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

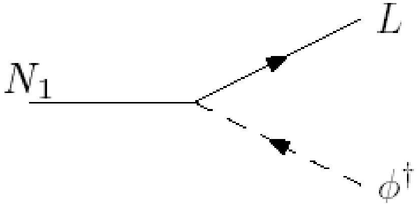
- Basic idea :generate L at higher temperature
- Use the electroweak phase transition near equilibrium to convert L → - B
  - Advantage: insensitive to the details of the sphaleron-based mechanism, provided the transition stays close to equilibrium until completion
- Use heavy Majorana neutrinos,
  -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

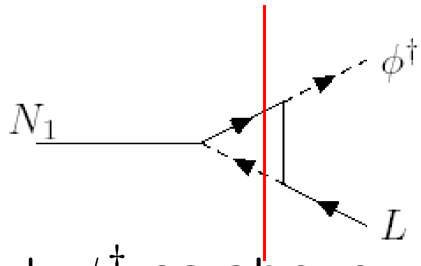
How leptogenesis works….

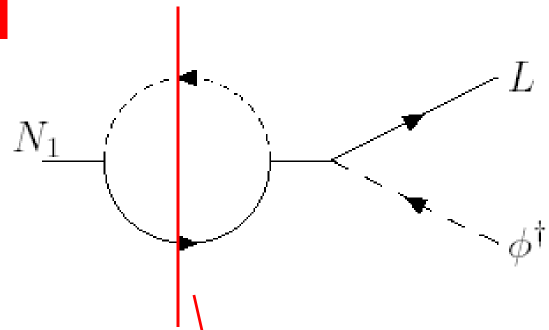
Assume that we have some population of heavy N particles…
(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.

Generation of lepton number

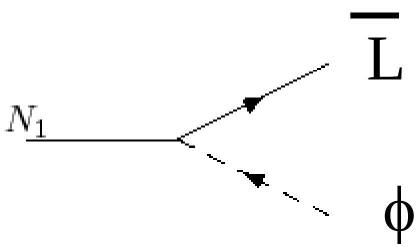
L =+1







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…

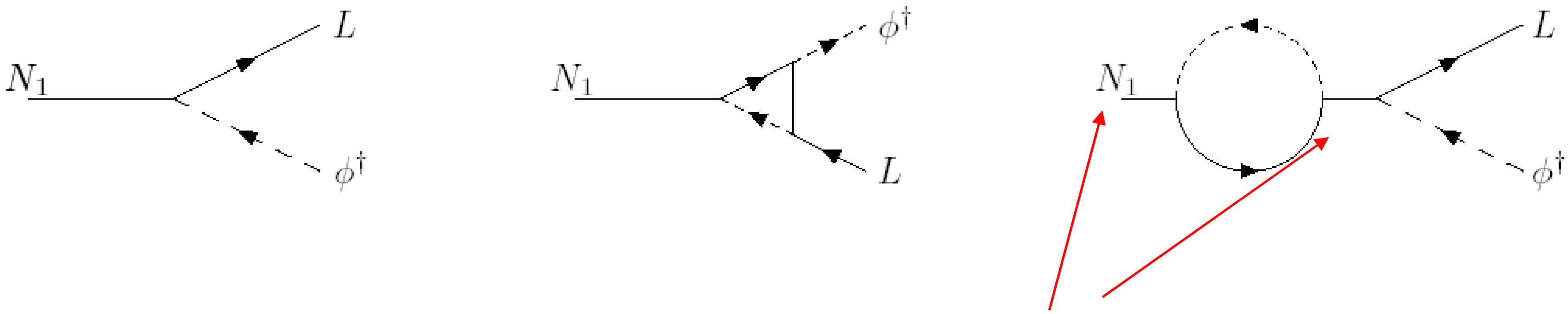
similar to τ lepton →

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

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

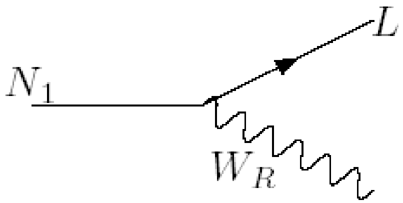
where "1" is precisely N_R

with the gauge inclusion

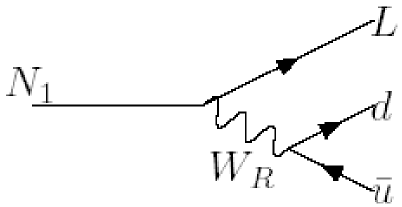
$$\epsilon_1 = \frac{\epsilon_1^0}{1 + X}$$

diluted CP asymmetry

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



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



In rough terms …

Dilution factor X ?

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

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

  } ✗

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

  } √

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 $\lambda\lambda^\dagger \neq f(U)$!

