Dirac Neutrinos, Baryogenesis and a Vanishing Higgs at the LHC

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also with A. Dedes, F. Krauss and T. Figy

hep-ph/to appear

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Introduction

- Introduce a minimal lepton number conserving "phantom" sector to the Standard Model
- "Phantom" $\rightarrow$ singlet under the Standard Model gauge group SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$
- Very simple extension leading to:

  - 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 SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$ singlet fields
  - a complex scalar Φ
  - a Weyl fermion s_R

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

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

- But, this model is no good $\rightarrow$ neutrinos would have large, electroweak scale masses

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

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

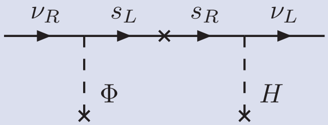
- Forbid other terms by imposing a “phantom sector” global $\mathrm{U}(1)_{\rm D}$ symmetry, such that only

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

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

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

Small effective Dirac neutrino masses – Dirac See-Saw



- Spontaneous breaking of both SU(2)$_L \times$U(1)$_Y$ and U(1)$_{\rm D}$ 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

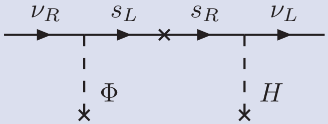
$$\mathbf{m}_\nu = -v\,\sigma\,\mathbf{h}_\nu\,\hat{\mathbf{M}}^{-1}\,\mathbf{h}_{\rm p} \qquad\qquad \mathbf{m_N} = \hat{\mathbf{M}}$$

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

Essentially the Froggatt-Nielsen mechanism!

C. D. Froggatt and H. B. Nielsen, NPB**147**(1979)277.

Small effective Dirac neutrino masses – Dirac See-Saw



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

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- Dirac Neutrino Masses
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- Higgs Phenomenology

We can measure the baryon asymmetry of the universe but do we understand where it came 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 that 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
- 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

V. A. Kuzmin, hep-ph/9701269
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

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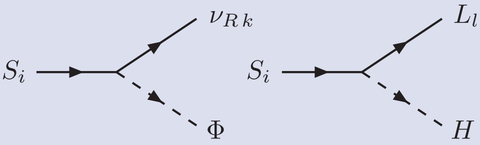
Generation of the L_{ν_R} ($L_{\rm SM}$) asymmetry

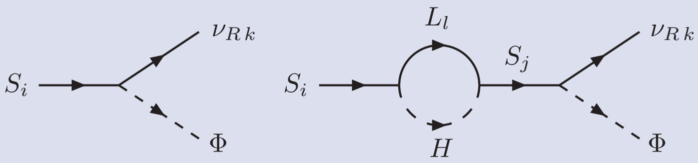


$S \equiv s_L + s_R$

- Heavy particle decay – similar to Majorana leptogenesis
- In analogy with Davidson and Ibarra, the CP-asymmetry is bounded

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

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



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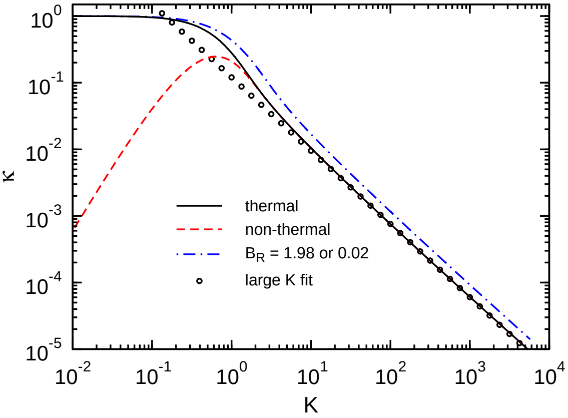
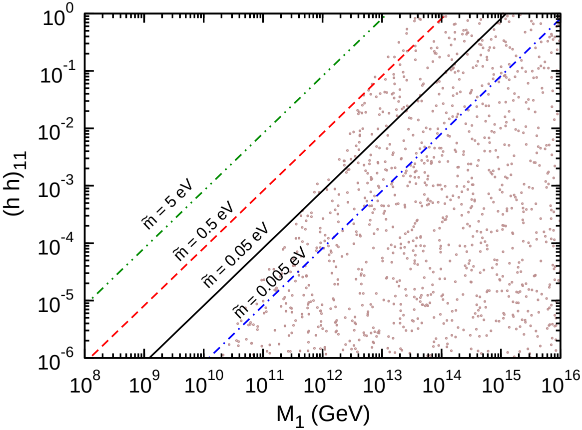


Leptogenesis efficiency, κ, versus K for thermal and zero initial abundance of S_1 ($\bar{S}_1$). Also shown is the efficiency for differing left-right branching ratios.



