Can LHC falsify Leptogenesis ?

- Why focus on Leptogenesis ?
- Is it provable?
- We should take extra gauge interactions into account
- A discovery of W_R at LHC would kill it !

Roadmap to generating the observed matter-antimatter (baryon) excess

Generate B or L asymmetry at high scale

Electroweak phase transition occurs

Out of Equilibrium

Independently of pre-existing B or L
a new creation of B is possible, (with B-L=0 for the new contribution)

Electroweak Baryogenesis ??

Need many additions to SM,
Very difficult to establish or
to get a realiable estimate

At (or near) Equilibrium

Pre-existing B or L erased attacked by sphalerons / topological solutions but B-L is conserved

For SU(5) baryo, B-L=0, so
B and L totally erased. → no effect!

IF B-L ≠0, the proportions of
B and L are simply changed;
In particular, if only L was generated,
it can be changed into B

→ Leptogenesis

Leptogenesis

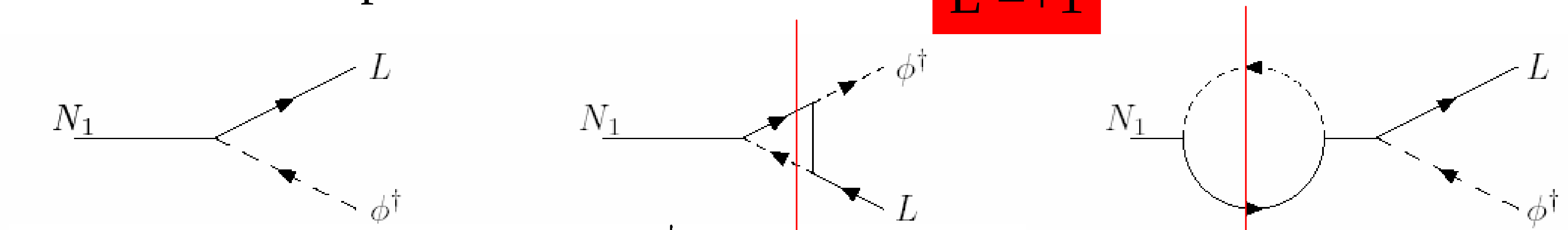
- Basic idea :generate L at higher temperature
- Use the electroweak phase transition near equilibrium to convert L → - B
  - Advantage: insensitive to the details of the sphaleron-based mechanism, provided the transition stays close to equilibrium until completion
- Use heavy Majorana neutrinos,
  - … because their inclusion has recently become very popular

How leptogenesis works….

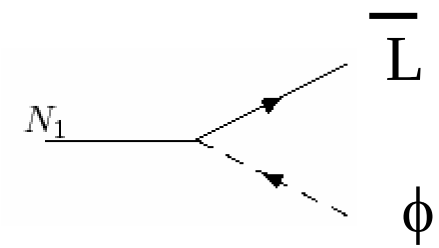
Assume that we have some population of heavy N particles…
(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.

Generation of lepton number

L =+1



N can decay to Lepton L + $\phi^\dagger$ as above, or to the opposite channel $\bar{L}\phi$



CP violation + Interference term leads to excess of L or anti-L

L =-1

Possible unitarity cuts

Constraints:

Heavy neutrinos must decay out of equilibrium

$$\tau(X) >> H^{-1}$$

$H = \dot{a}/a$ is the Hubble constant,

$$\tau^{-1} = \Gamma \cong g^2 M$$

$$H = \sqrt{g^*} \frac{T^2}{10^{19} GeV}$$

g^* is the number of degrees of freedom at the time

at decay : $T \approx M$,

Need enough CP violation;

for large splitting between neutrino masses, get

$$\varepsilon_i^{\phi} = -\frac{3}{16\pi} \frac{1}{\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ii}} \sum_{j \neq i} \mathrm{Im}\left(\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ij}^2\right) \frac{M_i}{M_j}.$$

Some rough estimations…

…What are the suitable values of λ and M?

Assume there is only one generic value of λ (in reality, a matrix)

$$\epsilon < \lambda^4/\lambda^2 \approx \lambda^2 > 10^{-8}$$

$$m_\nu = m^2/M \approx \lambda^2/M \approx .01eV$$

rough estimate of M scale (in GeV) needed…

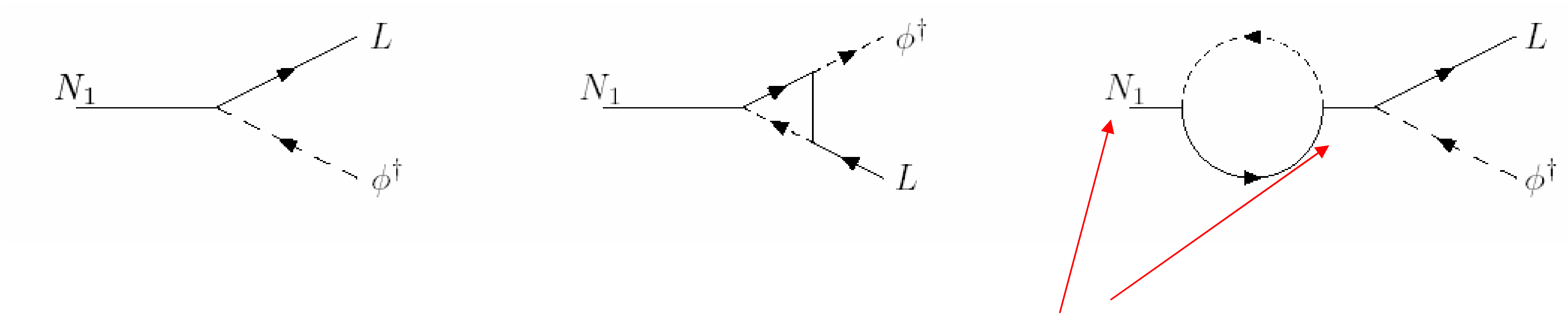
similar to τ lepton →

At the difference of baryogenesis, the Yukawa matrix λ leaves a lot of freedom

λ	light neutrino .01 eV M ~	decay out of equil. M>	enough CP viol
.00001	10^7	10^8	need tuning
.0001	10^9	10^10	
.001	10^11	10^12	
.01	10^13	10^14	
.1	10^15	10^16	
1	10^17	10^18	large

Could much lower values be reached?

