Conformal neutrinos: an alternative to the see-saw

Workshop on Higgs Boson Phenomenology
7-9 January 2009, ETH Zurich

Mariano Quirós

Institució Catalana de Recerca i Estudis Avançats
(ICREA), and **IFAE** Barcelona (Spain)

Based on work done in collaboration with:
G.v. Gersdorff, arXiv:0901.0006

Outline

The outline of this talk is

Outline

- Introduction
- Neutrino masses from "conformal sequestering"
- Bounds on FCNC: $\mu \to e\gamma$
- Signal from $(0\nu\beta\beta)$-decay process
- Invisible Higgs decay $h \to \nu\nu$
- Conclusion

Introduction

- It is by now a well established fact that neutrinos have non-zero masses
- The most important theoretical implication is that there exist right-handed neutrinos fields as direct mass term for left-handed neutrinos are forbidden in the SM

See-saw mechanism

- It is possible to get Dirac mass terms after EWSB: $h_Y \bar{\ell}_L H \nu_R \Longrightarrow m_\nu^D = h_Y v$
- One can also allow for Majorana mass terms for right-handed neutrinos: $m^M_{\nu_R} \nu_R \nu_R$

$$m_\nu \simeq \frac{(m_\nu^D)^2}{m^M_{\nu_R}} .$$

See-saw implies either physics at an inaccessible energy or unnaturally small Yukawa couplings!

- An alternative 4D solution happens if the right-handed neutrino $\mathcal{N}_R$ belongs to a conformal theory with a fixed point at the scale Λ: unparticle
- If the theory is strongly coupled the field $\mathcal{N}_R$ may acquire a large anomalous dimension γ with propagator

Unparticle propagator

$$\Delta(p,\gamma) = -iB_\gamma \bar{\sigma}^\mu p_\mu (-p^2 - i\epsilon)^{-1+\gamma}$$

$$B_\gamma = \frac{8\pi^{3/2}}{(2\pi)^{2+2\gamma}} \frac{\Gamma(1-\gamma)\Gamma(3/2+\gamma)}{\Gamma(2+2\gamma)}$$

- The renormalizable operator with the Standard Model fields

$\Lambda^{-\gamma}\bar{\ell}_L H \mathcal{N}_R$ becomes irrelevant for $\gamma > 0$

- The neutrino Majorana mass

$\Lambda^{1-2\gamma}\mathcal{N}_R\mathcal{N}_R$ also becomes irrelevant if $\gamma > 1/2$

Neutrino masses

- The effective Lagrangian at the scale Λ is given by

$$\mathcal{L}(\Lambda) = \Lambda^{-\gamma}\,\bar{\ell}_L H \mathcal{N}_R + \frac{1}{2}\Lambda^{1-2\gamma}\,\mathcal{N}_R\mathcal{N}_R + h.c.$$

- The fact that the operators are sequestered by the conformal dynamics for scales $\mu < \Lambda$ can be made explicit by redefining $\mathcal{N}_R$ in terms of fields ν_R with canonical dimension as

$$\mathcal{N}_R = B_\gamma^{1/2}\,\mu^\gamma\,\nu_R\,.$$

- For scales $\mu < \Lambda$ one can write the effective Lagrangian

$$\mathcal{L}(\mu) = B_\gamma^{1/2}\left(\frac{\mu}{\Lambda}\right)^\gamma\,\bar{\ell}_L H\nu_R + \frac{1}{2}\Lambda\,B_\gamma\left(\frac{\mu}{\Lambda}\right)^{2\gamma}\,\nu_R\nu_R + h.c.$$

- When $\langle H\rangle = v/\sqrt{2}$ the Dirac mass term triggers the

Conformal breaking

Electroweak breaking is responsible for the breaking of the conformal symmetry

Dirac mass

- Conformal dynamics will still be governing the right-handed neutrino sector until the mass becomes of the order of the renormalization group scale
- This happens when

$$\mu_c = B_\gamma^{1/2} \frac{v}{\sqrt{2}} \left(\frac{\mu_c}{\Lambda}\right)^\gamma \Longrightarrow m_\nu^D = \mu_c = \Lambda \left(\frac{B_\gamma^{1/2}\, v}{\Lambda\sqrt{2}}\right)^{\frac{1}{1-\gamma}}$$

