

MASSIVE NEUTRINOS
AND
LHC PHYSICS
IN THE
RANDALL-SUNDRUM MODEL

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GDR *Neutrino* (3ème Réunion)

I) Introduction: the RS model

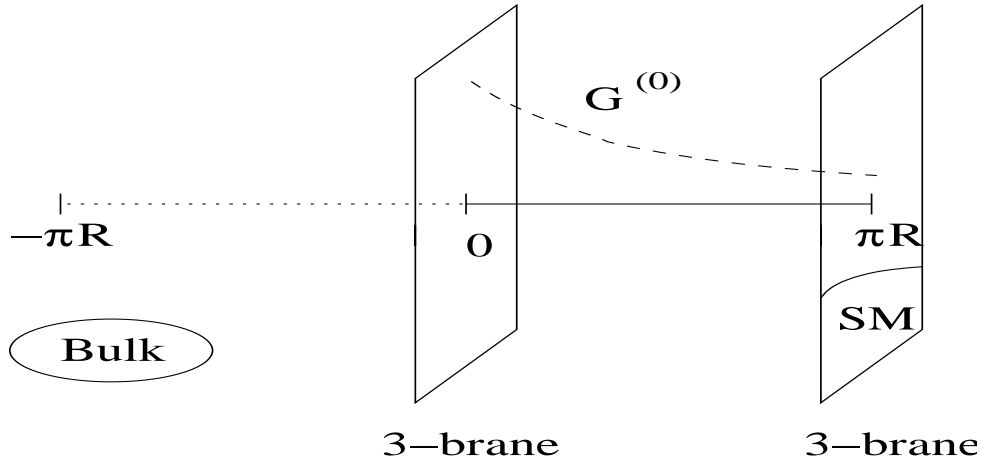
II) The fermion mass hierarchy problem (in RS)

III) Production of KK excitations of gauge bosons at LHC (in RS)

IV) Conclusion: summary

I) INTRODUCTION: THE RANDALL-SUNDRUM (RS) MODEL

[A] Geometrical configuration:



One extra dimension compactified on a S^1/\mathbb{Z}_2 orbifold:

$$-\pi R \leq x_5 \leq \pi R.$$

$M_5 \equiv$ fundamental 5-dimensional mass scale of gravity

$1/k \equiv$ curvature radius for the slice of Anti-de-Sitter (AdS_5) space

$\Lambda \equiv$ cosmological constant in the bulk

The tensions of the 2 branes are tuned such that:

$$\Lambda_{(y=0)} = -\Lambda_{(y=\pi R)} = -\Lambda/k = 24kM_5^3.$$

[B] How is solved the gauge hierarchy problem ?

$M_{Pl} \equiv$ mass scale of gravity on the Planck-brane

$M_\star \equiv$ mass scale of gravity on our TeV-brane

$$M_\star = e^{-\sigma(\pi R)} M_{Pl},$$

$$\sigma(x_5) = k|x_5| \quad \text{in} \quad ds^2 = e^{-2\sigma(x_5)} \eta_{\mu\nu} dx^\mu dx^\nu + dx_5^2$$

$$kR \approx 11 \Rightarrow M_\star = \mathcal{O}(TeV)$$

- SM fields feel a TeV cut-off (M_\star) which solves the problem of instability of the Higgs boson mass (Q_{EW}) with respect to quadratically divergent quantum corrections.

