Neutrino Mass Seesaw, Baryogenesis and LHC

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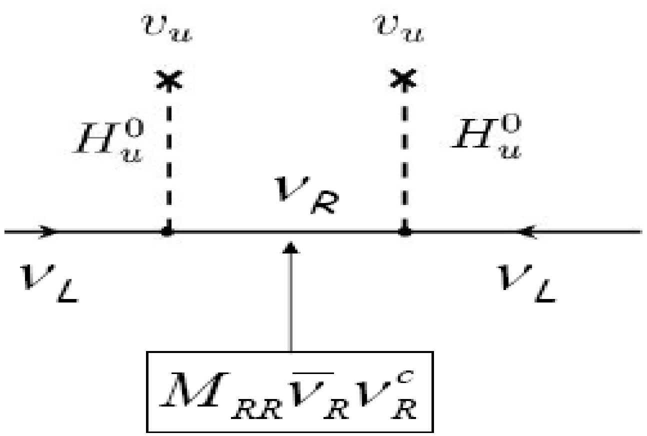
Blanchet,Chacko, R. N. M., 2008
arXiv:0812:3837

Why $m_\nu << m_{q,l}$?

Seesaw Paradigm

- **Three types of Seesaw:**
- **Type I:** **Add right handed neutrinos** N_R **to SM with Majorana mass:** $L_Y = h_\nu \bar{L} H N_R + M_R N N$
- M_R Breaks B-L : New scale and new physics beyond SM.



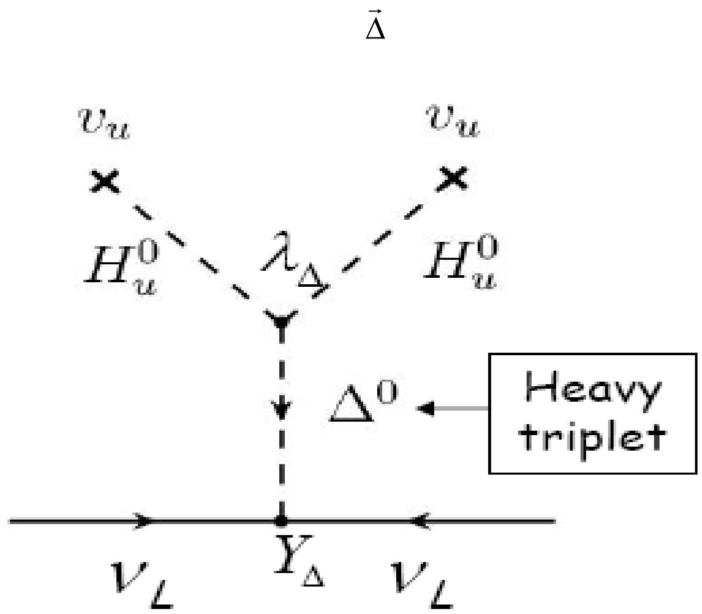
- After electroweak symmetry breaking

$$m_\nu \cong -\frac{h_\nu^{\ 2} v_{wk}^{\ 2}}{M_R}$$

Type II Seesaw

- **Type II:** Break B-L symmetry by adding a triplet Higgs $\vec{\Delta} = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- $\vec{\Delta}$ acquires a vev:

$$v_{\Delta} = \lambda_{\Delta}\mu \frac{v_{wk}^2}{M_{\Delta}^2}$$



$$m_{\nu} = Y_{\Delta} v_{\Delta}$$

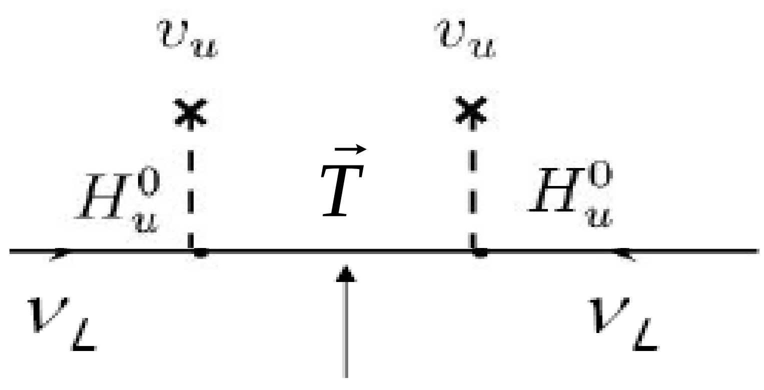
Type III seesaw

- **SU(2)-triplet fermion with Y=0:** $\vec{T}$

$$L = h\overline{L}\,\vec{\tau}H\vec{T} + M_R\vec{T}\cdot\vec{T} + h.c.$$

- **Same formula as in type I.**

$$m_\nu \cong -\frac{h_\nu{}^2 v_{wk}{}^2}{M_R}$$



Testing the seesaw idea at LHC

Most seesaw models prefer MR scale in the hard to test range above 10^9 GeV –nothing wrong with having it in LHC avvessible range of a few TeV's:

(i) The seesaw scale be in the TeV range

- **Type I and III case:** M_R **can naturally be in the TeV range if** $h_\nu \approx 10^{-5.5}$ **;**
  (Natural since h_ν **=0 is protected by chiral sym.** $N \leftrightarrow -N$ **)**

$$m_\nu \cong -\frac{h_\nu^{\,2} v_{wk}^{\,2}}{M_R}$$

(ii) New particles associated with seesaw $(N, \vec{T}, \vec{\Delta})$ accessible at LHC:

LHC prospects for minimal seesaws

- **Type I: No new interaction**: N production can happen only through $\nu - N$ mixing for M_N in sub-TeV range and only if $\nu - N$ mixing is > 10^{-2} **(del Aguila,Aguilar-Savedra, Pittau; Han, Zhang)** – However for type I case**,**
- **Tiny** m_ν **and 100 GeV** M_N **implies** $h_\nu \approx 10^{-5.5}$ **and** $\theta_{\nu N} \approx 10^{-6}$**; production at LHC suppressed.**
- **II and III case, the new particles are SU(2) nonsinglets and produced enough in pp coll.**

Situation different with Type I + new forces

- With new gauge forces e.g. B-L coupled to RH neutrinos, Type I seesaw can be tested despite tiny $\theta_{\nu N}$;
- Simple possibility is a B-L gauge force coupling to matter e.g. $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$

  or $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- This provides new signals for seesaw at LHC e.g. Z', doubly charged Higgs etc.

$$Z' \rightarrow NN; N \rightarrow lH$$

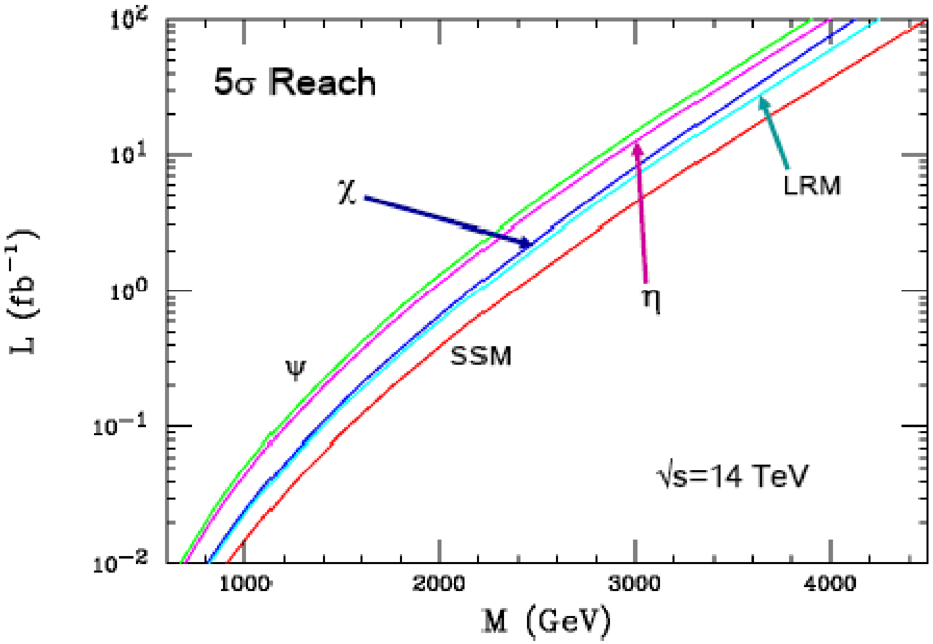
Justification for B-L Sym:

- **No symmetry restriction->** natural seesaw scale could be Planck scale but expts say it is much lower: **B-L gauge symmetry would provide rational for lower seesaw scale.**
- There should then be a gauge boson associated with this: **Z';** This theory also has **N -> -N** sym, so that seesaw can give small nu-masses naturally.
- **Z' could be in the TeV range and visible at LHC.**
- $Z' \rightarrow NN; N \rightarrow lH$ **a rich source of information about neutrino mass physics.**

Z'- Reach at LHC:

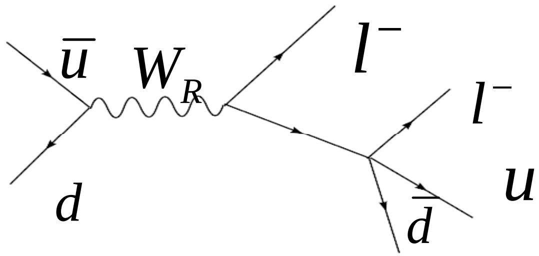
- (Petriello, Quackenbush; Rizzo; Del Aguila, Aguilar-Savedra)
- **LHC can detect Z' upto 4 TeV**
- Ascertaining Z' corresponds to B-L via SM fermion decays; (Clean upto $M_{Z'}$ =2 TeV)
- Search for Z'-> NN

  with each N->ljj



Type I seesaw and Parity Invariance at TeV Scale

- **LR gauge group:** $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- New gauge bosons **W_R and Z':**
- **Collider limits on W_R and Z':** around 780- 800 GeV.
- **Low energy limits:** K-K-bar, CPV, edm etc: WR mass > 2.5 TeV. **(Zhang et al. 2007-08)**
- **Limits from Neutrinoless double beta decay+ vacuum stability:** **(RNM; M.Hirsch, Kovalenko,Klapdor)** WR mass > 1.5 TeV.
- Like sign dilepton signal:



- **(Keung, Senjanovic'82)**

Type II and III case

- Type II case: Doubly charged Higgs decaying only to like sign dileptons;

$$\Delta^{++} \rightarrow \mu^{+}\mu^{+}, ee, \tau\tau$$

$$\Delta^{++} \rightarrow H^{+}H^{+}$$

Gunion, Loomis and Petit; Akyroid, Aoki; Azuelos et al.,Lusignioli, Petrarca,Mukhopadhyaya,Perez, Han,Wang,Si; Huitu,Malaampi,Raidal; Dutta.., Xing,..

- Type III case: fermion triplet production:

$$T^{+} \rightarrow \nu H^{+}; T^{-} \rightarrow l^{-}H^{0}$$

- (Bajc, Senjanovic, Nemec; Franschesini, Hambye, Strumia)

Type II case: Triplet Higgs decay mode:

- Key parameter in LHC search is triplet vev: v_Δ
- L= $h_{\alpha\beta}\ell^T_{L\alpha}Ci\sigma_2\Delta\ell_{L\beta} + \mu H^T i\sigma_2\Delta^\dagger H + h.c.$

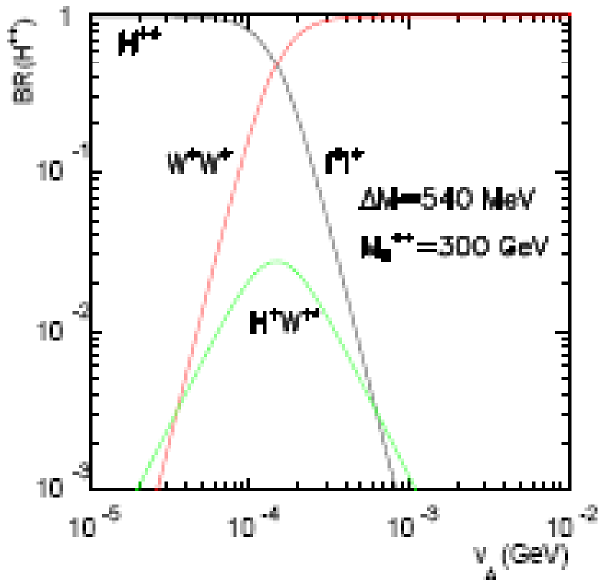
$$m_\nu = h v_\Delta$$

Current Delta mass limit >150 GeV:

- $v_\Delta < 10^{-4} GeV$: dominant decay to like sign leptons

(possible LHC Δ mass reach-1 TeV)

- $v_\Delta \geq 10^{-4} GeV$: dominant decay to WW; WH, HH



Han et. Al.

Baryogenesis:

- Understanding the origin of matter is a fundamental problem in both cosmology and particled physics.
- There are many ways of implementing Sakharov's requirements for solving this problem:

Moment of genesis

- (i) GUT baryogenesis
- (ii) Leptogenesis
- (iii) Spontaneous baryogenesis
- (iv) Dirac Leptogenesis
- (v) Affleck-Dine baryogenesis
- (vi) EW baryogenesis
- (vii) Post-sphaleron baryogenesis
- Low scale seesaw, we don't have std leptogenesis; we do not discuss resonant leptogenesis:

$$\left.\right\} T_B \geq T_{wk}$$

$$T \leq T_{wk}$$

Baryogenesis constrains weak scale seesaw (strongly)

- **New Result:** if baryogenesis is high scale origin: $T_B > T_{sphaleron}$ and seesaw is at TeV scale, signals of seesaw physics at LHC must be highly restricted:
- For type I seesaw and TeV scale Z',

(i) Normal nu hierarchy: at least one of the N's must be electrophobic;

(ii) Inverted and quasi-degen. Neutrinos, all RH nus must be: $M_N <$ 1 TeV or < 300 GeV

(iii) Similar restrictions for type II and III.

(Blanchet, Chacko, RNM'08)

Basic Idea-Type I case

- **With TeV scale seesaw, there are L-violating decays and inverse decays in equilibrium;**

e.g. $l + H \rightleftarrows N, \ldots$ With rates,

$$\Gamma \sim m_\nu \frac{M^3}{v_{wk}^2 T} \sim 10^{-11} GeV \quad ; \quad H(TeV) \sim 10^{-11} GeV$$

- **These processes can then be in equilibrium above T=80+0.45 M_H, the sphaleron dec. temp. above certain mass for N;** (Same way for $\vec{\Delta}'s, \vec{T}'s$)
- **In combination with B+L violating sphaleron effects, they will then erase any pre-existing B- asymmetry; restrict TeV scale seesaw physics.**

Few Preliminaries:

- We do a model indep. discussion using **Casas-Ibarra** parameterization:

$$h_{\alpha i} = (U\sqrt{D_m}\Omega\sqrt{D_M})_{\alpha i} / v_{wk}$$

- K-parameter relevant in washout:

$$K_{i\alpha} = \frac{\widetilde{\Gamma}_{\rm D}(N_i \to \ell_\alpha H + \bar{\ell}_\alpha H^\dagger)}{H(z_i = 1)} = \frac{1}{m_\star}\left|\sum_j \sqrt{m_j} U_{\alpha j} \Omega_{ji}\right|^2 .$$

- $m_* \sim 0.001$ eV
- Ω is complex orthogonal matrix relating Dirac Yukawa to masses and mixings and model dependent; we take it ~1 or less. Larger Ω means more washout.