Possible tuning: resonant leptogenesis



If the 2 neutrinos are nearly degenerate,
Pole amplification: CP interference becomes

of order 1 instead of λ^2

This far, the introduction of (heavy) right-handed neutrinos is quite arbitrary:f or light neutrino masses, it amounts to introducing a large M instead of a very small Yukawa.

It only makes sense if the new, heavy neutrinos are involved in some unification scheme.
This could be SO(10), E(6), or other groups,
(even badly broken)
W_R and Z' bosons linked to e_R and N exist;

Contributions to N mass also contribute to W_R, and these should not be neglected.

$$SU(5) \subset SO(10)$$

and the fermions come in nice representations

$$16 = \bar{5} \oplus 10 \oplus 1$$

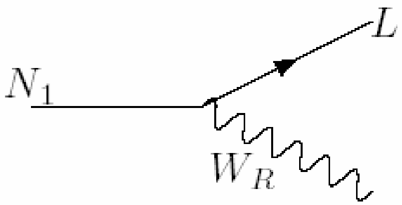
where "1" is precisely N_R

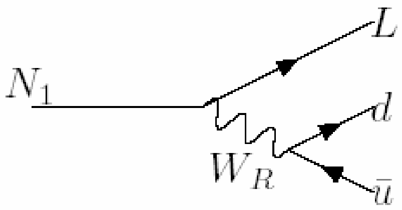
with the gauge inclusion

$$\epsilon_1 = \frac{\epsilon_1^0}{1+X}$$

diluted CP asymmetry

$\underline{M_{W_R} < M_{N_1}}$ $\underline{M_{W_R} > M_{N_1}}$





In rough terms …

Dilution factor X ?

$$a_w = \frac{M_{W_R}^2}{M_1^2}$$

- $M_{W_R} < M_1 \quad \Rightarrow \quad$ 2-body decay
  - $\Rightarrow$ X Large $\sim 10^4 - 10^5$
  - $\Rightarrow$ too much dilution

  $\times$

- $M_{W_R} > M_1 \quad \Rightarrow \quad$ 3-body decay
  - $\Rightarrow X = \frac{3g^4 v^2}{2^7 \pi^2} \frac{1}{\tilde{m}_1 M_1 a_w^2}$
  - $\Rightarrow a_w \sim 10 \Rightarrow X \sim 10$

  $\surd$

In fact, the presence of WR will prove beneficial in some cases (re-heating after inflation)

Final Baryon asymmetry:

$$Y_{\mathcal{B}}^{\text{fin}} = Y_{\mathcal{L}}^{\text{fin}}\, r_{\mathcal{L}\to\mathcal{B}} = Y_N^{eq}\, \varepsilon_{CP}\, \eta\, r_{\mathcal{L}\to\mathcal{B}}$$

Conversion to Baryon nb through Sphalerons Approx . -28/79

Initial heavy neutrino population

Efficiency, Suppression by scattering, including dilution by R sector

CP asymmetry

Testing Leptogenesis

Type I Leptogenesis Testability:

1. If N_{iR} are hierarchical Then successful Leptogenesis requires $m(N_R) > 10^8$ GeV ✘
2. If N_{iR} are degenerate Then Leptogenesis possible at low scales, but $m(\nu_\alpha)$ require suppressed Yukawa couplings ✘
3. ▸ Casas-Ibarra parameterization of Yukawa [NPB 618(2001)171]

   $$\lambda = \sqrt{m_N}\, R \sqrt{m_\nu}\, U^\dagger$$

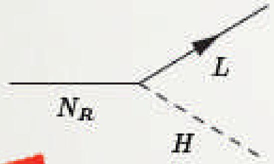
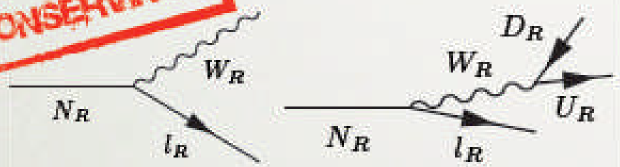
   CP violation at low energies governed by U ✘
   CP violation at high energies governed by $\lambda\lambda^\dagger \neq f(U)$!

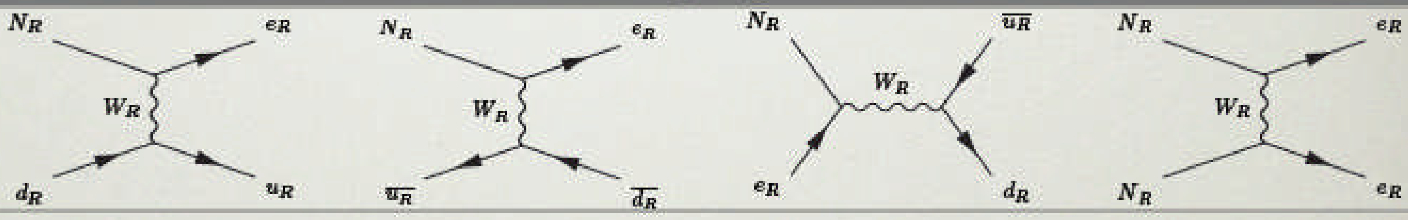
   $\Rightarrow \nexists$ direct link between CP violation at high & low energies
   [Branco et al. 2001, Pascoli et al. 2006, Davidson et al. 2007, ...]
4. ??

If not testable, could leptogenesis at least be *falsified* ?

Can LHC disprove Leptogenesis ?