Majorana mass

- The right-handed Majorana mass operator remains irrelevant after electroweak breaking

$$m_{\nu_R}^M = m_\nu^D \left(\frac{m_\nu^D}{\Lambda}\right)^{2\gamma-1}$$

- For $\gamma > 1/2$ ($m_{\nu_R}^M \ll m_\nu^D$) the scale at which conformal breaking is induced by electroweak breaking is self-consistently fixed to m_ν^D

$\gamma(\Lambda)$ for fixed m_ν^D

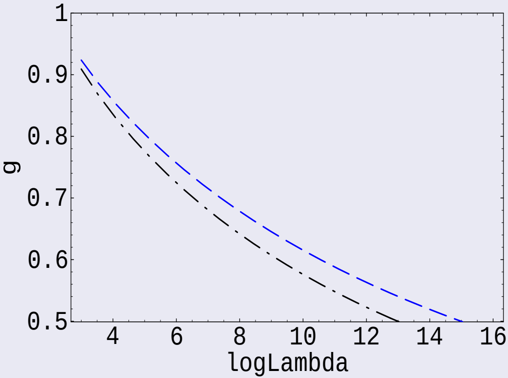


Figure: The anomalous dimension γ of the right-handed neutrino as functions of $\log_{10}(\Lambda/GeV)$. The two lines correspond to $m_\nu^D = 0.01$ eV (dashed blue) and 1 eV (dash-dotted black)

$\log_{10}(m^M_{\nu_R}/m^D_\nu)$ for fixed m^D_ν

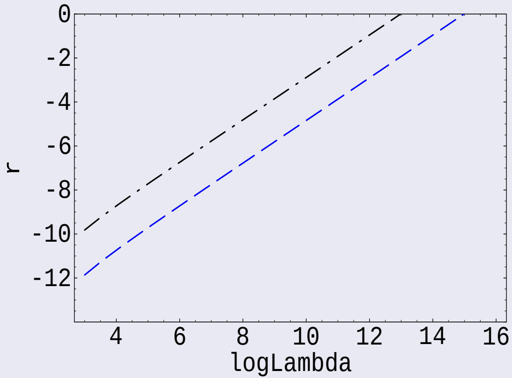


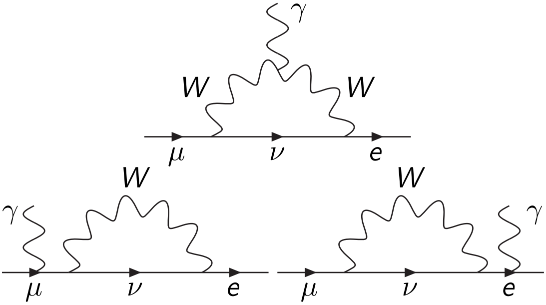
Figure: $\log_{10}(m^M_{\nu_R}/m^D_\nu)$ as function of $\log_{10}(\Lambda/GeV)$. The two lines correspond to $m^D_\nu = 0.01$ eV (dashed blue) and 1 eV (dash-dotted black)

Three neutrino flavors: normal hierarchy

- The first possibility is having all the three right-handed neutrinos with identical anomalous dimension
- The ratio of the two heavier masses is close to unity, and the small splitting might be accounted for by SM corrections to the Yukawa couplings
- The same holds true if the lightest neutrino mass is of the same order
- A much lighter state can also be naturally achieved if
  - The light state has a different anomalous dimension γ_1
  - The lightest state has a smaller Yukawa coupling
- The solution depends on the theory (conformal theory vs. weakly coupled theory) below μ_c
- The last (obvious) possibility is that different neutrinos ν_i belong to different conformal theories at the scale Λ_i and develop different anomalous dimensions γ_i

FCNC: $\mu \to e\gamma$

- There are strong experimental bounds on decay channels such as $\mu \to e\gamma$ and $\mu \to 3e$
- One needs to evaluate the diagrams



- The leading contribution comes from two Dirac mass insertions and one right-handed neutrino (unparticle) propagator

$\mu \to e\gamma$

- Normalizing to the main channel $\mu \to e\nu\nu$

γ-dependence: unparticle effect

$$B(\mu \to e\gamma) = \frac{3}{32}\frac{\alpha}{\pi}\left|\frac{\pi\gamma}{\sin(\pi\gamma)}\sum_i U_{ei}U^*_{\mu i}\left(\frac{m_i}{M_W}\right)^{2-2\gamma}\right|^2$$

