Neutrinos and the Origin of Matter

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Introduction

Problem #1: the universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

must have been generated during the evolution of the universe

Necessary ingredients (Sakharov, 1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

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Neutrino masses

- direct mass searches: $m_\nu \lesssim 2\,\text{eV}$
- Neutrino oscillations:
  atmospheric ν oscillations: $\Rightarrow m_{\nu_i} \gtrsim 0.05\,\text{eV}$
  solar ν oscillations: $\Rightarrow m_{\nu_j} \gtrsim 0.008\,\text{eV}$

Problem #2:

ν masses are $\neq 0$ but orders of magnitude smaller than any other known masses

Both problems cannot be solved in the Standard Model
$\Rightarrow$ need extended model

Standard Model:

- left- and right-handed quarks and charged leptons
- neutrinos only left-handed. Why?

Introduce right-handed neutrinos N

First prediction: neutrino masses (type I seesaw)

$$m_\nu \sim \frac{v^2}{M}$$

$v \sim 100\,\text{GeV}$: SM mass scale; M: mass of N.
Observed light neutrino masses yield clues on M

$$m_\nu \gtrsim 0.05\,\text{eV} \quad \Rightarrow \quad M \lesssim 10^{14}\,\text{GeV}$$

Second prediction: lepton number L is violated

Baryon and lepton number violation

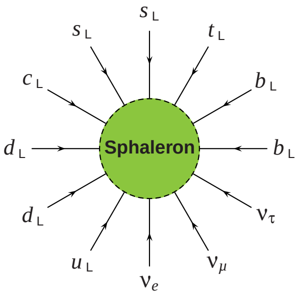
SM: $B+L$ is violated by instantons

('t Hooft '76; Klinkhammer & Manton '84; Kuzmin et al. '85)

Sphalerons are in thermal equilibrium above electroweak 'phase transition':

$$T_{ew} \sim 100\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$$

$B+L$ violated, $B-L$ conserved.



B and L are not independent at $T \gtrsim 100\,\mathrm{GeV}$

$$\eta_B = c\,\eta_{B-L} = \frac{c}{c-1}\,\eta_L\,, \quad \text{with} \quad c \sim \frac{1}{3}$$

L violating processes can generate η_B!

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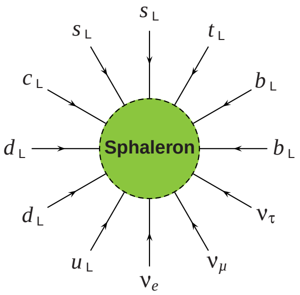

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Leptogenesis

A free lunch: Leptogenesis in type I seesaw

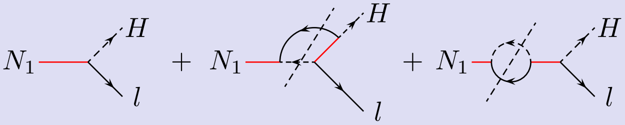
Right-handed neutrinos can also give rise to η_B (Fukugita and Yanagida '86)
Yukawa couplings:

$$\mathcal{L}_Y \simeq \overline{N} \lambda_\nu l H - \overline{N} M N$$

- Ns are unstable, decay to lepton-Higgs pairs:

$$\Gamma_D \propto \widetilde{m}_1 = \frac{v^2}{M_1} (\lambda_\nu^\dagger \lambda_\nu)_{11}$$

- N interactions violate $L \rightarrow L \neq 0$, partially converted to $B \neq 0$ by sphalerons
- λ_ν complex $\Rightarrow$ CP violation ε_i

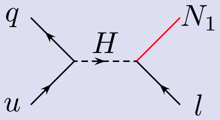


Challenge #1: How do the N get produced?

