MASSIVE NEUTRINOS
AND
LHC PHYSICS
IN THE
RANDALL-SUNDRUM MODEL

Grégory MOREAU
Centro de Física Teórica de Partículas
(Lisbon)

In collaboration with:

F. LEDROIT-GUILLON (LPSC, GRENOBLE)
G. C. BRANCO, J. I. SILVA-MARCOS (CFTP, LISBOA)

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PLAN

I) Introduction: the RS model

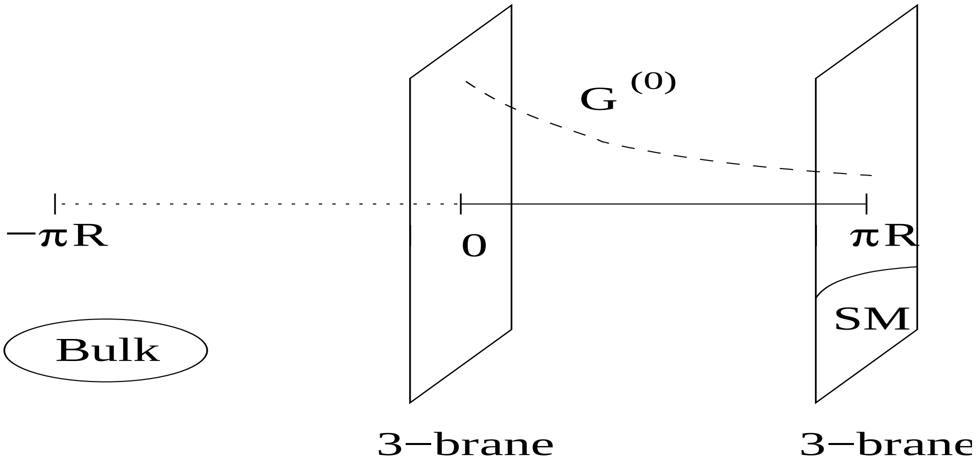
II) The fermion mass hierarchy problem **(in RS)**

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

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

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

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

- 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

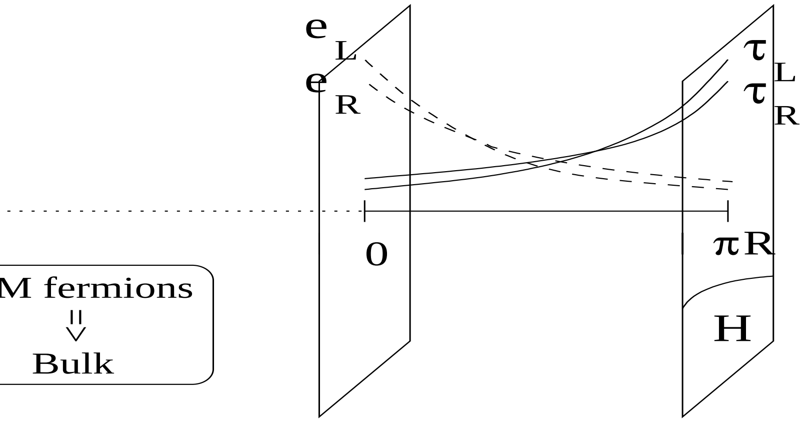
$$\boxed{\langle h \rangle \approx M_5}$$

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

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**:



SM fermions
⇓
Bulk

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:

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

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

Concrete realizations in the lepton sector:

[hep-ph/0507145, G.M. and J.Silva-Marcos]

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

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

$\Downarrow$

All the current experimental data on leptons:

$\star$ 3 charged lepton masses (with an uncertainty of 5%)

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

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

as well as the leptonic mixing angles:

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

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

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

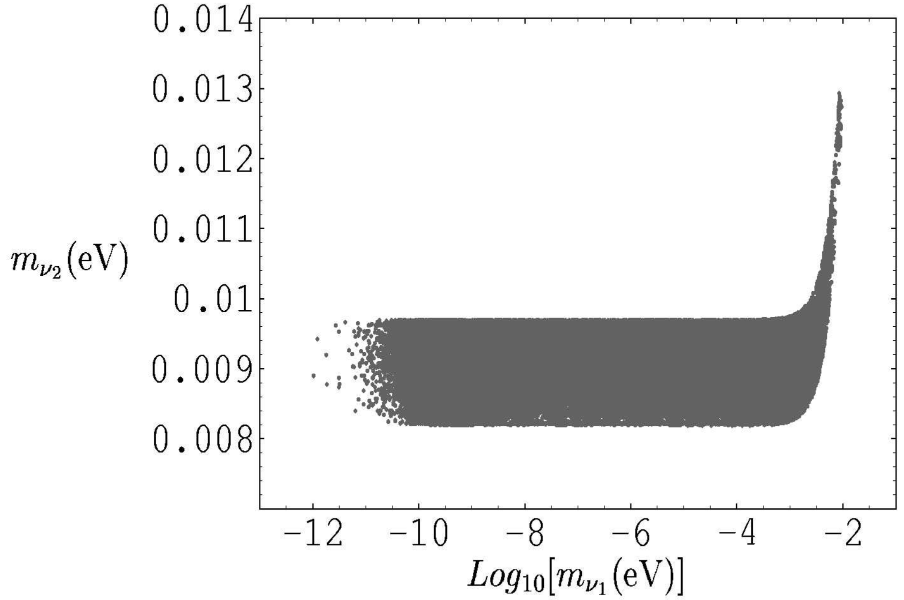
Example for $kR = 10.83$ ($\Rightarrow M_\star = 4TeV$) and $Y^5_{ij} \in [0.9, 1.1] \times g_5$:

$$\left\{ \begin{array}{lll} c_1^{L_L} = 0.27 & c_2^{L_L} = 0.41 & c_3^{L_L} = 0.49 \\ c_1^{l_R^\pm} = 0.66 & c_2^{l_R^\pm} = 0.62 & c_3^{l_R^\pm} = 0.70 \\ c_1^{\nu_R} = 1.42 & c_2^{\nu_R} = 1.37 & c_3^{\nu_R} = 1.38 \end{array} \right.$$

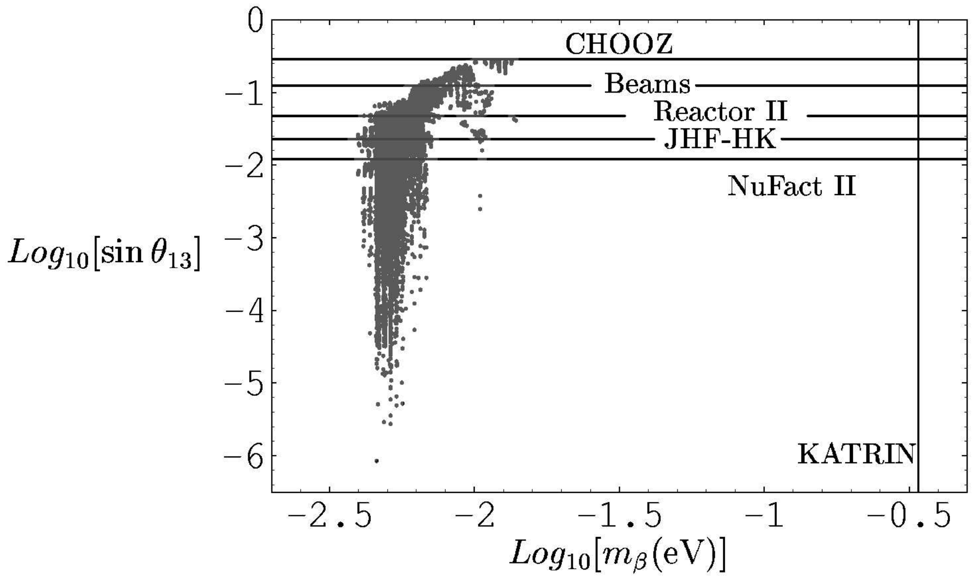
Obtained values of $c_i^{L_L}, c_j^{l_R^\pm}, c_k^{\nu_R}$ $\longrightarrow$ Predictions on neutrinos

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.