EFFECTS OF A LOW SCALE W_R

Decays	Diagrams	CP Violation	Efficiency
Yukawa		$\varepsilon_{CP}^{(0)} \equiv \frac{\Gamma_{N\to LH} - \overline{\Gamma}_{N\to \bar{L}H^*}}{\Gamma_{\rm tot}^{(l)}}$ "Each N decay could gives ΔL=1"	$\eta \leq 1$
Gauge	CP CONSERVING ! 	$\varepsilon_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}}$ Dilution ! $= \frac{\Gamma - \overline{\Gamma}}{\Gamma_{\rm tot}^{(l)}} \frac{\Gamma_{\rm tot}^{(l)}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}}$	$\eta \leq \frac{\Gamma_{\rm tot}^{(l)}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}}$

Scatterings	Diagrams
Gauge	

Strong Thermalization

$\Rightarrow$ Easier to produce neutrinos @ Reheating ✓

$\Rightarrow$ Harder decoupling @ Low T° (Washout) ✗

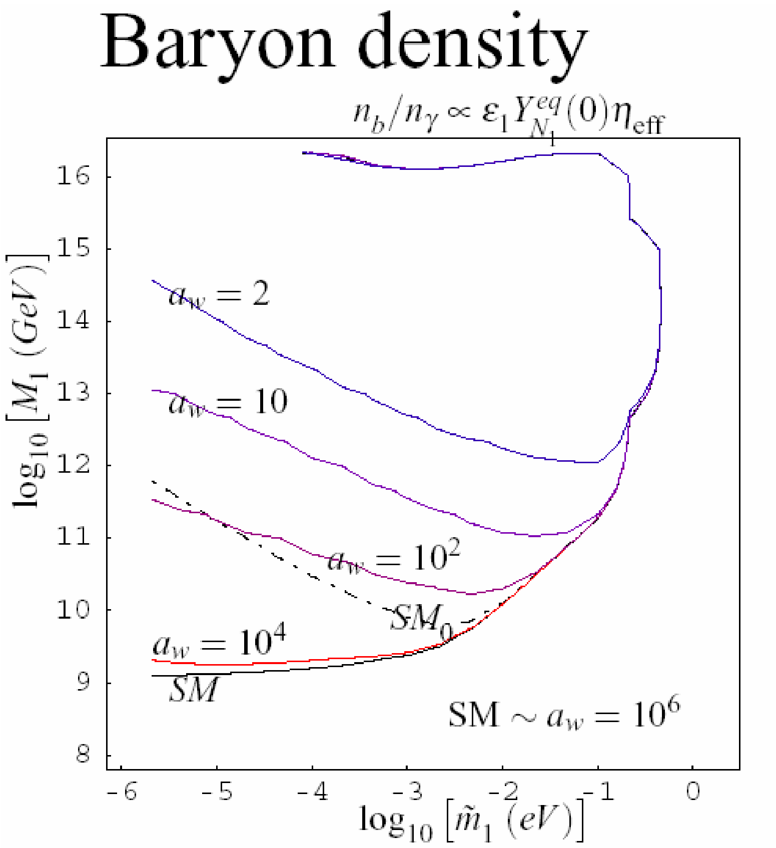
Due to the relatively high abundance of targets

Right-handed W
Can have both enhancing
And damping effects

Allowed contours in $M_1 - \tilde{m}_1$ plane,

solid line = thermal Majorana initial population

dashed line = Majorana population rebuilt after reheating



2 effects :

- more dilution leading to heavier MR,
- suppression in re-heating scheme lifted .

$$a_W = \frac{M^2_{W_R}}{M^2_1}$$

N Cosme JHEP 0408:027,2004.

hep-ph/0403209

A few usefull references… among many :
initial work :
85-86 Kuzmin, Rubakov, Shaposhnivov L--B transition
Fukugita, Yanagida
96 Covi, Roulet,Vissani
around 2000 : revival by Buchmüller,Plümacher,
… large number of papers…

Very strong constraints claimed…

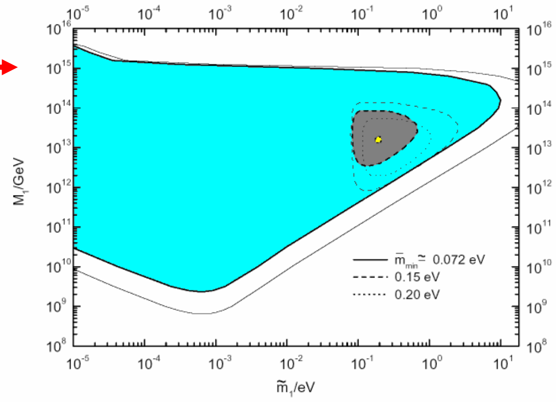


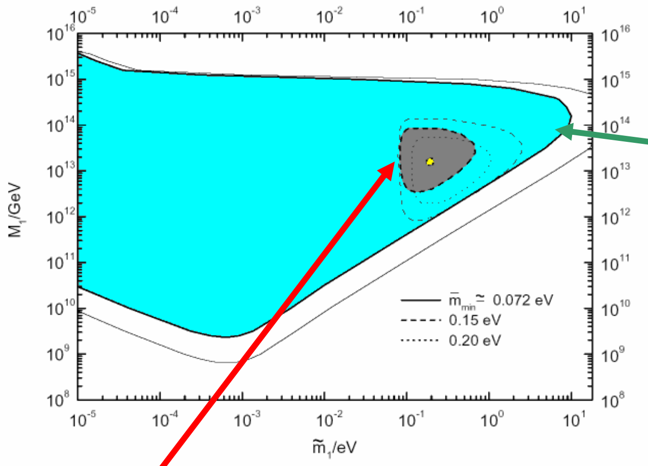
Figure 4: Inverted hierarchy case. Curves, in the ($\tilde{m}_1$-M_1)-plane, of constant $\eta_{B0}^{max} = 10^{-10}$ (thin lines) and $\eta_{B0}^{max} = 3.6 \times 10^{-10}$ (thick lines) for the indicated values of $\overline{m}$. The filled regions for $\eta_{B0}^{max} \geq 3.6 \times 10^{-10}$ are the *allowed regions* from CMB. There is no allowed region for $\overline{m} = 0.20\,$eV.

detailed study and review:
Giudice, Notari, Raidal, Riotto , Strumia hep/ph0310123

critical discussion on limits on masses and couplings
Hambye, Lin, Notari, Papucci, Strumia hep/ph0312203