(Luty '92; M.P. '96; Pilaftsis and Underwood '03)

N scattering processes are important
all production processes $\propto \widetilde{m}_1$

need large $\widetilde{m}_1$ for efficient production



Challenge #2: L violating scatterings can destroy η_B

(Fukugita & Yanagida '90; Buchmüller, Di Bari & M.P. '02; Giudice et al. '03)

Two contributions to reaction rate:

- resonant contribution from N_1: $\propto \widetilde{m}_1$
- remainder: $\propto M_1 \overline{m}^2$, $\overline{m}^2 = \sum m_{\nu_i}^2$

need small $\widetilde{m}_1$ and $M_1 \overline{m}^2$ to avoid washout

Two conflicting requirements

$\longrightarrow$ network of Boltzmann equations

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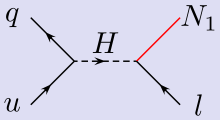

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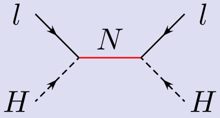

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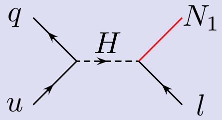

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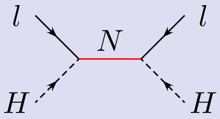

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Quantitative analysis via Boltzmann equations

competition between production and washout:

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

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\,D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\,N_{B-L}$$

$z = M_1/T \quad \propto \sqrt{t}$

N_i : number densities in comoving volume

D : decays

S : $\Delta L = 1$ scatterings

W : washout due to L violating scatterings

Quantitative analysis via Boltzmann equations

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produced baryon asymmetry:

$$\eta_B \simeq 10^{-2}\,\varepsilon_1\,\kappa(\widetilde{m}_1, M_1\overline{m}^2)$$

need to know:

- CP asymmetry ε_1 (from neutrino mass model)
- efficiency factor κ parametrizes N interactions (from integration of Boltzmann eqs.)

(Barbieri et al. ’00; Buchmüller, Di Bari & M.P. ’02)

Baryon asymmetry determined by four parameters

1. *CP* asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass (coupling strength of N_1)

$$\widetilde{m}_1 = \frac{v^2}{M_1}\left(\lambda_\nu^\dagger \lambda_\nu\right)_{11}$$

4. light neutrino masses

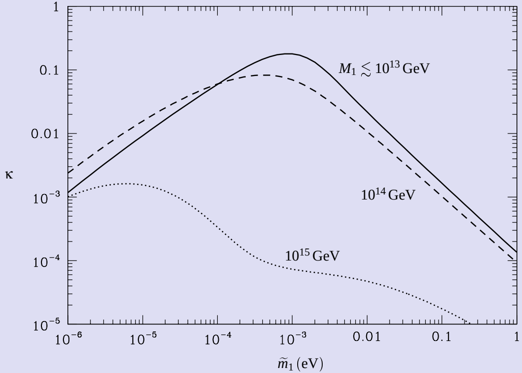
$$\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$$

since

$$\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$$

Efficiency factor κ as function of $\widetilde{m}_1$

(M.P. '96; Buchmüller, Di Bari & M.P. '02)



hierarchical light νs:
$\overline{m} = 0.05\,\mathrm{eV}$

maximal efficiency:

$\kappa^{\max} \simeq 0.18$

for $\widetilde{m}_1 \simeq 10^{-3}$ eV
and $M_1 \lesssim 10^{13}$ GeV

$\rightarrow$ N interactions reduce efficiency:

- for $\widetilde{m}_1 \ll 10^{-3}$ eV: N production inefficient
- for $\widetilde{m}_1 \gg 10^{-3}$ eV: washout too strong
- for $M_1 \gtrsim 10^{13}$ GeV: $\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$ becomes important

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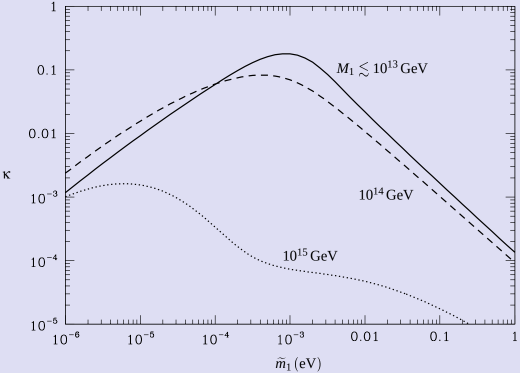

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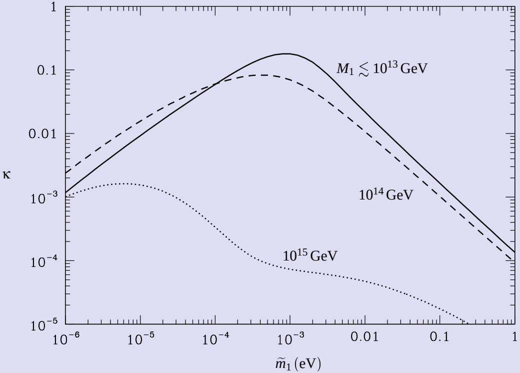

