Lepton Flavor Violation in Quarkonium and Tau Decays

Mauro Napsuciale

Departamento de Física, Universidad de Guanajuato

November 5, 2015

In collaboration with David Delepine and Eduardo Peinado [arXiv:1509.04057]

Mauro Napsuciale
Overview

1. The Standard Model
2. CMS new results on LFV
3. $H_{\mu\tau}$ induced decays
4. Quarkonium non-relativistic techniques
5. Calculation of the $H_{\mu\tau}$ LFV decays
6. conclusions
Modelo Estándar

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \]

<table>
<thead>
<tr>
<th>Boson</th>
<th>spin</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs</td>
<td>0</td>
<td>125.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2</th>
<th></th>
<th>Quarks</th>
<th>spin = 1/2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c^2</td>
<td>Electric charge</td>
<td>Flavor</td>
<td>Approx. Mass GeV/c^2</td>
<td>Electric charge</td>
</tr>
<tr>
<td>( \nu_e ) electron neutrino</td>
<td>&lt;1×10^{-8}</td>
<td>0</td>
<td>( u ) up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>( e ) electron</td>
<td>0.000511</td>
<td>-1</td>
<td>( d ) down</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>( \nu_\mu ) muon neutrino</td>
<td>&lt;0.0002</td>
<td>0</td>
<td>( c ) charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>( \mu ) muon</td>
<td>0.106</td>
<td>-1</td>
<td>( s ) strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>( \nu_\tau ) tau neutrino</td>
<td>&lt;0.02</td>
<td>0</td>
<td>( t ) top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>( \tau ) tau</td>
<td>1.7771</td>
<td>-1</td>
<td>( b ) bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong (color)</th>
<th>spin = 1</th>
<th></th>
<th>Unified Electroweak</th>
<th>spin = 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass GeV/c^2</td>
<td>Electric charge</td>
<td>Name</td>
<td>Mass GeV/c^2</td>
<td>Electric charge</td>
</tr>
<tr>
<td>g</td>
<td>0</td>
<td>0</td>
<td>( \gamma ) photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( W^- )</td>
<td>80.4</td>
<td>-1</td>
<td>( W^+ )</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>( Z^0 )</td>
<td>91.187</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mixing in the quark sector
Weak interaction eigenstates differ from the mass eigenstates
Mixing in the lepton sector

Neutrinos oscillate changing flavor...but charged leptons do not!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$$

$$e \leftrightarrow \mu \leftrightarrow \tau$$
Charged lepton flavor violation occurs at one loop level in the SM but it is highly suppressed.

\[ B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} |\sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu i}^2}{m_W^2}|^2 \approx 10^{-54} \]

This is an example of a highly suppressed LFV process in the SM. New physics can provide mechanisms yielding a larger decay rate.
Where to look for LFV?

- LFV leptonic decays
  1. radiative: $l_i \rightarrow l_j \gamma$
  2. leptonic: $l_i \rightarrow l_j l_k l_k$
  3. semi-leptonic: $l_i \rightarrow l_j M$, $l_i \rightarrow l_j M_1 M_2$

- $\mu - e$ conversion in nuclei

- Higgs and gauge boson decays:
  1. $Z \rightarrow l_i l_j$
  2. $H \rightarrow l_i l_j$

- Quarkonium decays:
  1. $V \rightarrow l_i l_j$
Searches for LFV processes: leptonic decays

