Santa Fe Summer Neutrino Workshop

Implications of Neutrino Flavor Oscillations

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Testing leptogenesis at the LHC

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Outline

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- One exception: model with extra local U(1)
    - Leptogenesis works at the TeV scale
    - For accessible Z' masses, the model predicts striking signals at the LHC
- Summary and conclusion

The matter-antimatter puzzle

- ★ Matter and antimatter are governed by the same interactions.
- ★ The observable Universe is composed of matter. Antimatter is only seen in particle accelerators and in cosmic rays.
- ★ The rate observed in cosmic rays is consistent with the secondary emission of antiprotons:

$$n_{\bar{p}}/n_p \sim 10^{-4}$$

- ★ Ordinary matter is made of baryons (protons, neutrons) and leptons (electrons). One can assign an experimentally conserved number to baryons and leptons. Baryons and leptons carry one unit of these numbers, and antibaryons and antileptons carry one negative unit.

⇒ The predominance of matter over antimatter is equivalent to the existence of a net baryon number.

The matter-antimatter puzzle

★ It is not difficult to estimate the relic density of baryons, according to SM interactions (annihilations into pions). The result is

$$n_B/n_\gamma = n_{\bar{B}}/n_\gamma \simeq 10^{-20}$$

★ How does this number compare to experiment?

★ Two independent sources of information, the temperature anisotropy in the CMB, as well as the synthesis of light elements in the early Universe (BBN) point to a much larger value:

$$\boxed{\eta_B \equiv n_B/n_\gamma \simeq 6 \times 10^{-10}}$$

★ To avoid the baryon annihilation catastrophe and to separate baryons from anti-baryons, a small asymmetry must be generated primordially.

The matter-antimatter puzzle

1´000´000´001

Matter

1´000´000´000

Antimatter

➡ The annihilation occurs then very efficiently and one is left only with the small excess of matter!

The matter-antimatter puzzle

- ★ In order to produce a baryon asymmetry in the Early Universe, one needs to fulfill three conditions [Sakharov, 1967]

□ Baryon number violation	Anomalous processes
□ *C* and *CP* violation	Quark CKM matrix
□ Departure from thermal equilibrium	At the electroweak phase transition

- ★ The Standard Model contains all ingredients!

➡ **ELECTROWEAK BARYOGENESIS** ☺

- ★ To produce enough baryon asymmetry, the phase transition needs to be strongly first order $\Rightarrow M_H < 40\ \text{GeV}$
- ★ EW baryogenesis in the SM is ruled out by LEP II, which puts the bound $M_H > 114\ \text{GeV}$ ☹

➡ ☺

The puzzle of neutrino masses

- ★ The Standard Model of particle physics predicts massless neutrinos.
- ★ Today, after 10 years of great successes in neutrino oscillation experiments, the evidence is overwhelming that neutrinos have masses and mix. One has measured quite precisely two mass-squared differences :

Sol.+ Reac. $\sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.009\ \mathrm{eV}$

Atm.+ Acc. $\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.05\ \mathrm{eV}$

- ★ From the the measurement of the Z width at LEP, there should be 3 neutrino flavors, and thus 3 neutrino masses.
- ★ Neutrino oscillation experiments provide no information on the absolute neutrino mass scale! Fortunately, there are other probes possible…

The puzzle of neutrino masses

- Direct measurement (Tritium β-decay)

[Mainz and Troitsk exps., 04]

$$m_{ee} \lesssim 2.2 \text{ eV}$$

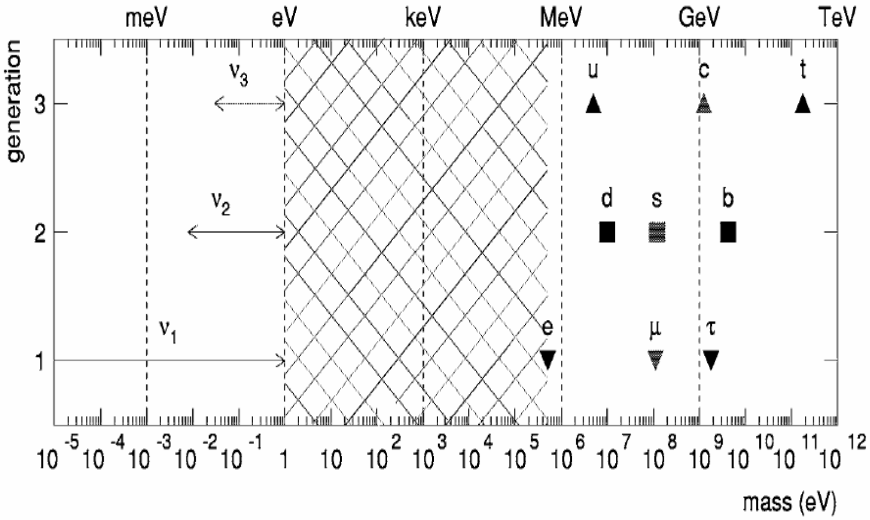
- Neutrinoless Double-β-Decay

[CUORICINO exp., 08]

$$m_{\beta\beta} \lesssim 0.2\text{–}0.7 \text{ eV}$$

- Cosmology (CMB+LSS) [WMAP,08]

