Search for Lepton Flavor Violation in Bottomonium Decays

Sourav Patra*, Vishal Bhardwaj*, Karim Trabelsi**

*IISER Mohali, India
**IJCLab Orsay, France

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• Lepton family number is an accidental symmetry in SM. It appears in higher order corrections.

• Charged lepton flavor violating processes are suppressed in SM by the quantity $(\Delta m^2/M_W^2)^2 \sim 10^{-54}$.

• With several extension to SM including SUSY and leptoquarks models, it is predicted that lepton flavor is NOT a universal conserved quantity.

• Even if no significant is found, NP parameters can be constrained with the precise measurement of CLFV transitions in $\Upsilon(nS)$ decays.

\[ \Upsilon(1S) \rightarrow \mu^+\tau^- \]

CLEO $6.0 \times 10^{-6} \ @ 95\% \ CL$

Resonance | CLEO (fb⁻¹) | BaBar (fb⁻¹) | Belle (fb⁻¹)
--- | --- | --- | ---
ϒ(1S) | 1.1 | -- | 6
ϒ(2S) | 1.3 | 14 | 25
ϒ(3S) | 1.4 | 30 | 3

Belle Experiment

Beam crossing angle: 22 mrad

Belle Detector

1.3 million $\bar{B}B$ pairs / day
Total $\sim 770 \times 10^6$ $\bar{B}B$ pairs
For $\Upsilon(1S) \rightarrow e\mu$ decay, we extract the signal with the mass difference between $\Upsilon(2S)$ and $\Upsilon(1S)$, $\Delta M$.

$$\Delta M = M_{\Upsilon(2S)} - M_{\Upsilon(1S)}$$

For extracting the signal for $\Upsilon(1S) \rightarrow \mu\tau/\eta\tau$ decays, we look at the recoil mass of $\pi\pi e/\pi\pi\mu$ $[M_{\text{recoil}}(\pi\pi\ell)]$ which should peak at the tau mass.

$$M_{\text{recoil}}(\pi\pi\ell) = [(E_{CM} - E^*_{\pi\ell})^2 - (p^*_{\pi\ell})^2]^{1/2}$$

To reduce the background coming from the $\Upsilon(1S) \rightarrow \mu\mu/ee$ the decays we choose the following $\tau$ channels.

- $\Upsilon(1S) \rightarrow \mu\tau, \tau \rightarrow e\nu\nu$
- $\Upsilon(1S) \rightarrow \eta\tau, \tau \rightarrow \mu\nu\nu$
Event selection

$\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S) \rightarrow e\mu/\mu\tau/e\tau$

Charged track selections:
- $|dr| < 1\text{ cm}$, $|dz| < 3.5\text{ cm}$

Pion selection:
- Pion Vs Kaon likelihood > 0.6

Lepton selection:
- Muon selection likelihood ($L_{\mu}$) > 0.1
- Electron selection likelihood ($L_e$) > 0.1

$\tau$ selection for $\Upsilon(1S) \rightarrow \mu\tau/e\tau$:
- $\tau \rightarrow l\nu\nu ::$
  - $L_e > 0.1$ and $L_{\mu} > 0.1$

- $\tau \rightarrow \pi\pi\pi\nu ::$
  - Pion vs Kaon likelihood > 0.6
  - Number of pions < 8
  - $M_{\pi\pi\pi} < 1.8\text{ GeV}/c^2$, $E_{\pi\pi\pi} > 2.6\text{ GeV}$
  - $\chi^2_{vtx} < 15$ (accept 99% of the signal events)
Mass of $\Upsilon(1S)$

$\Upsilon(1S) \rightarrow e\mu$

Search window:
- $L_\mu > 0.95$
- $L_e > 0.6$

Selected region:
- $9.09 < M_{\Upsilon(1S)} < 9.65 \text{ GeV/c}^2$

Efficiency:
- Signal rejection – 9 %
- Background rejection – 34%
Continuum background rejection

$\Upsilon(1S) \rightarrow e\mu$

<table>
<thead>
<tr>
<th>Signal MC</th>
<th>Generic MC</th>
<th>$\Upsilon(4S)$ off-resonance</th>
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</thead>
</table>

Selected region:
- Momentum of $\Upsilon(1S)$ ($P_{\Upsilon(1S)} < 4.4$ GeV/c)

Efficiency:
- Signal rejection < 1 %
- Background rejection – 37 %

Search window:
- $L_{\mu} > 0.95$
- $L_e > 0.6$
- $9.09 < M_{\Upsilon(1S)} < 9.65$ GeV/c$^2$
- $N_\mu = 1$, $N_e = 1$
• Signal efficiency 35 %.

• Using Frequentist method, UL of branching fraction at 90 % CL is expected to be \(~10^{-7}\).
Lepton beam momentum (p_{beam}^\mu)

\(\Upsilon(1S)\rightarrow\mu\tau\)

Ratio of momentum of muon (p_{\mu}) with half of the recoil energy of two pion from \(\Upsilon(2S)\) [E_{recoil}(\pi\pi)] in the lab frame.

\[
p_{\mu,\text{beam}} = 2p_{\mu}/E_{\text{recoil}}(\pi\pi)
\]

Selected region:
- \(p_{\mu,\text{beam}} > 0.6\)

Efficiency:
- Signal rejection – 1.5 %
- Background rejection – 86%
Angle between two pions \((\cos\theta^*_{\pi\pi})\)

\(\Upsilon(1S)\rightarrow\mu\tau\)

Search window:
- \(L^\mu > 0.95\)
- \(p^\mu_{\text{beam}} > 0.6\)
- \(N^\mu = 1\)

Selected region:
- Cosine of angle between two pions in \(\Upsilon(2S)\) frame \((\cos\theta^*_{\pi\pi}) < 0.8\)

Efficiency:
- Signal rejection < 1%
- Background rejection – 28%
Background fit
\( \Upsilon(1S) \rightarrow \mu \tau \)

\[
L(x; m, \sigma, a, b, Fr^\tau, M_{th}) = \frac{e^{-N}}{N!} \prod_{i=1}^{N} \left[ \left( 1 - Fr^\tau \right) \exp \left( \frac{-(x - m)^2}{2 \sigma^2} \right) + Fr^\tau \exp \left( a(x - M_{th}) + b(x - M_{th})^2 \right) \right]
\]
Simultaneous fit is performed for $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \pi\pi\nu \nu$ modes.

Using Frequentist method, UL of branching fraction at 90% CL is expected to be $\sim 10^{-6}$. 
Simultaneous fit is performed for $\tau \rightarrow \mu \nu \nu$ and $\tau \rightarrow \pi \pi \nu \nu$ modes.

Using Frequentist method, UL of branching fraction at 90 % CL is expected to be $\sim 10^{-6}$. 
CLFV decays are deeply suppressed in the SM. Observation of any CLFV transition would be a clear signal for new physics.

We perform a blind analysis for the CLFV transitions in $\Upsilon(1S)$ decays.

Expected upper limits for $\Upsilon(1S) \rightarrow e\mu, \mu\tau, e\tau$ decays @ 90% CL are expected to be $\sim 10^{-7}, 10^{-6}, 10^{-6}$.

The study is under internal review and we hope to finalize soon.

Thank You