# *Matter-Antimatter asymmetry, and*

# How we could  falsify Leptogenesis at LHC.

# Baryo- and leptogenesis

**Purpose : explain the current excess of matter/antimatter**

- **Is there an excess of matter?**
  - Baryons: excess directly observed;
    Antibaryons seen in cosmic rays are
    compatible with secondary production
  - Leptons: excess of electrons similar to baryons,
    - BUT WE DON'T KNOW about neutrinos,
      no direct observations + they may even be
      Majorana particles → lepton number not defined.

Today, direct observation suggests:

$$3\ 10^{-11} < n_B/n_\gamma < 6\ 10^{-8}$$

While standard cosmological constraints at the nucleosynthesis stage give the stronger, still compatible limit:

$$4\ 10^{-10} < n_B/n_\gamma < 7\ 10^{-10}$$

And the Cosmic Microwave Background estimate is in the range:

$$\eta_B^{CMB} = (6.1 \pm 0.5)10^{-10}$$

If we assume however that the asymmetry comes from earlier times, before the annihilation of most particles into photons, and assume a roughtly isentropic evolution, this suggests an initial value:

$$\boxed{\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-8}}$$

This small number suggests to start from a symmetrical universe, like we expect if it arises through interaction with gravity, and to generate the asymmetry by particle physics interactions.

## Program

- LEARNING EXERCISE:
  - Direct approach to baryogenesis (Sakharov Conditions)
  - Baryon number violation limits
  - CP vs TCP : how to generate the asymmetry
  - Out-of-Equilibrium transitions
  - Difficulties with the Electroweak phase transition (sphalerons)
- LEPTOGENESIS as a solution : exploits the same mechanisms,but uses the sphalerons instead of suffering from them!
- Can we prove/disprove leptogenesis ?

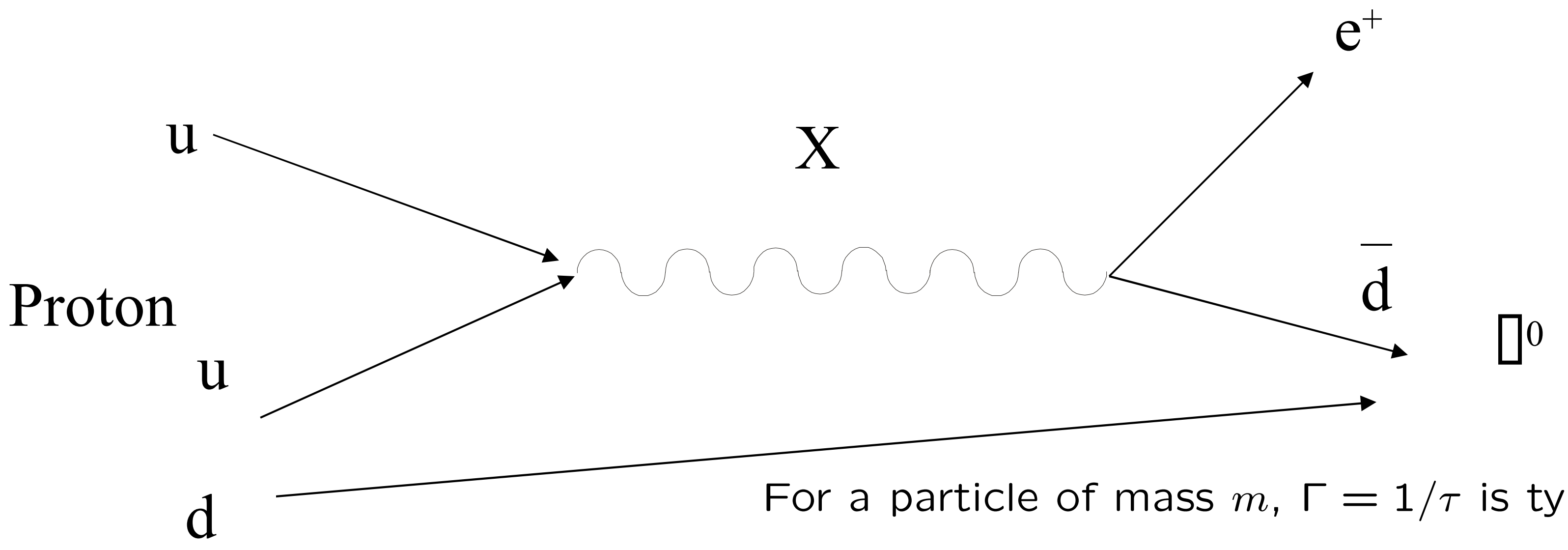
# Baryogenesis

Constraints on **Baryon number** conservation

- a number just invented to « explain » or « ensure » the proton stability :

$$\tau_n \approx 15 min$$

$$\tau_p > 10^{32} years$$



For a particle of mass $m$, $\Gamma = 1/\tau$ is typically

$$\Gamma = \kappa \cdot m$$

$$\kappa \approx 1, \quad m = 1GeV \rightarrow \tau = 610^{-25}s$$

Proton decay goes through exchange X,

$$\Gamma \approx g^4 m_{proton}^5 / M_X^4$$

a simple calcuation leads to

$$M_X/m_p \approx 10^{(25+32+7)/4} GeV = 10^{16} GeV$$

Typical proton instability in grand unification SU(5);

Need unification scale $10^{16}$ GeV

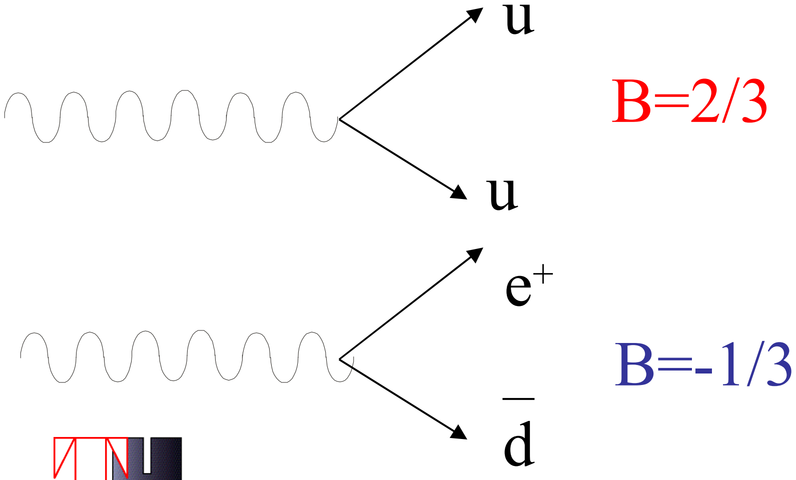
We will take SU(5) baryogenesis as an example in the next slides..

This is not sufficient to generate the baryon number!
Sakharov’s conditions:

- Violation of Baryon number

- Out-of-equilibrium

- Violation of C, (and CP, and ..) symmetries

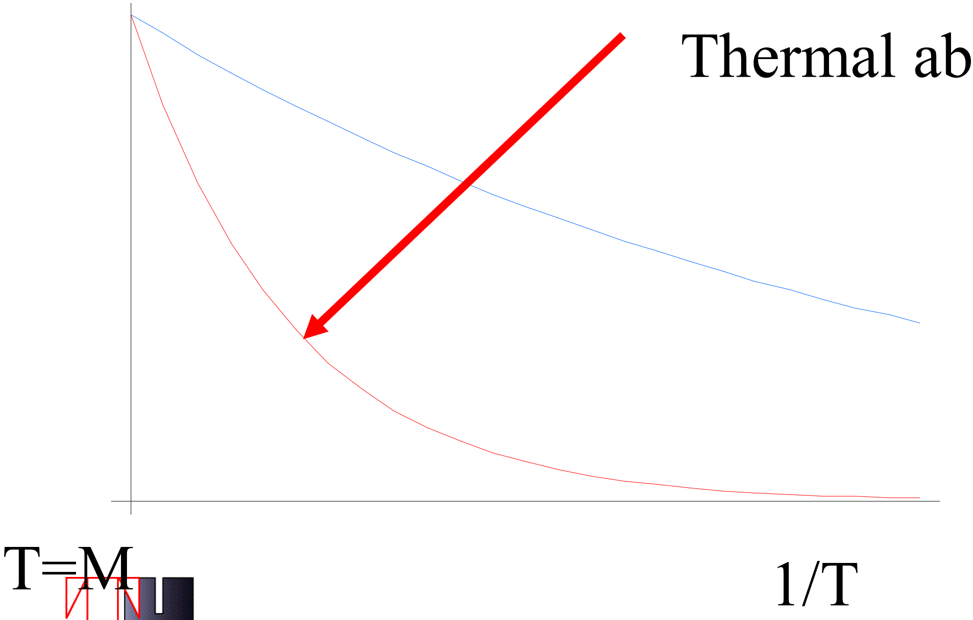


The decay of X violates Baryon number…., it could generate the baryon number in the early universe!

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

Out-of equilibrium: needed to avoid « return » reaction.

Simplest approach, in case of baryogenesis (also OK for Lepto-): use the expansion of the Universe….



