A possible connection between neutrino mass generation and the lightness of a NMSSM pseudoscalar

Debottam Das

Laboratoire de Physique Theorique d'Orsay

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Ref: arXiv:1011.5037 (Physics Letters B 700 (2011) pp. 351-355)

(Asmaa Abada, Gautam Bhattacharyya, Cédric Weiland)

Motivation & Plan

- $\mathcal{NMSSM}$ can offer a very light pseudo-scalar Higgs boson A_1
  $\Rightarrow$ interesting phenomenology related to

  - Higgs physics

  - dark matter annihilations

- Strong constraints coming from Upsilon decays, B physics and accelerator bounds

- Proposing a definite model for neutrino mass generation in $\mathcal{NMSSM}$, we reanalyze the status of all those experimental constraints

More specifically :

Can we evade the experimental constraints which are otherwise very stringent ?

$\mathcal{MSSM}$: μ problem

- Superpotential:

$$W_{\text{MSSM}} = \overline{u}\mathbf{y_u}\,QH_u - \overline{d}\mathbf{y_d}\,QH_d - \overline{e}\mathbf{y_e}\,LH_d + \mu H_u\,H_d$$

H_u, H_d, Q, L, $\overline{u}$, $\overline{d}$, $\overline{e} \Rightarrow$ chiral superfields

$\Rightarrow$ Provides all Yukawa interactions in SM

$\Rightarrow \mathbf{y_u}, \mathbf{y_d}, \mathbf{y_e}$ are the dimensionless Yukawa couplings $\Rightarrow 3 \times 3$ matrices in family space

- Proper SUSY phenomenology requires

• $\mu << M_P$ (Plank scale), M_G (Gut scale)

• And, $\mu > 100$ GeV (From LEP limit on chargino mass)

$\Rightarrow \mu \sim M_{SUSY} \sim TeV$ is required

The so-called μ problem in $\mathcal{MSSM}$

- An elegant way to solve this problem is by introducing an additional singlet superfield S with a coupling $\lambda S H_u H_d$ in the superpotential $\Rightarrow$

  $W_{NMSSM} = \lambda S H_u H_d + \frac{k}{3} S^3$ +.... ($\mathbb{Z}_3$ invariant superpotential)

  The VEV $\underline{v_S}$ of the real scalar component of $\underline{S}$ generates

  $\Rightarrow \mu_{eff} = \lambda v_S \Rightarrow \quad \mu_{eff} \sim M_{SUSY}$

  This is known as Next-to-Minimal Supersymmetric Standard Model ($\mathcal{NMSSM}$)

Simplest SUSY standard model with M_{SUSY} as the only scale in the Lagrangian

NMSSM : Spectrum

- The SM singlet scalar $S \Rightarrow$ can leave the footprints only in the neutral Higgs sector and in the neutralino sector $\Rightarrow$
  - Neutralinos χ_i^0, $i = 1 \ldots 5$,
    $\Rightarrow$ mixtures of the $\tilde{B}$, $\tilde{W}$, $\tilde{H}_u$, $\tilde{H}_d$ and $\tilde{S}$
  - 3 CP-even neutral Higgs bosons H_i (H_1, H_2, H_3)
    H_1 is the lightest CP-even Higgs boson
  - 2 CP-odd neutral Higgs bosons A_1 and A_2 ($A_2 \simeq A_{MSSM}$)

    $\Rightarrow$ The lightest pseudoscalar A_1 can be very light

    Recent analysis shows that $m_{A_1} > 210$ MeV

    Ref: S. Andreas, O. Lebedev, S. Ramos-Sanchez and A. Ringwald, JHEP 1008 (2010) 003

Light A_1 : What is *so* attractive

Higgs Physics:

- The interest of a light A_1 is that *it provides a new and dominant decay channel for the lightest Higgs boson* $h \Rightarrow$ **LEP search strategy does not work !**

  $h \to A_1 A_1 \to 4f$ final state ! where $A_1 \to 2\mu, 2\tau, 2b$

  • Particular interest is in the zone when $m_{A_1} < 10$ GeV
  $\Rightarrow$ Allows to accommodate *lightest CP-even Higgs mass* $m_h \sim 95 - 105$ GeV

