Probing Randall-Sundrum Model through FCNC

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on New Physics, Flavors and Jets

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Outline

1. Motivations for WED:

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

2. Randall-Sundrum Scenario:

- The Model analyzed
- New Features in the Flavor Sector (FCNC at Tree Level and non Unitarity of CKM)
- Neutral Meson Mixing: Theory and Numerics
- Rare Decays of B and K Mesons: Theory and Numerics

3. Conclusions

- M. Blanke, A.J.Buras, B.Duling, S.Gori, A.Weiler **[JHEP03(2009)001**]
- M. Blanke, A. J. Buras, B. Duling, K. Gemmler, S. Gori **[JHEP 0903:108,2009]**
- M. Albrecht, M. Blanke, A. J. Buras, B. Duling, K. Gemmler **arXiv:0903.2415** [hep-ph]
- A. J. Buras, B. Duling, S. Gori .... **arXiv of this week**!

Flavor Problem & its Solution (1)

- Experiments tell us:

hierarchies

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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How to solve it in the WED Contexts?

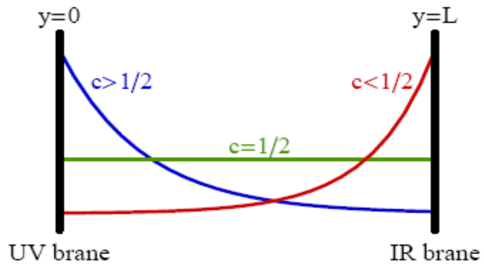
- Preliminaries
  - Gauge fields and matter fields can propagate into the 5th dimension
  - For each particle species, there is an infinite number of solutions:

Kaluza-Klein tower of particles

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

Flavor Problem & its Solution (2)

- Zero Modes of Fermions:



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

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

Strong dependence on bulk masses

Flavor Problem & its Solution (2)

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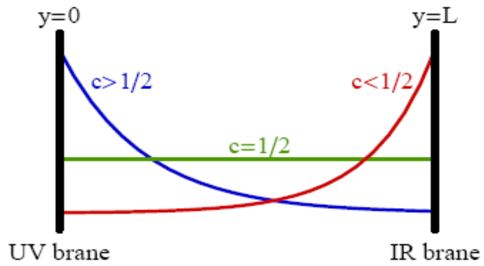

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Strong dependence on bulk masses

The Solution of the Flavor Problem:

I. 4D Yukawas in terms of shape functions:

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

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

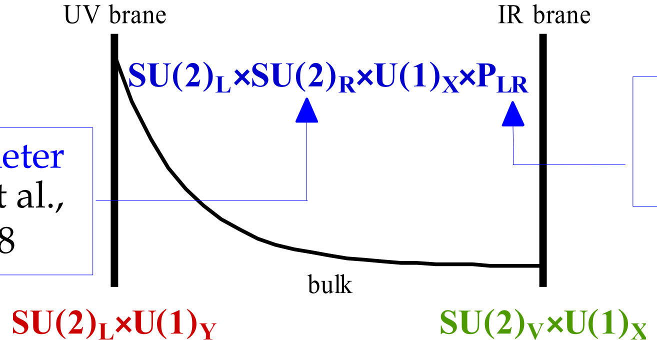
1. Symmetry group and geometric structure:

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

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

WED with Custodial Protection

T parameter
Csaki et al., 0308038



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

No protection:
Neubert et al. 0807.4937

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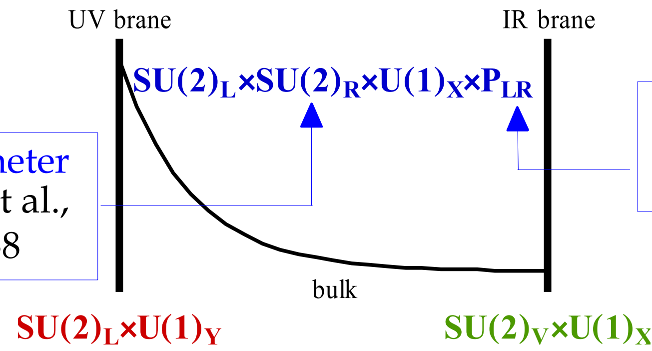

