Dark Matter and Leptogenesis in Inverse Seesaw models of Neutrino Mass Generation

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In collaboration with E. Molinaro

Introduction

Although the SM Higgs may have been observed,
many observations are left unexplained in the SM:

WMAP

Dark Matter: $\Omega_{DM} h^2 = 0.112 \pm 0.006$

Baryon asymmetry of the Universe: $\Omega_b h^2 = 0.0226 \pm 0.006$

Neutrino masses:

solar $\Delta m^2_{\odot} \simeq 7.5 \times 10^{-5} \quad \mathrm{eV}^2$

atmospheric $\Delta m^2_{atm} \simeq 2.5 \times 10^{-3} \quad \mathrm{eV}^2$

Eg Gonzalez-Garcia et al

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Eg Gonzalez-Garcia et al

Introduction

Dirac masses
Seesaws
Loop induced

$$m_\nu$$

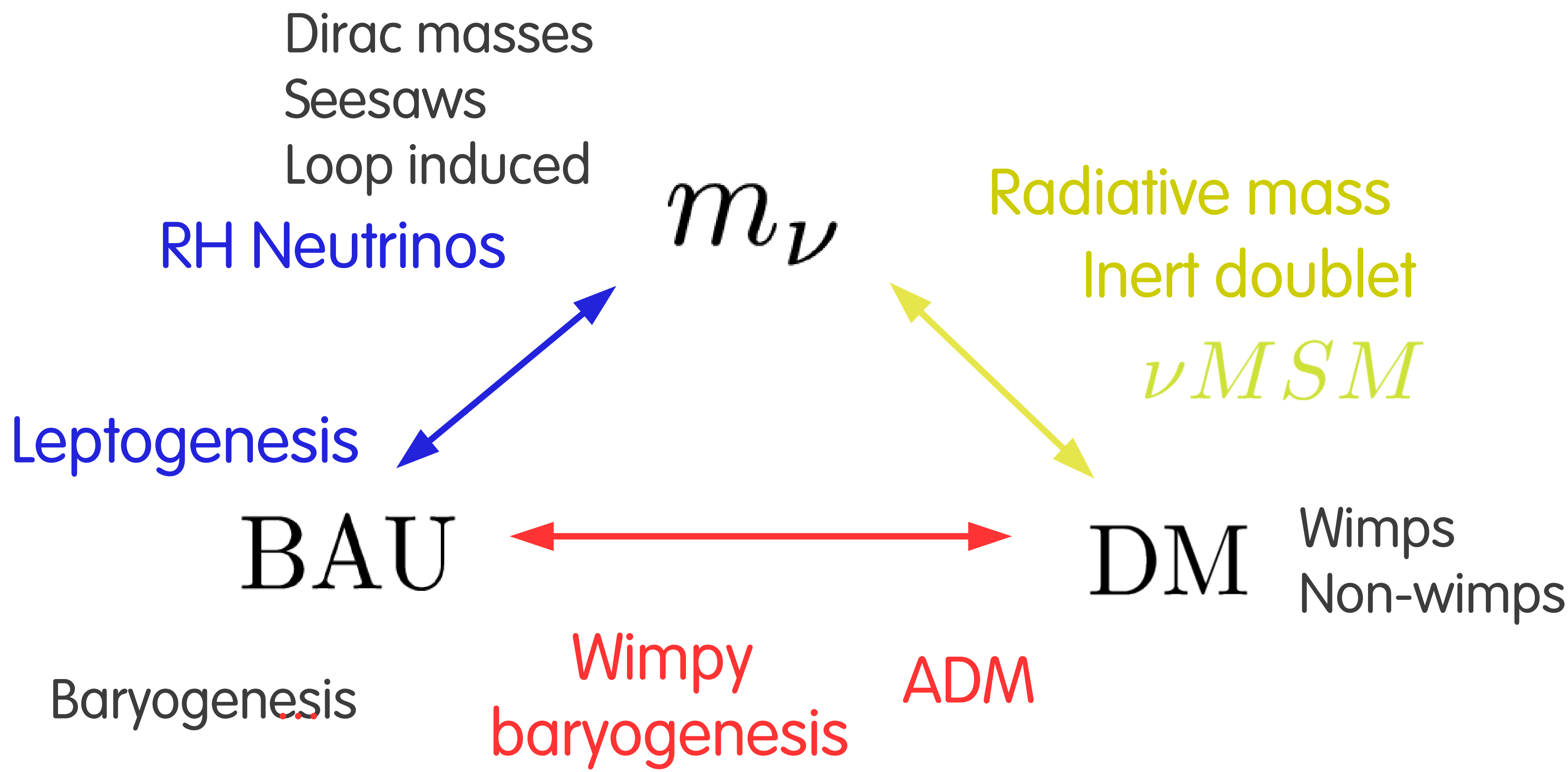
BAU

DM

Wimps
Non-wimps

Baryogenesis

Introduction



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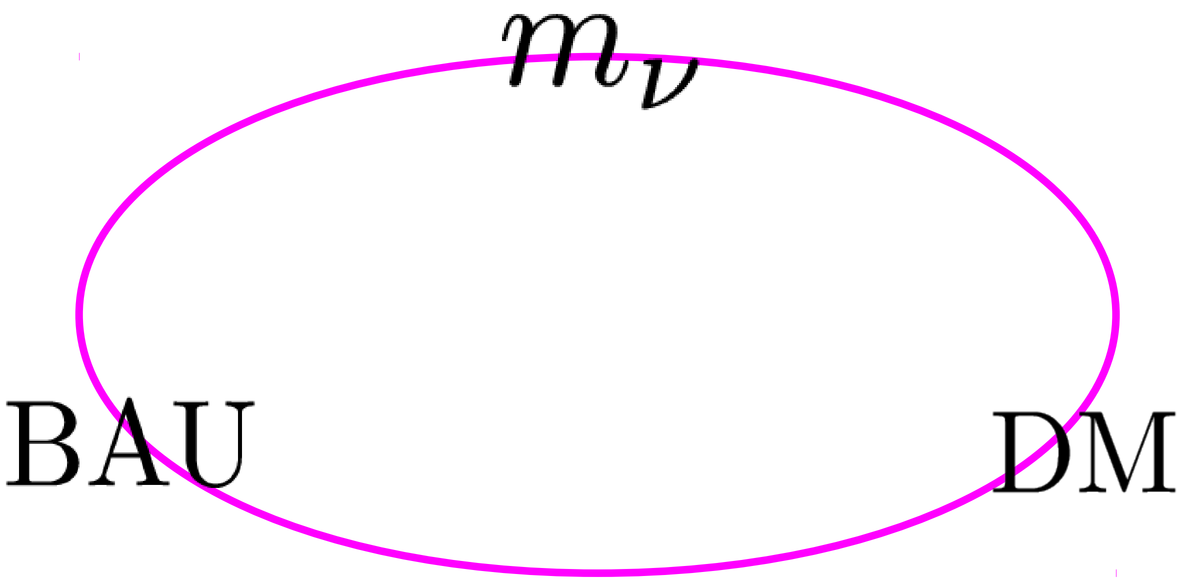

