Warped Alternatives to Froggatt-Nielsen Models

with A. Iyer, arXiv: 1304.3558 [hep-ph]

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FN models and RS

Heavy Fermions

$$\mathcal{W} \supset Y_t Q_3 u_3 H_u + Y_1^u Q_2 F_1 H_u$$
$$+ Y_2^u \bar{F}_1 u_1 S + M_1 F_1 \bar{F}_1 + \cdots$$

Extra Dimension

$$S_{kin} = \int d^4x \int dy \sqrt{-g} \left(\bar{L}(i \not{D} - m_L) L \right.$$
$$\left. + \bar{E}(i \not{D} - m_E) E + \ldots \right)$$

$$S_{\mathrm{Yuk}} = \int d^4x \int dy \sqrt{-g} \left(Y_U \bar{Q} U \tilde{H} \right.$$
$$\left. + Y_D \bar{Q} D H + Y_E \bar{L} E H \right) \delta(y - \pi R)$$

Integrating Out

$$W \supset Y_{ij}^u \left(\frac{S}{M_{Pl}}\right)^{c_{Q_i} + c_{u_j} + c_{H_u}} Q_i H_u U_j$$

$$(\mathcal{M}_F)_{ij} = \frac{v}{\sqrt{2}} (Y_F')_{ij} e^{(1-c_i-c_j')kR\pi} \; \xi(c_i) \; \xi(c_j')$$

$$\xi(c_i) = \sqrt{\frac{(0.5 - c_i)}{e^{(1-2c_i)\pi kR} - 1}},$$

$$m_F = c_F k$$

FN models and RS

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$$\xi(c_i) = \sqrt{\frac{(0.5 - c_i)}{e^{(1-2c_i)\pi k R} - 1}},$$

$$m_F = c_F k$$

FN models and RS

U(1) Charges	Bulk Masses
fitting both O(1) as well U(1) charges	fitting both O(1) as well bulk masses

Additional Conditions

Anomalies should be cancelled, which leads to very strong constraints	Unification of the gauge couplings leads to strong constraints on bulk masses
Green Schwarz conditions	E. Dudas et.al, JHEP 1012 (2010) 015
	If one doesn't consider unification, reasonably relaxed framework

FN models and RS

Scale

Typically at Planck scale

$$< S > \sim \lambda_c M_{Pl}$$

SUSY models have D-terms

Single flavon fields strongly constrained in SUSY

Ross, Lalak etc..

Warp Factor

$$kR\pi \sim \mathcal{O}(11)$$

first KK scale around TeV

Buras, Neubert, Shafi, Huber, Agashe, Grossman, Soni, etc

strong constraints from Hadronic and leptonic flavour

Iyer & Vempati, PRD 2012

LHLH : very large bulk masses, 10^6 M_Planck

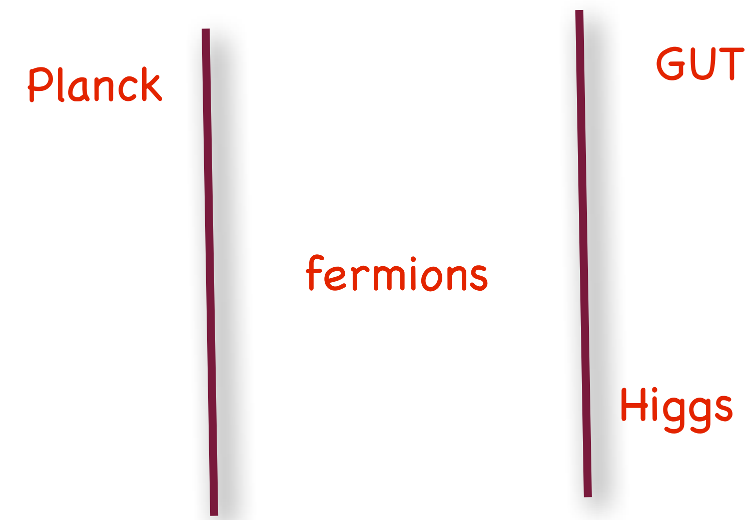
Dirac : strong flavour constraints

Majorana : strong flavour constraints

MFV ideas

Perez, Randall, M. C. Chen etc..

$$kR\pi \sim \mathcal{O}(1)$$



Randall Sundrum at GUT scale

K. Choi et.al, Eur. Phys C 35 (2004) 267

Nomura et. al JHEP 0807 (2008) 055 ,

E. Dudas et.al, JHEP 1012 (2010) 015

F. Brummer et.al, JHEP 1112 (2011) 061

- RS as a theory of flavour at GUT scale
- Fit the fermion masses in SUSY and non-SUSY models
- Two cases for Neutrino Masses : Dirac and Planck scale Lepton number violation
- An interesting SUSY scenario where fermion hierarchy determines sfermion mass structure.

Fermion masses at GUT scale

Mass (MeV)	Mass (GeV)	Mass MeV	Mass squared Differences eV^2
$m_u = 0.48^{+0.20}_{-0.17}$	$m_c = 0.235^{+0.035}_{-0.034}$	$m_e = 0.4696^{+0.00000004}_{-0.00000004}$	$\Delta m^2_{12} = 1.5^{+0.20}_{-0.21} \times 10^{-4}$
$m_d = 1.14^{+0.51}_{-0.48}$	$m_b = 1.0^{+0.04}_{-0.04}$	$m_\mu = 99.14^{+0.000008}_{-0.0000089}$	$\Delta m^2_{23} = 4.6^{+0.13}_{-0.13} \times 10^{-3}$
$m_s = 22^{+7}_{-6}$	$m_t = 74.0^{+4.0}_{-3.7}$	$m_\tau = 1685.58^{+0.19}_{-0.19}$	-

mixing angles(CKM)	Mixing angles (PMNS)
$\theta_{12} = 0.226^{+0.00087}_{-0.00087}$	$\theta_{12} = 0.59^{+0.02}_{-0.015}$
$\theta_{23} = 0.0415^{+0.00019}_{-0.00019}$	$\theta_{23} = 0.79^{+0.12}_{-0.12}$
$\theta_{13} = 0.0035^{+0.001}_{-0.001}$	$\theta_{13} = 0.154^{+0.016}_{-0.016}$

Results for SM

parameter	range	parameter	range	parameter	range
c_{Q_1}	[0,3.0]	c_{D_1}	[0.78,4]	c_{U_1}	[-0.97,3.98]
c_{Q_2}	[-1.95,2.36]	c_{D_2}	[0.39,3.02]	c_{U_2}	[-1.99,2.43]
c_{Q_3}	[-3,1]	c_{D_3}	[0.39,2.21]	c_{U_3}	[-4,1.0]

