May 18-21, 2010 **QWG7**
Fermilab, Batavia, IL, USA

Bottomonium spectroscopy with mixing of η_b *states* & a *light CP-odd Higgs boson*

Miguel Ángel Sanchis Lozano

IFIC

University of Valencia - CSIC

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

Higgs sector

> *Things should be as simple as possible, but not simpler*
>
> A. Einstein

$$\hat{H}_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \quad \underset{\substack{\uparrow \\ \text{New gauge-singlet} \\ \text{superfield}}}{\hat{S}}$$

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

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

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

$$A_1 = \overbrace{\cos\theta_A \, A_{MSSM}}^{\text{Non-singlet component}} + \overbrace{\sin\theta_A \, A_s}^{\text{Singlet component}}$$

$$\tan\beta = v_u / v_d$$

↓

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

A_λ = -200 GeV
A_κ = -15 GeV
μ = 150 GeV
tan β= 40

A_λ ~ - K μ / λ

K - *(4/3)* λ =0

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

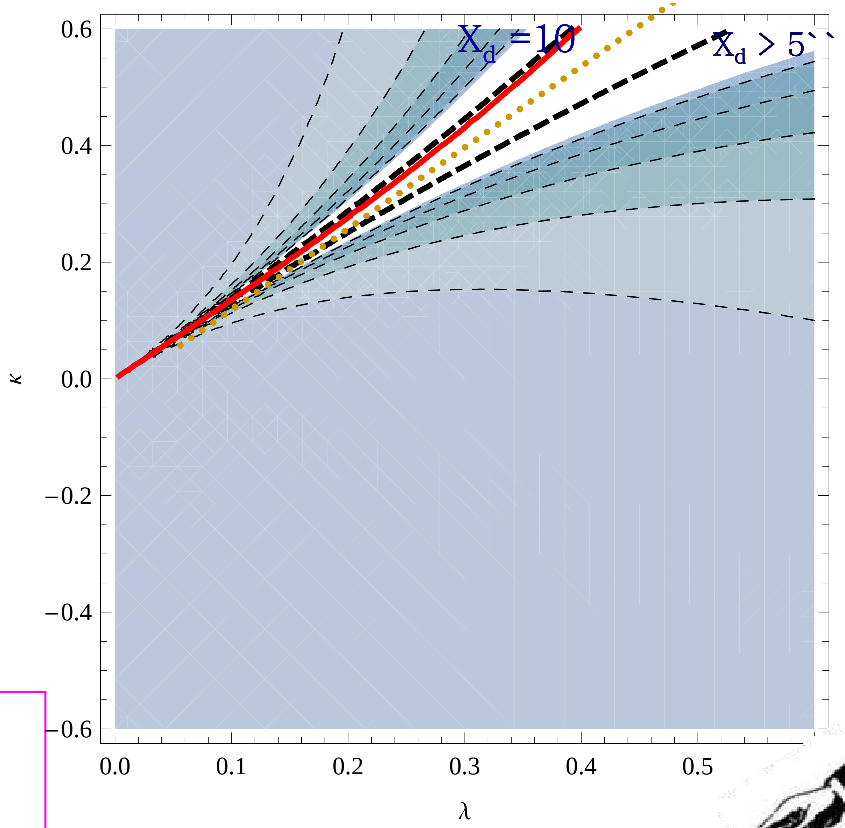
$X_d = \cos\theta_A \tan\beta$

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

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

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

tanβ ~ 1/ [A_λ+ K μ / λ]
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 Υ(1S,2S,3S) decays to taus at (below) the few percent level @ a (Super) B factory

Mod. Phys. Lett. A17, 2265-2276 (2002)

More recently

2) Possible distorsion of bottomonium spectroscopy due to mixing of η_b states and a light CP-odd Higgs

Phys. Rev. Lett. 103, 111802 (2009)

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

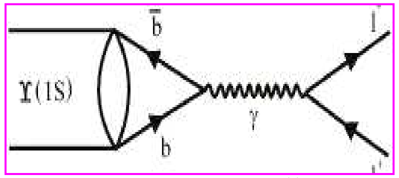
Confucius

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

Test of Lepton Universality

(update)

Leptonic width of Υ resonances



Lowest Feynman diagram

- Γ_{ll} (as presented in the PDG tables) is an ***inclusive*** **quantity:**

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

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

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

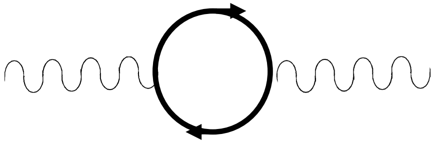
δ_{vac}: 7.6%

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

Present status of Lepton Universality (PDG)