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2. Field content:

Gauge bosons:

I. Gauge eigenstates:

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

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

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

II. Mass eigenstates:

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

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

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

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

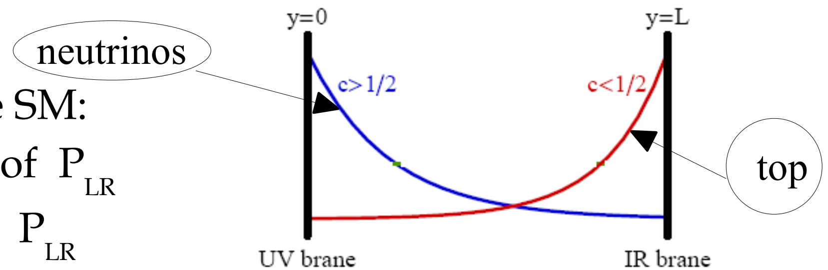
Gauge bosons of the SM

Higgs boson:

I. Bi-doublet 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. LH down quarks (all three generations) are eigenstates of P_{LR}
III. RH up quarks (all three generations) are eigenstates of P_{LR}



Protection Mechanism

Generalization of Agashe et al., 0605341

Theorem: In theories with $SU(2)_L \times SU(2)_R \times P_{LR}$ gauge symmetry

if a fermion F has $T_L = T_R \,,\ T_L^3 = T_R^3$ or $T_L^3 = T_R^3 = 0$

then

its coupling $ZF\bar{F}$ is **SM like**

In RS model: relation not spoiled by the mixing with KK-fermions

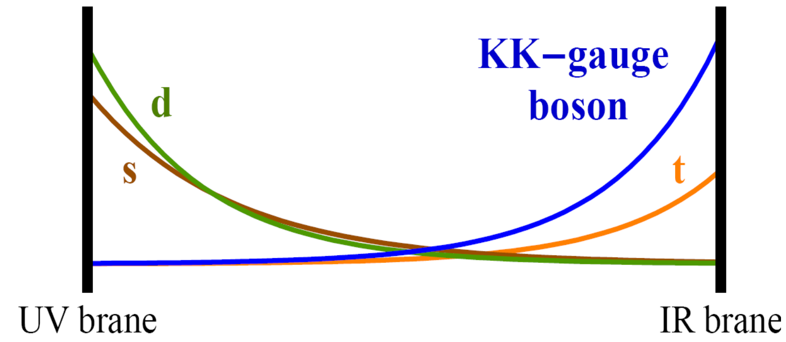
Buras, Duling, SG

Consequence for SM fermions: $Zd_L^i\bar{d}_L^j$ and $Zu_R^i\bar{u}_R^j$ are mainly SM like

Blanke, Buras, Duling, Gemmler, SG
JHEP 0903:108,2009

Small contributions to flavor violation due to the breaking of P_{LR} symmetry

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

Flavor 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 flavor and CP violation beyond CKM: **model is non-MFV**