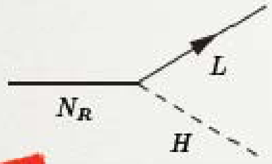
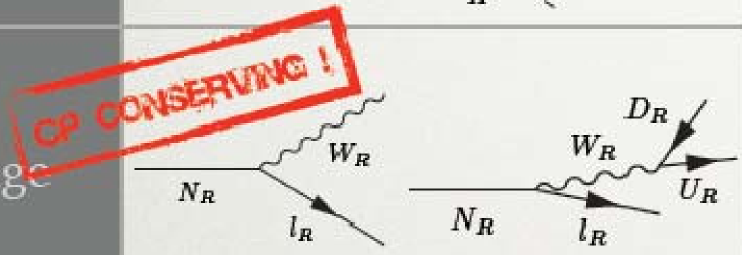
   $\Rightarrow \nexists$ direct link between CP violation at high & low energies
   [Branco et al. 2001, Pascoli et al. 2006, Davidson et al. 2007, ...]

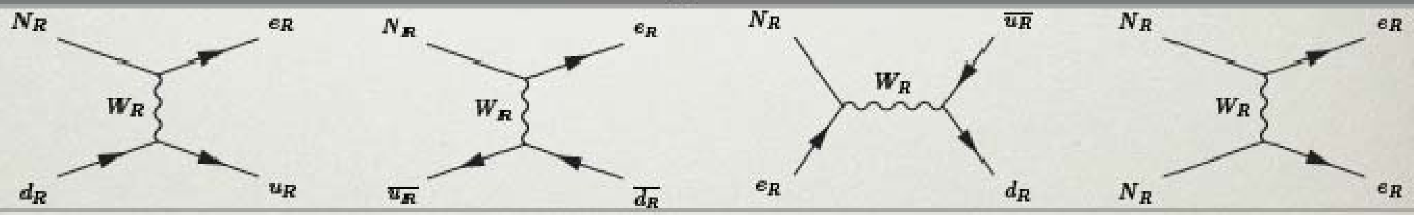
4. ??

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 $\triangle$L=1"	$\eta \leq 1$
Gauge		$\varepsilon_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}} = \frac{\Gamma - \overline{\Gamma}}{\Gamma_{\rm tot}^{(l)}} \cdot \frac{\Gamma_{\rm tot}^{(l)}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}}$ Dilution !	$\eta \leq \frac{\Gamma_{\rm tot}^{(l)}}{\Gamma_{\rm tot}^{(l)} + \Gamma_{\rm tot}^{(W_R)}}$

Scatterings	Diagrams
Gauge	

Strong Thermalization

$\Rightarrow$ Easier to produce neutrinos @ Reheating ✓

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

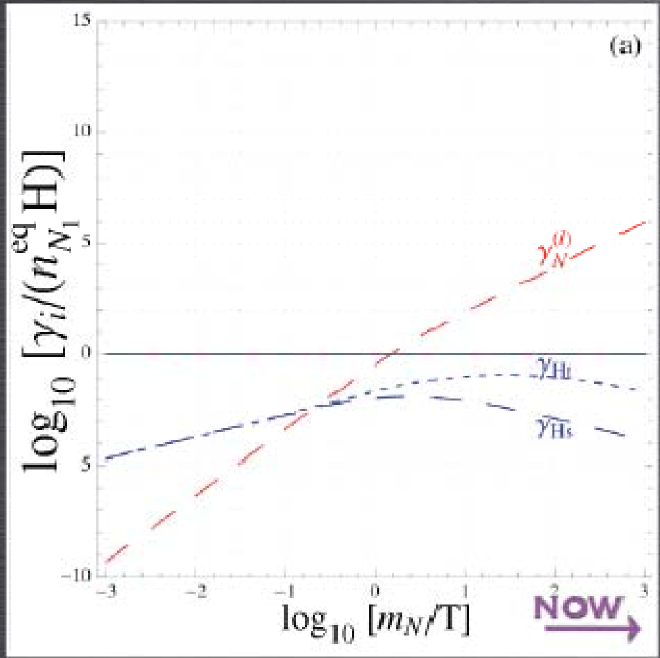
Due to the relatively high abundance of targets

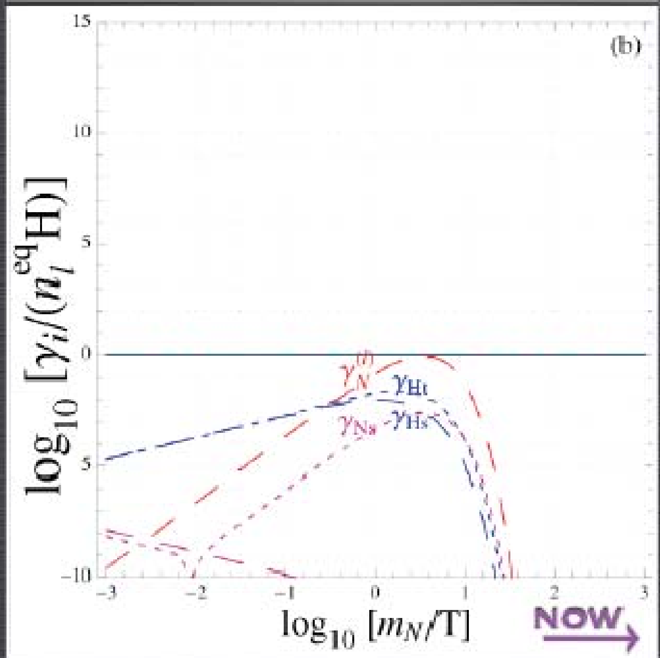
CAN LHC DISPROVE LEPTOGENESIS ?

