Patterns of Flavour Violation in a Warped Extra Dimensional Model with Custodial Protection

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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
- Neutral Meson mixing: Theory
- Neutral Meson mixing: Numerics
- Rare Decays of B and K mesons: Theory
- Rare Decays of B and K mesons: Numerics

3. Conclusions

- M. Blanke, A.J.Buras, B.Duling, S.Gori, A.Weiler,
$\Delta F = 2$ Observables and Fine-Tuning in a Warped Extra Dimension with Custodial Protection [hep-ph/0809.1073]

- M. Blanke, A. J. Buras, B. Duling, K. Gemmler, S. Gori,
Rare K and B decays in a Warped Extra Dimension with Custodial Protection [hep-ph/0812.3803]

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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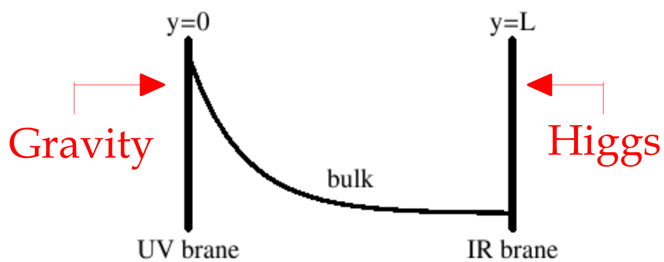
How to address it in WED Contexts?



Solution to the 5D Einstein equations in the bulk:

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

Warping-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 is addressed!

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?**

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

How to solve it in WED Contexts?

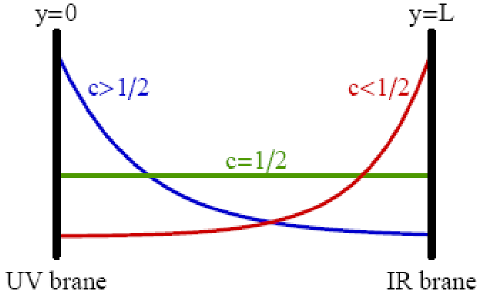
- Preliminaries
  - Gauge fields and matter fields can propagate into the 5th dimension
  - For each particle species, there is an infinite number of solutions:

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)

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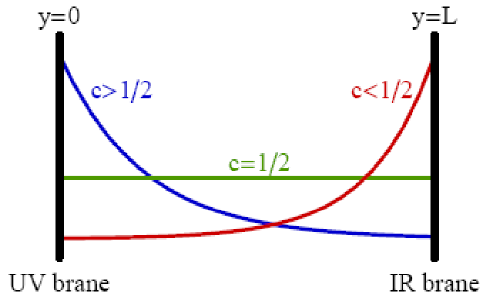

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Strong dependence on bulk masses

- 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:

$$c_1 = 0.66\ ,\quad c_2 = 0.59\ ,\quad c_3 = 0.41$$
$$Y_1 = 0.0017\ ,\quad Y_2 = 0.017\ ,\quad Y_3 = 0.42$$

