$B \longrightarrow \pi\pi$, New Physics in $B \longrightarrow \pi K$ and Implications for Rare Decays

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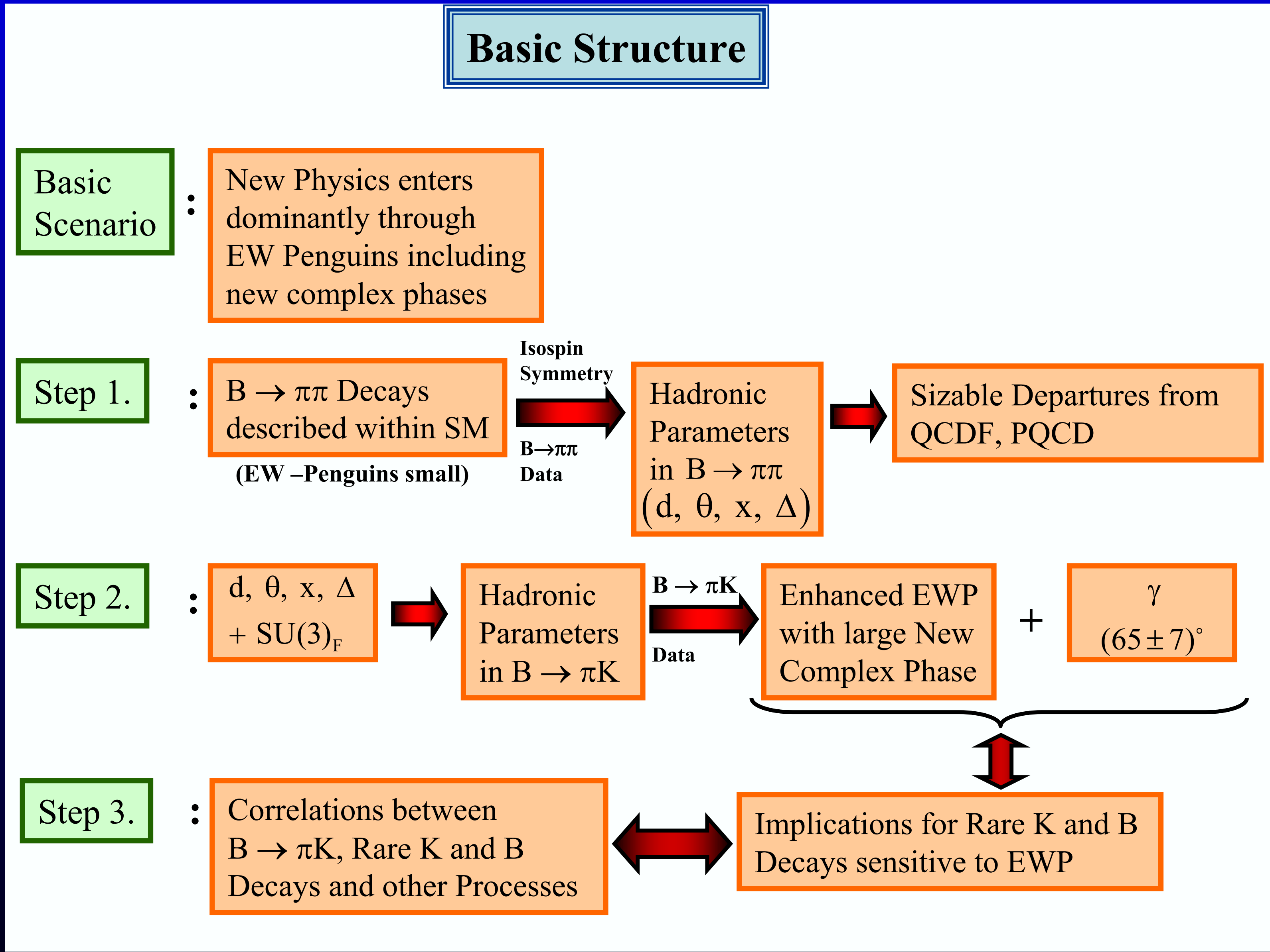
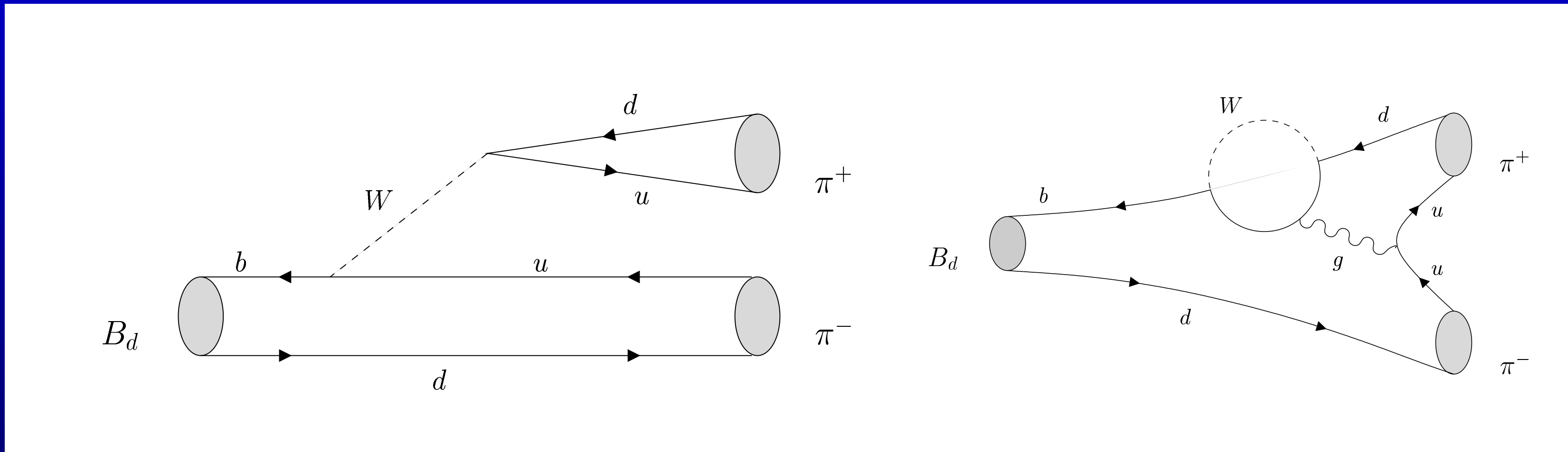
A Look Ahead