Implications for LHC signals of seesaw

- **Assume, baryon asymmetry generated by some higher scale (> TeV) mechanism.**
- The washout factor is W(z) with $W(z) \propto \sum_i K_{i\alpha}$

$$Y_{B/3-L_\alpha}(z) = Y^{\text{in}}_{B/3-L_\alpha} \exp\left[-\int_{z_{\text{in}}}^{z} dz'\, W_\alpha(z')\right];$$

- m_* ~ 0.001 eV; Roughly K > 12 is “bad” **(All our bounds are based on 10^6 washout- a very conservative requirement);**

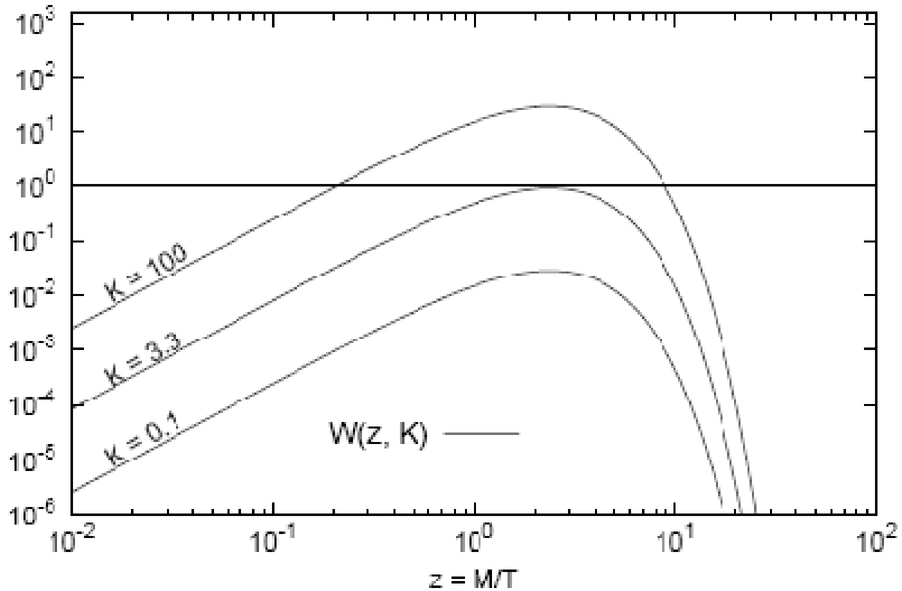
More Precise Information:

- Washout curves: **(Buchmuller, Di Bari, Plumacher)**

- **Z=M$_N$/T**

Washout of 10^6 puts precise upper bounds on M$_N$. Less washout means stronger bounds:

W(z)



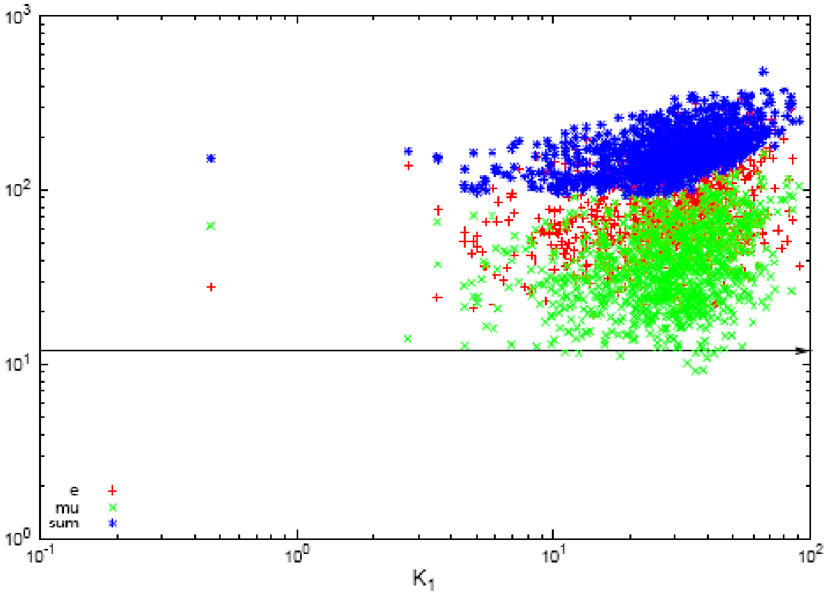
$$W_\alpha(z) = \frac{1}{4}\sum_i K_{i\alpha}\kappa_1(z_i)z_i^3$$

