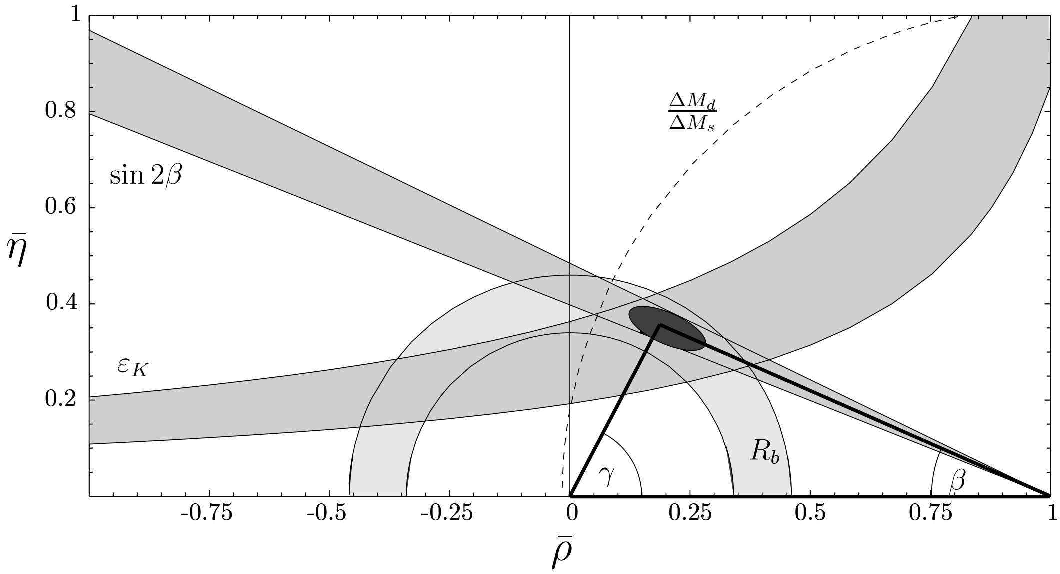
[See also talk by G. Branco @ this workshop]

Current Status

- Thanks to BaBar and Belle, mixing-induced CP violation is now a well-established phenomenon in the B-meson system:

$$B_d \to J/\psi K_S \quad \Rightarrow \quad \sin 2\beta = 0.725 \pm 0.037$$

- Unitarity Triangle:



[Buras, Schwab & Uhlig, hep-ph/0405132; for other analyses, see `http://ckmfitter.in2p3.fr/`, `http://www.utfit.org`]

- Further constraints on the Unitarity Triangle:
  - $B \to \pi\pi,\ \rho\pi,\ \rho\rho$,
  - $B \to D^{(*)\pm}\pi^{\mp}$,
  - $B \to DK$ decays:

$\Rightarrow$ remarkably consistent with the KM picture!

But we should not be "desparate" ...

- Despite tremendous progress, the picture of CP-violating as well as rare B and K decays is still pretty limited:
  - Example: $b \to d\bar{s}s$ penguins, i.e. decays of the kind $B_d \to K^0\bar{K}^0$ (BaBar @ ICHEP '04), are now emerging.
- It is to be seen whether modifications of the SM description of quark flavour dynamics and CP violation will be required...
- Interestingly, the current BaBar and Belle data indicate also a couple of potential *inconsistencies* with the SM:
  - $B \to \phi K$:
    * $(\sin 2\beta)_{\phi K_S}$ may differ from $(\sin 2\beta)_{\psi K_S}$.
    * Polarization analysis of $B \to \phi K^*$, although hadronic effects complicate the search for NP significantly.
  - $B \to \pi K$:
    * The decays with prominent EW penguin contributions exhibit a puzzling pattern of their branching ratios, suggesting NP in the EW penguin sector.
    * Should this actually be the case, spectacular NP effects in several rare decays can be expected:
      $\underbrace{K_L \to \pi^0\nu\bar{\nu},\ K_L \to \pi^0 e^+e^-}_{\text{E391(a), KOPIO, NA48 ...}}$, $B_{s,d} \to \mu^+\mu^-$, ...
- Moreover, an important element is still *missing*:

The B_s-Meson System	→ the domain of LHCb ...

