Lepton Flavor Violation in Quarkonium and Tau Decays

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

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

(0,0)

Boson spin=0	Mass (GeV)
H Higgs	125.6

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

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

(1/2,0), (0,1/2)

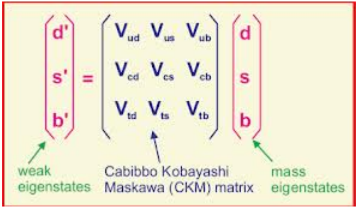
Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

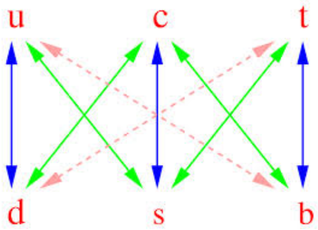
Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

(1/2,1/2)

Mixing in the quark sector

Weak interaction eigenstates differ from the mass eigenstates





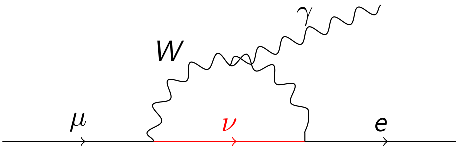
Mixing in the lepton sector

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

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{matrix} \nu_e & \leftrightarrow & \nu_\mu & \leftrightarrow & \nu_\tau \\ e & & \mu & & \tau \end{matrix}$$

Charged lepton flavor violation occurs at one loop level in the SM but it is highly suppresed.



$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2 \approx 10^{-54}$$

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: $l_i \to l_j \gamma$
  2. leptonic: $l_i \to l_j \bar{l}_k l_k$
  3. semi-leptonic: $l_i \to l_j M$, $l_i \to l_j M_1 M_2$
- $\mu - e$ conversion in nuclei
- Higgs and gauge boson decays:
  1. $Z \to l_i l_j$
  2. $H \to l_i l_j$
- Quarkonium decays:
  1. $V \to l_i l_j$

Searches for LFV processes: leptonic decays

LFV process	Present best UL (90% CL)		Future sensitivity	
$\mathcal{B}(\mu \to e\gamma)$	1.2×10^{-11}	[MEGA 1999]		
	2.8×10^{-11}	[MEG 2010]	$10^{-13} - 10^{-14}$	[MEG]
$\mathcal{B}(\tau \to e\gamma)$	3.3×10^{-8}	[BaBar 2010]	3×10^{-9}	[SuperB]
$\mathcal{B}(\tau \to \mu\gamma)$	4.4×10^{-8}	[BaBar 2010]	2.4×10^{-9}	[SuperB]
$\mathcal{B}(\mu \to ee\bar{e})$	1×10^{-12}	[SINDRUM 1988]	$10^{-13} - 10^{-14}$	[MEG]
$\mathcal{B}(\tau \to ee\bar{e})$	2.7×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to \mu\mu\bar{\mu})$	2.1×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to e\mu\bar{\mu})$	2.7×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to \mu e\bar{e})$	1.8×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]

Searches for LFV processes: $\mu - e$ conversion and Z decays

LFV process	Present best UL (90% CL)		Future sensitivity	
$\mathcal{R}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	[SINDRUM2 2004]	10^{-16}	[Mu2E (Fermilab)]
$\mathcal{R}(\mu \to e, \mathrm{Al})$			10^{-16}	[COMET (J-PARC)]
$\mathcal{R}(\mu \to e, \mathrm{Ti})$	4.3×10^{-12}	[SINDRUM2 2004]	10^{-18}	[PRISM/PRIME (J-PARC)]
$\mathcal{B}(Z \to \mu^{\pm} e^{\mp})$	1.7×10^{-6}	[LEP 1995]	2×10^{-9}	[GigaZ]
$\mathcal{B}(Z \to \tau^{\pm} e^{\mp})$	9.8×10^{-6}	[LEP 1993]	$6.5\kappa \times 10^{-8}$	[GigaZ] $\kappa \in [0.2, 1]$
$\mathcal{B}(Z \to \tau^{\pm} \mu^{\mp})$	1.2×10^{-5}	[LEP 1997]	$2.2\kappa \times 10^{-8}$	[GigaZ]