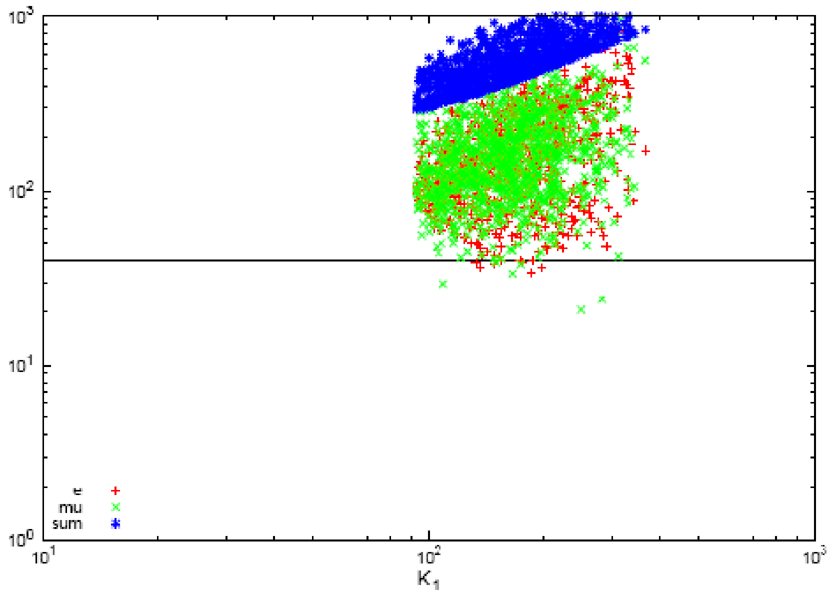
FIG. 1: Washout function $W(z)$ for different values of K.

Origin of the mass limit

Inverted case: **Deg case:**

$\sum_i K_{i\alpha}$





e.g. in the deg. Case, if M>300 GeV, then in 99% of parameter space for neutrino mass parameters, there is more than 10^6 washout. (the remaining highly fine tuned)

Neutrino mass patterns and LHC implications:

- **(i) Inverted mass hierarchy**: All RH neutrinos **(N)** must have **M_N <1 TeV**
- **(ii) Quasi-degenerate case**: **M_N < 300 GeV**
- **(iii) Normal hierarchy:** $\sum_i K_{ie} \cong 2$ whereas all other K's are >12; e-flavor escapes washout constraint. In this case, at least one of the RH neutrinos must be electrophobic i.e. it decays predominantly to mu and taus.

How to see electrophobicity ?

- All RH (N) neutrino decays depend on nu-N mixing-
- Using $$B_{i\alpha} \equiv \frac{\left|\sum_j \sqrt{m_j} U_{\alpha j} \Omega_{ji}\right|^2}{\sum_j m_j |\Omega_{ji}|^2}.$$;For $|\Omega| \leq 1$

for $m_1 << m_{solar}, U_{e3}$ small, one gets

$$B_{ie} << B_{i\mu, i\tau}$$

Type II Seesaw case:

- **One triplet with Y=2:**
- What is the wash out parameter ?
- It must involve a product of $ll \rightarrow \Delta$ process with $\Delta \rightarrow HH$. Both essential.
- We define it as :

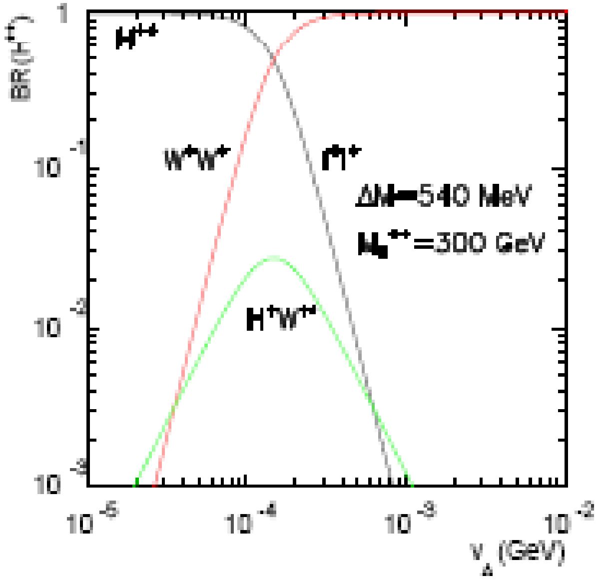
$$K^{II} = \frac{\Gamma_1 \Gamma_2}{H(\Gamma_1 + \Gamma_2)}$$

