Leptogenesis in type-III seesaw models and the implications of flavor effects

Diego Aristizabal

IFPA Group, AGO Department, University of Liége, Belgium

Partially based on

[arXiv:1007.1907] JHEP 1010:036

J. Kamenik (IJS, Slovenia-Ljubljana) and M. Nemevsek (Universität Hamburg)

Motivations

Baryon asymmetry

The cosmic baryon asymmetry is derived from measurements of light elements abundances and the CMB

$$Y_{\Delta B} = (8.75 \pm 0.23) \times 10^{-11}$$

Unlikely to be an “initial condition”. Should be dynamically generated (baryogenesis)!

Sakharov Conditions

❶ B asymmetry generating interations (BAGI) must violate B.

❷ BAGI must violate CP.

❸ BAGI must departure (at some point) from Thermodynamical Equilibrium.

Qualitatively SM satisfy the conditions:

- B is broken at the non-perturbative level (sphalerons processes)
- CP violation is provided by the CKM quark mixing matrix (too small) ✘
- Departure from TEQ provided by EWPT. Succesful baryogenesis requires strongly $1^{\underline{st}}$ order PT $\Rightarrow m_h < 40$ GeV while LEP: $m_h > 115$ GeV ✘

Fails at the quantitative level

Explanation of $Y_{\Delta B}$ requires BSM physics

Possible approaches

A large number of mechanisms (models) for baryogenesis exist. Among them two of the most widely studied are:

EW baryogenesis

EW baryogenesis models “cure” the SM pitfalls via extended scalar sectors

$$V_{\rm SM}(\Phi) \longrightarrow V(S_i,\Phi_i) \Rightarrow \left\{\begin{array}{l} \text{Strongly } 1^{\rm st} \text{ order EWPT: relaxing } m_h^{\max} \\ \text{Additional CP violating sources}\end{array}\right.$$

SM+S, 2HDMs, MSSM... EWB will be strengthened or weakened at LHC!

Leptogenesis:

The asymmetry is firstly generated in the lepton sector ($\Delta B \neq 0 \to \Delta L \neq 0$). The resulting lepton asymmetry is reprocessed into a baryon asymmetry by SM sphalerons. $L \to B$ through $B+L$ violating EW sphalerons interactions

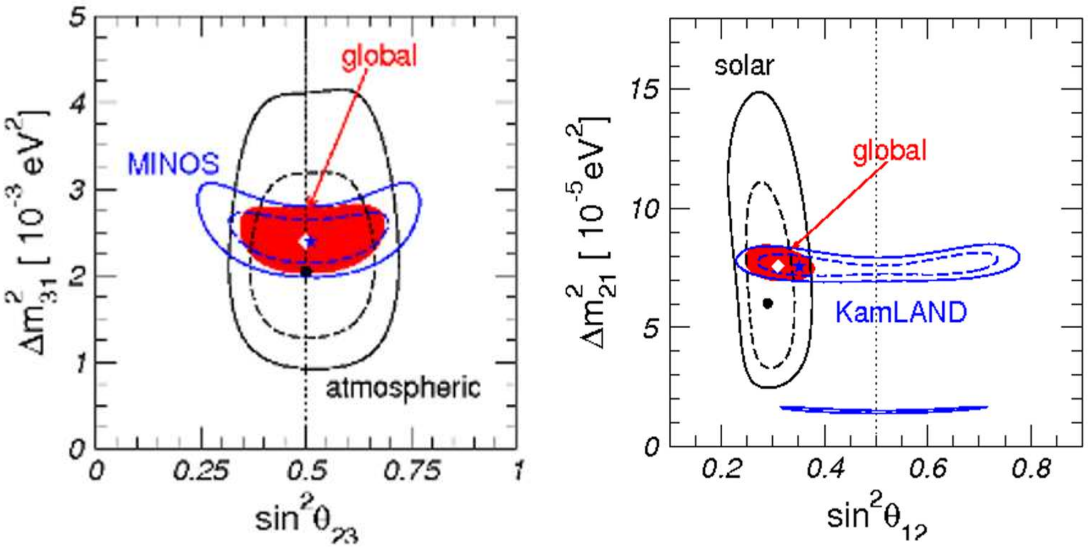
$$\mathcal{O}_{B+L} = \prod_{i=1,2,3} (q_{L_i} q_{L_i} q_{L_i} \ell_{L_i})$$

Qualitatively (quantitatively in some cases) viable in models of Majorana neutrino masses. Linked with the origin of neutrino masses

Present status of ν data

Present values of neutrino mixing angles as well as of the solar and the atmospheric mass-squared differences are derived from global fits of current experimental data.

M. Tortola *et. al*, New J. Phys. **10**, 113011 (2008). Updated version V5 (Feb 2010)



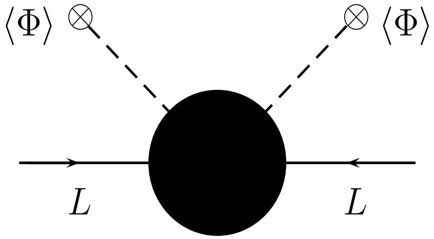
parameter	2σ
Δm^2_{21} $[10^{-5}]$ eV	7.22–8.03
Δm^2_{31} $[10^{-3}]$ eV	2.18–2.64
$\sin^2\theta_{12}$	0.29–0.36
$\sin^2\theta_{23}$	0.39–0.63
$\sin^2\theta_{13}$	0.039