Dirac Case

parameter	range	parameter	range	parameter	range
c_{L_1}	[-1,2.9]	c_{E_1}	[0.39,3.62]	c_{N_1}	[5.29,8.97]
c_{L_2}	[-0.99,2.7]	c_{E_2}	[-1.0,2.63]	c_{N_2}	[5.31,8.99]
c_{L_3}	[-0.99,1.98]	c_{E_3}	[-0.99,1.93]	c_{N_3}	[5.12,8.97]

LHLH Case

parameter	range	parameter	range
c_{L_1}	[-1.5,-1.15]	c_{E_1}	[2.8,4.0]
c_{L_2}	[-1.5,-0.97]	c_{E_2}	[1.8,2.4]
c_{L_3}	[-1.5,-1.22]	c_{E_3}	[1.2,1.69]

SUSY Set up

The 5D action is given by

$$S_5 = \int d^5x \left[\int d^4\theta e^{-2ky} \left(\Phi^\dagger \Phi + \Phi^c \Phi^{c\dagger} \right) + \int d^2\theta e^{-3ky} \Phi^c \left(\partial_y + M_\Phi - \frac{3}{2}k \right) \Phi \right]$$

The 4D superpotential is given by with only zero modes

$$\mathcal{W}^{(4)} = \int dy e^{-3ky} \Big(e^{(\frac{3}{2}-c_{q_i})ky} e^{(\frac{3}{2}-c_{u_j})ky} Y^u_{ij} H_U Q_i U_j + e^{(\frac{3}{2}-c_{q_i})ky} e^{(\frac{3}{2}-c_{d_j})ky} Y^d_{ij} H_D Q_i D_j$$
$$+ \quad e^{(\frac{3}{2}-c_{L_i})ky} e^{(\frac{3}{2}-c_{E_j})ky} Y^E_{ij} H_D L_i E_j + \ldots \Big) \delta(y - \pi R)$$

$$\xi(c_i) = \sqrt{\frac{(0.5 - c_i)}{e^{(1-2c_i)\pi k R} - 1}}$$

c are the bulk mass parameters

Results for MSSM

tanbeta =10

parameter	range	parameter	range	parameter	range
c_{Q_1}	[-0.16,3.12]	c_{D_1}	[-0.5,4]	c_{U_1}	[-1.6,4.0]
c_{Q_2}	[-1.32,2.34]	c_{D_2}	[-1.9,2.5]	c_{U_2}	[-2,2.4]
c_{Q_3}	[-3,1]	c_{D_3}	[-2,1.7]	c_{U_3}	[-4,1.0]

Dirac Neutrinos

parameter	range	parameter	range	parameter	range
c_{L_1}	[-1,2.6]	c_{E_1}	[-0.86,3.46]	c_{N_1}	[5.68,8.9]
c_{L_2}	[-0.99,2.21]	c_{E_2}	[-1,2.24]	c_{N_2}	[5.67,8.99]
c_{L_3}	[-1,1.54]	c_{E_3}	[-1,1.49]	c_{N_3}	[5.64,8.99]

LHLH case

parameter	range	parameter	range
c_{L_1}	[-1.5,-0.22]	c_{E_1}	[2.6,3.7]
c_{L_2}	[-1.5,0.08]	c_{E_2}	[2.0,2.57]
c_{L_3}	[-1.5,0.04]	c_{E_3}	[1.1,1.8]

SUSY Breaking

scalar masses

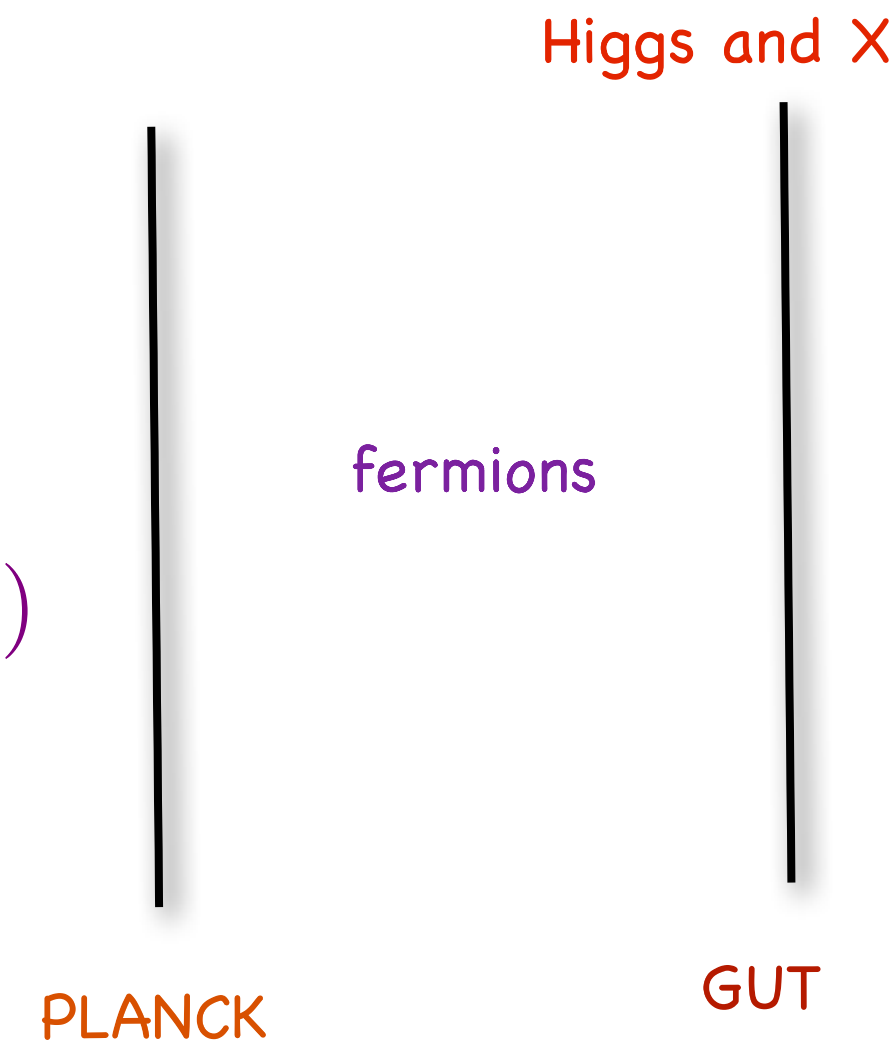
$$(m^2_{\tilde{f}})_{ij} = m^2_{3/2}\ \hat{\beta}_{ij}\ e^{(1-c_i-c_j)kR\pi}\xi(c_i)\xi(c_j)$$