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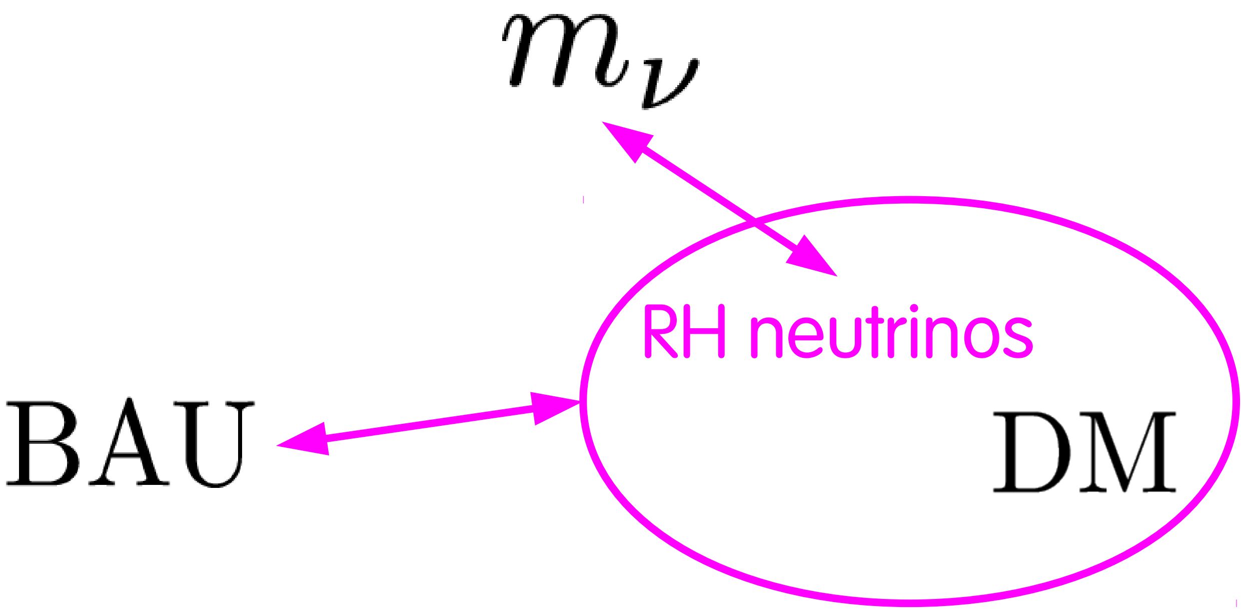


Plan

1) Neutrino mass generation   via Inverse Seesaw

2) Scalar Dark Matter: singlet or triplet

... *A* leptogenesis

.... the extended Higgs sector

Neutrino masses

Seesaw

Add n RH Majorana Neutrinos, $n \geq 2$ $\quad -\mathcal{L} \supset M_i \bar{N}_i N_i^c + Y_\nu^{i\alpha} \bar{N}_i \tilde{H}^* \ell_\alpha + \text{H.c.}$

Neutrino mass matrix $\quad \mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}$

Seesaw: $M \gg m_D$ $\quad m_\nu \simeq -m_D . M^{-1} . m_D^T \quad m_N \simeq M$

Majorana masses violate L

Naturally suppressed vs SM if M very heavy $\quad M \gtrsim 10^{10}\,\text{GeV}$

-High energy realizations perfectly viable but...hopeless to probe

mixing $\quad m_D/M \sim 10^{-10}$

-Low-energy realizations: suppressed Yukawas

$$M \sim \text{TeV} \longrightarrow m_D/M \sim 10^{-7}$$

...not much better

Inverse seesaw

Impose a global U(1) Lepton, with eg: $L(\ell) = L(N_1) = -L(N_2)$

$$-\mathcal{L} \supset M\, \bar{N}_1\, N_2^c + m_D\, \bar{N}_1\, \nu_L$$

Conserve L

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

Light neutrino mass

$$m_\nu = 0$$

Heavy Dirac $N = P_R\, N_1 + P_L\, N_2^c$

$$m_N = M$$

Inverse seesaw

Impose a global U(1) Lepton, with eg: $L(\ell) = L(N_1) = -L(N_2)$

$$-\mathcal{L} \supset M\,\bar{N}_1\,N_2^c + m_D\,\bar{N}_1\,\nu_L$$ Conserve L

$$+\mu_1\,\bar{N}_1\,N_1^c + \mu_2\,\bar{N}_2\,N_2^c$$ Break L

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu_1 & M \\ 0 & M & \mu_2 \end{pmatrix}$$

Light majorana neutrino mass

$$m_\nu \simeq (m_D/M)^2\,\mu_2$$

Heavy Pseudo-Dirac N1, N2

$$m_{N_{1,2}} \simeq M \mp (\mu_1 + \mu_2)/2$$

$$\mu_2 \ll 1\mathrm{GeV}$$

Suppressed LNV parameter, while large possible mixing

~Inverse seesaw

Impose a global U(1) Lepton, with eg: $L(\ell) = L(N_1) = -L(N_2)$

$$-\mathcal{L} \supset M\, \bar{N}_1\, N_2^c + m_D\, \bar{N}_1\, \nu_L$$ Conserve L

$$+\mu_1\, \bar{N}_1\, N_1^c + \mu_2\, \bar{N}_2\, N_2^c$$ Break L

$$+m_\varepsilon\, \bar{N}_2\, \nu_L$$ Break L

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & m_\varepsilon \\ m_D^T & \mu_1 & M \\ m_\varepsilon^T & M & \mu_2 \end{pmatrix}$$

Light majorana neutrino mass

$$m_\nu \simeq (m_D/M)^2\, \mu_2 + 2(m_D/M)\, m_\varepsilon$$

Heavy Pseudo-Dirac N1, N2

$$m_{N_{1,2}} \simeq M \mp (\mu_1 + \mu_2)/2$$

$$\mu_2 \ll 1\text{GeV} \qquad m_\varepsilon \ll \mu_{1,2}$$

Suppressed LNV parameter, while large possible mixing

→ Build a spontaneous model for this

Model Content

Field	ℓ_α	$e_{R\alpha}$	N_D	N_3	H_1	H_2	ϕ	S
$SU(2)_L$	**2**	**1**	**3**	**1**	**2**	**2**	**1**	**3**
$U(1)_Y$	-1/2	-1	0	0	1/2	1/2	0	0
$U(1)_{B-L}$	-1	-1	-1	0	0	2	-2	-1

A global U(1) is imposed

RH Neutrinos: singlet (type I) or triplet (type III) of SU(2)

H1~SM Higgs doublet, couple to SM leptons and quark $\langle H_1^0 \rangle = v_1/\sqrt{2} \sim 174\,\mathrm{GeV}$

H2 "almost inert" Higgs doublet, couples only to N and L $\langle H_2^0 \rangle = v_2/\sqrt{2} \ll v/\sqrt{2}$

ϕ Complex singlet, Majorana mass for N after EWSB $\langle \phi \rangle = v_\phi/\sqrt{2}$

Their vev break U(1) → Z2

Neutrino masses:

$$\mathcal{L} \supset -m_N \overline{N_D^a} N_D^a - \left(Y_{\nu 1}^{\beta} \overline{N_D^a} \widetilde{H}_1^{j\,*} (T_2^a)_{jk} \ell_\beta^k + Y_{\nu 2}^{\gamma} \overline{N_D^a}^C \widetilde{H}_2^{j\,*} (T_2^a)_{jk} \ell_\gamma^k + \frac{\delta_N}{\sqrt{2}} \phi \overline{N_D^a} N_D^{a\,C} + \text{h.c.} \right)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathbf{y_1}\, v_1 & \mathbf{y_2}\, v_2 \\ \mathbf{y_1}^T v_1 & \delta_N\, v_\phi & m_N \\ \mathbf{y_2}^T v_2 & m_N & \delta_N\, v_\phi \end{pmatrix}$$

$$m_N \sim TeV$$

Neutrino mass suppression:

$$Y_{\nu 2}\, v_2 \ll \delta_N\, v_\phi \ll 1\,\text{GeV}$$

$$m_\nu^{ij} = -y_1^{\{i,} y_2^{j\}} \frac{v_1\, v_2}{2\, m_N} + \delta_N\, v_\phi \left(y_1^i\, y_1^j \frac{v_1^2}{m_N^2} + y_2^i\, y_2^j \frac{v_2^2}{m_N^2} \right)$$

Light neutrinos

$$M_{\mathcal{N}_{1,2}} = m_N \mp \delta_N\, v_\phi / 2$$

Heavy Pseudo-Dirac pair

Neutrino masses: tuning issues?

