Flavour and Extra-dimensions

Workshop on Flavour Changing and Conserving Processes

Anacapri
07-09 September 2017

Abhishek M. Iyer
(INFN Sezione di Napoli)

Direct searches at the LHC have not yielded any positive so far

It's likely any new resonances could be just outside the reach of LHC

However, these NP states could manifest in terms of additional contributions to any SM process/ flavour changing process

Observation of anomalies in the B sector have fuelled a lot of hope in this sector

Models of extra-dimensions are one of the widely pursued NP candidates

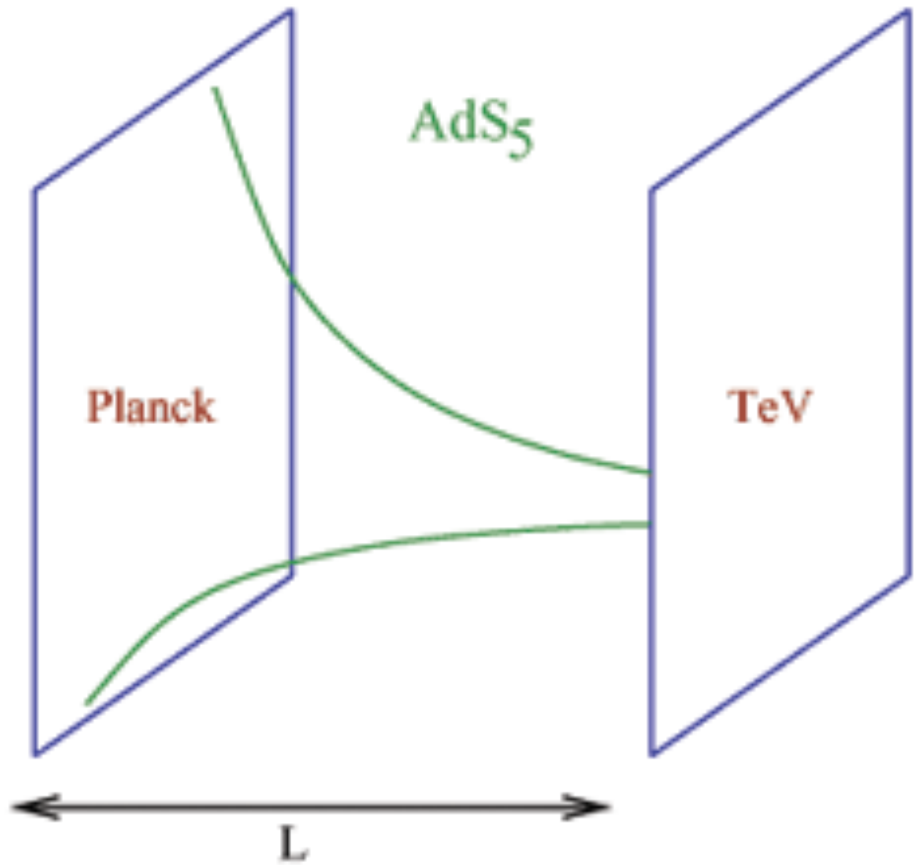
Motivated as solutions to the hierarchy problem

RS model is a strong candidate-not only for this feature

It has interesting flavour effects-leptonic and hadronic

Randall Sundrum Model

Randall, Sundrum



S_1/Z_2 compactified

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

effective 4D scale depends on the position in the bulk

One Fundamental gravity scale!!

Hierarchy problem Solved!!

$$M_{ew} = e^{-kL} M_{Pl}$$

- Provides insight on strongly coupled theories #win
- Solution to the Yukawa hierarchy problem #win

Gherghetta, Pomarol

Fermions in RS

Bulk fermionic lagrangian in a warped background is written as

$$\mathcal{L}_{\text{fermion}} = e^{-3\sigma}\overline{\Psi}\left[i\gamma^\mu\partial_\mu - \gamma_5\, e^{-\sigma}\left(\partial_5 - 2\sigma'\right)\right]\Psi$$

where $\sigma = k|y|$. Expanding the bulk field as

$$\Psi(x,y) = \frac{1}{\sqrt{\pi R}}\sum_n \left[\psi_L^{(n)}(x) f_L^{(n)}(y) + \psi_R^{(n)}(x) f_R^{(n)}(y)\right]$$

But

5D theory is non-chiral

How do we reproduce chiral SM ?

$$\Big\downarrow Z_2$$

$$\Psi = \begin{bmatrix} \psi_L(+) \\ \psi_R(-) \end{bmatrix}$$

even -massless zero mode

odd -no zero mode

Zero mode for the Z_2 even field say $f_L^{(0)}$ satisfies

Localized profiles!!

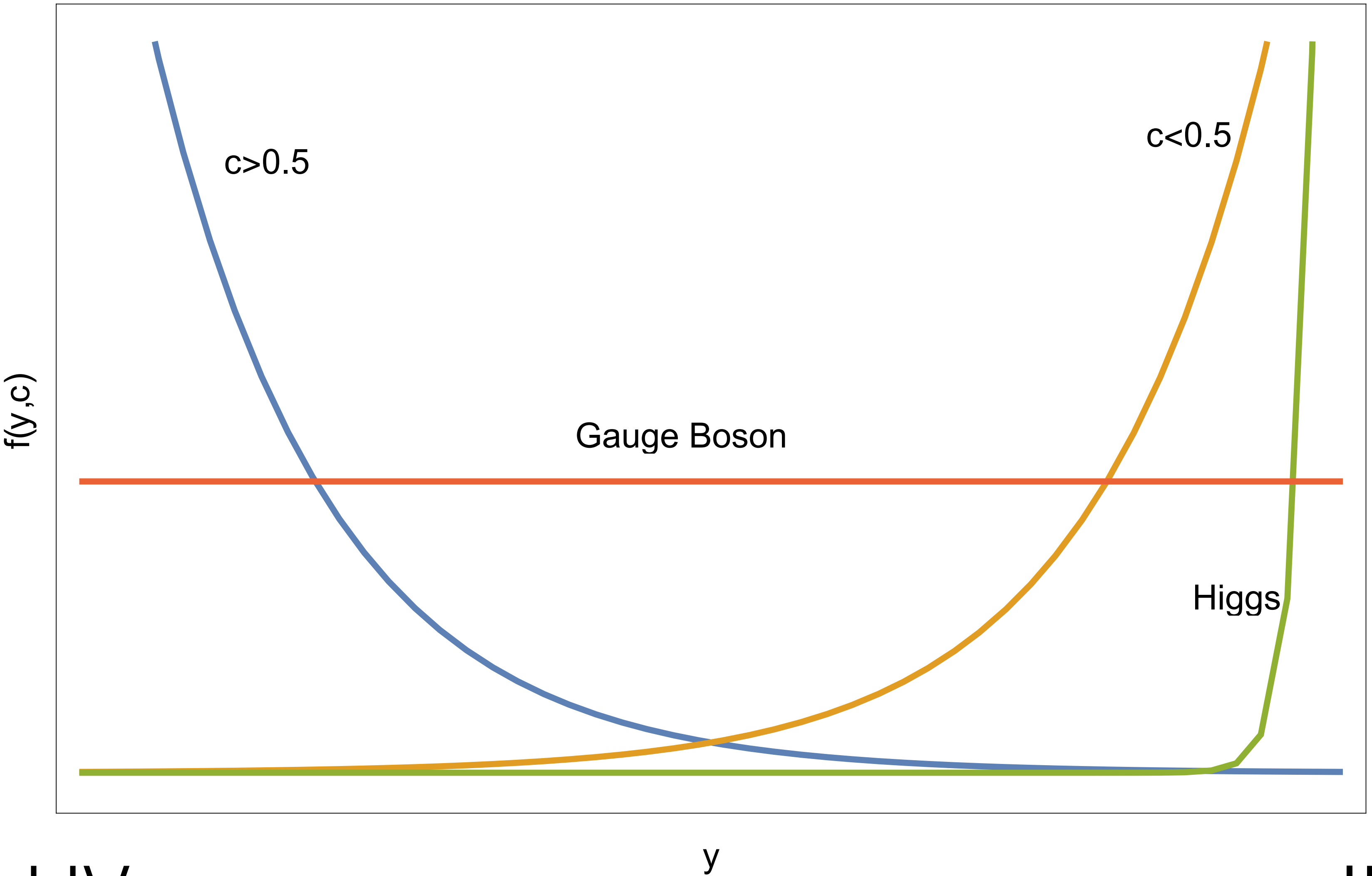
$$e^{-\sigma}\left(\partial_y - 2\sigma'\right) f_L^{(0)} = 0 \xrightarrow[\text{field re-definitions}]{\text{Using orthonormality}} f_L^{(0)} = N e^{k0.5(y-\pi R)}$$