Thermal abundance $e^{-E/kT}$

If the particle X decays slower than the Universe expands
→**RELIC PARTICLE,**
Decays later and
**OUT OF EQUILIBRIUM**

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

$H = \dot{a}/a$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 : $T \approx M$ ,

$$\Longrightarrow \quad M > 10^{16} GeV$$

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

We still need one condition:
the violation of Charge conjugation

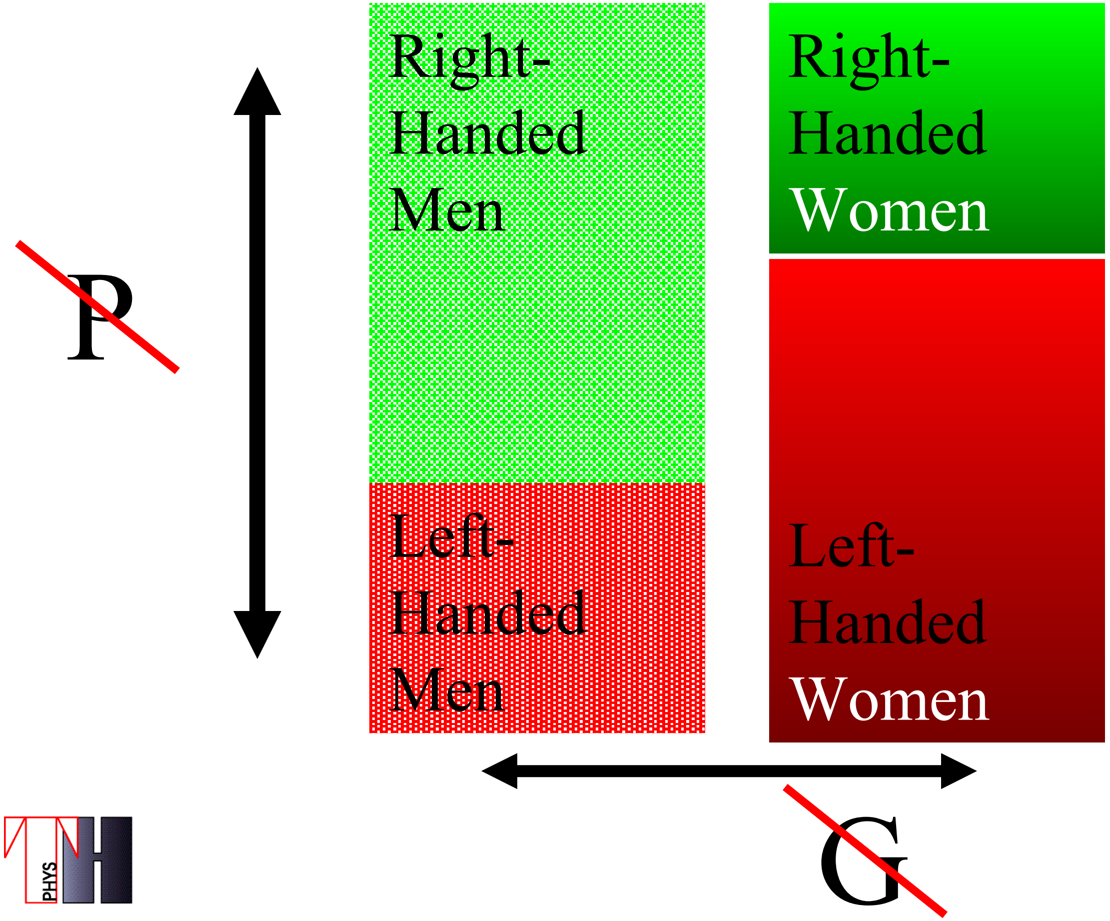
Indeed, if

The decay of X generates a baryon number B=( 2/3-1/3 )/2=1/6
BUT
The decay of anti-X will generate B=-1/6
If Charge conjugation holds….

→ $\cancel{C}$

$\cancel{C}$ is NOT sufficient , we need also to violate combined symmetries involving C , in particular CP

A toy example : replace C by G: Gender = Man ←→Woman,
P is the parity : Left-Handed ←→Right-Handed



If P and G are violated,
But PG is a valid symmetry,
→ same numbers of men and women!

NEED CP Violation!

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

We need CP violation , but :

- HOW is it introduced?
- HOW does it work ?

need complex coefficients

Gauge interactions ="real", CP-conserving

→ NEED scalar (Yukawa) couplings

$$\lambda\bar{\Psi}\phi^{\dagger}\xi + \lambda^{*}\bar{\xi}\phi\Psi$$

We need CP violation , but :
- HOW is it introduced?
- HOW does it work ?

# CP vs TCP

TCP implies

$$< X \mid S \mid Y >=< \bar{Y} \mid S \mid \bar{X} >$$

$$< X \mid S \mid X >=< \bar{X} \mid S \mid \bar{X} >$$

$X$ and $\bar{X}$ have the same lifetime ...but they may die differently

consider:

$$\Gamma_{X\to uu} = r_u \qquad n_B = 2/3; \qquad n_L = 0$$

$$\Gamma_{X\to e^+\bar{d}} = r_d \qquad n_B = -1/3 \qquad n_L = -1$$

$$\Gamma_{\bar{X}\to \bar{u}\bar{u}} = \bar{r}_u \qquad n_B = -2/3 \qquad n_L = 0$$

$$\Gamma_{\bar{X}\to e^- d} = \bar{r}_d \qquad n_B = 1/3 \qquad n_L = 1$$

TCP only implies

$$\Gamma(X) = \Gamma(\bar{X})$$

but we may have

$$r_u \neq \bar{r_u}$$

provided it is compensated by another channel:

$$r_u + r_d = \bar{r_u} + \bar{r_d}$$

This is sufficient to generate a NET BARYON NUMBER:

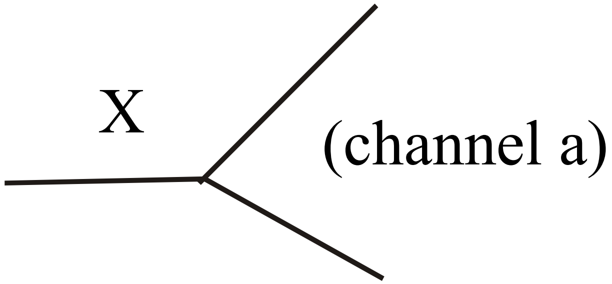
Take the decay of a pair $X + \bar{X}$, it gives

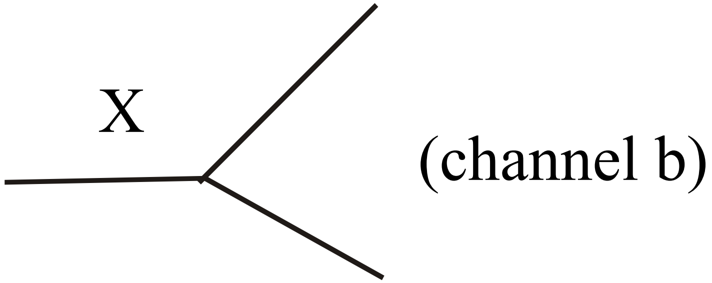
$$n_B = 2/3\ (r_u - \bar{r_u}) - 1/3\ (r_d - \bar{r_d}) \neq 0$$

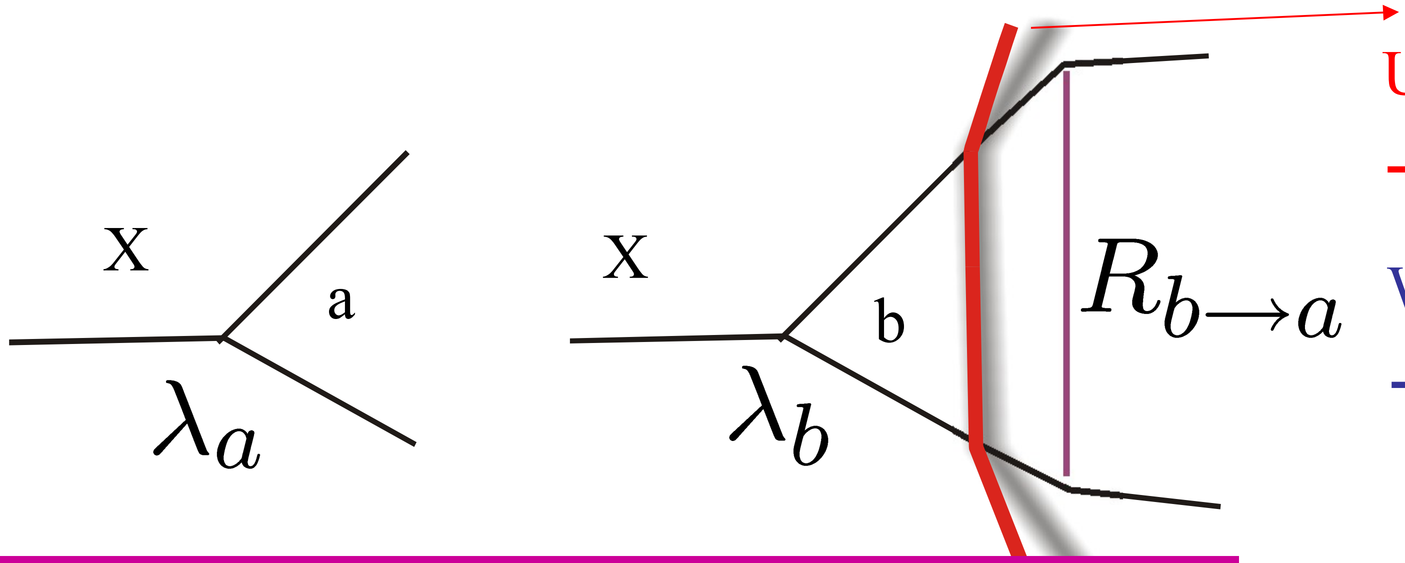
Thus, we can generate baryon number despite TCP, provided the branching ratios of X and anti-X are different, but compensate for the total lifetime

**HOW is this compensation implemented in the calculation?**

Consider 2 decay channels (say, a and b) for the particle X, and the conjugate channels for the anti-X







Unitarity cut

→ $e^{i\xi}$

Weak Phase

→ $e^{i\alpha}$

One channel learns about the compensation by the other through interference …

$$\Gamma(X \to a) \sim |\lambda_a + \lambda_b e^{i\alpha} R_{b\to a} e^{i\xi}|$$

$$\Gamma(\bar{X} \to \bar{a}) \sim |\lambda_a + \lambda_b e^{-i\alpha} R_{\bar{b}\to\bar{a}} e^{i\xi}|$$

$$\Gamma(X \to a) - \Gamma(\bar{X} \to \bar{a}) \sim \lambda_a \lambda_b R_{b\to a} sin(\alpha) sin(\xi)$$

- the electroweak phase transition would destroy the B number just created (although this is a specific SU(5) problem)

We have seen indeed that SU(5) violates Baryon number by processes like

$$u + u \to \bar{d} + e^{+}$$

where $\Delta B = -1/3 - 2/3 = \Delta L = -1 - 0$

in other terms, SU(5) baryogenesis keeps (B-L) conserved !

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

We have thus met all the conditions to generate baryon number through « thermal baryogenesis », i.e., through the baryon-number violating decay of relic particles from SU(5).
Yet, this scenario is no longer favored !

WHY ?