BASED ON JHEP 0901(2009)051

J.M.FRÈRE, T.HAMBYE & G.VERTONGEN
(UNIVERSITÉ LIBRE DE BRUXELLES)

Interaction Rates



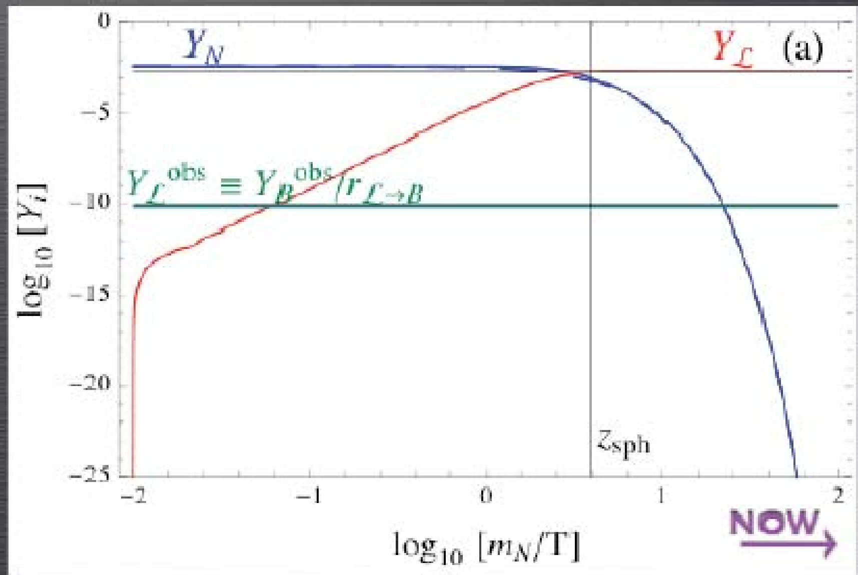


Example of Gauge Effects

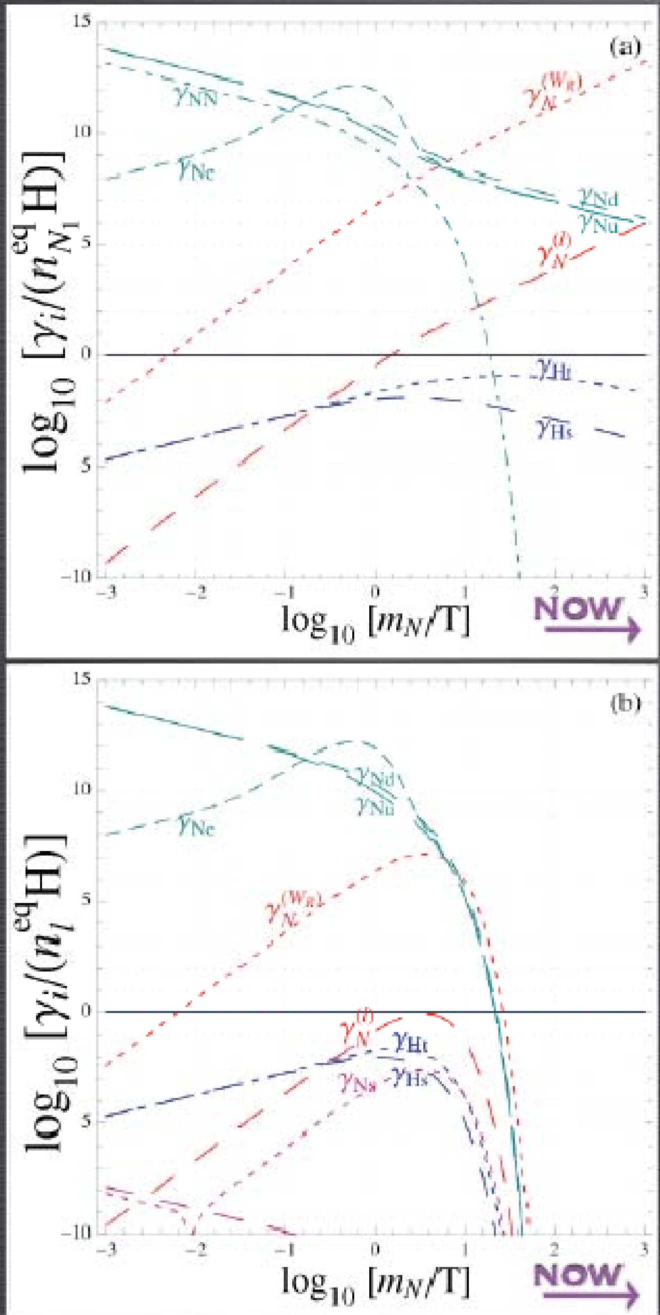
m(N) = 500 GeV m(W_R) = 3 TeV m1 = 10^{-3} eV