Neutrino oscillations experiments have firmly established that neutrinos have non-zero mass and mixing angles among the different generations

Neutrino mass generation

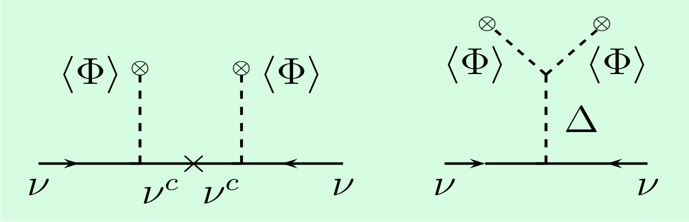
An effective dimension-five operator $L\Phi L\Phi$ can be added to the SM. Once the EW symmetry breaks through the vev of Φ neutrino Majorana masses are induced

S. Weinberg, Phys. Rev. D **22**, 1694 (1980)

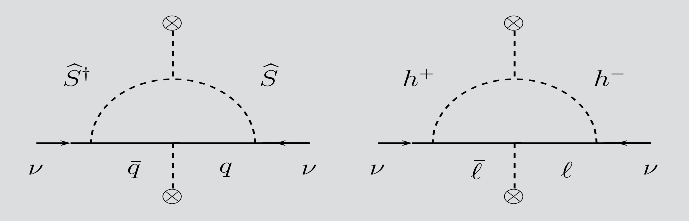


Several realizations of this operator exist

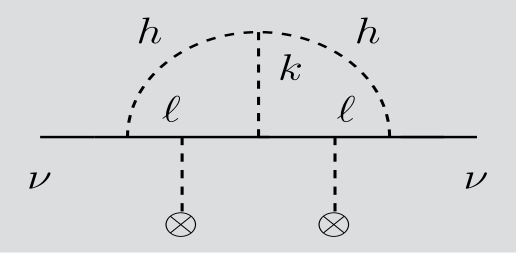
Seesaw mechanism



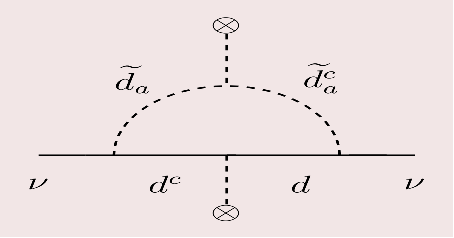
One-loop radiative mechanism



Two-loop radiative mechanism



R-parity violating SUSY



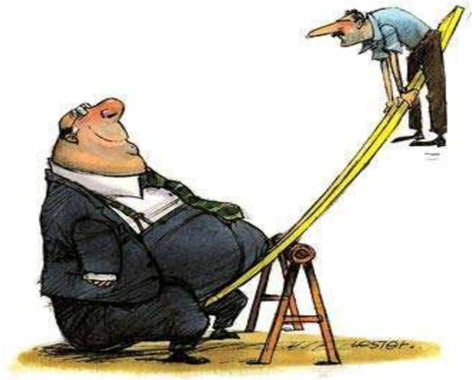
Type-I seesaw

All these realizations satisfy (at least qualitatively) the Sakharov conditions.

Standard seesaw Add new fermionic EW singlets, N_R to the SM

$$\mathcal{L} = -\lambda^*_{i\alpha}\bar{\ell}_i N_{R\alpha}\tilde{H} - \frac{1}{2}\bar{N}_{R\alpha} m_{R\alpha} N^c_{R\alpha} + \text{h.c}$$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$



Diagonalization yields 3 heavy masses for the fermionic EW singlets M_i and 3 light masses m_i (Assumming $m_R \gg m_D$).

$$M_\nu^{\text{eff}} = -m_D m_R^{-1} m_D^T$$

The smallness of light neutrinos masses is due to the suppression of the heavy R-H neutrino masses

The standard seesaw model is the framework for standard leptogenesis

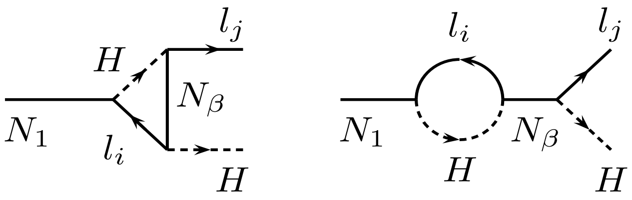
Standard leptogenesis

The fermionic singlet mass spectrum: $M_1 \ll M_{2,3}$. The lepton asymmetry proceeds via N_{R1} out-of-equilibrium and CP violating decays

