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

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Ref: arXiv:**1011.5037**

(Asmaa Abada, Gautam Bhattacharyya, Cédric Weiland)

Outline

- $\mathcal{NMSSM}$ 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 acclerator 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 $\Rightarrow$ 3×3 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 $\mathcal{MSSM}$

NMSSM

- Embedding $MSSM$ in a *Supergravity* framework, $\mu \sim M_{SUSY}$ can be generated via a particular Higgs dependent *(ad-hoc)* term in the Kähler potential
  $\Rightarrow$ Giudice-Masiero mechanism

This is true only for Supergravity inspired SUSY breaking models

- 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 $\Rightarrow$

  $W_{NMSSM} = \lambda S H_u H_d + \frac{k}{3} S^3$ +.... (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 ($NMSSM$)

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

$\mathcal{NMSSM}$: Spectrum

- The SM singlet scalar $S \Rightarrow$ can leave the footprints only in the Higgs sector and in the neutralino sector $\Rightarrow$
  - 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 ($A_2 \simeq A_{MSSM}$)
  - One charged Higgs boson $H^{\pm}$
  - Five neutralinos χ_i^0, $i = 1 \ldots 5$, which are mixtures of the Bino, the neutral Wino, the neutral Higgsinos and the Singlino

Our focus will be on the lightest pseudoscalar A_1

Light pseudoscalar in the $\mathcal{NMSSM}$

- In the $\mathcal{MSSM}$, $\Rightarrow$ $m_A > 93.4$ GeV (From LEP : $e^+ e^- \to A\, h$)
- In the $\mathcal{NMSSM}$, 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 boson leads to exciting phenomenology related to both Higgs hunting and dark matter annihilations

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

  - This allows to accommodate *lightest CP-even Higgs mass* $m_h \sim 95 - 105$ GeV
  - Such a light h boson does not require large stop mass

  $\Rightarrow$ This helps to ameliorate the **SUSY fine-tuning problem**

  - m_h (~ 98 GeV) could explain the slight excess of events as reported by the LEP2

Light A_1 : Blessings for light DM

- Lightest neutralino (LSP) $\Rightarrow$ neutral, massive having only weak interactions $\Rightarrow$ ideal candidate for DM
- DAMA.. CoGeNT..$\Rightarrow$ reported events in excess of the expected background $\Rightarrow$ compatible with $m_{DM} \sim 5 - 12$ GeV

Light DM ~ 10 GeV is favoured !

- WMAP constraint is satisfied via CP-odd Higgs (A_1) exchange $\Rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to A_1^* \to f\bar{f}$

In *MSSM*, $m_{\chi_1^0} \lesssim 20$ GeV is practically ruled out *since A boson cannot be too light*

Ref: D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 81 (2010) 117701

But NMSSM can ! thanks to lightness of A_1

A_1 : How it couples with matter

- 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

-

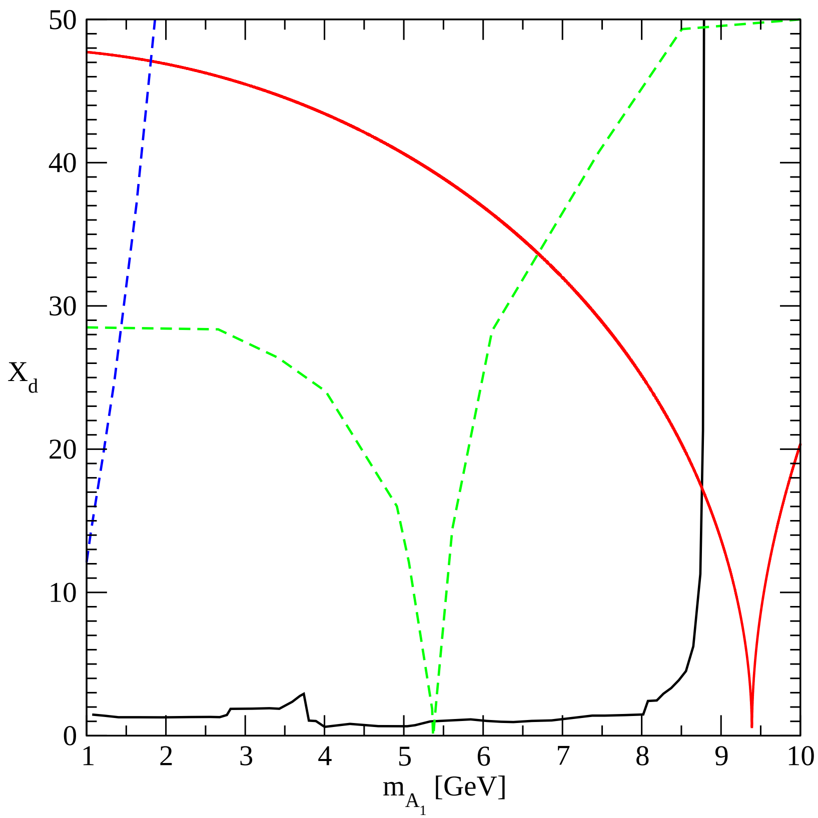
$$\mathcal{L}_{Af\bar{f}} \equiv C_{Af\bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f}\gamma_5 f A\,,$$