Systematic Search for NP: An Example

- Addresses $B \to \pi\pi, \pi K$ modes and rare B & K decays:

  – We shall stay within the SM as long as “possible”;

  – pattern of the $B \to \pi K$ data guides us to a NP scenario with enhanced EW penguins + new weak phases.

$\Rightarrow$ **3 interrelated steps:**

1 SM analysis of the $B \to \pi\pi$ data (isospin symmetry):

* Allows a *clean* extraction of hadronic parameters.
* CP violation in $B_d \to \pi^0\pi^0$ can be *predicted*.

2 The hadronic $B \to \pi K$ parameters can be determined through their $B \to \pi\pi$ counterparts with the help of $SU(3)$ and plausible assumptions (can be checked!):

* Insights into $SU(3)$-breaking effects can be obtained and γ extracted, in accordance with the UT fits.
* We can accommodate the $B \to \pi K$ data in the SM, with the exciting *exception* of those observables that are significantly affected by EW penguins!
* However, sizeably enhanced EW penguins with a large NP phase allow us to describe the current data!
* CP violation in $B_d \to \pi^0 K_S$ can be *predicted*.

3 The enhanced EW penguins with large CP-violating NP phases have also important implications for rare decays!

[A.J. Buras, R.F., S. Recksiegel, F. Schwab, *Phys. Rev. Lett.* **92** (2004) 101804; *Nucl. Phys.* **B697** (2004) 133; new data: $\to$ hep-ph/0410407]

Step 1:

$B \to \pi\pi$:

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

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

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

$\Rightarrow$ ... non-factorizable hadronic interference effects (SM)!

Input Observables & Hadronic Parameters

- Two independent ratios of the CP-averaged BRs:

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

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

  – Surprising experimental results, which differ significantly from the QCDF picture of $R_{+-}^{\pi\pi} \sim 1.24$ and $R_{00}^{\pi\pi} \sim 0.07$.

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

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = -0.37 \pm 0.11$$

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = +0.61 \pm 0.14$$

  – 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...

- Observables involve the following hadronic parameters:

  – Ratio of "penguin" to "tree" amplitudes:

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

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

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

Output & Predictions

- Hadronic parameters can be *unambiguously* determined:

$$\Rightarrow \left\{ \begin{array}{ll} d = 0.51^{+0.26}_{-0.20}, & \theta = +(140^{+14}_{-18})^\circ \\ x = 1.15^{+0.18}_{-0.16}, & \Delta = -(59^{+19}_{-26})^\circ \end{array} \right. \quad (1)$$

  – On the other hand:

$$d|_{\rm QCDF} = 0.29 \pm 0.09, \quad \theta|_{\rm QCDF} = -(171.4 \pm 14.3)^\circ$$

$$d|_{\rm PQCD} = 0.23^{+0.07}_{-0.05}, \quad +139^\circ < \theta|_{\rm PQCD} < +148^\circ$$

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

- (1) allows the *prediction* of CP violation in $B_d \to \pi^0\pi^0$:

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

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

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

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

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

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

$\Rightarrow$ encouraging argeement with our prediction!

  – Measurement of *one* of the CP-violating $B_d \to \pi^0\pi^0$ observables will allow a *clean determination* of γ.

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)

$\Rightarrow$ ... may indicate NP in the EW penguin sector!

Preliminaries

- The $B \to \pi K$ dynamics is very different from $B \to \pi\pi$:
  - QCD penguins play the dominant rôle.
  - EW penguins complicate the analysis, but provide also a nice avenue for NP to manifest itself in the data!
    [R.F. & Mannel ('97); Grossman, Neubert & Kagan ('99); ...]

- 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 EWPs).
  - 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 relevant hadronic $B \to \pi K$ parameters through their $B \to \pi\pi$ counterparts:

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

- Key Question:

  Will we encounter discrepancies?

