Dirac neutrinos from a second Higgs doublet

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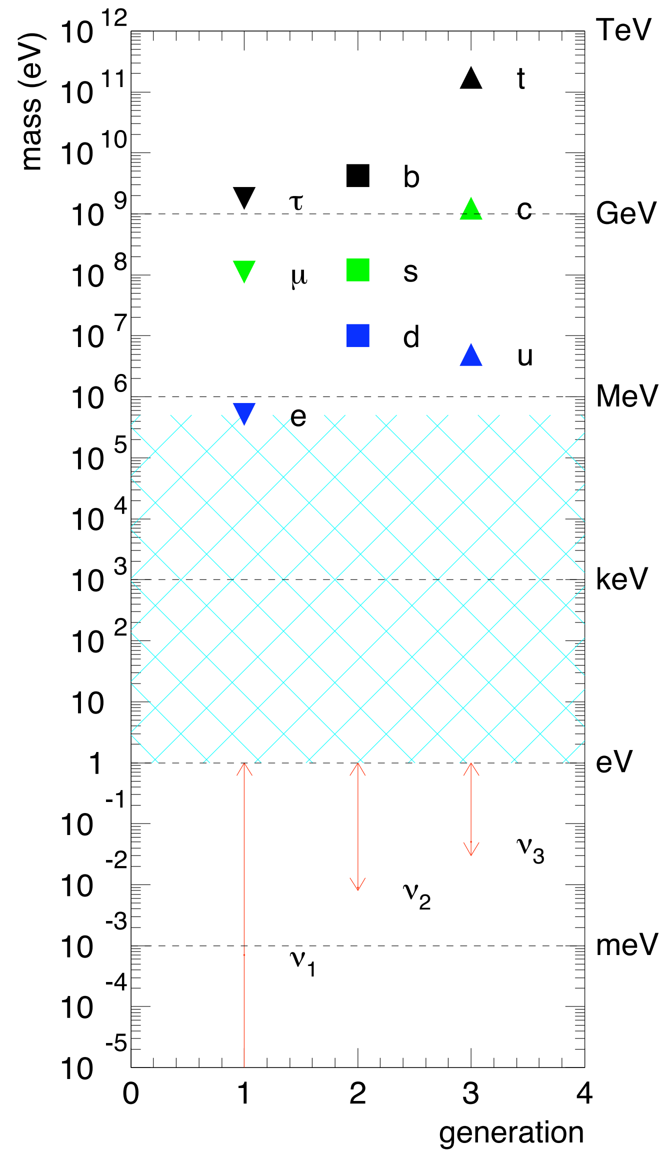
Based on work with Shain Davidson, to appear soon.

Dirac neutrinos?

Easy to make Dirac neutrinos in the SM: just add ν_{R_i} and Yukawa couplings.

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij} \bar{e}_{R_i} \Phi^\dagger L_{L_j} - y^{\nu}_{ij} \bar{\nu}_{R_i} \tilde{\Phi}^\dagger L_{L_j} + \text{h.c.}$$

+ Straightforward!
– 9 elements of y^{ν}_{ij} all $\mathcal{O}(10^{-13})$, by hand.
– No signatures other than absence of $0\nu\beta\beta$.
– Why no $M \nu_R \nu_R$ Majorana mass term?
  $\rightarrow$ usual Type-1 seesaw with Majorana νs



(stolen from A. de Gouvea)

Other possibilities:

New physics at EW scale could generate m_{ν_i}.

Ex: Type-2 seesaw, $y_{ij} L_i \Delta L_j + \text{h.c.}$

Δ = SU(2) triplet scalar with $Y = 2$

$\Delta^{++} \rightarrow \ell_i^+ \ell_j^+$ collider signatures

Majorana neutrino masses $\sim y_{ij} v_\Delta$

This talk:

Simple new model for Dirac νs from a second Higgs doublet.

Somewhat similar to Gabriel & Nandi, hep-ph/0610253

New field content:

3 right-handed two-component neutrinos ν_{R_i} (EW singlets)

Second scalar doublet Φ_2, same EW charges as SM Higgs

New symmetry: global U(1)

ν_{R_i} and Φ_2 have charge +1; all SM fields uncharged

$M\nu_R\nu_R$ Majorana mass term forbidden by global U(1).