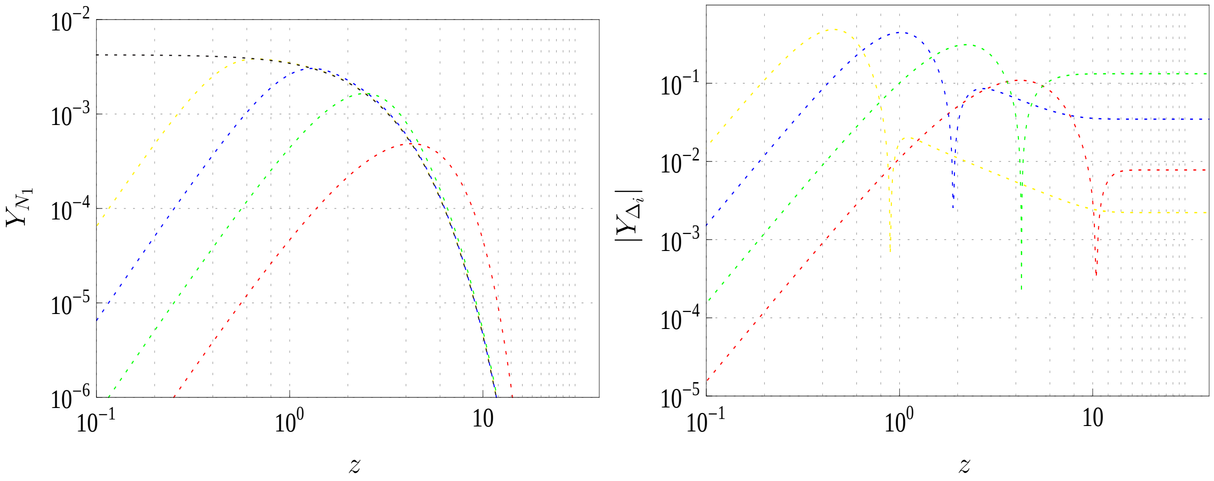
$$\Gamma_D = \Gamma(N_{R1} \to \ell\tilde{H}, \bar{\ell}\tilde{H}^\dagger) = \frac{M_1^2}{8\pi v^2}\sum_{i=e,\mu,\tau}\tilde{m}_{i1} \qquad \boxed{\tilde{m}_{i\alpha} \propto \lambda^*_{i\alpha}\lambda_{i\alpha}}$$

- Majorana mass term m_R is a L violating source ($\Delta L = 2$).
- $\lambda_{i\alpha} \longrightarrow$ contain new physical CPV phases. CPV asymmetries arise at the one-loop level

$$\boxed{\epsilon^{\ell_i}_{N_1} = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}}$$



- Departure from thermal equilibrium provided by the expansion. $\Gamma_D \lesssim H(z = M/T = 1)$



SUCCESSFUL LEPTOGENESIS!

Flavor effects

Flavor effects become relevant at $T \lesssim 10^{13}$ GeV when $Y_{b,\tau}$ enter into TEQ. Depending on T the propagating states are L_i, $i = e, \mu, \tau$

G. F. Giudice *et. al*, NPB,**685**,89; A. Abada *et. al*, JHEP,**09**,010; E. Nardi *et. al*, JHEP,**01**,164

Possible T regimes

1. 10^{12} GeV $\lesssim T \lesssim 10^{13}$ GeV: h_b and h_τ Yukawa interactions are in TEQ
2. 10^{9} GeV $\lesssim T \lesssim 10^{12}$ GeV: Also EW sphalerons are in TEQ
3. 10^{8} GeV $\lesssim T \lesssim 10^{11}$ GeV: Second Yukawa generation enter into TEQ
4. $T \ll 10^{8}$ GeV: All SM Yukawa interactions and EWS are in TEQ

Case 2: The $B - L$ asymmetry is redistributed distributed along ℓ_τ and ℓ_1 (admixture of μ and e flavors).

Determination of $Y_{\Delta_{B-L}}$ is a 2-flavor problem

Beyond standard leptogenesis

Type-III seesaw

In type-III seesaw neutrino masses are generated via the interchange of fermionic EW triplets

$$\mathcal{L} = \overline{T}^A_\alpha \gamma^\mu D_\mu T^A_\alpha - \lambda^*_{i\alpha} \overline{\ell}_i \tau^A T^A_\alpha \widetilde{H} - \frac{1}{2} \overline{T}^A_\alpha M_{T_\alpha} (T^A_\alpha)^C + \text{h.c.}$$

$$T_\alpha = \begin{pmatrix} T^0_\alpha & \sqrt{2} T^+_\alpha \\ \sqrt{2} T^-_\alpha & -T^0_\alpha \end{pmatrix}$$

T^0_α responsible for ν masses

$$\boldsymbol{m_\nu}^{eff} = -v^2 \boldsymbol{\lambda} \cdot \boldsymbol{\hat{M}_T}^{-1} \cdot \boldsymbol{\lambda}^T$$

The new CP violating sources in $\boldsymbol{\lambda}$ induce CP violating T_α decays: ☞

- Hierarchical T_α spectrum $\omega_\beta = M^2_{T_\beta}/M^2_{T_\alpha} \gg 1$

$$\epsilon^{\ell_j}_{T_\alpha} \lesssim 10^{-5} \left(\frac{M_{T_\alpha}}{10^{10}\ \text{GeV}}\right) \left(\frac{m_3}{1\ \text{eV}}\right) \frac{\widetilde{m}_{j\alpha}}{\widetilde{m}_\alpha}$$

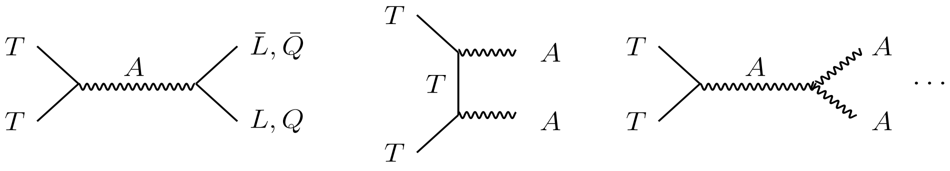
Succesful leptogenesis only possible for $M_T \gtrsim 10^{10}$ GeV

- Quasi-degenerate T_α spectrum $\sqrt{\omega_\beta} \sim 1 + \Gamma_\beta / M_\alpha$