Observables with *tiny* impact of EW penguins

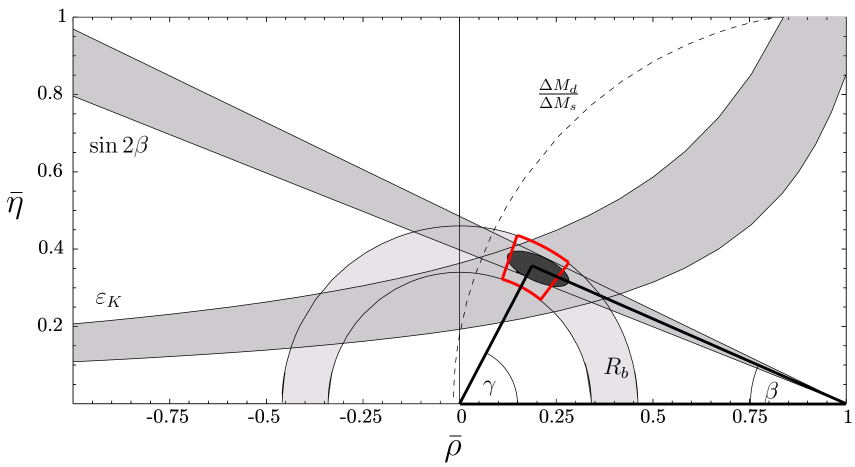
- Important recent development @ ICHEP '04:
  - Observation of direct CP violation in $B_d \to \pi^\mp K^\pm$ modes by BaBar and Belle, with the following average:

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

  - In our strategy, we obtain the following prediction:

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

- We may convert the CP asymmetries of $B_d \to \pi^+\pi^-$ into a range for γ with the help of $B_d \to \pi^\mp K^\pm$:



- 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 sizeable impact of a hadronic parameter $\rho_{\rm c}$.
  - Constrained through the emerging $B^\pm \to K^\pm K$ signal.

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

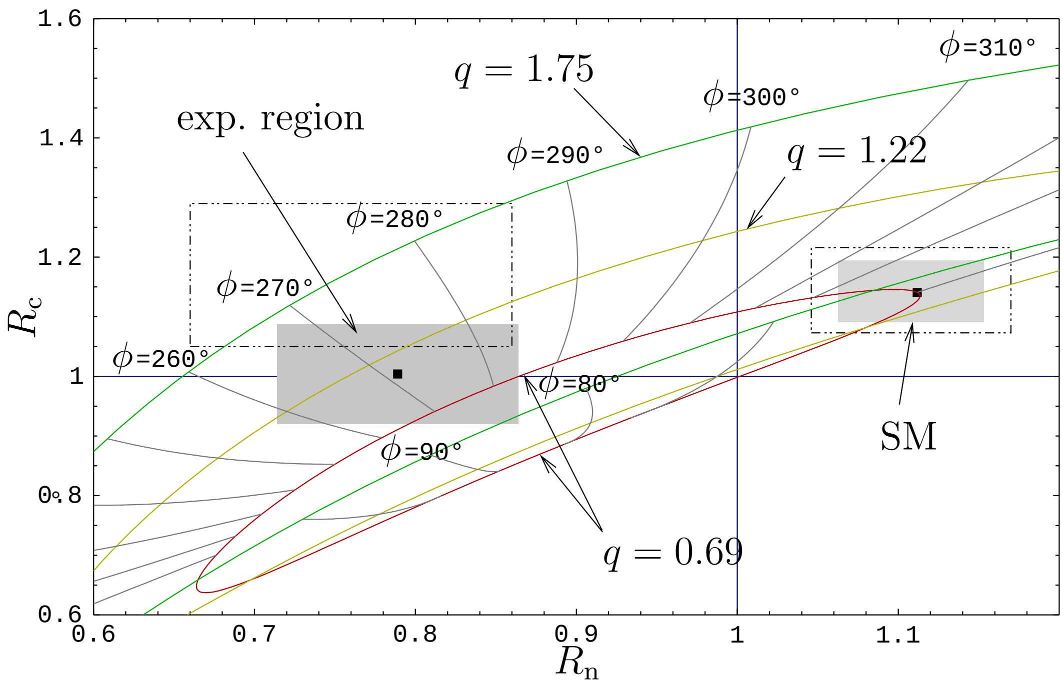
Observables with *sizeable* impact of EWPs

- Key Observables: $\longrightarrow$ involve EWP parameters q and ϕ ...