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.

- 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

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

- 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

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

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The potential

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

where $H \equiv H^0$

- After spontaneous breaking of U(1)$_{\mathrm{D}}$, Φ develops a non-zero vev. 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 as usual) 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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Goldstone Bosons and the “Phantom” Sector

$$\mathcal{L}_{\rm int} = \frac{1}{2\,F}\,\mathcal{J} \cdot \partial_\mu j^\mu$$

where F is the scale of symmetry breaking, $\mathcal{J}$ is the Goldstone boson, and j^μ is the current corresponding to the spontaneously broken symmetry.

- In this case, the only objects charged under the spontaneously broken symmetry are part of the “phantom sector”, and the phantom sector only links to neutrinos and Higgs bosons.

$$\partial_\mu j^\mu = m_f\,\bar{f}\,\gamma_5\,f$$

- The coupling of the Goldstone boson to neutrinos is suppressed by m_ν/F, which is tiny.

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

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

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

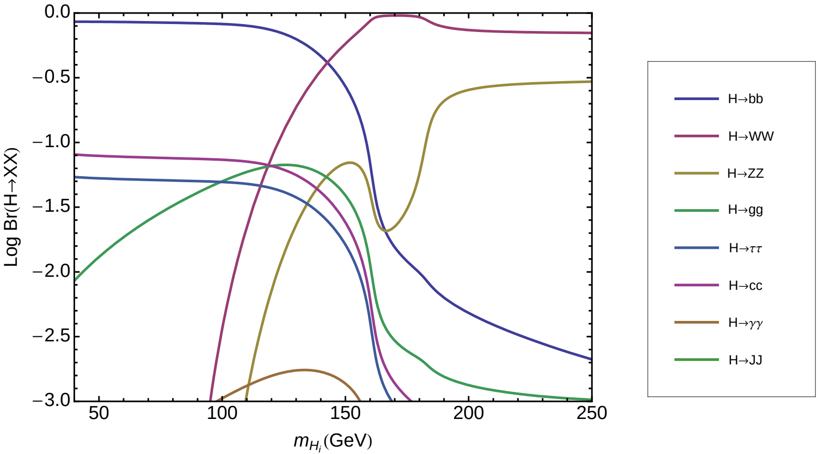
- Couplings of the H_i to SM fermions and gauge bosons will be reduced by a factor O_{i1} (relative to the SM)

- The H_i couple to the massless Goldstone bosons J

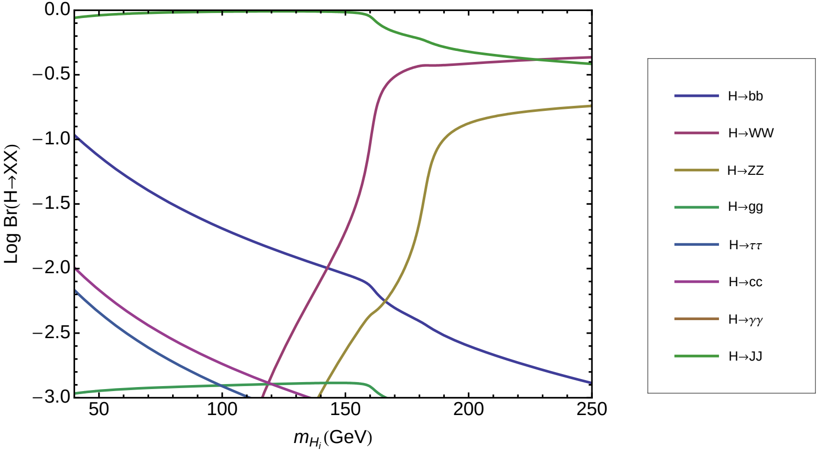
- In the SM, for $m_H \lesssim 140$ GeV the $H \to b\bar{b}$ decay mode is dominant. Now we find that

$$\begin{aligned} \frac{\Gamma(H_1 \to JJ)}{\Gamma(H_1 \to bb)} &= \frac{1}{12}\left(\frac{m_{H1}}{m_b}\right)^2 \tan^2\beta \, \tan^2\theta \\ \frac{\Gamma(H_2 \to JJ)}{\Gamma(H_2 \to bb)} &= \frac{1}{12}\left(\frac{m_{H2}}{m_b}\right)^2 \tan^2\beta \, \cot^2\theta \end{aligned}$$

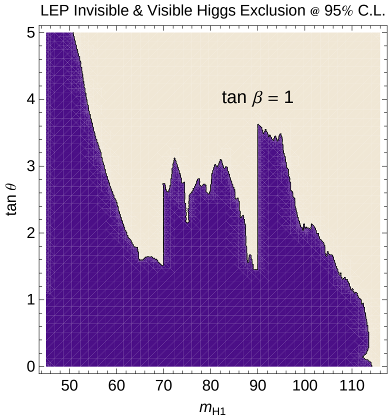
- In this scenario, a light Higgs can dominantly decay into **invisible** Goldstone bosons.