Wave function piece resonantly enhanced
Sucessful leptogenesis $M_T \sim \mathcal{O}$(TeV)

BEQs

Gauge reactions drive the T distribution close to a thermal equilibrium



Precise determination of the lepton asymmetry requires solution of BEQs

$$\frac{dY_{T_\alpha}}{dz_\alpha} = -\frac{1}{sHz_\alpha}\left[\left(\frac{Y_{T_\alpha}}{Y^{\rm Eq}_{T_\alpha}}-1\right)\gamma_{D_\alpha}+\left(\frac{Y^2_{T_\alpha}}{\left(Y^{\rm Eq}_{T_\alpha}\right)^2}-1\right)\gamma_{A_\alpha}\right]$$

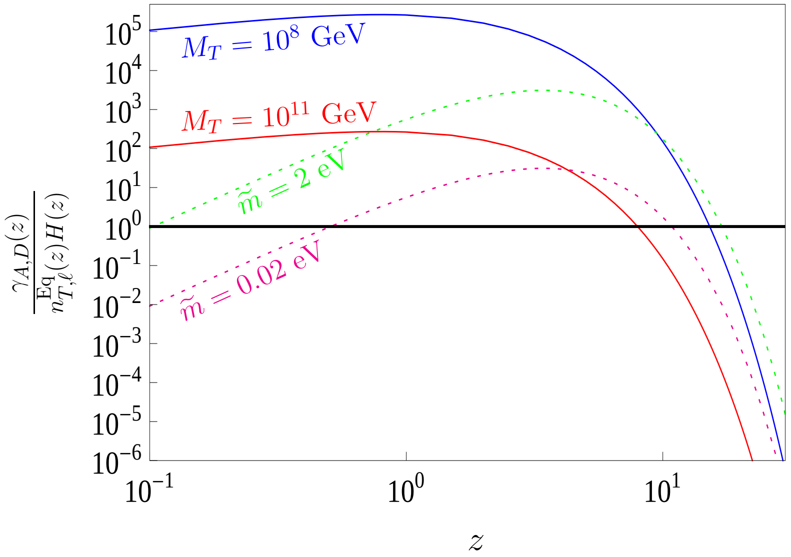
$$\frac{dY_{\Delta_i}}{dz_\alpha} = -\frac{1}{sHz_\alpha}\left[\left(\frac{Y_{T_\alpha}}{Y^{\rm Eq}_{T_\alpha}}-1\right)\epsilon^{\ell_i}_{T_\alpha}+\frac{K_{i\alpha}}{2Y^{\rm Eq}_\ell}\sum_{j=e,\mu,\tau}C^\ell_{ij}Y_{\Delta_j}\right]\gamma_{D_\alpha}$$

Flavor projectors: $K_{i\alpha}=\frac{\tilde{m}_{i\alpha}}{\tilde{m}_\alpha}$

$Y_{\ell_i}=\sum_{i=e,\mu\tau}C^\ell_{ij}Y_{\Delta_i}$

The generation of a L asymmetry proceeds according to:

$$\frac{\gamma_A}{n^{\rm Eq}_T H}\lesssim 1 \Rightarrow \begin{cases} \frac{\gamma_D}{n^{\rm Eq}_\ell H}\lesssim 1 & \text{ID decoupled} \\ \frac{\gamma_D}{n^{\rm Eq}_\ell H}\gtrsim 1 & \text{ID still active} \\ \frac{\gamma_A}{\gamma_D}\sim\frac{g^4}{M_T\tilde{m}} & \end{cases}$$



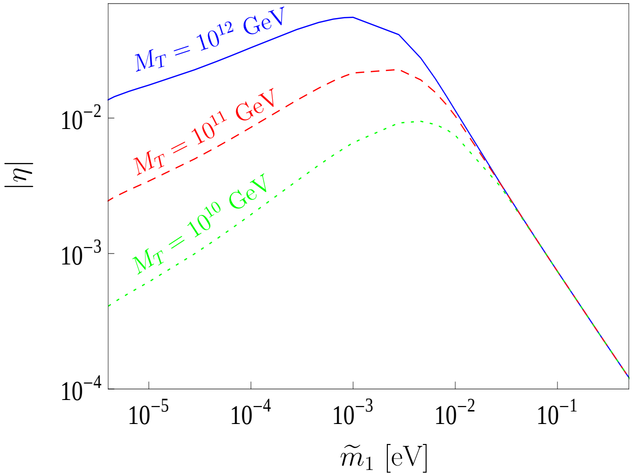
Lepton asymmetry: aligned case

In the case of a hierarchical triplet spectrum the asymmetry is determined by the lightest triplet (T_1):

$$Y_{\Delta_{B-L}} = 3 \times \sum_{i=e,\mu,\tau} \epsilon_{T_1}^{\ell_i} Y_T^{\text{Eq}} \eta_i$$

$\eta_{i\alpha}$: Efficiency in flavor ℓ_i ([0,1])

Compared with the standard case due to the couplings with $A = W_a, B$ there are several differences:



Small $\tilde{m}$

- η strongly depends on M_T
- $M_T \lesssim 10^{12} \Rightarrow \eta_{III} \ll \eta_I$

