Possible lepton universality breaking in Upsilon decays: a light CP-odd Higgs interpretation and consequences

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

A_λ ~ - K μ / λ

K - *(4/3)* λ *=0*

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

$$\mathbf{X_d = \cos\theta_A \tan\beta}$$

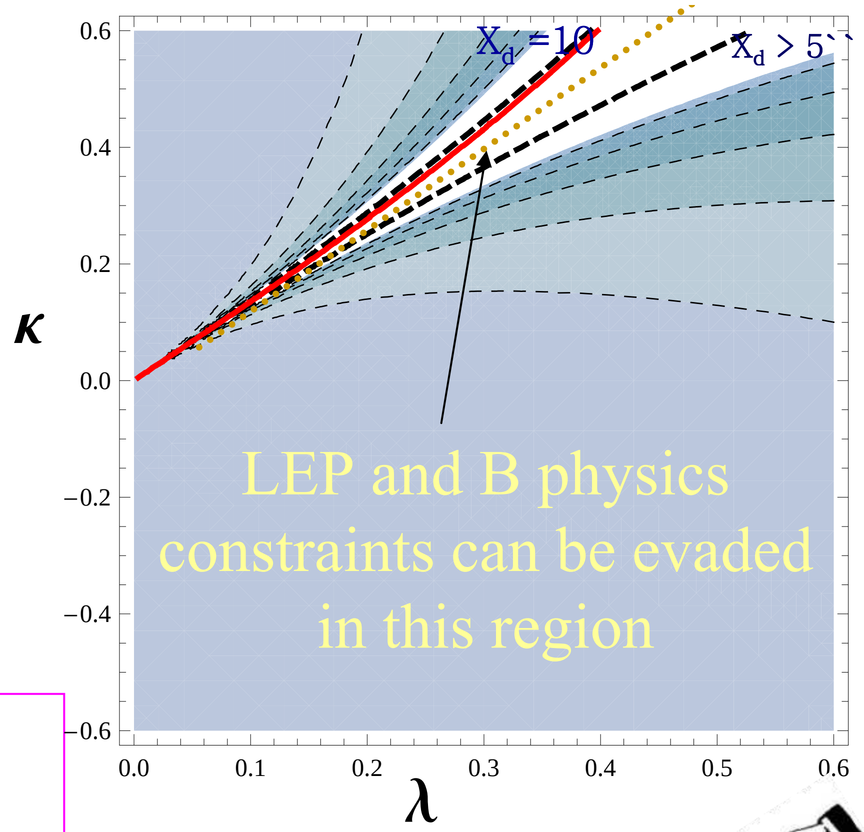
At large tanβ: $\sin 2\beta \approx \dfrac{2}{\tan\beta}$

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

$$B_{eff}, \quad (\lambda A_\lambda + \kappa\mu) \to 0$$

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

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 $\Upsilon(1S,2S,3S)$ 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 η_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)

