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

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Based on

[arXiv:1007.1907] JHEP 1010:036

J. Kamenik (IJS, Slovenia) and M. Nemevsek (ICTP, Italy & IJS, Slovenia)

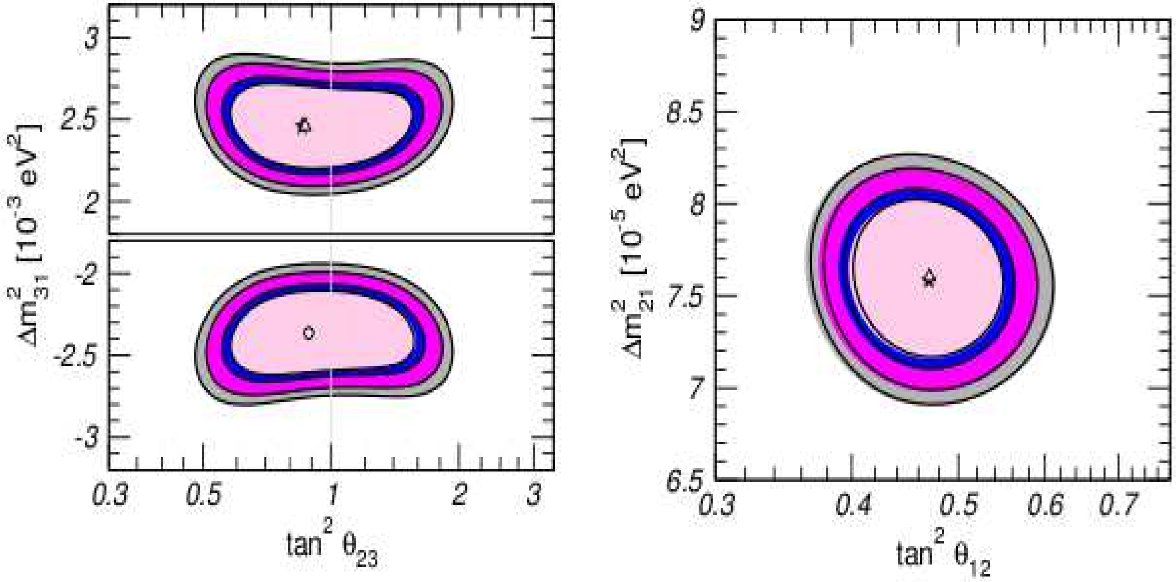
Generalities

Neutrino masses: experimental status (I)

- **Neutrino oscillation experiments**

Neutrino oscillation parameters are extracted from solar, atmospheric, reactor and long-baseline experiments

M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, JHEP 1004:056 (2010)



$$\Delta m^2_{21} = 7.59 \pm 0.20 \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

$$\theta_{12} = 34.4 \pm 1.0 \left({}^{+3.2}_{-2.9}\right)^\circ$$

$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \left({}^{+10.7}_{-7.3}\right)^\circ$$

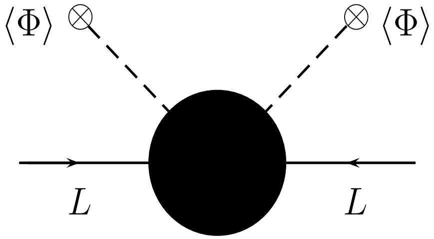
$$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7}\ (\le 12.5)^\circ$$

$$\left[\sin^2\theta_{13} = 0.0095\,{}^{+0.013}_{-0.007}\ (\le 0.047)\right]$$

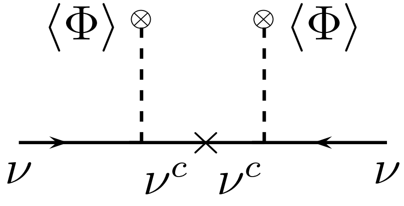
Neutrino mass generation

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

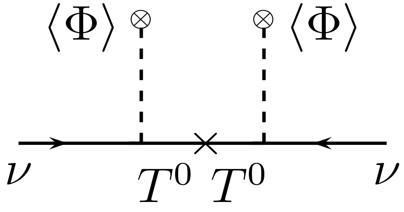
S. Weinberg, Phys. Rev. D **22**, 1694 (1980)