Searches for LFV processes: Quarkonium decays

$$
\begin{aligned}
B(\phi \to e\mu) &< 2.0 \times 10^{-6}, & & \\
B(J/\psi \to e\mu) &< 1.6 \times 10^{-7}, & B(J/\psi \to e\tau) &< 8.3 \times 10^{-6}, \\
B(J/\psi \to \mu\tau) &< 2.0 \times 10^{-6}, & & \\
B(\Upsilon \to \mu\tau) &< 6.0 \times 10^{-7}, & & \\
B(\Upsilon(2S) \to e\tau) &< 8.3 \times 10^{-6}, & B(\Upsilon(2S) \to \mu\tau) &< 2.0 \times 10^{-6}, \\
B(\Upsilon(3S) \to e\tau) &< 4.2 \times 10^{-6}, & B(\Upsilon(3S) \to \mu\tau) &< 3.1 \times 10^{-6},
\end{aligned}
$$

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 $\mathrm{H} \to \mu\tau_{\mathrm{e}}$ and $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ channels, where τ_{e} and τ_{h} 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 $\sqrt{s} = 8\,\mathrm{TeV}$ with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. 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 $M_{\mathrm{H}} = 125\,\mathrm{GeV}$ is 0.010. The best fit branching fraction is $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint on the branching fraction, $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95% confidence level is set. This limit is subsequently used to constrain the μ-τ Yukawa couplings to be less than 3.6×10^{-3}.

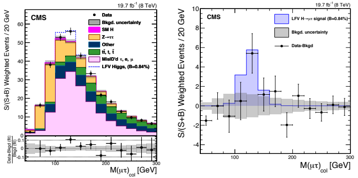


Figure 5: Left: Distribution of M_{col} for all categories combined, with each category weighted by significance $(\mathrm{S}/(\mathrm{S}+\mathrm{B}))$. The significance is computed for the integral of the bins in the range $100 < M_{\mathrm{col}} < 150\,\mathrm{GeV}$ using $\mathcal{B}(\mathrm{H} \to \mu\tau) = 0.84\%$. The MC Higgs signal shown is for $\mathcal{B}(\mathrm{H} \to \mu\tau) = 0.84\%$. The bottom panel shows the fractional difference between the observed data and the fitted background. Right: background subtracted M_{col} distribution for all categories combined.

$H\mu\tau$ coupling

$$y \lesssim 3.6 \times 10^{-3}$$

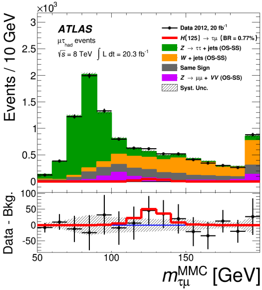
Same excess detected by ATLAS, but less sensitivity

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

The ATLAS Collaboration

Abstract

A direct search for lepton–flavour–violating (LFV) $H \to \mu\tau$ decays of the recently discovered Higgs boson with the ATLAS detector at the LHC is presented. The analysis is performed in the $H \to \mu\tau_{\text{had}}$ channel, where τ_{had} is a hadronically decaying τ–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($H \to \mu\tau$), 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

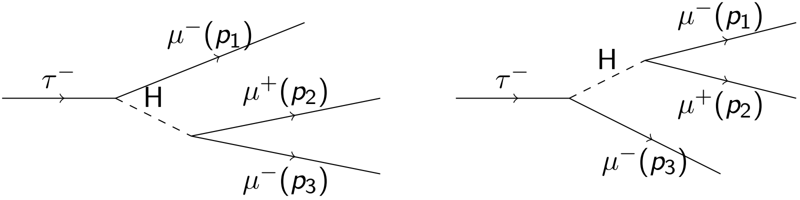


Figure: The $\tau^- \to \mu^-\mu^+\mu^-$ decay.

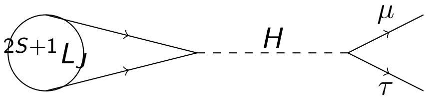


Figure: The $\overline{Q}Q[^{2S+1}L_J] \to \mu\tau$ decay.