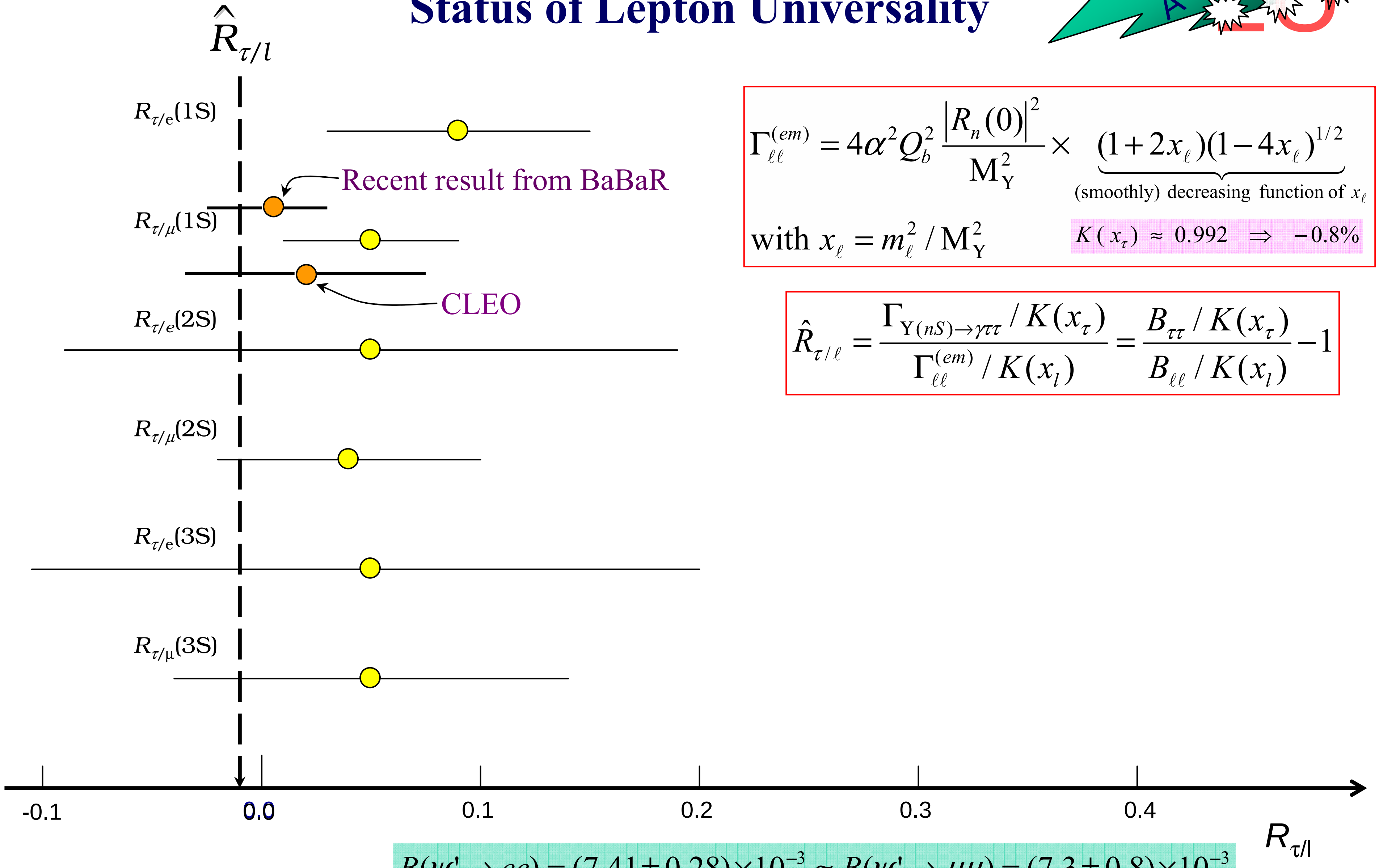
$$\text{BF}\ [\text{Y} \to e^+e^-] = \text{BF}\ [\text{Y} \to \mu^+\mu^-] = \text{BF}\ [\text{Y} \to \tau^+\tau^-]$$

Channel	BF [e^+e^-]	BF [$\mu^+ \mu^-$]	BF [$\tau^+\tau^-$]	$R_{\tau/e}$	$R_{\tau/\mu}$
Υ(1S)	2.38 ± 0.11 %	2.48 ± 0.05 %	2.60 ± 0.10 %	0.09 ± 0.06	0.05 ± 0.04
Υ(2S)	1.91 ± 0.16 %	1.93 ± 0.17 %	2.00 ± 0.21 %	0.05 ± 0.14	0.04 ± 0.06
Υ(3S)	2.18 ± 0.21 %	2.18 ± 0.21 %	2.29 ± 0.30 %	0.05 ± 0.16	0.05 ± 0.09

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

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

Status of Lepton Universality



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

with $x_\ell = m_\ell^2 / \mathrm{M}_\Upsilon^2$ $K(x_\tau) \approx 0.992 \;\Rightarrow\; -0.8\%$

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

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

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

↑ *As suggested by J. Gunion 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 η_b channels