FCNC for the Z boson of the SM

Two sources of FCNC at tree level: due to EWSB we have

- Mixing between gauge bosons: $Z = aZ^{(0)} + bZ^{(1)} + cZ_X^{(1)}$

Flat shape function

Localized towards the IR brane

→ Z: NOT flat shape function → **FCNC**

- Mixing between SM and KK fermions: $Up = (u, U^i)\,,\quad Down = (d, D^i)$

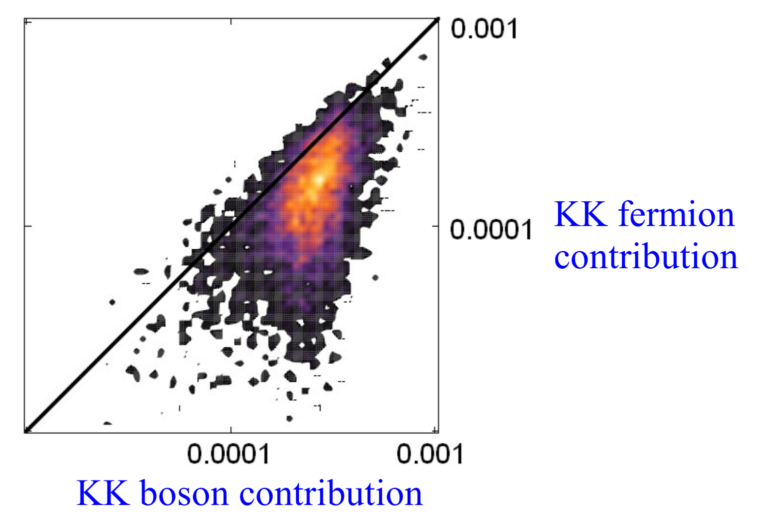
1st KK-fermions

$$\begin{cases} Up \rightarrow Up^{mass} \\ Down \rightarrow Down^{mass} \end{cases}$$

In this rotation
FCNCs appear

Example: $Zt_L\bar{c}_L$

$$\frac{|\Delta_Z^{KK} - \Delta_Z^{SM}|}{|\Delta_Z^{SM}|}$$



General feature:
1st KK fermion contributions
subdominant

Buras, Duling, SG

Unitarity of CKM matrix

$$V_{CKM} = \frac{\sqrt{2}}{g^{4D}} \tilde{U}_L G_L(W^+) \tilde{D}_L$$

$$U_L = \left(\begin{array}{c|c} \tilde{U}_L & \\ \hline & \end{array} \right)$$

$$D_L = \left(\begin{array}{c|c} \tilde{D}_L & \\ \hline & \end{array} \right)$$

Rotation matrices for Up and Down quarks

Two sources of non unitarity: due to EWSB we have

Mixing between gauge bosons

↓

non universality in $G_L(W^+)$

Mixing between SM and 1st KK fermions:

↓

$V_{CKM}^{18\times 12} = \frac{\sqrt{2}}{g^{4D}} U_L \mathcal{G}_L(W^+) D_L$ is unitary

Numerically: gauge boson contribution predominant

$$\begin{cases} V_{CKM} \cdot V_{CKM}^{\dagger} = \mathbb{1} + \mathcal{O}(\frac{v^2}{M_{KK}^2}) \\ V_{CKM}^{\dagger} \cdot V_{CKM} = \mathbb{1} + \mathcal{O}(\frac{v^2}{M_{KK}^2}) \end{cases}$$

Largest contributions when quarks of the third family involved: **2%** effects

Comparison with experimental bounds:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 > 0.9982 \qquad (PDG, 2007)$$

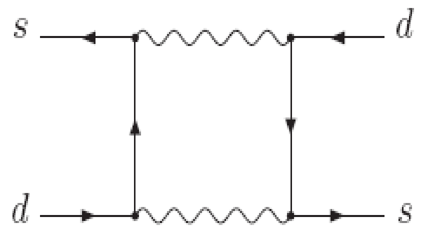
We are inside this limit for 95% of the points analyzed

Meson Mixing: some Theoretical Aspects

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

Standard Model

Process through boxes



Q_1^{VLL}

action of the GIM-mechanism

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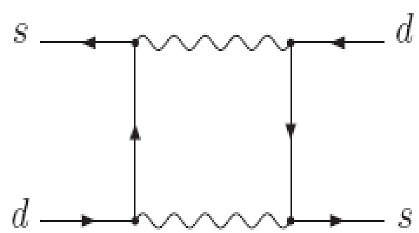
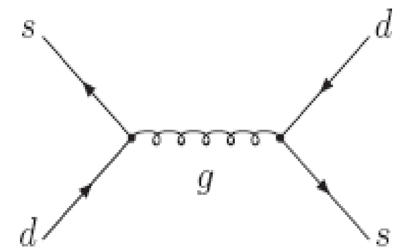