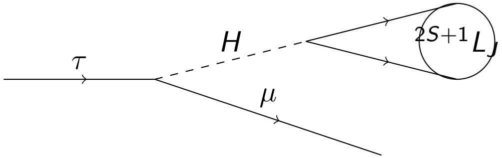


Figure: The $\tau \to \mu \overline{Q} Q[^{2S+1}L_J]$ decay.

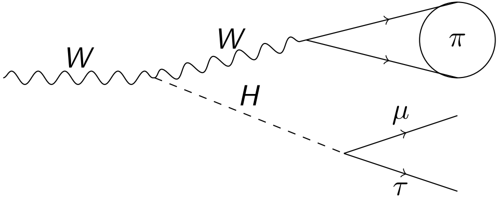


Figure: The $W \to \tau\mu\pi$ decay.

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 α_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 $\overline{Q}Q[{}^{2S+1}L_J] \to X$ is given by [18]

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

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

$$\mathcal{M}[\overline{Q}(\frac{Q}{2}-q,s_2),Q(\frac{Q}{2}+q,s_1) \to X] = \overline{v}(\frac{Q}{2}-q,s_2)\mathcal{O}(Q,q)u(\frac{Q}{2}+q,s_1),$$

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

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

[18] Kuhn et.al 1979, Guberina et.al. 1980

Here, P_{S,S_z} stands for the spin projectors

$$P_{S,S_z}(Q,q) = \sqrt{\frac{N_c}{m_Q}}\sum_{s_1,s_2} u(\frac{Q}{2}+q,s_1)\overline{v}(\frac{Q}{2}-q,s_2)\langle\frac{1}{2}s_1;\frac{1}{2}s_2|SS_z\rangle$$
$$= \sqrt{\frac{N_c}{8m_Q^3}}(\frac{\not{Q}}{2}+\not{q}+m_Q)\left\{\begin{array}{c}\gamma^5\\ \not{\varepsilon}(Q,S_z)\end{array}\right\}(\frac{\not{Q}}{2}+\not{q}-m_Q)$$

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 $\mathcal{O}(Q,0)$. In the zero-binding approximation: $M \approx 2m_Q$

$$\mathcal{M}[\overline{Q}Q[^{2S+1}S_J] \to X] = \sqrt{\frac{3|R(0)|^2}{16\pi M}}\, Tr\left[\mathcal{O}(Q,0)\left\{\begin{array}{c}\gamma^5 \\ \not{\epsilon}(Q,S_z)\end{array}\right\}(\not{Q}-M)\right] \text{fo}$$

with M denoting the quarkonium physical mass and

$$\int \frac{d^3q}{(2\pi)^3}\psi_{00}(\mathbf{q}) = \frac{R(0)}{\sqrt{4\pi}}.$$

p-wave quarkonium

The wave function at the origin vanishes ⇒ leading terms given by the linear term in the expansion in q.

$$\mathcal{M}[\overline{Q}Q[^{2S+1}P_J] \to X] = -i \sum_{M,S_z} \langle 1M; SS_z | JJ_z \rangle \times$$

$$\varepsilon_\alpha(M) \sqrt{\frac{3}{4\pi}} R'(0)\, Tr \left[\mathcal{O}^\alpha(Q,0) P_{S,S_z}(Q,0) + \mathcal{O}(Q,0) P^\alpha_{S,S_z}(Q,0) \right],$$

where

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

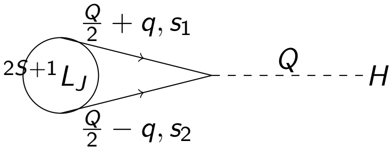
and in this case

$$\int \frac{d^3q}{(2\pi)^3} q^\alpha \psi_{1M}(\mathbf{q}) = -i \sqrt{\frac{3}{4\pi}} R'(0) \varepsilon_\alpha(M).$$

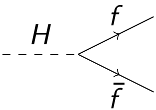
The polarization vector $\varepsilon_\alpha(M)$ satisfy the following relations

$$
\begin{aligned}
\sum_{M,S_z} \langle 1M;1S_z|00\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) &= -g_{\alpha\beta} + \frac{Q_\alpha Q_\beta}{M^2}, \\
\sum_{M,S_z} \langle 1M;1S_z|1J_z\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) &= \frac{-i}{M}\frac{1}{\sqrt{2}}\varepsilon_{\alpha\beta\mu\nu}Q^\mu\varepsilon^\nu(J_z), \\
\sum_{M,S_z} \langle 1M;1S_z|2J_z\rangle \varepsilon_\alpha(M)\varepsilon_\beta(S_z) &= \varepsilon_{\alpha\beta}(J_z).
\end{aligned}
$$