Lepton Yukawa couplings: structure fixed by U(1)

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij}\bar{e}_{R_i}\Phi_1^\dagger L_{L_j} - y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}_2^\dagger L_{L_j} + \text{h.c.}$$

To generate neutrino masses, break U(1) explicitly:

$$\begin{aligned} V &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 \\ &+ \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \end{aligned}$$

Particles and couplings

3 SM neutrinos are Dirac particles; no additional fermionic d.o.f.
4 new scalar degrees of freedom: $H^\pm$, H^0, A^0

Mixing effects: new scalars $\sim \Phi_2 + \mathcal{O}(v_2/v_1)\Phi_1$: completely negligible

Scalar masses: SM-like Higgs: $M_h^2 = \lambda_1 v_1^2$

$$\text{New states}: \quad M_{H+}^2 = m_{22}^2 + \frac{1}{2}\lambda_3 v_1^2,$$
$$M_A^2 = M_H^2 = M_{H+}^2 + \frac{1}{2}\lambda_4 v_1^2$$

Vev of Φ_2: $v_2 = m_{12}^2 v_1 / M_A^2$

Another seesaw: $m_{12}^2 \sim$ (few hundred keV)^2 $\longrightarrow$ $v_2 \sim$ eV $\longrightarrow$ m_ν proper size

Yukawa couplings of physical scalars:

$$\mathcal{L}_{Yuk} = \frac{m_{\nu_i}}{v_2} H^0 \bar{\nu}_i \nu_i - \frac{i m_{\nu_i}}{v_2} A^0 \bar{\nu}_i \gamma_5 \nu_i - \sqrt{2}\frac{m_{\nu_i}}{v_2}[U_{\ell i}^* H^+ \bar{\nu}_i P_L e_\ell + \text{h.c.}]$$

$U_{\ell i}$ is the Maki-Nakagawa-Sakata-Pontecorvo matrix

Constraints: big bang nucleosynthesis

ν_{R_i} thermalized in early universe via Φ_2 exchange $\rightarrow \Delta N_\nu = 3$?

E.g., $e^+e^- \rightarrow \nu_R \bar{\nu}_R$ via t-channel H^+

But: primordial ^{4}He abundance $\rightarrow \Delta N_\nu^{eff} \leq 1.44$!

Cyburt et al, Astropart.Phys.23, 313 (2005)

Need ν_R to be colder than ν_L so they count less towards relativistic energy density.

Freeze out ν_R before quark-hadron transition: Enough extra d.o.f. to dump energy into ν_L, $e^\pm$, γ leaving ν_R colder.

$$\frac{T_{\nu_R}^{decoup}}{T_{\nu_L}^{decoup}} \gtrsim \frac{300 \text{ MeV}}{3 \text{ MeV}} \approx \left(\frac{\sigma_L}{\sigma_R}\right)^{1/3} = \left[\frac{1}{v_1^4}\frac{4v_2^4 M_{H^+}^4}{m_{\nu_i}^4 |U_{\ell i}|^4}\right]^{1/3}$$

This gives an upper bound on neutrino Yukawa couplings:

$$y_i^\nu \equiv \sqrt{2}\frac{m_{\nu_i}}{v_2} \lesssim \frac{1}{30}\left[\frac{M_{H^+}}{100 \text{ GeV}}\right]\left[\frac{1/\sqrt{2}}{|U_{\ell i}|}\right]$$