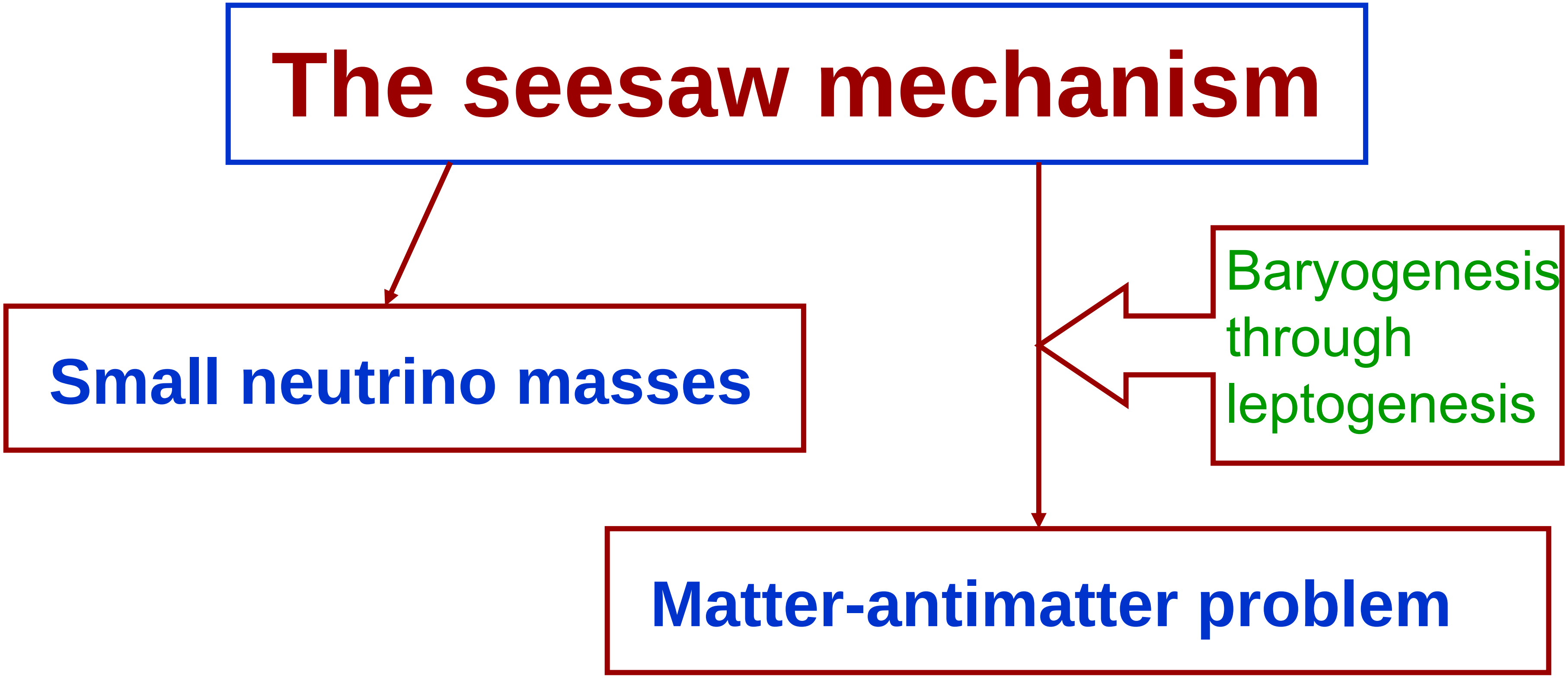
$$\sum_i m_i \lesssim 0.6 \text{ eV}$$



Bottom line: neutrinos involve a scale much smaller than all other mass scales in the SM!

New physics is required to explain it!

Resolution of the two puzzles



The seesaw mechanism

Small neutrino masses

Baryogenesis through leptogenesis

Matter-antimatter problem

The type I seesaw mechanism

- ★ The seesaw mechanism originates from the following extension of the SM Lagrangian:

$$\boxed{\delta L = \overline{N_{Ri}}\, i\partial_\mu \gamma^\mu N_{Ri} - \underbrace{h_{\alpha i}\overline{\ell_{L\alpha}}\tilde{\Phi} N_{Ri}}_{\text{Yukawa coupling}} - \frac{1}{2}\underbrace{M_i \overline{N^c_{Ri}} N_{Ri}}_{\text{Majorana mass term}} + h.c.}$$

where $\tilde{\Phi} = (\phi_0^\star, \phi_+^\star)^T$ and $\ell_\alpha = (\nu_\alpha, \alpha^-)^T$, $\alpha = e, \mu, \tau$ are the Higgs and left-handed lepton doublets, respectively, and $N_{Ri},\ i = 1, 2, 3$ are RH neutrinos.

- ★ This extension is clearly acceptable on grounds of gauge invariance and renormalizability, and is minimal in its particle content (here: 3 new particles).

The type I seesaw mechanism

- ★ The masses of the singlet neutrinos are essentially free parameters, and thus can be taken to be very large ($\gg 100$ GeV).

➡ Seesaw mechanism!

[Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, …]

- ★ After spontaneous symmetry breaking, the vev $\langle\Phi\rangle$ of the Higgs leads to a Dirac mass term $m_{\text{D}} = h\langle\Phi\rangle$. The seesaw assumes $M \gg m_{\text{D}}$ so that the neutrino mass term can be block-diagonalized as:

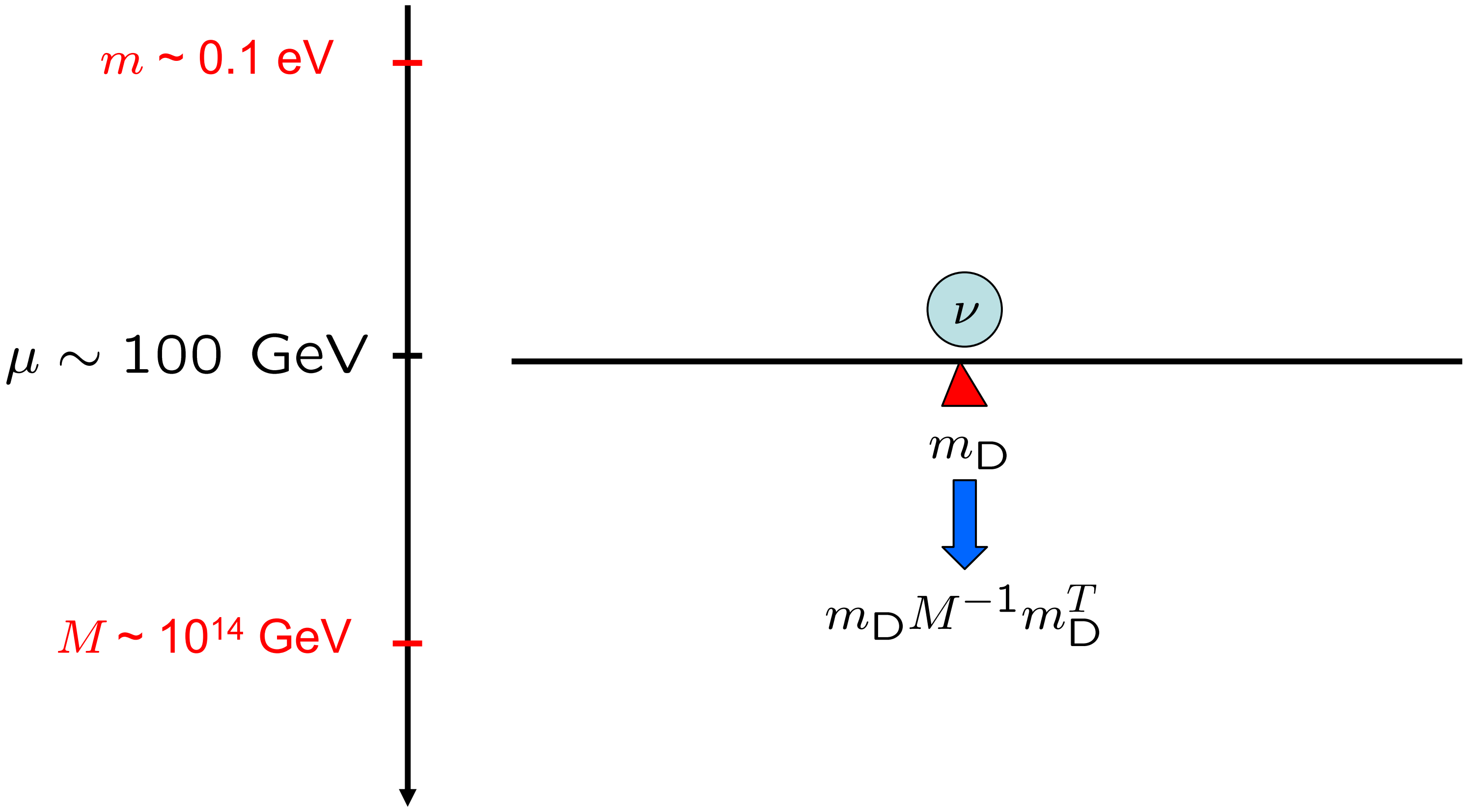
$$\begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}}^T & M \end{pmatrix} \xrightarrow{\text{1st order}} \begin{pmatrix} m_{\text{D}} M^{-1} m_{\text{D}}^T & 0 \\ 0 & M \end{pmatrix}$$

After diagonalization: 3 light Majorana neutrinos, mass $m_1 \leq m_2 \leq m_3$

3 heavy Majorana neutrinos, mass $M_1 \leq M_2 \leq M_3$

The type I seesaw mechanism

- ★ Conventional picture



m ~ 0.1 eV

$\mu \sim 100$ GeV

M ~ 10^{14} GeV

ν

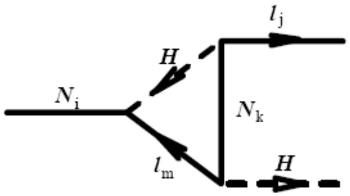
m_{D}

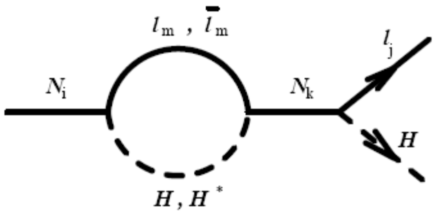
$m_{\mathrm{D}} M^{-1} m_{\mathrm{D}}^{T}$

Baryogenesis through leptogenesis

- Baryogenesis through leptogenesis [Fukugita, Yanagida, 86] is the generation of a lepton asymmetry by the decay of heavy RH neutrinos $N \to \ell\Phi \;\; (\bar{\ell}\Phi^\dagger)$, and the subsequent conversion into a baryon asymmetry by the anomalous sphaleron processes.

- The three Sakharov conditions are fulfilled :
  - Baryon number is violated in anomalous processes
  - *CP* is violated in the decay of the heavy neutrinos: interference between tree level and 1-loop diagrams





$$\varepsilon_i = -\frac{\Gamma(N_i \to \ell_i\Phi) - \Gamma(N_i \to \bar{\ell}_i\Phi^\dagger)}{\Gamma(N_i \to \ell_i\Phi) + \Gamma(N_i \to \bar{\ell}_i\Phi^\dagger)}$$

CP asymmetry parameter

  - Decays are out of equilibrium at some point, parametrized by

$$K_i \equiv \frac{\Gamma(N_i \to \ell_i\Phi + \bar{\ell}_i\Phi^\dagger)|_{T\to 0}}{H(T=M_i)}$$ ``decay parameter´´

Leptogenesis

- ★ Leptogenesis is a well-posed problem which has been extensively studied ever since the discovery of neutrino masses in 1998. The dynamics is described by a set of Boltzmann equations as

$$z = \frac{M_1}{T}$$

$$\boxed{\begin{aligned}\frac{dN_{N_i}}{dz} &= -D_i(N_{N_i} - N_{N_i}^{\mathrm{eq}})\\ \frac{dN_{B-L}}{dz} &= \sum_i \varepsilon_i D_i(N_{N_i} - N_{N_i}^{\mathrm{eq}}) - W N_{B-L}\end{aligned}}$$

