# *Effect of a light CP-odd Higgs boson on bottomonium spectroscopy and decays & the (light) dark matter quest*

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**SUSY 10**
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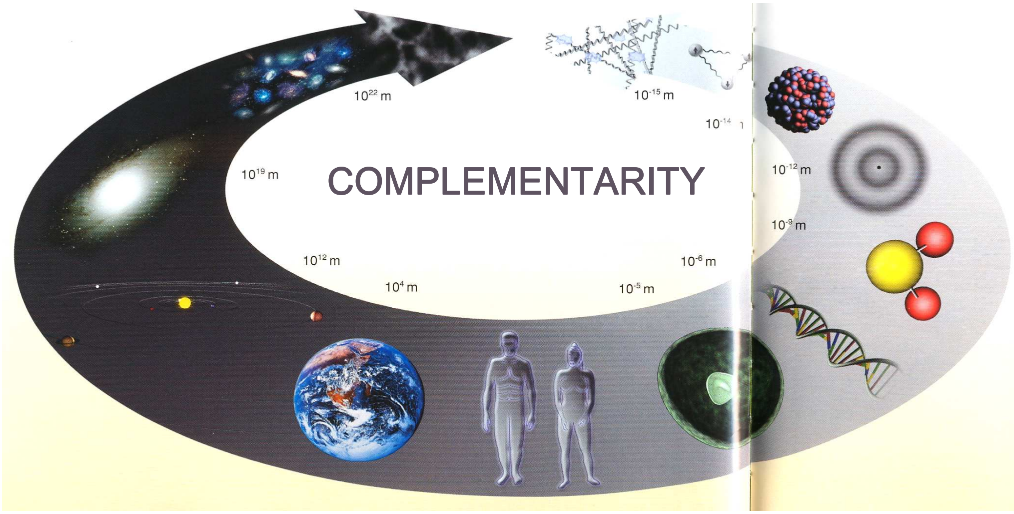


# Next-to-Minimal-Supersymmetric Standard Model (NMSSM)

*Things should be as simple as possible, but not simpler*

A. Einstein

Higgs sector

$$\hat{H}_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \quad \hat{S}$$

New gauge-singlet superfield

$$W = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \cdots$$

$$V_{soft} = \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c. + \cdots$$

Six "free" parameters vs three in the MSSM :

$\kappa \quad \lambda \quad A_\kappa \quad A_\lambda \quad \mu \ \tan\beta$

$$B_{eff} = A_\lambda + \kappa s$$

**Physical Higgs bosons: (seven)**

2 neutral CP-odd Higgs bosons ($A_{1,2}$)
3 neutral CP-even Higgs bosons ($H_{1,2,3}$)
2 charged Higgs bosons ($H^{\pm}$)

PQ symmetry or $U(1)_R$ slightly broken

↓

**light pseudoscalar Higgs**

Non-singlet component

Singlet component

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

$\tan\beta = v_u / v_d$

$A_1$ coupling to down type fermions $\propto X_d = \cos\theta_A \tan\beta$

Might be not too small for high tanβ

$A_\lambda$ = -200 GeV
$A_\kappa$ = -15 GeV
μ = 150 GeV
*tan* β= 40

$A_\lambda \sim - K \mu / \lambda$

$K - (4/3)\lambda = 0$

$0.1 \leq |\cos\theta_A| \leq 0.5$

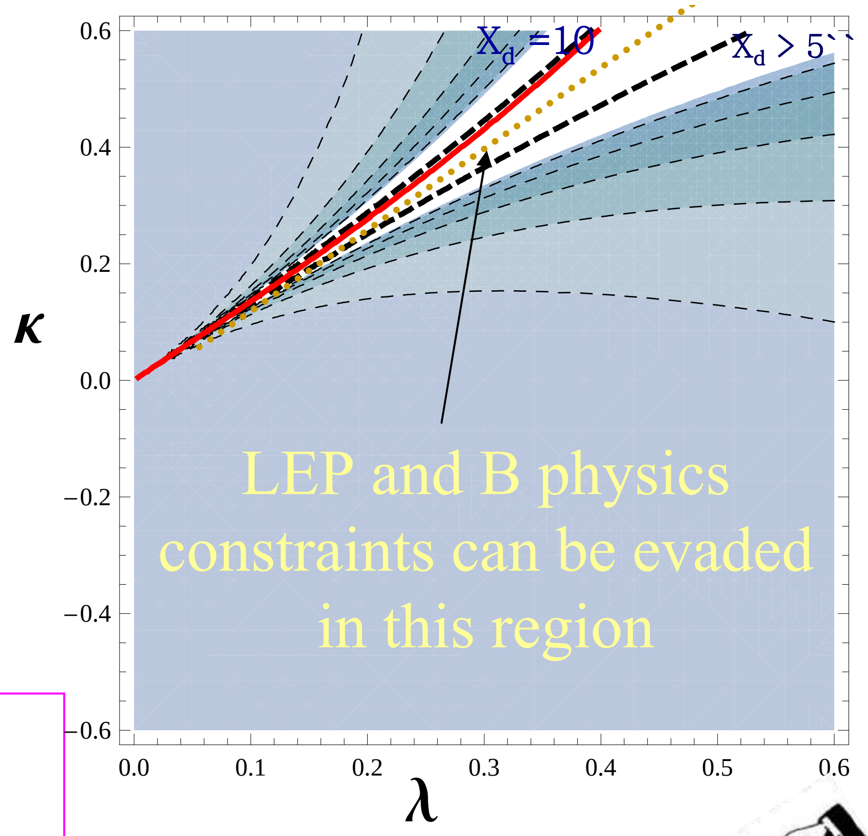
$X_d = \cos\theta_A \tan\beta$

At large tanβ: $\sin 2\beta \approx \dfrac{2}{\tan\beta}$

$$\cos\theta_A \cong -\frac{\lambda v\,(A_\lambda - 2\kappa s)\sin 2\beta}{2\lambda s\underbrace{(A_\lambda + \kappa s)}_{B_{eff}} + 3\kappa A_\kappa s \sin 2\beta}, \quad (\lambda A_\lambda + \kappa\mu) \to 0$$

$$m_{A_1}^{\;2} \cong 3s\left(\frac{3\lambda A_\lambda \cos^2\theta_A}{3\sin 2\beta} - 2\kappa A_\kappa \sin^2\theta_A\right)$$

$\tan\beta \sim 1/[\,A_\lambda + K\mu/\lambda\,]$
Ananthanarayan & Pandita, hep-ph/9601372




The same region of the parameter space of the NMSSM yields simultaneously:

**$A_1$ mass near 10 GeV**

**Large $X_d$**

$$M_A^2 = \frac{2\mu B_{eff}}{\sin 2\beta} = \frac{A_\lambda + \kappa s}{\sin 2\beta} \Rightarrow \text{Moderate!}$$

# *The Proposal*

*Since 2002*

1) Test of Lepton Universality* in $\Upsilon(1S,2S,3S)$ decays to taus at (below) the few percent level @ a (Super) B factory

Mod. Phys. Lett. A17 (2002) 2265
Int. J. Mod. Phys. A19 (2004) 2183

*More recently*

2) Possible Distorsion of Bottomonium Spectroscopy due to mixing of $\eta_b$ states and a light CP-odd Higgs

