Probing leptogenesis at the LHC

ArXiv:0904.2174 ; with Z. Chacko, S. Granor and R. Mohapatra

Steve Blanchet

September 22, 2009
Outline

★ The type-I seesaw mechanism and leptogenesis
★ Why is it hard to test?
★ Alternative seesaw models
  □ Leptogenesis is hard to reconcile with signals at LHC
★ An 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
**Seesaw and leptogenesis**

★ The simplest explanation to small neutrino masses is perhaps the Type I seesaw mechanism, which involves the introduction of 3 RH neutrinos which are SM gauge singlets.

\[-h_{\alpha i} L_{\alpha \alpha} \Phi N_{Ri} - \frac{1}{2} M_{N_i} N_{Ri}^T C N_{Ri} + h.c.\]

\[m_\nu = \left( h \frac{1}{M_N} h^T \right) \nu^2\]

[Type I seesaw
Fermionic singlet $N_R$]

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

★ The seesaw model is particularly attractive because it incorporates (with the help of anomalous sphalerons) a mechanism to generate naturally the required matter-antimatter asymmetry by the out-of-equilibrium CP-violating decays of the RH neutrinos $N \rightarrow \ell \Phi \ (\bar{\ell} \Phi^\dagger)$

LEPTOGENESIS
Seesaw and leptogenesis

★ In its simplest form, assuming hierarchical RH neutrinos,
\[ M_1 \ll M_2 \ll M_3 \]
a lower bound on the scale of leptogenesis was derived

\[ M_1(T_{\text{reh}}) \gtrsim 3(1.5) \times 10^9 \text{GeV} \]

[Davidson, Ibarra, 02; Buchmüller, Di Bari, Plümacher, 02]

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 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]
Testing leptogenesis?

★ With very high degeneracies (1 part in $10^{14}$), the scale of leptogenesis can be lowered to TeV! [Pilaftsis, Underwood, 2005]

Accessible at colliders?? Is problem 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 typically neutrino mass suppressed!

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

Production cross section negligible!
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

\[ \eta_B = 0.01 \varepsilon \kappa \]

\( \varepsilon \sim 10^{-5} \)

* CP asymmetry parameter, interference between loop and tree diagrams, adjustable.

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

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 $M_\Sigma$.

\[ M_\Sigma \downarrow \Rightarrow \kappa \downarrow \]

[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:

\[ M_{\Delta, \Sigma} > 1.6 \text{ TeV} \]  

[Strumia, 08]

Unfortunately beyond the discovery reach of LHC!

★ In the context of left-right symmetric theories broken around the TeV scale, gauge interactions such as \( N_{ReR} \leftrightarrow u_{dR} \) lead also to the washout of lepton number. Therefore, it is possible to derive a bound on the \( W_R \) mass for successful leptogenesis:

\[ M_{W_R} > 18 \text{ TeV} \]  

[Frere, Hambye, Vertongen, 08]

Clearly outside of the LHC reach.

Bottom line: LHC signals and leptogenesis are hard to reconcile!
... An exception: $Z'$ models!
Motivation for a $Z'$ at TeV

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

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

- 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:

- **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.

\[ \mathcal{L} \ni i \overline{N}_{Ri} D_\mu \gamma^\mu N_{Ri} - h_{\alpha i} \overline{L}_\alpha \Phi N_{Ri} - \frac{1}{2} M_{N_i} N_{Ri}^T C N_{Ri} + h.c. \]

\[ D_\mu = \partial_\mu - i g_1 Y_{B-L} B'_\mu \]

★ The gauge interactions $N \overline{N} \leftrightarrow \overline{q} (\overline{l} \ell)$ 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!

\[ \eta_B \sim 10^{-2} \sum_{i, \alpha} \varepsilon_{i, \alpha} K_{i, \alpha} (z \rightarrow \infty) \]

{\begin{align*}
3 \text{ RH neutrinos contribute} \\
\text{Flavor effects unavoidable}
\end{align*}}
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.:

  
  ![Diagram of RH neutrino decays](image)

- The $CP$ asymmetry from the RH neutrino decays is calculated precisely from the same graphs as in leptogenesis. Considering only decays into leptons and $W$'s, we have

  \[
  \varepsilon_i = \frac{\sum_{\alpha} [\Gamma(N_i \rightarrow \ell_\alpha^+ W^-) - \Gamma(N_i \rightarrow \ell_\alpha^- W^+)]}{\sum_{\alpha} [\Gamma(N_i \rightarrow \ell_\alpha^+ W^-) + \Gamma(N_i \rightarrow \ell_\alpha^- W^+)]}
  \]

  It 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:

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

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 dilepton events because there are no such events without missing energy in the SM. The backgrounds are then purely instrumental.
We estimate that the total LHC cross section \( pp \rightarrow Z' \rightarrow NN \) is about 1 fb for \( M_{Z'} = 3 \) TeV. 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 the invariant mass cut obtained from the lepton and \( W \) renders backgrounds negligible.

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

Such a large \( CP \) asymmetry can only be obtained if at least 2 RH neutrinos are quasi-degenerate. In order to assess the number of RH neutrinos, we found a very simple linear algebra argument which allows to distinguish 1 from 2 and 3 RH neutrinos.
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 to be explored 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) 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
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 $\alpha$ as $P_{i\alpha}$. Clearly

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

★ Then the probability of a given dilepton event to involve flavors $\alpha$ and $\beta$, 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 $\rightarrow$ 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 $\rightarrow$ still overconstrained. Therefore, the case of 2 RH neutrinos can potentially be distinguished from 3.
Since RH neutrinos are tracking closely equilibrium, it is possible to express the efficiency factor in a convenient form:

\[ \kappa_{i\alpha}(z, z_{in}) \simeq \int_{z_{in}}^{z} dz' \frac{dN_{i}^{eq}}{dz'} \frac{D(K_{i}, z')}{D(K_{i}, z') + 4S_{Z'}(z')N_{N_{i}}^{eq}(z')} \times \exp \left( - \int_{z'}^{z} \sum_{i} W_{ID}(K_{i\alpha}, z'')dz'' \right) \]

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!