Natural Nightmares for the LHC

Dirac Neutrinos and a vanishing Higgs at the LHC

Athanasios Dedes

with T. Underwood and D. Cerdeño, JHEP 09(2006)067, hep-ph/0607157

and in progress with F. Krauss, T. Figy and T. Underwood.

Durham University

Clarification

- Minimal Lepton Number Conserving Phantom Sector
- "Phantom" $\rightarrow$ singlet under the Standard Model gauge group SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$
- Simple model leading to interesting phenomenology:

  - Dirac Neutrino Masses
  - Dirac Leptogenesis
  - Higgs Phenomenology

Outline

- Dirac Neutrino Masses
- Dirac Leptogenesis
- Higgs Phenomenology

Model building

- Just 2 openings in the SM for renormalisable operators coupling $SU(3)_c \times SU(2)_L \times U(1)_Y$ singlet fields to SM fields[1]

- Higgs mass term: $H^\dagger H \, ?^* ?$
- Lepton-Higgs Yukawa interaction: $\bar{L} \widetilde{H} \, ?_R$

- What would happen if we filled in the gaps?
- But, no evidence for $B - L$ violation yet, so could try to build a $B - L$ conserving model
- Will try to be "natural" in the 't Hooft and the aesthetic sense - couplings either $\mathcal{O}(1)$ or strictly forbidden

[1] B. Patt and F. Wilczek, hep-ph/0605188

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- Augment the SM with two singlet fields
  - a complex scalar Φ
  - a Weyl fermion s_R

$$-\mathcal{L}_{\rm link} = \left(h_\nu \, \overline{L_L} \cdot \widetilde{H} \, s_R \; + \; {\rm H.c.} \right) - \eta \, H^\dagger H \;\, \Phi^* \Phi$$

Note: $\widetilde{H} = i\sigma_2 H^*$, h_ν and η will be $\mathcal{O}(1)$ and s_R carries lepton number $L = 1$.

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- Solution: Postulate the existence of a purely gauge singlet sector; add ν_R and s_L.

$$-\mathcal{L}_\mathrm{p} = h_\mathrm{p}\, \Phi\, \overline{s_L}\, \nu_R \; + \; M\, \overline{s_L}\, s_R \; + \; \mathrm{H.c.}$$

- Forbid other terms by imposing a “phantom sector” global $\mathrm{U}(1)_\mathrm{D}$ symmetry, such that only

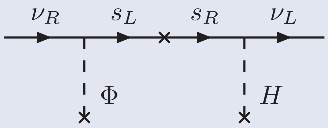
$$\nu_R \to e^{i\alpha}\, \nu_R \quad , \quad \Phi \to e^{-i\alpha}\, \Phi$$

transform non-trivially.

- If we require small Dirac neutrino masses this is the simplest choice for the phantom sector

$$\mathcal{L} = \mathcal{L}_\mathrm{SM} \; + \; \mathcal{L}_\mathrm{link} \; + \; \mathcal{L}_\mathrm{p}$$

Small effective Dirac neutrino masses – Dirac See-Saw



- Spontaneous breaking of both SU(2)$_L\times$U(1)$_Y$ and U(1)$_\mathrm{D}$ will result in the effective Dirac mass terms

$$-\mathcal{L} \supset \overline{\nu'_L}\,\mathbf{m}_\nu\,\nu'_R + \overline{s'_L}\,\mathbf{m_N}\,s'_R$$

assuming $M \gg v$ and where

$$\mathbf{m}_\nu = -v\,\sigma\,\mathbf{h}_\nu\,\hat{\mathbf{M}}^{-1}\,\mathbf{h}_\mathrm{p} \qquad\qquad \mathbf{m_N} = \hat{\mathbf{M}}$$

with $\sigma \equiv \langle\Phi\rangle$ and $v \equiv \langle H\rangle = 175$ GeV.

M. Roncadelli and D. Wyler, PLB**133**(1983)325

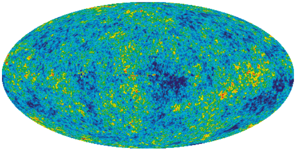
Outline

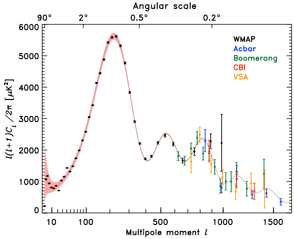
- Dirac Neutrino Masses
- Dirac Leptogenesis
- Higgs Phenomenology

Dirac Leptogenesis

We know the Universe possesses a baryon - antibaryon asymmetry and the baryon abundance has now been “measured” reasonably well:

- using cosmic microwave background (+ large scale structure) measurements

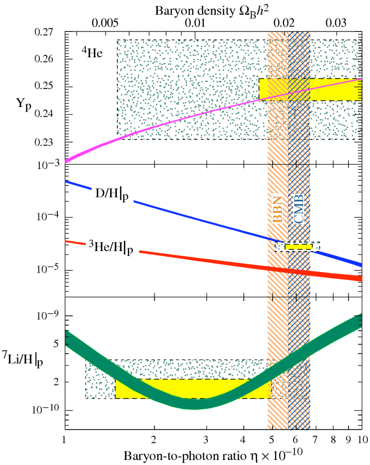




D. N. Spergel *et al.* [WMAP Collaboration], ApJS**148**(2003)175

$$\frac{n_B}{n_\gamma} \equiv \eta = (6.14 \pm 0.25) \times 10^{-10}$$

- using measurements of the primordial abundances of the light elements and calculations of their synthesis



$$4.7 \leq (\eta \times 10^{10}) \leq 6.5 \quad (95\,\%\,\text{C.L.})$$

In remarkable agreement with the CMB determination

B. Fields and S. Sarkar, astro-ph/0601514

We can measure the baryon asymmetry but do we understand where did it come from?

Sakharov's famous conditions

- Baryon number violation
- C and CP violation
- Conditions out of thermal equilibrium

Leptogenesis is commonly cited as a possible explanation

- In the SM, $B + L$ violation occurs at high temperatures allowing a lepton asymmetry to be partially converted to a baryon asymmetry
- In the Majorana see-saw, lepton number and CP are generally violated in the decays of the heavy Majorana neutrinos
- These decays can occur out of thermal equilibrium

M. Fukugita and T. Yanagida, PLB**174**(1986)45

This model exactly conserves $B - L$, so it seems we cannot create a lepton asymmetry in the same way.
However

- $B + L$ violation in the SM does not directly affect right handed gauge singlet particles
  - the large Yukawa couplings of quarks and charged leptons will tend to equilibrate any asymmetries in the right and left sectors of these parts of the model
- Small effective Yukawa couplings between the left and right handed neutrinos could prevent asymmetries in this sector from equilibrating
  - L_{ν_R} could “hide” from the rapid $B + L$ violating processes

K. Dick, M. Lindner, M. Ratz and D. Wright, PRL**84**(2000)4039

see also: H. Murayama and A. Pierce, PRL**89**(2002)271601
S. Abel and V. Page, JHEP**0605**(2006)024
B. Thomas and M. Toharia, PRD**73**(2006)063512

One can derive relations between the chemical potentials of particle species in thermal equilibrium.

- At temperatures above $T_c \simeq 130$ GeV

$$Y_B = \frac{28}{79}(Y_B - Y_{L_{\rm SM}})$$

where $Y_B \equiv n_B/s$ etc.

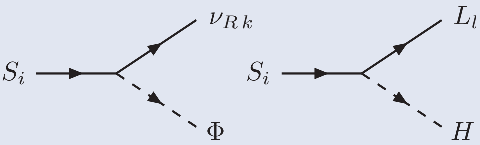
- Initially we can suppose $B - L$ was zero

$$Y_B - Y_{L_{\rm SM}} - Y_{L_{\nu_R}} = 0$$

therefore

$$Y_B = -\frac{28}{79} Y_{L_{\nu_R}}$$

Generation of the L_{ν_R} (L_{SM}) asymmetry



$S \equiv s_L + s_R$

- Heavy particle decay – similar to Majorana leptogenesis
- Define CP-asymmetry

$$\delta_{R\,i} = \frac{\sum_k \left[\Gamma(S_i \to \nu_{R\,k}\,\Phi) - \Gamma(\bar{S}_i \to \bar{\nu}_{R\,k}\,\Phi^*)\right]}{\sum_j \Gamma(S_i \to \nu_{R\,j}\,\Phi) + \sum_l \Gamma(S_i \to L_l\,H)}$$

$\delta_{L_i} = -\delta_{R_i}$

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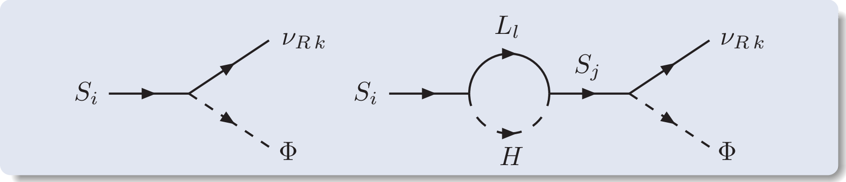

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$$\delta_{L_i} = -\delta_{R_i}$$

- If we require that S_1 be produced thermally after inflation there exists an approximate bound $M_1 \lesssim T_{RH}$.
- Given the same reasonable assumptions, this implies an approximate upper bound on σ

$$0.1\ \mathrm{GeV} \ \lesssim\ \sigma\ \lesssim\ 2\ \mathrm{TeV}\left(\frac{T_{RH}}{10^{16}\,\mathrm{GeV}}\right)$$

An electroweak-scale σ is compatible with successful Dirac leptogenesis, and is maybe even suggested.