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathbf{y_1}\, v_1 & \mathbf{y_2}\, v_2 \\ \mathbf{y_1}^T\, v_1 & \delta_N\, v_\phi & m_N \\ \mathbf{y_2}^T\, v_2 & m_N & \delta_N\, v_\phi \end{pmatrix}$$

Neutrino mass suppression:

$v_2 \ll 1\,\mathrm{GeV}$ $\quad V \supset \mu'\, H_2^\dagger\, H_1\, \phi + \mathrm{H.c}$ $\quad v_2 \propto (v_\phi/v_1)\mu'$

$\mu', Y_{\nu\,2} \to 0$ Gain U(1) : naturally small parameters

Incidentally, the breaking of U(1) → Goldstone boson : Majoron J

→ Suppressed couplings J to SM fermions

→ $v_2 \lesssim 0.2\,\mathrm{GeV}\sqrt{v_\phi/v_1}$

$\delta_N\, v_\phi \ll 1\,\mathrm{GeV}$ Satisfied easilly

$\delta_N \sim \mathcal{O}(10^{-2})$ $\quad v_\phi \sim \mathcal{O}(1)\,\mathrm{GeV}$

Neutrino masses: gains&losses

This UV completion assumes a global U(1) at high-energies

Explains -small neutrino masses

-the Majorana nature of light and heavy neutrinos

However: above EWSB, N are Dirac particles

Standard Leptogenesis scenario cannot explain the BAU

But: N are charged under U(1): they can bear a L asymmetry

U(1)-conserving scatterings can transfer a N asymmetry to SM leptons

$\Longrightarrow$ A Leptogenesis variant

Via inclusion of new particles: a DM candidate

Leptogenesis (in a nutshell)

Field	ℓ_α	$e_{R\alpha}$	N_D	N_3	H_1	H_2	ϕ	S
$SU(2)_L$	**2**	**1**	**3**	**1**	**2**	**2**	**1**	**3**
$U(1)_Y$	-1/2	-1	0	0	1/2	1/2	0	0
$U(1)_X$	-1	-1	-1	0	0	2	-2	-1

Add Majorana N3

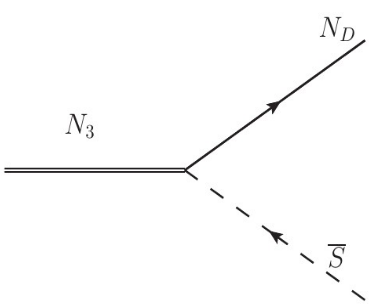
Add a scalar S partner of N

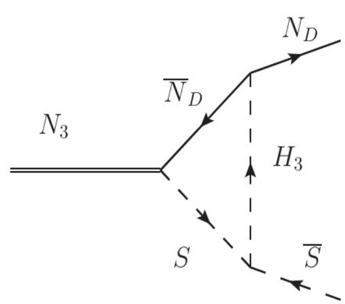
$$\mathcal{L} \supset -m_N \overline{N_D^a} N_D^a - \left(Y_{\nu 1}^{\beta} \overline{N_D^a} \widetilde{H}_1^{j*} (T_2^a)_{jk} \ell_\beta^k + Y_{\nu 2}^{\gamma} \overline{N_D^a}^C \widetilde{H}_2^{j*} (T_2^a)_{jk} \ell_\gamma^k + \frac{\delta_N}{\sqrt{2}} \phi \overline{N_D^a} N_D^{a\,C} + \text{h.c.} \right)$$

$$-\frac{1}{2} M_3 \overline{N_3} N_3^C - \left(h S^a \overline{N_D^a} N_3 - \frac{\mu''}{\sqrt{2}} S^2 \phi^* + \text{h.c.} \right)$$

Allow N asymmetry creation

CP asymmetry in N3 decays:





works well at the TeV-scale in the singlet case

Triplet version is lower bounded mN > 1.5 TeV

Certain amount of tuning required: suppressed couplings to compensate strong washouts

Dark Matter

Dark Matter

Scalar Dark Matter candidate S
Singlet or Triplet of SU(2)

Charged under U(1)
→ stability by the remnant Z2

Relic density following the freeze-out of annihilations

Singlet case: Higgs portal couplings $|S|^2 H^\dagger H$

Triplet case: irreducible gauge-boson contribution

The only peculiar features of our model are
-the large number of Higgs portal channels
-the complex triplet S

Dark Matter: spectrum

Triplet case:

$$\mathcal{V}_{\rm DM} = \mu_S^2\, S^* S + \lambda_S\, (S^* S)^2 + \lambda'_S\, \left(S^\dagger T_G^a S\right) \left(S^\dagger T_G^a S\right) + \mathcal{F}_1\, H_1^\dagger\, H_1 S^* S + \mathcal{F}_2\, H_2^\dagger\, H_2 S^* S + \mathcal{F}_3\, \phi^* \phi S^* S$$
$$+ \mathcal{F}'_1 \left(H_1^\dagger T_2^a H_1\right) \left(S^\dagger T_G^a S\right) + \mathcal{F}'_2 \left(H_2^\dagger T_2^a H_2\right) \left(S^\dagger T_G^a S\right) + \mathcal{H}\, S^2 H_1^\dagger\, H_2 + \mathcal{H}^*\, S^{*2} H_2^\dagger\, H_1$$
$$- \frac{\mu^{"}}{\sqrt{2}} (S^2 \phi^* + S^{*2}\phi)$$

$$S = \left(\cos(\theta_s)\, S_L^+ + \sin(\theta_s)\, S_H^+,\, S_N,\, \cos(\theta_s)\, S_H^- - \sin(\theta_s)\, S_L^-\right)^T$$

$$m^0_{S_{L(H)}} = \left(m_0^2 \mp \frac{\delta_0^2}{2}\right)^{1/2}, \quad m^\pm_{S_{L(H)}} = \left(m_0^2 \mp \frac{1}{2}\sqrt{\delta_0^4 + \delta_\pm^4}\right)^{1/2}$$

$$m_0^2 = \mu_S^2 + \left(\mathcal{F}_1\, v_1^2 + \mathcal{F}_2\, v_2^2 + \mathcal{F}_3\, v_\phi^2\right)/2$$
$$\delta_0^2 = 2\mu^{"}\, v_\phi - 2\,\mathcal{H}\, v_1\, v_2$$
$$\delta_\pm^2 = (\mathcal{F}'_1\, v_1^2 + \mathcal{F}'_2\, v_2^2)/2$$

=0 in the singlet case

But: in the triplet case, at tree-level
S0 is heavier than SL+

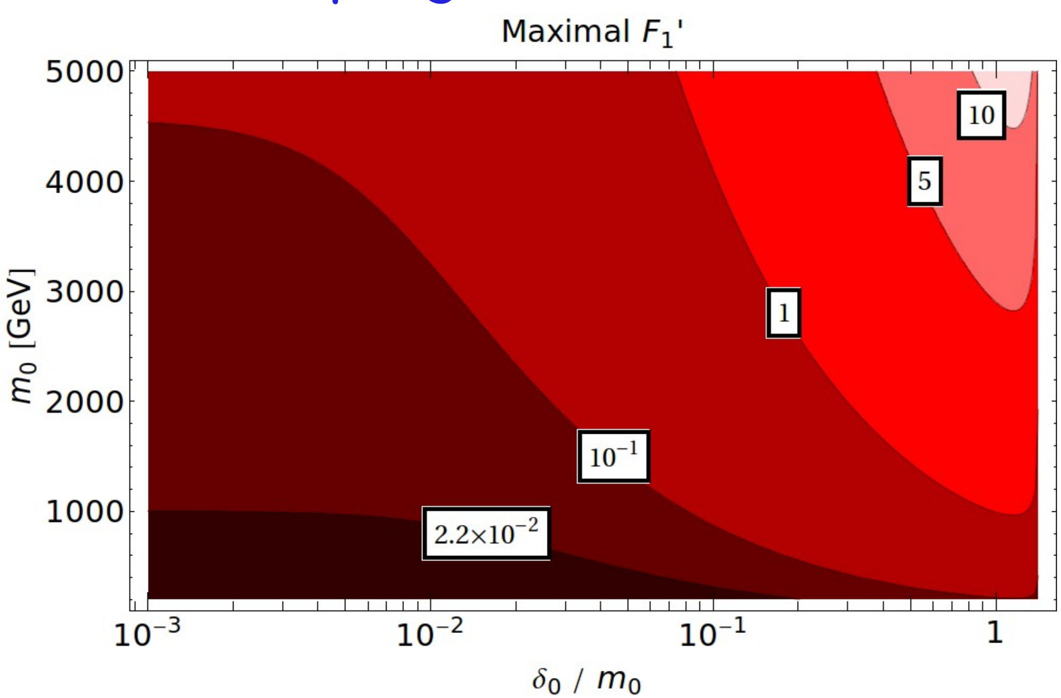
Dark Matter : triplet viability

Loop-corrections:

$$\left(m^{\pm}_{S_L(H)} - m^{0}_{S_L(H)}\right)_{|1\text{loop}} = \left(m^{\pm}_{S_L(H)} - m^{0}_{S_L(H)}\right)_{|\text{tree}} + \delta_m \qquad \delta_m \simeq 166\ \text{MeV}$$

Cirelli et al

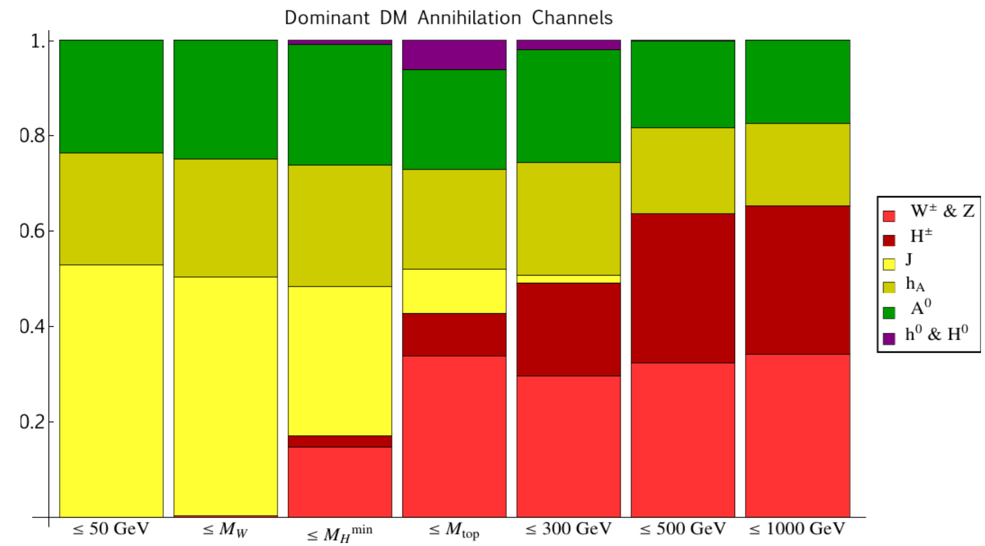
Constraints on the coupling F1'

