Happy Birthday Costas!

PROLOGUE: MY LIFE AFTER I MET COSTAS

Kounnas-Fest, NICOSIA, 28-30 SEPT 2012

MARIANO QUIRÓS, ICREA/IFAE

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- After that my life changed because
    - I was intoxicated by the smoke
    - Even if he is (was) younger than me he taught me to do research
- That year we started a fruitful collaboration
- And a better friendship

- After that we met in other places
    - July 1984: CERN
    - September 1984: CERN
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- C. Kounnas, J. Leon and M. Quiros, Phys. Lett. B **129** (1983) 67.
- C. Kounnas, D. V. Nanopoulos, M. Quiros and M. Srednicki, Phys. Lett. B **127** (1983) 82.
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- K. Enqvist, D. V. Nanopoulos, M. Quiros and C. Kounnas, Nucl. Phys. B **262** (1985) 556.
- C. Kounnas and M. Quiros, Phys. Lett. B **151** (1985) 189.
- C. Kounnas, M. Quiros and F. Zwirner, Nucl. Phys. B **302** (1988) 403.

- Still if those early papers were not the best ones in our careers they have an average number of citations per paper ~ 70
- After 1988 I came back to Madrid and we followed different roads

- As I could not compete with Costas in what he was doing
- I decided to work on something else!

- Anyway I would like to take advantage of this opportunity to thank you Costas

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- Let me come to the (5D) bulk of my talk

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NEUTRINO ANARCHY IN WARPED SPACE

Kounnas-Fest, NICOSIA, 28-30 SEPT 2012

MARIANO QUIRÓS, ICREA/IFAE

OUTLINE

The outline of this talk is

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- Introduction: hierarchical quark sector
- Lepton sector: anarchic neutrinos
- Majorana neutrinos
- Flavor from Wilson Lines
    - Gauge group
    - A model for U_{PMNS}
    - Lepton number violation
- Conclusion

INTRODUCTION: HIERARCHICAL QUARK SECTOR

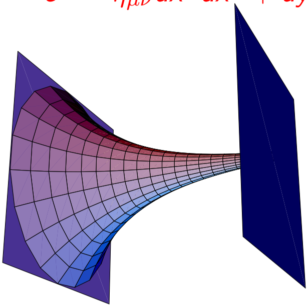
- Warped Extra Dimensional (WED) theories can accomodate a solution to the hierarchy and flavor problems if all SM fields propagate in the bulk of the extra dimension when

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

- The bulk Higgs is leaning towards the IR brane:

$h(y) \sim e^{aky}$, $a > 2$ (hierarchy prob)

- Light fermion profiles are leaning towards the UV brane
- Heavy fermion profiles are leaning towards the IR brane



$y = 0$ $\qquad$ $y = y_1 \simeq 35/k$

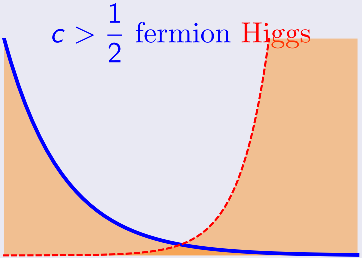
Fermion localization is controlled by the 5D Dirac mass term

$$\mathcal{L}_m = -\int dy e^{-4ky} c_\psi k \bar{\psi}_R \psi_L + h.c. \quad c_\psi = (-c_L, c_R)$$

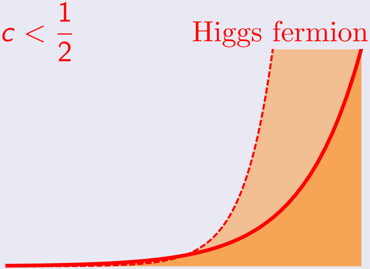
$$\psi(x,y) \simeq f_\psi^{(0)}(y)\psi^{(0)}(x) + \cdots , \quad f_\psi^{(0)}(y) \simeq e^{(\frac{1}{2}-c_\psi)ky}$$

as

Light fermions



Heavy fermions



- The structure of Yukawa couplings is ($\epsilon = e^{-ky_1} \simeq k/m_{KK}$)

$$Y_{ij} \simeq \hat{Y}_{ij} f(c_L^i) f(c_R^j), \quad f(c) = \sqrt{|2c-1|} \left\{ \begin{array}{cc} 1 & (c < 1/2) \\ \epsilon^{c-1/2} & (c > 1/2) \end{array} \right.$$

