

Low-energy aspects of the Phenomenology of the NMSSM

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NMSSM and Low-energy aspects

NMSSM: remember U.Ellwanger's talk

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

What is new with respect to the MSSM?

- Additional neutralino state → singlino tends to decouple;
- Slightly displaced charged Higgs masses;
- Broader range in $\tan\beta$ ($\gtrsim 1.8$ GeV);
- Possibility of a **light CP-odd Higgs A_1** ($m_{A_1} \lesssim 2 m_B$);
- ...

NMSSM Light Pseudoscalar

CP-odd Higgs sector in the NMSSM

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

- 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!

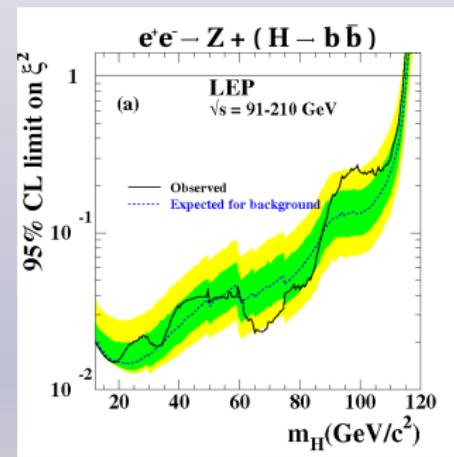
Advantages of the light A_1 scenario?

→ Allows for **unconventional decays** of the lightest CP-even Higgs: $h_1 \rightarrow A_1 A_1$ → hard to see (since $A_1 \rightarrow b\bar{b}$ 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)**
 $e^+ e^- \rightarrow Z + (H \rightarrow b\bar{b})$ [Dermisek, Gunion 2006]:
 $m_{h_1} \sim 100$ GeV but reduced $BR(h_1 \rightarrow b\bar{b})$.

BUT: Preliminary ALEPH constraints...

... Scenario still marginally consistent [Dermisek, Gunion 2010]?
+ *Other advantages at low energy!*



Significant Effects / Possible Probe in low energy observables?

→ Scenario hard to observe at LHC: Alternative probe?

- Coupling to b-quarks / leptons $\propto \frac{m_b}{V} X_d$: $X_d \equiv \cos \theta_A \tan \beta$;
⇒ **Coupling to b-quarks/leptons possibly enhanced.**
- **Therefore:** Possible effects in / constraints from
 - B -physics;
 - $(g - 2)_\mu$;
 - Bottomonium spectroscopy and decays.

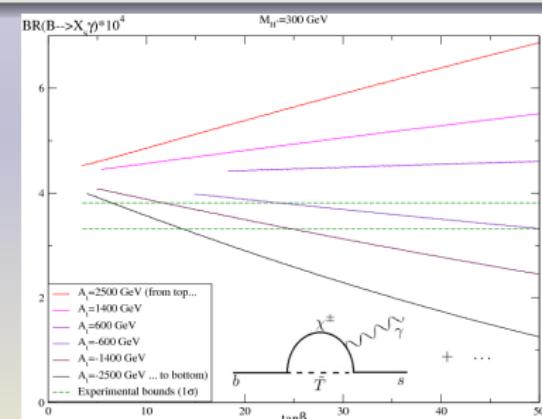
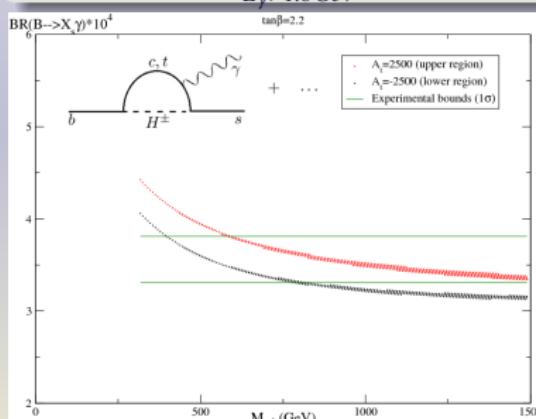
$BR(B \rightarrow X_s \gamma)$: Status and Contributions

Experiment and SM

$$BR(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}}^{\text{exp.}} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \cdot 10^{-4} \quad \text{Exp. World Average, 2005}$$

$$BR(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}}^{\text{NNLO}} = (3.15 \pm 0.23) \cdot 10^{-4} \quad \text{SM NNLO, [Misiak et al., 2006]}$$