$\langle h \rangle \equiv$ SM Higgs boson VEV from the bulk point of view

$$\langle h \rangle \approx M_5$$

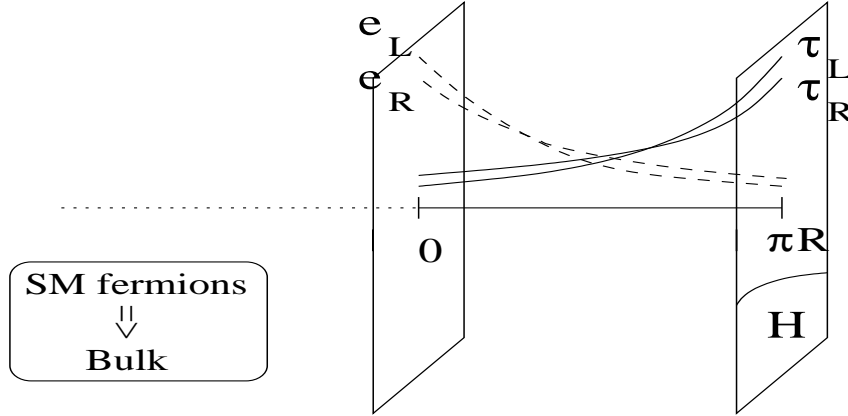
- The 2 fundamental scales M_5 and $\langle h \rangle$ (or Q_{EW}) are of the same order of magnitude ($\sim M_{Pl}$).

(And only 1 scale for the fundamental parameters !

$$k \sim M_{Pl}, \quad R^{-1} \sim M_{Pl}, \quad \Lambda_{(y=0,\pi R)} \sim M_{Pl}^4, \quad \Lambda \sim M_{Pl}^5$$

II) THE FERMION MASS HIERARCHY PROBLEM (IN RS)

The RS model also provides a framework for generating the large mass hierarchies among SM fermions of different flavor and type ($m_{top}/m_{\nu_1} \sim 10^{11}$ at least!) **without introducing a symmetry:**



Fermion localization:

$$\int d^4x \int dx_5 \sqrt{G} m_i \bar{\Psi}_i \Psi_i, \quad m_i = c_i \frac{d\sigma(x_5)}{dx_5} = \pm c_i k$$

$$\Psi_i(x^\mu, x_5) = \sum_{n=0}^{\infty} \psi_i^{(n)}(x^\mu) f_i^{(n)}(x_5), \quad f_i^{(0)}(x_5) = N(c_i) e^{(1/2-c_i)\sigma(x_5)}$$

Yukawa couplings:

$$\int d^4x \int dx_5 \sqrt{G} \left(Y_{ij}^5 H \bar{\Psi}_{+i} \Psi_{-j} + h.c. \right) = \int d^4x M_{ij} \bar{\psi}_{Li}^{(0)} \psi_{Rj}^{(0)} + \dots$$

$$M_{ij} = \int_{-\pi R}^{\pi R} dx_5 \sqrt{G} Y_{ij}^5 H_0 f_i^{(0)} f_j^{(0)} \Rightarrow M_{ij} = M_{ij}(Y_{ij}^5, kR, c_i^L, c_j^R)$$

Minimal SM extension generating (Dirac) neutrino masses:
SM + $\nu_R \Rightarrow$ neutrino masses from Yukawa couplings

All the values of $c_i^{LL}, c_j^{l_R^\pm}, c_k^{\nu_R}$ [$i, j, k = \{1, 2, 3\}$]
 \Downarrow

All the current experimental data on leptons:

★ 3 charged lepton masses (with an uncertainty of 5%)

★ A 3-flavor fit to neutrino data (from solar, atmospheric, reactor [KamLAND and CHOOZ] and accelerator [K2K] experiments) leads to (4σ level):

$$6.8 \leq \Delta m_{\nu_{21}}^2 \leq 9.3 \quad [10^{-5} \text{eV}^2], \quad 1.1 \leq \Delta m_{\nu_{31}}^2 \leq 3.7 \quad [10^{-3} \text{eV}^2]$$

as well as the leptonic mixing angles:

$$0.21 \leq \sin^2 \theta_{12} \leq 0.41, \quad 0.30 \leq \sin^2 \theta_{23} \leq 0.72, \quad \sin^2 \theta_{13} \leq 0.073$$

★ Limit extracted from the tritium beta decay experiments (relevant whatever is the nature of neutrino mass) at 95% C.L.:

$$m_\beta = \left(\sum_{i=1}^3 |U_{MNS_{ei}}|^2 m_{\nu_i}^2 \right)^{1/2} \leq 2.2 \text{ eV} \quad [\text{Mainz}]$$