Q_1^{VLL}

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, **[JHEP 0809:008,2008]**

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

totally anarchic Yukawas and constraint from ε_K → $M_{KK} \geq 21\,\mathrm{TeV}$

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Issues (ε_K and beyond) Blanke, Buras, Duling, SG, Weiler, **[JHEP03(2009)001]**

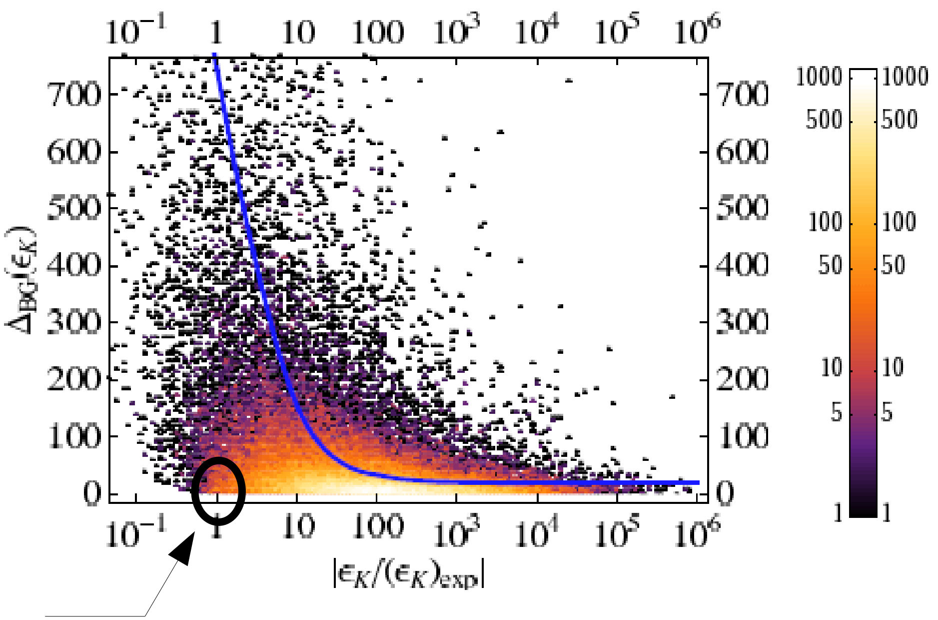
- Consider full operator basis and NLO RG running
- → Take into account also EW contributions
- Partially give up complete anarchy of Yukawas
- → Fix a high energy scale in the reach of LHC (**M_{KK}~(2-3) TeV**)
- Fit all the well measured $\Delta F=2$ observables
- → Identify areas in parameter space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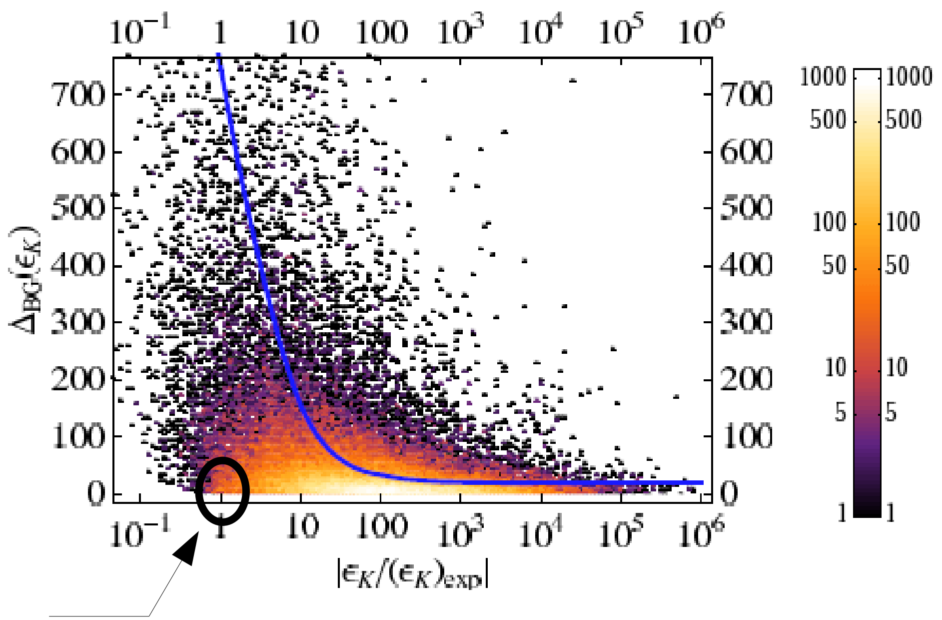