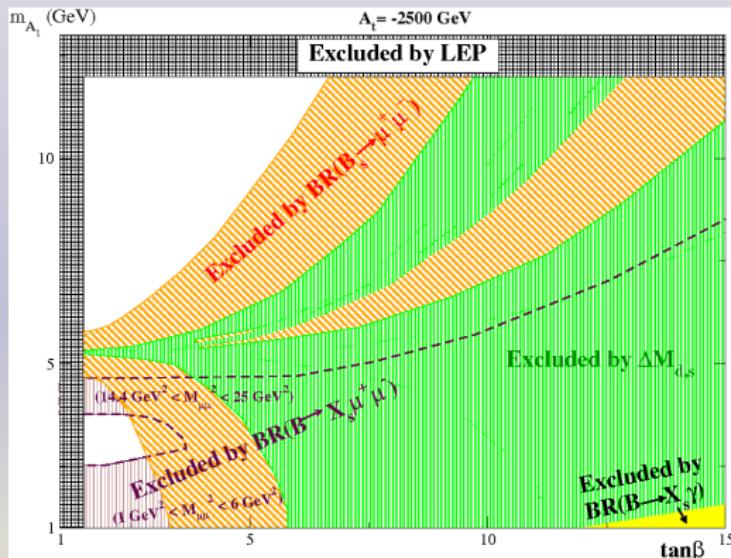
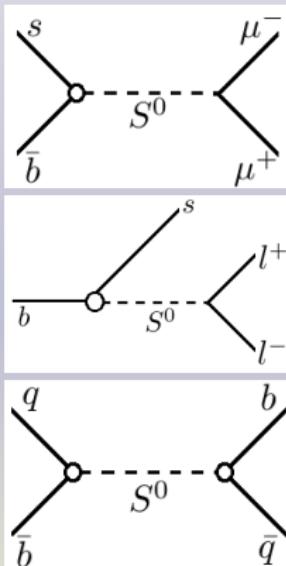
$$BR(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}}^{\text{NNLO}} = (2.98 \pm 0.26) \cdot 10^{-4} \quad \text{SM NNLO, [Becher, Neubert, 2006]}$$



Two main enhancing effects

- Few NMSSM specific effects.
- **Light Charged Higgs** lead to large (positive) contributions;
- **Large $\tan\beta$** enhance the SUSY contributions; sign depends on $\mu \cdot A_t$.

Light CP-odd Higgs and Penguin diagrams

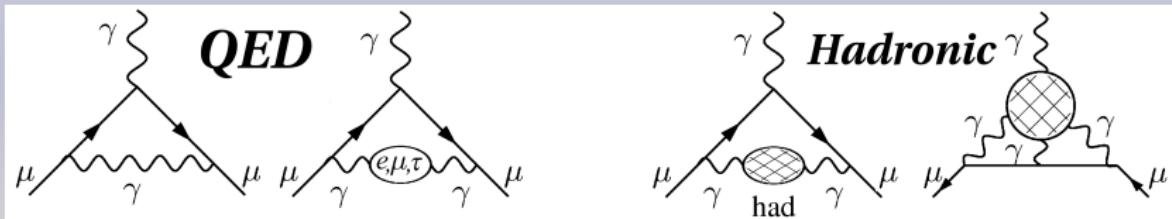


- $BR(\bar{B}_s \rightarrow \mu^+ \mu^-)$ particularly constraining;
- "Pole" regions are always excluded;
- Effect enhanced for large $\tan \beta$;
- For small A_t , LEP constraints restrict the large $\tan \beta$ region.