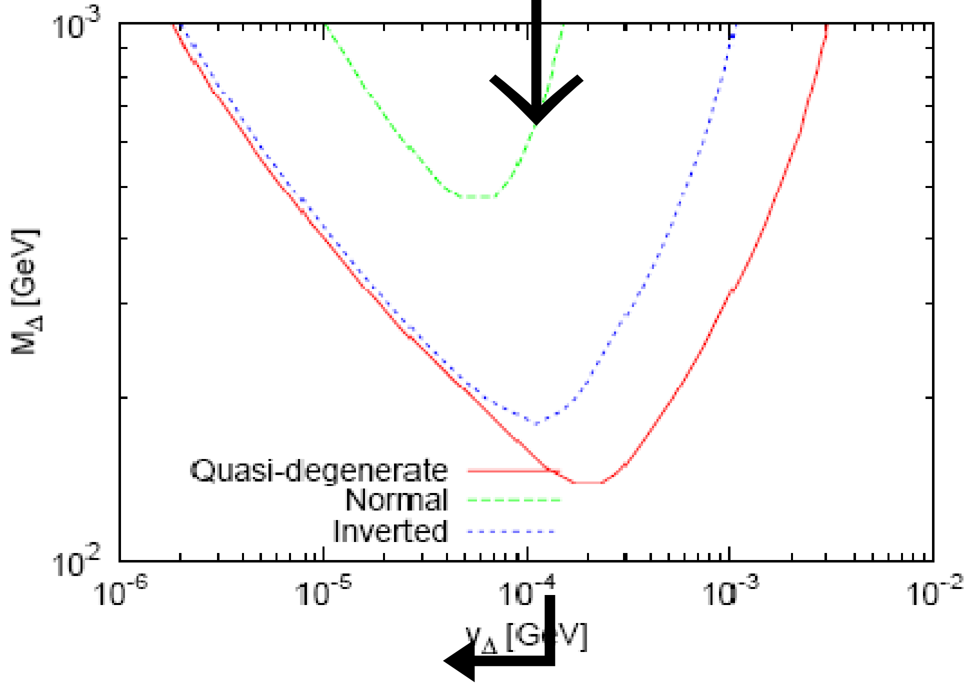
Type II seesaw (contd)

- Effective washout parameter is:

$$K_\alpha^{\rm II} = 12 \frac{M_\Delta^3 v_\Delta^2 \sum_k m_k^2 V_{\alpha k}^\star V_{\alpha k}}{m_\star (v_\Delta^4 M_\Delta^2 + v^4 \sum_k m_k^2)},$$

excess washout





dominant leptonic modes region

Other applications:

- **Type III Case:** Constraints very similar to type I case except that there are now 3 states and washout factor is 3 times larger than the type I case.
- **Low Scale Parity case:** Low scale parity also always leads to large washout due to the W_R mediated scattering processes e.g.

$$e_R + u_R \to N + d_R$$

when M_{W_R} < 100 TeV. Observing WR at LHC will rule out high scale baryogenesis.

(Frere,Hambye,Vertongen'08)

Weak scale One loop neutrino mass models:

- **Previous conclusion also applies to radiative loop models for nu masses**
- **However, if there is a low scale (< v_wk) lepton number violation, some weak scale radiative models can escape the bounds.**
- There are then light SM singlet Higgs fields below 100 GeV mass.
- **Double seesaw models also escape the constraints if there is a low scale L-violation.**

What have we learnt ?

- If we find the seesaw mediators at LHC in our forbidden range, we will eliminate the baryogenesis models for which $T > T_{wk}$.

- **LHC can throw light on one of the major mysteries of the universe.**

- **We will of course know what mass range the seesaw scale is.**