Rare K and B Decays in a Warped Extra Dimension with Custodial Protection

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Discrete '08, IFIC Valencia, Spain

December 11th 2008

Outline

1. Motivations for WED:

- Addressing Gauge Hierarchy Problem
- Natural Generation of Hierarchies in Masses and Mixings
- ...

2. Randall-Sundrum Scenario:

- The Model analyzed
- New Features in the Flavour Sector
- Rare Decays of B and K mesons: Theoretical Analysis
- Rare Decays of B and K mesons: Numerical Analysis

3. Conclusions

M. Blanke, A. J. Buras, B. Duling, K. Gemmler, S. Gori,
Rare K and B decays in a Warped Extra Dimension with Custodial Protection, in preparation

Gauge Hierarchy Problem & its Solution

Gauge Hierarchy Problem in 3 sentences:

I. Huge hierarchy between the fundamental gravity scale M_{pl} & the EW scale Λ_{EWSB}

II. Tremendous fine-tuning required to keep $\Lambda_{EWSB} \sim 1$ TeV

III. Even if $\frac{\Lambda_{EWSB}}{M_{pl}} \approx 10^{-16}$ is imposed at tree-level, loop corrections push $\Lambda_{EWSB} \sim M_{pl}$

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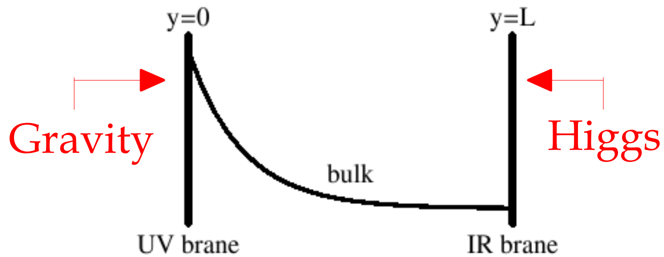
How to solve it in WED Contexts?



Solution to the 5D Einstein equations

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \;, \qquad 0 \le y \le L$$

Warped-Factor

I. Warped-factor along extra dimension leads to: $\Lambda_{eff}(y) = e^{-ky}\Lambda_{fund}$

II. With $\Lambda_{fund} \sim O(M_{pl})$ only a moderate hierarchy is required to obtain $\Lambda_{eff}(IR\,brane) \approx O(1TeV)$

$kL \approx 30$

III. fundamental gravity scale however still given by M_{pl}

If Higgs lives on the IR brane, gauge hierarchy problem does not arise!

Flavour Problem & its Solution (1)

hierarchies

- Experiments tell us:

  I. quarks and charged leptons have

  $m_e \approx 0.5\ MeV\ ,\ m_\tau \approx 1800\ MeV, \ldots$

  $m_u \approx 2.5\ MeV\ ,\ m_t \approx 170\ GeV, \ldots$

  II. also CKM mixing between quark

  $|V_{ud}| \approx 1\ ,\ |V_{us}| \approx 0.226$

  $|V_{cb}| \approx 0.041\ ,\ |V_{ub}| \approx 0.0038$

- ... and the theory:

  III. at the same time CKM picture describes data surprisingly well

SM Yukawa couplings have to exhibit an extremely hierarchical structure, **why?**

Flavour Problem & its Solution (1)

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SM Yukawa couplings have to exhibit an extremely hierarchical structure, **why?**

How to solve it in WED Contexts?

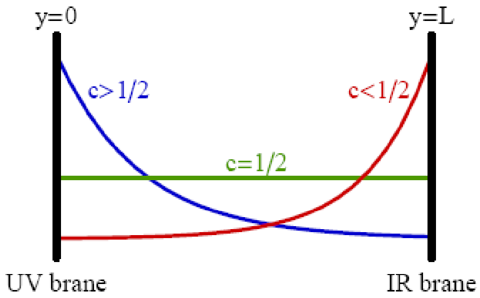
- Preliminaries
  - Gauge fields and matter fields can propagate into the 5^{th} dimension
  - For each particle species, there is an infinite number of solutions:

Kaluza-Klein tower of particles

- Zero mode solutions (if existent) are identified with the SM particles (with BC (++))

Flavour Problem & its Solution (2)

- Zero Modes of Fermions:

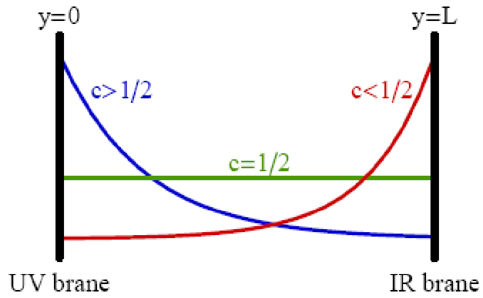


$$f^{(0)}(y,c) = \sqrt{\frac{(1-2c)\,kL}{e^{(1-2c)kL}-1}}\,e^{\left(\frac{1}{2}-c\right)ky}$$

Strong dependence on bulk masses

Flavour Problem & its Solution (2)

Zero Modes of Fermions:



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Strong dependence on bulk masses

The Solution of the Flavour Problem:

I. 4D Yukawas in terms of shape functions:

$$Y_{ij} = \int_0^L \frac{dy}{L^{3/2}} \lambda_{ij} h(y) f_L^{(0)}(y,c^i)\, f_R^{(0)}(y,c^j)$$

5D Yukawas

λ_{ij} assumed to be **anarchical** and O(1)

Higgs localized on the IR brane: $h(y) = \sqrt{2(\beta-1)kL}\; e^{kL} e^{\beta k(y-L)}\ , \quad \beta > 1$

II. Result: slightly different c parameters of O(1) lead to a large hierarchy in Y_{ij}

Hierarchy of quark masses and mixings explained by a purely geometrical approach!

BUT Still missing a theory for the bulk masses

Numerical example:

$c_1 = 0.66\ , \quad c_2 = 0.59\ , \quad c_3 = 0.41$

$Y_1 = 0.0017\ , \quad Y_2 = 0.017\ , \quad Y_3 = 0.42$

Definition of the Model

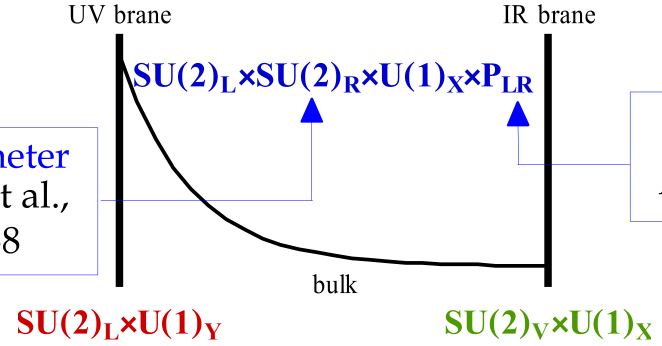
1. Symmetry group and geometric structure:

WED with Custodial Protection

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \ , \qquad 0 \le y \le L$$

$$\begin{cases} e^{-kL} \approx 10^{-16} \\ M_{KK} \approx 2.45 k e^{-kL} \approx 2.45\, TeV \end{cases}$$

T parameter
Csaki et al., 0308038



$Zb_L\bar{b}_L$ coupling
Agashe et al., 0605341

Alternative framework:
Neubert et al. 0807.4937

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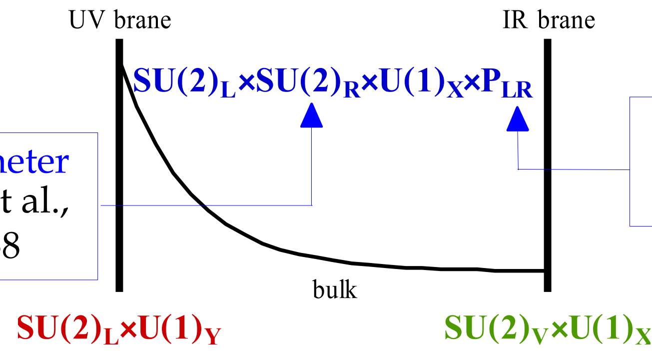

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2. Field content:

Gauge bosons:

I. Gauge eigenstates:

$W^a_{L\mu}(++)\,,\quad B_\mu(++),\quad G^c_\mu(++),$

$W^b_{R\mu}(-+)\,,\quad Z_{X\mu}(-+)$

$a=1,2,3\;;\; b=1,2;\; c=1,\ldots,8$

II. Mass eigenstates:

$W^\pm_\mu \quad W^\pm_{H\mu} \quad \tilde{W}^\pm_\mu$

$A_\mu \quad A^{(1)}_\mu$

$Z_\mu \quad Z_{H\mu} \quad Z'_\mu$

$G^{(0)}_\mu \quad G^{(1)}_\mu$

Gauge bosons of the SM

Higgs boson:

I. Bidoublet of $SU(2)_L \times SU(2)_R$

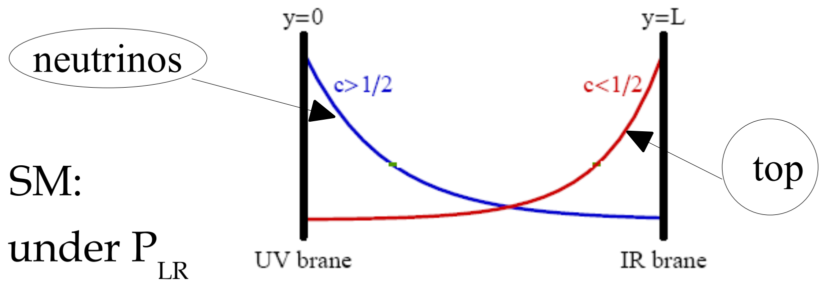
II. EWSB mechanism is not specified

Fermions:

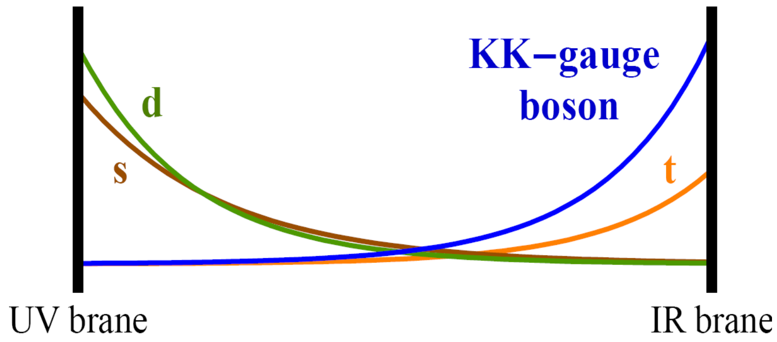
I. Three different representations of $SU(2)_L \times SU(2)_R$

II. Different localizations in the bulk of the fermions of the SM:

III. Left down quarks (all three generations) are symmetric under P_{LR}



Non Universality & FCNC at Tree Level



- KK tower of heavy gauge bosons
  ...that are all localized towards the IR brane

- Their couplings to SM fermions are non-universal
  ...because couplings to SM fermions depend on their localization

$$\Delta_{L,R} \propto \int_0^L dy\, e^{ky} \left[f^{(0)}_{L,R}(y, c^i_\Psi) \right]^2 g(y)$$

Rotation to mass eigenstates:
non universalities
off-diagonal terms
Flavour Changing Neutral Currents at Tree Level

$$\Delta_{L,R} \sim U^\dagger \begin{pmatrix} \clubsuit & & \\ & \spadesuit & \\ & & \heartsuit \end{pmatrix} U$$

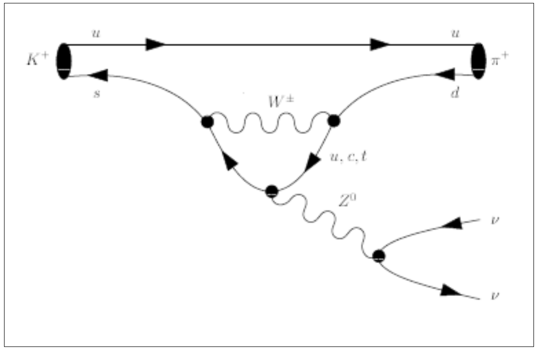
Non universalities

- New sources of flavour and CP violation beyond CKM: **model is non-MFV**

Rare Decays: some Theoretical Aspects

Example: $K^+ \to \pi^+ \nu \bar{\nu}$

Standard Model



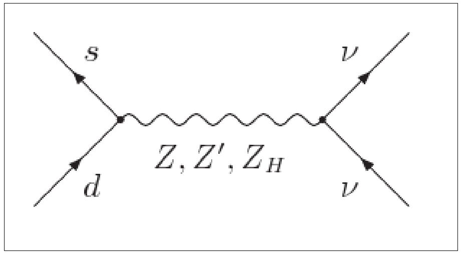
first at one loop level

I. The effective Hamiltonian:

$$\mathcal{H}_{eff}^{SM} \propto V_{ts}^* V_{td} X_{SM} \left(\bar{s}\gamma_\mu \left(1-\gamma_5\right) d\right) \left(\bar{\nu}\gamma_\mu \left(1-\gamma_5\right) \nu\right)$$