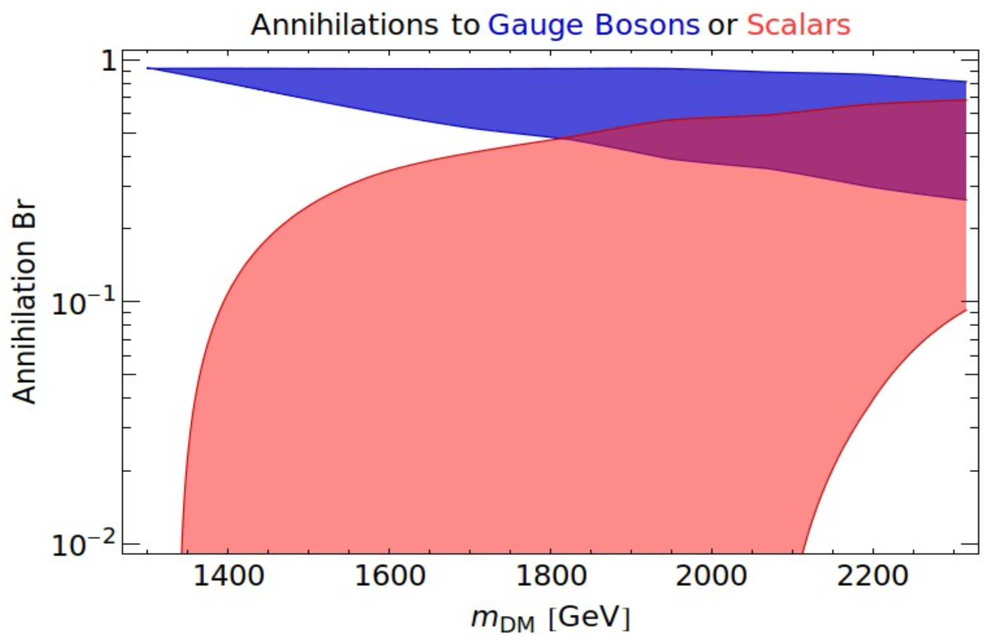


DM: relic abundance

Freeze-out mechanism

-Singlet case: Annihilations through Higgs portal couplings

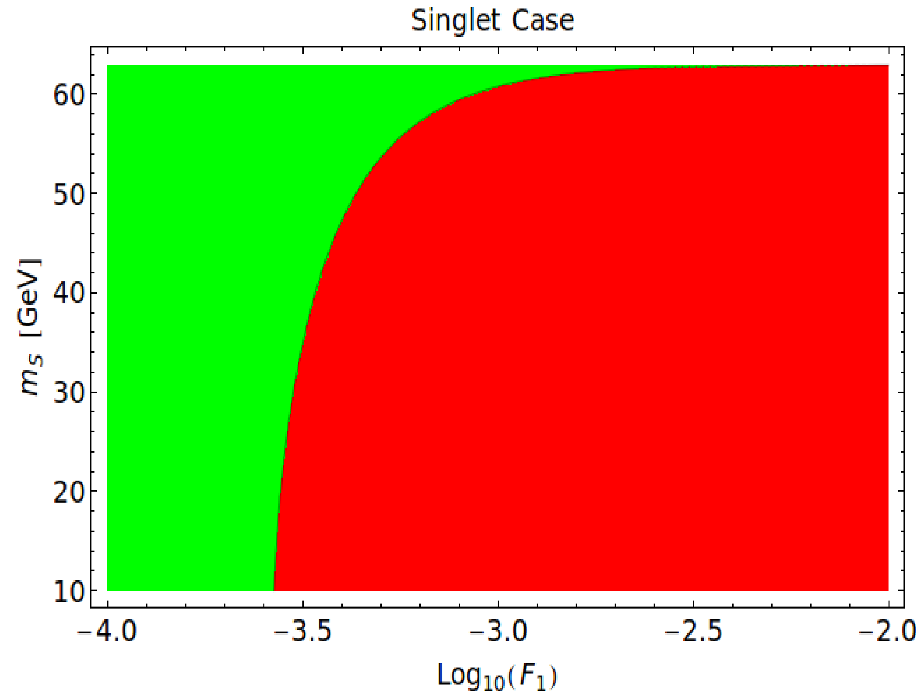




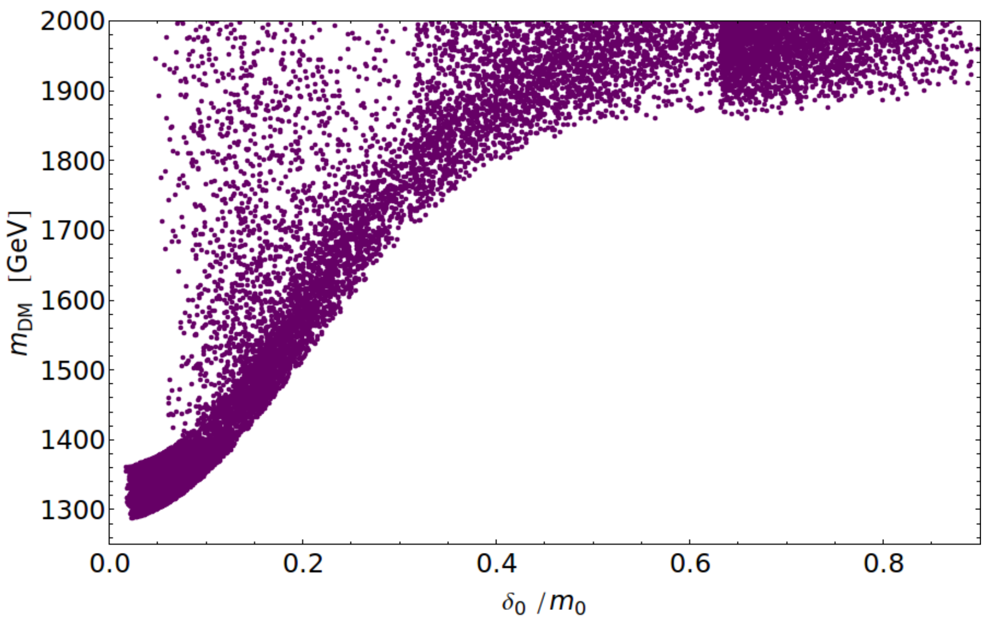
-Triplet case: gauge contribution dominate at low mass

DM: mass

In the Singlet case:
Large hSS couplings →Large Invisble Higgs



In the Triplet case, mS > 1290 GeV



$$m^0_{S_{L(H)}} = \left(m_0^2 \mp \frac{\delta_0^2}{2}\right)^{1/2},$$

$$m^\pm_{S_{L(H)}} = \left(m_0^2 \mp \frac{1}{2}\sqrt{\delta_0^4 + \delta_\pm^4}\right)^{1/2}$$

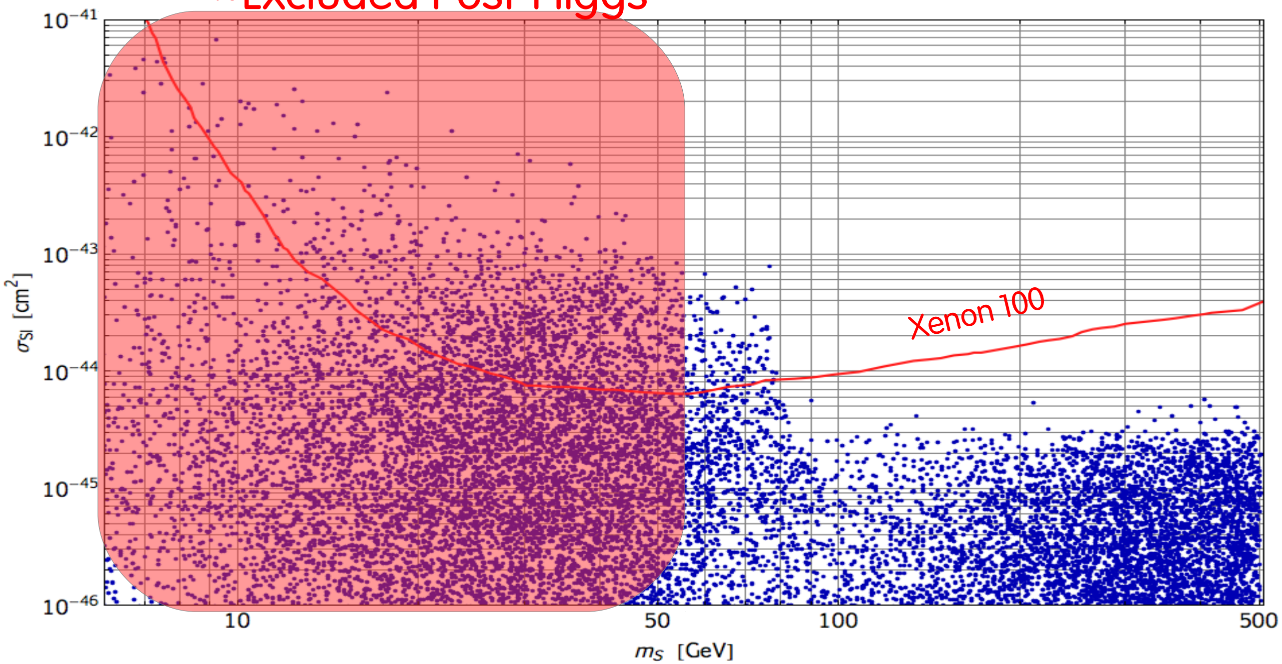
Small d0/m0 : Effectively doubles the number of DM particles

DM: detection

Singlet case

~Excluded Post-Higgs

Direct Detection



Triplet case : only large couplings F1 $^{(\prime)}$ can be probed by XENON 1T

At colliders: $SL^+ \rightarrow SL^0$ + pions : SL cannot be determined

Cirelli et al, Hambye et al,
Fileviez Perez et al

Conclusions

-We propose a UV-completion of the Inverse Seesaw

+ 2 RH Neutrinos, singlet or triplet of SU(2)
+ 1 Higgs doublet
+ 1 Higgs singlet

→ Large Higgs sector: potentially large deviations from SM

-Dark Matter in the same irrep than RHN

MDM >~ 60 GeV for singlet
MDM >~ 1300 GeV for triplet
Observation prospects are hard.

-BAU via leptogenesis, by the addition of a Majorana fermion N3

Couples DM and RHN
Requires tuning of the parameters, specially in the triplet case
Triplet case can be ruled out by observation of a triplet fermion @ LHC

→ Alternative BAU mechanism within this model to reduce tunings and RHN mass scale

Baryon asymmetry of the Universe

Standard Leptogenesis

Generation of a lepton asymmetry transmitted to baryons via sphalerons

In type I or III seesaw:
- introduction of *Majorana* Neutrinos N
- their decays to leptons or anti-leptons are slightly differents
- L asymmetry produced in N decays; subject to washouts.

High-energy realizations are perfectly viable, but unobservable

Low-energy O(TeV) ones require tuning or symmetry

For resonant enhancement of the CP asymmetry in N decays

No-lower bound on mN in singlet case

mN > 1.6 TeV in the triplet one Strumia

The scenario contemplated

It's a leptogenesis ⟶ Active sphalerons ⟶ Above EWSB

⟶ The global U(1) is conserved and RHN are Dirac particles

⟶ The standard scenario cannot work

But: through the presence of a scalar S and of a Majorana singlet N3

A 2-step scenario is possible:

-N3 decays produce an asymmetry in RHN

-transfer to lepton via U(1) conserving scatterings (Yukawa&gauge)

The scenario contemplated

Field	ℓ_α	$e_{R\alpha}$	N_D	N_3	H_1	H_2	ϕ	S
$\mathrm{SU(2)_L}$	**2**	**1**	**3**	**1**	**2**	**2**	**1**	**3**
$\mathrm{U(1)_Y}$	-1/2	-1	0	0	1/2	1/2	0	0
$\mathrm{U(1)_X}$	-1	-1	-1	0	0	2	-2	-1

$$\mathcal{L} \supset -m_N \overline{N_D^a} N_D^a - \left(Y_{\nu 1}^{\beta} \overline{N_D^a} \widetilde{H}_1^{j\,*} (T_2^a)_{jk} \ell_\beta^k + Y_{\nu 2}^{\gamma} \overline{N_D^a}^C \widetilde{H}_2^{j\,*} (T_2^a)_{jk} \ell_\gamma^k + \frac{\delta_N}{\sqrt{2}} \phi \overline{N_D^a} N_D^{a\,C} + \text{h.c.} \right)$$

$$-\frac{1}{2} M_3 \overline{N_3} N_3^C - \left(h S^a \overline{N_D^a} N_3 - \frac{\mu''}{\sqrt{2}} S^2 \phi^* + \text{h.c.} \right)$$