Blessings for **light DM:**

- Lightest neutralino ($\simeq \tilde{B}, \tilde{S}$) can be very light ($\simeq 5 - 10$ GeV)
  $\Rightarrow$ ideal candidate for DM
- WMAP constraint is satisfied via CP-odd Higgs (A_1) exchange
  $\Rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to A_1^* / A_1 \to f\bar{f}$

A_1 : **What makes it** so light

- In general

$$A_1 = \cos\theta_A \, A_{MSSM} + \sin\theta_A \, S_I$$

  - A_{MSSM} is the doublet like CP-odd scalar in the $MSSM$ sector of the NMSSM
  - S_I represents the pseudoscalar component of the singlet scalar in the $NMSSM$

- Phenomenology related to A_1 is principally governed by its couplings to the SM fermions $\Rightarrow$ includes the doublet component ($\cos\theta_A$) only

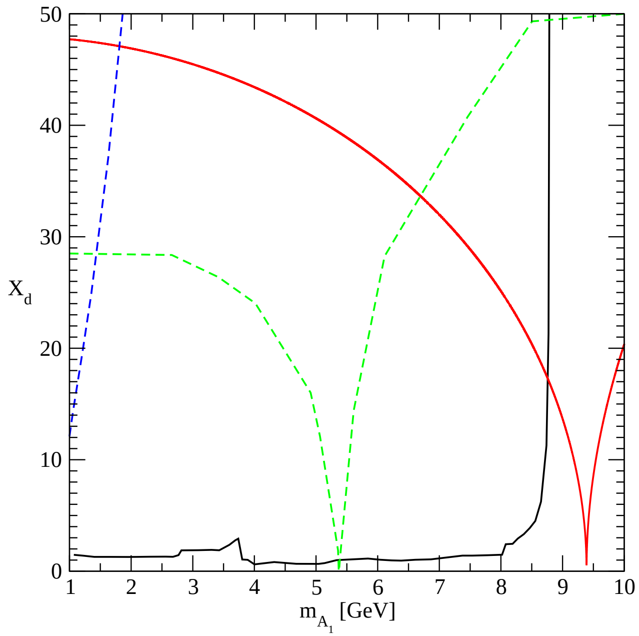
- $$\mathcal{L}_{Af\bar{f}} \equiv C_{Af\bar{f}} \frac{i g_2 m_f}{2 m_W} \bar{f} \gamma_5 f A \, ,$$

  - $C_{A_1 \mu^- \mu^+} = C_{A_1 \tau^- \tau^+} = C_{A_1 b \bar{b}} = X_d = \cos\theta_A \tan\beta$, $(\tan\beta = v_u / v_d)$
  - $C_{A_1 t\bar{t}} = C_{A_1 c\bar{c}} = \cos\theta_A \cot\beta$

- However, light or ultra-light CP-odd scalars are highly constrained via Upsilon decays, B physics and collider searches

Most of these constraints *exploit* the $A_1 f\bar{f}$ coupling $\Rightarrow$ thus couples via $\cos\theta_A$ only

Constraint on the A_1 mass : Upsilon & B physics



Domingo et.al. JHEP 0901:061,2009

- $\Upsilon(ns) \equiv b\bar{b}$ ($m_\Upsilon \geq 9.46$ GeV) $\Rightarrow$ $\Upsilon \to \gamma + X$ searched in B-factories like BaBar, CLEO..

- $\Upsilon \to \gamma + A_1$ followed by $A_1 \to \tau^+\tau^-$, $\mu^+\mu^-$ $\Rightarrow$ visible if A_1 is quite light ($A_1 \leq 10$ GeV)

- B physics constraints :

$\Rightarrow$ $\Delta M_s, \Delta M_d$ ($\equiv m_{\bar{B}_{s,d}} - m_{B_{s,d}}$)

$\Rightarrow$ $Br(B_s \to \mu^+\mu^-)$

STRINGENT bounds on m_{A_1} and in particular on X_d

Light A_1 : Other constraints

- ALEPH collaboration reanalysed of LEP-2 data for $h \to A_1 A_1 \to 4\tau$ final states (relevant for $m_{A_1} < 2m_b$)
- D0 collaboration (Fermilab Tevatron) analyzed $h \to A_1 A_1 \to 4\mu$ mode (relevant for $m_{A_1} < 2m_\tau$):
- Similarly, other searches in this direction are :
  - $h \to A_1 A_1 \to 4b,\ gg,\ c\bar{c},\ \tau^+\tau^-,\ \mu^+\mu^-\tau^+\tau^-$

