Test of lepton universality
in Upsilon Decays:

Searching for a light Higgs boson

Miguel A. Sanchis-Lozano*

Department of Theoretical Physics & IFIC
University of Valencia – CSIC
Spain

*email: mas@IFIC.uv.es
### Testing Lepton Universality

BF(\(\Upsilon \rightarrow e^+ e^-\)) \(\neq\) BF(\(\Upsilon \rightarrow \mu^+ \mu^-\)) \(=\) BF(\(\Upsilon \rightarrow \tau^+ \tau^-\))

<table>
<thead>
<tr>
<th>Channel: *</th>
<th>BF(e^+e^-)</th>
<th>BF((\mu^+ \mu^-))</th>
<th>BF((\tau^+ \tau^-))</th>
<th>(R_{\tau/\ell}(\text{nS}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Upsilon(1S))</td>
<td>2.38 ± 0.11 %</td>
<td>2.66 ± 0.11 %</td>
<td>0.12 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(1S))</td>
<td>2.48 ± 0.06 %</td>
<td>2.66 ± 0.11 %</td>
<td>0.07 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(2S))</td>
<td>1.92 ± 0.17 %</td>
<td>2.03 ± 0.28 %</td>
<td>0.06 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(2S))</td>
<td>1.93 ± 0.17 %</td>
<td>2.03 ± 0.28 %</td>
<td>0.05 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(3S))</td>
<td>1.92 ± 0.24 %</td>
<td>2.51 ± 0.26 %</td>
<td>0.31 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(3S))</td>
<td>2.18 ± 0.21 %</td>
<td>2.51 ± 0.26 %</td>
<td>0.15 ± 0.15</td>
<td></td>
</tr>
</tbody>
</table>

*Obtained from recent CLEO data and already existing PDG values
Statistical and systematic (conservative) errors are summed in quadrature
Error bars should decrease according to CLEO on-going analysis
New results from CLEO expected very soon

\[<R_{\tau/\ell}> = 0\]

\[R_{\tau/\ell}(\text{nS}) = \frac{\Gamma_{\Upsilon(nS)\rightarrow\tau^+\tau^-}}{\Gamma_{\ell\ell}^{(em)}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1\]
Lepton Universality Breaking?

**Hypothesis test**

Null hypothesis: lepton universality predicting $<R_{\tau/l}> = 0$

Alternative hypothesis: $<R_{\tau/l}> > 0$

From this set of data Lepton Universality can be rejected at a level of significance of 1%.

Flavour in the LHC era
May 15-17 CERN

Miguel A. Sanchis-Lozano
IFIC-Valencia
(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.

\[
B_{ee} = B_{\mu\mu} = B_{\tau\tau}
\]

\[
B_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_Y} = \frac{\tilde{B}_{\mu\mu}}{1 + 3\tilde{B}_{\mu\mu}} \quad \Rightarrow \quad B_{\mu\mu} = \frac{\tilde{B}_{\mu\mu}}{1 + B_{ee} + B_{\mu\mu} + B_{\tau\tau}}
\]

☆ The muonic branching fraction would be **overestimated** if \( \tilde{B}_{\mu\mu} \leq \tilde{B}_{\tau\tau} \).

\[
B_{ee} = B_{\mu\mu} = B_{\tau\tau}
\]

\[
B_{\tau\tau} = \frac{\Gamma_{\tau\tau}}{\Gamma_Y} = \frac{\tilde{B}_{\tau\tau}}{1 + 3\tilde{B}_{\tau\tau}} \quad \Rightarrow \quad B_{\tau\tau} = \frac{\tilde{B}_{\tau\tau}}{1 + B_{ee} + B_{\mu\mu} + B_{\tau\tau}}
\]

☆ The tauonic branching fraction would be **underestimated** if \( \tilde{B}_{\mu\mu} \leq \tilde{B}_{\tau\tau} \).

☆ Besides phase space disfavors the tauonic decay mode by \( \sim 1\% \) (Van-Royen Weisskopf formula).
**Searching for a light non-standard Higgs**

Our conjecture to interpret a possible Lepton Universality breakdown

\[ \Upsilon(nS) \rightarrow \gamma_s \ A^0 \rightarrow \ell^+\ell^- \]

\[ \Upsilon(nS) \rightarrow \gamma_s \ \eta_b^{(*)} \rightarrow A^0 \rightarrow \ell^+\ell^- \]

\[ \Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q^2_b \left| R_n(0) \right|^2 \frac{M^2_Y}{M^2_W} \left( 1 + 2x_\ell \right) \left( 1 - 4x_\ell \right)^{1/2} \]

with \( x_\ell = m^2_\ell / M^2_Y \)

Van Royen-Weisskopf formula

(n=1,2,3 and \( A^0 \) stands for a light (possibly CP-odd) Higgs particle

**Key ideas:**

- Such NP contribution would be unwittingly ascribed to the leptonic branching fraction (photon undetected!*) actually only for the tauonic decay mode.