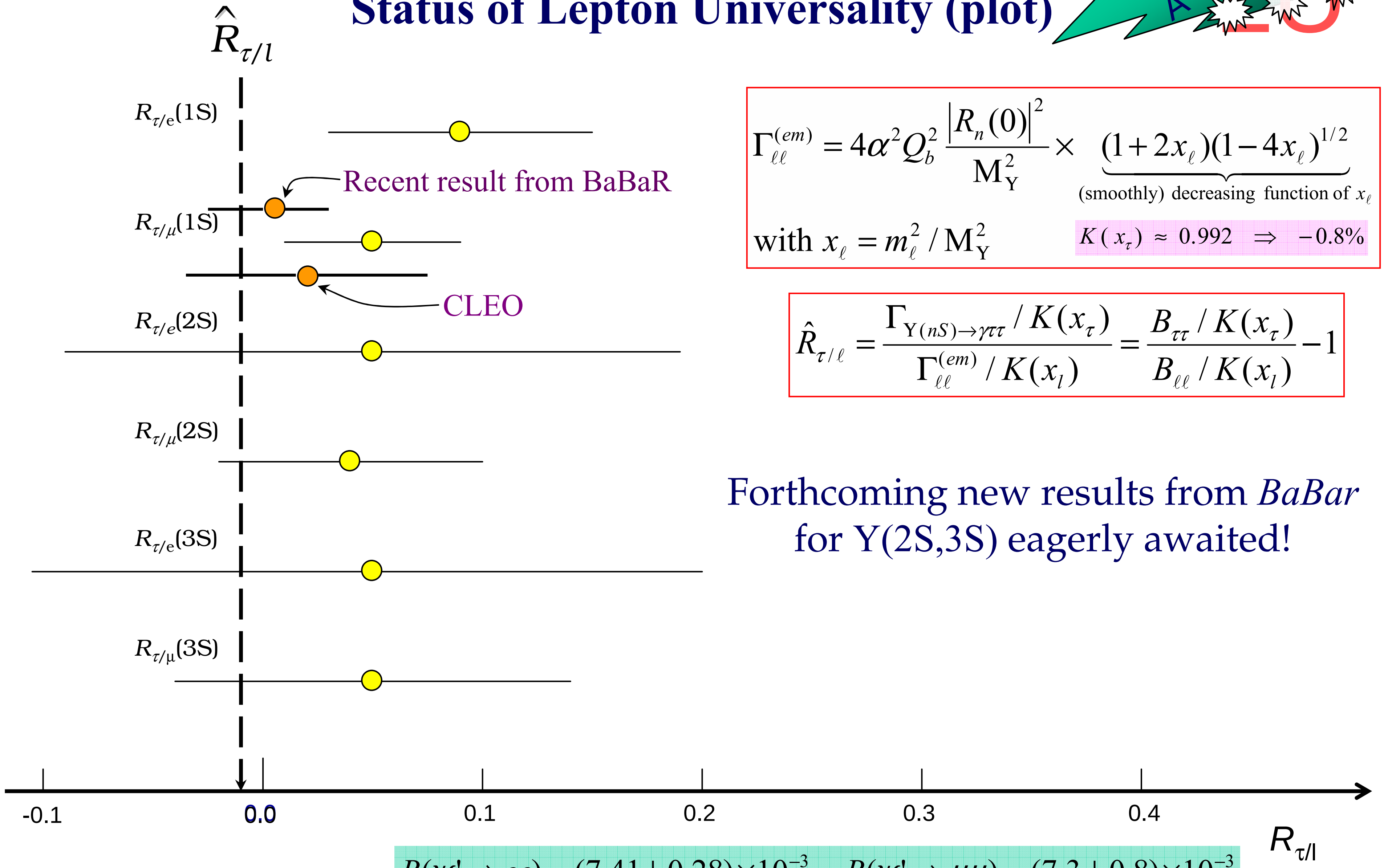
$$\text{BF}\ [\Upsilon \to e^+e^-] = \text{BF}\ [\Upsilon \to \mu^+\mu^-] = \text{BF}\ [\Upsilon \to \tau^+\tau^-]$$

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

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

Forthcoming new results from *BaBar* for Y(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 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