trilinear terms

$$A^{u,d}_{ij} = m_{3/2}A'_{ij}e^{(1-c_i-c'_j)kR\pi}\xi(c_i)\xi(c'_j)$$

gaugino masses

$$m_{1/2} = f m_{3/2}$$



SUSY breaking spurion and Higgs placed on GUT brane

SUSY Breaking

Higgs and X

scalar masses

fermions

$$(m^2_{\tilde{f}})_{ij} = m^2_{3/2}\ \hat{\beta}_{ij}\ e^{(1-c_i-c_j)kR\pi}\xi(c_i)\xi(c_j)$$

trilinear terms

PLANCK

GUT

$$A^{u,d}_{ij} = m_{3/2}A'_{ij}e^{(1-c_i-c'_j)kR\pi}\xi(c_i)\xi(c'_j)$$

gaugino masses

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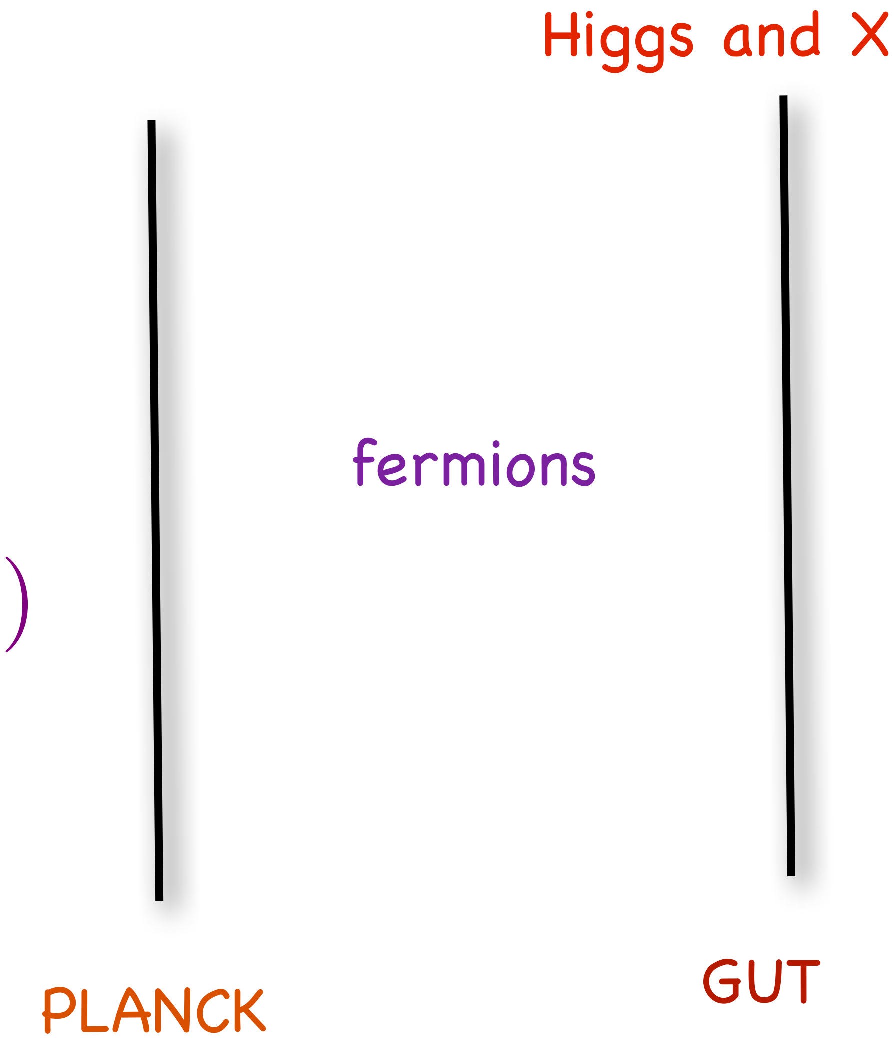
SUSY Breaking



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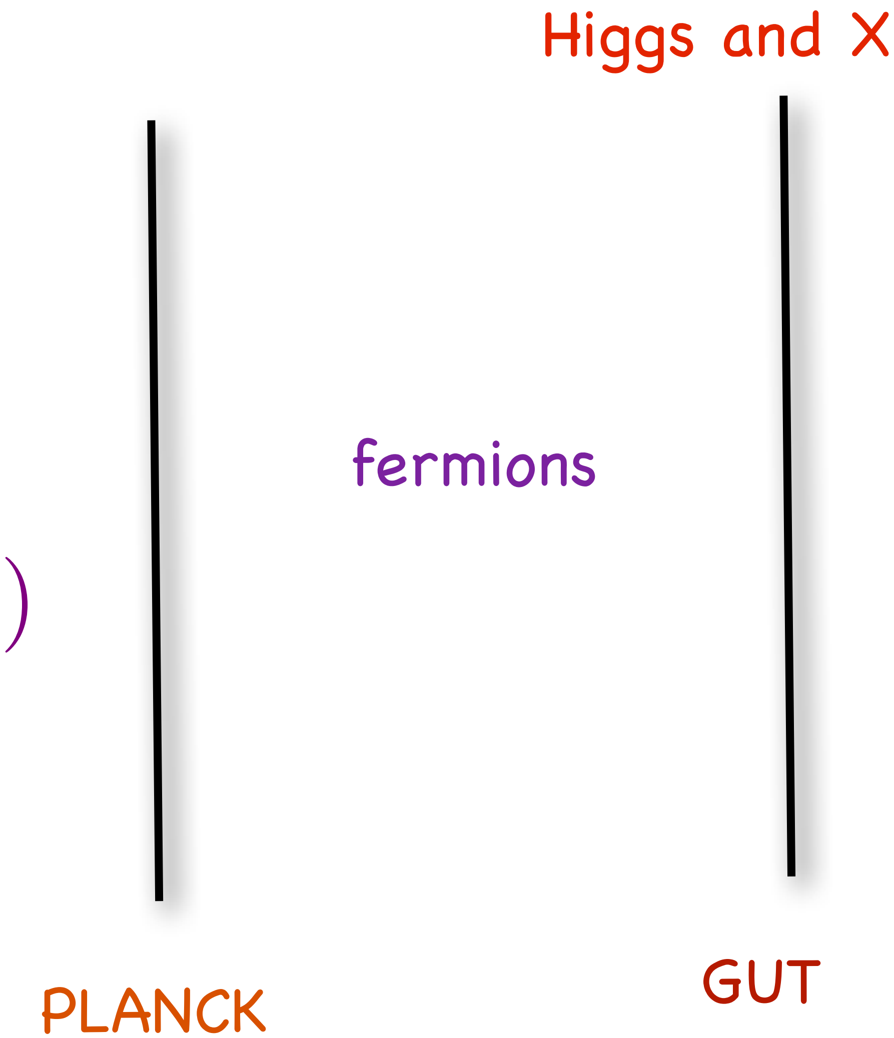