Phys. Rev. Lett. 103 (2009) 111802

***It is hard to find a black cat in a dark room, especially if there is no cat***
Confucius

* Lepton universality: Gauge bosons couple to all lepton species with equal strength in the SM

# Present status of Lepton Universality (PDG)

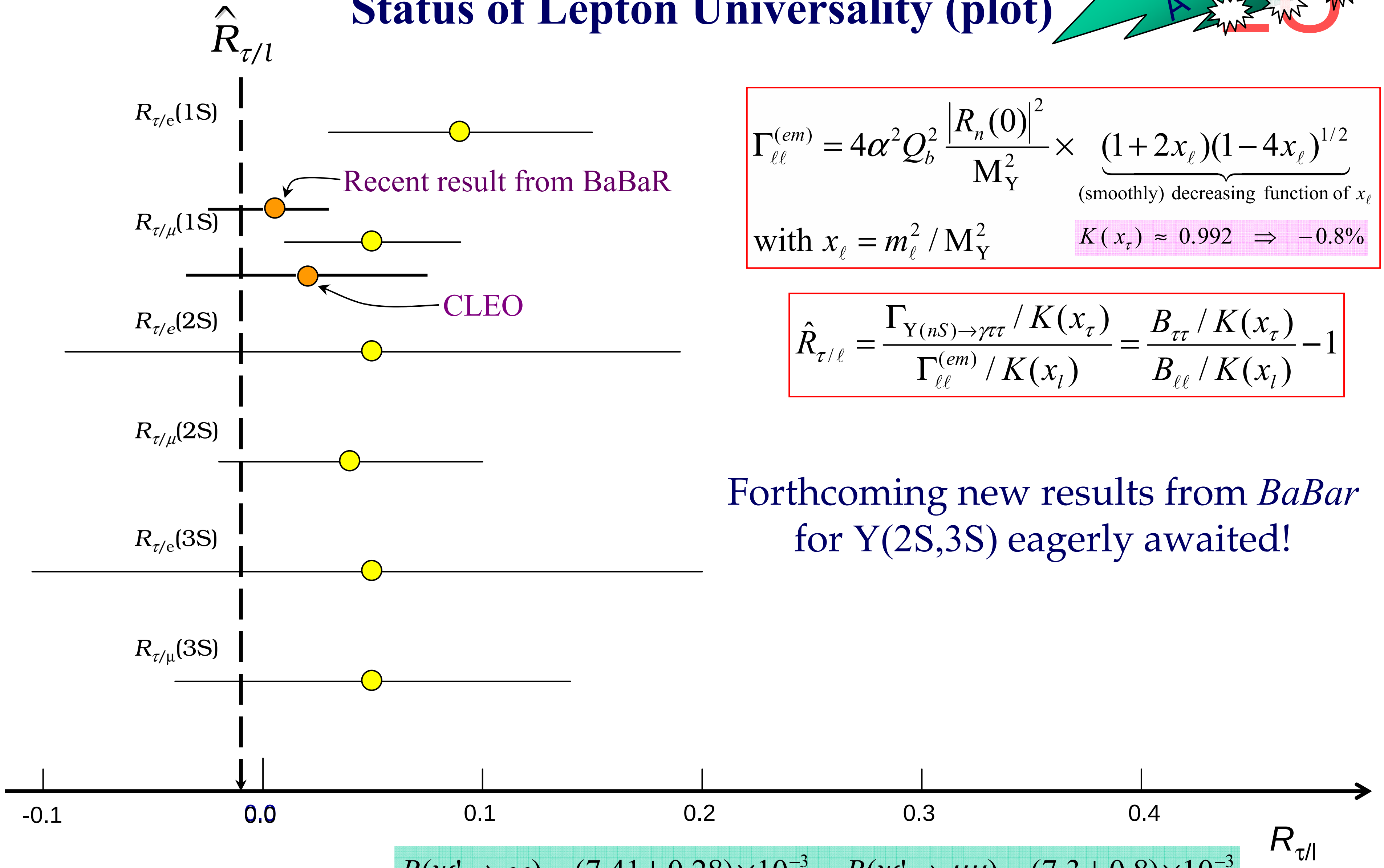
$$\text{BF }[\Upsilon \to e^+e^-] = \text{BF }[\Upsilon \to \mu^+\mu^-] = \text{BF }[\Upsilon \to \tau^+\tau^-]$$

| Channel | $BF$ [$e^+e^-$] | $BF$ [$\mu^+\mu^-$] | $BF$ [$\tau^+\tau^-$] | $R_{\tau/e}$ | $R_{\tau/\mu}$ |
|---|---|---|---|---|---|
| $\Upsilon(1S)$ | 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 ± 0.09 |

$$R_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma_s\tau\tau}}{\Gamma^{(em)}_{\ell\ell}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1$$

Lepton Universality in Upsilon decays implies $< R_{\tau/l} > = 0$ (actually -0.08)

# Status of Lepton Universality (plot)




$$\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2} \times \underbrace{(1+2x_\ell)(1-4x_\ell)^{1/2}}_{\text{(smoothly) decreasing function of } x_\ell}$$

with $x_\ell = m_\ell^2 / M_\Upsilon^2$ $\qquad K(x_\tau) \approx 0.992 \Rightarrow -0.8\%$

$$\hat{R}_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma\tau\tau} / K(x_\tau)}{\Gamma_{\ell\ell}^{(em)} / K(x_l)} = \frac{B_{\tau\tau} / K(x_\tau)}{B_{\ell\ell} / K(x_l)} - 1$$

Forthcoming new results from *BaBar* for Υ(2S,3S) eagerly awaited!

For charmonium

$$B(\psi' \to ee) = (7.41 \pm 0.28)\times 10^{-3} \approx B(\psi' \to \mu\mu) = (7.3 \pm 0.8)\times 10^{-3}$$
$$> B(\psi' \to \tau\tau) = (2.8 \pm 0.7)\times 10^{-3}$$

# Why should LU be useful to search for a light CP-odd Higgs?

- **Direct observation of monochromatic photons from radiative decays** of Upsilon resonances may not be that easy especially for

$$m_{A_1} \in [\ 9.4,\ 10.5\ ]\ \text{GeV}$$

*As suggested by **J. Gunion***
*hep-ph/0502105*
*also historically employed in the search for a light Higgs*

- The peak in the photon energy spectrum could be **broader than expected**

because **two (or more)** peaks resulting from both $A_1$ and $\eta_b$ channels **might not be easily disentangled**