  $\Rightarrow$ Again constrain on the $Br(A_1 \to f\bar{f})$ and X_d

SUMMARY :

Constraints	$m_{A_1} < 2m_\tau$	$[2m_\tau, 9.2\ \text{GeV}]$	$[9.2\ \text{GeV}, M_{\Upsilon(1S)}]$	$[M_{\Upsilon(1S)}, 2m_B]$
$\Upsilon(nS) \to \gamma A_1 \to \gamma(\mu^+\mu^-)$	✓	×	×	×
$\Upsilon(nS) \to \gamma A_1 \to \gamma\tau^+\tau^-$	×	✓	×	×
$e^+e^- \to Z + 4\tau$	×	✓	×	×
A_1-η_b mixing	×	×	✓	✓
$e^+e^- \to b\bar{b}\tau^+\tau^-$	×	×	×	✓

Light neutrino mass: Can it be a blessing for light A_1

- Neutrinos are massless in the $\mathcal{NMSSM}$
- Previous studies :
  - RpV-$\mathcal{NMSSM} \Rightarrow$ not compatible with DM motivation
  - RpC-$\mathcal{NMSSM} \Rightarrow$ introducing $\hat{N}_i$ to the $\mathcal{NMSSM}$ field content $\Rightarrow$ $f^{\nu} \sim 10^{-6}$
- We propose an extension of the $\mathcal{NMSSM}$ with two additional gauge singlets carrying lepton numbers :

$\Rightarrow$ The $so-called$ 'inverse seesaw' mechanism

Features

- Singlet neutrinos can be *very light (few GeV)*
- The neutrino Yukawa couplings ($f^{\nu} \sim \mathcal{O}(1)$)

- We will see *how this seesaw mechanism* can
  - influence the *existing decay pattern* of A_1
  - generates neutrino mass $m_{\nu} \sim$ eV

- Superpotential :

$$W = W_{\text{NMSSM}} + W'$$
$$W' = f^{\nu}_{ij} H_u L_i N_j + (\lambda_N)_i S N_i X_i + \mu_{X i} \hat{X}_i \hat{X}_i$$

• N_i and X_i : Gauge singlets carrying the lepton numbers -1 and $+1$

• $(\lambda_N)_i S N_i X_i$: Lepton number conserving term

• $\mu_{X i}$: Effective mass term provides lepton number violation

- Once the scalar component of S acquires a vev (v_S), we have

• Lepton number conserving mass terms

(i)$M_{N i} \Psi_{N i} \Psi_{X i}$ with $M_{N i} \equiv (\lambda_N)_i v_S$ and

(ii)$(m_D)_{ij} \Psi_{\nu i} \Psi_{N j}$ with $(m_D)_{ij} = f^{\nu}_{ij} v_u$

Neutrino masses in the NMSSM

- Considering one generation, the (3×3) mass matrix in the $(\Psi_\nu, \Psi_N, \Psi_X)$ basis $\Rightarrow$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_N \\ 0 & M_N & \mu_X \end{pmatrix}$$

- The mass eigenvalues ($m_1 << m_2, m_3$)

$$m_1 = \frac{m_D^2 \mu_X}{m_D^2 + M_N^2}, \quad m_{2,3} = \mp\sqrt{M_N^2 + m_D^2} + \frac{M_N^2 \mu_X}{2(m_D^2 + M_N^2)}.$$

• m_1 is the lightest mass eigenvalue : Small values of μ_X provides $m_\nu \sim eV$ scale

• $\mu_X \sim O(eV)$ is natural as $\mu_X \to 0$ restores *lepton number symmetry*

• Thus M_N or m_D is unconstrained

$M_N \sim O(10)$ GeV can influence substantially the decay pattern of A_1

Reanalyzing A_1 decay modes

- The lightest CP-odd scalar A_1 has additional interactions with the sterile neutrinos $\Rightarrow$ thus new decay final states
  - $A_1 \to \Psi_\nu \Psi_N$: Depends on the $\cos\theta_A$ component of A_1
  - $A_1 \to \Psi_N \Psi_X$: Depend on the $\sin\theta_A$ component of A_1