Basic Structure
Basic Scenario
:
New Physics enters dominantly through EW Penguins including new complex phases
Step 1.
:
$B \to \pi\pi$ Decays described within SM
(EW –Penguins small)
Isospin Symmetry
$B \to \pi\pi$ Data
Hadronic Parameters in $B \to \pi\pi$ $(d,\ \theta,\ x,\ \Delta)$
Sizable Departures from QCDF, PQCD
Step 2.
:
$d,\ \theta,\ x,\ \Delta$ $+\ SU(3)_F$
Hadronic Parameters in $B \to \pi K$
$B \to \pi K$ Data
Enhanced EWP with large New Complex Phase
+
γ $(65 \pm 7)^\circ$
Step 3.
:
Correlations between $B \to \pi K$, Rare K and B Decays and other Processes
Implications for Rare K and B Decays sensitive to EWP

The $B \to \pi\pi$ System

The decay $B \to \pi\pi$ is tree dominated with sizable penguin contributions.



Recent measurements of $B \to \pi\pi$ branching ratios differ significantly from QCD Factorization predictions (in units of 10^{-6}):

Mode	Theory	S1	S2	S3	S4	Experiment
$B^- \to \pi^-\pi^0$	$6.0\,^{+3.0\,+2.1\,+1.0\,+0.4}_{-2.4\,-1.8\,-0.5\,-0.4}$	5.8	5.5	6.0	5.1	5.5 ± 0.6
$\bar{B}^0 \to \pi^+\pi^-$	$8.9\,^{+4.0\,+3.6\,+0.6\,+1.2}_{-3.4\,-3.0\,-1.0\,-0.8}$	6.0	4.6	9.5	5.2	4.6 ± 0.4
$\bar{B}^0 \to \pi^0\pi^0$	$0.3\,^{+0.2\,+0.2\,+0.3\,+0.2}_{-0.2\,-0.1\,-0.1\,-0.1}$	0.7	0.9	0.4	0.7	1.5 ± 0.3

Numbers from Beneke, Neubert, 2003

Observables

Introduce two observables:

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

$$R_{00}^{\pi\pi} \equiv 2\left[\frac{Br(B_d^0 \to \pi^0\pi^0) + Br(\bar{B}_d^0 \to \pi^0\pi^0)}{Br(B_d^0 \to \pi^+\pi^-) + Br(\bar{B}_d^0 \to \pi^+\pi^-)}\right] = 0.67 \pm 0.14.$$

- In QCD Factorization, the default values are: $R_{+-}^{\pi\pi} = 1.24$ and $\mathrm{R}_{00}^{\pi\pi} = 0.07$.
- Study also CP asymmetries – the asymmetries in $B_d \to \pi^+\pi^-$ are measured to be large (though exp. situation is a bit unclear):

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

Parameterization of Observables

The observables can be phenomenologically parameterized:

$$R_{+-}^{\pi\pi} = F_1(d, \theta, x, \Delta; \gamma), \quad R_{00}^{\pi\pi} = F_2(d, \theta, x, \Delta; \gamma),$$

x and d are color-suppressed tree and penguin topologies respectively, and Δ and θ are the respective strong phases.

Similarly,

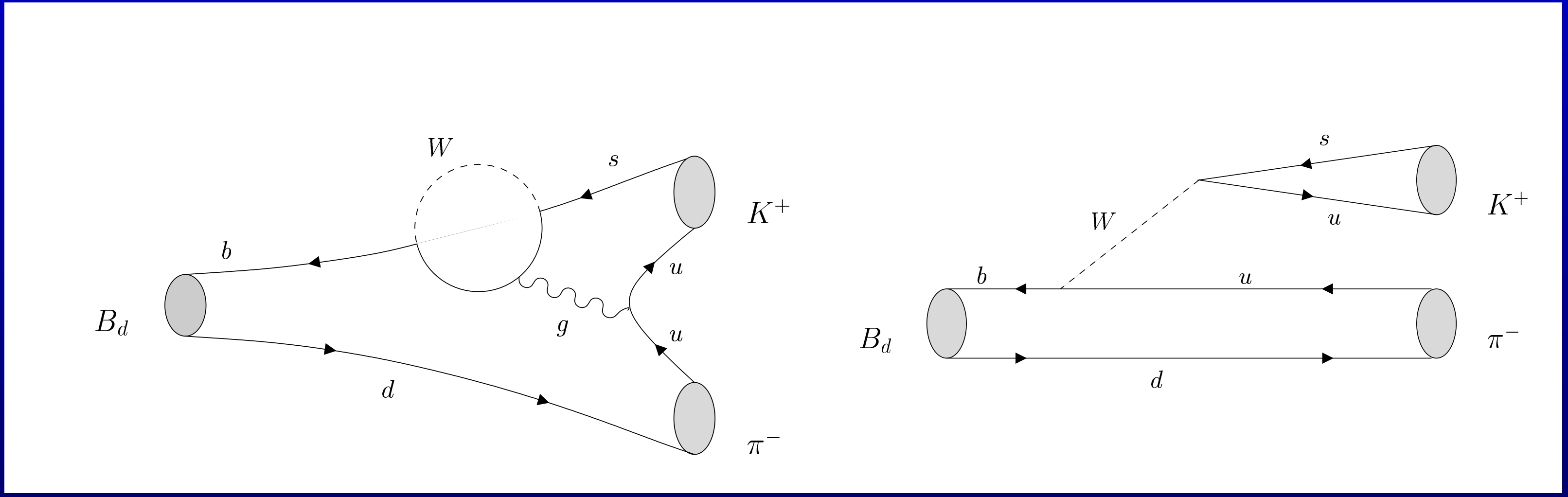
$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = G_1(d, \theta; \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = G_2(d, \theta; \gamma, \phi_d),$$

Determine hadronic parameters:

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

The $B \longrightarrow \pi K$ Puzzle

Due to CKM factors, $B \to \pi K$ are penguin dominated decays
$\Rightarrow$ Much more likely to be affected by new physics.



