Leptogenesis and Neutrino Masses

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OUTLINE

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- Introduction: Motivation, Requirements, Experimental Input
- Neutrinos: see-saw
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- Bounds for $L_{(MS)SM} + 3\nu_R$
- Leptogenesis for TeV-scale Models
- Leptogenesis with $\not{R}_p$.
- Leptogenesis with Four Gauge Singlets

Introduction

Motivation

- Explain within a consistent theoretical model the mechanism for Baryogenesis.
  Need a dynamical mechanism that will start out with $\eta_B = 0$ and lead to $\eta_B \neq 0$.
- Model that will produce neutrino masses and mixings consistent with recent neutrino data.
- Need extension of the Standard Model (SM).
- Bias: Models that are testable.

Experimental Input

WMAP, Boomerang, DASI

Predicted primordial abundances of light elements are $\propto \eta$.

$$\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10}$$

$$\Omega_b h^2 = 0.0224 \pm 0.001$$

where,

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Experimental Input cont'd

SK, SNO, Kamland

Atmospheric ν and Reactor Data

	$\Delta m^2_{atm}(eV^2)$	$\sin^2 2\theta_{atm}$	U_{e3}
	$(1-5)10^{-3}$	>0.92	<0.22

Solar ν

LMA	$\Delta m^2_{sol}(eV^2)$	$\sin^2 2\theta_{sol}$
	$(0.5-1.1)\times 10^{-4}$	>0.70 <0.96
WMAP +2dGR	$\sum_i m_{\nu_i}$ <0.7 eV	

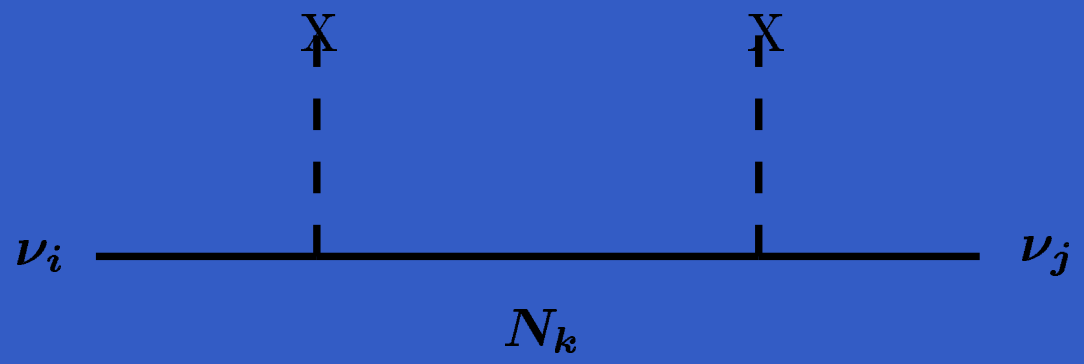
Neutrinos:see-saw

See-saw mechanism: elegant solution to produce neutrino mass and explain ν mass scale.

- heavy Majorana fermion, with mass M_i, for each generation of SM.
- Additional particles are singlets of the SM gauge group
- Have Yukawa couplings to the Higgs doublet.

See-saw mass

$$L_y = y_{ik} L_k \phi N_i + h.c.$$



Neutrinos:see-saw and fits

At low-energies,

$$L = -\frac{1}{2}\nu^T M_\nu \nu + h.c.$$

with

$$M_\nu = m_D^T M^{-1} m_D = Y_\nu^\dagger M^{-1} Y_\nu v_u^2$$

Baryogenesis Requirements

Sakharov

1. **Baryon Number Violation** If all interactions conserve Baryon number, $\rightarrow n_B = 0$.
2. **C and CP Violation**
   If not rates of interactions and their CP conjugates will be the same.
3. **Disequilibrium:** then $n_B \neq n_{\bar{B}}$

B, C and CP violation is model dependent.

Out-of-Equilibrium Decay

Out-of Equilibrium obtained due to expansion of the Universe as a background for heavy decaying particles.