*Naive approach*

$$\Upsilon(nS) \to \gamma\ A_1 (\to \tau^+ \ \tau^-)$$

n, n' = 1,2,3

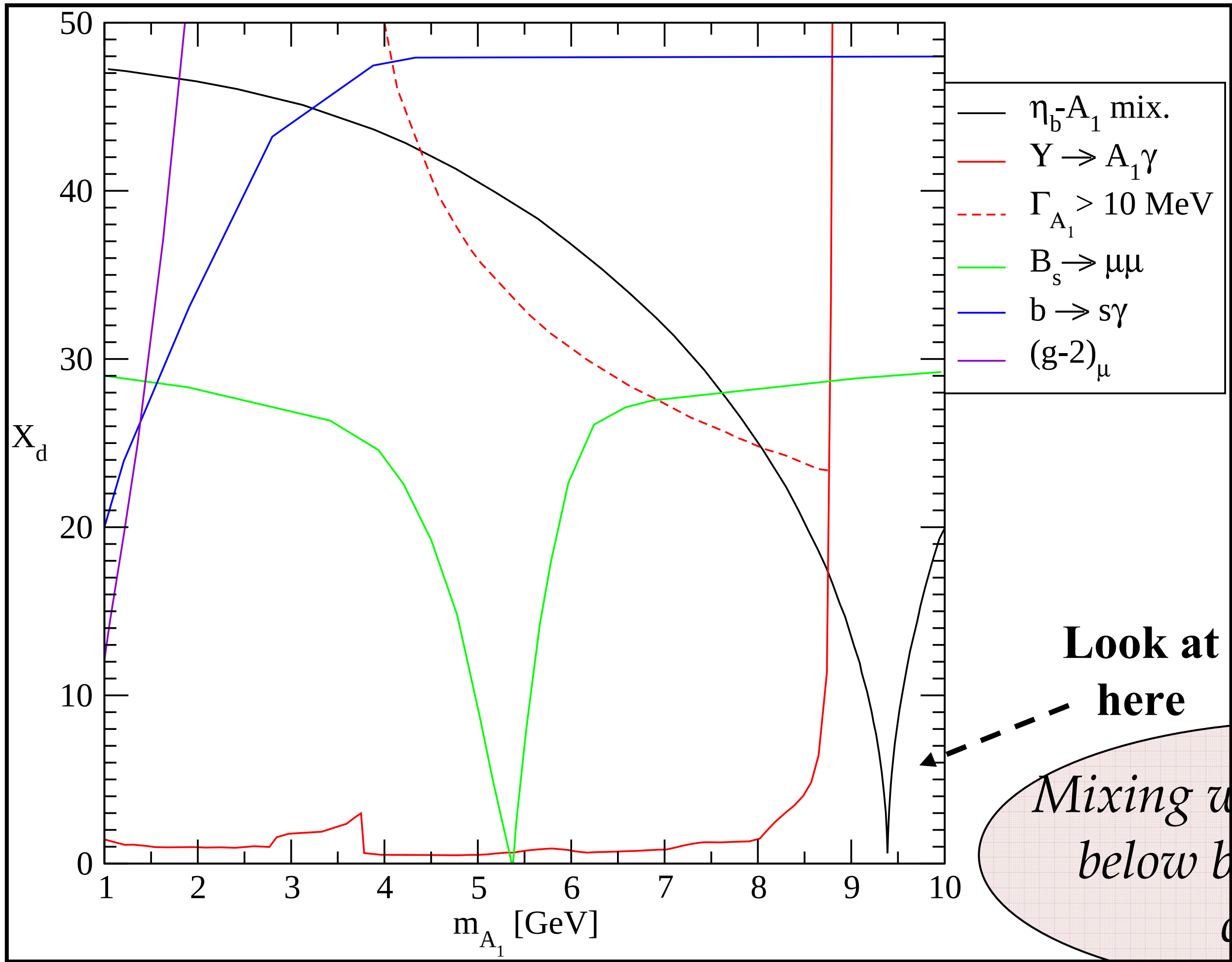
$$\Upsilon(nS) \to \gamma\ \eta_b\ (n'S)\ [\to A_1^* \to \tau^+ \tau^-]$$

Cerro dos picos - Argentina

$A_1$-$\eta_b$ mixing yields additional difficulties for exp detection as we shall see!

# Upper bounds for all parameters scanned in the NMSSM

F.Domingo, U. Ellwanger, E. Fullana, C. Hugonie and M.A.S.L., arXiv: 0810.4736




**Look at here**

*Mixing with $\eta_b$ resonances below b-bbar threshold can occur*

$B_s \to \mu\mu$ puts limits about the $B_s$ mass

CLEO, BaBaR searches for $\Upsilon \to \gamma\, A_1$ puts stringent limits for $m_{A1} < 9$ GeV

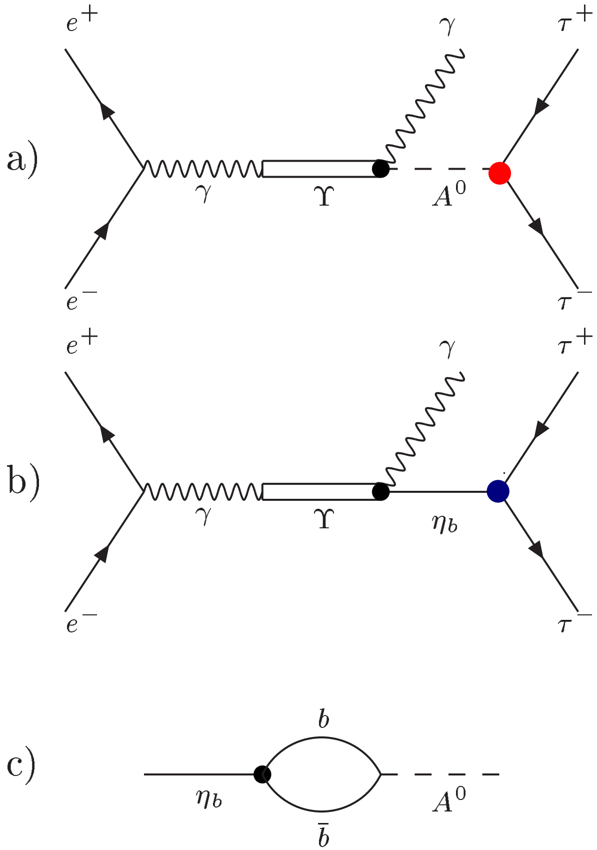
BaBar discovery of $\eta_b(1S)$ puts limits about 9.4 GeV

# *Mixing of a pseudoscalar Higgs $A_1$ and a $\eta_b$ resonance*

$e^+ e^- \to \Upsilon \to \gamma \tau^+ \tau^-$

Drees & Hikasa
PRD 41 (1990) 1547

hep-ph/0702190




$$\mathbf{M}^2 = \begin{pmatrix} m^2_{A_{10}} - i m_{A_{10}} \Gamma_{A_{10}} & \delta m^2 \\ \delta m^2 & m^2_{\eta_{b0}} - i m_{\eta_{b0}} \Gamma_{\eta_{b0}} \end{pmatrix}$$

$A_{10}$ , $\eta_{b0}$
unmixed states

$A_1$ , $\eta_b$
mixed (physical) states

$$A_1 = \cos\alpha \; A_{10} + \sin\alpha \; \eta_{bo}$$
$$\eta_b = \cos\alpha \; \eta_{b0} - \sin\alpha \; A_{10}$$

$$g_{A^0\tau\tau} = \cos\alpha \; g_{A^0_0\tau\tau} + \sin\alpha \; g_{\eta_{bo}\tau\tau}$$
$$g_{\eta_b\tau\tau} = \cos\alpha \; g_{\eta_{b0}\tau\tau} - \sin\alpha \; g_{A^0_0\tau\tau}$$