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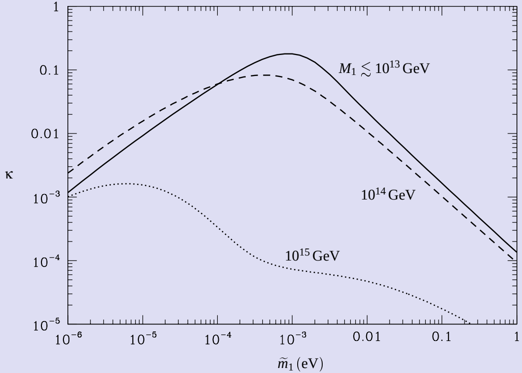

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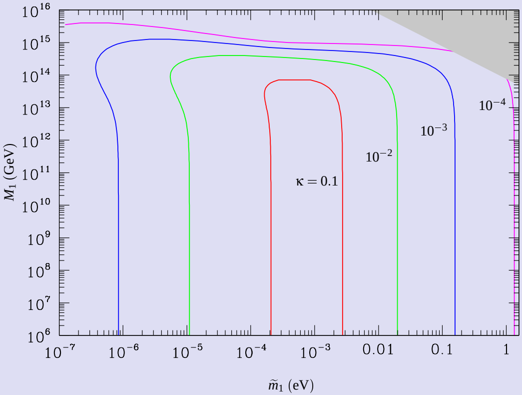
lines of constant κ in $(\widetilde{m}_1, M_1)$ plane



hierarchical light ν's:
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maximal efficiency in the mass range

$$10^{-4}\,\mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-2}\,\mathrm{eV}$$

$$M_1 \lesssim 10^{13}\,\mathrm{GeV}$$

Baryon asymmetry determined by four parameters

1. *CP* asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass $\widetilde{m}_1$ ($\propto$ decay width of N_1)
4. light neutrino masses $\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$

Final baryon asymmetry

$$\eta_B \simeq 10^{-2}\, \varepsilon_1\, \kappa(\widetilde{m}_1, M_1 \overline{m}^2)$$

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CP asymmetry

$$\varepsilon_1 = \frac{\Gamma(N \to l) - \Gamma(N \to \bar{l})}{\Gamma(N \to l) + \Gamma(N \to l)}$$

for $M_{2,3} \gg M_1$: upper bound on ε_1 in terms of light ν masses:

(Davidson & Ibarra ’02; Buchmüller, Di Bari & M.P. ’03; Hambye et al. ’03)

$$\varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2} f\left(m_{\nu_i}, \widetilde{m}_1\right)$$

two limiting cases:

- hierarchical light νs: $m_{\nu_1} \to 0 \quad \Rightarrow \quad \varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2}$
- degenerate light νs: $m_{\nu_3} = m_{\nu_1} \quad \Rightarrow \quad \varepsilon_1^{\max} = 0$

$\to$ CP asymm. suppressed if light ν spectrum quasi-degenerate

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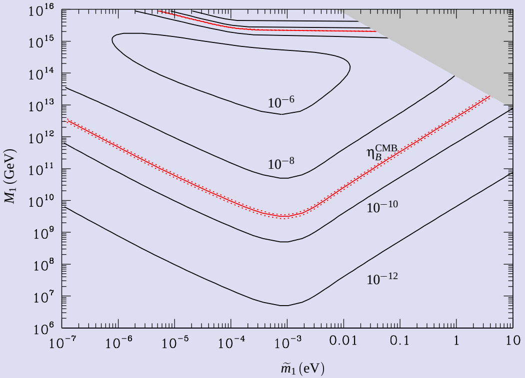
$\rightarrow$ *CP* asymm. suppressed if light ν spectrum quasi-degenerate

Maximal baryon asymmetry

$$\eta_B^{max} = 10^{-2}\,\varepsilon_1^{max}\,\kappa(\widetilde{m}_1, M_1\overline{m}^2)$$

hierarchical light νs: $\overline{m} = 0.05\,\text{eV}$ $\Rightarrow$ $\eta_B^{max} = 10^{-2}\,\frac{3}{16\pi}\,\frac{M_1 m_{\nu_3}}{v^2}\,\kappa$