Introducing a bulk mass term $m_{1/2} = c\sigma' = ck$ modifies the solution to

$$f_L^{(0)} = N e^{(0.5-c)\sigma(y)}$$

Gherghetta, Pomarol

SM Couplings are given by the \`overlap' of these profiles:



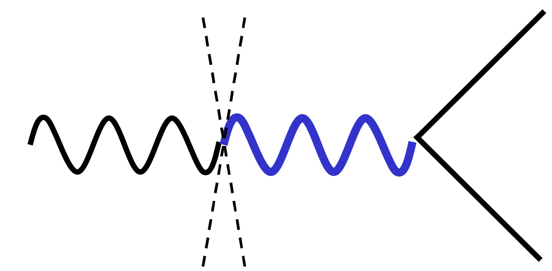
UV IR

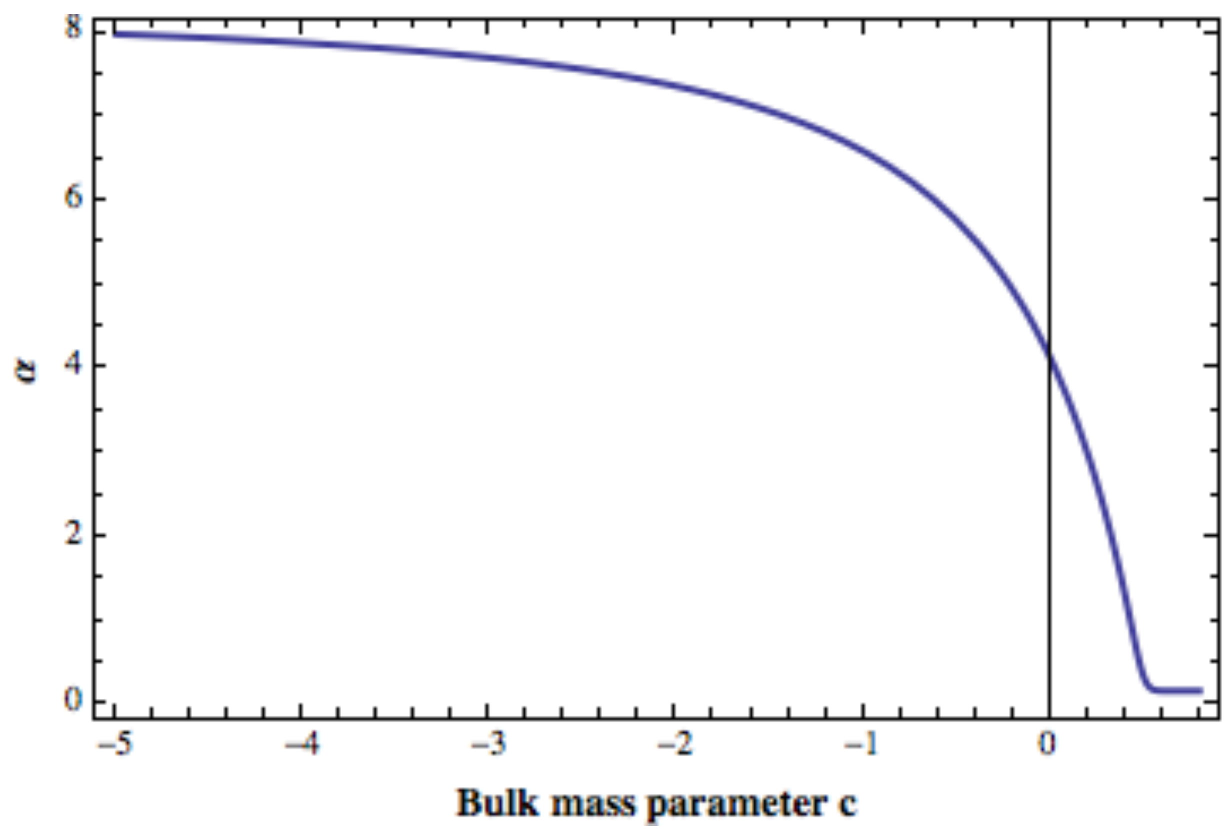
Yukawa hierarchy solved!!

$$Y^{(4)} = Y^{(5)} \int_0^{\pi R} dy\; f_0^{(0)}(b,y) f_{1/2}^{(0)}(c_L,y) f_{1/2}^{(0)}(c_R,y)$$

The fermion coupling to the gauge bosons get modified

Also induced due to mixing of gauge boson with corresponding KK states

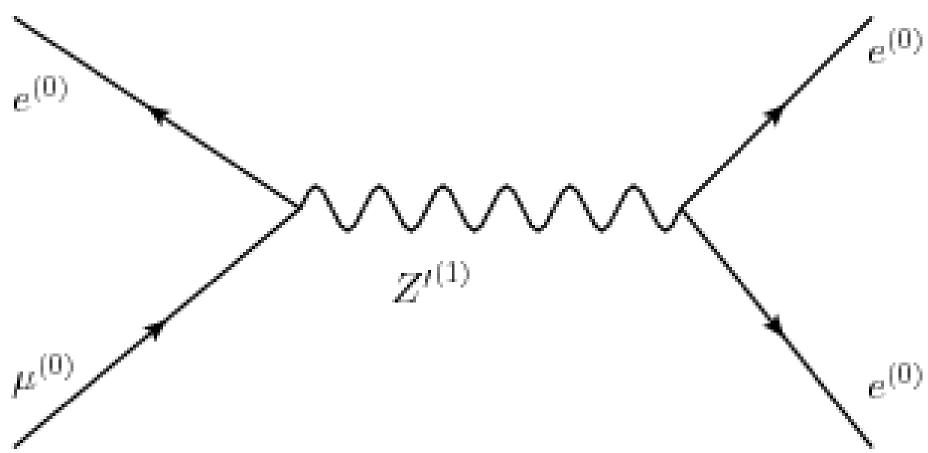


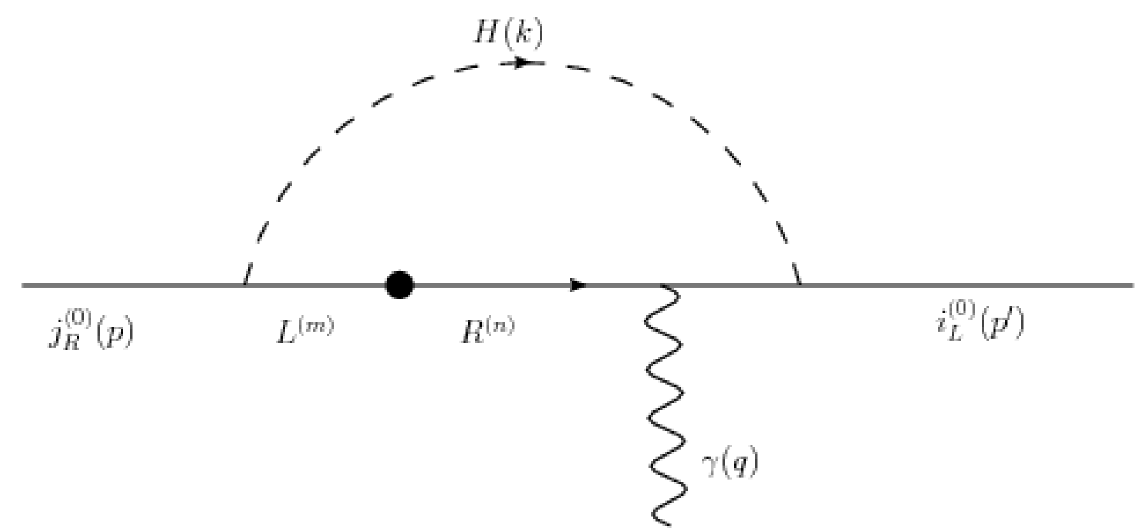


$$\alpha \sim \int_0^{\pi R} f_1^{(1)}(y) f_{1/2}^{(0)}(c,y) f_{1/2}^{(0)}(c,y)$$