scalar masses

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$$m_{1/2} = f m_{3/2}$$

SUSY breaking spurion and Higgs placed on GUT brane

Structure of Soft terms

Nomura et.al

flavourful SUSY

c are the bulk masses ,
epsilon is small parameter

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

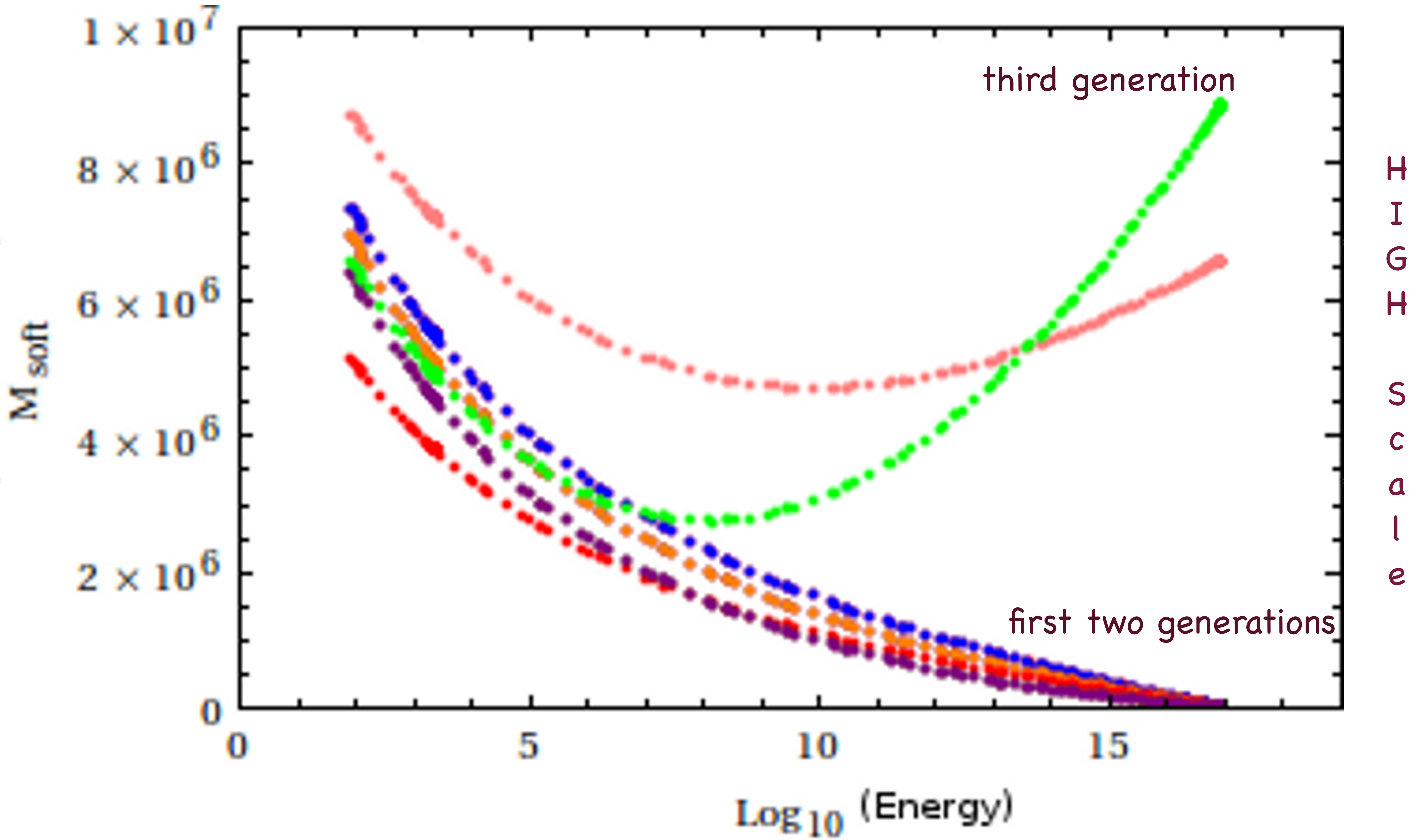
$$\alpha = 2c_1 - 1, \beta = 2c_2 - 1\gamma = c_2 + c_1 - 1.$$

$$\tilde{M}^2_{D} = m^2_{3/2} e^{(1-2c_3)kr\pi} \begin{pmatrix} \epsilon^{2\alpha'} & \epsilon^{\gamma'} & \epsilon^{\alpha'} \\ \epsilon^{\gamma'} & \epsilon^{2\beta'} & \epsilon^{\beta'} \\ \epsilon^{\alpha'} & \epsilon^{\beta'} & 1 \end{pmatrix}$$