Large $\tilde{m}$

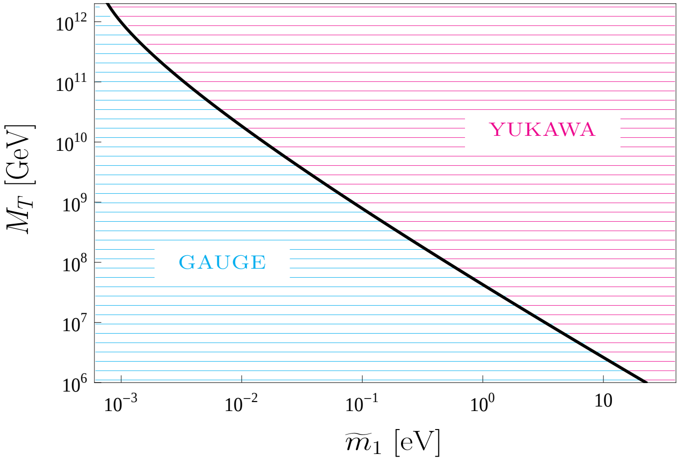
- $\eta \neq \eta(M_T) \Rightarrow$ as in standard leptogenesis
- There is a $\tilde{m}_{\text{min}}$ for which $\gamma_A < \gamma_D$

Gauge region

- At gauge decoupling ID are decoupled too

Yukawa region

- ID are active when $\gamma_A / n_T^{\text{Eq}} H \lesssim 1$



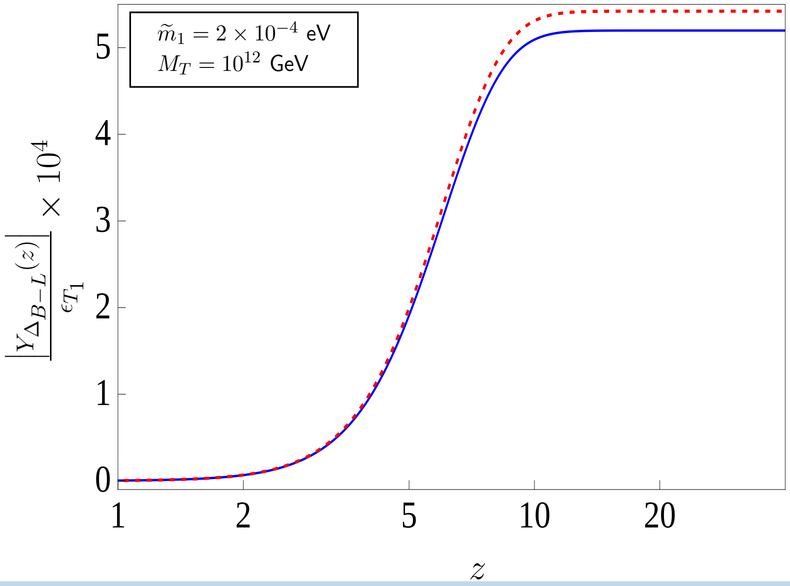
Including flavor I

The inclusion of flavor should have an impact on the final asymmetry. Numerical results for a representative “point”

★ $K_{11} = 0.99\ (K_{\tau 1} = 1 - K_{11})$, $\epsilon_{T_1}^{\ell_1} = -0.1 \times \epsilon_{T_1}$, $\epsilon_{T_1}^{\ell_\tau} = 1.1 \times \epsilon_{T_1}$ with $\epsilon_{T_1} = 10^{-5}$

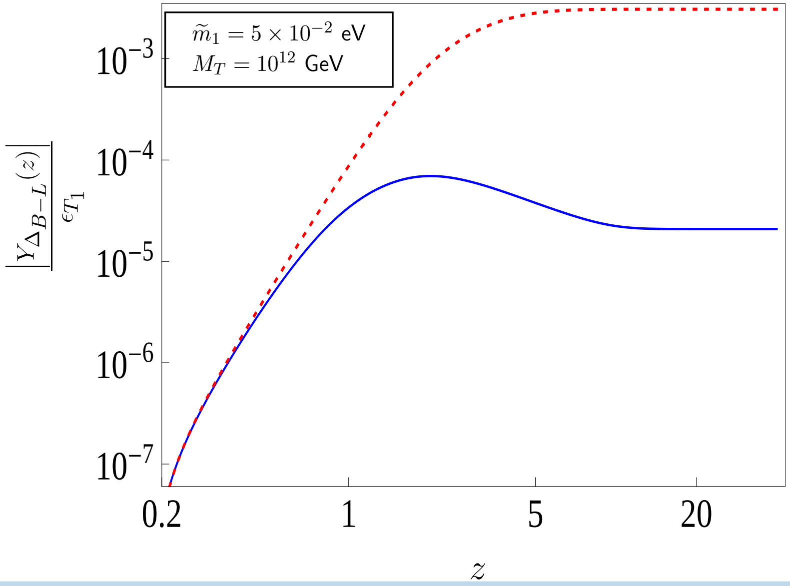
Gauge “region”

The T_1 abundance is efficiently diminished by γ_A. Flavor effects are tiny (∼5% for ★)