<table>
<thead>
<tr>
<th>LFV process</th>
<th>Present best UL (90% CL)</th>
<th>Future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\mu \rightarrow e\gamma)$</td>
<td>$1.2 \times 10^{-11}$ [MEGA 1999]</td>
<td>$10^{-13} - 10^{-14}$ [MEG]</td>
</tr>
<tr>
<td>$\mathcal{B}(\mu \rightarrow e\gamma)$</td>
<td>$2.8 \times 10^{-11}$ [MEG 2010]</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow e\gamma)$</td>
<td>$3.3 \times 10^{-8}$ [BaBar 2010]</td>
<td>$3 \times 10^{-9}$ [SuperB]</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu\gamma)$</td>
<td>$4.4 \times 10^{-8}$ [BaBar 2010]</td>
<td>$2.4 \times 10^{-9}$ [SuperB]</td>
</tr>
<tr>
<td>$\mathcal{B}(\mu \rightarrow e\bar{e}e)$</td>
<td>$1 \times 10^{-12}$ [SINDRUM 1988]</td>
<td>$10^{-13} - 10^{-14}$ [MEG]</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow e\bar{e}e)$</td>
<td>$2.7 \times 10^{-8}$ [Belle 2010]</td>
<td>$10^{-9} - 10^{-10}$ [SuperB]</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu\mu\bar{\mu})$</td>
<td>$2.1 \times 10^{-8}$ [Belle 2010]</td>
<td>$10^{-9} - 10^{-10}$ [SuperB]</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow e\mu\bar{\mu})$</td>
<td>$2.7 \times 10^{-8}$ [Belle 2010]</td>
<td>$10^{-9} - 10^{-10}$ [SuperB]</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau \rightarrow \mu\epsilon\bar{e})$</td>
<td>$1.8 \times 10^{-8}$ [Belle 2010]</td>
<td>$10^{-9} - 10^{-10}$ [SuperB]</td>
</tr>
</tbody>
</table>
# Searches for LFV processes: $\mu - e$ conversion and $Z$ decays

<table>
<thead>
<tr>
<th>LFV process</th>
<th>Present best UL (90% CL)</th>
<th>Future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(\mu \rightarrow e, Au)$</td>
<td>$7.0 \times 10^{-13}$ [SINDRUM2 2004]</td>
<td>$10^{-16}$ [Mu2E (Fermilab)]</td>
</tr>
<tr>
<td>$R(\mu \rightarrow e, Al)$</td>
<td></td>
<td>$10^{-16}$ [COMET (J-PARC)]</td>
</tr>
<tr>
<td>$R(\mu \rightarrow e, Ti)$</td>
<td>$4.3 \times 10^{-12}$ [SINDRUM2 2004]</td>
<td>$10^{-18}$ [PRISM/PRIME (J-PARC)]</td>
</tr>
<tr>
<td>$B(Z \rightarrow \mu^\pm e'^\mp)$</td>
<td>$1.7 \times 10^{-6}$ [LEP 1995]</td>
<td>$2 \times 10^{-9}$ [GigaZ]</td>
</tr>
<tr>
<td>$B(Z \rightarrow \tau^\pm e'^\mp)$</td>
<td>$9.8 \times 10^{-6}$ [LEP 1993]</td>
<td>$6.5\kappa \times 10^{-8}$ [GigaZ] $\kappa \in [0.2, 1]$</td>
</tr>
<tr>
<td>$B(Z \rightarrow \tau^\pm \mu'^\mp)$</td>
<td>$1.2 \times 10^{-5}$ [LEP 1997]</td>
<td>$2.2\kappa \times 10^{-8}$ [GigaZ]</td>
</tr>
</tbody>
</table>
Searches for LFV processes: Quarkonium decays

\[ B(\phi \rightarrow e\mu) < 2.0 \times 10^{-6}, \]
\[ B(J/\psi \rightarrow e\mu) < 1.6 \times 10^{-7}, \quad B(J/\psi \rightarrow e\tau) < 8.3 \times 10^{-6}, \]
\[ B(J/\psi \rightarrow \mu\tau) < 2.0 \times 10^{-6}, \quad B(\Upsilon \rightarrow \mu\tau) < 6.0 \times 10^{-7}, \]
\[ B(\Upsilon(2S) \rightarrow e\tau) < 8.3 \times 10^{-6}, \quad B(\Upsilon(2S) \rightarrow \mu\tau) < 2.0 \times 10^{-6}, \]
\[ B(\Upsilon(3S) \rightarrow e\tau) < 4.2 \times 10^{-6}, \quad B(\Upsilon(3S) \rightarrow \mu\tau) < 3.1 \times 10^{-6}, \]
Recently

Search for lepton-flavour-violating decays of the Higgs boson

The CMS Collaboration

Abstract

The first direct search for lepton-flavour-violating decays of the recently discovered Higgs boson (H) is described. The search is performed in the $H \rightarrow \mu \tau e$ and $H \rightarrow \mu \tau \tau$ channels, where $\tau_e$ and $\tau_\tau$ are tau leptons reconstructed in the electronic and hadronic decay channels, respectively. The data sample used in this search was collected in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8\text{ TeV}$ with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of 19.7 fb$^{-1}$. The sensitivity of the search is an order of magnitude better than the existing indirect limits. A slight excess of signal events with a significance of 2.4 standard deviations is observed. The $p$-value of this excess at $M_H = 125\text{ GeV}$ is 0.010. The best fit branching fraction is $B(H \rightarrow \mu \tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint on the branching fraction, $B(H \rightarrow \mu \tau) < 1.51\%$ at 95% confidence level is set. This limit is subsequently used to constrain the $\mu-\tau$ Yukawa couplings to be less than $3.6 \times 10^{-3}$.