$$\alpha' = c_1 - c_3, \beta' = c_2 - c_3\gamma' = c_2 + c_1 - 2c_3$$

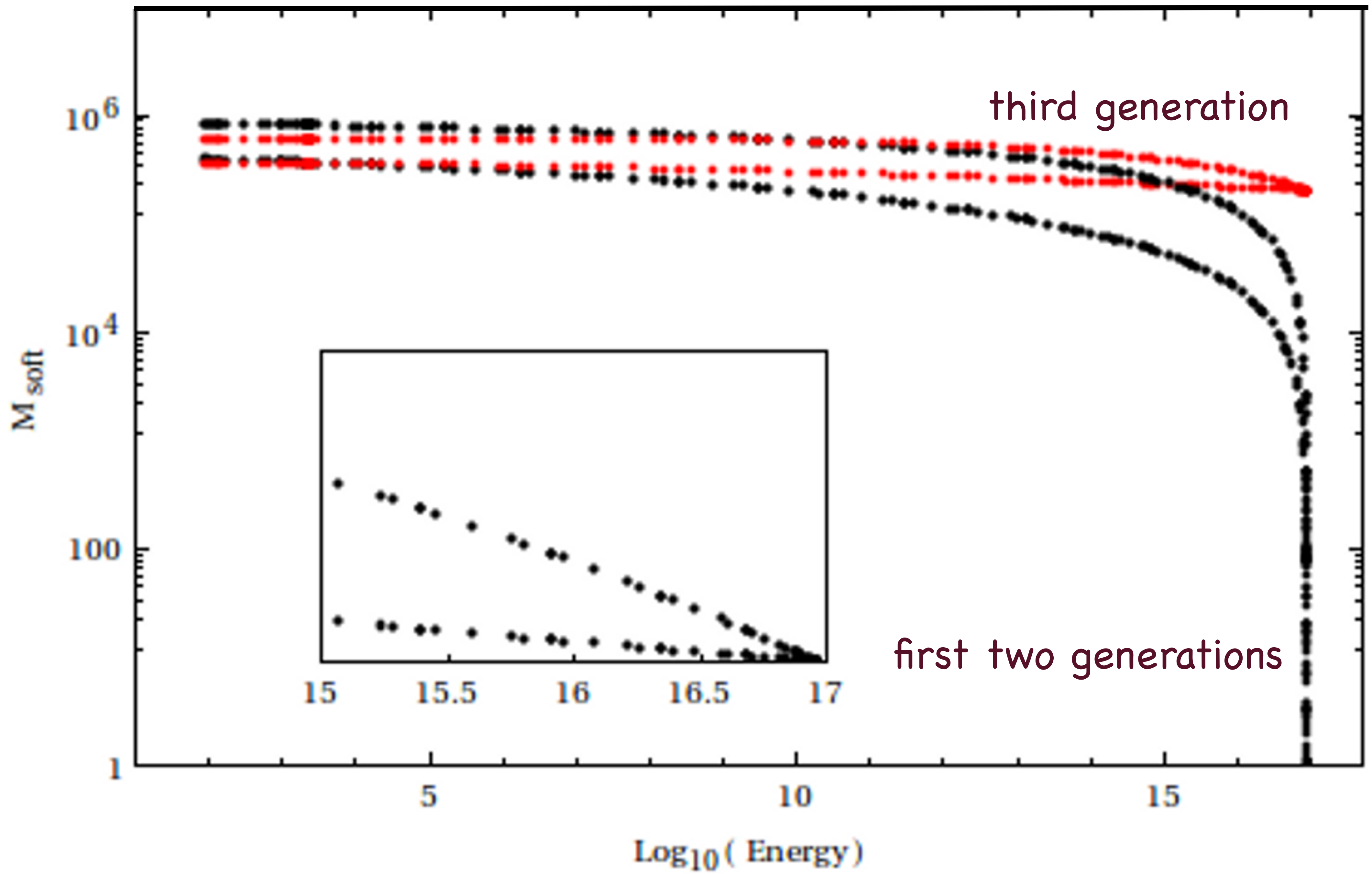
weak scale spectrum

(squark mass squared)



weak scale spectrum

(slepton mass squared)