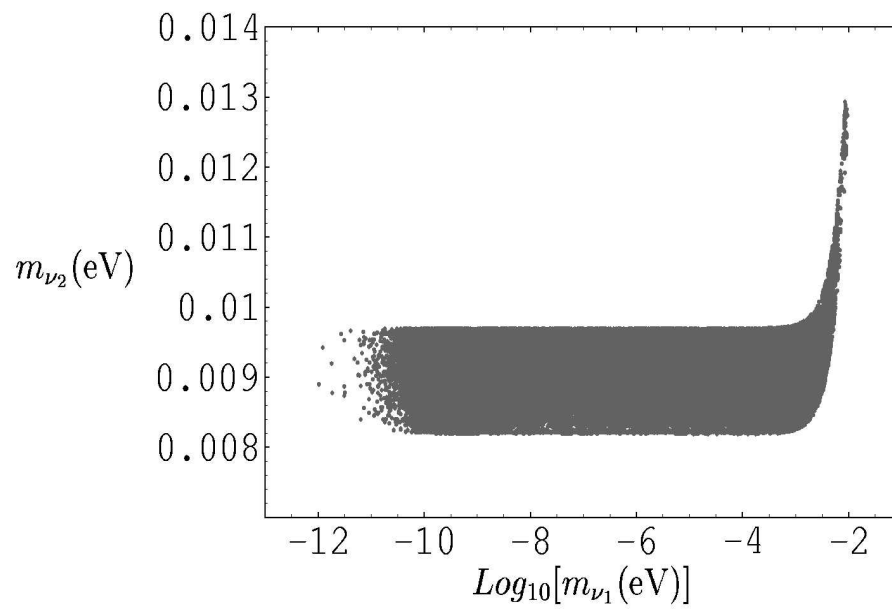
Example for $kR = 10.83$ ($\Rightarrow M_\star = 4\text{TeV}$) and $Y_{ij}^5 \in [0.9, 1.1] \times g_5$:

$$\begin{cases} c_1^{LL} = 0.27 & c_2^{LL} = 0.41 & c_3^{LL} = 0.49 \\ c_1^{l_R^\pm} = 0.66 & c_2^{l_R^\pm} = 0.62 & c_3^{l_R^\pm} = 0.70 \\ c_1^{\nu_R} = 1.42 & c_2^{\nu_R} = 1.37 & c_3^{\nu_R} = 1.38 \end{cases}$$

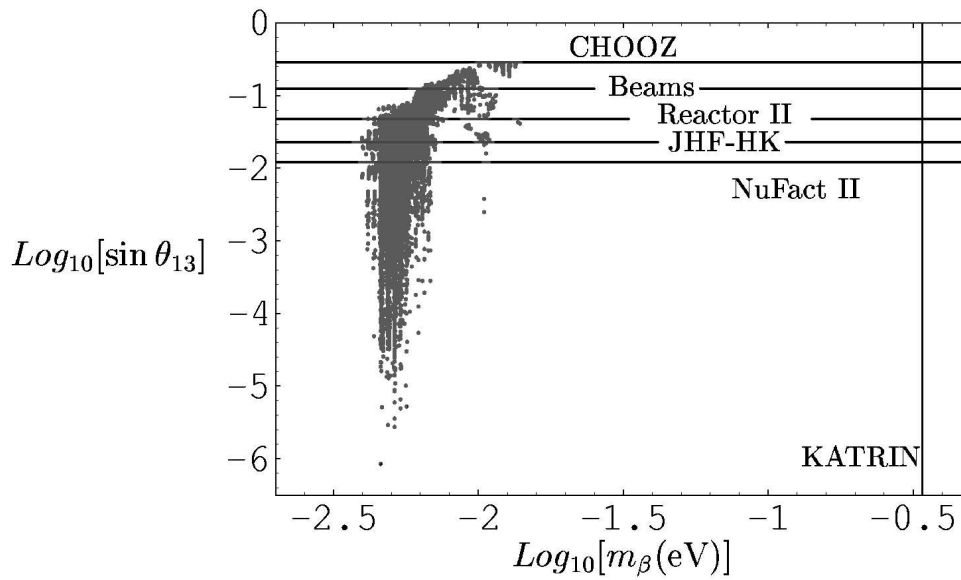
Obtained values of $c_i^{LL}, c_j^{lR}, c_k^{\nu R} \rightarrow$ Predictions on neutrinos