Washouts and transfer to leptons

As in standard leptogenesis, many interactions participate to washout interactions

Inverse decays

$$N_3 \leftrightarrow N_D \, \overline{S}$$

$$\Delta N = 2$$

$$N_D \, N_D \leftrightarrow S \, S + \text{c.s.}$$

$$N_D \, N_D \leftrightarrow \phi \, A_\mu + \text{c.s.}$$

$$\Delta N = 1$$

$$N_D \, S \leftrightarrow N_3 \, \phi + \text{c.s.}$$ Singlet & triplet

$$N_3 \, S \leftrightarrow N_D \, A_\mu + \text{c.s.}$$ Triplet

The washouts are typically very fast at low-scale: **small couplings required**

Transfer to leptons:

$$N_D \, t \leftrightarrow \ell \, Q + \text{c.s.}$$

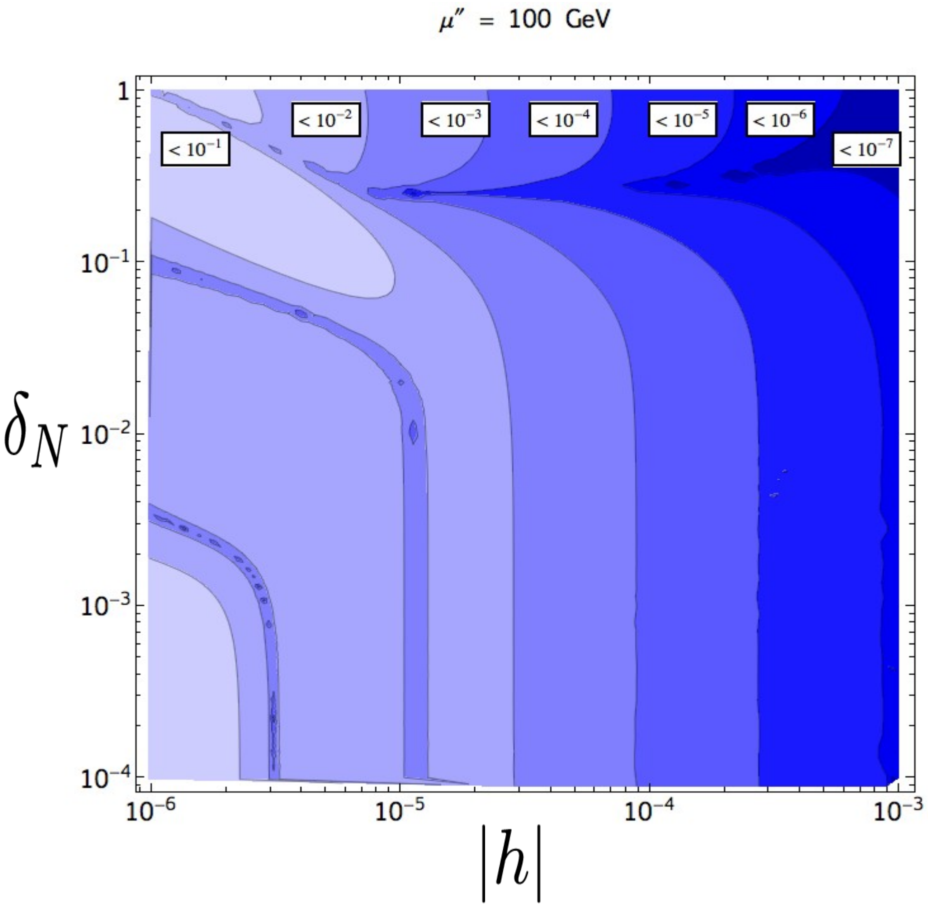
$$N_D \, H_1 \leftrightarrow \ell \, V + \text{c.s.}$$

The scatterings should be fast enough for efficient transfer:
Neutrino mass constraints on neutrino Yukawa couplings suffice