$\Rightarrow$ Lower bound on the baryogenesis temperature

$$T_B \sim M_1 \gtrsim 10^9\,\text{GeV}$$

Constraints on neutrino parameters

1. N_1 production processes $\propto \widetilde{m}_1 \Rightarrow$ lower limit on $\widetilde{m}_1$
2. Washout processes:

   res. contrib. from $N_1 \propto \widetilde{m}_1 \Rightarrow$ upper limit on $\widetilde{m}_1$

   remainder $\propto M_1 \overline{m}^2 \Rightarrow$ upper limit on M_1 for fixed $\overline{m}$
3. maximal CP asymmetry $\propto M_1 \Rightarrow$ lower limit on M_1
   since $\eta_B \propto \varepsilon_1$

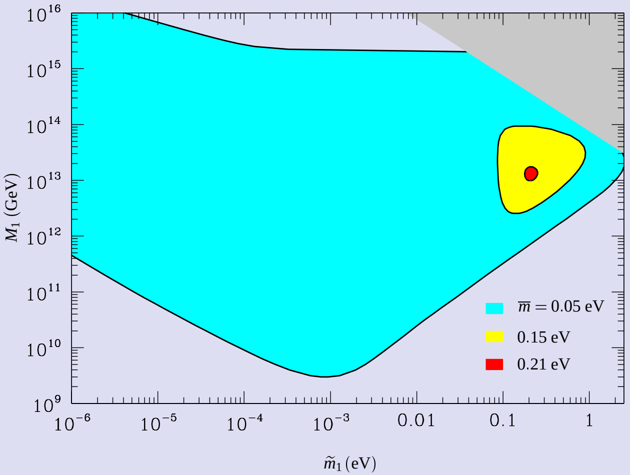
for fixed $\overline{m} \Rightarrow$ allowed region in $(\widetilde{m}_1, M_1)$ plane

Size of allowed region depends on $\overline{m}$ since:

- max. CP asymm. suppressed for quasi-degenerate light νs
- $\widetilde{m}_1 \geq m_{\nu_1}$

$\Rightarrow$ upper bound on $\overline{m}$

(Buchmüller, Di Bari & M.P. '03, '04)



light ν masses: $\overline{m} < 0.22\,\mathrm{eV} \quad \Rightarrow \quad m_{\nu_i} < 0.13\,\mathrm{eV}$

RHN masses: $T_B \sim M_1 \gtrsim 10^9$ GeV

The neutrino mass window for baryogenesis

- upper bound on light ν masses $m_{\nu_i} \lesssim 0.1\,\text{eV}$
- no dependence on initial conditions for $\widetilde{m}_1 \gtrsim 10^{-3}\,\text{eV}$

since $\widetilde{m}_1 \geq m_{\nu_1}$ → leptogenesis window for neutrino masses

$$10^{-3}\,\text{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\text{eV}$$

compatible with ν oscillations $(m_{\text{atm}} \sim 0.05\,\text{eV})$

Analytical solution for efficiency factor in leptogenesis window:

$$\kappa = (2 \pm 1) \times 10^{-2} \left(\frac{0.01\,\text{eV}}{\widetilde{m}_1} \right)^{1.1 \pm 0.1}$$

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Conclusions

- Type I seesaw naturally explains the cosmological baryon asymmetry and the smallness of neutrino masses
- Quasi-degenerate light ν masses are incompatible with leptogenesis:

$$m_{\nu_i} < 0.13\ \text{eV}$$

- lower bound on the baryogenesis temperature:

$$T_B \gtrsim 10^9\ \text{GeV}\ , \qquad t_B \sim 10^{-25}\ \text{s}$$

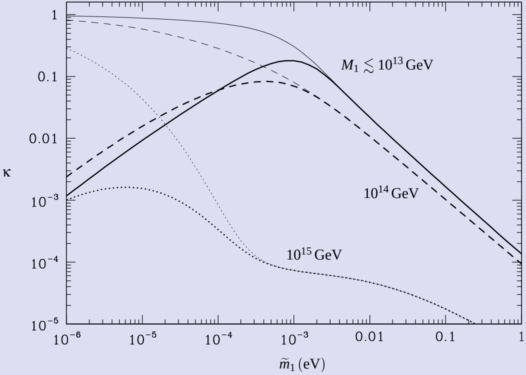
  possible way out: resonant leptogenesis
- leptogenesis works best in neutrino mass window

$$10^{-3}\,\text{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\text{eV}$$

  consistent with neutrino oscillations


COSMOLOGY MARCHES ON
Where did it all come from?
Where did it all come from?
S. Harris