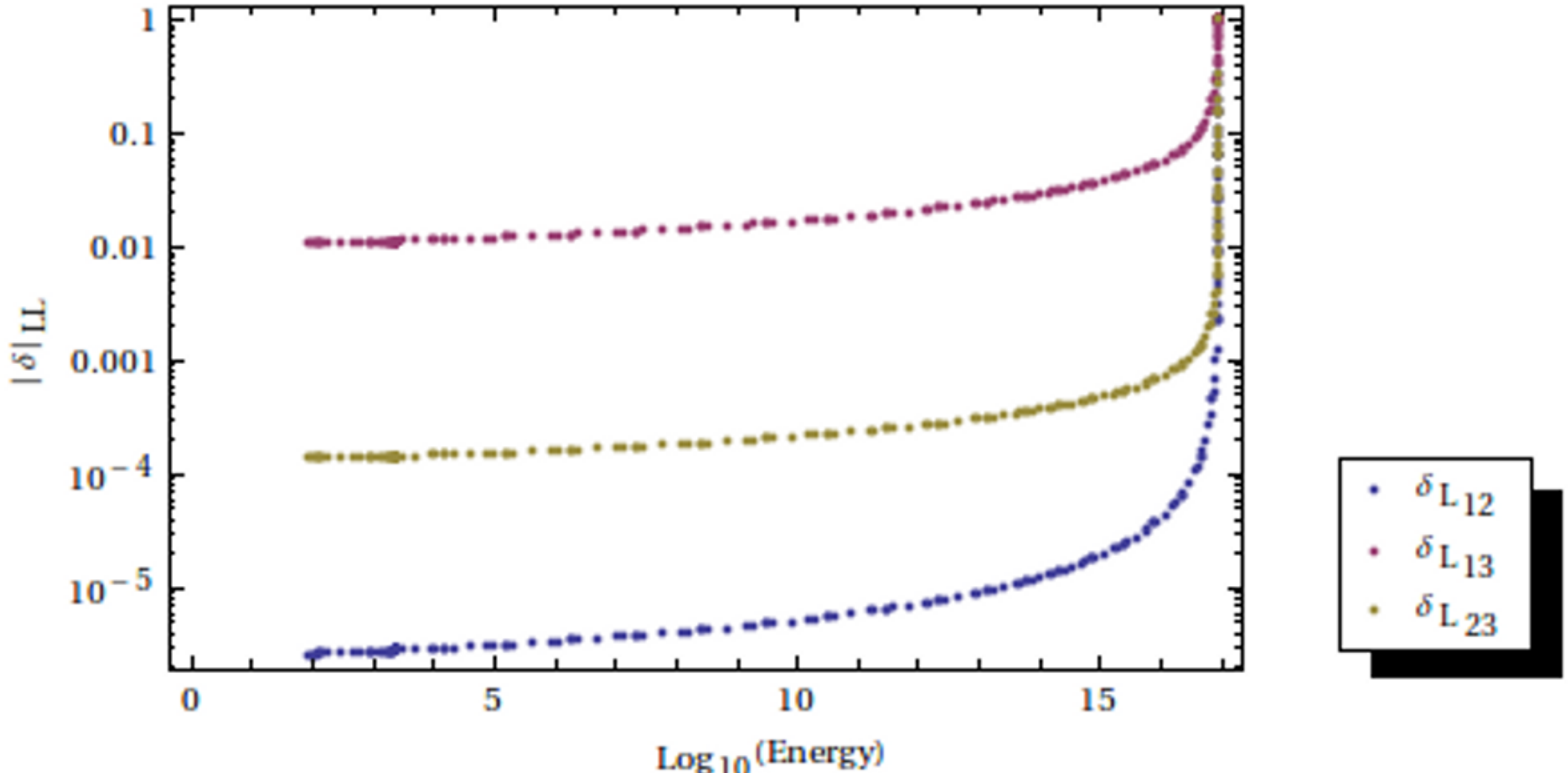


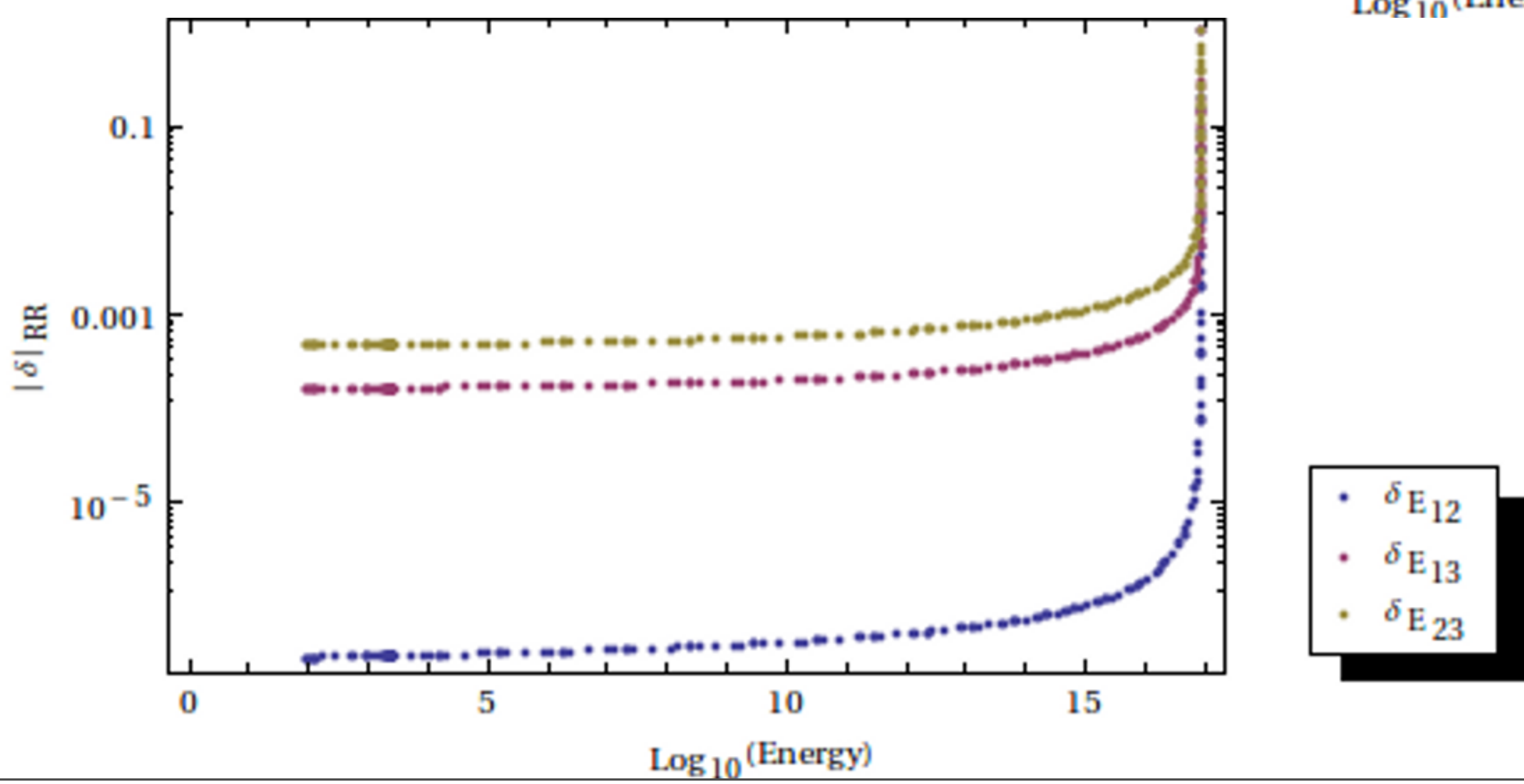
Perez, Ramond, Zhang, arxiv: 1209.6071

focussing feature similar to other flavour models