0 ($g_{\eta_{bo}\tau\tau}$), 0 ($g_{\eta_{b0}\tau\tau}$)

The $\eta_b$ decays to leptons because of its mixing with the CP-odd Higgs

$$\delta m^2 \approx \left( \frac{3 m^3_{\eta_b}}{4\pi v^2} \right)^{1/2} | R_{\eta_b}(0) | \times X_d \qquad \sin 2\alpha \approx \delta m^2$$

$$\Gamma_{A^0} = |\cos\alpha|^2 \; \Gamma_{A^0_0} + |\sin\alpha|^2 \; \Gamma_{\eta_{bo}}$$
$$\Gamma_{\eta_b} = |\cos\alpha|^2 \; \Gamma_{\eta_{b0}} + |\sin\alpha|^2 \; \Gamma_{A^0_0}$$

# Resonant and non-resonant decays with $\eta_b(nS)$ –$A_1$ mixing

The "Higgs" is to be produced through the $A_1$- components of the mixed states no matter which production mechanism is considered.
In turn, the decay of physical pseudoscalar states into taus should also take place via their $A_1$- components.

$$R_{\tau/\ell} = R^{A_1}_{\tau/\ell} + R^{\eta_b}_{\tau/\ell}$$

*Non-resonant*

$$R_{\tau/\ell} = \frac{B[\Upsilon(nS) \to \gamma A_1]}{B[\Upsilon(nS) \to \ell^+\ell^-]} \times B[A_1 \to \tau^+\tau^-] + \frac{B[\Upsilon(nS) \to \gamma \eta_b(kS)]}{B[\Upsilon(nS) \to \ell^+\ell^-]} \times B[\eta_b(kS) \to \tau^+\tau^-]$$

*Resonant*

$$B[A_1 \to \tau\tau] = B[A_{10} \to \tau\tau] \times \frac{\cos^2\alpha\,\Gamma_{A_{10}}}{\cos^2\alpha\,\Gamma_{A_{10}} + \sin^2\alpha\,\Gamma_{\eta_{bo}}}$$

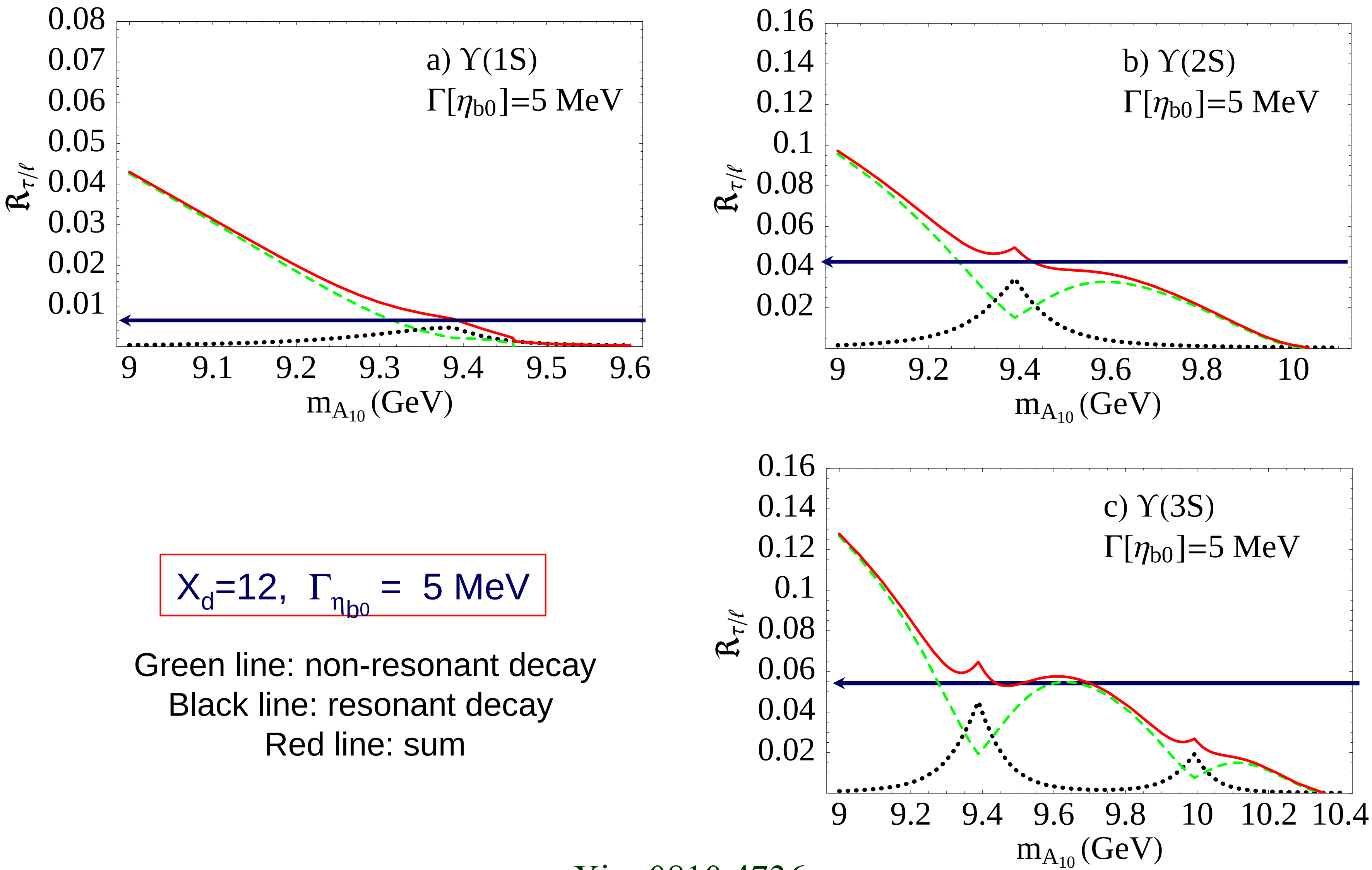
$$B[\eta_b(nS) \to \tau\tau] = B[A_{10} \to \tau\tau] \times \frac{\sin^2\alpha\,\Gamma_{A_{10}}}{\cos^2\alpha\,\Gamma_{A_{10}} + \sin^2\alpha\,\Gamma_{\eta_{bo}}}$$

Mixing effect in the decay

hep-ph/0702190 arXiv: 0810.4736

# *Expected LU breaking*

$$R^{non-res}_{\tau/\ell} + R^{res}_{\tau/\ell} = R_{\tau/\ell}$$




$X_d$=12, $\Gamma_{\eta_{b0}}$ = 5 MeV

Green line: non-resonant decay
Black line: resonant decay
Red line: sum

arXiv: 0810.4736

# Spectroscopic consequences for the bottomonium family

## *General mixing matrix*

(in collaboration with F. Domingo & U. Ellwanger)

$$\mathcal{M}^2 = \begin{pmatrix} m^2_{\eta_b^0(1S)} & 0 & 0 & \delta m_1^2 \\ 0 & m^2_{\eta_b^0(2S)} & 0 & \delta m_2^2 \\ 0 & 0 & m^2_{\eta_b^0(3S)} & \delta m_3^2 \\ \delta m_1^2 & \delta m_2^2 & \delta m_3^2 & m_A^2 \end{pmatrix} .$$

$$\begin{aligned} \delta m_1^2 &\simeq (0.14 \pm 10\%)\ \mathrm{GeV}^2 \times X_d\ , \\ \delta m_2^2 &\simeq (0.11 \pm 10\%)\ \mathrm{GeV}^2 \times X_d\ , \\ \delta m_3^2 &\simeq (0.10 \pm 10\%)\ \mathrm{GeV}^2 \times X_d\ . \end{aligned}$$