$H\mu\tau$ coupling

$y \lesssim 3.6 \times 10^{-3}$
Same excess detected by ATLAS, but less sensitivity

Search for lepton–flavour–violating $H \rightarrow \mu \tau$ decays of the Higgs boson with the ATLAS detector

The ATLAS Collaboration

Abstract

A direct search for lepton–flavour–violating (LFV) $H \rightarrow \mu \tau$ decays of the recently discovered Higgs boson with the ATLAS detector at the LHC is presented. The analysis is performed in the $H \rightarrow \mu \tau_{\text{had}}$ channel, where $\tau_{\text{had}}$ is a hadronically decaying $\tau$–lepton. The search is based on the data sample of proton–proton collisions collected by the ATLAS experiment corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a centre–of–mass energy of $\sqrt{s} = 8$ TeV. No statistically significant excess of data over the predicted background is observed. The observed (expected) 95% confidence–level upper limit on the branching fraction, $Br(H \rightarrow \mu \tau)$, is 1.85% (1.24%).

Is this coupling consistent with existing data in other channels?

What is the new physics behind this coupling?
Here we address the first question: Higgs mediated LFV processes

Figure: The $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decay.

Figure: The $\overline{Q}Q[2S+1L_J] \rightarrow \mu \tau$ decay.
Figure: The $\tau \rightarrow \mu \bar QQ^{2S+1LJ}$ decay.

Figure: The $W \rightarrow \tau \mu \pi$ decay.
Heavy Quarkonium annihilation and creation

- Non-relativistic systems: \( v \approx \alpha_s(Mv) \) three different energy scales:
  1. Quarkonium mass: \( M \) : perturbative calculations.
  2. Quarkonium inverse size: \( Mv \) : NP
  3. Quarkonium energy levels: \( Mv^2 \) : NP

- NRQCD: Systematic expansion in \( v \) and \( \alpha_s \).

- Novelty: contributions from color octet \( \bar{Q}Q \) configurations.

- Here we are interested in the order of magnitude of the BR’s. In a first approximation we consider only color singlet contributions \( \Rightarrow \) old quarkonium techniques.
The invariant amplitude for the annihilation of color-singlet quarkonium in a $^{2S+1}L_J$ angular momentum configuration $\bar{Q}Q[^{2S+1}L_J] \rightarrow X$ is given by

$$
\mathcal{M}[\bar{Q}Q[^{2S+1}L_J] \rightarrow X] = \int \frac{d^4q}{(2\pi)^4} Tr[\mathcal{O}(Q, q)\chi(Q, q)]
$$

$\mathcal{O}(Q, q)$ is the operator entering the free quarks transition

$$
\mathcal{M}[\bar{Q}(\frac{Q}{2} - q, s_2), Q(\frac{Q}{2} + q, s_1) \rightarrow X] = \bar{\nu}(\frac{Q}{2} - q, s_2)\mathcal{O}(Q, q)\nu(\frac{Q}{2} + q, s_1),
$$

and $\chi(Q, q)$ denotes the wave function for the $\bar{Q}Q[^{2S+1}L_J]$ bound state

$$
\chi(Q, q) = \sum_{M, S_z} 2\pi\delta(q^0 - \frac{q^2}{2m_Q})\psi_{LM}(q)P_{S,S_z}(Q, q)\langle LM; SS_z|JJ_z\rangle. \tag{1}
$$

---

18Kuhn et.al 1979, Guberina et.al. 1980
Here, $P_{S,S_z}$ stands for the spin projectors

$$
P_{S,S_z}(Q,q) = \sqrt{\frac{N_c}{m_Q}} \sum_{s_1,s_2} u\left(\frac{Q}{2} + q, s_1\right) \bar{v}\left(\frac{Q}{2} - q, s_2\right) \langle \frac{1}{2}s_1; \frac{1}{2}s_2|SS_z \rangle
$$

$$
= \sqrt{\frac{N_c}{8m_Q^3}} (\frac{Q}{2} + \gamma + m_Q) \left\{ \frac{\gamma^5}{\gamma(Q,S_z)} \right\} (\frac{Q}{2} + \gamma - m_Q)
$$

where $\varepsilon(Q,S_z)$ denotes the polarization vector of the spin one system.
s-wave quarkonium

