Phenomenology
2013 Symposium

6-8 May 2013
University of Pittsburgh

NEUTRINO MASSES and FREED LEPTOGENESIS

Dmitry Zhuridov
(WSU)

Based on:

- arXiv:1204.4581 (under review in Int.J.Mod.Phys. **A**)
- Mod.Phys.Lett. **A26** (2011) 2983 [arXiv:1107.1087]
- JHEP **07** (2011) 102 [arXiv: 1105.4546]

(In collaboration with K. Kannike)

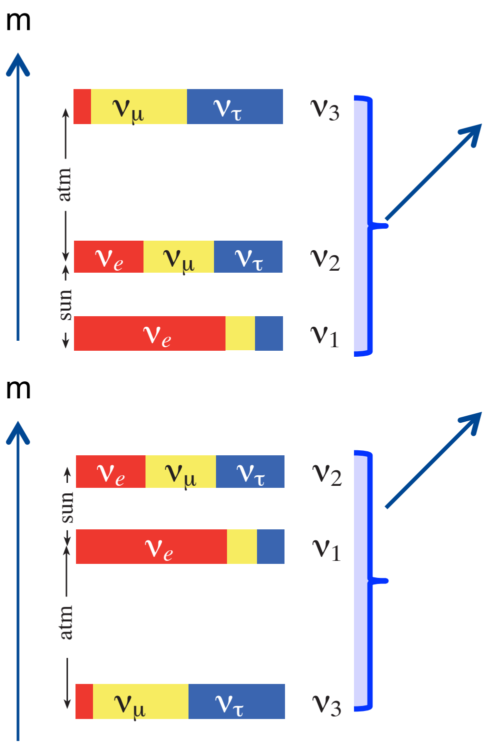
Outline

- NEUTRINO MASSES
- LEPTOGENESIS
- FREED LG
- TESTABILITY
- CONCLUSION

Neutrino masses

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k}\, \nu_{kL}$$

Experiment: neutrino masses & mixing



A.Strumia
hep-ph/0606054

Possible ν mass spectra allowed by the oscillation data are:

- Normal Hierarchical (NH)

$$m_1 \ll m_2 < m_3, \quad m_2 = \sqrt{m_1^2 + \Delta m^2_{\rm sol}}, \quad m_3 = \sqrt{m_1^2 + \Delta m^2_{\rm atm}};$$

- Inverted Hierarchical (IH)

$$m_3 \ll m_1 < m_2, \quad m_1 = \sqrt{m_3^2 + \Delta m^2_{\rm atm} - \Delta m^2_{\rm sol}}, \quad m_2 = \sqrt{m_3^2 + \Delta m^2_{\rm atm}};$$

- Quasi-Degenerate (QD)

$$m_1 \simeq m_2 \simeq m_3 \simeq m_0, \quad m_i^2 \gg \Delta m^2_{\rm atm};$$

where $\Delta m^2_{\rm sol} = 7.6 \times 10^{-5}\ {\rm eV}^2$, $\Delta m^2_{\rm atm} = 2.4 \times 10^{-3}\ {\rm eV}^2$ and $m_0 \gtrsim 0.1$ eV.

$$|U|_{2\sigma} \simeq \begin{pmatrix} 0.78 - 0.86 & 0.51 - 0.61 & 0.00 - 0.18 \\ 0.19 - 0.57 & 0.39 - 0.73 & 0.61 - 0.80 \\ 0.20 - 0.57 & 0.40 - 0.74 & 0.59 - 0.79 \end{pmatrix}$$

C.Giunti and C.W.Kim
Fundamentals of Neutrino Physics and Astrophysics, OUP, 2007

$$U^{\rm D} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

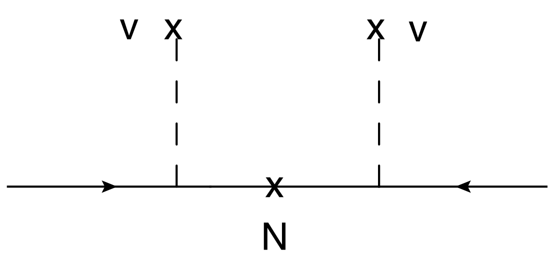
$$D^{\rm M} = {\rm diag}\left(e^{i\lambda_1}, e^{i\lambda_2}, e^{i\lambda_3}\right), \quad \text{with} \quad \lambda_1 = 0$$

Theory: generation of neutrino masses

$$\boxed{M_{\nu_e}/M_e \lesssim 10^{-6} \quad !}$$

$$\mathcal{L}_{\mathrm{SM}+N} \supset Y_{i\alpha}\bar{L}_\alpha \phi N_i + \frac{1}{2}\bar{N}_i M_{ij} N_j^c + \mathrm{H.c.} \Rightarrow M_\nu^{\mathrm{tree}} = v_0^2\, Y^T D_M^{-1}\, Y \Rightarrow \begin{array}{ccc} \dfrac{v_0}{M_N} & \sim & 10^{-6} \\ Y_{\nu_e} & \sim & Y_e \end{array}$$

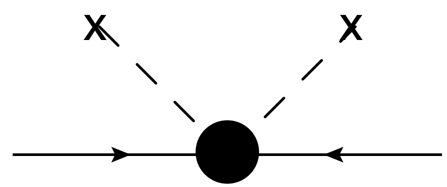
Type I see-saw



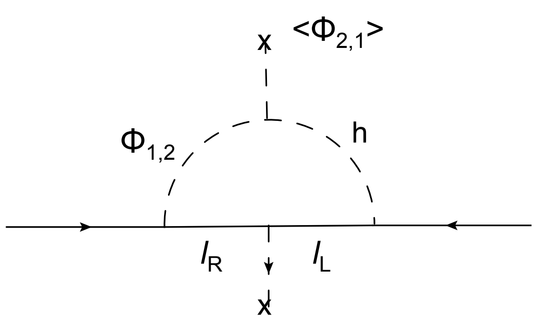
$\Rightarrow$

Weinberg dim.5 operator

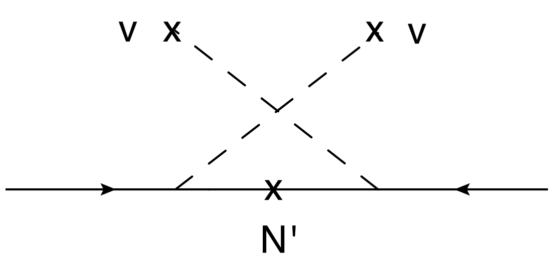
$$\mathcal{L}_Y^{eff} = \frac{1}{2}\bar{L}\phi(Y^T D_M^{-1} Y)\phi^T L^c + \mathrm{H.c.}$$



1-loop examples

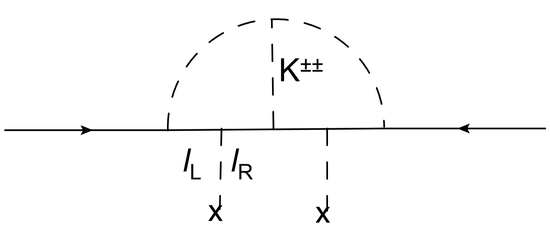


Zee (1980)



Ma (2006) & Perez-Wise models (2009)

2-loop example

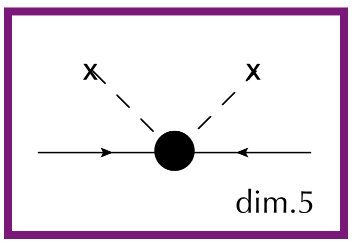


Zee (1986) – Babu (1988)

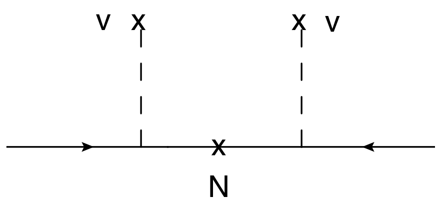
More generic: $$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm eff}^{d=5} + \mathscr{L}_{\rm eff}^{d=6} + \cdots, \quad \text{with} \quad \mathscr{L}_{\rm eff}^{d} \propto \frac{1}{\Lambda_{\rm NP}^{d-4}}\,\mathcal{O}^d$$

Tree level: see-saw   Loop level

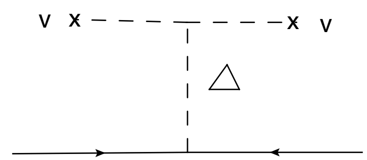
See-saw models:



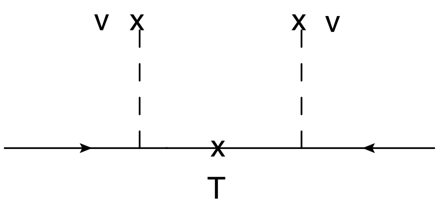
Type I



Type II



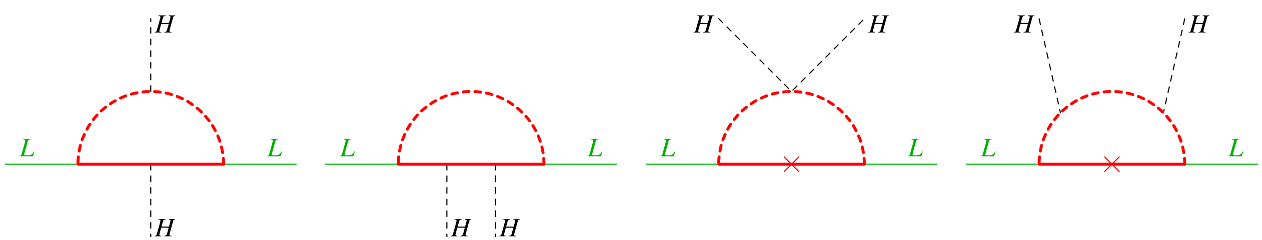
Type III



Models with hybrid I+II see-saw, I+III see-saw, etc., also present in the market.

Some 1-loop diagrams

dim.5 :



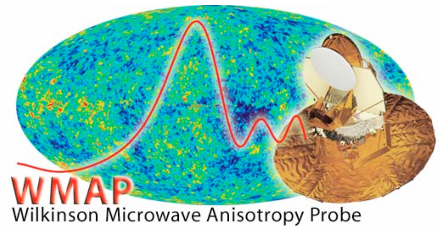
A. Strumia
hep-ph/0606054

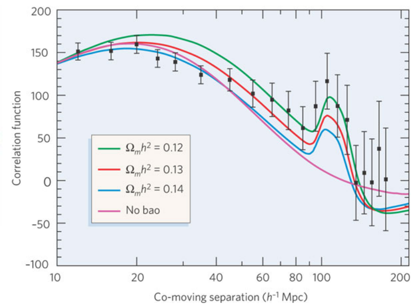
Leptogenesis

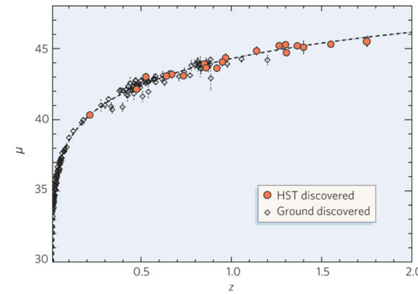
Baryon asymmetry of the Universe (BAU)

- Astro-Phys. Exp. (WMAP5+BAO+SN) or BBN:

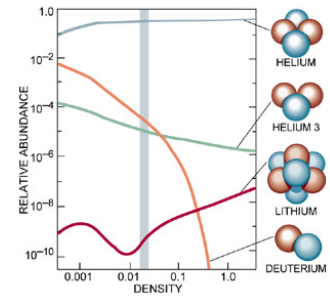
$$\boxed{\eta_B = \frac{n_B - \bar{n}_B}{n_\gamma} \sim 10^{-10}}$$





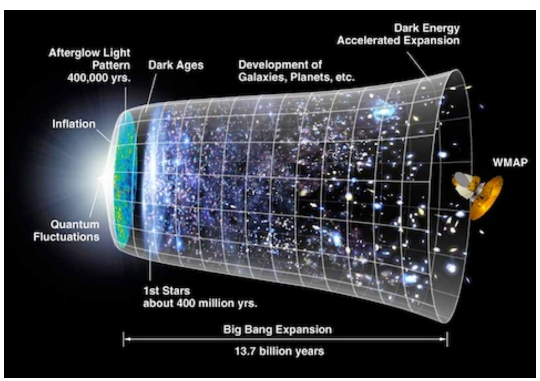


Charles L. Bennett
Nature **440**, 1126-1131 (2006)



http://astro.berkeley.edu/~mwhite/darkmatter/bbn.html

- Big Bang Theory: $n_p = n_{\bar{p}} \implies \eta_B^{\rm SM} \ll 10^{-10}$



NASA WMAP Science Team

Possible primordial baryon asymmetry would have been:

- a highly fine-turned one;
- diluted away by the required amount of inflation.

➔ **BAU should be generated dynamically**

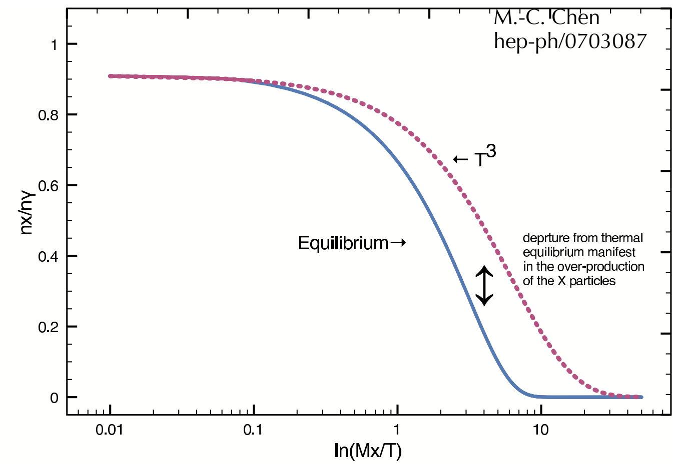
Sakharov conditions for dynamical generation of BAU:

A. Sakharov
Pisma Zh.E.T.F.5 (1967) 32

1. $\not{B}$

2. $\not{C}$ and CPV (otherwise the overall $\Delta B = 0$) ➔ ***CP* asymmetry** $\epsilon \neq 0$

3. Departure from equilibrium:
   - $\boxed{\text{Decay}}$
   - EW phase transition
   - Topological defects

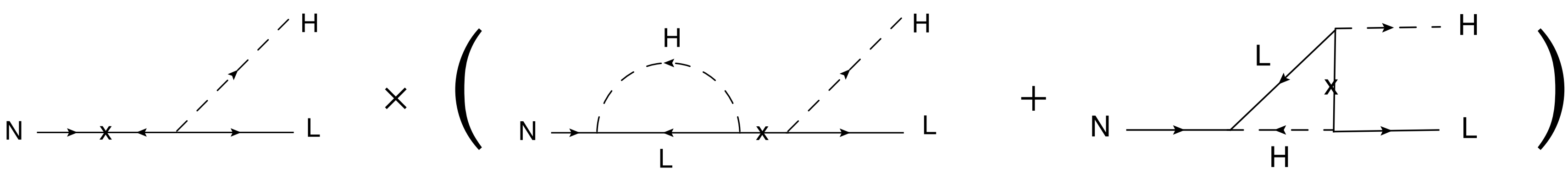


Leptogenesis

M. Fukugita and T. Yan
Phys.Lett. **B**174 (1986)

- $N \to \{\ell\phi, \bar{\ell}\bar{\phi}\} \quad \Longrightarrow \quad \Delta L \neq 0$
- sphaleron processes $\quad \Longrightarrow \quad \Delta B \neq 0$

V. Kuzmin, V. Rubakov and M. Shaposhnikov
Phys.Lett. **B**155 (1985) 36
S. Khlebnikov and M. Shaposhnikov
Nucl.Phys. **B**308 (1988) 885



Self energy

Vertex

CP asymmetry

$$\epsilon_i = \frac{\sum_\alpha \left[\Gamma(N_i \to e_\alpha \phi^\dagger) - \Gamma(N_i \to \bar{e}_\alpha \phi)\right]}{\sum_\alpha \left[\Gamma(N_i \to e_\alpha \phi^\dagger) + \Gamma(N_i \to \bar{e}_\alpha \phi)\right]}$$

(Similar to direct *CP*-violation in meson decays.)

$$\boxed{\epsilon_1 = -\sum_j \frac{3}{2} F_j \frac{M_1}{M_j} \frac{\Gamma_j}{M_j} I_j}$$

j = 2,…

$$I_j = \frac{\mathrm{Im}[(YY^\dagger)^2_{1j}]}{(YY^\dagger)_{11}(YY^\dagger)_{jj}}$$

$$\frac{\Gamma_j}{M_j} = \frac{(YY^\dagger)_{jj}}{8\pi}$$

CPC loop factor

CPV Yukawa factor

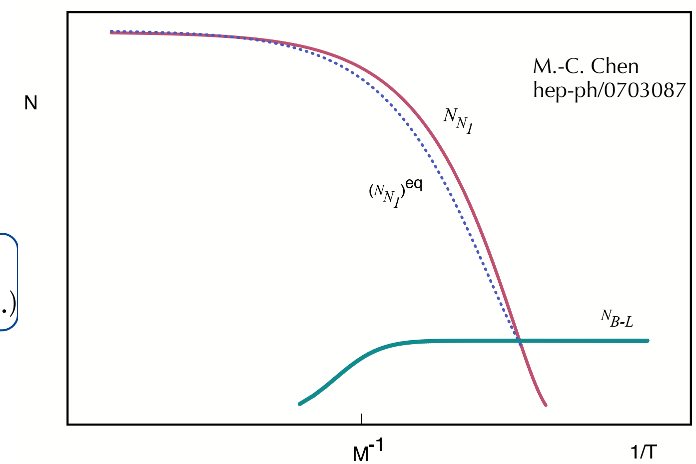
Boltzmann equations

Decay + Scattering terms (Higgs mediated)

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{\mathrm{eq}}),$$

Washout factor (ID+lepton med. scatt.)