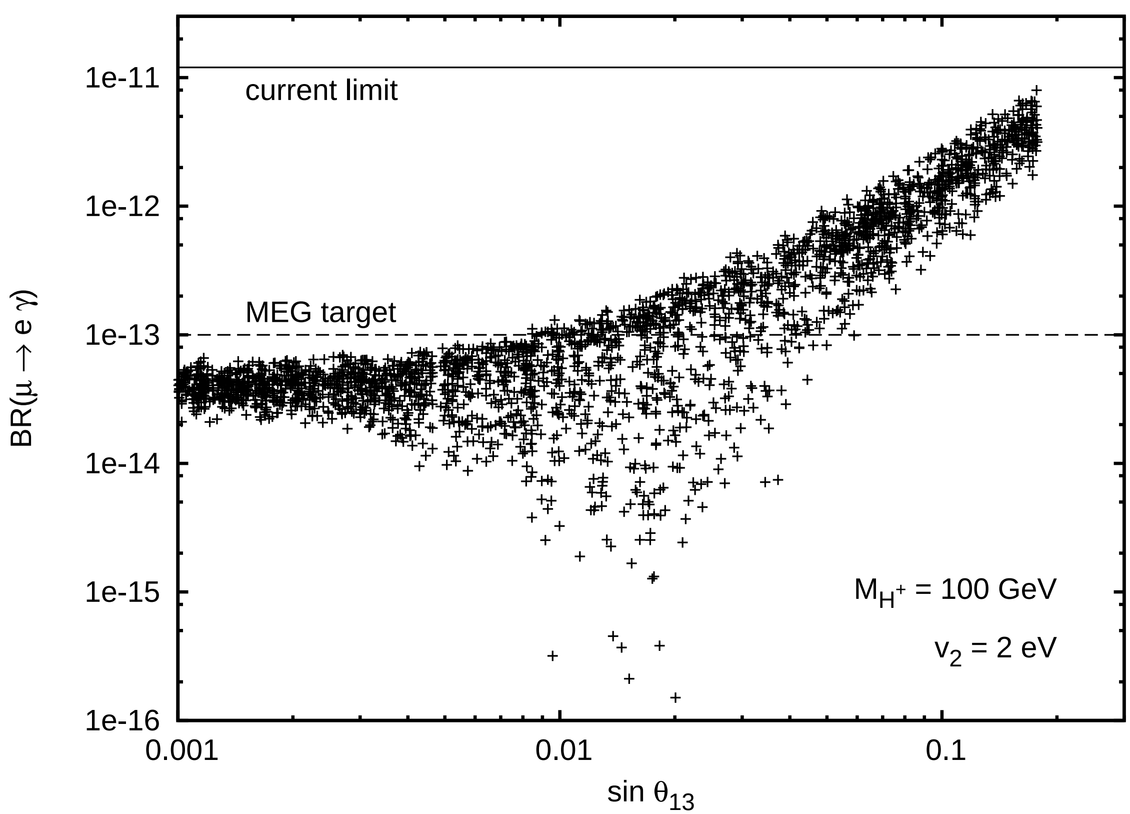
a little bigger than SM bottom quark Yukawa coupling

or $v_2 \gtrsim 2$ eV (scales with heaviest neutrino mass).

Phenomenology: $\mu \to e\gamma$

$$H^+ \text{ loop}: \qquad \text{BR}(\mu \to e\gamma) = \frac{\alpha_{em}}{96\pi} \frac{v_1^4}{v_2^4} \frac{|\sum_i m_{\nu_i}^2 U_{ei} U_{\mu i}^*|^2}{M_{H^+}^4}.$$

Unitarity of $U_{\ell i}$: $\sum_i m_{\nu_i}^2 U_{ei} U_{\mu i}^* = -\Delta m_{21}^2 U_{e1} U_{\mu 1}^* + \Delta m_{32}^2 U_{e3} U_{\mu 3}^*$



- Goes like $v_2^{-4} M_{H^+}^{-4}$; plot for $v_2 \sim$ BBN limit

- Doesn't depend on lightest neutrino mass, only differences

- Same range covered for normal hierarchy and inverted hierarchy

- MEG expt target from data-taking to end of 2011

Numerics: 2σ ν parameter ranges from Fogli et al, Prog. Part. Nucl. Phys. **57**, 742 (2006).

Phenomenology: decays of new scalars

Fermionic modes: $H^+ \to \ell^+\nu$, $A^0/H^0 \to \nu\bar{\nu}$ (via y_i^ν)

Bosonic modes: $A^0/H^0 \to W^+H^-$ or $H^+ \to W^+A^0/H^0$ (gauge int)

depends on masses: $M_A^2 = M_H^2 = M_{H^+}^2 + \lambda_4 v_1^2/2$

Most interesting decays: $H^+ \to \ell^+\nu$.