might not be easily disentangled

Naive approach

$$\boxed{\Upsilon(nS) \to \gamma\ A_1\,(\to \tau^+\ \tau^-)}$$

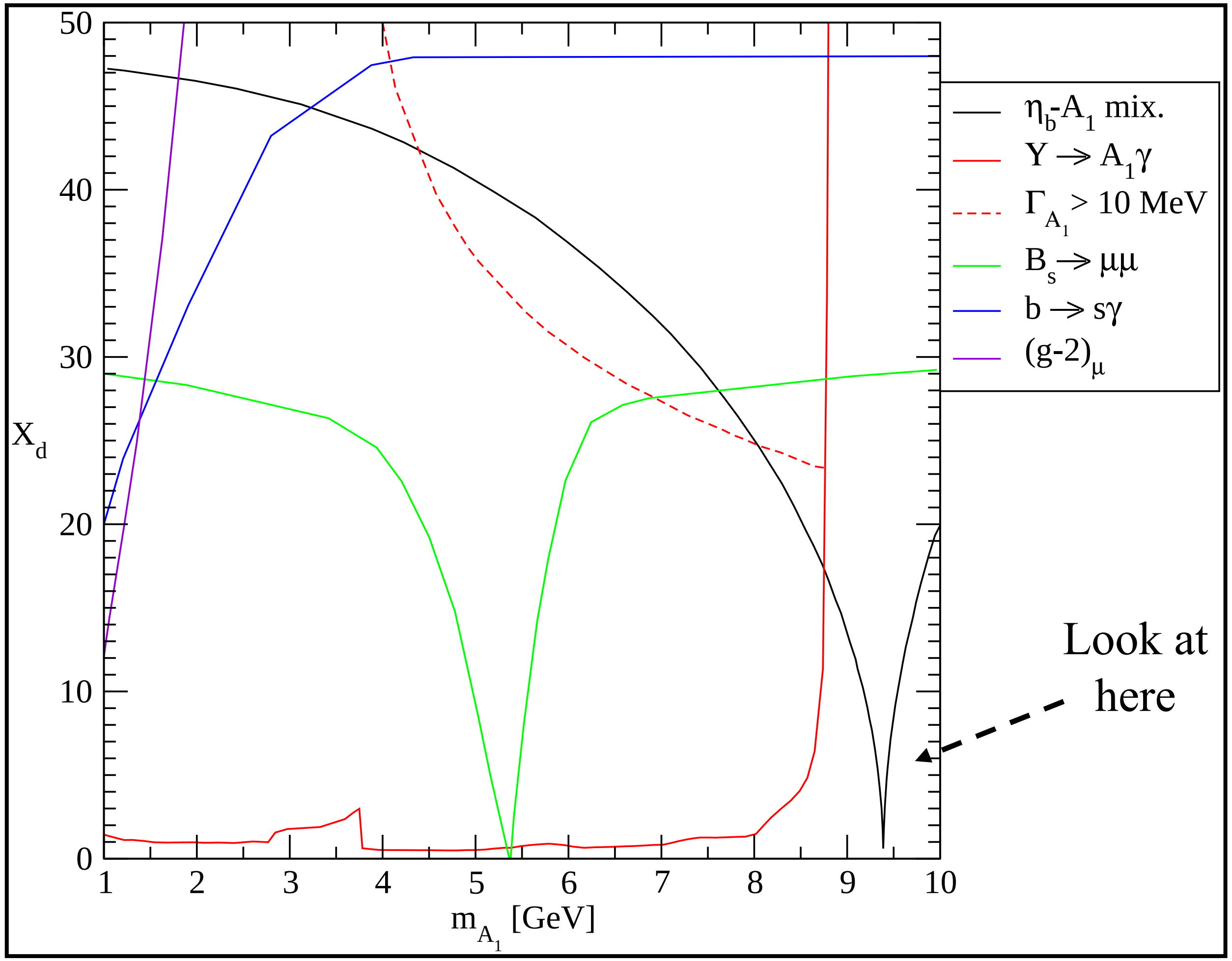
n, n' = 1,2,3

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

Cerro dos picos - Argentina

A_1-η_b mixing yields additional difficulties for exp detection as we shall see!

Upper bounds for all parameters scanned in the NMSSM



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

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

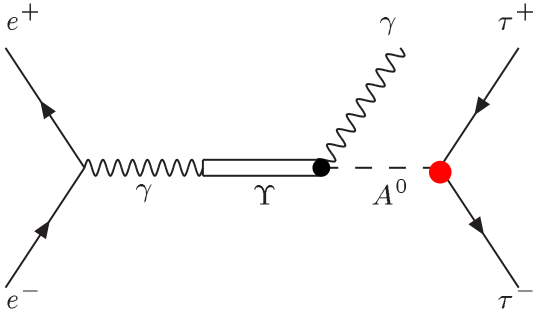
BaBar discovery of $\eta_b(1S)$ puts limits about 9.4 GeV

Mixing of a pseudoscalar Higgs A_1 and a η_b resonance

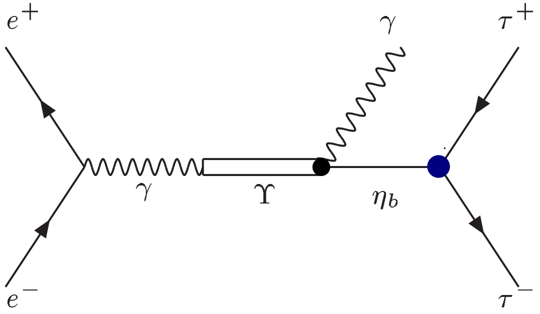
$$\boxed{e^+ e^- \rightarrow \Upsilon \rightarrow \gamma\, \tau^+ \tau^-}$$

hep-ph/0702190

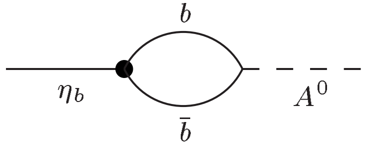
a)



b)



c)



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

A_{10} , η_{b0}
unmixed states

A_1 , η_b
mixed (physical) states

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

$$\eta_b = \cos\alpha\ \eta_{b0} - \sin\alpha\ A_{10}$$

$$g_{A^0\tau\tau} = \cos\alpha\ g_{A^0_0\tau\tau} + \sin\alpha\ \overset{0}{g_{\eta_{bo}\tau\tau}}$$

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

The η_b decays to leptons because of its mixing with the CP-odd Higgs

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

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

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

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!

Resonant and non-resonant decays with η_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.