- Need to introduce CP violation « by hand »,
through new complex scalar fields → no relation to low energy pheno

- We assumed standard big-bang cosmo: the baryon number would be diluted in an inflation scheme, or we would need re-heating to re-create the X particles

- More importantly : the electroweak phase transition would destroy the B number just created (although this is a specific SU(5) problem)

# Quantum anomalies can destroy/create B and L

considering the fermionic Lagrangian,

$$L = \bar{\psi}_L D^\mu \gamma_\mu \psi_L$$

the transformation $\psi_L \to e^{i\alpha}\psi_L$ implies, at the classical level, the conservation

$$\partial_\mu {j_L}^\mu = 0$$

where ${j_L}^\mu = \bar{\psi}_L \gamma^\mu \psi_L$, and similarly for the baryons

The existence of extended (topological) solutions for the gauge fields (instantons) or, in the electroweak breaking scheme, the existence of a barrier measured by the "Sphaleron" mass, DESTROYS this conservation. For instance:

$$\partial_\mu j^\mu_{lepton,L} + \partial_\mu j^\mu_{baryon,L} = \kappa \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

(we have neglected fermion masses effects here, and concentrated to the Left-handed part, which is coupled to the gauge group $SU(2)_L$).

$$\partial_\mu j^\mu_{lepton,L} + \partial_\mu j^\mu_{baryon,L} = \kappa\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

allows to "exchange" some Baryon number for Lepton number and a change in the vacuum fields configuration

Observe that in this process,
one unit of B is exchanged for – 1 unit of L, which means that the exchange is permitted provided B-L is conserved (technically, their left-handed part)

These processed are normally extremely weak at current energies, but, are assumed to become fast if the temperature approaches the »sphaleron » Or the electroweak phase transition, at T ≈ 100 GeV

$$e^{-M_{sphaleron}/kT}$$

# 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 cheap, readily available heavy Majorana neutrinos,
  - … because their inclusion has recently become very popular

# Possible situations if the Electroweak phase transition takes place

## Out of Equilibrium

Independently of previous B or L, a new creation of B is possilbe, (but with B-L=0 for the new contribution)

**Electroweak Baryogenesis ??**

## At (or near) Equilibrium

Pre-existing B or L can be erased, but B-L is conserved

For SU(5) baryo, B-L=0, so B and L can be totally erased.

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

**Leptogenesis**

# Do we need heavy (Majorana) neutrinos?

$\nu$ oscillations → neutrino masses

Must explain how they are introduced in the Standard Model, and why they are so small

light $\nu$ masses are $\leq 1 eV$

$$m_\nu/m_e \leq 10^{-6}$$

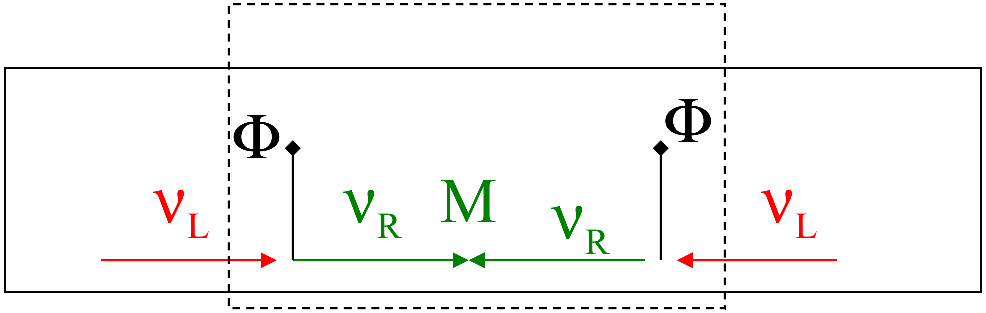
of course,such ratios are found:

$$m_e/m_t \leq 310^{-6}$$

but the significant comparison in the Standard Model is

$$m_\nu/m_W \leq 10^{-11}$$

# See-saw mechanism = Poor Man's Triplet



Results in effective Majorana mass term for the light neutrino

$$\epsilon_{ij}\nu_i\nu_j \bullet \chi$$

Where the triplet is in fact simulated by 2 doublets, linked by a heavy particle, the right-handed Majorana neutrino

Thus, mixes high and low energy scales

$$m_\nu^{ab} \approx v^2/2 \sum \lambda^{ai}(\frac{1}{M})_{ij}\lambda^{\dagger jb}$$

The mass of the neutrinos comes both from some high-energy structure (the heavy Majorana terms) and from low-energy symmetry breaking

$$m_\nu^{ab} \approx v^2/2 \ \sum \lambda^{ai} \left(\frac{1}{M}\right)_{ij} \lambda^{\dagger jb}$$

We will need to return to this formula in the next lecture, as we will see that a SIMILAR, but DIFFERENT parameter governs CP violation and Leptogenesis

$$\tilde{m}_1 = (\lambda^\dagger \lambda)_{11} v^2 / M_1$$

Nice feature: CP violation is already present in the complex couplings (total of 6 phases !)

This far, the introduction of (heavy) right-handed neutrinos is quite arbitrary:

It amounts to replacing a small Yukawa $\lambda$ by a ratio (vev)/M which is of the same order

Another reason (and a justification for the new scale M) comes from grand unification :

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

and the fermions come in nice representations

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

where "1" is precisely $N_R$

Anomalies automatically cancelled !

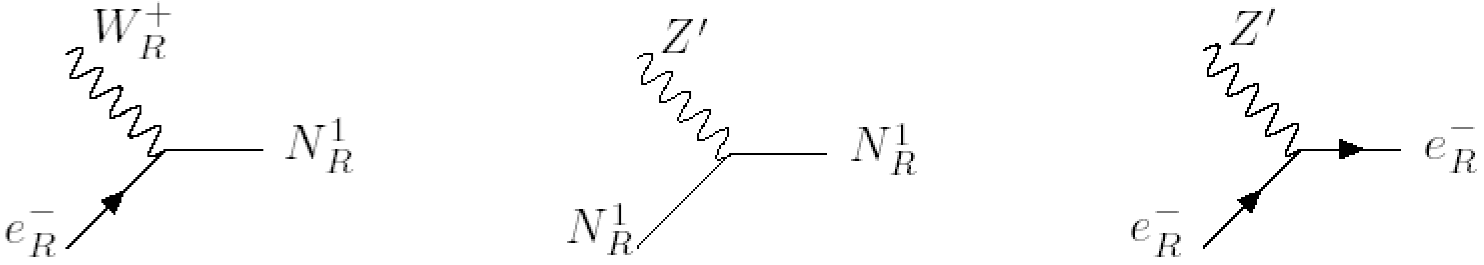
In fact, giving a Majorana mass to the SU(5) singlet N is the simplest way to break SO(10) intoSU(5) !

# A few more words about SO(10)…

In fact, the breaking of SO(10) into SU(5)

- breaks also the conservation of B-L (usefull for leptogenesis)
- gives mass to extra gauge bosons associated to $SU(2)_R$

- the masses of WR and Z' are similar to M, the mass of the heavy Majorana fermions.



These extra bosons must not be forgotten, and change the conclusions

# 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 !

# Leptogenesis

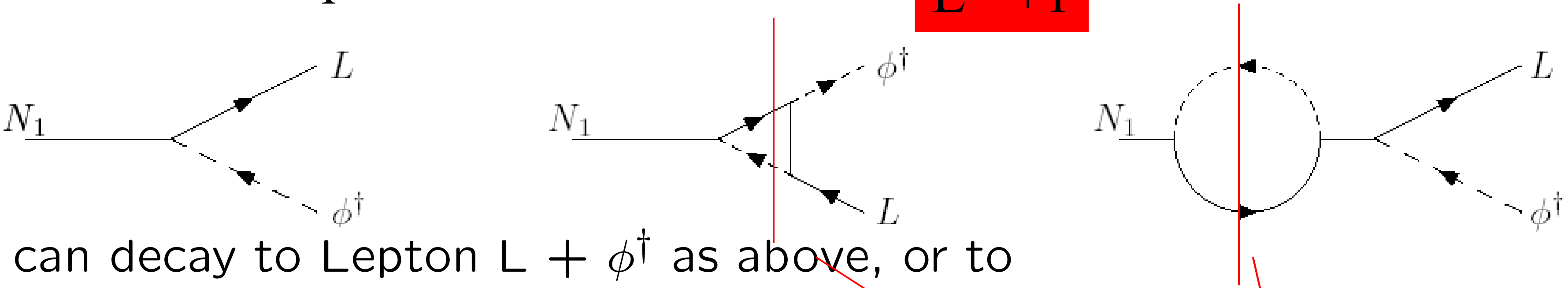
- Basic idea :generate L at higher temperature
- Use the electroweak phase transition near equilibrium to convert L → - B
  - Advantage: insensitive to the details of the sphaleron-based mechanism, provided the transition stays close to equilibrium until completion
- Use heavy Majorana neutrinos,
  -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

# How leptogenesis works….

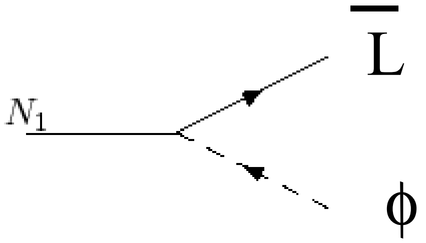
Assume that we have some population of heavy N particles…
*(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.*

