Bottomonium Physics and a light CP-odd Higgs in the NMSSM[1]

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

[*F. Domingo, U. Ellwanger and M. A. Sanchis-Lozano*, Phys. Rev. Lett. **103** (2009) 101802 arXiv:0907.0348 [hep-ph].]

A Light CP-odd Higgs in the NMSSM?

Next-to-Minimal SuperSymmetric Model (NMSSM)

- MSSM + Gauge-Singlet superfield $\hat{S} = (S, \tilde{s})$ *[Fayet (1975)]*
- Scale invariant Superpotential: $W = \frac{\kappa}{3}\hat{S}^3 + \lambda \hat{S}\hat{H}_u.\hat{H}_d + \ldots$
- Solution to the "μ-problem" of the MSSM

CP-odd Higgs sector in the NMSSM

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

- Light mass state: $A_1 = \cos\theta_A \, A_{MSSM} + \sin\theta_A \, A_S$
- Vanishing coupling to gauge bosons: Few Direct Constraints…
- …Only indirect constraints via relations in the Higgs sector: Additional freedom due to the Singlet component!

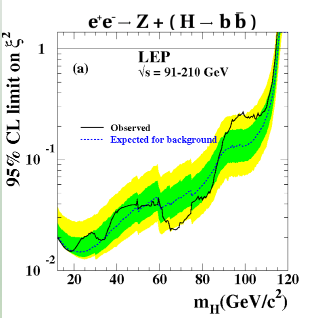
CONCLUSION: Masses below the $B - \bar{B}$ threshold (10.5 GeV) can be achieved!

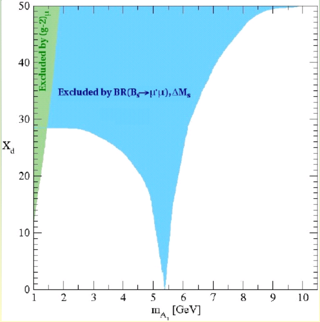
Advantages of the light A_1 scenario

$\longrightarrow$ Allows for **unconventionnal decays** of the lightest CP-even Higgs: $h_1 \to A_1 A_1$ $\to$ hard to see (since $A_1 \to b\bar{b}$ kinematically forbidden).

- **Alleviates the Little Fine-Tuning Problem**: $m_{h_1} \sim 90$ GeV still consistent with LEP;
- **Interpretation of the** 2.3σ **excess** in (LEP) $e^+e^- \to Z + (H \to b\bar{b})$ *[Dermisek, Gunion 2006]*: $m_{h_1} \sim 100$ GeV but reduced $BR(h_1 \to b\bar{b})$.

$\Longrightarrow$ **A Realistic (Favoured) NMSSM scenario**.





Probing with the fermionic sector?

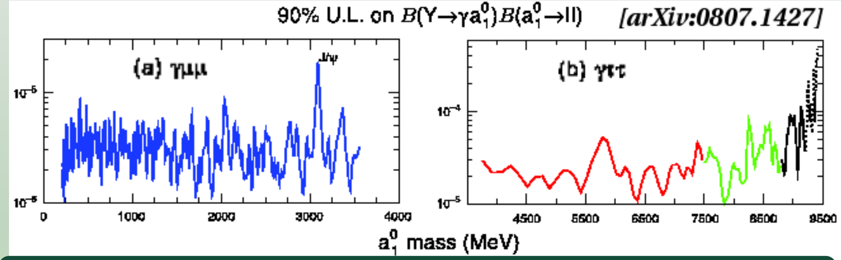
$\longrightarrow$ Scenario hard to observe at LHC: Alternative probe?

- Coupling to b-quarks (leptons) $\propto \frac{m_b}{V} X_d$: $X_d \equiv \cos\theta_A \tan\beta$;
- Low energy constraints (B-physics,$(g-2)_\mu$) can be circumvented.

$\Longrightarrow$ **Coupling to** b**-quarks/leptons** possibly **enhanced**.