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

Asymmetry Evolution



Interaction Rates

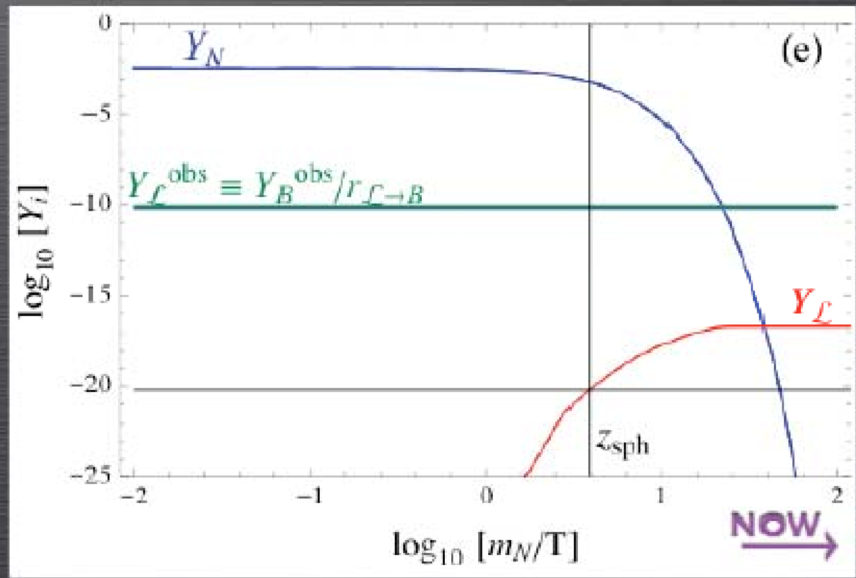


Example of Gauge Effects

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

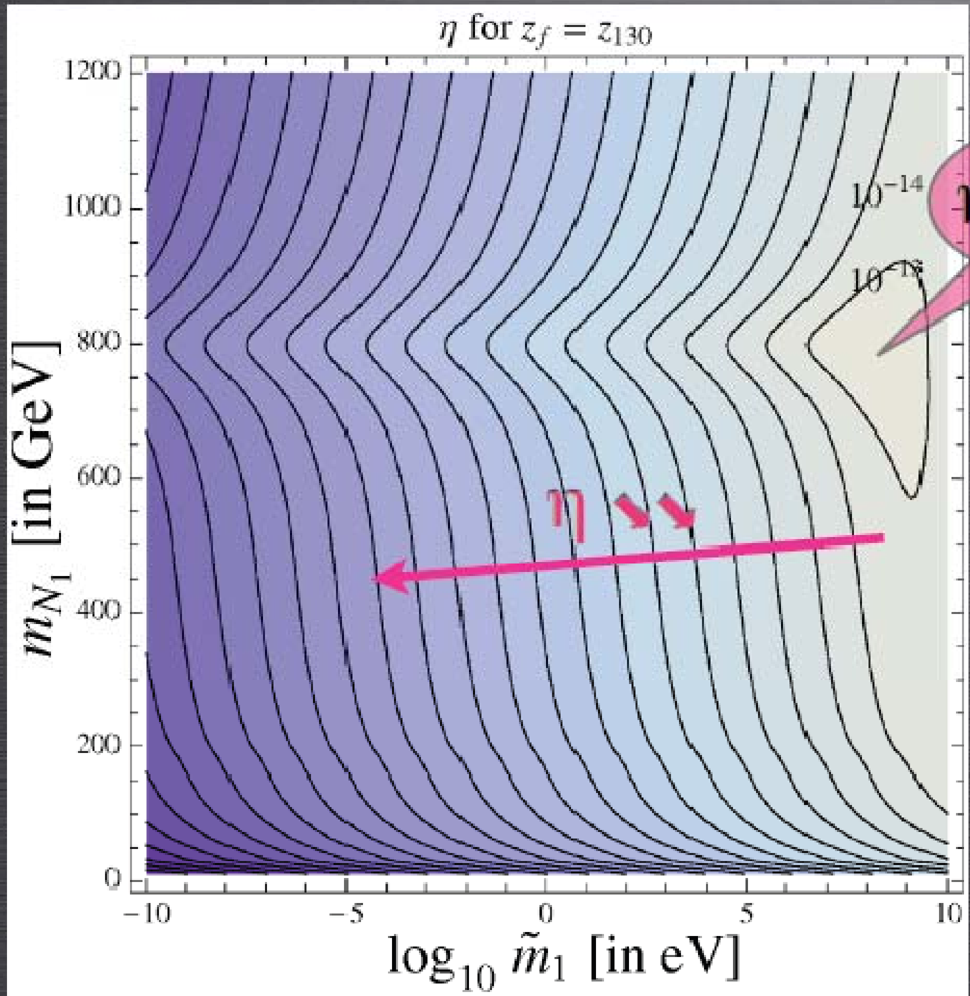
Case	Content	η	Y_B
(a)	Standard Leptogenesis	0,5	6.10^{-4}
(b)	(a)+W_R decays in Y_N	3.10^{-8}	4.10^{-11}
(c)	(b)+W_R scatterings in Y_N	2.10^{-10}	2.10^{-13}
(d)	(c)+W_R decays in Y_L	2.10^{-18}	2.10^{-21}
(e)	(d)+W_R scatterings in Y_L	2.10^{-18}	2.10^{-21}

Asymmetry Evolution



Can LHC disprove Leptogenesis ?

