Invisible decays of Higgs in models with singlet neutrinos in extra dimensions

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Outlines

1. *Introduction*
2. *Invisible decay of Higgs in minimal model*
3. *Invisible decay of Higgs in sub-dimensional model.*
4. *Conclusions*

♣ Introduction

- In Standard Model, the EW symmetry breaking requires existence of a scalar particle (Higgs boson) with mass $m_H \sim 100$ GeV

- But: a scalar mass is not protected by gauge or chiral symmetries

- Expect $m_H \sim \Lambda \sim 10^{16}$ GeV(at one loop) , unless we are willing to fine-tune the bare Higgs mass against the mass acquired through quantum effects.

- Problem of EWSB: Why is $m_H \ll \Lambda$?

♣ *Supersymmetry*

- Higgs mass is protected by a new symmetry relating fermions $\leftrightarrow$ bosons.
- To each known particle must associate a new particle with identical mass (in exact SUSY limit) but different spin
- No such *Superpartner* has been seen to date

♣ *Technicolor*

- EW symmetry breaking could be explained by a new strong force
- Higgs may be a composite, not an elementary particle
- Higgs $= (t\bar{t})$ condensate ?
  [Talk by R. Shrock]

♣ Extra Dimensions

- The gauge hierarchy problem of SM can be solved by extra dimensions.

  [N. Arkhani-Hamed *et al.* Phys. Lett. **B429**,263 (1998); Phys. Rev. D **59**, 086004 (1999); I. Antoniadis *et al.* Phys. Lett. **B436**,257 (1998)]

- Our space-time has $D = 4 + n$ dimensions.
- SM particles lives on $(3 + 1)$-dimensional wall, gravity propagates in the extra-dimensions.
- The effective Planck scale (M_{Pl}) can be related to the *fundamental scale* (M_S) by:

$$M_{Pl}^2 = V_n M_S^{n+2}$$

- where V_n is volume of extra space.
- $n \geq 2$, $R \leq 1$ mm, $M_S \sim 1$ TeV
- Since the fundamental Planck scale is now at TeV, the hierarchy problem no longer exists.

- Large extra dimensions provide a natural geometric way to understand small neutrino masses.

  [N. Arkani-Hamed *et al.*(1998); K. R. Dienes *et al.* (1999); G. Dvali and A. Smirnov (1999); R.N. Mohapatra *et al.* (1999); R.N. Mohapatra and A. Perez-Lorenzana (2000), (2001);H. Davoudiasl *et al.* (2002)]

- For simplicity, we consider the case of a single extra dimensions labeled by y (x labels $4D$). A massless Dirac fermion N which is a singlet lives in $5D$.
- The Dirac spinor N in the Weyl basis :

$$N = \begin{pmatrix} \psi \\ \bar{\chi} \end{pmatrix}$$

- In the effective $4D$ theory, N appears as a tower of KK states $\psi = \sum_n \frac{1}{\sqrt{R}} \psi^{(n)}(x) e^{iny/R}$, with $\psi^{(n)}(x)$ are $4D$ states. The kinetic term for N in $4D$ is:

$$\begin{aligned} S_{\text{free}} &= \int d^4x \sum_n \Big[\bar{\psi}^{(n)} \bar{\sigma}^\mu \psi^{(n)} + \bar{\chi}^{(n)} \bar{\sigma}^\mu \chi^{(n)} \\ &\quad + \Big(\frac{n}{R} \psi^{(n)} \chi^{(n)} + \text{h.c.} \Big) \Big] \end{aligned}$$

- n/R is the Dirac mass for the KK states.