CP violation

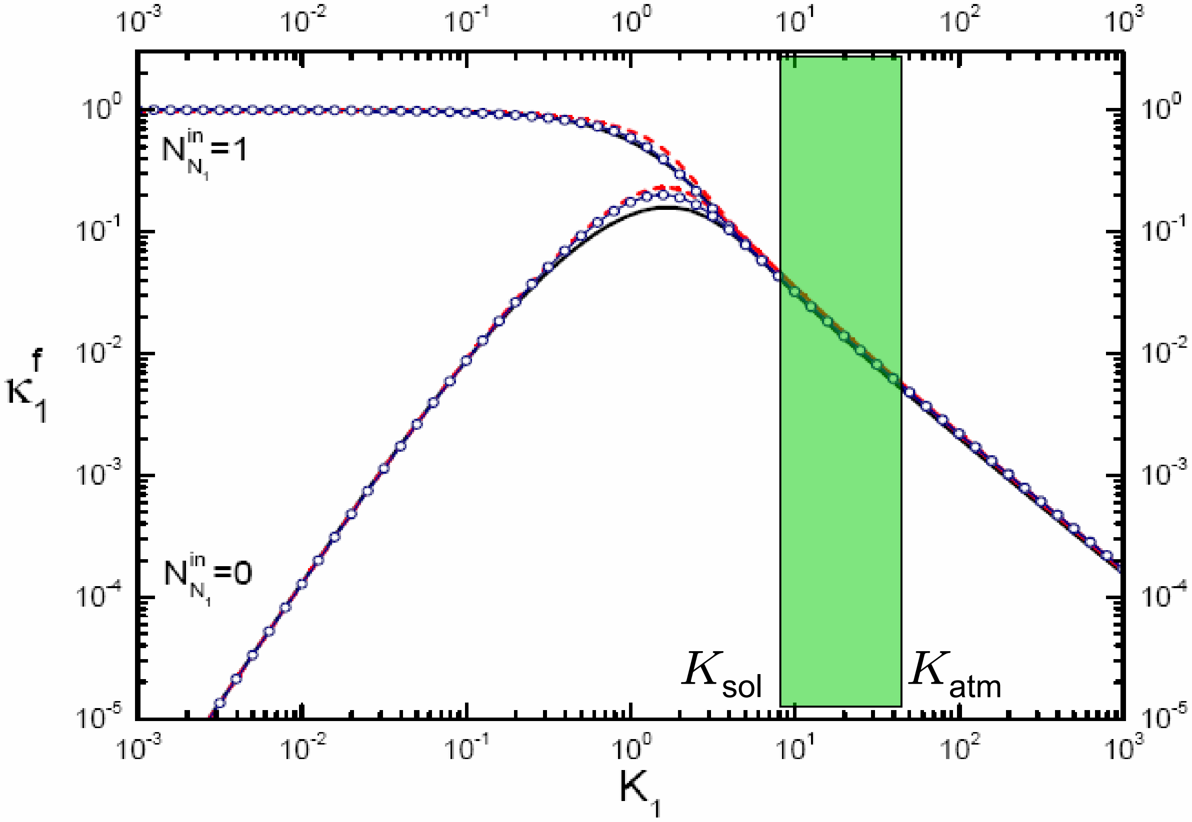
Out-of-equilibrium condition

Sphalerons conserve *B-L* !

- ☐ The crucial parameters are K_i and ε_i. The dynamics in particular is described by K_i, which enters in D_i and W.
- ☐ Strong washout when $K_i \gtrsim 1$. Weak washout when $K_i \lesssim 1$
- ☐ All the effects of the dynamics can be included in an efficiency factor, and the final result for N_1 reads $\eta_B = 0.01\,\varepsilon_1 \kappa_1(z \to \infty)$

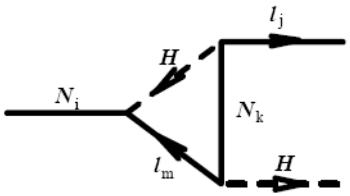
Leptogenesis

- The efficiency can be computed numerically for each value of K, and one obtains

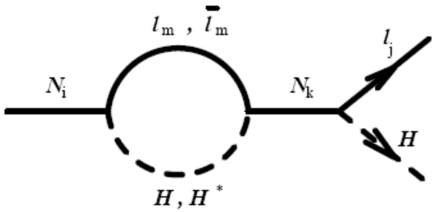


Leptogenesis

- ★ Assuming hierarchical RH neutrinos, $M_1 \ll M_2 \ll M_3$ both graphs contribute roughly equally to the *CP* asymmetry



Vertex correction



Self-energy correction

- ★ The fact that the Yukawa couplings are involved in the neutrino mass matrix leads to an upper bound on the *CP* asymmetry [Asaka et al., 01; Davidson, Ibarra, 02]

$$\varepsilon_1 \leq \overline{\varepsilon}(M_1) \simeq 10^{-6} \frac{(m_3 - m_1)}{m_{\rm atm}} \left(\frac{M_1}{10^{10}\,\text{GeV}} \right)$$

from which one obtains a lower bound on M_1 and on the reheat temperature [Davidson, Ibarra, 02; Buchmüller, Di Bari, Plümacher, 02] :

$$\boxed{M_1(T_{\rm reh}) \gtrsim 3(1.5) \times 10^9 \text{GeV}}$$

Leptogenesis

- ★ There are two main problems with this high scale:

  1 **Problem with gravitino overproduction in mSUGRA. Generic moduli problem in SUSY theories.**

  2 **Beyond reach of collider experiments! Therefore, no direct way to prove that this mechanism is the right one.**

- ★ Problem **1** can be resolved by taking quasi-degenerate RH neutrinos: $M_1 \simeq M_2 \simeq M_3$ [Flanz, Paschos, Sarkar, Weiss, 1996; Pilaftsis, 1997; Pilaftsis, Underwood, 2005]

In that case, the *CP* asymmetry (the self-energy graph only!) is enhanced as : $M_i/(M_i - M_j)$

This enhancement stops once the resonance is reached, when

$$M_i - M_j \sim \Gamma_j/2$$

The *CP* asymmetry can then be of O(1) for any RH neutrino mass!!