- The result for the SM with massive Dirac neutrinos (the limit $\gamma \to 0$) is many orders of magnitudes below the experimental bound $B(\mu \to e\gamma) < 1.2 \times 10^{-11}$
- Due to its exponential dependence on the anomalous dimension $B(\mu \to e\gamma)$ can reach this bound if γ becomes close enough to one
- E.g. the existing bound implies that $\gamma \lesssim 0.86$ for the case of a regular hierarchy with $m_1 \ll m_2, m_3$
- Future experiments will improve the sensitivity to $\sim 10^{-14}$ which $\Longrightarrow \gamma \lesssim 0.81$

$\log_{10} B(\mu \to e\gamma)$ for fixed m_ν^D

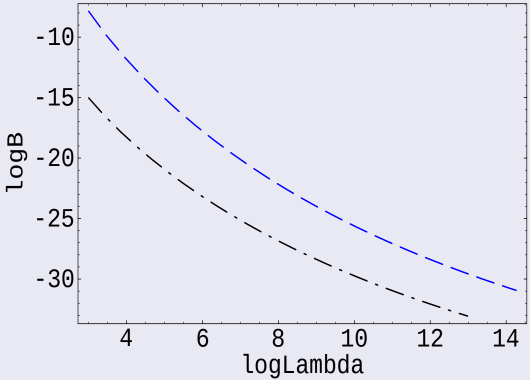
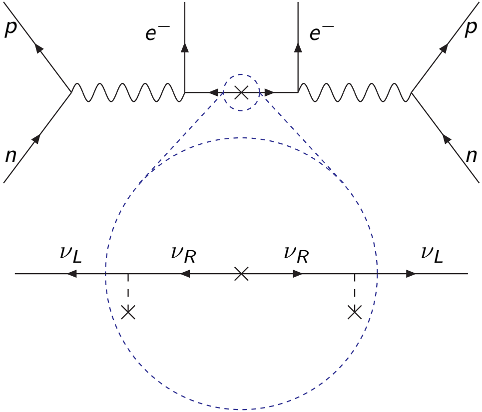


Figure: The branching ratio as a function of $\log_{10}(\Lambda/GeV)$. The two lines correspond to $m_3 = 0.05$ eV (dashed blue) and 1 eV (dash-dotted black)

Signal from $(0\nu\beta\beta)$-decay

- The unparticle nature of the right-handed neutrino implies that the lepton number violating operator $\nu_R \nu_R$ can have an important effect at intermediate scales
- The diagram is



$0\nu\beta\beta$

- Current experiments give a bound on the effective mass $|m_{\beta\beta}| \equiv |\sum_k m^M_{\nu_{Lk}} U^2_{ek}| \lesssim 1$ eV
- The typical momentum in $(A, Z) \to (A, Z+2) + e^- + e^-$ is

$$p \sim 1/r_{(A,Z)} \sim 100\, MeV$$

- Since both Dirac and right-handed Majorana masses are much smaller than ($p \sim 100$ MeV) we can treat both perturbatively
- This leads to (using two unparticle propagators)

Effective mass

$$m^M_{\nu_L}(p^2) \propto v^2 \Delta^2(p, \gamma) \simeq B^2_\gamma \frac{v^2}{\Lambda} \left(\frac{p^2}{\Lambda^2}\right)^{2\gamma-1} \Longrightarrow m_{\beta\beta}(p^2)$$

$\log_{10}(m_{\beta\beta}/eV)[\Lambda]$

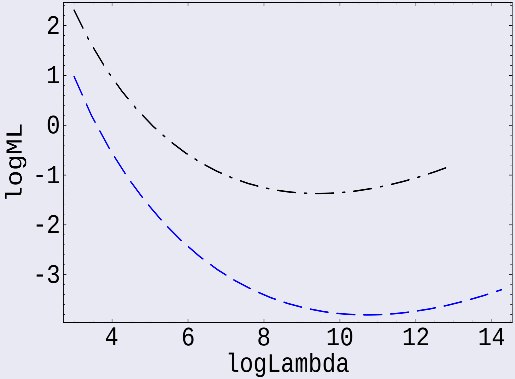


Figure: $\log_{10}(m_{\beta\beta}/eV)[\Lambda]$ evaluated at $p = 100$ MeV, as a function of the high scale $\log_{10}(\Lambda/GeV)$. The two lines correspond to $m_3 = 0.05$ eV (dashed blue) and 1 eV (dash-dotted black)