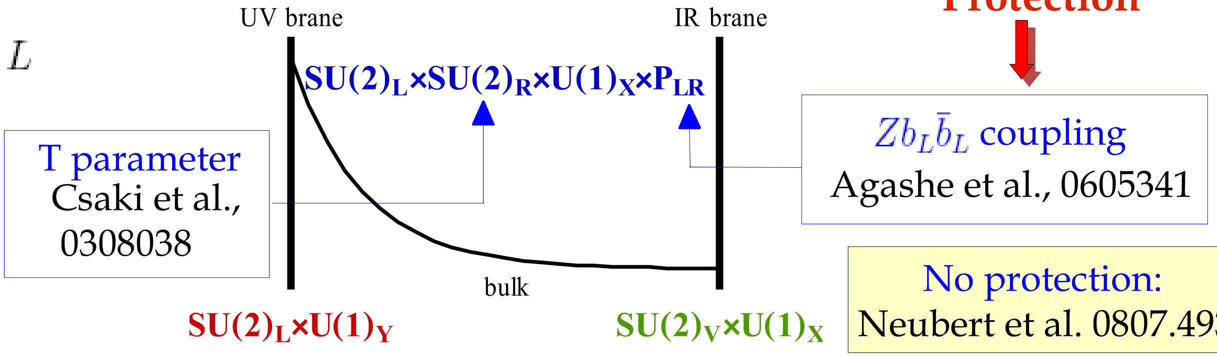
Definition of the Model

1. Symmetry group and geometric structure:

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

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

WED with Custodial Protection



No protection:
Neubert et al. 0807.4937

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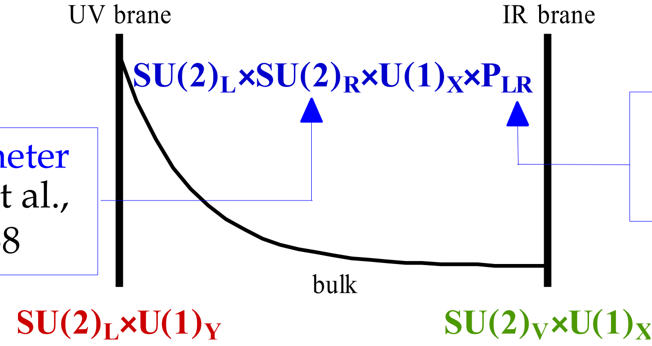
T parameter
Csaki et al., 0308038



WED with Custodial Protection

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

No protection:
Neubert et al. 0807.4937

2. Field content:

Gauge bosons:

I. Gauge eigenstates:

$$W^a_{L\mu}(++)\,,\quad B_\mu(++),\quad G^c_\mu(++),$$
$$W^b_{R\mu}(-+)\,,\quad Z_{X\mu}(-+)$$
$$a=1,2,3\;;\;\; b=1,2;\;\; c=1,...,8$$

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:

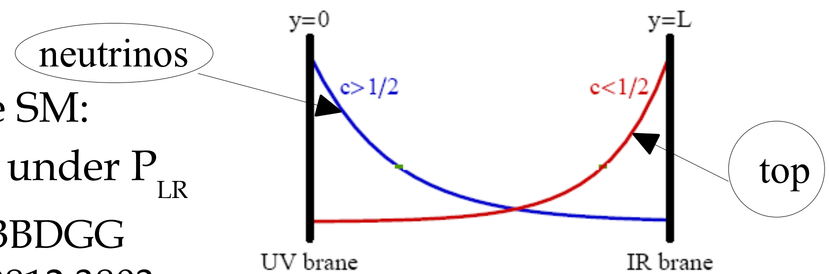
I. Bidoublet of $SU(2)_L \times SU(2)_R$
II. EWSB mechanism is not specified
III. Resides on the IR brane

Fermions:

I. Different localizations in the bulk of the fermions of the SM:
II. Left down quarks (all three generations) are symmetric under P_{LR}

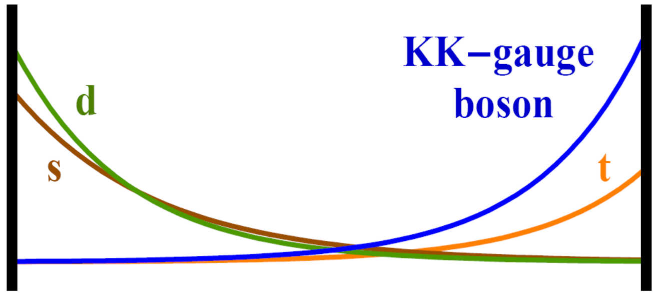
→ generalization of the protection to $Zd^i_L\bar{d}^j_L$

BBDGG
0812.3803



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

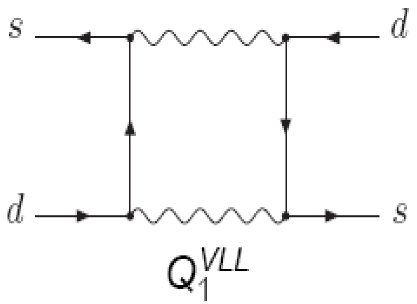
- New sources of flavour and CP violation beyond CKM: **model is non-MFV**