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

- 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 decays



Ref: Florian Domingo, Ulrich Ellwanger, Esteban Fullana, Cyril Hugonie, Miguel-Angel Sanchis-Lozano : JHEP 0901:061,2009

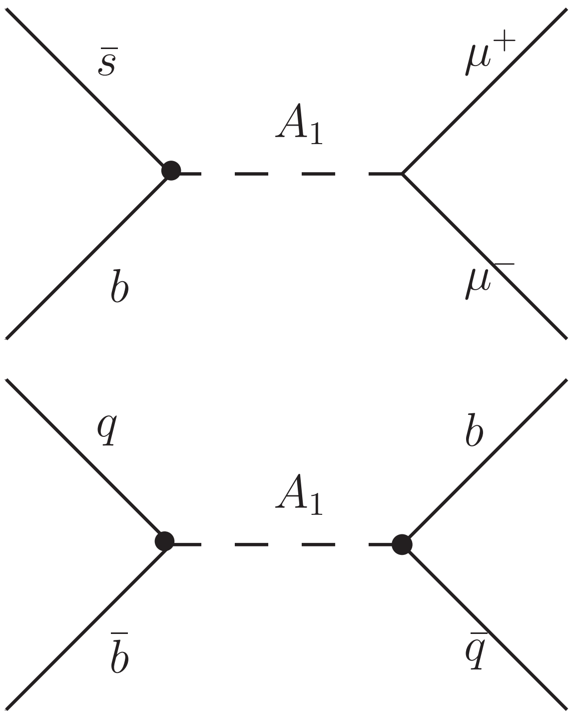
- Radiative Upsilon decays ($\Upsilon(ns) \equiv b\bar{b}$ vector-like bound state with $m_\Upsilon \geq 9.46$ GeV) i.e. $\Upsilon \to \gamma + X$ searched in B-factories like BaBar, CLEO..

- $\Upsilon \to \gamma + A_1$ followed by $A_1 \to \tau^+\tau^-$, $\mu^+\mu^- \Rightarrow$ visible if A_1 is quite light ($A_1 \leq 10$ GeV) $\Rightarrow$ put bounds on m_{A_1} and in particular on X_d

For $m_{A_1} > 10$ GeV $\Rightarrow$ Strong bounds from B physics and accelerator results

Light A_1 : Constraints from B physics

- List of dominant constraints :
  - $Br(b \to s\gamma)$
  - $\Delta M_s, \Delta M_d \ (\equiv m_{\bar{B}_{s,d}} - m_{B_{s,d}})$
  - $Br(B_s \to \mu^+\mu^-)$
  - $Br(B^+ \to \tau^+\nu_\tau)$



- A_1 in s channel dominantly contributes to the process like $\Delta M_s, \Delta M_d$, and $Br(B_s \to \mu^+\mu^-)$ via flavor changing vertices $b - s(d) - A_1$
  $\Rightarrow$ *via* so-called penguin diagrams

- Other constraints are more dependent on $m_{H^\pm}$

- 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

Outline :

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	×	×	✓	✓
$e^+e^- \to b\bar{b}\tau^+\tau^-$	×	×	×	✓

We ask the following question: Is it possible that a light A_1 can avoid elimination

We remind that all constraints depend on : $A_1 \to f\bar{f} \Rightarrow \underline{m_{A_1}\ \&\ X_d}$

We recall that Neutrinos are massless in the $NMSSM$

We propose an extension of the $NMSSM$ with two additional gauge singlets carrying lepton numbers :

- **Provides a substantial invisible decay route for A_1 &**
- **Generates the right size of neutrino mass through lepton number violating interactions**

we examine the connection between neutrino masses and the pseudoscalar A_1

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

- Previous studies are for neutrino masses in the $NMSSM$:
  • R-parity violating interactions in the $NMSSM$ superpotential
  $\Rightarrow$ not compatible with DM motivation

  • Adding gauge-singlet neutrino superfields N_i to the $NMSSM$ field content
  $\Rightarrow$ $M_{N_i} \sim O(\text{TeV})$ (via SN_iN_i) but Yukawa coupling $f^\nu \sim 10^{-6}$