## 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…

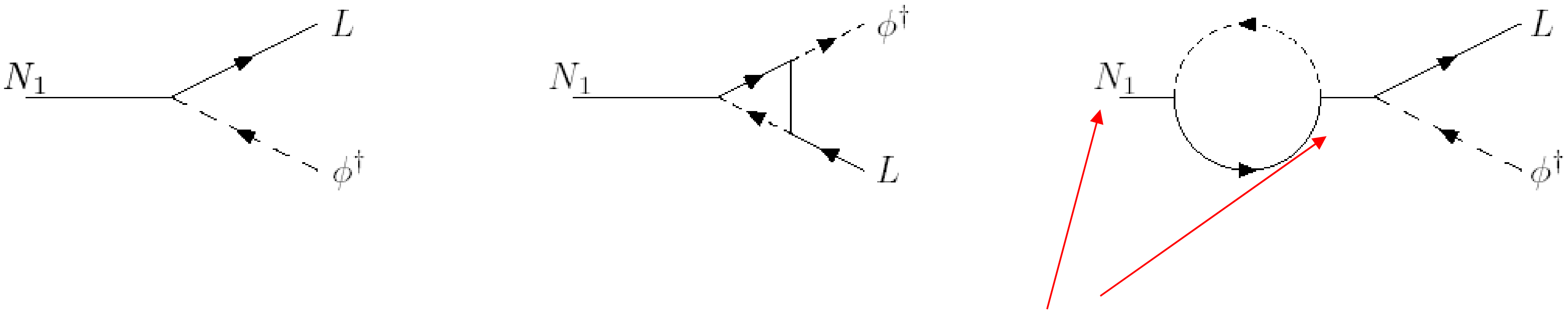
similar to τ lepton →

| 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 |

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

# 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 $\lambda^2$

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

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

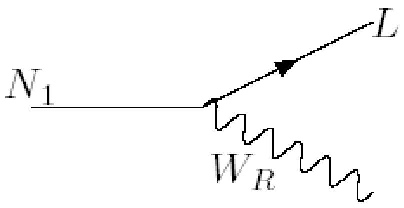
where "1" is precisely $N_R$

## with the gauge inclusion

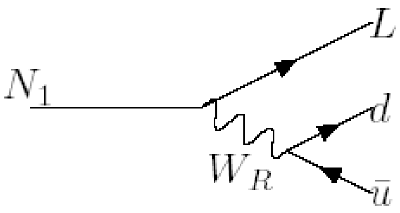
$$\epsilon_1 = \frac{\epsilon_1^0}{1+\textcircled{X}}$$

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

  $\Bigg\} \times$

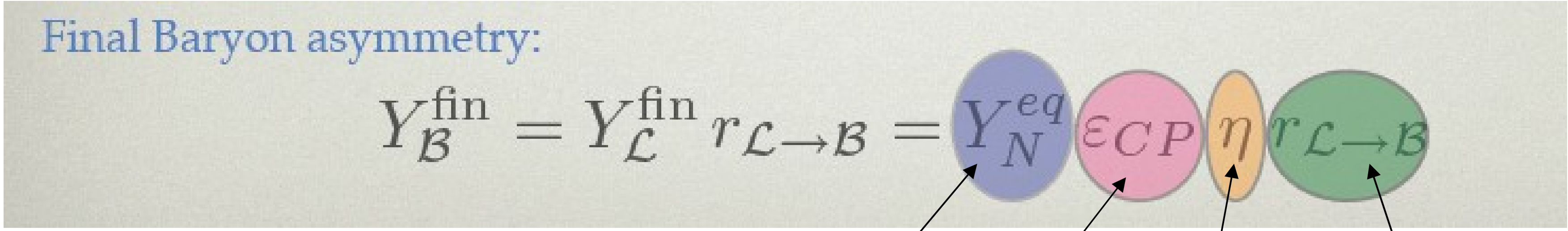
- $M_{W_R} > M_1 \quad \Rightarrow$ 3-body decay

  $\Rightarrow \; X = \frac{3g^4v^2}{2^7\pi^2}\frac{1}{\tilde{m}_1 M_1 a_w^2}$

  $\Rightarrow \; a_w \sim 10 \Rightarrow X \sim 10$

  $\Bigg\} \surd$

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



Final Baryon asymmetry:

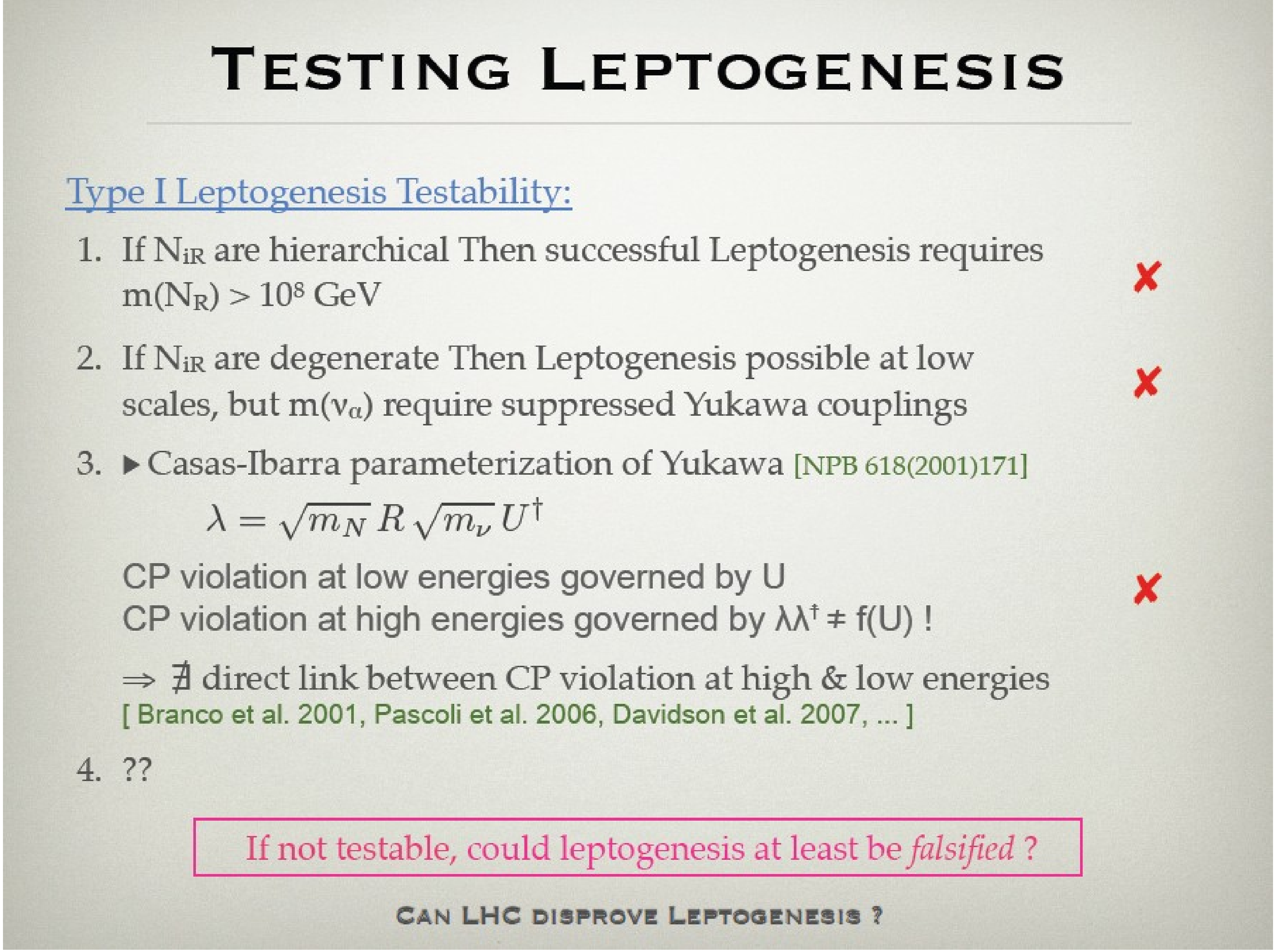
$$Y_{\mathcal{B}}^{\rm fin} = Y_{\mathcal{L}}^{\rm fin}\, r_{\mathcal{L}\to\mathcal{B}} = Y_N^{eq}\,\varepsilon_{CP}\,\eta\, r_{\mathcal{L}\to\mathcal{B}}$$

Initial heavy neutrino population

CP asymmetry

Efficiency,
Suppression by scattering,
including dilution
by R sector

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



# 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]

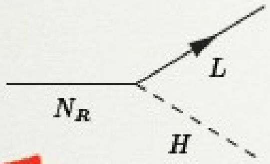
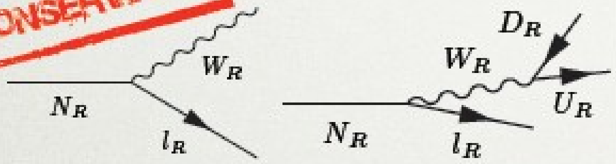
   $$\lambda = \sqrt{m_N}\, R \,\sqrt{m_\nu}\, U^\dagger$$

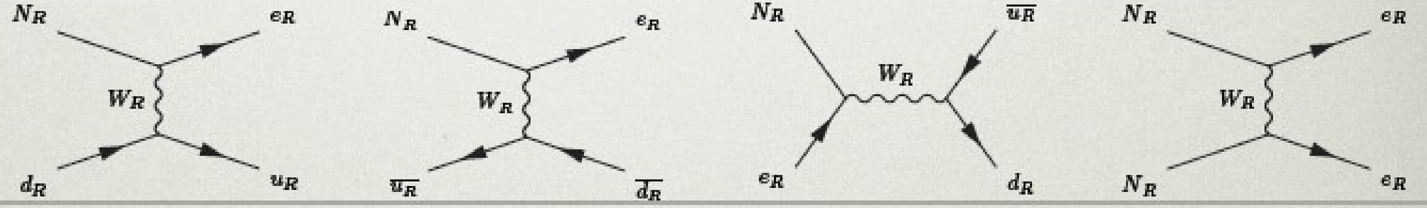
   CP violation at low energies governed by U
   CP violation at high energies governed by $\lambda\lambda^\dagger \neq f(U)$ ! ✗

   $\Rightarrow \nexists$ 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* ?