$$\Gamma_X \sim \alpha_X M_x$$

Rule of thumb for out-of-equilibrium decay,

$$\Gamma_D < H|_{T=M_X}.$$

Abundances

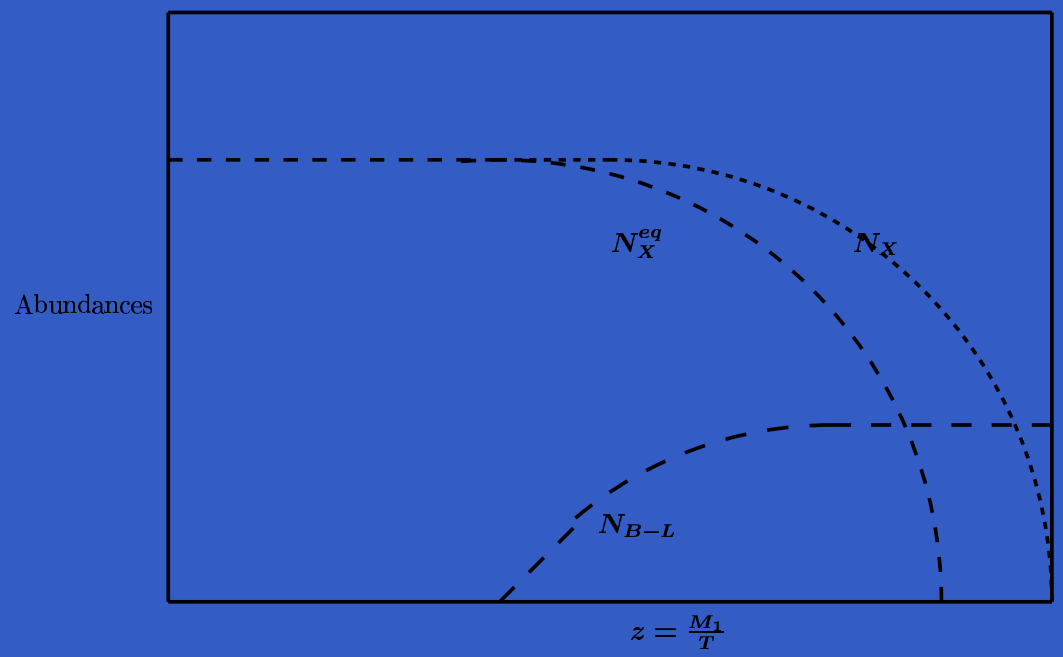


Figure 1: Abundances.

Boltzmann Equations Gral. Case

Interactions are too slow to catch up with expanding Universe. So N_X start to become overabundant.
Must consider inverse decays, scatterings, annihilations.

$$\frac{dn_X}{dt} + 3Hn_X = \sum_{j,l,m} \int \Pi f_l f_m \cdots (1 \pm f_X)(1 \pm f_j) \cdots W(l + m + \cdots \to X + j \cdots)$$
$$- f_X f_j \cdots (1 \pm f_l)(1 \pm f_m) \cdots W(X + j + \cdots \to l + m \cdots)$$

R.H.S. N_X variation due to all elementary processes for X.

cont'd

Coupled system for n_X and n_{B-L},

$$\frac{dn_X}{dt} + 3Hn_X = [\frac{n_X}{n_X^{eq}} - 1](\gamma_D + \gamma_a)$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \epsilon[\frac{n_X}{n_X^{eq}} - 1]\gamma_D - \frac{n_{B-L}}{n_L^{eq}}\gamma_{LV,BV}$$

$\epsilon \rightarrow$ CP Asymmetry

$\gamma_{LV,BV}$ dissipation at $T < M$

Constraints

- Interactions that produce the asymmetry must *turn off* at some point in order not to ERASE the BAU.
- In the SM not all of the dynamics is described by perturbative effects; There are non-perturbative interactions that violate B+L.

Sphalerons

Non-perturbative finite temperature interactions, involving all left chiral fermions (due to chiral nature of weak interactions)

- at high-T $\Gamma \sim \alpha_W T^4$
- below EW-scale $\Gamma \sim T^4 e^{-\xi}$

Above EW-scale sphaleron processes are in equilibrium and **conserve B-L.**

cont'd

Kuzmin, Rubakov, Shaposhnikov

$$T_{EW} < T < T_{SPH} \sim 10^{12} GeV \quad (1)$$

Below EW-scale Higgs vev suppresses sphaleron rates

$\rightarrow$ Constrains models of EW Baryogenesis.

Basic Leptogenesis Mechanism

Fukugita and Yanagida ’86

Based on standard out-of-equilibrium decay of a heavy particle:

1. CP violating decay of a heavy particle through an L-violating interation can produce a lepton asymmetry.
2. This lepton asymmetry is transformed into a *baryon asymmetry* through sphaleron interactions. $n_B = \frac{C}{C-1} n_L$

CP Asymmetry

- CP violation through phases in neutrino sector.
- CP asymmetry produced through interference of tree and one-loop contribution of decay rate.

$$\epsilon = \frac{\Gamma(N_1 -> \phi + \bar{l}) - \Gamma(N_1 -> l + \bar{\phi})}{\Gamma(N_1 -> \phi + \bar{l}) + \Gamma(N_1 -> l + \bar{\phi})}$$

CP-Asymmetry cont'd

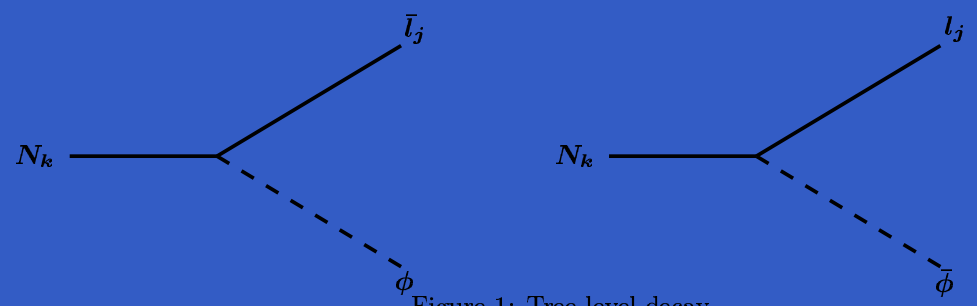


Figure 1: Tree-level decay.