Meson Mixing: some Theoretical Aspects

Example: $K^0 - \bar{K}^0$ mixing

Standard Model

Process through boxes



action of the GIM-mechanism

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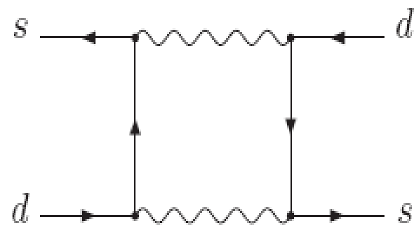
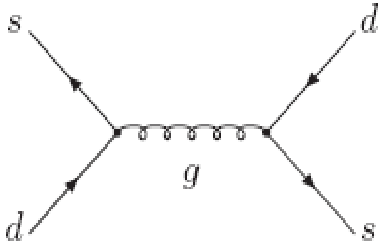


Q_1^{VLL}

action of the GIM-mechanism

Warped Extra Dimensions

Process already at tree level



Q_1^{VLL}, Q_1^{VRR}, Q_1^{LR}, Q_2^{LR}

Operators involved:

$$Q_1^{VLL} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_L d)$$ (also in the SM)

$$Q_1^{VRR} = (\bar{s}\gamma_\mu P_R d)(\bar{s}\gamma_\mu P_R d)$$

$$Q_1^{LR} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_R d)$$

$$Q_2^{LR} = (\bar{s}P_L d)(\bar{s}P_R d)$$ (only for gluons)

Particles exchanged at tree level:

- KK gluons
- KK photons
- Z, Z_H, Z'

Operator Structure in Meson Mixing

In the K system:

- Large chiral enhancement of Q_2^{LR} $\propto \left(\frac{m_K}{m_s + m_d}\right)^2$
- Strong RG running of Q_2^{LR}

Q_2^{LR} dominates → contribution of the gluons is predominant

In the B system:

- Less pronounced chiral enhancement of Q_2^{LR} $\propto \left(\frac{m_B}{m_b + m_{d,s}}\right)^2$
- A bit weaker RG running of Q_2^{LR}

Both Q_1^{VLL} and Q_2^{LR} are important → EW gauge bosons are competitive
(missed in the literature)

In both systems:

- Z boson not relevant:
  I. left-handed couplings protected by P_{LR}
  II. right-handed couplings enter only at higher order

Our Approach to the Analysis of Meson Mixing

Previous analysis:

Csaki, Falkowski, Weiler, 0804.1954

tension between anarchic Yukawas, ε_K, and a low high energy scale M_{KK}

totally anarchic Yukawas and constraint from ε_K → $M_{KK} \geq 20\,\text{TeV}$

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Issues (ε_K and beyond) Blanke, Buras, Duling, S. G., Weiler, 0809.1073

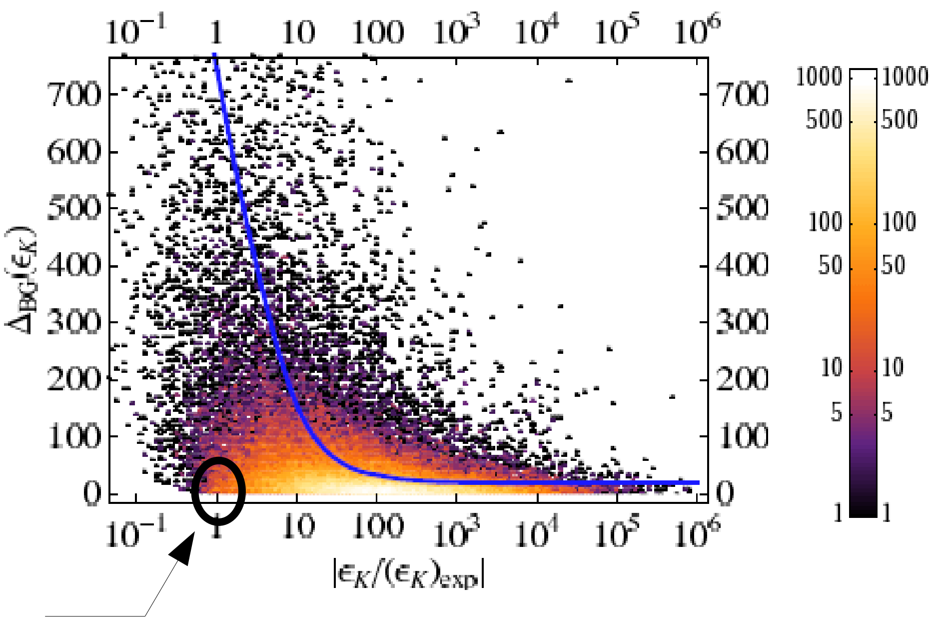
- Consider full operator basis and NLO RG running
- → Take into account also EW contributions
- Partially give up complete anarchy of Yukawas
- → Fix a high energy scale in the reach of LHC (**M_{KK}~(2-3) TeV**)
- Fit all the well measured ΔF=2 observables
- → Identify areas in parameter space with only moderate fine tuning
- Make prediction for the not well measured ΔF=2 observables