- A leptonic mass dependence of the decay width would break lepton universality. Contribution from the SM should be negligible.

*Missing energy technique employed
But photons can be searched for in data recorded on tape
However, they likely would not be monochromatic!

Notice that a light non-standard Higgs boson has not been excluded by LEP direct searches for a broad range of model parameters in different scenarios
Two-Higgs Doublet Model (II)

Higgs sector

\[ \hat{H}_u = \begin{pmatrix} H^+_u \\ H^0_u \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} H^+_d \\ H^0_d \end{pmatrix} \]

Coupling of fermions and the CP-odd Higgs $A^0$

In a 2HDM of type II

\[ L^{\tau \mu}_{\text{int}} = -\tan \beta \frac{A^0}{v} \begin{pmatrix} m_f \\ (i \gamma_5) d \end{pmatrix}, \quad d = d, s, b, \ell, \mu, \tau \]

\[ L^{\nu \nu}_{\text{int}} = -\cot \beta \frac{A^0}{v} \begin{pmatrix} m_f \\ (i \gamma_5) u \end{pmatrix}, \quad u = u, c, t, \nu_e, \nu_\mu, \nu_\tau \]

A large value of $\tan \beta$ would imply a large $A^0$ coupling to the bottom quark but a small coupling (i.e. small $\cot \beta$) to the charm quark. Therefore, in the quest for NP effects we will focus on bottomonium decays and spectroscopy but not on charmonium as this is the case (see PDG)

CPV MSSM

At one-loop level, MSSM with complex parameters is not CP conserving

The three Higgs neutral bosons mix together and the resulting three physical mass eigenstates $H_1$, $H_2$ and $H_3$ ($M_{H1} < M_{H2} < M_{H3}$) have mixed parities

Higgs couplings to the Z boson would vary: the $H_1ZZ$ coupling can be significantly suppressed raising the possibility of a relatively light $H_1$ boson having evaded detection at LEP [hep-ph/0211467]

Other scenarios

- composite Higgs [hep-ph/0008192]
- extra dimensions: e.g. graviscalars, radions [hep-ph/9811350], little Higgs models

---

*The MSSM is a particular 2HDM(II) realization

**CPC:**
- 1 CP-odd Higgs ($A^0$)
- 2 CP-even Higgses

\[ h^0 = -\eta_1 \sin \alpha + \eta_2 \cos \alpha \]

\[ H^0 = \eta_1 \sin \alpha - \eta_2 \cos \alpha \]

- 2 charged $H^\pm$

At tree level:

\[ M_{H^\pm}^2 = M_{A^0}^2 + M_{W^\pm}^2 \]

In a general 2HDM:

\[ M_{H^\pm}^2 = M_{A^0}^2 + \frac{1}{2} (\lambda_3 - \lambda_4) v^2 \]

$\tan \beta$ stands for the 2 Higgs VEVs ratio $<H_u>/<H_d>$ and $v=246$ GeV
Light Higgs windows at LEP (2HDM(II))

Excluded $(m_A, m_h)$ region independent of the CP even Higgs mixing angle $\alpha$, from flavor-independent and b-tagging searches at LEP interpreted according to a 2HDM(II)

Excluded regions in the $(m_A, \tan\beta)$ plane for different choices of $\alpha$. In the MSSM $-\pi/2 \leq \alpha \leq 0$; in a general 2HDM(II) $-\pi/2 \leq \alpha \leq \pi/2$.
Light Higgs windows at LEP (MSSM CPV)

Diagram illustrating the effective coupling of a Higgs mass eigenstate $H_1$ to the $Z$. Only the CP-even admixture $h$ and $H$ couple to $Z$ while the CP-odd $A$ does not: hence the coupling of the $H_1$ is reduced wrt a CPC scenario.