Only operator involved

Warped Extra Dimensions



additional diagrams at tree level

I. Modification of the coefficient of the SM operator

II. New operator is induced:

$$\mathcal{H}_{eff}^{new} \propto V_{ts}^* V_{td} X^V \left(\bar{s}\gamma_\mu d\right) \left(\bar{\nu}\gamma_\mu \left(1-\gamma_5\right) \nu\right)$$

III. Main contributions from the coupling of Z to right handed down quarks

Rare Decays: K physics vs B physics

$$s \to d\,\bar{\nu}\,\nu \quad vs \quad \left(b \to d\,\bar{\nu}\,\nu \;\vee\; b \to s\,\bar{\nu}\,\nu\right)$$

- Effective Hamiltonian:

$$\mathcal{H}^{tot}_{eff} \propto V^*_{tq_1} V_{tq_2} \left(X_{SM} + X^{V-A}_{q_1,q_2}\right) \left(\bar{q}_1 \gamma_\mu \left(1-\gamma_5\right) q_2\right) \left(\bar{\nu} \gamma_\mu \left(1-\gamma_5\right) \nu\right) +$$
$$+ V^*_{tq_1} V_{tq_2} X^{V}_{q_1,q_2} \left(\bar{q}_1 \gamma_\mu q_2\right) \left(\bar{\nu} \gamma_\mu \left(1-\gamma_5\right) \nu\right)$$

$$q_1 \to q_2\,\bar{\nu}\,\nu$$

- where the new functions:

$$X^{V-A,V}_{q_1,q_2} \propto \frac{1}{\lambda^{(q)}_t} F\left(\Delta^{\nu\nu}_L, \Delta^{q_1,q_2}_{L,R}\right)$$

K meson: $\lambda^{(q)}_t = V^*_{ts} V_{td} \approx 4 \cdot 10^{-4}$

B mesons: $\lambda^{(q)}_t = V^*_{tb} V_{tq} \approx 10^{-2} \quad , \qquad q = d, s$

- **Main Messages:**

I. Non universalities

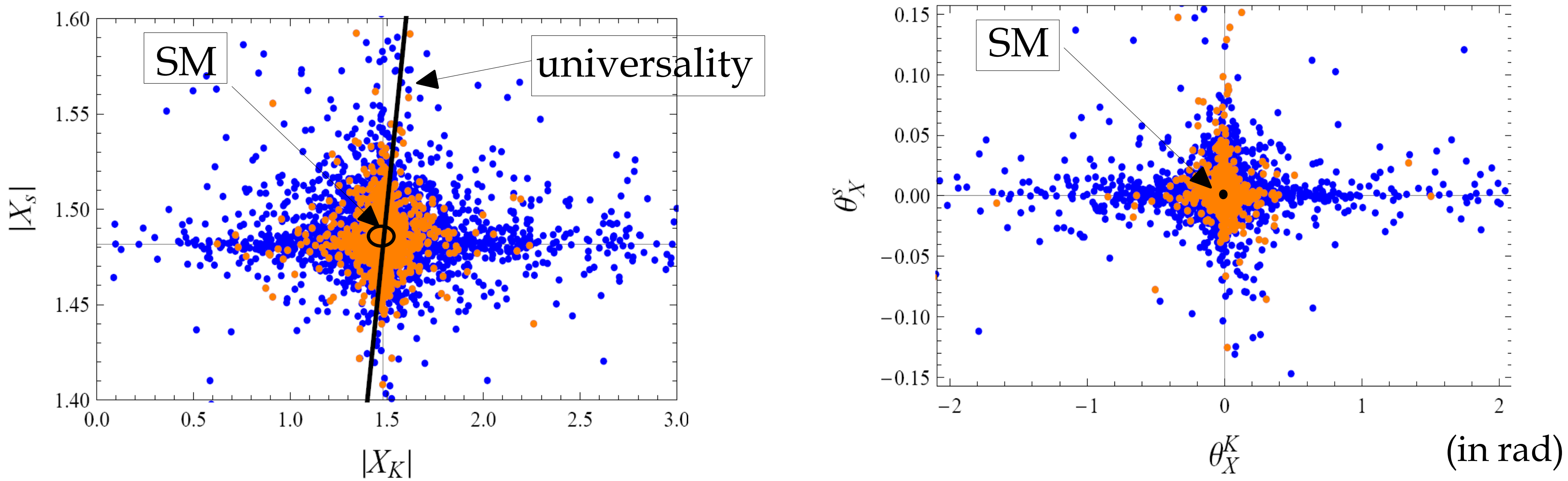
II. Expected: bigger contributions of the new physics in the K sector