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The potential of the neutral scalars in the model reads

$$V \;=\; \mu_H^2 H^* H + \mu_\Phi^2 \Phi^* \Phi + \lambda_H (H^* H)^2 + \lambda_\Phi (\Phi^* \Phi)^2 - \eta H^* H \Phi^* \Phi$$

where $H \equiv H^0$

- After spontaneous breaking of U(1)$_{\mathrm{D}}$, Φ will develop a non-zero vev, and this through the η term would trigger electroweak SU(2)$_L \times$U(1)$_Y$ symmetry breaking
- Expanding the fields around their minima

$$H \;=\; v + \frac{1}{\sqrt{2}}(h + iG) \quad , \quad \Phi \;=\; \sigma + \frac{1}{\sqrt{2}}(\phi + iJ)$$

- We have
  - the Goldstone bosons: G (eaten...) and J
  - h and ϕ mix (due to the η term) and become two massive Higgs bosons H_1 and H_2

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$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = O \begin{pmatrix} h \\ \phi \end{pmatrix} \quad \text{with} \quad O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

and the mixing angle

$$\tan 2\theta = \frac{\eta v \sigma}{\lambda_\Phi \sigma^2 - \lambda_H v^2}$$

- The limits $v \ll \sigma$ and $\sigma \ll v$ both lead to the SM with an isolated hidden sector
- These limits need an unnaturally small η, and would present problems with baryogenesis and small neutrino masses.
- A ‘natural’ choice of parameters (with e.g., $\eta \sim 1$) would lead to

$$\tan\beta \equiv v/\sigma \sim 1 \quad , \quad \tan\theta \sim 1$$

Four Parameters Model

$$\tan\beta \quad , \quad \tan\theta \quad , \quad m_{H_1} \quad , \quad m_{H_2}$$

Triviality and Positivity

- We require that the parameters λ_H, λ_Φ and η do not encounter Landau poles at least up to the scale where we encounter "new physics".
- We also require that the potential remain positive definite everywhere, at least up to the scale of "new physics".
- After solving 1-loop RGEs, we can plot the maximum scale up to which our effective theory satisfies the above constraints.

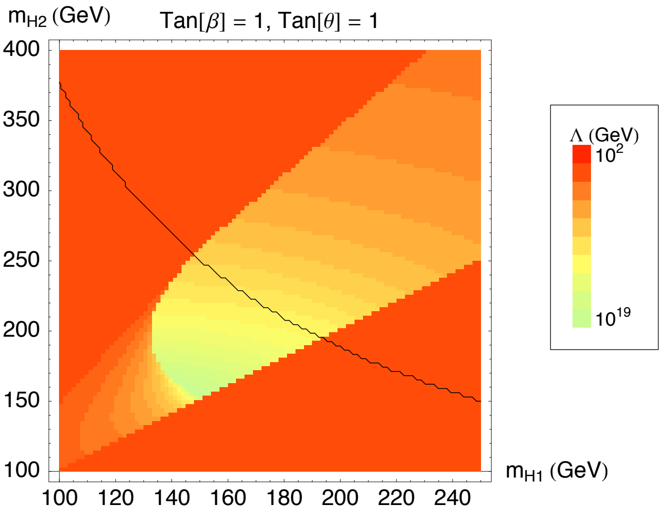
EW observables

- One can use the limit on the SM Higgs mass, m_H <194 GeV (95% C.L.) to set limits on the Higgs masses in this model

$$\cos^2\theta \log(m_{H1}^2) + \sin^2\theta \log(m_{H2}^2) < \log(194^2 \text{ GeV}^2) \quad (95\% \text{ C.L.})$$

- In the scenario previously, $\theta = \pi/4$ and so $m_{H1} m_{H2} < 194^2 \text{ GeV}^2$

e.g. $m_{H1} \lesssim 115$ GeV and $m_{H2} \lesssim 327$ GeV


m_{H2} (GeV)
Tan[β] = 1, Tan[θ] = 1
400
350
300
250
200
150
100
100
120
140
160
180
200
220
240
m_{H1} (GeV)
Λ (GeV)
10^2
10^{19}