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

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

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

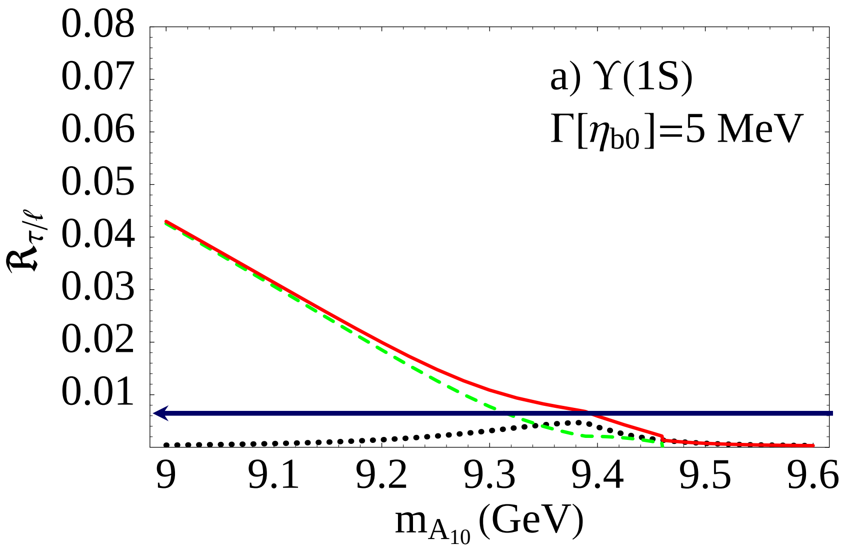
Mixing effect in the decay

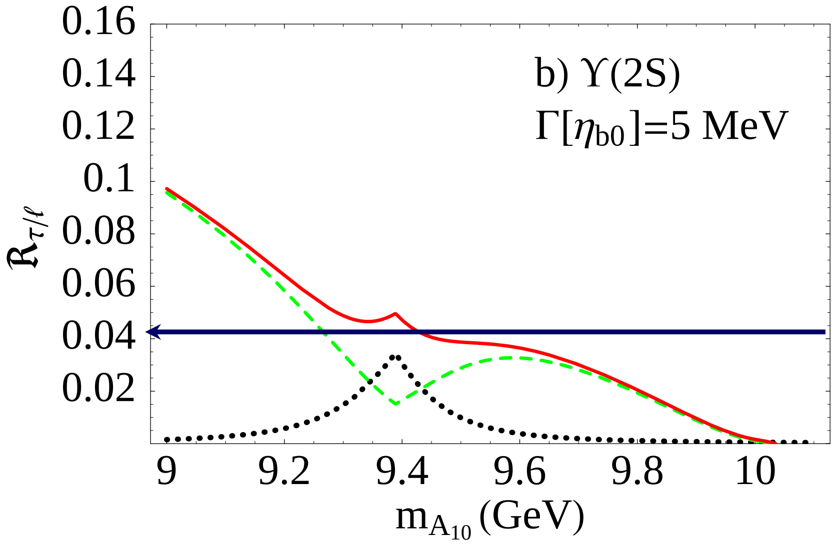
$$B[\eta_b(nS) \to \tau\tau] = B[A_{10} \to \tau\tau] \times \frac{\sin^2\alpha\,\Gamma_{A_{10}}}{\cos^2\alpha\,\Gamma_{A_{10}} + \sin^2\alpha\,\Gamma_{\eta_{bo}}}$$

hep-ph/0702190 arXiv: 0810.4736

Expected LU breaking

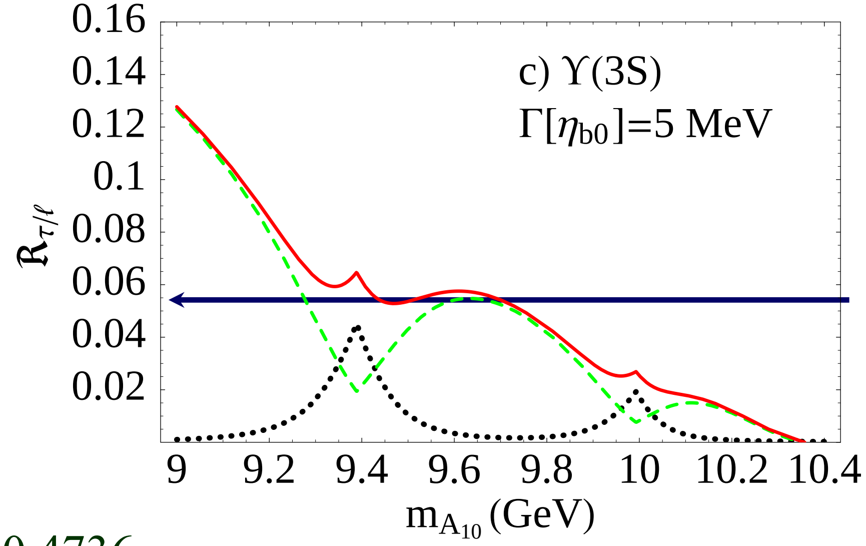
$$R_{\tau/\ell}^{non-res} + R_{\tau/\ell}^{res} = R_{\tau/\ell}$$





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

Mixing

η_b *resonance* / A^0 *Higgs boson*

Petit bourgeois

Enfant terrible

General mixing matrix

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

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

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

What we should understand as a Higgs boson is to some extent a matter of convention; it seems natural to call "Higgs" the state with the largest $P_{i,4}$

1003.0312

“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)