..many papers on alternate mechanisms…

also : influence of lepton flavours, N2 and N3:
Abada, Davidson, Josse-Michaux, Losada, Riotto hep/ph O601083
Nardi, Nir, Roulet, Racker hep/ph O601084



on this side, too large λ leads to excessive wash-out

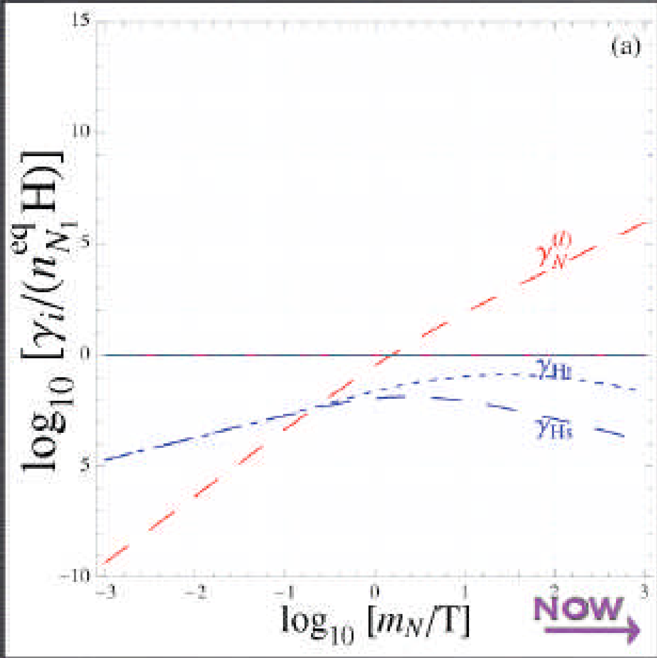
for instance, this side of the constraint assumes zero initial N after reheating, and requires large λ to re-generate them
this is very model-depdt!

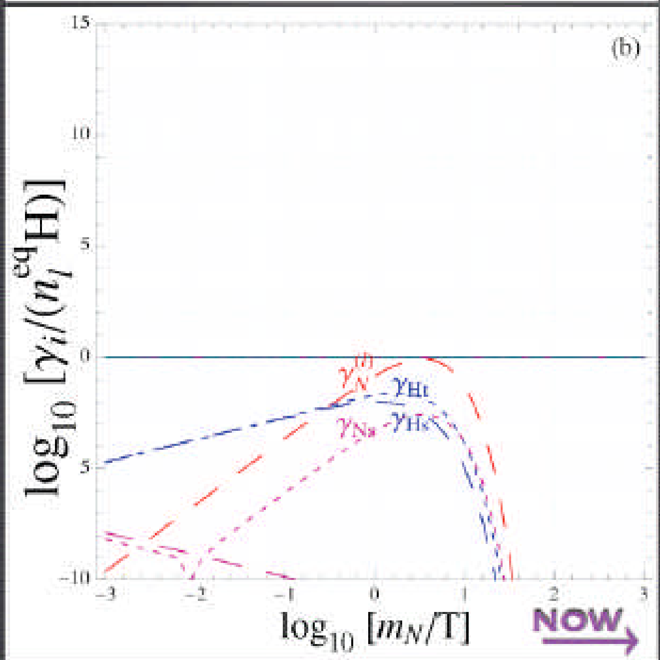
Can LHC disprove Leptogenesis ?

based on JHEP 0901(2009)051

J.M.Frère, T.Hambye & G.Vertongen
(Université Libre de Bruxelles)

Interaction Rates



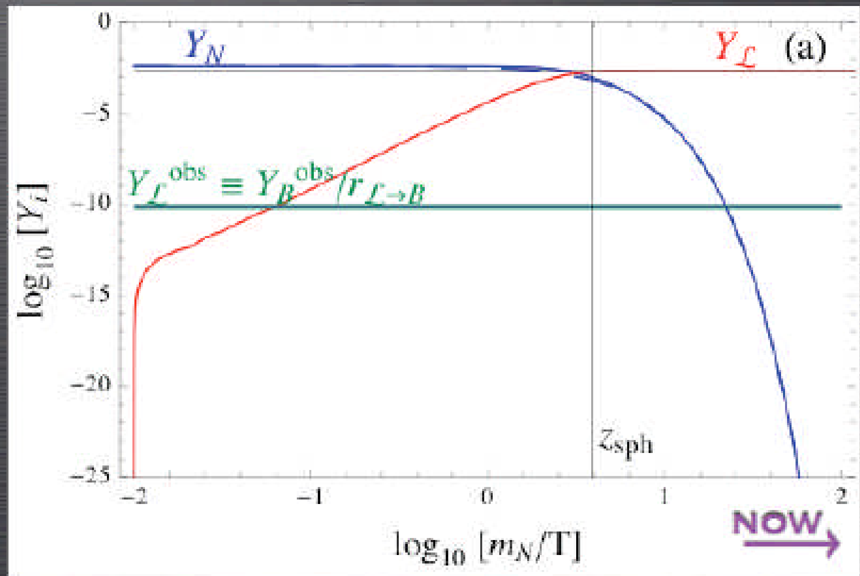


Example of Gauge Effects

m(N) = 500 GeV $m(W_R)$ = 3 TeV   m1 = 10^{-3} eV

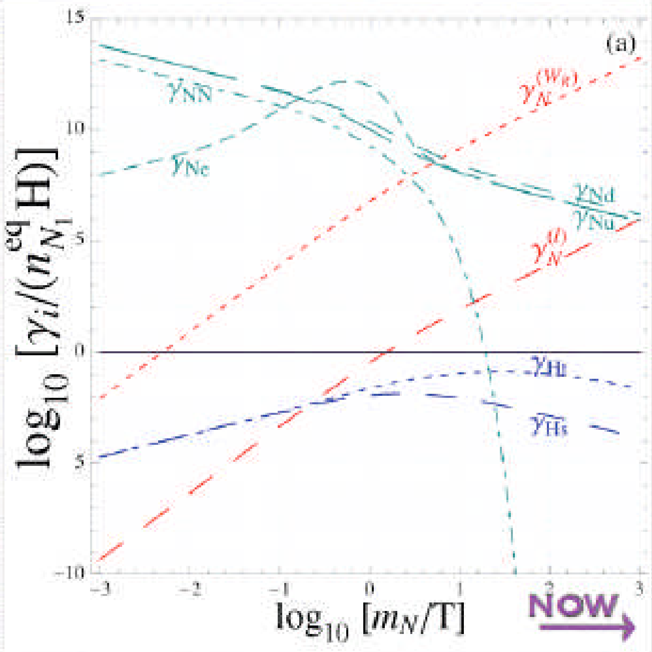
Case	Content	η	Y_B
(a)	Standard Leptogenesis	0,5	6.10^{-4}