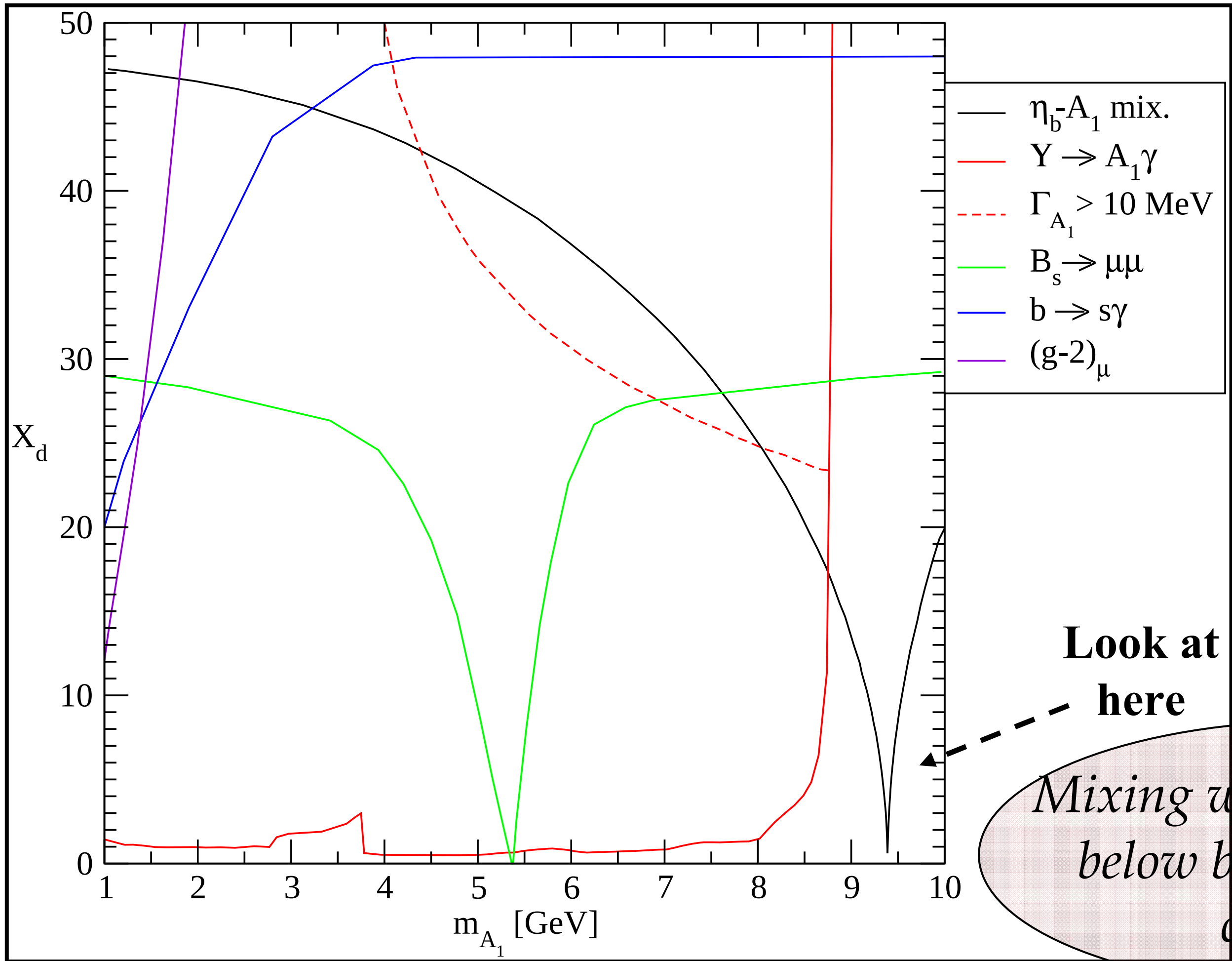
$$\boxed{\Upsilon(nS) \to \gamma\ \eta_b(n'S)\ [\to A_1^* \to \tau^+\ \tau^-\ ]}$$

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

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



Look at here

Mixing with η_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

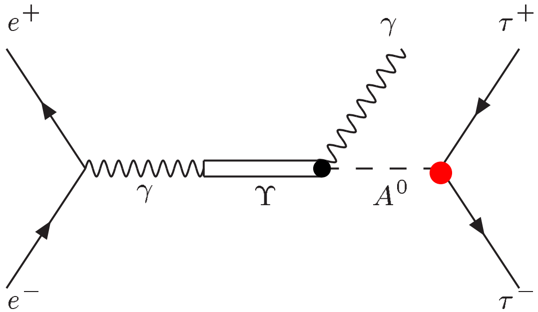
BaBar discovery of $\eta_b(1S)$ puts limits about 9.4 GeV

Mixing of a pseudoscalar Higgs A_1 and a η_b resonance

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

Drees & Hikasa
PRD 41 (1990) 1547

hep-ph/0702190

a)