# EFFECTS OF A LOW SCALE $W_R$

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

| Scatterings | Diagrams |
|---|---|
| Gauge |  |

**Strong Thermalization**

⇒ Easier to produce neutrinos @ Reheating ✓

⇒ Harder decoupling @ Low T° (Washout) ✗

Due to the relatively high abundance of targets

# Can LHC disprove Leptogenesis ?

based on JHEP 0901(2009)051

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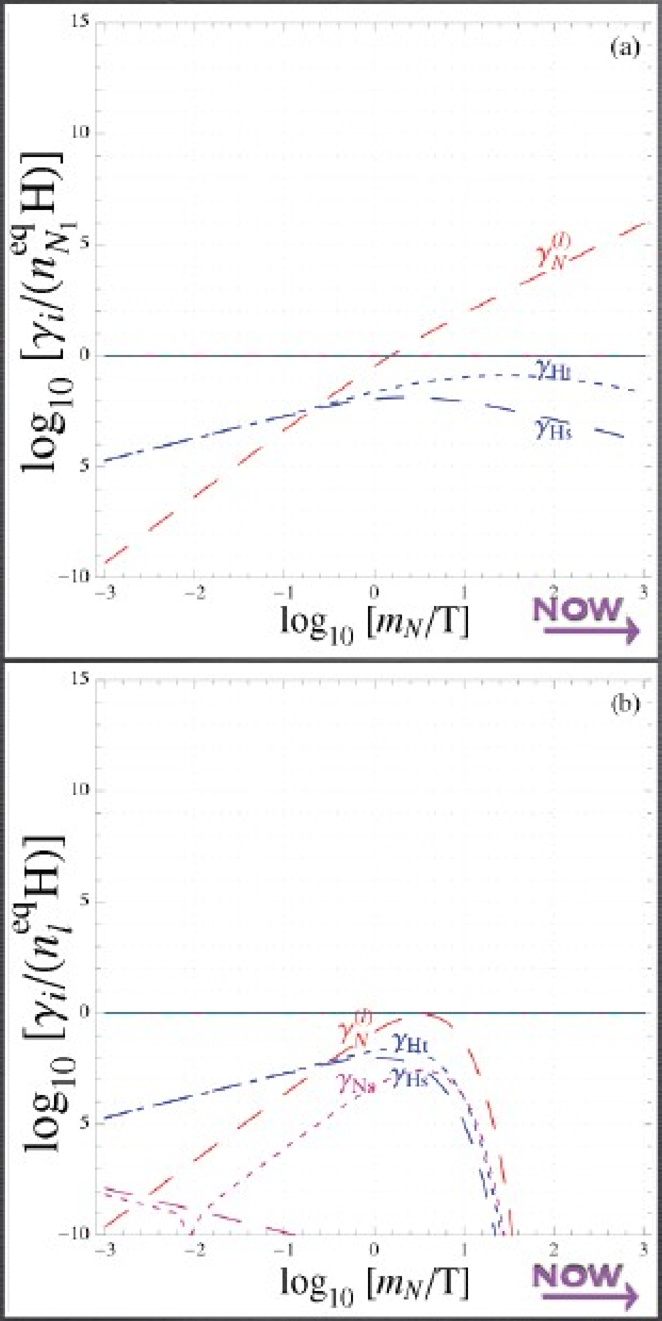
# EXAMPLE OF GAUGE EFFECTS

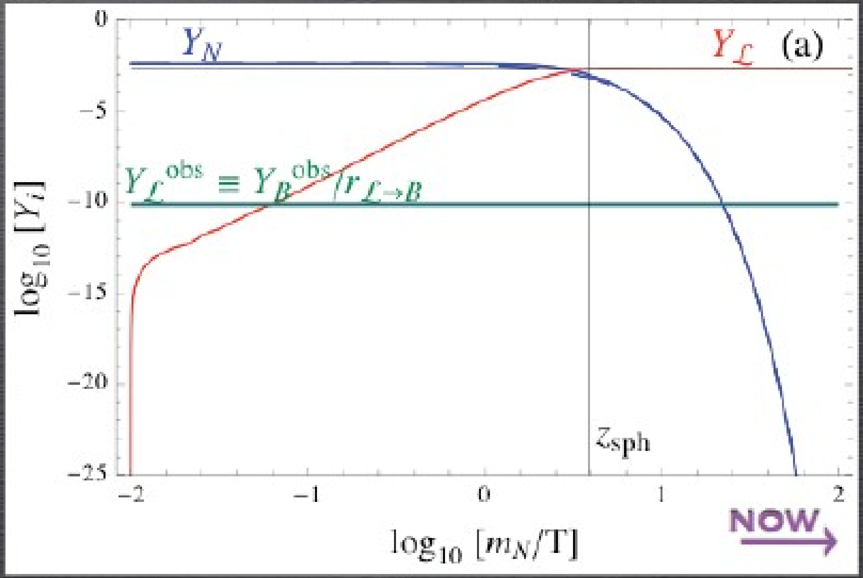
m(N) = 500 GeV m($W_R$) = 3 TeV m1 = $10^{-3}$ eV

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

## INTERACTION RATES



## ASYMMETRY EVOLUTION

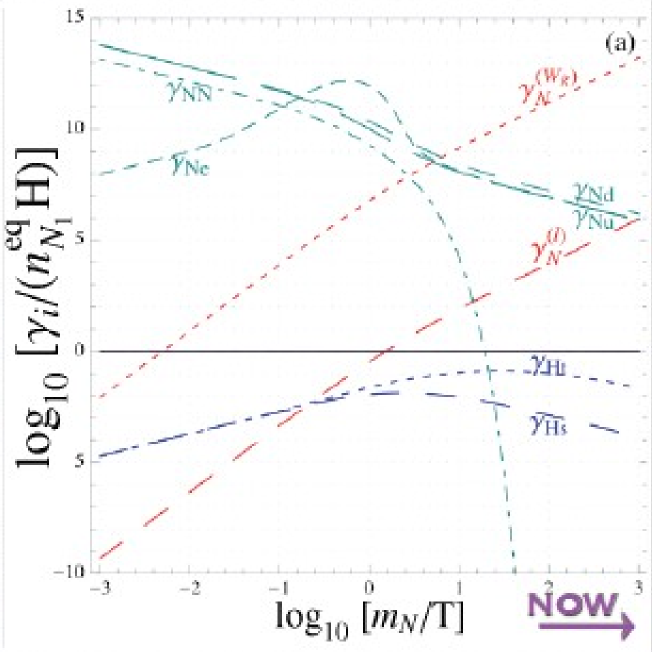


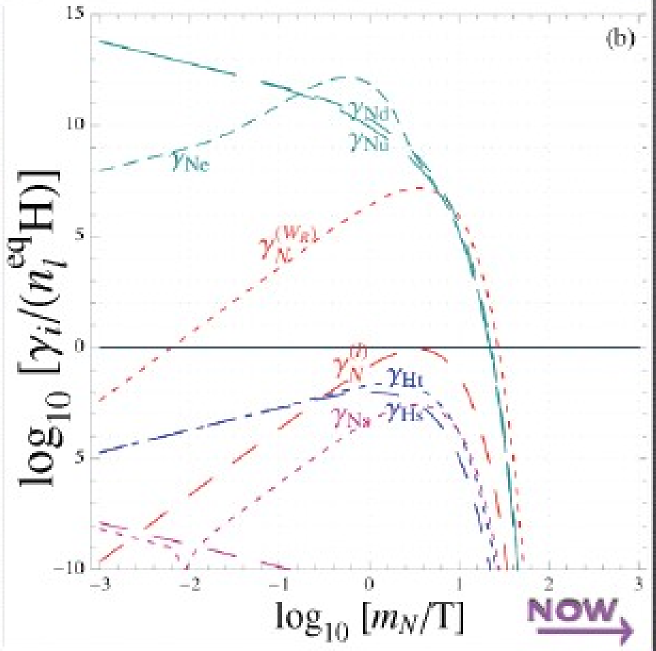
# EXAMPLE OF GAUGE EFFECTS

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

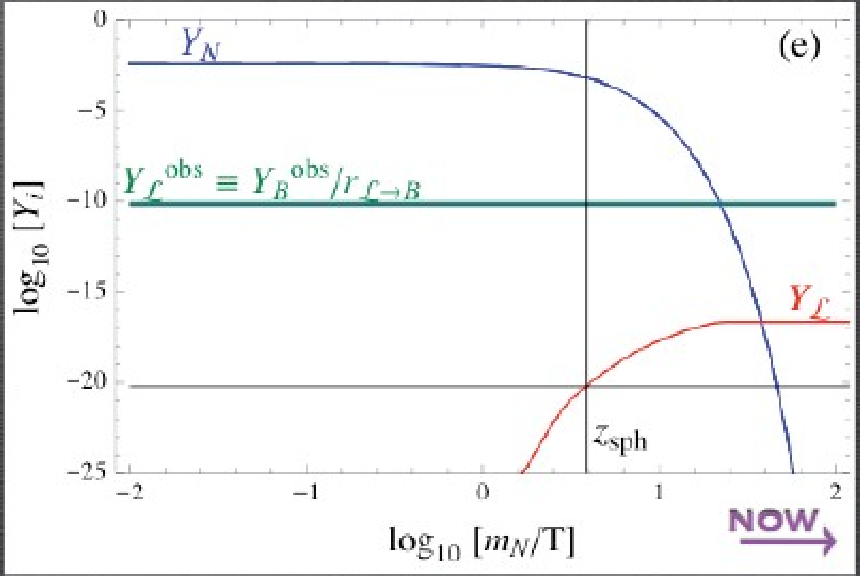
| Case | Content | η | $Y_B$ |
|---|---|---|---|
| (a) | Standard Leptogenesis | 0,5 | $6.10^{-4}$ |
| (b) | (a)+$W_R$ decays in $Y_N$ | $3.10^{-8}$ | $4.10^{-11}$ |
| (c) | (b)+$W_R$ scatterings in $Y_N$ | $2.10^{-10}$ | $2.10^{-13}$ |
| (d) | (c)+$W_R$ decays in $Y_L$ | $2.10^{-18}$ | $2.10^{-21}$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

