Radiative Upsilon Decays and a Light Pseudoscalar Higgs in the NMSSM[1]

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Super B Workshop - Orsay 2009

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January, 16th 2009

[1] F. Domingo, U. Ellwanger, E. Fullana, C. Hugonie and M. A. Sanchis-Lozano, JHEP **0901** (2009) 061, arXiv:0810.4736 [hep-ph].

Introduction: *Why consider a light CP-odd scalar in Υ Physics? Why in the NMSSM?*

Recent experimental data in the Υ sector:

- **CLEO**: bounds on $\Upsilon \to \gamma(A_1 \to l^+ l^-)$ *[arXiv:0807.1427]*
  $\Rightarrow$ constraints m_{A_1}/coupling to $b\bar{b}$;
- **BABAR**: discovery of the $\eta_b(1s)$ $b\bar{b}$ hadronic state *[arXiv:0807.1086]*... or perhaps?
  $\longrightarrow$ Possible Mixing of a light CP-odd scalar A_1 with the η_b: could explain why the observed mass is lower than what most QCD-based models for the hyperfine splitting $\Upsilon(1s) - \eta_b(1s)$ predict?

A light CP-odd Higgs A_1 in the NMSSM:

- $m_{A_1} \leq 10.5$ GeV: theoretical and phenomenologically realistic.
- Even a Favoured scenario: could explain the 2.3σ excess in $e^+e^- \to Z + 2b$ for $M_{2b} \sim 100$ GeV at LEP *[Dermisek,Gunion 2006]*:
  $\longrightarrow$ Possible signal for a NMSSM CP-even Higgs h_1, $m_{h_1} \sim 100$ GeV, decaying mostly in $A_1 A_1$ (then, $A_1 \to \tau\tau$).

A light CP-odd A_1 in the NMSSM…
…With strong coupling to $b\bar{b}$!

NMSSM

- MSSM + Gauge-Singlet Superfield $\hat{S} = (S, \tilde{s})$
- Scale invariant Superpotential: $\lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 + \ldots$
- Solution to the "μ-problem": $\langle S \rangle = s \neq 0 \Rightarrow \mu_{eff} = \lambda s$

CP-odd Higgs states (once Goldstone Boson removed)

$$\begin{pmatrix} \frac{2\lambda s(A_\lambda + \kappa s)}{\sin 2\beta} & \lambda v(A_\lambda - 2\kappa s) \\ \lambda v(A_\lambda - 2\kappa s) & -3\kappa s A_\kappa + \frac{\lambda v^2 \sin 2\beta}{2s}(A_\lambda + 4\kappa s) \end{pmatrix} \begin{matrix} \leftarrow \text{Doublet} \\ \leftarrow \text{Singlet} \end{matrix}$$

- Light mass state: $A_1 = \cos\theta_A \, A_{MSSM} + \sin\theta_A \, A_S$
- Coupling to b quarks $\propto \frac{m_b}{v} X_d$, $X_d \equiv \cos\theta_A \tan\beta$

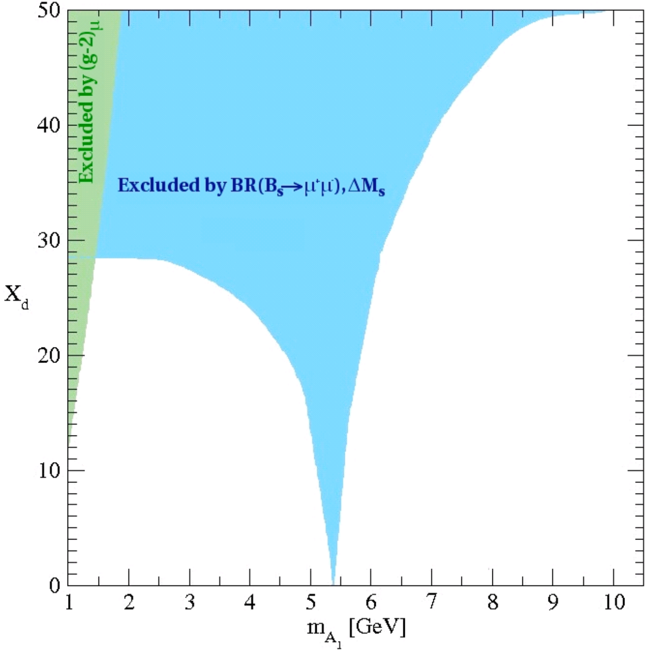
$$\Rightarrow m_{A_1} \leq 2m_B \sim 10.5\ GeV + Large\ X_d \sim 20\ achievable$$