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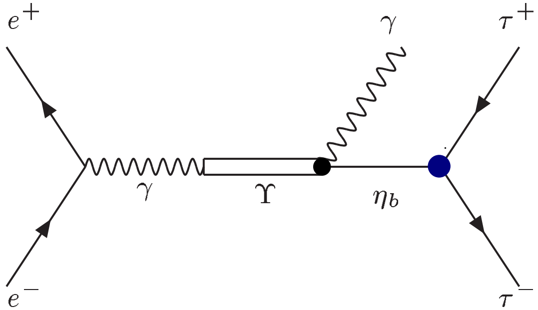
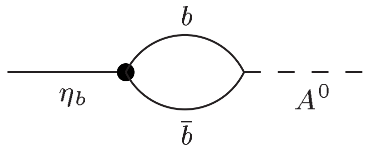


c)


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

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

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

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

Resonant and non-resonant decays with 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.

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

$$R_{\tau/\ell} = \overbrace{\frac{B[\Upsilon(nS)\to\gamma A_1]}{B[\Upsilon(nS)\to\ell^+\ell^-]}\times B[A_1\to\tau^+\tau^-]}^{\textit{Non-resonant}} + \underbrace{\frac{B[\Upsilon(nS)\to\gamma\eta_b(kS)]}{B[\Upsilon(nS)\to\ell^+\ell^-]}\times B[\eta_b(kS)\to\tau^+\tau^-]}_{\textit{Resonant}}$$

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

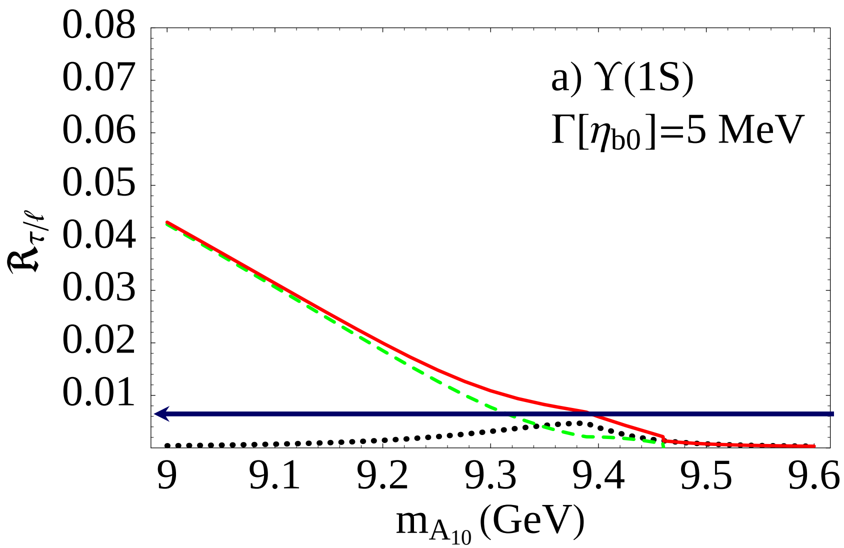
Mixing effect in the decay

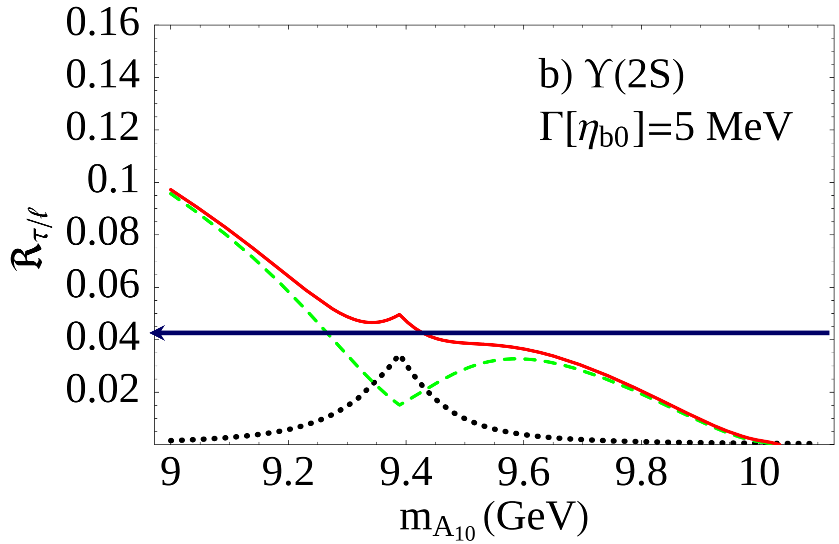
$$B[\eta_b(nS)\to\tau\tau] = B[A_{10}\to\tau\tau]\times\frac{\sin^2\alpha\Gamma_{A_{10}}}{\cos^2\alpha\Gamma_{A_{10}}+\sin^2\alpha\Gamma_{\eta_{bo}}}$$