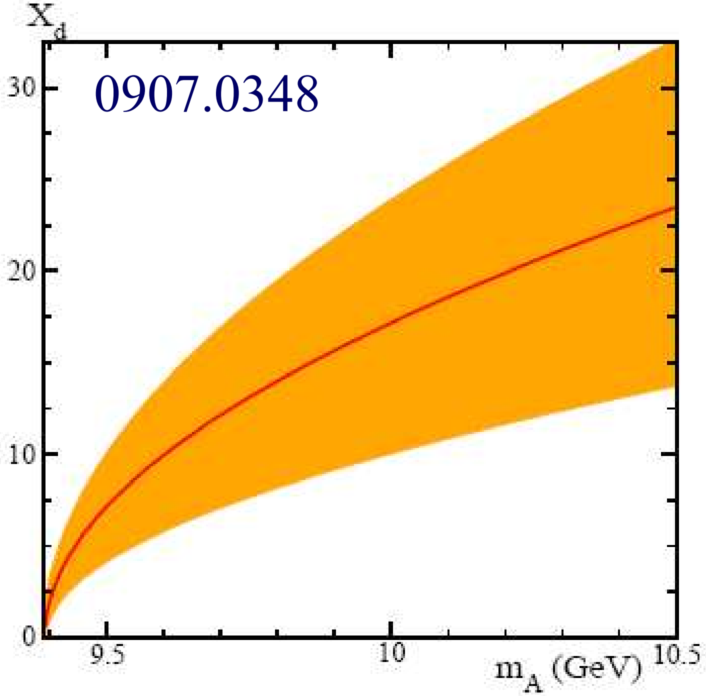
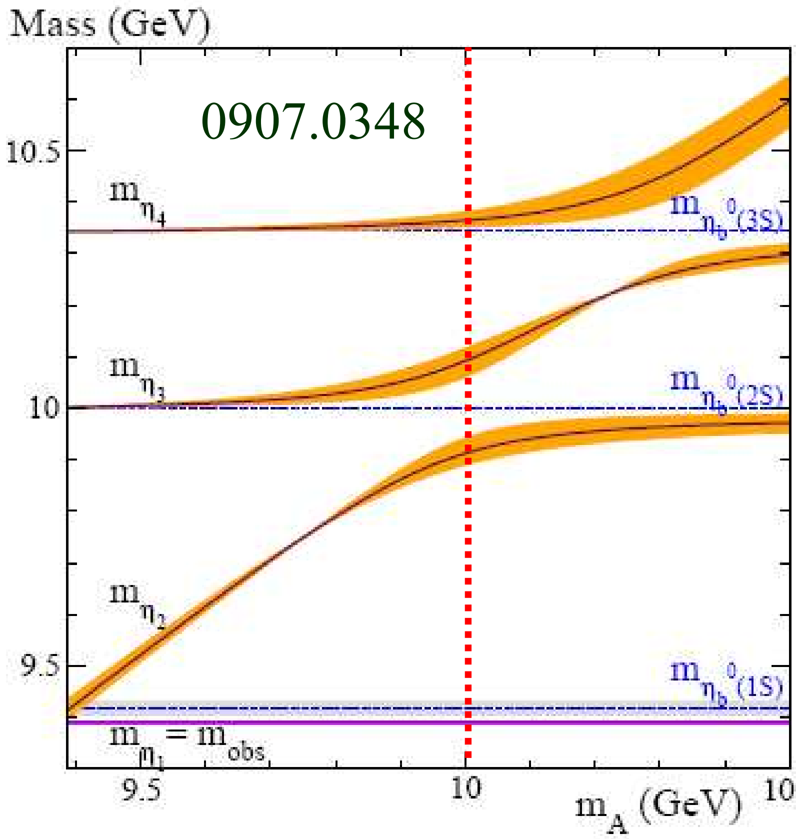


FIG. 1: X_d as a function of m_A (in GeV) such that one eigenvalue of $\mathcal{M}^2$ coincides with the BABAR result (1).

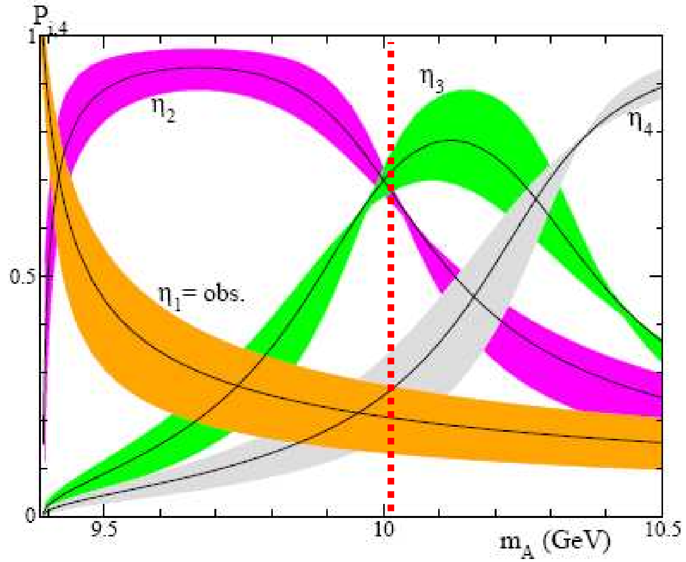


0907.0348

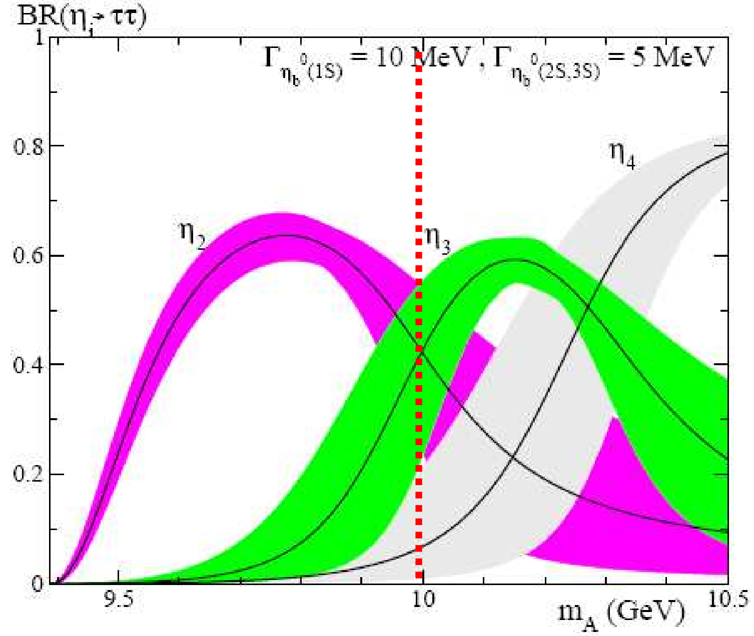
FIG. 2: The masses of all eigenstates as function of m_A.