$\longrightarrow$ **Leads to important effects in the Υ sector**

Previous Phenomenological Constraints on a light NMSSM Pseudoscalar

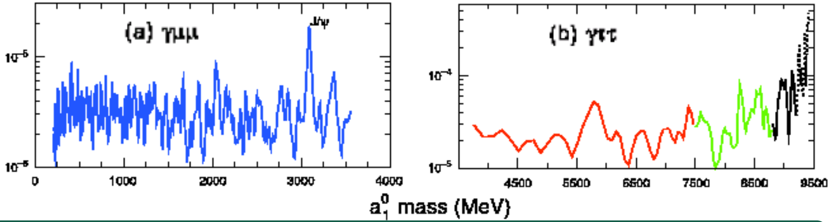
Investigation of the plane (m_{A_1}, X_d)

- Scan on a wide range of the parameter space of the NMSSM. (NMSSMTools Package)
- LEP Constraints.
- Constraints from B-physics:
  $BR(B \to X_s\gamma)$, $BR(B^+ \to \tau^+\nu_\tau)$, $BR(B_s \to \mu^+\mu^-)$, ΔM_s
- Anomalous Magnetic Moment of the Muon.


Excluded by (g-2)μ
Excluded by BR(Bs→μ+μ-), ΔMs
X_d
m_A1 [GeV]
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10

CLEO Bounds on Radiative Υ Decays

90% U.L. on $B(\Upsilon \to \gamma a_1^0) B(a_1^0 \to ll)$ *[arXiv:0807.1427]*

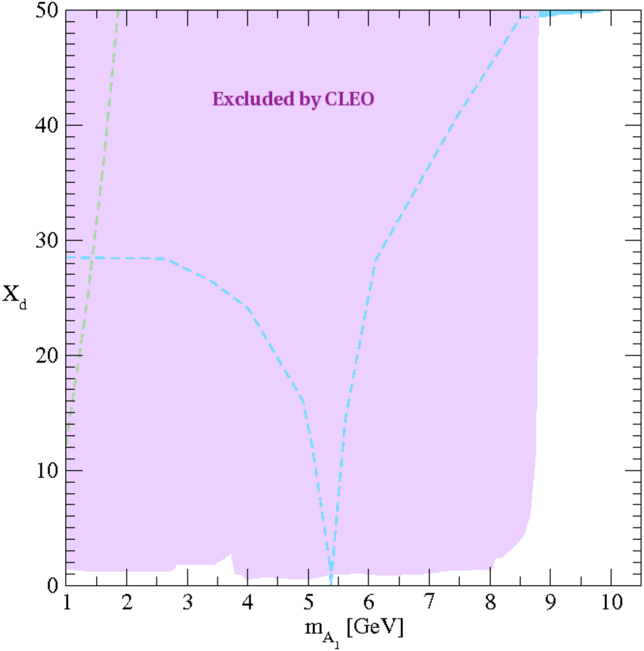


$BR(\Upsilon(1s) \to \gamma A_1)$: theoretical analysis

- **Wilczek Formula** (Wilczek 1978; Haber *et al.* 1987):

$$\frac{BR\left(\Upsilon(1S) \to \gamma A_1\right)}{BR\left(\Upsilon(1S) \to \mu^+\mu^-\right)} = \frac{G_F m_b^2 X_d^2}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A_1}^2}{m_{\Upsilon(1S)}^2}\right) \times F$$

- Correction factor F: from Bound states, QCD and relativistic corrections… *Poorly controled!*
  $\Rightarrow$ Conservative approach: we keep F even if $F \to 0$ for $m_{A_1} \to 8.8$ GeV.
- No bound for $m_{A_1} \geq 8.8$ GeV… Mixing A_1/η_b significant?