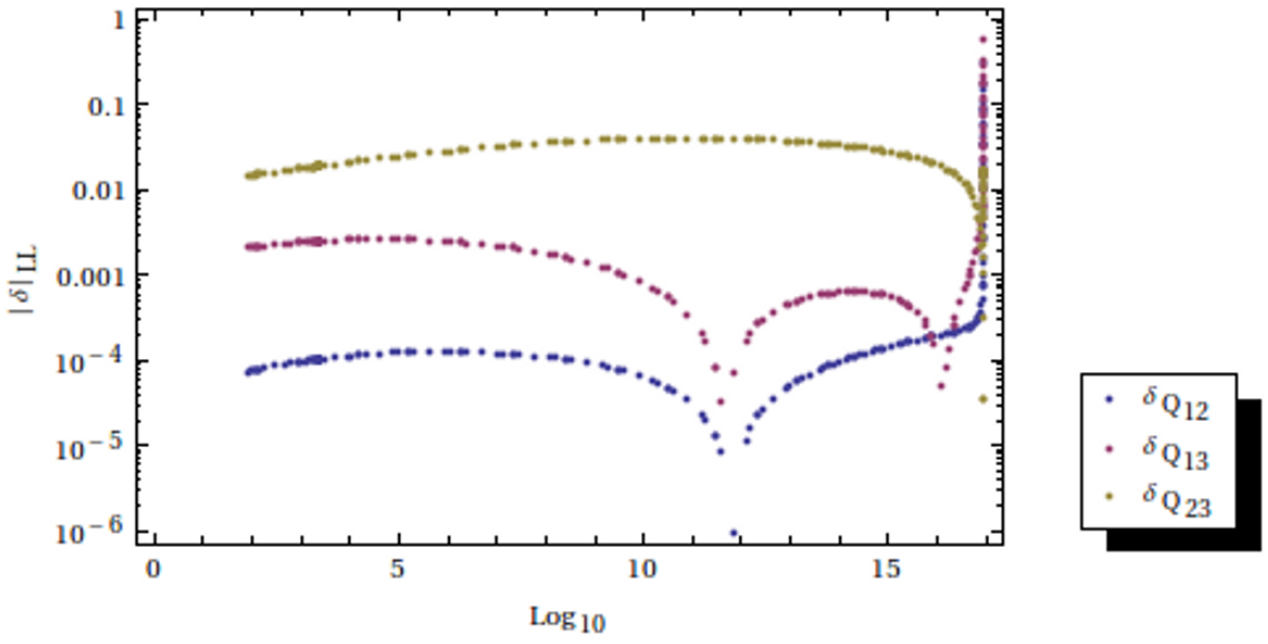
flavour constraints

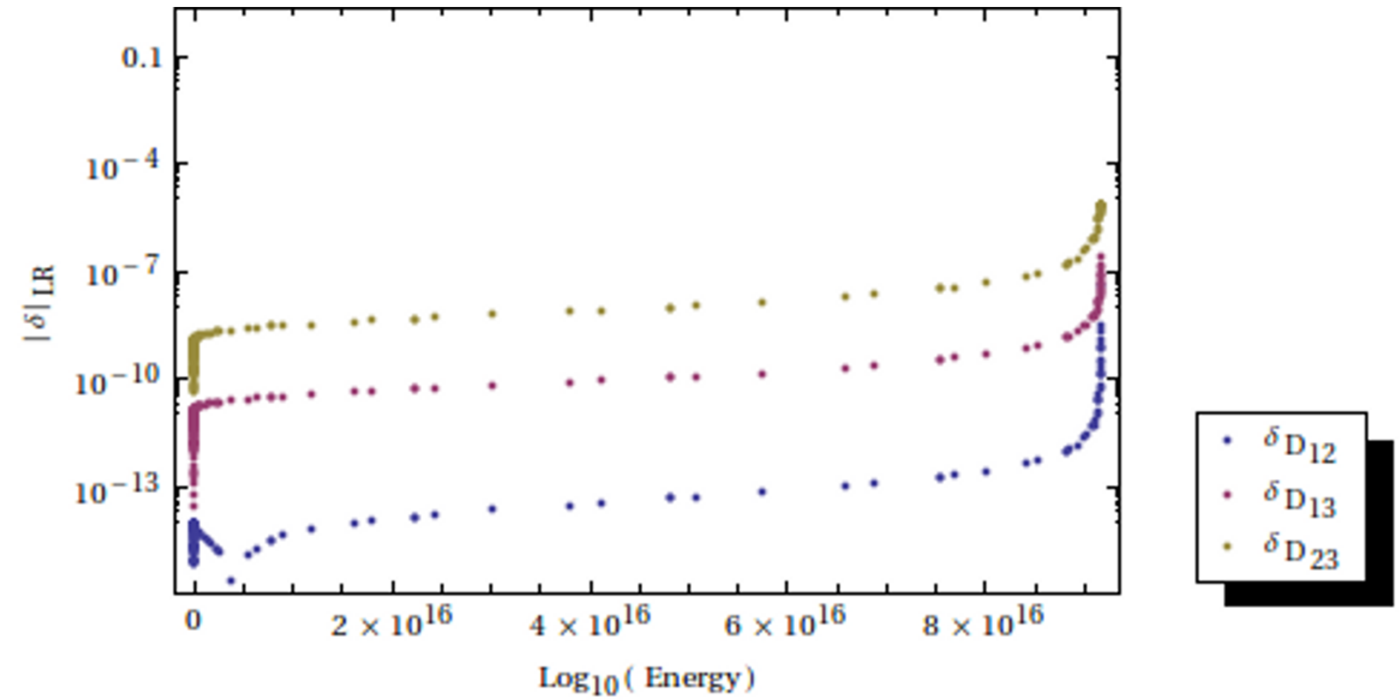
leptonic sector
is well within the
bounds