Non-relativistic calculation

Physical states = (mass) eigenstates of the above matrix

$$\eta_i = P_{i,1}\ \eta_b^0(1S) + P_{i,2}\ \eta_b^0(2S) + P_{i,3}\ \eta_b^0(3S) + P_{i,4}\ A\ .$$

*i=1,2,3,4*

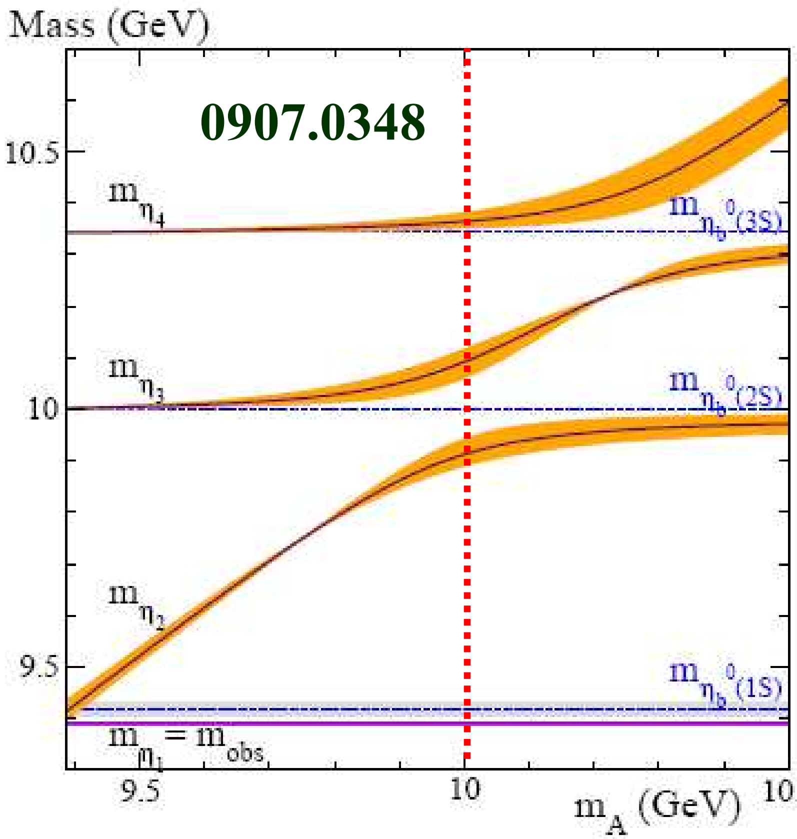
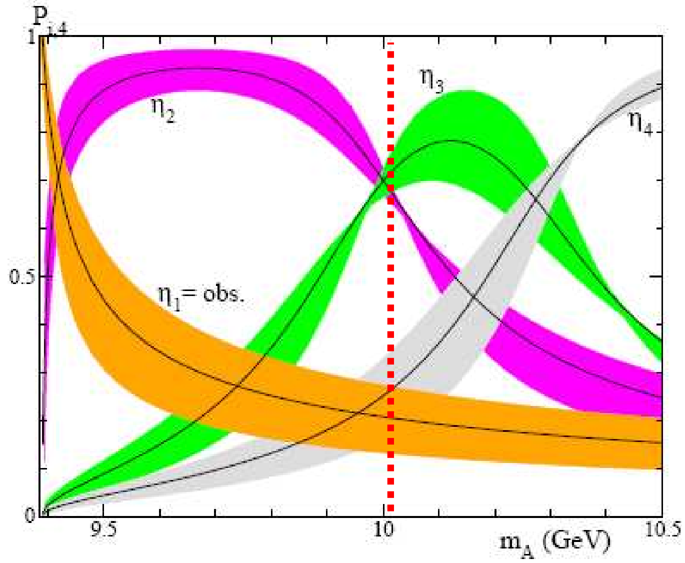
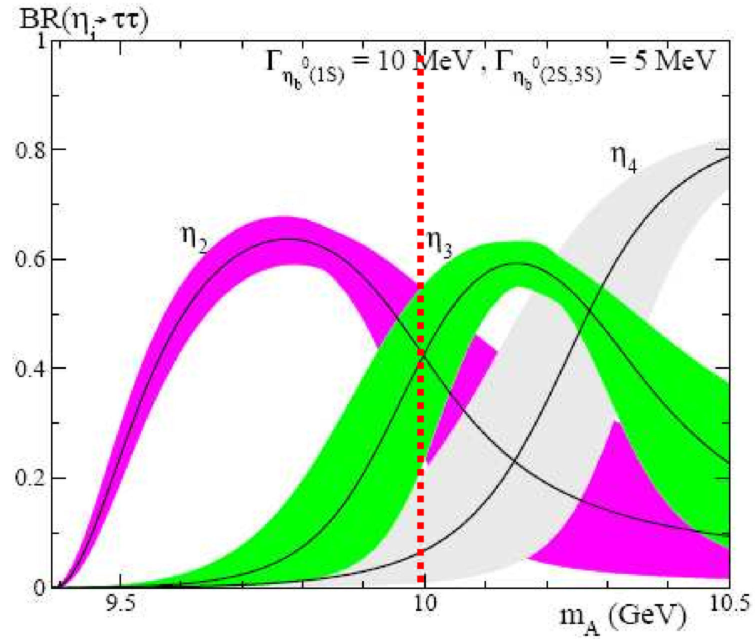



FIG. 2: The masses of all eigenstates as function of $m_A$.