ε_K: the most Challenging Observable

Our definition of fine tuning:

$$\left(\frac{1}{t}\right)_{BG} = max_i \frac{d\log(Obs.)}{d\log(x_i)} = max_i \frac{x_i}{Obs.}\frac{dObs.}{dx_i}$$

Barbieri, Giudice
Nucl.Phys.B306:63



fitting SM quark masses and CKM elements within 2σ

- Generically $\varepsilon_K \sim 10^2\, \varepsilon_K^{exp}$
- Average of the fine tuning decreases with increasing ε_K

- Parameter sets with moderate fine tuning and $\varepsilon_K \sim \varepsilon_K^{exp}$ exist

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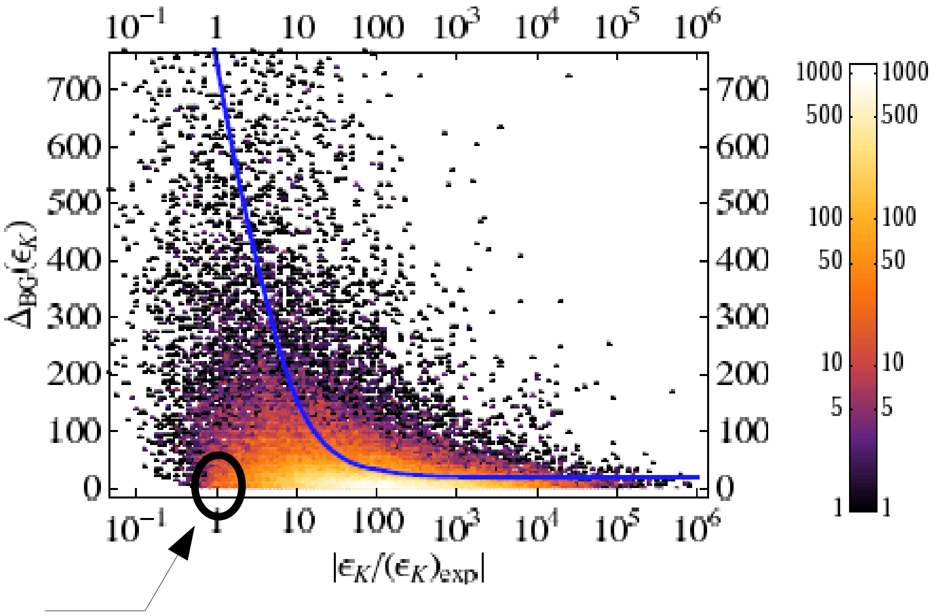

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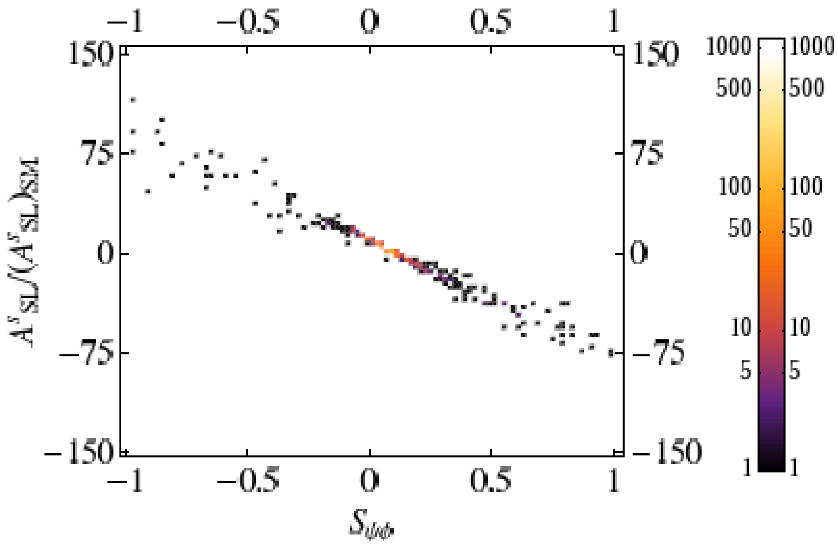
No problem in fitting all the other well measured $\Delta F=2$ observables (ΔM_K, ΔM_d, ΔM_s, $S_{\psi Ks}$) with small fine tuning