Efficiency Results



M(W_R)= 3 TeV

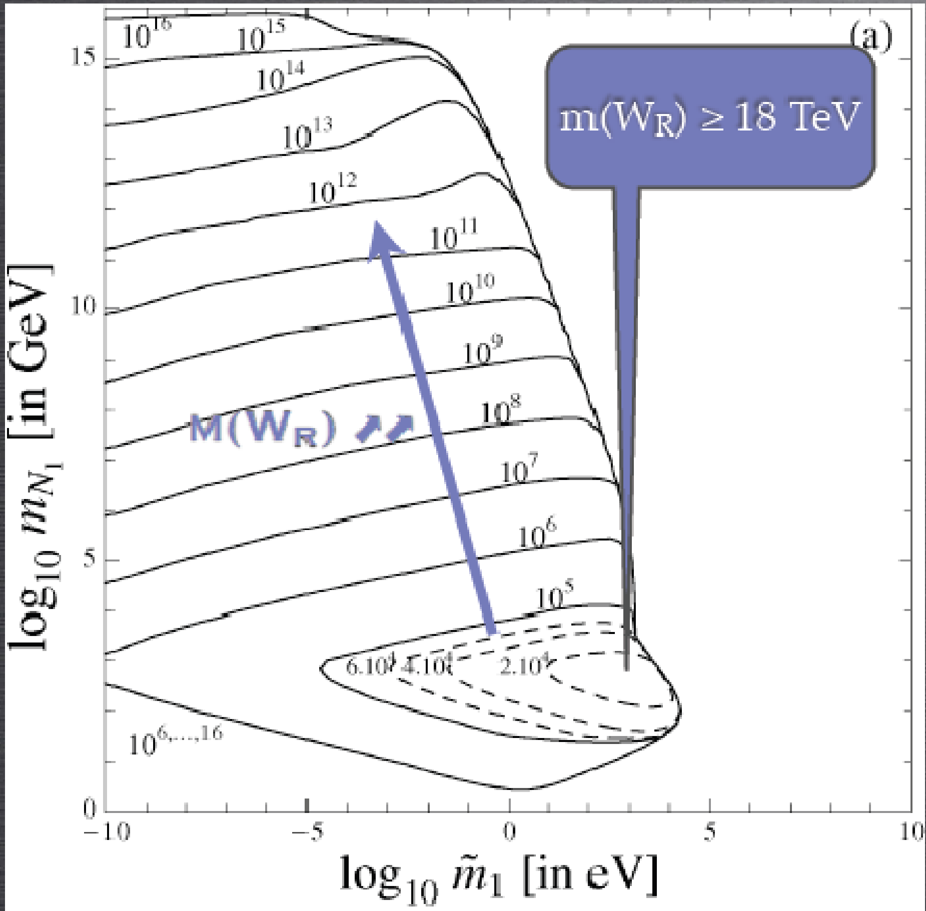
In any case :

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

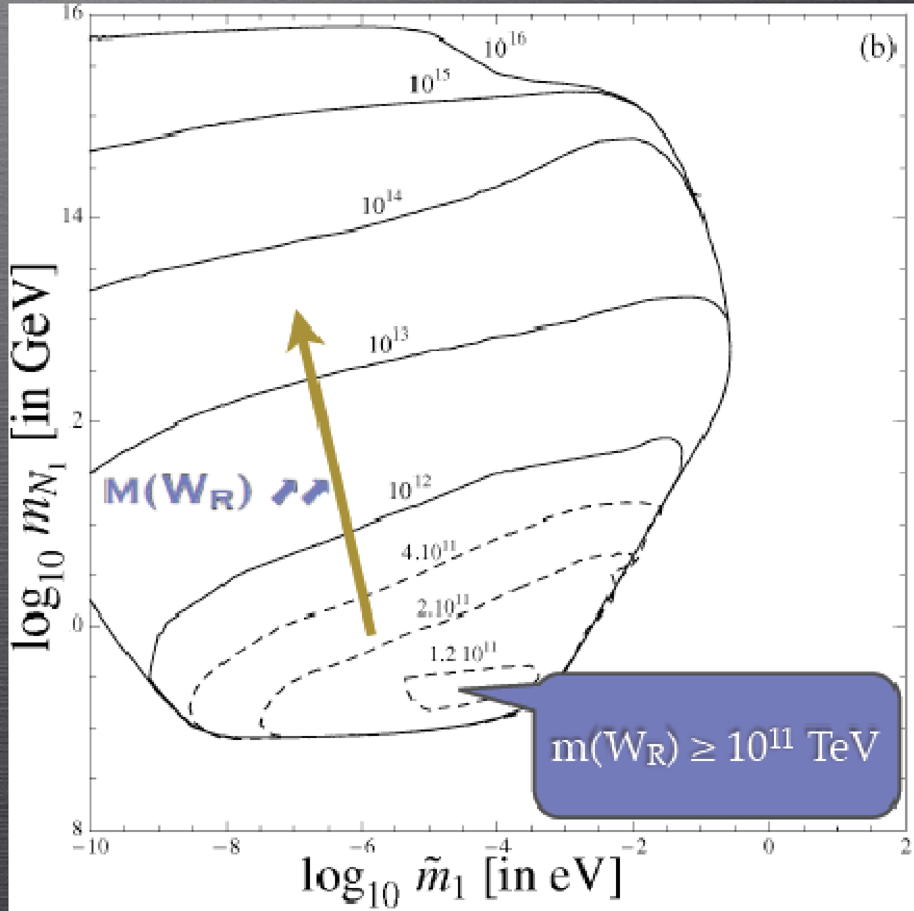
Type I Leptogenesis Disproved if W_R Discovered @ LHC