Test in the bottomonium sector?

CLEO Bounds on Radiative Υ Decays

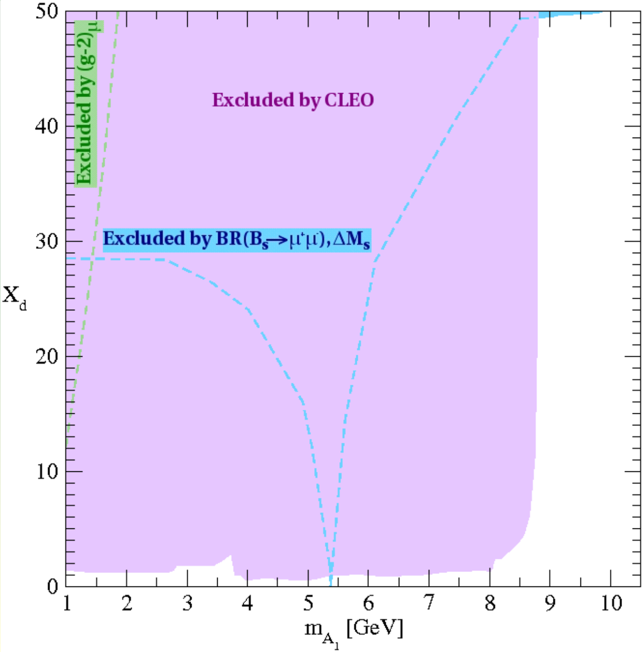


$BR(\Upsilon(1s) \to \gamma A_1)$: theoretical analysis

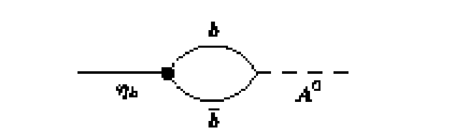
- **Wilczek Formula** (Wilczek 1978; Haber *et al.* 1987):

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

- Correction factor F: from Bound states, QCD and relativistic corrections... *Poorly controlled!* (For $m_{A_1} > 8$ GeV)
  $\Rightarrow$ 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 (g-2)μ
Excluded by CLEO
Excluded by BR(Bs→μ+μ-), ΔMs
Xd
mA1 [GeV]
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10

Mixing of A_1 with a η_b resonance



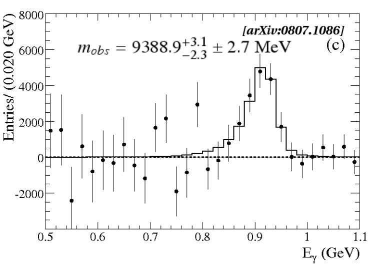
- Effective Mass Matrix *([Drees, Hikasa 1990]; [Fullana, Sanchis-Lozano 2007])*

$$\mathcal{M}^2 = \begin{pmatrix} m^2_{A10} - i m_{A10}\Gamma_{A10} & \delta m^2 \\ \delta m^2 & m^2_{\eta b0} - i m_{\eta b0}\Gamma_{\eta b0} \end{pmatrix} \begin{matrix} \leftarrow A_{10} \\ \leftarrow \eta_{b0} \end{matrix} \quad , \quad \delta m^2 = \left(\frac{3 m^3_{\eta_b}}{8\pi v^2}\right)^{1/2} |R_{\eta_b}(0)| \times X_d$$

- Physical states:

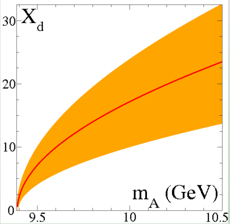
$$\begin{cases} A_1 & = & \cos\alpha \, A_{10} & + & \sin\alpha \, \eta_{b0} \\ \eta_b & = & \cos\alpha \, \eta_{b0} & - & \sin\alpha \, A_{10} \end{cases}$$