Muon Anomalous Magnetic Moment $a_\mu = (G - 2)_\mu / 2$: Standard Model Computation

Pure QED: 4-loop+estimated 5-loop [Laporta, Remiddi (1996); Kinoshita *et al.* (2007)]

$$a_\mu^{QED} = 11\,658\,471.8113(162) \times 10^{-10}$$

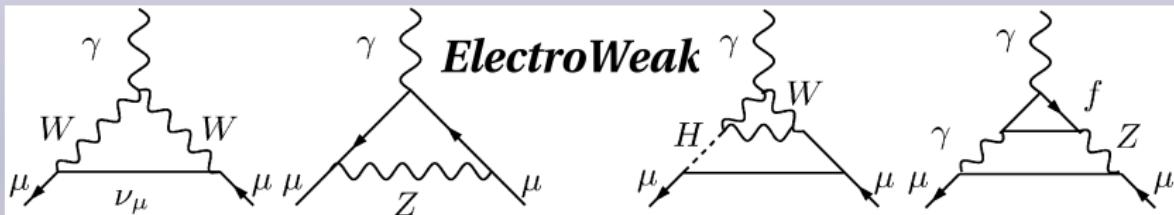


Hadronic contributions: e^+e^- data [Davier *et al.* (2009)]

- Leading Order: $a_\mu^{HLO}(e^+e^-) = (690.2 \pm 5.2) \times 10^{-10}$;
 $a_\mu^{HLO}(\tau) = (705.3 \pm 4.5) \times 10^{-10}$;
 $a_\mu^{HLO}(e^+e^- ISR) = (699.9 \pm 4.5) \times 10^{-10}$ (BABAR)
- Next to Leading Order: $a_\mu^{HNLO} = (-10.03 \pm 0.22) \times 10^{-10}$;
- Light-by-Light Scattering: $a_\mu^{LBL} = (11.6 \pm 4.0) \times 10^{-10}$ [Nyffeler (2010)]

Electroweak: [Czarnecki *et al.* (2003,2006)]

$$a_\mu^{EW} = (15.4 \pm 0.2) \times 10^{-10}$$



Experimental Measurement: E821 experiment at Brookhaven National Laboratory [Bennett *et al.* (2006); Hoecker, Marciano (2008)]

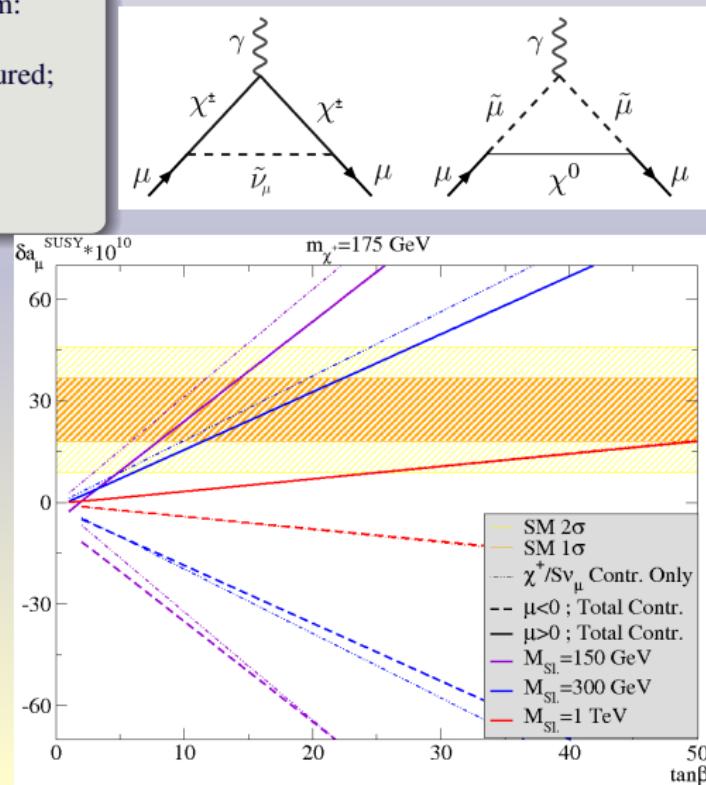
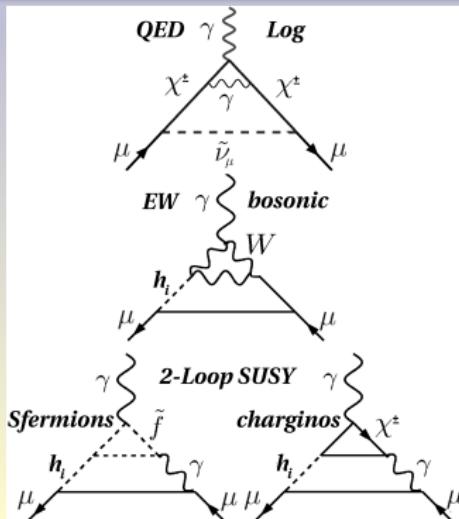
$$a_\mu^{EXP} = 11\,659\,208.9(5.4)(3.3) \times 10^{-10}$$