- If we assign N the opposite lepton number from the usual lepton doublet $L = (\nu, e)$ then the interaction between L and N which conserves lepton number is

$$S_{\text{int}} = \int d^4x \sum_n \frac{\lambda}{\sqrt{M_{Pl}}} L(x) H^*(x) \psi(x, y = 0)$$

- H is the SM Higgs doublet ($Y_H = -1/2$) and λ is dimensionless.
- In the effective $4D$ theory S_{int} becomes :

$$S_{\text{int}} = \int d^4x \sum_n \frac{\lambda}{\sqrt{RM_*}} L(x) H^*(x) \psi^{(n)}(x)$$

- Using relation $M_{Pl}^2 = R^\delta M^{\delta+2}$, we get :

$$S_{\text{int}} = \int d^4x \sum_n \lambda \frac{M_*}{M_{Pl}} L(x) H^*(x) \psi^{(n)}(x)$$

- This is for $5D$, which can be generalized to the case of δ dimensions resulting in the same effective $4D$ coupling.

- Dirac mass for the SM neutrino:

$$m = \frac{\lambda}{\sqrt{2}} \frac{M_*}{M_{Pl}} v \;\sim\; \lambda \frac{M_*}{\mathrm{TeV}} 10^{-4} \text{ eV}.$$

- where $v = 246$ GeV is the SM Higgs vev.
- The full mass matrix for ν, $\psi^{(0)}$, $\psi^{(n)}$ and $\chi^{(n)}$ ($n = .., -2, -1, 1, 2, ..$) in the case of one extra dimension is:

$$\mathcal{L}_{mass} = \nu_+ M \nu_-^T$$

$$M = \begin{pmatrix} m & m & m & m & \dots \\ 0 & 1/R & 0 & 0 & \dots \\ 0 & 0 & -1/R & 0 & \dots \\ 0 & 0 & 0 & 2/R & \dots \\ \dots & \dots & \dots & \dots & \dots \end{pmatrix}$$

where

$$\nu_+ = \left(\nu, \chi^{(1)}, \chi^{(-1)}, \chi^{(2)}, \dots\right)$$

and

$$\nu_- = \left(\psi^{(0)}, \psi^{(1)}, \psi^{(-1)}, \psi^{(2)}, \dots\right)$$

- In the limit $mR \ll 1$ we have a Dirac fermion $(\nu, \psi^{(0)})$ with mass m
- Dirac fermions $(\psi^{(n)}, \chi^{(n)})$ $(n \neq 0)$ with masses n/R, with mixing between $\chi^{(n)}$ and ν given by $\sim mR/n$.
- The SM neutrino is dominantly the lightest neutrino with mass $\sim m$, but it has a small mixture ($\sim mR/n$) of heavier neutrinos (in δ dimensions).

$$m_\nu \approx \frac{m}{\sqrt{1 + \frac{m^2}{M_*^2}\frac{M_{Pl}^2}{M_*^2}\frac{2\pi^{\delta/2}}{\Gamma(\delta/2)(\delta-2)}}}$$

- The Yukawa coupling λ can be expressed in terms of m_ν, M_* and δ:

$$\lambda = \frac{(m_\nu/M_*) \times 10^{16}}{\sqrt{1 - \frac{m_\nu^2}{M_*^2}\frac{M_{Pl}^2}{M_*^2}\frac{2\pi^{\delta/2}}{\Gamma(\delta/2)(\delta-2)}}}$$

- The higher dimensional Yukawa coupling $(\lambda) \sim O(1)$ otherwise $(4+\delta)D$ theory might reach strong coupling.

♣ Invisible decay of Higgs

♣ Many models predict invisible decay of Higgs boson:

- SUSY : $H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- Majoron models : $H \to JJ$

- Extra dimensions with ν_R in bulk : $H \to \nu_L \bar{\nu}_R^i$

- Since we study Higgs decay into $\nu\bar{\nu}$, we are interested in the atmospheric neutrino oscillation mass^2 range [hep-ex/0212035]:

$$m^2 \sim \Delta m^2_{atm} \sim (1.5 - 4.0) \times 10^{-3}\ \mathrm{eV}^2$$

- For $\delta = 2$, even for $M_* \sim 10$ TeV, $1/R$ is quite small $\sim 0.01 - 0.1$ eV so that with $m^2 \sim \Delta m^2_{atm}$, we get $mR \sim 1$.