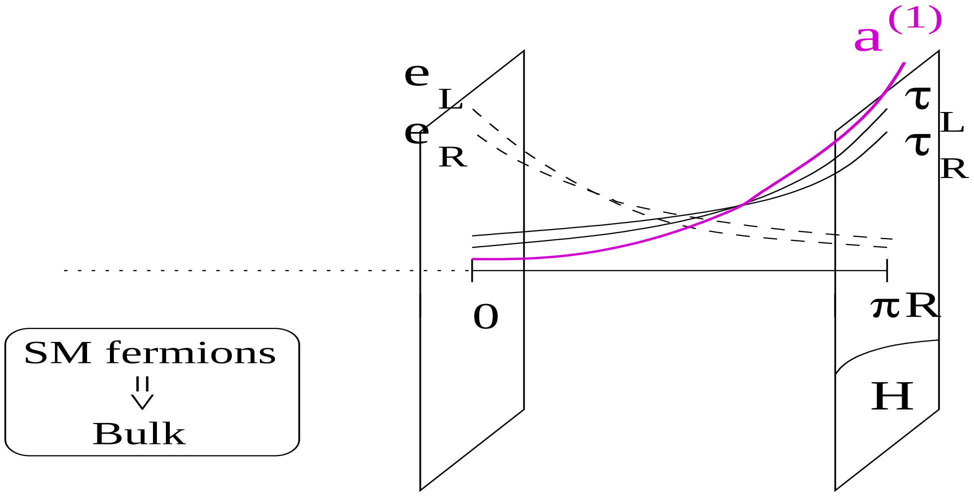
Testable quantities at next neutrino experiments:



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 <u>fermion mass</u> matrices

$\Downarrow$

localizations of fermions (parameterized by the c_i)

$\Downarrow$

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

$\Downarrow$

cross sections for production of
gauge boson KK excitations at <u>colliders</u>.

Study on a clear signature of the RS model at LHC: $pp \longrightarrow Z^{(1)}/\gamma^{(1)} \longrightarrow l^+l^-$

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

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

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

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

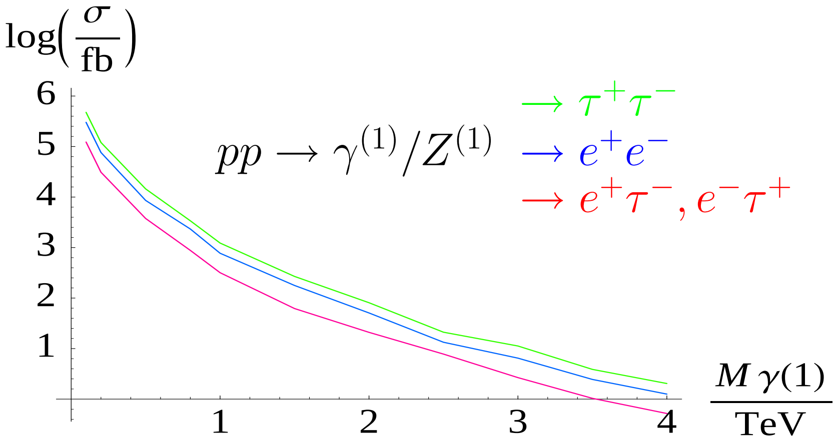
⇝ flavor violating couplings: $\underline{\underline{\text{e.g.}}}$ $Z^{(1)}\bar{e}\mu$

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

Leptons: previous set of $c_i^{L_L}, c_j^{l^\pm_R}, c_k^{\nu_R}$ values

Hadrons:

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

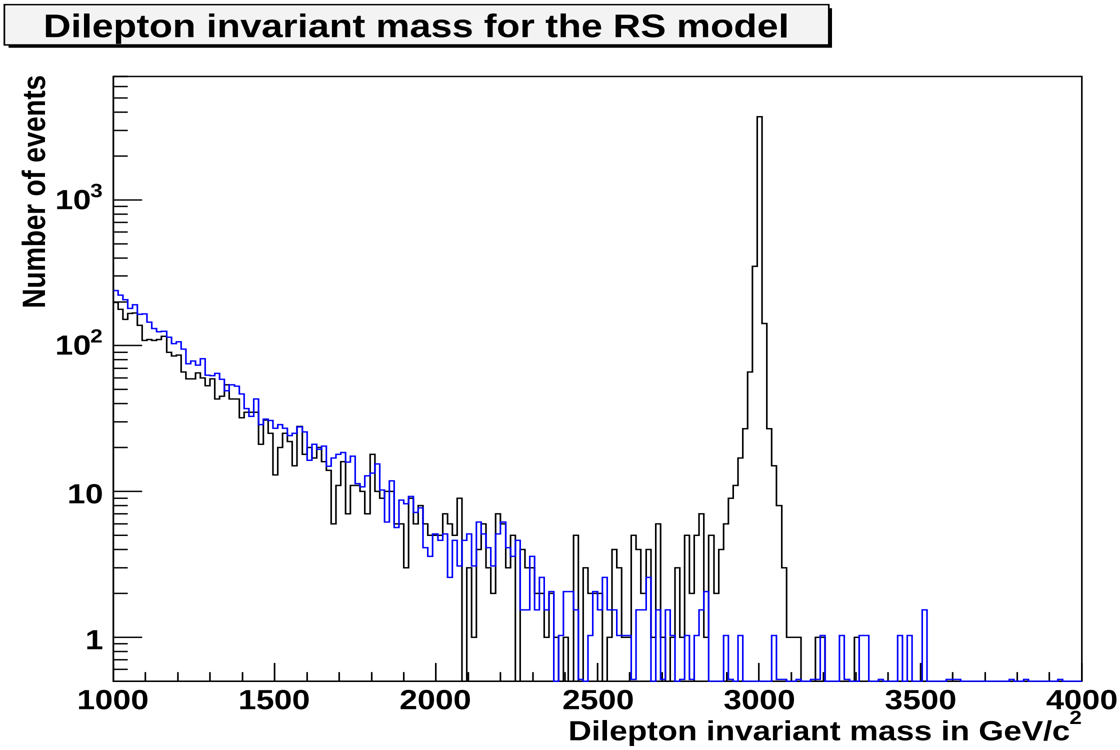


$(M_{Z^{(1)}} = \sqrt{M^2_{\gamma^{(1)}} + M^2_{Z^0}}$; initial parton state: $u\bar{u}$, $d\bar{d}$, $u\bar{c}$, $d\bar{s}$ $\dots$)

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

Example of distribution

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



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

↪ **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: $\gamma^{(2)}$, $Z^{(2)}$, $\ldots$
- **“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: $\{k, R, M_5, \Lambda\text{'s}\}$)

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

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

IV) CONCLUSION: SUMMARY

RS model:

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

⋆
- Tevatron Run II: $M_{G^{(1)}} > 675$GeV
- LHC (with $\mathcal{L} = 100\ fb^{-1}$) can exclude the RS model !
  ($\Leftrightarrow$ full parameter space $\{k, R\}$ testable)

RS model with SM bulk fields:

Motivations:

$\longrightarrow$ explain fermion mass hierarchies
(we have constructed realistic models)
$\longrightarrow$ is interesting as a GUT framework
$\longrightarrow$ provides a new WIMP candidate for dark matter

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

⋆
- Tevatron Run II: bounds on $M_{\gamma^{(1)}}$?
- Can LHC exclude the RS model (with SM bulk fields) ?
  (next neutrino experiments will only
  test a region of parameter space)