$$\Rightarrow a_\mu^{EXP} - a_\mu^{SM} = \begin{cases} (15.7 \pm 8.2) \times 10^{-10}, & (\tau \text{ data}) \\ (31.2 \pm 8.1) \times 10^{-10}, & (e^+ e^- \text{ data}) \\ (21.1 \pm 8.1) \times 10^{-10}, & (e^+ e^- \text{ ISR data}) \end{cases} \sim 2 \text{ to } 4\sigma!$$

MSSM-like contributions

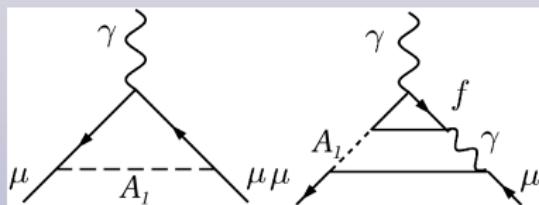
[Martin, Wells (2001); Arhrib, Baek (2002); Heinemeyer et al. (2004); Stöckinger (2006)]

- **Leading** 1-loop Chargino/Sneutrino diagram:
 - Linear dependance on $\tan\beta$;
 - Same sign as the parameter μ : $\mu > 0$ favoured;
 - Light chargino/Sneutrino required.
- Possibly significant bino/smilon loop;
- Leading 2-loop effects taken into account.



Specific NMSSM Contributions: Light Pseudoscalar

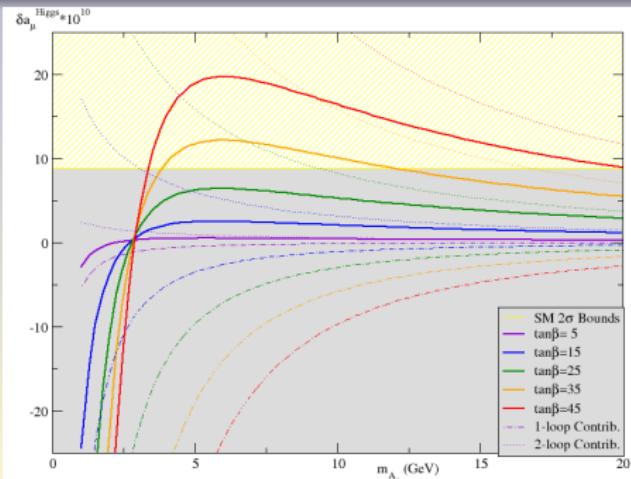
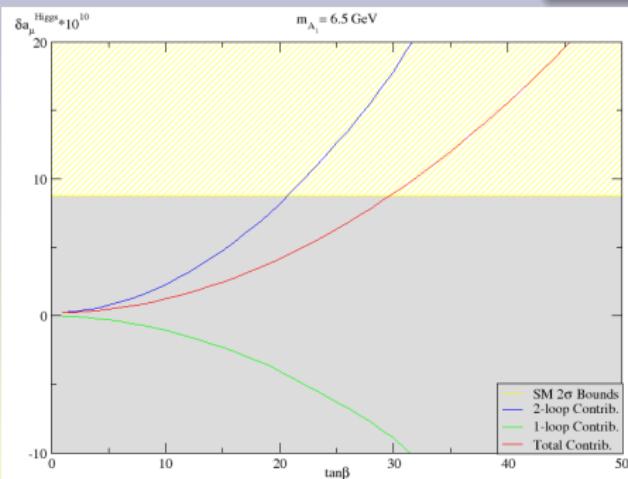
[Krawczyk (2002), Gunion et al. (2006)]