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W N_{B-L}$$



$$\eta_B \approx 0.88 \times 10^{-2}\, N^{\mathrm{fin}}_{B-L}, \qquad N^{\mathrm{fin}}_{B-L} = N_{B-L}(t \to \infty)$$

Calculated assuming standard photon production from the onset of LG till recombination, and taking 12/37 factor for B-L to B asymmetry conversion (sphalerons go out-of-eq. below T_{EWPT}).

Consider the SM extended by SU(2) singlet or/and triplet heavy Majorana fermions.

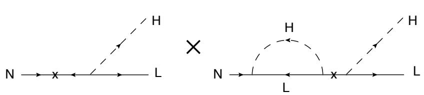
$$\boxed{\epsilon_1 = -\sum_j \frac{3}{2} F_j \frac{M_1}{M_j} \frac{\Gamma_j}{M_j} I_j}$$

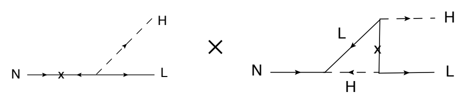
Table 1: Characteristics of the four basic types of fermionic LG.

#	Type of LG	New fermions	F_j	F	$M_1^{\rm min}$ (resonant LG)
1	Pure singlet	$\{N_i\}$	$\frac{2S_j+V_j}{3}$	1	well below 1 TeV
2	Pure triplet	$\{T_i\}$	$\frac{2S_j-V_j}{3}$	$1/3$	~ 1.6 TeV
3	Singlet-Triplet	$N_1,\ \{T_j\}$	V_j	1	—
4	Triplet-Singlet	$T_1,\ \{N_j\}$	$\frac{V_j}{3}$	$1/3$	—

$\boxed{0 < M_1 < M_2 < \ldots .}$ $i = 1, 2, \ldots$ and $j = 2, \ldots$ $F = \lim_{M_j/M_1 \to \infty} F_j$

$$S_j = \frac{M_j^2 \Delta M_{1j}^2}{(\Delta M_{1j}^2)^2 + M_1^2 \Gamma_j^2} \qquad V_j = 2\frac{M_j^2}{M_1^2}\left[\left(1 + \frac{M_j^2}{M_1^2}\right)\log\left(1 + \frac{M_1^2}{M_j^2}\right) - 1\right] \qquad \Delta M_{ij}^2 = M_j^2 - M_i^2$$





Resonant LG quasi-degenerate masses M_i

$$M_j - M_1 \approx \frac{\Gamma_j}{2} \ll M_1 \quad \Longrightarrow \quad S_j \gg V_j \quad \text{and} \quad \frac{S_j M_1 \Gamma_j}{M_j^2} \approx 1$$

$$\Longrightarrow \quad |\epsilon_1| \sim 1 \quad \text{for} \quad I_j \sim 1$$

Flanz, Covi, Roulet, Pilaftsis *et al.*

Hierarchical case $\boxed{M_j/M_1 \to \infty}$ Using Casas-Ibarra parametriz. $Y = v_0^{-1} D_M^{1/2} R D_\nu^{1/2} U^\dagger,$

$RR^T = 1$

the CP asymmetry can be rewritten as

$$\epsilon_1^0 = -\frac{3F}{16\pi}\frac{M_1}{v_0^2}\frac{\sum_k m_k^2\,\mathrm{Im}[R_{1k}^2]}{\sum_k m_k |R_{1k}|^2}.$$

For $0 < m_1 < m_2 < m_3$ the upper bound is

$$\boxed{|\epsilon_1|^{\max} = \frac{3F}{16\pi}\frac{M_1}{v_0^2}(m_3 - m_1),}$$

NH, IH

$$m_3 - m_1 \approx \sqrt{\Delta m^2_{\mathrm{atm}}}.$$

Davidson–Ibarra bound

$\eta_B \approx 6 \times 10^{-10}$ ⇨ $|\epsilon_1|^{\max} \gtrsim 10^{-6}$

$\Delta m^2_{\mathrm{atm}} = 2.40 \times 10^{-3}\ \mathrm{eV}^2$ ⇨ $\boxed{M_1 \gtrsim 10^9\ \mathrm{GeV}}$

Pay your attention!

NH, IH

For $0 < m_1 < m_2 < m_3$ the upper bound is

$$\boxed{|\epsilon_1|^{\max} = \frac{3F}{16\pi}\frac{M_1}{v_0^2}(m_3 - m_1),} \qquad m_3 - m_1 \approx \sqrt{\Delta m^2_{\rm atm}}.$$

However in the case with one massless neutrino, using

$$R = \begin{pmatrix} 0 & \cos z & \pm \sin z \\ 0 & -\sin z & \pm \cos z \end{pmatrix},$$

where $z = \alpha + \mathrm{i}\beta$ is the complex angle, and maximizing over α we have

$$\frac{3F}{16\pi}\frac{M_1}{v_0^2}(m_3 - m_2)\tanh 2\beta.$$

IH NH

Hence for $0 = m_1 < m_2 < m_3$

$$\boxed{|\epsilon_1|^{\max} = \frac{3F}{16\pi}\frac{M_1}{v_0^2}(m_3 - m_2),} \qquad m_3 - m_2 \approx \sqrt{\Delta m^2_{\rm sol}}/2, \ \sqrt{\Delta m^2_{\rm atm}}.$$

Gravitino problem

Davidson–Ibarra bound

$T_{\mathrm{RH}} \gtrsim$ $\boxed{M_1 \gtrsim 10^9 \text{ GeV}}$

to produce N_1 thermally

$\boxed{T_{\mathrm{RH}} < 10^{6-7} \text{ GeV}}$

However such a high T_{RH} can lead to over-production of light states, e.g., gravitinos.

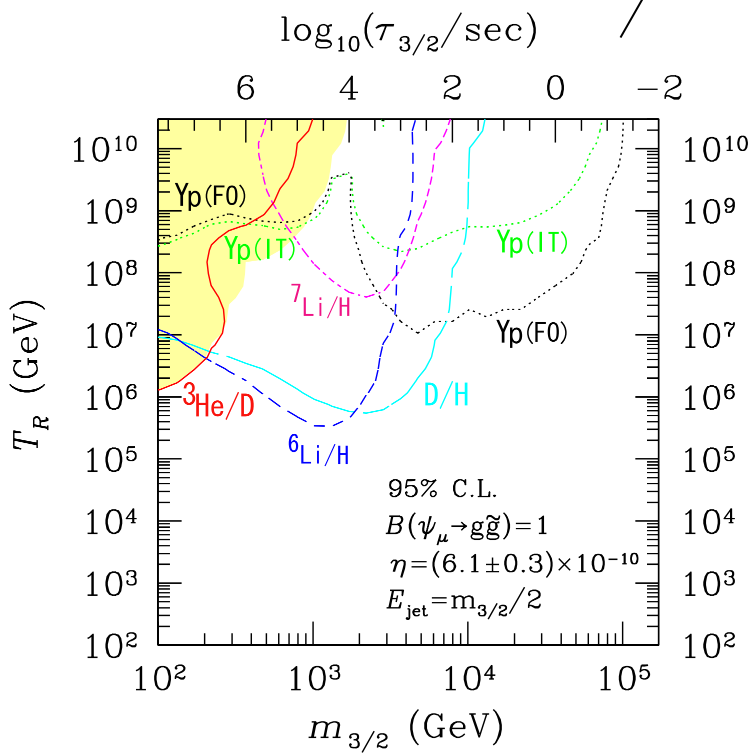
M. Khlopov, A. Linde
Phys.Lett. **B**138 (1984) 265

$$\frac{n_{3/2}}{s} \simeq 10^{-2}\frac{T_{RH}}{M_{\mathrm{Pl}}}$$

In particular, high energy γ emitted in $\psi_{3/2}$ decays may destroy light elements through photo-dissociation reactions:

reaction	threshold (MeV)
$D+\gamma \to n+p$	2.225
$T+\gamma \to n+D$	6.257
$T+\gamma \to p+n+n$	8.482
$^3He+\gamma \to p+D$	5.494
$^4He+\gamma \to p+T$	19.815
$^4He+\gamma \to n+^3He$	20.578
$^4He+\gamma \to p+n+D$	26.072