Non universality & New Sources of CP Violation

1) Points which satisfy all the ΔF=2 constraints;
2) Also small fine tuning is required

real function

$$X_K = X_{SM} + X_{sd}^{V-A} + X_{sd}^{V} = |X_K|\, e^{i\theta_X^K}$$
$$X_s = X_{SM} + X_{bs}^{V-A} + X_{bs}^{V} = |X_s|\, e^{i\theta_X^s}$$



I. Deviation from the universality:

$$|X_K| \neq |X_s|$$

II. Bigger new physics contribution in X_K

I. New phases:

↓

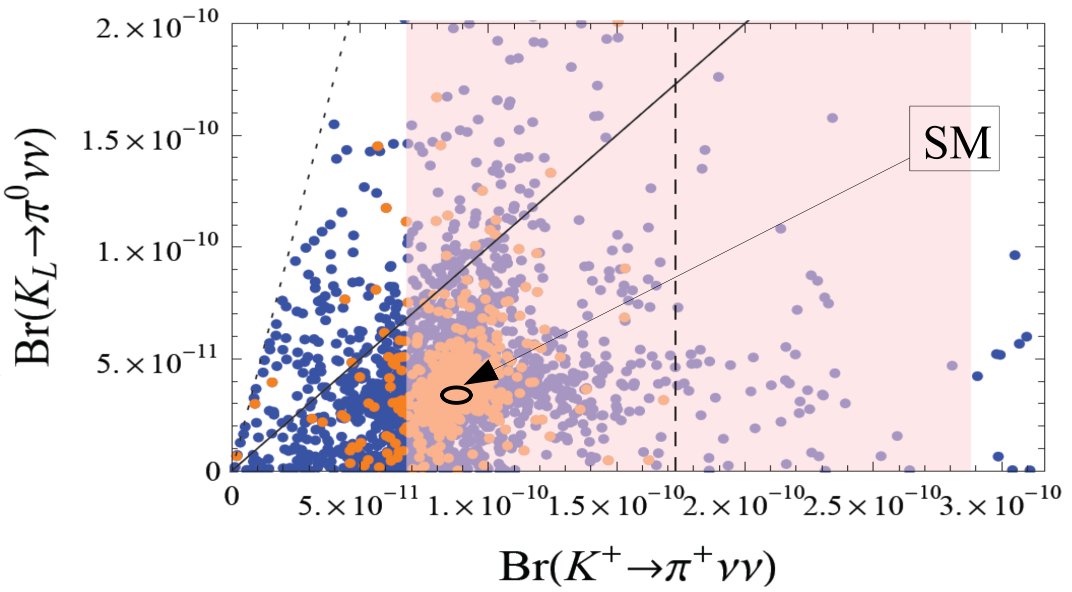
new sources of CP violation

II. Bigger contribution in θ^K_X

Rare Decays of K mesons...