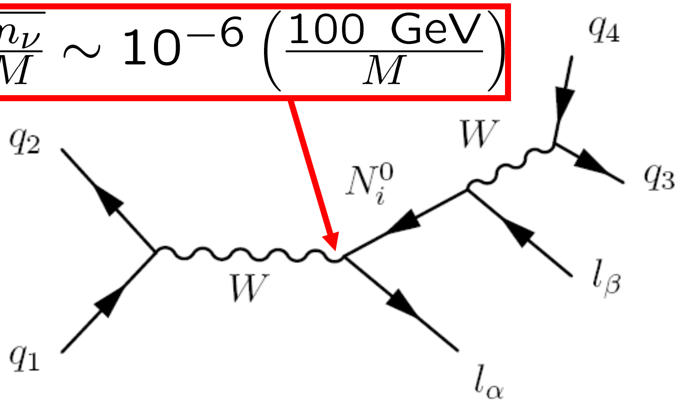
Testing leptogenesis?

★ With very high degeneracies (1 part in 10^{10}), the scale of leptogenesis can be lowered to TeV! [Pilaftsis, Underwood, 2005]

➡ **Accessible at colliders?? Is problem $\boxed{2}$ solved as well?**

★ The answer is unfortunately NO, because the production of RH neutrinos in this simple model goes through the mixing, which is neutrino mass suppressed (barring cancellations)!

$$\boxed{V_{N\nu} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-6}\left(\frac{100\ \text{GeV}}{M}\right)}$$



Testing leptogenesis?

★ But note that even if the production cross section was large enough, it is not clear that the actual leptogenesis scenario could be tested.

★ The reason is that one needs to be sensitive to a small number

$$\eta_B^{\text{CMB}} \equiv n_B/n_\gamma \simeq 6 \times 10^{-10}$$

and standard leptogenesis leads to a prediction of the form

$$\eta_B = 0.01\, \varepsilon\, \kappa$$

CP asymmetry parameter, adjustable.

Efficiency factor, naturally of order 10^{-2}.

$$\boxed{\varepsilon \sim 10^{-5}}$$

Such a tiny *CP* asymmetry is hopeless to observe at colliders. A LARGE *CP* asymmetry, which is the portal to testable leptogenesis (the only Sakharov condition which can be directly tested), is not guaranteed in the minimal model!

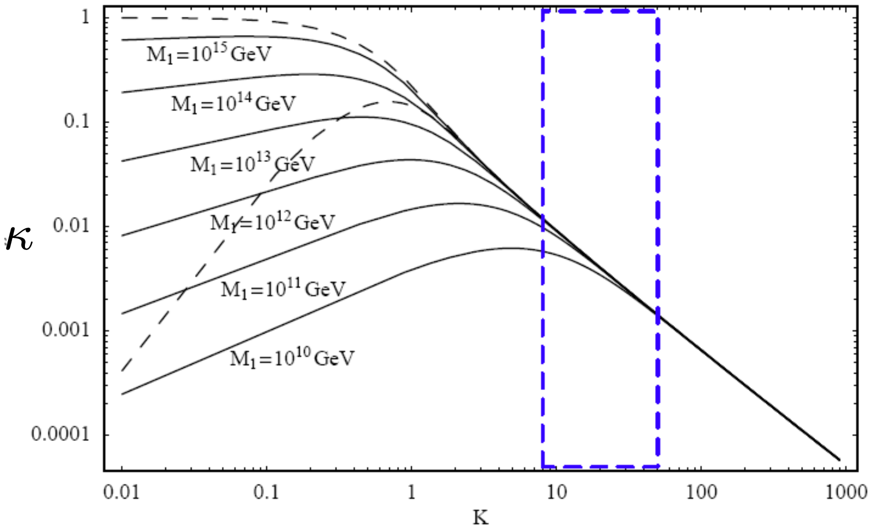
What about the seesaw alternatives?

- ★ In order to be sure that the *CP* asymmetry is large, and therefore observable, one needs to consider models where the efficiency of leptogenesis is lower.
- ★ In Type II and III seesaw, the mediators are not SU(2) singlets, and therefore they have gauge interactions. This has important consequences for leptogenesis. The mediators will follow very closely equilibrium, thus reducing the efficiency factor.

For Type III :

The annihilation cross section (e.g. $\Sigma\Sigma \rightarrow AA$) decreases with M_Σ.

$$\boxed{M_\Sigma \searrow \quad \Rightarrow \quad \kappa \searrow}$$



[Fischler, Flauger, 07]

What about the seesaw alternatives?

- ★ Pushing the mediator scale to TeV implies a reduction of the efficiency by many orders of magnitude. The following bounds on the mediator masses for both Type II and III were derived by Strumia in **0806.1630** :

$$M_{\Delta,\Sigma} > 1.6\ \text{TeV}$$

This bound comes about because sphaleron decoupling occurs around 100 GeV, and most of the asymmetry is produced when $T < M_1/15$, i.e. late!

➡ These new states are unfortunately beyond the discovery reach of LHC!

- ★ In the context of left-right symmetric theories broken around the TeV scale, the role of the right-handed SU(2) gauge bosons was studied by Frere, Hambye and Vertongen in **0806.0841**.

What about the seesaw alternatives?

- ★ In this framework, leptogenesis is affected in two ways:
  1. Gauge interactions keep RH neutrinos very close to thermal equilibrium.
  2. There are pure gauge interactions that contribute to the washout of lepton number, e.g. $N_R e_R \leftrightarrow \bar{u}_R d_R$
- ★ The authors conclude that the constraints on W_R are typically very stringent for leptogenesis to work:

$$M_{W_R} > 18 \text{ TeV}$$

Turning the argument around, the discovery of right-handed gauge interactions at the LHC would rule out leptogenesis as the origin of the matter-antimatter asymmetry of the Universe!