- $h = O_{i1} H_i$ – the couplings of the Higgs bosons H_i to SM fermions and gauge bosons will be reduced by a factor O_{i1} (relative to the SM)
- H_i will also couple to the invisible massless Goldstone pair JJ
- For light Higgs masses $\lesssim$ 160 GeV, in the SM the $H \to b\bar{b}$ decay mode dominates. Here we find a different picture:

$$\frac{\Gamma(H_1 \to JJ)}{\Gamma(H_1 \to bb)} = \frac{1}{12}\left(\frac{m_{H1}}{m_b}\right)^2 \tan^2\beta\ \tan^2\theta$$

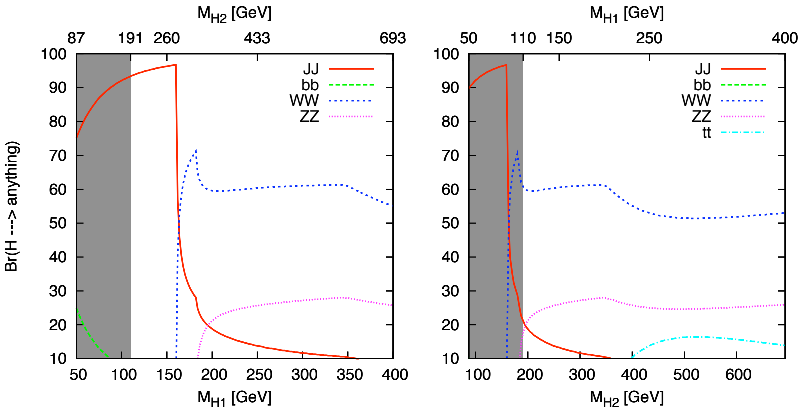
$$\frac{\Gamma(H_2 \to JJ)}{\Gamma(H_2 \to bb)} = \frac{1}{12}\left(\frac{m_{H2}}{m_b}\right)^2 \tan^2\beta\ \cot^2\theta$$

- In this model a ‘light’ Higgs boson will decay dominantly into invisible JJ as long as it is heavier than 60 GeV.

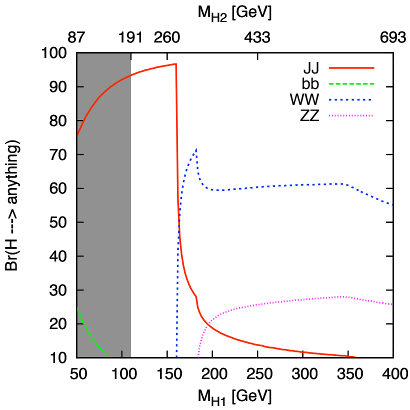
- In 2001 LEP presented limits on invisible Higgs masses as a function of ξ^2

$$\begin{aligned} \xi_i^2 &\equiv \frac{\sigma(e^+e^- \to HZ)}{\sigma(e^+e^- \to HZ)|_{\text{SM}}} \times \text{Br}(H \to \text{ invisible}) \\ &= O_{i1}^2 \times \text{Br}(H \to \text{ invisible}) \end{aligned}$$

- For $\xi^2 =$1, LEP excludes Higgs boson masses up to its kinematical limit, $m_H \leq$114.4 GeV



Dominant branching ratios of the two Higgs bosons H_1 (left) and H_2 (right) for the parameters $\theta = \beta = \pi/4$, with couplings equal to one. The shaded area is excluded by LEP.



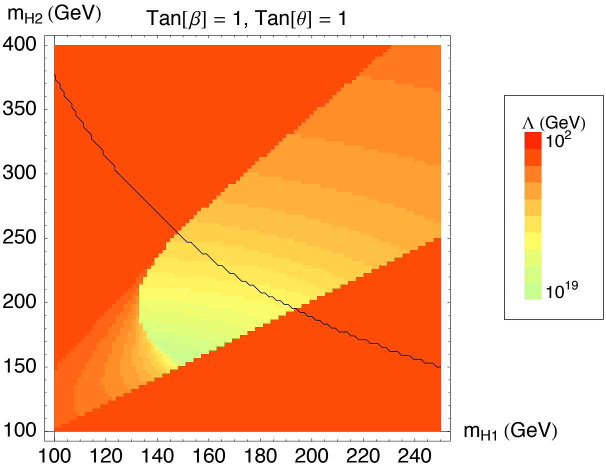
- LEP excludes a light invisible Higgs with a mass $m_{H1} \lesssim$ 110 GeV.
- It therefore sets a lower bound on the heavier Higgs $m_{H2} \gtrsim$ 191 GeV.

- Let us compare the number of Higgs events at the LHC in this model vs. the SM (for an identical Higgs mass)
- Compare numbers of visible events, in the narrow width approximation and assuming that the vector bosons produced in Higgs decays are on-shell.