Excluded by CLEO
X_d
m_A1 [GeV]
0
10
20
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40
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5
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7
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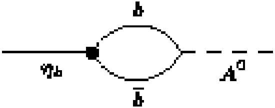
9
10

Mixing of A_1 with a η_b resonance



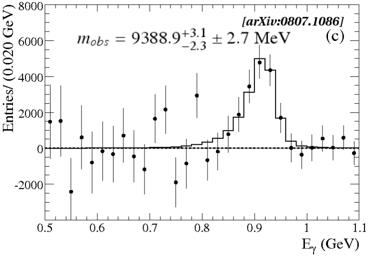
- Effective Mass Matrix *([Drees, Hikasa 1990]; [Fullana, Sanchis 2007])*

$$\mathcal{M}^2 = \begin{pmatrix} m_{A_{10}}^2 - i m_{A_{10}}\Gamma_{A_{10}} & \delta m^2 \\ \delta m^2 & m_{\eta_{b0}}^2 - i m_{\eta_{b0}}\Gamma_{\eta_{b0}} \end{pmatrix} \begin{matrix} \leftarrow A_{10} \\ \leftarrow \eta_{b0} \end{matrix} \quad , \quad \delta m^2 = \left(\frac{3 m_{\eta_b}^3}{8\pi v^2}\right)^{1/2} |R_{\eta_b}(0)| \times X_d$$

- Physical states:

$$\begin{cases} A_1 &= \cos\alpha\, A_{10} + \sin\alpha\, \eta_{b0} \\ \eta_b &= \cos\alpha\, \eta_{b0} - \sin\alpha\, A_{10} \end{cases}$$

Observed Mass State at BABAR



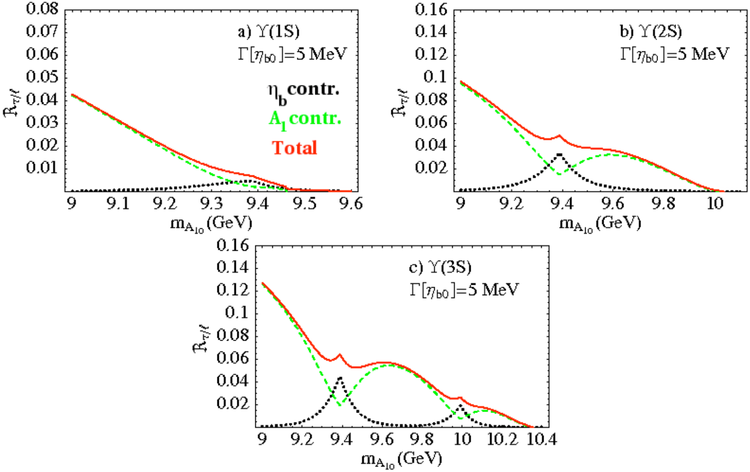
- Observed mass lower than what was predicted in most QCD-based models for the hyperfine splitting *→effect of a A_1?*
- **Bounds** from such models apply to the **diagonal entry** $m_{\eta_{b0}}$.
- **Observed mass** = **eigenvalue** of the 2×2 mass matrix:

$$m^2_{obs} \simeq \frac{1}{2}\left[m^2_{A_{10}} + m^2_{\eta_{b0}} \pm \sqrt{(m^2_{A_{10}} - m^2_{\eta_{b0}})^2 + 4\,\delta m^4}\right]$$

Lepton Universality: A possible Signal for a light A_1?

	$\mathcal{B}(e^+e^-)$	$\mathcal{B}(\mu^+\mu^-)$	$\mathcal{B}(\tau^+\tau^-)$	$R_{\tau/e}(nS)$	$R_{\tau/\mu}(nS)$
$\Upsilon(1S)$	2.38 ± 0.11	2.48 ± 0.05	2.60 ± 0.10	0.09 ± 0.06	0.05 ± 0.04
$\Upsilon(2S)$	1.91 ± 0.16	1.93 ± 0.17	2.00 ± 0.21	0.05 ± 0.14	0.04 ± 0.06
$\Upsilon(3S)$	2.18 ± 0.21	2.18 ± 0.21	2.29 ± 0.30	0.05 ± 0.16	0.05 ± 0.16

- Inclusive leptonic decays of Υ: photon undetected
  $\Rightarrow$ possible excess in $\Upsilon \to \tau\tau$ due to $\Upsilon \to \gamma A_1$;
- Experimental status $\to$ a general trend: $\sim 1\sigma$ excess in $\Upsilon \to \tau\tau$?
- Correction factor F? Optimistic estimate $F \sim 1/2\ldots$
- Expecting improved data from (Super-)B factories!

