LHC and neutrino physics

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See also: Senjanovic and Mohapatra

The origin of neutrino masses

* A compelling understanding:

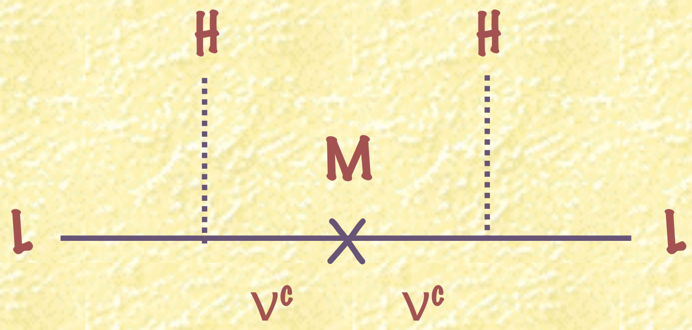
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM}^{\rm ren} + h_{ij}\frac{L_i L_j H H}{\Lambda} + \dots$$

Lepton number is an accidental symmetry of the SM

$$m_\nu = hv \times \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\left(\frac{0.05\,\text{eV}}{m_\nu}\right) h$$

* (close to $M_{GUT} \approx 2 \times 10^{16}$ GeV)
* L_{eff} is sensitive to $\Lambda = \Lambda_L \approx 10^{15}$ GeV, $\Lambda_B > 4 \times 10^{15}$ GeV » TeV (L- and B-violating operators = window to the GUT scale)
* No or very small L, B violation at TeV scale



$$\frac{h}{\Lambda}LLHH$$

$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M}\lambda$$

$$m_\nu = -m_D^T \frac{1}{M} m_D$$

$\Lambda \lesssim$ TeV?

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* $\Lambda \lesssim$ TeV needs $h < 10^{-11}$: why?
  - L is "exactly" conserved: h = 0
  - L is violated by interactions at $\Lambda \lesssim$ TeV and $h \approx 10^{-11}$–10^{-13}

Lepton number is conserved (at first)

* Neutrino masses need a 'right-handed' neutrino (Dirac neutrinos)
* In SM: $\lambda \overline{\nu_R} L H \to m_\nu = \lambda\, v$ (like the other fermions)
* Need λ < 10^{-11}: why?
    - L is conserved + $\lambda \overline{\nu_R} L H$ forbidden by a symmetry, e.g. because it is charged under a U(1) symmetry:

$$\lambda \overline{\nu_R} L H \to \lambda \left(\frac{\phi}{M}\right)^n \overline{\nu_R} L H, \quad \lambda_{\text{eff}} = \lambda \left(\frac{\langle\phi\rangle}{M}\right)^n$$

[Chacko Hall Okui Oliver ph/0312267
Chacko, Hall Oliver Perelstein ph/0405067
Davoudiasl Kitano Kribs Murayama ph/0502176]

        - interesting (model dependent) consequences for cosmology (and LSND)
        - no consequences for LHC: $\frac{\langle H\rangle}{M} \sim \frac{m_\nu}{\langle\phi\rangle} \sim g_{\phi\nu\nu^c} \lesssim 10^{-5} \quad (\text{BBN})$ (n=1)

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  - L is conserved + λ originates in extra-dimensions
    - ν_R lives in the flat bulk of large extra dimensions:

$$\lambda_{\rm eff} = \frac{\lambda}{(2\pi R M_*)^{\delta/2}} = \lambda \frac{M_*}{M_{\rm Pl}}$$

[Arkani-Hamed et al. ph/9811448
Dienes Dudas Gherghetta ph/9811428]

    - ν_R and L are localized in distant points of a (warped) extra dimension:

$$\lambda \propto e^{-(\text{superposition of the wave functions})}$$

[Grossman Neubert ph/9912408]

Large extra-dimensions

* 5D $\nu_R \leftrightarrow$ 4D $(\nu_R)_n$
* $M_n \approx n/R$ (large n)
* Brane-bulk mixing: $m \approx \lambda_{eff}$ <H> (for each active neutrinos)

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$$\nu_i = U_{ik}\hat{\nu}_k + \frac{m_i}{M_n} N_n$$

In the presence of bulk mass terms

[Lukas Ramond R Ross ph/0008049, ph/0011295]

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[Lukas Ramond R Ross ph/0008049, ph/0011295]

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Small (mainly) sterile component

* Signatures from the interaction $\frac{\lambda}{M_*}\overline{\nu_R}LH$:
  - e^+e^- colliders
  - H decay