Assume $M_{A,H} > M_{H^+}$: no $H^+ \to W^+H^0/A^0$.

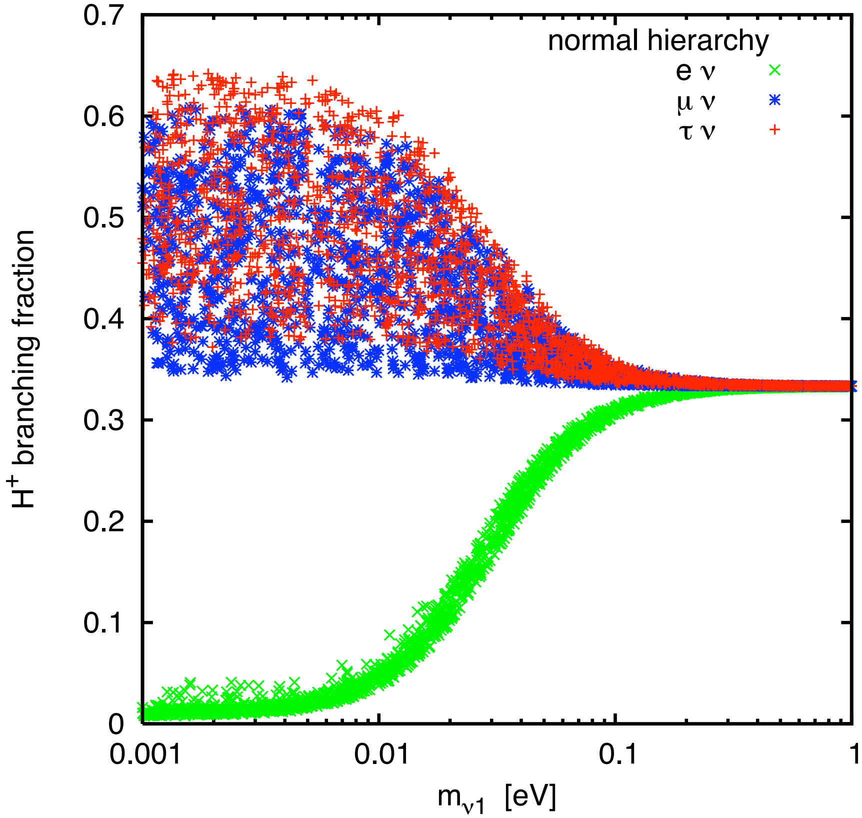
$$\Gamma\left(H^+ \to \ell^+\nu\right) = \frac{M_{H^+}}{8\pi v_2^2} \sum_i m_{\nu_i}^2 |U_{\ell i}|^2$$

Depends on "expectation value" of m_ν^2 in *flavor* eigenstate ν_ℓ.

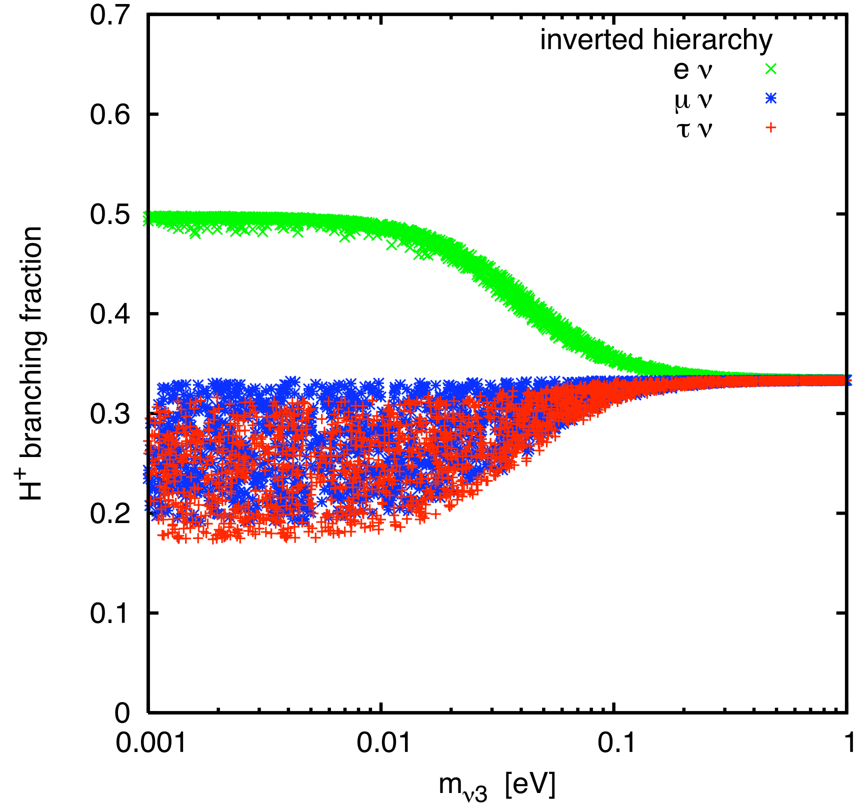
$$\mathrm{BR}(H^+ \to \ell^+\nu) = \frac{\sum_i m_{\nu_i}^2 |U_{\ell i}|^2}{\sum_\ell \left[\sum_i m_{\nu_i}^2 |U_{\ell i}|^2\right]}$$