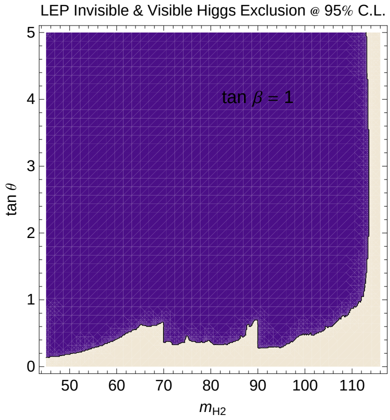


- Higgs branching ratios in the SM



- Higgs branching ratios, with $\tan\theta = 1$ and $\tan\beta = 1$

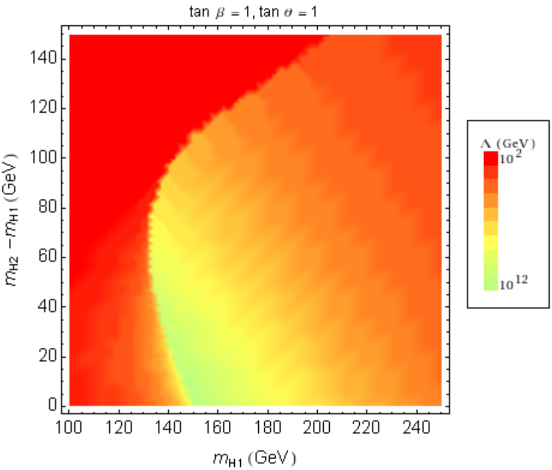




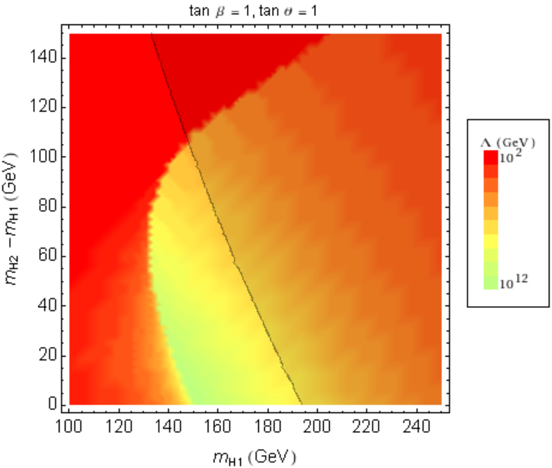
- LEP Higgs exclusion limits at 95% C.L. for $\tan\beta = 1$, using both visible and invisible search results

Triviality and Positivity

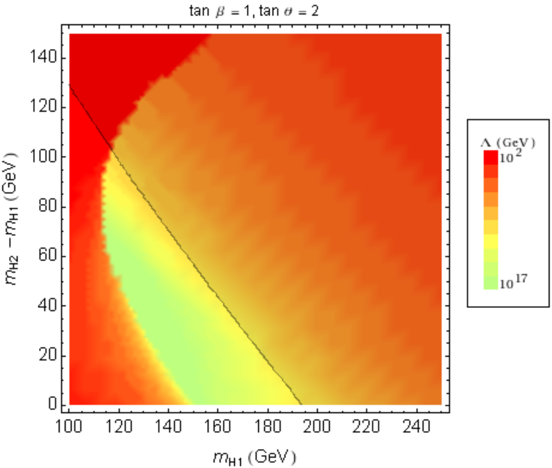
- We require that the parameters λ_H, λ_Φ and η do not encounter Landau poles at least up to the scale where we encounter "new physics".
- We also require that the potential remain positive definite everywhere, at least up to the scale of "new physics".
- After solving 1-loop RGEs, we can plot the maximum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



Triviality and vacuum stability constraints on Λ for $\tan\theta = 1$ and $\tan\beta = 1$



Triviality and vacuum stability constraints on Λ for $\tan\theta = 1$ and $\tan\beta = 1$. Contour shows the upper limit on the Higgs masses from precision electroweak data.