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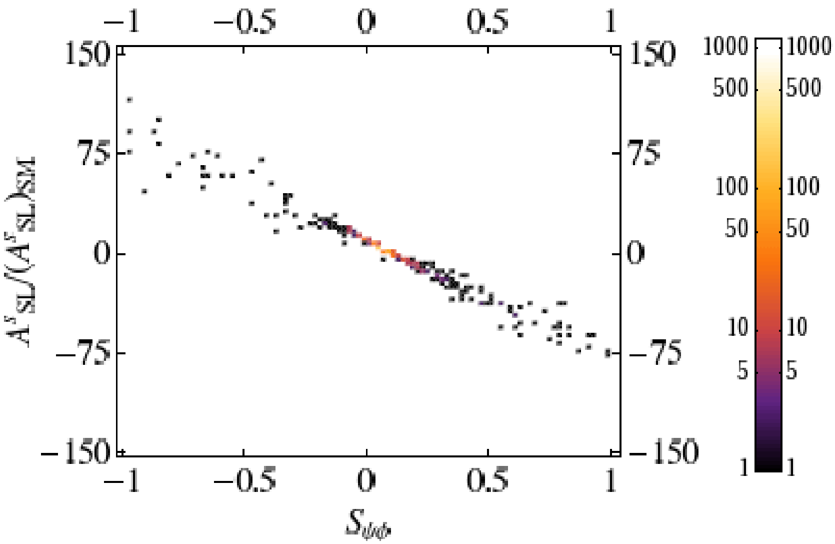
- Generically $\varepsilon_K \sim 10^2\, \varepsilon_K^{exp}$
- Average of the fine tuning decreases with increasing ε_K
- Parameter sets with moderate fine tuning and $\varepsilon_K \sim \varepsilon_K^{exp}$ exist

No problem in fitting all the other well measured $\Delta F=2$ observables (ΔM_K, ΔM_d, ΔM_s, $S_{\psi K_S}$) 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, DØ hint at $S_{\psi\varphi} \sim 0.4$ → significant effects in A^s_{SL}

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&

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

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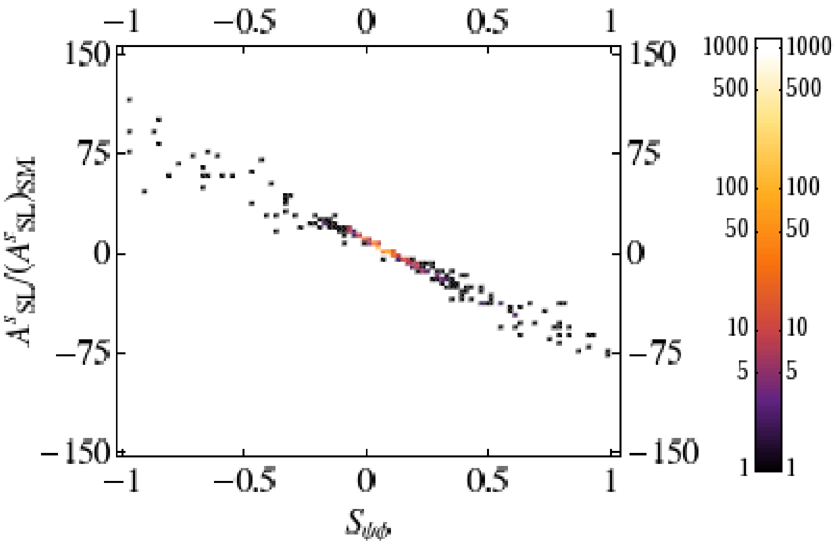