Observed Mass State at BABAR

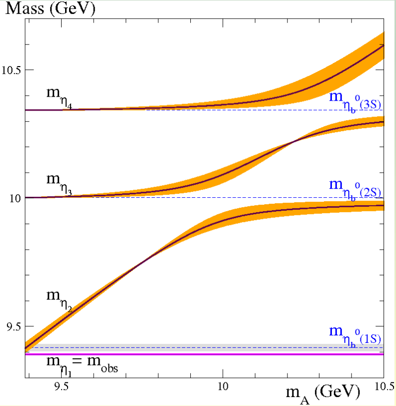


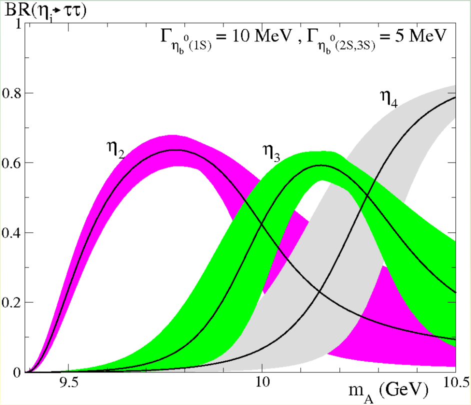
- Observed mass lower than what predicted in most QCD-based models for the hyperfine splitting (*[Recksiegel,Sumino (2004)], [Kniehl, Penin,Pineda,Smirnov,Steinhauser (2004)], [Penin (2009)]*) *→effect of a A_1?*
- **Predictions** of such models apply to the **diagonal entry** $m_{\eta_{b0}}$.
- **Observed mass** = **eigenvalue** of the 2×2 mass matrix:

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



- Assuming $m_{\text{Eigenstate}} = m_{obs}$ constrains $X_d = f(m_{A_1})$ ($+1\sigma$ error bars).
- Effect of the heavier $\eta_b(2,3S)$ taken into account;
- Possible perturbations over the whole η_b spectrum;
- Branching ratio of the heavier states into $\tau^+\tau^-$ possibly significant.

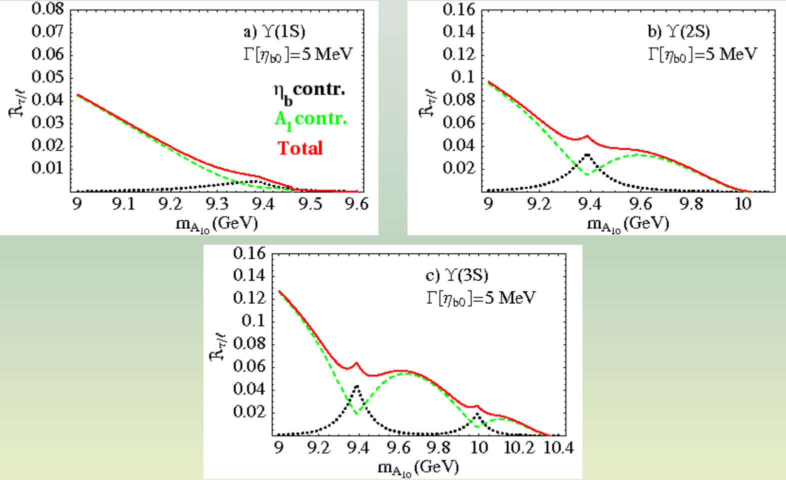




Lepton Universality: A possible Signal for a light A_1?

	$\mathcal{B}(e^+e^-)$	$\mathcal{B}(\mu^+\mu^-)$	$\mathcal{B}(\tau^+\tau^-)$	$R_{\tau/e}(nS)$	$R_{\tau/\mu}(nS)$
$\Upsilon(1S)$	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!



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

Conclusion

- 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.
  $\to$ Possible explanation for the "light" mass observed at BABAR?
  $\Rightarrow$ Consequences over the whole η_b spectrum...
- For future searches of the light A_1, the Breakdown of Lepton Universality in Inclusive $\Upsilon \to \tau\tau$ could be an interesting signal.