- So the Yukawa matrices are $x \equiv c_x - 1/2,\ x = q_i, u_i, d_i$ $(q_1 > q_2 > q_3,\ u_1 > u_2 > u_3,\ d_1 > d_2 > d_3)$

$$Y_{ij}^U \sim \begin{pmatrix} \epsilon^{q_1+u_1} & \epsilon^{q_1+u_2} & \epsilon^{q_1} \\ \epsilon^{q_2+u_1} & \epsilon^{q_2+u_2} & \epsilon^{q_2} \\ \epsilon^{u_1} & \epsilon^{u_2} & 1 \end{pmatrix}, \quad Y_{ij}^D \sim \begin{pmatrix} \epsilon^{q_1+d_1} & \epsilon^{q_1+d_2} & \epsilon^{q_1+d_3} \\ \epsilon^{q_2+d_1} & \epsilon^{q_2+d_2} & \epsilon^{q_2+d_3} \\ \epsilon^{d_1} & \epsilon^{d_2} & \epsilon^{d_3} \end{pmatrix}$$

- Typical of hierarchical mixing angles and mass eigenvalues

$$s_{ij} \sim \epsilon^{q_i - q_j}, \quad (i < j), \quad m_i \sim v\epsilon^{q_i}, \quad q_3 \equiv 0$$

- This qualitative behavior is consistent with the hierarchical behavior of quark masses and mixing angles in CKM matrix

$$s_{12} \simeq 0.226, \quad s_{23} \simeq 0.042, \quad s_{13} \simeq 0.004$$

$$\mathrm{mass}/m_t : (u, c, d, s, b) \simeq (2 \cdot 10^{-5}, 7 \cdot 10^{-3}, 3 \cdot 10^{-5}, 6 \cdot 10^{-4}, 2 \cdot 10^{-2})$$

- We have performed a χ^2 fit to the experimental quark masses and CKM matrix elements [1].
- We have randomly generated a set of 40,000 complex 5D Yukawas and fitted the 9 parameters c_ψ

The result of the fit (including 1σ)

$c_{(u,d)L} = 0.66 \pm 0.02$	$c_{(c,s)L} = 0.59 \pm 0.02$	$c_{(t,b)L} = -0.11^{+0.45}_{-0.53}$
$c_{uR} = 0.71 \pm 0.02$	$c_{cR} = 0.57 \pm 0.02$	$c_{tR} = 0.42^{+0.05}_{-0.17}$
$c_{dR} = 0.66 \pm 0.03$	$c_{sR} = 0.65 \pm 0.03$	$c_{bR} = 0.64 \pm 0.02$

---

[1] J.A. Cabrer, G.v. Gersdorff and MQ, arXiv:1110.3324 [hep-ph]

LEPTON SECTOR: ANARCHIC NEUTRINOS

- While the charged lepton sector spectrum is hierarchical

$$\mathrm{mass}^2/m_\tau^2 : (e,\mu) \simeq (9\cdot 10^{-8}, 4\cdot 10^{-3})$$

and can be described by a "quark-like" formalism where $c_{\mathcal{E}_1} > c_{\mathcal{E}_2} > c_{\mathcal{E}_3}$

- The neutrino sector is *anarchic* [2] which means that masses are not so different and mixing angles (in the PMNS matrix) are $\mathcal{O}(1)$

$$s_{12} \simeq 0.559, \quad s_{23} \simeq 0.721, \quad s_{13} \simeq 0.152$$

$$\Delta m_\odot^2/\Delta m_A^2 \simeq 3\cdot 10^{-2}$$

and suggests a non-hierarchical scenario where

$$\text{SYMMETRY} \Rightarrow c_{\ell^i} \simeq c_\ell, \quad c_{\mathcal{N}^i} \simeq c_{\mathcal{N}}, \quad \forall i$$

---

[2] L.J. Hall, H. Murayama, N. Weiner, arXiv:hep-ph/9911341

MAJORANA NEUTRINOS

- For 5D RH neutrinos one can introduce a Dirac $c_{\mathcal{N}}$ AND a Majorana mass matrix (in the bulk c_M and on the branes $n_{0,1}$)

$$\mathcal{L}_{\rm mass} = \int e^{-4ky}\, k\left(-\bar{\mathcal{N}}_R c_{\mathcal{N}} \mathcal{N}_L + \text{h.c.} + \frac{1}{2}[\mathcal{N}_L c_M \mathcal{N}_L - \mathcal{N}_R c_M \mathcal{N}_R + \text{h.c.}]\right)$$

$$\mathcal{L}_{\rm bd} = \left[\frac{1}{2}\bar{\mathcal{N}}_R n_0 \bar{\mathcal{N}}_R + \text{h.c.}\right]_{y=0} - \left[e^{-4ky_1}\frac{1}{2}\bar{\mathcal{N}}_R n_1 \bar{\mathcal{N}}_R + \text{h.c.}\right]_{y=y_1}$$