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Small summary of the results in meson mixing:

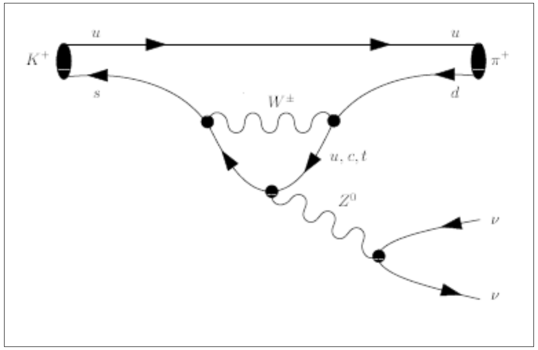
It is possible to:

- 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:

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

Only operator involved

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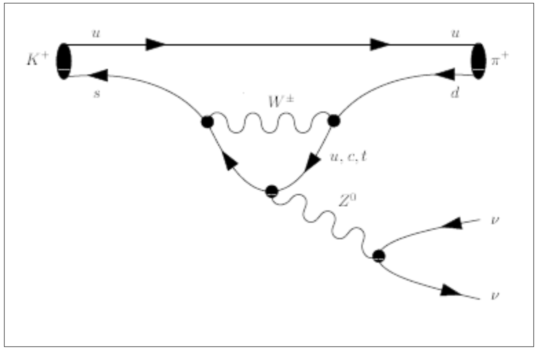

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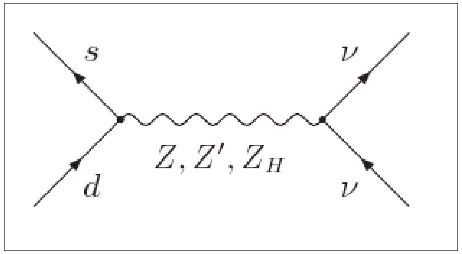


additional diagrams at tree level

I. Modification of the coefficient of the SM operator

II. New operator is induced:

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

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:

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

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

- where the new functions:

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

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

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

- **Main Messages:**

I. Non universalities

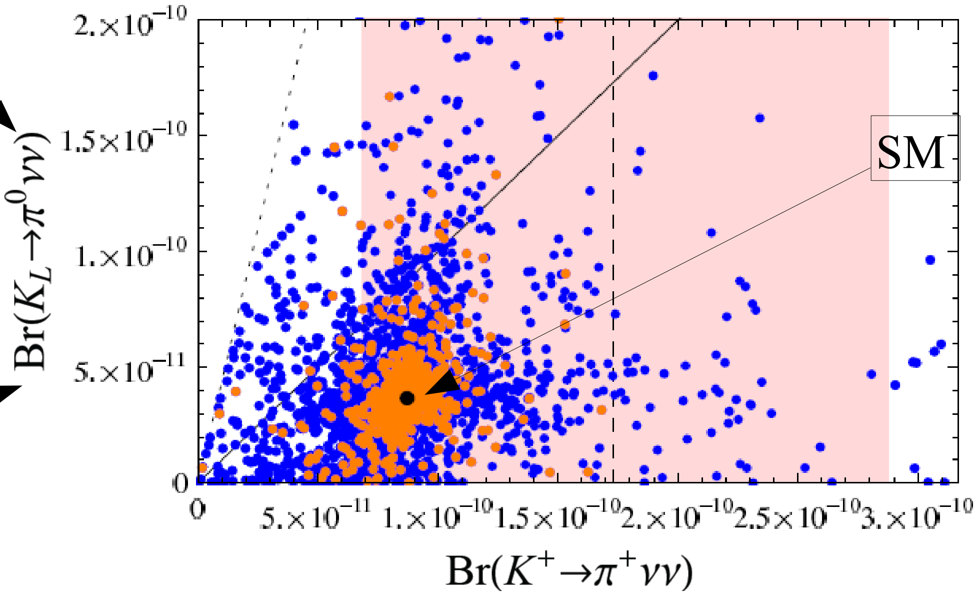
II. Expected: bigger contributions of new physics in the K sector

III. X function is now complex ⟶ new sources of CP violation

Rare Decays of K mesons...