$$R_c \equiv 2\left[\frac{\text{BR}(B^+ \to \pi^0 K^+)+\text{BR}(B^- \to \pi^0 K^-)}{\text{BR}(B^+ \to \pi^+ K^0) + \text{BR}(B^- \to \pi^- \bar{K}^0)}\right]$$

$$R_n \equiv \frac{1}{2}\left[\frac{\text{BR}(B_d^0 \to \pi^- K^+) + \text{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\text{BR}(B_d^0 \to \pi^0 K^0)+\text{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right]$$

- The situation in the R_n–R_c plane:



- Allow for NP in the EW penguin sector:

$$\underbrace{q = 1.08^{+0.81}_{-0.73}}_{\text{SM} \to 0.69}, \quad \underbrace{\phi = -(88.8^{+13.7}_{-19.0})^\circ}_{\text{SM} \to 0^\circ}$$

$\Rightarrow$ predictions of CPV in $B^\pm \to \pi^0 K^\pm$, $B_d \to \pi^0 K_S$ ...

Step 3:

Rare B and K Decays

Z^0 penguins

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

Preliminaries

- Enhanced Z^0 penguins with a large new complex phase provide an attractive scenario for NP effects in rare and CP-violating 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)]

- In our analysis, we determine the size of the enhancement of the Z^0-penguin Inami–Lim function C and the size of its complex phase through the $B \to \pi K$ data:
  - Performing a renormalization-group analysis yields

$$C(\bar{q}) = 2.35\,\bar{q}e^{i\phi} - 0.82, \quad \bar{q} = q\left[\frac{|V_{ub}/V_{cb}|}{0.086}\right] \quad (2)$$

  - Evaluating the relevant box-diagram contributions within the SM and using (2), we obtain the SD functions

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

    which govern the rare K, B decays with $\nu\bar{\nu}$ and l^+l^- in the final states, respectively.

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

Constraints from Rare Decays

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

$$\Rightarrow \quad q = 1.75^{+1.27}_{-0.99}, \quad \phi = -(85^{+11}_{-14})^\circ$$

$$\Rightarrow |X| \approx |Y| \approx |Z| \approx 4.3^{+3.0}_{-2.4}$$

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

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

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

  - Compatible with all current data on rare decays!
  - Nicely compatible with the *new* $B \to \pi K$ data:

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

  - We may still encounter significant deviations from the SM predictions for rare decays ...

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:

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

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

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

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

- SM corresponds to the following values:

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

$$\theta_C = \theta_X = \theta_Y = \theta_Z = 0^\circ$$

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

- The current experimental picture:

$$\begin{aligned} \text{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= (14.7^{+13.0}_{-8.9}) \times 10^{-11} \quad \text{[E949 + E787]} \\ \text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu}) &< 5.9 \times 10^{-7} \quad \text{[KTeV; wait for E391a ...]} \end{aligned}$$

- Branching ratios in the SM:

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

- Branching ratios in our NP scenario:

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

  - Pattern is dominantly the consequence of $\beta_X \approx 111^\circ$:

$$\frac{\text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu})}{\text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu})_\text{SM}} = \left|\frac{X}{X_\text{SM}}\right|^2 \left[\frac{\sin\beta_X}{\sin(\beta-\beta_s)}\right]^2$$

$$\frac{\text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu})}{\text{BR}(K^+ \to \pi^+\nu\bar{\nu})} \approx 4.4 \times (\sin\beta_X)^2 \approx (4.2 \pm 0.2)$$