## INTERACTION RATES

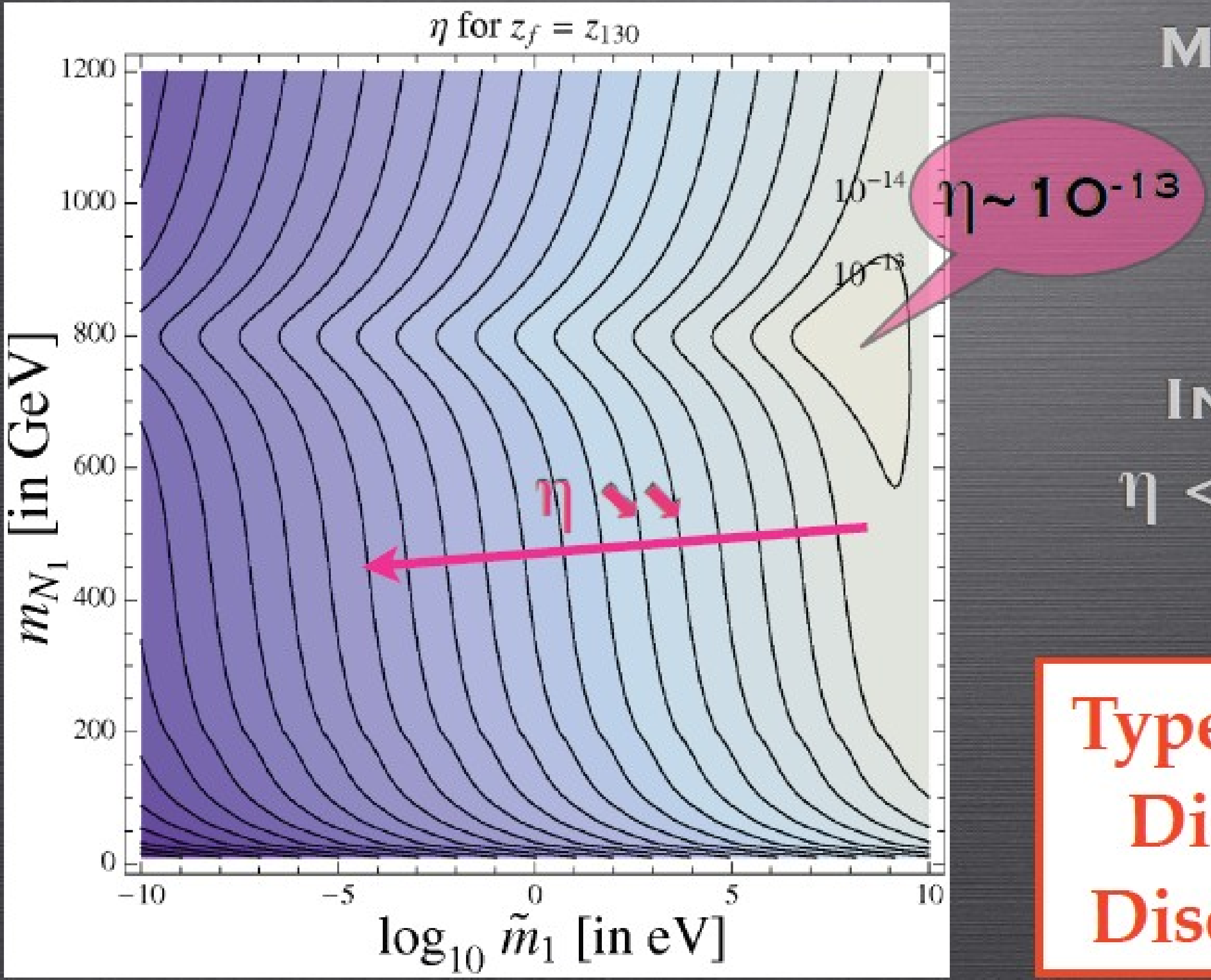




## ASYMMETRY EVOLUTION



# EFFICIENCY RESULTS



M($W_R$)= 3 TEV

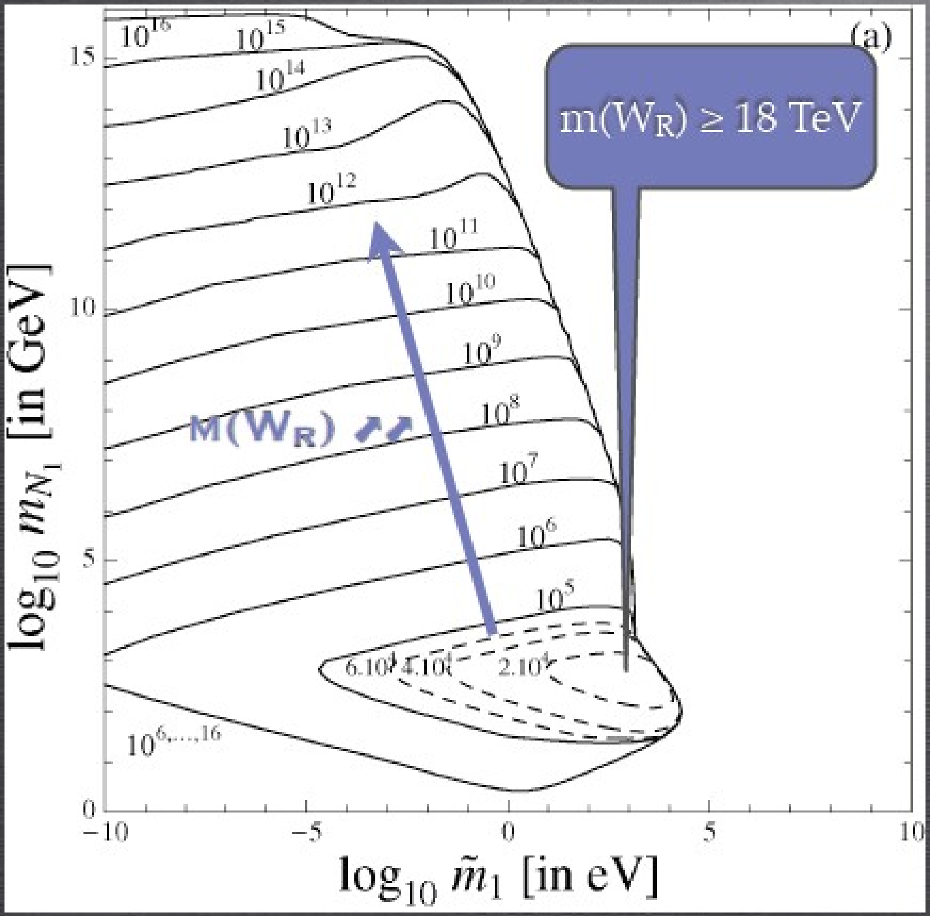
IN ANY CASE :

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

**Type I Leptogenesis Disproved if $W_R$ Discovered @ LHC**

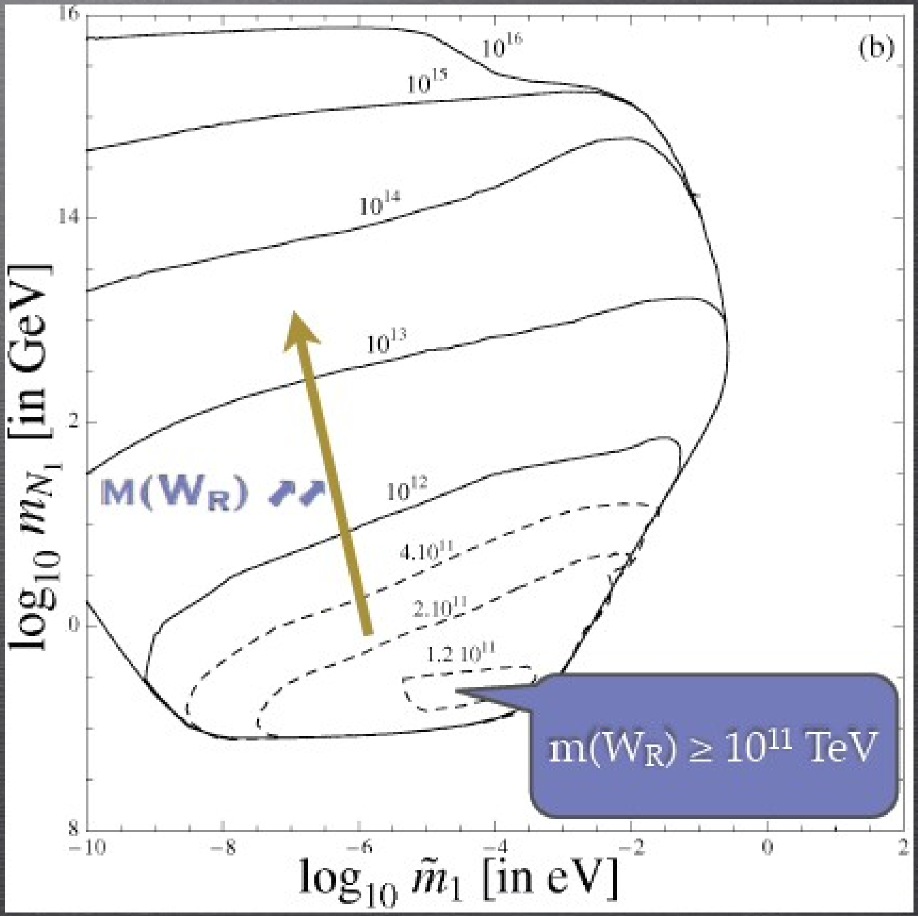
# BOUNDS ON M($W_R$) & M($N_R$)

## FOR $\varepsilon_{CP} = 1$



m($W_R$) ≥ 18 TeV

## FOR $\varepsilon_{CP} = \varepsilon_{DI}$



m($W_R$) ≥ $10^{11}$ TeV

# Prospects at LHC..

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

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

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)