- We will mostly consider $\delta \geq 3$ for which $1/R \gg 0.1$ eV.
- Measurement of Supernova SN1987a neutrino flux $\Longrightarrow 1/R$ should be larger than ~ 10 keV.
  [R. Barbieri *et al.* (2000)]
- This implies that KK states are much heavier than SM neutrinos $\Longrightarrow$ both solar and atmospheric neutrino anomalies have to be explained by oscillations among active neutrinos.

♣ **Supernova (SN) constraints:**

- Coherent conversion of SM neutrinos to singlet neutrinos (due to the large mixing) in a supernova(SN) results in energy loss, reducing its active neutrino flux.
- Measurement of Supernova SN1987a neutrino flux $\Longrightarrow 1/R$ should be larger than ~ 10 keV.
  [R. Barbieri *et al.* (2000)]
- This implies that KK states are much heavier than SM neutrinos $\Longrightarrow$ both solar and atmospheric neutrino anomalies have to be explained by oscillations among active neutrinos.

- ♣ LEP searches for invisible Higgs bosons

$$e^+e^- \to ZH; (H \to \text{invisible})(Z \to jj/ll)$$

- • ADLO 95% CL limit is 114.4 GeV for $Br(H \to \text{inv.}) = 100\%$.

  [LHWG Note 2001-06, (August 8, 2002)]

- ♣ At Tevatron Run II :

$$p\bar{p} \to ZH; (H \to \text{inv.})(Z \to \ell^+\ell^-)$$

  can exclude at 95% CL $M_H \leq 150$ GeV for 30 fb^{-1}. [S.P. Martin and J.D.Wells, Phys. Rev. D 60, 035006 (1999)]

- ♣ At LHC $ZH \Longrightarrow M_H \leq 150$ GeV for 100 fb^{-1}

  [D. Choudhury and D.P. Roy, Phys. Lett. B 322, 368 (1994)]

- ♣ At LHC, through ZH mode, with BR_{inv} larger than $\sim 0.42(0.70)$ can be probed at 5σ level for $M_H = 120(160)$ GeV, for $\mathcal{L} = 100$ fb^{-1}.

  [Godbole *et al.*, hep-ph/0304137]

- ♣ At LHC $t\bar{t}H \Longrightarrow M_H \leq 250$ GeV

  [J.F. Gunion, Phys.Rev.Lett. 72, 199 (1994)]

- The standard model Higgs can decay into $\nu_L \bar{\nu}_R^i$ with the strength $\sim \frac{\lambda}{\sqrt{2}} \frac{M_*}{M_{Pl}}$ (a small number).
- Sum over KK excitations of ν_R^i states with masses below M_H : large enhancement.
- The sum of partial widths of the Higgs into KK excitations of neutrinos is of the order of:

$$\sum_i \Gamma\left(H \to \nu_L \bar{\nu}_R^i\right) \sim \frac{M_H}{16\pi} Y_\nu^2 \left(M_H R\right)^\delta$$