- We compute the 5D propagator at zero momentum [3]

$$G^{ab}_{RR}(y,y') = \sum_n \frac{f^{(n)}_{\mathcal{N}^a_R}(y) f^{(n)}_{\mathcal{N}^b_R}(y')}{m_n}$$

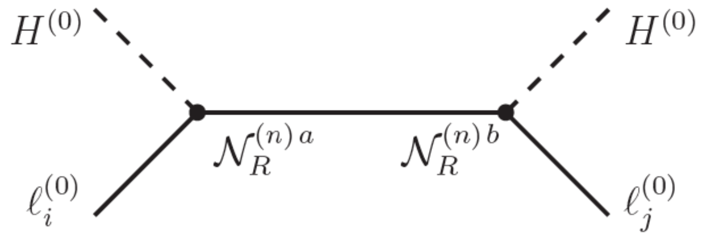
---

[3] G.v. Gersdorff, MQ, M. Wiechers, arXiv:1208.4300 [hep-ph]

- Integrating out (the whole tower of) RH neutrinos gives rise to the 4D neutrino operator

5D SEESAW

$$\mathcal{L}_W = c_W^{ij}\left[\bar{\ell}_i^{(0)}(x)\cdot\tilde{H}^{(0)}(x)\right]\left[\tilde{H}^{T(0)}(x)\cdot\ell_j^{c(0)}(x)\right] + \text{h.c.}$$



- and the neutrino mass matrix

$$m_\nu^{ij} = c_W^{ij} v^2 .$$

A summary of results for neutrino mass matrix (assuming a bulk symmetry $\Rightarrow c_{\ell^i} \simeq c_\ell,\ c_{\mathcal{N}^i} \simeq c_{\mathcal{N}},\ \forall i$) follows:

The case $c_M \neq 0$: violation of lepton number in the bulk

- For bulk and/or IR localized Yukawa coupling

$$m_\nu^{ij} \simeq \mathcal{O}(1)^{ij}\, \frac{v^2}{\epsilon k}\, \epsilon^{2c_\ell - 1} \simeq\ \epsilon^{2c_\ell-1}\, 10^{11}\ \mathrm{eV} \gtrsim 10\ \mathrm{MeV}\ \text{exc. by } \tau \text{ mass}$$

- For UV Yukawa coupling: $m_\nu^{ij} \sim \mathcal{O}(1)^{ij}\ \frac{v^2}{\epsilon k}\, \epsilon^{2a-1}$ excluded (too small)

The case $c_M = 0$ (but $n_i \neq 0$): lepton number conservation in the bulk

- For bulk and/or IR localized Yukawa coupling

$$m_\nu^{ij} \sim \mathcal{O}(1)^{ij}_{ab}\, \frac{v^2}{\epsilon\, k}\, \epsilon^{2c_\ell - 1} \cdot \epsilon^{c^a_{\mathcal{N}}} (n_0)^{-1}_{ab} \epsilon^{c^b_{\mathcal{N}}},\ \text{allowed}$$

- For UV Yukawa coupling: $m_\nu^{ij} \sim \mathcal{O}(1)^{ij}\ \frac{v^2}{\epsilon k}\, \epsilon^{2a-1}$ excluded (too small)

FLAVOR FROM WILSON LINES

- Naturalness & anarchic neutrino structure requires a bulk symmetry
- According to the AdS/CFT correspondence a local symmetry implies the existence of an exact (or spontaneously broken) global symmetry of the 4D dual theory.
- Consider a bulk group $G \to H_0$ (H_1) at the UV (IR) boundary
- The theory has zero modes for $A_\mu \in H_0 \cap H_1 \equiv H$ and $A_5 \in K_0 \cap K_1 \equiv K$ with $K_i \equiv G/H_i$
- One can transform away A_5 by a gauge transformation which changes the UV BC's of all fields

$$\Lambda(y) = i \int_y^{y_1} A_5(y), \quad \psi(0) \to e^{i\Lambda(0)} \psi(0)$$

- The UV boundary condition for the RH neutrinos changes as

$$n_0 \to e^{-i\Lambda(0)} n_0 e^{-i\Lambda(0)^T}$$

CHOICE OF GAUGE GROUP

In choosing G one should take into account the following requirements:

- G needs to be large enough such that the breaking $G \to H$ allows for nontrivial Wilson lines.
- In general, the larger G, the more the theory will be protected from flavor changing neutral currents (FCNC).
- G should ensure degeneracy of the c_ℓ, but allow for non-degenerate $c_\mathcal{E}$.
- G should not be so large such that the breaking $G \to H$ leaves over unwanted zero modes for A_μ (4D gauge symmetries).