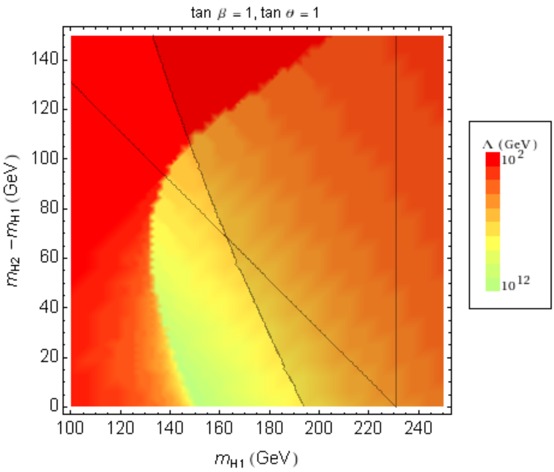


Triviality and vacuum stability constraints on Λ for $\tan\theta = 2$ and $\tan\beta = 1$. Contour shows the upper limit on the Higgs masses from precision electroweak data.

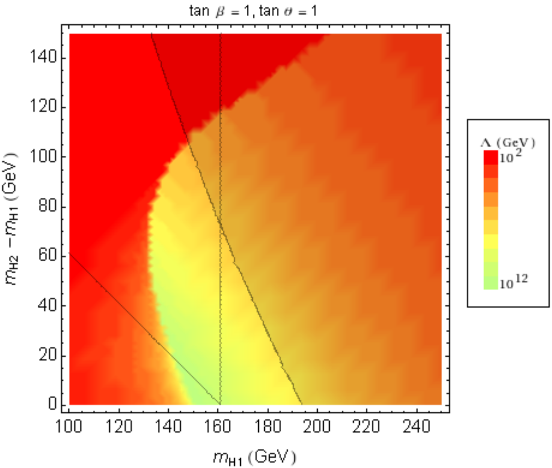
- Let's compare the number of Higgs events at the LHC in this model vs. the SM (for an identical Higgs mass)
- Compare numbers of visible events, in the narrow width approximation and assuming that the vector bosons produced in Higgs decays are on-shell.

Define a parameter $\mathcal{R}_i$

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



$\mathcal{R}_i = 0.3$ contours for both Higgses. To the left of each line, the number of "visible" H_i events is 30% of the S.M. prediction.



$\mathcal{R}_i = 0.1$ contours for both Higgses. To the left of each line, the number of "visible" H_i events is 10% of the S.M. prediction.

- There is a mass region where one, or both H_i decay to invisible JJ dominantly.
- How could this Higgs be found at the LHC?

S. G. Frederiksen, N. Johnson, G. L. Kane and J. Reid, PRD**50**(1994)4244
J. P. Eboli and D. Zeppenfeld, PLB**495**(2000)147
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:
  - $Z + H$
  - W-boson fusion
  - central exclusive diffractive production

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

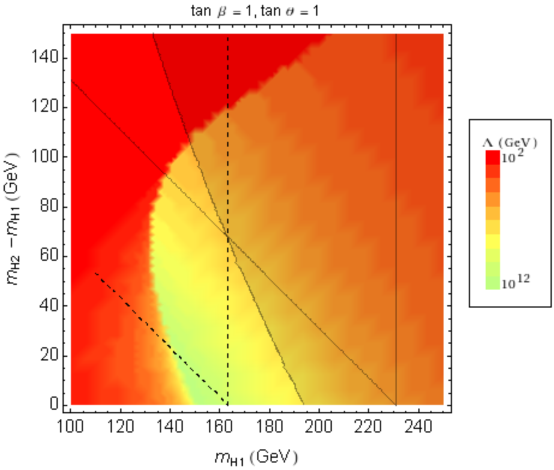
using H. Davoudiasl, T. Han and H. E. Logan, PRD**71**(2005)115007

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

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



ATLAS 95 % C.L. exclusion with 10 fb^{-1} integrated luminosity in the vector boson fusion then $H \rightarrow$ invisible channel. Based on estimates from ATL-PHYS-2003-006 (Neukermans, Di Girolamo), using fast detector simulation.

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]
- One of the advantages of SHERPA is that it is built to make it “easy” to implement specific 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)
- In this model, $\mathcal{O}(1)$ couplings, correct neutrino masses and baryogenesis seem to suggest an electroweak scale vev in the minimal phantom sector
- In this case, interesting invisible Higgs phenomenology is possible – the relevance of this to the ILC is clear

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

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