Identical to Δ^+ decay BRs in Type-2 seesaw model.

Normal hierarchy



Inverted hierarchy



Behavior controlled by $\theta_{23} \sim 45^\circ$, U_{e3} small.

Normal hierarchy: eigenstate 3 contains half of ν_μ, half of ν_τ, very little ν_e

$\rightarrow$ BR($\mu\nu$) $\simeq$ BR($\tau\nu$) $\simeq 1/2$, BR($e\nu$) $\ll 1$

Inverted hierarchy: eigenstates 1 & 2 contain all of ν_e, half of ν_μ, half of ν_τ

$\rightarrow$ BR($e\nu$) $\simeq 1/2$, BR($\mu\nu$) $\simeq$ BR($\tau\nu$) $\simeq 1/4$

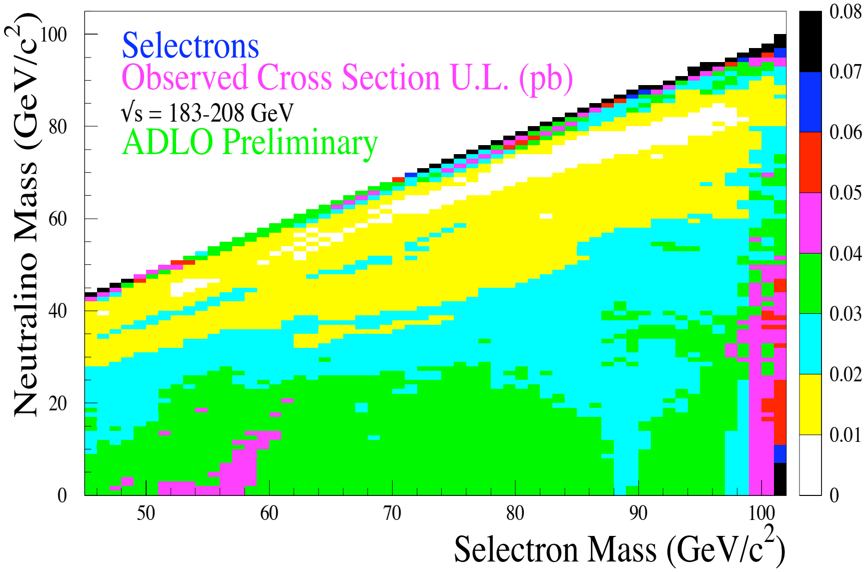
Degenerate spectrum

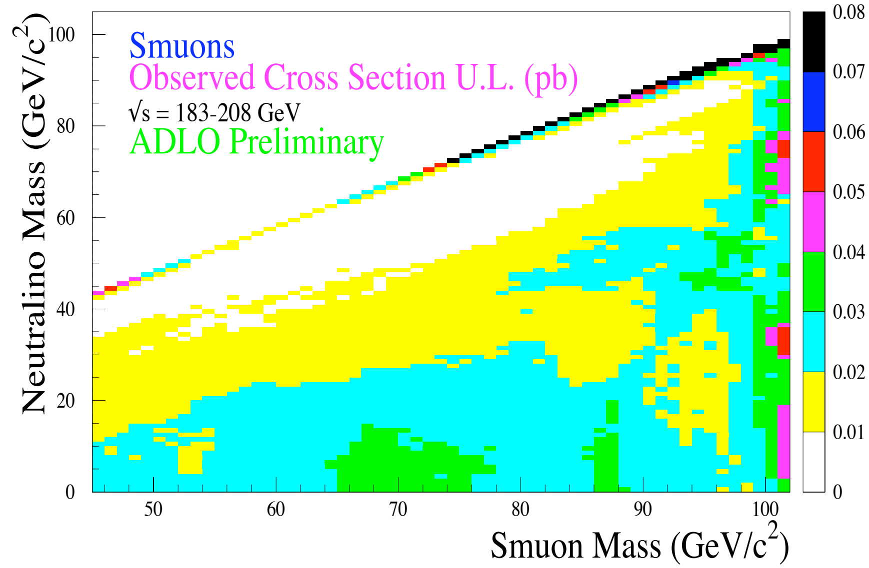
$\rightarrow$ all three BRs $= 1/3$.

Constraints: LEP limit on H^+H^-

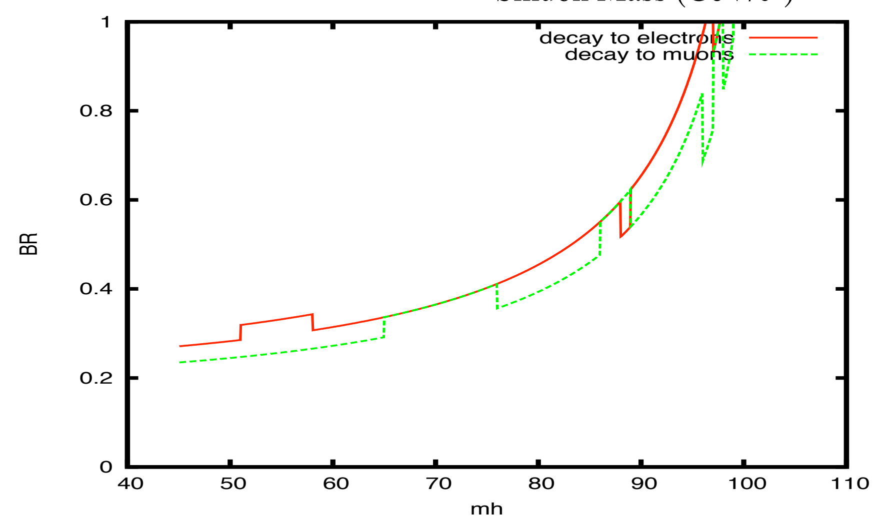
BR($H^+ \to \tau\nu$) too small for usual LEP charged Higgs search.

Look at LEP slepton searches instead with massless "neutralino".