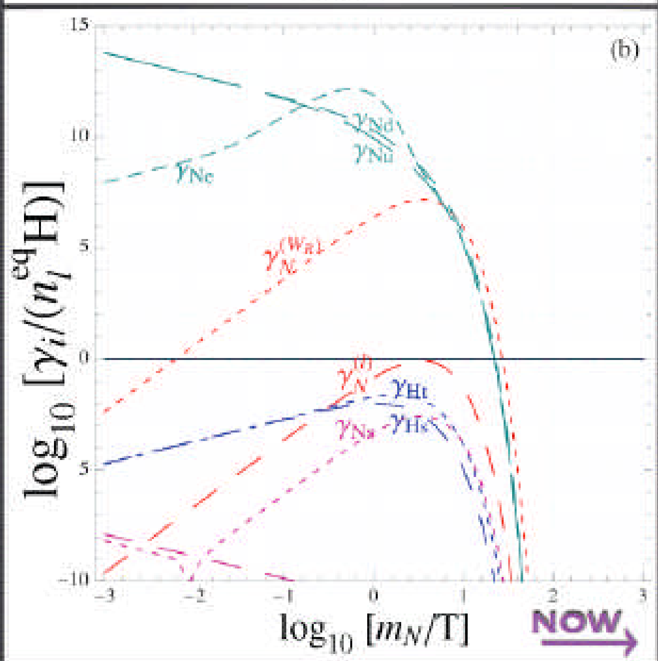
Asymmetry Evolution



Can LHC disprove Leptogenesis ?

Interaction Rates



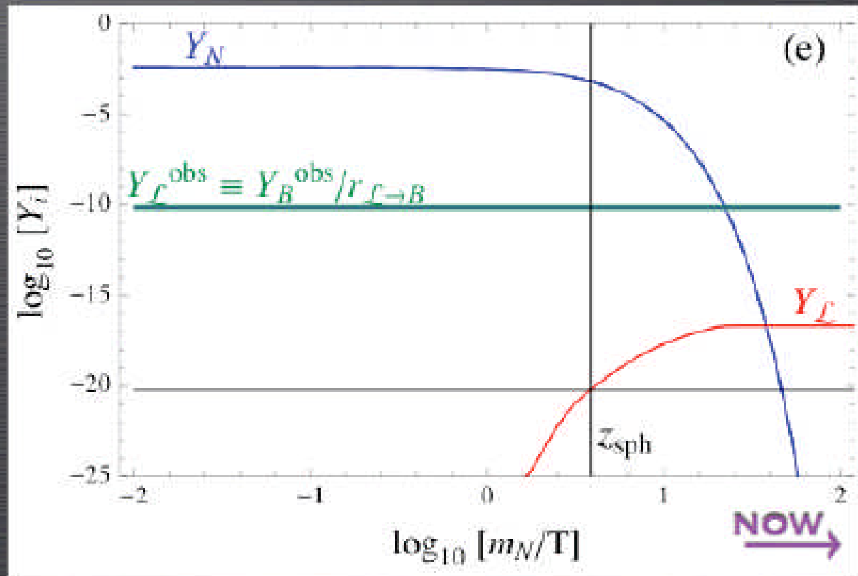


Example of Gauge Effects

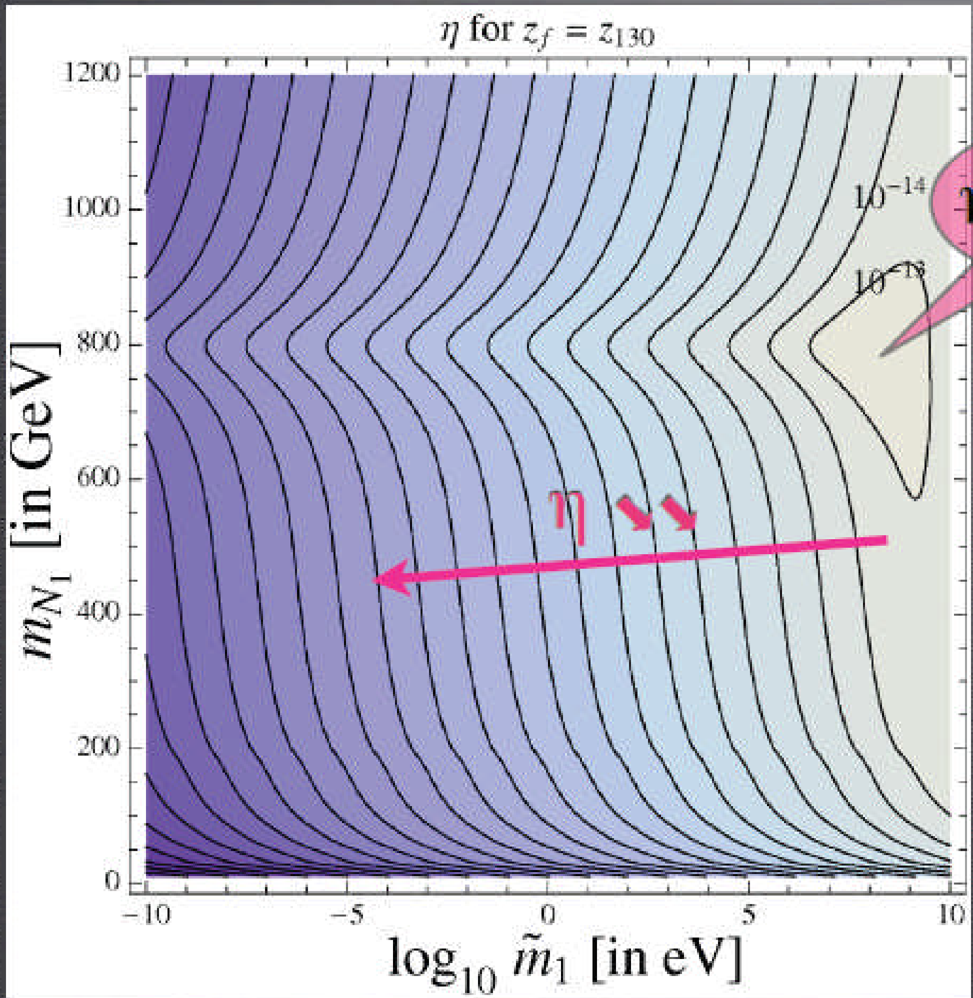
m(N) = 500 GeV $m(W_R)$ = 3 TeV   m1 = 10^{-3} eV