Signatures

* $h \to \overline{\nu_L}(\nu_R)_n$ proceeds through $\lambda_{\text{eff}}^2 \sim \left(\frac{M_*}{M_{\text{Pl}}}\right)^2$
  but is enhanced by the $(M_* R)$ final states (D=5)

$$\frac{\Gamma(H^0 \to \overline{\nu_L}\nu_R)}{\Gamma(H^0 \to b\bar{b})} \sim 10^{6-\delta} \frac{m^2}{10^{-5}\,\text{eV}^2} \left(\frac{m_H}{100\,\text{GeV}}\right)^{\delta} \left(\frac{\text{TeV}}{M_*}\right)^{2+\delta}$$ (D=4+δ)

The invisible decay can easily dominate

[Arkani-Hamed et al. ph/9811448
Martin Wells ph/9903259]

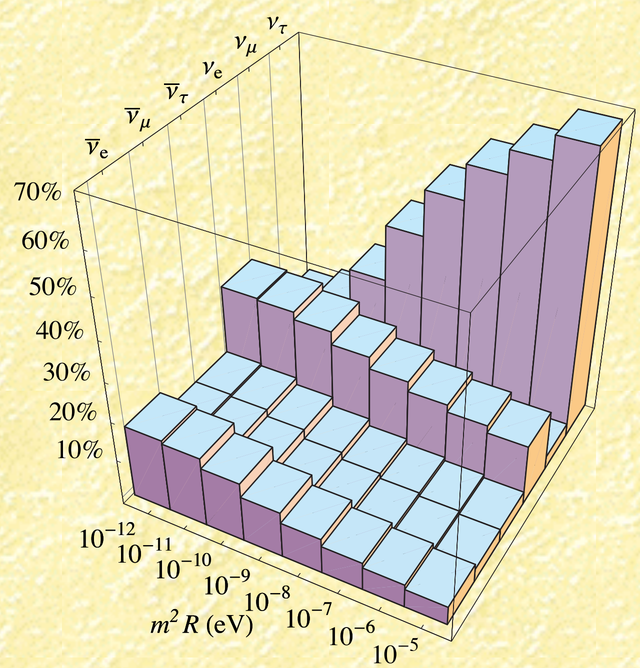
* For a 2HDM (type II):

$$\frac{\Gamma(H^- \to \overline{\tau_L}\nu_R)}{\Gamma(H^- \to \overline{\tau_R}\nu_L)} \sim \cot^4\beta \left(\frac{\lambda}{\lambda_\tau}\right)^2 \left(\frac{m_H}{M_*}\right)^{\delta}$$

[Agashe Deshpande Wu ph/0006122]

Large extra-dimensions and SN

* Neutrino KK = dangerous invisible energy loss channel (resonantly enhanced)
* A double feedback mechanism weakens the naive bounds on m^2R by 5 orders of magnitude to 5 10^{-5}eV
* The neutrino spectrum is modified