Predictions for Observables not Measured yet



- $S_{\psi\varphi}$ can be enhanced well beyond the SM prediction ~ 0.04
- **Strong correlation** between the 2 observables exists

CDF, D0 hint at $S_{\psi\varphi}$ ~ 0.4 → significant effects in A^s_{SL}

fitting SM quark masses and CKM elements within 2σ

&

fitting all the well measured ΔF=2 observables, with small fine tuning (≤20)

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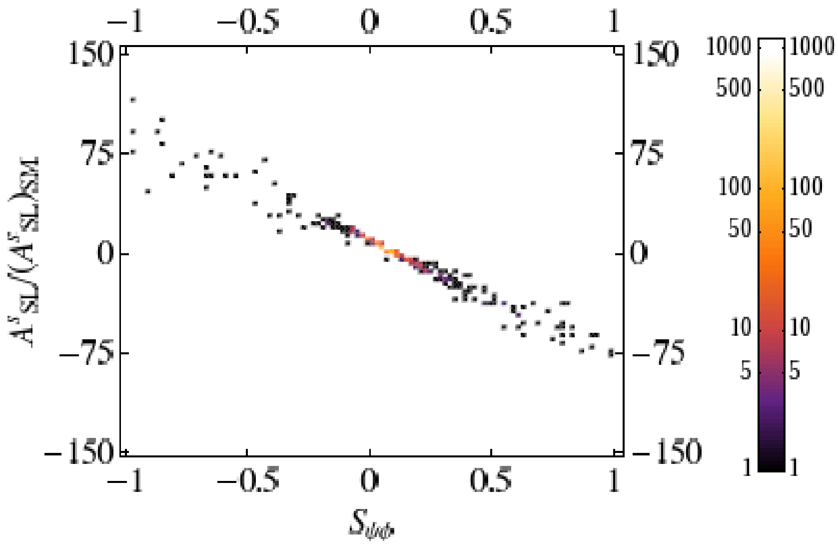

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fitting SM quark masses and CKM elements within 2σ

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fitting all the well measured ΔF=2 observables, with small fine tuning (≤20)

Small summary of the results in meson mixing:

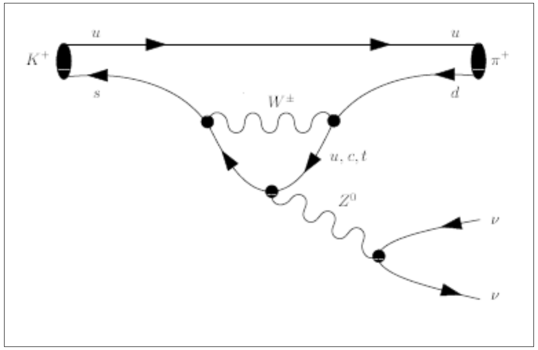
It is possible to:

- Fit SM quark masses and CKM mixings
- Address the tension with ε_K even with a low KK scale
- Fit all the precisely measured ΔF=2 observables
- Obtain large deviations from the SM of the not yet measured observables ($S_{\psi\varphi}$)

Rare Decays: some Theoretical Aspects

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

Standard Model



first at one loop level

I. The effective Hamiltonian:

$$\mathcal{H}_{eff}^{SM} \propto V_{ts}^* V_{td} X_{SM} \underline{(\bar{s}\gamma_\mu P_L d)(\bar{\nu}\gamma_\mu P_L \nu)}$$

Only operator involved

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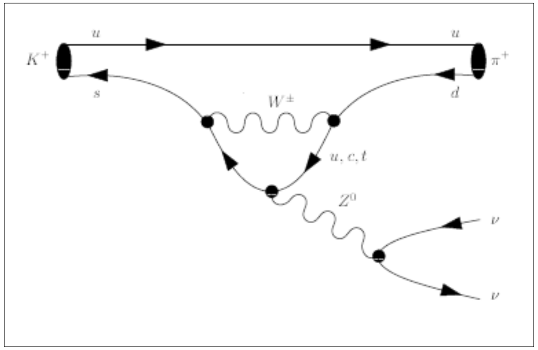