Introduce again observables:

$$R_{\mathrm{c}} \equiv 2\left[\frac{Br(B^+ \to \pi^0 K^+) + Br(B^- \to \pi^0 K^-)}{Br(B^+ \to \pi^+ K^0) + Br(B^- \to \pi^- \bar{K}^0)}\right] = 1.00 \pm 0.08$$

$$R_{\mathrm{n}} \equiv \frac{1}{2}\left[\frac{Br(B_d^0 \to \pi^- K^+) + Br(\bar{B}_d^0 \to \pi^+ K^-)}{Br(B_d^0 \to \pi^0 K^0) + Br(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right] = 0.79 \pm 0.08.$$

More on Observables

Both R_n and R_c are affected by electroweak penguin amplitudes. A third observable,

$$R \equiv \left[\frac{Br(B_d^0 \to \pi^- K^+) + Br(\bar{B}_d^0 \to \pi^+ K^-)}{Br(B^+ \to \pi^+ K^0) + Br(B^- \to \pi^- \bar{K}^0)}\right] \frac{\tau_{B^+}}{\tau_{B_d^0}} = 0.82 \pm 0.06,$$

only has color suppressed EWP contributions.
Parameterize observables:

$$R_{\rm c,n} = 1 + 2 r_{\rm c,n} (q - \cos\gamma) \cos\delta_{\rm c,n} + [(q - \cos\gamma)^2 + \sin^2\gamma] r_{\rm c,n}^2,$$

$$R = 1 - 2 r \cos\delta \cos\gamma + r^2.$$

The r_i correspond to the tree contributions, q describes the electroweak penguin amplitude.

Hadronic Parameters II: From $\pi\pi$ to πK

Using SU(3) flavor symmetry,

$$\boxed{B \to \pi\pi \overset{\mathrm{SU(3)}}{\Longrightarrow} B \to \pi K}$$

Predictions of R and $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to K^+\pi^-)$:

$$R = 0.943^{+0.028}_{-0.021}, \quad (R_{\mathrm{exp}} = 0.82 \pm 0.06)$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to K^+\pi^-) = 0.127^{+0.102}_{-0.066}, \quad (\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to K^+\pi^-)_{\mathrm{exp}} = 0.113 \pm 0.019)$$

More checks:

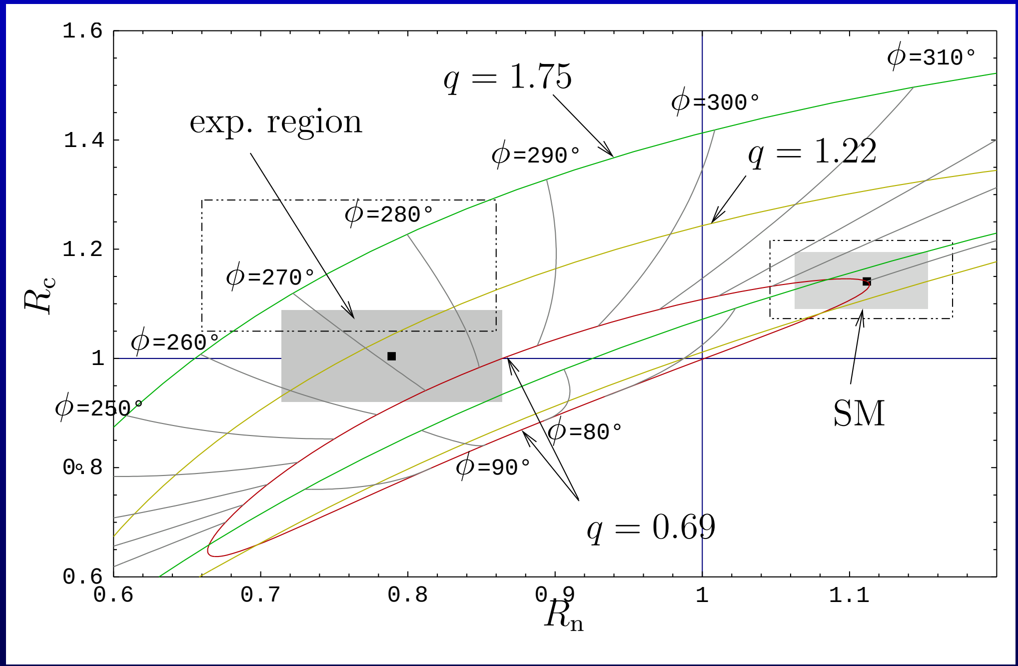
- Determination of γ from $B \to \pi\pi$ and $B \to \pi K$.
- The value of r_c agrees with an alternative determination using $B \to \pi K$ data: $r_c^{BFRS} = 0.20 \pm 0.08$; $r_c^{\pi K} = 0.190 \pm 0.011$.
- Assumptions on annihilation topologies and certain rescattering effects can be tested in $B \to KK$ system (Fleischer Recksiegel, 2004).