Non-universality leads to both tree level and loop level FCNC effects

$$
\begin{aligned}
-\mathcal{L}_{\rm eff} \;=\; & A_R(q^2)\frac{1}{2m_\mu}\bar{e}_R\sigma^{\mu\nu}F_{\mu\nu}\mu_L + A_L(q^2)\frac{1}{2m_\mu}\bar{e}_L\sigma^{\mu\nu}F_{\mu\nu}\mu_R \\
& + \frac{4G_F}{\sqrt{2}}\left[a_3(\bar{e}_R\gamma^\mu\mu_R)(\bar{e}_R\gamma_\mu e_R) + a_4(\bar{e}_L\gamma^\mu\mu_L)(\bar{e}_L\gamma_\mu e_L)\right. \\
& \left. + a_5(\bar{e}_R\gamma^\mu\mu_R)(\bar{e}_L\gamma_\mu e_L) + a_6(\bar{e}_L\gamma^\mu\mu_L)(\bar{e}_R\gamma_\mu e_R)\right] + \text{h.c.}
\end{aligned}
$$





Effects are visible in both the hadron and the lepton sector

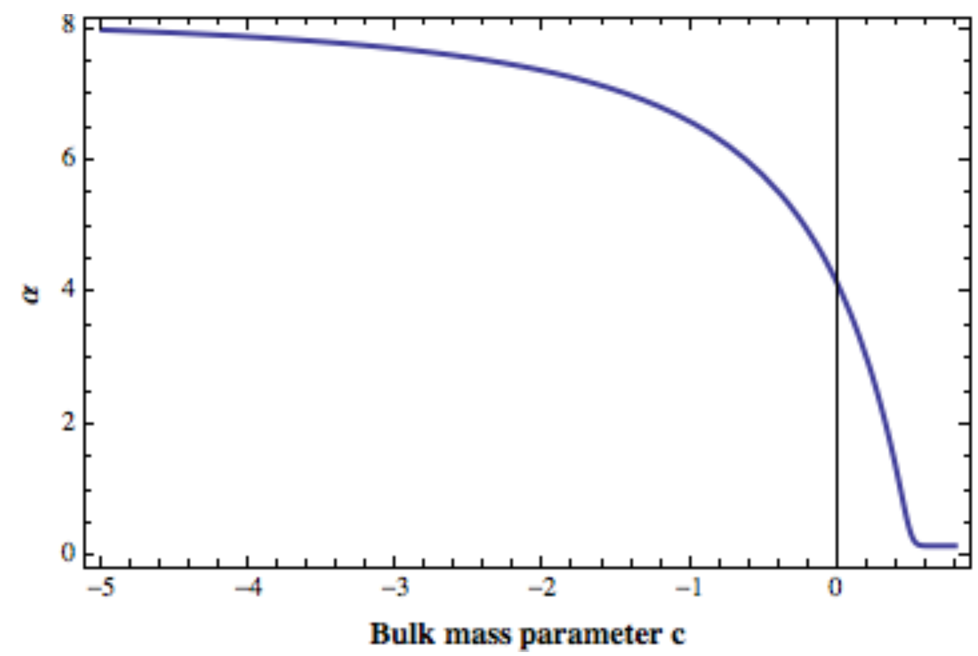
Iyer, Vempati

Parameter	Point A	Point B
χ^2	0.28	0.39
c_{L_1}	0.6263	0.7166
c_{L_2}	0.5932	0.6382
c_{L_3}	0.5293	0.6126
c_{E_1}	0.6704	0.5911
c_{E_2}	0.5541	0.1939
c_{E_3}	0.5131	0.2647
c_{N_1}	1.2233	1.2791
c_{N_2}	1.2692	1.1215
c_{N_3}	1.2948	1.2343
m_e	5.09×10^{-4}	5.09×10^{-4}
m_μ	0.1055	0.1055
m_τ	1.77	1.77
θ_{12}	0.59	0.589
θ_{23}	0.80	0.792
θ_{13}	0.153	0.153
δm^2_{sol}	7.49×10^{-23}	7.49×10^{-23}
δm^2_{atm}	2.39×10^{-21}	2.40×10^{-21}

In the lepton sector the observables are

$$\mu \to e\gamma, \mu \to eee \ldots$$

The non universality (in terms of the couplings) between the first two generations and third



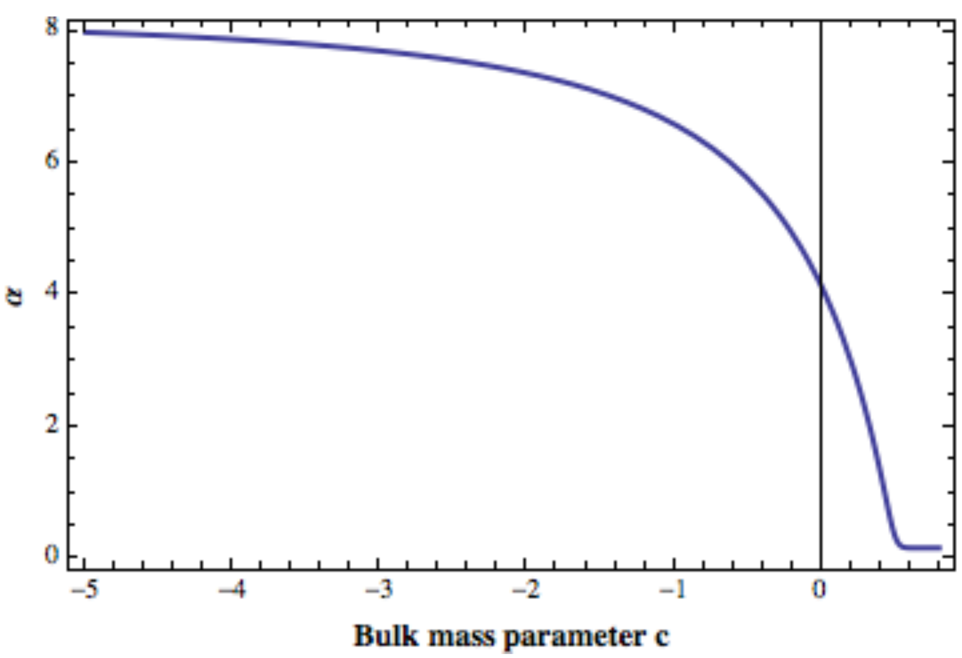
The coupling in the flavour basis is given as

$$g^{SM}\left(\bar{e}_F, \bar{\mu}_F, \bar{\tau}_F\right) \not{Z}^{(1)} \begin{pmatrix} \alpha_e & 0 & 0 \\ 0 & \alpha_\mu & 0 \\ 0 & 0 & \alpha_\tau \end{pmatrix} \begin{pmatrix} e_F \\ \mu_F \\ \tau_F \end{pmatrix}.$$

After rotating to the mass basis the flavour violating couplings are:

$$\begin{aligned} g_{L,R}^{(1)\mu e} &= g_{L,R}\left[U_{12}^{L,R}U_{22}^{L,R*}(\alpha_\mu-\alpha_e)+U_{13}^{L,R}U_{23}^{L,R*}(\alpha_\tau-\alpha_e)\right], \\ g_{L,R}^{(1)\tau\mu} &= g_{L,R}\left[U_{21}^{L,R}U_{31}^{L,R*}(\alpha_e-\alpha_\mu)+U_{23}^{L,R}U_{33}^{L,R*}(\alpha_\tau-\alpha_\mu)\right], \\ g_{L,R}^{(1)\tau e} &= g_{L,R}\left[U_{12}^{L,R}U_{32}^{L,R*}(\alpha_\mu-\alpha_e)+U_{13}^{L,R}U_{33}^{L,R*}(\alpha_\tau-\alpha_e)\right]. \end{aligned}$$

Non-universality!!



The coupling to the first two generation is nearly universal

The coupling to the first two generation is nearly universal

KK scales required to suppress 1-2 transitions in lepton sector are too High!!

30 TeV!!

Standard techniques are to use flavour symmetries like MFV

d'Ambrosio et al, Cirigliano et al.
Sundrum Perez etc.