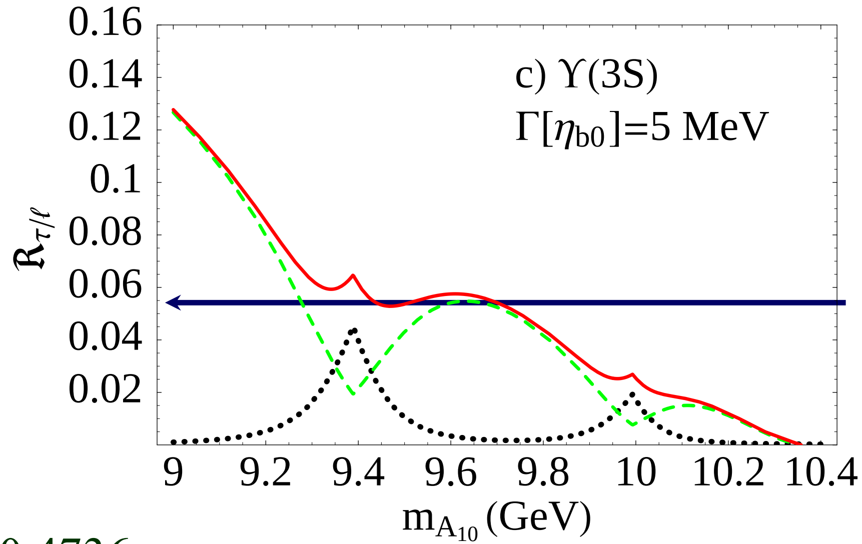
hep-ph/0702190 arXiv: 0810.4736

Expected LU breaking

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







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

"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)

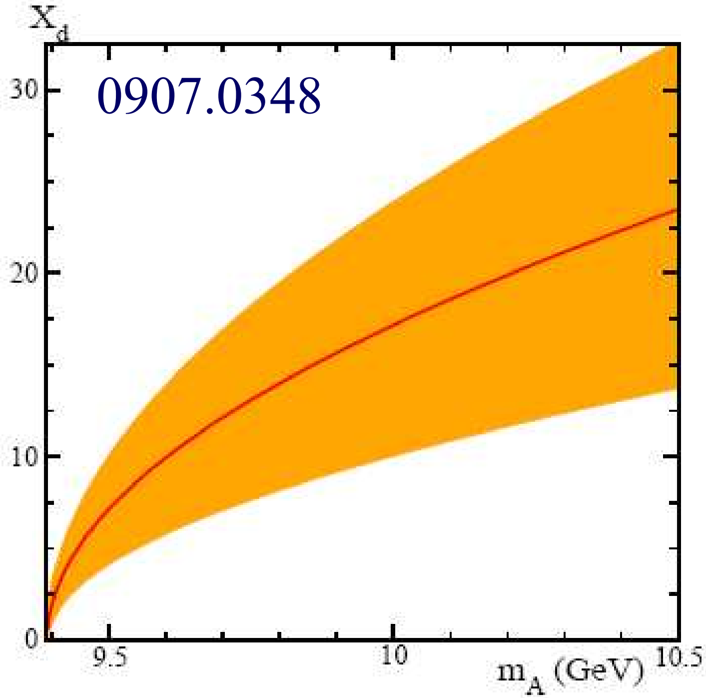


FIG. 1: X_d as a function of m_A (in GeV) such that one eigenvalue of $\mathcal{M}^2$ coincides with the BABAR result (1).