CPX MSSM 95% exclusion areas using scans with different values of $\arg(A_{t,b})$. The region excluded by Yukawa searches, $Z$-width constraints or decay independent searches is shown in red.
A new singlet superfield is added to the Higgs sector:

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

The \( \mu \) problem of the MSSM would be solved by introducing in the superpotential the term

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

where \( \mu = \lambda x, \quad x = \langle S \rangle = \mu / \lambda \)

leading to a light CP-odd scalar for small \( \kappa \), i.e. slight U(1) Peccei-Quinn symmetry breaking

Spontaneous breaking \( \rightarrow \) NGB (massless), an “axion” (+QCD anomaly) ruled out experimentally

If the PQ symmetry is not exact but explicitly broken \( \rightarrow \) provides a mass to the (pseudo) NGB

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\(^\pm\))

For small \( \kappa \) the A\(_1\) would be the lightest Higgs:

\[
M^2_{A_1} \equiv -3 \left( \frac{\kappa}{\lambda} \right) A \mu
\]

Favored decay mode: \( H_{1,2} \rightarrow A_1 A_1 \)

hard to detect at the LHC [hep-ph/0406215]

\[
A_1 = \cos \theta_A A_{\text{MSMS}} + \sin \theta_A A_s
\]

Coupling of A\(_1\) to down type fermions: [hep-ph/0404220]

\[
\sim \frac{m_f^2 v}{x} \delta, \quad \Rightarrow \cos \theta_A \tan \beta
\]

\[
\cos^2 \theta_A \equiv \frac{v^2}{x^2 \tan^2 \beta} \delta^2, \quad \delta = \frac{A \lambda - 2 \kappa x}{A \lambda + \kappa x}
\]
Let us perform a perturbative calculation of the contribution from the “continuum”, i.e. without formation of intermediate $b\bar{b}$ bound states assuming the Higgs boson off-shell.

$$\Gamma(Y \rightarrow \gamma \ell^+\ell^-) = \frac{1}{32M_Y^2 (2\pi)^3} \int |A(Y \rightarrow \gamma \ell^+\ell^-)|^2 \, dm^2_{\ell\ell} \, dm^2_{\gamma} \quad \text{for} \quad M_Y \leq M_{A^0}$$

where the square amplitude is

$$|A(Y \rightarrow \gamma \ell^+\ell^-)|^2 = \frac{64 \alpha m^2_{\ell\ell} m^2_\tau |R_n(0)|^2 \tan^4 \beta}{9 M_Y^2 [m^2_{\ell\ell} - M^2_A]^2 v^4}$$

and the decay width (leading term):

$$\Gamma[Y(nS) \rightarrow \gamma \ell^+\ell^-] \approx \frac{\alpha |R_n(0)|^2 \tan^4 \beta}{144\pi^3 v^4} \left[ \log\left( \frac{M^2_{A^0}}{M^2_{A^0} - M^2_Y} \right) - 1 \right] \times m^2_\tau, \quad M_{A^0} > M_Y$$

One should also consider:

$$\gamma(nS) \rightarrow \gamma A^0 (\rightarrow \tau^+ \tau^-)$$

Higgs boson on-shell

$$M_{A^0} \leq M_Y$$

Experimentally excluded region $\gamma \rightarrow \gamma + "nothing":$

$$\text{BF} < 1.3 \times 10^{-5} \text{ for } M_{A^0} < 5 \text{ GeV}$$

[CLEO, PRD 51, 2053 (1995)]

Flavour in the LHC era
May 15-17 CERN

Miguel A. Sanchis-Lozano
IFIC-Valencia
We consider that a prior magnetic dipole transition of the Upsilon yields an intermediate bound state, subsequently annihilating into a lepton pair via $A^0$ (or $H_1$)-exchange.

$$\Upsilon(nS) \rightarrow \gamma_s \eta_b \left( \rightarrow A^{0*} (H_1^*) \rightarrow l^+ l^- \right)$$

In a 2HDM(II) intermediate real $0^+$ state

$$\Gamma(\eta_b \rightarrow \ell^+ \ell^-) = \frac{3m^4_\ell m^2_\eta (1-4x_\ell)\frac{1}{2} |R_n(0)|^2 \tan^4 \beta}{2\pi^2 (M^2_{\eta_b} - M^2_{A^0})^2 \nu^4}$$

The NP contribution would almost saturate the $\eta_b$ decay rate even for moderate $\tan \beta$ if $\Delta M$ is not too large!