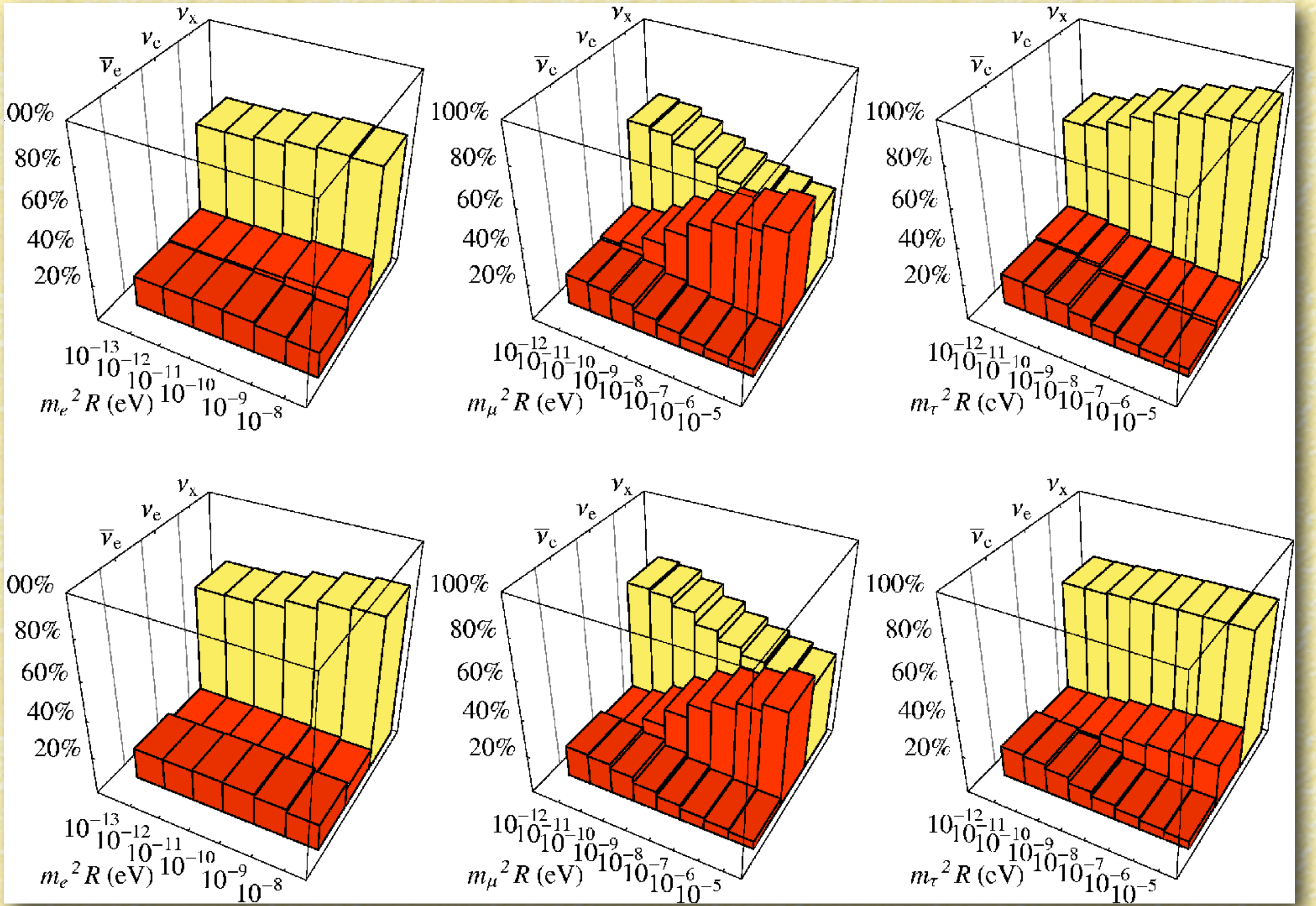


KK neutrinos mix predominantly with ν_τ

[Cacciapaglia Cirelli Yin R ph/0209063
Cacciapaglia Cirelli R ph/0302246]

ν_R mixes predominantly with

ν_e ν_μ ν_τ



(normal hierarchy)

$\Lambda \lesssim$ TeV?

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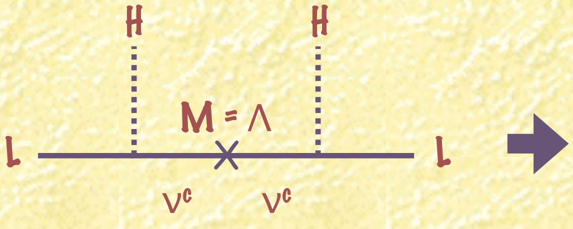
* Need h ≈ 10^{-11}–10^{-13}: why?

  LLHH forbidden by a symmetry

$$h\frac{LLHH}{\Lambda} \to h\left(\frac{\phi}{M}\right)^n \frac{LLHH}{\Lambda}, \quad h_{\text{eff}} = h\left(\frac{\langle\phi\rangle}{M}\right)^n$$

  as before: consequences for cosmology but not for LHC

* Assume h ≈ 10^{-11}–10^{-13}, Λ ≈ TeV: what is the origin of LLHH?
  - TeV-scale see-saw



$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

$$m_\nu = -m_D^T \frac{1}{M} m^D$$

  - Supersymmetry

TeV-scale see-saw

- ν_R with M_R ~ TeV
- Probe ν_R through $\lambda \overline{\nu_R} L H$: $m_\nu = -m_D^T \frac{1}{M} m_D, \quad m_D = \lambda \langle H \rangle$
- M_R ~ TeV $\Rightarrow$ $\lambda = \frac{m_D}{M_R} \approx 2 \times 10^{-7} \left(\frac{m_\nu}{0.05\,\mathrm{eV}}\right)^{1/2} \left(\frac{\mathrm{TeV}}{M_R}\right)^{1/2}$ too small for LHC
- Unless λ » 10^{-7} + cancellations in $m_\nu = -m_D^T \frac{1}{M} m_D$ (2 or more ν_R's)
  - "magical", e.g.:

    $m^D_{nj} = \alpha_n \beta_j \, m_0, \quad M_R = \mathrm{Diag}(M_1 \ldots M_n), \quad \sum_n \alpha_n^2 M_n = 0$ [Buchmuller Greub NPB363]

    $m_\nu = 0 + \text{corrections}$
  - natural, e.g.:

    $L_e, L_\mu, L_\tau, (\nu_R)_1 \equiv N$ have L = 1, $(\nu_R)_2 \equiv N'$ has L = -1 then $-\mathcal{L}^{\nu}_{\text{mass}} = (L_e, L_\mu, L_\tau, N, N')\,\mathcal{M}\,(L_e, L_\mu, L_\tau, N, N')^T$

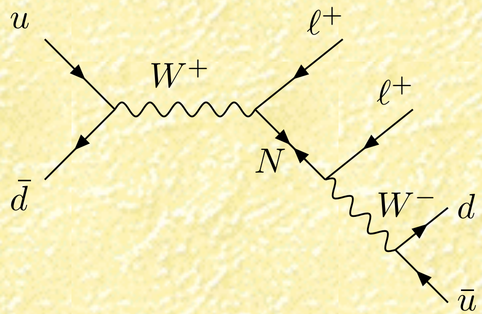
$$\mathcal{M} = \begin{pmatrix} & \mathbf{0} & & 0 & m_e \\ & & & 0 & m_\mu \\ & & & 0 & m_\tau \\ 0 & 0 & 0 & 0 & M \\ m_e & m_\mu & m_\tau & M & 0 \end{pmatrix}$$

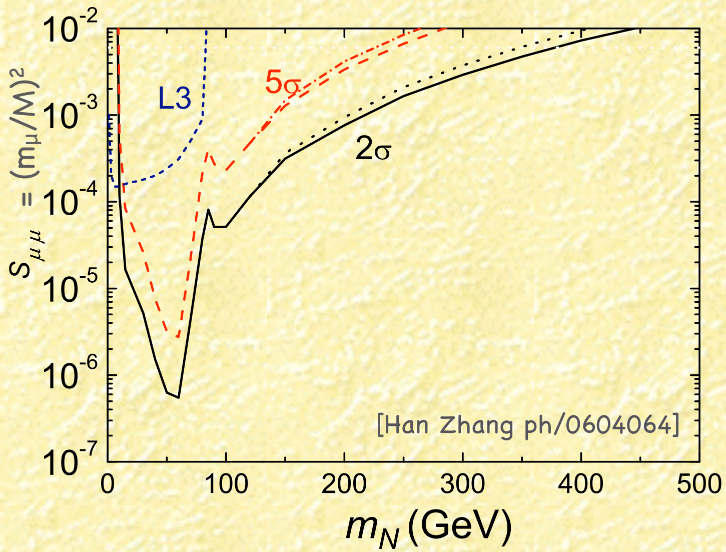
- rank = 2: 3 massless neutrinos independently of the size of m_i
- $\nu_i = U_{ik}\hat{\nu}_k + \frac{m_i}{M} N$

* Constraints: $(m_e/M)^2 < 0.006$, $(m_\mu/M)^2 < 0.003$, $(m_\tau/M)^2 < 0.003$

[Nardi Roulet Tommasini NPB386 (1992), ph/9402224, ph/9409310 Bergmann Kagan, ph/9803305]

* LNV at LHC (!): $qq' \to \mu^\pm \mu^\pm W^\mp$ cleanly probes m_μ/M





[Dicus Karatas Roy PRD44 (1991)
Datta Guchait Pilaftsis ph/9311257
Almeida et al ph/0002024
Ali Borisov Zamorin ph/0104123
Panella et al ph/0107308
Han Zhang ph/0604064
Aguila Aguilar-Saavedra Pittau ph/0606198
Bar-Shalom et al ph/0608309
Atwood Bar-Shalom Soni ph/0701005
Bray Lee Pilaftsis ph/0702294]

* No connection with m_ν

* Need h ≈ 10^{-11}-10^{-13}: why? Extra structure:

  LLHH forbidden by a symmetry

$$h\frac{LLHH}{\Lambda} \to h\left(\frac{\phi}{M}\right)^n \frac{LLHH}{\Lambda}, \quad h_{\rm eff} = h\left(\frac{\langle\phi\rangle}{M}\right)^n$$