Define a parameter $\mathcal{R}_i$

$$\mathcal{R}_i \equiv \frac{\sigma(pp \to H_i\, X)\,\mathrm{Br}(H_i \to YY)}{\sigma(pp \to H_{\mathrm{SM}}\, X)\,\mathrm{Br}(H_{\mathrm{SM}} \to YY)}$$

- It turns out that always is : $\mathcal{R}_i < 1$!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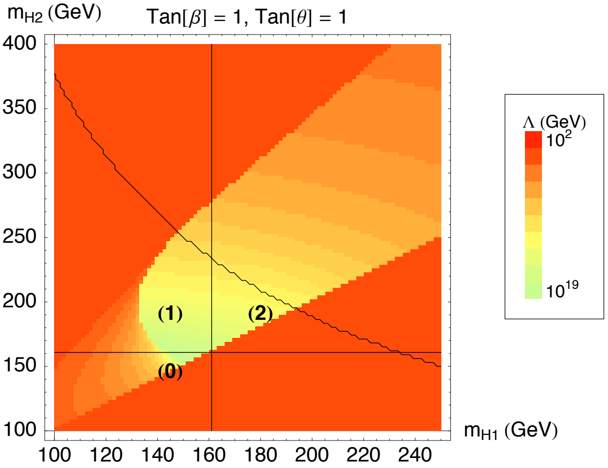
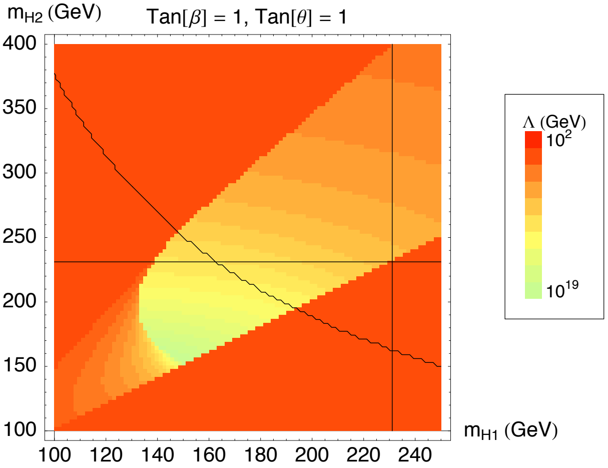
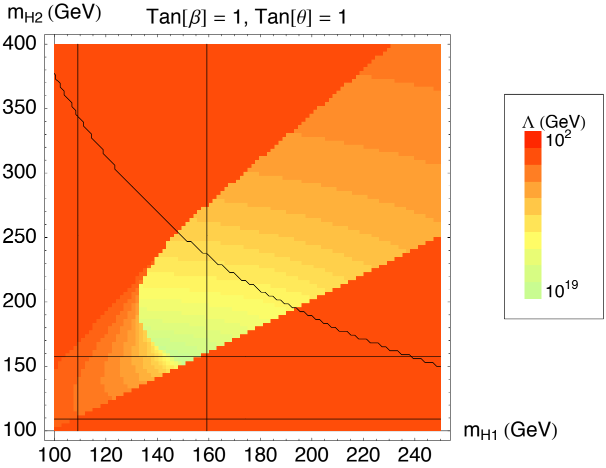


$\mathcal{R}_i = 0.1$



$\mathcal{R}_i = 0.3$



$\mathcal{R}_i = 0.01$

- Q : How could this Higgs be found at the LHC?
- A : Search for an invisible Higgs decays !

S. G. Frederiksen, N. Johnson, G. L. Kane and J. Reid, PRD**50**(1994)4244
R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy, PLB**571**(2003)184
K. Belotsky, V. A. Khoze, A. D. Martin and M. G. Ryskin, EPJC**36**(2004)503
H. Davoudiasl, T. Han and H. E. Logan, PRD**71**(2005)115007

- Strategies:
  - $Z + H_1$
  - W-boson fusion
  - central exclusive diffractive production

$Z(\to l^+l^-) + H_{\mathrm{inv}}$

using H. Davoudiasl, T. Han and H. E. Logan, PRD**71**(2005)115007

- multiply $S/\sqrt{B}$ by $1/2$ because of mixing
- assume LHC integrated luminosity of 30fb^{-1}

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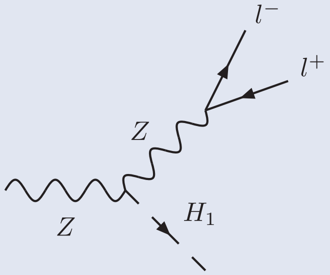

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Signal significance for discovering the invisible H_1 is

- m_{H1} = 120 GeV 4.9σ
- m_{H1} = 140 GeV 3.6σ
- m_{H1} = 160 GeV 2.7σ

- Although this applies to $\theta = \pi/4$, the situation is rather generic in this region
- Note that for $m_{H1} \lesssim$ 140 GeV, the $H_1 \to \gamma\gamma$ channel may still be usable.