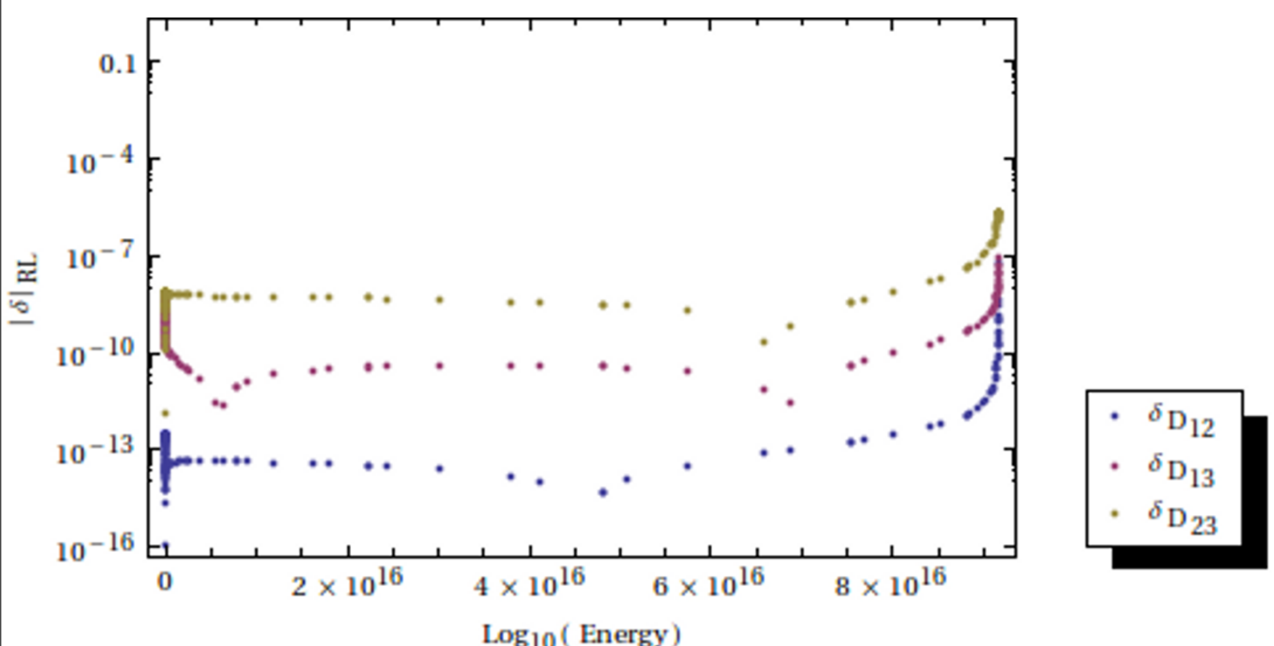


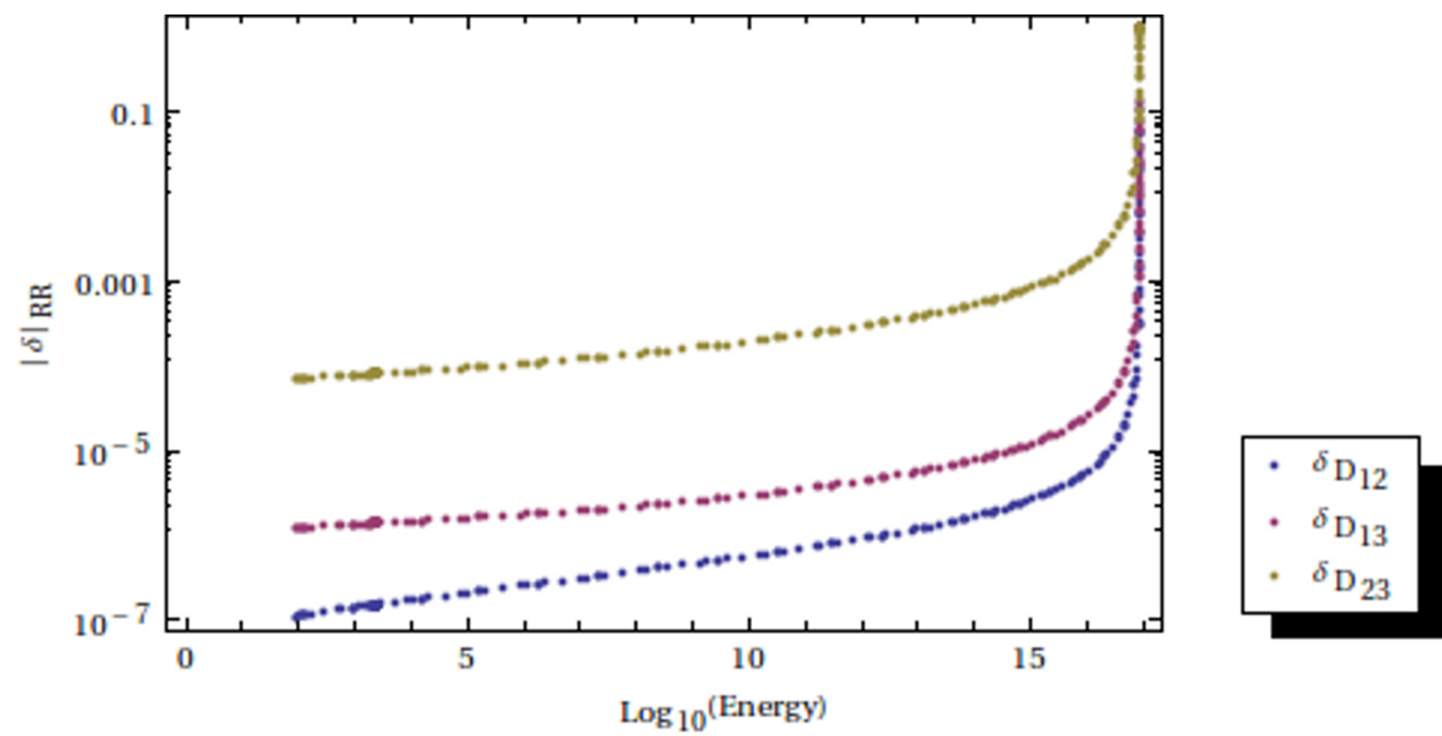


hadronic flavour constraints









Example Point

Parameter	Mass(TeV)	Parameter	Mass(TeV)	Parameter	Mass(TeV)	Parameter	Mass(Tev)	Parameter	Mass(TeV)
$\tilde{t}_1$	0.702	$\tilde{b}_1$	2.06	$\tilde{\tau}_1$	0.480	$\tilde{\nu}_\tau$	0.570	N_1	0.465
$\tilde{t}_2$	2.31	$\tilde{b}_2$	2.32	$\tilde{\tau}_2$	0.802	$\tilde{\nu}_\mu$	0.624	N_2	0.928
$\tilde{c}_R$	2.25	$\tilde{s}_R$	2.36	$\tilde{\mu}_R$	0.608	$\tilde{\nu}_e$	0.625	N_3	4.26
$\tilde{c}_L$	2.45	$\tilde{s}_L$	2.45	$\tilde{\mu}_L$	0.902	-	-	N_4	4.26
$\tilde{u}_R$	2.25	$\tilde{d}_R$	2.36	$\tilde{e}_R$	0.610	-	-	C_1	0.894
$\tilde{u}_L$	2.45	$\tilde{d}_L$	2.45	$\tilde{e}_L$	0.903	-	-	C_2	4.32
m_{A^0}	4.18	$m_H^\pm$	4.18	m_h	0.1235	m_H	3.96	-	-

(ij)	$\lvert\delta^Q_{LL}\rvert$	$\lvert\delta^L_{LL}\rvert$	$\lvert\delta^D_{LR}\rvert$	$\lvert\delta^U_{LR}\rvert$	$\lvert\delta^D_{RL}\rvert$	$\lvert\delta^U_{RL}\rvert$	$\lvert\delta^D_{RR}\rvert$	$\lvert\delta^E_{RR}\rvert$	$\lvert\delta^U_{RR}\rvert$
12	0.0003	10^{-6}	10^{-10}	10^{-8}	10^{-8}	10^{-5}	10^{-7}	10^{-7}	0.00005
13	0.01	0.007	10^{-8}	10^{-8}	10^{-5}	0.002	10^{-6}	10^{-4}	0.06
23	0.06	10^{-4}	10^{-6}	10^{-5}	10^{-5}	0.01	10^{-4}	0.0006	0.001

Dirac case $m_{3/2} = 800$ GeV; $M_{1/2} = 1200$ GeV

Summary

Randall Sundrum is considered as a theory of flavour only, between Planck and GUT scale.

The framework is good for lepton mass fitting, and also for GUTs.

Supersymmetry can be a solution of hierarchy problem at low scales.

The nature of soft terms is like "Flavourful Supersymmetry" if SUSY broken on the GUT brane. Viable spectrum at weak scale.