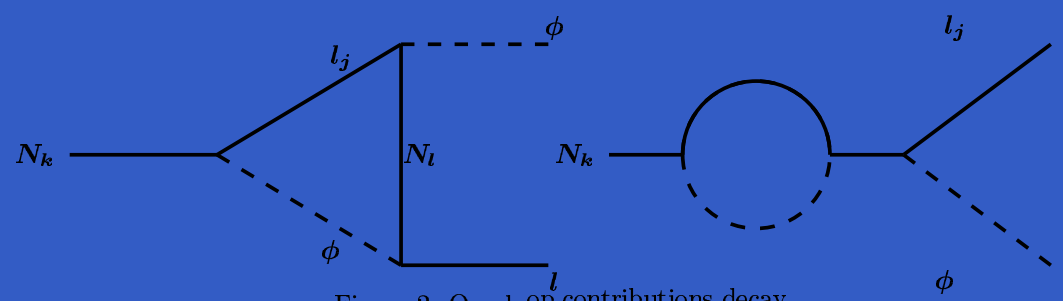


Figure 2: One-loop contributions decay.

LAU

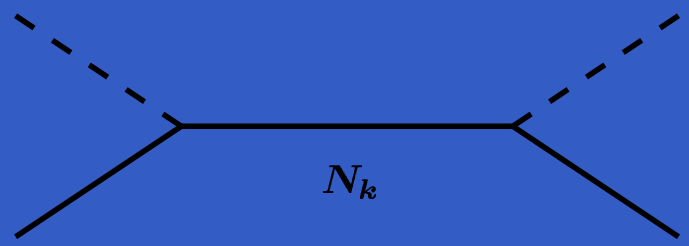
Decay rate: $\Gamma_D = \frac{1}{8\pi}(h^\dagger h)_{11} M_1$

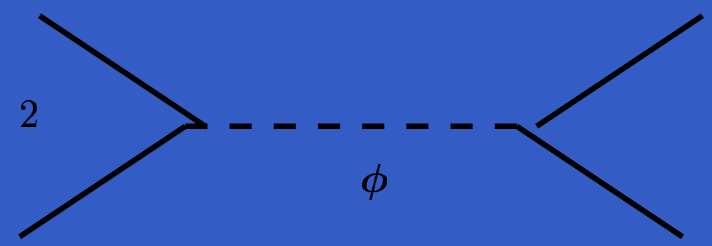
Lepton asymmetry $\eta_L \equiv \frac{n_{\nu_R} - n_{\bar{\nu_R}}}{s} \epsilon \delta$

- ϵ: CP asymmetry determined by the particle physics model that produces couplings and masses for ν_R.
- $\frac{n_{\nu_R} - n_{\bar{\nu_R}}}{s}$ initial abundance of RH ν's. Depends on the production mechanism.
- δ incorporates washout effects by L-violating interactions after the RH neutrinos decay.

Relevant processes

1. N decays and inverse-decays
2. $\Delta L = 2$ scatterings
3. $\Delta L = 1$ scatterings





Boltzmann Eqns. Leptogenesis Case

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{eq})$$

$$\frac{dN_{B-L}}{dz} = -\epsilon D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L}$$

$D, S, W - \Delta W \propto \frac{M_{pl}\tilde{m}_1}{v^2}$ $\qquad$ $\Delta W \propto \frac{M_{pl} M_1 \bar{m}^2}{v^4}$

$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \qquad \bar{m}^2 = m_1^2 + m_2^2 + m_3^3$$

LAU cont'd

- Now out of equilibrium condition is given by: $\tilde{m}_1 \leq 5 \times 10^{-3}$ eV.
- η_L is a function of $(M_1, \epsilon, \tilde{m}_1, \bar{m})$.
- If ΔW can be neglected then η_L *does not* depend on M_1.
- For an initial thermal abundance for N_1 *and* if all washout processes are small $\delta \sim 1$ $N_{B-L} = -\frac{3}{4}\epsilon$.