Bounds on $M(W_R)$ & $M(N_R)$

For $\mathcal{E}_{CP} = 1$



For $\mathcal{E}_{CP} = \mathcal{E}_{DI}$



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)

CMS Physics TDR2
(similar plots for Atlas)

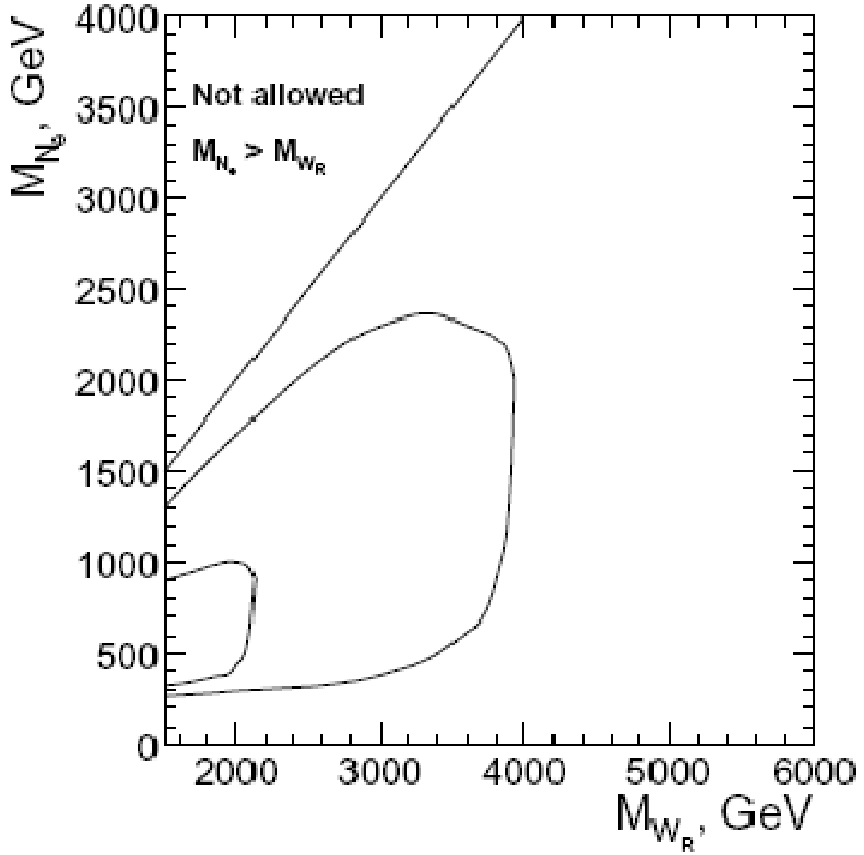


Figure 15.7: CMS discovery potential of the W_R boson and right-handed Majorana neutrinos of the Left-Right Symmetric model for the integrated luminosity $L_t = 30\ \mathrm{fb}^{-1}$ (outer contour) and for $L_t = 1\ \mathrm{fb}^{-1}$ (inner contour)

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 !