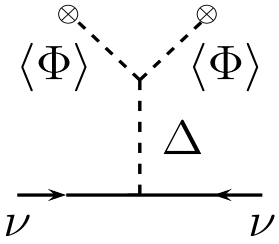
Tree level realizations



Type-I



Type-III



Type-II

P. Minkowski

R. Mohapatra & G. Senjanovic

T. Yanagida

R. Foot, H. Lew *et. al.*

J. Schechter & J.W.F. Valle

G. Lazarides *et. al.*

C. Wetterich

Type-I seesaw (Standard seesaw) defines the framework for (Standard leptogenesis)

Standard leptogenesis

Cosmic baryon asymmetry derived from measurements of light elements abundances and the CMB

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

Standard Leptogenesis generation of Y_{Δ_B} in the context of type-I seesaw with $M_1 \ll M_{2,3}$:

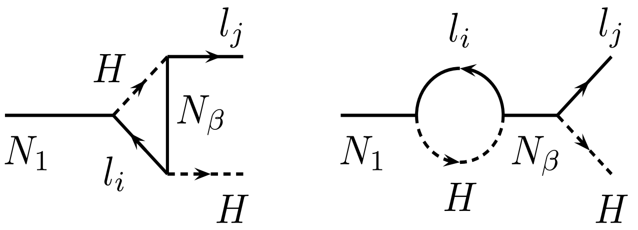
A lepton asymmetry Y_{Δ_L} proceeds via N_{R1} out-of-equilibrium and CP violating decays

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

Reprocessed by SM Sphaleron process into a Y_{Δ_B}

- 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

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



☞

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

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, A. Ibarra *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

Generalities

Beyond standard leptogenesis
- Type-III seesaw
- BEQs
- Lepton asymmetry: aligned case
- Including flavor

TeV Scale Triplets

Conclusions

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

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

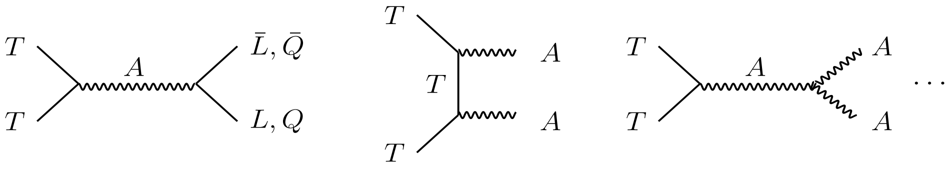
Succesful leptogenesis only possible for $M_T \gtrsim 10^{10}$ GeV

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

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

BEQs

Gauge reactions drive the T distribution close to a thermal equilibrium



Precise determination of the lepton asymmetry requires solution of BEQs

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

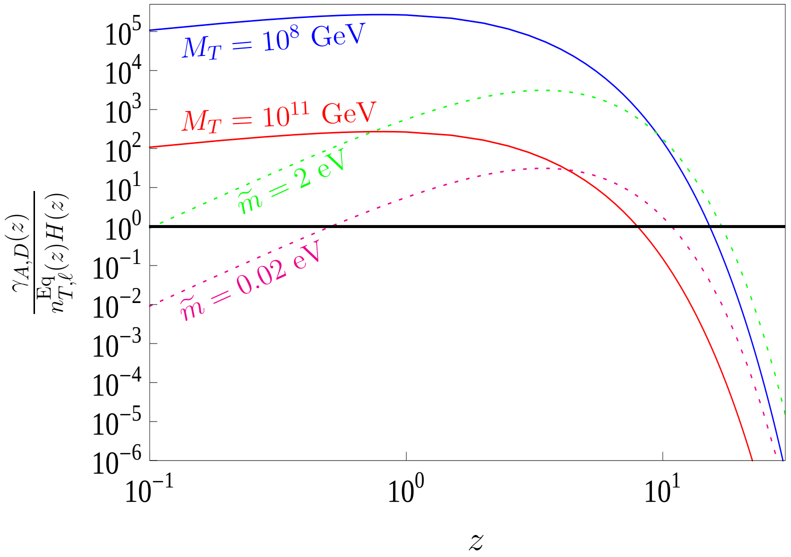
$$\frac{dY_{\Delta_i}}{dz_\alpha} = -\frac{1}{sHz_\alpha}\left[\left(\frac{Y_{T_\alpha}}{Y^{\rm Eq}_{T_\alpha}}-1\right)\epsilon^{\ell_i}_{T_\alpha} + \frac{K_{i\alpha}}{2Y^{\rm Eq}_\ell}\sum_{j=e,\mu,\tau} C^\ell_{ij} Y_{\Delta_j}\right]\gamma_{D_\alpha}$$

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:

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



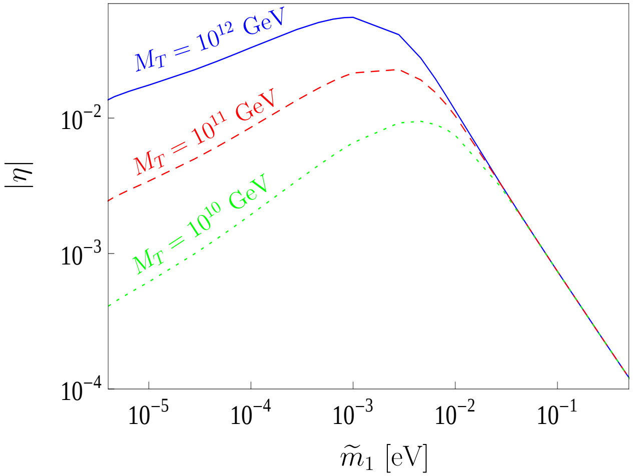
Lepton asymmetry: aligned case

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 $\tilde{m}$

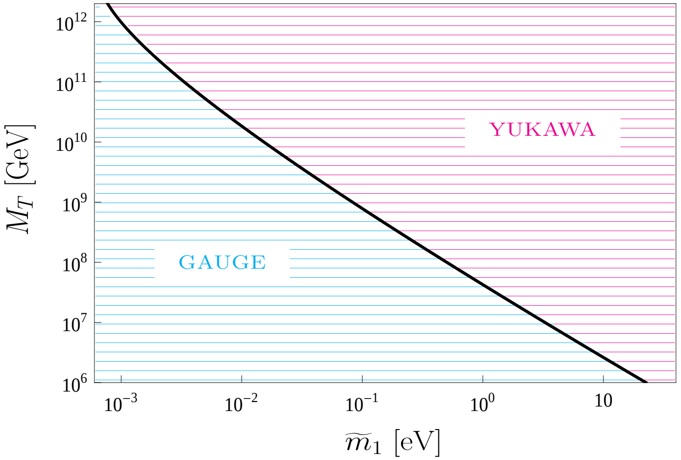
- $\eta \neq \eta(M_T) \Rightarrow$ as in standard leptogenesis
- There is a $\tilde{m}_{\text{min}}$ for which $\gamma_A < \gamma_D$