*Possible scenarios:*
***deeply entangled with search strategies***



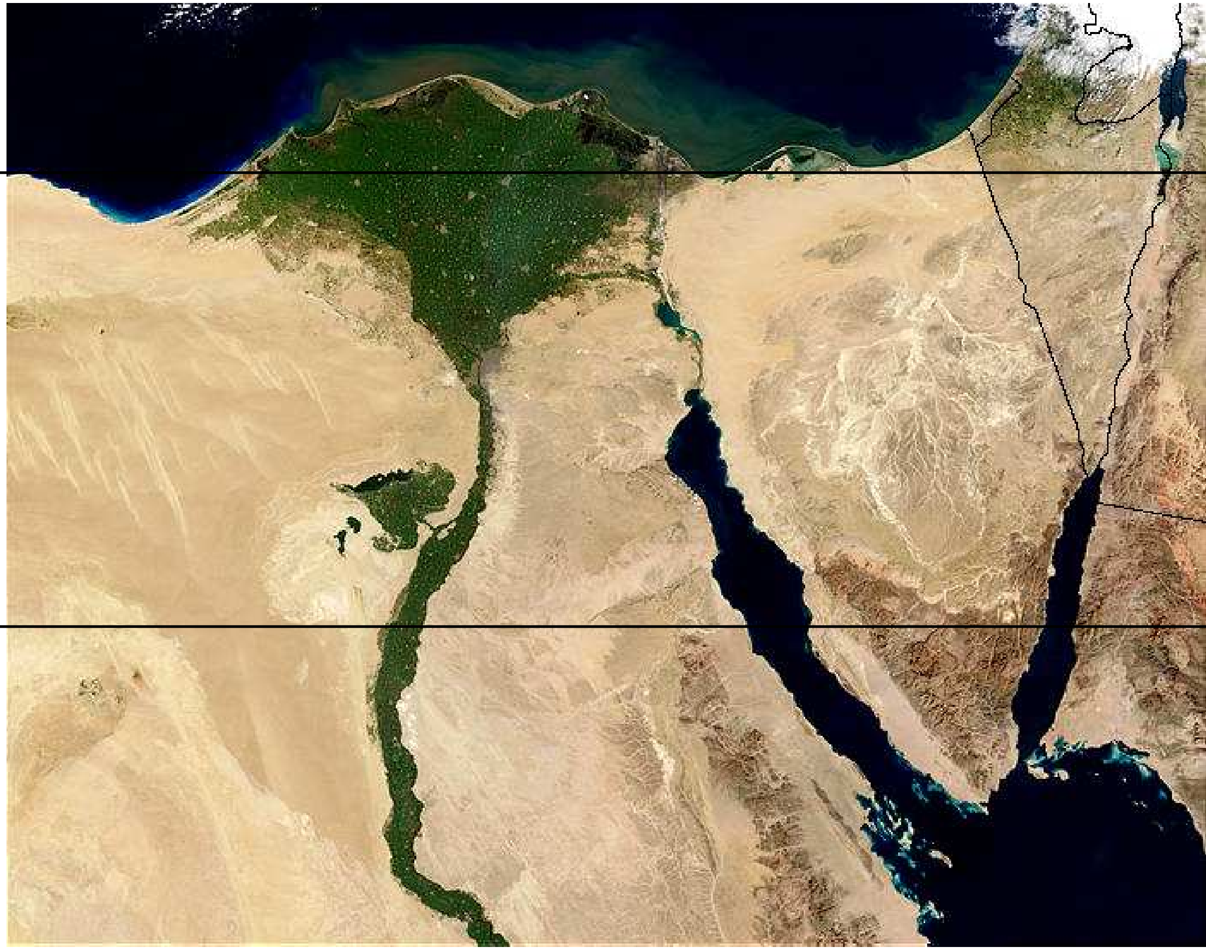

G. 3: The $A$-components $|P_{i,4}|$ for all 4 eigenstates as func
ns of $m_A$.




IG. 4: The branching ratios into $\tau^+\tau^-$ for the eigenstates
$_2$, $\eta_3$ and $\eta_4$ as functions of $m_A$.

# *An analogy: the Nile delta*

“Scanning”



Actually seen!

Many channels spreading over a broad region

Expected Signal:

Narrow river with plenty of water

A “naïve” explorer moving across the delta:

*The Nile river does not exist!*


# *(Light) Dark Matter @ the NMSSM*

with a singlet component

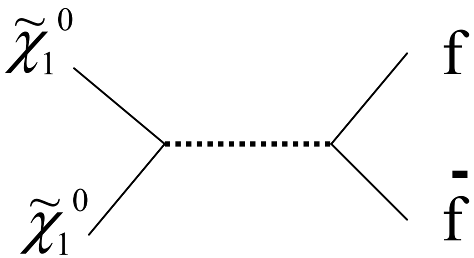
## WIMP candidate = lightest neutralino $\tilde{\chi}_1^0$

J.F. Gunion, D, Hooper, B. McElrath: hep-ph/0509024

For a recent analysis see Das and Ellwanger, **arXiv:1007.1151** [hep-ph]

and talk by **D. Das in this Conference**

- Efficient annihilation could happen through **a light CP-odd Higgs $A_1$** yielding the observed relic abundance




However it may eventually lead to an exceedingly efficient annihilation if $m_{A_1} \approx 2\, m_\chi$

- Scattering off nuclei

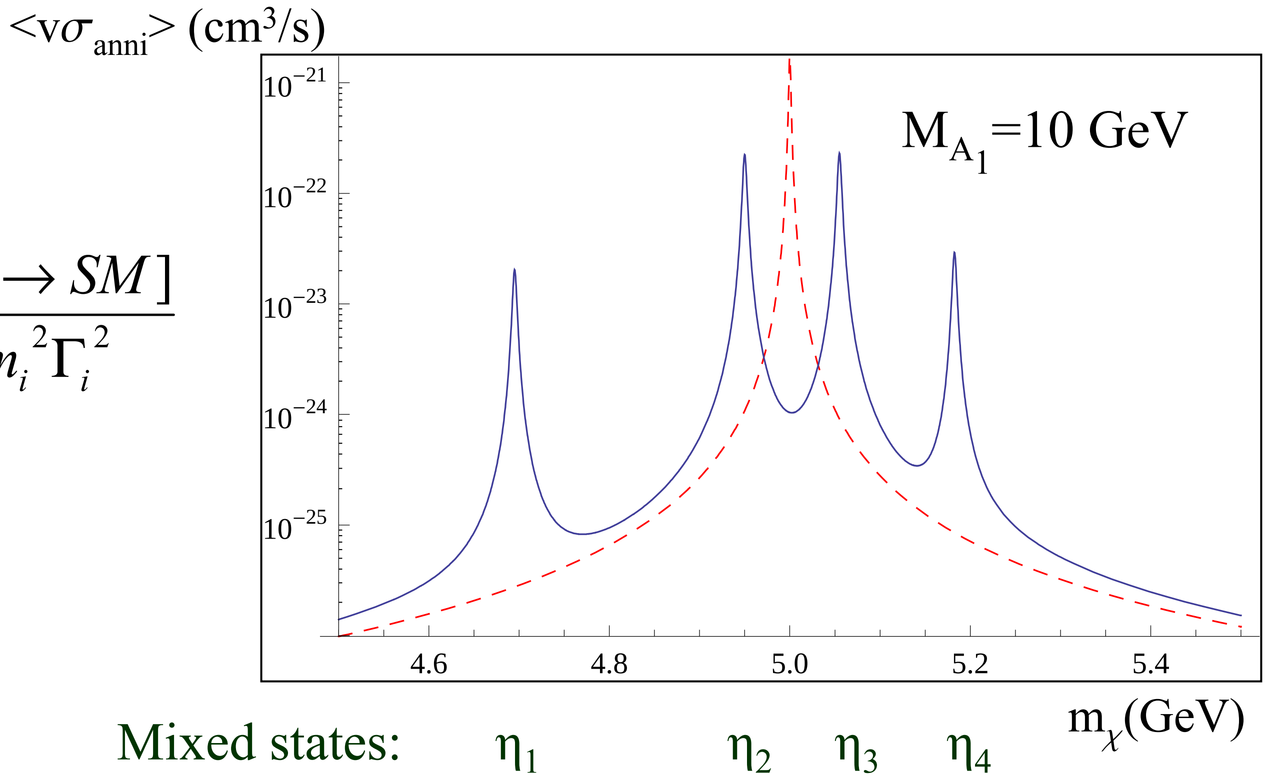
  - Spin-independent: through CP-even Higgs exchange
  - Spin-dependent: through $Z^0$ vector meson exchange