The bulk mass are aligned with the Yukawa couplings

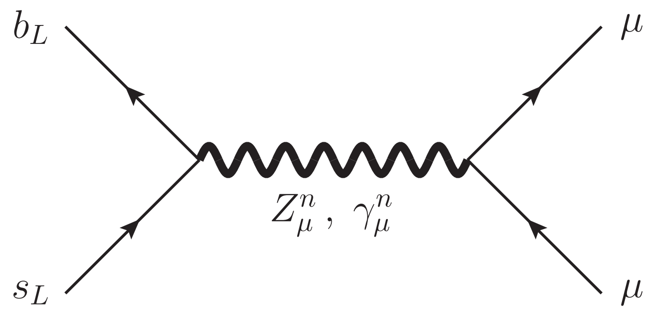
$$c_L = a_1 I + a_2 Y'_E Y'^{\dagger}_E + a_3 Y'_N Y'^{\dagger}_N \qquad c_E = b Y'^{\dagger}_E Y'_E \qquad c_N = c Y'^{\dagger}_N Y'_N$$

Reduces the misalignment between the fermion mass and the flavour violating operators

3 TeV!!

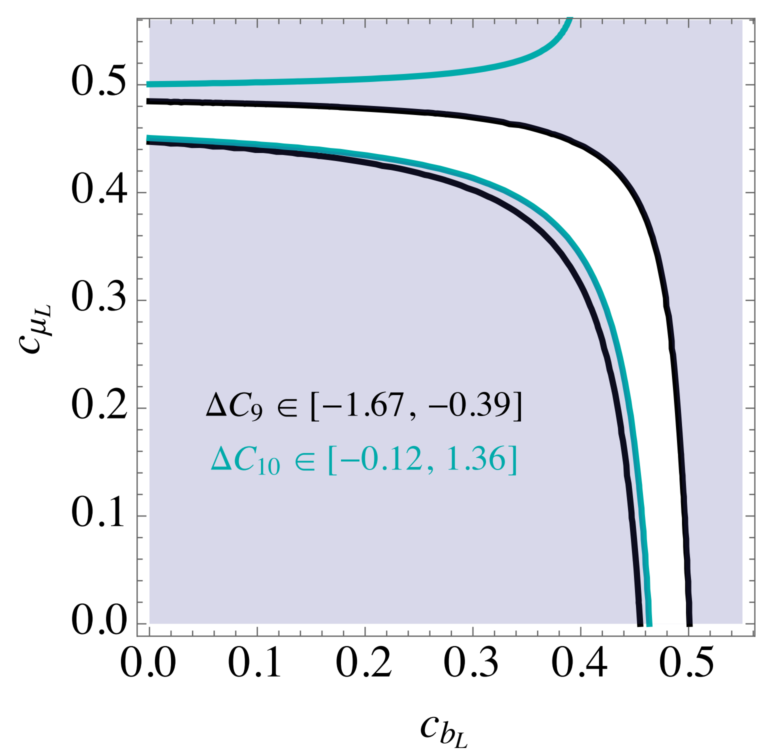
Megios, Panico, Pujolas, Quiros

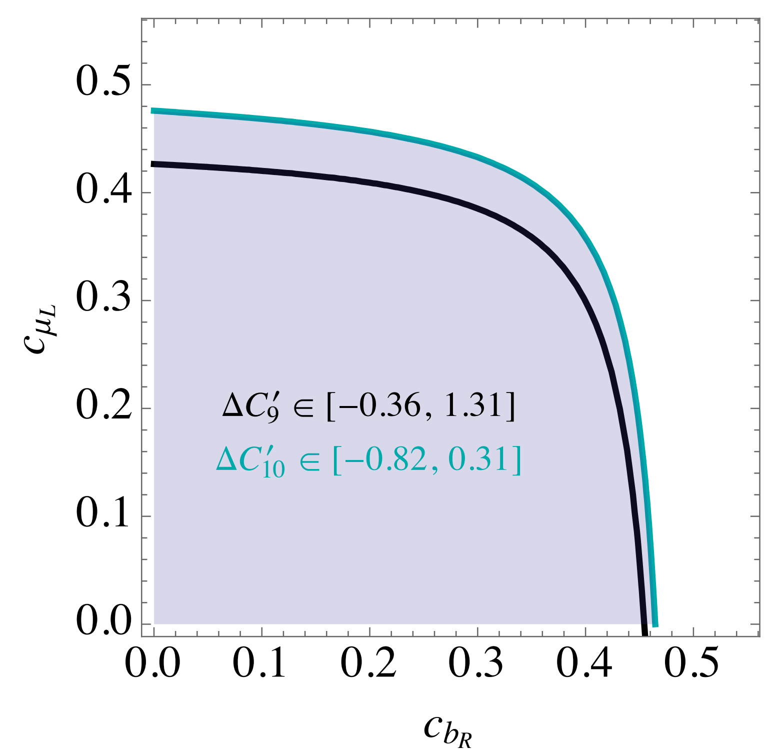
b->s transitions (Neutral Current)



$$\Delta C_9 = -\sum_{X=Z,\gamma}\sum_n \frac{\pi g_{\mu_V}^{X_n}\left(g_{b_L}^{X_n} - g_{s_L}^{X_n}\right)}{2\sqrt{2}G_F\alpha c_W^2 M_n^2}\,, \quad \Delta C_9' = -\sum_{X=Z,\gamma}\sum_n \frac{\pi g_{\mu_V}^{X_n}\left(g_{b_R}^{X_n} - g_{s_R}^{X_n}\right)}{2\sqrt{2}G_F\alpha c_W^2 M_n^2}\,,$$

$$\Delta C_{10} = \sum_{X=Z,\gamma}\sum_n \frac{\pi g_{\mu_A}^{X_n}\left(g_{b_L}^{X_n} - g_{s_L}^{X_n}\right)}{2\sqrt{2}G_F\alpha c_W^2 M_n^2}\,, \quad \Delta C_{10}' = \sum_{X=Z,\gamma}\sum_n \frac{\pi g_{\mu_A}^{X_n}\left(g_{b_R}^{X_n} - g_{s_R}^{X_n}\right)}{2\sqrt{2}G_F\alpha c_W^2 M_n^2}\,.$$





Disclaimer:RS model with a soft wall

Megios, Quiros, Salas

Like KK modes of Z, those of W also exist (Neutral Current)

b->c transitions (Charged Current)

Possibility of a unified description of R(k) and R(D*)

Explanation of R(D*) requires a composite tau, and may be in tension if Ztau tau data

Explanation of R(D*) requires a composite tau, and may be in tension if Ztau tau data, if wolfenstein like parametrization is assumed

$$V_{d_L} = \begin{pmatrix} 1-\frac{1}{2}\lambda_0^2 & \lambda_0 & A\lambda^2\lambda_0(1-r)(\rho_0 - i\eta_0) \\ -\lambda_0 & 1-\frac{1}{2}\lambda_0^2 & A\lambda^2(1-r) \\ A\lambda^2\lambda_0(1-r)(1-\rho_0-i\eta_0) & -A\lambda^2(1-r) & 1 \end{pmatrix} \quad V_{u_L} = \begin{pmatrix} 1-\frac{1}{2}(\lambda-\lambda_0)^2 & (\lambda_0-\lambda)\left(1+\frac{1}{2}\lambda_0\lambda\right) & (V_{u_L})_{13} \\ -(\lambda_0-\lambda)\left(1+\frac{1}{2}\lambda_0\lambda\right) & 1-\frac{1}{2}(\lambda-\lambda_0)^2 & -A\lambda^2\, r \\ (V_{u_L})_{31} & A\lambda^2\, r & 1 \end{pmatrix},$$

Disclaimer:RS model with a soft wall

In progress with D'Ambrosio

One possibility is to consider custodial models

$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$$

Extra- contributions from the custodial gauge bosons

Consider a general computation without the assumption of a wolfenstein like parametrisation (Numerical Scan)

Consider correlations with other channels like s->d transitions

Modifications of RS

Large contributions to oblique parameters!!

PUSH the KK scale very high!!

Large contributions to FCNC

Little hierarchy problem!!

Is there a setup in which the KK scales are naturally high?

The KK masses are proportional to $M_{Pl} e^{-kR\pi} \sim \text{TeV}$

Depends on $\epsilon = e^{-kR\pi}$

Depends on the choice of R!

Choi et al., Dudas Gersdorff, Iyer Vempati..