The simplest bulk and boundary gauge groups:

- Bulk group:

$$G = U(3)_\ell \otimes U(3)_\mathcal{N} \otimes_i U(1)_{\mathcal{E}^i}\{\lambda^3_\mathcal{E}, \lambda^8_\mathcal{E}, \lambda^0_\mathcal{E}\}$$

$$\Downarrow$$

$$Y^B_\mathcal{N} = Y^B_\mathcal{E} = c_M = 0, \quad c_\ell,\ c_\mathcal{N},\ c_{\mathcal{E}^i}$$

- IR group:

$$H_1 = \otimes_i U(1)_{(\ell+\mathcal{E}+\mathcal{N})^i} = \{\lambda^3_\mathcal{E}+\lambda^3_\ell+\lambda^3_\mathcal{N},\ \lambda^8_\mathcal{E}+\lambda^8_\ell+\lambda^8_\mathcal{N},\ \lambda^0_\mathcal{E}+\lambda^0_\ell+\lambda^0_\mathcal{N}\}$$

$$\Downarrow$$

$$Y^1_{\mathcal{E}ij} = Y^1_{\mathcal{E}i}\,\delta_{ij}, \quad Y^1_{\mathcal{N}ij} = Y^1_{\mathcal{N}i}\,\delta_{ij}, \quad \Rightarrow Y^1_\mathcal{N} \equiv Y \propto diag(y_1, y_2, 1)$$

- UV group:

$$H_0 = U(3)_\ell \otimes U(1)_{\lambda^1_\mathcal{N}} \otimes_i U(1)_{\mathcal{E}^i}$$

$$\Downarrow$$

$$Y^0_\mathcal{N} = Y^0_\mathcal{E} = 0, \quad n_0\lambda^1_\mathcal{N} + \left(\lambda^1_\mathcal{N}\right)^T n_0 = 0 \Rightarrow n_0^{-1} \propto diag\left(\frac{y_3}{2}, -\frac{y_3}{2}, 1\right)$$

A WL MODEL FOR U_{PMNS}

- A quick glance at Yukawas shows that they belong to the case where neutrino mass matrix can be accomodated
- One can easily check that

$$H = H_0 \cap H_1 = \varnothing, \quad K = \left\{\lambda_{\mathcal{N}}^{2,4,5,6,7}\right\} \supset \left\{\lambda_{\mathcal{N}}^{2,5,7}\right\} = SO(3)_{\mathcal{N}}$$

- And the mass matrix is

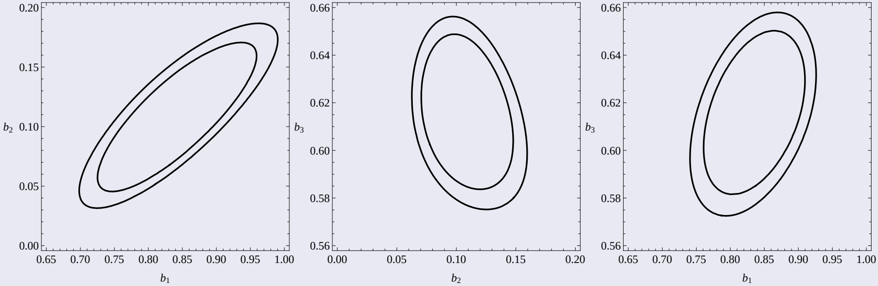
$$m_\nu(b_k, y_k) \propto diag(y_1, y_2, 1)\cdot\widehat{U}^T(b_k)\cdot diag\left(\frac{y_3}{2}, -\frac{y_3}{2}, 1\right)\cdot\widehat{U}(b_k)\cdot diag(y_1 . y_2, 1)$$