Discrepancy!?

ascribed to NP on account of $A_1 - \eta_b$ mixing

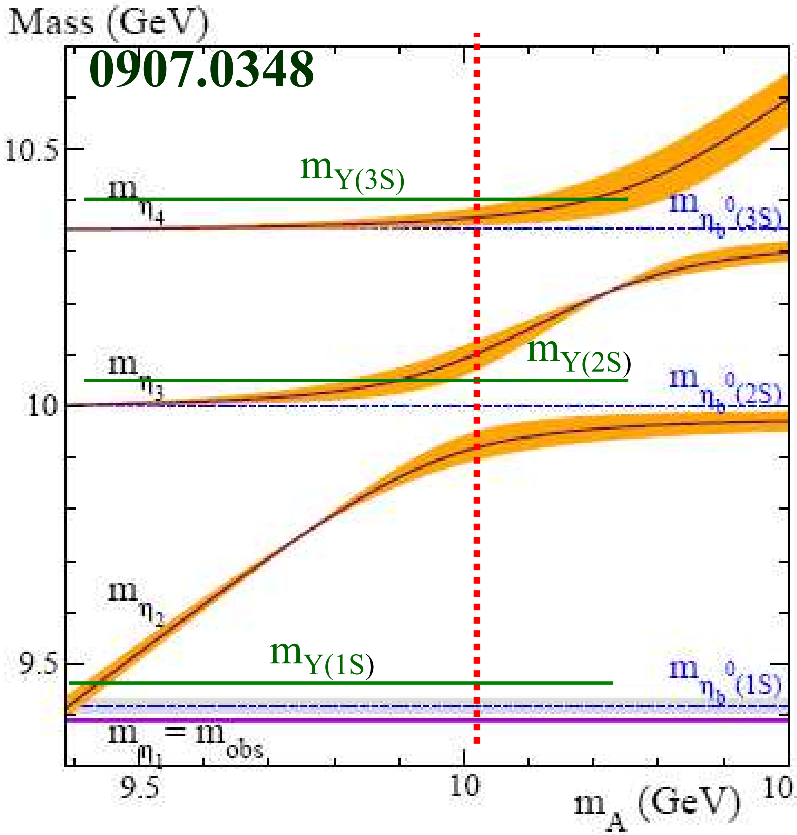
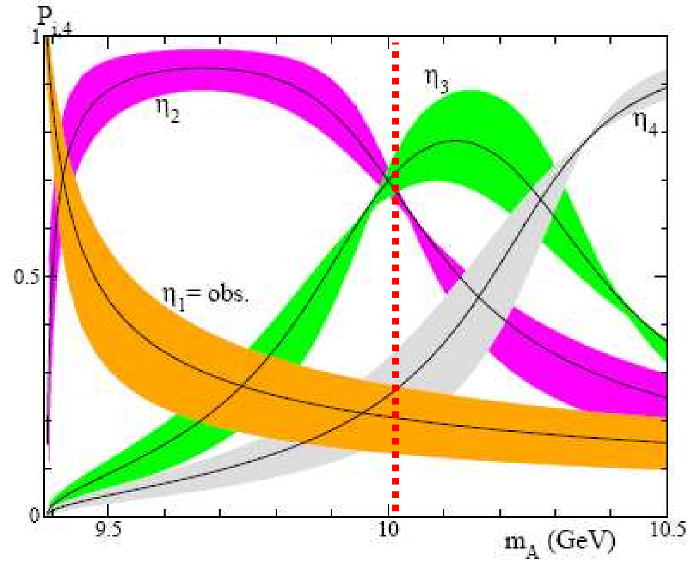
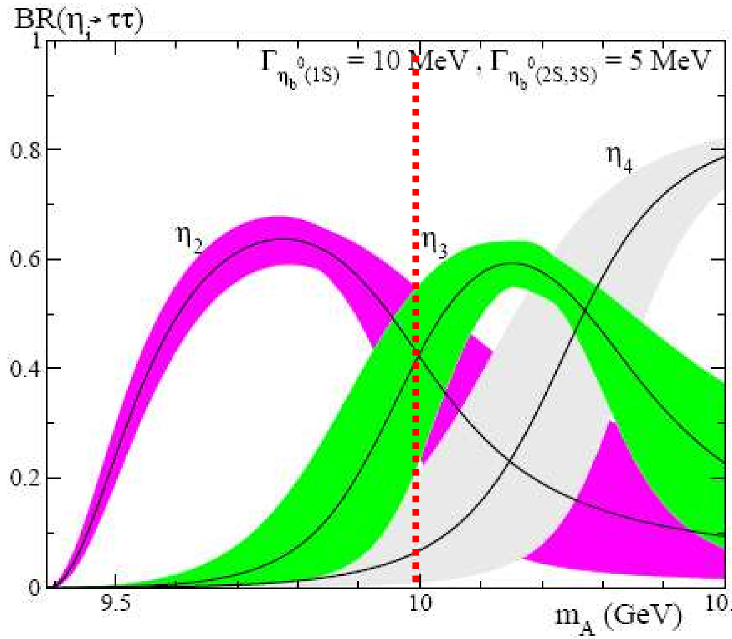