Case	Content	η	Y_B
(a)	Standard Leptogenesis	0,5	6.10^{-4}
(b)	(a)+W_R decays in Y_N	3.10^{-8}	4.10^{-11}
(c)	(b)+W_R scatterings in Y_N	2.10^{-10}	2.10^{-13}
(d)	(c)+W_R decays in Y_L	2.10^{-18}	2.10^{-21}
(e)	(d)+W_R scatterings in Y_L	2.10^{-18}	2.10^{-21}

Asymmetry Evolution



Efficiency Results



M(W_R)= 3 TeV

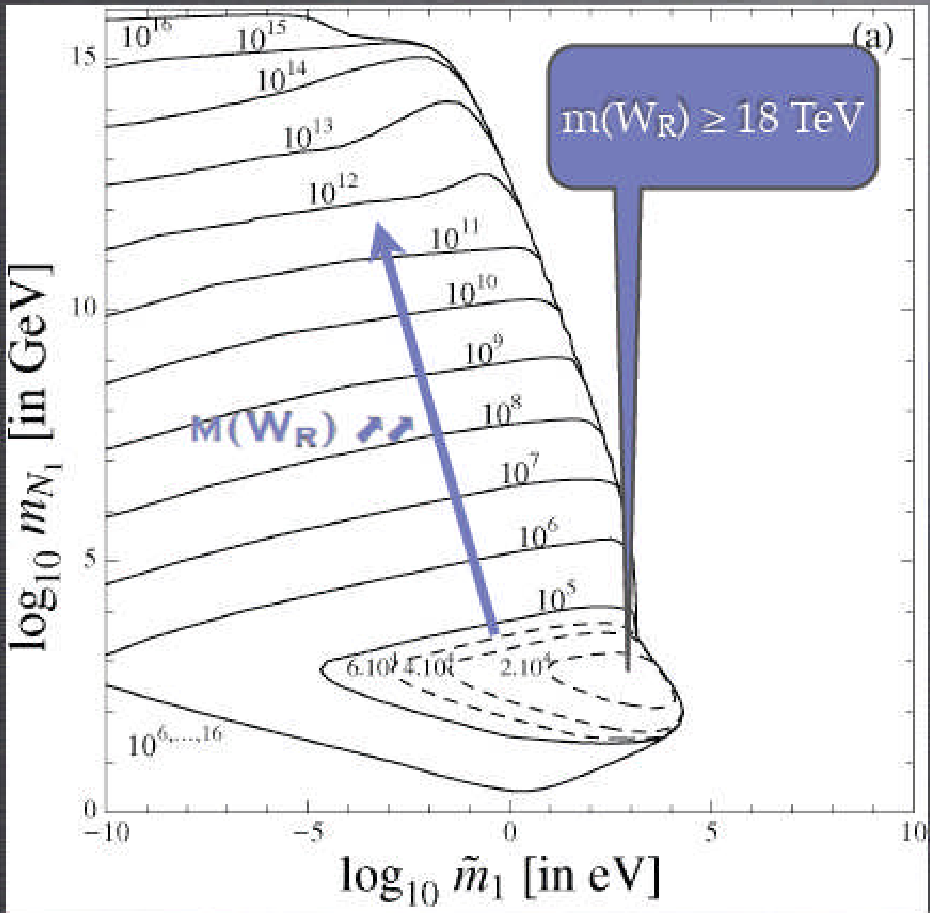
In any case :

$\eta < \eta_{MIN} = 7.10^{-8}$

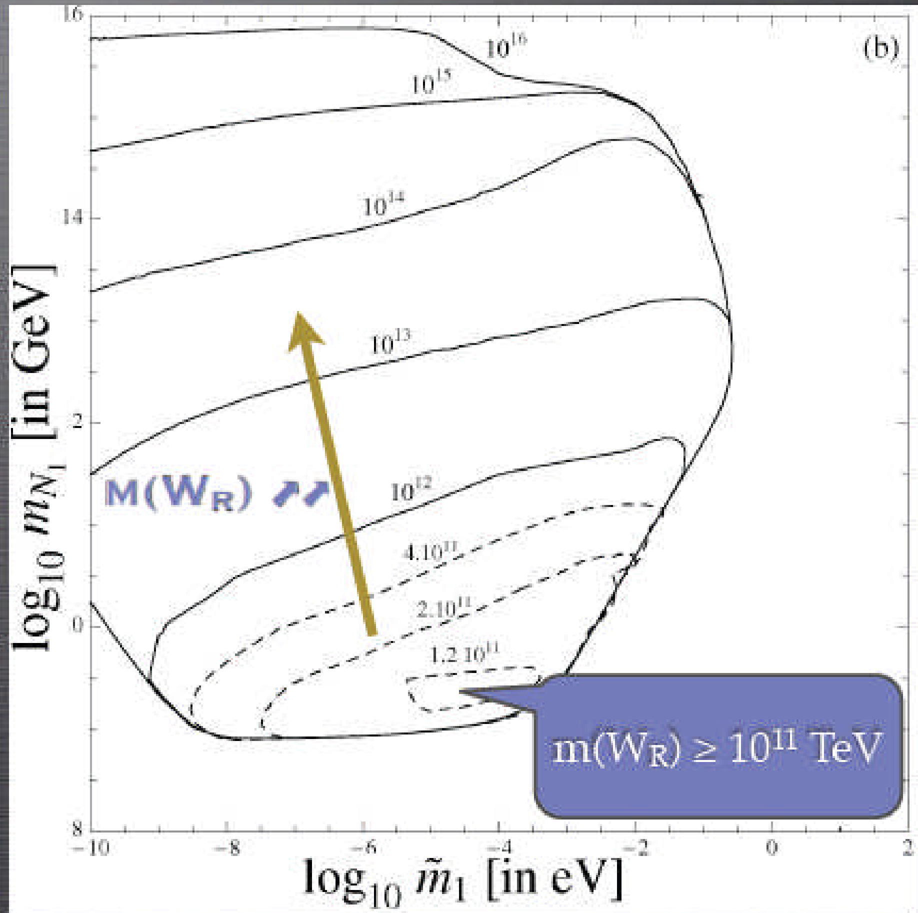
Type I Leptogenesis Disproved if W_R Discovered @ LHC