with

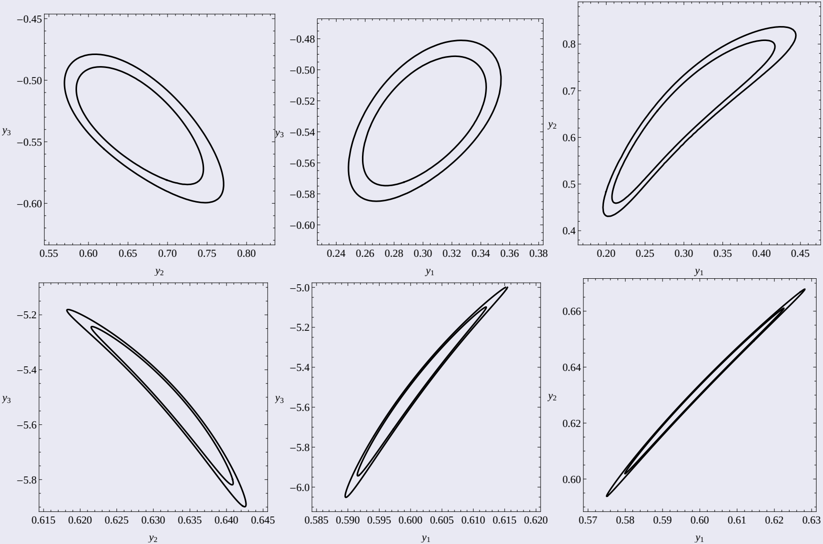
$$\Lambda_0(b_k) = \left(\begin{array}{ccc} 0 & -b_3 i & b_2 i \\ b_3 i & 0 & -b_1 i \\ -b_2 i & b_1 i & 0 \end{array}\right), \quad \widehat{U}(b_k) \equiv e^{i\Lambda_0(b_k)}$$

- There is a qualitative difference between the parameters b_k and y_k
    - Parameters b_k should be obtained dynamically from CW potential
    - The Yukawas y_k are free (anarchic) $\mathcal{O}(1)$ parameters
- Here we will make a χ^2 fit to mass eigenvalues and neutrino mixing angles
- As it is clear that there is room for the fit we will consider some examples first for fixed values of y_k and then b_k

$y_k = (0.90, 0.95, 0.90)$ with best fit @ $\chi^2_{min} \simeq 0$ for $b_k^0 = (0.84, 0.11, 0.62)$ and $m_i \simeq (0.022, 0.024, 0.055)$ eV: direct hierarchy spectrum



$b_k = 0.7$, $m_i \simeq (0.004, 0.010, 0.050)$ eV, $\chi^2_{min} \simeq 1.3$: direct hierarchy
$b_k = 0.4$, $m_i \simeq (0.057, 0.058, 0.031)$ eV, $\chi^2_{min} \simeq 2$: inverted hierarchy

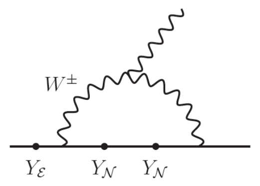


LEPTON FLAVOR VIOLATION

- $c_{\mathcal{E}}$, c_L and $Y_{\mathcal{E}}$ are diagonal
- *All charged lepton* couplings to electroweak KK gauge bosons preserve flavor, and there are no tree-level mediated FCNC's as

$$\mu \to 3e,\ \mu - e \text{ conversion}$$

- At one-loop the leading diagram contributing to $\mu \to e\gamma$ [4]



$$\mathcal{E}_1 \to \ell_1 \to \mathcal{N}_i \to \ell_2$$

$$Y_{\mathcal{N}} \to \hat{U} Y_{\mathcal{N}}$$
$$m_{KK} \gtrsim 2 - 3\,TeV$$

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[4] C. Csaki, Y. Grossman, P. Tanedo and Y. Tsai, arXiv:1004.2037 [hep-ph]

CONCLUSION

A realistic spectrum and mixing angle pattern for neutrinos requires

- A bulk symmetry implementing that $c_\ell^i \equiv c_\ell$ and $c_\mathcal{N}^j \equiv c_\mathcal{N}$ independently on i, j
- A Yukawa matrix $Y_\mathcal{N}$ with non-vanishing components along the bulk and/or the IR brane. A UV localized Yukawa matrix alone would provide too small neutrino masses
- Lepton number should not be violated in the bulk. Otherwise the charged lepton spectrum whould lead to a too heavy neutrino spectrum. Lepton number violating effects are thus dominated by those from the UV brane

We have constructed a simple model leading to the above required pattern for 5D masses, Yukawa couplings and lepton number violation

- The Majorana mass matrix will then depend on the WL and lead to nontrivial mixing
- A priori the background $\langle A_5 \rangle$ is a flat direction at tree-level (a classical modulus) which will however be dynamically determined at one-loop by the Coleman-Weinberg effective potential (the Hosotani mechanism). This will then result in a dynamical determination of the Majorana neutrino mass matrix
- Computing the one-loop radiative corrections is to a large extent model dependent and it is a future task
- One can extend these ideas to the quark sector as $c_d^i \equiv c_d \ \forall i$: and improve naturalness and flavor violation
- We have worked out RS metric but other metrics (e.g. soft-wall like) can be easily worked out