where,

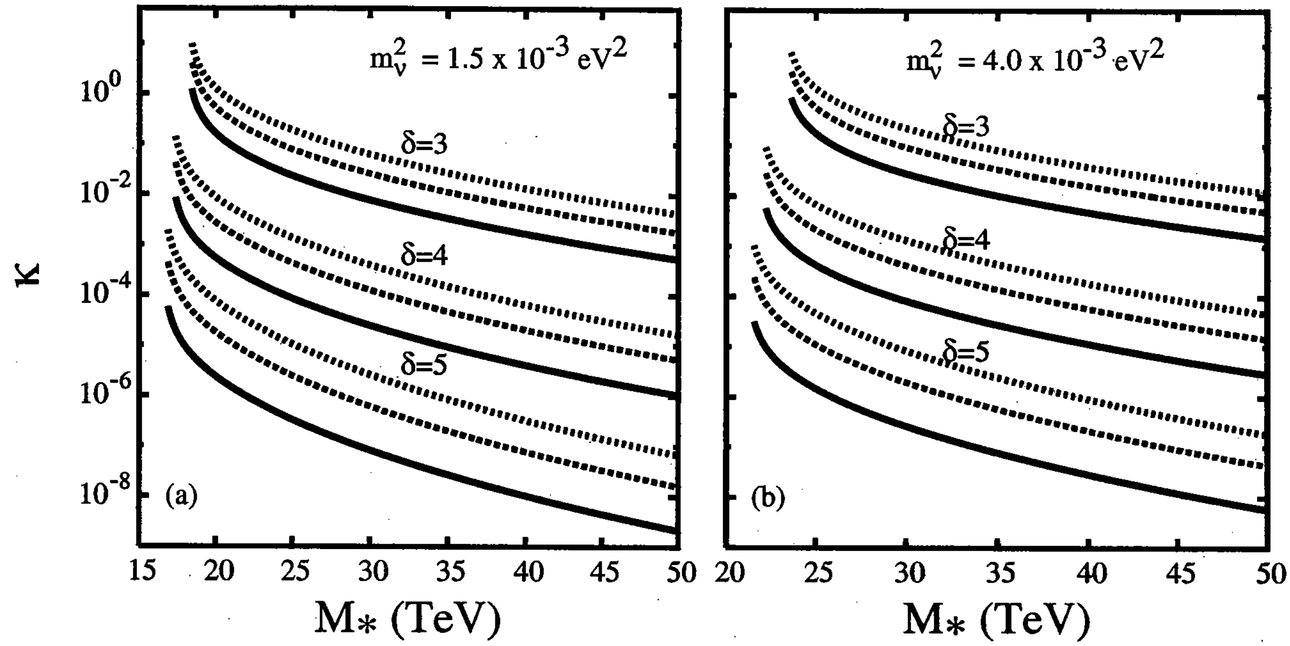
$$Y_\nu = \frac{\lambda}{\sqrt{2}} \frac{M_*}{M_{Pl}}$$

- We define the ratio:

$$\kappa \equiv \sum_i B(H \to \nu_L \bar{\nu}_R^i)/B(H \to b\bar{b})$$

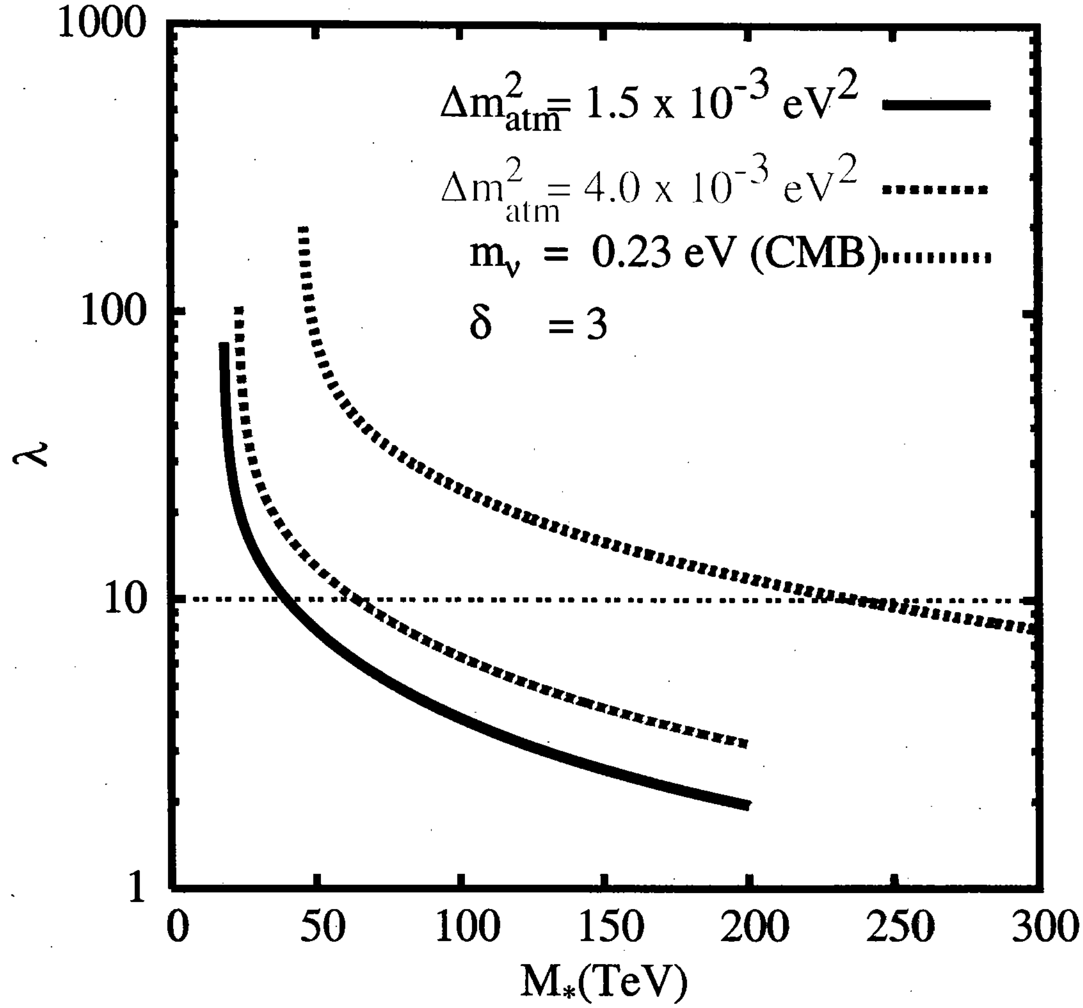
[S.P. Martin and J.D.Wells, Phys. Rev. D 60, 035006 (1999)]