Bounds from Leptogenesis on ν Masses

Casas, Ibarra

If U diagonalizes m_ν, we define

$$\tilde{h} = U^\dagger h \tag{2}$$

Then the matrix $\Omega_{ij} = \frac{v}{(m_i M_j)} \tilde{h}_{ij}$ is orthogonal.
The CP asymmetry

$$\epsilon = -\frac{3}{16\pi} \frac{M_1}{v^2} \frac{1}{(h^\dagger h)_{11}} Im[h M_\nu^\dagger h^T]_{11}] \tag{3}$$

Bounds from Leptogenesis on ν Masses

Davidson, Ibarra

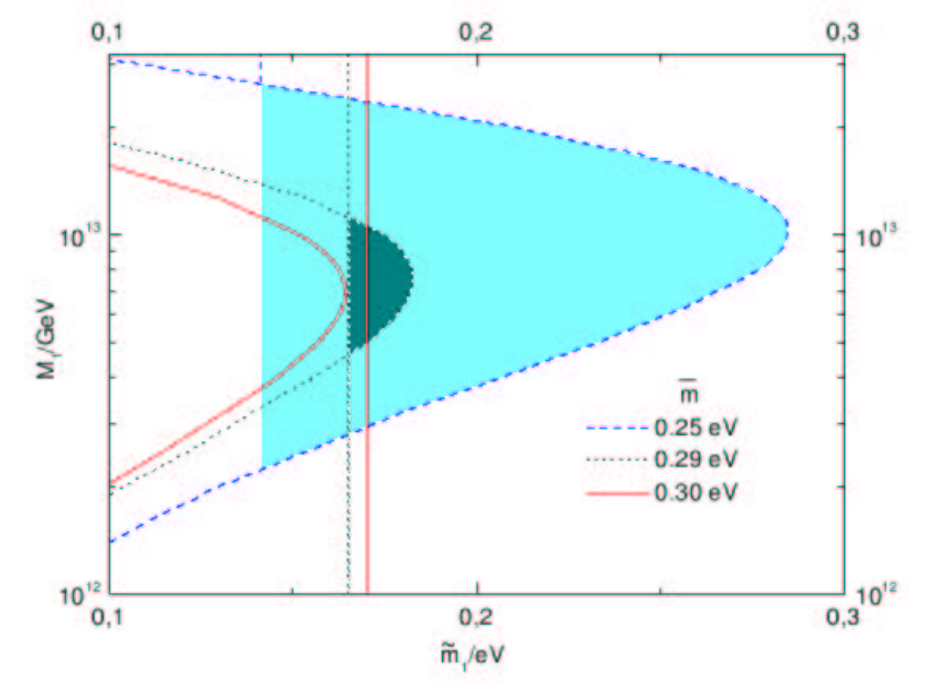
$$\epsilon \leq \epsilon_{max} = \frac{3}{16\pi}\frac{M_1}{v^2}\frac{(\Delta m^2_{atm} + \Delta m^2_{sol})}{m_3} \qquad (4)$$

Solve for:
(m_3^2, m_2^2, m_1^2) in terms of $(\bar{m}^2, \Delta m^2_{atm}, \Delta m^2_{sol})$

$\rightarrow \epsilon_{max} = \epsilon(M_1, \bar{m})$

Bounds (Figs.)

Buchmuller, Di Bari, Plumacher 02, 03



Bounds (Figs.)