FIG. 2: The masses of all eigenstates as function of m_A.

Possible scenarios:
deeply entangled with search strategies



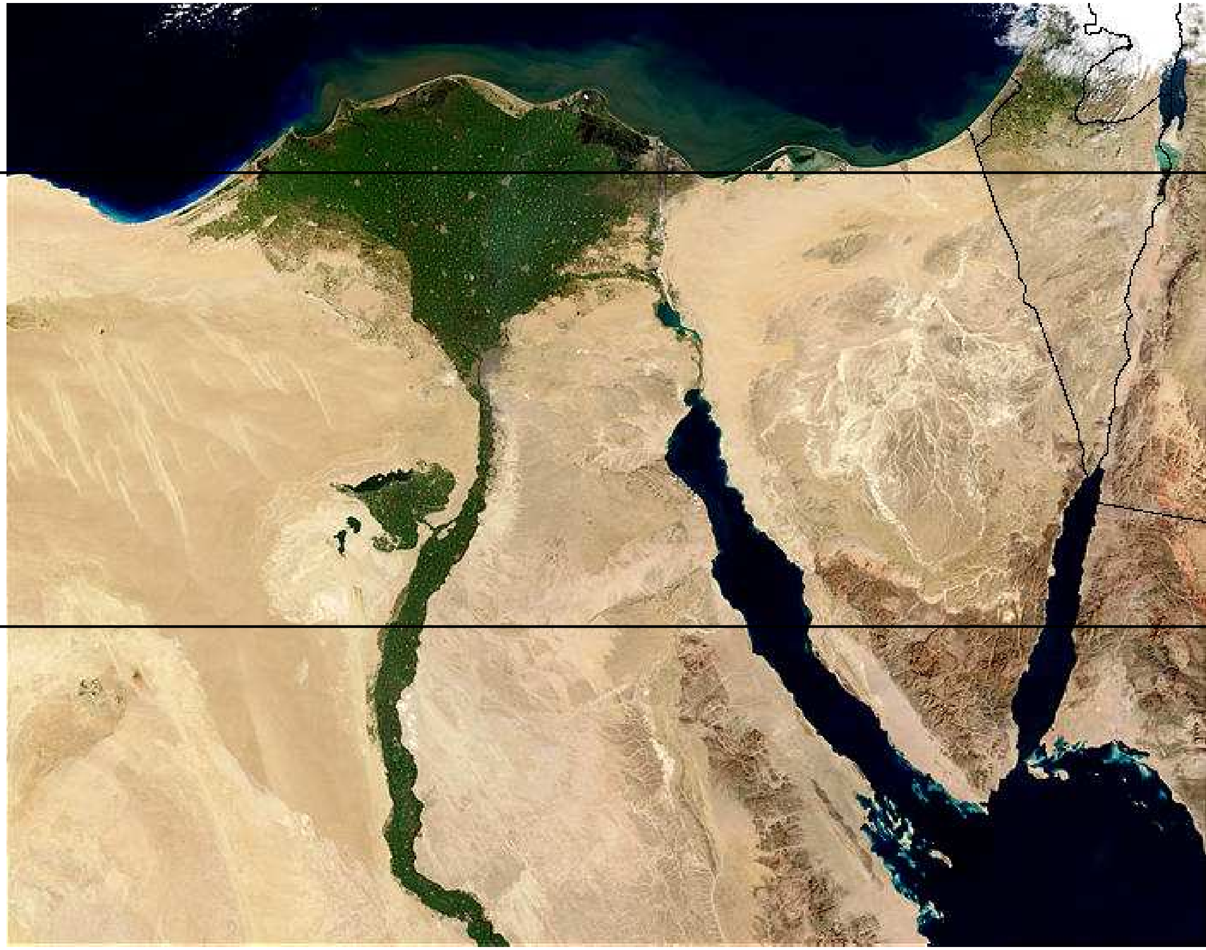
G. 3: The A-components $|P_{i,4}|$ for all 4 eigenstates as func
ns of m_A.