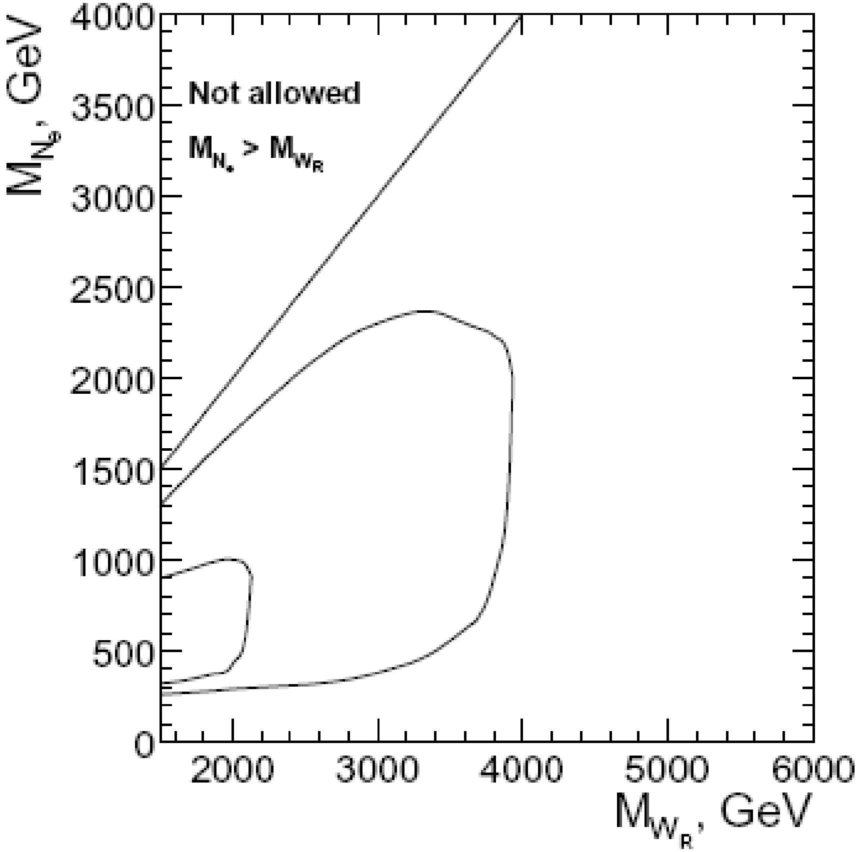


Figure 15.7: CMS discovery potential of the $W_R$ boson and right-handed Majorana neutrinos of the Left-Right Symmetric model for the integrated luminosity $L_t = 30$ fb$^{-1}$ (outer contour) and for $L_t = 1$ fb$^{-1}$ (inner contour)

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

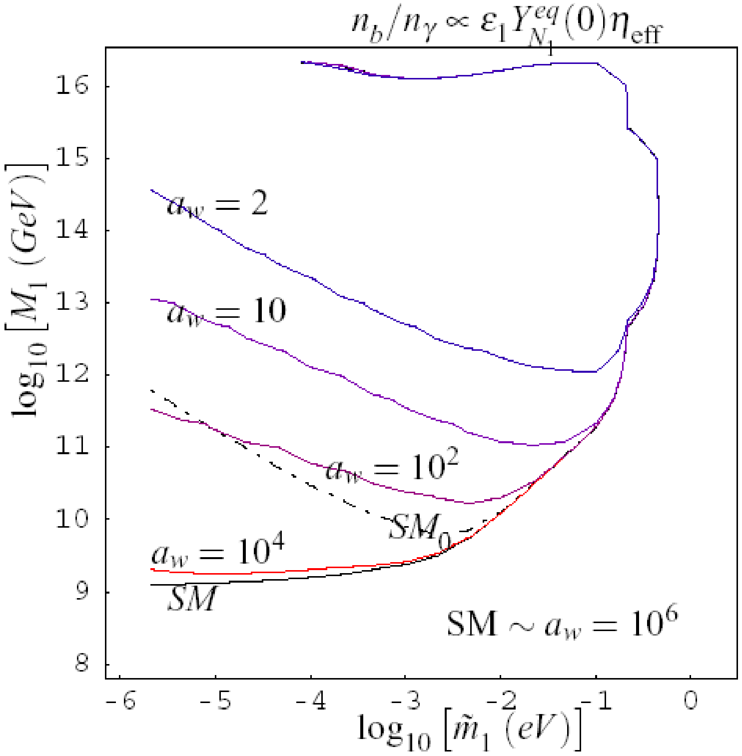
finding a $W_R$ at a collider near you would kill at least the « type 1 » leptogenesis (= through asymmetrical N decay)

probably the only realistic way to EXCLUDE simple leptogenesis !

# Backup slides

Right-handed W
Can have both enhancing
And damping effects

# Baryon density



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 .

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

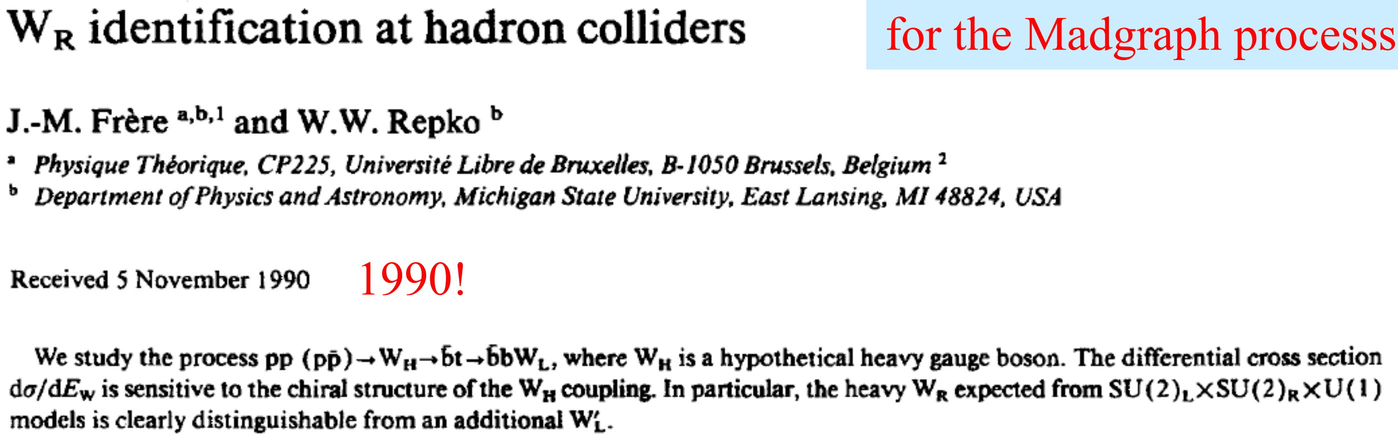
**N Cosme JHEP 0408:027,2004**.

**hep-ph/0403209**

# 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]

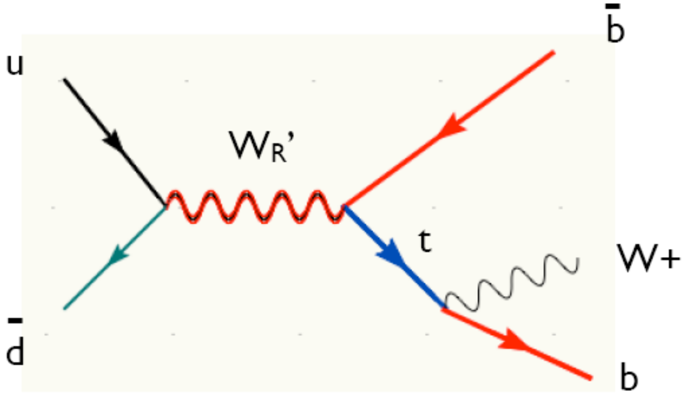
[a] *Physique Théorique, CP225, Université Libre de Bruxelles, B-1050 Brussels, Belgium* [2]
[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

Received 5 November 1990

1990!

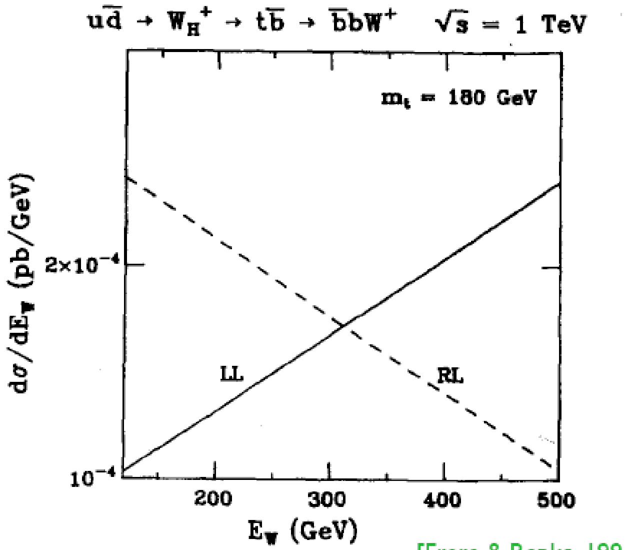
We study the process pp $(p\bar{p}) \to W_H \to \bar{b}t \to \bar{b}bW_L$, where $W_H$ is a hypothetical heavy gauge boson. The differential cross section $d\sigma/dE_W$ is sensitive to the chiral structure of the $W_H$ coupling. In particular, the heavy $W_R$ expected from $SU(2)_L \times SU(2)_R \times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