Electroweak penguins

Introduce possible CP violating EWP parameter: $q = |q|e^{i\phi}$.

Also, the EWP parameter q can be calculated in the SM: $q = 0.69$ (Neubert, Rosner)

$\Rightarrow$ Allows SM prediction of observables



This calculation gives also connection to Inami Lim Function:

$$C = 2.35q\, e^{i\phi} - 0.82$$

Bounds from Rare Decays

- Semileptonic rare decays are clean and sensitive to EWPs.
- Assume universal CP violating couplings in EWPs (simplest and most predictive scenario).
- Then $B \to X_s l^+ l^-$ gives strong bounds on C and rules out values of q that are as large as implied by the $B \to \pi K$ data (also the bound on $K_L \to \pi^0 e^+ e^-$ would be violated and $\varepsilon^{'}/\varepsilon$ is in trouble).
- Since $B \to \pi K$ data point towards enhanced EWPs, we can still consider them, but impose these constraints ($|Y| = 2.2$).
  This leads to

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

Predictions for 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
$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^0 K_{\rm S})$	$-0.98^{+0.04}_{-0.02}$	$-0.34^{+0.29}_{-0.27}$

All quite OK!!

Predictions for Rare Decays I: $K \longrightarrow \pi\bar{\nu}\nu$

- The decays $K^+ \to \pi^+\bar{\nu}\nu$ and $K_L \to \pi^0\bar{\nu}\nu$ are very clean theoretically and sensitive to electroweak penguins.
  $\Rightarrow$ Very well suited to test the scenario.
- In our scenario, $Br(K_L \to \pi^0\bar{\nu}\nu)$ changes as

$$\frac{Br^{NP}(K_L)}{Br^{SM}(K_L)} = \left(\frac{\left|X^{NP}\right|}{\left|X^{SM}\right|}\frac{\sin\beta_X}{\sin\beta}\right)^2, \qquad \beta_X \approx 111^\circ$$

- Standard Model values (Buras, F.S., Uhlig, 2004):

$$Br(K^+) = 7.8 \cdot 10^{-11} \quad Br(K_L) = 3.0 \cdot 10^{-11}$$

- We find:

$$Br(K^+) = 7.5 \cdot 10^{-11} \quad Br(K_L) = 3.1 \cdot 10^{-10}$$

Predictions for Rare Decays II: Compilation

Decay	SM prediction	Our scenario	Exp. bound (90% C.L.)
$K^+ \to \pi^+\bar{\nu}\nu$	$(7.8 \pm 1.2) \cdot 10^{-11}$	$(7.5 \pm 2.1) \cdot 10^{-11}$	$(14.7^{+13.0}_{-8.9}) \cdot 10^{-11}$
$K_L \to \pi^0\bar{\nu}\nu$	$(3.0 \pm 0.6) \cdot 10^{-11}$	$(3.1 \pm 1.0) \cdot 10^{-10}$	$< 5.9 \cdot 10^{-7}$
$K_L \to \pi^0 e^+ e^-$	$(3.2^{+1.2}_{-0.8}) \cdot 10^{-11}$	$(7.8 \pm 1.6) \cdot 10^{-11}$	$< 2.8 \cdot 10^{-10}$
$B \to X_s\bar{\nu}\nu$	$(3.5 \pm 0.5) \cdot 10^{-5}$	$\approx 7 \cdot 10^{-5}$	$< 6.4 \cdot 10^{-4}$
$B_s \to \mu^+\mu^-$	$(3.42 \pm 0.53) \cdot 10^{-9}$	$\approx 17 \cdot 10^{-9}$	$< 9.5 \cdot 10^{-7}$

- ε'/ε has large hadronic uncertainties, and can be "made compatible" with measurements.

Conclusions and Outlook

- Data in both $B \to \pi\pi$ and $B \to \pi K$ systems show features that present some challenge to theory.
- The $B \to \pi\pi$ decays are tree dominated, and the data can be described by hadronic interference effects within the Standard Model.
- Still, modern QCD-based approaches seem to be in trouble.
- The $B \to \pi K$ data signal new physics, if $R_{\rm n} \neq R_{\rm c}$ is confirmed with further (more precise) data.
- The simple model of enhanced EWP with a CP violating phase can easily be tested in rare decays. So can many, more sophisticated, extensions of that model.

$\Longrightarrow$ Keep an eye on the data!