Simulation for High Energy Reactions of PArticles

[1] F. Krauss *et al*

- We have implemented this model in the matrix element monte carlo program SHERPA[1]
- SHERPA is built to make it "easy" to implement new physics models in a monte carlo simulation – essential for being able to talk about realistic LHC phenomenology
- Will the invisible Higgs remain invisible?

Summary

- Proposed a minimal, L conserving, phantom sector of the SM leading to
  - Viable Dirac neutrino masses
  - Successful baryogenesis (through Dirac leptogenesis)
  - Interesting ‘invisible’ Higgs phenomenology for the LHC

- $\mathcal{O}(1)$ couplings, correct neutrino masses and baryogenesis seem to suggest an electroweak scale vev in the minimal phantom sector
- Phantom $\mathrm{U}(1)_{\mathrm{D}}$ symmetry breaking at this scale would trigger consistent electroweak symmetry breaking

Other Astro/Cosmo Constraints

H_i couples to JJ as

$$-\mathcal{L}_J \supset \frac{(\sqrt{2}G_F)^{1/2}}{2} \tan\beta\, O_{i2}\, m_{H_i}^2\ H_i\, JJ$$

- After electroweak/U(1)$_{\mathrm{D}}$ symmetry breaking the Js are kept in equilibrium via reactions of the sort $JJ \leftrightarrow f\bar{f}$ mediated by H_i
- A GIM-like suppression exists for these interactions from the orthogonality condition $\sum_i O_{i1}O_{i2} = 0$
- J falls out of equilibrium just before the QCD phase transition and remains as an extra relativistic species thereafter

- BBN/CMB yield a bound on the effective number of neutrino species $N_\nu = 3.24 \pm 1.2$ (90% C.L.)
- Early decoupling of J implies T_J is much lower than T_ν

$$\left(\frac{T_J}{T_\nu}\right)^4 = \left(\frac{g_*(T_\nu)}{g_*(T_D)}\right)^{4/3} \lesssim \left(\frac{10.75}{60}\right)^{4/3}$$

- The increase in the effective number of light neutrinos, due to J, at BBN ΔN_ν^J is then

$$\Delta N_\nu^J = \frac{4}{7}\left(\frac{T_J}{T_\nu}\right)^4 \lesssim 0.06$$

Assume that S_i are hierarchical in mass, then

$$\delta_{R1} \simeq \frac{1}{8\pi} \sum_j \frac{M_1}{M_j} \frac{\mathrm{Im}\left[(\mathbf{h}_\mathrm{p}\,\mathbf{h}_\mathrm{p}^\dagger)_{1j}\,(\mathbf{h}_\nu^\dagger\,\mathbf{h}_\nu)_{j1}\right]}{(\mathbf{h}_\mathrm{p}\,\mathbf{h}_\mathrm{p}^\dagger)_{11} + (\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11}}$$

- $\mathbf{h}_\nu$ and $\mathbf{h}_\mathrm{p}$ can be parameterised as

$$\begin{aligned} \mathbf{h}_\nu &= \frac{1}{v}\,\mathbf{A}\,\mathbf{D}_{\sqrt{\hat{\mathbf{m}}_\nu}}\,\mathbf{W}\,\mathbf{D}_{\sqrt{\hat{\mathbf{M}}}} \\ \mathbf{h}_\mathrm{p} &= \frac{1}{\sigma}\,\mathbf{D}_{\sqrt{\hat{\mathbf{M}}}}\,\mathbf{X}^\dagger\,\mathbf{D}_{\sqrt{\hat{\mathbf{m}}_\nu}}\,\mathbf{B}^\dagger \end{aligned}$$

  where $\mathbf{A}$ and $\mathbf{B}$ are unitary matrices and $\mathbf{W}\,\mathbf{X}^\dagger = \mathbf{1}$ for the matrices $\mathbf{W}$ and $\mathbf{X}$

Then, in analogy with Davidson and Ibarra

$$|\delta_{R1}| \lesssim \frac{1}{16\pi}\,\frac{M_1}{v\,\sigma}\,(m_{\nu_3} - m_{\nu_1})$$

- To protect the asymmetry after it is generated, the left and right handed neutrinos must not reach equilibrium until after the electroweak phase transition
- Consider processes such as $LH \leftrightarrow \Phi\nu_R$ mediated by s-channel S exchange.

$$\Gamma_{L\leftrightarrow R}(T) \sim \frac{|h_\nu|^2\,|h_\mathrm{p}|^2}{M_1^4}\,T^5$$