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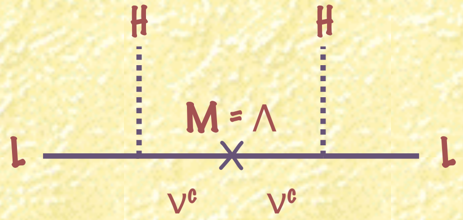

  - Supersymmetry

(R$_P$ violating) supersymmetry

* Supersymmetry does not guarantee (accidental) L (or B) conservation, unlike the SM: $H_d \approx \tilde{L}_i$

$$W = \lambda^U_{ij} u^c_i Q_j H_u + \lambda^D_{ij} d^c_i Q_j H_d + \lambda^E_{ij} e^c_i L_j H_d + \mu H_u H_d$$
$$+ \lambda''_{ijk} u^c_i d^c_j d^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \lambda_{ijk} L_i L_j e^c_k + \mu_i H_u L_i$$

$$\mathcal{L}_{\rm soft} = A^U_{ij} \tilde{u}^c_i \tilde{Q}_j H_u + A^D_{ij} \tilde{d}^c_i \tilde{Q}_j H_d + A^E_{ij} \tilde{e}^c_i \tilde{L}_j H_d + B\mu H_u H_d$$
$$+ A''_{ijk} \tilde{u}^c_i \tilde{d}^c_j \tilde{d}^c_k + A'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{d}^c_k + A_{ijk} \tilde{L}_i \tilde{L}_j \tilde{e}^c_k + (B\mu)_i H_u \tilde{L}_i$$

$$+ \tilde{m}^2_Q \tilde{Q}^\dagger \tilde{Q} + (\tilde{m}^2_i H^\dagger_d \tilde{L}_i + \text{h.c.}) + \text{gaugino masses}$$

* L and B violating terms controlled by $R_P = (-1)^{3(B-L)+2s}$
* A small R$_P$ breaking:
  - induces $(h_{ij}/\Lambda) L_i L_j H H$, with $\Lambda = \tilde{m}$, h ↔ small R$_P$ breaking parameters
  - makes the LSP unstable (could be any susy partner)

Bilinear R_P violation

[Hall Suzuki NPB231 (1984), Lee PLB138 (1984), NPB246 (1984), Dawson NPB261 (1985), Hempfling ph/9511288, Nilles Polonsky ph/9606388, Kaplan Nelson ph/9901254, Chun Kang ph/9909429, Hirsch Diaz Porod Romao Valle ph/0004115, Joshipura Vempati ph/9808232, Takayama Yamaguchi ph/9910320, Joshipura Vaidya Vempati ph/0203182, Chun Jung Park ph/0211310]

- In an appropriate basis for $L_\alpha = (H_d, L_e, L_\mu, L_\tau)$:
  - No R_P-violating trilinear terms
  - $W \supset \mu H_u H_d + \mu_i H_u L_i$, $\mathcal{L}_{soft} \supset B\mu H_u H_d + (B\mu)_i H_u L_i$ +

[Aulakh Mohapatra PLB119, Ellis et al PLB150, Ross Valle PLB151, Chikashige Mohapatra Peccei PLB98]

- Predictive + might follow from spontaneous R_P breaking
- $\langle H_u \rangle_2 = v_u$, $\langle H_d \rangle_1 = v_d$, $\langle \tilde{L}_i \rangle_2 = v_i$ → neutrino-neutralino mixing → m_ν
- Tree level: $\frac{h_{ij}}{\Lambda} \approx \frac{g^2}{2M_2}\xi_i\xi_j \to (m_\nu)_{ij} \approx \frac{M_Z^2}{M_2}\xi_i\xi_j$ controlled by $\xi_i = \frac{v_i\mu - \mu_i v_d}{\mu v_d}$ (misalignment of μ_α and $(B\mu)_\alpha$): $\xi = |\vec{\xi}| \approx 2.5 \times 10^{-6}/\cos\beta\left(\frac{M_2}{\text{TeV}}\right)$
  - $m_1 = m_2 = 0$ (normal hierarchy), $\tan\theta_{23} = \xi_2/\xi_3$, $\tan\theta_{13} = \xi_1/(\xi^2_2+\xi^2_3)^{1/2}$
- $(\Delta m^2)_{12}$ and θ_{12} at 1-loop, controlled by μ_i/μ, $\tan\theta_{12} = \mu_1/(\mu^2_1+\mu^2_2)^{1/2}$
- LHC: production and decay to LSP almost unaffected
- Small R_P breaking effect ξ_i, μ_i visible through LSP decay