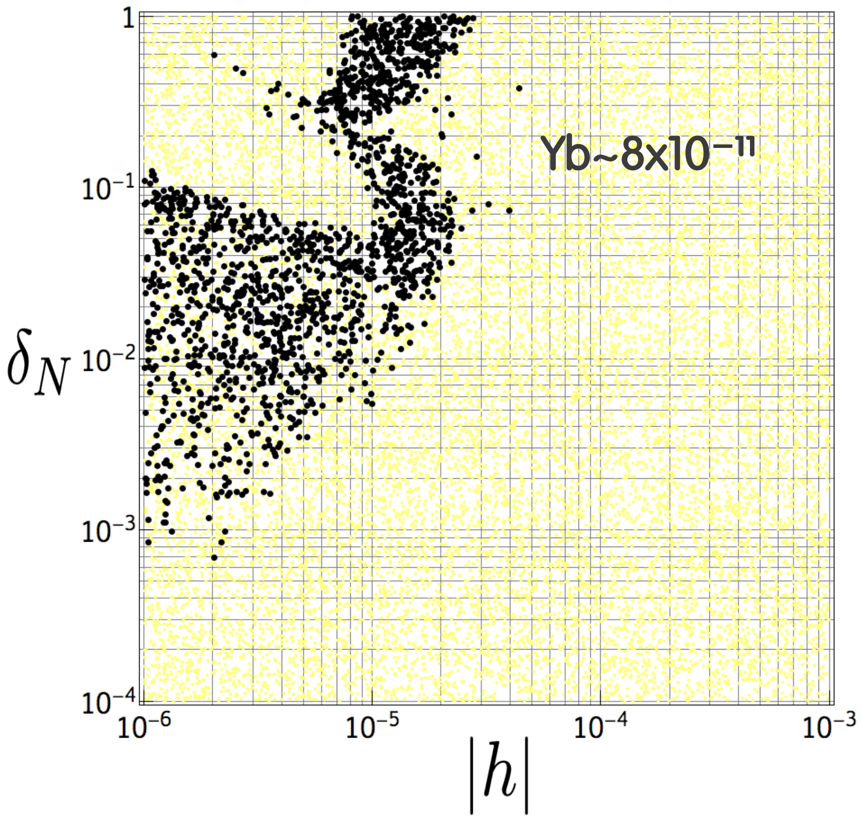
Succesfull BAU: singlet case

eg mN=10TeV and μ"=100 GeV

Efficiency of N asymmetry creation



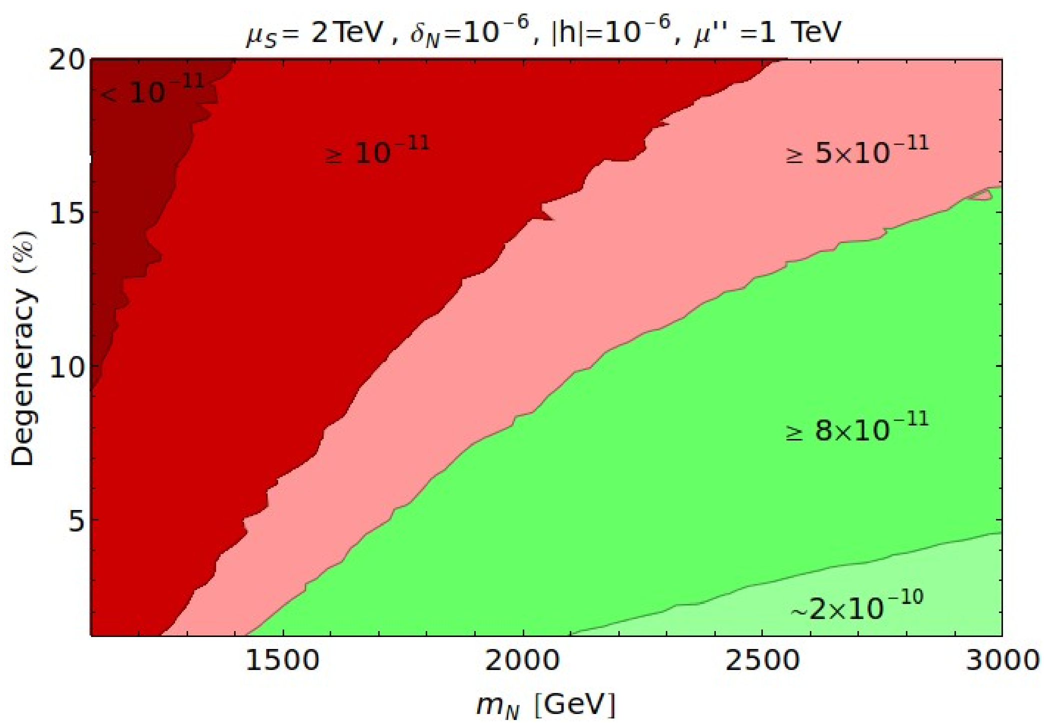
Succesfull BAU

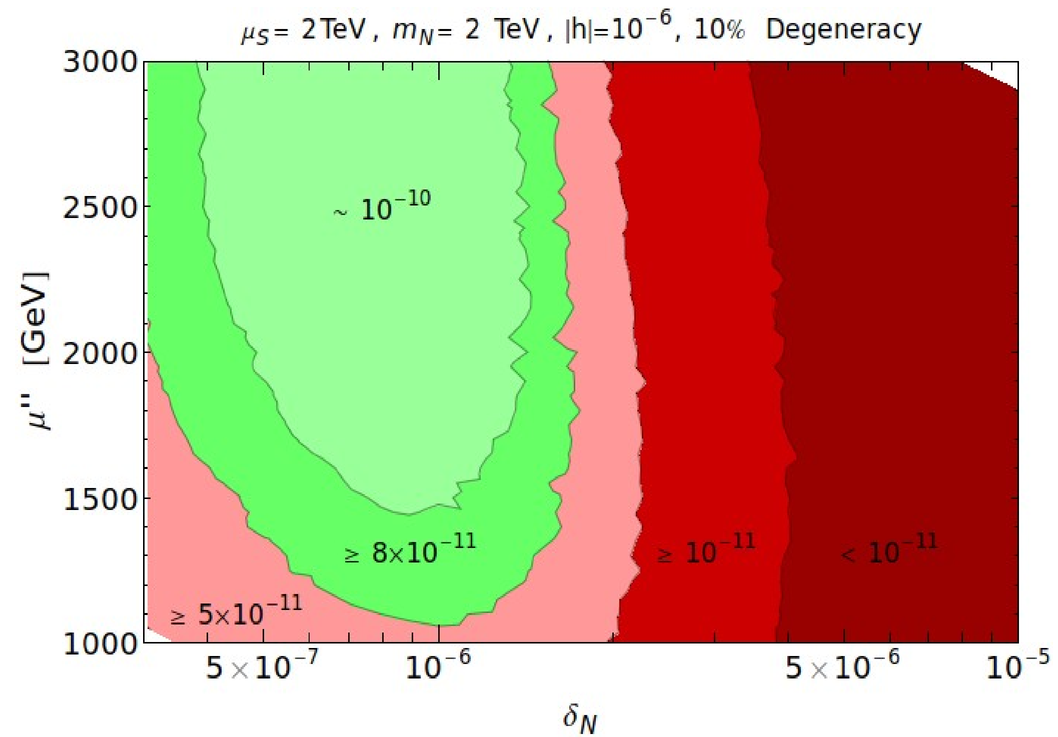


N asymmetry production mostly fixes BAU production as the transfer to lepton is efficient

Succesfull BAU: triplet case

Singlet and triplet cases are similar, were it not for the gauge scatterings





- Smaller coupling values are necessary to suppress the washouts
- Larger μ” to increase the CP asymmetry
- Lighter N at the cost of a (potentially large) tuning between N3 and N&S masses

Succesfull BAU

-The singlet case works well at the TeV scale:

Potentially large LFV are possible

-The triplet case is lower bounded: typically mN> 1.5 TeV

The observation of a TeV fermion triplet can exclude this BAU mechanism
(as in usual type III seesaw)

Higgs sector phenomenology

Scalar spectrum

2 doublets H1, H2 and 1 singlet ϕ

$$\begin{aligned}\mathcal{V}_{\rm SB} &= -\mu_1^2\,(H_1^\dagger\,H_1) + \lambda_1\,(H_1^\dagger\,H_1)^2 - \mu_2^2\,(H_2^\dagger\,H_2) + \lambda_2\,(H_2^\dagger\,H_2)^2 - \mu_3^2\,\phi^*\phi + \lambda_3\,(\phi^*\phi)^2 \\ &+ \kappa_{12}\,(H_1^\dagger\,H_1)\,(H_2^\dagger\,H_2) + \kappa_{12}'\,(H_1^\dagger\,H_2)\,(H_2^\dagger\,H_1) + \kappa_{13}\,(H_1^\dagger\,H_1)\phi^*\phi + \kappa_{23}\,(H_2^\dagger\,H_2)\phi^*\phi \\ &- \frac{\mu'}{\sqrt{2}}\left((H_1^\dagger\,H_2)\phi + (H_2^\dagger\,H_1)\phi^*\right)\end{aligned}$$

Spectrum:

3 CP-even scalars

$h^0 \quad H^0$

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = R(-\theta)\begin{pmatrix} \sqrt{2}\,\mathrm{Re}(H_1^0) \\ \sqrt{2}\,\mathrm{Re}(\phi) \end{pmatrix}$$

$h_A \sim \sqrt{2}\mathrm{Re}(H_2^0)$

$$m_{h^0} \simeq 126\,\mathrm{GeV}$$

2 CP-odd scalars

$A^0 \sim \sqrt{2}\,\mathrm{Im}(H_2^0)$

$J \sim \sqrt{2}\mathrm{Im}(\phi)$

J: Majoron, Goldstone boson associated to the spontaneous breaking of the global U(1).

A charged scalar $H^\pm \sim H_2^\pm$

The coupling of J to SM fermions fixes the Vev Hierarchy $v_2 \ll v_\phi, v_1$

Analysis of LHC data

Higgs signal strength:

$$\mu_i(H) \equiv \frac{\sigma(pp \to H)_i \times \mathrm{Br}(H \to i)}{\sigma(pp \to h)_i^{\mathrm{SM}} \times \mathrm{Br}(h \to i)^{\mathrm{SM}}}$$

Production: -No colored particles introduced: the loop h $\leftrightarrow$ gg not affected

-All production channels equally rescaled: $\dfrac{\sigma(pp \to h^0)_i}{\sigma(pp \to h)_i^{\mathrm{SM}}} = \cos^2(\theta)$

Decays: -All couplings rescaled

-Extra invisible decay channels: in particular h $\to$ J J

-Extra charged particles: h diphoton decay affected

Analysis

Fit of ATLAS and CMS data (pre-HCP)

Channel:	$\tau\,\tau$	$b\,b$	$W\,W$	$Z\,Z$	$\gamma\,\gamma$
$\hat{\mu}_i$	0.15	0.49	0.9	0.88	1.67
σ_i	0.7	0.73	0.3	0.34	0.34

-B and tau channels considered as upper bound only
-W, Z and photon channels fitted