Possible scenarios:

deeply entangled with search strategies



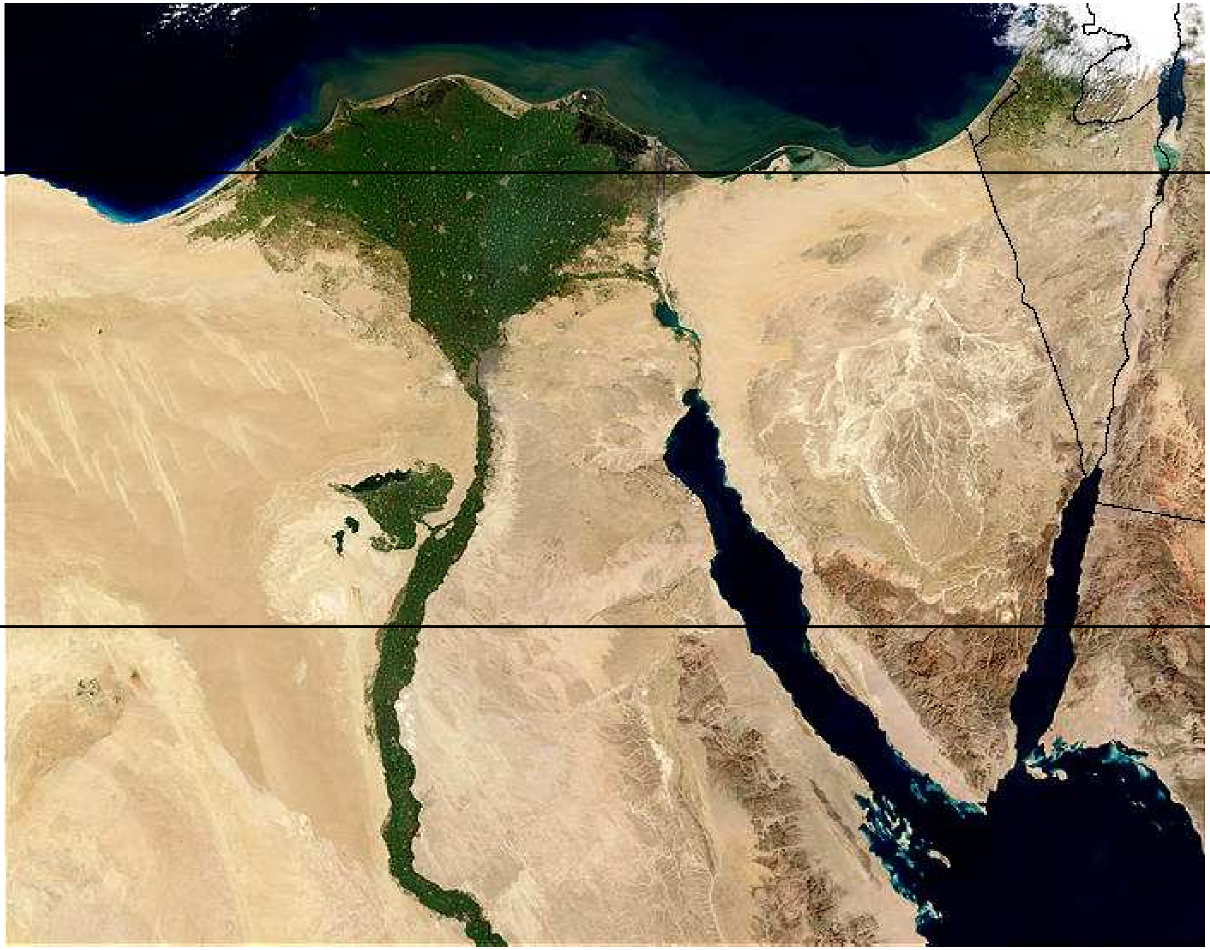
G. 3: The A-components $|P_{i,4}|$ for all 4 eigenstates as func
ns of m_A.



IG. 4: The branching ratios into $\tau^+\tau^-$ for the eigenstates
$_2$, η_3 and η_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!

Conclusions / *Outlook*

The search for the $\boldsymbol{\eta_b}$ **(2S)** state(s) by BaBar/Belle is ***crucial***
to rule out/discover a light CP-odd Higgs
in the range $2m_\tau < m_{A_1} < 2m_B$
(Relevant for NP searches at Tevatron/LHC
since light and heavier sectors are entangled)

The η_b(2S)-like state mass measurement might
yield a hyperfine splitting Υ(2S) - η_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)

Related topics: **light dark matter**, muon anomalous g-2

Thank you very much!

Back-up

Light neutral Higgs scenarios

Susy scale ~ *O* (100) GeV-*O* (1) TeV
sets the expected Higgs mass

↓

Protective symmetry?

↓

Light Higgs !

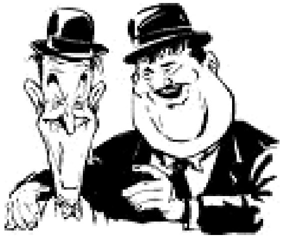
Well-known example:

The photon is massless while W^+, W^- & Z^0 are quite heavy!