- Consequently, the invisible BRs (normalized them with the visible modes)

$$\frac{\mathrm{Br}\,(A_1 \to \Psi_\nu \Psi_N)}{\mathrm{Br}\left(A_1 \to f\bar{f}\right) + \mathrm{Br}\,(A_1 \to c\bar{c})} \simeq \frac{m_D^2}{m_f^2 \tan^4\beta + m_c^2},$$

$$\frac{\mathrm{Br}\,(A_1 \to \Psi_N \Psi_X)}{\mathrm{Br}\left(A_1 \to f\bar{f}\right) + \mathrm{Br}\,(A_1 \to c\bar{c})} \simeq \tan^2\theta_A \frac{M_N^2}{m_f^2 \tan^2\beta + m_c^2 \cot^2\beta} \frac{v^2}{v_S^2}$$

(neglecting phase-space effects)

Reanalyzing A_1 decay modes....contd

- Invisible decay prefers large $\tan^2\theta_A$, thus large singlet component and moderate values for $\tan\beta$
- The BR into $A_1 \to \Psi_N \Psi_X$ dominates over the other modes
- For numerical illustration: we choose
  $\tan\beta = 3, 20$, $\cos\theta_A = 0.1$, $M_N = 5, 30$ GeV

  • $m_{A_1} > M_N$ to allow the two-body decays

  • We consider $m_{A_1} < 10$ GeV and $m_{A_1} < 40$ GeV

  • Our parameter choice reflects two regimes where

  (i) Upsilon constraints and (ii) B-physics or constraints from LEP are strong

Results

	$\tan\beta = 20$, $\cos\theta_A = 0.1$		$\tan\beta = 3$, $\cos\theta_A = 0.1$	
M_N (GeV)	5	30	5	30
Br $(A_1 \to \Psi_\nu \Psi_N)$	7×10^{-5}	3×10^{-6}	4×10^{-3}	1×10^{-4}
Br $(A_1 \to \Psi_N \Psi_X)$	0.7	0.9	~ 1	~ 1

- With the above choices of $\cos\theta_A$ and $\tan\beta$, the resultant X_d is ruled out in general NMSSM for $m_{A_1} < 10$ GeV
- A_1 has significant BRs into the invisible modes thus
  $\Rightarrow$ relaxing the constraints from its visible decays
- Phase space suppression : $\left(\left\{1 - (\frac{2m_f}{m_{A_1}})^2\right\} / \left\{1 - (\frac{2M_N}{m_{A_1}})^2\right\}\right)^{1/2}$
  Our choice $m_{A_1} > M_N$, m_f makes phase space contribution quite insignificant

Connection between light neutrino and light $NMSSM$ pseudoscalar : Summary

- light A_1 in $NMSSM$
  $\Rightarrow$ attractive phenomenology related to Higgs hunting & DM annihilations

- Challenged by different experiments
  $\Rightarrow$ associated with the decays of a light $A_1 \rightarrow f\bar{f}$

- We augment the $NMSSM$ Superpotential with two singlet neutrinos N and X
  $\Rightarrow$ $\underline{\mathit{Minimal\ extension}}$ that serves twin purpose

  • generates $m_\nu \sim$ eV

  • Significant BRs into $A_1 \rightarrow NX$
  $\Rightarrow$ $BR(A_1 \rightarrow f\bar{f})$ is reduced

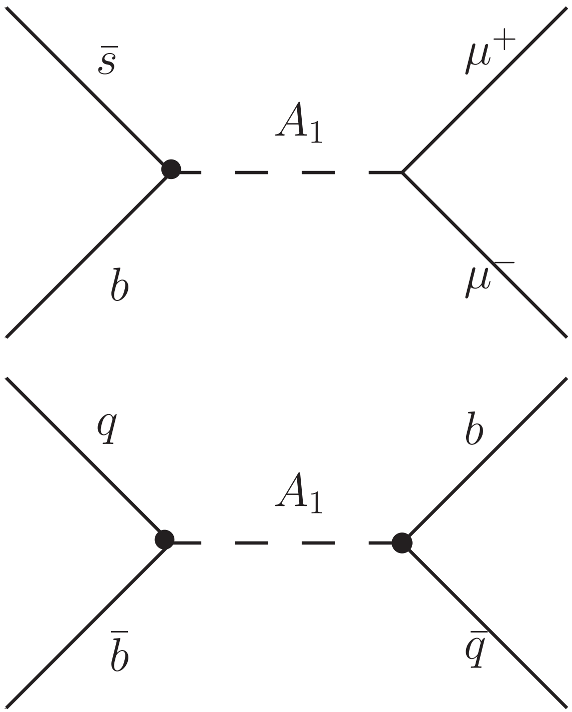
- This naturally weakens the constraints on the A_1 mass and on its couplings X_d