$$\kappa \equiv \frac{m^2}{3m_b^2} \left(\frac{M_H}{M_*}\right)^\delta \left(\frac{M_{Pl}}{M_*}\right)^2$$

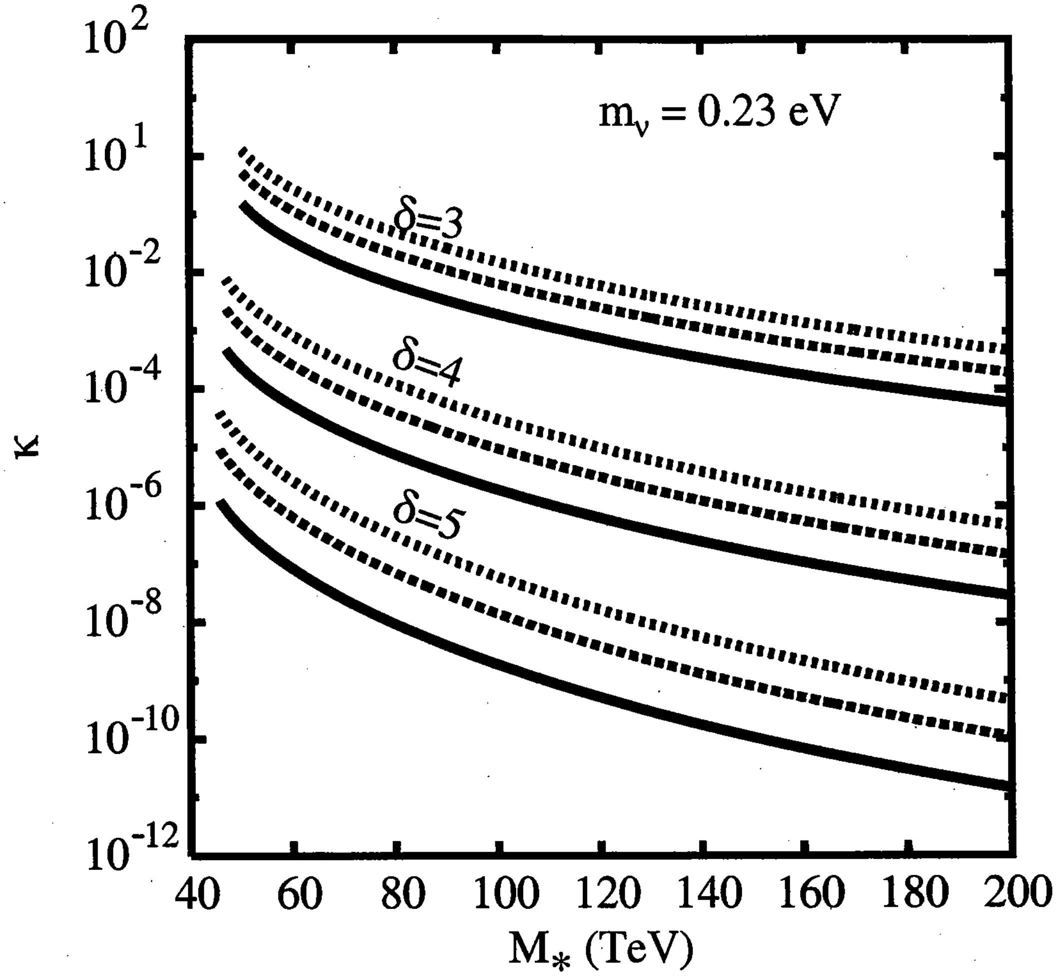


- Variation of κ with M_*. The solid, broken and dotted lines correspond to $M_H = 100, 150$ and 200 GeV respectively.

- For the value of $M_*(\sim\ 15{-}20\text{TeV})$ at which $\kappa \geq 1$, corresponding Yukawa coupling $\lambda \sim O(100)$.
  [Deshpande and Ghosh, hep-ph/0303160]



Variation of λ with M_*.



- Variation of κ with M_*. The solid, broken and dotted lines correspond to $M_H = 100, 150$ and 200 GeV respectively for $\sum_i m_{\nu_i} < 0.71$ eV (CMB) [D.N. Spergel *et al.*, astro-ph/030220; Talk by N. Bell]

- In this case, for $\lambda \lesssim 10 \Longrightarrow M_* > 200$ TeV

- Such a high value of M_* is disfavored by the motivation to solve the gauge hierarchy problem.

- Recently WMAP has provided new information on cosmic microwave background anisotropies [C. Bennett *et al.*, astro-ph/0302207; D.N. Spergel *et al.*, astro-ph/0302209]

- After combining the data from 2dF Galaxy Redshift Survey, CBI and ACBAR, WMAP places stringent limits on the contributions of neutrinos to the energy density of the universe :

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{93.5 \text{ eV}} < 0.0076 \quad (95\% \text{ C.L.})$$

$\Longrightarrow \sum_i m_{\nu_i} < 0.71$ eV (for single active neutrino) or $m_\nu < 0.23$ eV for 3 degenerate neutrinos.

- Using $m_\nu = 0.23$ eV we estimate κ.