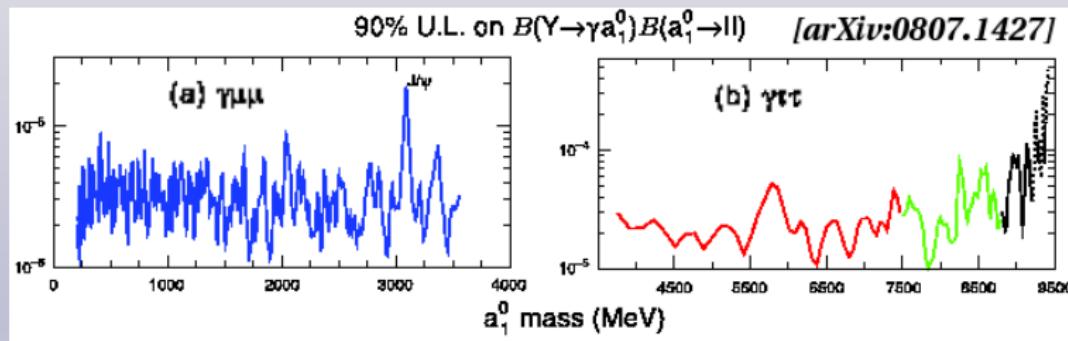
- Proportional to $\tan^2 \beta (X_d^2)$;
- 1-loop contribution negative / 2-loop contribution positive;
- When $m_{A_1} \geq 3 \text{ GeV}$, 2-loop contribution dominates.

Can reach the 2σ level by itself.

⇒ Alleviates the requirements on the slepton/chargino masses.



Bounds from Radiative Υ Decays



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

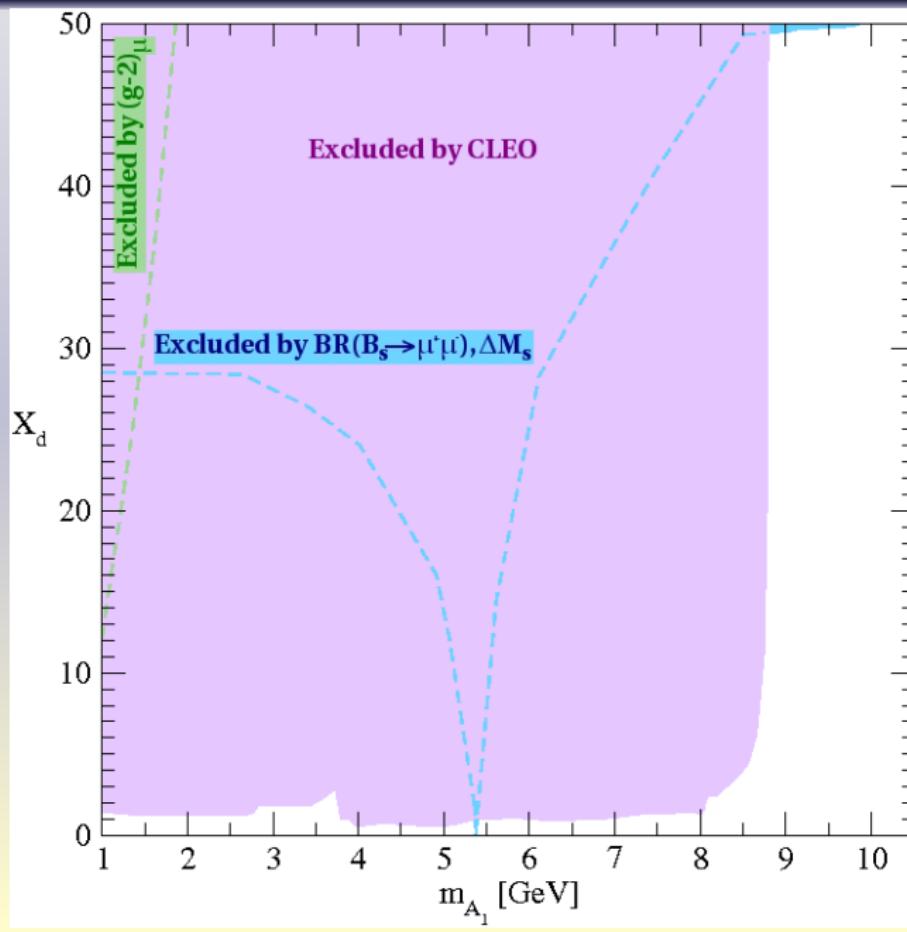
- Wilczek Formula (Wilczek 1978; Haber *et al.* 1987):

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

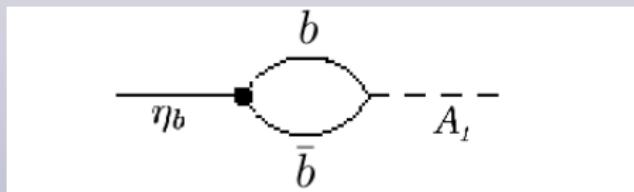
- Correction factor F : from Bound states, QCD and relativistic corrections... *Poorly controlled!* (For $m_{A_1} > 8$ GeV)

⇒ **Conservative approach:** we keep F even if $F \rightarrow 0$ for $m_{A_1} \rightarrow 8.8$ GeV.