Bounds on M(W_R) & M(N_R)

For ε_{CP} = 1



For ε_{CP} = ε_{DI}



Prospects at LHC..

$u_R \bar{d}_R \rightarrow W_R \rightarrow N\, l^+ \rightarrow l^+ l^+ \bar{u}_R d_R$

$\rightarrow l^+ l^- u_R \bar{d}_R$

This analysis assumes N lighter than W_R;
should be generalized (one less mass constraint) or extended to quark sector (correlations in top decay)

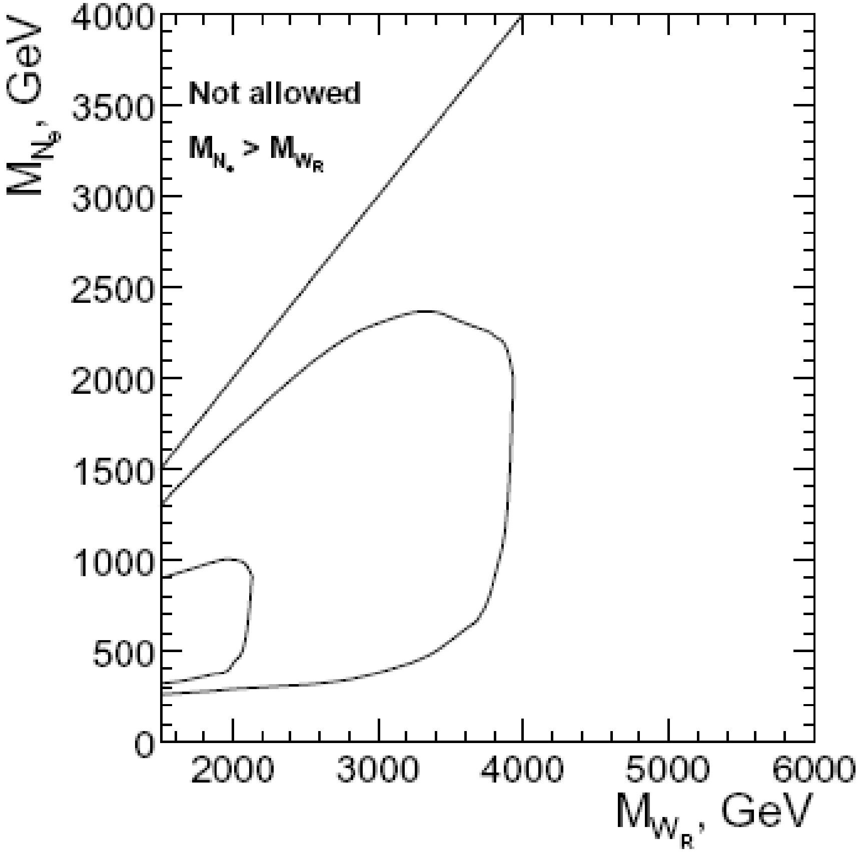


Figure 15.7: CMS discovery potential of the W_R boson and right-handed Majorana neutrinos of the Left-Right Symmetric model for the integrated luminosity $L_t = 30\ \text{fb}^{-1}$ (outer contour) and for $L_t = 1\ \text{fb}^{-1}$ (inner contour)

CMS Physics TDR2
(similar plots for Atlas)

Spotting a W_R without using the N

Pick up a paper:

Thks to Fabio Maltoni
for the Madgraph processsing

W_R identification at hadron colliders

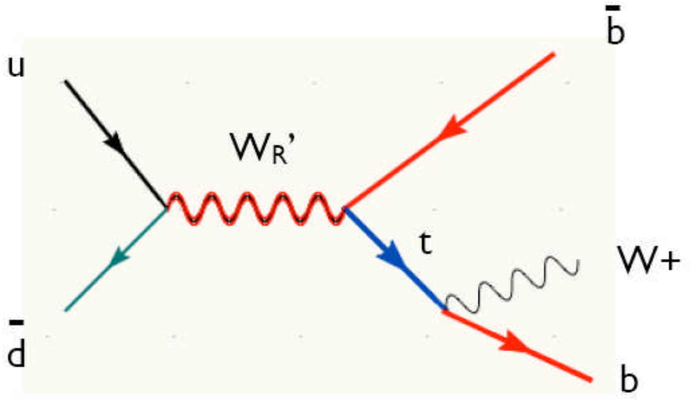
J.-M. Frère [a,b,1] and W.W. Repko [b]

[a] *Physique Théorique, CP225, Université Libre de Bruxelles, B-1050 Brussels, Belgium* [2]
[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

Received 5 November 1990 1990!