M.-C. Chen
hep-ph/0703087



M. Kawasaki *et al.*
astro-ph/0408426

Figure 44: Upper bounds on the reheating temperature as a function of the gravitino mass for the case where the gravitino dominantly decays into gluon-gluino pair. Here, we take $B_h = 1$, $E_{\mathrm{vis}} = m_{3/2}$, and $E_{\mathrm{jet}} = \frac{1}{2}m_{3/2}$. The shaded region is the excluded region for the case with $B_{\mathrm{h}} = 0$.

Freed LG

Weinberg dim.5 operator

$$\mathcal{L}_Y^{\rm eff} = \frac{1}{2}\bar{L}\phi\frac{M_\nu^{\rm tree}}{v_0^2}\phi^T L^c + {\rm H.c.}$$

$M_\nu^{\rm tree} = v_0^2\, Y^T D_M^{-1}\, Y$

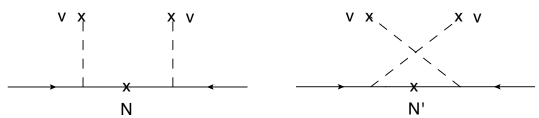
Additional dim.5 operator

$$\mathcal{L}_h^{\rm eff} = -\frac{1}{2\Lambda}\bar{L}_\alpha\phi(h_\alpha h_\beta^T)\phi^T L_\beta^c + {\rm H.c.}$$

$\Lambda > 0$ is the high-energy mass scale

$$h_\alpha^T = a_i Y_{i\alpha} \quad \Rightarrow \quad M_\nu^{\rm tree} - v_0^2\frac{Y^T a^T a Y}{\Lambda} \equiv M_\nu = v_0^2\, Y'^T D_{\mathcal{M}}^{-1} Y'$$

Natural in many GUTs

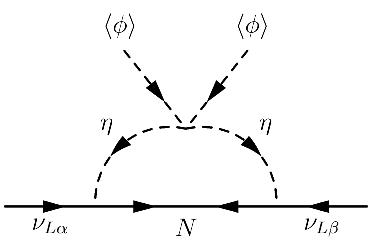


$QY = Y'$

$D_{\mathcal{M}} = {\rm diag}(\tilde{M}_1, \tilde{M}_2, \ldots)$

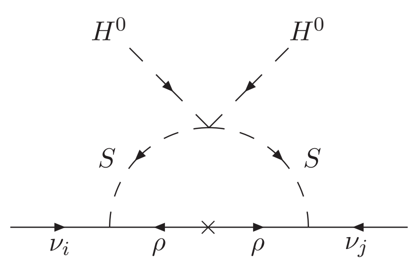
If there is a cancellation between the loop term and N_2 tree contribution to the neutrino mass matrix then ***CP* asymmetry is less restricted**!

Examples for loop generation of this new dim.5 operator



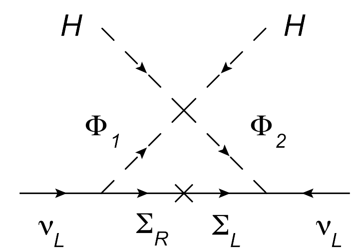
$G_{SM} \times Z_2$

E. Ma
Phys.Rev.**D**73 (2006) 077301
[hep-ph/0601225]



$S_1 \sim (8, 2, 1/2)$

P. Fileviez Perez, M. B. Wise
Phys.Rev.**D**80 (2009) 053006
[hep-ph/0906.2950]



$\Sigma_{L,R}\ (5, 2)$ $\quad$ $\Phi_1,\ \Phi_2$ $\quad$ $(4, -3),\ (4, -1)$

K.Kumiricki, I.Picek, B.Radovcic
Phys.Rev.**D**784 (2011) 093002
[arXiv:1106.1069 [hep-ph]]

$$M_\nu^{\rm tree} \;\Rightarrow\; M_\nu^{\rm tree} - v_0^2 \frac{Y^T a^T a Y}{\Lambda} \equiv M_\nu = v_0^2\, Y'^T D_{\mathcal{M}}^{-1} Y'$$

$$QY = Y'$$

$$D_{\mathcal{M}} = {\rm diag}(\tilde{M}_1, \tilde{M}_2, \dots)$$

In the hierarchical limit $\boxed{M_2/M_1 \to \infty}$

$$\epsilon_1 = -\frac{3F}{16\pi}\frac{M_1 \Sigma_\nu^{\rm tree}}{(YY^\dagger)_{11}}, \qquad \Sigma_\nu^{\rm tree} = \sum_j {\rm Im}[(YY^\dagger)^2_{1j} M_j^{-1}] = \frac{1}{v_0^2}{\rm Im}\left\{\left[Y\left(M_\nu^{\rm tree}\right)^\dagger Y^T\right]_{11}\right\}.$$

$$\left.\begin{aligned} \Sigma_\nu^{\rm tree} &= \sum_j \frac{X_j}{M_j}, \\ X_j &= {\rm Im}[((YY^\dagger)_{1j})^2] \end{aligned}\right\} \;\Rightarrow\; \begin{aligned} \Sigma_\nu &= \sum_j \frac{X_j}{M'_j}, \\ M'_j &\equiv \left(\frac{1}{M_j} - \frac{a_j^2}{\Lambda}\right)^{-1} \end{aligned}$$

cancellation between loop & N_2 tree contributions

$X_1 = 0$ since $(YY^\dagger)_{11} = |y_1|^2$ is real.

$$\Sigma_\nu^{\rm tree} = \frac{X_2}{M_2} + \frac{X_3}{M_3} + \dots$$

If $M_2 \ll M_3 < \dots$ and X_j are not hierarchical than $\Sigma_\nu^{\rm tree} \simeq \frac{X_2}{M_2}$.

$$\mu = \frac{\Lambda}{\Lambda - a_2^2 M_2}$$

$\Sigma_\nu = \frac{X_2}{\mu M_2} + \frac{X_3}{\mu_3 M_3} + \dots,$ where $\mu_j = \frac{M'_j}{M_j}$ and $\mu \equiv \mu_2$.

If also $|\mu M_2| \ll |\mu_k M_k|$ with $k \geq 3$ than $\Sigma_\nu \simeq \frac{1}{\mu}\Sigma_\nu^{\rm tree}$.

$$\Rightarrow \boxed{\epsilon_1^{\rm freed} \simeq -\mu \frac{3F}{16\pi}\frac{M_1 \Sigma_\nu}{(YY^\dagger)_{11}}}$$

$$M_\nu^{\rm tree} \quad \Rightarrow \quad M_\nu^{\rm tree} - v_0^2 \frac{Y^T a^T a Y}{\Lambda} \equiv M_\nu = v_0^2\, Y'^T D_{\mathcal{M}}^{-1} Y'$$

$$QY = Y'$$

$$D_{\mathcal{M}} = {\rm diag}(\tilde{M}_1, \tilde{M}_2, \dots)$$

The *CP* asymmetry can be enhanced by μ!