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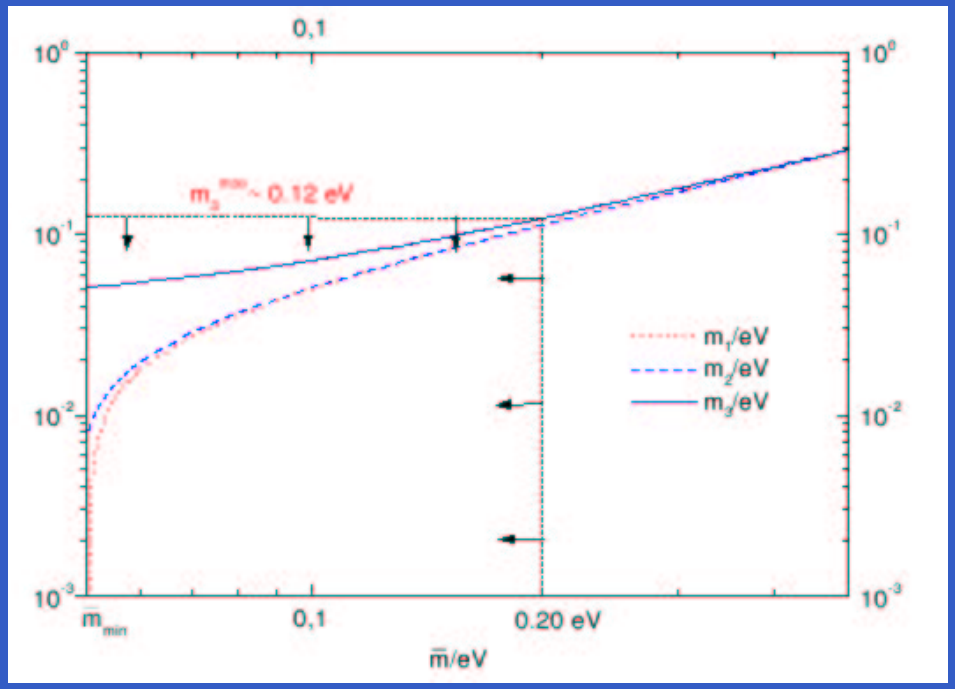
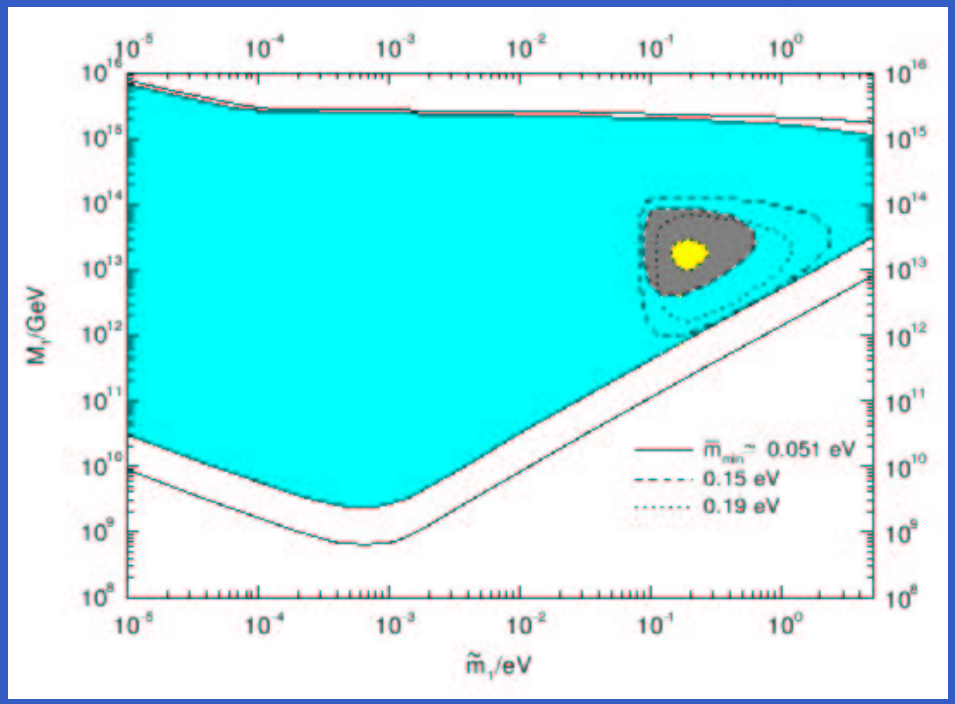


Bounds (Figs.)

Buchmuller, Di Bari, Plumacher 02, 03



Bounds cont'd

For $N_{N_1}^{in} = 0$

$$\bar{m} < 0.2eV \qquad \epsilon_{max} \geq 2.4 \times 10^{-7}$$

For thermal initial N_1 abundance

$$\bar{m} < 0.3eV \qquad \epsilon_{max} \geq 3.8 \times 10^{-8}$$

and

$$M_1 \geq 2.4(0.4) \times 10^9 GeV (\frac{2.5 \times 10^{-3} eV^2}{\Delta m_{atm}^2})^{1/2}$$

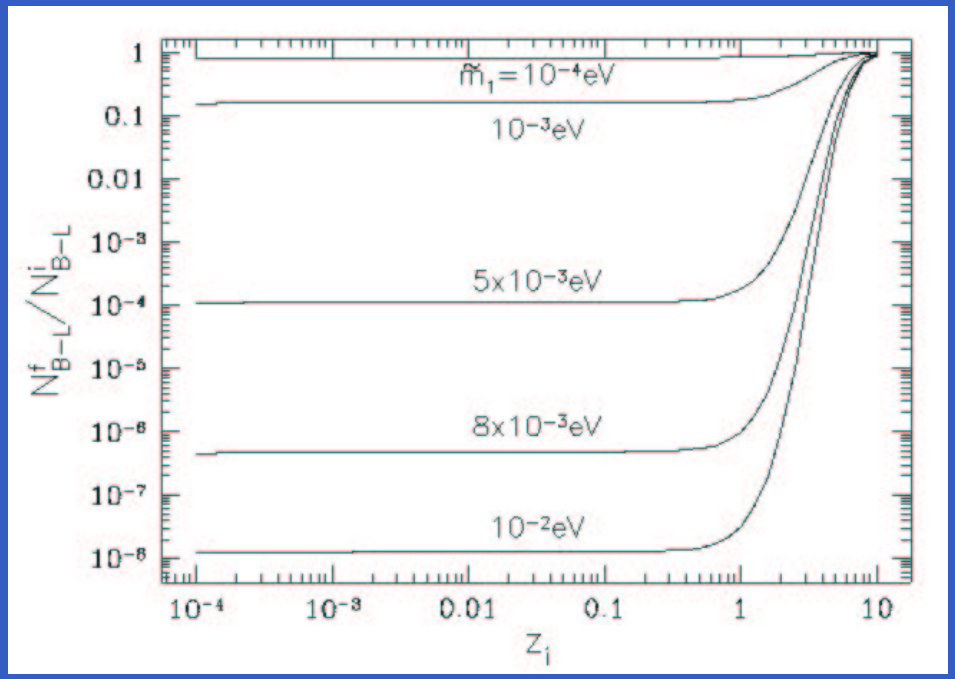
Bounds cont'd

Other conclusions:

- Leptogenesis strongly disfavours quasi-degenerate neutrinos.
- Cannot discriminate between normal and inverted hierarchy.
- Using Ω, $\tilde{m}_1 = \frac{\tilde{m}_D^\dagger \tilde{m}_D}{M_1} \geq m_1$.
- For most interesting range of $\tilde{m}_1$, dependence on initial N_1 abundance is small.

Bounds (Figs.)

Buchmuller, Di Bari, Plumacher 02, 03



TeV-scale Leptogenesis

Hambye

Difficulties:

- $\Gamma < H|_{z=1}$ requires very small couplings. So typically ϵ too small.
- At TeV-scale other processes can be fast with respect to H. Lepton number conserving processes can damp the asymmetry.
- Hard to simultaneously get right m_ν. See-saw or radiative masses.

Leptogenesis (with $\not{R}_p$)

- All MSSM particles have *gauge interactions* which would eliminate any asymmetry.
- Normally inverse decays, 2-2 scatterings can be ignored if coupling involved in these processes *is the same one* involved in decays.
- LSP has lepton number violating interactions, but it annihilates and decays *after* reaching relic density.

Enhancement mechanisms

Hambye

1. Mass degeneracy: $M_2 - M_1 << M1$. Resonant behaviour which induces enhancement in ϵ.Flanz et al.
2. Three body decays: phase space, more couplings; $y_1^2 y_2^4/(y_1^2 y_2^2)$.
3. Hierarchy of couplings: $(y_1 y_2)^2/y_1^2 \sim y_2^2$.

Leptogenesis with Four Gauge Singlets

$$L = L_{SM} + \bar{\psi}_{R_I} i\partial\psi_{R_I} - \frac{M_{N_I}}{2}(\bar{\psi}_{R_I}\psi^c_{R_I} + h.c.)$$
$$+ (Y_{IJ}\bar{L}_J\psi_{R_I}\phi + h.c.)$$

Decay Rate

$$\Gamma_{N_I} = \frac{1}{8\pi}[Y_\nu Y_\nu^\dagger]_{II} M_{N_I}$$

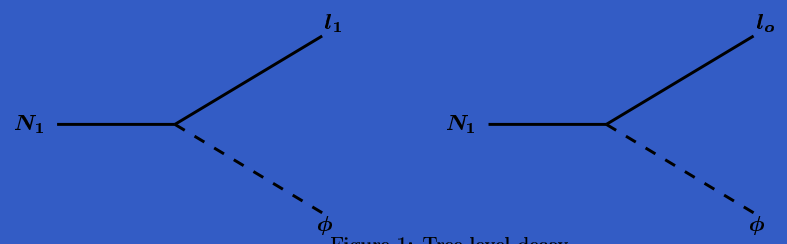
CP asymmetry

$$\epsilon_I = \frac{1}{8\pi}\frac{1}{[Y_\nu Y_\nu^\dagger]_{II}}\sum_J Im[[Y_\nu Y_\nu^\dagger]^2_{IJ}(f(x_{JI}) + g(x_{JI}))]$$

(5)

Toy Model:(2-generation)

Consider the model with only two generations.



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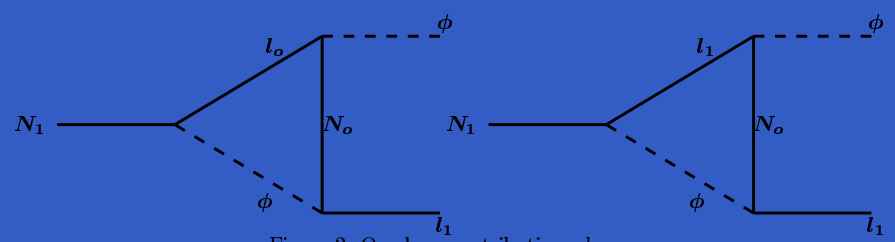


Figure 2: One-loop contributions decay.

Toy Model: Detail and Figs.