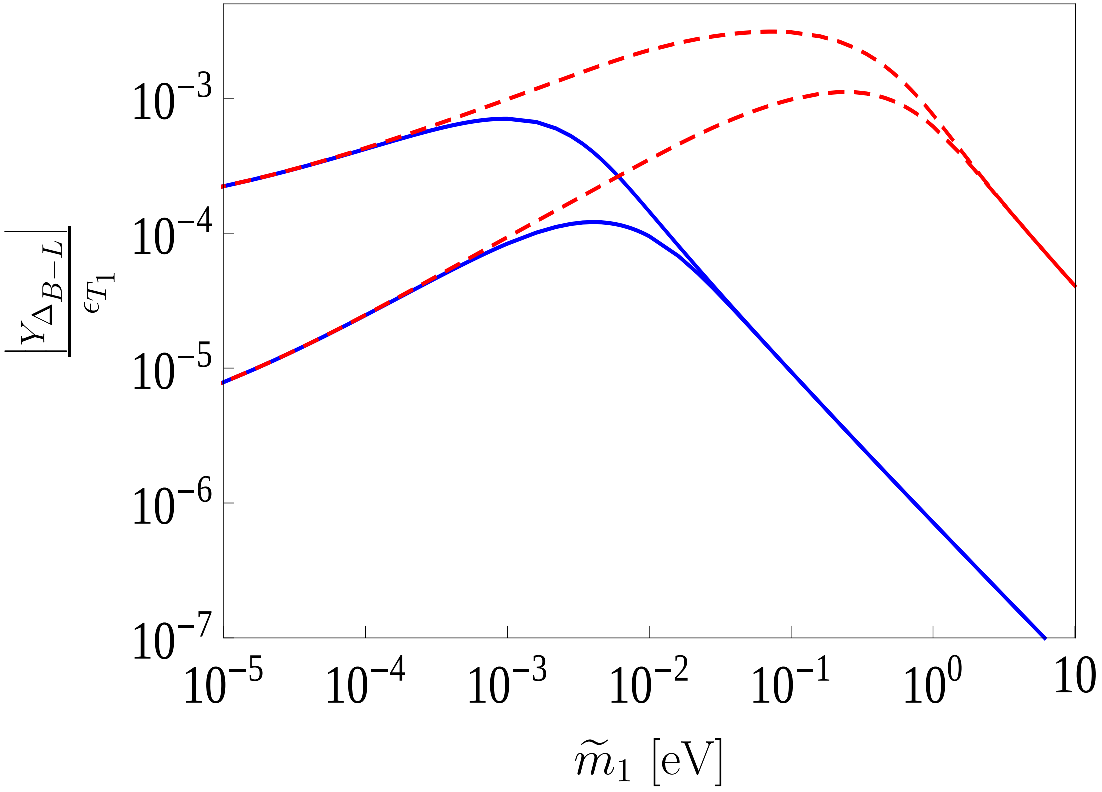
Yukawa “region”

At $z_1 \gg 1$ the dynamics of T_1 is entirely determined by γ_D. Flavor effects are sizable (a factor $\sim 10^2$ for ★)



Including flavor II

Flavor effects are relevant as long as leptogenesis takes place within the "Yukawa region". The minimum $\tilde{m}$ for which flavor effects become relevant depends upon M_T.



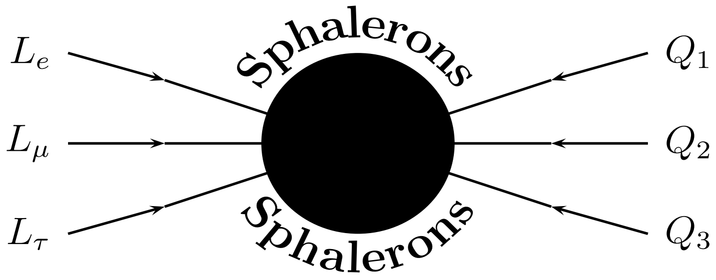
TeV Scale Triplets

Constraints from Leptogenesis

“Light” triplets could be produced at LHC as long as $M_T \lesssim$ 1 TeV

T. Hambye *et. al*,PRD,**78** 033002, F. del Aguila *et. al*,NPB,**813** 22

- Gauge reactions are active up to $z_1 \gtrsim 6$ $\Rightarrow$ The $Y_{\Delta_{B-L}}$ is produced above this z_1 and partially reprocessed to Y_{Δ_B} up to sphaleron decoupling



$T_{\rm dec} = [80 + 0.45(m_h/{\rm GeV})]$ GeV

Y. Burnier *et. al*, JCAP,**02**,007

$z_1 \sim 7.5$

$M_{T_1} \gtrsim 1.6$ TeV

A. Strumia,NPB,**809**,308

- Flavor only relevant in the “Yukawa region” $\boxed{\gamma_D/\gamma_A > 1}$ $\Rightarrow$ Due to inverse Yukawa decays the $Y_{\Delta_{B-L}}$ is produced at $z_1 \gg 7.5$.

The bound still holds in the presence of flavor effects

Observation of fermionic triplets at LHC would rule out
FERMIONIC TRIPLET LEPTOGENESIS

T_2 leptogenesis

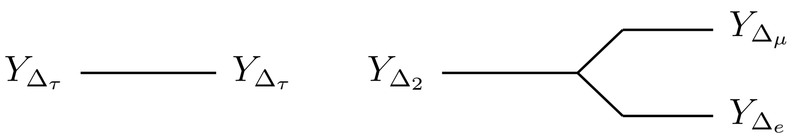
$Y_{\Delta_{B-L}}$ generated by the dynamics of the next to lightest triplet T_2. The bound on T_1 no longer holds: $\boxed{M_{T_1} < 1 \text{ TeV while } M_{T_2} > 1.6 \text{ TeV}}$