GUT scale RS framework

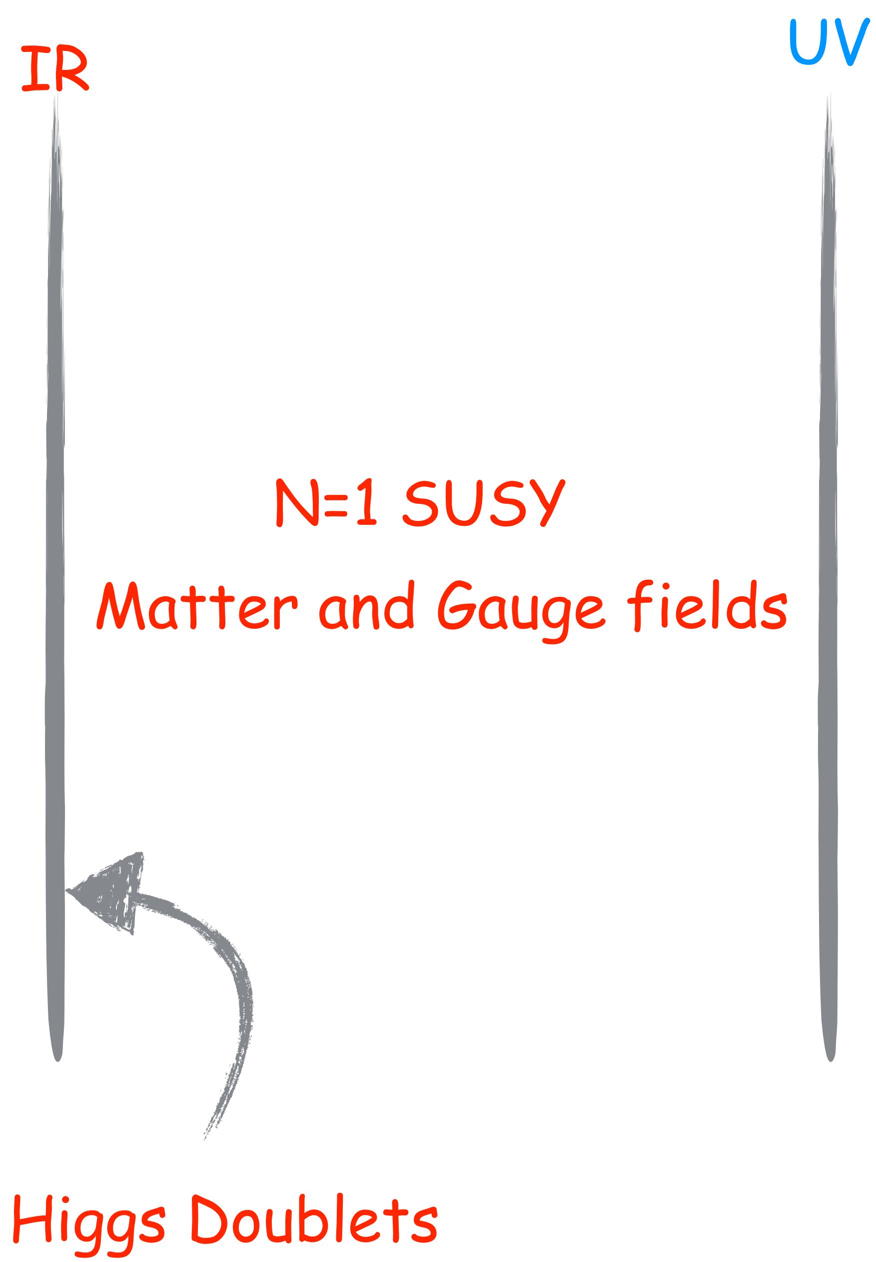
R is reduced to R/6 → warp factor $\epsilon = 0.01$ → Scale of physics on IR brane is GUT scale

Features of GUT RS model

Lowest KK scale is GUT scale

RS is no longer solution to hierarchy problem

Supersymmetrize!!



Effective 4D theory contains N=2 supersymmetry

$\Big\downarrow Z_2$

N=2 to N=1 (MSSM)

This scenario can explain the hierarchy of fermion masses and mixing at the GUT scale.

	FN Models	Extra-dimensions
ϵ	Value of $\epsilon = 0.2$ is set by the ratio of the vev of S and mass of the vector like fields	$\epsilon = 10^{-kR\pi} \sim 0.02$ is set by curvature scale k and the compactification radius R
charges	The FN charger are restricted to be integers	The c parameters are real numbers.
UV scale	Effective UV scale is at $\langle S \rangle \simeq M_{Pl}$	Effective UV scale is $\tilde{M}_{uv} e^{-kR\pi} M_{Pl}$ *i.e.* mass of KK gauge bosons.
UV completion	HEavy fermions	Profiles in 5D
Flavour	Non-universal D term contributions to soft masses lead to FCNC	Non-universal coupling of the KK-gauge bosons to the fermions lead to FCNC.

Next question: How does one break SUSY?

Contact interactions on the IR (GUT) brane

Brane localized Interaction

$$\mathcal{L}^{(4)}_{breaking} = \delta(y - \pi R)\left[d^4\theta e^{-2k\pi R} k^{-2} X^\dagger X \left(\beta_{\Phi,ij}\Phi_i^\dagger \Phi_j\right) + d^2\theta k^{-1} X \mathcal{W}_{A\alpha}\mathcal{W}_A^\alpha + d^2\theta e^{-3ky} k^{-1} X \left(\tilde{A}^u_{ij} H_u Q_i u_j + \ldots\right)\right]$$

SUSY Breaking spurion $X = \theta^2\ F$

F term of X develops a vev giving a gravitino mass

$$m_{3/2} = \frac{\langle F \rangle}{k} \sim TeV$$

In the canonical basis

$$
\begin{aligned}
m_{1/2} &= f m_{3/2} \\
(m^2_{\tilde{f}})_{ij} &= m^2_{3/2}\ \hat{\beta}_{ij}\ e^{(1-c_i-c_j)kR\pi}\xi(c_i)\xi(c_j) \\
A^{u,d}_{ij} &= m_{3/2}A'_{ij}e^{(1-c_i-c'_j)kR\pi}\xi(c_i)\xi(c'_j)
\end{aligned}
$$

where $\hat{\beta}_{ij}, A'$ are dimensionless $\mathcal{O}(1)$ parameters.

Some features:

Structure of the soft masses is predicted by the fits to the fermion masses.

Soft masses are flavourful may possibly lead to large FCNC

The trilinear coupling for the third generation is naturally large.

Structure of soft mass matrix

Typical soft mass matrix for the up type squarks looks like

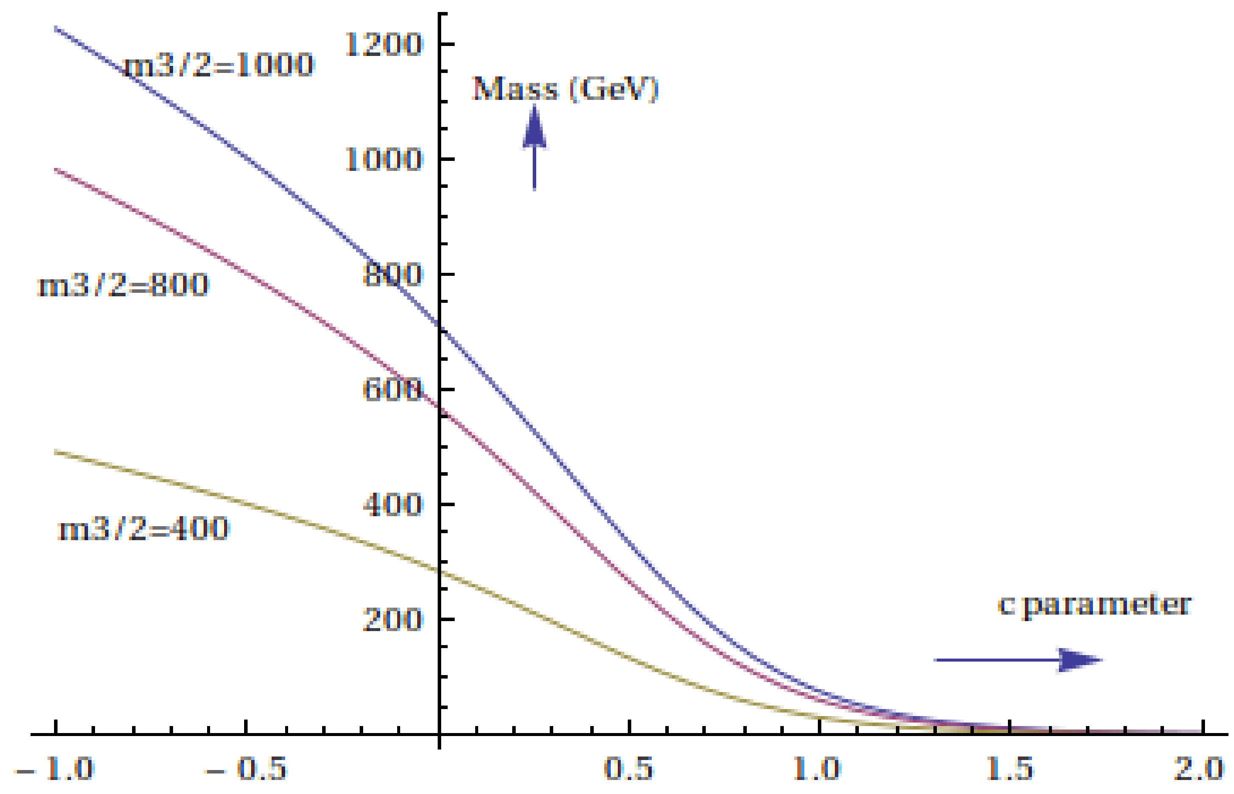
$$\tilde{M}^2_{Q,U} = m^2_{3/2}(0.5 - c_{Q_3,U_3}) \begin{pmatrix} \epsilon^{\alpha} & \epsilon^{\gamma} & \epsilon^{\frac{\alpha}{2}} \\ \epsilon^{\gamma} & \epsilon^{\beta} & \epsilon^{\frac{\beta}{2}} \\ \epsilon^{\frac{\alpha}{2}} & \epsilon^{\frac{\beta}{2}} & 1 \end{pmatrix}$$