Neutrino production?



hierarchical light νs: $\overline{m} = 0.05$ eV

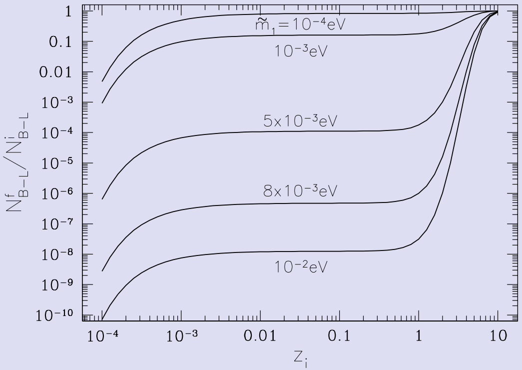
initial conditions

- $N_{N_1} = N_{N_1}^{eq}$ at $T \gg M_1$: thin lines
- $N_{N_1} = 0$ at $T \gg M_1$: thick lines

no dependence on initial conditions for $\widetilde{m}_1 \gtrsim 10^{-3}$ eV

Primordial Asymmetry?

initial asymmetry before leptogenesis:
effect of washout?



Washout factor for hierarchical light νs:
$\overline{m} = 0.05\,$eV
and
$M_1 = 10^{10}\,$GeV

Initial temperature:
$z_i = \dfrac{M_1}{T_i}$

efficient washout of initial asymmetry at $z_i \sim 1$ for $\tilde{m}_1 \gtrsim 10^{-3}\,$eV

no dependence on initial conditions for $\tilde{m}_1 \gtrsim 5\times10^{-3}\,$eV

Alternatives?

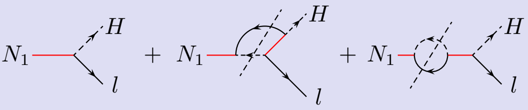
What if light neutrinos are quasi-degenerate?

What if the reheating temperature is lower than $\sim 10^9$ GeV?

- decouple light neutrino masses from baryogenesis, i.e. contribution to light ν masses and/or baryogenesis from triplet Higgs
  some other mechanism for light ν masses,...
- resonant leptogenesis, soft leptogenesis in SUSY models
- non-thermal leptogenesis, i.e. through inflaton decay or Affleck-Dine, ...

Resonant Leptogenesis

Resonant enhancement of CP-asymmetry for $M_{2,3} - M_1 \ll M_1$:



Almost no effect on bound on light ν masses, but lower limit on T_B, M_1 can be evaded.
However: many different results in literature !?

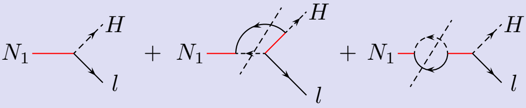
Problem: N_i unstable, i.e. cannot appear as in- or out-states of S-matrix elements

Solution: scattering amplitudes of stable particles with N_i as intermediate states

Factorisation: effective one-loop couplings of N_i

Resonant Leptogenesis

Resonant enhancement of CP-asymmetry for $M_{2,3} - M_1 \ll M_1$:



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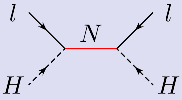

Factorisation: effective one-loop couplings of N_i

Resummation of self-energies

regularizes resonant propagator ⇒ mixing effects

$$\left(S^{-1}\right)_{ij} = \not{p} - M_i - \Sigma_{ij}$$

Renormalization known (Kniehl & Pilaftsis '96)

Chiral decomposition of propagator:

$$S = P_R S^{RR} + P_L S^{LL} + P_L \not{p} S^{LR} + P_R \not{p} S^{RL}$$

Contribute to different scattering processes:

$$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto h_{ri} S^{LL}_{ij} h_{sj} \qquad \mathcal{M}\left(\bar{l}_r \to l_s\right) \propto h^*_{ri} S^{RR}_{ij} h^*_{sj}$$

$$\mathcal{M}\left(l_r \to l_s\right) \propto h^*_{ri} S^{RL}_{ij} h_{sj} \qquad \mathcal{M}\left(\bar{l}_r \to \bar{l}_s\right) \propto h_{ri} S^{LR}_{ij} h^*_{sj}$$

Contributions of different N_i mass eigenstates?