LSP decay

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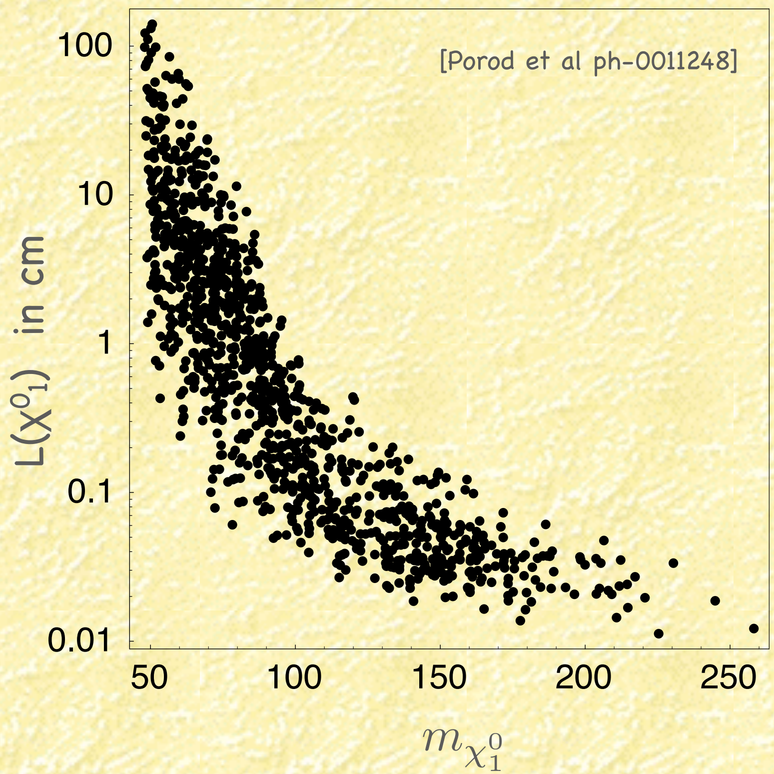

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- In particular:

$$\frac{\mathrm{BR}(\chi_1^0 \to \mu^\mp \bar{q} q')}{\mathrm{BR}(\chi_1^0 \to \tau^\mp \bar{q} q')} \approx \frac{\mathrm{BR}(\chi_1^0 \to W^\pm \mu^\mp)}{\mathrm{BR}(\chi_1^0 \to W^\pm \tau^\mp)} \approx \left(\frac{\xi_2}{\xi_3}\right)^2 \approx \tan^2\theta_{23}$$

[Mukhopadyaya Roy Vissani ph/9808265
Datta Mukhopadyaya Vissani ph/9910296
Porod et al ph/0011248]

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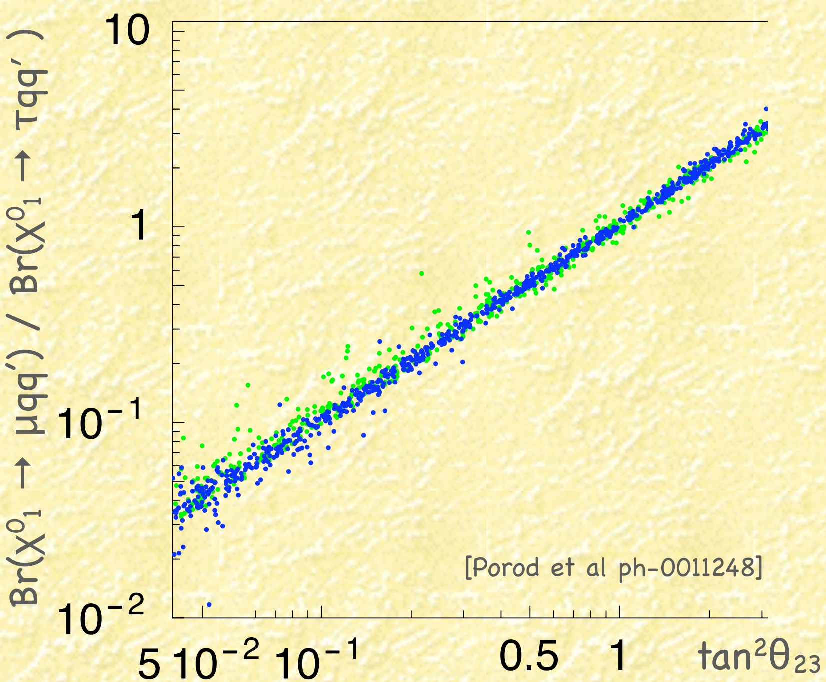

m_0 = (0.2-1) TeV

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tanβ = (2.5-10)