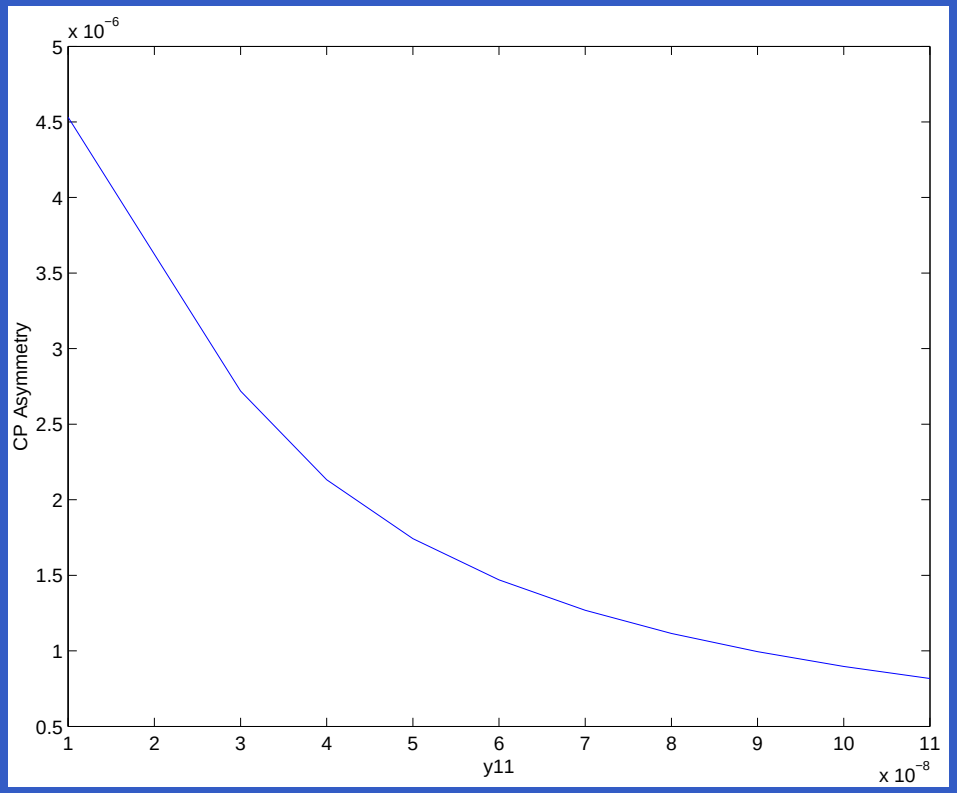
Upper bound on ϵ is now:

$$\epsilon \leq \frac{M_1 m_0}{v^2}$$

and easily,
$\tilde{m}_1 \sim 10^{-4} \rightarrow$ washout is a small effect.

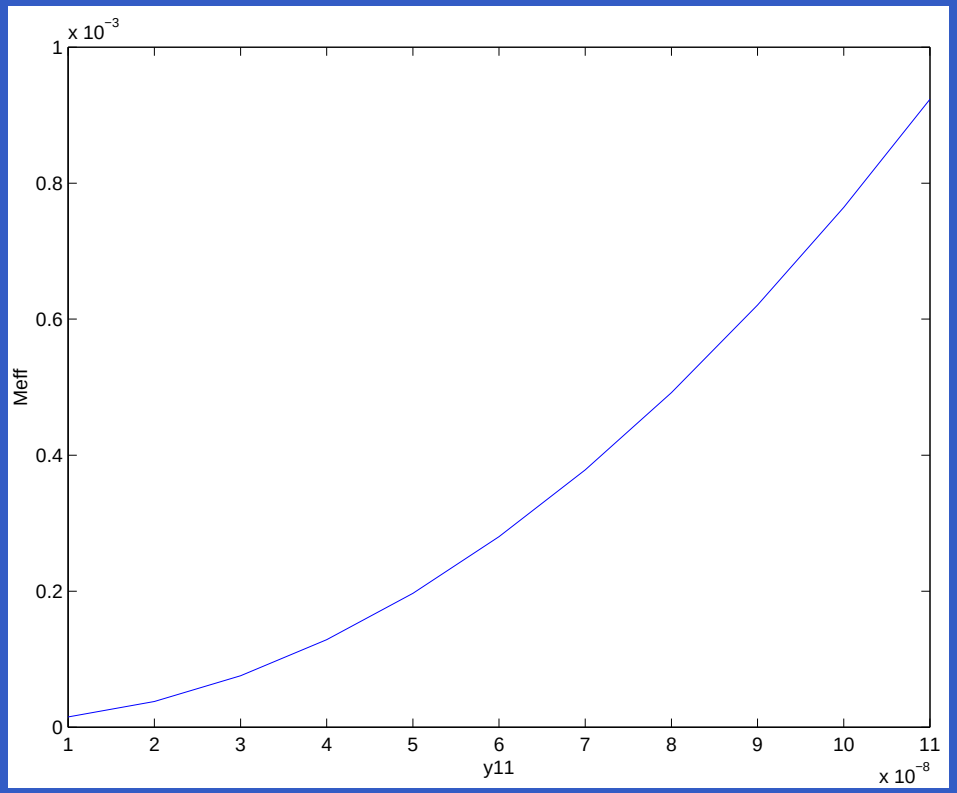
Figs.