➡ Bottom line: LHC signals and leptogenesis are hard to reconcile!!

… One exception: Z´ models!

Motivation for a Z' at TeV

★ BSM physics often comes with a Z' (which can be at the TeV scale):

- GUTs
- Non-minimal SUSY models
- Little Higgs models

extra local U(1)´s

- Extra-dimensional models, both flat and warped

★ With a new U(1)´ gauge group, anomaly cancellation requires the presence of new fermions: e.g. the RH neutrinos needed for neutrino masses!

★ Tevatron sets a limit of 900 GeV on the Z' mass when it has the same couplings to fermions as Z.

Motivation for a Z' at TeV

- ★ In general the operator that leads to Majorana neutrino masses is forbidden by the new gauge symmetry associated with Z'.

➡ The Weinberg operator $(LH)^2/\Lambda$ is forbidden!

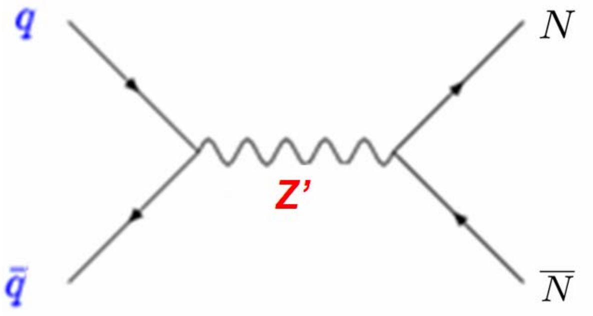
- ★ How do neutrino masses arise in such a scenario? The simplest possibility is that this operator is generated by integrating out new states (RH neutrinos!) that acquire mass once the symmetry associated with Z' is broken.

➡ Seesaw mechanism at the TeV scale!

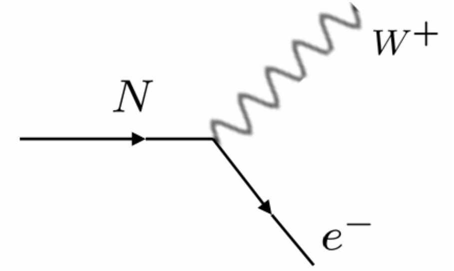
- ★ For RH neutrino masses of order TeV, the neutrino Yukawa couplings need to be of order 10^{-6}, i.e. the size of the electron Yukawa coupling.

Motivation for a Z' at TeV

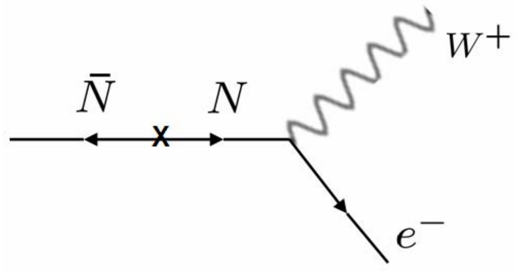
- ★ Contrary to the usual Type I scenario, the production of RH neutrinos at the LHC is not neutrino mass-suppressed in this model!



- ★ Each RH neutrino dominantly decays into W + lepton:



N is Majorana ! ➡



➡ Striking signature of same-sign dileptons without missing energy!

Leptogenesis at TeV scale with Z'

- When RH neutrinos are charged under the extra U(1), which we choose to be B-L, the Boltzmann equations will be obviously modified compared to the standard case.

$$\mathcal{L} \supset \mathrm{i}\overline{N_{Ri}} D_\mu \gamma^\mu N_{Ri} - h_{\alpha i} \overline{L_{L\alpha}} \tilde{\Phi} N_{Ri} - \frac{1}{2} M_{Ni} N_{Ri}^T C N_{Ri} + h.c.$$

$$D_\mu = \partial_\mu - \mathrm{i} g_1' Y_{B-L} B_\mu'$$

- The gauge interactions $N\bar{N} \leftrightarrow \bar{q}q\,(\bar{\ell}\ell)$ when $T > M_{Z'}$ will keep RH neutrinos very close to thermal equilibrium, which implies a reduction of the efficiency factor, as in the Type II and III seesaw case.

- It is therefore a quantitative question whether the reduction in the efficiency factor is enough to imply large *CP* asymmetries, and to keep mass constraints within LHC reach!

$$\eta_B \simeq 10^{-2} \sum_{i\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}(z \to \infty)$$

3 RH neutrinos contribute

Flavor effects unavoidable

Leptogenesis at TeV scale with Z'

- ★ Since RH neutrinos are tracking closely equilibrium, it is possible to express the efficiency factor in a convenient form:

Source term

Fraction of RH neutrinos which decay before scattering

$$\kappa_{i\alpha}(z,z_{\rm in}) \simeq \int_{z_{\rm in}}^{z} {\rm d}z' \boxed{\frac{{\rm d}N_{N_i}^{\rm eq}}{{\rm d}z'}} \boxed{\frac{D(K_i,z')}{D(K_i,z')+4S_{Z'}(z')N_{N_i}^{\rm eq}(z')}}$$

$$\times \boxed{\exp\left(-\int_{z'}^{z}\sum_i W^{\rm ID}(K_{i\alpha},z''){\rm d}z''\right)}$$