$$\boxed{\epsilon_1^{\rm freed} = -\frac{3F}{16\pi}\mu \frac{M_1 \Sigma_\nu}{(YY^\dagger)_{11}}}$$

$$\mu = \frac{\Lambda}{\Lambda - a_2^2 M_2}$$

Magnification factor

$$\Sigma_\nu = \frac{1}{v_0^4} \sum_k m_k^2 \, {\rm Im}\left[\left(Q^T D_{\mathcal{M}}^{1/2} R'\right)^2_{1k}\right],$$

$$(YY^\dagger)_{11} = \frac{1}{v_0^2} \sum_k m_k \left|(Q^T D_{\mathcal{M}}^{1/2} R')_{1k}\right|^2,$$

where the partly orthogonal matrix R' comes from the parametrization of Y' as

If not quadratic

$$Y' = v_0^{-1} D_{\mathcal{M}}^{1/2} R' D_\nu^{1/2} U^\dagger$$

➔ **Upper bound on the *CP* asymmetry can be derived**

In particular, for only two heavy neutrinos in the limit $M_1 \ll \min(\Lambda, M_2)$

$$Q \approx \begin{pmatrix} 1 & q \\ -q & 1 \end{pmatrix}$$

with $q \approx \sin q \approx -a_1 a_2 M_1/\Lambda$, and the eigenvalues of the matrix $D_{\mathcal{M}}$

$$\tilde{M}_1 \approx M_1 \left(1 + a_1^2 \frac{M_1}{\Lambda}\right), \qquad \tilde{M}_2 \approx M_2'.$$

Using $\hat{m}_i = \sum_k m_k^2 (R'_{ik})^2$, $\hat{m}_{12} = \sum_k m_k^2 R'_{1k} R'_{2k}$, $\tilde{m}_i = \sum_k m_k |R'_{ik}|^2$, $\tilde{m}_{12} = \sum_k m_k R'_{1k} R'^{*}_{2k}$ and $r = M_2'/M_1$, we have

$$\epsilon_1^{\rm freed} \approx -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{{\rm Im}[\hat{m}_1] + q^2 r\,{\rm Im}[\hat{m}_2] - 2q\,{\rm Im}[\sqrt{r}\,\hat{m}_{12}]}{\tilde{m}_1 + q^2|r|\tilde{m}_2 - 2q\,{\rm Re}[\sqrt{r}\,\tilde{m}_{12}]}$$

$q^2\,|r| \ll 1$

$$\boxed{\epsilon_1^{\rm freed} \approx -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 {\rm Im}[R'^2_{1k}]}{\sum_k m_k |R'_{1k}|^2}}$$

Standard expression, but **multiplied by** μ !!!

$q^2\,|r| \gg 1$

$$\boxed{\begin{aligned}\epsilon_1^{\rm freed} &\approx -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 {\rm Im}[R'^2_{2k}]}{\sum_k m_k |R'_{2k}|^2}\\ &\times\ {\rm sign}[\Lambda - a_2^2 M_2]\end{aligned}}$$

Energy scale

Take $|a_i| \sim 1.$

$\Lambda,\ M_2$

1) $\frac{\Lambda^2}{|\mu| M_2}$ $\Rightarrow$ $$\epsilon_1^{\rm freed} = -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 {\rm Im}[R'^2_{1k}]}{\sum_k m_k |R'_{1k}|^2}$$

M_1

(For the intermediate case the result is also approximately valid.)

2) $\frac{\Lambda^2}{|\mu| M_2}$ $\Rightarrow$ $$\epsilon_1^{\rm freed} = -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 {\rm Im}[R'^2_{2k}]}{\sum_k m_k |R'_{2k}|^2}\,{\rm sign}[\Lambda - a_2^2 M_2]$$

v_0

The resulting bound:

$$\boxed{|\epsilon_1^{\rm freed}|^{\rm max} = |\mu||\epsilon_1|^{\rm max}}$$

$$\mu = \frac{\Lambda}{\Lambda - a_2^2 M_2}$$

Enhanced CP asymmetry gives more freedom to M_1: $\boxed{M_1 \gtrsim \frac{1}{|\mu|} \times 10^9\ {\rm GeV}}$

Gravitino problem is solved!

Example of freed LG realization in Adjoint $SU(5)$ model

Plot μ in AdSU(5) model with

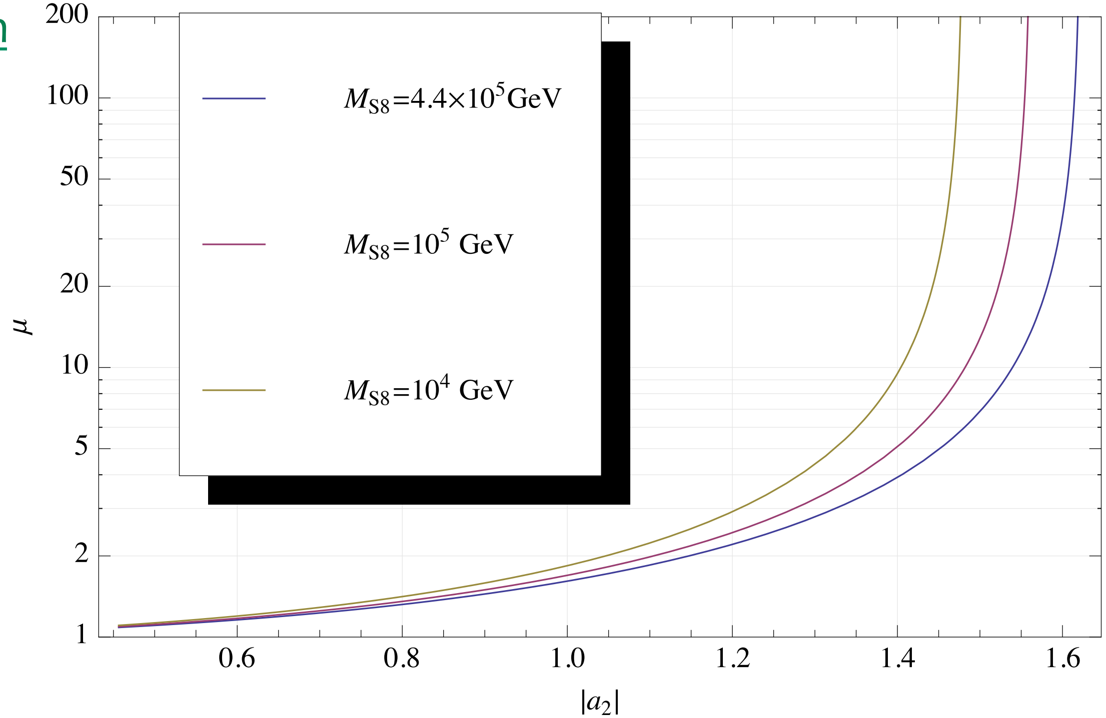
$$M_{\rho_3} = 5 \times 10^{11}\ \text{GeV}, \quad \hat{m} = 200,$$

$$\lambda_5 = -0.5$$

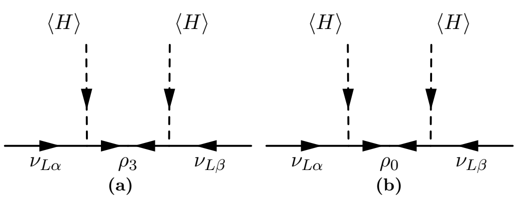
$$\boxed{a_2 = \pm \frac{\sqrt{5}}{24\sqrt{2}} \frac{v_0}{|v_{45}|}}$$

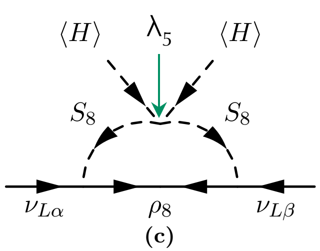
For successful unification

$$M_{\rho_3} \ll \hat{m} M_{\rho_3} = M_{\rho_8} \simeq \frac{5}{2} M_{\rho_0}$$



Interactions, which generate ν masses





Under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L$, the scalar fields are decomposed as

$$\mathbf{5}_H = H_1 \oplus T_{(3,1)}, \tag{A.1}$$

$$\mathbf{24}_H = \Sigma_8 \oplus \Sigma_3 \oplus \Sigma_{(3,2)} \oplus \Sigma_{(\bar{3},2)} \oplus \Sigma_{24}, \tag{A.2}$$

$$\mathbf{45}_H = S_8 \oplus S_{(\bar{6},1)} \oplus S_{(3,3)} \oplus S_{(\bar{3},2)} \oplus S_{(3,1)} \oplus S_{(\bar{3},1)} \oplus H_2. \tag{A.3}$$

and the matter fields are decomposed as

$$\bar{\mathbf{5}}_\alpha = \ell_{\alpha L} \oplus (d^c_\alpha)_L, \tag{A.4}$$

$$\mathbf{10}_\alpha = (u^c_\alpha)_L \oplus q_L \oplus (e^c_\alpha)_L, \tag{A.5}$$

$$\mathbf{24} = (\rho_8)_L \oplus (\rho_3)_L \oplus (\rho_{(3,2)})_L \oplus (\rho_{(\bar{3},2)})_L \oplus (\rho_0)_L, \tag{A.6}$$