# Effect of the $A_1$- $\eta_b$ mixing on the neutralino annihilation

Instead of a single mass region for enhancement around the $A_1$ mass one should face a more complicated situation, dealing again with a **multi-peak** structure in the plot of the cross section as a function of the neutralino mass:

$$\sigma_i \propto \frac{\Gamma[\eta_i \to \chi\chi] \times \Gamma[\eta_i \to SM]}{(m_i^{\,2} - 4m_\chi^2)^2 + m_i^{\,2}\Gamma_i^{\,2}}$$

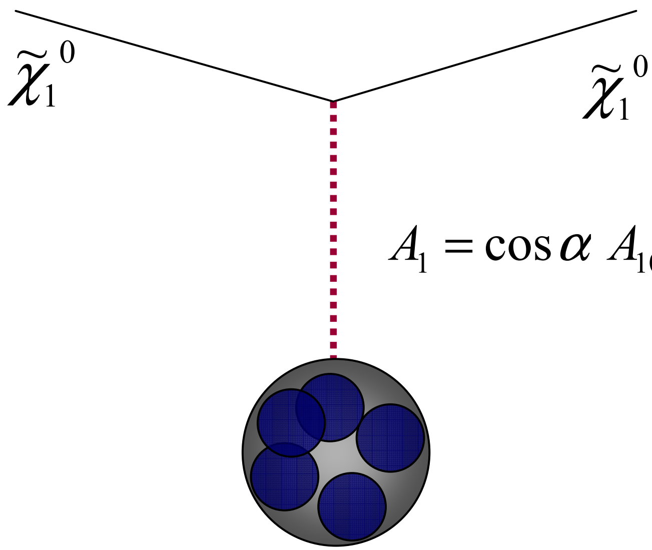
$$\sigma_{annihilation} = \sum_{i=1,2,3,4} \sigma_i$$




(same NMSSM parameters as in previous plots)

# *Direct observation of dark matter*

WIMP scattering off a nucleus




$$A_1 = \cos\alpha\ A_{10} + \sin\alpha\ \eta_{bo}$$

Possible enhancement

$$BF[\eta_c \to p\,\bar{p}] \approx 10^{-3}$$ PDG

Perhaps substantial coupling of $\eta_b$ to nucleons too

**EMC nuclear effect**

**Vector Meson Dominance** for the photon: the physical photon as a superposition of a bare photon and ρ, ω, ϕ,..

pseudoscalar interaction

Velocity suppression factor $(v/c)^2 \sim 10^{-6}$; v neutralino velocity ⟷ $(m_b/m_s)^2 \sim 10^2$

$(m_Z/m_A)^2 \sim 10^2$

$g_{\eta_b pp}$ *not small?*

Still negligible contribution (?)

# *Conclusions*

The search for the $\boldsymbol{\eta_b}$ **(2S)** state(s) by BaBar is ***crucial***
to rule out/discover a light CP-odd Higgs
in the range $2m_\tau < m_{A_1} < 2m_B$ (open window: 9.4-10.5 GeV)

The $\eta_b$(2S)-like state mass measurement might
yield a hyperfine splitting $m_{\Upsilon(2S)} - m_{\eta_b(2S)}$
in (quite) disagreement with SM expectations

Test of lepton universality in Υ(2S) decays
should be another hint of NP
LU breaking expectedly larger than for the Υ(1S)

Search for light **dark matter** to be continued
at B factories covering as much mass interval as possible

Physical (mixed) states $\eta_i$ (i=1,2,3,4) might modify
the coupling of neutralinos to ordinary matter
(affecting annihilation and scattering cross sections)

# Back-up

# Next-to-Minimal Supersymmetric Standard Model (NMSSM)

A new singlet superfield is added to the Higgs sector: $\hat{H}_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \quad \hat{S}$

In general more extra SM singlets can be added: hep-ph/0405244

The μ-problem of the MSSM would be solved by introducing in the superpotential the term

$$W_{Higgs} = \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{\kappa}{3}\hat{S}^3 \quad \Rightarrow \quad V_{soft} = \lambda A_\lambda S(H_u \circ H_d) + \frac{\kappa}{3} A_\kappa S^3 + h.c.$$

Spontaneous breaking of the PQ symmetry — Breaks explicitly the PQ symmetry

where $\mu = \lambda x, \quad x = \langle S \rangle = \mu / \lambda$ If $\kappa$ =0 → U(1) Peccei-Quinn symmetry

Spontaneous breaking → NGB (massless), an "axion" (+QCD anomaly) ruled out experimentally

If the PQ symmetry is not exact but explicitly broken → provides a mass to the (pseudo) NGB leading to a light CP-odd scalar for small $\kappa$

If $\lambda$ and $\kappa$ zero → $U(1)_R$ symmetry; if $U(1)_R$ slightly broken → a light pseudoscalar Higgs boson too

## Higgs sector in the NMSSM: (seven)

- 2 neutral CP-odd Higgs bosons ($A_{1,2}$)
- 3 neutral CP-even Higgs bosons ($H_{1,2,3}$)
- 2 charged Higgs bosons ($H^\pm$)

The $A_1$ would be the lightest Higgs:

$$M_{A_1}^2 \cong -3\left(\frac{\kappa}{\lambda}\right) A_\kappa \mu$$

Favored decay mode: $H_{1,2} \to A_1 A_1$
hard to detect at the LHC [hep-ph/0406215]

$$A_1 = \cos\theta_A \, A_{MSMS} + \sin\theta_A \, A_s$$

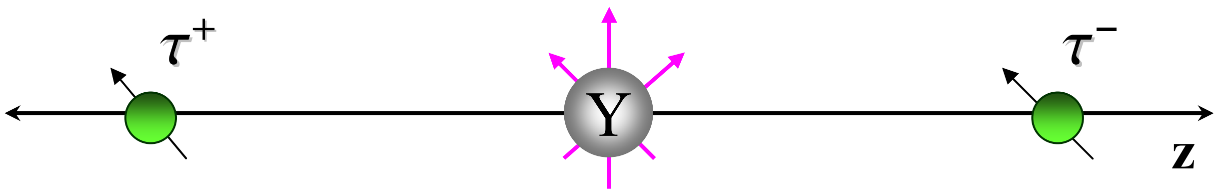
Coupling of $A_1$ to down type fermions:

$$\propto \frac{m_f^2 v}{x}\delta, \quad \Rightarrow \cos\theta_A \tan\beta$$

[hep-ph/0404220]

$$\cos^2\theta_A \cong \frac{v^2}{x^2 \tan^2\beta}\delta^2, \quad \delta = \frac{A_\lambda - 2\kappa x}{A_\lambda + \kappa x}$$