Gauge symmetry explains such a mass difference

A possible (and promising) scenario in the NMSSM

$$\underset{\sim 10\text{ GeV}}{m_{A_1}} < \underset{\substack{\downarrow \\ \sim 100\text{ GeV} \\ \text{SM-like}}}{m_{H_1}} < \underbrace{m_{A_2} \approx m_{H_1} \approx m_{H_2} \approx m_{H^+} = m_{H^-}}_{\sim 300/400\text{ GeV almost degenerate}}$$



L & H

Light and heavy Higgs
bosons can live together!

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 $\mu = \lambda x, \quad x =< S >= \mu / \lambda$ If κ =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 κ

If λ and κ 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:

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

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:

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

[hep-ph/0404220]

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

(Hidden) systematic errors?

There could be hidden systematic errors in the extraction of the muonic and tauonic branching fractions from experimental data, e.g. use is made of lepton universality as an intermediate step

hep-ex/9409004
hep-ex/0409027

$B_{ee} = B_{\mu\mu} = B_{\tau\tau}$

Defining: $\widehat{B}_{\mu\mu} = \Gamma_{\mu\mu} / \Gamma_{\text{had}}$

$$B_{\mu\mu} = \Gamma_{\mu\mu} / \Gamma_{\Upsilon} = \boxed{\frac{\widetilde{B}_{\mu\mu}}{1+3\widetilde{B}_{\mu\mu}}} \Rightarrow \quad B_{\mu\mu} = \frac{\widetilde{B}_{\mu\mu}}{1+\widetilde{B}_{ee}+\widetilde{B}_{\mu\mu}+\widetilde{B}_{\tau\tau}}$$

- The muonic branching fraction would be **overestimated** if $\widetilde{B}_{\mu\mu} \leq \widetilde{B}_{\tau\tau}$

$B_{ee} = B_{\mu\mu} = B_{\tau\tau}$

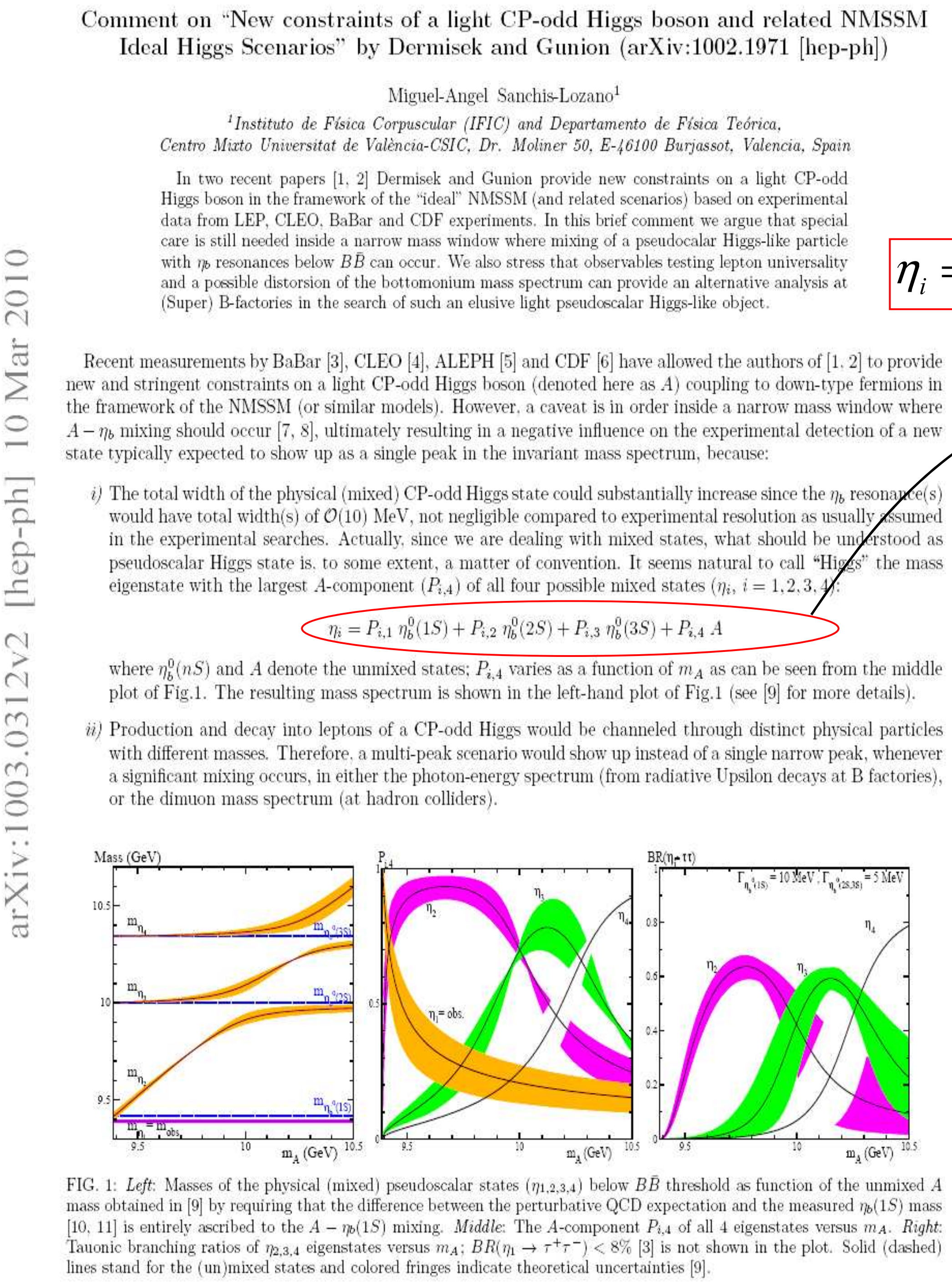
Defining: $\widehat{B}_{\tau\tau} = \Gamma_{\tau\tau} / \Gamma_{\text{had}}$

$$B_{\tau\tau} = \Gamma_{\tau\tau} / \Gamma_{\Upsilon} = \boxed{\frac{\widetilde{B}_{\tau\tau}}{1+3\widetilde{B}_{\tau\tau}}} \Rightarrow \quad B_{\tau\tau} = \frac{\widetilde{B}_{\tau\tau}}{1+\widetilde{B}_{ee}+\widetilde{B}_{\mu\mu}+\widetilde{B}_{\tau\tau}}$$

- The tauonic branching fraction would be **underestimated** if $\widetilde{B}_{\mu\mu} \leq \widetilde{B}_{\tau\tau}$

In the opposite direction !