Gauge region

- At gauge decoupling ID are decoupled too

Yukawa region

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



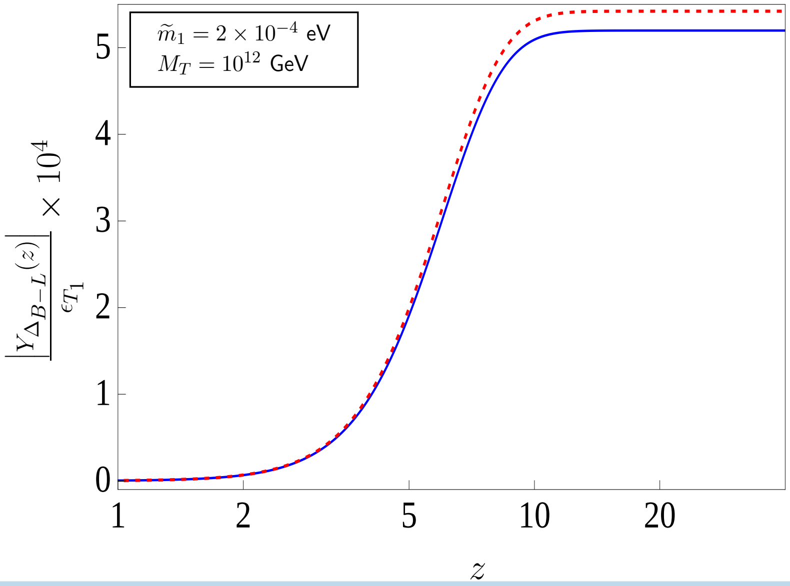
Including flavor

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

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

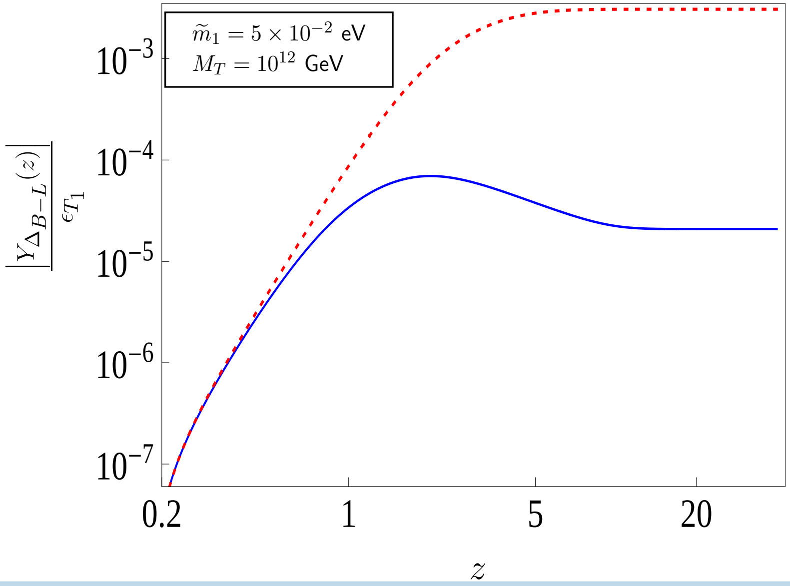
Gauge "region"

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 ★)



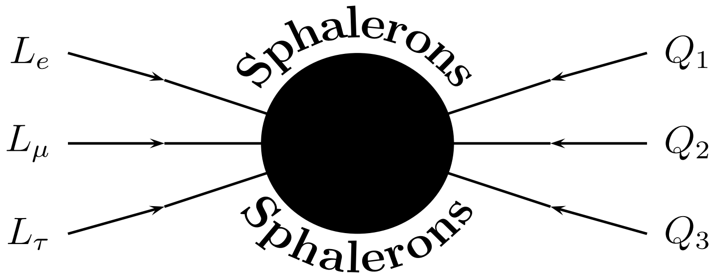
TeV Scale Triplets

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



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

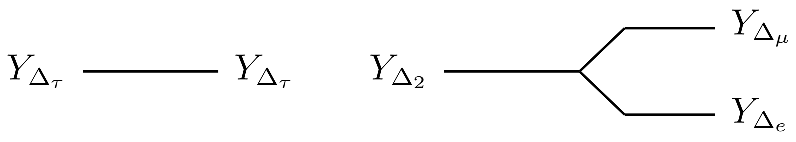
$Y_{\Delta_{B-L}}$ generated by the dynamics of the next to lightest triplet T_2. The bound on T_1 no longer holds: $\boxed{M_{T_1} < 1 \text{ TeV while } M_{T_2} > 1.6 \text{ TeV}}$

Conditions

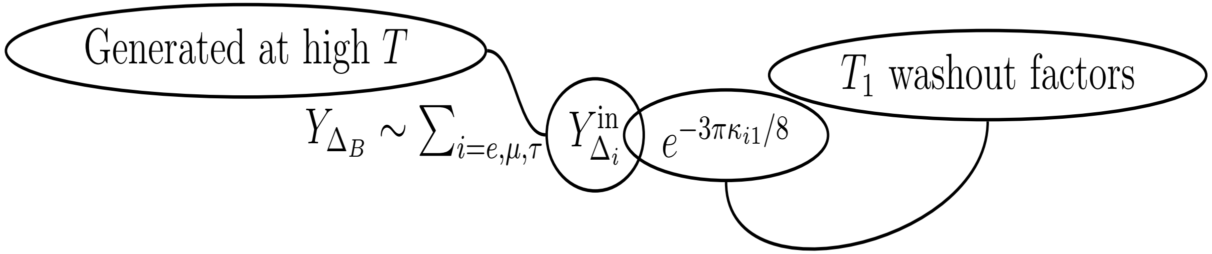
- At least a $3^{\underline{rd}}$ triplet (T_3) $\Rightarrow \epsilon_{T_2}^{\ell_j}$ sufficiently large
- Circumvent washout from T_1 $10^9 \text{ GeV} \lesssim M_{T_2} \lesssim 10^{12} \text{ GeV}$:

✓ $Y_{\Delta_{B-L}}$ 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 $\kappa_{i1} \gtrsim 1$.