$\alpha = 2c_1 - 1,\ \beta = 2c_2 - 1,\ \gamma = c_2 + c_1 - 1.$ c_1 and c_2 are bulk mass parameters for first two generation squarks.

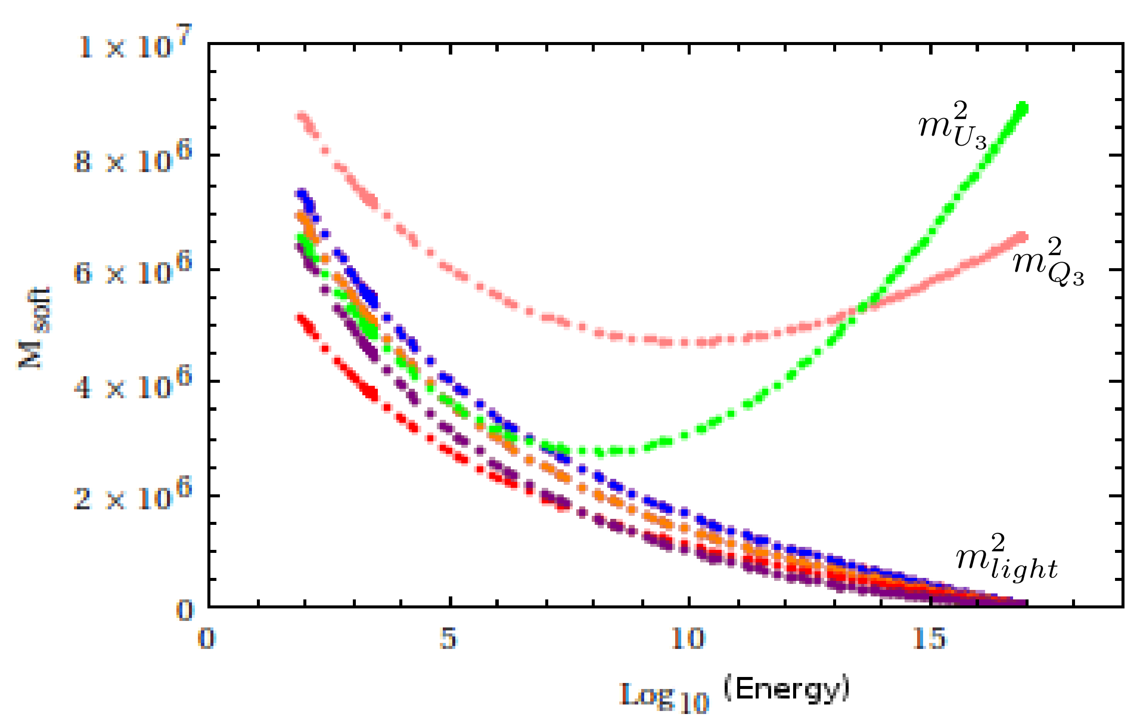
Significant amount of flavour violation present at the high scale!!