Neutrino Mass spectrum:

Normal mass hierarchy: $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$ with $m_{\nu_3} \in [0.03, 0.06]$ eV.



Testable quantities at next neutrino experiments:

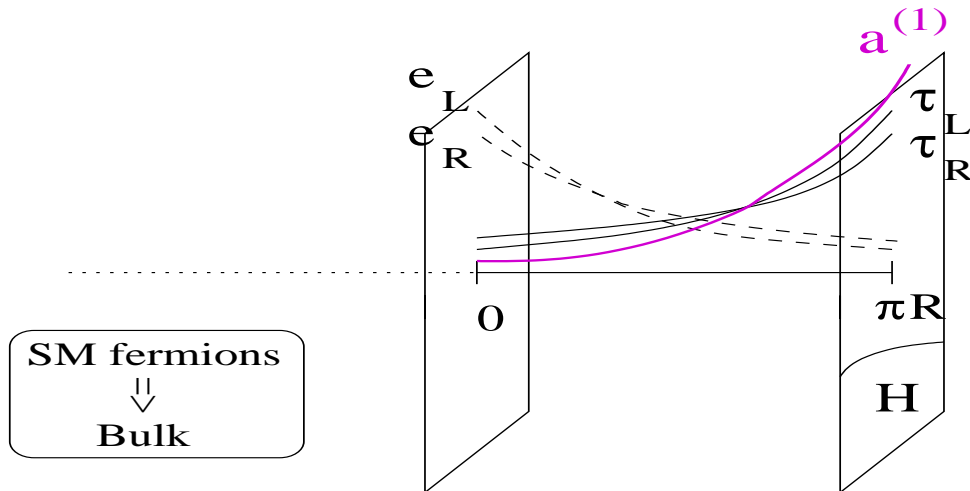


Future neutrino experiments will test partially the RS model (SM bulk fields) as a generator of fermion mass hierarchies.

III) PRODUCTION OF KK EXCITATIONS OF GAUGE BOSONS AT LHC

(IN RS)

[Work in progress,
G.Branco, F.Ledroit, G.M. and J.Silva-Marcos]



Experimental data on fermion mass matrices



localizations of fermions (parameterized by the c_i)



effective 4-dimensional couplings:
fermions / gauge boson KK excitations



cross sections for production of
gauge boson KK excitations at colliders.

$pp \rightarrow Z^{(1)}/\gamma^{(1)} \rightarrow l^+l^-$

$$S_4^{Z^{(1)}/\gamma^{(1)}l^+l^-} = \int d^4x g_4 A_\mu^{(1)} \overline{\begin{pmatrix} \Psi_e^{(0)} \\ \Psi_\mu^{(0)} \\ \Psi_\tau^{(0)} \end{pmatrix}} \gamma^\mu U_l^\dagger \mathcal{C} U_l \begin{pmatrix} \Psi_e^{(0)} \\ \Psi_\mu^{(0)} \\ \Psi_\tau^{(0)} \end{pmatrix}$$

$$\mathcal{C} = \begin{pmatrix} \int dx_5 \sqrt{G} a^{(1)} |f_{\mathbf{1}}^{(0)}|^2 & 0 & 0 \\ 0 & \int dx_5 \sqrt{G} a^{(1)} |f_{\mathbf{2}}^{(0)}|^2 & 0 \\ 0 & 0 & \int dx_5 \sqrt{G} a^{(1)} |f_{\mathbf{3}}^{(0)}|^2 \end{pmatrix}$$

$$A_\mu(x^\mu, x_5) = \sum_{n=0}^{\infty} A_\mu^{(n)}(x^\mu) a^{(n)}(x_5)$$

↔ violation of coupling universality: e.g. $Z^{(1)}\bar{e}e \neq Z^{(1)}\bar{\mu}\mu$