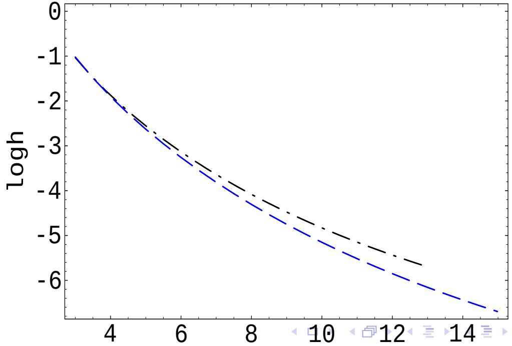
$h \longrightarrow \nu\bar{\nu}$-DECAY

- A very interesting effect is that at a given scale μ the neutrino Yukawa coupling is given by

Yukawa coupling

$$h_\nu(\mu) = B_\gamma^{1/2} \left(\frac{\mu}{\Lambda}\right)^\gamma h_\nu(\Lambda)$$

$m_\nu^D = 0.01$ eV (dashed blue) and 1 eV (dash-dotted black)



$\Gamma(h \to \nu\bar{\nu})$

- One can easily compute the width $\Gamma(h \to \nu\bar{\nu})$ as the imaginary part of the one-loop correction to the Higgs inverse propagator with an internal loop with an unparticle right-handed neutrino propagator

$$\Gamma(h \to \nu\bar{\nu}) = h_\nu^2(m_H)\,\frac{m_H}{16\pi}\,\frac{2}{\Gamma(1-\gamma)\Gamma(3+\gamma)}$$

- In the particle limit $\gamma \to 0$ one recovers the Standard Model expression

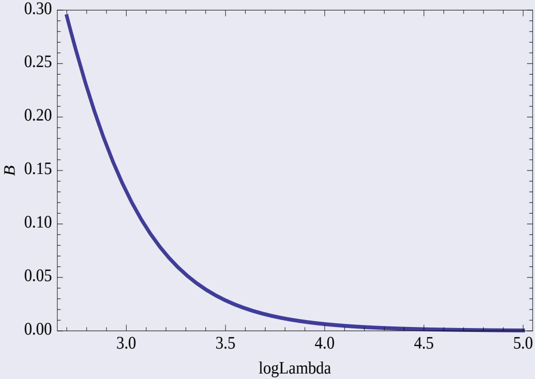
$$\Gamma_{SM}(h \to \nu\bar{\nu}) = h_{\nu\,SM}^2\,\frac{m_H}{16\pi}$$

- The main difference between both expressions is the "conformal running" of the neutrino Yukawa coupling

$B(h \to \nu\bar{\nu})$ Vs. $\log_{10}(\Lambda/GeV)$

The branching ratio with respect to $h \to b\bar{b}$ for $m_H = 130$ GeV and three (almost) degenerate neutrinos with mass $m_\nu^D \simeq 0.1$ eV

$$B(h \to \nu\bar{\nu}) = \frac{\sum_i \Gamma(h \to \nu_i\bar{\nu}_i)}{\sum_i \Gamma(h \to \nu_i\bar{\nu}_i) + \Gamma(h \to b\bar{b})}$$



Conclusion 1/2

- A conformally invariant right-handed neutrino sector represents a natural way to obtain sub-eV neutrino masses if the anomalous dimensions lie in the interval $1/2 < \gamma < 1$
- Electroweak symmetry breaking triggers conformal breaking at the neutrino mass scale
- The model predicts a non-zero rate for $0\nu\beta\beta$ decay despite the fact that the neutrinos are quasi-Dirac
- This shows that $0\nu\beta\beta$ decay does not necessarily prove that neutrinos are Majorana particles as usually claimed
- Our model also predicts lepton flavor violating reactions such as $\mu \to e\gamma$ at a much larger rate than in the SM and even opens up the possibility to experimentally determine the anomalous dimensions in forthcoming experiments

Conclusion 2/2

- For rather low scales $\Lambda \sim 10$ TeV the neutrino Yukawa couplings can be comparable with those for charm and tau at the weak scale and induce sizable (invisible) Higgs decay into the $\nu\bar{\nu}$ channel
- If the conformal theory conserves lepton number there is neither Majorana-mass term nor any $(0\nu\beta\beta)$-rate and the whole interval $0 < \gamma < 1$ is available

Open questions

- What is the 4D conformal theory? A sort of (non-perturbative) Banks-Zaks model?
- What is (if any) the 5D theory? A 5D soft-wall model with right-handed propagating neutrinos?
- Other phenomenological applications: $\mu \to 3e$, $\mu \to e$ conversion, LHC/NLC Higgs phenomenology,...