Higgs-Quarkonium Coupling



In the Standard Model



$g_{H\bar{f}f} = i\frac{m_f}{v} \quad \Rightarrow$

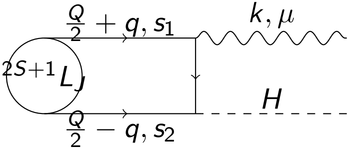
$$\mathcal{O}(Q,q) = i\frac{m_Q}{v},$$

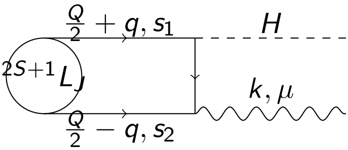
The Higgs couples only to $^3P_0$ quarkonium

$$\mathcal{M}[\overline{Q}Q[^3P_0] \to H] = \frac{3R'(0)}{v}\sqrt{\frac{3M}{\pi}}. \tag{2}$$

This coupling is proportional to $R'(0)$ which is $\mathcal{O}(v^2)$ as compared with $R(0)$.
Radiative decays involving s-wave quarkonium are of the same order!

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





$$\mathcal{M}[H \to \overline{Q}Q[^3S_1]\gamma] = \frac{ee_Q R(0)}{v}\sqrt{\frac{3M}{\pi}}\, T_{\mu\nu}\varepsilon^{\mu}\eta^{\nu}$$

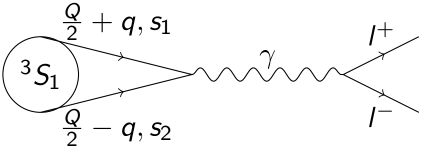
with

$$T_{\mu\nu} = g_{\mu\nu} - \frac{Q^{\mu}k^{\nu}}{Q \cdot k}.$$

We calculate:

1. $\chi_{b0} \to \mu\tau$
2. $\Upsilon \to \mu\tau\gamma$
3. $\chi_{c0} \to \mu\tau$
4. $J/\psi \to \mu\tau\gamma$
5. $\tau \to \mu f_0(980)$
6. $\tau \to \mu\phi\gamma$
7. $\tau \to 3\mu$
8. $\tau \to \mu e^+e^-$
9. $W \to \mu\tau\pi$

These decays depend on y and on $|R_M(0)|^2$, $|R'_M(0)|^2$.
We extract the non-perturbative matrix elements from the $^3P_0 \to \gamma\gamma$ decays and from $^3S_1 \to e^+e^-$ calculated in the same formalism.



$$\Gamma(\overline{Q}Q[^3P_0] \to \gamma\gamma) = \frac{432\alpha^2 e_Q^2 |R'(0)|^2}{M^4}$$

$$\Gamma(\overline{Q}Q[^3S_1] \to l^+l^-) = \frac{4\alpha^2 e_Q^2 |R(0)|^2}{M^2}$$

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

Process	Branching Ratio	Upper limit
$\chi_{b0} \to \mu\tau$	5.5×10^{-17} [28]	
$\Upsilon \to \mu\tau\gamma$	5.7×10^{-14}	
$\chi_{c0} \to \mu\tau$	1.5×10^{-17}	
$J/\psi \to \mu\tau\gamma$	5.1×10^{-17}	
$\tau \to \mu f_0(980)$	8.4×10^{-12}	$< 3.4 \times 10^{-8}$
$\tau \to \mu\phi\gamma$	1.7×10^{-14}	
$\tau \to 3\mu$	2.3×10^{-12}	$< 2.1 \times 10^{-8}$
$\tau \to \mu e^+ e^-$	7.3×10^{-17}	$< 1.8 \times 10^{-8}$
$W \to \mu\tau\pi$	3.2×10^{-17}	

[28] $|R'_{\chi_b}(0)|^2 = 1 GeV^5$ from quark model calculations [*Likhoded 2012*]

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 τ 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?

$\mathcal{GRACIAS}$