Mass difference between the Higgs boson and the $\eta_b$

$$\Delta M = |M_{A^0} - M_{\eta_b}|$$

Numerical estimates

For $\tan \beta \geq 30$ and $\Delta M=0.25$ GeV

$$B(Y(\rightarrow \gamma_s \ell^+ \ell^-)) \equiv B(Y(\rightarrow \gamma_s \eta_b)) \times B(\eta_b \rightarrow \ell^+ \ell^-)$$

$$B(Y(\rightarrow \gamma_s \eta_b)) = \frac{\Gamma_{Y(\rightarrow \gamma_s \eta_b)}}{\Gamma_Y} = \frac{1}{\Gamma_Y} \times \frac{4\alpha I_Q^2 \eta_b (3\sec^2 k^3)}{3m^2_\eta_b}$$

$$P^Y(\eta^*_b \gamma_s) \approx 10^{-3} - 10^{-4}$$

Allowed and hindered M1 Transitions between $\Upsilon(3S), \Upsilon(2S)$ and $\Upsilon(1S)$ States

$\sim 600$ MeV

$\sim 1000$ MeV

$\sim 100$ MeV

$\Delta M$ (GeV)
Numerical estimates

A light CP-even Higgs boson is not excluded by LEP searches for parameter ranges of a 2HDM

A CP-even Higgs boson can couple to an intermediate $\chi_{b0}$ resonance after an E1 transition of the $\Upsilon$

**Cascade decay via $\chi_{b0}$ resonances**

$h$ - $b\bar{b}/\ell^+\ell^-$ coupling: $\frac{\sin\alpha}{\cos\beta} = \sin(\alpha - \beta) - \tan \beta \cos(\beta - \alpha)$

$h^0$-mediated decay width under the assumption that $\sin(\alpha-\beta) \approx 0$

i.e. non-decoupling limit: $h^0$ couplings deviate maximally from SM whereas the $H^0$ becomes a SM-like Higgs:

$$\Gamma(\chi_{b0} \to \ell^+\ell^-) = \frac{27m_b^2m_{\ell}^2(1-4x_{\ell})^{3/2}|R'_n(0)|^2\tan^4\beta}{8\pi^2(M_{\chi_{b0}}^2 - M_{A^0}^2)^2v^4}$$

Normalizing the above partial width to

$$\Gamma_{\chi_{b0}} \approx \Gamma[\chi_{b0} \to gg] = \frac{96\alpha_s^2|R'_n(0)|^2}{M_{\chi_{b0}}^4}$$

setting $\alpha_s(M_t) = 0.15$ and $|R'_n(0)|^2 = 1.5 \text{ GeV}^5$ → $\Gamma_{\chi_{b0}} \approx 320 \text{ keV}$

Using $\Delta M = 0.25 \text{ GeV}$, $\tan\beta = 15 \rightarrow B(\chi_{b0} \to \tau^+\tau^-) \approx 6\%$ and $B(\Upsilon \to \gamma \chi_{b0}) \approx 3-6\%$ (PDG) as reference values, we get:

$B(Y \to \gamma_s \tau^+\tau^-) \approx B(Y \to \gamma_s \chi_{b0}) \times B(\chi_{b0} \to \tau^+\tau^-) \equiv 0.002 - 0.003$

Again only for the tauonic mode would the NP contribution be significant leading to lepton universality breaking!

Decay channel open only for $\Upsilon$(2S) and $\Upsilon$(3S) resonances
Possible spectroscopic consequences in bottomonium

Searches for $\eta_b$ states at CLEO: **No signal found!**

- **Broad $\eta_b$ states?** Widths of order 50 MeV could be expected even for moderate values of $\tan\beta$ ($\sim 30$)

- **$A^0$-$\eta_b$ mixing?** Mass shift yielding larger hyperfine splitting than expected in the SM (i.e. more than $\sim 100$ MeV).

  Higgs Yukawa couplings to fermions can be affected too, allowing quite large $\tan\beta$ for special Higgs mass values

  Drees and Hikasa, PRD 41, 1547 (1990)

If $\eta_b$ decay happens to be saturated by the $A^0$-mediated channel $\eta_b \rightarrow A^0 \rightarrow \tau^+ \tau^-$

The search for $\eta_b$ states would be a way of hunting a light non-standard Higgs!

Most theoretical models are ruled out!

**Flavour in the LHC era**
May 15-17 CERN
Miguel A. Sanchis-Lozano
IFIC-Valencia
If lepton universality is found to be (slightly) broken in Upsilon decays, the simplest explanation would require a light non-standard mediated Higgs contribution (subsequent to a M1 transition of the $\Upsilon$ resonance) unwittingly ascribed to the tauonic decay mode

- Reasonable values of $\tan\beta$ in a 2HDM(II) are needed to yield $R_{v\ell}$ of order 10%
- Different scenarios beyond the SM could explain such a LU breaking
- Further exp tests suggested: - search for soft (non-monochromatic) photons in the $\tau^+\tau^-$ sample of Upsilon decays
- seek after the $\eta_b$ resonance
- polarization studies of the tau...

If not, those light Higgs mass windows could be closed!