- No bound for $m_{A_1} \geq 8.8$ GeV... **Mixing A_1/η_b significant?**



Mixing of A_1 with a η_b resonance



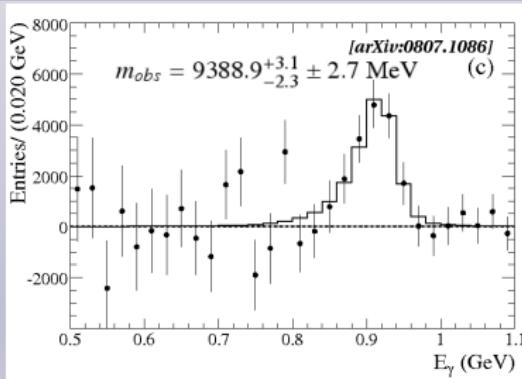
- Effective Mass Matrix ([Drees, Hikasa 1990]; [Fullana, Sanchis-Lozano 2007])

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

- Physical states:

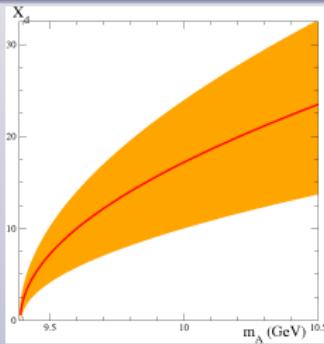
$$\begin{cases} A_1 &= \cos \alpha A_{10} + \sin \alpha \eta_{b0} \\ \eta_b &= \cos \alpha \eta_{b0} - \sin \alpha A_{10} \end{cases}$$

Observed Mass State at BABAR

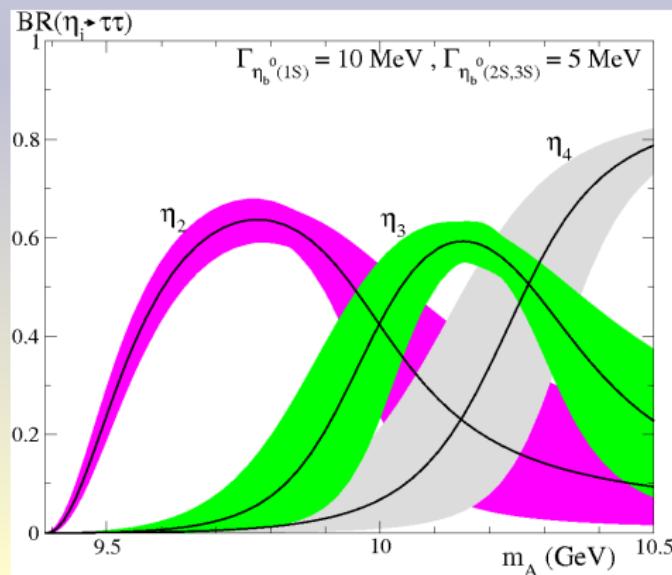
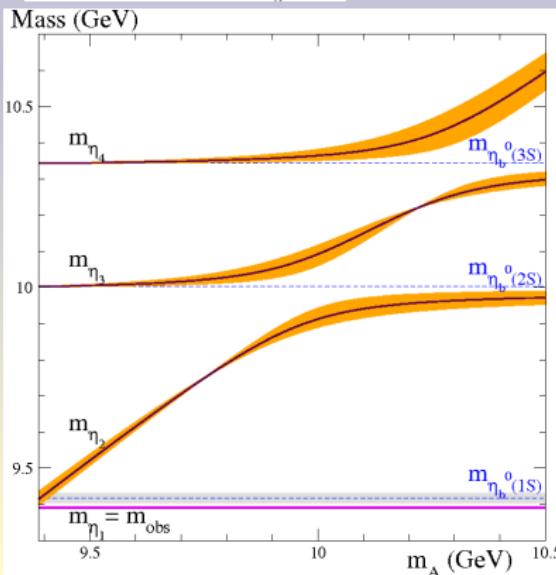