Washout

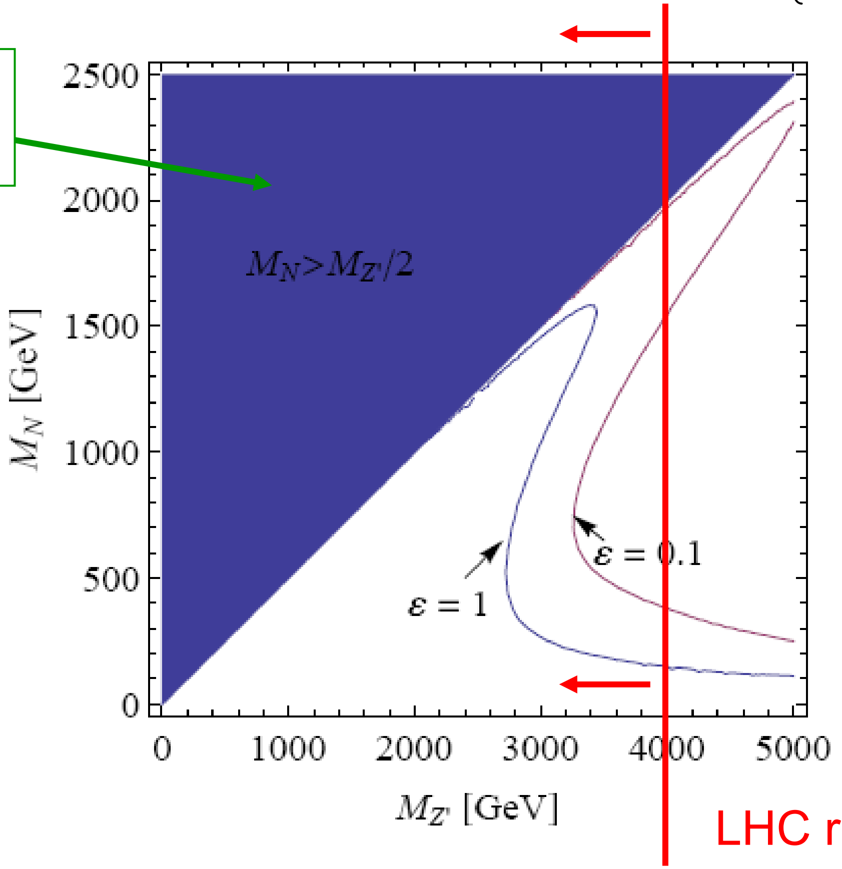
- ★ Because of the gauge scattering term $S_{Z'}$, the efficiency factor will be small, typically of order 10^{-7} – 10^{-6} for a TeV RH neutrino.

➡ The *CP* asymmetry must be of O(1) for successful leptogenesis!! Therefore, the LHC might be able to probe the mechanism of baryogenesis!

Leptogenesis at TeV scale with Z'

- ★ The quantitative result is given below for $\begin{cases} g'_1 = 0.2 \\ \varepsilon \equiv \varepsilon_1 = \varepsilon_2 = \varepsilon_3 \end{cases}$

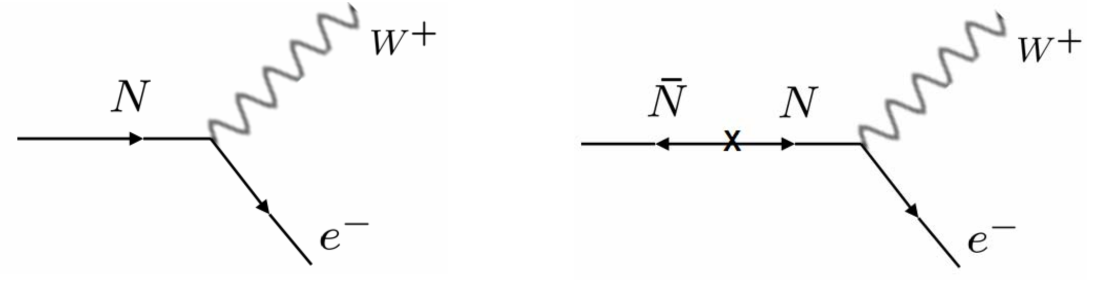
Collider unfriendly



LHC reach for a Z'

Signatures at the LHC

- ★ At the LHC the RH neutrinos can be pair produced from Z' decays. Each of them will then decay into leptons and anti-leptons, e.g.:



- ★ The *CP* asymmetry from the RH neutrino decays is calculated precisely from the same graphs as in leptogenesis. Considering only decays into leptons and Ws, we have

$$\varepsilon_i = \frac{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha^+ W^-) - \Gamma(N_i \to \ell_\alpha^- W^+)\right]}{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha^+ W^-) + \Gamma(N_i \to \ell_\alpha^- W^+)\right]}$$

which coincides with the cosmological *CP* asymmetry!!

➡ We have a direct test of baryogenesis at hand!

Signatures at the LHC

- ★ A meaningful observable is the difference in the number of positive and negative like-sign dileptons:

$$\frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = \frac{2\boxed{\sum_i \varepsilon_i}}{\sum_i 1}$$

This observable probes directly the magnitude of the cosmological *CP* asymmetry.

Note that an excess of antileptons is predicted from the sign of the baryon asymmetry of the Universe!

Note also that we concentrate on like-sign leptons events because there is no SM background with like-sign dileptons and no missing energy. The backgrounds are purely instrumental.

Signatures at the LHC

- The total LHC cross section for the process $pp \to Z' \to NN$

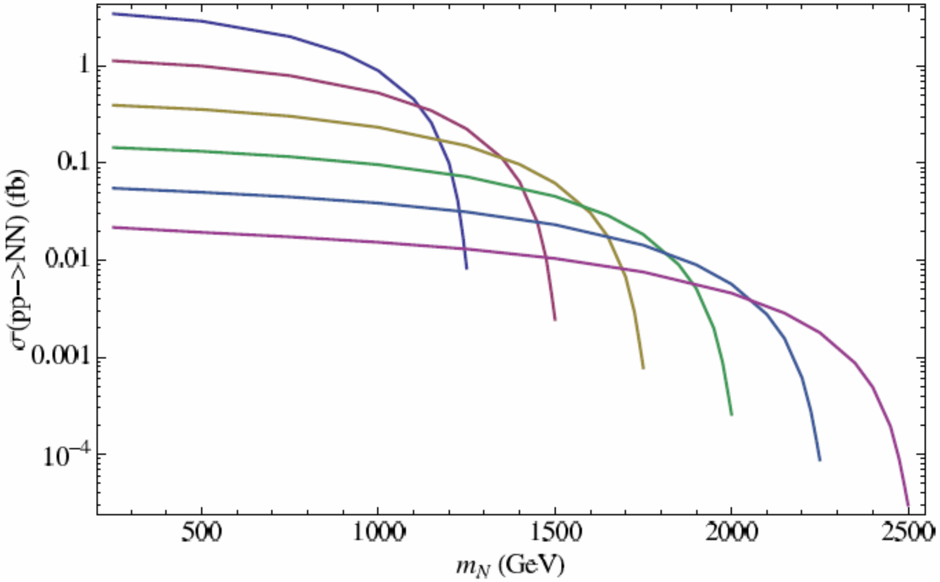


FIG. 3: Total cross section $pp \to Z' \to NN$ for $g_1' = 0.2$ and varying $M_{Z'}$ between 2.5 and 5 TeV in steps of 500 GeV (top to bottom).