Theoretically very clean and very sensitive to θ^K_x

Possible deviation of 500% from the SM



Possible deviation of 200% from the SM

- Values predicted by the SM:

$$Br\left(K^+\to\pi^+\nu\bar{\nu}\right) = (8.4\pm0.8)\,10^{-11}$$
$$Br\left(K_L\to\pi^0\nu\bar{\nu}\right) = (2.9\pm0.4)\,10^{-11}$$

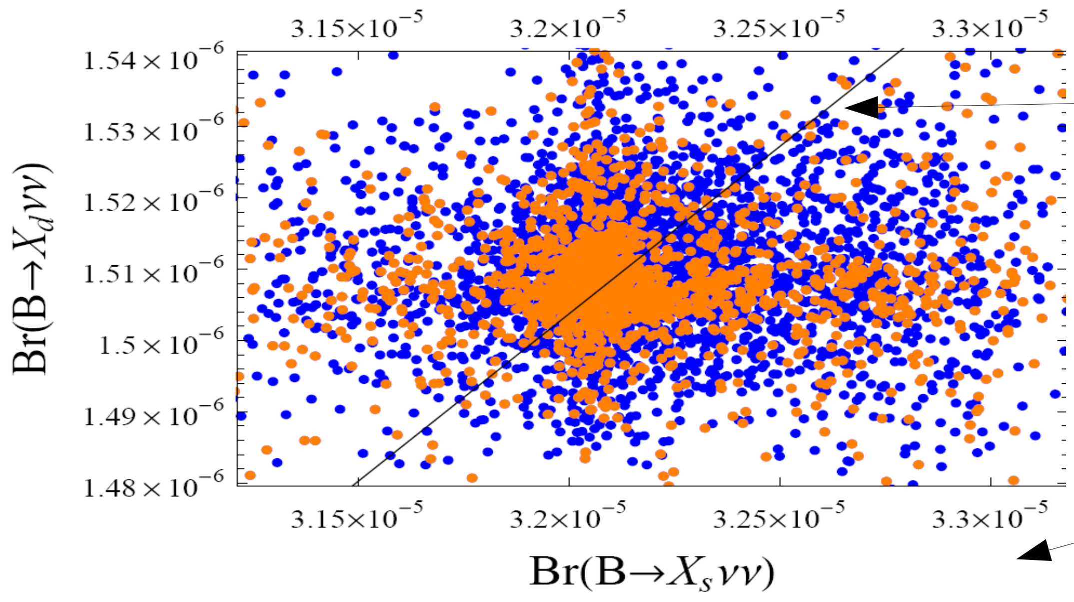
- Experimental bounds:

$$Br\left(K^+\to\pi^+\nu\bar{\nu}\right) = \left(17.3^{+11.5}_{-10.5}\right)10^{-11}$$
$$Br\left(K_L\to\pi^0\nu\bar{\nu}\right) < 2.1\cdot10^{-7} \quad (90\%\ CL)$$

- <u>Some Observations</u>:
  - I. It's possible to have **simultaneously big contributions** for both these branching ratios
  - II. The most part of the points stays **in the experimental range** for $K^+\to\pi^+\nu\bar{\nu}$

...and Rare Decays of B mesons

Inclusive Decay



Model with MFV

Possible deviation of 3% from the SM

Possible deviation of 5% from the SM

B decays not so sensitive to new physics

- Values predicted by the SM:

$Br\,(B \to X_s \nu\bar{\nu}) \approx 3.2 \cdot 10^{-5}$

$Br\,(B \to X_d \nu\bar{\nu}) \approx 1.5 \cdot 10^{-6}$

- Experimental bounds:

$Br\,(B \to X_s \nu\bar{\nu}) < 64 \cdot 10^{-5}$

$Br\,(B \to X_d \nu\bar{\nu}) < ??$

- Some Observations:

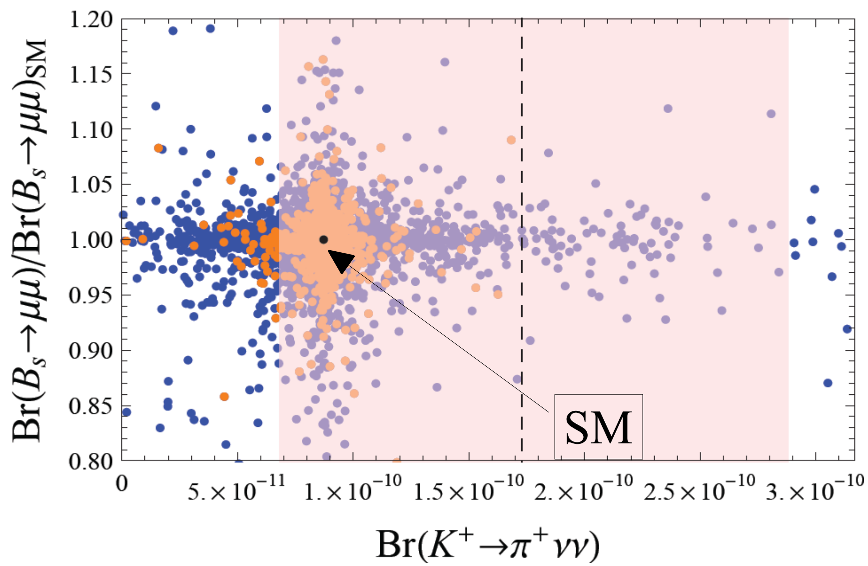
I. Very clean correlation between the two observables in models with MFV