CP Asymmetry



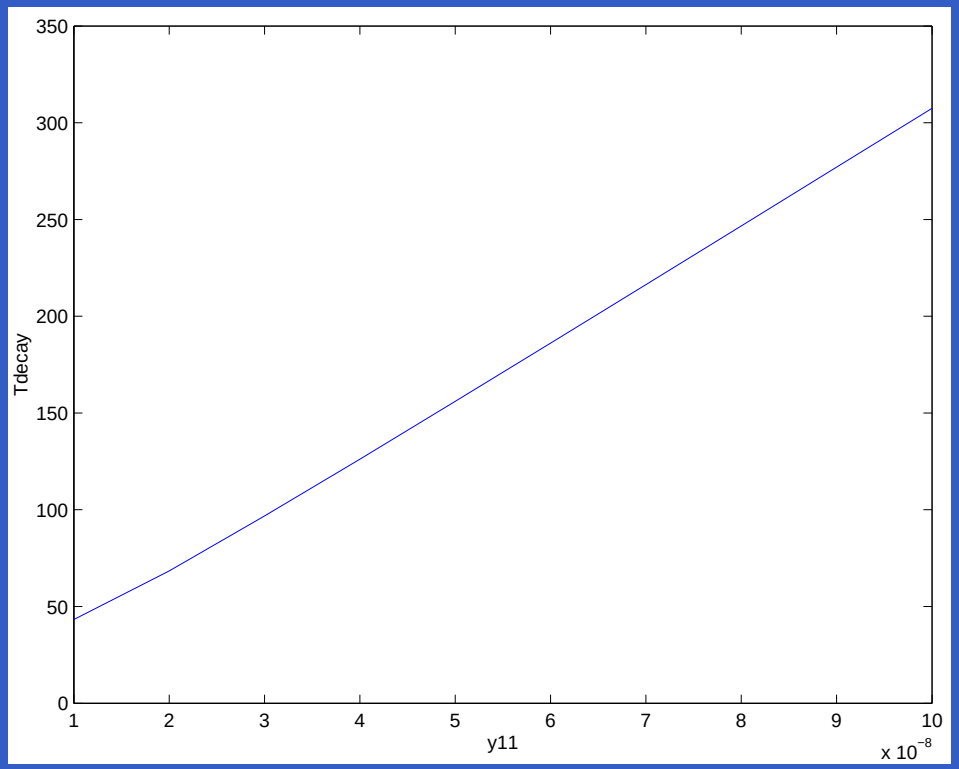
Figs.

$\tilde{m}_1$



Figs. cont'd

T_{decay}



4 Generations

$$h_{IJ} \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon & \epsilon \\ \epsilon & 1 & 1 & 0 \\ \epsilon & 1 & 1 & 0 \\ \alpha & 0 & 0 & 1 \end{pmatrix}$$

$$m_\nu \sim \frac{v^2}{M} \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

Comments

1. $m_1 \leq \tilde{m}_1$
2. Can fit neutrino oscillation data for full model.
3. Less constrained if only 3 LH lepton families.
4. Strong washout effects in l_0 asymmetry:$\propto \frac{M_{Pl} M_1 m_O^2}{v^4}$

Susy case

New/Benefits

Sneutrino decays contributing to the lepton asymmetry.

H_d takes place of l_o.

Less constrained M_o, as there are other contributions to the Higgsino mass.

$M_1 \sim 1 - 10 TeV$

Drawbacks

Gravitino problem H. Murayama's talk.

No Higgsino asymmetry due to washout from μ term.

Superpotential for Spontaneous $\not{R}_p$

Work in progress

$$W = W_{MSSM} + h_{IJ} L_I H_u N_J^c + s_{IJK} N_I^c N_J^c N_K^c$$

$$V = V_F + V_D + V_{soft}$$

$$\Delta V_{soft} = A\lambda_{IJ} L_I H_u N_J + m_{IJ}^2 N_I N_J + A_{IJK} N_I N_J N_J$$

cont'd

Rotating in N_I space,

- $\rightarrow < N_0 > \neq 0$.
- μ terms $\rightarrow \mu_I = h_{I0} < N_0 >$
- RH ν mass $\rightarrow M_{IJ} \sim S_{IJ0} < N_0 >$

Decay rate and asymmetry same as before.

Production

Thermal Production

- Need $T_{RH} > M_1$
- Yukawa couplings should not be too small, or the abundance of N will be too small.

Non-thermal production

- perturbative couplings to the inflaton
- non-perturbative interactions

Summary

- Leptogenesis is an interesting mecanism that can explain the BAU and simultaneously accomodate the neutrino oscillation scenario.
- Leptogenesis has been shown to work in SM + 3 RH ν's. Generates strong constraints on neutrino masses.
- Harder to obtain TeV-scale leptogenesis models.
- Simple model with 4 gauge singlets can be an interesting alternative.