For a 3 TeV Z', the cross section is about 1 fb.

Signatures at the LHC

- ★ With a 100 fb^{-1} of integrated luminosity and a detector acceptance of 85%, we find that the number of like-sign dileptons is

$$N(\ell^+\ell^+) = N(\ell^-\ell^-) = 5.3 \pm 1.6 \text{ at } 1\sigma$$

- ★ This looks like a tiny number of events. However, so highly energetic leptons are rare and same-sign dilepton events have purely instrumental backgrounds. Moreover, imposing that the invariant mass of the lepton + W adds up to the RH neutrino mass renders backgrounds negligible.

- ★ We therefore find that the LHC will be able to exclude the no-asymmetry hypothesis at 2σ for $\varepsilon > 0.26$ (0.17 with 300 fb^{-1})

Signatures at the LHC

- ★ An important ingredient for our scenario is that there must be at least 2 RH neutrinos which are quasi-degenerate (to 1 part in 10^{14}!). Can we distinguish 2 or 3 RH neutrinos from 1?

- ★ YES !! Obviously, it is not from invariant mass measurements… But rather from simple linear algebra. Define the decay probability of N_i into a certain lepton flavor α as $P_{i\alpha}$. Clearly

$$\sum_\alpha P_{i\alpha} = 1$$

- ★ Then the probability of a given dilepton event to involve flavors α and β , which can be directly measured at the LHC, is given by

$$P(\ell_\alpha \ell_\beta) = \frac{\sum_i P_{i\alpha} P_{i\beta}}{\sum_i 1}$$

These six equations sum to one, so 5 equations are independent.

Signatures at the LHC

- ★ With only one RH neutrino, two parameters P_{1e} and $P_{1\mu}$ must satisfy 5 equations → highly overconstrained! If no consistent solution is found, there must be more than 1 RH neutrinos.

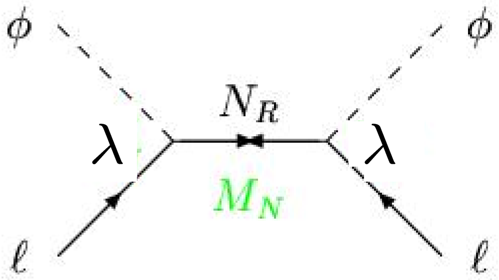
- ★ With 2 RH neutrinos, there are 5 equations for 4 unknowns → still overconstrained. Therefore, the case of 2 RH neutrinos can potentially be distinguished from 3.

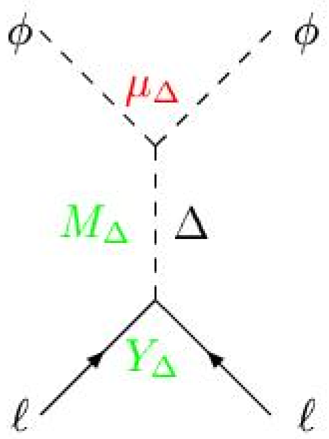
Summary

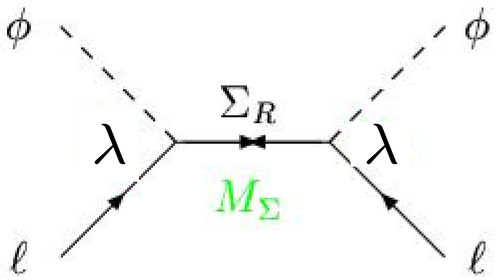
- ★ TeV scale models for neutrino masses can have a rich collider phenomenology. However, adding TeV-scale leptogenesis to the picture, one finds that there is either no *CP* asymmetry signal, or leptogenesis fails for the parameters accessible at the LHC.
- ★ We show that in the Type I seesaw with an additional Z', there exists a non-trivial region in the parameter space where leptogenesis is successful and Sakharov´s first condition might be tested.
- ★ A difference in the number of positive and negative like-sign dileptons points directly to the *CP* asymmetry required for leptogenesis. In particular, an excess of antileptons is predicted.
- ★ We find that with 100 (300) $\text{fb}^{-1}$of integrated luminosity, the no-asymmetry hypothesis can be excluded at the LHC if $\varepsilon > 0.26$ (0.17).
- ★ Even though they are expected to be extremely quasi-degenerate, it should even be possible to determine if there is more than 1 RH neutrino.

Back-up

Seesaw mechanisms







Type I seesaw

Fermionic singlet N_R

Type II seesaw

Scalar triplet Δ

Type III seesaw

Fermionic triplet Σ

$$m_\nu = \left(\lambda \boxed{\frac{1}{M}} \lambda^T\right) v^2$$

$$m_\nu = Y_\Delta \boxed{\frac{\mu_\Delta}{M_\Delta^2}} v^2$$

$$m_\nu = \left(\lambda \boxed{\frac{1}{M}} \lambda^T\right) v^2$$

[Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, …]

[Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, …]

[Foot, Lew, He, Joshi, Ma, Roy, …, Bajc, Nemevsek, Senjanovic, Dorsner, Fileviez-Perez]