Wave function is rapidly damped in the relative momentum $q$. Leading terms are given by $P_{S,S_z}(Q,0)$ and $O(Q,0)$. In the zero-binding approximation: $M \approx 2m_Q$

$$
\mathcal{M}[\bar{Q}Q^{[2S+1}S_J] \rightarrow X] = \sqrt{\frac{3|R(0)|^2}{16\pi M}} \text{Tr} \left[ O(Q,0) \left\{ \frac{\gamma^5}{\not\!q(Q,S_z)} \right\} (Q - M) \right]
$$

with $M$ denoting the quarkonium physical mass and

$$
\int \frac{d^3q}{(2\pi)^3} \psi_{00}(q) = \frac{R(0)}{\sqrt{4\pi}}.
$$
The wave function at the origin vanishes ⇒ leading terms given by the linear term in the expansion in $q$.

\[
\mathcal{M}[Q\bar{Q}[2^{S+1}P_J \rightarrow X] = -i \sum_{M,S} \langle 1M; SS_z|JJ_z \rangle \times \\
\varepsilon_\alpha(M) \sqrt{\frac{3}{4\pi}} R'(0) \text{Tr} \left[ \mathcal{O}_\alpha(Q,0) P_{S_z}(Q,0) + \mathcal{O}(Q,0) P^\alpha_{S_z}(Q,0) \right],
\]

where

\[
A^\alpha(Q, q) \equiv \frac{\partial A(Q, q)}{\partial q_\alpha}
\]

and in this case

\[
\int \frac{d^3q}{(2\pi)^3} q^\alpha \psi_{1M}(q) = -i \sqrt{\frac{3}{4\pi}} R'(0) \varepsilon_\alpha(M).
\]
The polarization vector $\varepsilon_\alpha(M)$ satisfy the following relations

$$\sum_{M,S_z}\langle 1M; 1S_z|00\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) = -g_{\alpha\beta} + \frac{Q_\alpha Q_\beta}{M^2},$$

$$\sum_{M,S_z}\langle 1M; 1S_z|1J_z\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) = -i\frac{1}{M}\sqrt{\frac{2}{\varepsilon_{\alpha\beta\mu\nu}} Q^\mu \varepsilon^\nu(J_z)},$$

$$\sum_{M,S_z}\langle 1M; 1S_z|2J_z\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) = \varepsilon_{\alpha\beta}(J_z).$$
Calculation of the $H\mu\tau$ LFV decays

Higgs-Quarkonium Coupling

\[ \frac{Q}{2} + q, s_1 \]

\[ \frac{Q}{2} - q, s_2 \]

\[ 2S+1 L_J \]

\[ Q \]

\[ H \]

In the Standard Model

\[ H \left< f \text{
\hspace{0.25cm} \begin{array}{c}
\hspace{0.25cm} \left< \bar{f} \\
\end{array}
\right. \right. \text{
\hspace{0.25cm} \begin{array}{c}
\hspace{0.25cm} f \\
\end{array} } \]

\[ g_{H\bar{f}f} = i \frac{m_f}{v} \Rightarrow \]

\[ \mathcal{O}(Q, q) = i \frac{m_Q}{v}, \]

The Higgs couples only to $^3P_0$ quarkonium

\[ \mathcal{M}[\bar{Q}Q[^3P_0] \rightarrow H] = \frac{3R'(0)}{v} \sqrt{\frac{3M}{\pi}}. \]
This coupling is proportional to $R'(0)$ which is $O(\nu^2)$ as compared with $R(0)$. Radiative decays involving $s$-wave quarkonium are of the same order!

$$H - \bar{Q}Q - \gamma \text{ coupling}$$

\[ M[H \rightarrow \bar{Q}Q[^3S_1] \gamma] = \frac{e e_Q R(0)}{\nu} \sqrt{\frac{3M}{\pi}} T_{\mu \nu} \varepsilon^\mu \eta^\nu \]

with

\[ T_{\mu \nu} = g_{\mu \nu} - \frac{Q^\mu k^\nu}{Q \cdot k}. \]
We calculate:

1. $\chi b_0 \rightarrow \mu \tau$
2. $\Upsilon \rightarrow \mu \tau \gamma$
3. $\chi c_0 \rightarrow \mu \tau$
4. $J/\psi \rightarrow \mu \tau \gamma$
5. $\tau \rightarrow \mu f_0(980)$
6. $\tau \rightarrow \mu \phi \gamma$
7. $\tau \rightarrow 3\mu$
8. $\tau \rightarrow \mu e^+ e^-$
9. $W \rightarrow \mu \tau \pi$

These decays depend on $y$ and on $|R_M(0)|^2$, $|R'_M(0)|^2$.