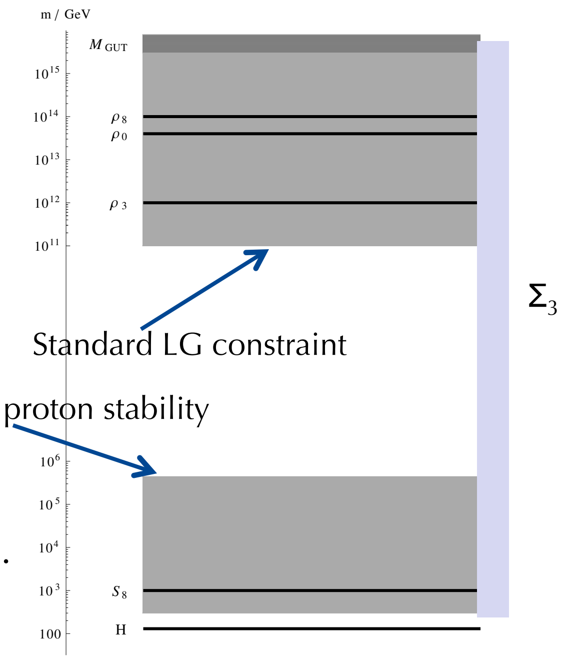
where $\alpha = 1,2,3$ is the generation index, $\ell_L = (\nu_L, e_L)^T$ is the SM lepton doublet, H_i are scalar SU(2) doublets, and we denote $\rho_0 \equiv \rho_{(1,1)}$, $S_8 \equiv S_{(8,2)}$, $\Psi_3 \equiv \Psi_{(1,3)}$ and $\Psi_8 \equiv \Psi_{(8,1)}$,

Testability

Testability

Ad SU(5) model

Some of new particles, e.g., Σ_3, S_8=S and $S_{(\bar{3},1)}$ may be light enough to be tested at the LHC and near future facilities.



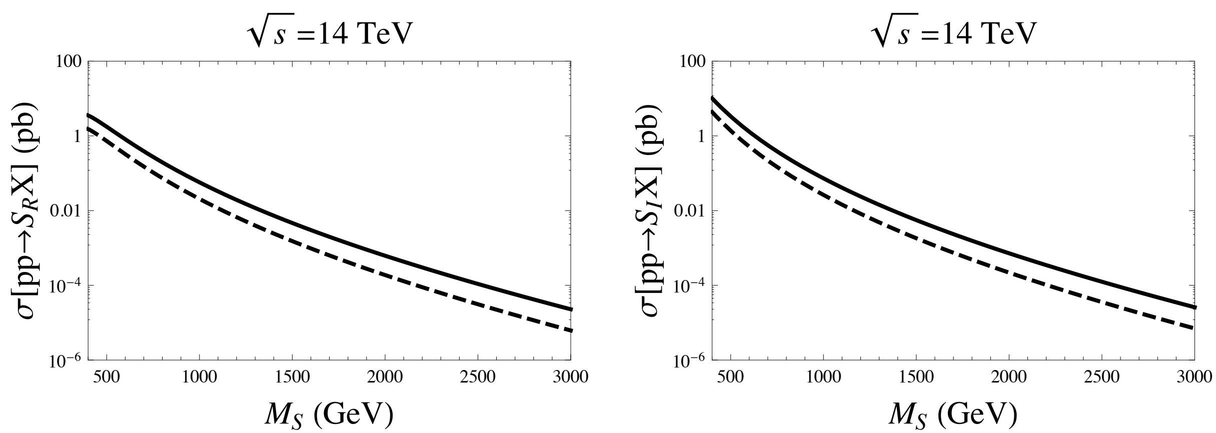
Standard LG constraint

M_S < 440 TeV for proton stability

Manohar-Wise model – color-octet scalars consistent with MFV; having also color-octet fermions one may generate **neutrino** masses.

P. Fileviez Perez, M. B. Wise
Phys.Rev.**D**80 (2009) 053006
[hep-ph/0906.2950]

A.Manohar, M.Wise
Phys.Rev.**D**74 (2006) 035009
[hep-ph/0606172]



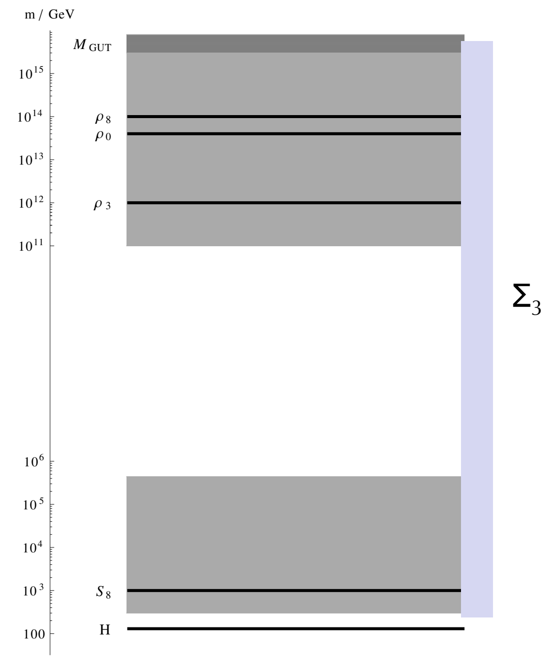
A.Idilbi, C.Kim, T.Mehen
Phys.Rev.**D**79 (2009) 114016
[arXiv:0903.3668]

FIG. 5: The scattering cross sections employing Manohar-Wise Model at the LHC. In the both plots, the straight (dashed) lines denote the results at NLL (LO).

Testability

Ad SU(5) model

Some of new particles, e.g., Σ_3, S_8=S and $S_{(\bar{3},1)}$ may be light enough to be tested at the LHC and near future facilities.



$S_{(\bar{3},1)}$ with low mass has impact on flavor phenomenology

I.Doršner, S.Fajfer, N.Košnik
Phys.Rev.**D**86 (2012) 015013
[arXiv:1204.0674]

I.Doršner *et al.*
JHEP1111 (2011) 002
[arXiv:1107.5393]

I.Doršner, S.Fajfer, J.Kamenik, N.Košnik
Phys.Rev.**D**82 (2010) 094015
[arXiv:1007.2604]

I.Doršner *et al.*
Phys.Lett.**B**682 (2009) 67-73
[arXiv:0906.5585]

- FCNC and CPV in K and B meson systems
- LFV dileptonic decays of neutral mesons
- μ-e conversion in nuclei
- Anomalous magnetic moments of charged leptons
- LFV decays of the muon and τ lepton
- …

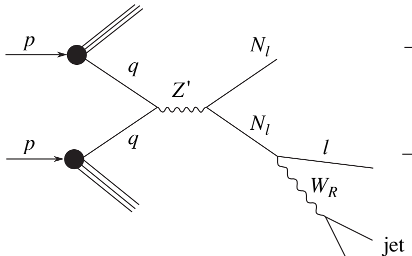
Note that the possibility of color-octet LG (if lightest new fermions are color-octet) was considered by Losada and Tulin.

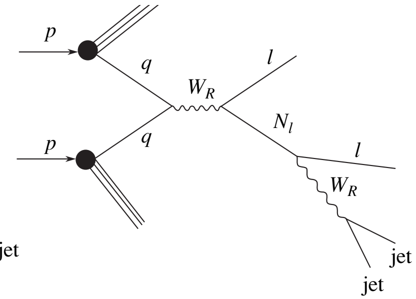
M.Losada and S.Tulin
arXiv:0909.0648

Testability

Heavy neutral fermions may be probed at the LHC

Singlet





$$pp \to W_R \to eN_e \to eejj$$

S.N.Gninenko *et al.*
Phys.At.Nucl.**70** (2007) 441-449
CERN-CMS-NOTE-2006-098

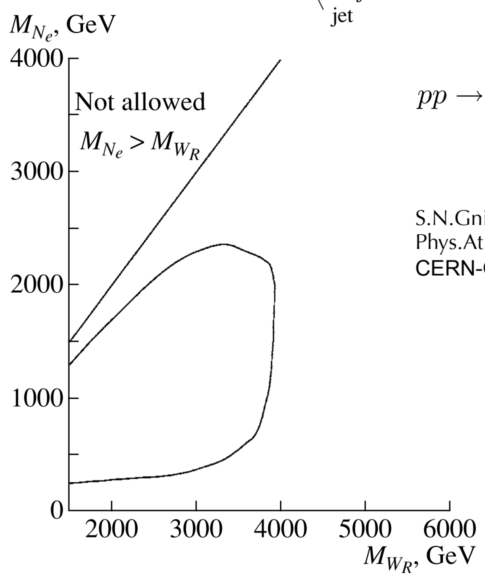


Fig. 11. CMS discovery potential of the W_R boson and right-handed Majorana neutrinos of the LR symmetric model for the integrated luminosity $L_t = 30\ \mathrm{fb}^{-1}$.

$$2(\sqrt{N_S + N_B} - \sqrt{N_B}) \geq 5,$$

where N_S and N_B are the numbers of signal and background events, respectively.