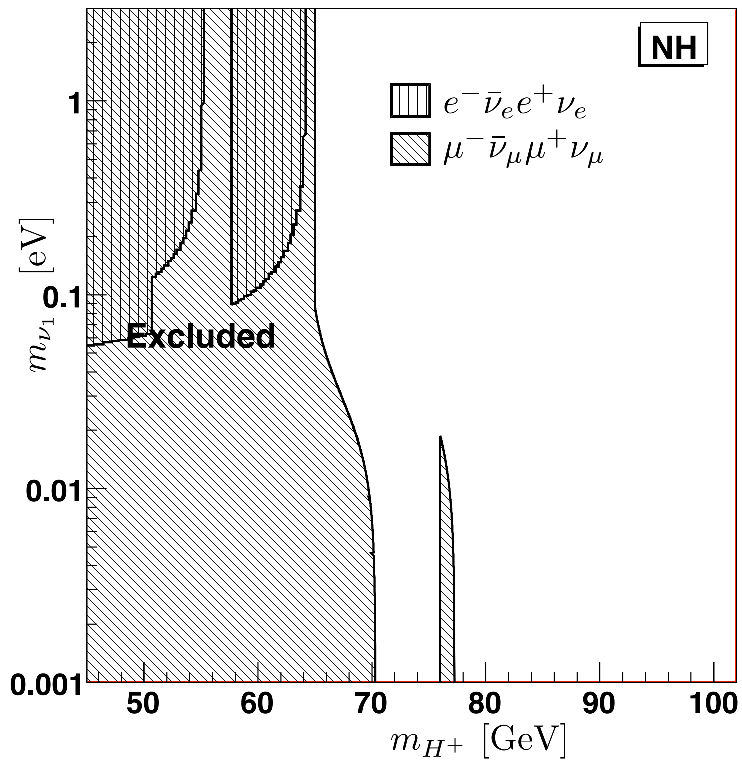


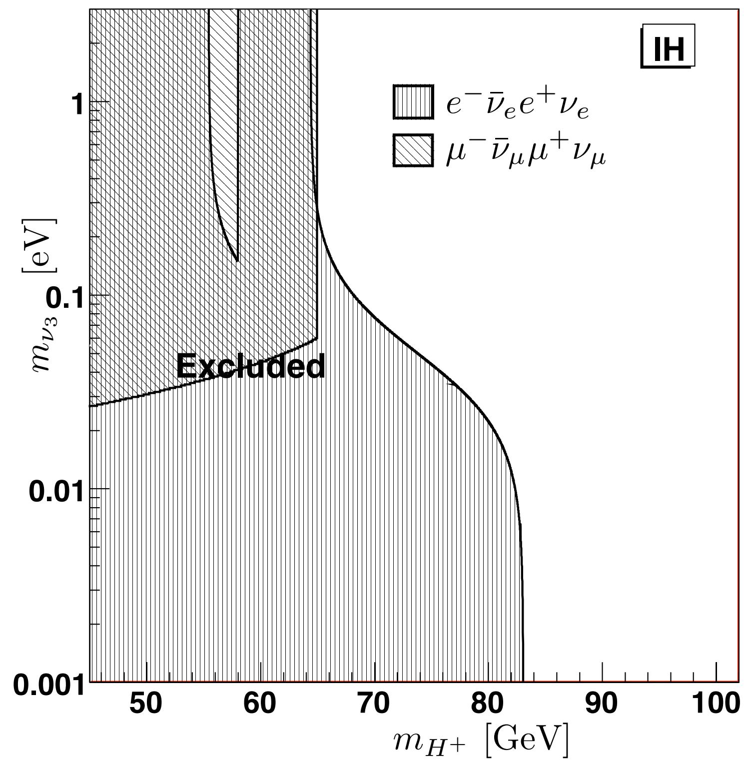


LEPSUSYWG/04-01.1

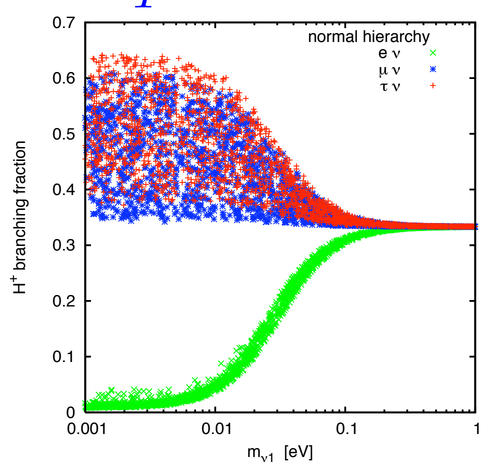


Put in $e^+e^- \to H^+H^-$ xsec, read off upper limit on BRs

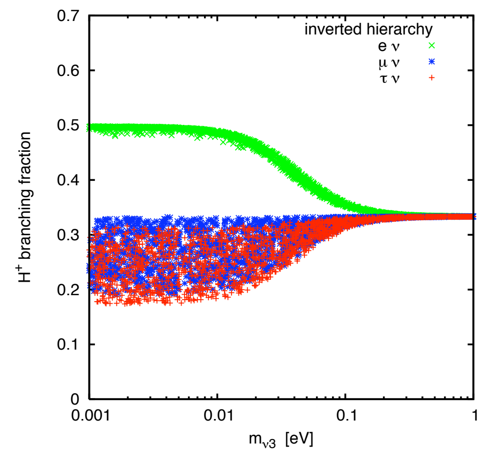




NH: $\mu\mu p_T^{miss}$ channel strongest



IH: eep_T^{miss} channel strongest



Phenomenology: LHC prospects

Rely on pair production: $pp \to H^+H^-$, $H^\pm A^0/H^0$, A^0H^0

- No coups to quarks; $H^+\ell_L^-\nu_R$ coupling $\lesssim 1/30$ (BBN constraint)
- Single production $\sim g^2 v_2$: super tiny