and a Ph.D. student*



*thanks to R. Frederix

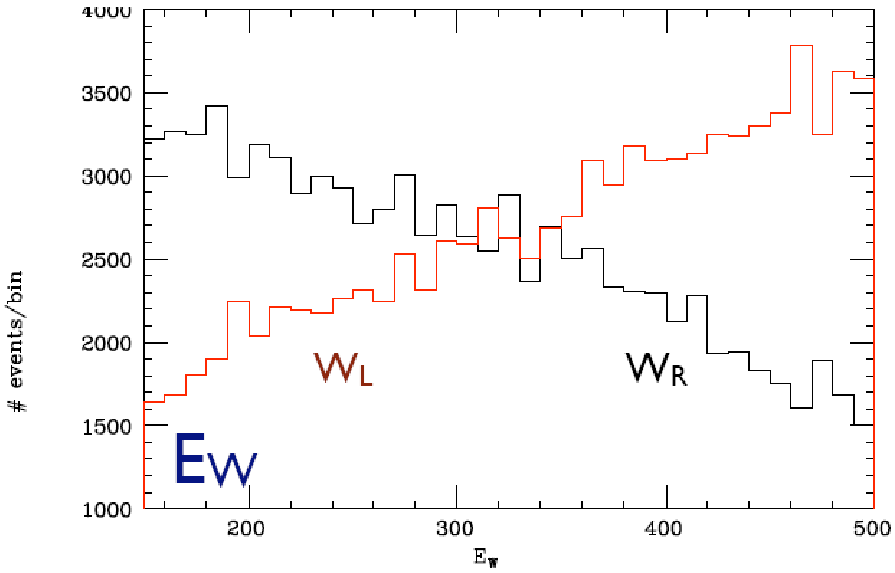
# 1.Validation

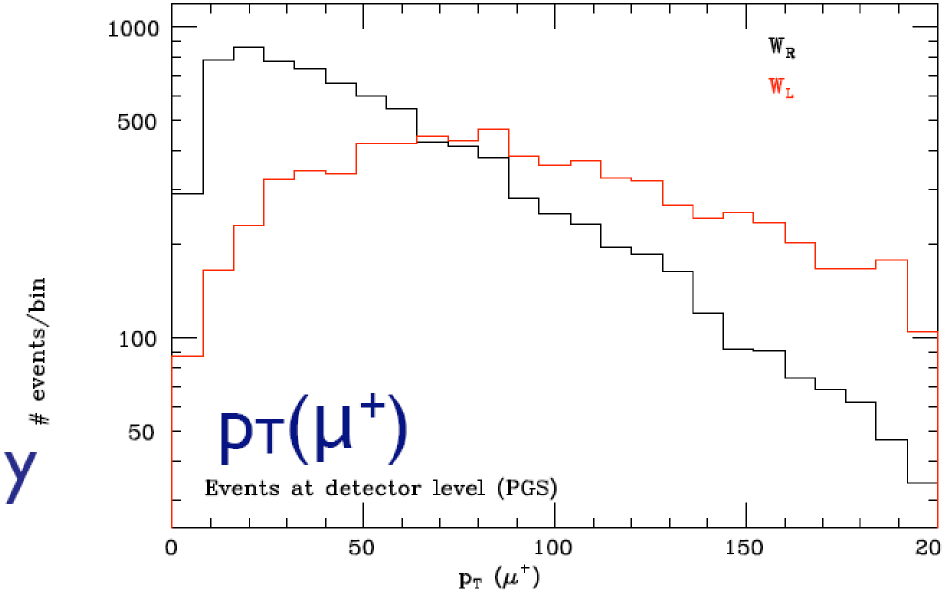


[Frere & Repko, 1991]

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





# Back-up slides

# Possible ways to introduce masses for the light neutrinos IN THE STANDARD MODEL:

## Don’t want to introduce $\nu_R$

*Such (heavy) triplet is not forbidden, but its v.expectation value must be <.03 doublet vev*

need to introduce at least one scalar complex triplet field: $\chi$

$$\lambda \bar{\Psi}^c_L \tau^a \Psi_L \chi^a$$

where

$$\Psi_L = \begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$$

## Don’t want to introduce $\chi$

need at least some $\nu_R$ - will be called N from now on

*Rem: in extended models, other solutions, eg: SUSY*

# $\nu$ masses with $\nu_R$ = N present

Again more options:

Simplest DIRAC mass term between $\nu_L$ and $\nu_R$ = N

$$\bar{\Psi}_L^i \lambda_{ij} N^j + h.c.$$

$i$ is the generation index, $\lambda$ are complex coefficients

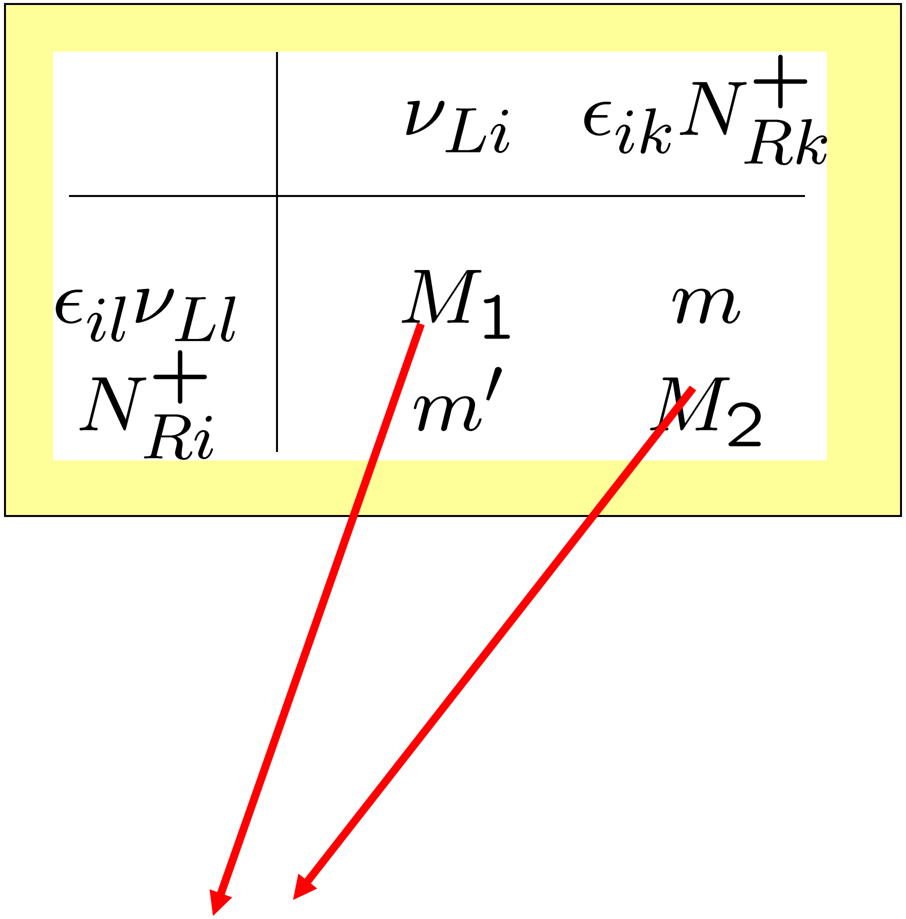
OR

Only difficulty : the Yukawa coëfficients must be very small

Allow for MAJORANA mass term for the neutrino singlet N

$$1/2 \bar{N}_i^c M^{ij} N_j$$

# Get usual See-Saw mechanism



$$\begin{array}{c|cc} & \nu_{Li} & \epsilon_{ik} N^{+}_{Rk} \\ \hline \epsilon_{il}\nu_{Ll} & M_1 & m \\ N^{+}_{Ri} & m' & M_2 \end{array}$$

VIOLATE Lepton number by 2 units

$$\begin{array}{c|cc} & \nu_{Li} & \epsilon_{ik} N^{+}_{Rk} \\ \hline \epsilon_{il}\nu_{Ll} & M_1 & m \\ N^{+}_{Ri} & m' & M_2 \end{array}$$

The diagonalisation leads to states;
For $M_1 = 0$ , and $m<<M_2$
one gets the familiar See-Saw eigenstates and values

$$\lambda_1 \approx \nu_L - m/M \ \epsilon \cdot N^{+}_{R} \qquad |m_1| \approx m/M^2$$

$$\lambda_2 \approx N_R + m/M \ \epsilon \cdot \nu^{+}_{L} \qquad |m_2| \approx M$$

# Very strong constraints claimed…

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…

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

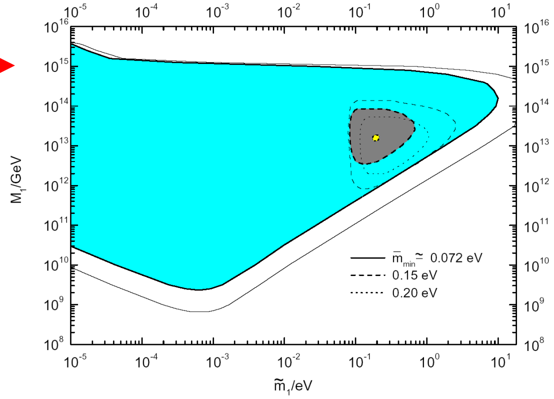
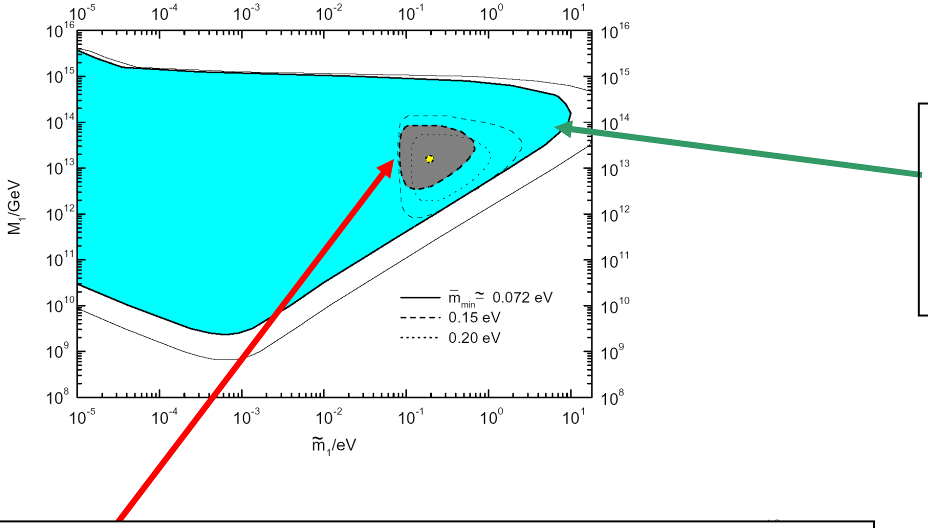


Figure 4: Inverted hierarchy case. Curves, in the ($\tilde{m}_1$-$M_1$)-plane, of constant $\eta_{B0}^{\max} = 10^{-10}$ (thin lines) and $\eta_{B0}^{\max} = 3.6 \times 10^{-10}$ (thick lines) for the indicated values of $\overline{m}$. The filled regions for $\eta_{B0}^{\max} \geq 3.6 \times 10^{-10}$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



on this side, too large $\lambda$ leads to excessive wash-out

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

# Electroweak Baryogenesis ??

- **NOT favoured in Standard Model** :
  - 1st 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.

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# Electroweak Baryogenesis – Enough CP violation?

In the Standard Model, CP violation is governed, in the Kobayashi-Maskawa mechanism, by the quantity

$$J = sin(\theta_1) sin(\theta_2) sin(\theta_3) sin(\delta) * P_u * P_d$$

$$P_u = ({m_u}^2 - {m_c}^2) * ({m_t}^2 - {m_c}^2) * ({m_t}^2 - {m_u}^2)$$

$$P_d = ({m_d}^2 - {m_s}^2) * ({m_b}^2 - {m_s}^2) * ({m_b}^2 - {m_d}^2)$$

This quantity has to be made dimensionless; for this, we can divide by $(100GeV)^{12}$, the result is $10^{-17}$, much too small for baryogenesis!

(the same result is obtained if one prefers to use the Yukawa couplings directly, instead of the quark masses)