- Observed mass lower than what predicted in most QCD-based models for the hyperfine splitting ([\[Recksiegel,Sumino \(2004\)\]](#), [\[Kniehl, Penin,Pineda,Smirnov,Steinhauser \(2004\)\]](#), [\[Penin \(2009\)\]](#)) → *effect of a A_1 ?*
- **Predictions** of such models apply to the **diagonal entry**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

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



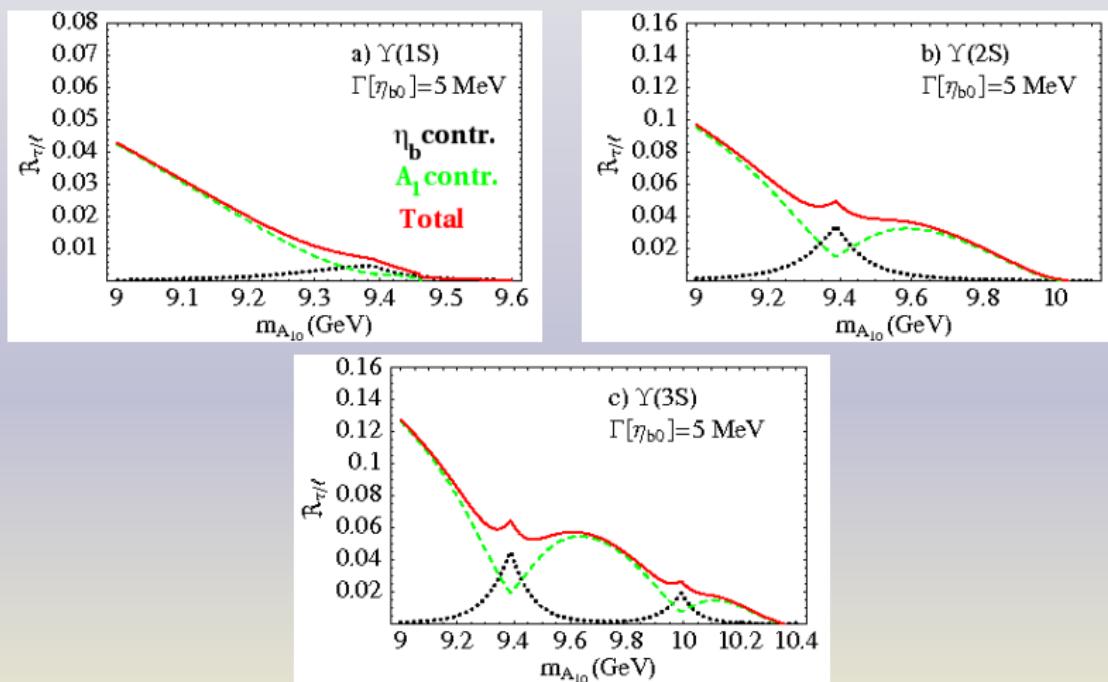
- Assuming $m_{\text{Eigenstate}} = m_{\text{obs}}$ constrains $X_d = f(m_{A_1})$ ($\pm 1\sigma$ error bars).
- Effect of the heavier $\eta_b(2, 3S)$ taken into account;
- Possible perturbations over the whole η_b spectrum;
- Branching ratio of the heavier states into $\tau^+\tau^-$ possibly significant.



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
⇒ possible excess in $\Upsilon \rightarrow \tau\tau$ due to $\Upsilon \rightarrow \gamma A_1$;
- Experimental status → a general trend: $\sim 1\sigma$ excess in $\Upsilon \rightarrow \tau\tau$?
- Correction factor F ? Optimistic estimate $F \sim 1/2\dots$
- Expecting improved data from (Super-)B factories!



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

[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].]

Conclusion

- The NMSSM is a well-motivated candidate for new-physics:
Several phenomenological improvements with respect to the MSSM.
- Low-energy observables: Comparable to the MSSM...
... Except in the presence of a light CP-odd scalar!
- Bottomonium Physics: An interesting probe for the light CP-odd Higgs scenario.