Factorization (Anisimov, Broncano & M.P. '05):

Different methods:

1. Decompose scattering ampl. into partial fractions, e.g.:

$$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto \lambda_{r1} \frac{1}{p^2 - \hat{M}_1^2} \lambda_{s1} + \lambda_{r2} \frac{1}{p^2 - \hat{M}_2^2} \lambda_{s2} + \dots$$

   λ_{ri}: resummed effective N_i Yukawa coupling

   Consistency: all 4 amplitudes can be factorized simultaneously.

2. Diagonalization of propagators, e.g.: $U S^{LL} U^T = S^{\text{diag}}$

$$\mathcal{M}\left(l_r \to \bar{l}_s\right) \propto \left(hU^T\right)_{ri} S_{ii}^{\text{diag}} \left(hU^T\right)_{si}$$

   $\left(hU^T\right)_{ri}$: resummed effective N_i Yukawa coupling

   Consistency: for $p^2 = M_i^2$ all 4 amplitudes can be factorized simultaneously.

Results:

Both methods yield identical results for physical quantities:

1. Decay widths: $\Gamma(N_i \to \bar{l}_r) \propto |\lambda_{ri}|^2 = \left|\left(hU^T\right)_{ri}\right|^2$, for $p^2 = M_i^2$
2. CP-asymmetries, e.g.:

$$\varepsilon_1 \propto \frac{M_2^2 - M_1^2}{\left(M_2^2 - M_1^2\right)^2 + \left(M_2\Gamma_2 - M_1\Gamma_1\right)^2},$$

Previous approaches, e.g., resum only self-energy Σ_{jj} of intermediate neutrino $N_j \Rightarrow$ regulator: Γ_j (Pilaftsis & Underwood '04)

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Different neutrino flavours are treated differently!

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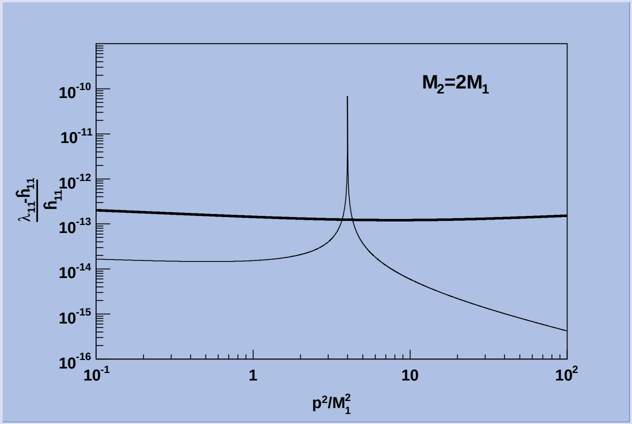
Relative one-loop correction to couplings of N_1

Our result (thick line) compared to the one of Pilaftsis et al.:



thin line has resonance at $p^2 = M_2^2$, i.e. contributions from different neutrino mass eigenstates not properly separated in previous approaches.

CP asymmetry

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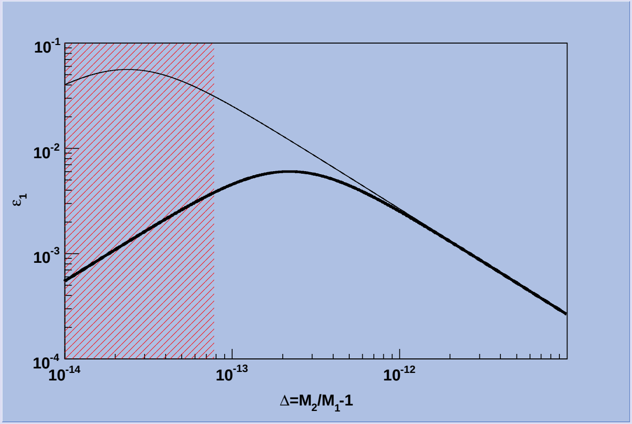

Both the position of the resonance and the maximum value for ε_1 have shifted by an order of magnitude (details depend on neutrino mass model used).