Backup slides

Right-handed W
Can have both enhancing
And damping effects

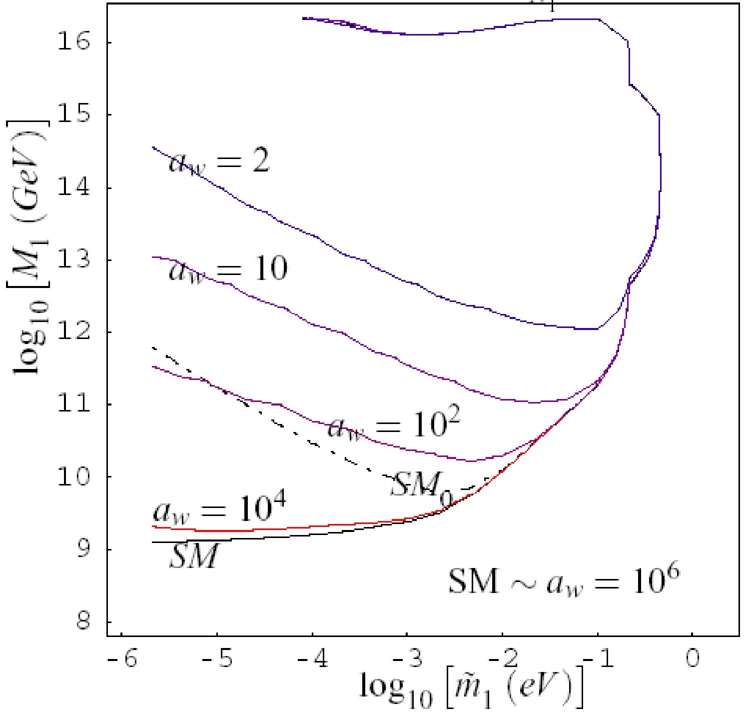
Allowed contours in $M_1 - \tilde{m}_1$ plane,

solid line = thermal Majorana initial population

dashed line = Majorana population rebuilt after reheating

Baryon density

$n_b/n_\gamma \propto \varepsilon_1 Y^{eq}_{N_1}(0)\eta_{\rm eff}$



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

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

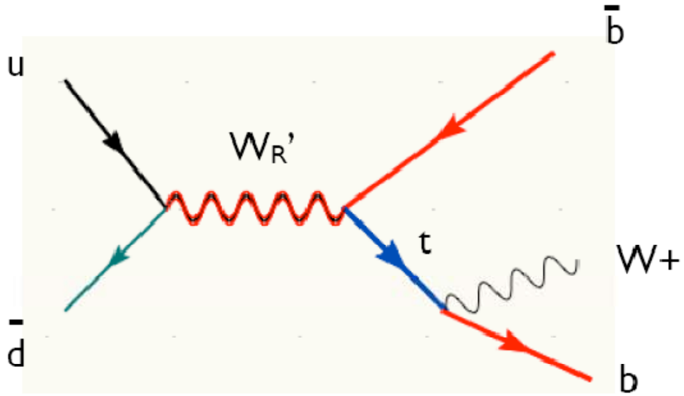
J.-M. Frère [a,b,1] and W.W. Repko [b]

[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!

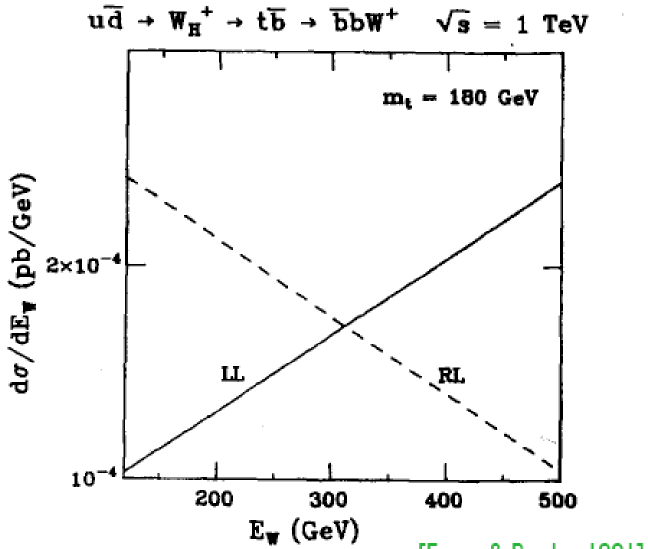
We study the process pp $(p\bar{p}) \to W_H \to \bar{b}t \to \bar{b}bW_L$, where W_H is a hypothetical heavy gauge boson. The differential cross section $d\sigma/dE_W$ is sensitive to the chiral structure of the W_H coupling. In particular, the heavy W_R expected from $SU(2)_L \times SU(2)_R \times U(1)$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