- This rate should be compared with the Hubble parameter $H(T) = \sqrt{\frac{8\pi^3 g_*}{90}}\,\frac{T^2}{M_P}$ where $g_* = 114$.
- The strongest constraint would come from the highest temperatures, i.e. where $T \simeq M_1$

$$\frac{|h_\nu|^2\,|h_\mathrm{p}|^2}{M_1} \lesssim \frac{1}{M_P}\sqrt{\frac{8\pi^3 g_*}{90}}$$

- An L_{ν_R} asymmetry could be generated during the out of equilibrium decays of S_1 and $\bar{S}_1$
- If far out of equilibrium, i.e. $\Gamma \ll H$, the number density of S_1 ($\bar{S}_1$) cannot decrease as rapidly as their equilibrium number density – the S decay 'late' and the rates of back-reactions are suppressed by the low T.

$$Y_{L_{\nu_R}} \equiv \frac{n_{L_{\nu_R}}}{s} \simeq \frac{\delta_R \, n_{S_1}}{g_* \, n_\gamma} \simeq \frac{\delta_R}{g_*}$$

- Quantify how far out of equilibrium the decays occur with K

$$\begin{aligned} K &\equiv \frac{\Gamma(S_1 \to \nu_R \Phi) + \Gamma(S_1 \to LH)}{H(T = M_1)} \\ &= \left[(\mathbf{h}_\mathrm{p}\mathbf{h}_\mathrm{p}^\dagger)_{11} + (\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11}\right] \frac{M_P}{16\pi \, M_1} \sqrt{\frac{90}{8\pi^3 g_*}} \end{aligned}$$

- Can define an “effective neutrino mass” $\widetilde{m}$ related to the equilibrium parameter K

$$\widetilde{m} \equiv \left[(\mathbf{h}_{\rm p}\mathbf{h}_{\rm p}^\dagger)_{11} + (\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11}\right] \frac{v\,\sigma}{M_1} = K\,v\,\sigma\,\frac{16\pi}{M_P}\sqrt{\frac{8\pi^3\,g_*}{90}}$$

  - clearly the connection with light neutrino data is model dependent, and is most valid when $(\mathbf{h}_{\rm p}\mathbf{h}_{\rm p}^\dagger)_{11} \simeq (\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11}$
- Also define an “efficiency” κ such that

$$Y_{L_{\nu_R}} = \frac{\delta_{R1}\,\kappa}{g_*}$$

  - for far out of equilibrium decays, $K \ll 1$ and $\kappa \simeq 1$
- Leptogenesis can be successful for $K > 1$, but the dynamics are more complicated and we need to solve the Boltzmann equations

Boltzmann equations should be solved for the S_1 abundance, and the asymmetries in S_1, L and ν_R. However $B-L$ conservation allows the elimination of one

$$\frac{d\eta_{\Sigma S_1}}{dz} = \frac{z}{H(z=1)}\left[2 - \frac{\eta_{\Sigma S_1}}{\eta^{\rm eq}_{S_1}} + \delta_R\left(\frac{3\,\eta_{\Delta L}}{2} + \eta_{\Delta S_1}\right)\right]\Gamma^{D1}$$

$$\frac{d\eta_{\Delta S_1}}{dz} = \frac{z}{H(z=1)}\left[\eta_{\Delta L} - \frac{\eta_{\Delta S_1}}{\eta^{\rm eq}_{S_1}} - B_R\left(\frac{3\,\eta_{\Delta L}}{2} + \eta_{\Delta S_1}\right)\right]\Gamma^{D1}$$

$$\frac{d\eta_{\Delta L}}{dz} = \frac{z}{H(z=1)}\left\{\left[\delta_R\left(1 - \frac{\eta_{\Sigma S_1}}{2\eta^{\rm eq}_{S_1}}\right) - \left(1-\frac{B_R}{2}\right)\left(\eta_{\Delta L} - \frac{\eta_{\Delta S_1}}{\eta^{\rm eq}_{S_1}}\right)\right]\Gamma^{D1} - \left(\frac{3\,\eta_{\Delta L}}{2} + \eta_{\Delta S_1}\right)\Gamma^{W}\right\}$$

where $\eta_{\Sigma S} = (n_S + n_{\bar{S}})/n_\gamma$, $\eta_{\Delta S} = (n_S - n_{\bar{S}})/n_\gamma$, $z = M_1/T$ and

$$\Gamma^{D1} = \frac{1}{n_\gamma}\left[\Gamma(S_1 \to \nu_R \Phi) + \Gamma(S_1 \to LH)\right] g_{S_1} \int \frac{d^3\mathbf{p}}{(2\pi)^3}\,\frac{M_1}{E_{S_1}}\, e^{-E_{S_1}/T}$$