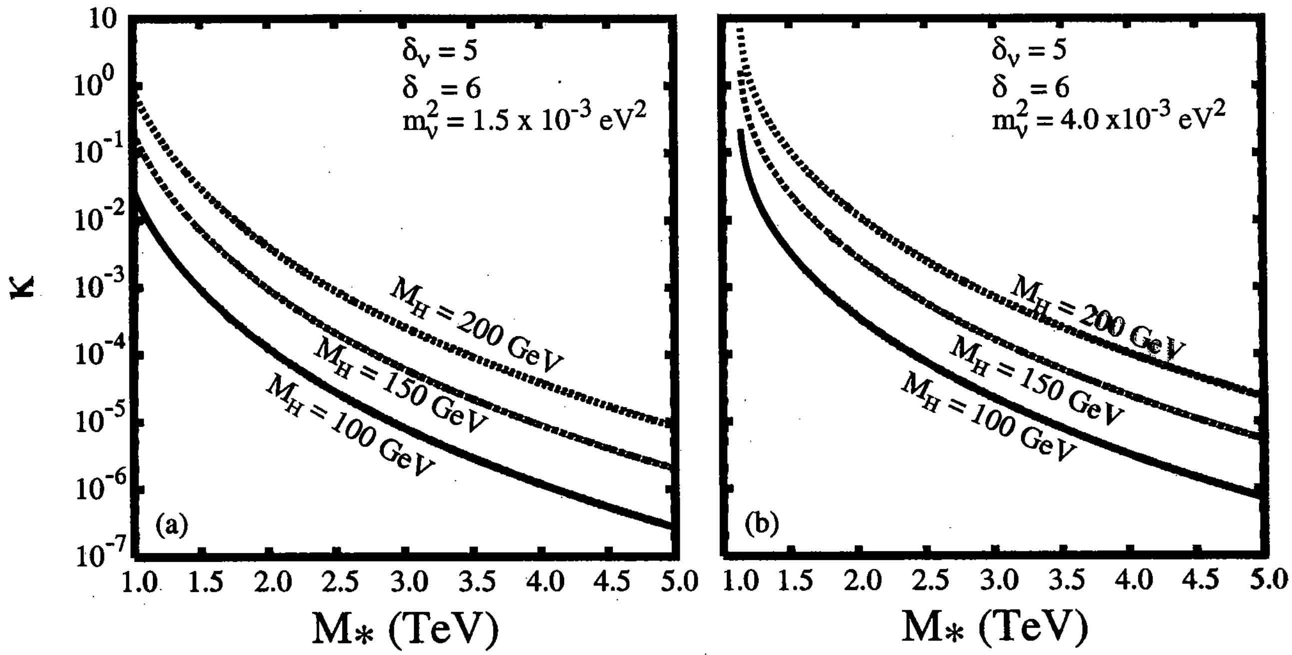
♣ Singlet neutrino in sub-spaces

- It is possible that the singlet neutrino lives in smaller number of extra dimensions, $\delta_\nu < \delta$, than the graviton.
  [N. Arkhani-Hamed *et al.* (1998)]

- In this case, the Dirac mass for the standard model neutrino becomes :

$$m \sim \lambda v \left(\frac{M_*}{M_{Pl}} \right)^{\delta_\nu/\delta}$$

- For $\delta_\nu = 5$ and $\delta = 6$ and with $M_* \sim$ TeV, $\lambda \sim O(1)$, we obtain $m^2 \sim \Delta m^2_{atm}$
  [N. Arkhani-Hamed *et al.* (1998)]



- Variation of κ with M_* for singlet neutrino in sub-space scenario.
- For $m_\nu^2 = 1.5 \times 10^{-3}\text{eV}^2$, $\kappa \sim 1$, only for $M_H =$ 200 at $M_* = 1$ TeV.
- For $m_\nu^2 = 4.0 \times 10^{-3}\text{eV}^2$, $\kappa \sim 1$, only for $M_H =$ 150 at $M_* = 1$ TeV and $\kappa \sim 10$, for $M_H = 200$ GeV, for $M_* = 1 - 1.3$ TeV
- For more practical value of Higgs mass ($M_H \leq$ 150 GeV), $\kappa \sim O(1)$ for $M_* \sim 1 - 1.5$ TeV.

Conclusions

- ♣ We have studied the possible enhancement of invisible decay widths of the Higgs bosons and other pseudoscalar mesons in the model of singlet neutrinos in extra dimensions.

- ♣ In the case of Higgs decay, we have found that in certain range of extra-dimension parameter space, $Br(H \to inv.) \geq Br(H \to b\bar{b})$, but $\lambda \sim O(100)$.

- ♣ For $\lambda \leq 10$, $H \to \nu\bar{\nu}$ rate is a tiny fraction of $H \to b\bar{b}$.

- ♣ In the sub-space scenario, with $\delta_\nu = 5$, $\delta = 6$, $\lambda \sim O(1)$, and $M_* = 1 - 1.5$ TeV; $\Gamma(H \to inv.) \sim \Gamma(H \to b\bar{b})$.