Conditions

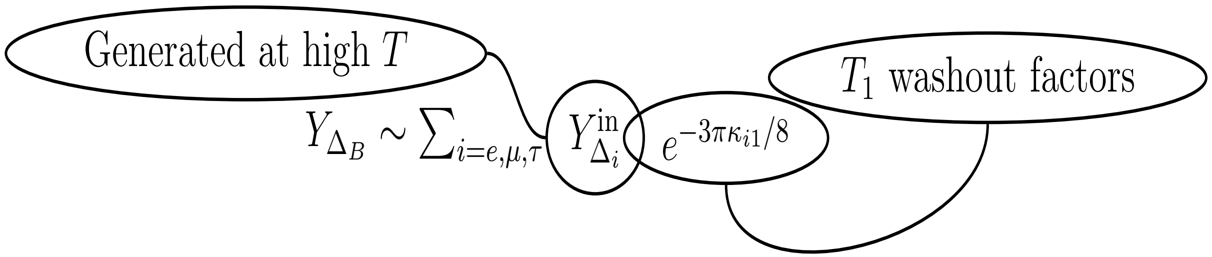
- At least a $3^{\underline{rd}}$ triplet (T_3) $\Rightarrow \epsilon_{T_2}^{\ell_j}$ sufficiently large
- Circumvent washout from T_1 10^9 GeV $\lesssim M_{T_2} \lesssim 10^{12}$ GeV :

✓ $Y_{\Delta_{B-L}}$ generated at $z_2 = M_2/T \sim 1$ in the two flavored regime (ℓ_τ, ℓ_2), no asymmetry generated in T_1 dynamics ($\epsilon_{T_1}^{\ell_j} \simeq 0$).

✓ At $z \ll z_2$ h_μ enter TEQ



✓ At $z \sim z_1$ T_1 related washouts become effective



$$Y_{\Delta_B} \sim \sum_{i=e,\mu,\tau} Y_{\Delta_i}^{\text{in}} \, e^{-3\pi\kappa_{i1}/8}$$

$\kappa_{i1} \simeq \tilde{m}_{i1}/2\text{eV} \propto \lambda_{i1}^2$

Succesful leptogenesis

determined by T_1

flavor structure (κ_{i1})

Scenarios

- There exist a $\kappa_{i1} > \kappa_{i1}^{\text{max}}$ for which flavor i will not contribute to Y_{Δ_B}.
- Generically washouts in flavor i are relevant if $\kappa_{i1} \gtrsim 1$.

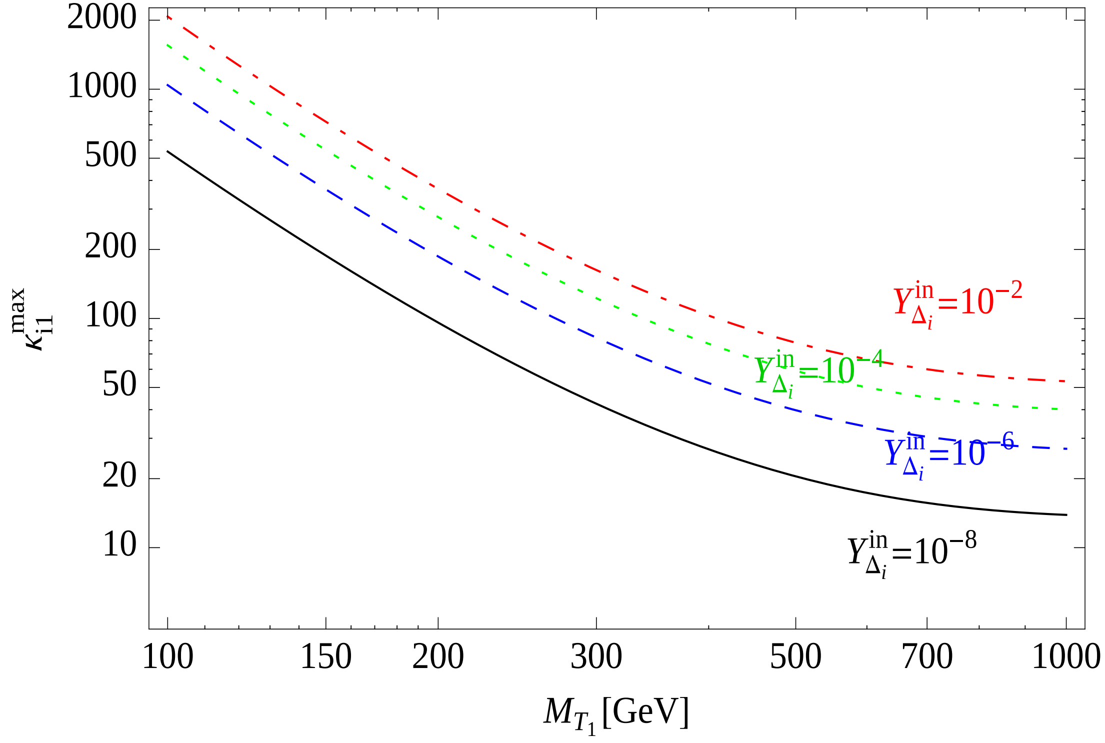
	SCENARIOS	LEPTOGENESIS
I.	$\kappa_{i1} \ll 1$ **for all flavors**	✓ or ✗
	Everything determined by T_2 dynamics	
II.	$\kappa_{i1} \ll 1$ **and** $\kappa_{j1} \gtrsim 1$	✓ or ✗
	In general will depend on T_2 dynamics	
III.	$\kappa_{i1} \gtrsim 1$ **for all flavors**	
	Succesful leptogenesis constraints κ_{i1}	
(A)	**Single flavor:** $\kappa_{i1} < \kappa_{i1}^{\text{max}}$ **and** $\kappa_{(j,k)1} > \kappa_{(j,k)1}^{\text{max}}$	✓
(B)	**Two flavors:** $\kappa_{(i,j)1} < \kappa_{(i,j)1}^{\text{max}}$ **and** $\kappa_{k1} > \kappa_{k1}^{\text{max}}$	✓
(C)	**Three flavors:** $\kappa_{(e,\mu,\tau)1} < \kappa_{(e,\mu,\tau)1}^{\text{max}}$	✓