'IG. 4: The branching ratios into $\tau^+\tau^-$ for the eigenstates
η_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 might conclude:

The Nile river does not exist!

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 η_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,3S) decays
should be another hint of NP
LU breaking expectedly larger than for the Υ(1S)

In view of the recent findings from *DAMA* and *CoGeNT*
the search for light **dark matter** should be pursued
at (Super) B factories covering as much mass interval as possible

Implications for muon g-2 anomaly

Thank you!

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

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

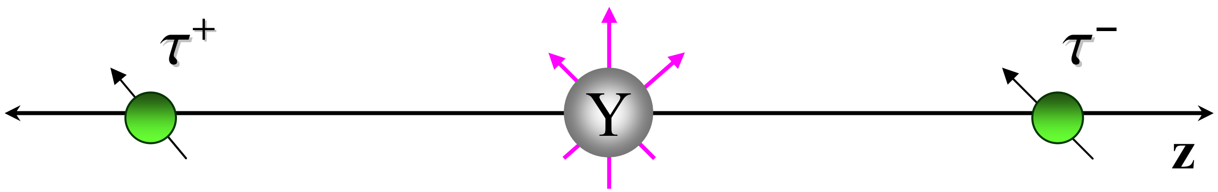
Coupling of A_1 to down type fermions:

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

[hep-ph/0404220]

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

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



- For transverse polarization of $\Upsilon(nS)$, the helicity of leptons gives no difference

- For longitudinal polarization of $\Upsilon(nS)$, **lepton helicity** favours the tauonic mode

  (as e.g. in $\pi \to \mu\,\nu_\mu$ versus $\pi \to e\,\nu_e$)

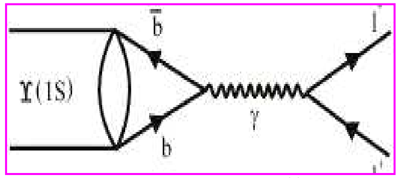
- **Phase space** favours the muonic decay mode

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

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

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

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

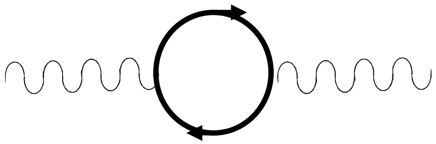
- To order α^3: $\Gamma_{ll} = \Gamma_{ll}^{\,0}[\,1+\delta_{vac}+\delta_{vertex}\,] \sim \Gamma_{ll}^{\,0}[\,1+\delta_{vac}\,]$

$3\alpha/4\pi \sim 0.17\%$

7.6%

Warning!

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



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

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

Resonant and non-resonant decays without mixing

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

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*

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

- *Resonant decay*

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

Wavefunction overlap

M1 transition probability

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

Naïve view!

Dark matter: bounds from B factories

BaBar

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

arXiv:0908.2840 [hep-ex]

scalar mediator

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

(pseudo) scalar mediator

arXiv:0808.0017 [hep-ex]

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

$$\boxed{2m_\chi \sim m_{A_1} \sim 10\,\mathrm{GeV}}$$

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

NOT YET EXCLUDED by B factories searches

Small photon energy
Detection not that easy!