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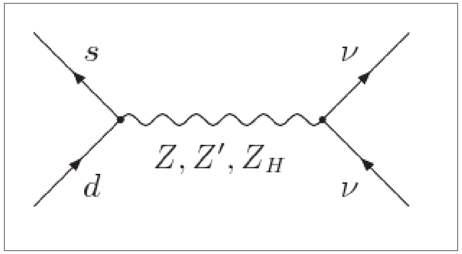
Warped Extra Dimensions



additional diagrams at tree level

I. Modification of the coefficient of the SM operator

II. New operator is induced:

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

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:

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

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

- where the new functions:

$$X_{q_1,q_2}^{V-A,V} \propto \frac{1}{\lambda_t^{(q)}} F^{V-A,V}\left(\Delta_L^{\nu\nu}, \Delta_{L,R}^{q_1,q_2}\right)$$

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

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

- **Main Messages:**

I. Non universalities

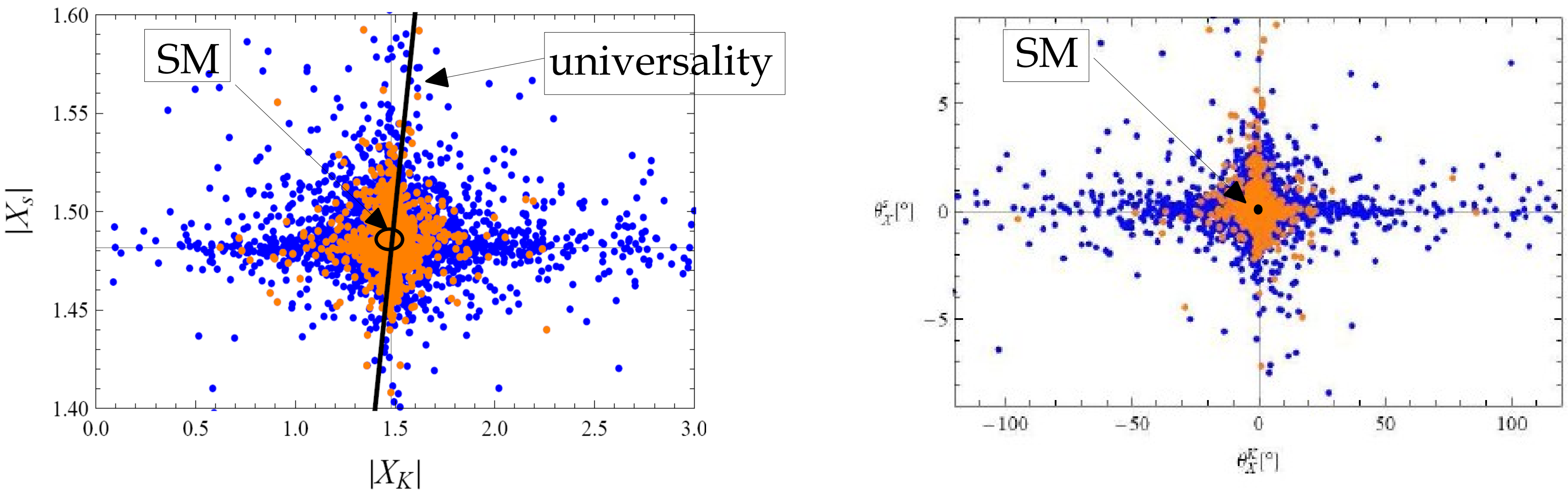
II. Expected: bigger contributions of the new physics in the K sector

Non universality & New Sources of CP Violation

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

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:

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

vs models with CMFV

II. Bigger new physics contribution in X_K

I. New phases:

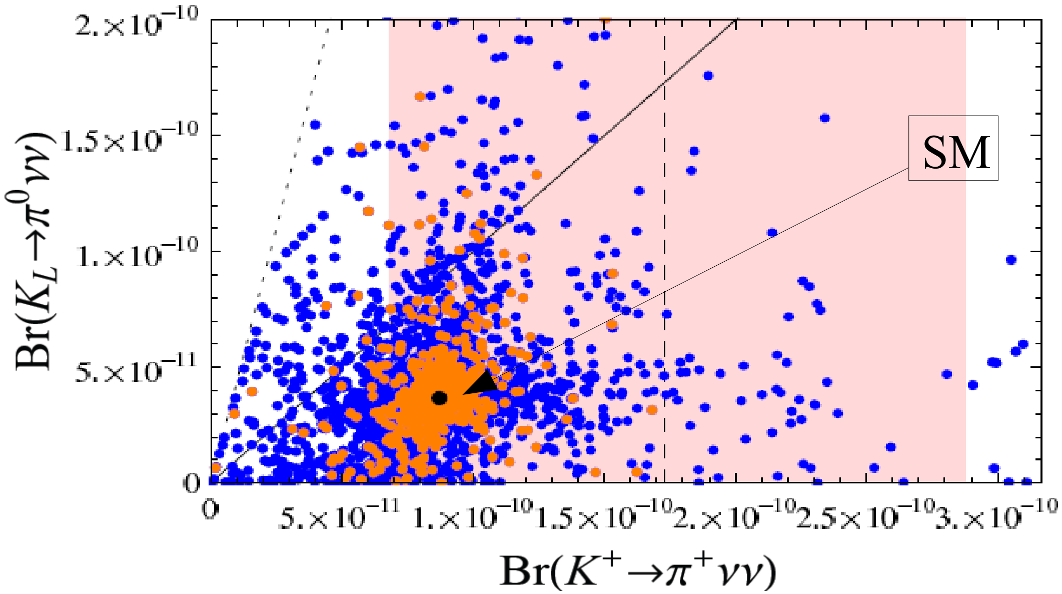
new sources of CP violation

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:

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.4 \pm 0.8)\, 10^{-11}$$
$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (2.9 \pm 0.4)\, 10^{-11}$$

- Experimental bounds:

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

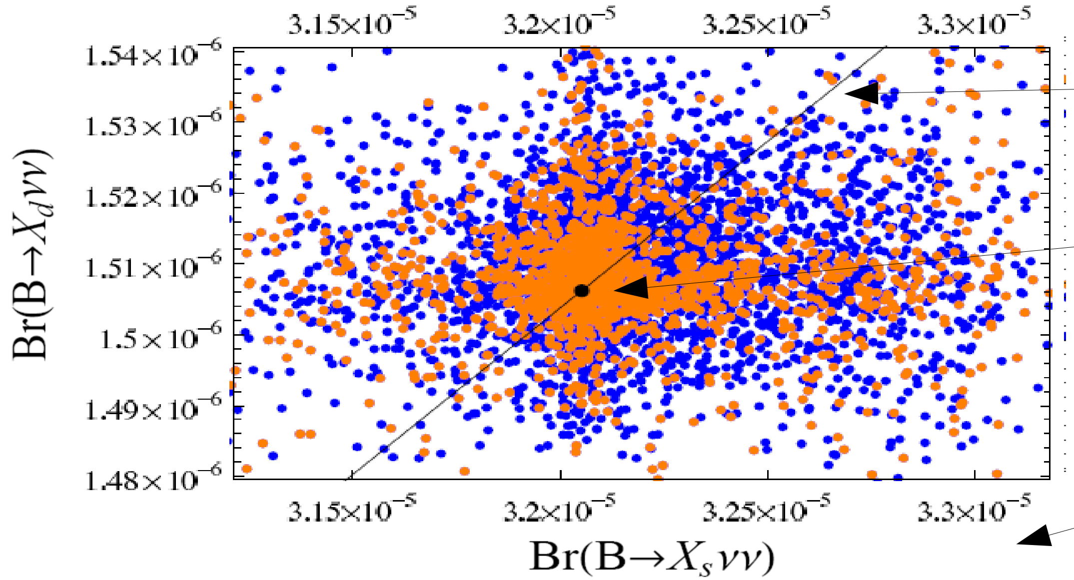
- Some Observations:

I. It is possible to have **simultaneously big contributions** for both the 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

SM

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:

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

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

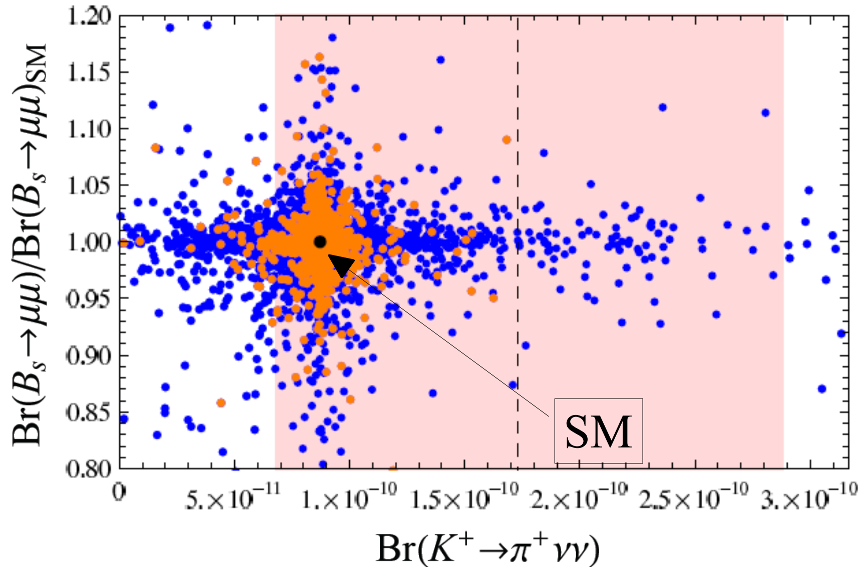
- Some Observations:

I. 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 $P \equiv \frac{|X_d^{V-A} + X_d^V/2|^2 + |X_d^V/2|^2}{|X_s^{V-A} + X_s^V/2|^2 + |X_s^V/2|^2}$

I. Very clean correlation between the two observables in models with MFV: P=1 (universality); in WED we have deviations

Correlations

B physics vs K physics



I. SM prediction

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

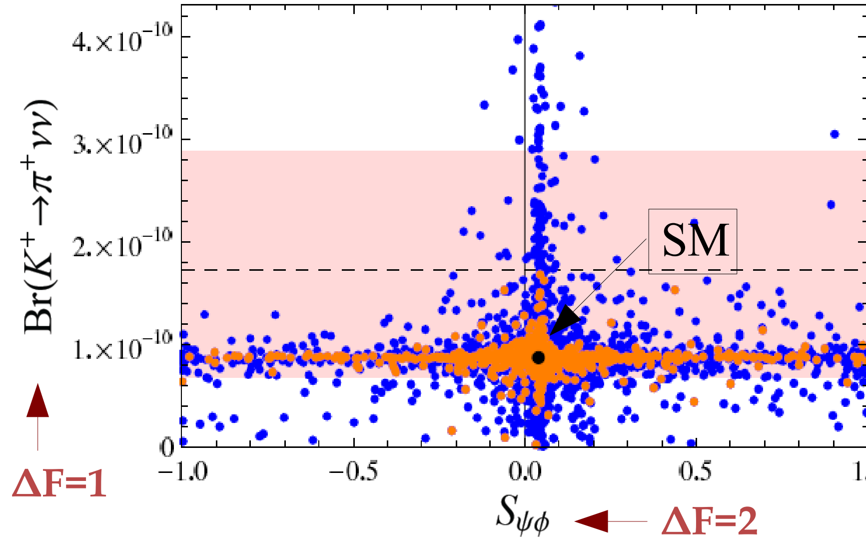
II. Measurement

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

For the 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 observables

Conclusions

Warped Extra Dimension with custodial Protection shows:

- Elegant addressing of:

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

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

- In the Flavour Sector:

I. Existence of regions of parameter space which:

- Fit masses of SM quarks and CKM elements
- Reproduce all the well measured $\Delta F=2$ observables (ε_K, ΔM_K, ΔM_d, ΔM_s, $S_{\psi K_S}$)
- Have a **small amount of fine tuning** on the observables → **Address the problem with ε_K**
- Can predict possible **large deviations** from the SM of observables not measured yet ($S_{\psi\varphi}$, A^s_{SL})

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II. Restricting to these regions:
If future measurements of $\mathbf{S_{\psi\varphi}}$ are:

- large: Branching ratios of **K meson** decays are small, **SM like**
- small: Room for **large deviations of K** meson decays from SM

In any case B meson decays **deviate slightly** from the SM

Predictions of the theory