- We implement the 'inverse seesaw' mechanism for *generating neutrino masses*
  • Singlet neutrinos can be *very light (few GeV)*
  • The neutrino Yukawa couplings $(f^\nu \sim O(1))$
  • Can enhance *lepton flavor violating processes*

- We will see *how this seesaw mechanism* can influence the *known existing decay pattern* of the A_1 boson

Inverse seesaw in the NMSSM

- Superpotential :

$$W = W_{\text{NMSSM}} + W'$$
$$W' = f^{\nu}_{ij} H_u L_i N_j + (\lambda_N)_i S N_i X_i + \frac{(\lambda_X)_i}{2} S X_i X_i$$

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

• $(\lambda_N)_i S N_i X_i$ is lepton number conserving term

• $\frac{(\lambda_X)_i}{2} S X_i X_i$ provides lepton number violation

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

• Lepton number conserving mass terms

(i)$M_{Ni} \Psi_{Ni} \Psi_{Xi}$ with $M_{Ni} \equiv (\lambda_N)_i v_S$ and

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

• Dynamically generated lepton number violating Majorana mass term $\mu_{Xi} \Psi_{Xi} \Psi_{Xi}$ with $(\mu_X)_i = (\lambda_X)_i v_S / 2$

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
  - $A_1 \to \Psi_N \Psi_X$ and $\Psi_X \Psi_X$: Depend on the $\sin\theta_A$ component of A_1
- Consequently, the invisible branching ratios (normalized them with the visible modes)

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

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

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

(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 branching ratio 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 have the two-body decay modes available

• Thus for the two study points, 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
Br $(A_1 \to \Psi_X \Psi_X)$	0	0	0	0

- 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
- Our results show that, in both cases, A_1 has significant branching ratios into the invisible modes thus relaxing the known constraints that would arise 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

- Scenarios with very light pseudoscalars in $NMSSM$ leads to attractive phenomenology related to both Higgs hunting and dark matter annihilations
- However, these scenarios are constrained due to experimental bounds associated with the decays of a light A_1 into a pairs of SM fermions
- Our primary goal was to rescue the scenarios with light A_1 bosons while at the same time providing an explanation for the smallness of neutrino masses
- We augment the $NMSSM$ Superpotential with two additional singlet neutrinos (carrying opposite lepton number) to meet our twin purpose
- Our results show that the invisible channels of light A_1 can have substantial branching fractions, thus suppressing the visible modes to a large extent
- This in turn weakens the existing constraints on the A_1 mass and on its couplings namely $\mathrm{X_d}$ to a large extent

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 $h \rightarrow A_1 A_1 \rightarrow 4\tau \Rightarrow$ constrainted 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

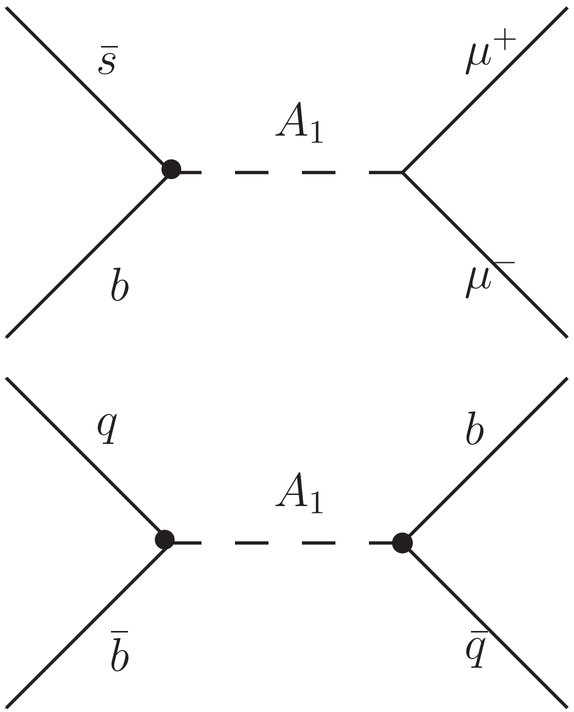
- The mass difference $Upsilon(1S) - \eta_b(1S) \Rightarrow$ hyperfine splitting ($E^{EXP}_{hfs}(1S)$)

- $E^{EXP}_{hfs}(1S) \sim 70$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

$Br(B_s \to \mu^+\mu^-)$ and $\Delta M_{s,d}$: Role of A_1



- 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
- $Br(B_s \to \mu^+\mu^-) \propto m_{A_1}^{-4} \cos\theta_A^4 \tan^6\beta$
- 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