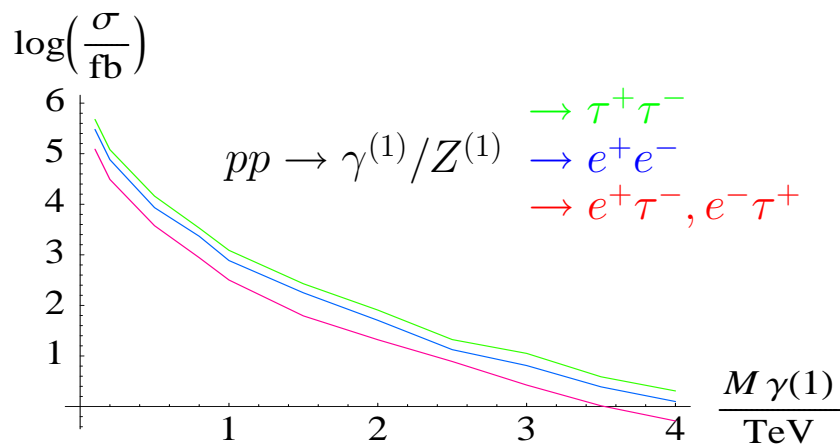
↪ flavor violating couplings: e.g. $Z^{(1)}\bar{e}\mu$

Examples of cross section values (for $kR = 10.83$)

Leptons: previous set of $c_i^{LL}, c_j^{l\pm}, c_k^{\nu R}$ values

Hadrons:

$$\left\{ \begin{array}{l} 6 \text{ quark masses} \\ 3 \text{ CKM angles} \end{array} \right\} \Leftrightarrow \left\{ \begin{array}{lll} c_1^{QL} = 0 & c_2^{QL} = 0.52 & c_3^{QL} = 0.57 \\ c_1^{dR} = 0.6 & c_2^{dR} = 0.67 & c_3^{dR} = 0.61 \\ c_1^{uR} = -4 & c_2^{uR} = 0.57 & c_3^{uR} = 0.51 \end{array} \right.$$



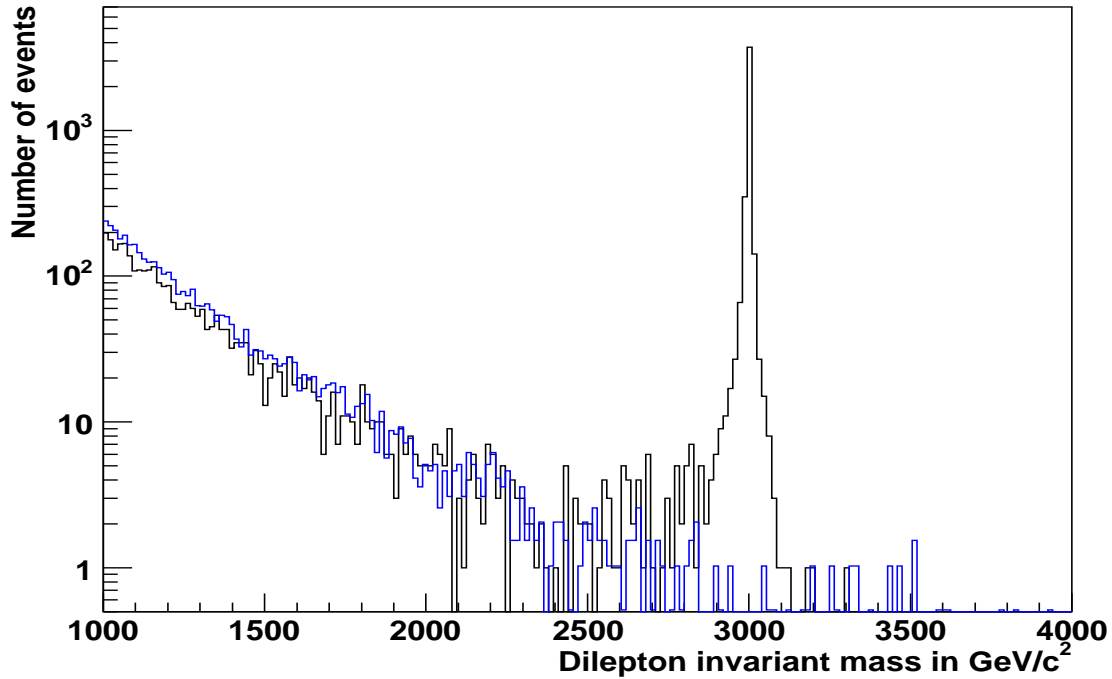
$$(M_{Z^{(1)}} = \sqrt{M_{\gamma^{(1)}}^2 + M_{Z^0}^2} ; \text{ initial parton state: } u\bar{u}, d\bar{d}, u\bar{c}, d\bar{s} \dots)$$