Relevance of a Super B Factory running on the $\Upsilon$ region !!!
Complementary to other searches at the LHC

Keep also an eye on the related issues:
- g-2 muon anomaly (which might require a CP-odd light Higgs contribution in a two-loop calculation)
- Searches for dark matter in the universe
Light Neutralino Dark Matter

- Neutralino dark matter is generally assumed to be relatively heavy, with a mass near the electroweak scale.

- It has been shown, however, that the claims of dark matter detection made by DAMA can be reconciled with null results of CDMS II if one considers a WIMP lighter than approximately 10 GeV [hep-ph/0504010].

- A very light CP-odd Higgs can make possible a very light neutralino to annihilate via such a light Higgs boson exchange [hep-ph/0509024]

\[ \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow A^0 \rightarrow \text{pions} \rightarrow \text{muons} \rightarrow \text{positrons} \]

leading to low-energy positrons which would generate the 511 keV gamma-ray emission observed from the galactic bulge by INTEGRAL/SPI experiment.
The 2σ allowed regions in the $(m_A, m_h)$ plane due to the constraints of $a_\mu$ and $R_\mu$ for $\tan\beta=40$. The blue region is where the total $\chi^2$ is less than 4 while the yellow region is where the total $\chi^2$ is less than the $\chi^2$ (SM).
MSSM (CPV)

- The Higgs potential is explicitly CP-conserving if all Higgs potential parameters are real. Otherwise, CP is explicitly violated.
- CP-violation is generated by loop effects involving top and bottom squarks.
- CP-violation can modify drastically the tree-level couplings of the Higgs particles to fermions and gauge bosons.
- The CP parities of the neutral Higgs bosons may be mixed by radiative effects involving the third generation of squarks.
- Under CP violation, the mass of the CP-odd Higgs scalar is no longer an eigenvalue but rather an entry in a general 3 x 3 neutral Higgs mass matrix.

\[ M_{SP} \sim m_t^4 \text{Im}(\mu A_t) / v^2 M_{SUSY}^2 \]

where
\( \mu \) is the mixing parameter of the two Higgs superfields.
\( A_t \) denotes the soft SUSY-breaking trilinear coupling of the Higgs bosons to top squarks.
\( v = 246 \text{ GeV} \) VEV of the Higgs.
\( M_{SUSY} \) stands for the common SUSY-breaking scale.
Testing Lepton Universality

\[ BF(\Upsilon \rightarrow e^+ e^-) = BF(\Upsilon \rightarrow \mu^+ \mu^-) = BF(\Upsilon \rightarrow \tau^+ \tau^-) \]

<table>
<thead>
<tr>
<th>Channel: *</th>
<th>[BF(e^+ e^-)]</th>
<th>[BF(\mu^+ \mu^-)]</th>
<th>[BF(\tau^+ \tau^-)]</th>
<th>[R_{\tau/\ell}(nS)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Upsilon(1S))</td>
<td>2.38 ± 0.11 %</td>
<td>2.60 ± 0.13 %</td>
<td>0.09 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(1S))</td>
<td>2.48 ± 0.06 %</td>
<td>2.60 ± 0.13 %</td>
<td>0.05 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(2S))</td>
<td>1.92 ± 0.17 %</td>
<td>2.11 ± 0.15 %</td>
<td>0.10 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(2S))</td>
<td>1.93 ± 0.17 %</td>
<td>2.11 ± 0.15 %</td>
<td>0.09 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(3S))</td>
<td>1.92 ± 0.24 %</td>
<td>2.55 ± 0.24 %</td>
<td>0.33 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>(\Upsilon(3S))</td>
<td>2.18 ± 0.21 %</td>
<td>2.55 ± 0.24 %</td>
<td>0.17 ± 0.15</td>
<td></td>
</tr>
</tbody>
</table>

\* Obtained from recent CLEO data and already existing PDG values
Statistical and systematic (conservative) errors are summed in quadrature
Error bars should decrease according to CLEO on-going analysis

Lepton Universality in Upsilon decays implies
\(<R_{\tau/\ell}> = 0\)

\[ R_{\tau/\ell}(nS) = \frac{\Gamma_{\Upsilon(nS) \rightarrow \gamma\tau\tau}}{\Gamma_{\ell\ell}^{(em)}} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1 \]
Lepton Universality Breaking?

Hypothesis test

Null hypothesis: lepton universality predicting $\langle R_{\tau/l} \rangle = 0$

Alternative hypothesis: $\langle R_{\tau/l} \rangle > 0$

From this set of data, Lepton Universality can be rejected at a level of significance of 1%.