Espinosa et al

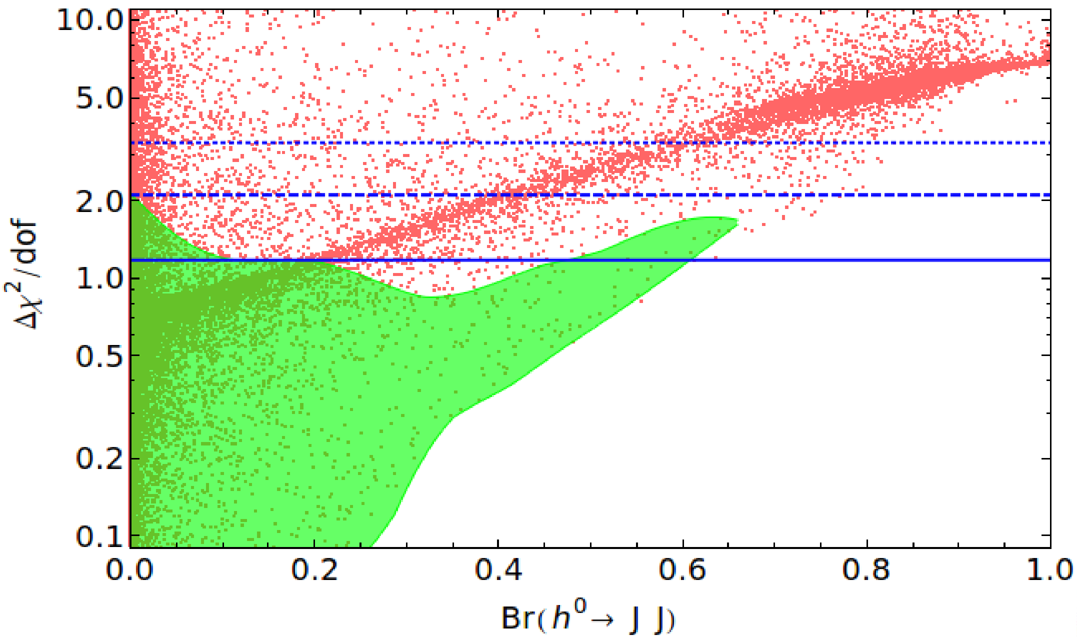
Electroweak precision data: $S = 0.0 \pm 0.1\,, \quad T = 0.02 \pm 0.11\,, \quad U = 0.03 \pm 0.09$

Form and minimize a Chi²

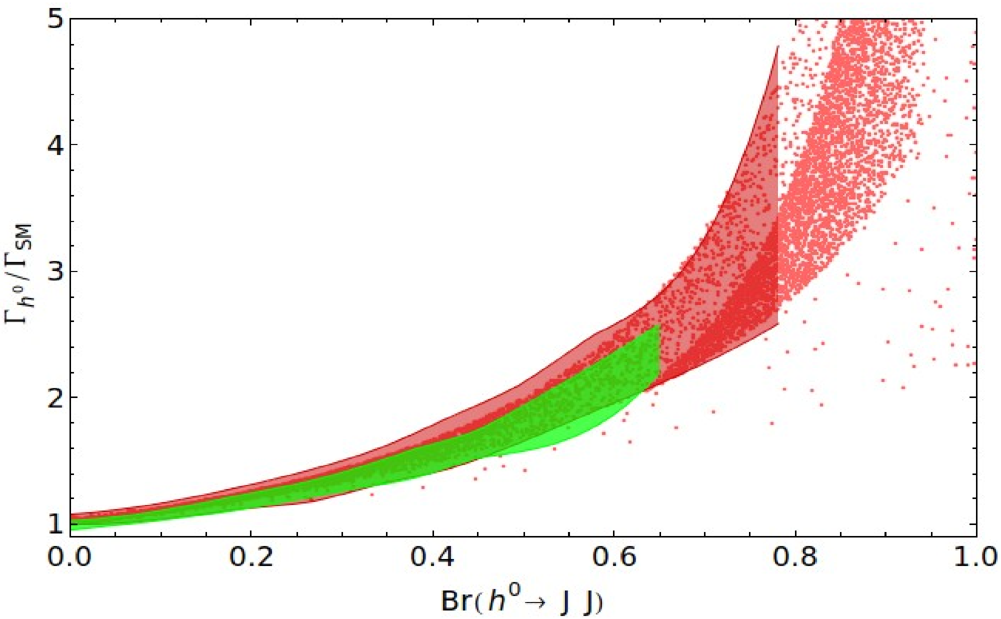
$$\chi^2(\mu_i(h^0)) = \sum_{i=\gamma,Z,W,S,T,U} \frac{(\mu_i(h^0) - \hat{\mu}_i)^2}{\sigma_i^2}$$

Invisible decays

Spectrum fixed: $h^0 \to J\,J$ only invisible decay



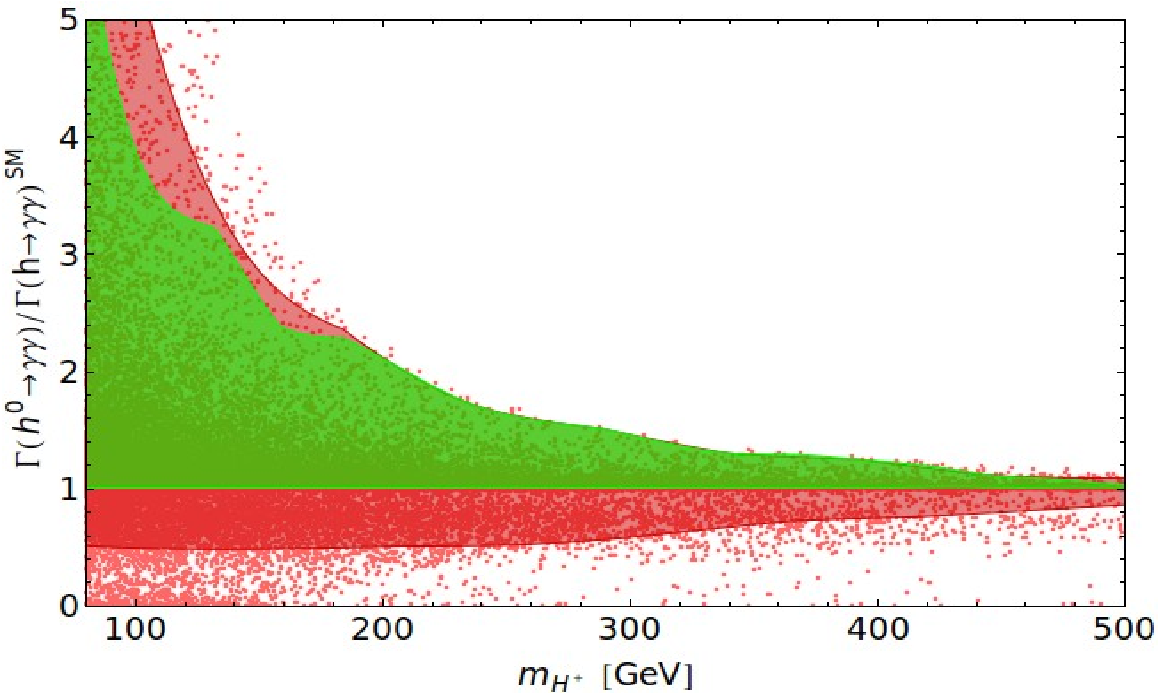
Large Br(inv) from larger decay width



The diphoton rate

$$\Gamma(h^0/H^0 \to \gamma\gamma) = \frac{G_\mu \alpha^2 m^3_{h^0/H^0}}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 \lambda_{ff}^{h^0/H^0} A_{1/2}\left(\frac{m^2_{h^0/H^0}}{4 m_f^2}\right) + \lambda_{WW}^{h^0/H^0} A_1\left(\frac{m^2_{h^0/H^0}}{4 m_W^2}\right) - \frac{v^2}{2 m^2_{H^+}} \lambda^{h^0/H^0}_{H^+ H^-} A_0\left(\frac{m^2_{h^0/H^0}}{4 m^2_{H^\pm}}\right) \right|^2$$

Eg: Djouadi



New contributions from charged particles:
In particular H^+ can be light enough

Large enhancement possible