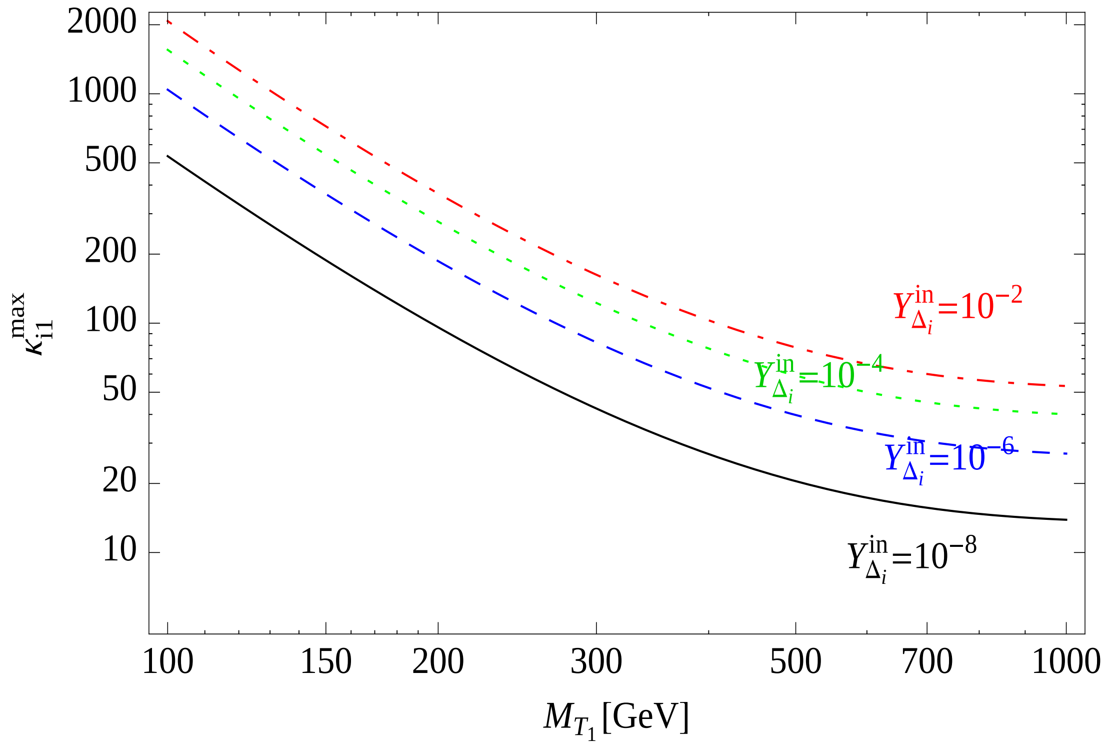
	SCENARIOS	LEPTOGENESIS
I.	$\kappa_{i1} \ll 1$ **for all flavors** Everything determined by T_2 dynamics	✓ or ✘
II.	$\kappa_{i1} \ll 1$ **and** $\kappa_{j1} \gtrsim 1$ In general will depend on T_2 dynamics	✓ or ✘
III.	$\kappa_{i1} \gtrsim 1$ **for all flavors** Succesful leptogenesis constraints κ_{i1}	
(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:

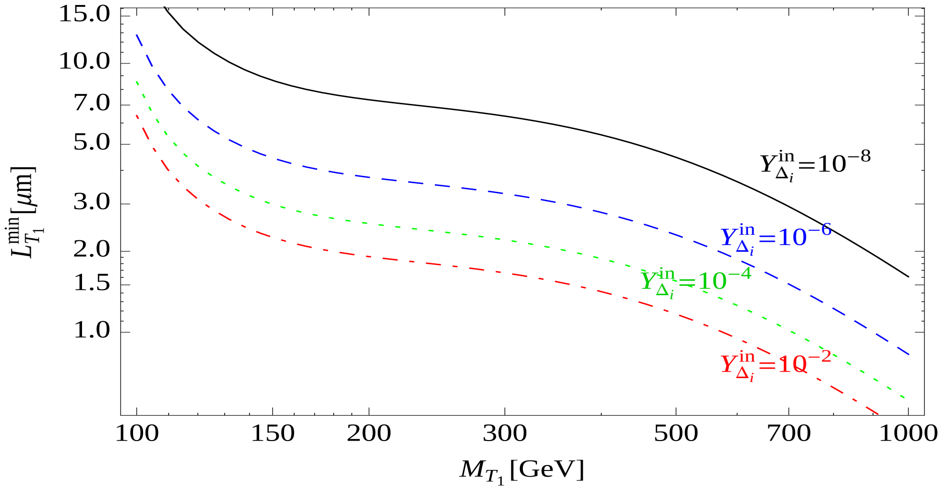
Experimentally

☐ "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

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



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

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

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.
- **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 (or any other L breaking state) parameters. Collider signals of these states might shed light on high energy leptonesis non-accesible at colliders.