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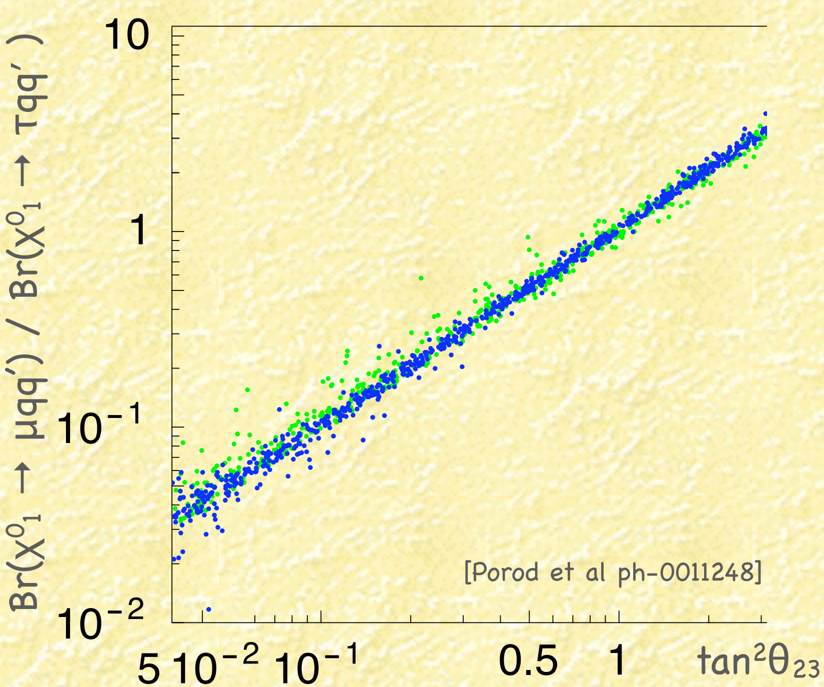
[Mukhopadyaya Roy Vissani ph/9808265
Datta Mukhopadyaya Vissani ph/9910296
Porod et al ph/0011248]

LHC: BR ratio at 3% with 100 fb^{-1}

[Porod Skands ph/0401077]



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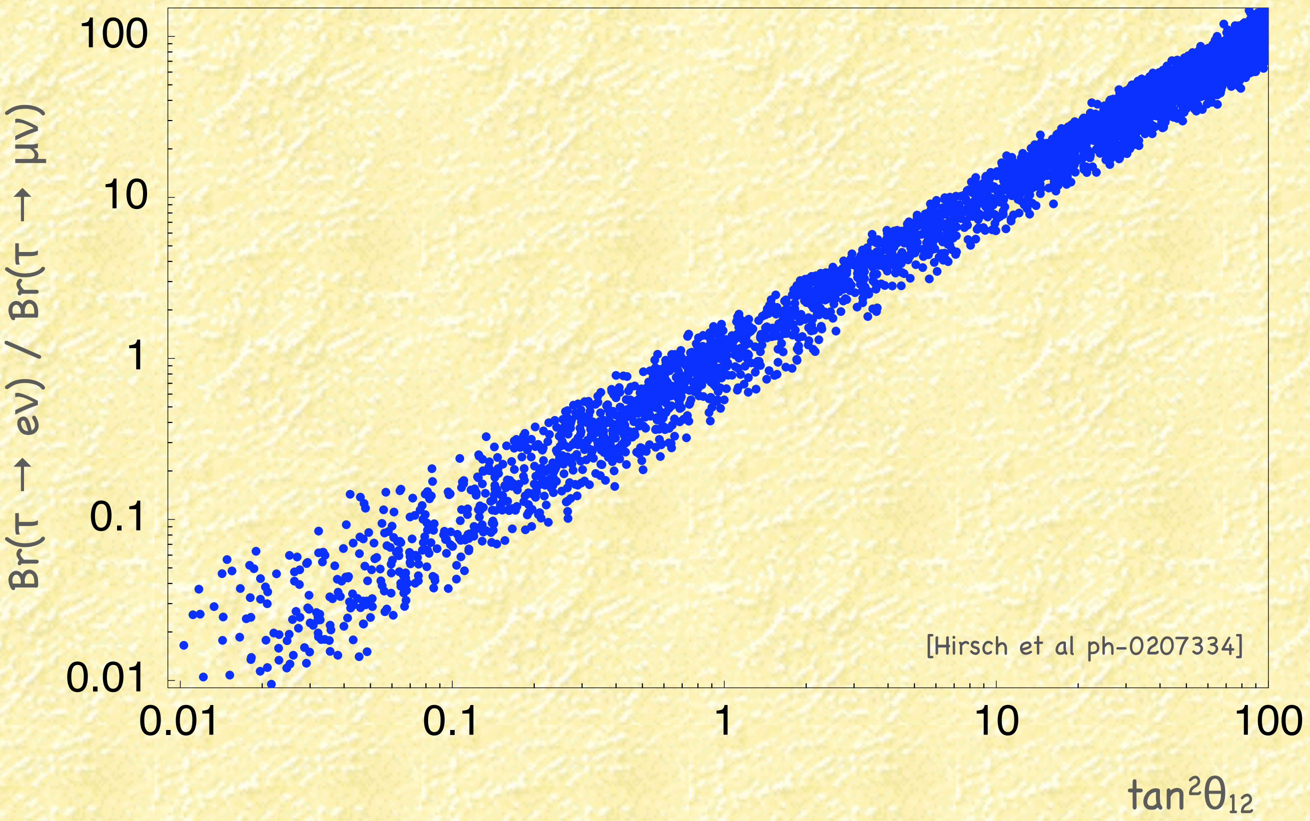