Theoretically very clean and very sensitive to $Im\left(X_{SM}+X_{sd}^{V}+X_{sd}^{V-A}\right)$

Possible deviation of 500% from the SM



1) Points which satisfy all the $\Delta F=2$ constraints;
2) Also small fine tuning is imposed (ε_K)

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>:

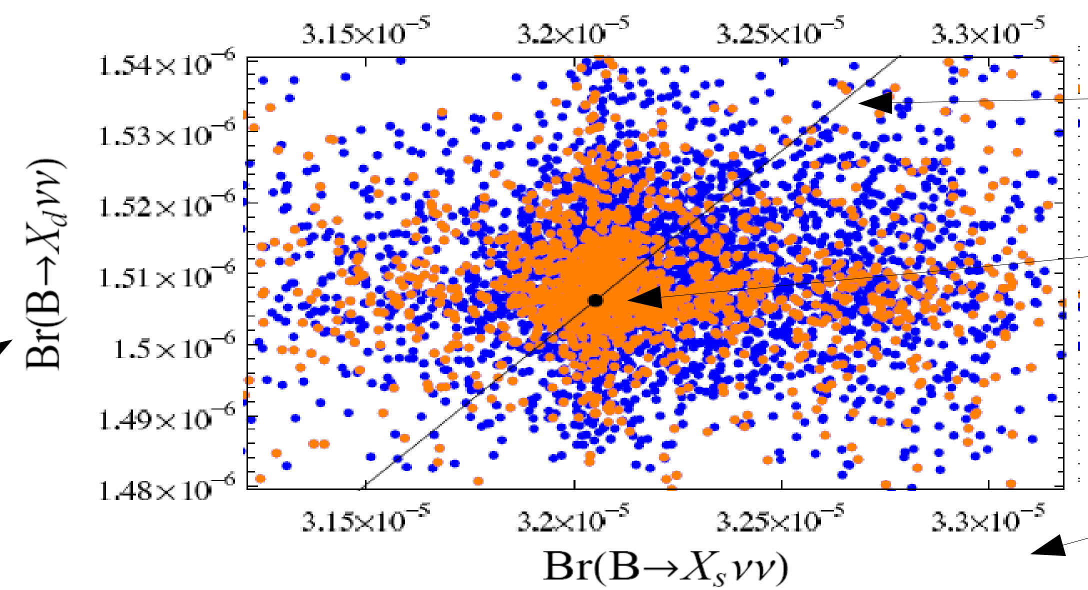
I. It is possible to have **simultaneously big contributions** for both the branching ratios

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

Possible deviation of 3% from the SM



Model with MFV

SM

Possible deviation of 5% from the SM

B decays not very 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:

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

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

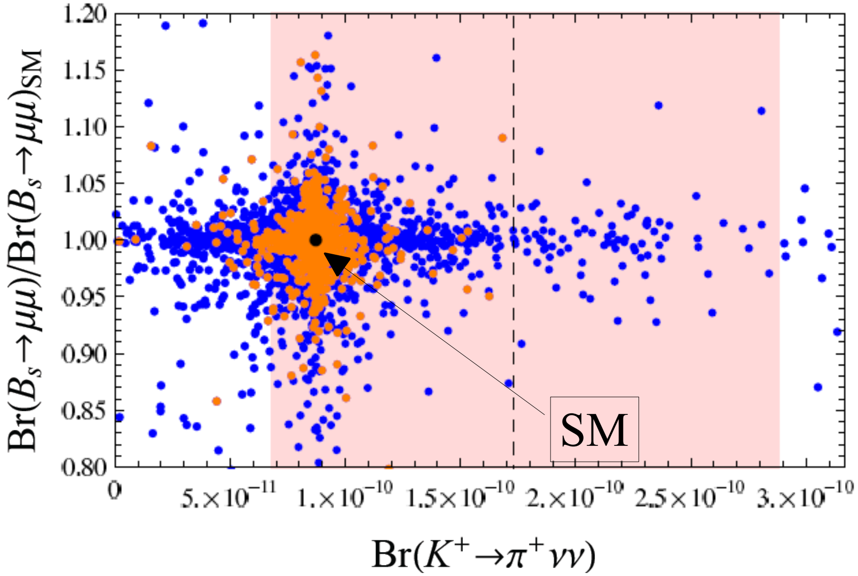
- Some Observations:

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

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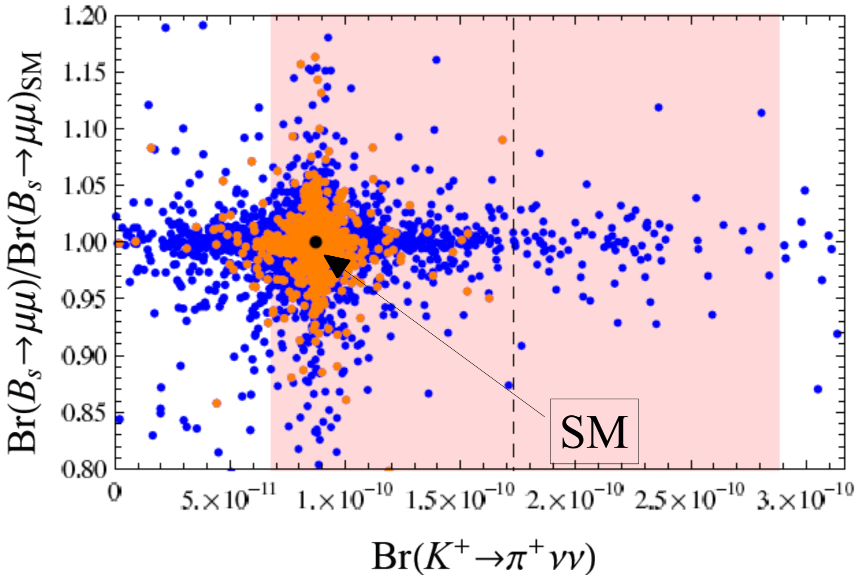

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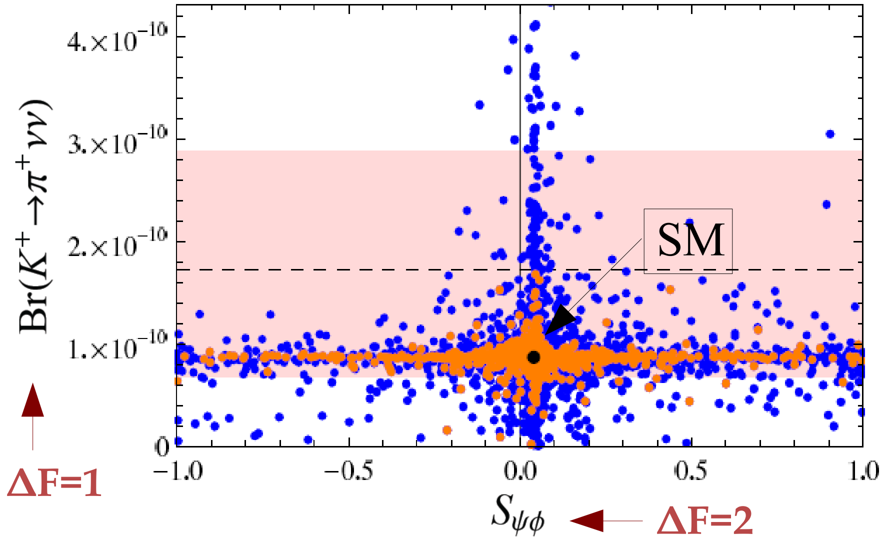
ΔF=1 vs ΔF=2 observables



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 way to address:

I. Flavor Problem
II. Gauge-Hierarchy Problem
III. ...

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

- In the Flavor 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 $S_{\psi\varphi}$ 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 can **deviate** only **slightly** from the SM

Predictions of the theory