H^+ BR to $\mu\nu$ or $e\nu$ always $\geq 1/3$: $\ell^+\ell^- p_T^{miss}$ signature

Nice feature: H^+H^-Z coupling.

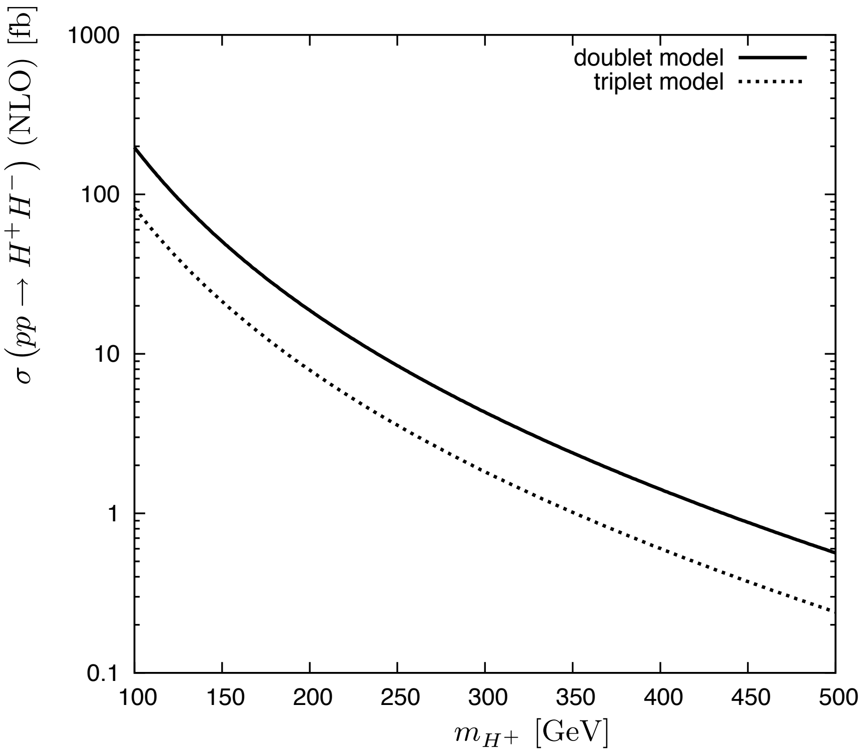
This model: SU(2) doublet:

$$g_{H^+H^-Z} = \frac{e}{s_W c_W}\left(\frac{1}{2} - s_W^2\right)$$

Type-2 seesaw: SU(2) triplet:

$$g_{\Delta^+\Delta^-Z} = \frac{e}{s_W c_W}\left(0 - s_W^2\right)$$

Doublet cross section ∼2.5x larger than triplet.



Summary

We introduce a simple new model to generate Dirac neutrino masses from couplings to a 2nd Higgs doublet with vev $v_2 \sim$ eV.

Dirac neutrinos: no neutrinoless double beta decay. (sorry EXO ppl)

Constraints from BBN ($v_2 \gtrsim 2$ eV) and LEP slepton searches ($M_{H+} \gtrsim 65$–83 GeV).

$\mu \to e\gamma$ signal at MEG if $\sin\theta_{13} \gtrsim 0.01$ and $v_2 \lesssim 6$ eV.

Decay BRs of H^+ reflect m_{ν_i} spectrum and PMNS matrix; BR to $\mu\nu$ or $e\nu$ always $\geq 1/3$. (Same as in Type-2 seesaw.)

Currently studying LHC signal & background in $pp \to H^+H^- \to \mu^+\mu^- p_T^{miss}$ channel. (LHC xsec ∼2.5x bigger than Type-2 seesaw.)