and a Ph.D. student*



*thanks to R. Frederix

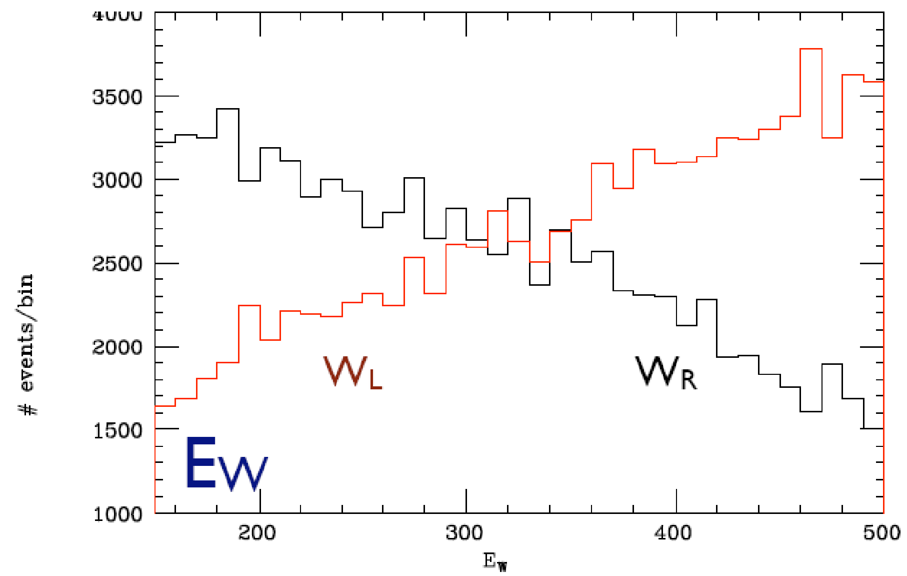
1.Validation

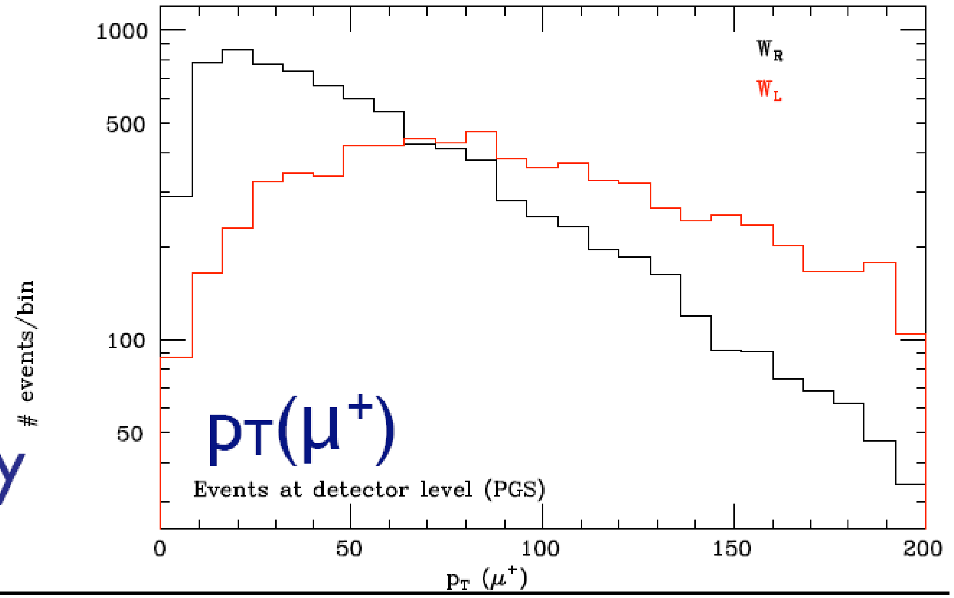


[Frere & Repko, 1991]

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





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…

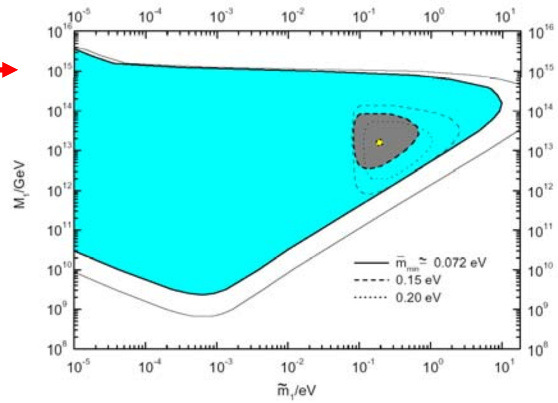


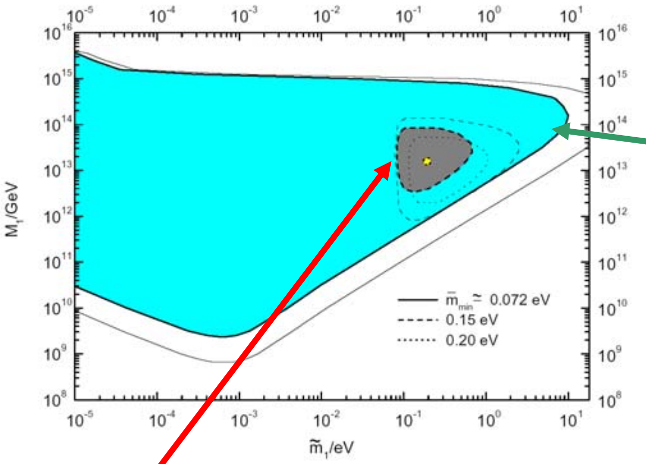
Figure 4: Inverted hierarchy case. Curves, in the ($\tilde{m}_1$-M_1)-plane, of constant $\eta_{B0}^{max} = 10^{-10}$ (thin lines) and $\eta_{B0}^{max} = 3.6 \times 10^{-10}$ (thick lines) for the indicated values of $\overline{m}$. The filled regions for $\eta_{B0}^{max} \geq 3.6 \times 10^{-10}$ are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

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!

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.