Triplet

A.Arhrib *et al.*
Phys.Rev.**D**82 (2010) 053004
[arXiv:0904.2390]

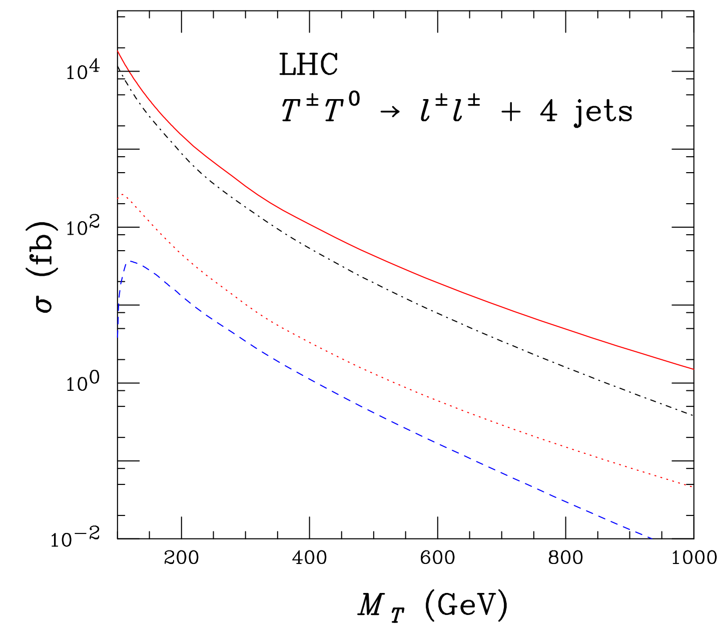


FIG. 17: Total cross section for $pp \to T^\pm T^0$ production and decay at the LHC energy at $\sqrt{S} = 14$ TeV as a function of the heavy lepton mass. The solid curve (top) is for the production rate of $T^+T^0 + T^-T^0$ before any decay or kinematical cuts. The cross section at the 10 TeV LHC is also plotted (the curve right below) for comparison. The dotted (middle) curve represents production cross section including appropriate branching fraction of Eq. (40), for the case of IH for illustration, with $\ell = e,\ \mu$ taken from the leading channels in Table II. The dashed (lower) curve shows variation of signal cross section after taking into account the cuts in Eqs. (44– 47).

Conclusion

- Davidson-Ibarra bound is revised: it is shown that in the case with one massless neutrino this bound essentially depends on the light neutrino mass hierarchy.

- The new theory of **freed leptogenesis**, which violates Davidson-Ibarra bound for special class of models and solves the gravitino problem, is introduced.

- Testability of possible realizations of the freed leptogenesis is discussed.

Backslides

Abstract

Observable nonzero neutrino masses and baryon asymmetry of the Universe can not be explained within minimal Standard Model. However many its extensions generate both the baryon asymmetry through leptogenesis (LG) scenario and the neutrino masses. The upper limit on the CP asymmetry relevant for LG with hierarchical heavy neutrinos, which is called Davidson-Ibarra bound, assumed to be model independent. I will introduce freed LG, which violates this bound in a special class of models.

Theory: generation of neutrino masses

$$\boxed{M_{\nu_e}/M_e \lesssim 10^{-6} \quad !}$$

$$\mathcal{L}_{\mathrm{SM}+N^{\mathrm{Dir}}} \supset Y_{i\alpha}\bar{L}_\alpha \phi N_i^{\mathrm{Dir}} + \mathrm{H.c.} \quad \Rightarrow \quad M_\nu^{\mathrm{Dir}} = v_0\, Y \quad \Rightarrow \quad \frac{Y_{\nu_e}}{Y_e} \sim 10^{-6}$$

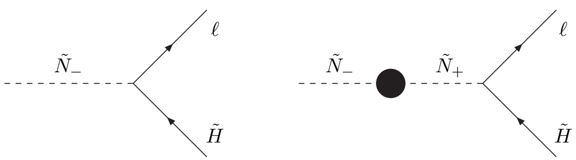
$$\mathcal{L}_{\mathrm{SM}+N} \supset Y_{i\alpha}\bar{L}_\alpha \phi N_i + \frac{1}{2}\bar{N}_i M_{ij} N_j^c + \mathrm{H.c.} \quad \Rightarrow \quad M_\nu^{\mathrm{tree}} = v_0^2\, Y^T D_M^{-1}\, Y \quad \Rightarrow \quad \left\{ \begin{array}{lcl} \dfrac{v_0}{M_N} & \sim & 10^{-6} \\ Y_{\nu_e} & \sim & Y_e \end{array} \right.$$

How to solve gravitino problem?

1) **Relaxing DI bound** (for the hierarchical case), more generic **reducing the mass of** lightest particle responsible for LG (**RH neutrino**, sneutrino, etc.), required for sufficient lepton asymmetry: *resonant LG, soft LG, Ma model, freed LG,* etc.

2) **RH neutrino** (etc.) **production at T > T_{RH}**, e.g., through inflaton decay: *non-thermal LG*.

Soft LG: SUSY soft breaking terms ➔ small mass splitting between CP-even & CP-odd RH sneutrinos ➔ required CPV



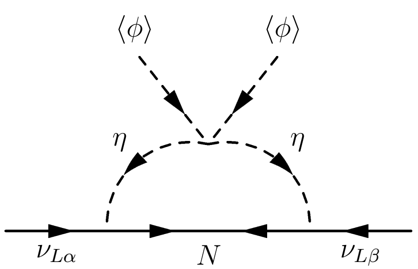
M. Flanz, E. Paschos, U. Sarkar
Phys.Lett.**B**345 (1995) 248-252, Err. **B**382
[hep-ph/9411366]

For review see
G.D'Ambrosio, G.Giudice, M.Raidal
Phys.Lett.**B**575 (2003) 75-84
[hep-ph/0308031]

Ma model: DI bound reduced by $16\pi^2$ ➔ $N > 2.5\times10^7$ GeV ~ T_{RH}
(this is a bound on Z_2 odd N, not ordinary RH neutrino)

E. Ma
Mod.Phys.Lett.**A**21(2006)1777
[hep-ph/0605180]

Field	N_i	N	η
Z_2	$+$	$-$	$-$
$SU(3)_c$	1	1	1
$SU(2)_L$	1	1	2
$U(1)_Y$	0	0	1/2



$$\mathcal{L}_Y^{\rm eff} = \frac{1}{2}\bar{L}\phi\frac{M_\nu^{\rm tree}}{v_0^2}\phi^T L^c + \text{H.c.}$$

$$\mathcal{L}_h^{\rm eff} = -\frac{1}{2\Lambda}\bar{L}_\alpha\phi(h_\alpha h_\beta^T)\phi^T L_\beta^c + \text{H.c.}$$

$M_\nu^{\rm tree} = v_0^2\, Y^T D_M^{-1}\, Y$

$\Lambda > 0$ is the high-energy mass scale

$$h_\alpha^T = a_i Y_{i\alpha} \Rightarrow M_\nu^{\rm tree} - v_0^2\frac{Y^T a^T a Y}{\Lambda} \equiv M_\nu = v_0^2\, Y'^T D_{\mathcal{M}}^{-1} Y'$$

$QY = Y'$

$D_{\mathcal{M}} = \text{diag}(\tilde{M}_1, \tilde{M}_2, \dots)$

If there is a specific partial cancellation among these tree and loop contributions to the neutrino mass matrix then ***CP* asymmetry is less restricted**, in particular:

For $i = 1, 2$ with $M_1 \ll \min(\Lambda, M_2)$, using $Y' = v_0^{-1} D_{\mathcal{M}}^{1/2} R' D_\nu^{1/2} U^\dagger$, we have

$$\epsilon_1^{\rm freed} = -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 \text{Im}[R'^2_{1k}]}{\sum_k m_k |R'_{1k}|^2}$$ for $a_1^2 a_2^2 M_1 M_2 \ll \Lambda|\Lambda - a_2^2 M_2|$

$$\epsilon_1^{\rm freed} = -\frac{3F}{16\pi}\frac{\mu M_1}{v_0^2}\frac{\sum_k m_k^2 \text{Im}[R'^2_{2k}]}{\sum_k m_k |R'_{2k}|^2}\,\text{sign}[\Lambda - a_2^2 M_2]$$ for $a_1^2 a_2^2 M_1 M_2 \gg \Lambda|\Lambda - a_2^2 M_2|$

$$\Rightarrow \boxed{|\epsilon_1^{\rm freed}|^{\rm max} = |\mu||\epsilon_1|^{\rm max}}$$

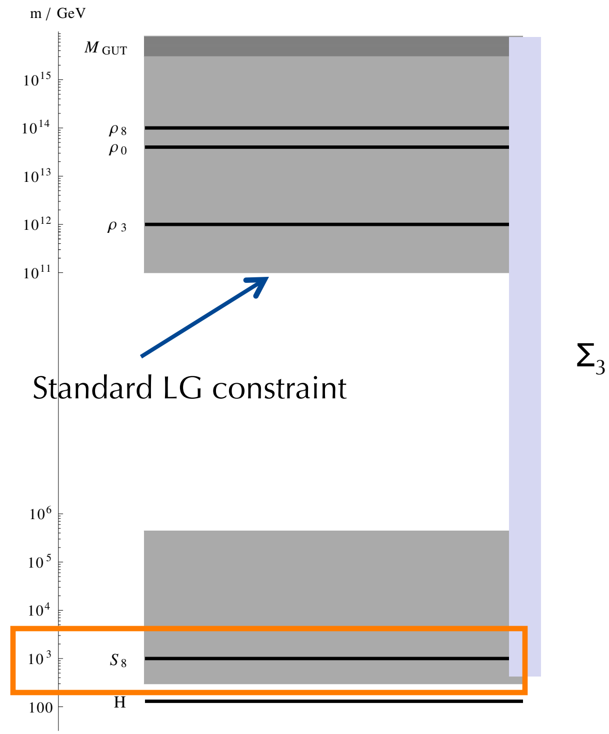
Magnification factor

$$\mu = \frac{\Lambda}{\Lambda - a_2^2 M_2}$$

$$|\mu| > 1 \quad \Rightarrow \quad |\epsilon_1^{\rm freed}|^{\rm max} > |\epsilon_1|^{\rm max}$$

Testability

Ad SU(5) ➔



H -> gamma gamma excess @ LHC

Models with color scalars

$$\mathcal{L} \ni -\lambda_\Phi(\Phi^\dagger_{ia}\Phi_{ia})(H^\dagger_j H_j) = -\lambda_\phi m_W \Phi^\dagger_{ia}\Phi_{ia} h + \ldots$$

Such $\Phi^\dagger\Phi H^\dagger H$ interaction can significantly modify the loop-induced processes $gg \to h$, $gg \to hh$, $h \to \gamma Z$ and $h \to \gamma\gamma$.

$SU(3) \times SU(2) \times U(1)$	χ^2_{min}	$\chi^2(ZZ,\ WW,\ \gamma\gamma,\ \gamma\gamma jj)$
$(\mathbf{\bar{3}}, \mathbf{1}, 1/3)$	6.8	(0.49, 0.25, 1.61, 4.5)
$(\mathbf{\bar{3}}, \mathbf{1}, -2/3)$	7.2	(0.22, 0.09, 2.20, 4.7)
$(\mathbf{3}, \mathbf{1}, -4/3)$	6.1	(0.31, 0.30, 2.36, 3.1)
$(\mathbf{3}, \mathbf{2}, 1/6)$	7.1	(0.35, 0.17, 1.91, 4.6)
$(\mathbf{3}, \mathbf{2}, 7/6)$	6.5	(0.20, 0.21, 2.55, 3.5)
$(\mathbf{3}, \mathbf{3}, -1/3)$	7.4	(0.04, 0.01, 2.62, 4.7)
$(\mathbf{\bar{6}}, \mathbf{1}, -1/3)$	6.7	(0.55, 0.28, 1.48, 4.4)
$(\mathbf{\bar{6}}, \mathbf{1}, 2/3)$	6.9	(0.44, 0.21, 1.73, 4.5)
$(\mathbf{\bar{6}}, \mathbf{1}, -4/3)$	7.4	(0.07, 0.03, 2.56, 4.7)
$(\mathbf{\bar{6}}, \mathbf{3}, -1/3)$	0.7	(0.02, 0.04, 0.12, 0.5)
$(\mathbf{8}, \mathbf{2}, 1/2)$	1.3	(0.03, 0.00, 0.01, 1.2)
SM	7.4	(0.04, 0.01, 2.63, 4.7)

I.Doršner *et al.*
JHEP 1211 (2012) 130
[arXiv:1208.1266]

🡐 Before Moriond (however CMS did not show the updated result for diphoton channel)

The list of colored scalars that couple to the SM fermions at renormalizable level and corresponding χ^2_{min} from a fit to Higgs production and decay measurements.

S_8 with $M_{S_8} \sim 300$ GeV can explain the observed $h \to \gamma\gamma$ excess and remain in excellent agreement with all available data.

Testability

H -> gamma gamma excess @ LHC

Systematic study of Higgs properties in the Manohar-Wise model:

J.Chao *et al.*
arXiv:1303.2426

$$S^A = \begin{pmatrix} S_+^A \\ \frac{1}{\sqrt{2}}(S_R^A + iS_I^A) \end{pmatrix}$$

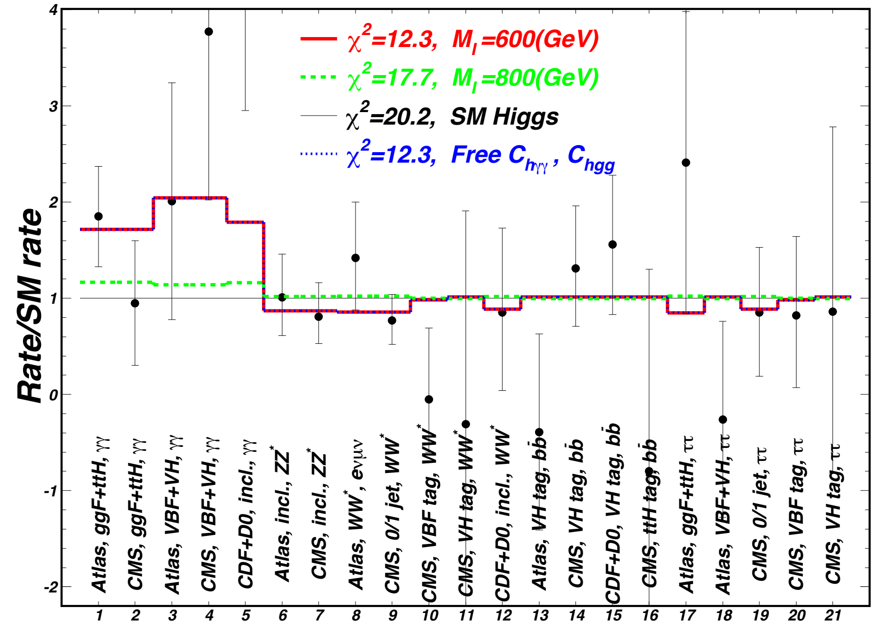


FIG. 7: Predictions of various Higgs signal rates for the second and third benchmark points presented in Table I. As a comparison, we also show the rates predicted by the best point of free C_{hgg} and $C_{h\gamma\gamma}$ scenario and their experimentally measured values, which is summarized in [16].

- In its broad parameter regions, the Manohar-Wise model is better than the SM in explaining the data. Especially, the best-fit points can be achieved for $M_\pm$ (the mass for the charged color-octet scalar) in the range of $300 - 750$GeV.

My experience of submission the paper arXiv:1204.4581 to journals

Date of final decision

- May 16, 2012 Europ. Phys. J. **C**

Negative decision: "…too few new results…"

- June 18, 2012 Phys. Rev. **D**

Negative decision: "…the presented material is not sufficient or genuine to be published…"

- Nov. 01, 2012 Phys. Lett. **B**

Negative decision: "…this paper… does not contain any new information…"

- Feb. 13, 2013 Phys. **G**

Negative decision: "…there is no analysis… of flavor effects in leptogenesis… …it is not acceptable in any paper dealing with leptogenesis…"

- Currently under review in: Int. J. Mod. Phys. **A** (submitted on Feb. 25, 2013)

Waiting for the conclusion…