Constraints on κ

Constraints on κ_{i1}^{max} can be derived by requiring $Y_{\Delta_B} \subset [8.52, 8.98] \times 10^{-11}$

$$\frac{dY_{\Delta_i}(z_1)}{dz_1} = -\frac{\kappa_{i1}}{4} \sum_{j=e,\mu,\tau} C^\ell_{ij} Y_{\Delta_j}(z_1) K_1(z_1) z_1^3$$

- Washout is relevant up to sphaleron decoupling $T_{\text{dec}} \sim 130$ GeV.
- Constraints depend upon the size of $Y^{\text{in}}_{\Delta_i}$



Discrimination I

Though T_2 parameters are not accesible, measurements of T_1 decay lenghts and decay BR at LHC might lead to some conclusions:

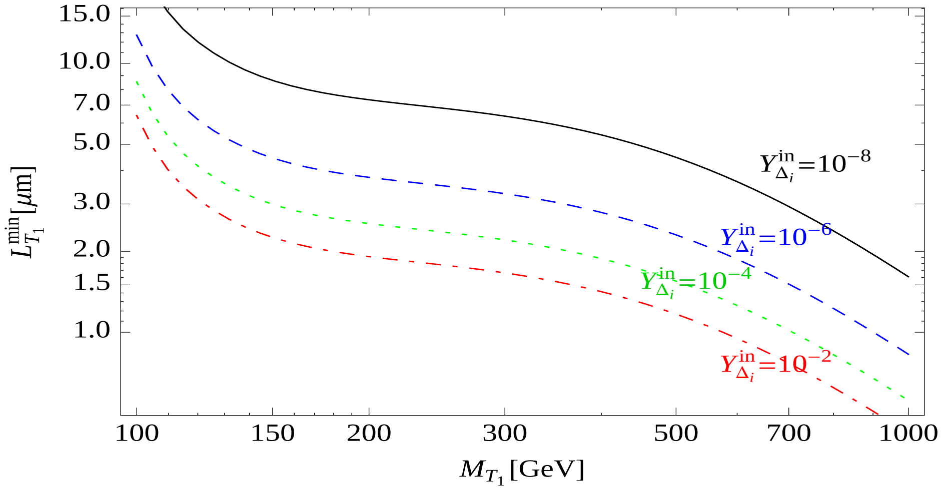
Experimentally

☐ "Smoking gun" signal: $pp \to T^{\pm}T^0 \to (\ell_1^{\pm} Z)(\ell_2^{\pm} W^{\mp}) \to \ell_1^{\pm}\ell_2^{\pm} + 4$ jets

☐ LHC vertex resolution: $\sim$ 100 μm

Experimental features of the scenarios

$$\Gamma(\ell_i) \simeq 10^{-12}\, \kappa_i \left(\frac{M_{T_1}}{1\ \text{TeV}}\right)^2\ \text{GeV}$$



$$\kappa_{i1}^{\max} \gtrsim 10 \ \Rightarrow\ L_{T_1}^{\min} \lesssim 10\ \mu\text{m}$$

Discrimination II

Decay Lengths

Scenarios I and III(C): Long lived triplet. Secondary vertices at LHC points towards these scenarios:

A long lived triplet accesible at LHC consistent with high scale leptogenesis

Scenarios II and III(A,B): Short lived triplet $L \sim 10\mu$m (possibly reachable at ILC).

Decay BRs

Scenarios I and III(C): Hierarchical or not hierarchical BRs possible.

Scenarios II and III(A,B): Hierarchical BRs, though in cases III(A,B) non-hierarchical BRs also possible.

Discrimination requires precise measurements of L_T and BRs

Exclusion requires $L_T \lesssim 1$ μm and BR(ℓ_i) $\simeq$ BR(ℓ_j) $\forall$ flavors

Conclusions

Final remarks

- Dynamical generation of a baryon asymmetry is a window to BSM physics. **Large list of models** which are able to explain the cosmic baryon asymmetry exist.

- Leptogenesis as a model for baryogensis links the problem of neutrino mass generation with the cosmic baryon asymmetry puzzle. **Qualitatively** any model for Majorana neutrino masses can be regarded as a framework for leptogenesis.

- Compared with the *standard case* in type-III seesaw leptogenesis is affected by the coupling of the triplets with gauge bosons.

- If the asymmetry is produced by the dynamics of the lightest state, successful leptogenesis implies $M_T \gtrsim$ 1.6 TeV even when flavor effects are taken into account.

- If the asymmetry is produced by heavier triplets (or other states e.g. heavy fermionic EW singlets), $\mathcal{O}$(TeV) triplets (accesible to LHC) could be produced without being in conflict with successful leptogenesis.

- Requirements of succesful leptogenesis “constraint” the lightest triplet parameters. Collider analysis of these states might shed light on high energy leptonesis non-accesible at colliders.