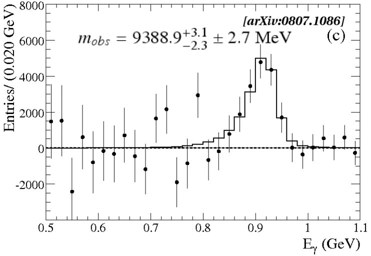


$$X_d = 12 \;\;,\;\; m_{\eta_{b0}(1S,2S,3S)} = 9.389, 9.997, 10.32 \text{ GeV} \;\;,\;\; \Gamma_{\eta_{b0}(1S,2S,3S)} = 5 \text{ MeV}$$

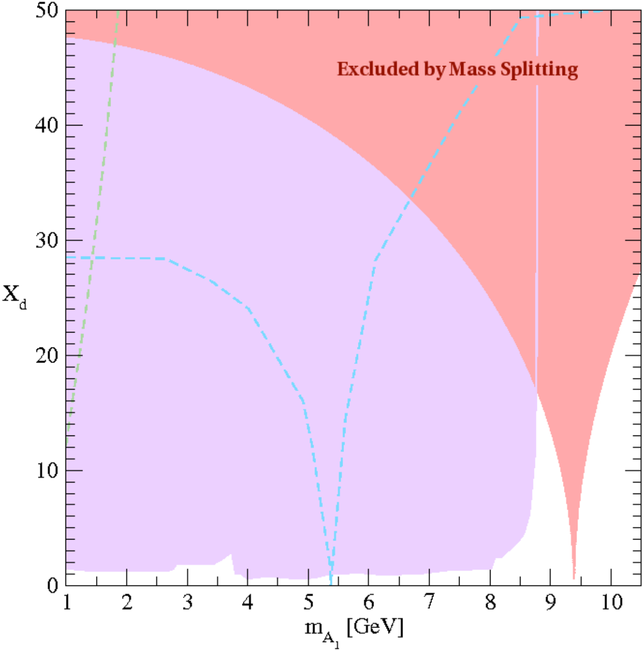
Conclusions:

- Light CP-odd Higgs in the NMSSM: well-motivated scenario (2.3σ excess at LEP)! $\Rightarrow$**Test it at B factories**.
- Strong constraints from CLEO in $\Upsilon \to \gamma A_1$: focus on the region where $m_{A_1} \sim m_{\eta_b}$.
- $m_{A_1} \sim m_{\eta_b}$: Mixing A_1/η_b relevant.
  $\Rightarrow$ Possible explanation for the "light" mass observed at BABAR?
- For future searches of the light A_1, the Breaking of Lepton Universality in inclusive $\Upsilon \to \tau\tau$ could be an interesting signal.

Observed Mass State at BABAR



- Observed mass lower than what was predicted by hyperfine splitting models → *effect of a A_1?*
- Properties of the 2×2-mass matrix:
  $X_d \simeq (125\text{GeV}^{-1})\sqrt{(m_{A_{10}} - m_{obs})(m_{\eta_{b0}} - m_{obs})}$
- Conservative Bounds on $m_{\eta_{b0}} - m_{obs}$ from hyp.-split. models:
  $-30\,\text{MeV} \leq m_{\eta_{b0}} - m_{obs} \leq 40\,\text{MeV} \;\Rightarrow\; X_d \leq \begin{cases} (22\ \text{GeV}^{-1/2})\sqrt{m_{obs} - m_{A_{10}}} & , m_{A_{10}} \leq m_{obs} \\ (25\ \text{GeV}^{-1/2})\sqrt{m_{A_{10}} - m_{obs}} & , m_{A_{10}} \geq m_{obs} \end{cases}$


Excluded by Mass Splitting
50
40
30
20
10
0
X_d
1
2
3
4
5
6
7
8
9
10
m_A1 [GeV]