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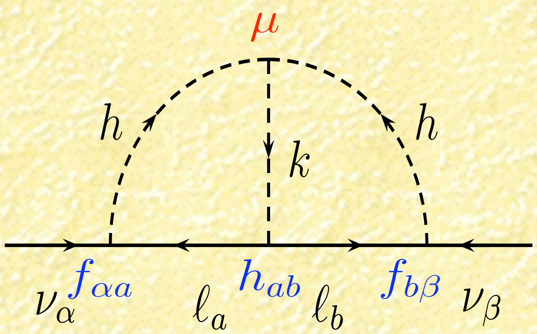
* Other candidates → [Hirsch Porod ph/0307364]

Babu-Zee model

- Fields: SM + h⁺ + k⁻⁻ (SU(3)xSU(2) singlets, Y = 1, -2 respectively)
- $\mathcal{L} = \mathcal{L}_{\rm SM} + f_{ij} l_i l_j h^+ + h_{ij} e^c_i e^c_j k^{--} + \mu\, h^+ h^+ k^{--}$ breaks L
- Neutrino masses generated at 2 loops



- $$\mathrm{BR}(h^+ \to e\nu) = \frac{\epsilon^2 + \epsilon'^2}{2(1+\epsilon^2+\epsilon'^2)}$$

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where $\epsilon = \tan\theta_{12}\dfrac{\cos\theta_{23}}{\cos\theta_{13}}$ or $-\dfrac{\sin\theta_{23}}{\tan\theta_{13}}$

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NH IH

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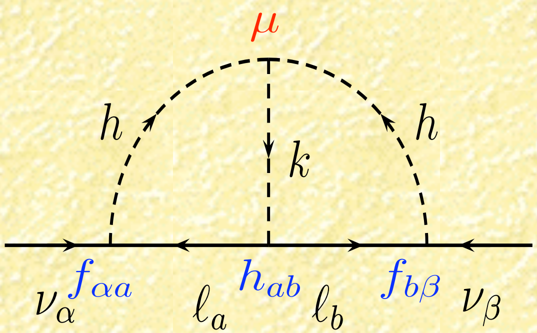

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$\epsilon' = \tan\theta_{12}\dfrac{\sin\theta_{23}}{\cos\theta_{13}}$ or $\dfrac{\cos\theta_{23}}{\tan\theta_{13}}$

NH IH

[Zee 1985, Babu 1988
Babu Macesanu ph/0703010
Aristizabal Hirsch ph/0609307]

Summary

* The standard understanding of neutrino masses in terms of a high scale breaking of an accidentally conserved lepton number is solid, economical, and general

* Alternative, TeV-scale origins of neutrino masses are also allowed and offer the opportunity to probe such an origin at the LHC