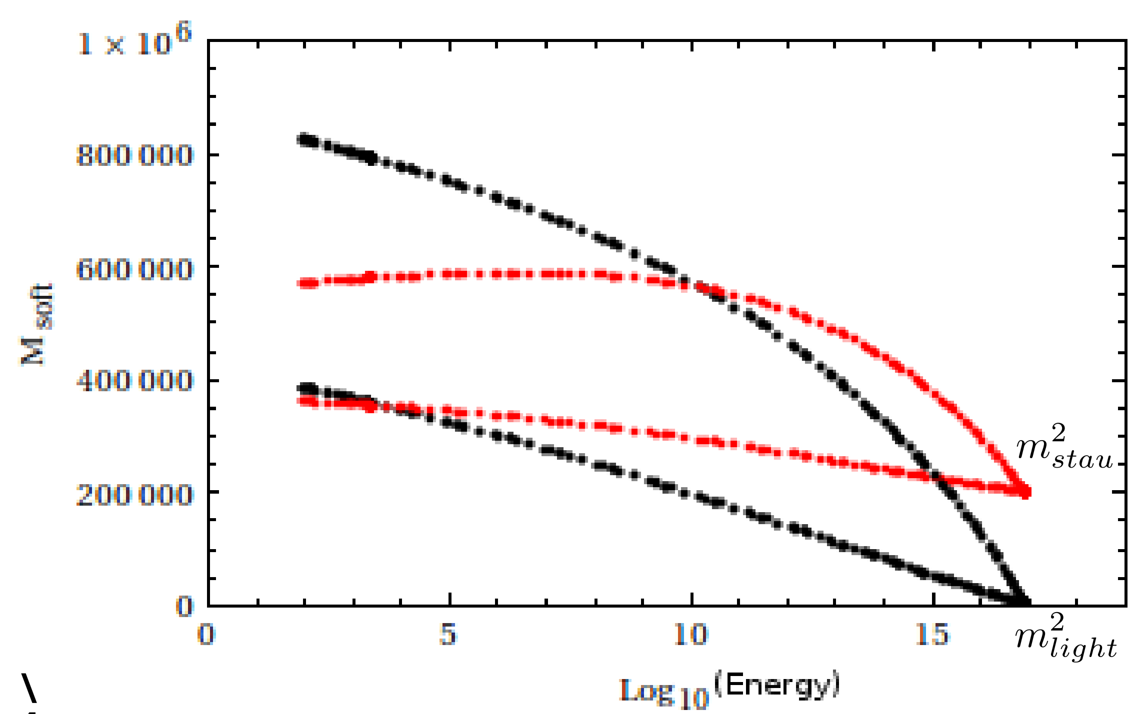
Dudas, Iyer Vempati
to appear

Soft masses at High scale



Running of masses

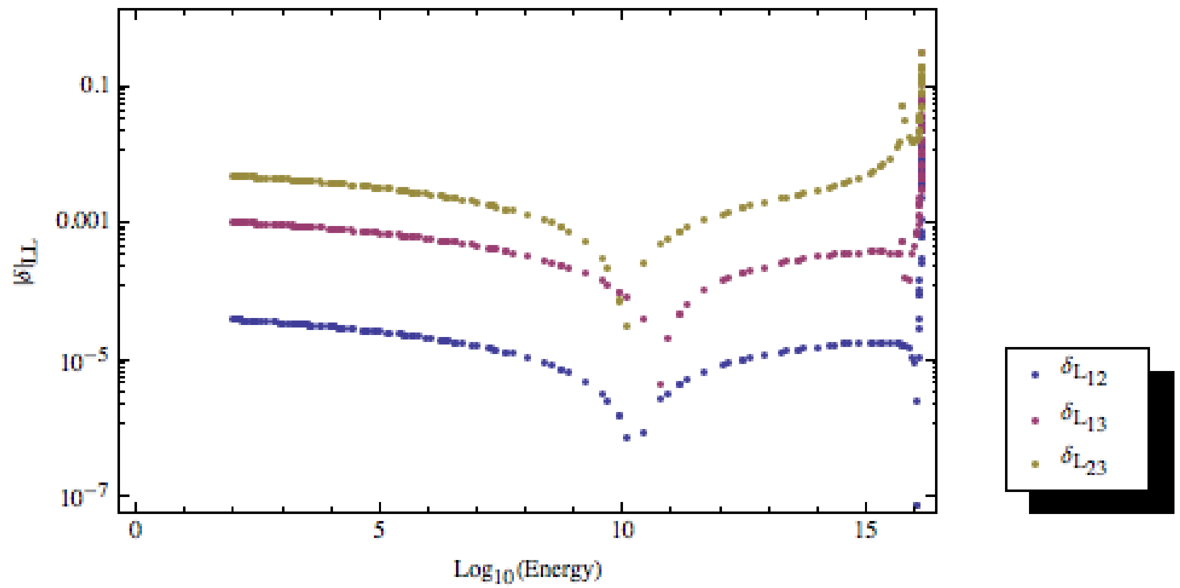


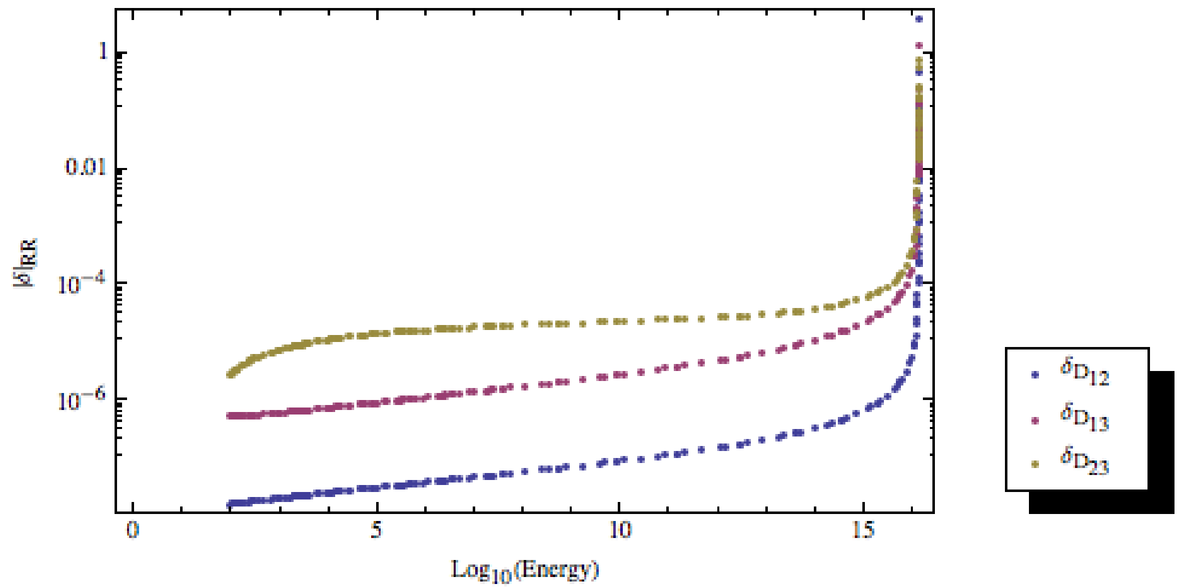


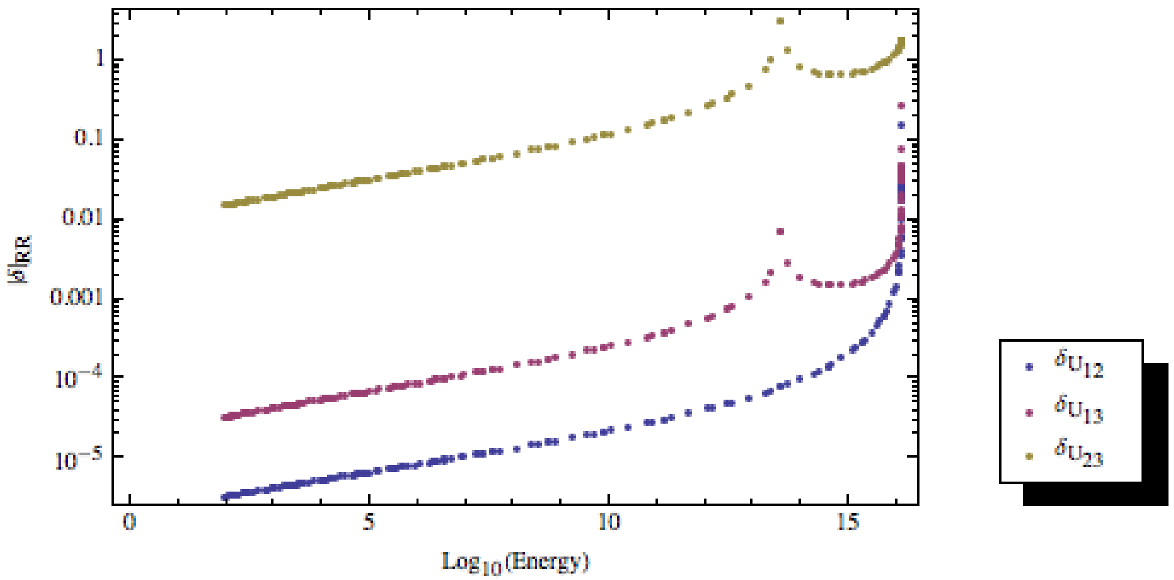
Dudas, Iyer Vempati
to appear

In the mass insertion approximation the flavour violating parameter is given as

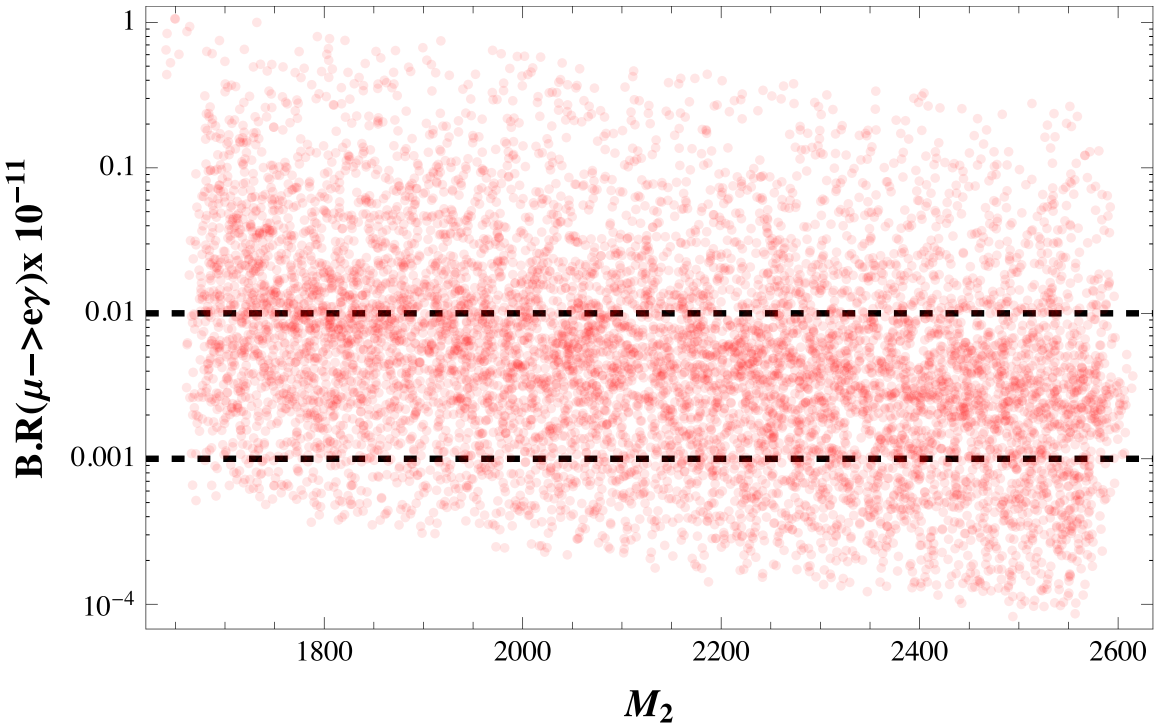
$$\delta_{ij} = \frac{\tilde{m}_{ij}^2}{\sqrt{\tilde{m}_i^2 \tilde{m}_j^2}} \quad i \neq j$$