# Leptonic decay mode: $\Upsilon(nS) \to \tau^+\tau^-$ vs $\Upsilon(nS) \to \mu^+\mu^-$




- For transverse polarization of Υ(nS), the helicity of leptons gives no difference
- For longitudinal polarization of Υ(nS), **lepton helicity** favours the tauonic mode

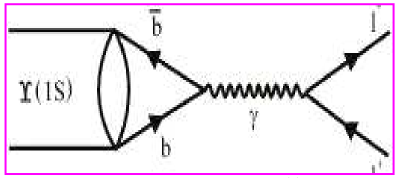
  (as e.g. in $\pi \to \mu\,\nu_\mu$ versus $\pi \to e\,\nu_e$)
- **Phase space** favours the muonic decay mode

$$\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2} \times \underbrace{(1+2x_\ell)(1-4x_\ell)^{1/2}}_{\text{(smoothly) decreasing function of } x_\ell}$$

with $x_\ell = m_\ell^2 / M_\Upsilon^2$ $\qquad K(x_\ell) \approx (1-6x_\ell)$

For Υ(1S): $K(x_\tau) \approx 0.992 \Rightarrow -0.8\%$

# Leptonic width of $\Upsilon$ resonances




Lowest Feynman diagram

- $\Gamma_{ll}$ (as presented in the PDG tables) is an ***<u>inclusive</u>*** **quantity:**

  $\Upsilon \to l^+ l^-$ is <u>accompanied by an infinite number of soft photons</u>

The test of lepton universality can be seen as complementary to searches for a (monochromatic) photon in the $\Upsilon \to \gamma\,\tau\tau$ channel

- To order $\alpha^3$: $\Gamma_{ll} = \Gamma_{ll}^{\,0}[\,1+\delta_{vac}+\delta_{vertex}\,] \sim \Gamma_{ll}^{\,0}[\,1+\delta_{vac}\,]$

$\delta_{vertex}$: $3\alpha/4\pi \sim 0.17\%$

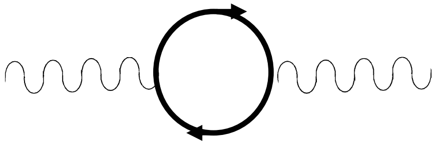
$\delta_{vac}$: 7.6%

*Warning!*

Contribution potentially dangerous for testing lepton universality **if final-state radiation is not properly taken into account in the MC to obtain the detection efficiency** in the analysis of experimental data

Albert et al. Nucl. Phys. B 166 (1980) 460

$\delta_{vac} = \delta_{ee} + \delta_{\mu\mu} + \delta_{\tau\tau} + \delta_{quarks}$



- Divergencies/singularities free at any order: Bloch and Nordsieck theorem & Kinoshita-Sirlin-Lee-Nauenberg theorem

# "Requirement" on $X_d$ from the $\eta_b(1S)$ mass measurement

Hyperfine splitting $M_{\Upsilon(1S)}$-$M_{\eta_b(1S)}$ = 69.9 ± 3.1 MeV (BABAR)

Hyperfine splitting $M_{\Upsilon(1S)}$-$M_{\eta_b(1S)}$ = 42 ± 13 MeV (pQCD)

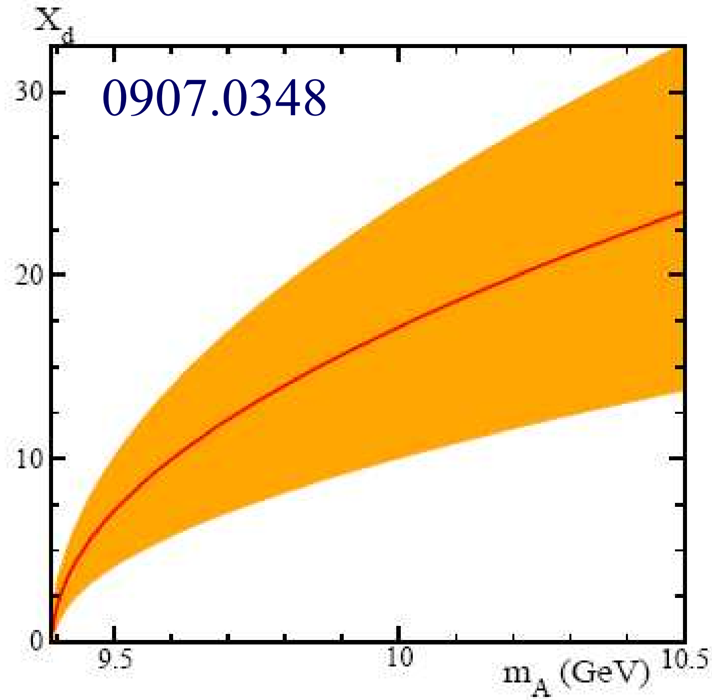



FIG. 1: $X_d$ as a function of $m_A$ (in GeV) such that one eigenvalue of $\mathcal{M}^2$ coincides with the BABAR result (1).

# Resonant and non-resonant decays without mixing

$$R_{\tau/\ell} = \frac{\Gamma_{\Upsilon(nS)\to\gamma_s\tau\tau}}{\Gamma^{(em)}_{\ell\ell}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1$$

QCD+binding energy effects small for a pseudoscalar $A^0$
Polchinski, Sharpe and Barnes
Pantaleone, Peskin and Tye
Nason

*Leading-order Wilczek formula*
*with binding-state, QCD + relativistic corrections:* $F = ½$

quite uncertain
especially ~ 9 GeV

- *Non-resonant decay*

$$R^{non-res}_{\tau/\ell} = \frac{G_F m_b^2 X_d^2}{\sqrt{2}\,\pi\,\alpha}\left(1 - \frac{m^2_{A^0}}{m^2_\Upsilon}\right)\cdot F$$

- *Resonant decay*

$$R^{res}_{\tau/\ell} = \frac{B[\Upsilon \to \gamma\eta_b]}{B[\Upsilon \to l^+l^-]}$$

Wavefunction overlap

M1 transition probability

$$B(\Upsilon \to \gamma_s \eta_b) = \frac{\Gamma^{M1}_{\Upsilon\to\gamma\eta_b}}{\Gamma_\Upsilon} \cong \frac{1}{\Gamma_\Upsilon} \times \frac{4\alpha I^2 Q_b^{\ 2} k^3}{3m_b^2}$$

*Naïve view!*

# *Dark matter: bounds from B factories*

*BaBar*

$$BF[Y(1S) \to invisible] < 3\times10^{-4}$$

arXiv:0908.2840 [hep-ex]

scalar mediator

$$BF[Y(3S) \to \gamma + invisible] < (0.7 - 31)\times10^{-6}\ ,\ m_A < 7.8\ \text{GeV}$$

(pseudo) scalar mediator

arXiv:0808.0017 [hep-ex]

Effort should be put on the search for light dark matter (e.g. neutralinos) such that

$$2m_\chi \sim m_{A_1} \sim 10\ \text{GeV}$$

$$Y(3S) \to \gamma A_1 (\to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

Small photon energy
Detection not that easy!

NOT YET EXCLUDED
by B factories searches