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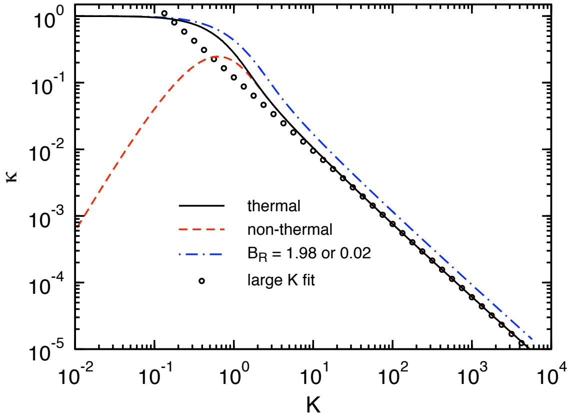
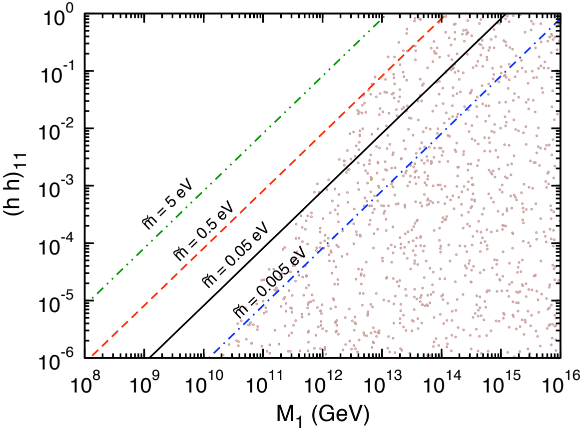


Leptogenesis efficiency, κ, versus K for thermal and zero initial abundance of S_1 $(\bar{S}_1)$. Also shown is the efficiency for differing left-right branching ratios.



Area in the M_1, $(\mathbf{h}^\dagger \mathbf{h})_{11}$ parameter space allowed by successful baryogenesis when $(\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11} = (\mathbf{h}_\mathrm{p} \mathbf{h}_\mathrm{p}^\dagger)_{11}$ and $\sigma = v = 175$ GeV.

- For $K \gtrsim 3$ the efficiency is the same regardless of initial conditions
- For $K \gtrsim 20$ the efficiency is well fitted by the power law

$$\kappa \simeq \frac{0.12}{K^{1.1}} = 6.4 \times 10^{-17} \left(\frac{\sigma}{\widetilde{m}}\right)^{1.1}$$

- If we take a 'natural' scenario with $(\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11} = (\mathbf{h}_\mathrm{p} \mathbf{h}_\mathrm{p}^\dagger)_{11} \simeq 1$ and $\widetilde{m} = 0.05$ eV (hierarchical light neutrinos) we can use the bound on the CP-asymmetry and the observed baryon asymmetry to put a bound on σ

$$\sigma \gtrsim 0.1 \ \mathrm{GeV}$$

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EW observables : The ρ parameter

- In a model with only Higgs doublets and singlets, at tree level $\rho \equiv m_W^2/M_Z^2 \cos^2\theta_W$ = 1.
- At one-loop, a correction $\Delta\rho$ appears.
- Φ will affect gauge boson loops because of the η term in the potential which mixes it with H.
- The Higgs contribution to $\Delta\rho$ is then

$$\Delta\rho^H \ = \ \frac{3G_F}{8\sqrt{2}\pi^2}\sum_{i=1}^{2} O_{i1}^2 \left[m_W^2 \ln\frac{m_{Hi}^2}{m_W^2} - m_Z^2 \ln\frac{m_{Hi}^2}{m_W^2} \right]$$

- From the diagonalisation of the Higgs mass matrix, $O^T m^2 O = diag(m_{H1}^2, m_{H2}^2)$, we have

$$\sum_{i=1,2} m_{Hi}^2 O_{i1}^2 \;=\; 4\lambda_H v^2 \;\equiv\; m_H^2$$

  where m_H is the SM Higgs mass expression
- One can Taylor expand the expression for $\Delta\rho$ around m_H^2

$$\sum_{i=1}^{2} O_{i1}^2 f(m_{Hi}^2) = \sum_{i=1}^{2} O_{i1}^2 \left[f(m_H^2) + (m_{Hi}^2 - m_H^2) f'(m_H^2) + ... \right]$$

- The second term vanishes thanks to the relation above, and $O^T O = 1$, leading to the SM Higgs contribution to $\Delta\rho^H$

$$\Delta\rho^H \;=\; \frac{3G_F}{8\sqrt{2}\pi^2}\left[m_W^2 \ln\frac{m_H^2}{m_W^2} - m_Z^2 \ln\frac{m_H^2}{m_W^2} \right]$$