- Besides phase space disfavors the tauonic decay mode by ~ 1% (Van-Royen Weisskopf formula)



Comment on "New constraints of a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios" by Dermisek and Gunion (arXiv:1002.1971 [hep-ph])

Miguel-Angel Sanchis-Lozano[1]

[1] *Instituto de Física Corpuscular (IFIC) and Departamento de Física Teórica, Centro Mixto Universitat de València-CSIC, Dr. Moliner 50, E-46100 Burjassot, Valencia, Spain*

In two recent papers [1, 2] Dermisek and Gunion provide new constraints on a light CP-odd Higgs boson in the framework of the "ideal" NMSSM (and related scenarios) based on experimental data from LEP, CLEO, BaBar and CDF experiments. In this brief comment we argue that special care is still needed inside a narrow mass window where mixing of a pseudocalar Higgs-like particle with η_b resonances below $B\bar{B}$ can occur. We also stress that observables testing lepton universality and a possible distorsion of the bottomonium mass spectrum can provide an alternative analysis at (Super) B-factories in the search of such an elusive light pseudoscalar Higgs-like object.

Recent measurements by BaBar [3], CLEO [4], ALEPH [5] and CDF [6] have allowed the authors of [1, 2] to provide new and stringent constraints on a light CP-odd Higgs boson (denoted here as A) coupling to down-type fermions in the framework of the NMSSM (or similar models). However, a caveat is in order inside a narrow mass window where $A-\eta_b$ mixing should occur [7, 8], ultimately resulting in a negative influence on the experimental detection of a new state typically expected to show up as a single peak in the invariant mass spectrum, because:

i) The total width of the physical (mixed) CP-odd Higgs state could substantially increase since the η_b resonance(s) would have total width(s) of $\mathcal{O}(10)$ MeV, not negligible compared to experimental resolution as usually assumed in the experimental searches. Actually, since we are dealing with mixed states, what should be understood as pseudoscalar Higgs state is, to some extent, a matter of convention. It seems natural to call "Higgs" the mass eigenstate with the largest A-component ($P_{i,4}$) of all four possible mixed states (η_i, $i = 1, 2, 3, 4$):

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

where $\eta_b^0(nS)$ and A denote the unmixed states; $P_{i,4}$ varies as a function of m_A as can be seen from the middle plot of Fig.1. The resulting mass spectrum is shown in the left-hand plot of Fig.1 (see [9] for more details).

ii) Production and decay into leptons of a CP-odd Higgs would be channeled through distinct physical particles with different masses. Therefore, a multi-peak scenario would show up instead of a single narrow peak, whenever a significant mixing occurs, in either the photon-energy spectrum (from radiative Upsilon decays at B factories), or the dimuon mass spectrum (at hadron colliders).

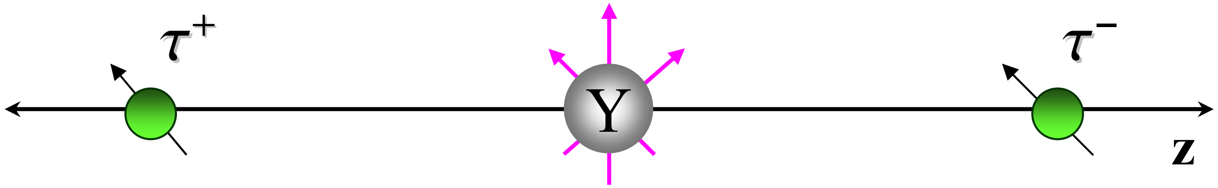
FIG. 1: *Left*: Masses of the physical (mixed) pseudoscalar states ($\eta_{1,2,3,4}$) below $B\bar{B}$ threshold as function of the unmixed A mass obtained in [9] by requiring that the difference between the perturbative QCD expectation and the measured $\eta_b(1S)$ mass [10, 11] is entirely ascribed to the $A-\eta_b(1S)$ mixing. *Middle*: The A-component $P_{i,4}$ of all 4 eigenstates versus m_A. *Right*: Tauonic branching ratios of $\eta_{2,3,4}$ eigenstates versus m_A; $BR(\eta_1 \to \tau^+\tau^-) < 8\%$ [3] is not shown in the plot. Solid (dashed) lines stand for the (un)mixed states and colored fringes indicate theoretical uncertainties [9].

$$\eta_i = P_{i,1}\,\eta_0(1S) + P_{i,2}\,\eta_0(2S) + P_{i,2}\,\eta_0(3S) + P_{i,4}\,A$$

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.

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

$$\boxed{\begin{aligned}&\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2} \times \underbrace{(1+2x_\ell)(1-4x_\ell)^{1/2}}_{\text{(smoothly) decreasing function of } x_\ell}\\ &\text{with } x_\ell = m_\ell^2 / M_\Upsilon^2 \qquad\qquad K(x_\ell) \approx (1-6x_\ell)\end{aligned}}$$

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