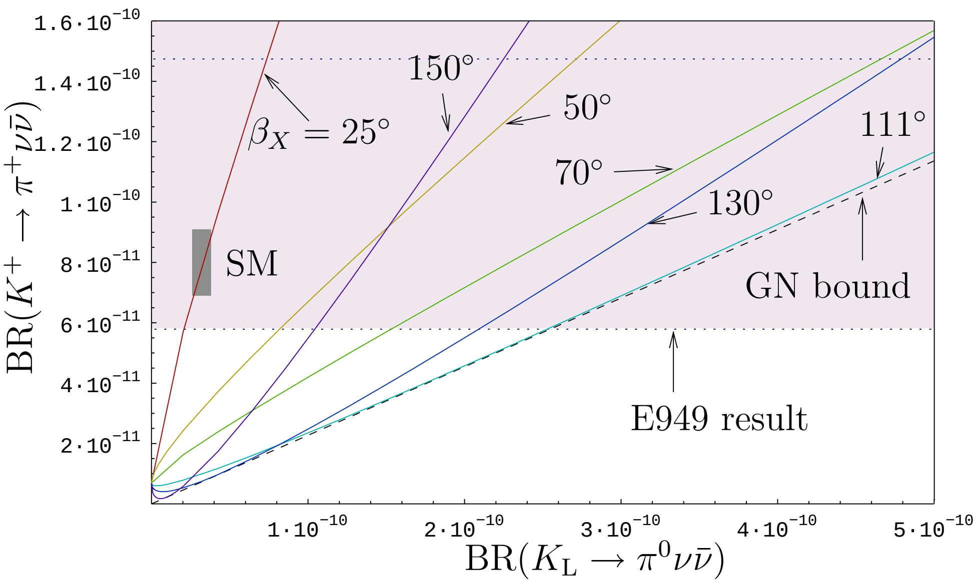
  - $\text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu})$ is close to its absolute upper bound:

    [Grossman & Nir (1997)]

$$\text{BR}(K_\text{L} \to \pi^0\nu\bar{\nu}) \leq 4.4 \times \text{BR}(K^+ \to \pi^+\nu\bar{\nu})$$

– BR($K^+ \to \pi^+\nu\bar{\nu}$) as a function of BR($K_L \to \pi^0\nu\bar{\nu}$):

[MFV: Buras & R.F. (2001)]



- 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:

$$(\sin 2\beta)_{\pi\nu\bar{\nu}} = \sin 2\beta_X = -(0.69^{+0.23}_{-0.41})$$

  – On the other hand: $(\sin 2\beta)_{\psi K_S} = +(0.725 \pm 0.037)$

$\Rightarrow$ $(\sin 2\beta)_{\pi\nu\bar{\nu}} \stackrel{\mathrm{MFV}}{=} (\sin 2\beta)_{\psi K_S}$ is strongly violated!

Other Spectacular NP Effects ...

- $K_{\rm L} \to \pi^0 e^+ e^-$:
  - SM $\longrightarrow$ decay is governed by indirect CP violation:

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

[Buchalla, D'Ambrosio & Isidori (2003)]

  - NP $\longrightarrow$ decay is governed by direct CP violation:

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

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

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

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

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

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

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

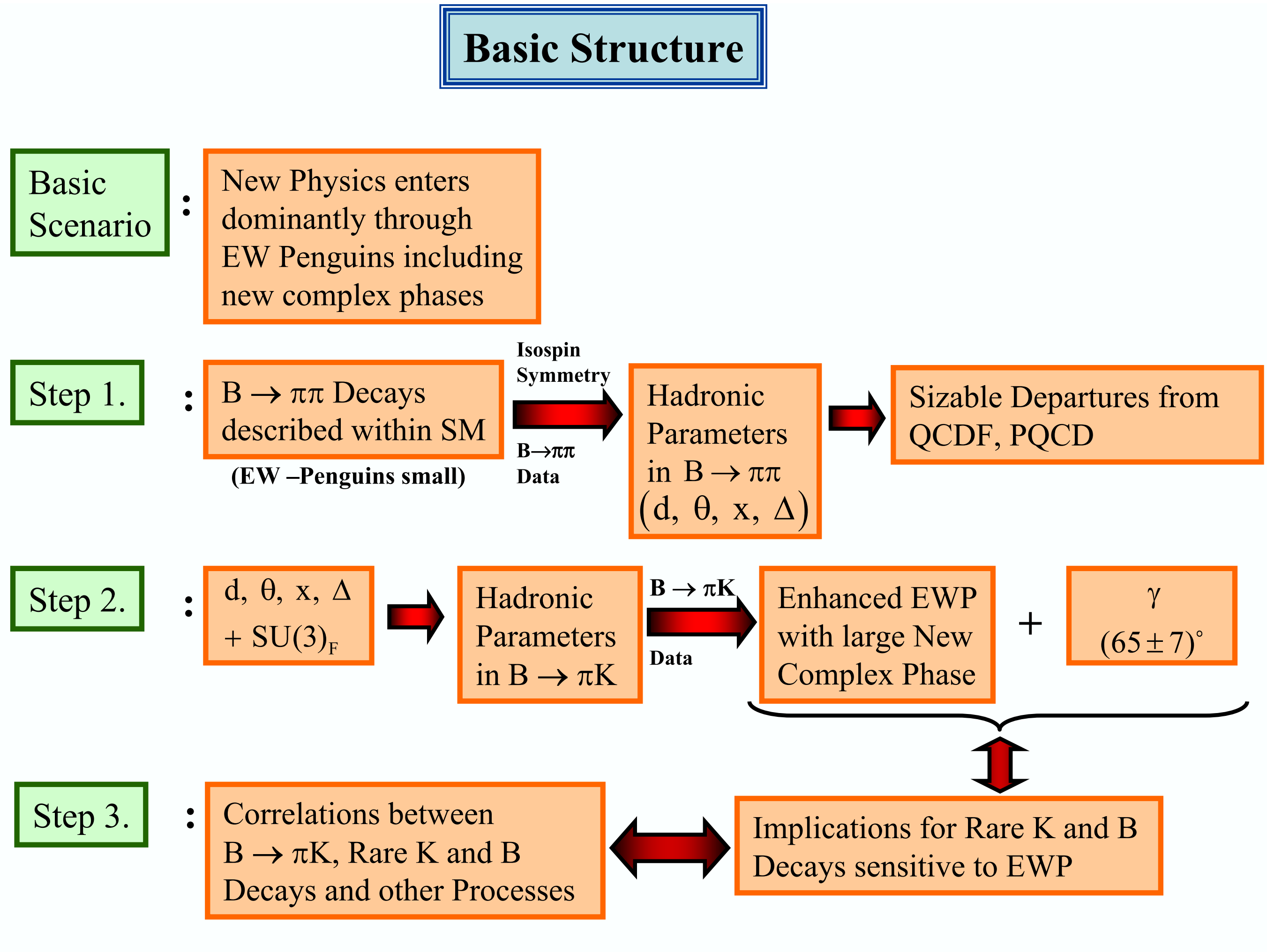
- $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to \mu^+ \mu^-$:

  BRs are enhanced by factors of 2 and 5, respectively, whereas the impact on $K_{\rm L} \to \mu^+ \mu^-$ is rather moderate.

- ε'/ε: $\longrightarrow$ large hadronic uncertainties [Buras (2003)], but ...
  - Enhanced Z^0 pengs may be important! [Buras & Silvestrini ('99)]
  - Enhanced value of $|C|$ and its large negative phase require a significant enhancement of $\langle Q_6 \rangle$ with respect to $\langle Q_8 \rangle$ in order to be consistent with the ε'/ε data!

Summary & Comments

- Flow diagram:



- Model-independent analysis within our scenario where NP enters the EW penguin sector through enhanced Z^0 penguins with a new CP-violating phase.

- This scenario can be accommodated in the general MSSM. [Buras, Ewerth, Jäger & Rosiek, hep-ph/0408142]

- There are other NP scenarios to address the $B \to \pi K$ puzzle, but usually no relation to $K \to \pi\nu\bar{\nu}$, $B \to \mu^+\mu^-$. [Barger, Chiang, Langacker and Lee, hep-ph/0406126; ...]

Concluding Remarks

- Flavour physics provides powerful tools to explore the SM:
  - B system:
    - On the one hand, the current BaBar and Belle data give a picture in impressive agreement with KM!
    - On the other hand, also potential discrepancies...

      $\longrightarrow$ LHCb, super-B factory (?)
  - K system:
    - Governed the stage of CPV for more than 35 years!
    - The future lies on rare decays $\longrightarrow$ NA48 @ CERN
  - Other important aspects:
    - D system: tiny CPV and mixing effects in SM.
    - Search for flavour-violating charged-lepton decays...

  Crucial to get the *whole* picture!

- In this talk, illustration through a specific strategy:

  $$\boxed{B \to \pi\pi} \xrightarrow{SU(3)} \boxed{B \to \pi K} \xrightarrow{Z^0} \boxed{\text{rare decays}}$$

  ... can be systematically improved through better data!

- Fruitful interplay with NP searches/discoveries at ATLAS and CMS expected; has to be further explored...