→ **significant numbers of events at LHC** (e.g. with $\mathcal{L} = 30 \text{ fb}^{-1}$)

Example of distribution

$$\begin{cases} pp \rightarrow \gamma/Z^0 \rightarrow e^+e^- \\ pp \rightarrow \gamma/Z^0/\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^- \end{cases}$$

Dilepton invariant mass for the RS model



$$(M_{\gamma^{(1)}} = 3 \text{ TeV} ; 7675 \text{ events} \leftrightarrow 600 \text{ fb}^{-1})$$

→ the RS signal can be extracted from the **SM background**

Complete study

- consider other kR values (gauge hierarchy $\Rightarrow kR \sim 11$)
- compare the studied $M_{\gamma(1)}$ values with EW precision constraints
- take into account first resonances: $\gamma^{(2)}, Z^{(2)}, \dots$
- **“Which maximum $M_{\gamma(1)}$ value can be probed by LHC ?”**

\Leftrightarrow **“Which k values testable at LHC ?”**

$$M_{\gamma(1)} = 2.45 k e^{-\pi k R}$$

(complete set of RS fundamental parameters: $\{k, R, M_5, \Lambda\}$'s)

\Leftrightarrow **“Can LHC exclude the RS model (with SM bulk fields) ?”**

$$|R_5| < M_5^2 \Rightarrow k < 0.1 M_{Pl}$$

RS model:

★ studies at colliders *only* based on the exchange of $G^{(n)}$
(\rightarrow *only* bulk field)

- ★ $\left\{ \begin{array}{l} - \text{Tevatron Run II: } M_{G^{(1)}} > 675\text{GeV} \\ - \text{LHC (with } \mathcal{L} = 100 \text{ fb}^{-1} \text{) can exclude the RS model !} \\ \quad (\Leftrightarrow \text{ full parameter space } \{k, R\} \text{ testable)} \end{array} \right.$

RS model with SM bulk fields:

Motivations: $\left[\begin{array}{l} \rightarrow \text{ explain fermion mass hierarchies} \\ \text{(we have constructed realistic models)} \\ \rightarrow \text{ is interesting as a GUT framework} \\ \rightarrow \text{ provides a new WIMP candidate for dark matter} \end{array} \right.$

★ **our study at colliders** (on exchange of $Z^{(n)}/\gamma^{(n)}$)
is the first realistic one.

- ★ $\left\{ \begin{array}{l} - \text{Tevatron Run II: bounds on } M_{\gamma^{(1)}} \text{ ?} \\ - \text{Can LHC exclude the RS model (with SM bulk fields) ?} \\ \quad \text{(next neutrino experiments will only} \\ \quad \text{test a region of parameter space)} \end{array} \right.$