We extract the non-perturbative matrix elements from the $^3P_0 \rightarrow \gamma \gamma$ decays and from $^3S_1 \rightarrow e^+ e^-$ calculated in the same formalism.
Calculation of the $H \mu \tau$ LFV decays

\begin{align*}
\Gamma(Q Q[^3P_0] \rightarrow \gamma \gamma) &= \frac{432 \alpha^2 e_Q^2 |R'(0)|^2}{M^4} \\
\Gamma(Q Q[^3S_1] \rightarrow l^+ l^-) &= \frac{4 \alpha^2 e_Q^2 |R(0)|^2}{M^2}
\end{align*}

| Process               | $\Gamma_{\text{exp}}$ (GeV) | $|R(0)|^2$ (GeV$^3$) | $|R'(0)|^2$ (GeV$^5$) |
|-----------------------|-----------------------------|---------------------|----------------------|
| $\Upsilon \rightarrow e^+ e^-$ | $1.28 \times 10^{-6}$ | 4.856               | -                    |
| $J/\psi \rightarrow e^+ e^-$    | $5.54 \times 10^{-6}$ | 0.560               | -                    |
| $\phi \rightarrow e^+ e^-$      | $1.26 \times 10^{-6}$ | $5.53 \times 10^{-2}$ | -                    |
| $\chi_c^0 \rightarrow \gamma \gamma$ | $2.34 \times 10^{-6}$ | -                   | $3.10 \times 10^{-2}$ |
| $f_0 \rightarrow \gamma \gamma$  | $0.29 \times 10^{-6}$ | -                   | $1.08 \times 10^{-4}$ |

**Table:** Numerical values of the non-perturbative matrix elements extracted from the leptonic and two photon decays of quarkonia.
Branching ratios for lepton flavor violating decays involving the $H_{\mu \tau}$ coupling.

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching Ratio</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{b0} \rightarrow \mu \tau$</td>
<td>$5.5 \times 10^{-17}$</td>
<td>$&lt; 3.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Upsilon \rightarrow \mu \tau \gamma$</td>
<td>$5.7 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow \mu \tau$</td>
<td>$1.5 \times 10^{-17}$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu \tau \gamma$</td>
<td>$5.1 \times 10^{-17}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu f_0(980)$</td>
<td>$8.4 \times 10^{-12}$</td>
<td>$&lt; 3.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \phi \gamma$</td>
<td>$1.7 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow 3\mu$</td>
<td>$2.3 \times 10^{-12}$</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu e^+ e^-$</td>
<td>$7.3 \times 10^{-17}$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>$W \rightarrow \mu \tau \pi$</td>
<td>$3.2 \times 10^{-17}$</td>
<td></td>
</tr>
</tbody>
</table>

$^{28}|R'_{\chi_{b}}(0)|^2 = 1\text{GeV}^5$ from quark model calculations \cite{Likhoded2012}.
Conclusions

1. Recently, CMS measured the $H\mu\tau$ decay finding $BR(H \to \mu\tau) = 0.84^{+0.39}_{-0.37}\%$ (best fit). The $H\tau\mu$ coupling $y$ is constrained to $y \lesssim 3.6 \times 10^{-3}$.

2. $y$ induces LFV decays of quarkonium and the $\tau$ meson.

3. We calculate these processes using quarkonium NR techniques.

4. The $V \to \mu\tau$ decay width vanishes at leading order.

5. The $p$ - wave decays are far from the reach of forthcoming experiments.

6. Radiative decays of $s$-wave quarkonia are induced with branching ratios even larger than the $p$-wave non-radiative decays in the case of $\bar{b}b$.

7. All the calculated BR’s induced by the $H\mu\tau$ coupling are smaller than the upper experimental limits.

8. The most interesting process is $\tau \to \mu f_0(980)$ and deserves a closer look.
Nature of the $H_{\mu\tau}$ coupling?

GRACIAS