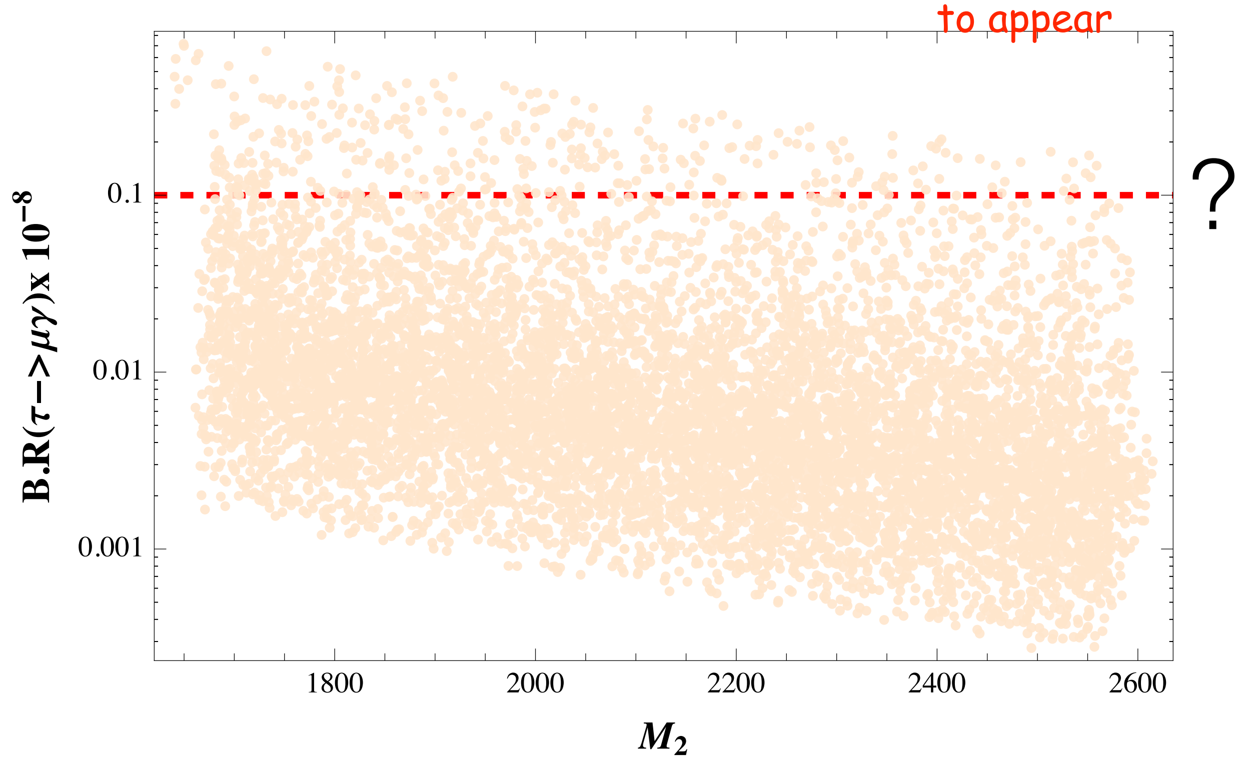


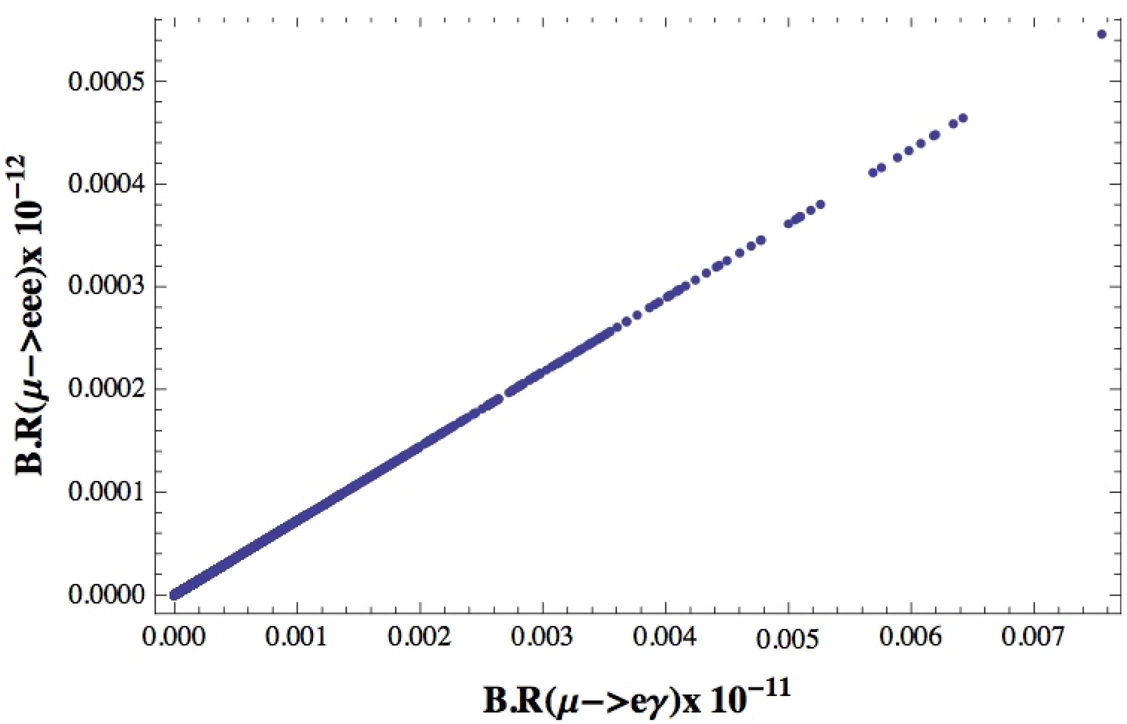


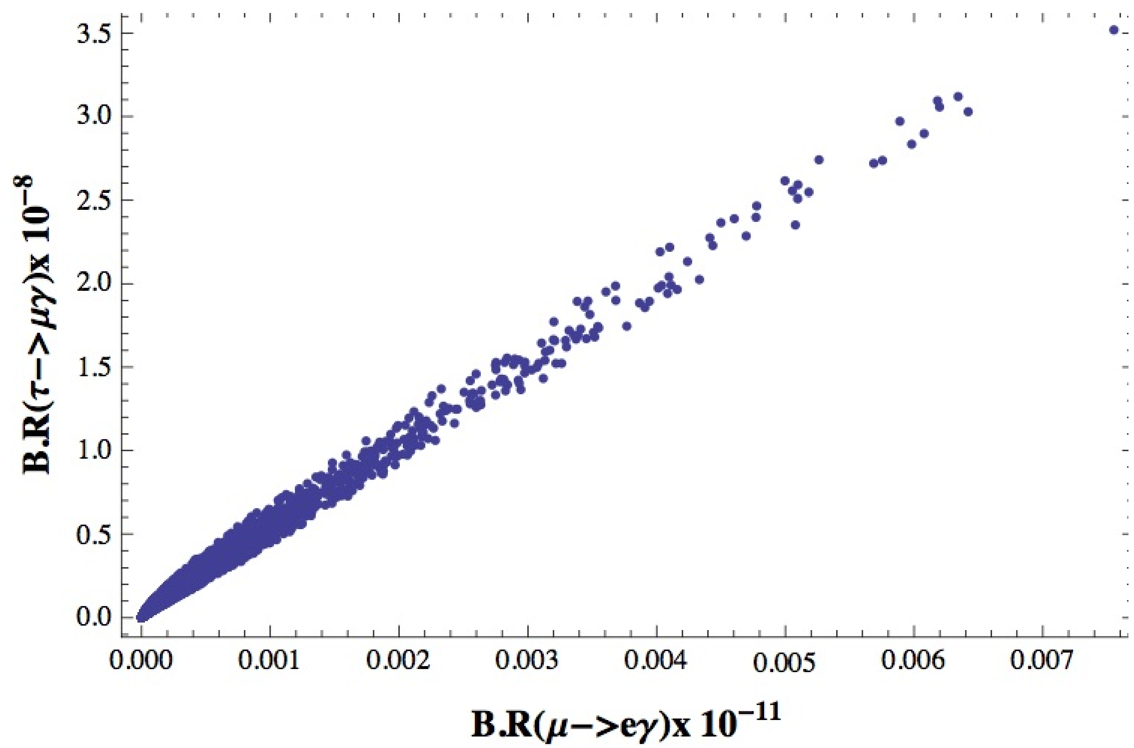


Dudas, Iyer Vempati
to appear









$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI

Interesting setup as a UV model of RPV SUSY as well - Allanach, Iyer, Sridhar

Flavour Physics offers an interesting mode to look for NP

RS models can be realised in many forms with different implications

Conventional RS

Bulk RS

Typically more constrained owing to precision/ fcnc data

Flavour symmetries required for the lepton sector

KK scales are naturally very high

Effective low energy theory has SM+SUSY

Imprints of RS may be visible in the flavour data

End