THANK YOU

Constraint on the Higgs masses : Light A_1

- Radiative Upsilon decays ($\Upsilon(ns) \equiv b\bar{b}$ vector like bound state with $m_\Upsilon \geq 9.46$ GeV)$\rightarrow \gamma + X$ searched in B-factories like BaBar, CLEO..
- $\Upsilon \equiv \gamma + A_1$ followed by $A_1 \rightarrow \tau^+\tau^-$, $\mu^+\mu^-$ $\Rightarrow$visible if A_1 is quite light ($A_1 \leq 10$)GeV $\Rightarrow$ put bounds on m_{A_1} and in particular on $\cos\theta_A$
- In this regime h decay leads $h \rightarrow A_1 A_1 \rightarrow 4\tau \Rightarrow$ constrained by the recent ALEPH results $(e^+e^- \rightarrow Z + 4\tau)$
- bottom-eta η_b meson $\equiv$ CP-odd scalar $b\bar{b}$ bound state with $m_{\eta_b} \sim 9.389$ GeV has recently been discovered
- The mass difference $Upsilon(1S) - \eta_b(1S) \Rightarrow$ hyperfine splitting ($E^{EXP}_{hfs}(1S)$)
- $E^{EXP}_{hfs}(1S) \sim 70$MeV $> E^{QCD}_{hfs}(1S)(42$MeV$)$ $\Rightarrow$could be explained by $\eta_b - A_1$ mixing

  (M.Drees and K.i.Hikasa: Phys.Rev.D 41, 1547 (1990); F.Domingo, U.Ellwanger and M.A.Sanchis-Lozano, Phys.Rev.Lett. 103, 111802 (2009))
- m_{A_1} with mass very close to m_{η_b} is constrained $\Rightarrow$physical states after mixing should provide the correct mass ~ 9.389 GeV



- SUSY contributions arise from box diagrams at the one-loop level, but also from penguin diagrams involving flavour-changing vertices like b-$s(d)$-A_1
- $\mathrm{Br}(B_s \to \mu^+\mu^-) \propto m_{A_1}^{-4} \cos\theta_A^4 \tan^6\beta$
- Information on the mass differences $\Delta M_{s,d} \equiv m_{\bar{B}_{s,d}} - m_{B_{s,d}}$ originates from measurements of B meson oscillations
- Clearly, both contributions involve X_d as multiplicative factor $\Rightarrow$ provide constraints on m_{A_1} and X_d

Small X_d : Constraints are much relaxed compared to the *MSSM A* boson

Light A_1 : Constraints from collider physics

- ALEPH collaboration has reanalysed of LEP-2 data for $\underline{h \to A_1 A_1 \to 4\tau}$ final states (relevant for $m_{A_1} < 2m_b$)

  Consequently upper limits have been placed on :

  $$\frac{\sigma(e^+e^- \to Zh)}{\sigma_{SM}(e^+e^- \to Zh)} \times Br(h \to A_1 A_1) \times \mathbf{Br(A_1 \to \tau^+\tau^-)^2}$$

- D0 collaboration (Fermilab Tevatron) has analyzed $\underline{h \to A_1 A_1 \to 4\mu}$ mode and placed an upper bound on (relevant for $m_{A_1} < 2m_\tau$):

  $$\sigma(p\bar{p} \to hX) \times Br(h \to A_1 A_1) \times \mathbf{Br(A_1 \to \mu^+\mu^-)^2}$$

- Similarly, other searches in this direction are :
  - $h \to A_1 A_1 \to 4b$ for $m_h < 110$ GeV (LEP)
  - $h \to A_1 A_1 \to gg,\ c\bar{c},\ \tau^+\tau^-$ for m_h $45 - 86$ GeV (OPAL)
  - $h \to A_1 A_1 \to \mu^+\mu^-\tau^+\tau^-$ (D0)

- All these observables constrain $Br(A_1 \to f\bar{f})$ and X_d