II. In general: $\frac{Br\,(B \to X_d \nu\bar{\nu})}{Br\,(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2} P$ where $P \equiv \frac{|X_d^{V-A} + X_d^V/2|^2 + |X_d^V/2|^2}{|X_s^{V-A} + X_s^V/2|^2 + |X_s^V/2|^2}$

III. In models with MFV, P=1 (universality); in WED we have deviations

Correlations

B physics vs K physics



I. SM prediction

$$Br\left(B_s \to \mu^+\mu^-\right) = (3.35 \pm 0.32) \cdot 10^{-9}$$

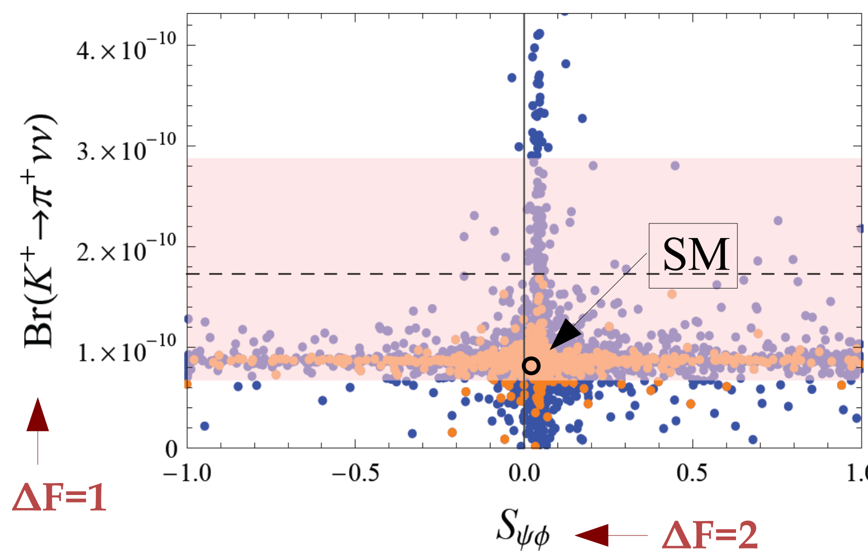
II. Measurements

$$Br\left(B_s \to \mu^+\mu^-\right) < 4.7 \cdot 10^{-8}$$

For these two decays:

Possible deviations of 15% in the B system;
Possible deviations of 200% in the K system

ΔF=1 vs ΔF=2 observables



I. SM prediction

$$S_{\psi\phi} \approx 0.04\,, \quad Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) = (8.4 \pm 0.8)\, 10^{-11}$$

II. Measurements

$$S_{\psi\phi} \approx 0.4\,, \quad Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \left(17.3^{+11.5}_{-10.5}\right) 10^{-11}$$

Difficult to obtain simultaneously large deviations from the SM for both the observables

See next talk...

Conclusions

<u>Warped Extra Dimension with custodial Protection shows:</u>

- Elegant solutions for:

  I. Gauge Hierarchy Problem;
  II. Flavour Problem;
  III. ...

Testability at LHC since $M_{KK} \approx (2-3)\,TeV$

- In the Flavour Sector:
  - <u>In Rare Decays:</u>

    I. Big Effects in K physics ⟵ Testable Deviations from the SM

    II. Smaller Effects in B physics ⟵ Challenging Testability of Deviations from Models with MFV

    III. Interesting Correlations between different Observables with ΔF=1

  - <u>In ΔF=2 Observables:</u> See next talk...

...and Correlations between ΔF=2 and ΔF=1 Observables