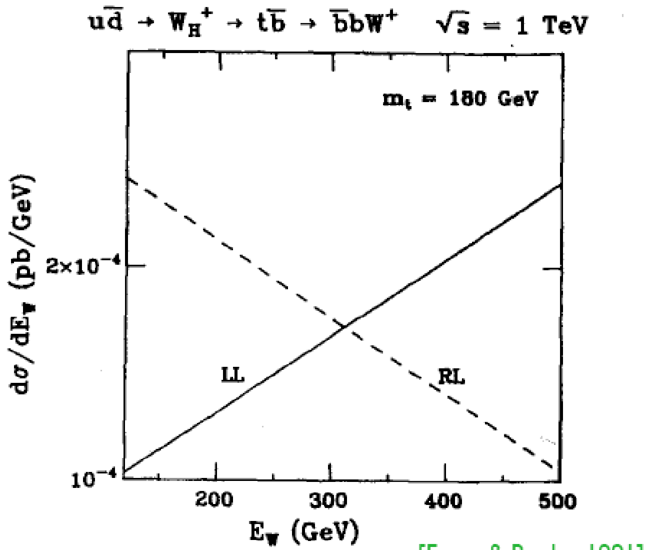
We study the process pp $(p\bar{p}) \to W_H \to \bar{b}t \to \bar{b}bW_L$, where W_H is a hypothetical heavy gauge boson. The differential cross section $d\sigma/dE_W$ is sensitive to the chiral structure of the W_H coupling. In particular, the heavy W_R expected from $SU(2)_L \times SU(2)_R \times U(1)$ models is clearly distinguishable from an additional W'_L.

and a Ph.D. student*



*thanks to R. Frederix

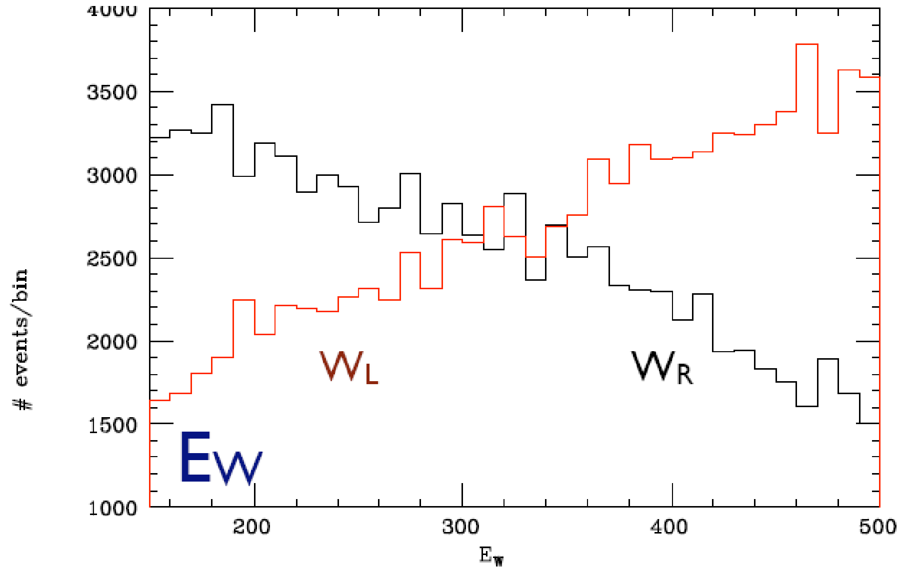
1.Validation

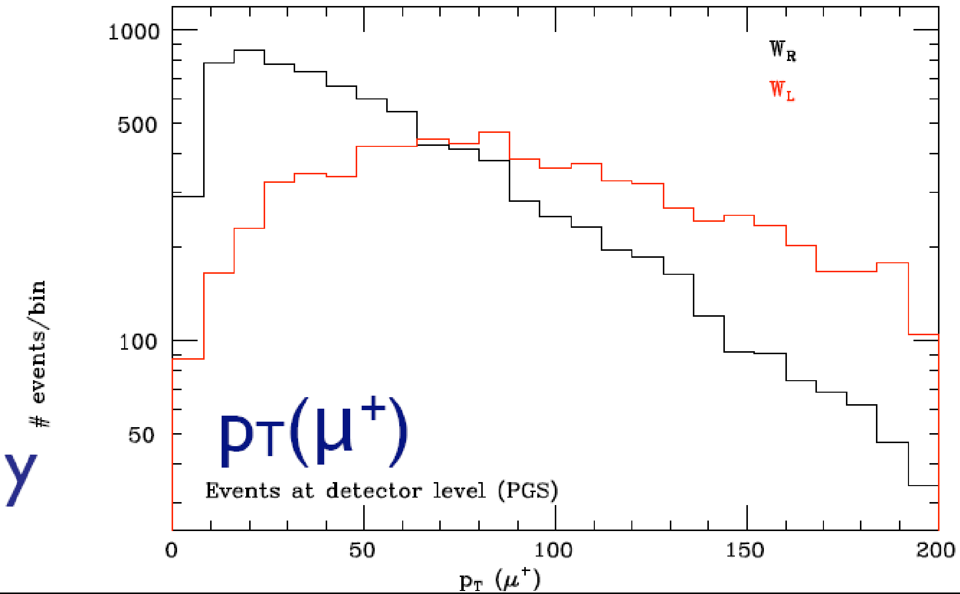


[Frere & Repko, 1991]

Fig. 1. The W energy distribution from t quark decay is shown for t production by the exchange of a heavy W_L (LL) and by the exchange of a heavy W_R(RL). The heavy W mass was taken to be 800 GeV.

2. Pheno⇒Exp study





Electroweak Baryogenesis ??

- **NOT favoured in Standard Model** :
  - •1^{st} order phase transition (requires light scalar boson) excluded by LEP
  - •CP violation insufficient in SM: (see next slide)
- **•Possible in some extensions, like SUSY**
  - •e.g. add extra scalars (including singlets and trilinear couplings to force a strong 1st order phase transition
  - •Extra CP violation needed
  - •Even in the best case, evaluation of the efficiency of the conversion mechanism difficult, due to extended solutions.

Leptogenesis is by far the most attractive way to generate the current baryon asymmetry,
It is extraordinarily sturdy and resilient, and almost hopeless to confirm

BUT

finding a W_R at a collider near you would kill at least the « type 1 » leptogenesis (= through asymmetrical N decay)

probably the only realistic way to EXCLUDE simple leptogenesis !